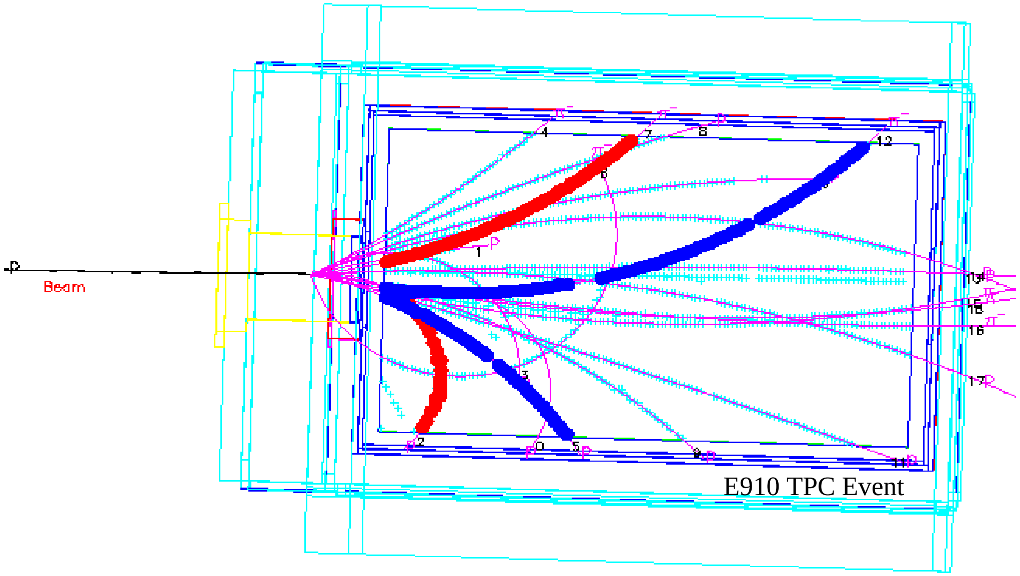
Hadron Production Experiments for the Prediction of Neutrino Fluxes

Workshop “Neutrino Physics at Accelerators”

DLNP, JINR, Dubna, 24th of January 2007

Boris A. Popov (DLNP, JINR, Dubna)

- Motivations
- Experiments
- Results
- Impacts
- Possibilities
- Conclusions

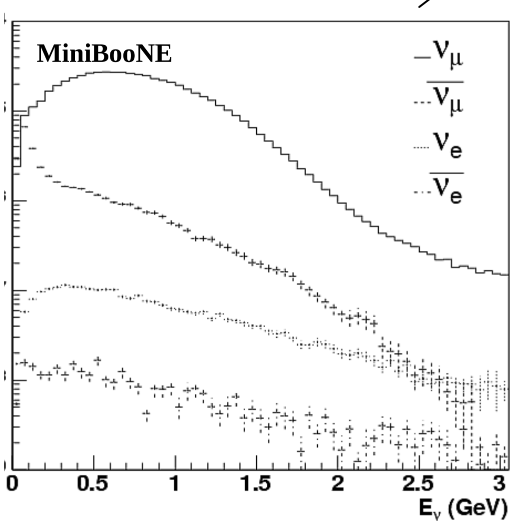


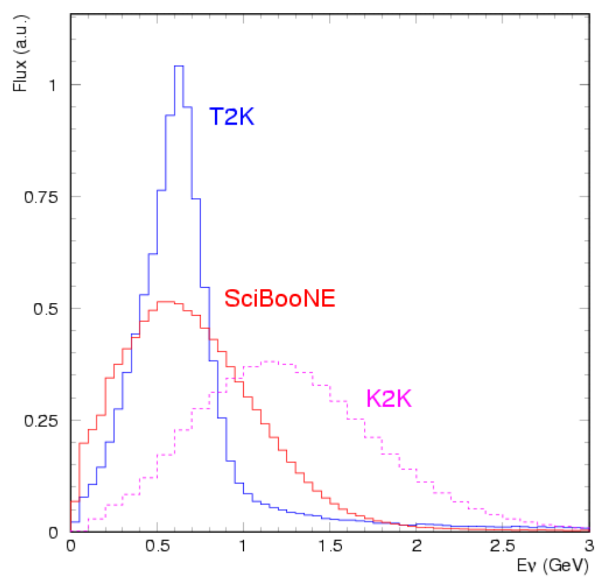
The Motivations

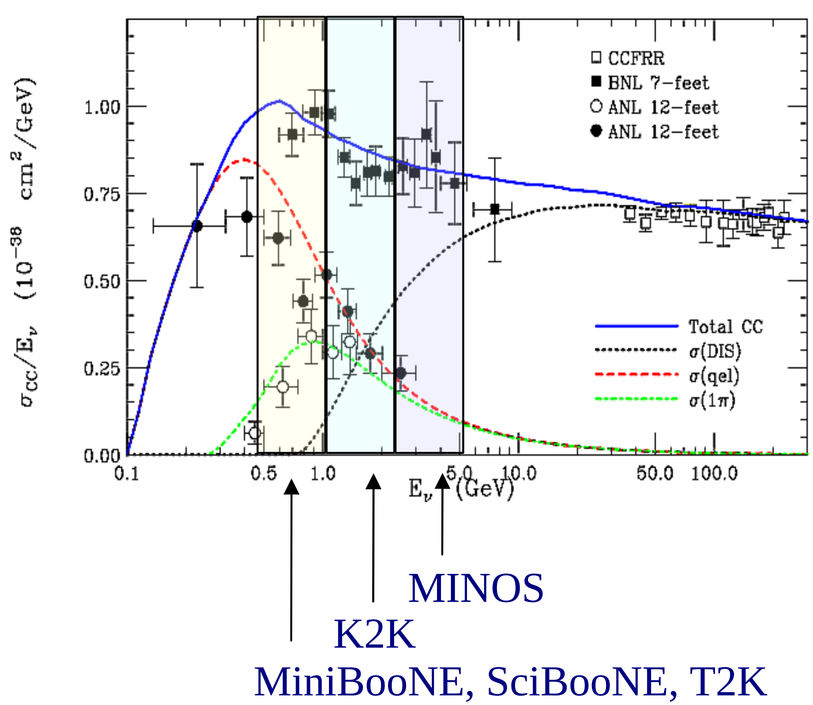
Why neutrino physicists care about hadronic cross-sections

the observed event rate compared to prediction is where we look for **interesting new physics**

$$N(E) = \Phi(E) \times \sigma(E) \times \varepsilon_{det}(E)$$



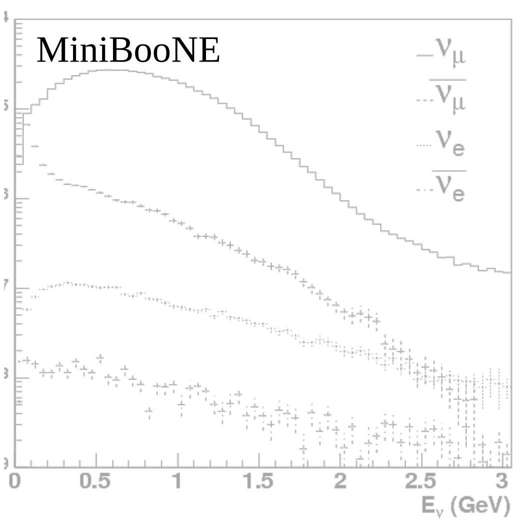




Why neutrino physicists care about hadronic cross-sections

because most of the uncertainty in the flux prediction comes from the modeling of primary meson production within the target

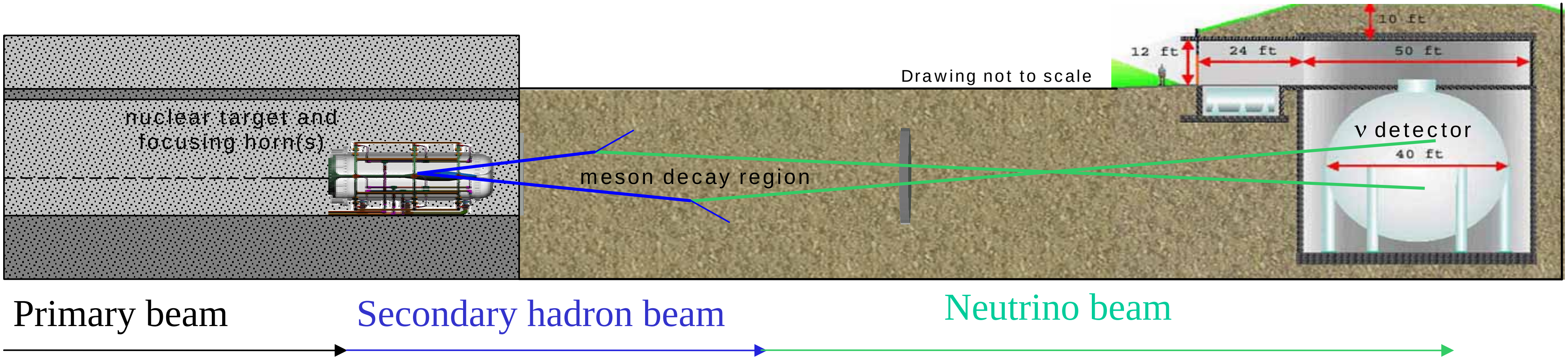
$$N(E) = \Phi(E) \times \sigma(E) \times \varepsilon_{det}(E)$$



flux prediction parameters	typical normalization error†
primary proton beam (targeting, p.o.t., etc)	~2-10%
total interaction cross-sections (p-A, inelastic, QE, etc)	<5%
primary meson production (p+A -> π, p+A -> K, etc)	~10-50%
secondary interactions (p-A, π-A, etc)	~<5%
meson decays	small

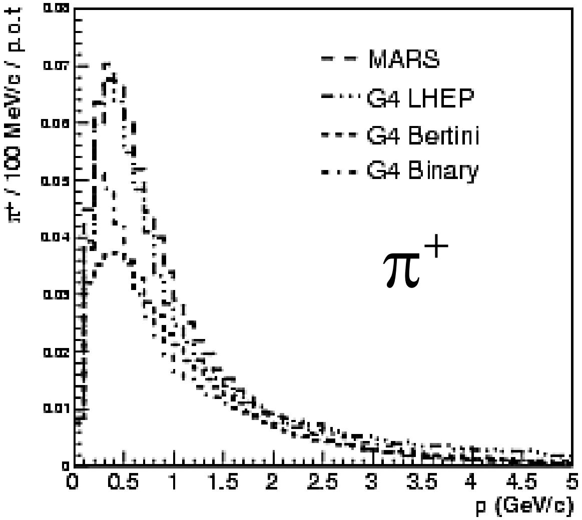
†typical contributions to normalization errors for lower energy beamlines such as the Fermilab booster beamline, 8.9 GeV/c

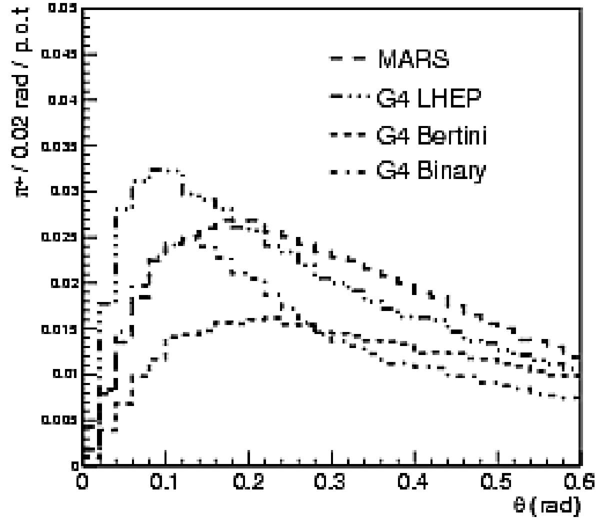
Why neutrino physicists care about hadronic cross-sections

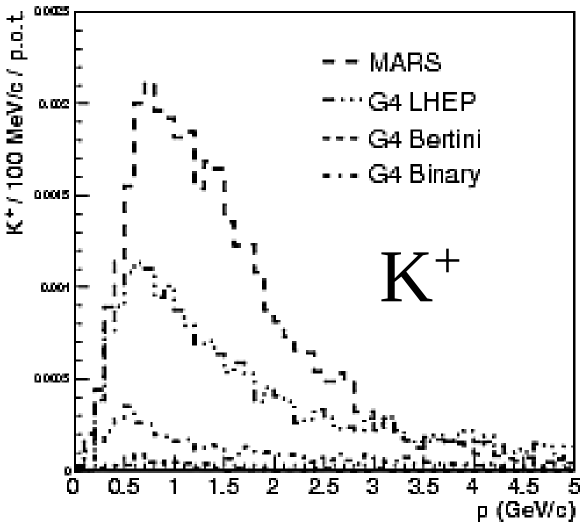


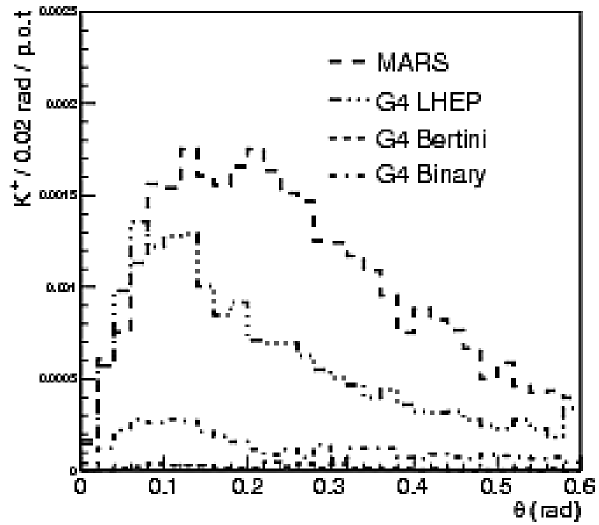
- primary proton energies range from **~10-500 GeV**
- nuclear targets tend to be **lighter elements** (Be, C, Al...) due to difficulty in dissipating large heat build-up in high-Z targets
- targets are thick to increase proton reaction rates, but **secondary interactions** become non-negligible
- relevant meson **production is typically forward**, but can extend out to ~20 degrees (350 mrad) due to effect of focusing horns
- need to know π^+, π^-, **K^+, K^-, and K^0** production to fully understand $\overset{(-)}{\nu}_\mu$ and $\overset{(-)}{\nu}_e$ fluxes (appearance, disappearance)
- branching ratios and neutrino spectra from meson decays are known and relatively straight-forward to simulate

Why neutrino physicists care about hadronic cross-sections (an example)







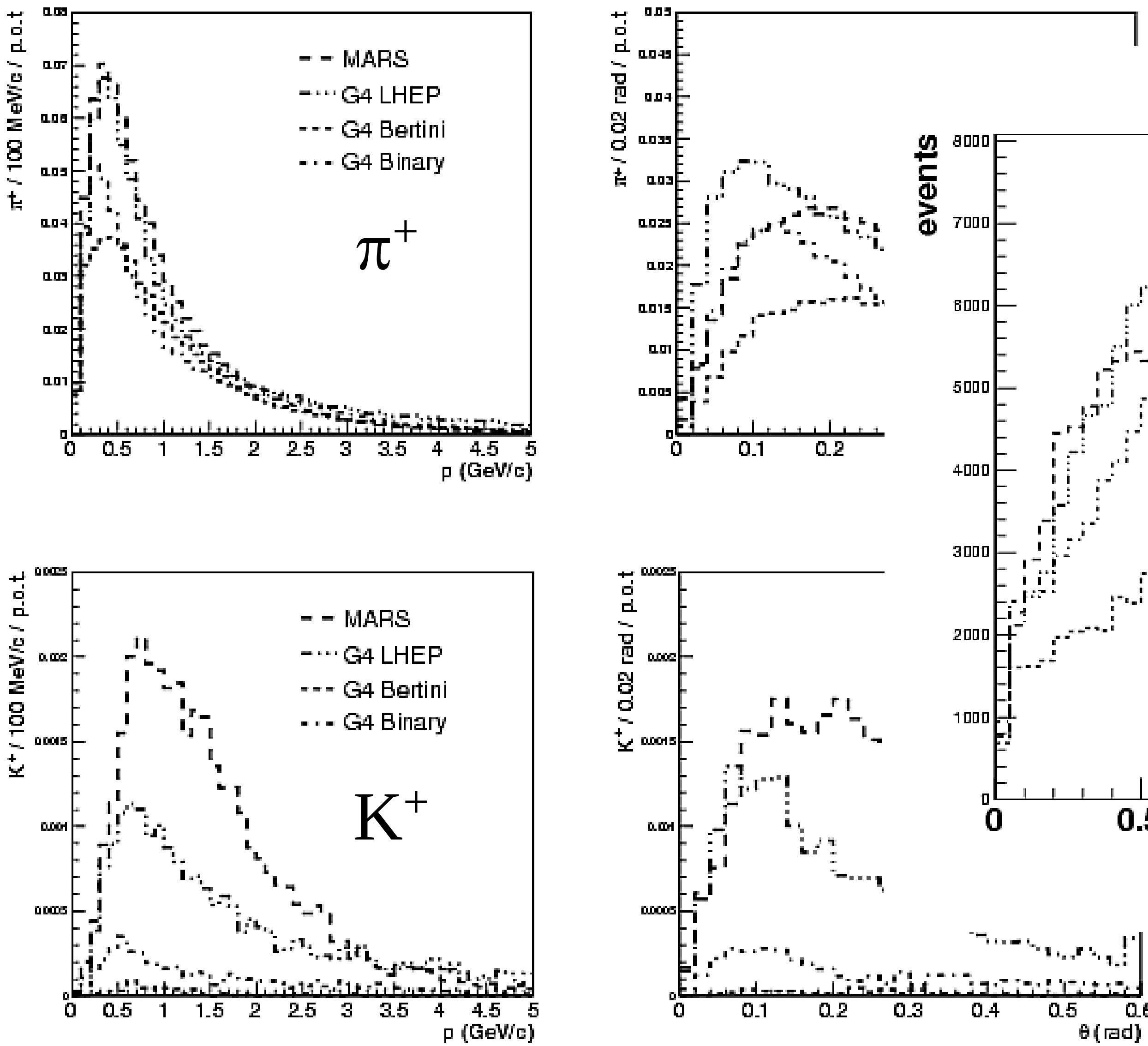


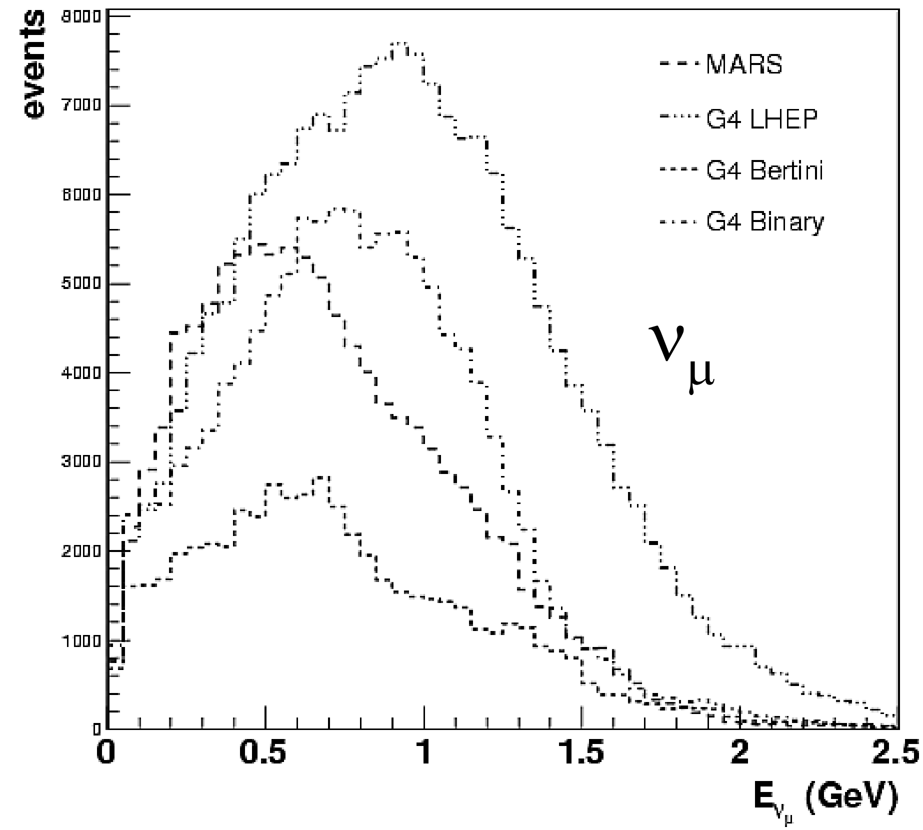
different simulations of 8 GeV/c protons on a thick Be target

note :

- some of these generators are at the limits of their ranges of applicability (8.9 GeV/c on Be)
- there are other Geant4 generators which are not shown here (QGSC, QGSP, . . .)
- nevertheless, something very important is learned : widely varying results are possible from available models (at least in this energy range) and care must be taken in constructing a model to simulate a neutrino beam

Why neutrino physicists care about hadronic cross-sections (an example)



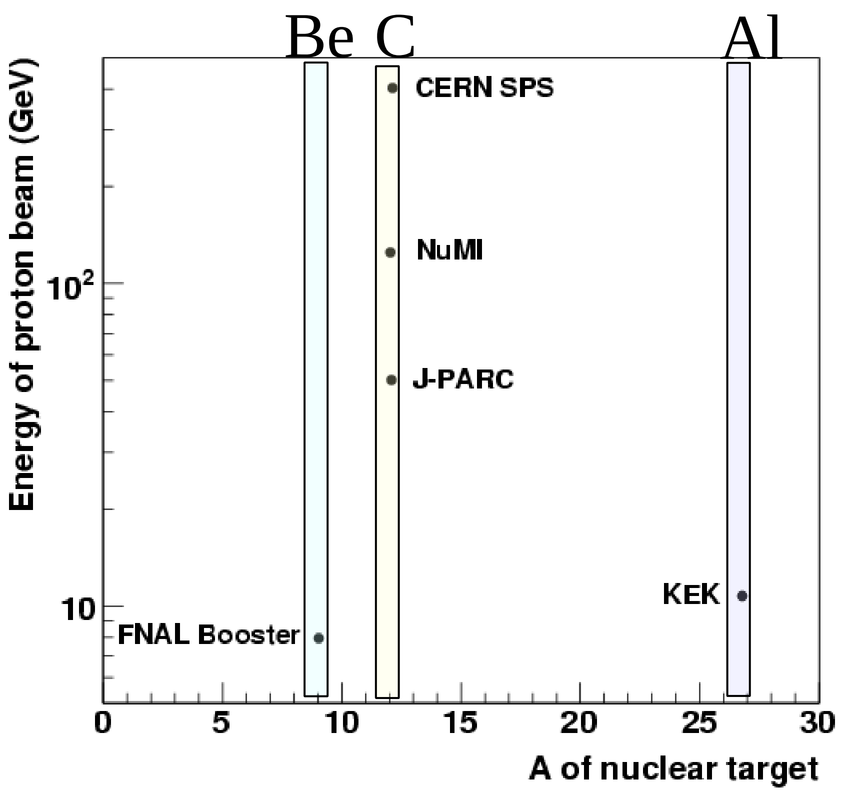


resulting ν_μ fluxes at a 550 m detector

The world's conventional neutrino beams

- **PAST** *(ν cross-section measurements)*
  - *Argonne ZGS – 12.4 GeV/c protons on beryllium [1,2,3]*
  - *Fermilab – 350 GeV/c protons on beryllium oxide [4,5]*
  - *Brookhaven AGS – 28.3 GeV protons on Al_2O_3 [6]*
  - *IHEP Protvino – 70 GeV protons [7]*
- **RECENT / PRESENT** *(ν cross-sections & oscillations)*
  - *KEK PS – 12 GeV protons on aluminum [K2K]*
  - *Fermilab Booster – 8 GeV protons on beryllium [MiniBooNE, SciBooNE]*
  - *Fermilab M.I. – 120 GeV protons on carbon [MINOS, Minerva]*
- **FUTURE** *(ν cross-section & oscillations)*
  - *J-PARC – 50 GeV protons on carbon [T2K]*
  - *CERN SPS – 400 GeV protons on carbon [CNGS]*

"neutrino beam-line parameter space"



[1] Kustom, et. al. "Quasielastic neutrino scattering" Phys. Rev. Lett., 22, 1014 (1969)
[2] Mann, et. al. "Study of the reaction ν + n -> μ + p" Phys. Rev. Lett., 31, 844 (1973)
[3] Barish, et. al. "Study of neutrino interactions in hydrogen and deuterium", Phys. Rev. D, 16, 3103 (1977)
[4] Kitagaki, et. al. "Neutrino flux and total charged-current cross sections in HE n-d interactions", Phys. Rev. Lett., 49, 98 (1982)
[5] Kitagaki, et. al. "High-energy quasielastic ν + n -> μ + p scattering in deuterium" Phys. Rev. D, 28, 436 (1983)
[6] Ahrens, et. al. "Determination of the neutrino fluxes in the Brookhaven wide-band beam" Phys. Rev. D. 34, 75 (1986)
[7] SKAT Collaboration "The characteristics of neutrinonuclear reactions at E = 1-3 GeV" hep:ex/0408128 (2004)

The Experiments

A note on past hadron production measurements

- some data does exist, but an exact match of primary beam energy, nuclear target material and kinematic acceptance between a measurement and a neutrino beam-line are necessary to avoid systematic errors associated with extrapolation or interpolation of data (E_{beam}, A_{targ}, p_{π}, θ_{π})
- above ~15-20 GeV energy scaling laws are applicable and interpolation aided. Below this range it is more difficult. Empirical/Phenomenological parameterizations do exist, however (Sanford-Wang, Tan-Ng, etc)
- most experiments existing before E910, MIPP and HARP were single-arm spectrometers measuring cross-sections in a few angular bins. These modern experiments are simultaneous 4π–acceptance experiments
- normalization uncertainties were often large, making them less constraining in global fits
- in many examples there is clearly tension between results from similar experiments further frustrating efforts to parameterize data sets and interpolate

Marmer, et. al (1969) – example of a single-arm spectrometer

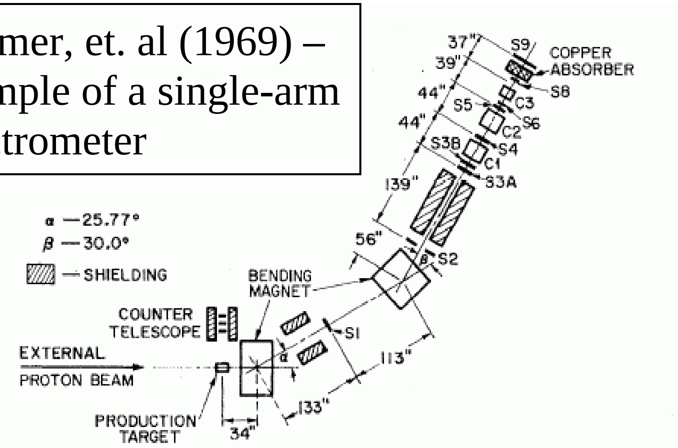


FIG. 1. Secondary particle beam (not to scale). S1–S9 ar scintillation counters, C1 and C2 are focusing differential Čerenko counters, and C3 is a gas threshold Čerenkov counter.

