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on behalf of the HARP Collaboration

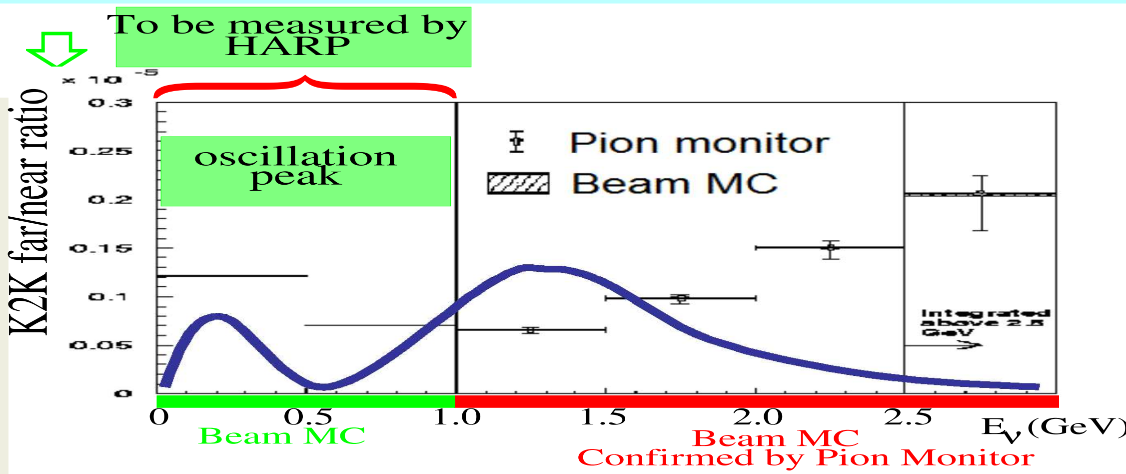
"Neutrino Hadroproduction (HARP)"

- **HARP: physics case for an hadroproduction experiment**
- **Measuring a cross section:**
  - **K2K Al results**
  - **MiniBooNE - preliminary results**
- **on going analysis:**
  - **tantalum large angle analysis for Neutrino Factory**
  - **the next**
- **Conclusions**

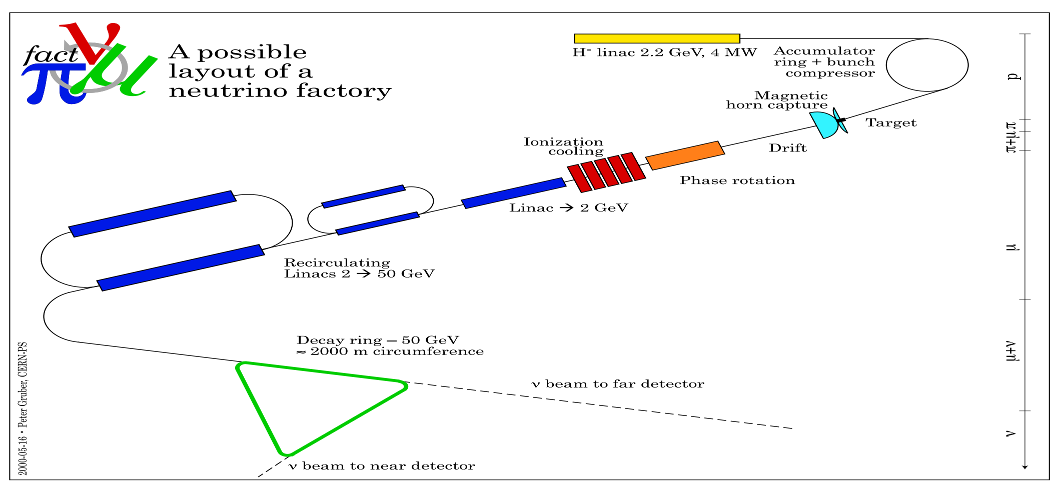
HARP at CERN PS: physics case

New era in Hadron Production for Neutrino Physics: a systematic study of secondary hadron production by incident p and $\pi^{\pm}$ with

- *p_{beam} from 1.5 to 15 GeV/c (more than 420 M pot)*
- *large range of target materials, from H to Lead*
- *measurements of targets of existing ν beams: K 2K and MiniBooNE*

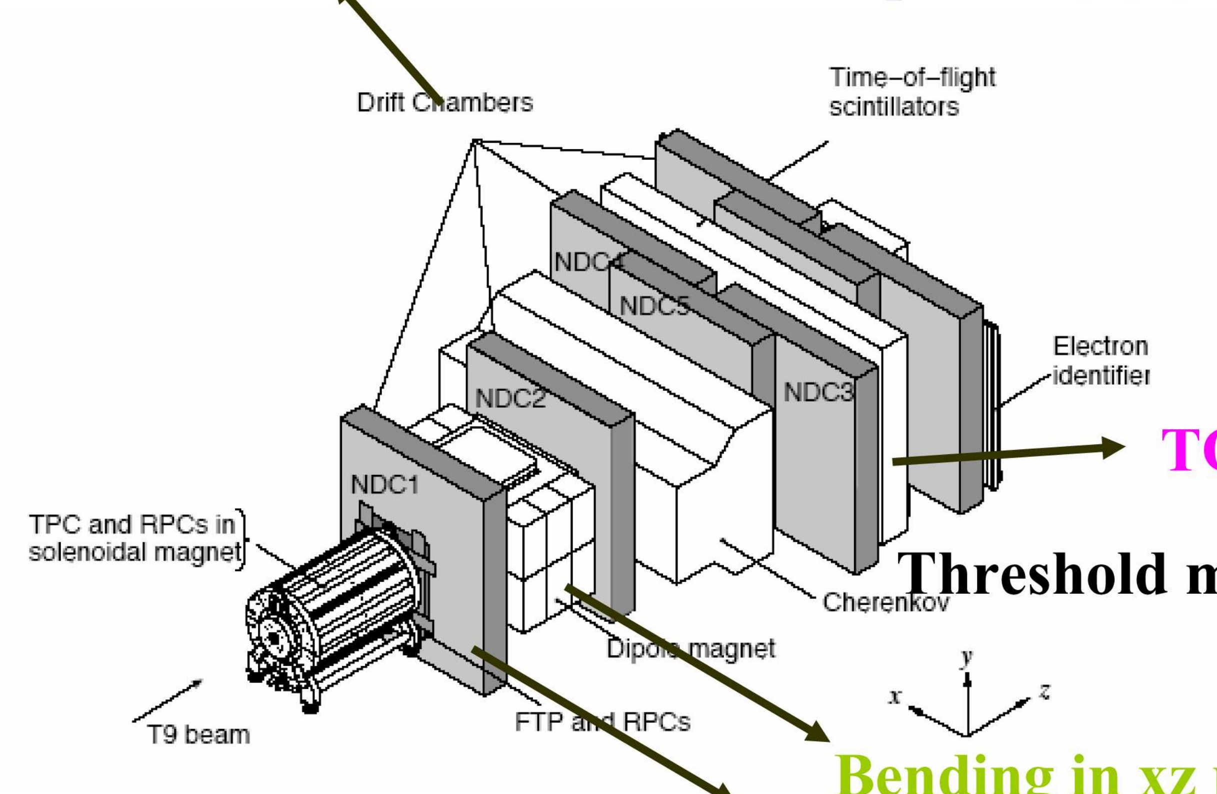


- *Inputs for the prediction of neutrino fluxes for K2K and MiniBooNE experiments*
- *Inputs for the precise calculation of atmospheric neutrino flux*
- *π, K yields for the design of the proton driver/target system of Neutrino Factories and super-beams*
- *Input for Monte Carlo generators*



