Status and Prospects for Hadron Production Experiments

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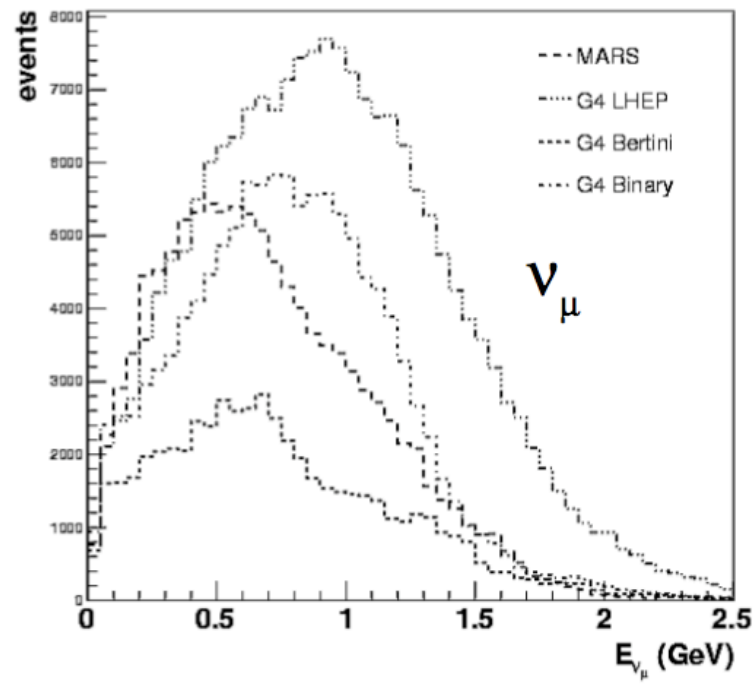
Outline

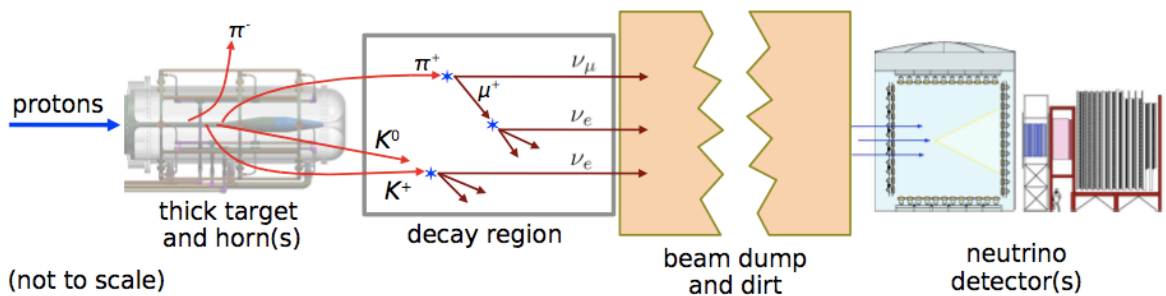
- Motivations
- Experiments
- Results
  - Accelerator-based neutrino beams
  - Advanced neutrino sources
  - Atmospheric neutrinos
- Future Prospects

Motivations

- Neutrino sources from hadron interactions: accelerators, cosmic rays
- Hadron production uncertainties have big impact on the energy, composition, geometry of the neutrino beam
- Various models of Monte Carlo generators are used: show large differences in ν rate predictions
- $\pi^{\pm}$, $K^{\pm}$ production to fully understand (anti-)ν_μ, (anti-)ν_e fluxes (appearance, disappearance)
- Design parameters of future neutrino beams influenced by target/energy choice
- Vital to calibrate neutrino production targets in a proton beam



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



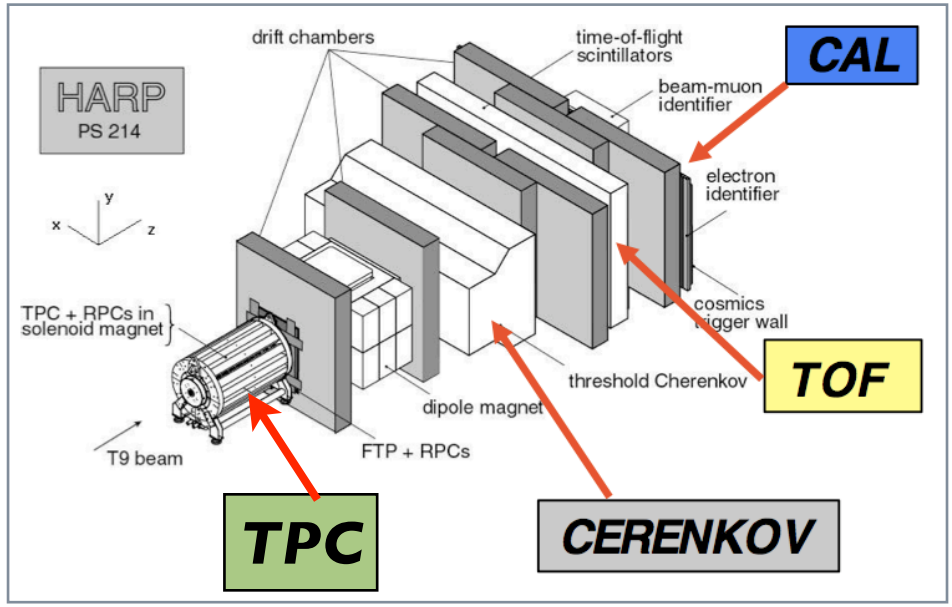
Motivations

		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	(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

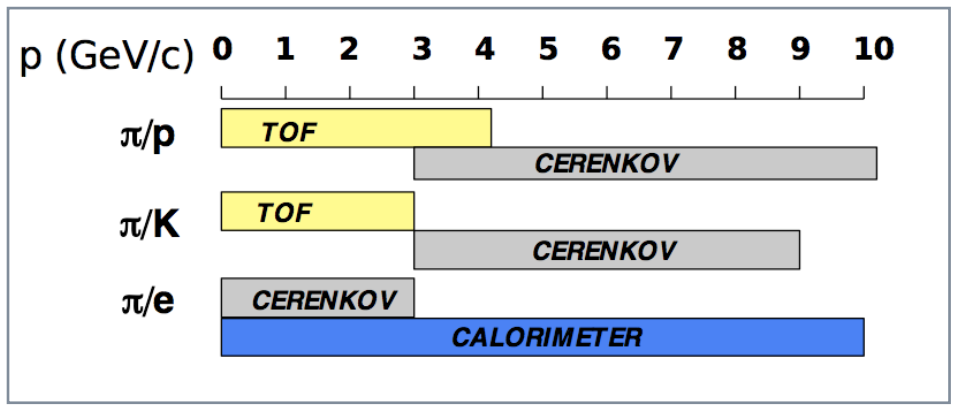
The Experiments

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

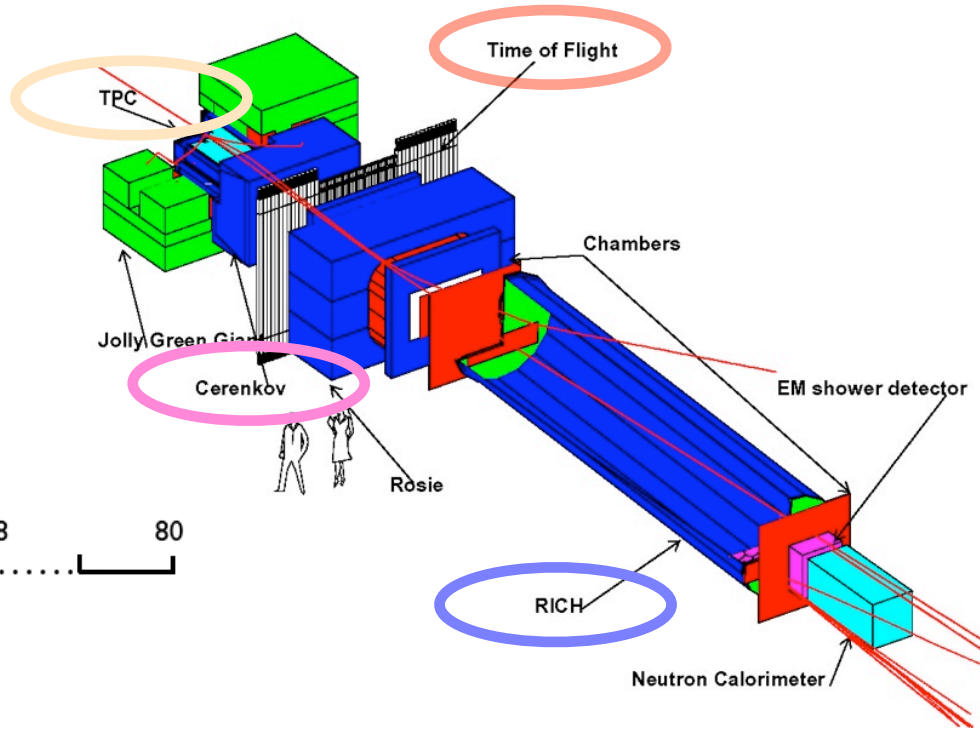


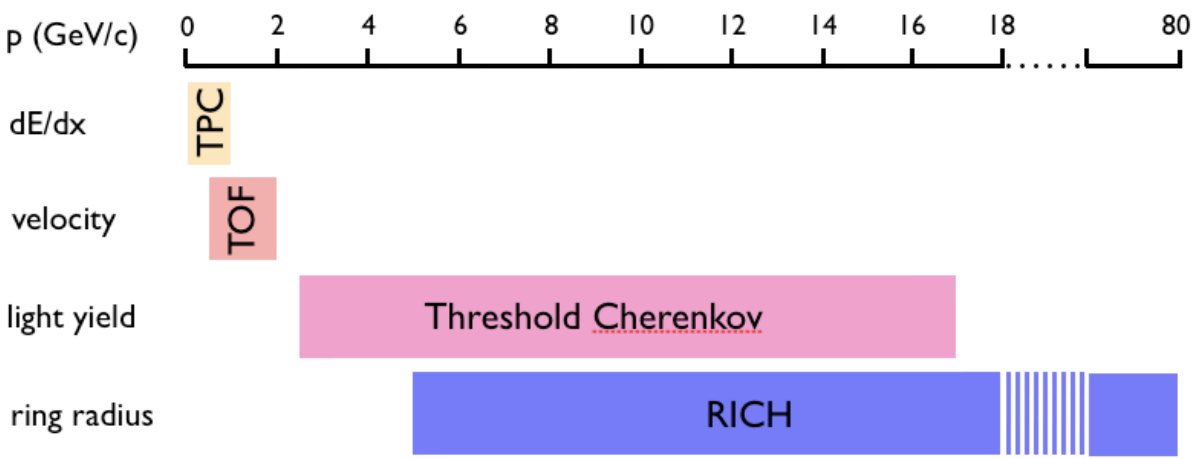
- Large-Angle Spectrometer
  $0.1 \leq p \leq 0.8$ GeV/c
  $350 \leq \theta \leq 2150$ mrad
  - track reconstruction & PID with solenoid magnet + TPC + RPCs

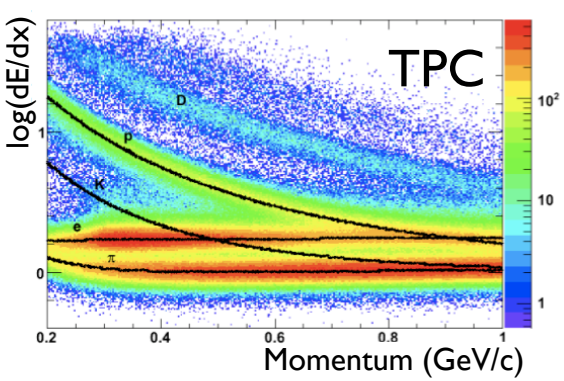


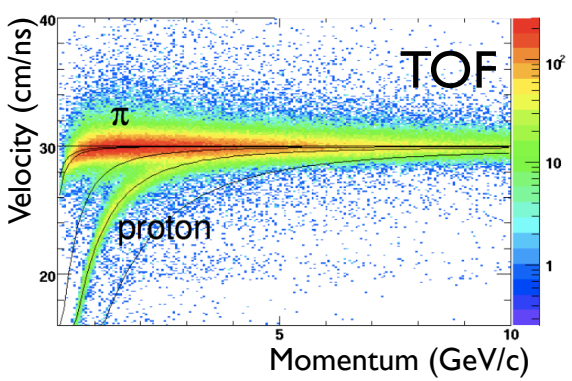
The MIPP detector

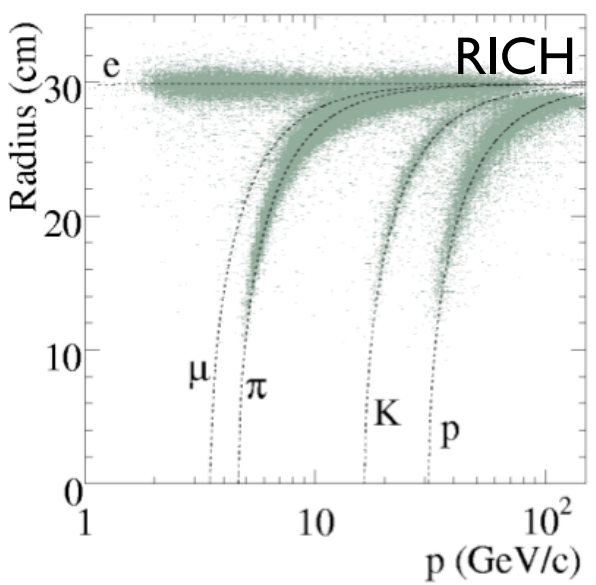
- Track Reconstruction:
  - Two dipole magnets deflecting in opposite direction
  - TPC + drift chambers + MWPCs
- Particle Identification