Modern experimental goals and capabilities

- **PS214 (HARP) at CERN**
  - **large-angle particle production in p-A collisions applicable to neutrino factory designs**
  - **reduce systematics on atmospheric neutrino flux predictions by measuring production from liquid cryogenic targets (H_2, D_2) and (N_2, O_2)**
  - **checking/improving simulations such as Geant4 hadronic libraries**
  - **reducing systematics on flux predictions for neutrino experiments using lower energy primary beams to create their neutrino beams (K2K, MiniBooNE, SciBooNE)**
- **E910 at Brookhaven National Laboratory**
  - **part of the heavy-ion program at BNL; study strangeness and resonance production in p-A collisions**
  - **large acceptance particle production measurements in p-A and A-A collisions**
- **E907 (MIPP) at Fermilab**
  - **scaling laws in secondary particle production at incident beam energies in the range 20-120 GeV/c on a wide range of nuclei, hydrogen-uranium**
  - **directly measure particle production from the NuMI target**
- **NA49 at CERN**
  - **study charged and neutral hadron production to search for deconfinement transition predicted by lattice QCD**
  - **large acceptance particle production measurements in p-p and p-A collisions**
- **NA56 (SPY) at CERN**
  - **measured p, K production in p+Be collisions at 450 GeV/c; used to predict fluxes by the NOMAD experiment**

HARP – PS214 at CERN

HARP collaboration

M.G. Catanesi, E. Radicioni

Università degli Studi e Sezione INFN, Bari, Italy

R. Edgecock, M. Ellis[1], S. Robbins[2,3], F.J.P. Soler[4]

Rutherford Appleton Laboratory, Chilton, Didcot, UK

C. Gößling

Institut für Physik, Universität Dortmund, Germany

S. Bunyatov, A. Chukanov, D. Dedovitch, M. Gostkin, A. Guskov, D. Khartchenko, O. Klimov, A. Krasnoperov, D. Kustov, B. Popov[5], V. Serdiouk, V. Tereshchenko, A. Zhemchugov

Joint Institute for Nuclear Research, JINR Dubna, Russia

E. Di Capua, G. Vidal–Sitjes[6,1]

Università degli Studi e Sezione INFN, Ferrara, Italy

A. Artamonov[7], P. Arce[8], S. Giani, S. Gilardoni[6], P. Gorbunov[7], A. Grant, A. Grossheim[6], P. Gruber[6], V. Ivanchenko[9], A. Kayis-Topaksu[10], J. Panman, I. Papadopoulos, J. Pasternak[6], E. Tcherniaev, I. Tsukerman[7], R. Veenhof, C. Wiebusch[3], P. Zucchelli[11,12]

CERN, Geneva, Switzerland

A. Blondel, S. Borghi, M. Campanelli, M.C. Morone, G. Prior[6,13], R. Schroeter

Section de Physique, Université de Genève, Switzerland

C. Meurer,

Institut für Physik, Universität Karlsruhe, Germany

I. Kato[14], T. Nakaya[14], K. Nishikawa[14], S. Ueda[14]

University of Kyoto, Japan

U. Gastaldi

Laboratori Nazionali di Legnaro dell' INFN, Legnaro, Italy

G. B. Mills[15]

Los Alamos National Laboratory, Los Alamos, USA

J.S. Graulich[16], G. Grégoire

Institut de Physique Nucléaire, UCL, Louvain-la-Neuve, Belgium

M. Bonesini, M. Calvi, A. De Min, F. Ferri, M. Paganoni, F. Paleari

Università degli Studi e Sezione INFN, Milano, Italy

M. Kirsanov

Institute for Nuclear Research, Moscow, Russia

A. Bagulya, V. Grichine, N. Polukhina

P. N. Lebedev Institute of Physics (FIAN), Russian Academy of Sciences, Moscow, Russia

V. Palladino

Università "Federico II" e Sezione INFN, Napoli, Italy

L. Coney[15], D. Schmitz[15]

Columbia University, New York, USA

G. Barr, A. De Santo[17], C. Pattison, K. Zuber[18]

Nuclear and Astrophysics Laboratory, University of Oxford, UK

F. Bobisut, D. Gibin, A. Guglielmi, M. Laveder, A. Menegolli, M. Mezzetto

Università degli Studi e Sezione INFN, Padova, Italy

J. Dumarchez, F. Vannucci

LPNHE, Universités de Paris VI et VII, Paris, France

V. Ammosov, V. Koreshev, A. Semak, V. Zaets

Institute for High Energy Physics, Protvino, Russia

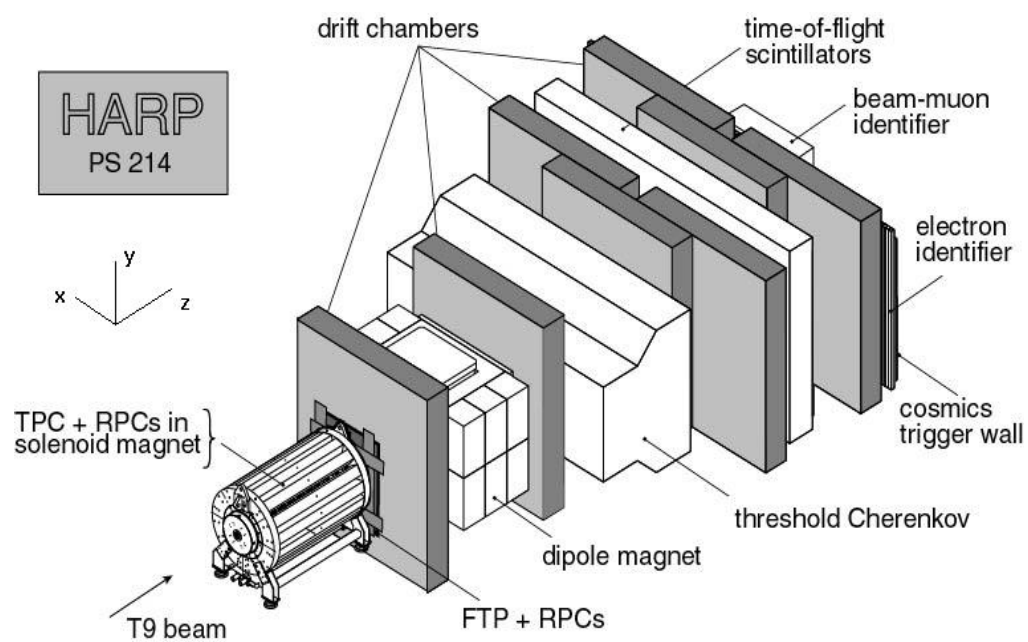
U. Dore

Università "La Sapienza" e Sezione INFN Roma I, Roma, Italy

D. Orestano, F. Pastore, A. Tonazzo, L. Tortora

Università degli Studi e Sezione INFN Roma III, Roma, Italy

C. Booth, C. Buttar[4], P. Hodgson, L. Howlett



Dept. of Physics, University of Sheffield, UK

M. Bogomilov, M. Chizhov, D. Kolev, R. Tsenov

Faculty of Physics, St. Kliment Ohridski University, Sofia, Bulgaria

S. Piperov, P. Temnikov

Institute for Nuclear Research and Nuclear Energy, Academy of Sciences, Sofia, Bulgaria

M. Apollonio, P. Chimenti, G. Giannini, G. Santin[19]

Università degli Studi e Sezione INFN, Trieste, Italy

Y. Hayato[14], A. Ichikawa[14], T. Kobayashi[14]

KEK, Tsukuba, Japan

J. Burguet–Castell, A. Cervera–Villanueva, J.J. Gómez–Cadenas, J. Martín–Albo, P. Novella, M. Sorel, A. Tornero

Instituto de Física Corpuscular, IFIC, CSIC and Universidad de Valencia, Spain

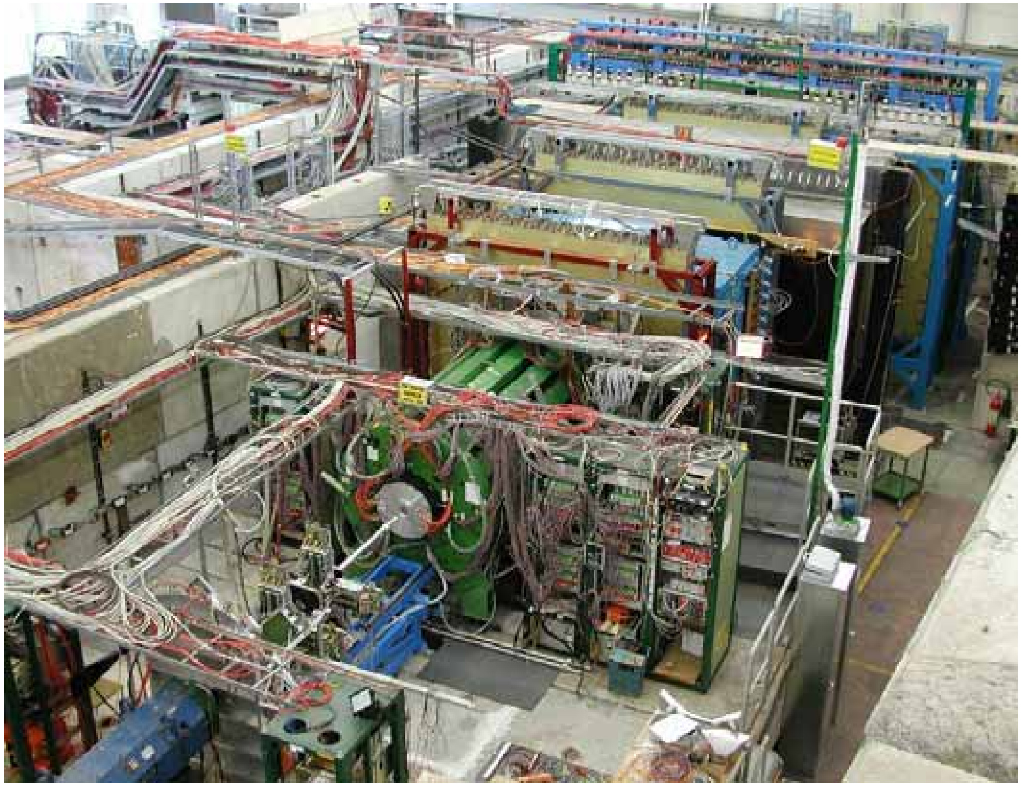
HARP – PS214 at CERN

HARP is a large angle spectrometer to measure hadron production from various nuclear targets and a range of incident beam momenta

- Nuclear target materials : A = 1 – 200
- Nuclear target thickness : λ = 2 – 100 %
- Beam particles : h = p, π^{+-},e^{+-}
- Beam momenta : p_{beam} = 1 – 15 GeV/c
- Secondaries measured : h = p, π^{+-},K^{+-}
- Kinematic acceptance of forward spectrometer

  p = 0.5 – 8.0 GeV/c

  θ = 20 – 250 mrad



hadron production measurements
in “*seven dimensions*”

Ingredients for Cross-section Calculation

$$\frac{d^2\sigma^\pi}{dp\,d\Omega} \sim \frac{\Delta N^\pi}{\Delta p \Delta\theta} \cdot \frac{\text{correction factors}(p,\theta)}{N_{pot}}$$

- Select events identified as primary protons interacting in the target
- For each event, reconstruct tracks and their 3-momentum
- Identify pions among secondary tracks
- Apply corrections, for reconstructed-to-true pion yield conversion:
  - Momentum resolution
  - Spectrometer angular acceptance
  - Track reconstruction efficiency
  - Efficiency and purity of pion identification
  - Other
- Count protons on target corresponding to selected events
- Multiply by physics constants and accurately measured target properties

Recipe for a cross-section

$$\frac{d^2\sigma^\pi}{dp\,d\Omega} = \frac{A}{N_A \rho\, t}\frac{1}{N_{\mathrm{pot}}}\left[\text{correction factors}(p,\theta)\right]\frac{\Delta^2 N^\pi}{\Delta p\,\Delta\Omega}$$

yield

- Select events identified as primary protons interacting in the target
- For each event reconstruct tracks and their 3-momentum
- Identify pions among secondary tracks

eff. & mig.

- Apply corrections for reconstructed-to-true pion yield conversion:
  - Momentum resolution
  - Spectrometer angular acceptance
  - Track reconstruction efficiency
  - Efficiency and purity of pion identification
  - Other

norm.

- Count protons on target corresponding to selected events
- Multiply by physics constants and accurately measured target properties

The Cross-section

$$\frac{d^2\sigma_\alpha}{dp_i d\theta_j} = \frac{1}{N_{\rm pot}} \frac{A}{N_A \rho t} M^{-1}_{ij\alpha i'j'\alpha'} \cdot \left[N^{\alpha'}_{i'j'}(\mathrm{T}) - N^{\alpha'}_{i'j'}(\mathrm{E}) \right]$$

$(p,\theta)_{true}$

absolute normalization

Efficiency/migration/correction matrix

Measured Pion Yield

Target-out Background

Primes denote reconstructed quantities

i,j are momentum and angular bins

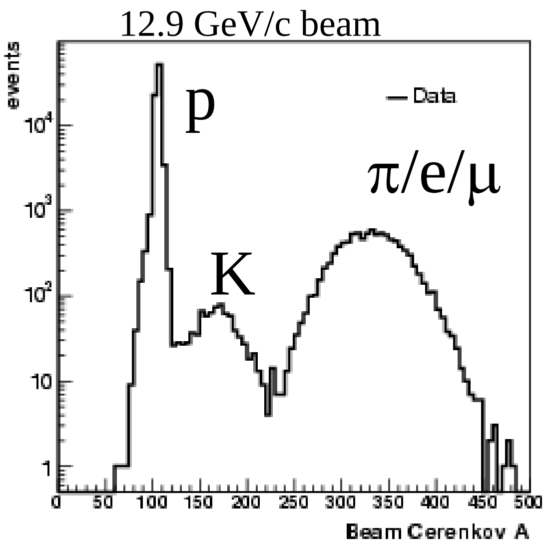
α is the particle type

Correction Factors

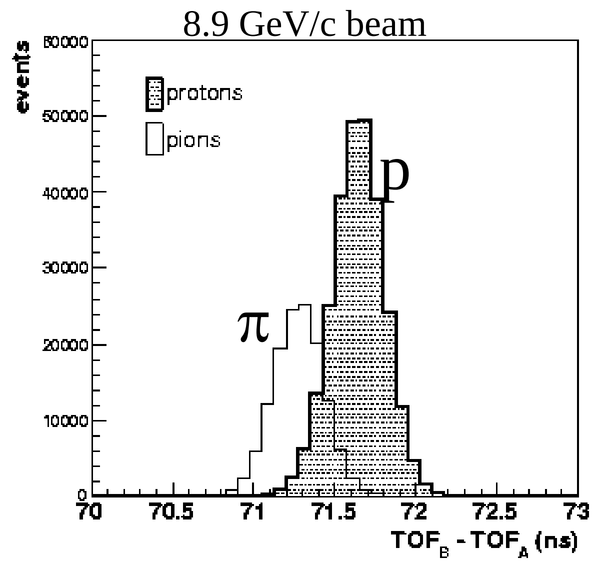
Correction Type	Impact On Cross-section	Method
Momentum Resolution	Shape	MC/Data
Track Rec Efficiency	~5% up	Data
Geometric Acceptance	~100-160% up	Analytic
Pion ID	Efficiency: ~2-5% up	Data
Pion ID	π-proton: migration<1% down	Data
Absorption/decay	10-30% up	MC
Tertiary Production	< 5% down	MC
Electron Veto Eff	1% up	MC
Kaon Subtraction	0-3% down	Data/MC
Target-out subtraction	~20%	Data

- for each correction applied a systematic error has been separately estimated

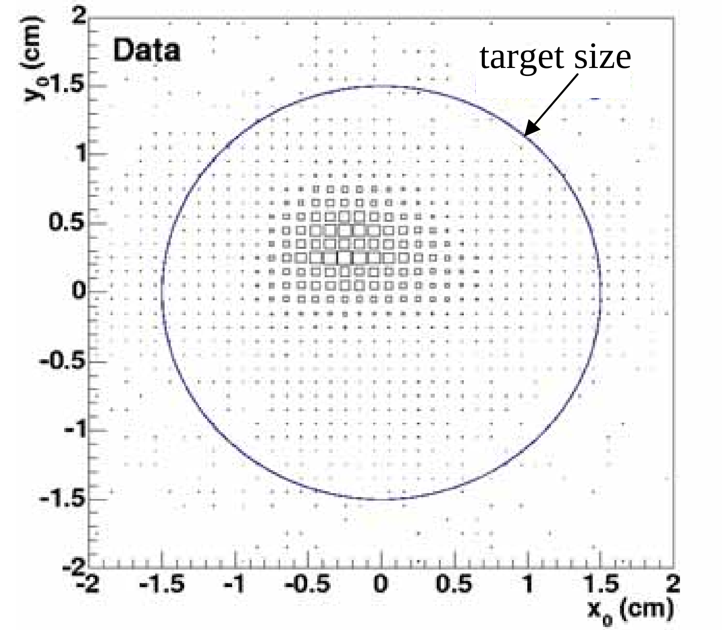
Event selection



2 Beam Cerenkov Detectors



3 Beam ToF Detectors

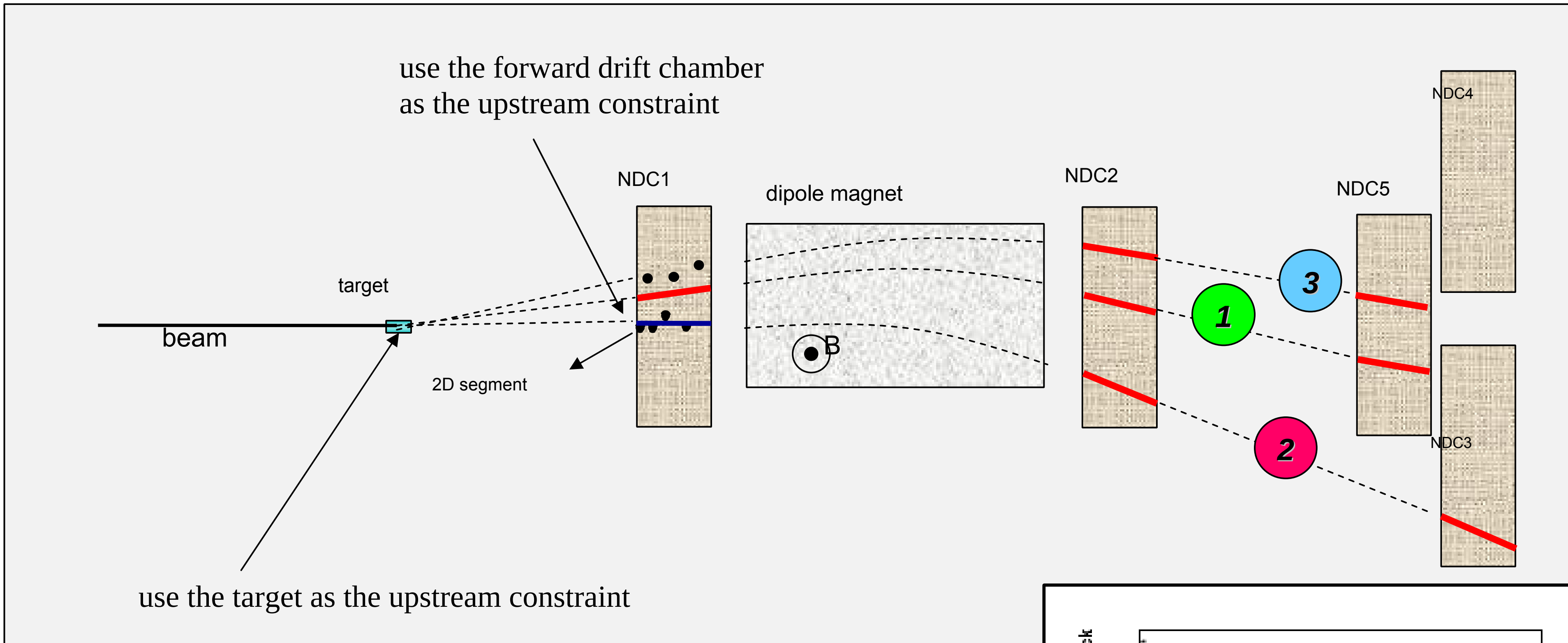


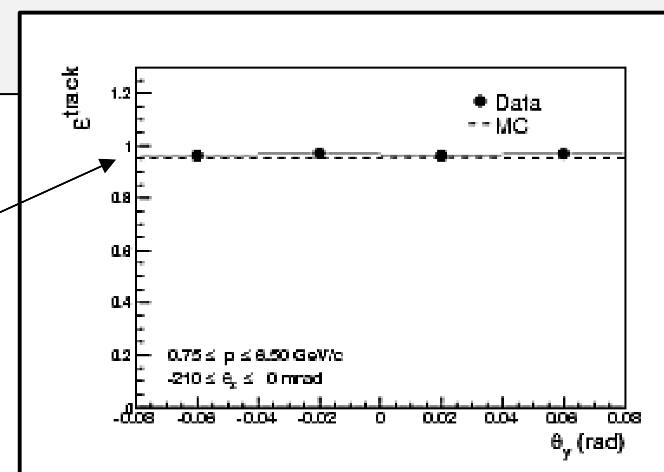
4 Multi-wire Proportional Counters

- **Event selection for protons on target** (“*normalization trigger*”)**:**
  - Well-behaved transverse impact point and direction of primaries via 4 MWPCs and scintillators (BS, TDS, HALO A, HALO B)
  - Primaries identified as protons via beam ToF and Cerenkov systems (TOFA, TOFB, BCA, BCB). Beam ToFs also used for interaction time.
- **Event selection for proton inelastic interactions** (“*physics trigger*”)**:**
  - Same as normalization trigger, plus signal in forward trigger scintillator plane (FTP)

Track reconstruction efficiency

- four overlapping downstream drift chamber modules and two independent methods of momentum reconstruction given a downstream segment

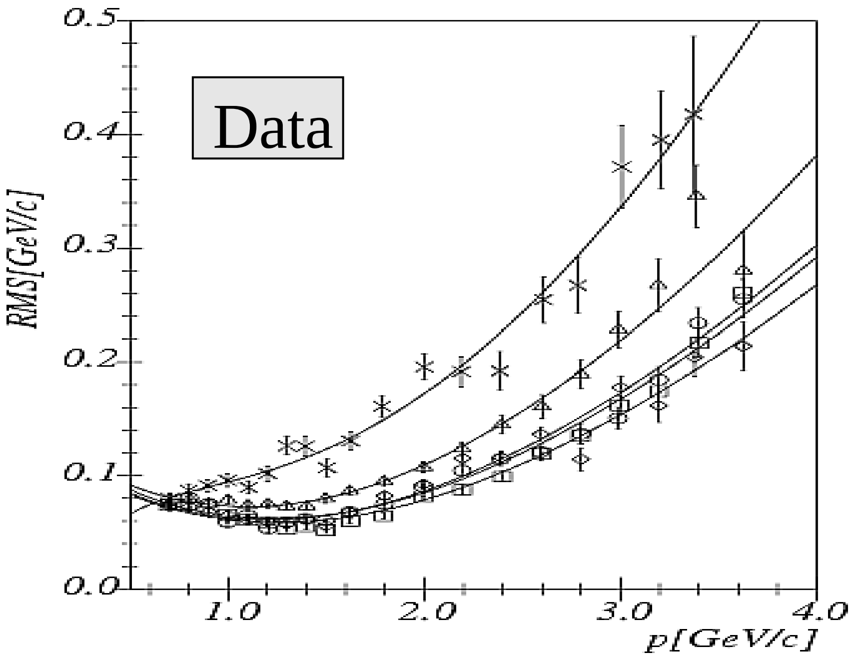


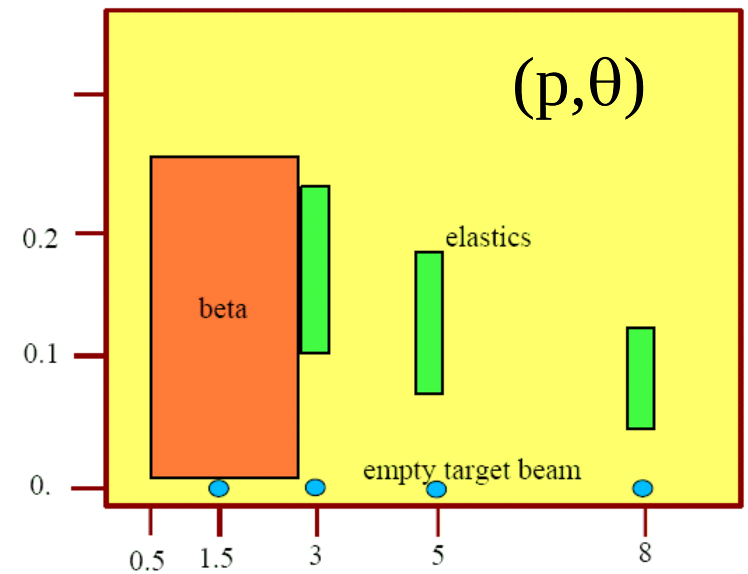


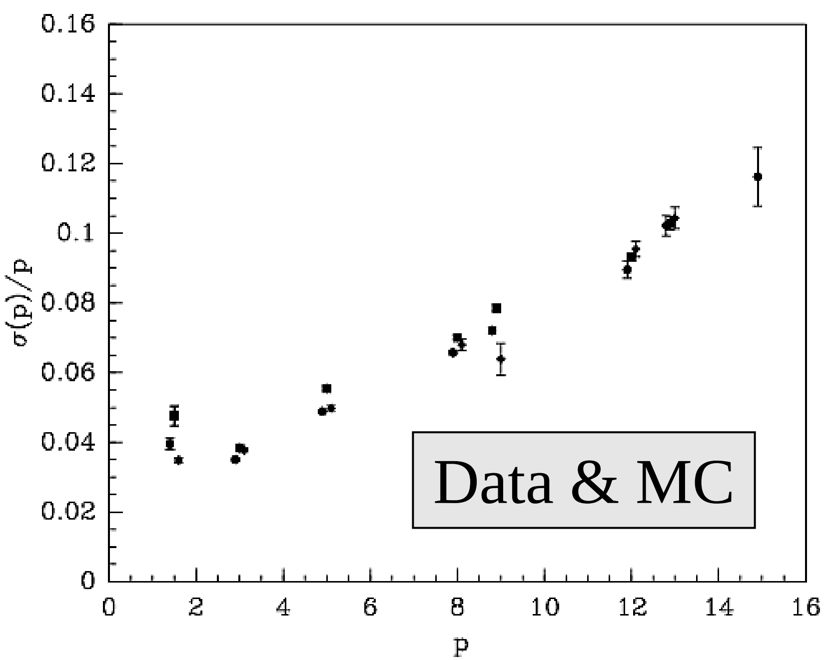
- redundancy in chambers and redundancy in vertex constraints allows determination of tracking efficiencies from the data themselves

- target constraint method **efficiency > 95%**.