HARP detector: large acceptance, P.Id capabilities, redundancy

NDC modules = 4 chamber x 3 planes (u,v,x) = 12 planes/module



TOFW + t0 Δt ~180 ps

Threshold mode: $E_{th}^{\pi} = 2.6$ GeV

Bending in xz plane: 0.4 T

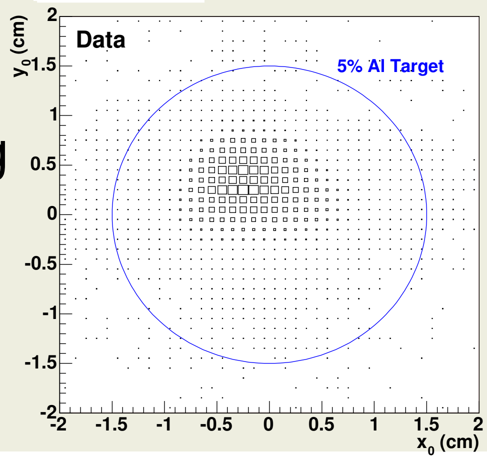
Beam instrumentation

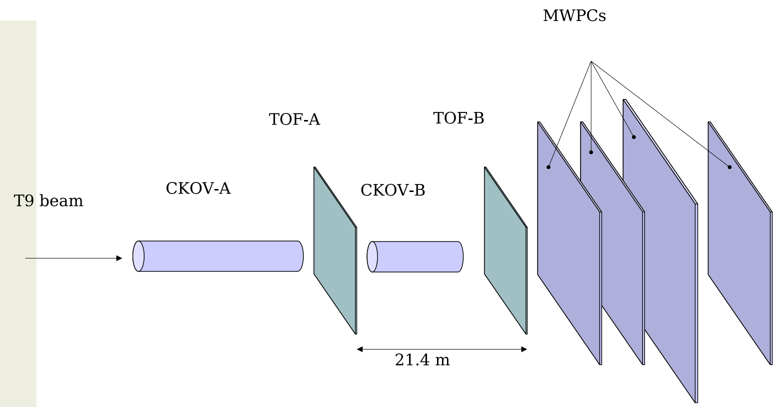
FTP gives interaction trigger

TPC + Forward Spectrometer: a 4π experiment!!

Beam Instrumentation: counting protons on target

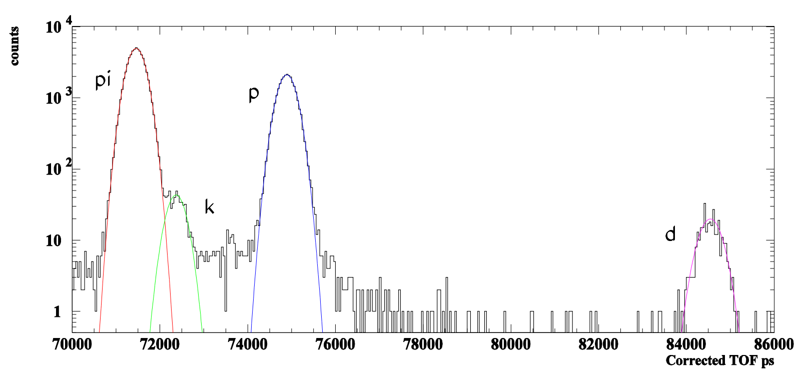
Beam tracking with MWPCs





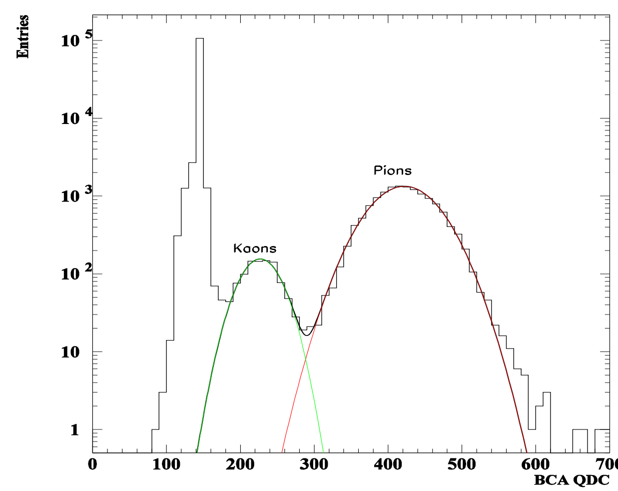
Beam Tof (three sets of counters)

- π /K/p separation at **low energy**
- 70 ps interaction time resolution



(two) Beam Cherenkov :

- π K separation at **high energy**
- $\sim$100% e-π tagging efficiency



Measurement of π^+ production cross section in Al (5% λ)@ 12.9 GeV/c

cross section

Absolute Normalization

pion yield (Empty target corrected)

$$\frac{d^2\sigma_\alpha}{dp_i\,d\theta_j}\Big|_{true} = \frac{1}{N_{pot}} \cdot \frac{A}{N_A \rho t} \cdot M^{-1}_{ij\alpha i'j'\alpha'} \cdot [N^{\alpha'}_{i'j'}(Al) - N^{\alpha'}_{i'j'}()]_{rec}$$

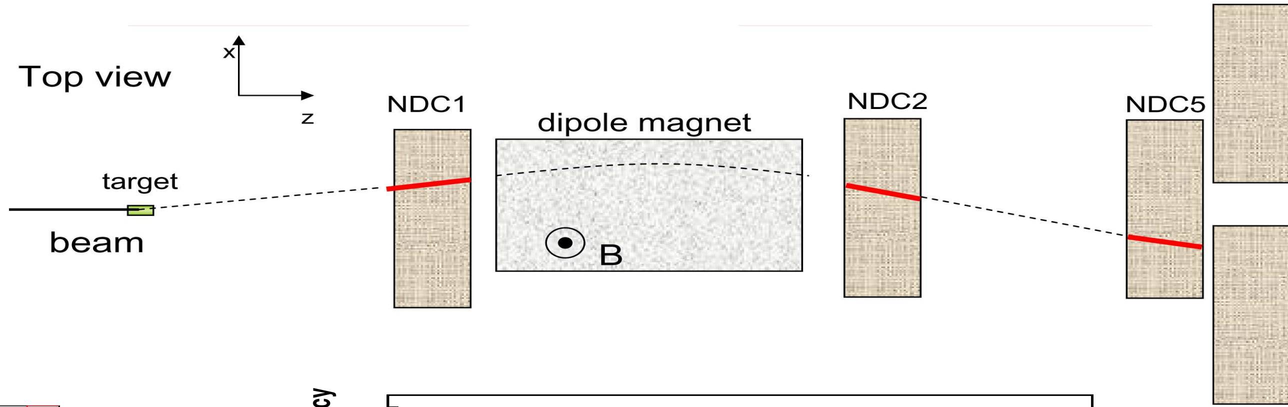
M^{-1} *corrects for PID efficiency and Migration, Acceptance and Reconstruction Efficiency, Absorption-Decay, Tertiary prod., e-Veto eff and Bck subtraction, detector resolution*

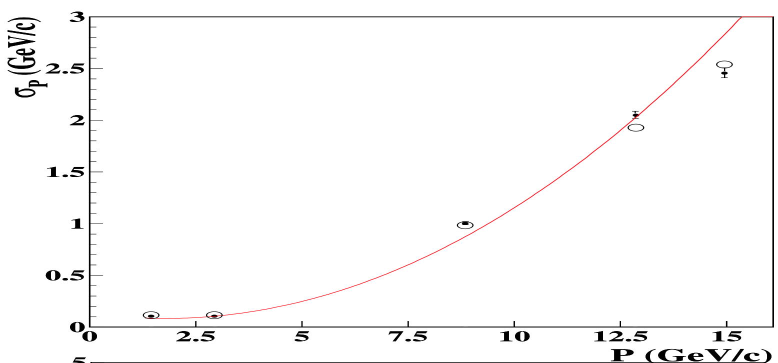
i,j are the momentum and angle bins, α is the particle type, Primes for recontructed quantities

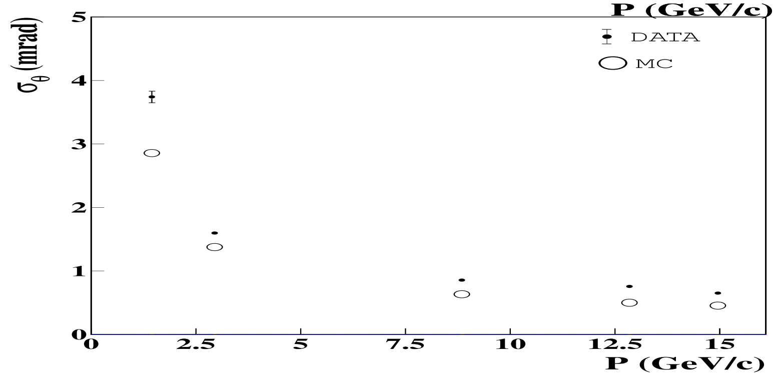
- *Event Selection & Counting protons*
- *Reconstructing Tracks*
- *π identification and background subtraction*
- *Corrections*
  - *Tracking Reconstruction Efficiency*
  - *Acceptance*
  - *PID efficiency and purity*
  - *Empty target subtraction*
  - *Correction for Tertiaries*
  - *...*