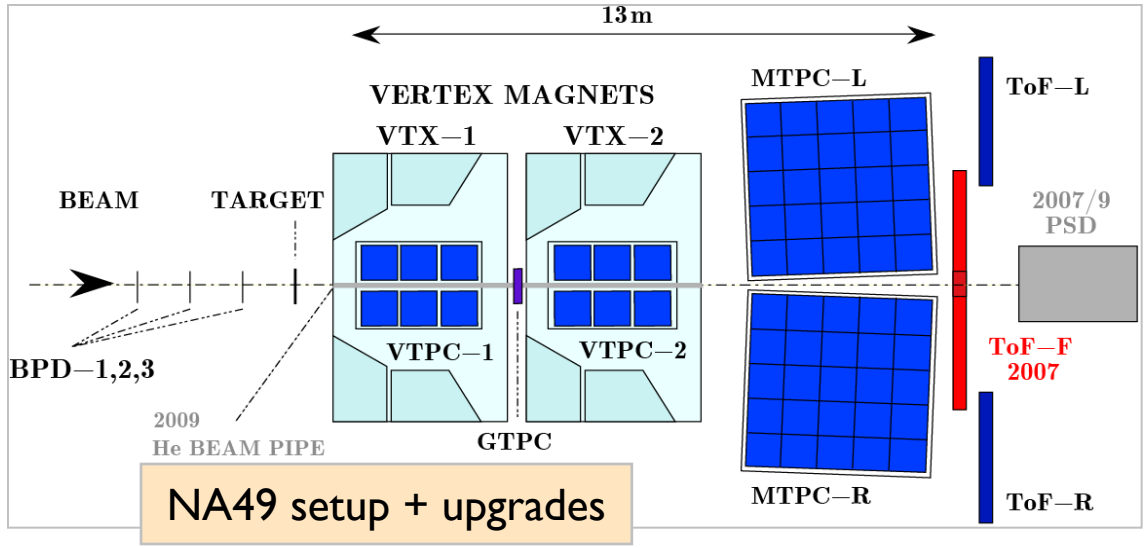


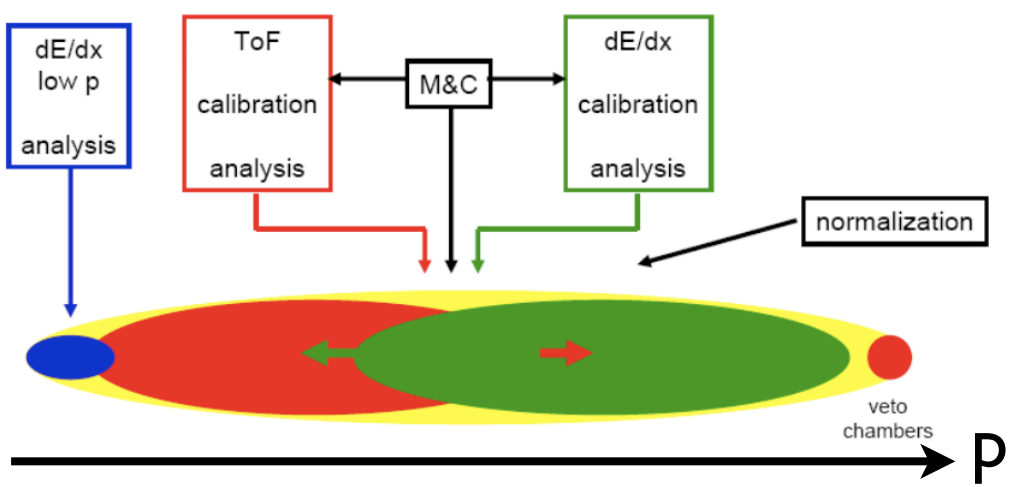


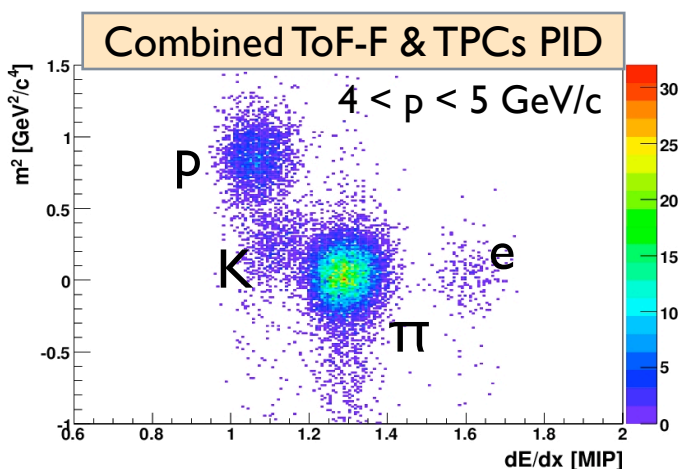
NA61 detector

- 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!





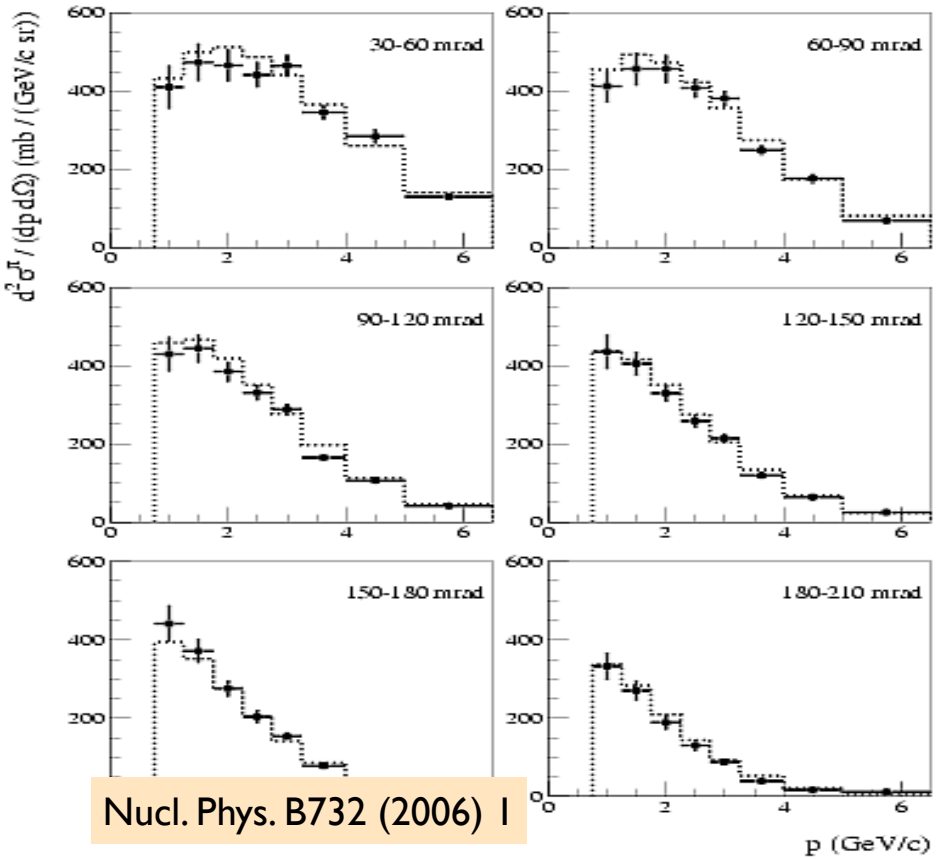


Studies for Accelerator-based Neutrino Beams

K2K

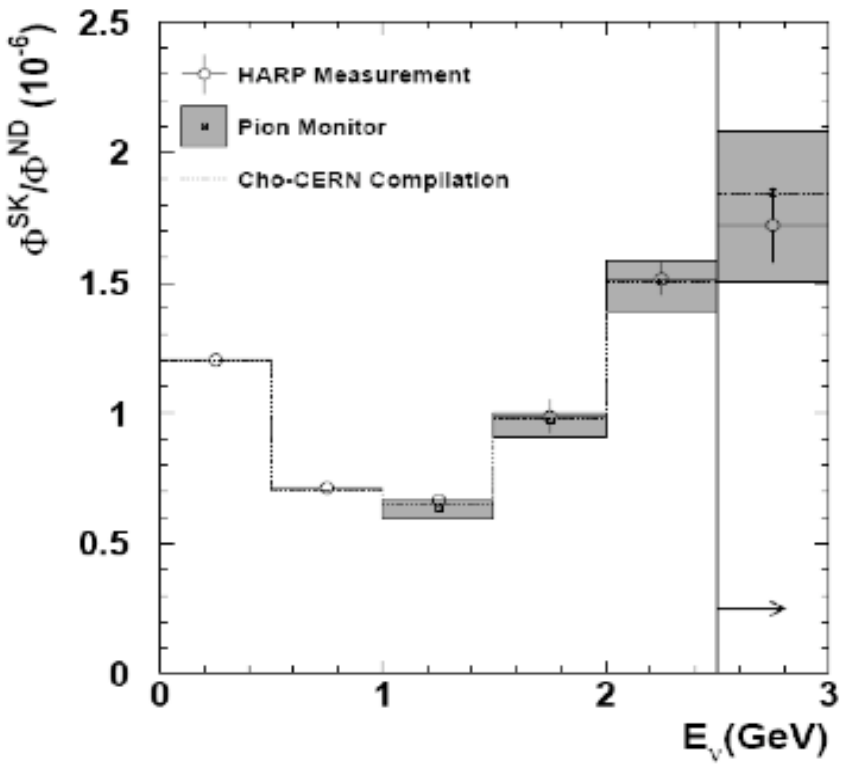
HARP

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

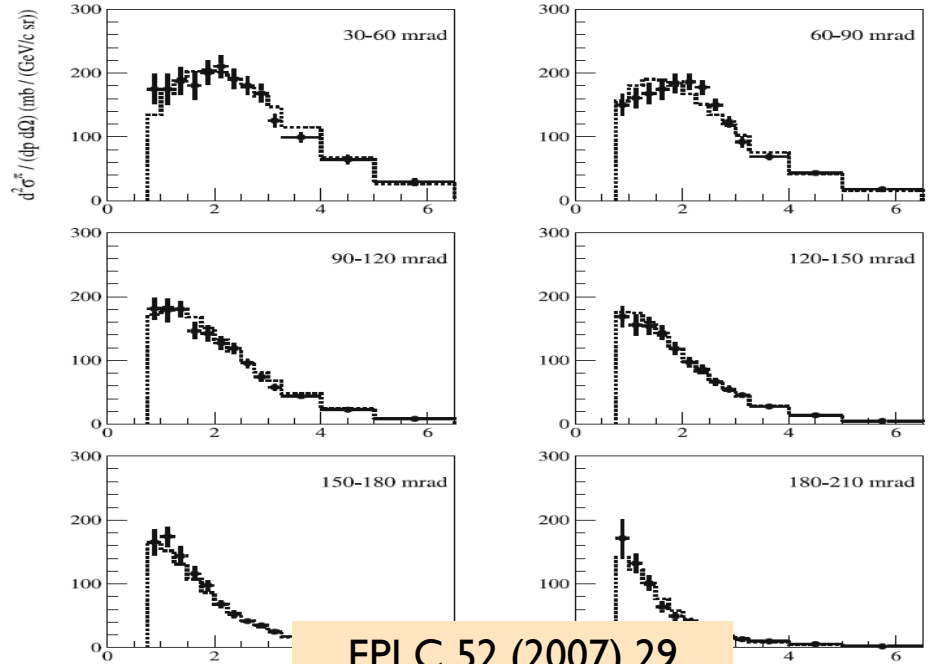
Phys. Rev. D74 (2006) 072003

MiniBooNE

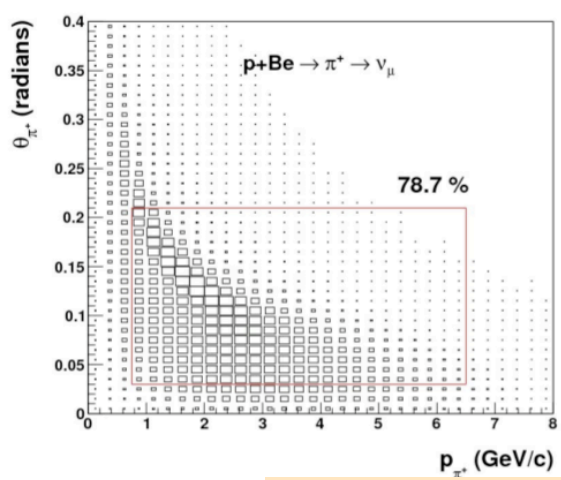
HARP

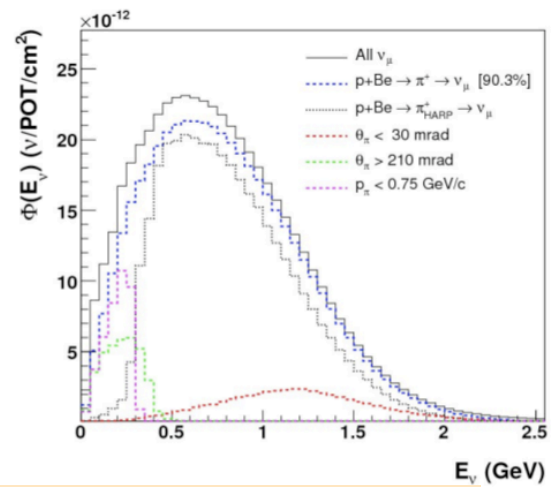
p(8.9 GeV/c) + Be → π^+ + X

- 5% λ, same (beam, target material) as FNAL Booster Neutrino Beam
- π^- preliminary data useful for ongoing BNB antineutrino run
- proton data to describe re-interaction effects in BNB thick target