Momentum resolution



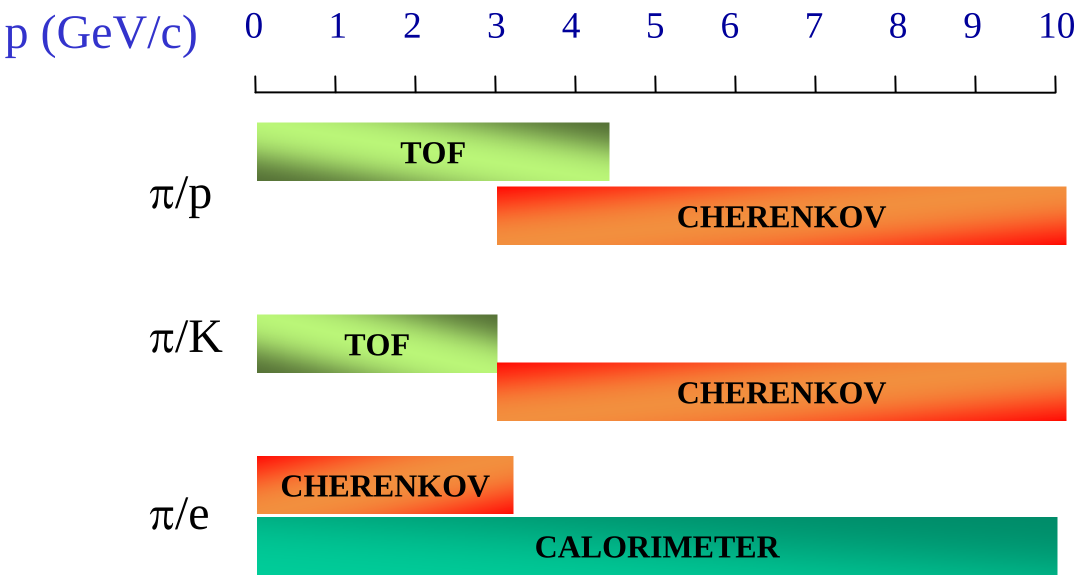


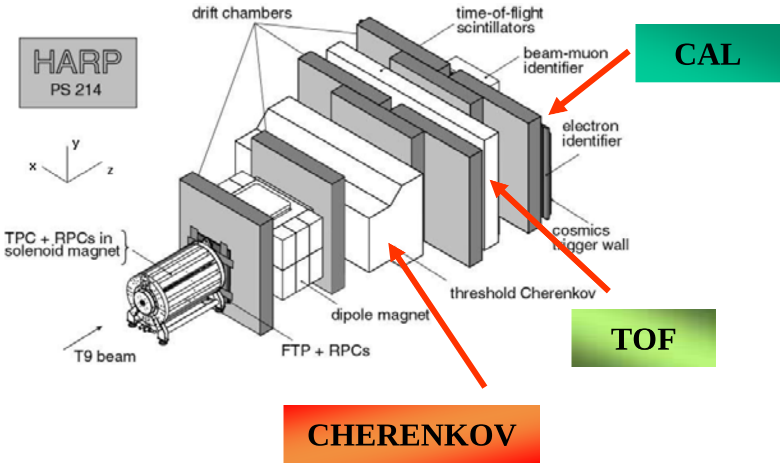


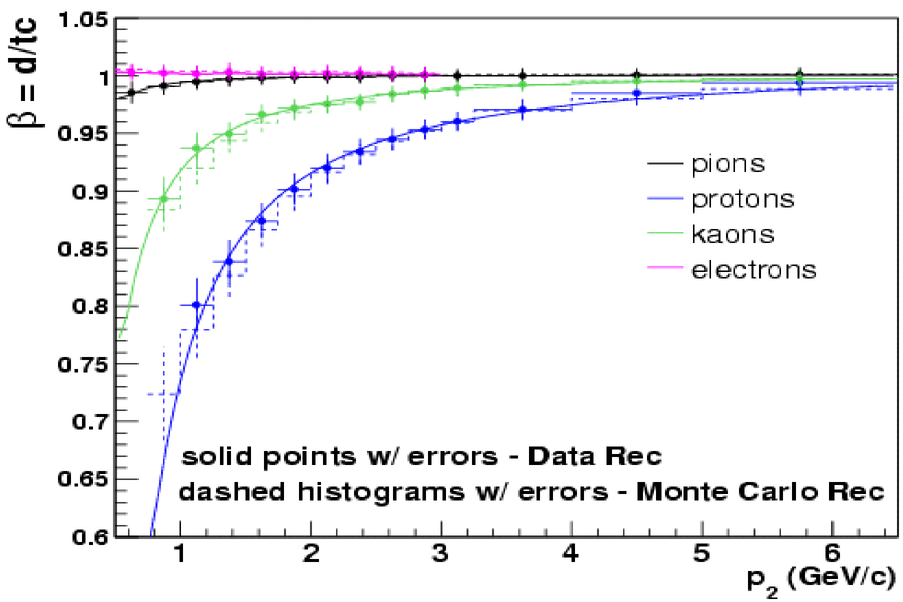
- momentum resolution can be mapped out directly from data using :
  - empty target data (bottom)
  - deconvolve beta and momentum (top)
  - elastic scattering events (not shown)
- simulation can be adjusted to match data resolutions so one can use Monte Carlo to generate unsmearing matrices

(C. Meurer and J. Panman)

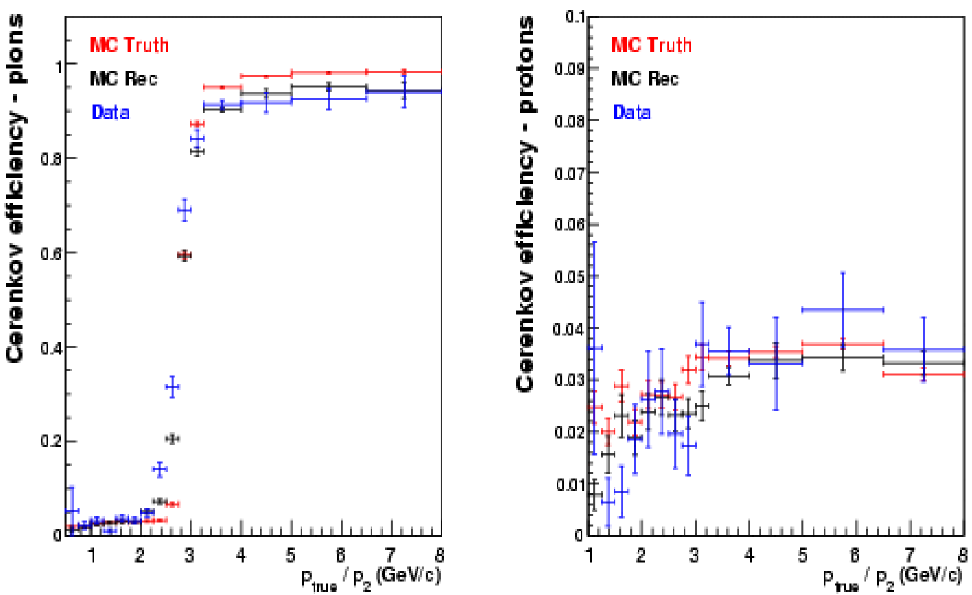
Particle identification







TOF π/p/K response



CHERENKOV π/p response

ELSEVIER

Available online at www.sciencedirect.com
SCIENCE DIRECT

Nuclear Physics B 732 (2006) 1–45

NUCLEAR PHYSICS B

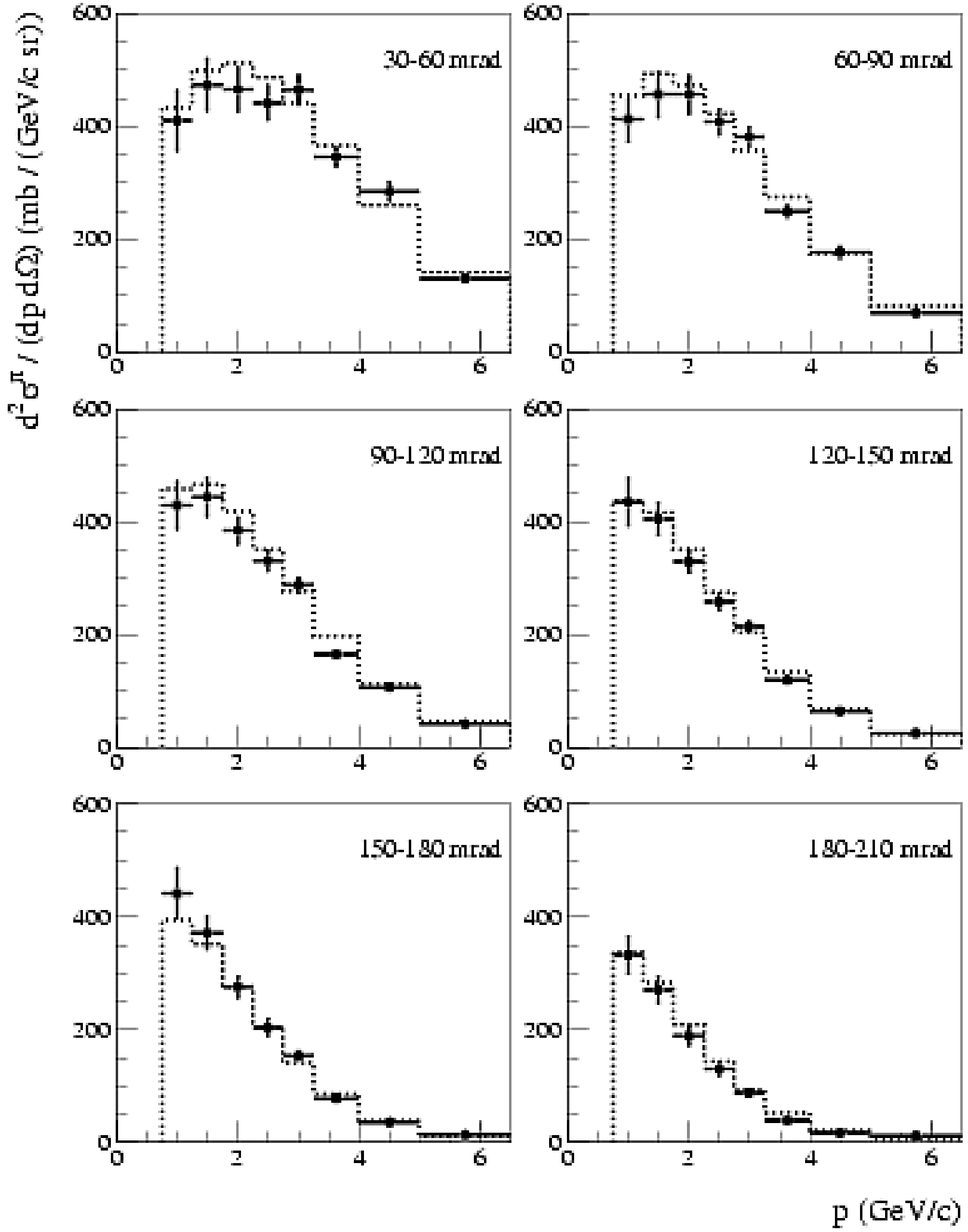
First HARP Physics Publication

Measurement of the production cross-section of positive pions in p–Al collisions at 12.9 GeV/c

HARP Collaboration

Abstract

A precision measurement of the double-differential production cross-section, $d^2\sigma^{\pi^+}/dp\,d\Omega$, for pions of positive charge, performed in the HARP experiment is presented. The incident particles are protons of 12.9 GeV/c momentum impinging on an aluminium target of 5% nuclear interaction length. The measurement of this cross-section has a direct application to the calculation of the neutrino flux of the K2K experiment. After cuts, 210 000 secondary tracks reconstructed in the forward spectrometer were used in this analysis. The results are given for secondaries within a momentum range from 0.75 to 6.5 GeV/c, and within an angular range from 30 mrad to 210 mrad. The absolute normalization was performed using prescaled beam triggers counting protons on target. The overall scale of the cross-section is known to better than 6%, while the average point-to-point error is 8.2%.



Nucl. Phys. B732 (2006) 1
hep-ex/0510039

θ_π = [30, 60, 90, 120, 150, 180, 210] mrad

p_π = [0.75 – 6.5] GeV/c

typical error on point = 8.7 %

error on integral = 4.7 %

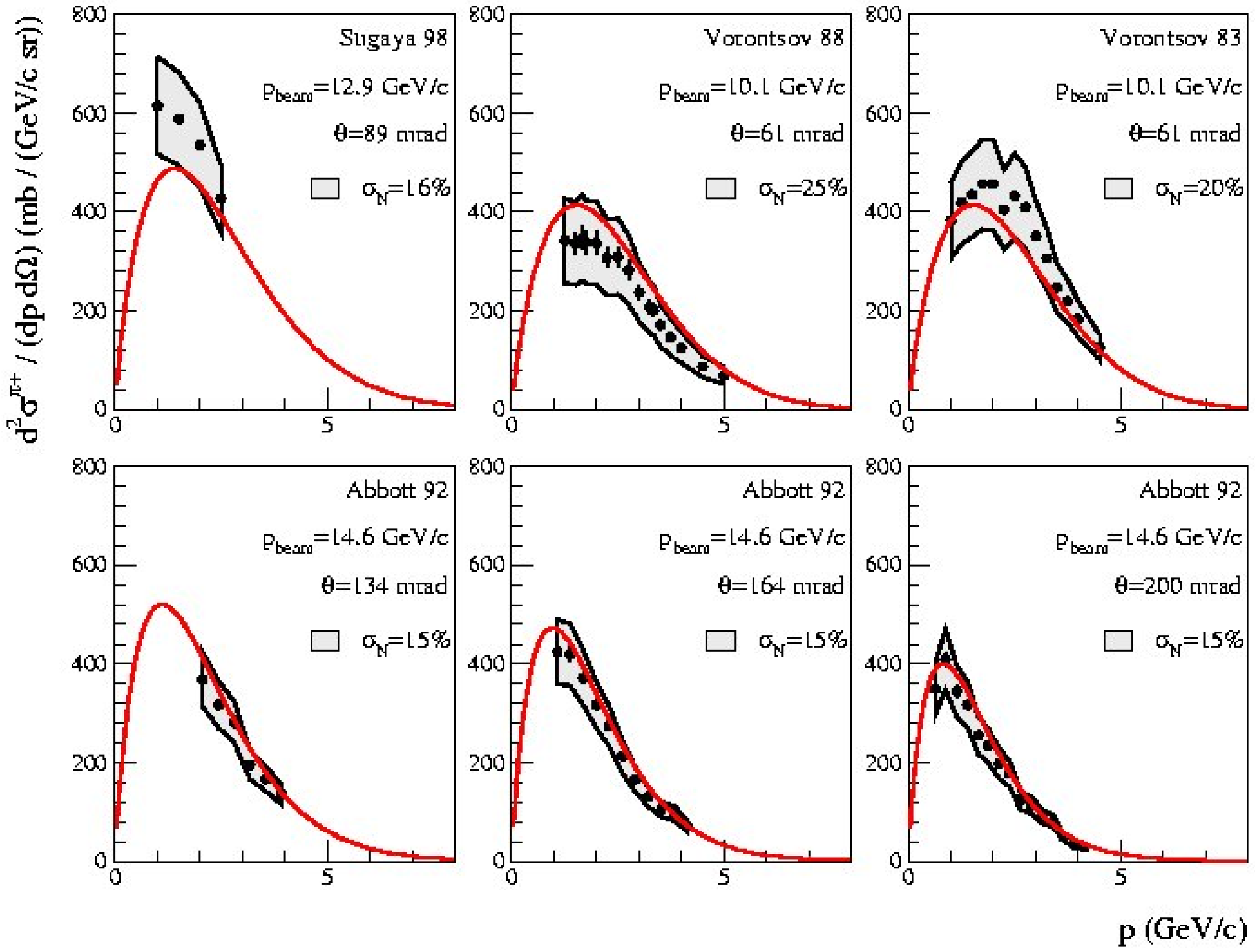
full covariance error matrix generated and used for fitting to parameterizations

diagonal errors shown on data points

p(12.9 GeV/c) + Al -> π^+ + X

Comparison to other aluminum cross-section measurements

Nucl. Phys. B732 (2006) 1
hep-ex/0510039



- find experiments that measured pion cross-sections from aluminum at near 13 GeV/c proton momentum and forward angles

Sugaya 98	12.9 GeV/c	89 mrad
Voronstov 88	10.1 GeV/c	61 mrad
Voronstov 83	10.1 GeV/c	61 mrad
Abbott 92	14.6 GeV/c	134-200 mrad

- use smooth fit to HARP data to extrapolate to p_{beam} and p_π, θ_π of other experimental results

Upcoming HARP Physics Publication

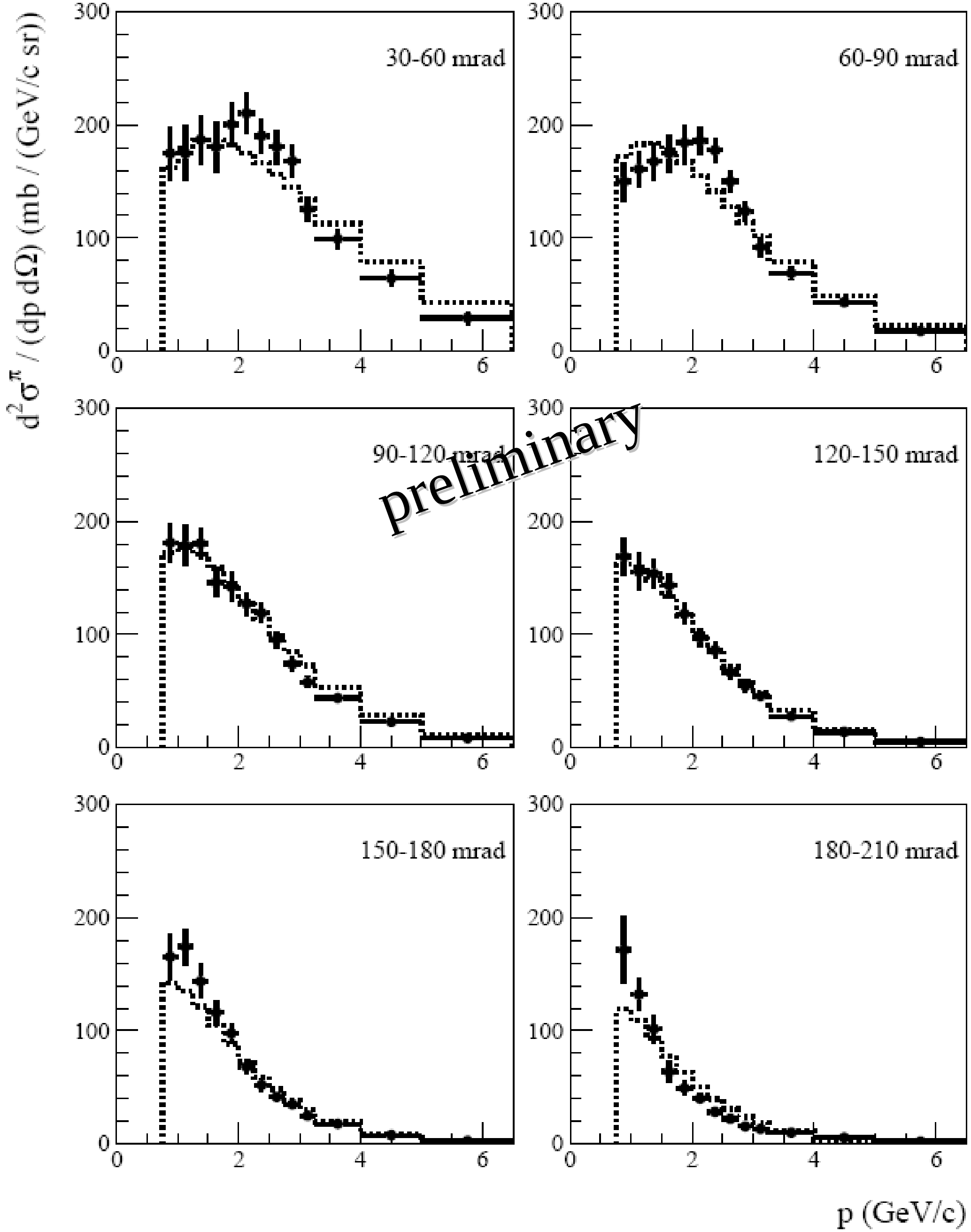
Measurement of the production cross-section of positive pions in the collision of 8.9 GeV/c protons on beryllium

HARP Collaboration

December 14, 2006

Abstract

The double-differential production cross-section of positive pions, $d^2\sigma^{\pi^+}/dpd\Omega$, measured in the HARP experiment is presented. The incident particles are 8.9 GeV/c protons directed onto a beryllium target with a nominal thickness of 2.0455 cm or approximately 5% of a nuclear interaction length. This cross-section has a direct impact on the prediction of neutrino fluxes for the MiniBooNE and SciBooNE experiments at Fermilab. After cuts, 13 million protons on target produced 96,000 reconstructable secondary tracks which were used in this analysis. Cross-section results will be presented in the kinematic range from 0.75 GeV/c $\leq p_\pi \leq$ 6.5 GeV/c and 30 mrad $\leq \theta_\pi \leq$ 210 mrad in the laboratory frame.



Internal draft

θ_π = [30, 60, 90, 120, 150, 180, 210] mrad

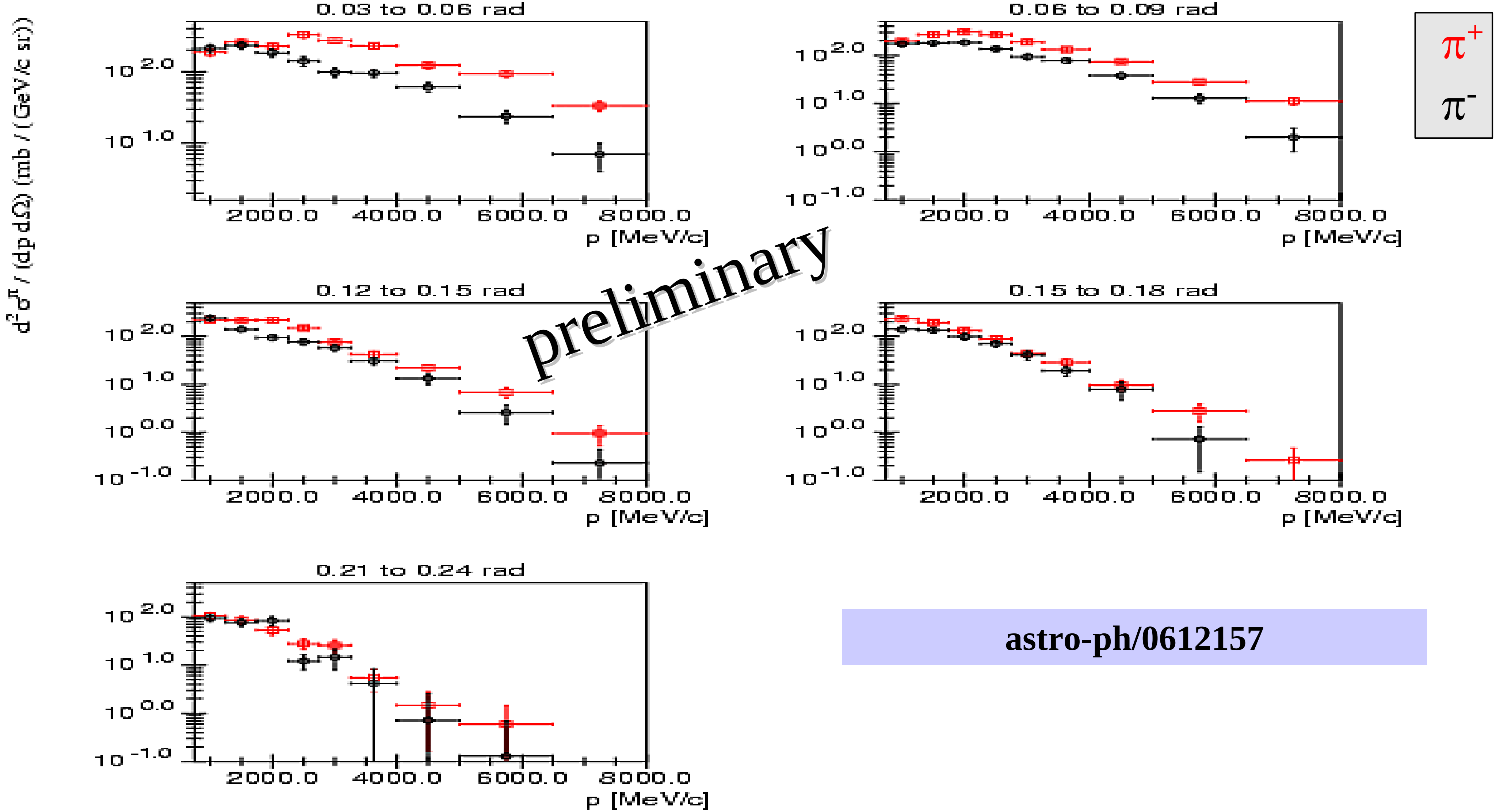
p_π = [0.75 – 6.5] GeV/c

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

p(8.9 GeV/c) + Be -> π^+ + X



astro-ph/0612157

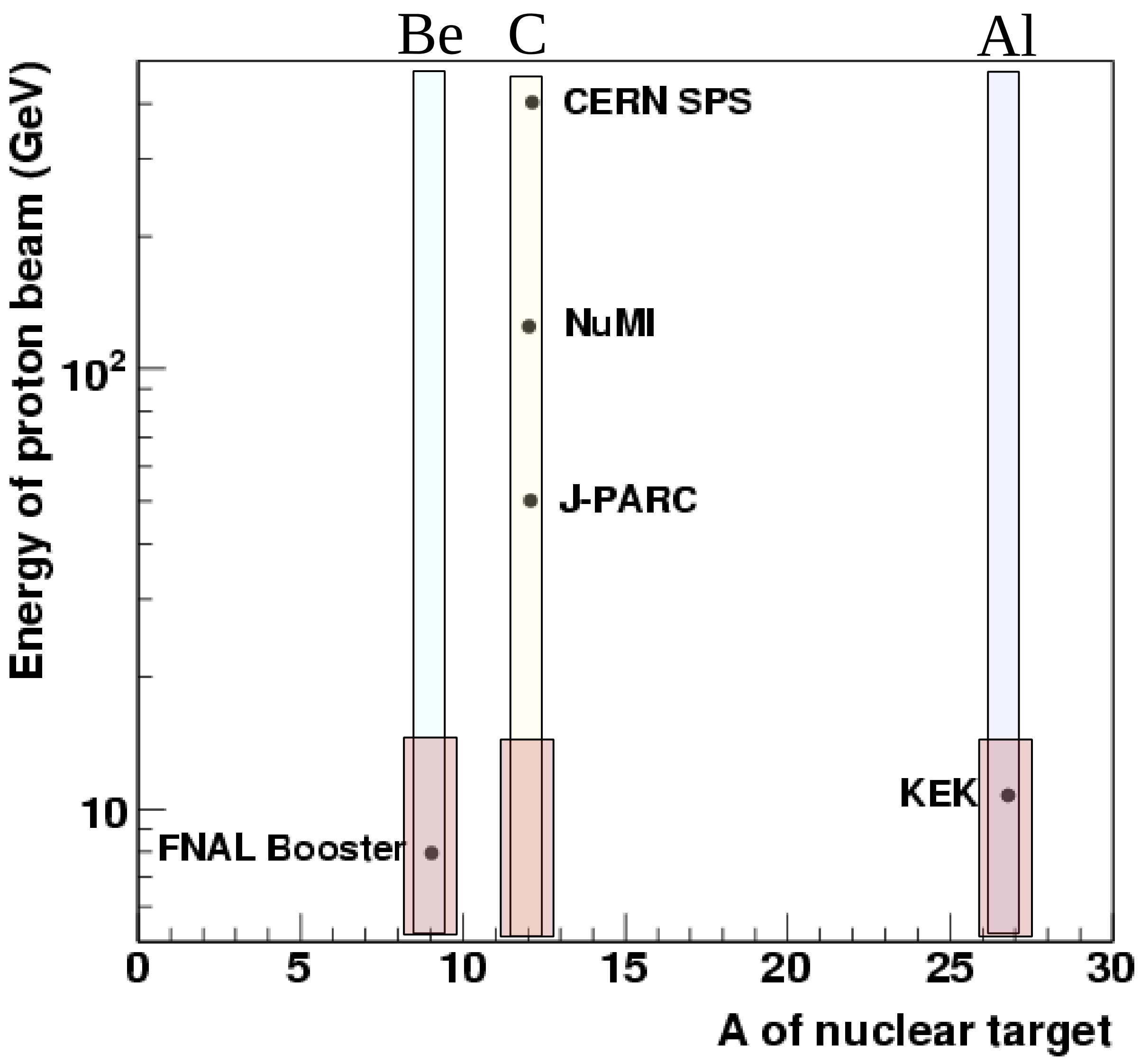
p(12 GeV/c) + C -> $\pi^{+/-}$ + X

θ_π = [30, 60, 90, 120, 150, 180, 210, 240] mrad

p_π = [0.75 – 8.0] GeV/c

(C. Meurer)

“neutrino beam-line parameter space”



HARP

3, 5, 8, 12, 15 GeV/c on Be, C, Al

E910 at Brookhaven

R. A. Fernow, S. Gushue, H. G. Kirk, R. B. Palmer, L. Remsberg
Brookhaven National Laboratory, Upton, New York 11973

I. Chemakin, B. A. Cole, H. Hiejima, M. Moulson, D. L. Winter, X. Yang, W. A. Zajc, Y. Zhang
Columbia University, New York, New York 10027