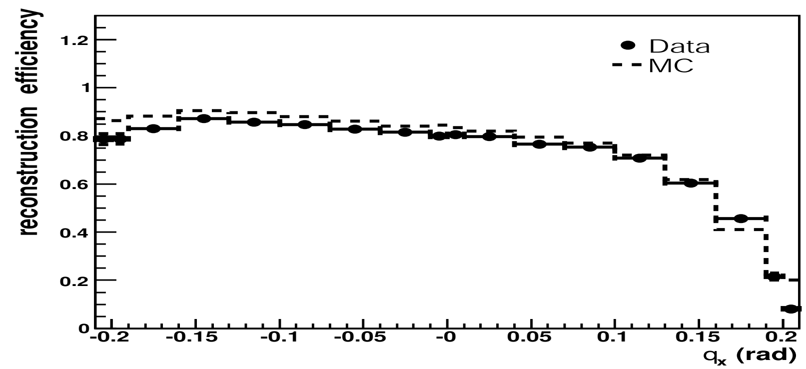
Reconstruction of tracks in p θ bins

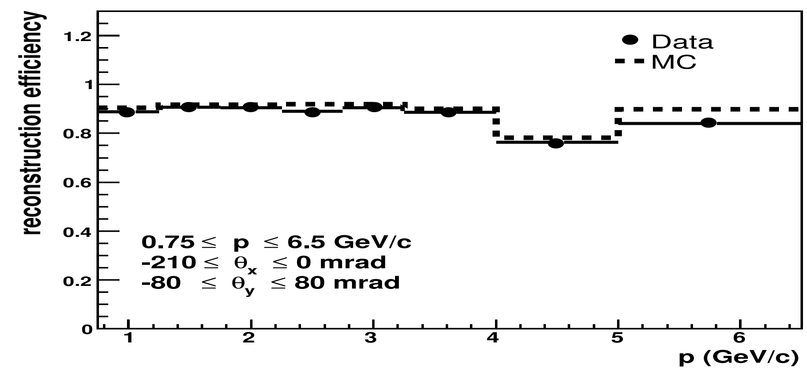
- p is measured (downstream segment + upstream constraint)
- charge is positive
- PID detectors (TOF,CHE)$\longrightarrow \pi$











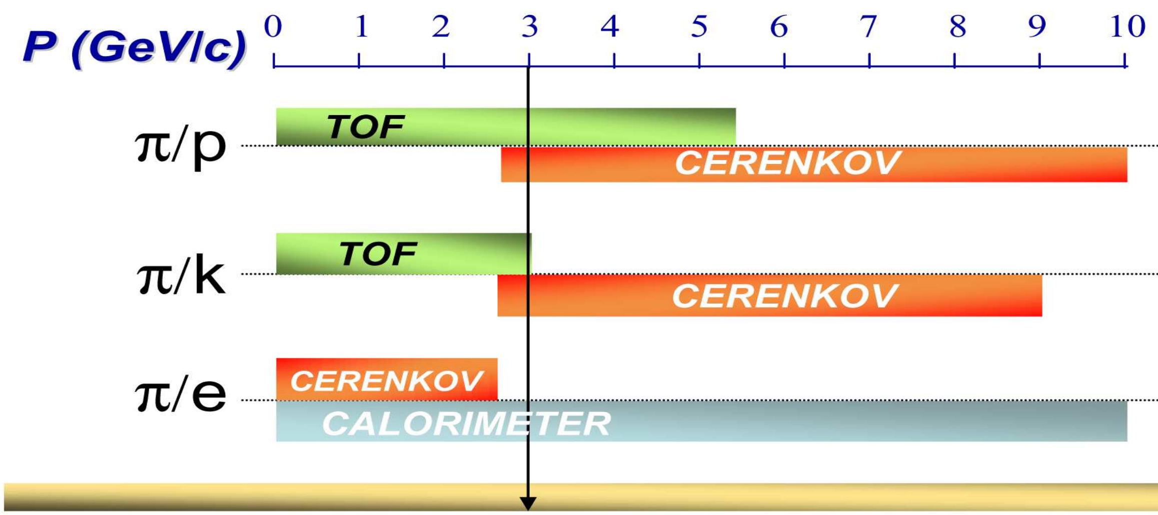
the phase space is splitted into bin far larger than the momentum $\&$ angular resolution:

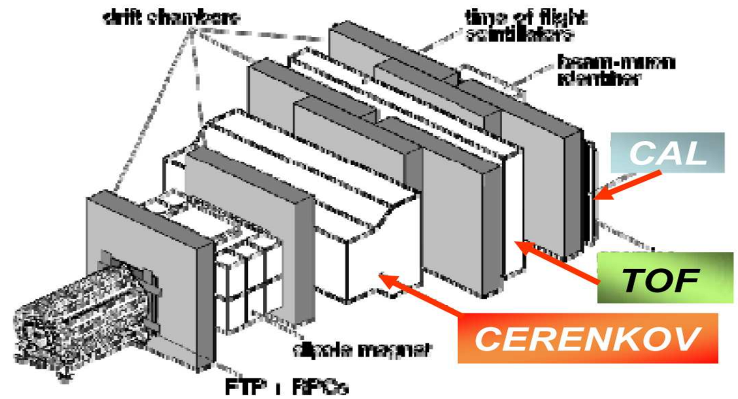
0.5 GeV/c bins $p < 4$ GeV/c, 1.5 GeV/c bins for $5 \div 6.5$ GeV/c and 30 mrad angular bins

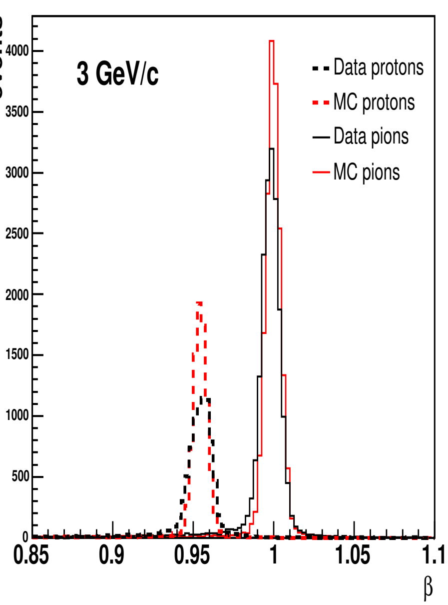
$\Rightarrow$ correction matrix M^{-1} almost diagonal in p θ