EPJ C 52 (2007) 29



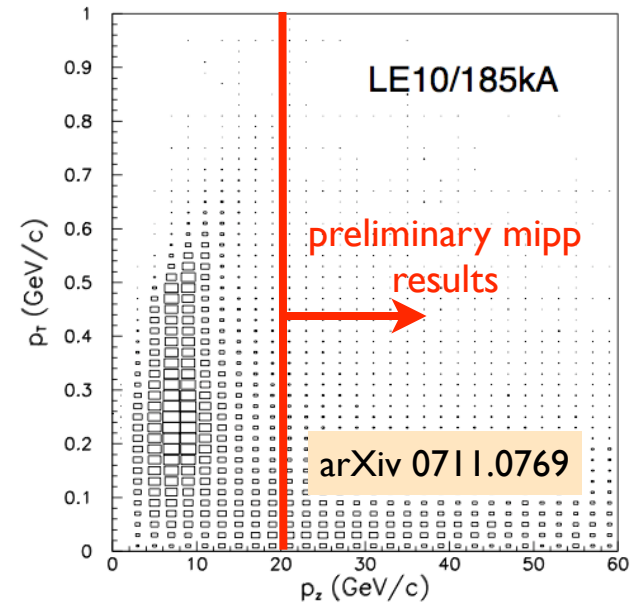


D. Schmitz, PhD Thesis, Columbia U. (2008)

MINOS

MIPP

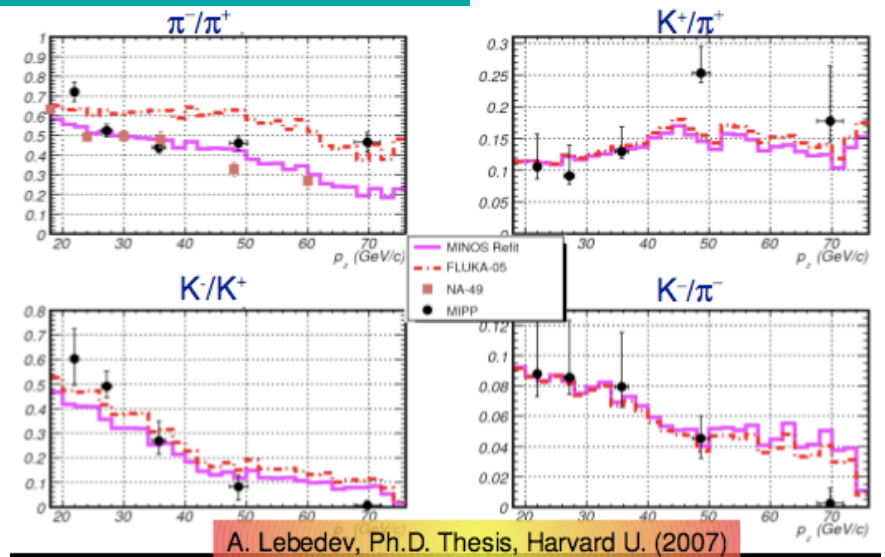
- Hadron production constrained in two ways
  1. MINOS near spectrum fit
  2. Hadron production data
- MIPP
  - Preliminary results cover high E_ν
  - NuMI beam momentum: 120 GeV/c
  - Both NuMI replica and thin C targets
  - Preliminary: fully corrected $\pi^\pm$, $K^\pm$ particle yields ratios only ($p_t < 0.2$ GeV/c)
  - $K^\pm$ important for MINOS $\nu_\mu \rightarrow \nu_e$



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

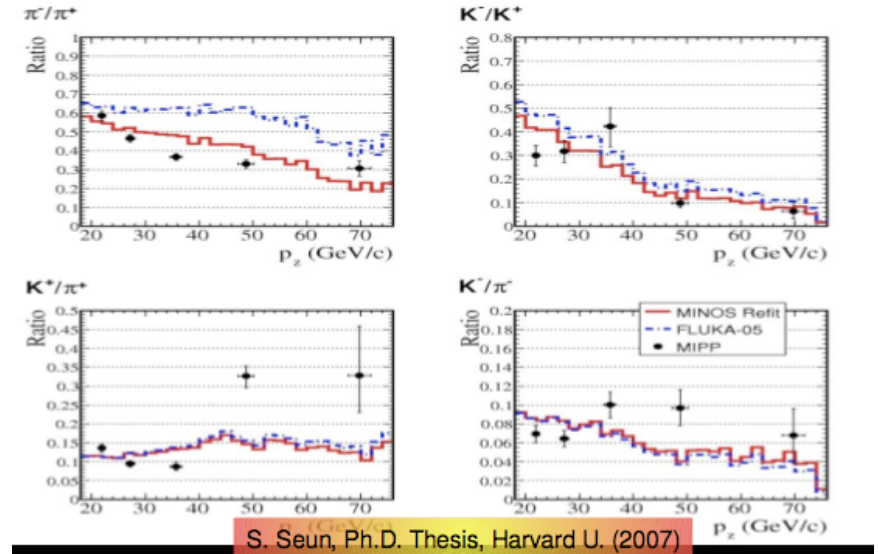
$p(120\ \text{GeV/c}) + C \rightarrow \pi^\pm, K^\pm$

Thin C target



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

NuMI target



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

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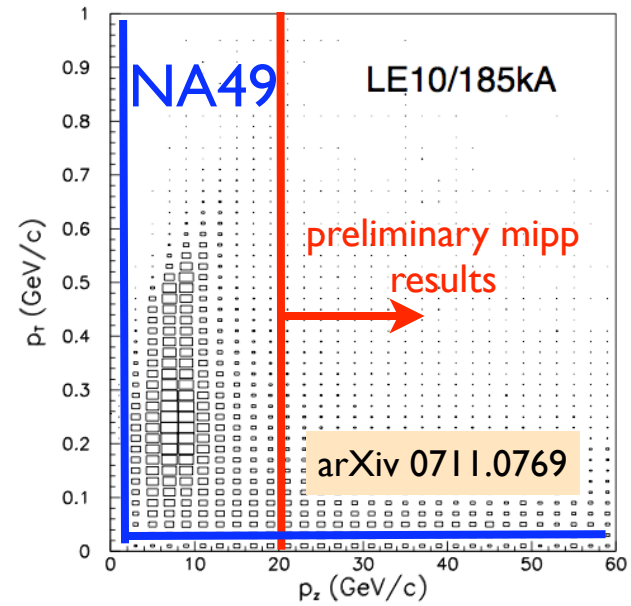

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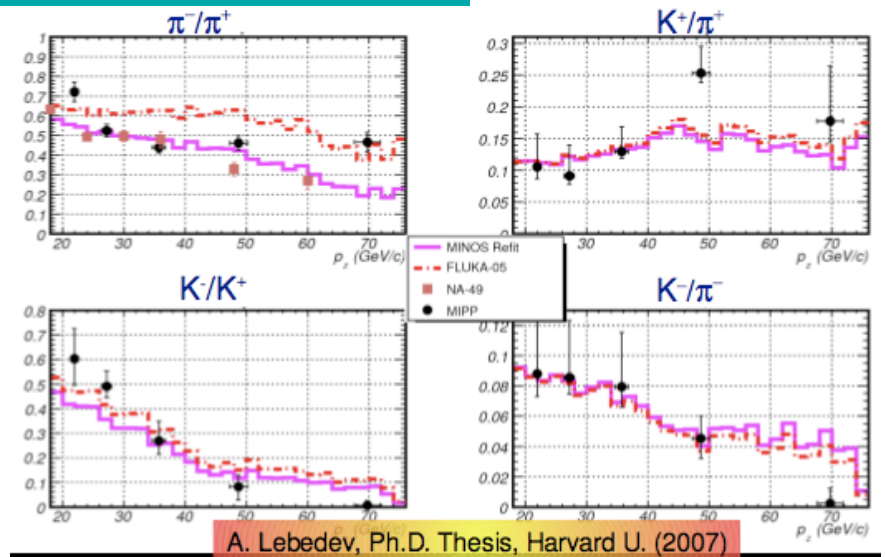
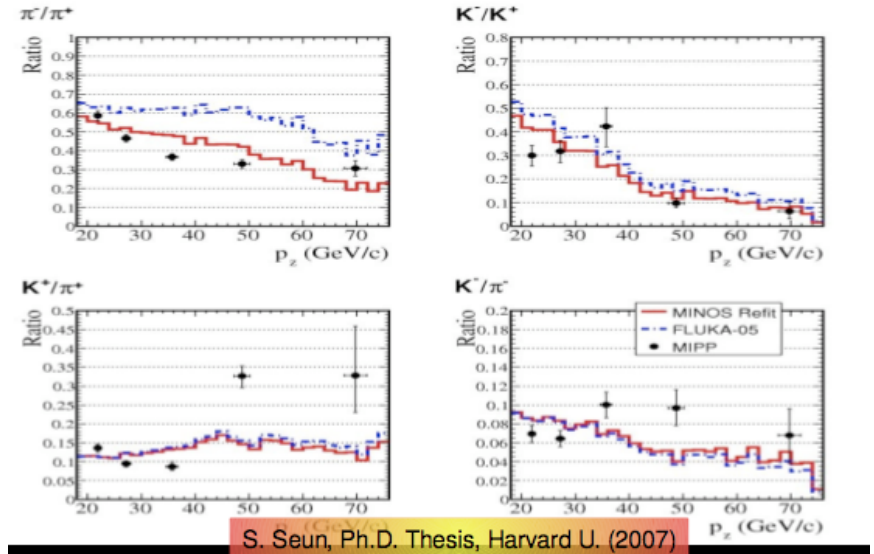


A. Lebedev, Ph.D. Thesis, Harvard U. (2007)

NuMI target



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

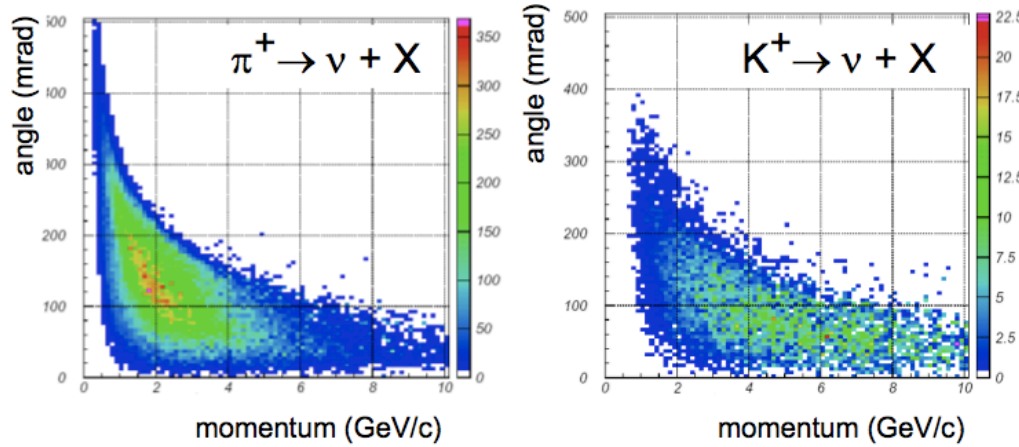
T2K off-axis

NA61

p(31 GeV/c) + C → $\pi^{\pm}$, $K^{\pm}$

- Targets:
  - T2K 190% λ replica target
  - Thin 4% λ C
- Goals:
  - predict the far-to-near ratio to 3%
  - predict neutrino flux to 5%

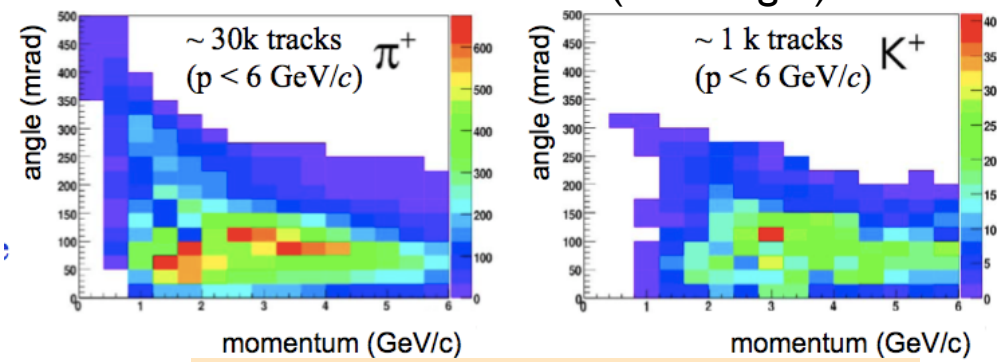
Simulated distribution of π, K contributing to ν flux @ SK



CERN-SPS-2007-019

- 2007 run (30 days) trigger counts:
  - ~230k (T2K replica)
  - ~670k (thin target)
- NA61 has requested acceptance and PID capability to fully cover T2K ν parent beam phase space!