A. D. Frawley, N. Maeda
Florida State University, Tallahassee, Florida 32306

M. Rosati
Iowa State University, Ames, Iowa 50010

M. Justice
Kent State University, Kent, Ohio 44242

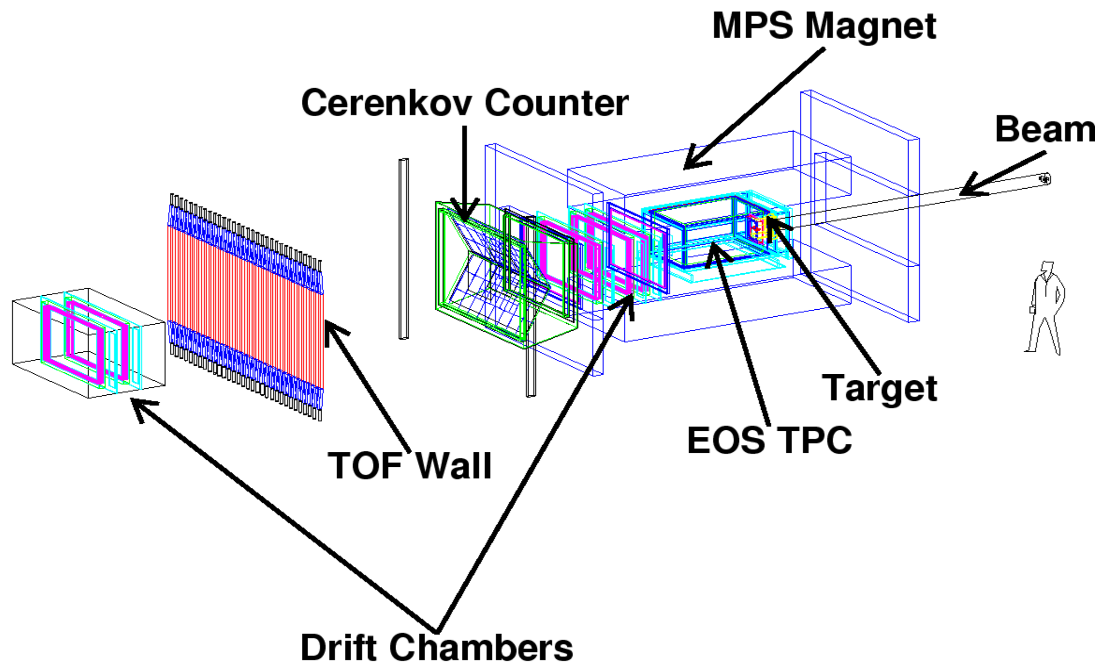
G. Rai
Lawrence Berkeley National Laboratory, Berkeley, California 94720

V. Cianciolo, E. P. Hartouni, M. N. Namboodiri, R. A. Soltz, J. H. Thomas
Lawrence Livermore National Laboratory, Livermore, California 94550

M. Gilkes, R. L. McGrath, Y. Torun
State University of New York at Stony Brook, Stony Brook, New York 11794

S. Mioduszewski, D. Morrison, K. Read, S. Sorensen
University of Tennessee, Knoxville, Tennessee 37996

J. H. Kang, Y. Shin
Yonsei University, Seoul 120-749, Korea



- the main objective is to study nuclear processes relevant to relativistic heavy ion collisions

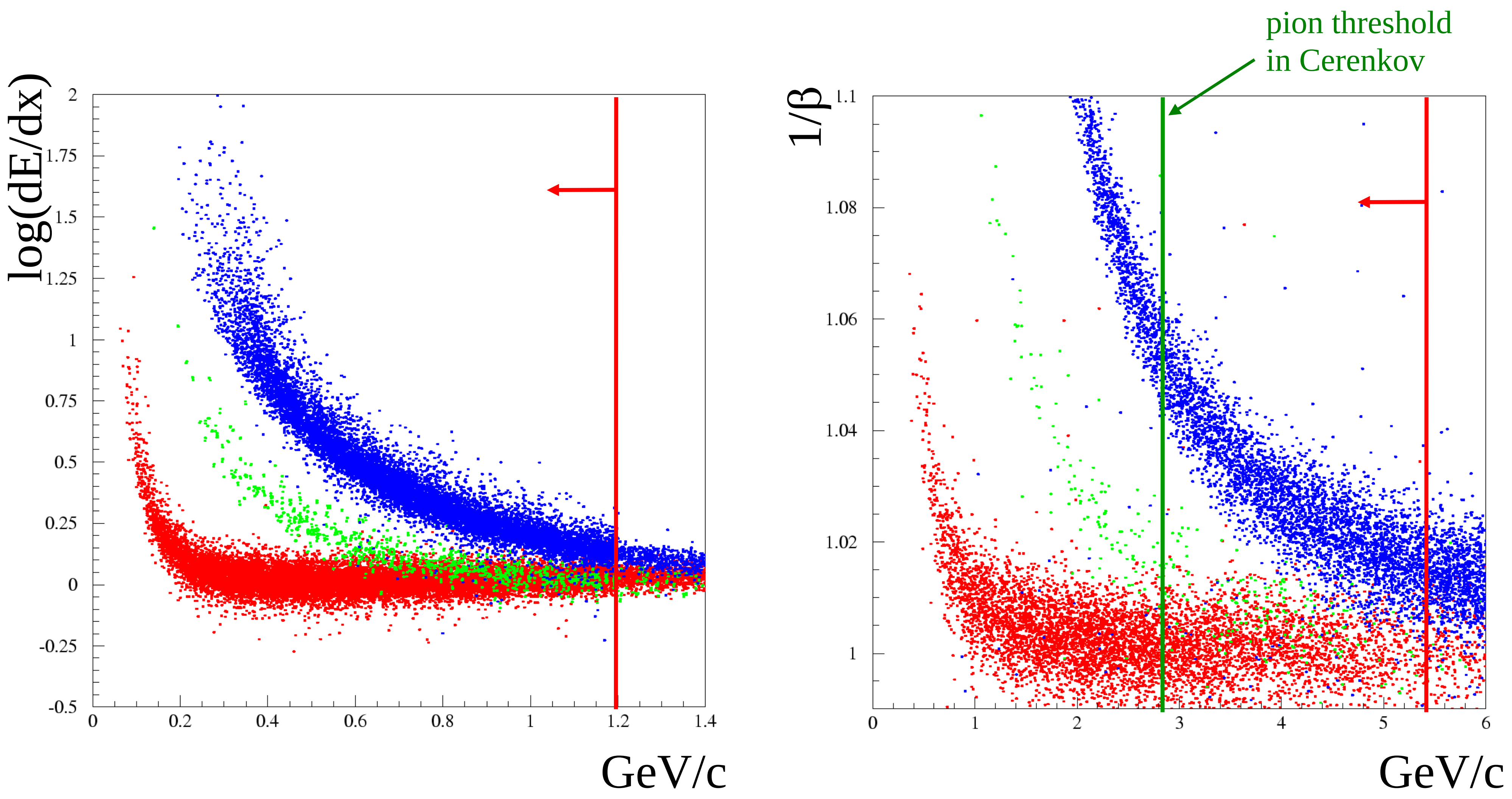
"Antiproton production in *p+A* collisions at 12.3 and 17.5 GeV/*c*" (Phys.Rev.C64:064908)

"Semi-inclusive Λ⁰ and K_s production in *p*-Au collisions at 17.5 *GeV/c*" (Phys.Rev.Lett.85:4868)

"Measuring centrality with slow protons in proton-nucleus collisions at 18 GeV/*c*" (Phys.Rev.C.60:024902)

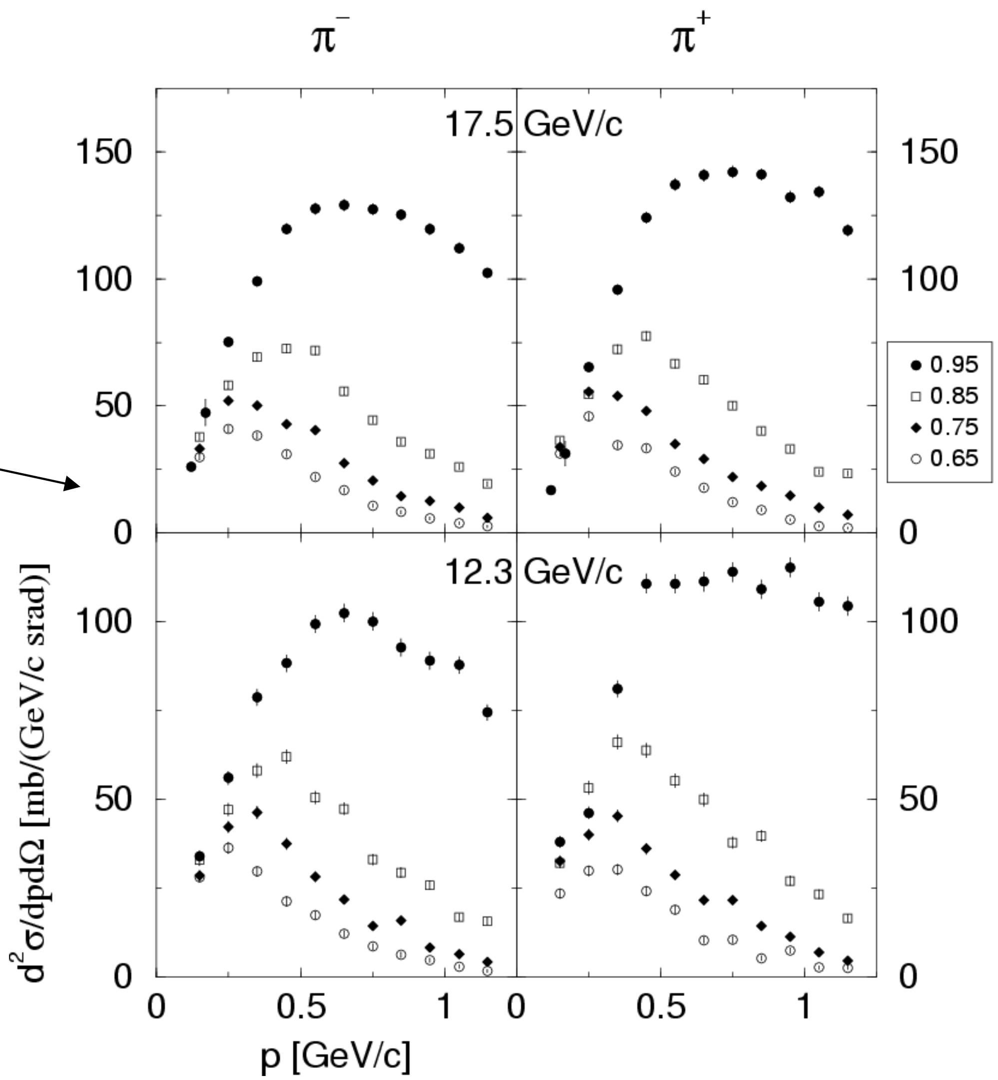
"Strange particle production and an H-dibaryon search in *p+A* collisions at the AGS" (Nucl.Phys.A639:407-416)

Particle identification



“Inclusive soft pion production from 12.3 and 17.5 GeV/c protons on Be, Cu and Au” (Phys. Rev. C65:024904)

p+Be data



- first published pion cross-section measurement was for low momentum, large angle production with a minimal impact on a conventional neutrino beam

p_{beam} = 12.3, 17.6 GeV/c

p = 0.1 – 1.2 GeV/c

θ = 300 – 800 mrad

Pion production by protons on a Be target at 6.4, 12.3 and 17.6 GeV/c using E910 data (in preparation)

- first published pion cross-section measurement was for low momentum, large angle production with a minimal impact on a conventional neutrino beam

p_{beam} = 12.3, 17.6 GeV/c

p = 0.1 – 1.2 GeV/c

θ = 300 – 800 mrad

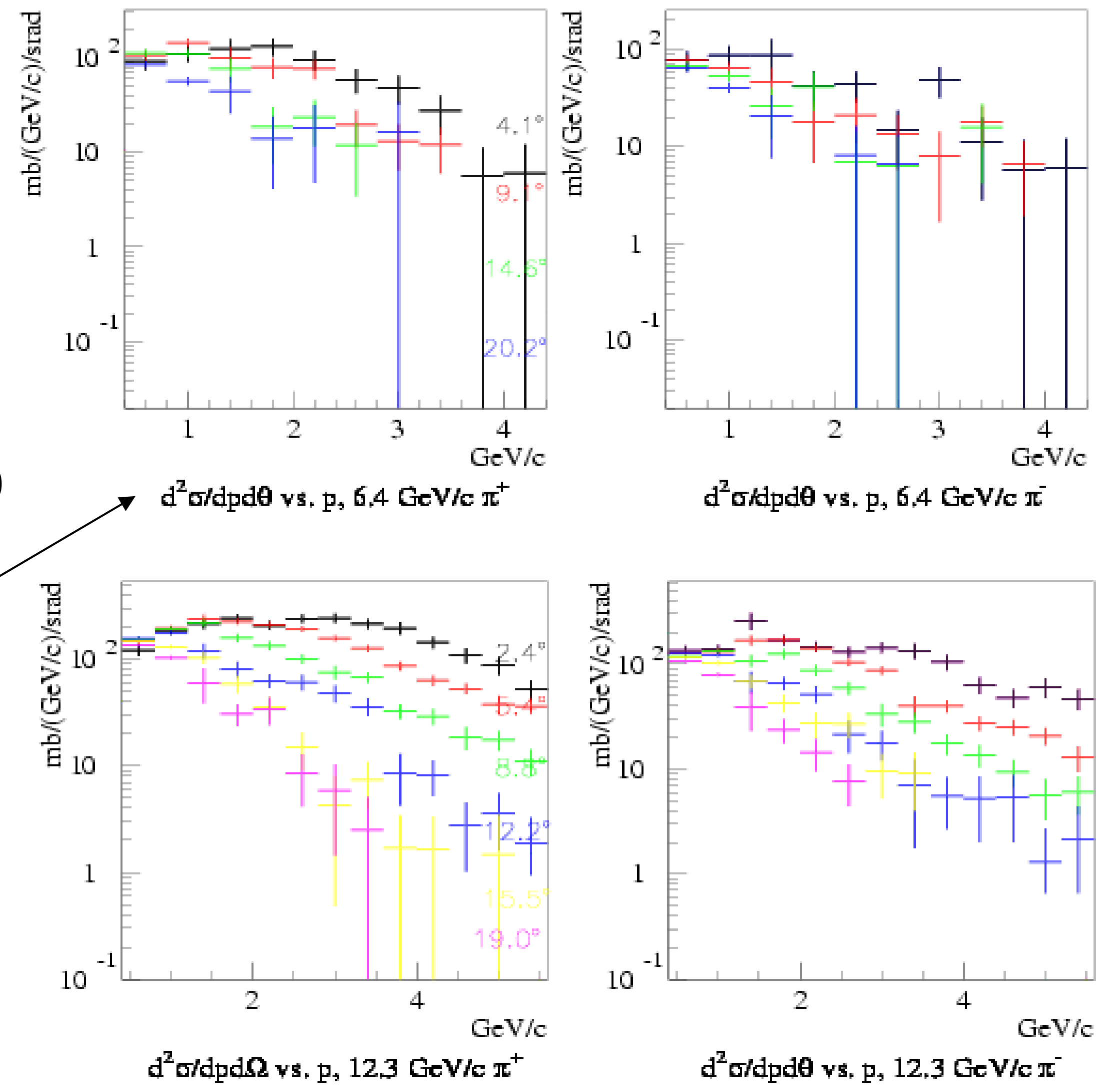
- the analysis by J. Link (contribution to NuFact'06) extended this measurement to forward angles and higher momenta

p_{beam} = 6.4, 12.3, 17.6 GeV/c

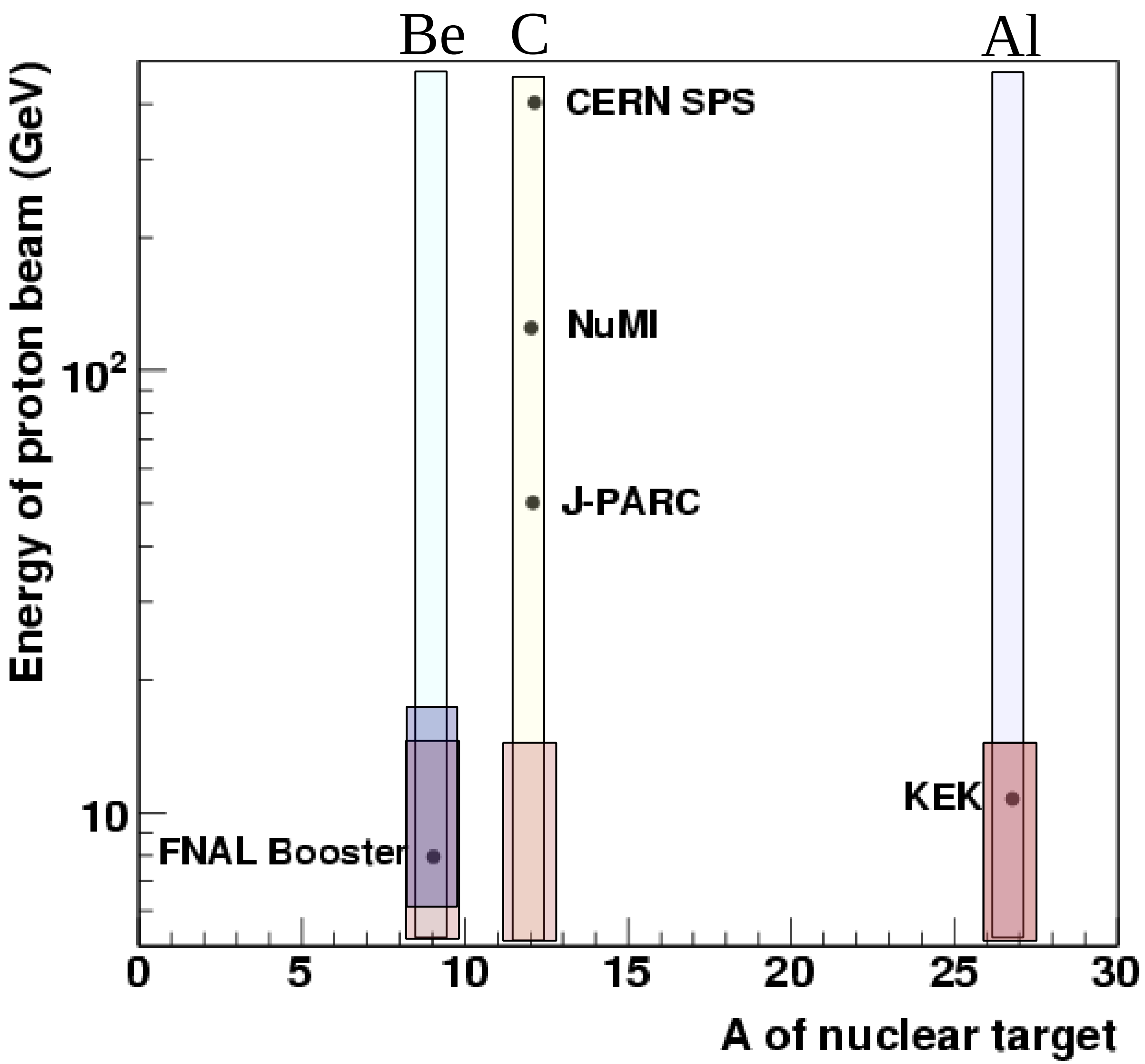
p = 0.4 – 5.6 GeV/c

θ = 0 – 320 mrad

p+Be data (J. Link)



“neutrino beam-line parameter space”



HARP

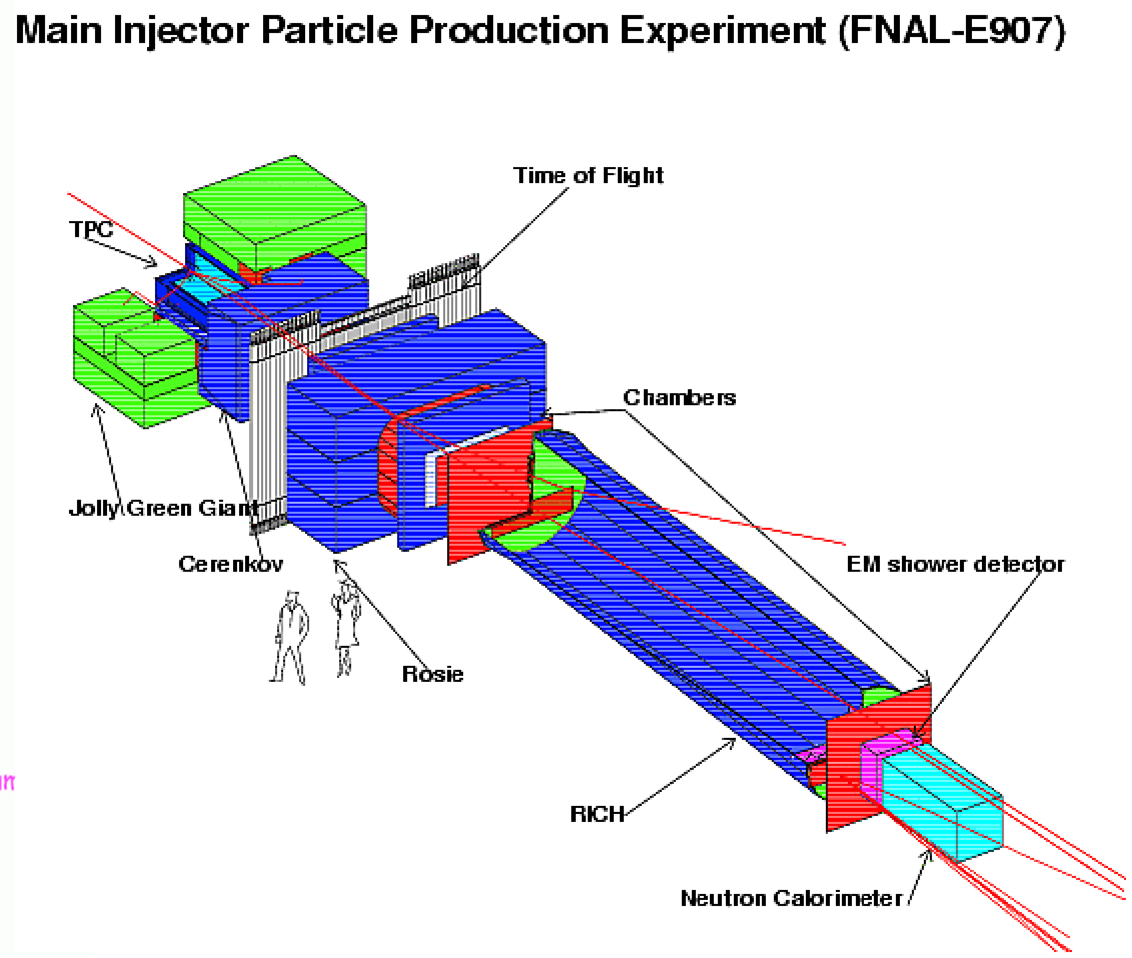
3, 5, 8, 12, 15 GeV/c on Be, C, Al

E910

6.4, 12.3, 17.5 GeV/c on Be

MIPP – E907 at Fermilab

D.Isenhower,M.Sadler,R.Towell,S.Watson
Abilene Christian University
R.J.Peterson
University of Colorado, Boulder
W.Baker,D.Carey, M.Demarteau,C.Johnstone, H.Meyer, R.Raja,W.Wester
Fermi National Accelerator Laboratory
G. Feldman, A.Lebedev, S.Seun
Harvard University
P.Hanlet, O.Kamaev,D.Kaplan, H.Rubin,N.Solomey
Illinois Institute of Technology
U.Akgun,G.Aydin,F.Duru,E.Gülmez,Y.Gunaydin,Y.Onel, A.Penzo
University of Iowa
N.Graf, M. Messier,J.Paley
Indiana University
V.Avdeichicov,R.Leitner,J.Manjavidze,V.Nikitin,I.Rufanov,T.Topuria
Joint Institute for Nuclear reseacrh, Dubna
D.M.Manley,
Kent State University
P.D.BarnesJr.,E.Hartouni,M.Heffner,J.Klay,D.Lange,R.Soltz, D.Wright
Lawrence Livermore Laboratory
H.R.Gustafson,M.Longo,T.Nigmanov, D.Rajaram
University of Michigan
S.P.Kruglov,I.V.Lopatin,N.G.Kozlenko,A.A.Kulbardis,D.V.Nowinsky, A.K.Radkov,V.V.Sun
Petersburg Nuclear Physics Institute, Gatchina, Russia
A.Bujak, L.Gutay,D.E.Miller
Purdue University
T.Bergfeld,A.Godley,S.R.Mishra,C.Rosenfeld
University of South Carolina
C.Dukes,C.Maternick,K.Nelson,A.Norman
University of Virginia

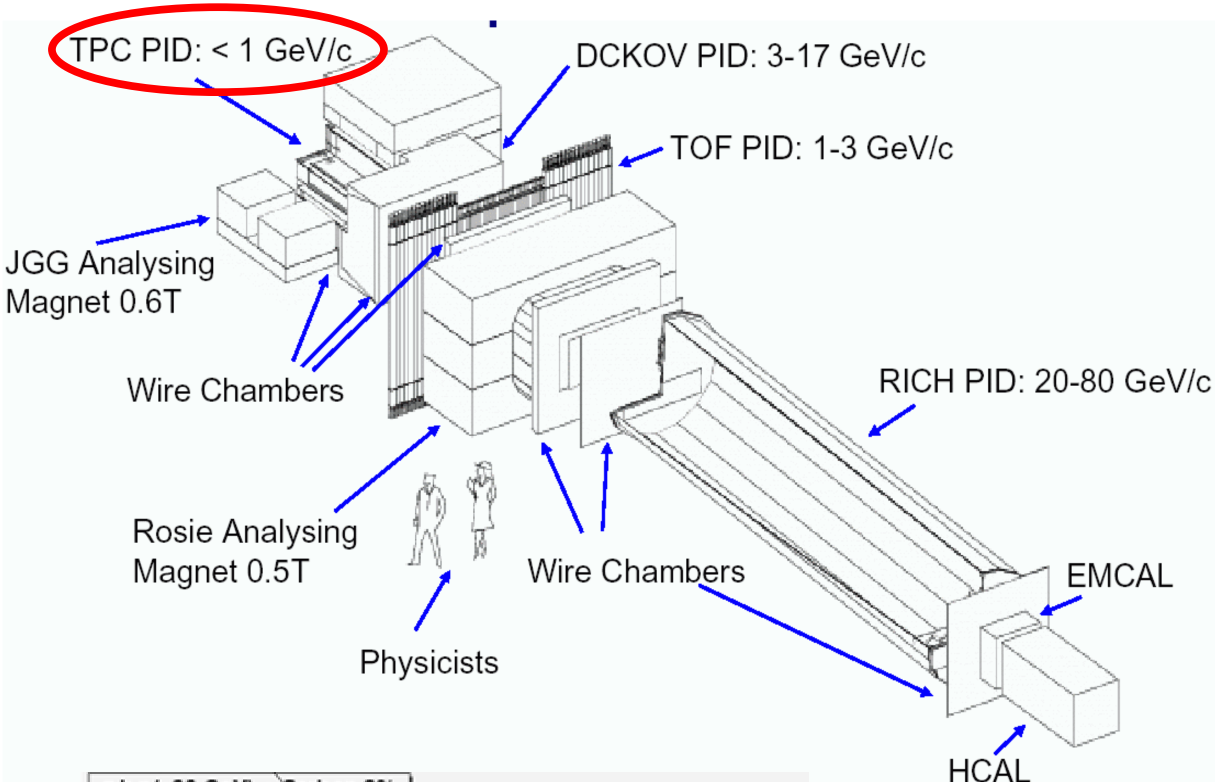


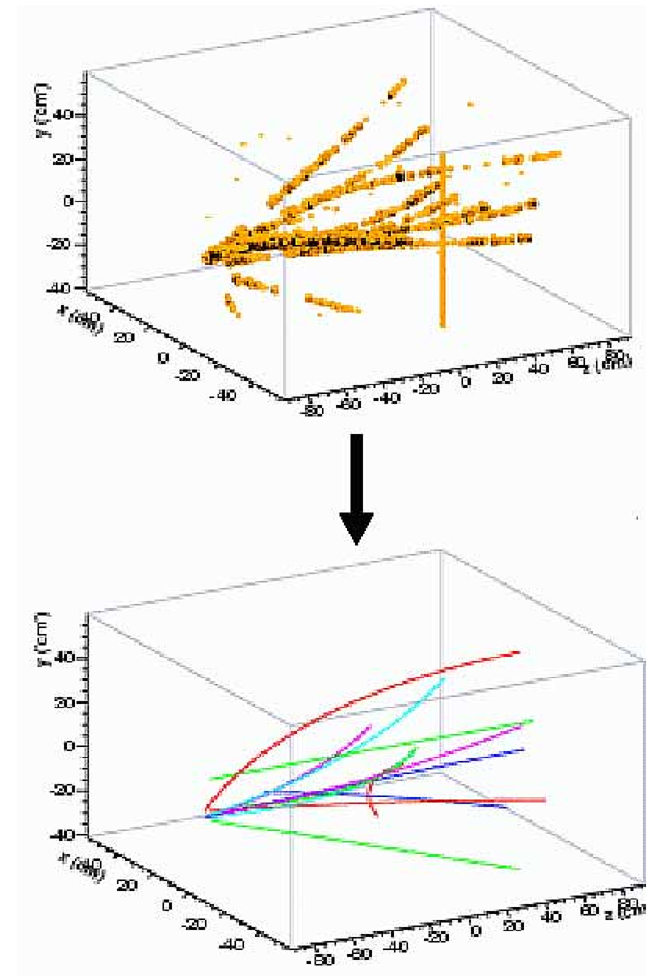
- Uses 120 GeV/c protons from the Fermilab Main Injector to produce a secondary beam of p^{+-}, π^{+-}, K^{+-} from 5 – 85 GeV/c
- Nuclear target materials : H, Be, C, Al, Bi, U
- 120 GeV/c protons on NuMI replica target
- particle ID with TPC, threshold Cerenkov, time-of-flight and RICH