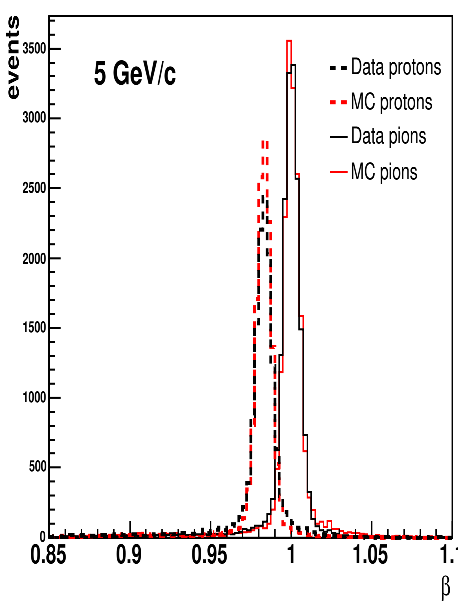
Particle identification

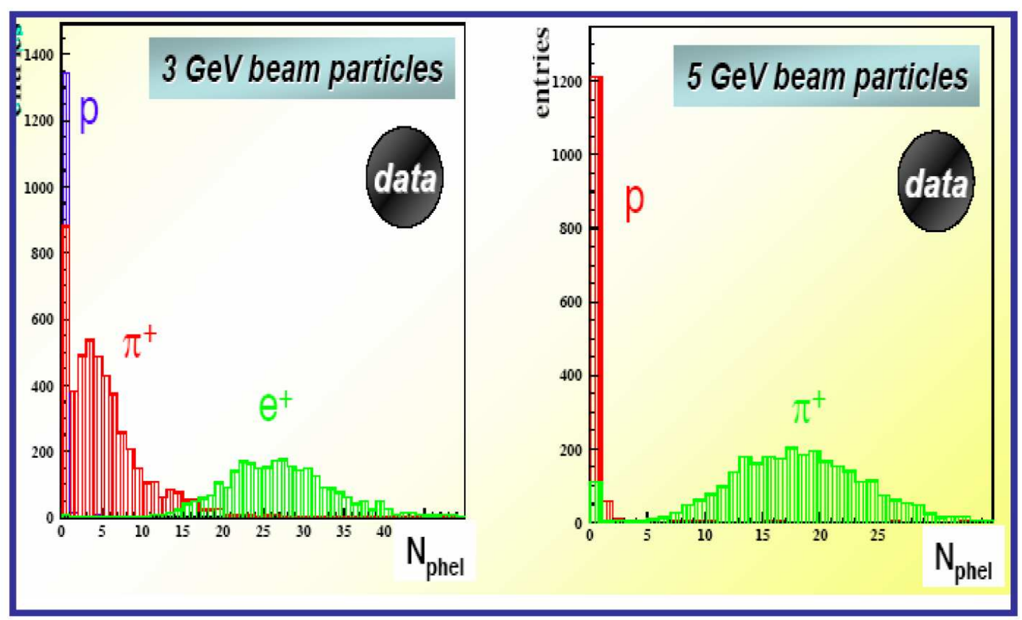
Redundancy and overlaps between Pid detectors



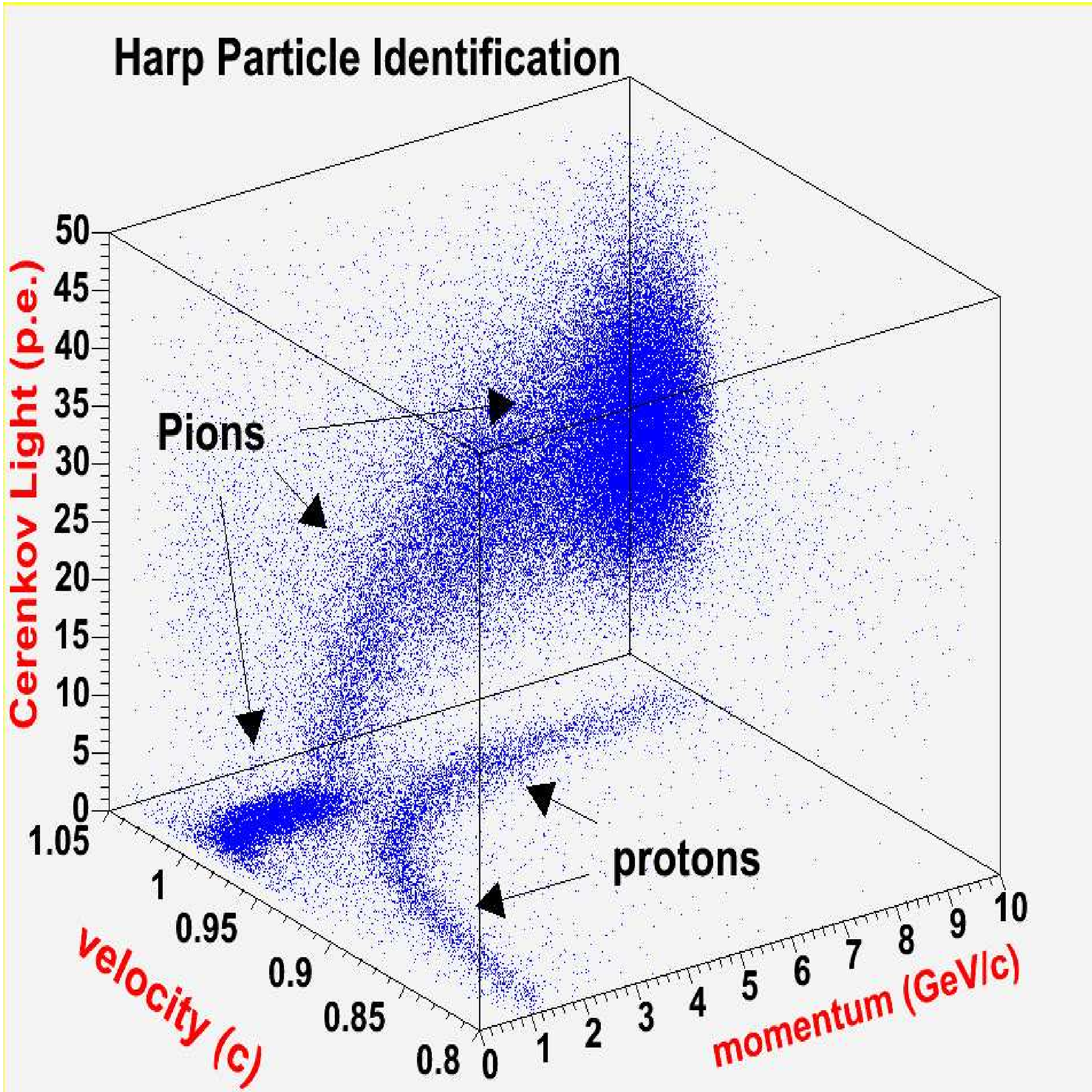






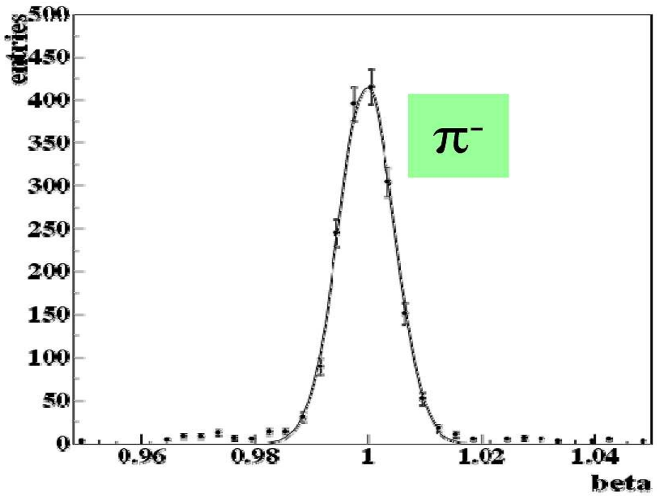


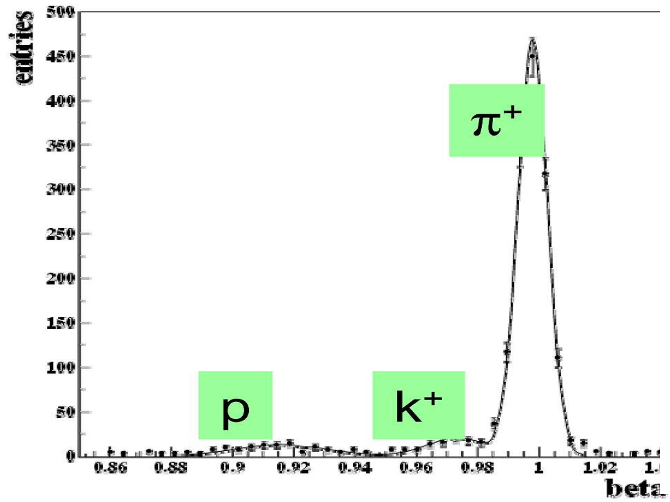
Particle identification in HARP

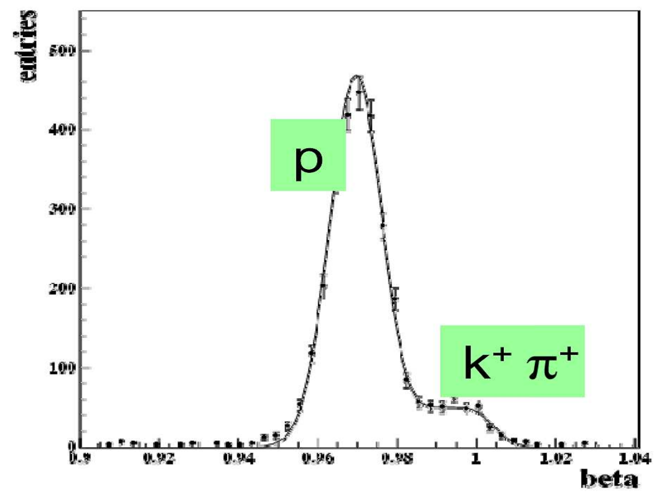


Detector response from data & combined PID probability

Pure Samples can be selected in data (Empty target and interaction events)