NA61 Data 2007 (thin target)



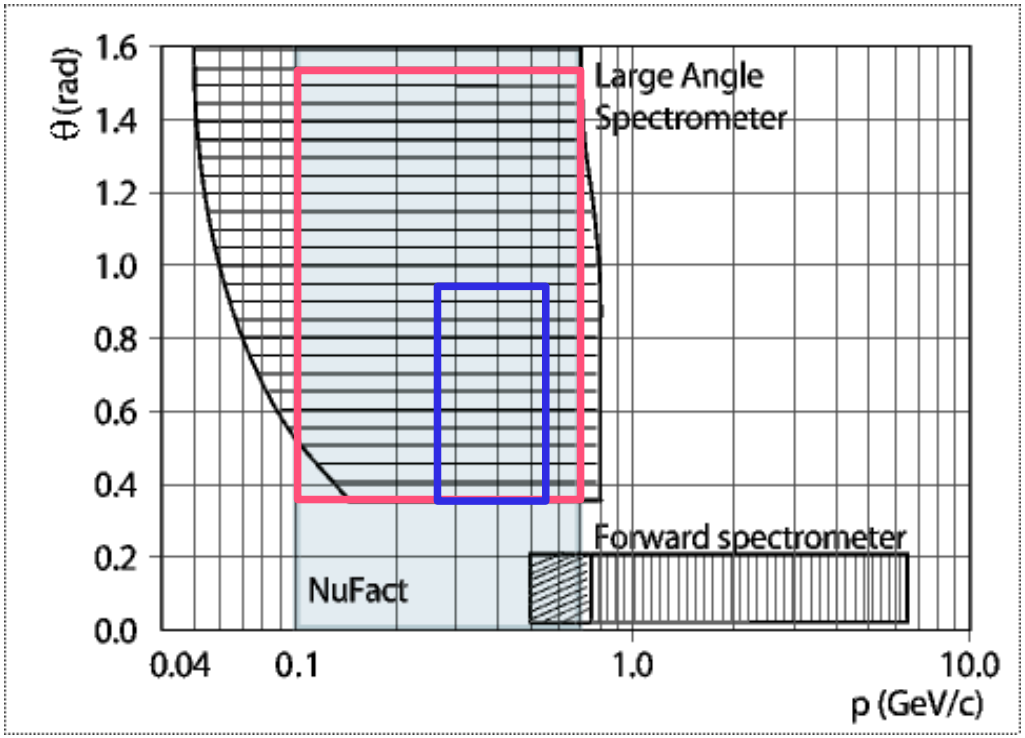
CERN-SPS-2008-018 / SPSC-SR-033

Studies for Advanced Neutrino Sources

NuFact

HARP

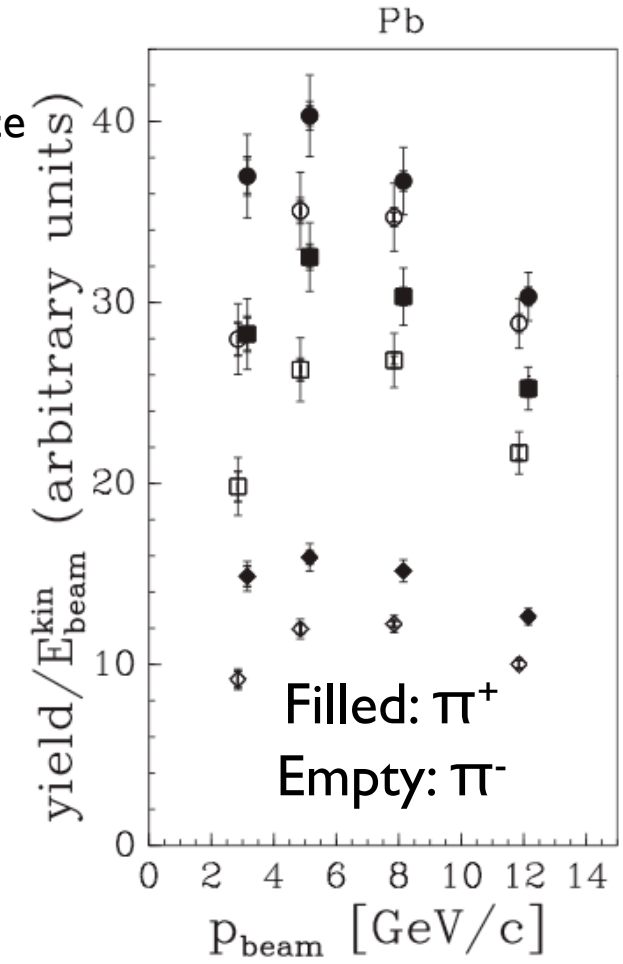
$p + Pb \rightarrow \pi^{\pm} + X$



Full forward acceptance

$350 < \theta < 950$ mrad

$0.25 < p < 0.50$ GeV/c



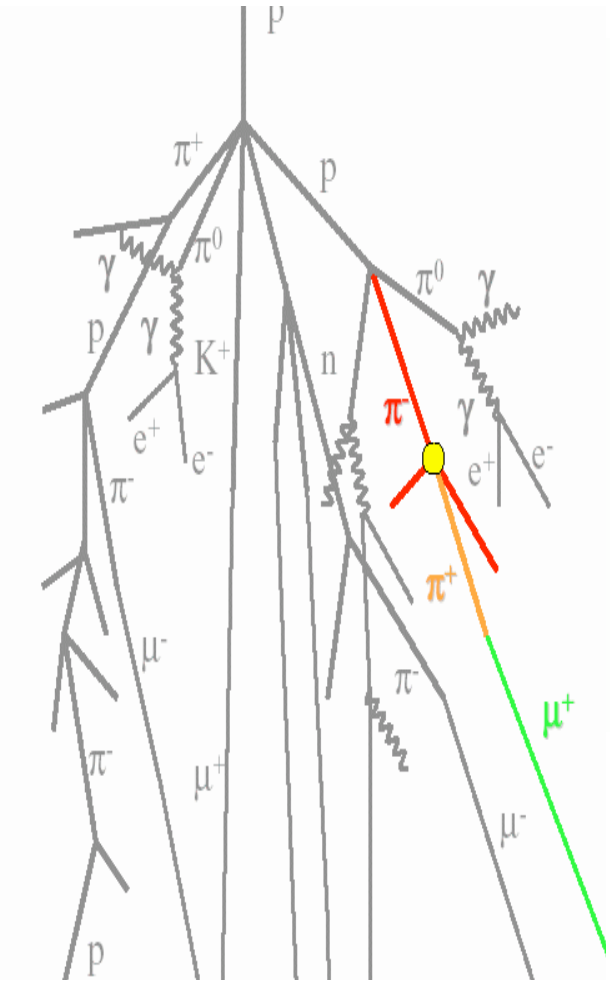
EPJC 54, 37 (2008)

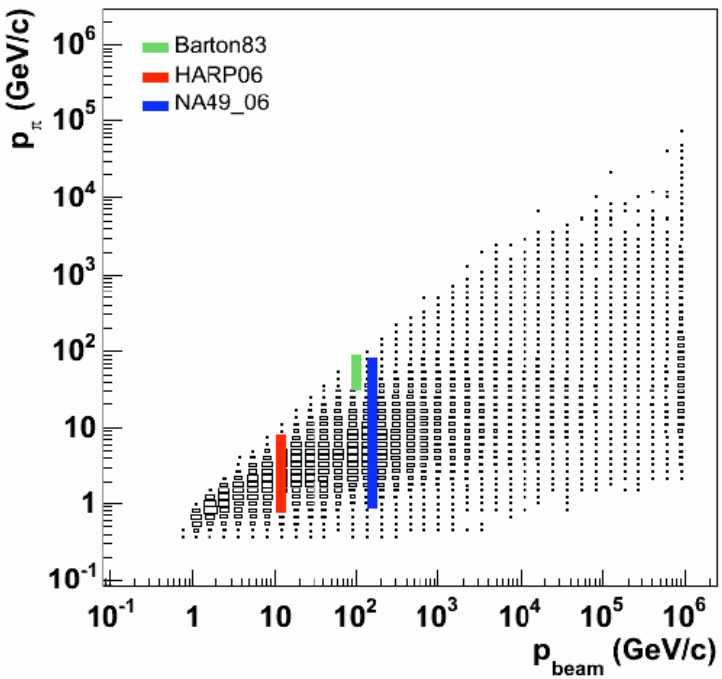
- Pion yield normalized to beam proton kinetic energy
- Restricted phase space most representative for NuFact design
- Optimum yield in HARP kinematic coverage for 5-8 GeV/c beam momenta
- Confirms Ta target results EPJC 51, 787 (2007)
- Quantitative optimization possible using full spectra range available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