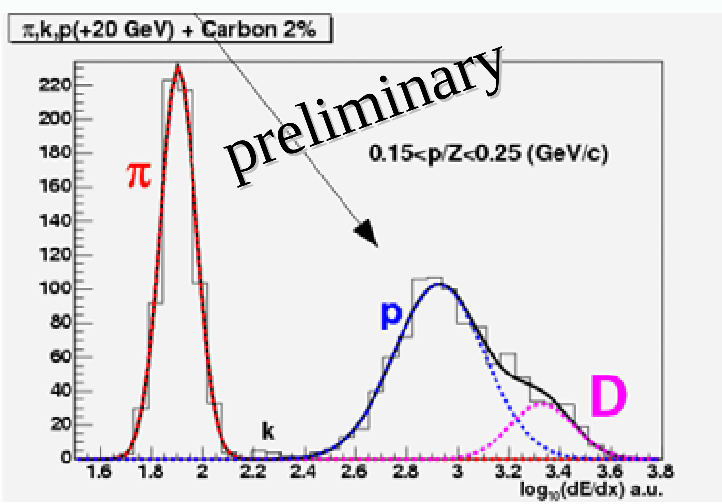
Data Summary 27 February 2006			Acquired Data by Target and Beam Energy Number of events, x 10^6									
Target			E									Total
Z	Element	Trigger Mix	5	20	35	40	55	60	65	85	120	
0	Empty[1]	Normal		*0.10*	*0.14*			*0.52*			*0.25*	***1.01***
	K Mass[2]	No Int.				*5.48*	*0.50*	*7.39*	*0.96*			***14.33***
	Empty LH[1]	Normal		*0.30*				*0.61*		*0.31*		**7.08**
1	LH	Normal	0.21	**1.94**				**1.98**		**1.73**		
4	Be	*p* only									1.08	**1.75**
		Normal			0.10			0.56				
6	C	Mixed						**0.21**				**1.33**
	C 2%	Mixed		**0.39**				**0.26**			**0.47**	
	NuMI	*p* only									**1.78**	**1.78**
13	Al	Normal			*0.10*							***0.10***
83	Bi	*p* only									1.05	**2.83**
		Normal			0.52			1.26				
92	U	Normal						1.18				**1.18**
Total			**0.21**	**2.73**	**0.86**	**5.48**	**0.50**	**13.97**	**0.96**	**2.04**	**4.63**	**31.38**

2005-2006 physics data set

Tracking and particle identification

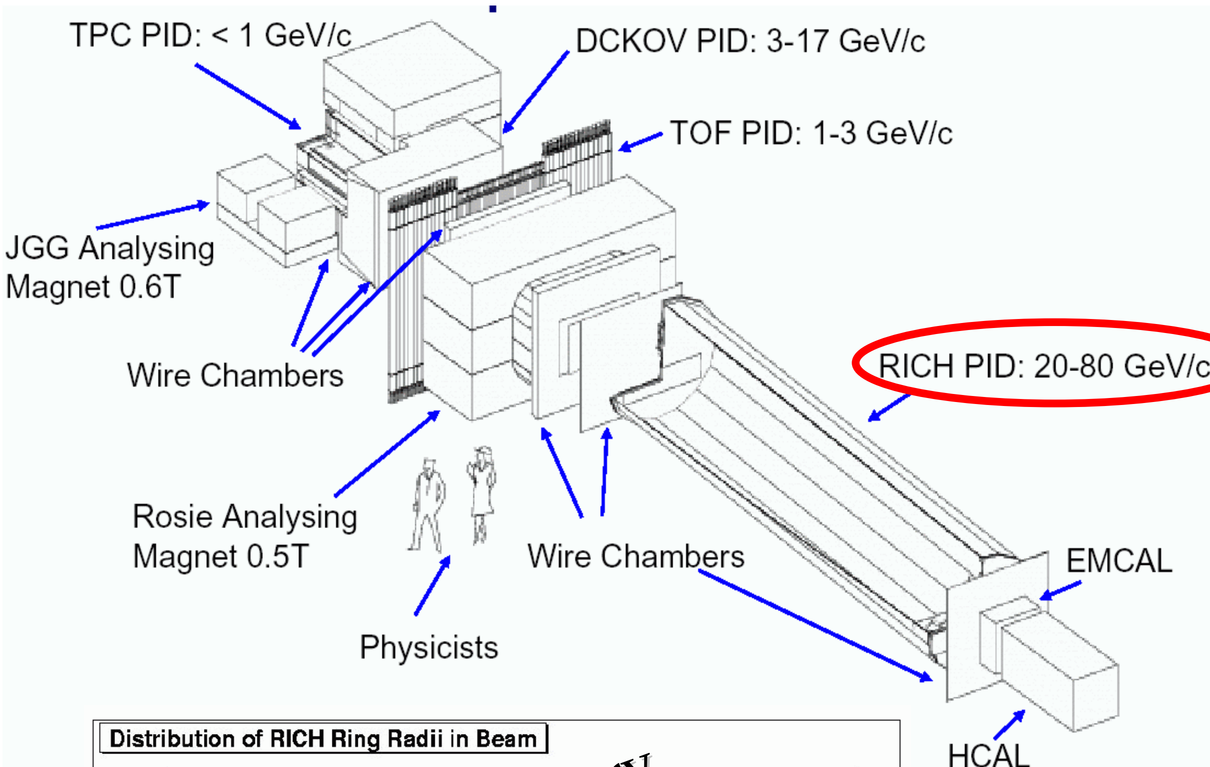


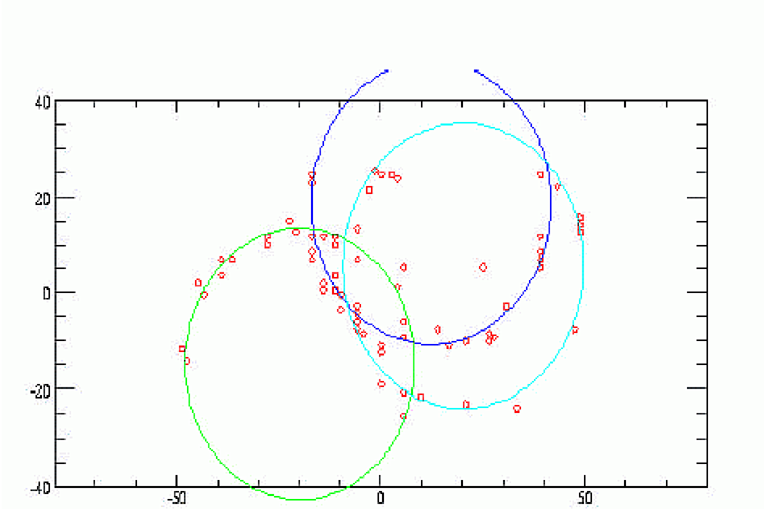


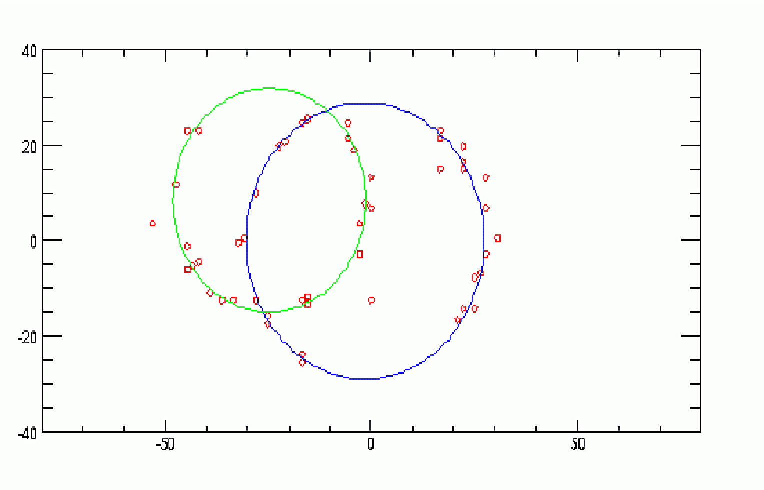


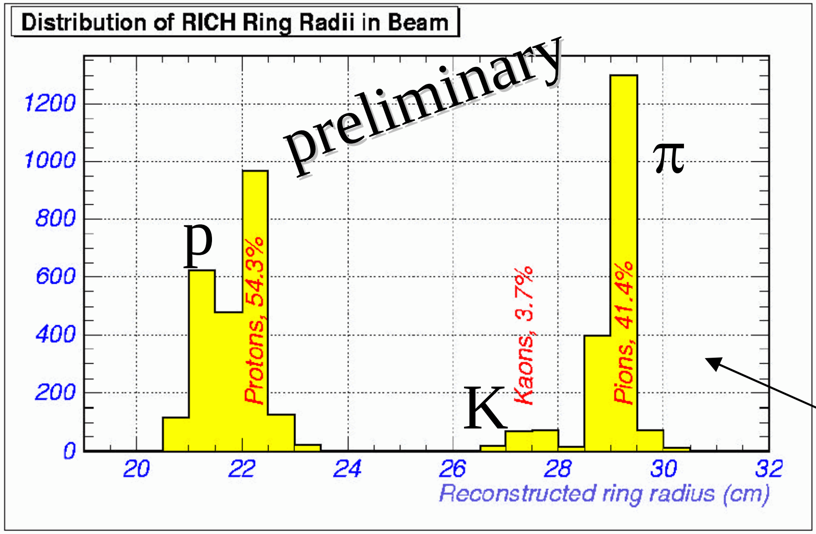
MIPP re-uses the **TPC** from the E910 experiment to get 4π coverage of charged particle tracks coming from the target

Tracking and particle identification





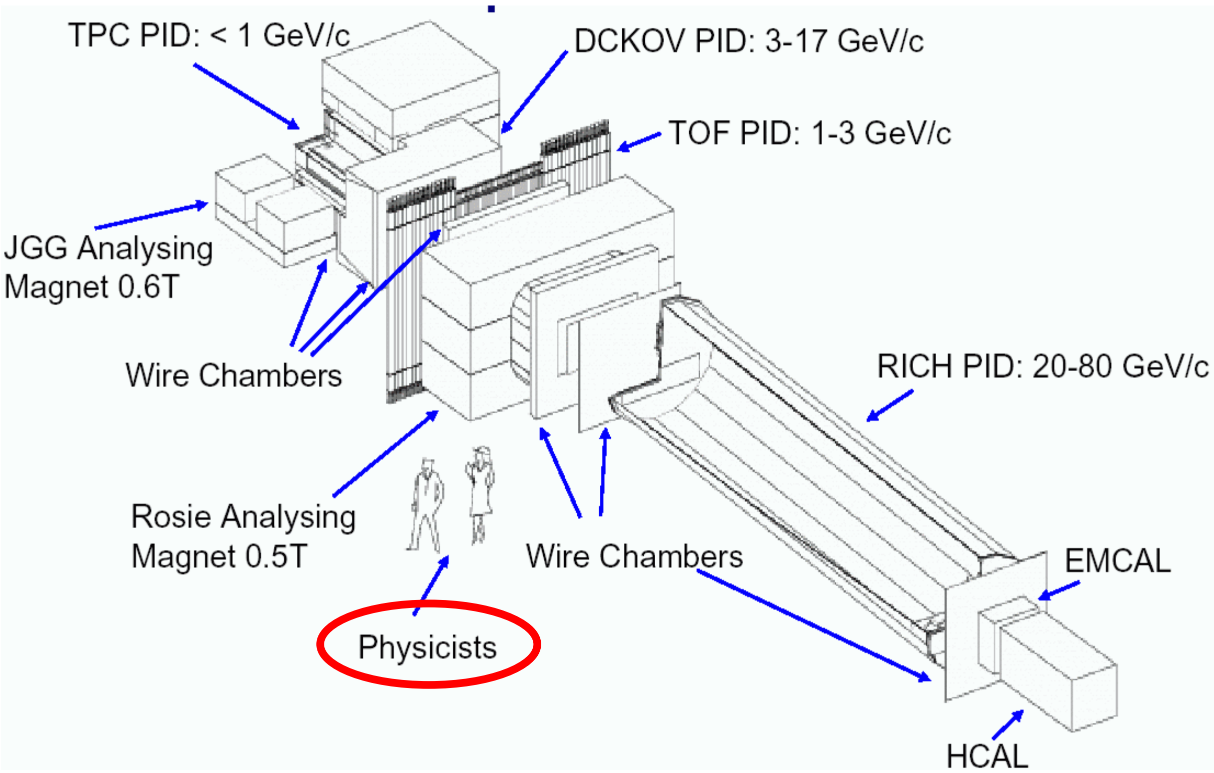




40 GeV/c beam triggers

MIPP uses both a threshold Cerenkov and a CO_2 filled **ring-imaging Cherenkov** detector (RICH) refurbished from SELEX

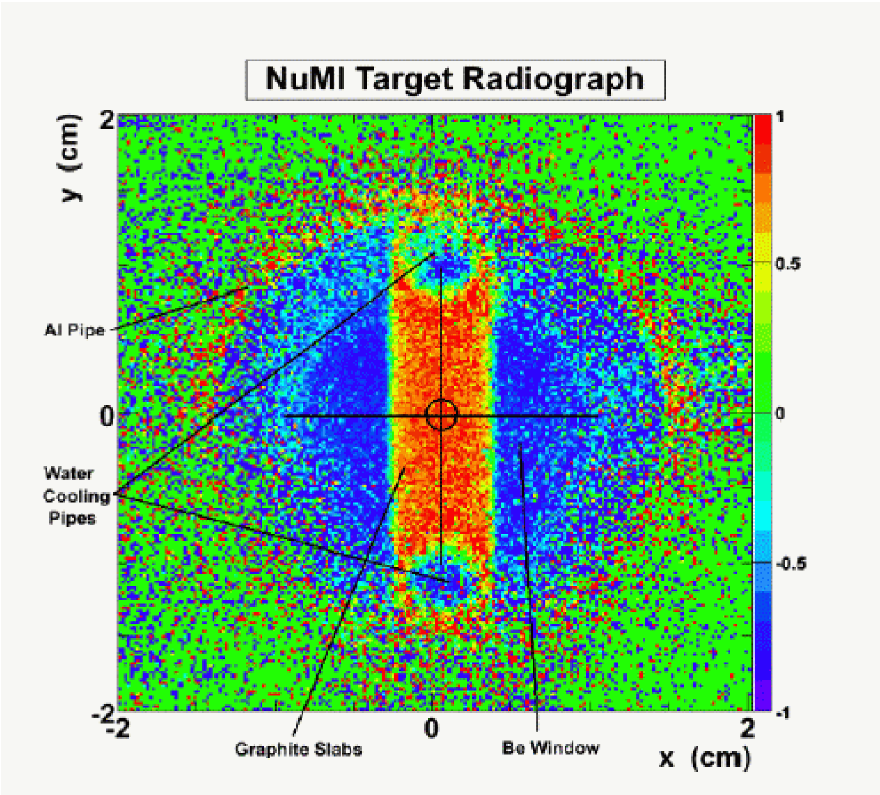
Tracking and particle identification

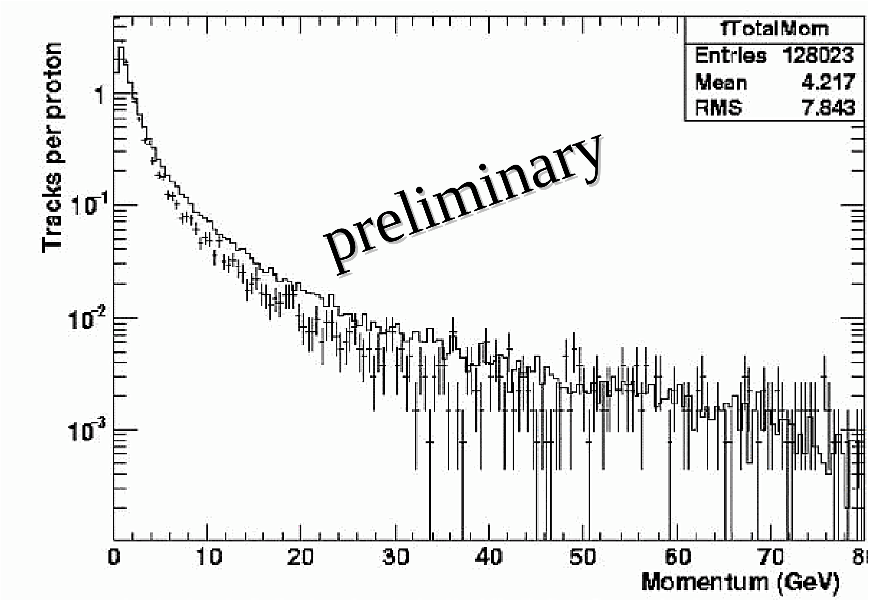


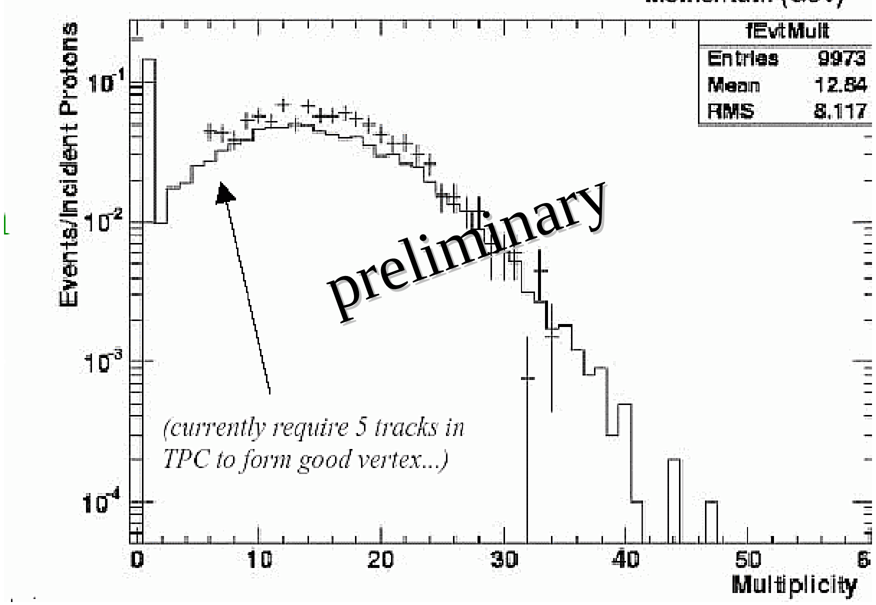
soliciting good physicists photos for this slot. slide 36 seemed a good place to wake people back up!

And all experiments use my personal favorite detector. . . the physicist.

Preliminary particle distributions



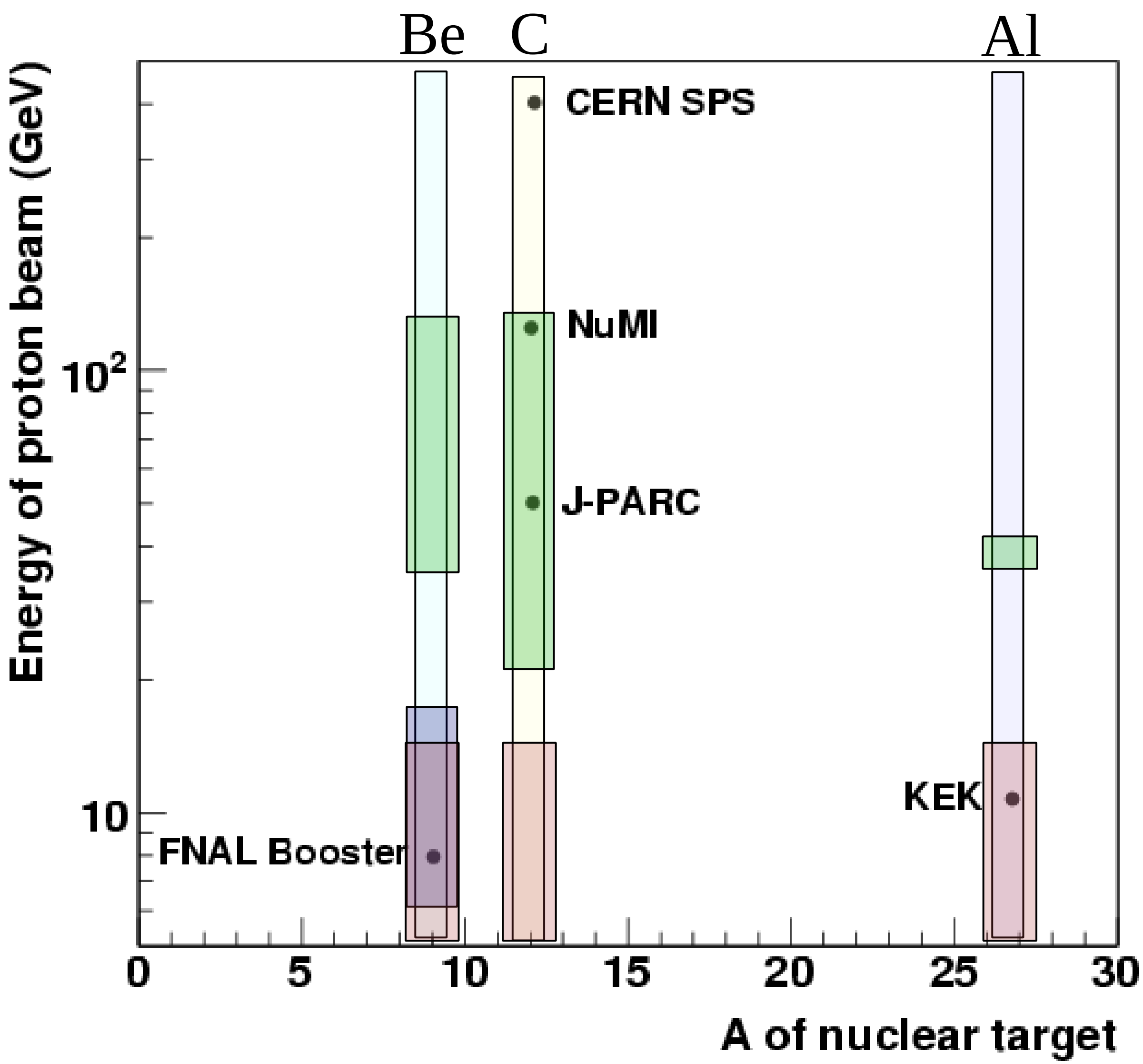




- very preliminary charged multiplicity distribution (bottom) and inclusive momentum distribution (top) for NuMI target at 120 GeV/c

- comparison is to a FLUKA simulation

“neutrino beam-line parameter space”



MIPP

35, 60, 120 GeV/c on Be
20, 35, 60, 120 GeV/c on C
35 GeV/c on Al

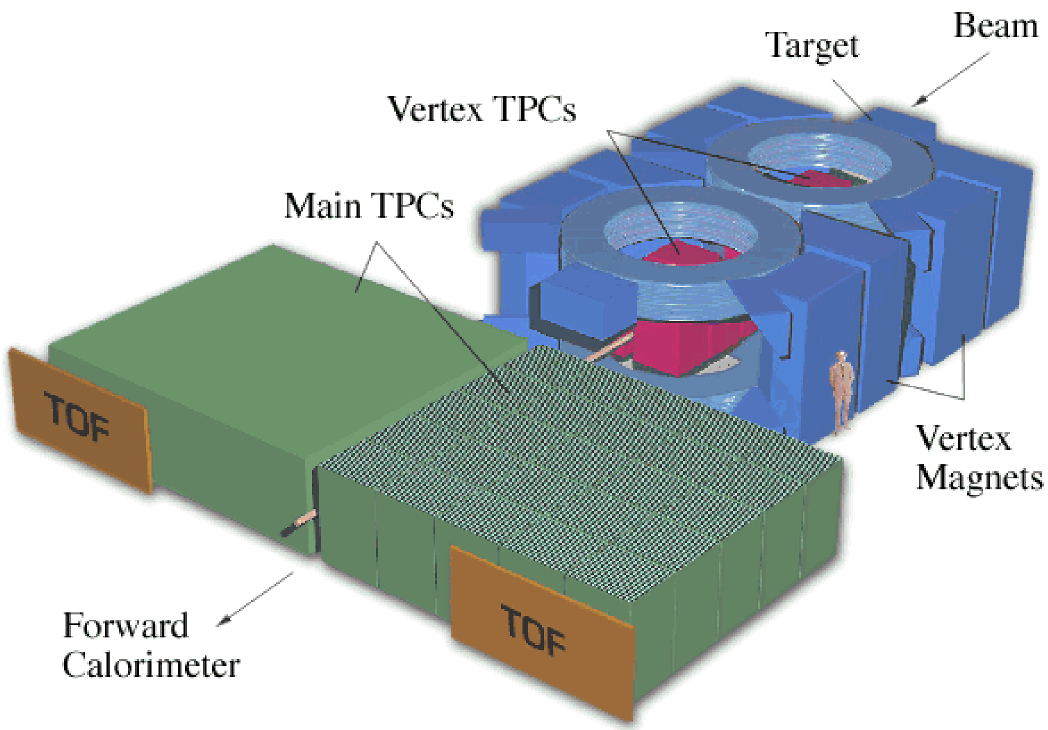
HARP

3, 5, 8, 12, 15 GeV/c on Be, C, Al

E910

6.4, 12.3, 17.5 GeV/c on Be

NA49 at CERN



NA49 Physics Author List

last modified: June 21, 2006

C. Alt[9], T. Anticic[21], B. Baatar[8], D. Barna[4], J. Bartke[6], L. Betev[10], H. Bialkowska[19], C. Blume[9], B. Boimska[19], M. Botje[1], J. Bracinik[3], R. Bramm[9], P. Bunčić[10], V. Cerny[3], P. Christakoglou[2], O. Chvala[14], J.G. Cramer[16], P. Csató[4], P. Dinkelaker[9], V. Eckardt[13], D. Flierl[9], Z. Fodor[4], P. Foka[7], V. Friese[7], J. Gál[4], M. Gaździcki[9,11], V. Genchev[18], G. Georgopoulos[2], E. Gladysz[6], K. Grebieszkow[20], S. Hegyi[4], C. Höhne[7], K. Kadija[21], A. Karev[13], M. Kliemant[9], S. Kniege[9], V.I. Kolesnikov[8], E. Kornas[6], R. Korus[11], M. Kowalski[6], I. Kraus[7], M. Kreps[3], A. Laszlo[4], M. van Leeuwen[1], P. Lévai[4], L. Litov[17], B. Lungwitz[9], M. Makariev[17], A.I. Malakhov[8], M. Mateev[17], G.L. Melkumov[8], A. Mischke[1], M. Mitrovski[9], J. Molnár[4], St. Mrówczyński[11], V. Nicolic[21], G. Pálla[4], A.D. Panagiotou[2], D. Panayotov[17], A. Petridis[2], M. Pikna[3], D. Prindle[16], F. Pühlhofer[12], R. Renfordt[9], C. Roland[5], G. Roland[5], M. Rybczyński[11], A. Rybicki[6], A. Sandoval[7], N. Schmitz[13], T. Schuster[9], P. Seyboth[13], F. Siklér[4], B. Sitar[3], E. Skrzypczak[20], G. Stefanek[11], R. Stock[9], C. Strabel[9], H. Ströbele[9], T. Susa[21], I. Szentpétery[4], J. Sziklai[4], P. Szymanski[10,19], V. Trubnikov[19], D. Varga[4,10], M. Vassiliou[2], G.I. Veres[4,5], G. Vesztergombi[4], D. Vranić[7], A. Wetzler[9], Z. Wlodarczyk[11] I.K. Yoo[15], J. Zimányi[4]

- many publications; these are the most recent. . .