99 % π's in a sample of negative particles with e-veto

$\pi/p/k$ clearly separated by TOFW below 3 GeV

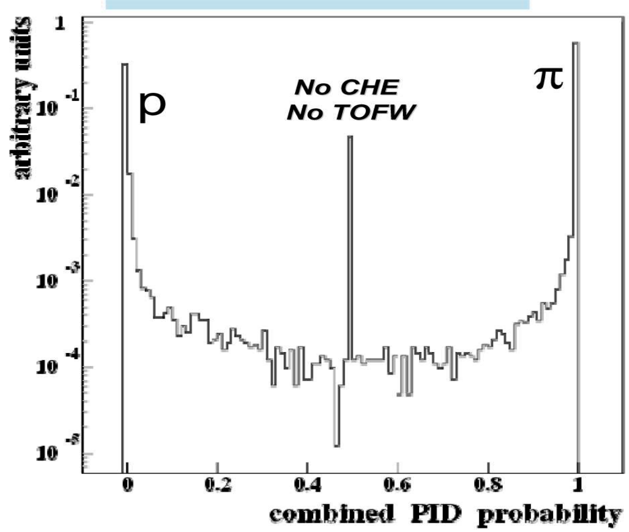
above CHE$_{\pi,thr}$ π's suppressed < 1 % by $N_{phe} < 3$

pdf from the data (MC in agreement)

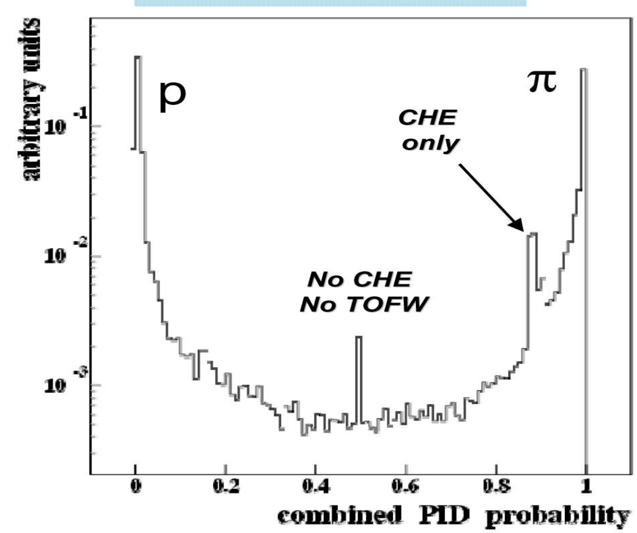
Combined PID $\Rightarrow$

Adopted cut: $P_\pi > 0.6$

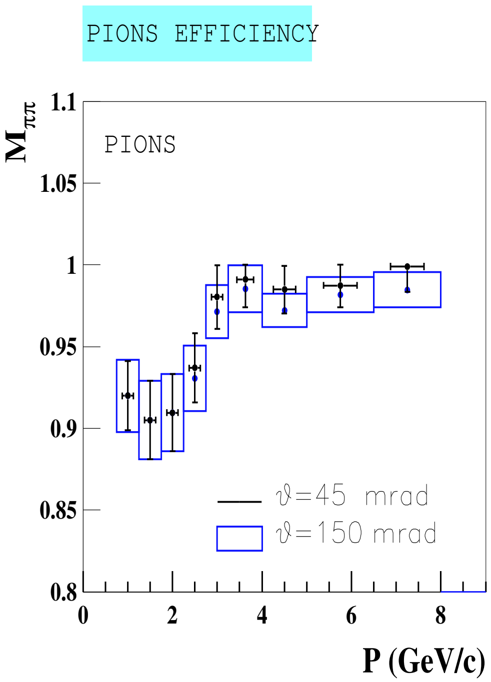
***0.75 < P < 2.25* GeV/c**

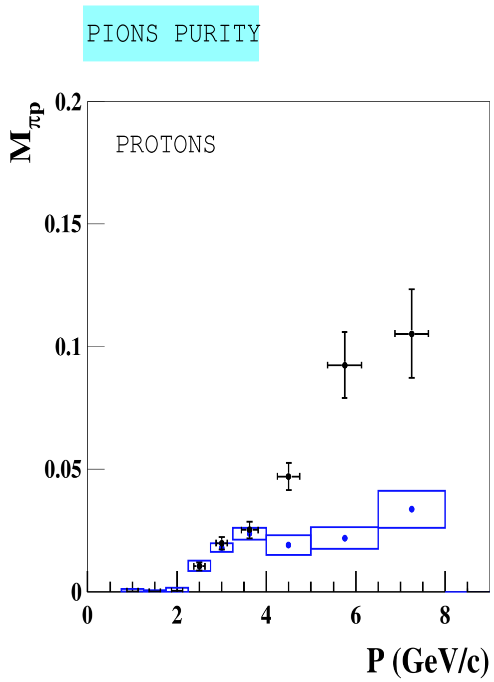


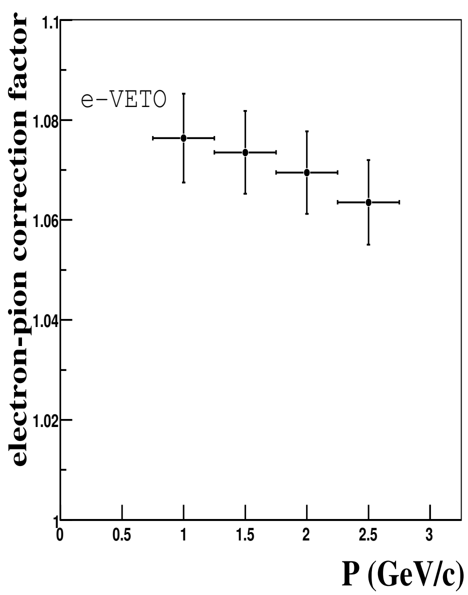
***2.75 < P < 6.5* GeV/c**

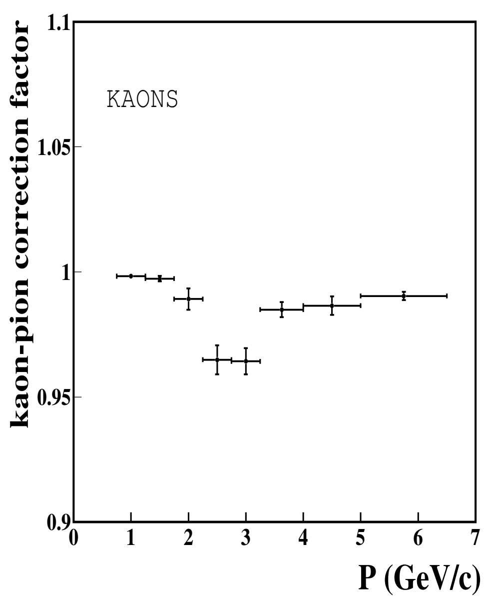


PID performance and migration matrix









π efficiency and purity decribed by the $(M^{id})^{-1}$ PiD term of the migration matrix, acting as:

$$\begin{pmatrix} n^{\pi'} \\ n^{p'} \end{pmatrix} = \begin{pmatrix} M_{\pi\pi} & M_{\pi p} \\ M_{p\pi} & M_{pp} \end{pmatrix} \cdot \begin{pmatrix} n^{\pi} \\ n^{p} \end{pmatrix}$$

$M_{\pi\pi}$: *fraction of observed π's that are true πs*

$M_{\pi p}$: *fraction of observed π's that are true ps*

$M_{p\pi}$: *fraction of observed p's that are true πs*

M_{pp}: *fraction of observed p's that are true ps*

- **electrons: vetoed**
- **kaons: subtracted**

both are accounted for by a correction factor

Error Analysis: Evaluation of the measurement precision

systematic error evaluated for all the terms of the cross-section, to quantify the precision of both differential and total cross section