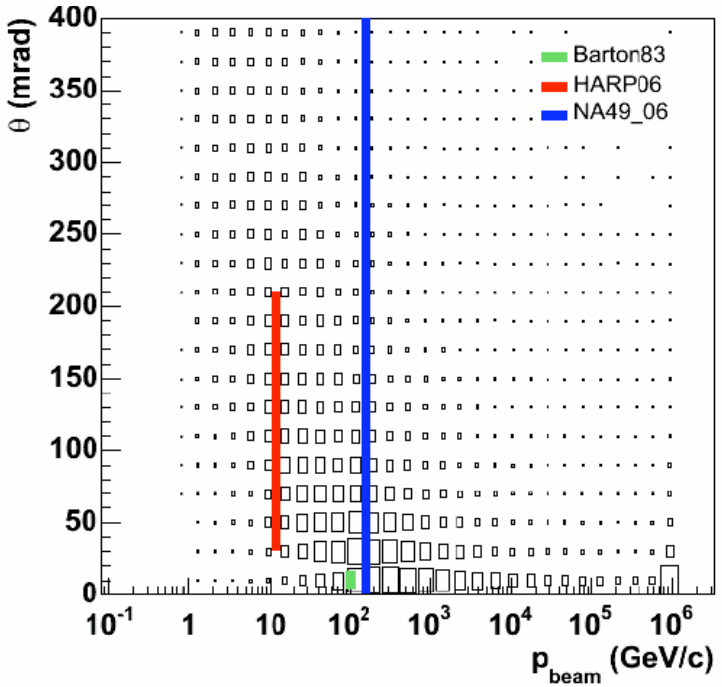
73	80	82
Ta	Hg	Pb

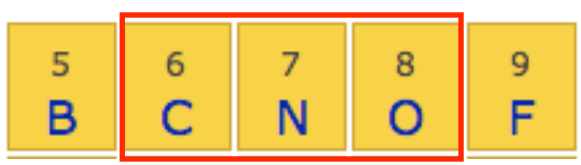
Atmospheric Neutrinos

Atmospheric Neutrinos







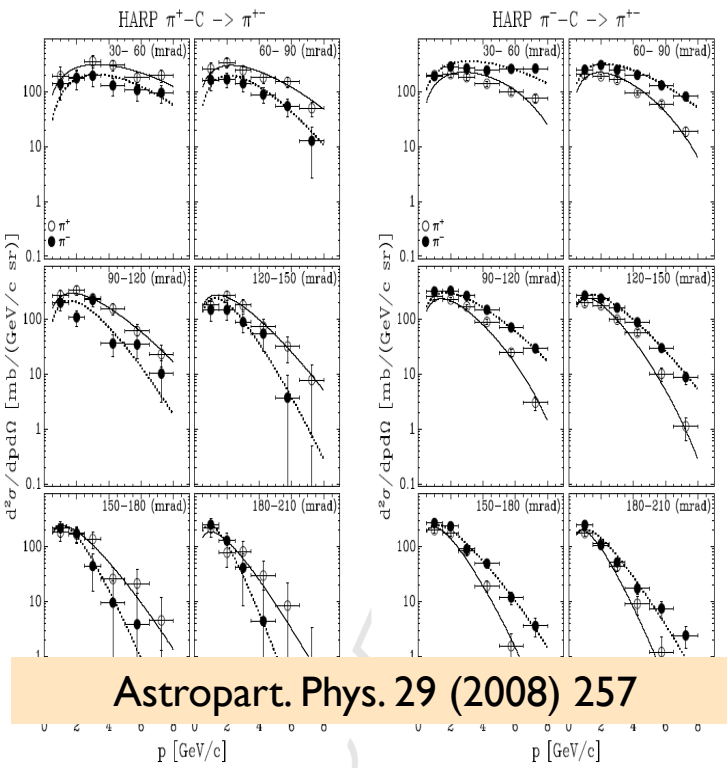


78% nitrogen
21% oxygen

- 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

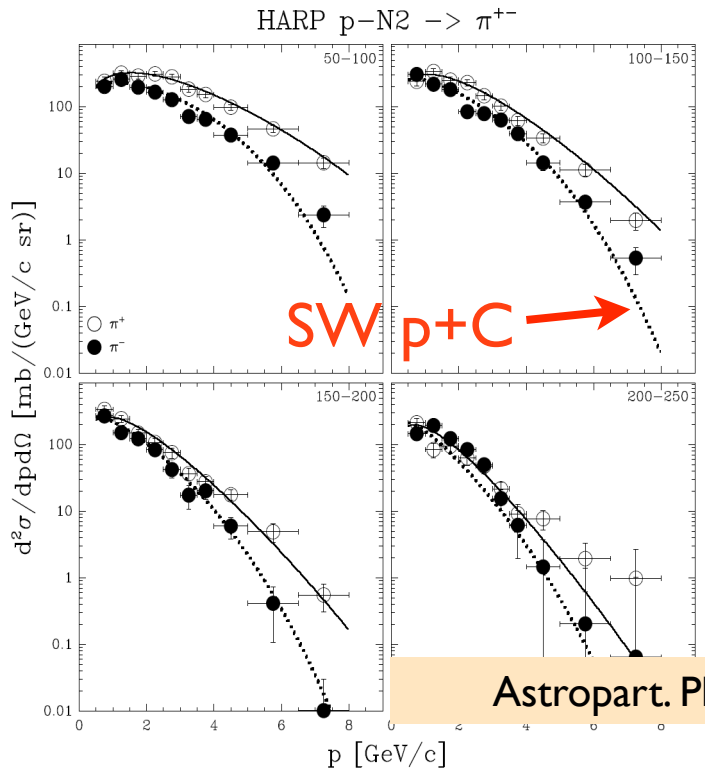
HARP

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

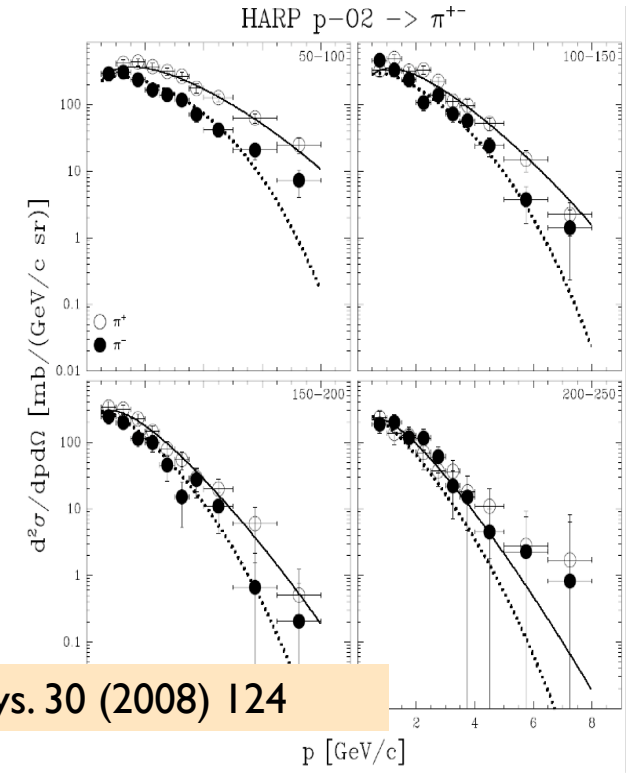


Astropart. Phys. 29 (2008) 257

p(12 GeV/c) + N → $\pi^{\pm}$ + X



p(12 GeV/c) + O → $\pi^{\pm}$ + X



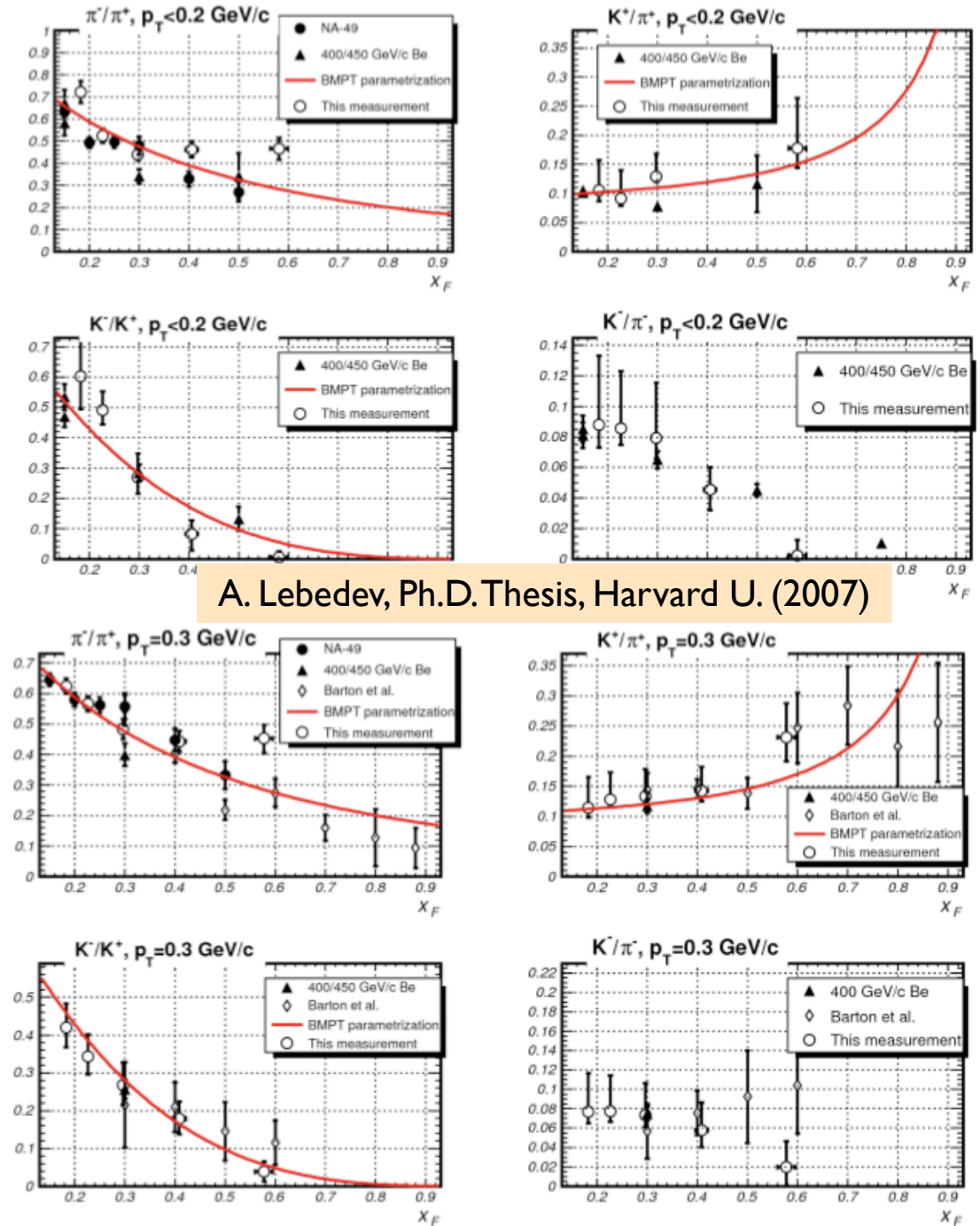
Astropart. Phys. 30 (2008) 124

- Incoming charged pion HARP data are 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 confirm that p+C data can be used to predict p+N_2 and p+O_2 pion production

MIPP

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

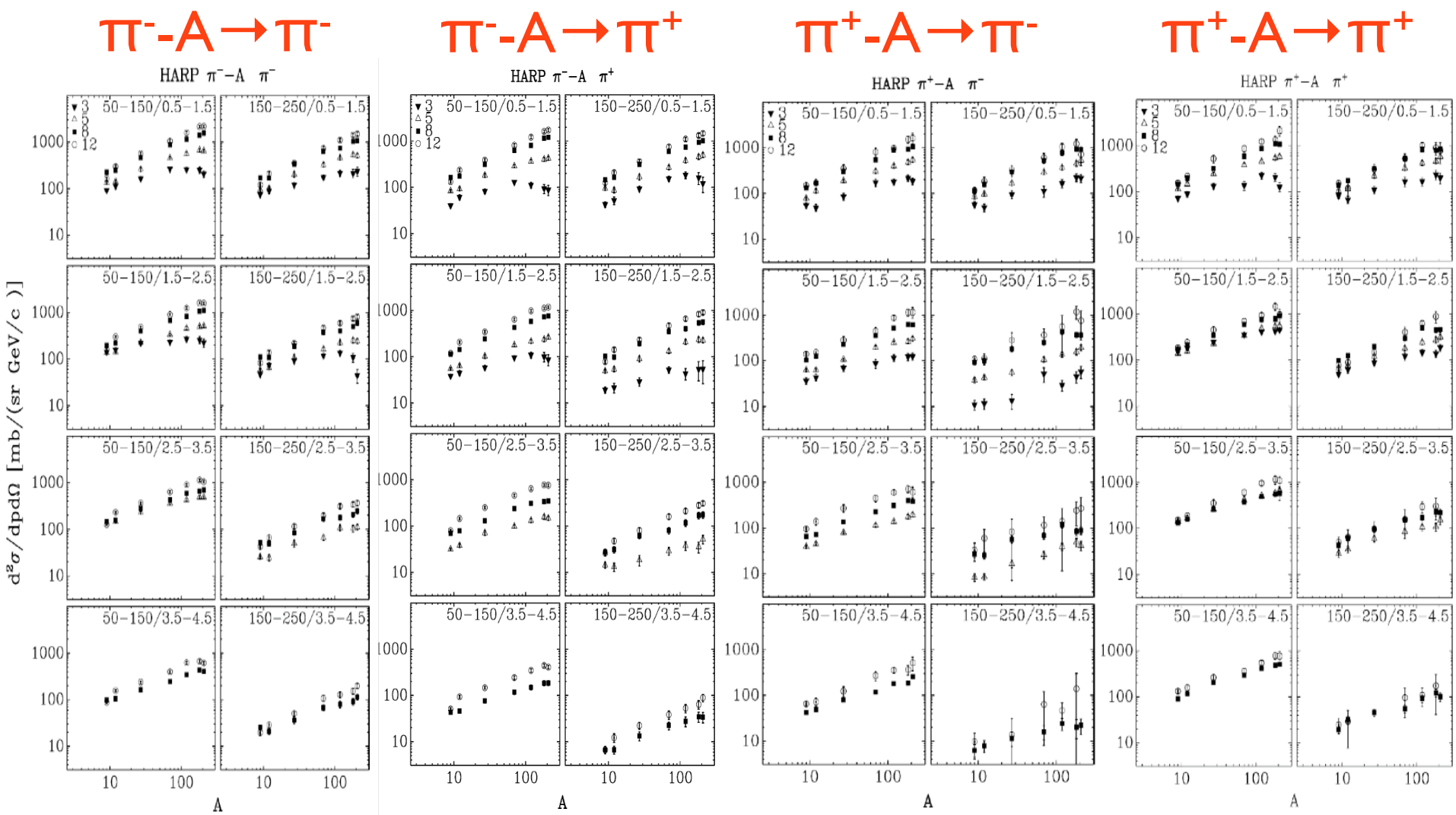
- 2% λ target
- Important for multi-GeV contained, uncontained atmospheric neutrinos
- Particle ratios for two p_t slices shown:
  - p_t < 0.2 GeV/c
  - 0.2 < p_t < 0.4 GeV/c
- Agreement with past C results and parameterizations from Be data at 30% level
- Opposite charge ratios important for atmospheric neutrino detectors with no final charge identification



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

Systematic Target Studies

HARP forward π-A



- All thin target FW taken in π beam now published !

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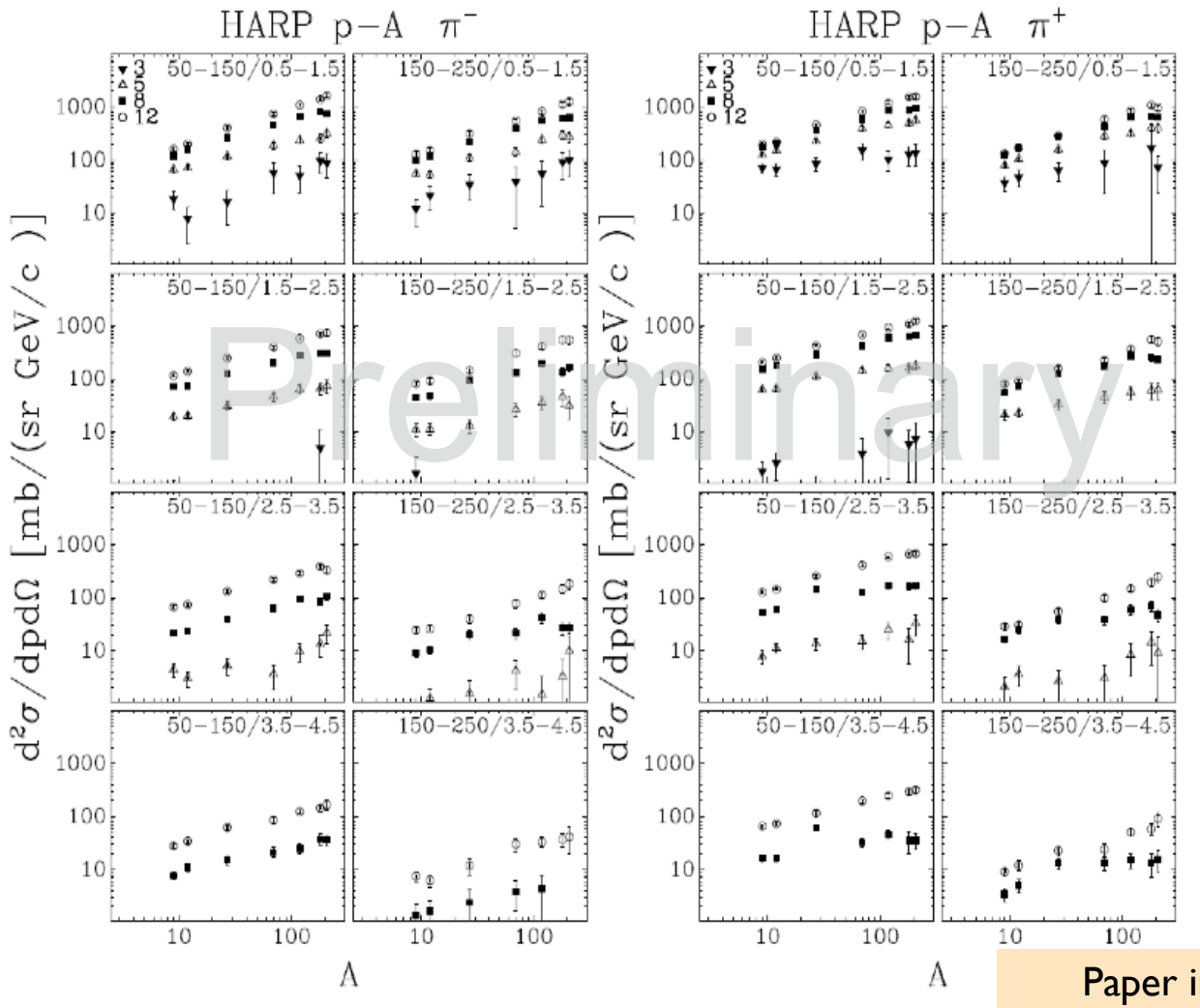
- Dependence on the atomic number A of the pion yields in π-A interactions averaged over two FW angular regions ([50,150], [150,250] rad) and four momentum regions ([0.5-1.5], [1.5,2.5], [2.5,3.5], [3.5,4.5] GeV/c) for incoming beam momenta 3,5,8,12 GeV/c