"Inclusive production of charged pions in p+p at 158 GeV/c beam momentum" (Eur.Phys.J.C45:343-381,2006)

"High p(T) spectra of identified particles produced in Pb+Pb collisions at 158-GeV/nucleon beam energy" (Nucl.Phys.A774:473-476,2006)

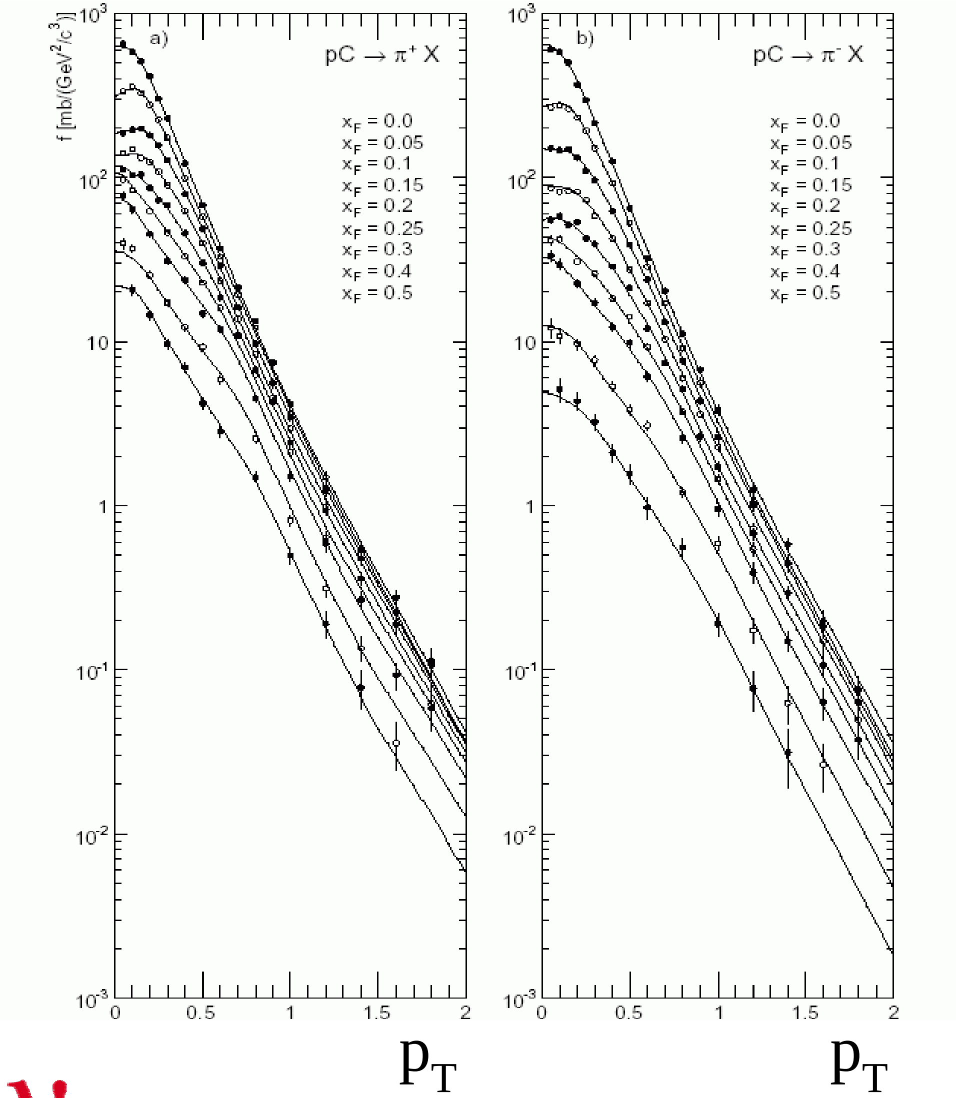
"Elliptic flow of Lambda hyperons in Pb+Pb collisions at 158-AGeV" (Nucl.Phys.A774:499-502,2006)

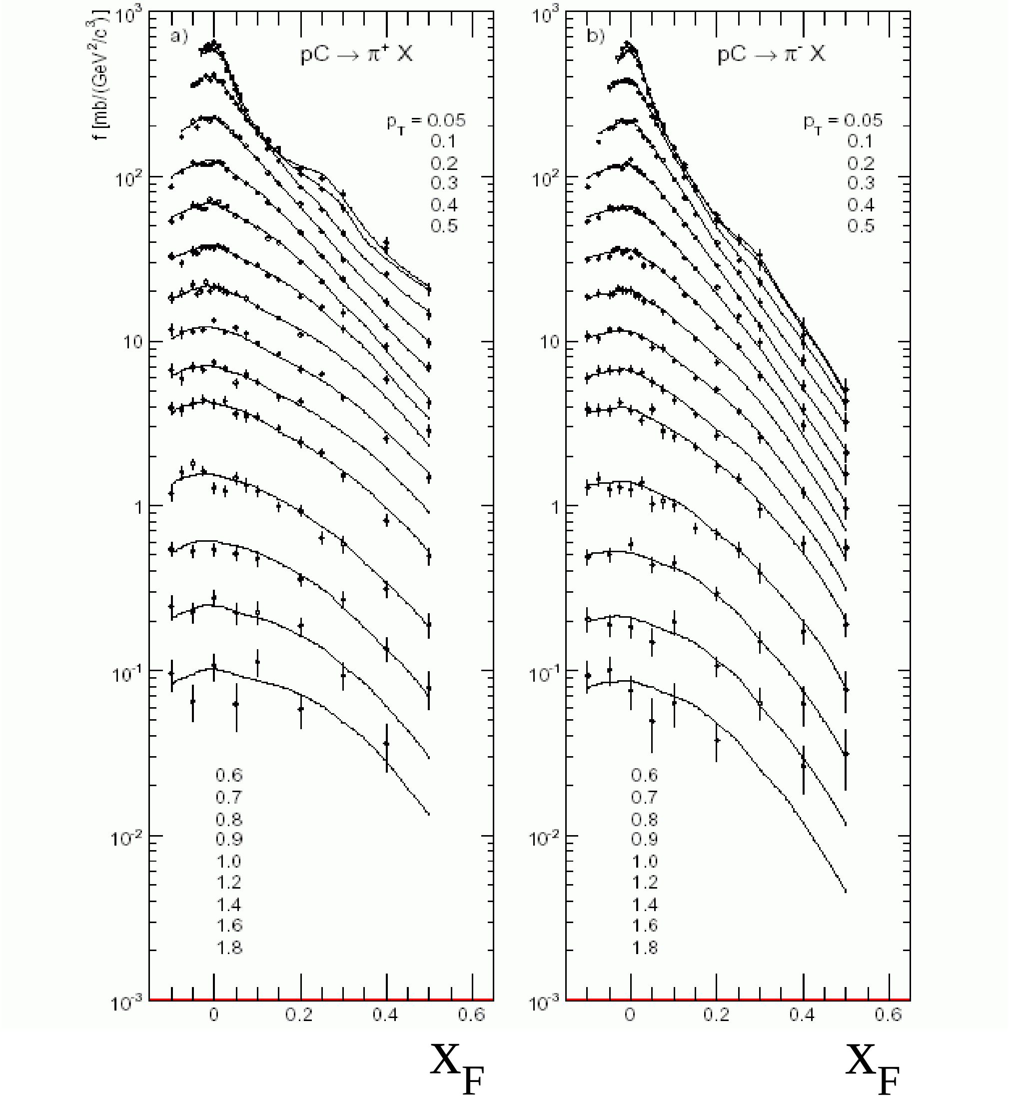
"Upper limit of D0 production in central Pb-Pb collisions at 158-A-GeV" (Phys.Rev.C73:034910,2006)

"Pion production in Pb Pb collisions at the SPS" (Nucl.Phys.A749:304-308,2005)

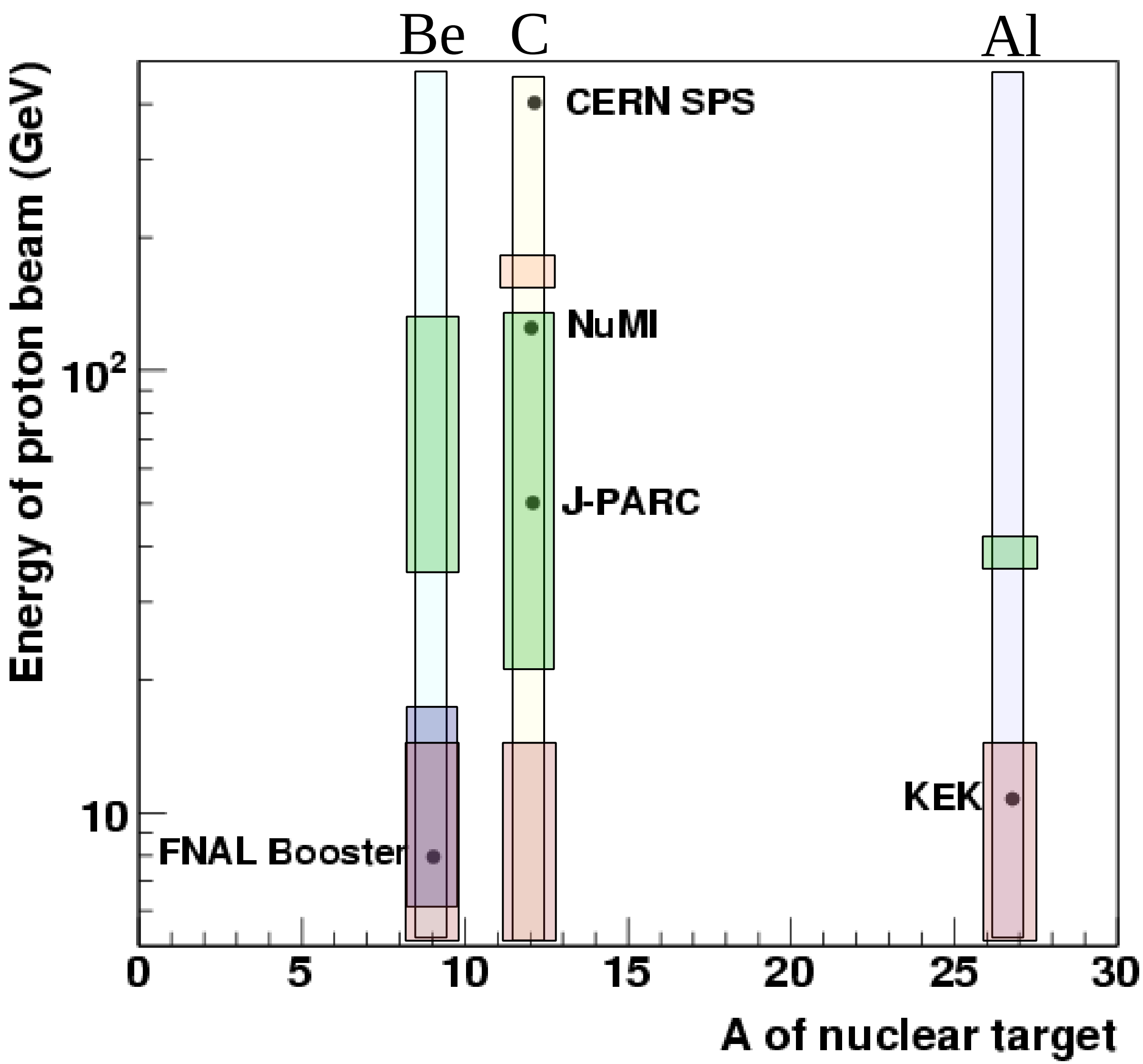
and here is the most relevant. . .

"Inclusive production of charged pions in p+C collisions at 158 GeV/c beam momentum" (hep-ex/0606028)





“neutrino beam-line parameter space”



NA49

158 GeV/c on C

MIPP

35, 60, 120 GeV/c on Be
20, 35, 60, 120 GeV/c on C
35 GeV/c on Al

HARP

3, 5, 8, 12, 15 GeV/c on Be, C, Al

E910

6.4, 12.3, 17.5 GeV/c on Be

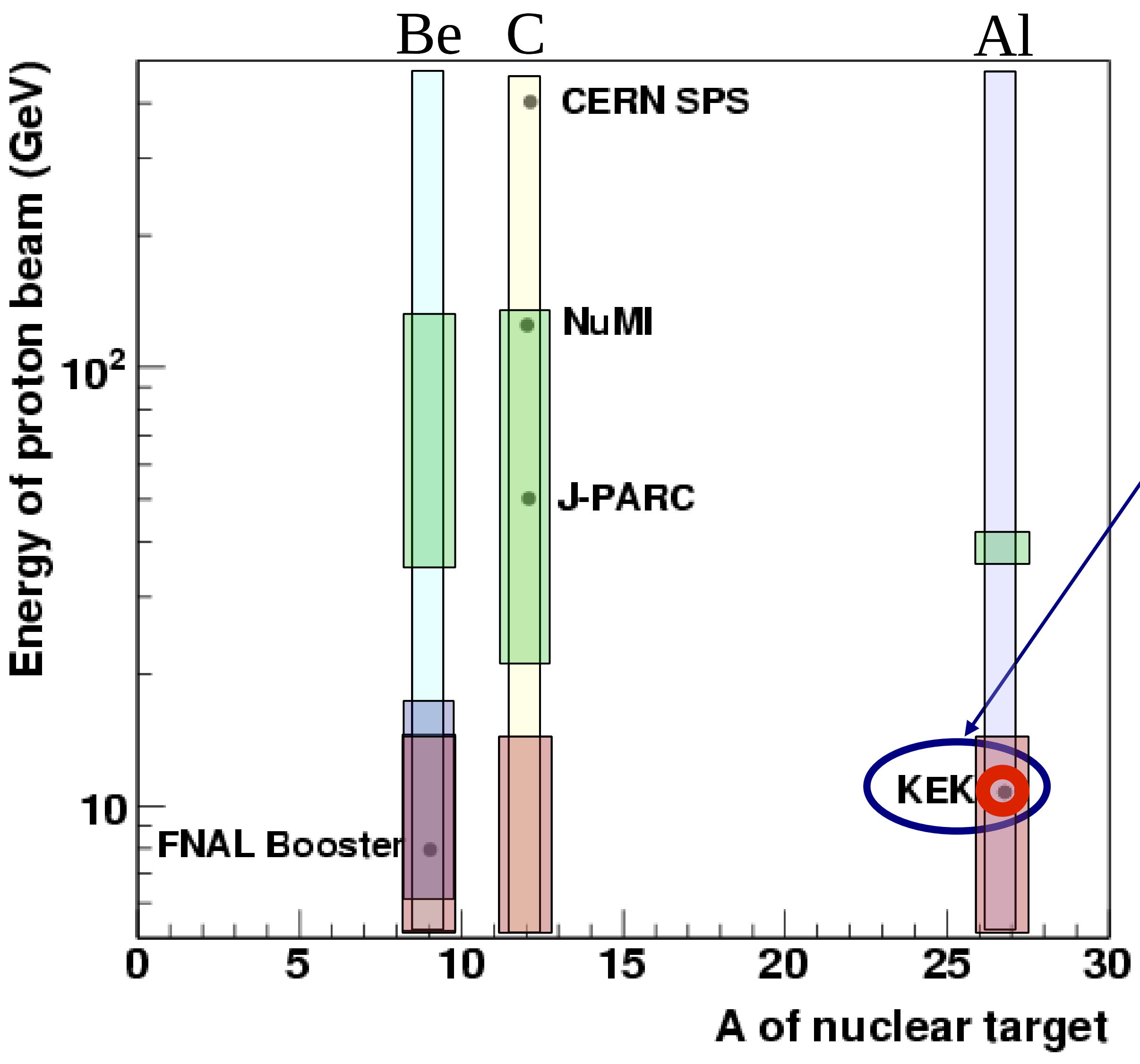
The Impacts

Four examples of the impacts of these data

- The **K2K** ν_μ disappearance experiment at KEK/SK
  - HARP p+Al pion measurement has been used to predict the **K2K F/N ratio**
  - the **final K2K oscillation paper** which uses the **HARP measurements** is available Phys.Rev.D74:072003,2006
- **The MiniBooNE** oscillation experiment at Fermilab
  - **HARP and E910 p+Be pion measurements are being used to predict neutrino fluxes**
- Preliminary comparisons to some **hadronic models**
- Impact on **atmospheric neutrino flux** predictions

K2K F/N flux ratio prediction

"neutrino beam-line parameter space"

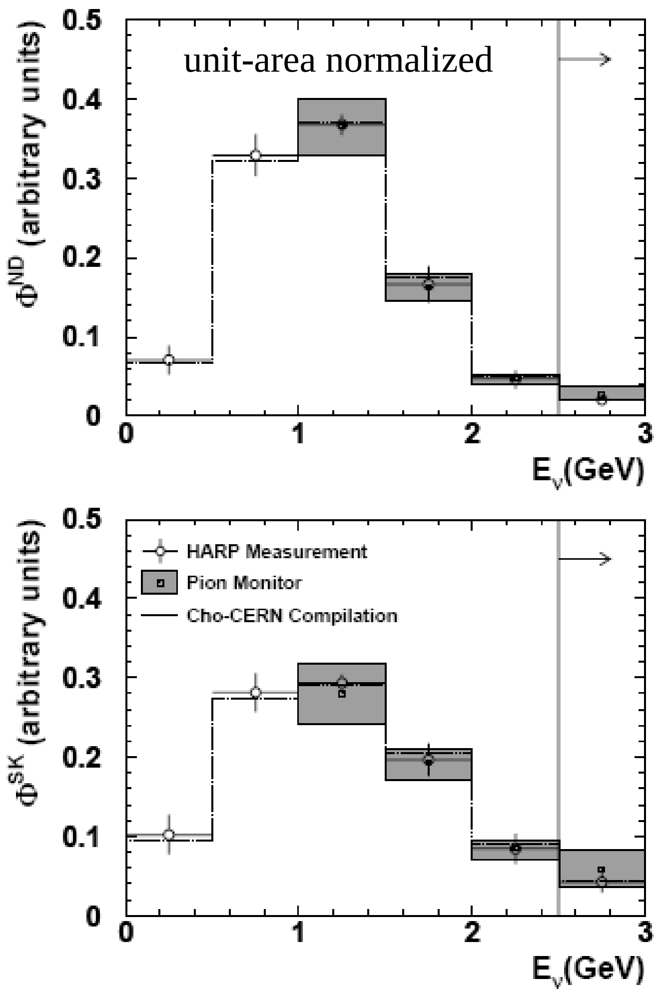


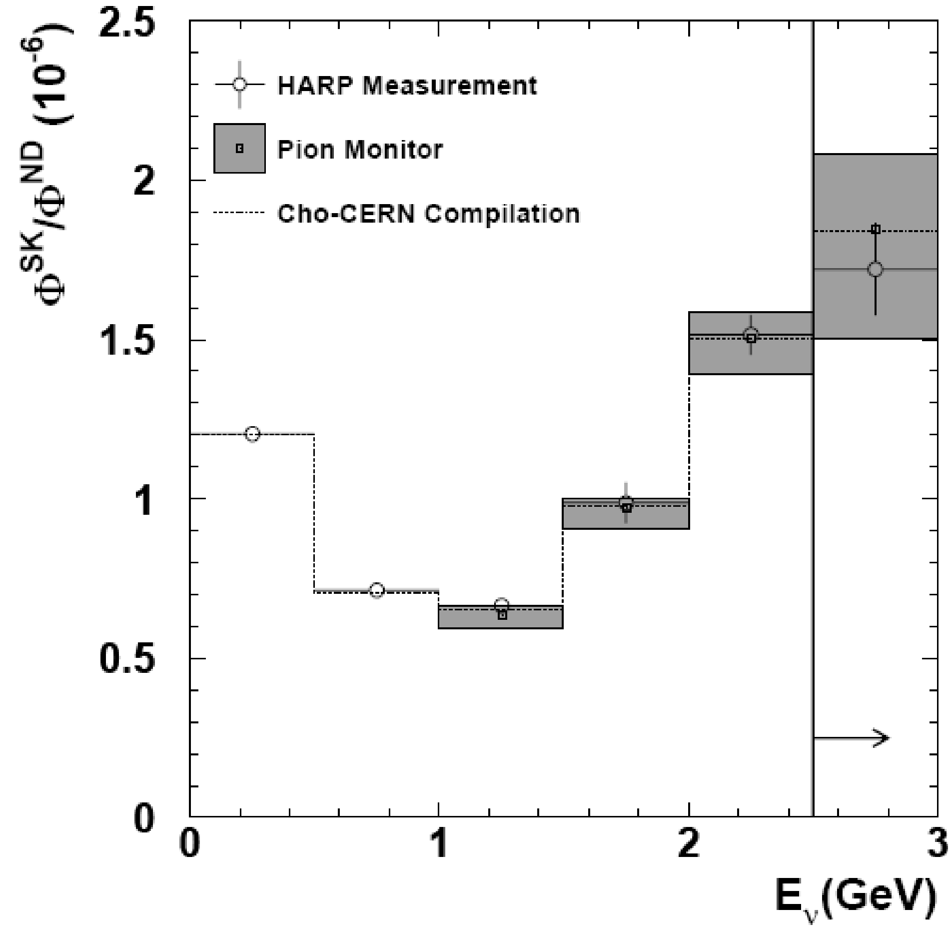
Ex. the K2K far-to-near ratio prediction. . .

HARP

3, 5, 8, 12, 15 GeV/c on Be, C, Al

K2K F/N flux ratio prediction



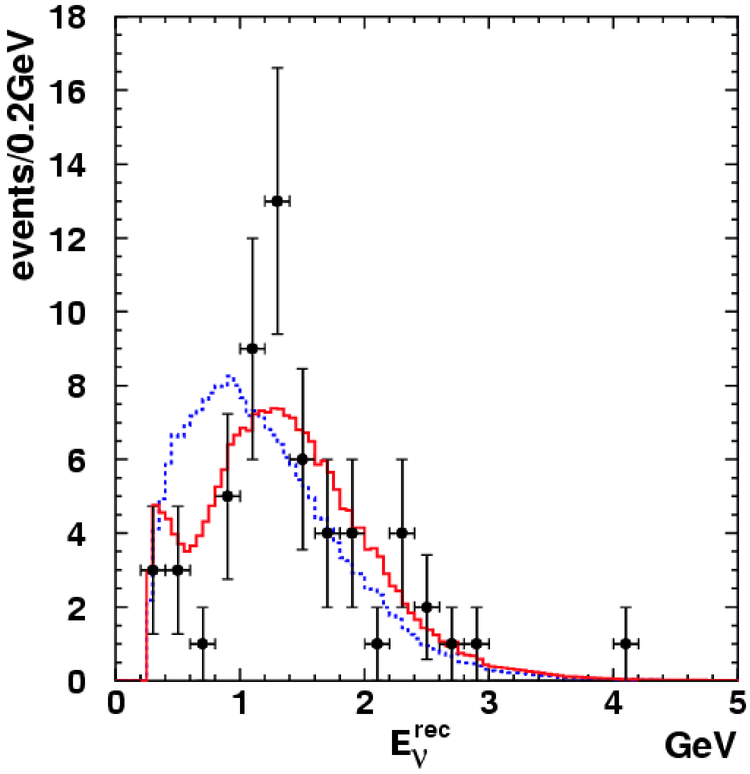


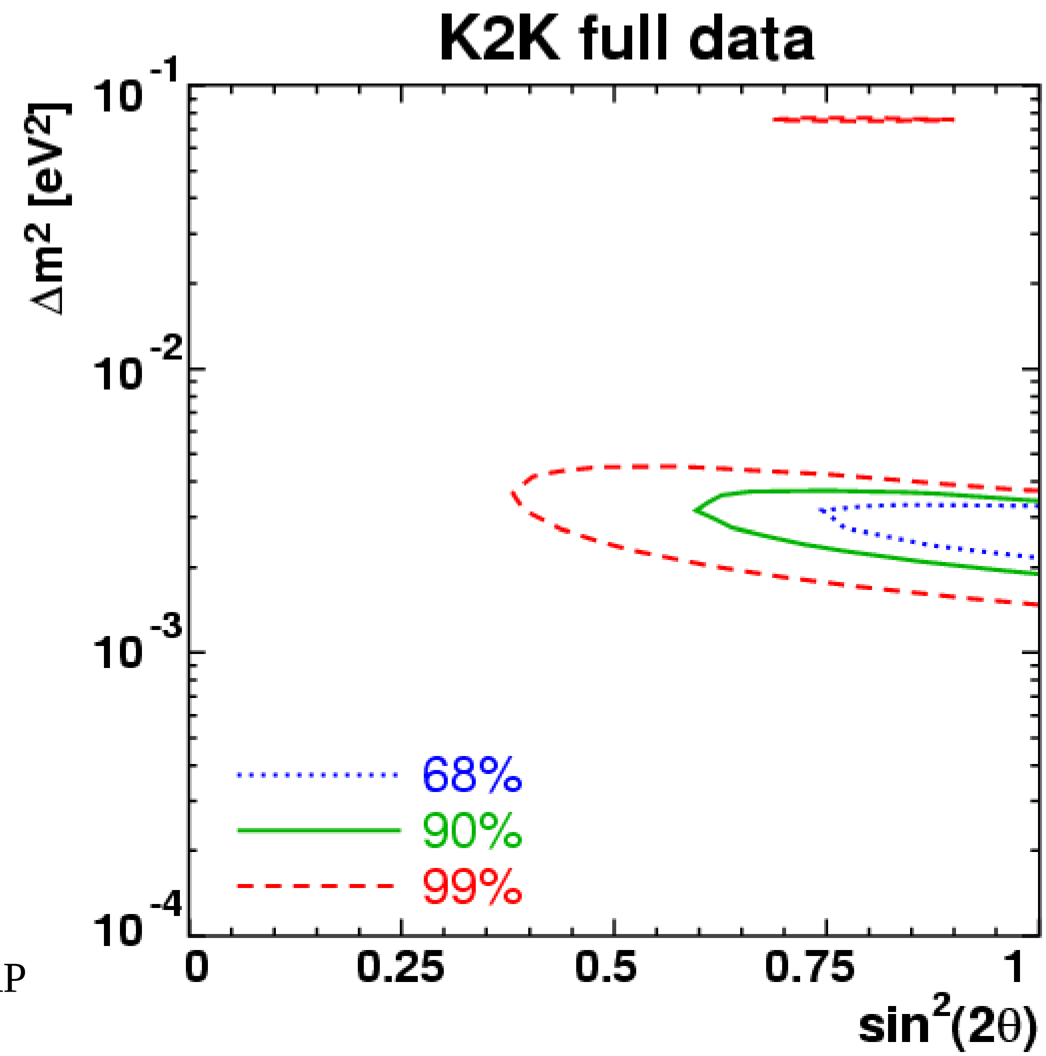
- HARP Al cross-section results have provided an important cross-check on previous K2K flux predictions. completely consistent in shape

Phys. Rev. D74:072003,2006

- F/N ratio no longer dominant systematic error

K2K F/N flux ratio prediction



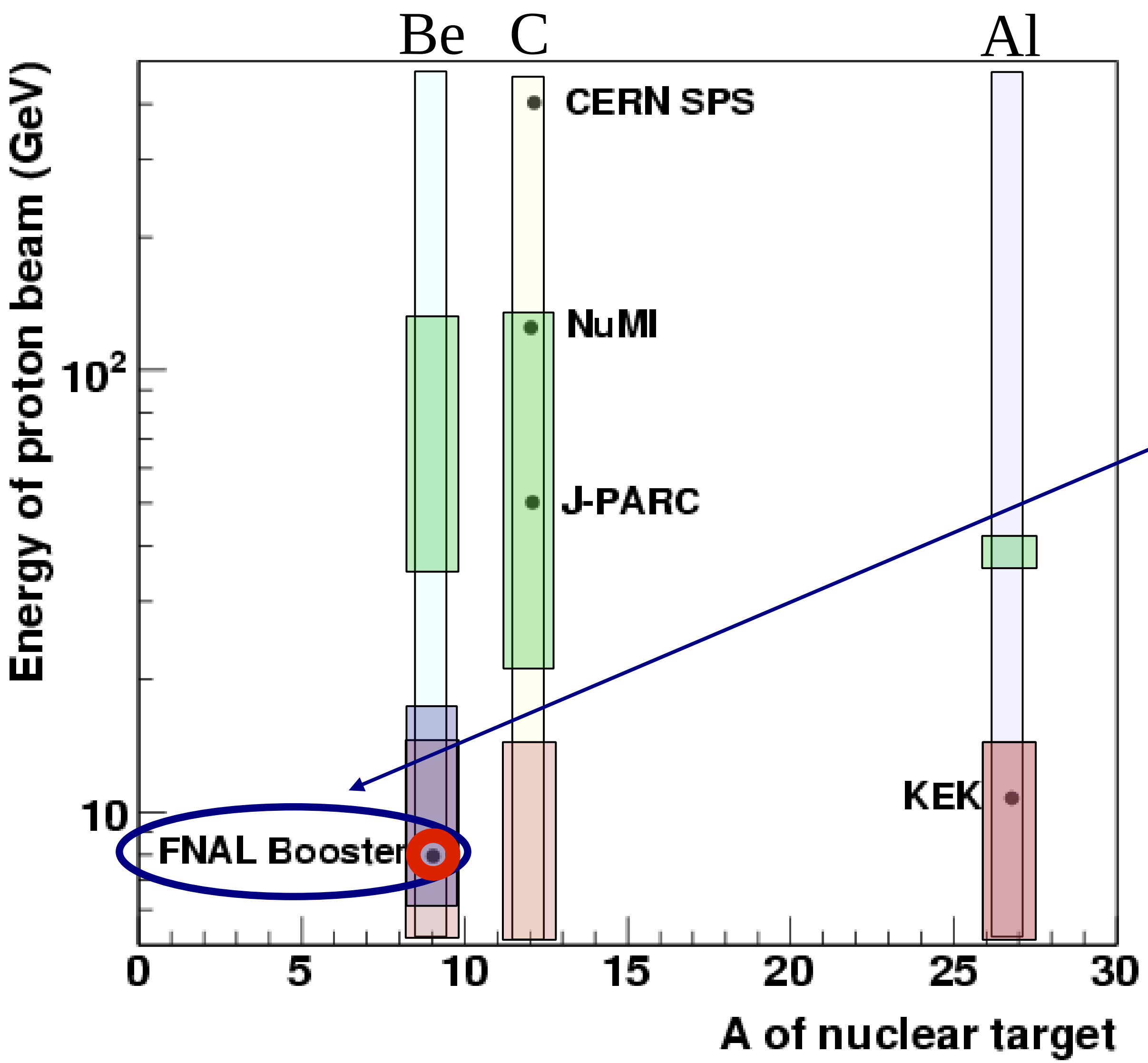


- The final K2K oscillation measurement has incorporated flux predictions based on the HARP Al measurement
  - 4.3 σ result
  - statistics limited

Phys. Rev. D74:072003,2006

MiniBooNE ν_μ flux prediction

"neutrino beam-line parameter space"



Ex. the ν_μ flux prediction at MiniBooNE. . .