- $\frac{d^2\sigma^\pi}{dp\,d\Omega}(p,\theta)$, *typical error:* $\delta_{diff} = 8.2$ %
- σ^π *for* $0.75 < p < 6.5$ *GeV/c and* $30 < \theta < 210$ *mrad, error on total cross-section:* $\delta_{int} = 5.8$ %

dominant error contributions to δ_{diff} *:*

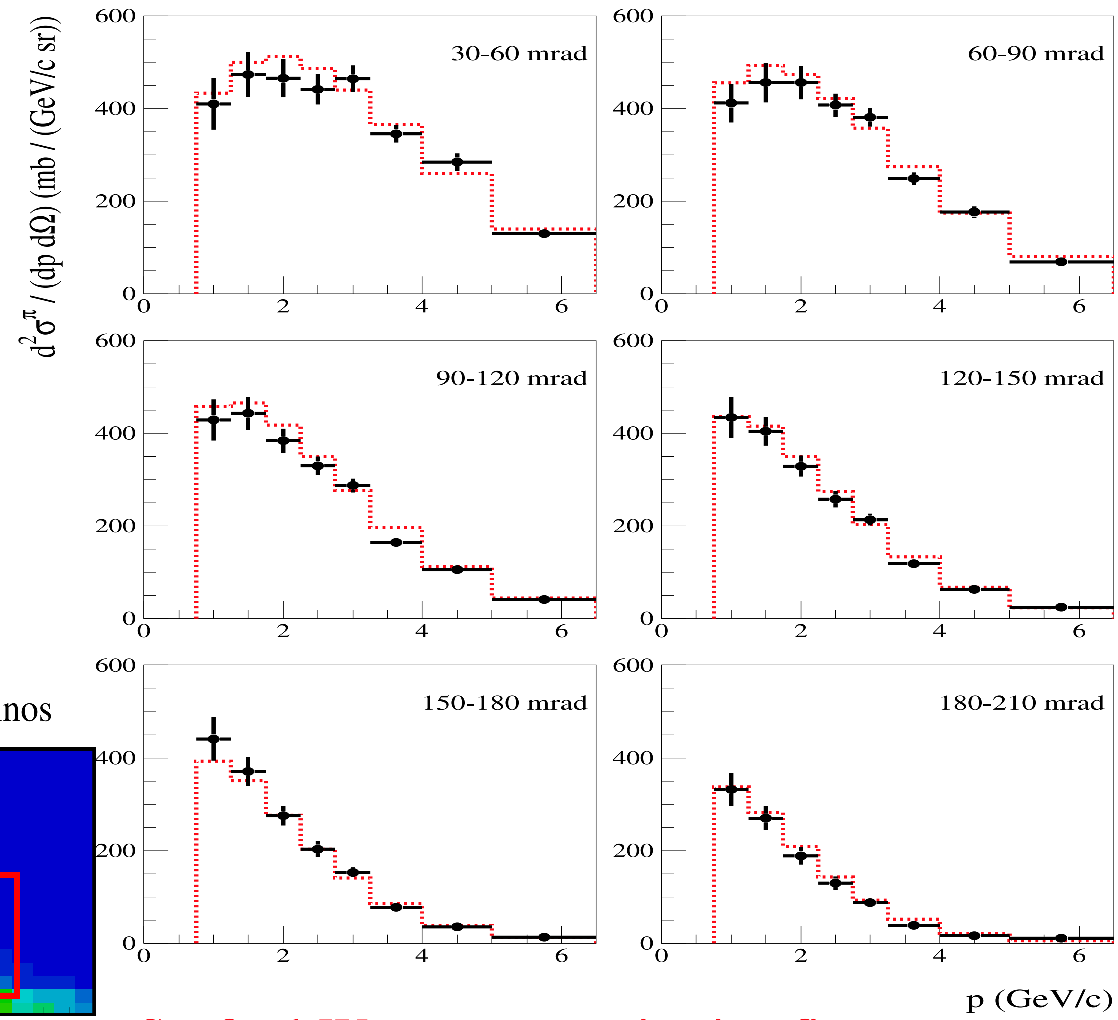
- *overall normalization*
- *terziary subtraction*
- *momentum scale*

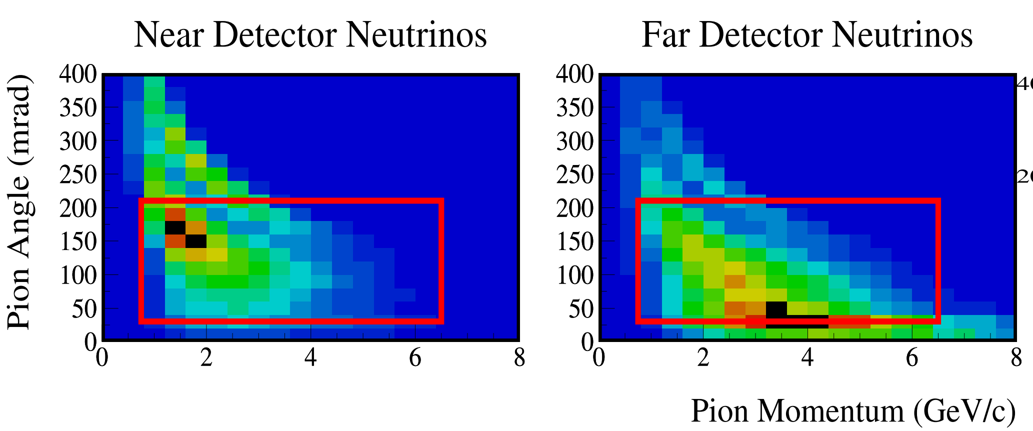
error category	error source	δ_{diff} (%)	δ_{int} (%)
statistical	Al target statistics	1.6	0.3
	empty target sub. (stat.)	1.3	0.2
track yield corr.	rec. eff.	0.8	0.4
	π, p absorption	2.4	2.6
	terziary subtract.	3.2	2.9
	empty target sub. (syst.)	1.2	1.1
part. identif.	PID prob. cut	0.2	0.2
	K subtract.	0.3	0.1
	e veto	2.1	0.5
	π, p, ID corr.	2.5	0.4
momentum rec.	momentum scale	3.0	0.3
	momentum resolution	0.6	0.6
overall normaliz.		4.0	4.0
all		8.2	5.8