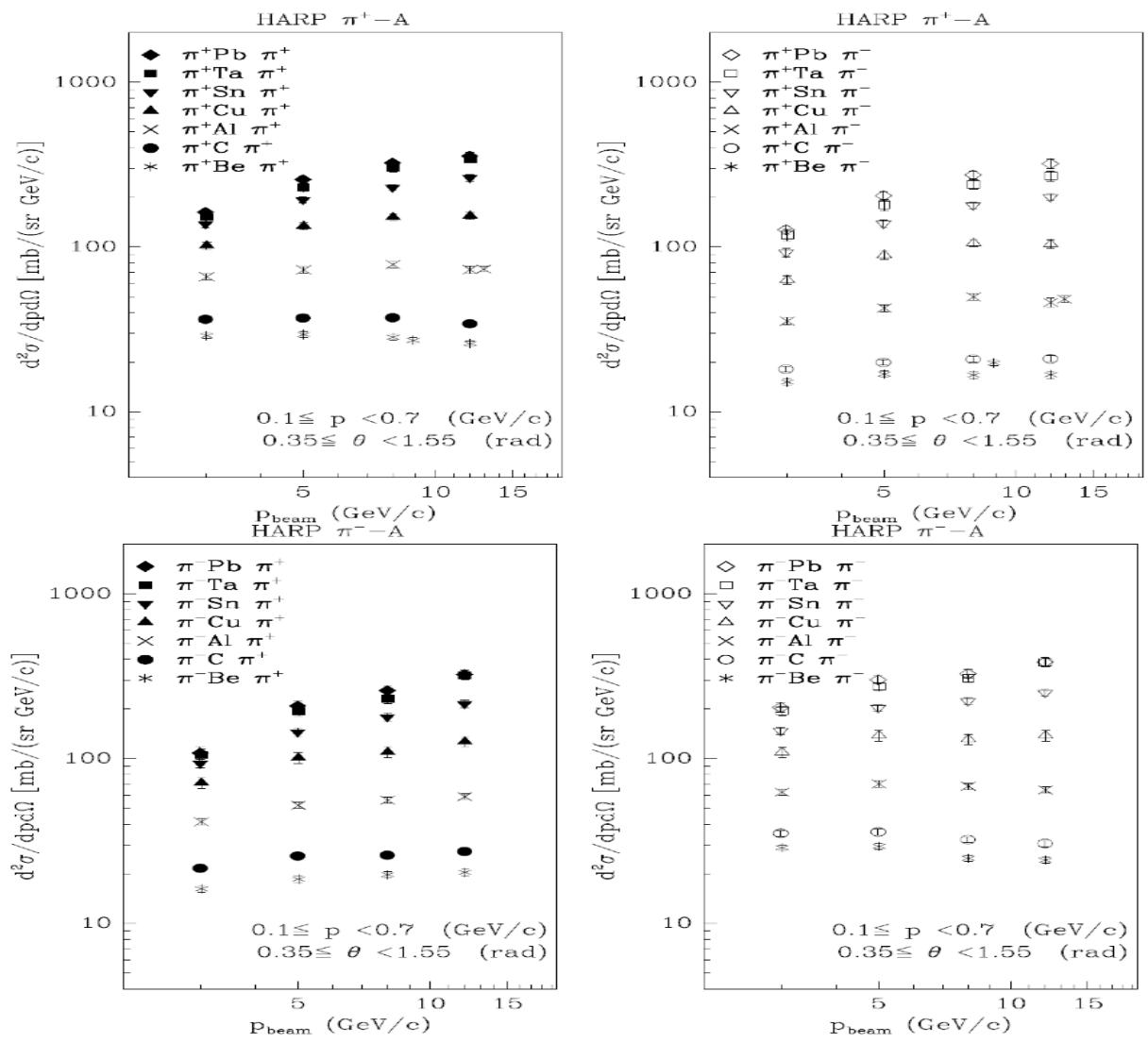
HARP forward p-A



Paper in preparation

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)

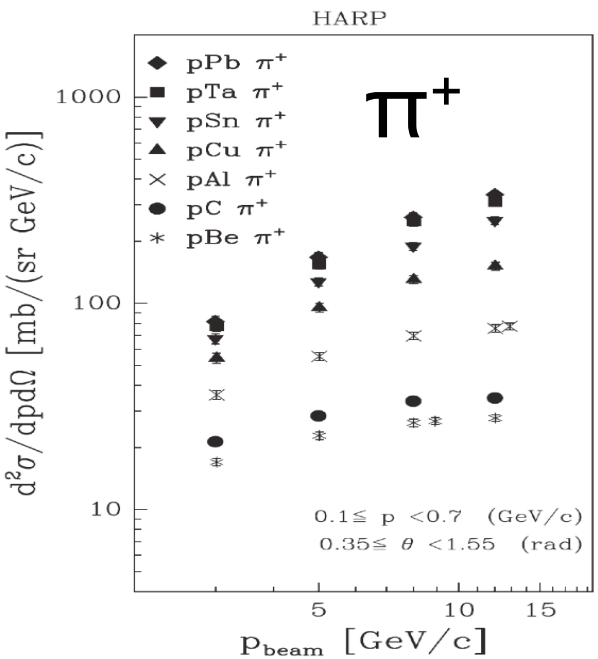
π^+

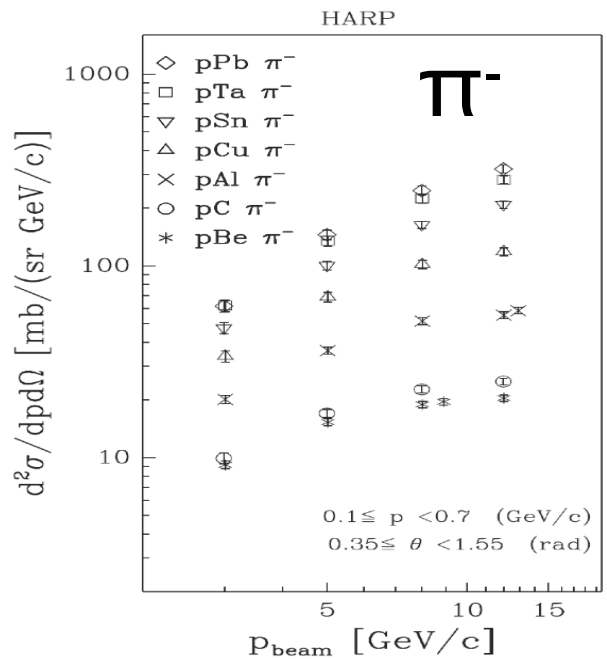
π^-

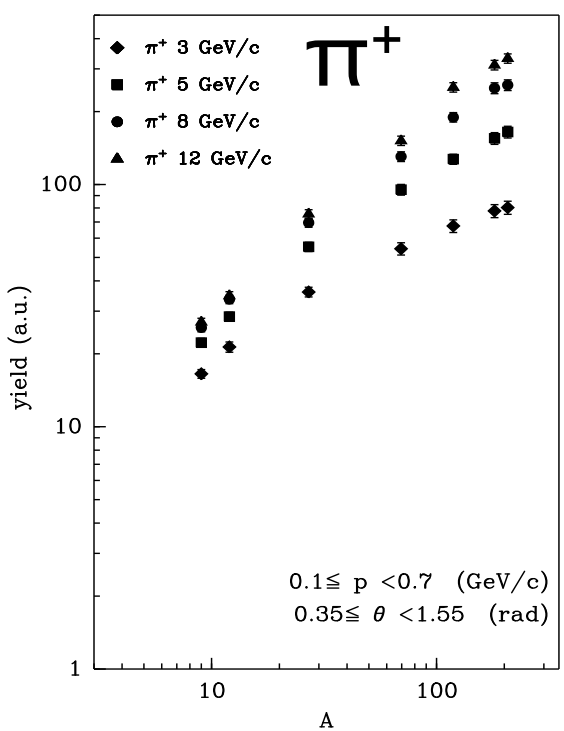
arXiv: hep-ex/0907.1428

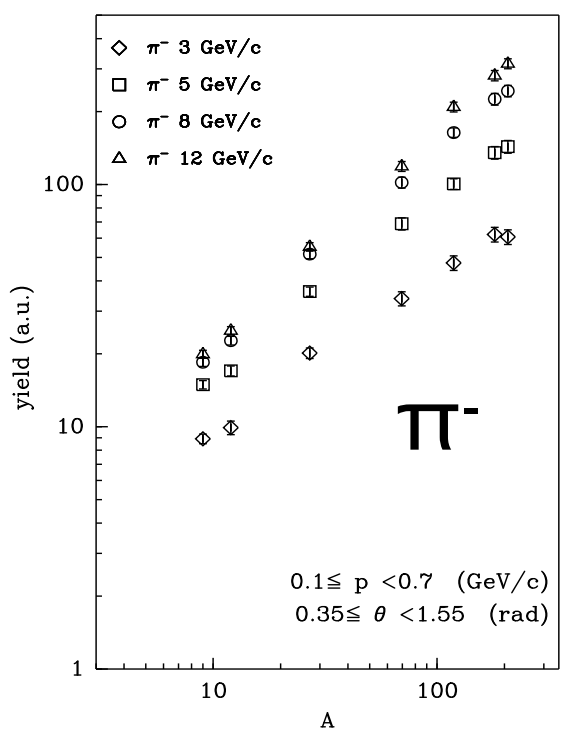
A-dependence of the π+ and π- yields in $\pi^{\pm}$-A interactions for Be, C, Al, Cu, Sn, Ta, Pb as a function of beam momentum (full spill data)

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 < θ < 1.55 (rad)

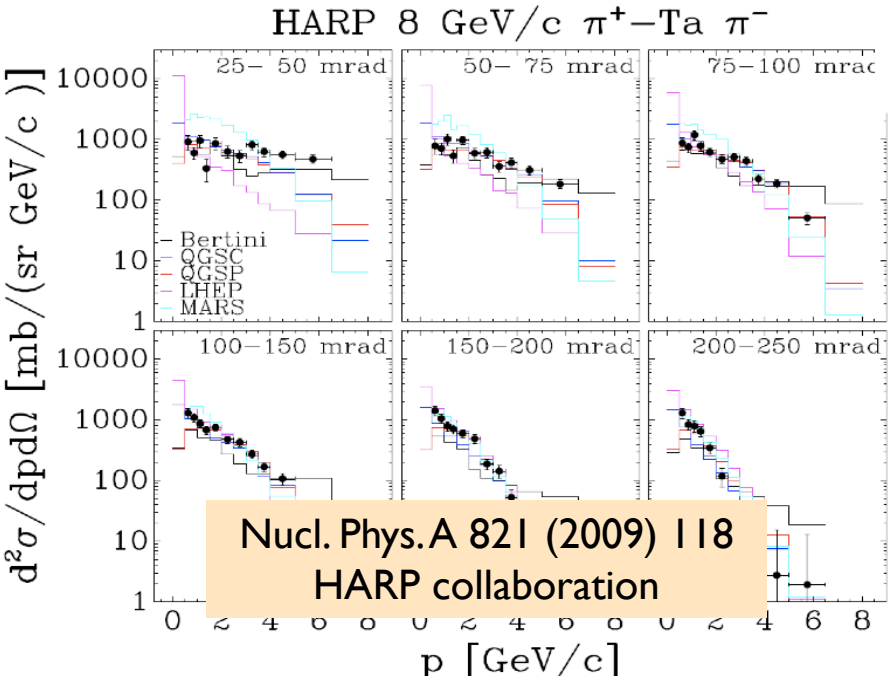
- A-dependence of the π+ and π- yields in p-A interactions for Be, C, Al, Cu, Sn, Ta and Pb (full spill data)

  0.35 < θ < 1.55 (rad)