HARP

3, 5, 8, 12, 15 GeV/c on Be, C, Al

E910

6.4, 12.3, 17.5 GeV/c on Be

An aside on the SW parameterization

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

- 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	$(4.4 \pm 1.3) \cdot 10^2$
c_2	$(8.5 \pm 3.4) \cdot 10^{-1}$
c_3	(5.1 ± 1.3)
$c_4 = c_5$	(1.78 ± 0.75)
c_6	(4.43 ± 0.31)
c_7	$(1.35 \pm 0.29) \cdot 10^{-1}$
c_8	$(3.57 \pm 0.96) \cdot 10^1$

Parameter	c_1	c_2	c_3	$c_4 = c_5$	c_6	c_7	c_8
c_1	1.000						
c_2	-0.056	1.000					
c_3	-0.145	-0.691	1.000				
$c_4 = c_5$	-0.322	-0.890	0.831	1.000			
c_6	-0.347	0.263	-0.252	-0.067	1.000		
c_7	-0.740	0.148	-0.067	0.077	0.326	1.000	
c_8	0.130	-0.044	0.205	-0.040	-0.650	0.189	1.000

example of HARP measurements for p-Al at 12.9 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)*

Sanford-Wang Parameterization

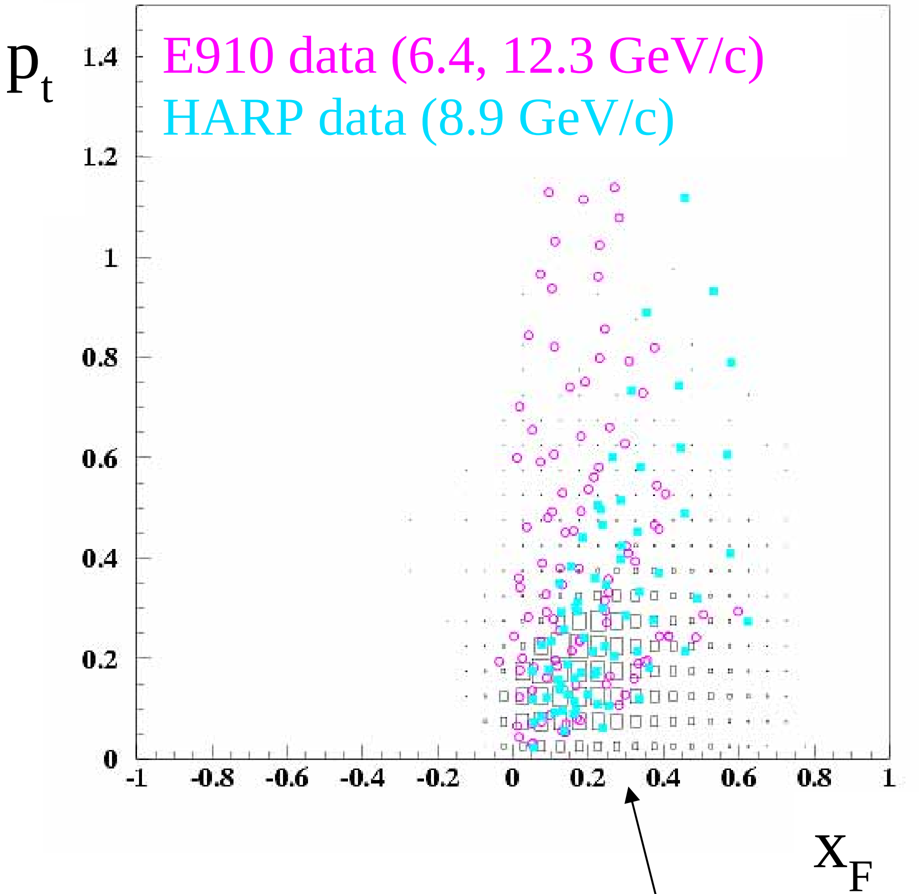
$$\frac{d^2\sigma(\mathrm{p+A} \to \pi^+ + X)}{dp d\Omega}(p,\theta) = c_1 p^{c_2}\left(1 - \frac{p}{p_{\mathrm{beam}}}\right)\exp\left[-c_3\frac{p^{c_4}}{p_{\mathrm{beam}}^{c_5}} - c_6\theta(p - c_7 p_{\mathrm{beam}}\cos^{c_8}\theta)\right]$$

Parameter	Value
c_1	$(4.4 \pm 1.3)\cdot 10^2$
c_2	$(8.5 \pm 3.4)\cdot 10^{-1}$
c_3	(5.1 ± 1.3)
$c_4 = c_5$	(1.78 ± 0.75)
c_6	(4.43 ± 0.31)
c_7	$(1.35 \pm 0.29)\cdot 10^{-1}$
c_8	$(3.57 \pm 0.96)\cdot 10^{1}$

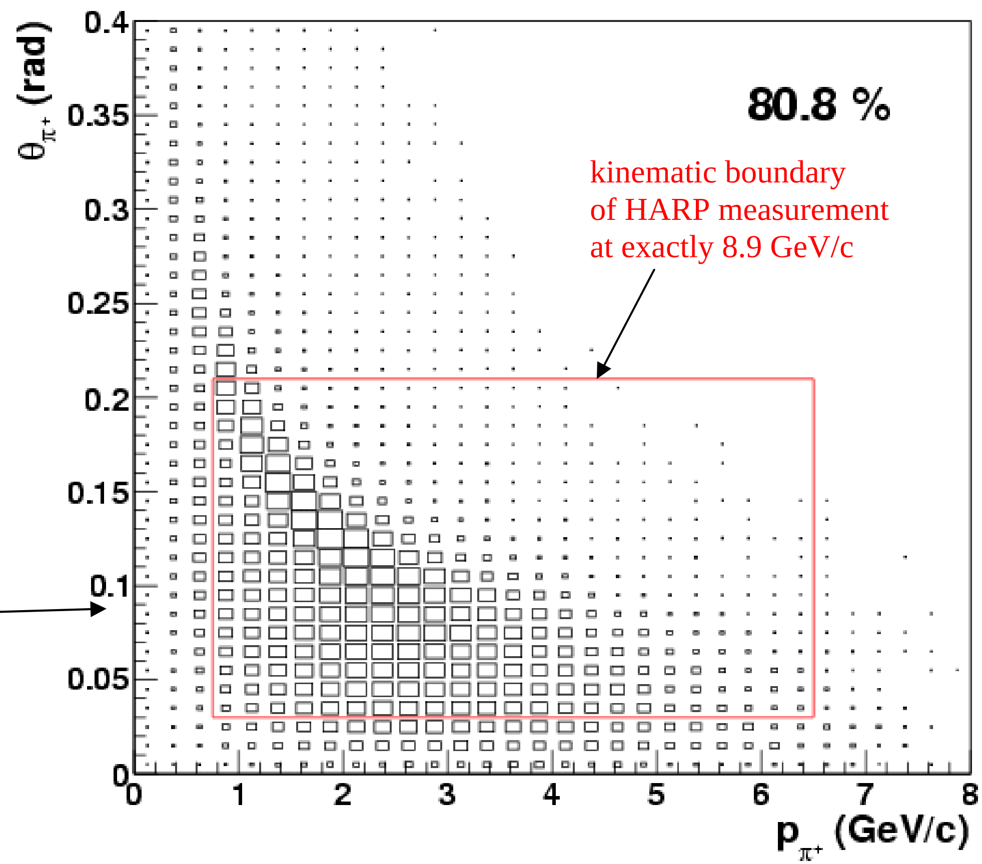
Parameter	c_1	c_2	c_3	$c_4 = c_5$	c_6	c_7	c_8
c_1	1.000						
c_2	-0.056	1.000					
c_3	-0.145	-0.691	1.000				
$c_4 = c_5$	-0.322	-0.890	0.831	1.000			
c_6	-0.347	0.263	-0.252	-0.067	1.000		
c_7	-0.740	0.148	-0.067	0.077	0.326	1.000	
c_8	0.130	-0.044	0.205	-0.040	-0.650	0.189	1.000

HARP measurements for p-Al at 12.9 GeV/c

MiniBooNE ν_μ flux prediction



- 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

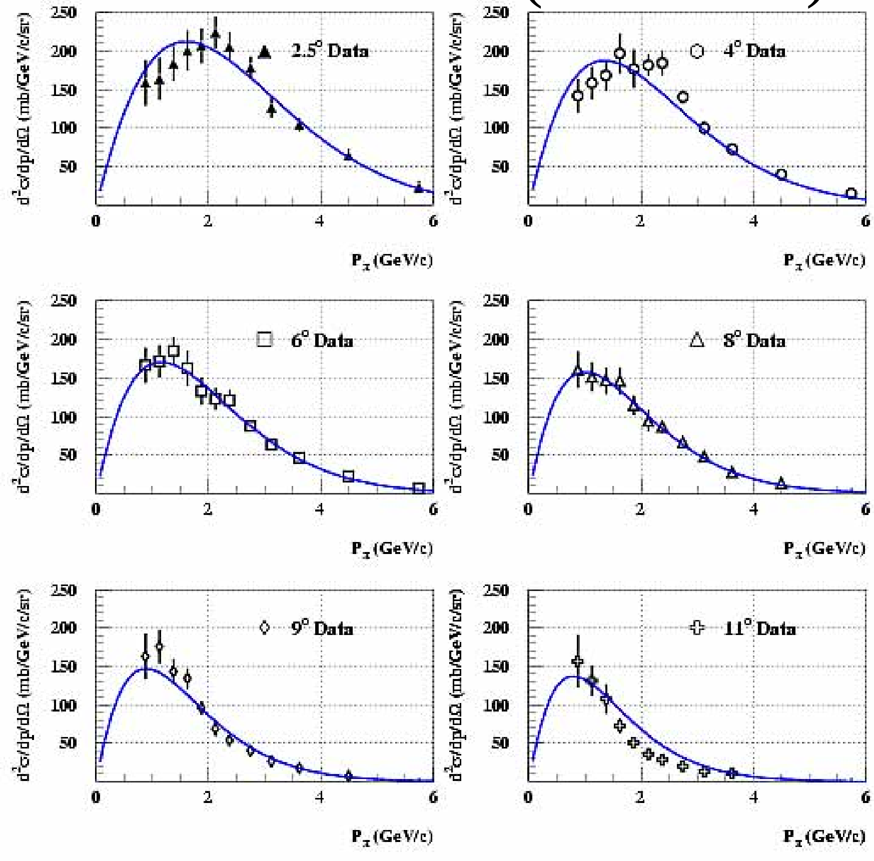


- black boxes are the distribution of π^+ which decay to a ν_μ that **passes through the MiniBooNE detector**

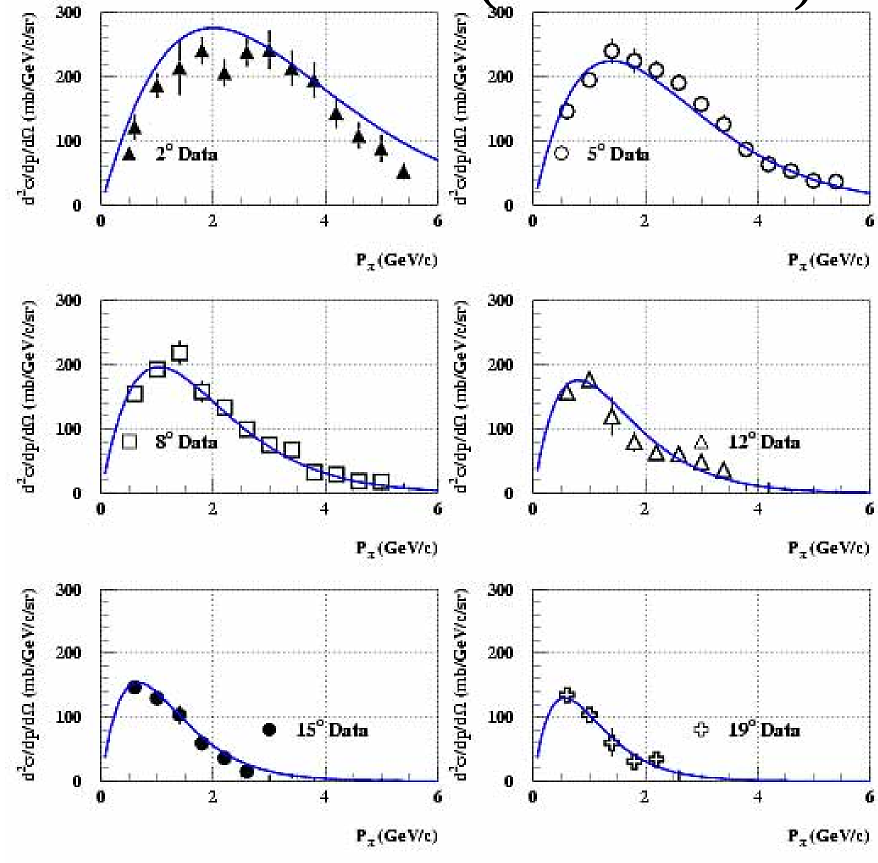
p

MiniBooNE ν_μ flux prediction

HARP data (8.9 GeV/c)



E910 data (12.3 GeV/c)

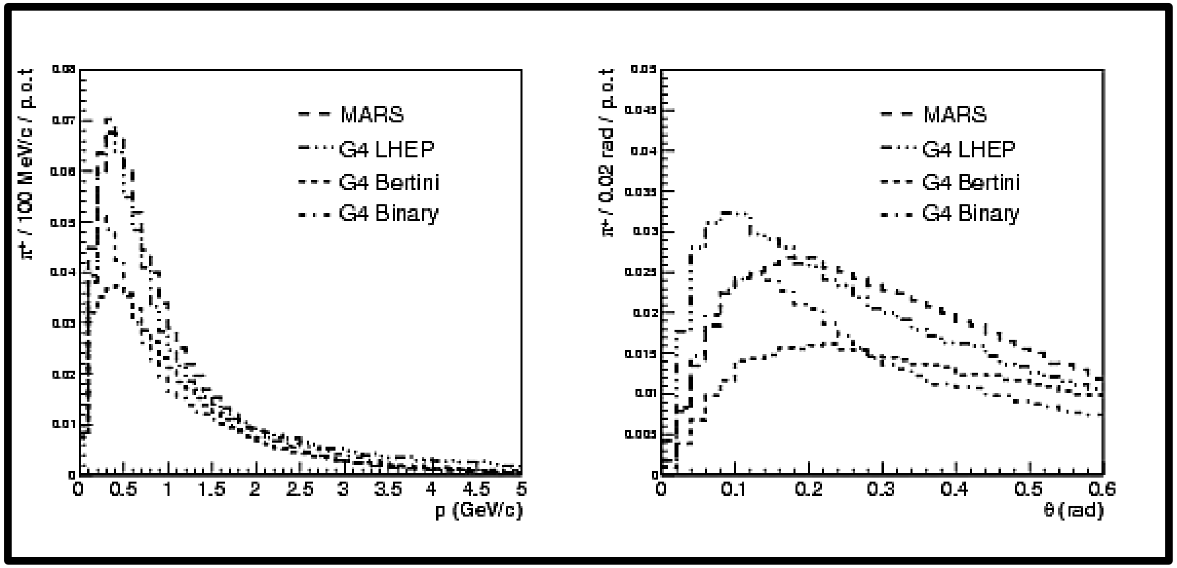


- the E910 and HARP data sets are **extremely compatible** in normalization, with some tension in shape

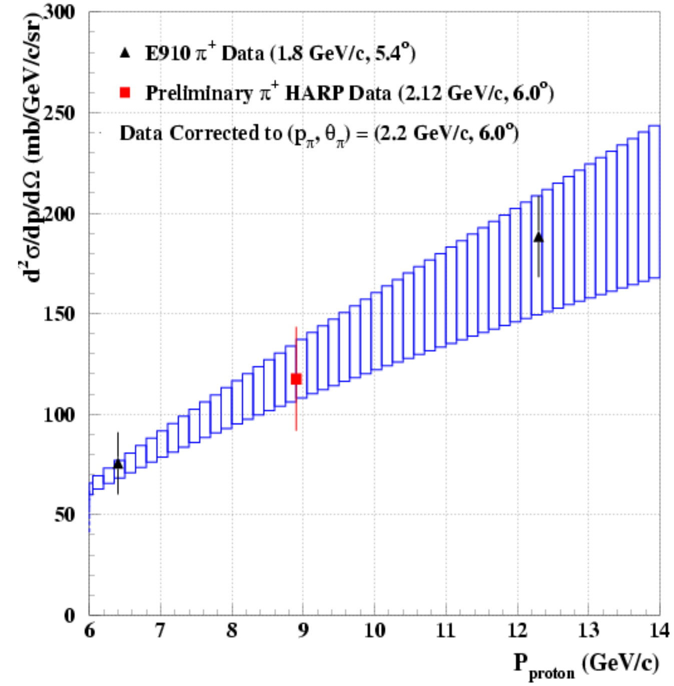
normalization pull term	fit result
n_{HARP}	1.00
$n_{E910\ 6.4}$	1.02 +- 0.06
$n_{E910\ 12.3}$	0.97 +- 0.03

MiniBooNE ν_μ flux prediction

in case you are not particularly impressed by this level of agreement between E910 and HARP data, recall the variations in available hadronic models



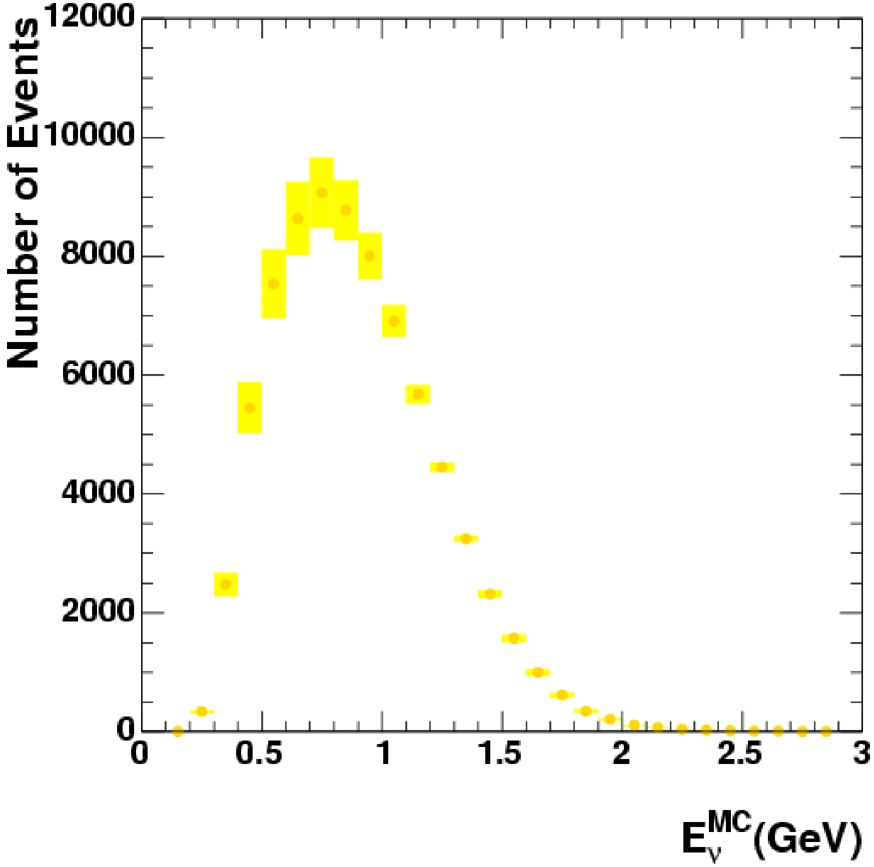
x-sec at “sweet spot”

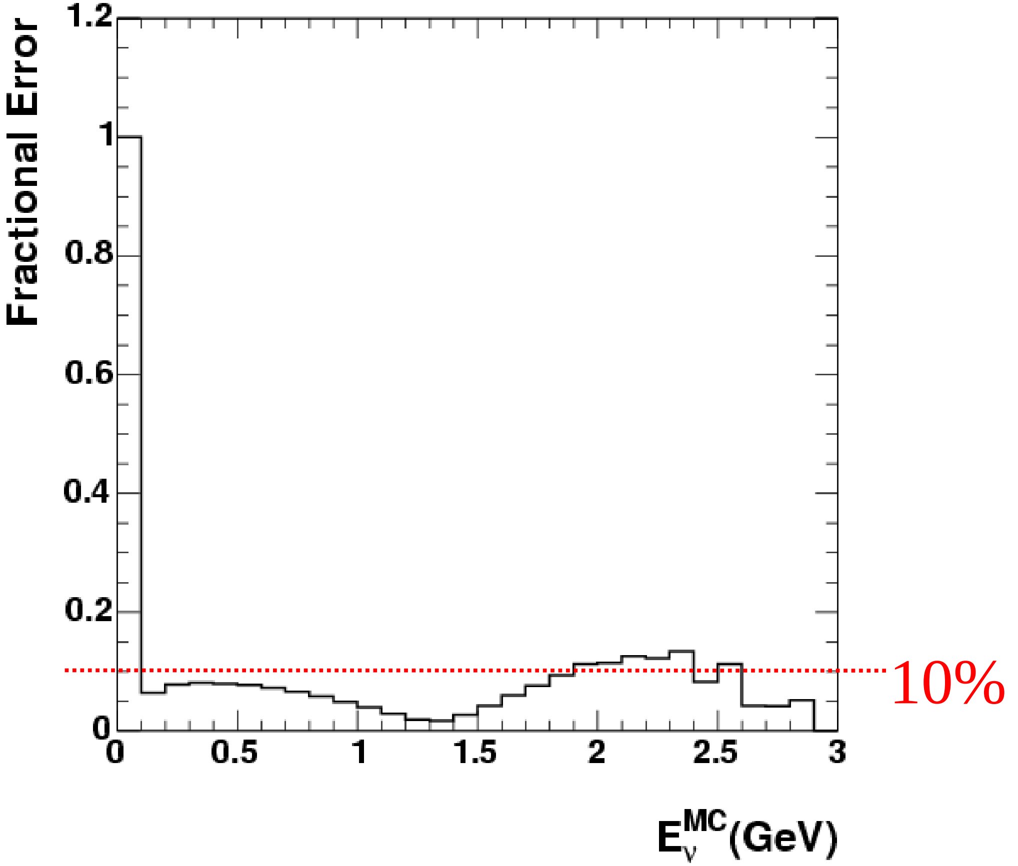


- the E910 and HARP data sets are **extremely compatible** in normalization, with some tension in shape

normalization pull term	fit result
n_{HARP}	1.00
$n_{E910\ 6.4}$	1.02 +- 0.06
$n_{E910\ 12.3}$	0.97 +- 0.03

MiniBooNE ν_μ flux prediction

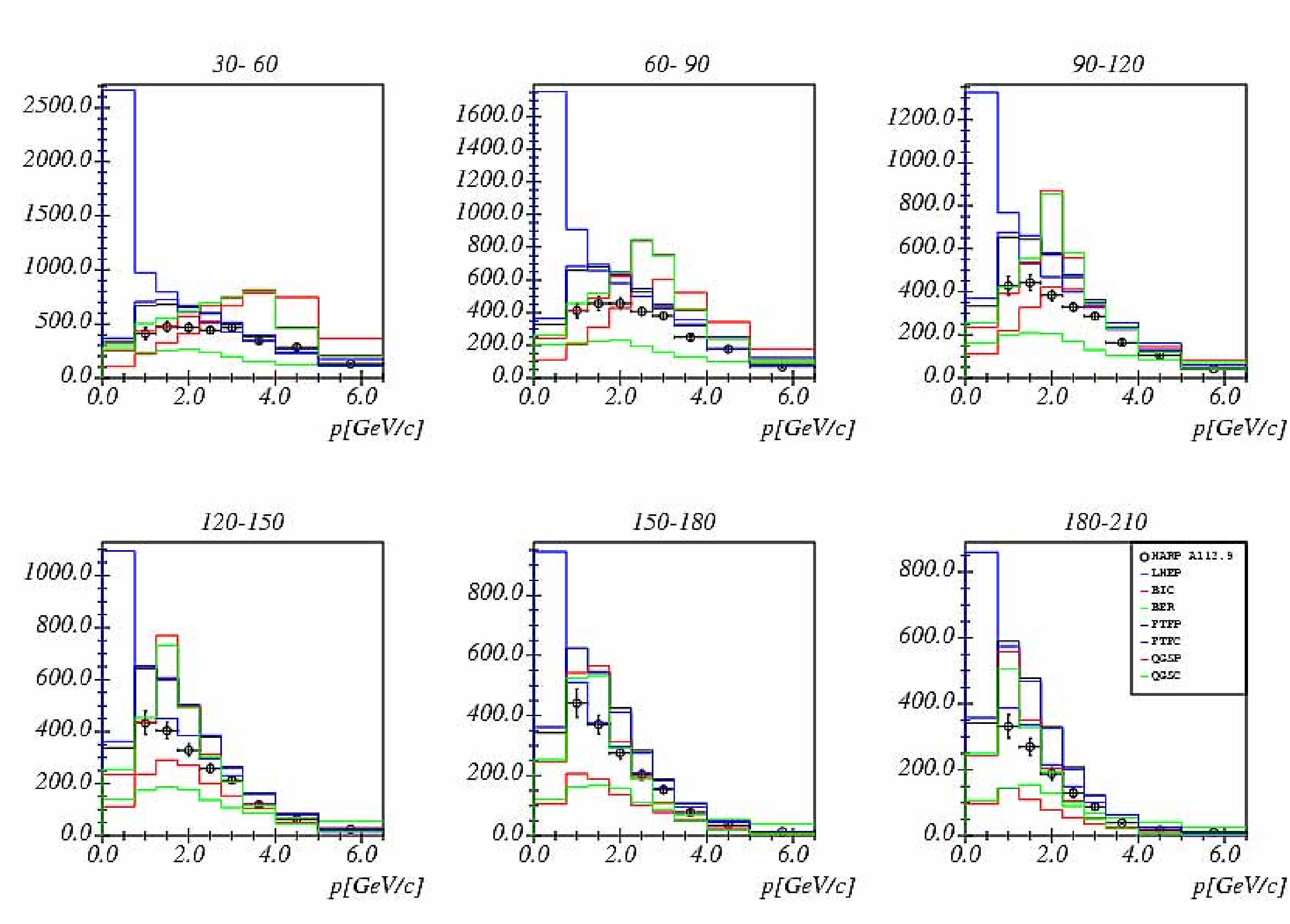




- errors generated by the SW fit are propagated to the predicted neutrino flux at the MiniBooNE detector