cross-section for K2K thin target @ 12.9 GeV/c (K2K)& SW parametrization

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

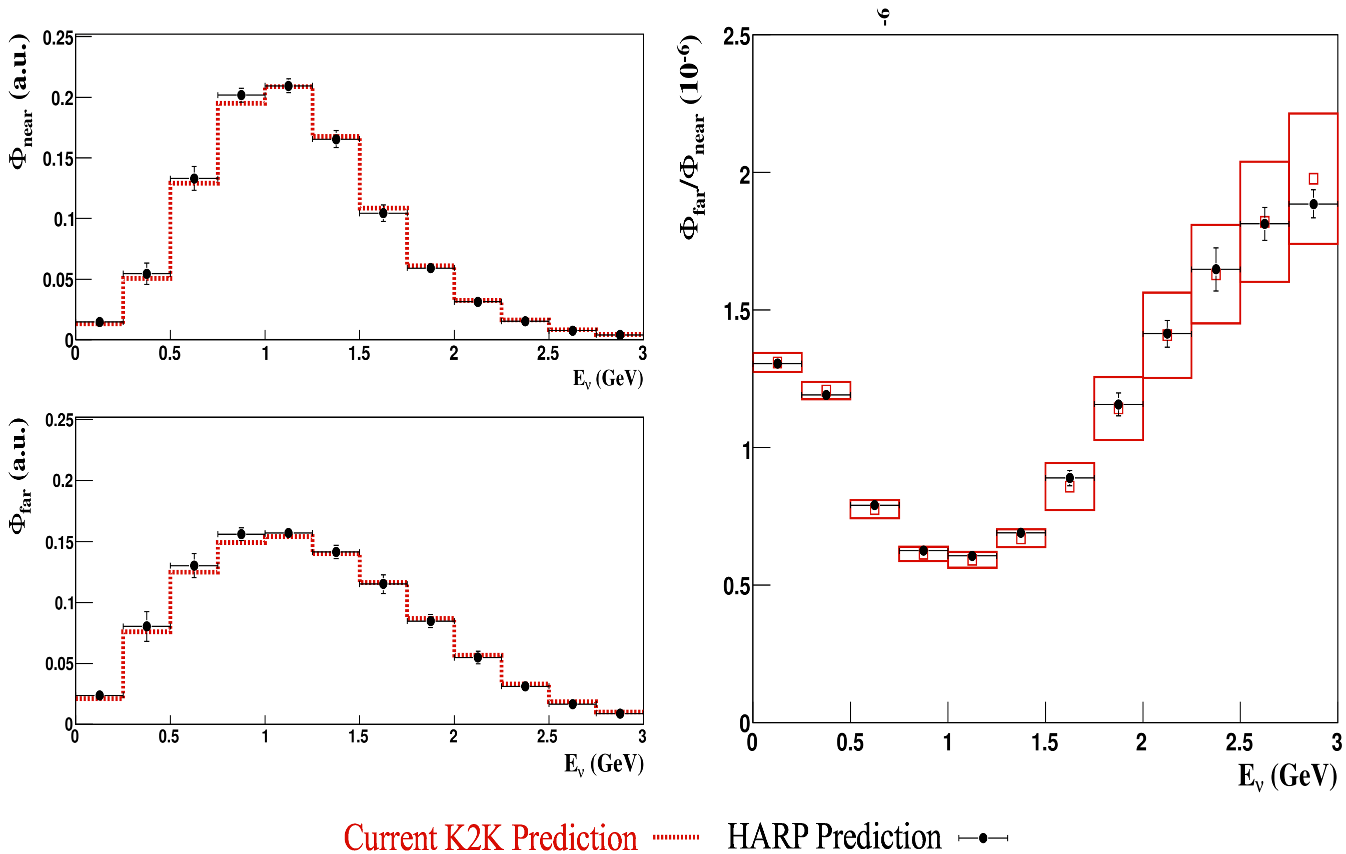
Parameter	*Value*
c_1	$(4.4 \pm 1.3) \cdot 10^2$
c_2	$(8.5 \pm 3.4) \cdot 10^{-1}$
c_3	(5.1 ± 1.3)
$c_4 = c_5$	(1.78 ± 0.75)
c_6	(4.43 ± 0.31)
c_7	$(1.35 \pm 0.29) \cdot 10^{-1}$
c_8	$(3.37 \pm 0.96) \cdot 10^1$





Sanford-Wang parametrization fit ......

Physics impact: Far and Near ν fluxes at K2K



- *similar E_ν spectra arising from K2K default (pre-HARP) and HARP S-W π^+ param.*
- *errors shown: HARP π^+ production uncertainties and MC statistics*
- *push to 1 % the systematics of Far to Near neutrino flux ratio associated to secondary particle production!*

$p + Be \rightarrow \pi^+ + X$ cross-section & SW param. -PRELIMINARY

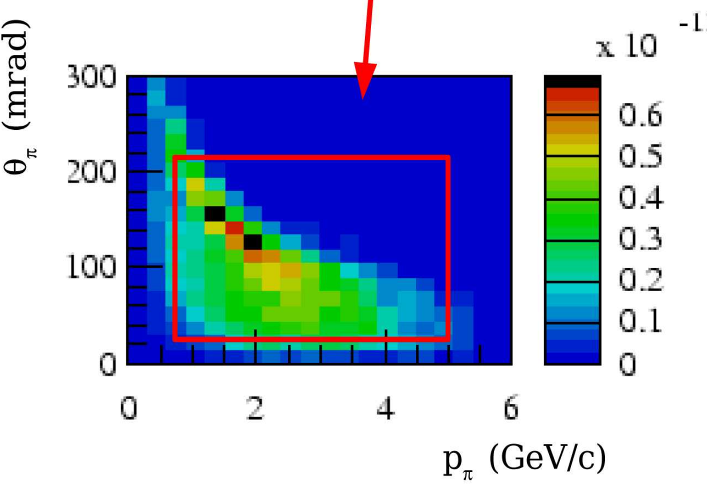
- *primary protons: 7.3 M pot,*

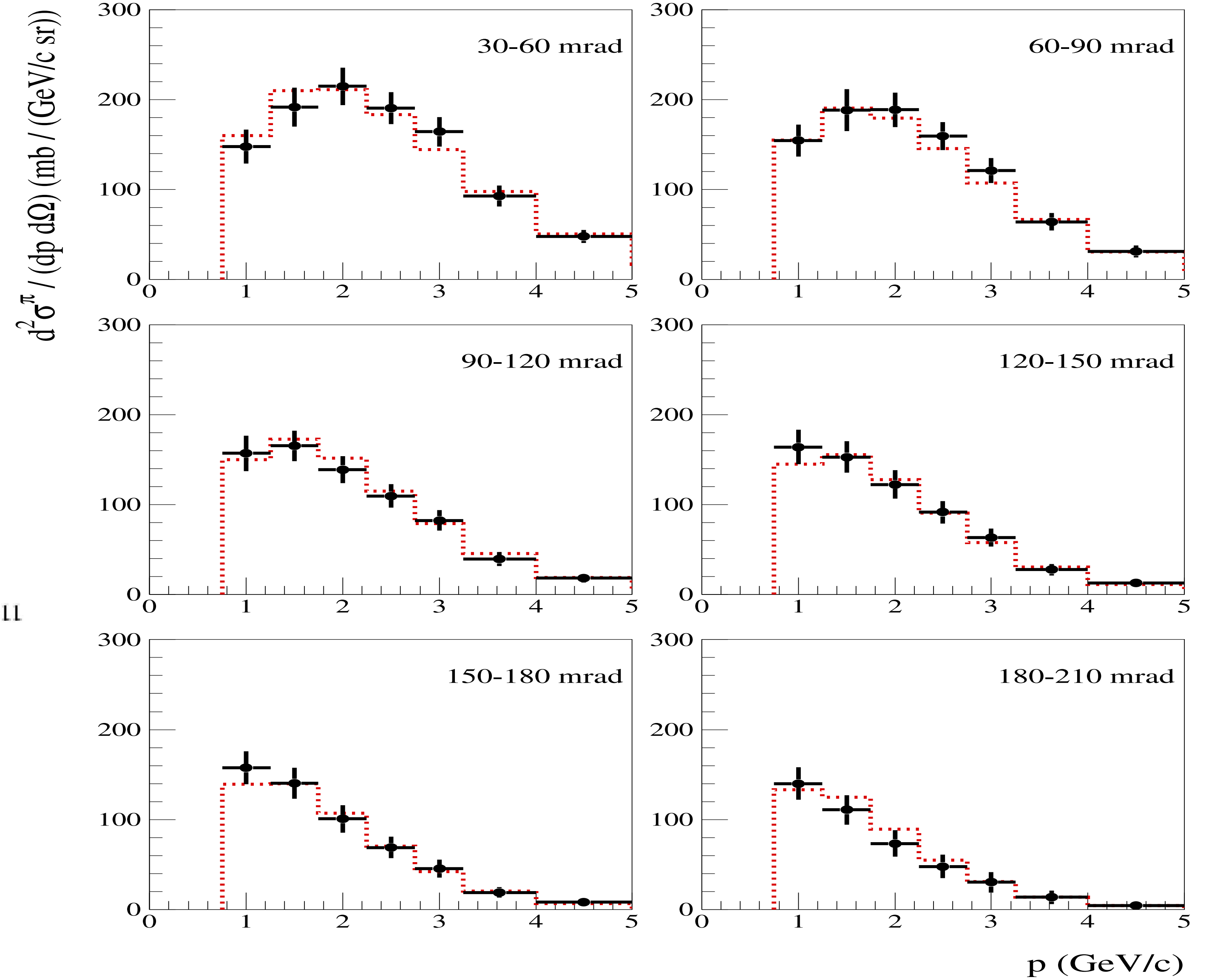
  $p_{beam} = 8.9$ *GeV/c*
- *5 % λ Be disc*
- *quite similar Al data analysis*