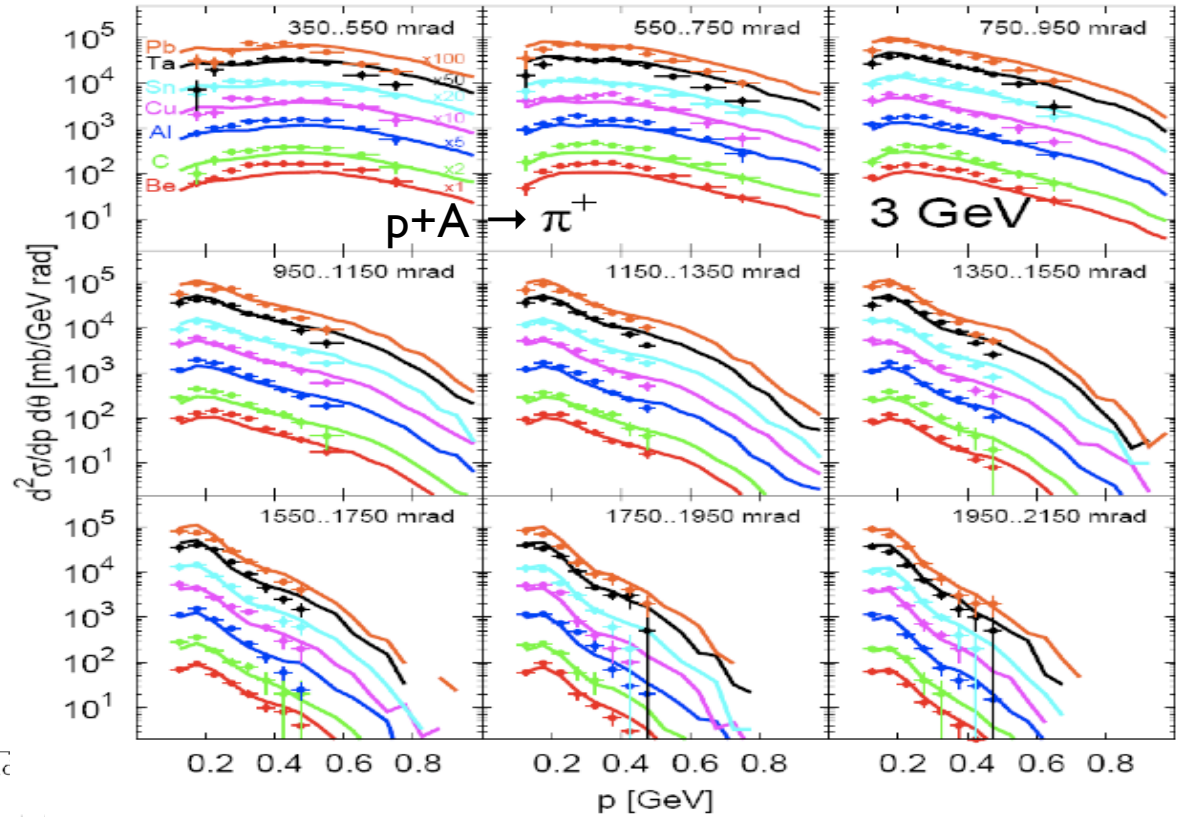
Phys. Rev. C 77 (2008) 055207

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



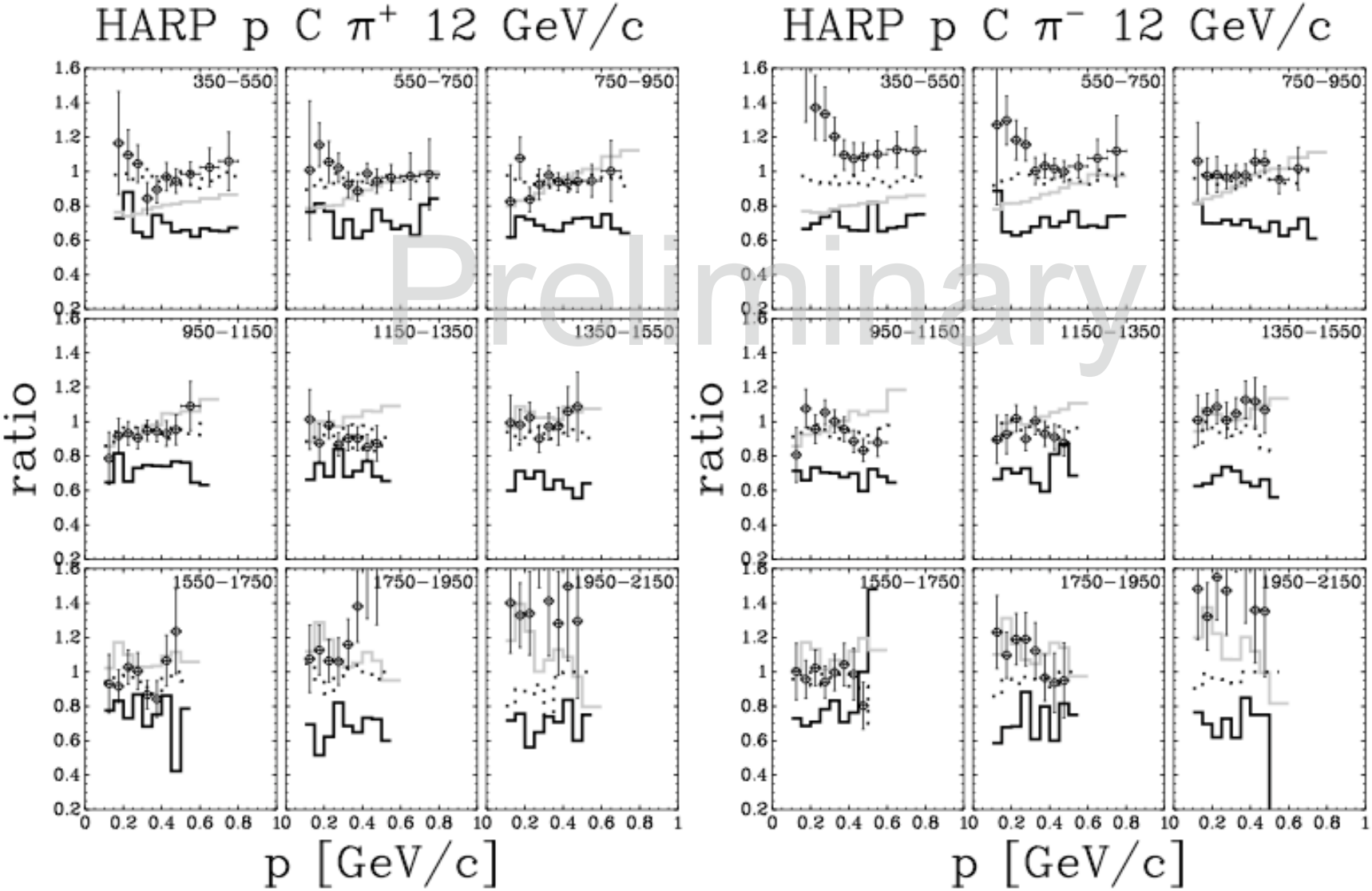
Nucl. Phys. A 821 (2009) 118
HARP collaboration



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 thick target



- Ratio of pion yields in 100% λ over 5% λ Carbon target

Paper in preparation

- Dotted line – ratio of pions produced by "first generation" beam proton to all pions produced by the beam in MARS

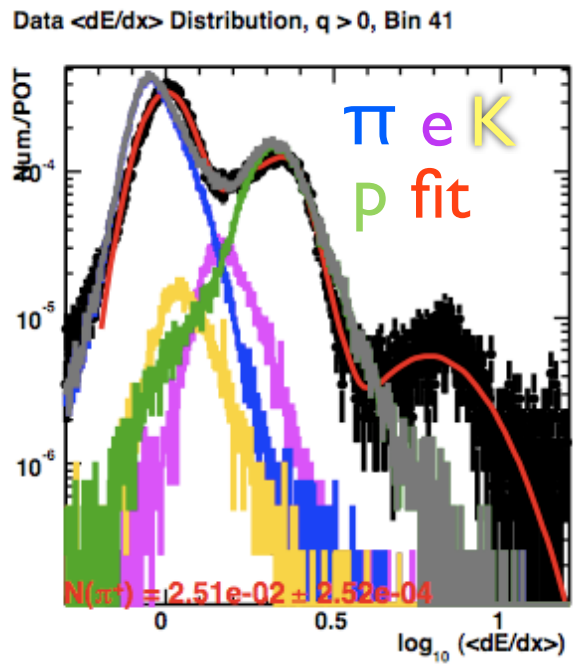
Future Prospects

HARP

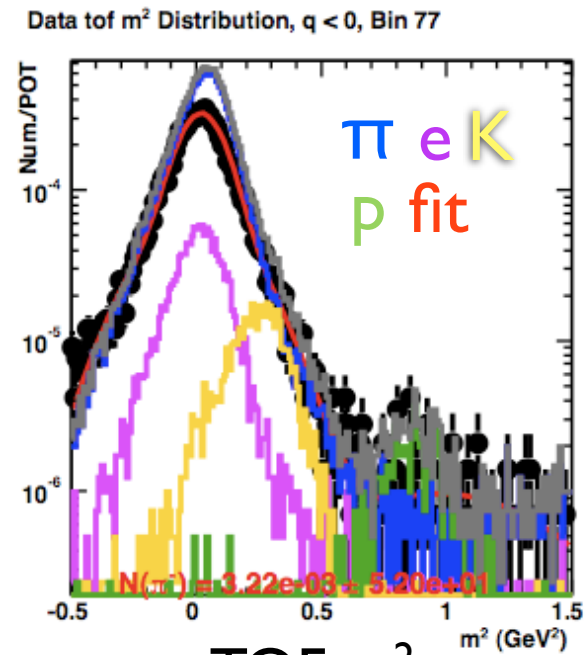
- Publication status: 9 physics papers published and two more submitted
- More analysis to come:
  - Thick target production
  - FW production with incident pions
  - Kaon production in highest beam momentum settings

MIPP

- Analysis in a good shape, reasonable data-MC agreement with respect to detector performance
- Yields for all momenta, including p < 20 GeV/c, when NuMI target analysis complete (later this summer)
- Future MIPP analyses, in order of highest priority:
  - NuMI target hadron production yield for 120 GeV/c proton beam
  - Pion/kaon production yields (& possibly cross sections) for 20, 60 GeV/c protons/pions/kaons on C & Be thin targets
  - K0 production cross sections
  - Also Hydrogen and Bi targets



TPC dE/dx

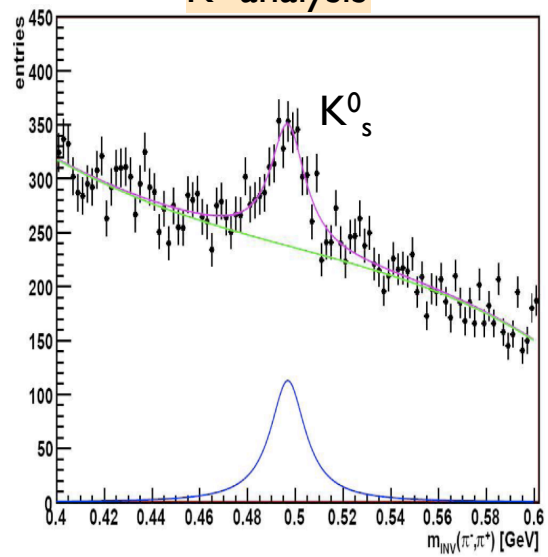


TOF m^2

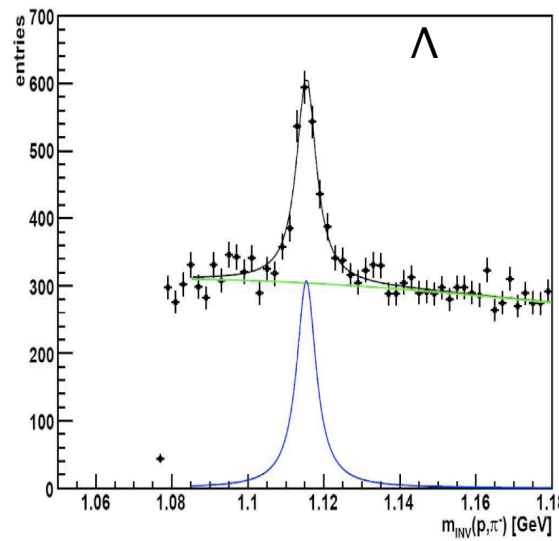
NA61

- Significant progress in data calibration and analysis status report to SPSC: http://cdsweb.cern.ch/record/1113279
- Good quality of 2007 data, though limited in statistics
  - high quality of track reconstruction and particle identification
  - first preliminary results for the thin target data to be released soon
  - work on T2K replica target in progress
- No physics data during 2008 run due to the LHC accident
- Important detector upgrades, TPC read-out and DAQ upgrade

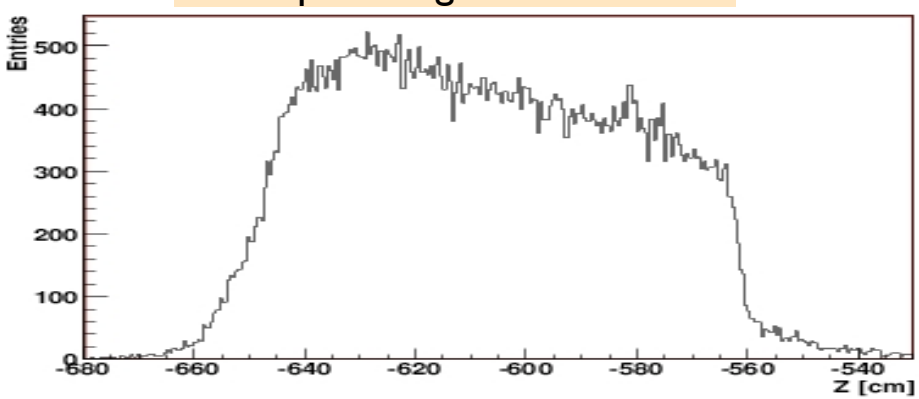
K^0 analysis



V0 analysis



T2K replica target: fitted vertex

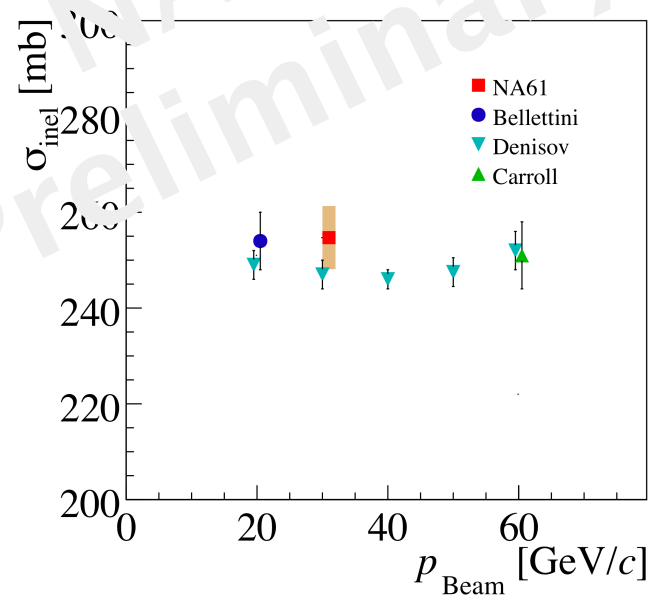


NA61 Analysis

- A double differential inclusive inelastic cross-section, σ_{inel}, is obtained from the thin C target (4% λ_I) data
- This is the inelastic cross-section for p+C interactions, including all processes due to strong interactions with exception of elastic p+C interactions (p+C in the final state)

Preliminary value for the σ_{inel} is in good agreement with previous measurements

Syst. error on $\sigma_{elastic}$ currently estimated by comparing GEANT4 simulations with known exp. values



G. Bellettini et al. Nucl. Phys. 79 (1966) 609; S.P. Denisov et. al. Nucl. Phys. B61 (1973) 62; recalculated from A. Carroll et al. Phys. Lett. B80 (1979) 319

NA61 Prospect

2009 test beams

July 26 - November 15 (almost 4 months)

- T2K measurements (p+C @ 31GeV/c)
- thin target, replica target, calibration data

- Thin target goals
  - 200k identified π^+ tracks in 'T2K phase space'
  - increase 2007 statistics (by 5 at least)
- Measurement for cosmic rays (π, p beams @ various energies, C target)
- Energy scan for critical point search (p beam @ various energies, H target)
- Very close to start releasing first NA61 cross section measurements

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
- HARP
  - Useful results for conventional ν beams study, NuFact design, EAS, atmospheric ν studies and for general MC tuning (G4, FLUKA, etc.)
  - Data taken with the same detector for a wide range of nuclear target: systematic effects are minimized
  - Lots of results!
- MIPP
  - Multi-GeV neutrinos (MINOS, atmospheric neutrinos, NuMI future: NOvA, MINERvA)
  - Detector performances well understood, physics analysis well underway, first hadron production cross section by september 2009
- NA61
  - Good quality of 2007 data, about to release π^- spectra

See also A. Bravar poster contribution for full experiment description and analysis status

Backup Slides

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 π± in p-C and π±-C interactions at 12 GeV/c, Astr. Phys. 29 (2008) 257, [arXiv: 0802.0657]
- Forward π± 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 π± on nuclear targets as measured at CERN PS, Nucl. Phys. A821(2009) 118 [arXiv: 0902.2105]