- avg. uncertainty on CCQE event rate coming from the flux prediction is < 10%

Hadronic models in Geant4



LHEP

Binary

Bertini

FTFP

FTFC

QGSP

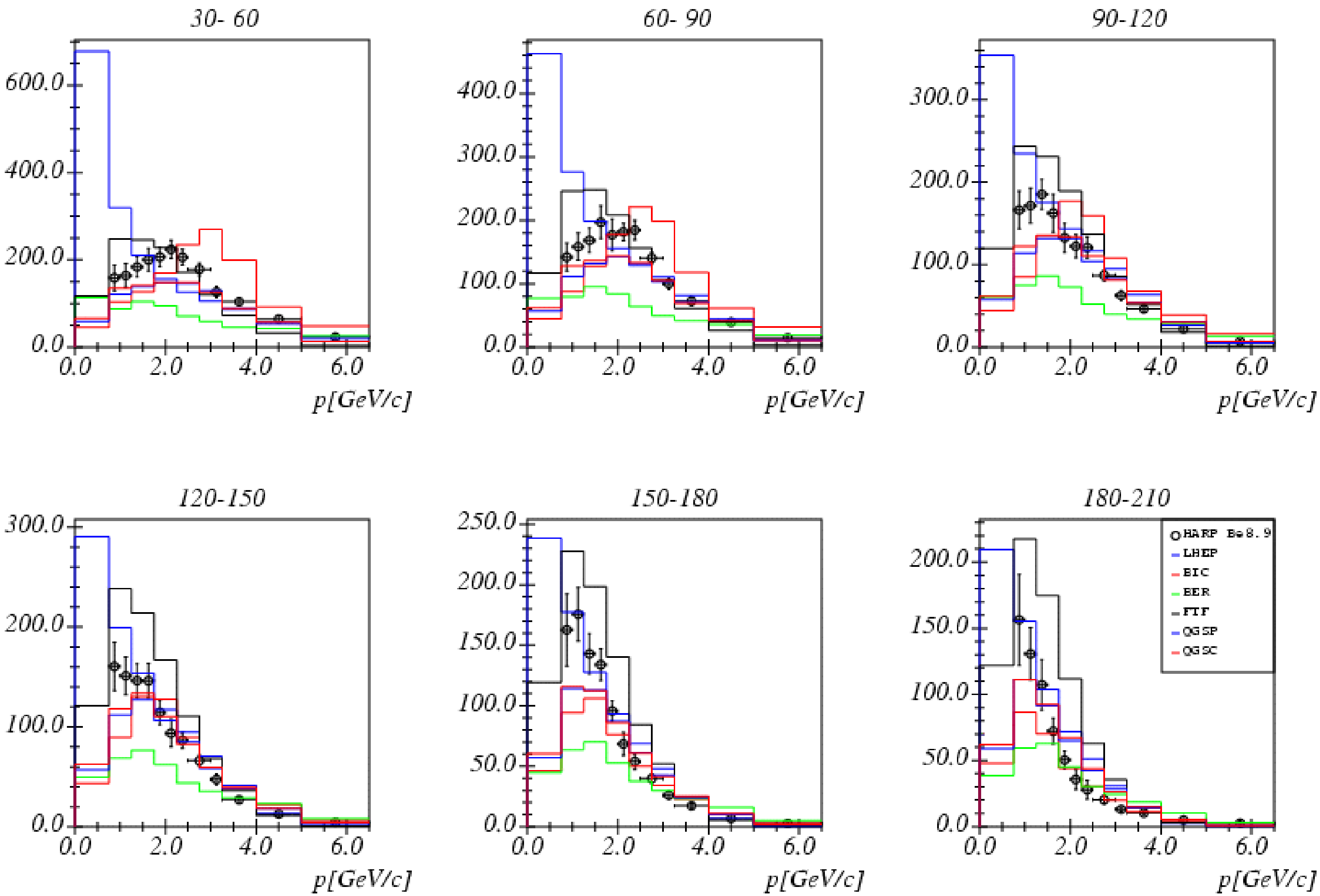
QGSC

black points are HARP data

(V. Ivantchenko)

p+Aluminum 12.9 GeV/c

Hadronic models in Geant4



LHEP

Binary

Bertini

FTF

QGSP

QGSC

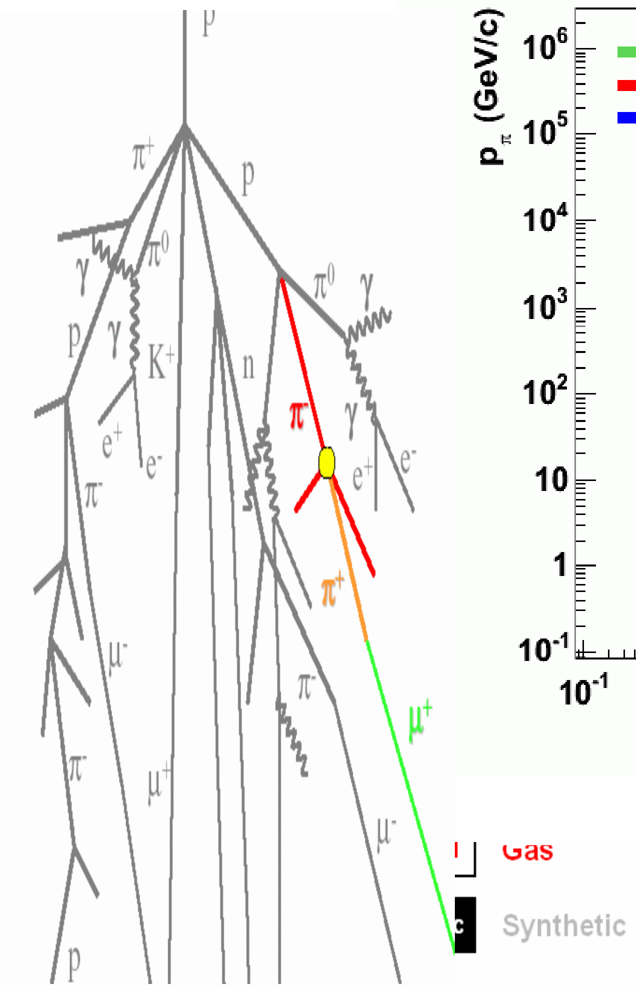
black points are HARP data

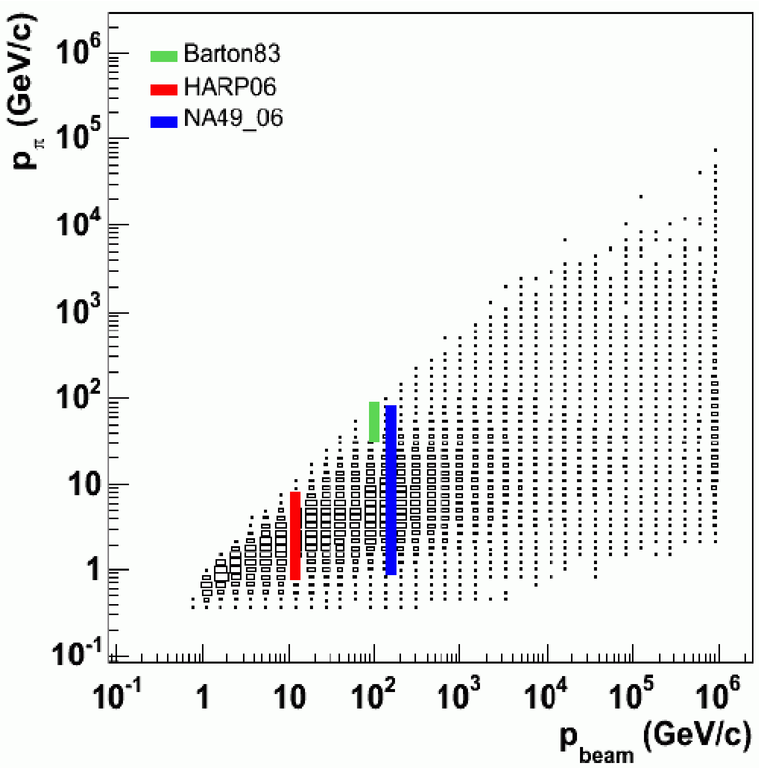
(V. Ivantchenko)

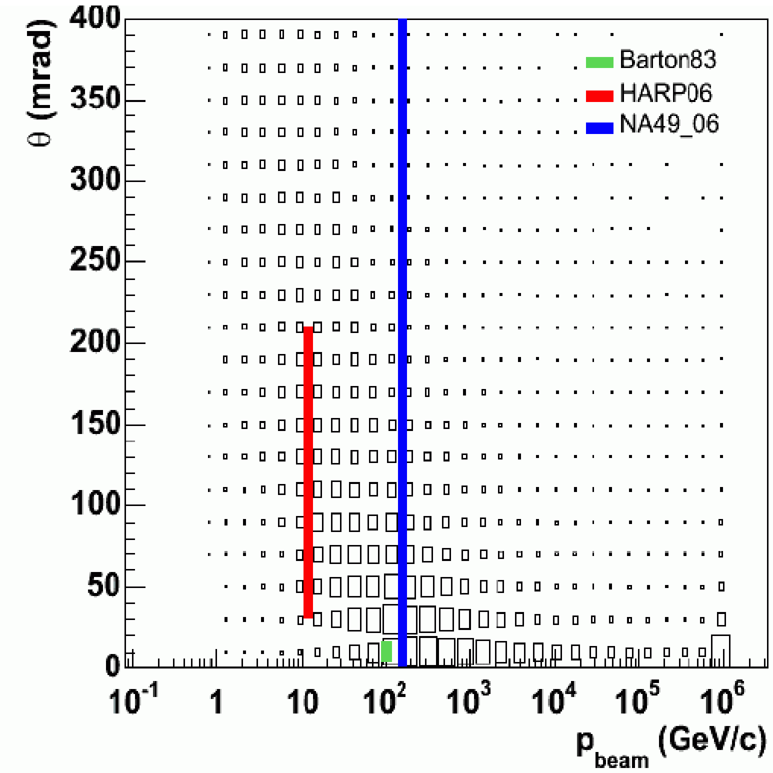
p+Beryllium 8.9 GeV/c

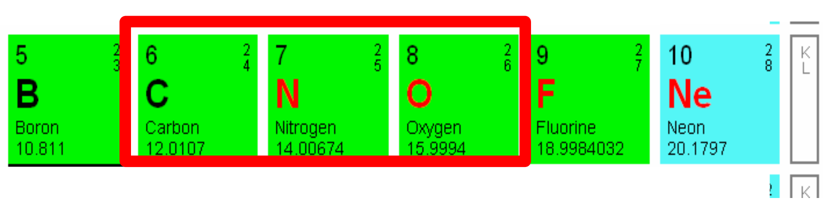
Atmospheric neutrino flux predictions

- the **HARP p+C @ 12 GeV/c** and the **NA49 p+C @ 158 GeV/c** are both relevant to the prediction of atmospheric neutrino fluxes









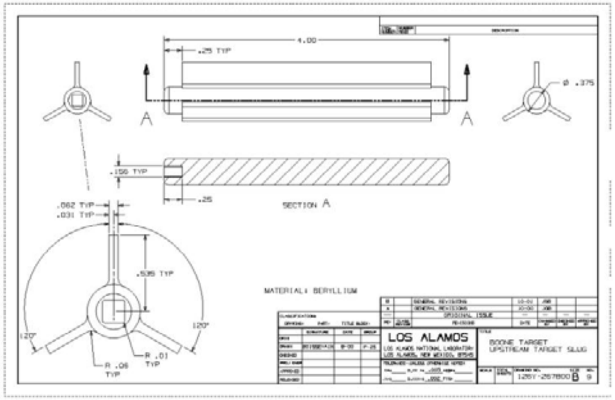
78% nitrogen

21% oxygen

The Possibilities

Coming soon for MiniBooNE / SciBooNE

- HARP data is the one relevant to the 8.9 GeV/c Fermilab booster line

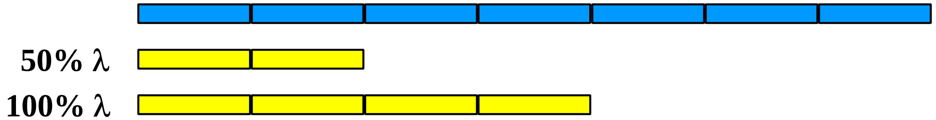


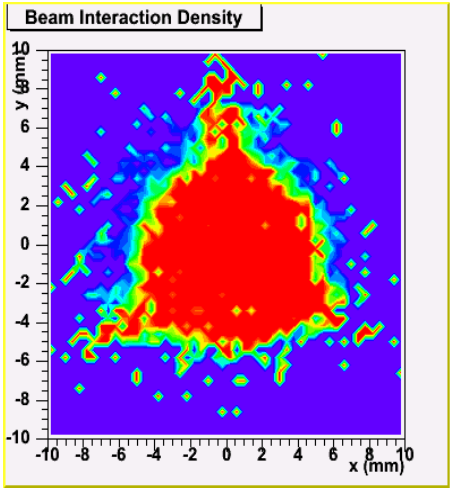
- in addition to the π^+ cross-section measured from the thin beryllium target data at p_{beam} = 8.9 GeV/c (shown today), there is a plan to provide :

  - a π^- **measurement** for anti-neutrino running mode in the booster beam line

  - a K^+ **measurement** for prediction of intrinsic ν_e backgrounds from K decays

  - particle yields from **thick beryllium targets** and **MiniBooNE replica targets**





No target	5.7 M events	Subtraction
5% Be Disc	7.3 M events	p+Be x-section
50% λ MB replica	5.2 M events	Effects specific to MB target reinteraction absorption scattering
100% λ MB replica	6.4 M events	

Much more data. . .

- the **HARP** experiment recorded ~400 M triggers

1.5 **/ 3 / 5 / 8 /** 8.9 **/ 12 /** 12.9 **/ 15 GeV/c Beams**

H_2/D_2/Be/C/N_2/O_2/Al/Cu/Sn/Ta/Pb Targets (5%,100%)

- possibility for careful study of energy dependence and A dependence of hadron production – development of scaling laws and improved parameterizations

- π+A interactions as well as p+A interactions

- cryogenic targets for atmospheric neutrino production

- large-angle analyses incorporating the TPC and RPCs

Important MIPP upgrade

- the limiting factor in MIPP data taking rate is TPC electronics (1990 vintage ~60Hz max, ~20Hz for complex events)

- proposal to replace electronics with those developed for the ALICE collaboration at the LHC. will increase data acquisition rate to 3000Hz – x100

- by upgrading all systems to 3kHz a data taking rate of 5 million events per day should be achievable.

- the entire data set recorded in 05-06 can be achieved in ~ 1 week!!

multiple beam momenta and both charges

H_2/D_2/Li/Be/B/C/N_2/O_2/Mg/Al/Si/P/S/Ar/K/Ca/Fe/ Ni/Cu/Zn/Nb/Ag/Sn/W/Pt/Au/Hg/Pb/Bi/U Targets

- full data set will be used to tune hadronic shower generators across energies and atomic masses

- 10 million events from NuMI target

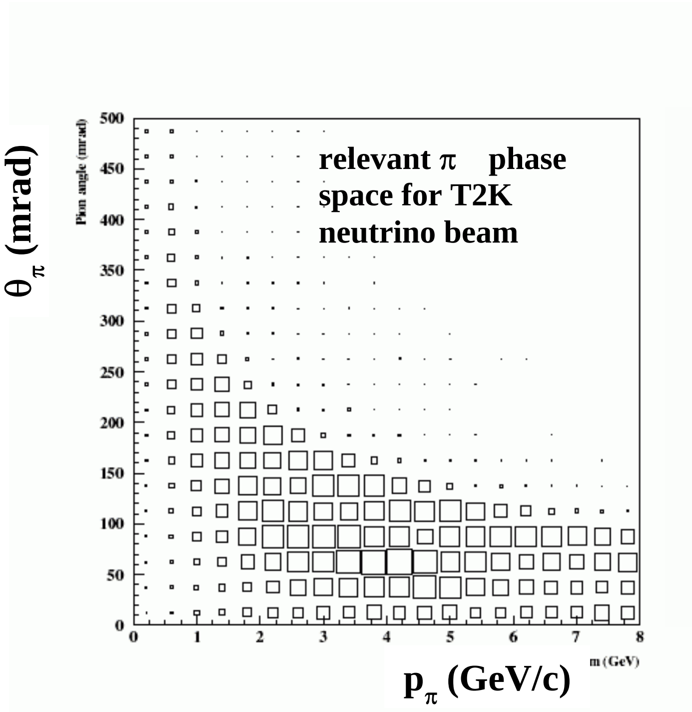
Similar NA49 upgrade

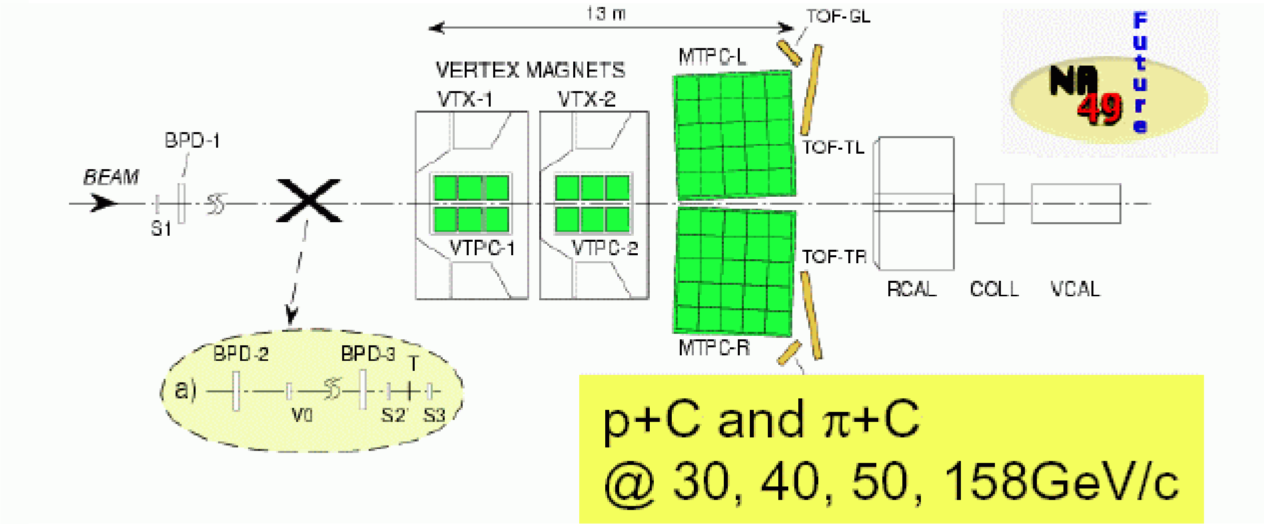
- Proposal submitted to CERN SPSC in November, “Study of Hadron Production in Collisions of Protons and Nuclei at CERN SPS”

- will also increase TPC data taking rate by using ALICE electronics technology (~x20 to 30 Hz)

- Proposal includes a measurement of π and K production from carbon targets at 30, 40 and 50 GeV/c with direct relevance to the **T2K experiment**

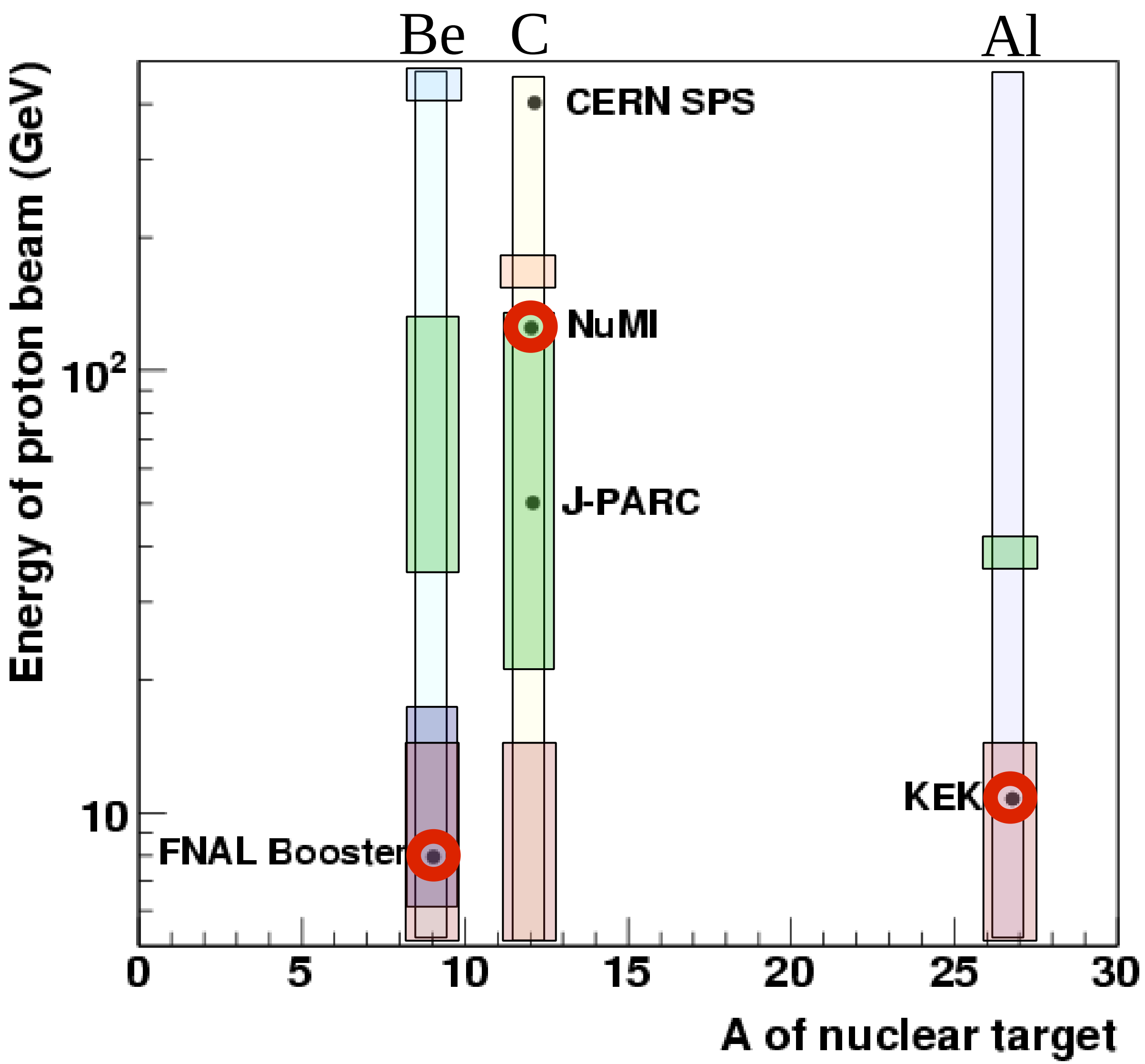
- these same p+C and π+C cross-sections are also directly relevant to **atmospheric neutrino flux** predictions





The Conclusions

“neutrino beam-line parameter space”



data taken at exactly the beam momentum with a replica target from the experiment

SPY

450 GeV/c on Be

NA49

158 GeV/c on C

MIPP

35, 60, 120 GeV/c on Be
20, 35, 60, 120 GeV/c on C
35 GeV/c on Al

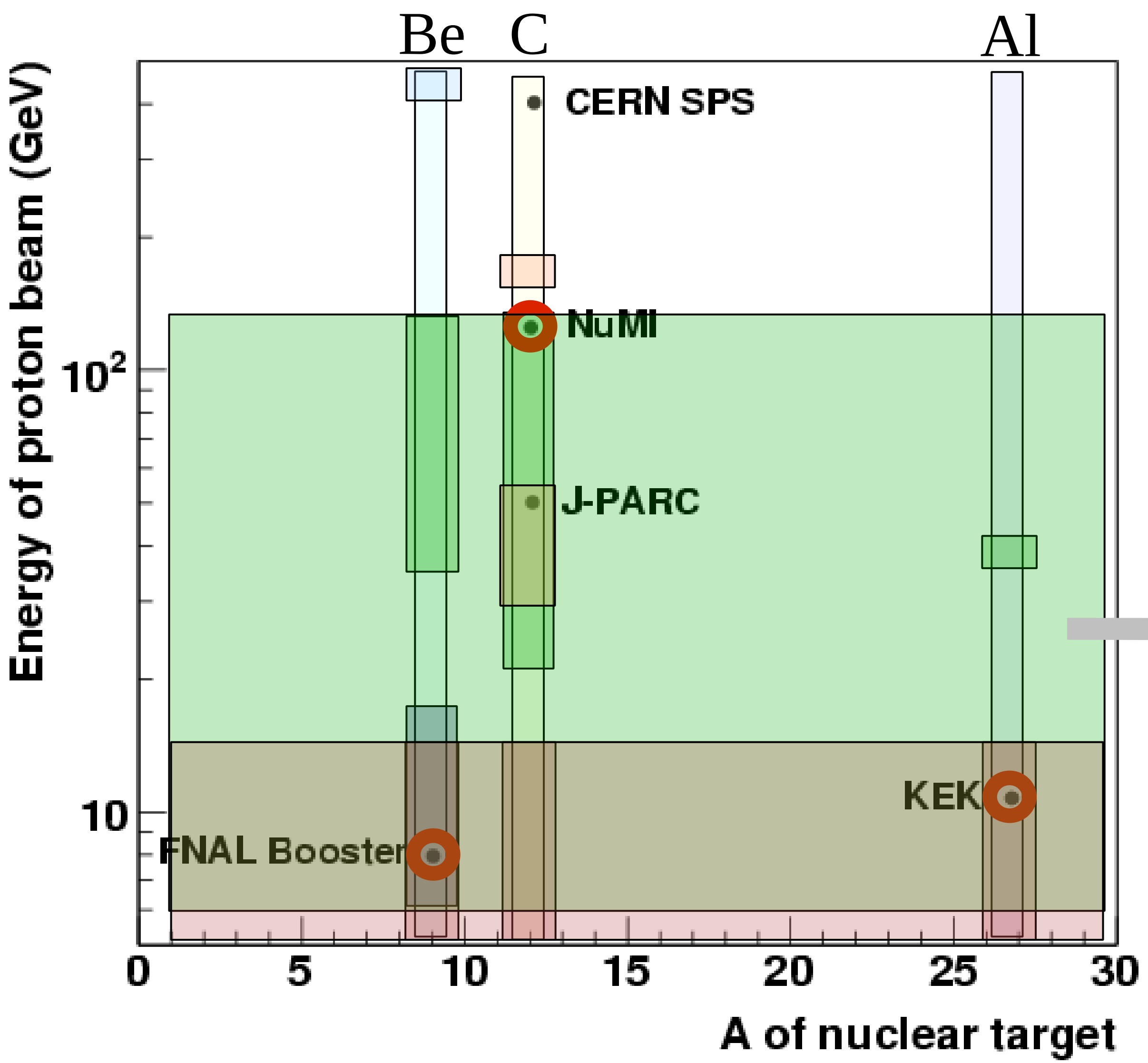
HARP

3, 5, 8, 12, 15 GeV/c on Be, C, Al

E910

6.4, 12.3, 17.5 GeV/c on Be

"neutrino beam-line parameter space"



SPY

NA49 upgrade

MIPP upgrade

HARP full data

E910

with upgrades there becomes a nearly continuous coverage across beam momenta and nuclear targets

with overlap regions between different experiments allowing for important cross-checks

Conclusions

- hadron production experiments like **HARP, E910, MIPP and NA49** have already made important contributions to hadronic cross-sections relevant to neutrino experiments
- there is more data to be analyzed already on disk from HARP and MIPP
  - **kaons**
  - **thick targets**
  - **other nuclear materials**
  - **range of beam momenta**
- proposed MIPP and NA49 upgrades could provide the data to definitively constrain hadronic simulators in the next few years
- we have, or are near to having, all the hadronic data we need to **tightly constrain the fluxes from the world's present and near future neutrino beams**. . . need physicists and time to analyze and interpret the wealth of data