SW parameterization

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

- 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	$(4.28 \pm 1.36) \cdot 10^1$

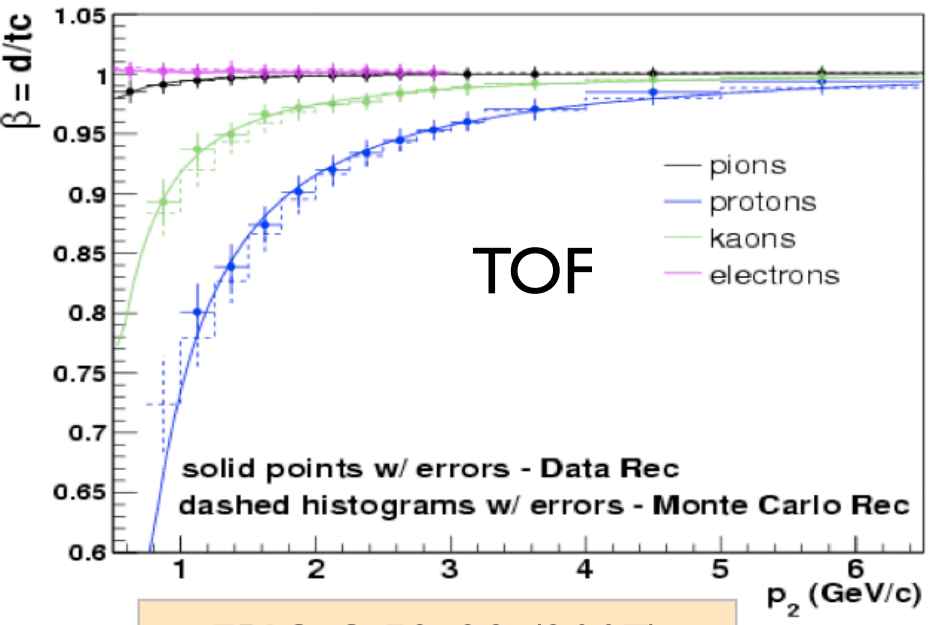
Parameter	c_1	c_2	c_3	$c_4 = c_5$	c_6	c_7	c_8
c_1	1.000						
c_2	0.327	1.000					
c_3	0.986	0.482	1.000				
$c_4 = c_5$	-0.559	0.596	-0.411	1.000			
c_6	0.091	-0.467	-0.006	-0.545	1.000		
c_7	0.011	-0.101	-0.004	-0.129	0.234	1.000	
c_8	-0.080	0.411	0.006	0.471	-0.776	0.215	1.000

HARP measurements for p+Be at 8.9 GeV/c

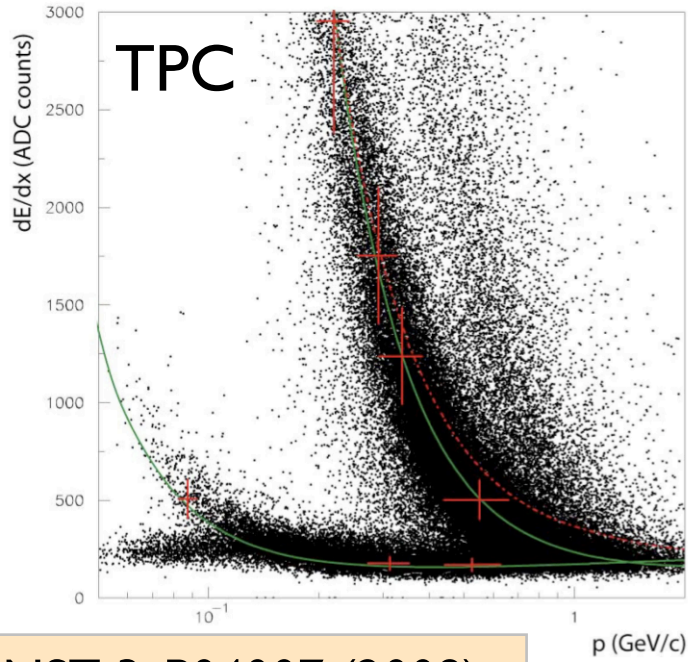
J. R. Sanford and C. L. Wang "Empirical formulas for particle production in p-Be collisions between 10 and 35 BeV/c", Brookhaven National Laboratory, AGS internal report, (1967) (unpublished)

EPJ C 52 (2007) 29

HARP PID

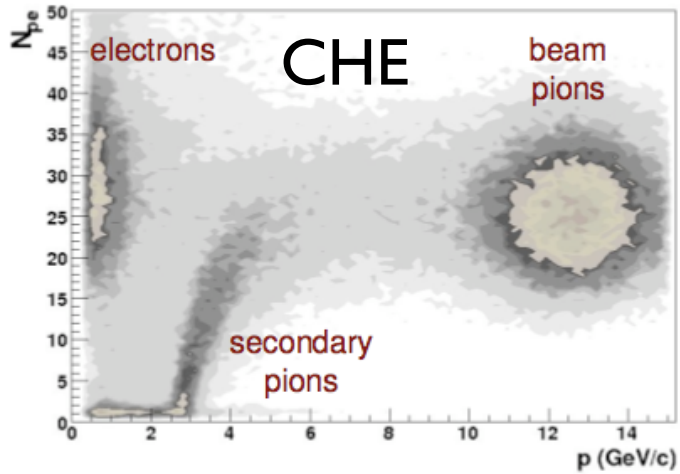


EPJC C 52, 29 (2007)



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

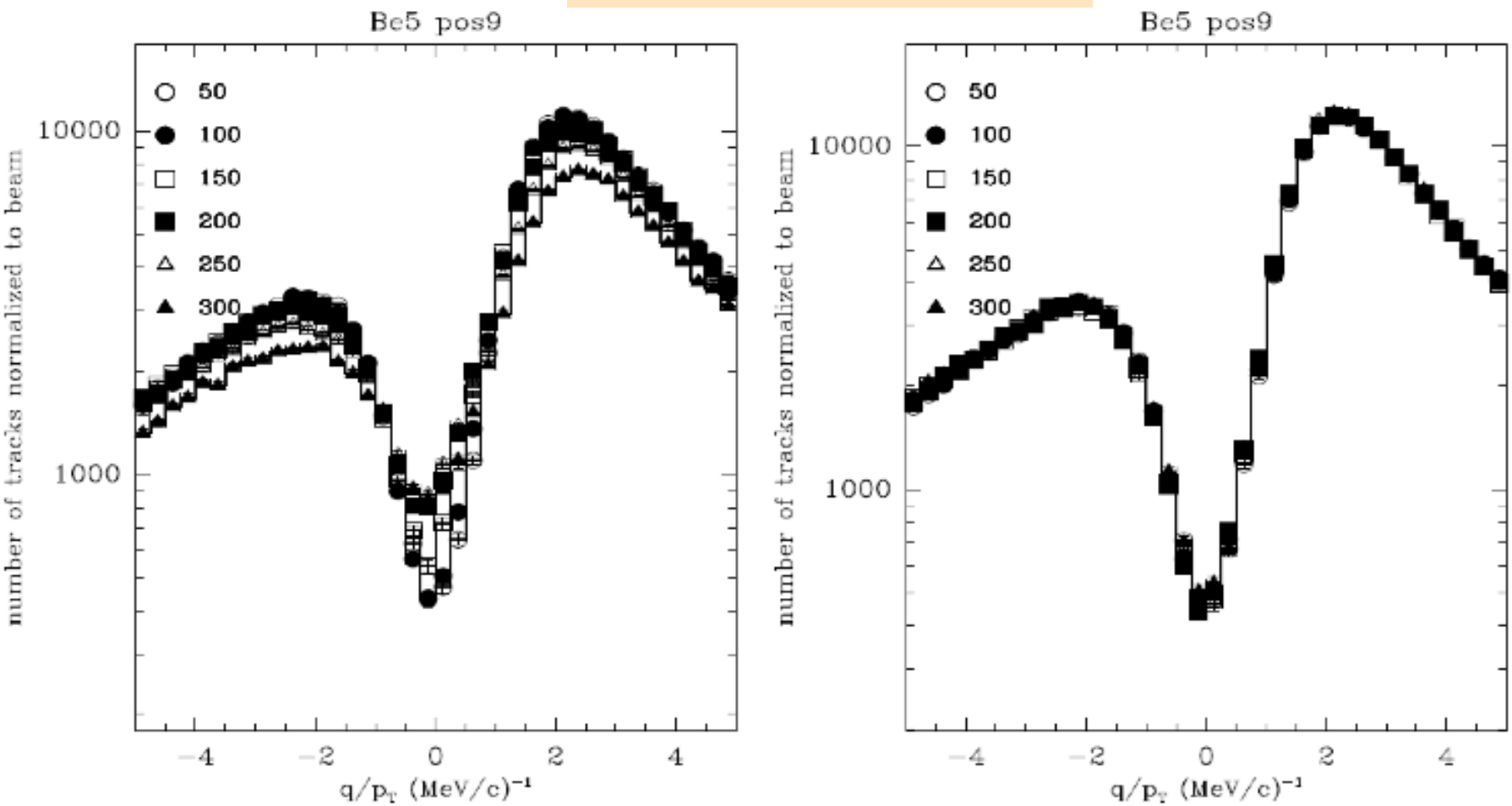


HARP TPC dynamic distortion corrections

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

NA61 targets (2007 pilot run)

- 2 different carbon targets (isotropic graphite)

Thin Carbon Target
- length=2 cm, cross section 2.5x 2.5 cm^2
- ρ = 1.84 g/cm^3
- ~0.04 λ_{int}

T2K replica Target
- length = 90 cm, Ø=2.6 cm
- ρ = 1.83 g/cm^3
- ~1.9 λ_{int}

- During October 2007 Run (~30 days):

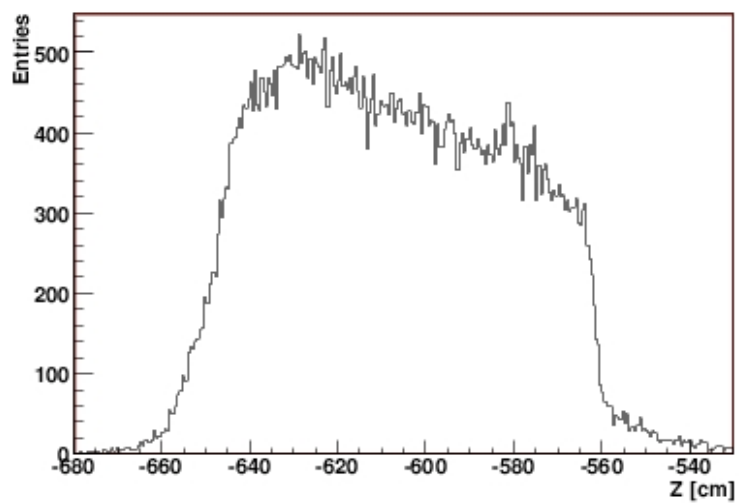
- taken pilot physics data for T2K with 30.9 GeV/c protons (~2 weeks)

Thin target: ~670k triggers

Replica target: ~230k triggers

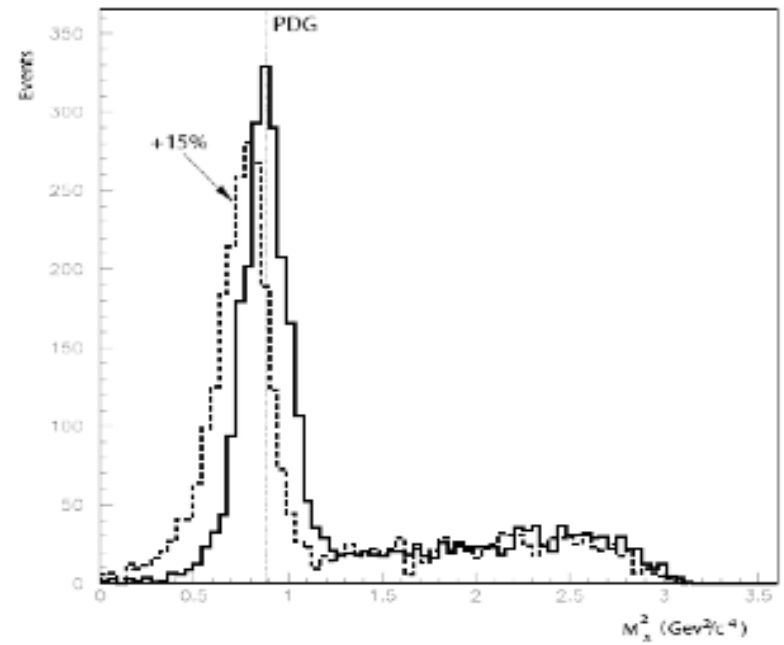
Empty target: ~80k triggers

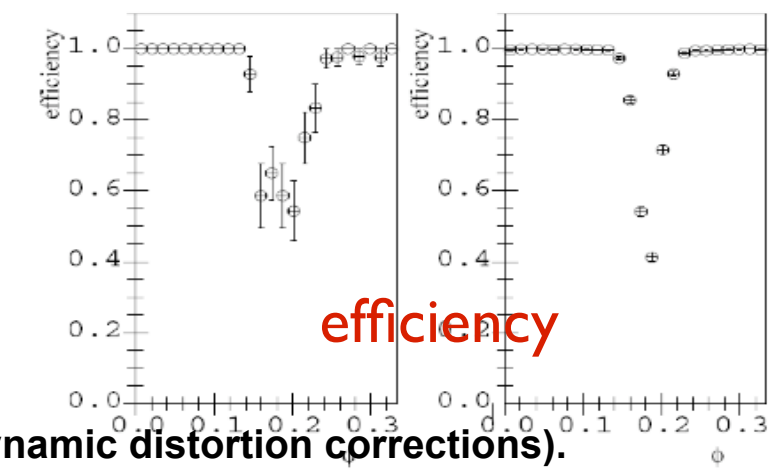
T2K replica target: fitted vertex (raw distr)



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