  well covering MiniBooNE

  phase space

0.75 < p_π < 5 GeV/c
30 < θ_π < 210 mrad



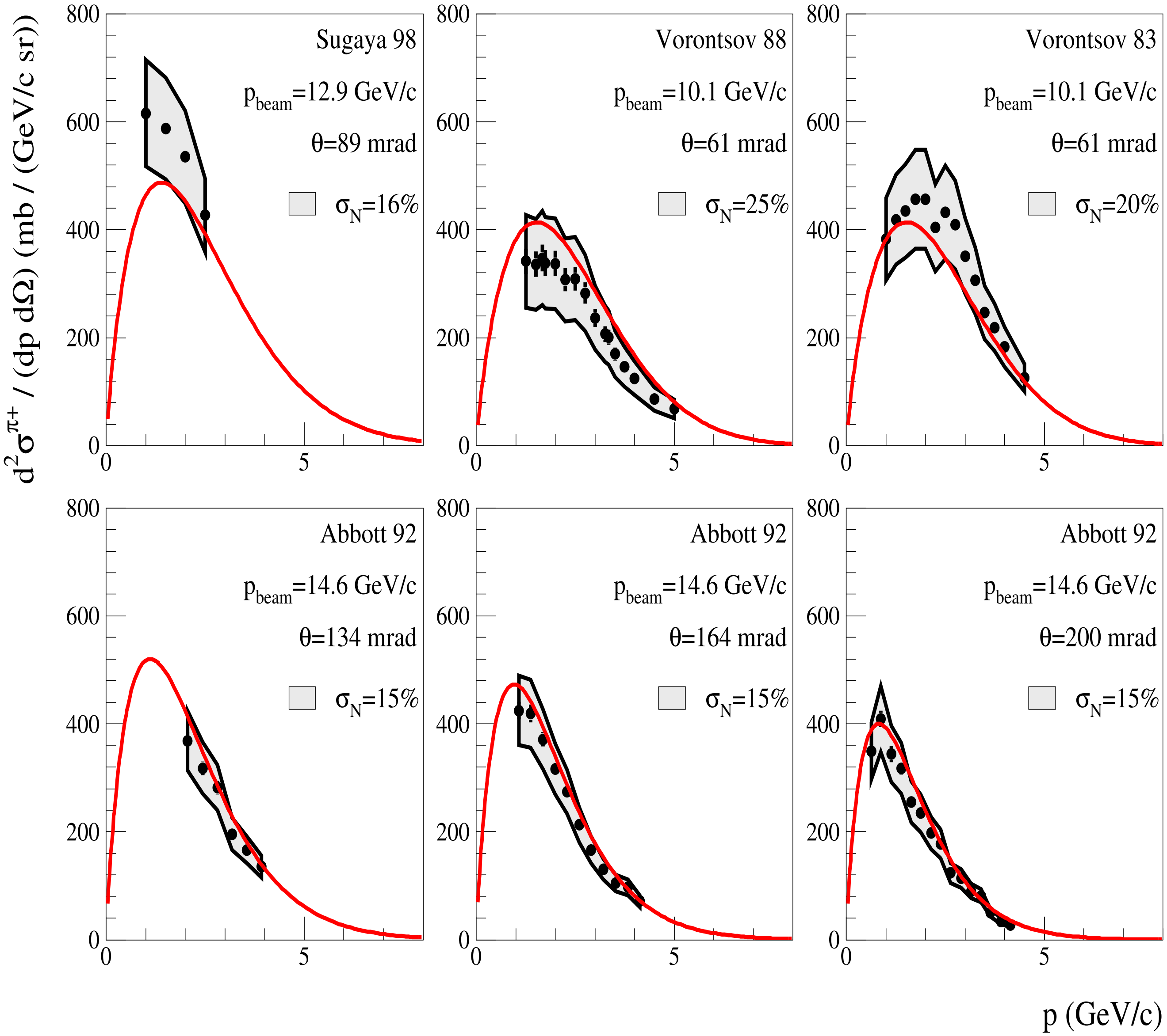


Comparing HARP with previous results

HARP results vs. previous data on $p + Al \rightarrow \pi^+ + X$

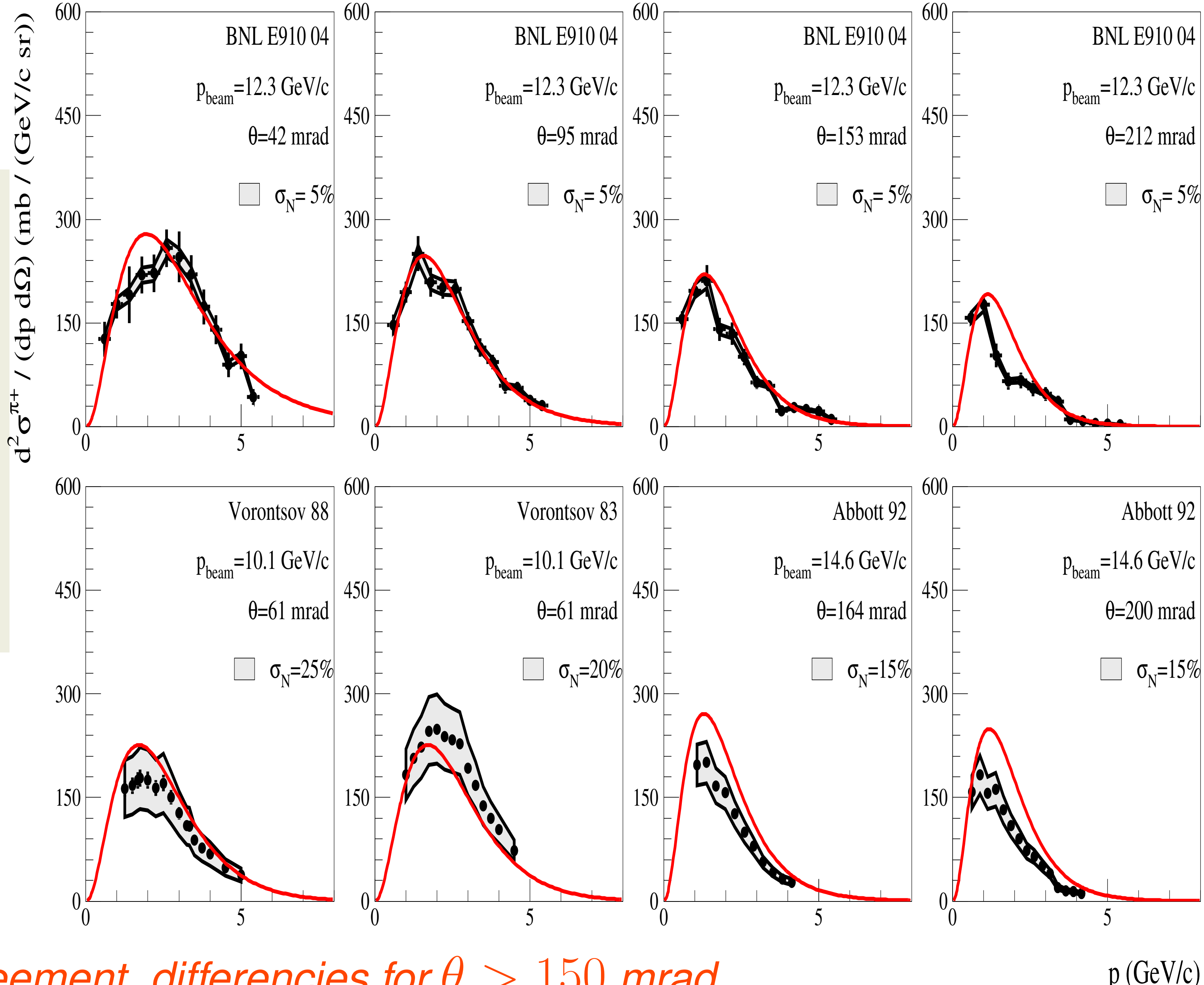
- *restricted comparison to proton beam momenta close to K2K:* $10 < p_{beam} < 15$ *GeV/c*
- *forward production pion:* $\theta < 200$ *mrad*
- *—HARP Sanford-Wang param. at 12.9 GeV rescaled to* p_{beam} *of old experiments*

... reasonable agreement



HARP PRELIMINARY results vs. previous data on $p + Be \rightarrow \pi^+ + X$

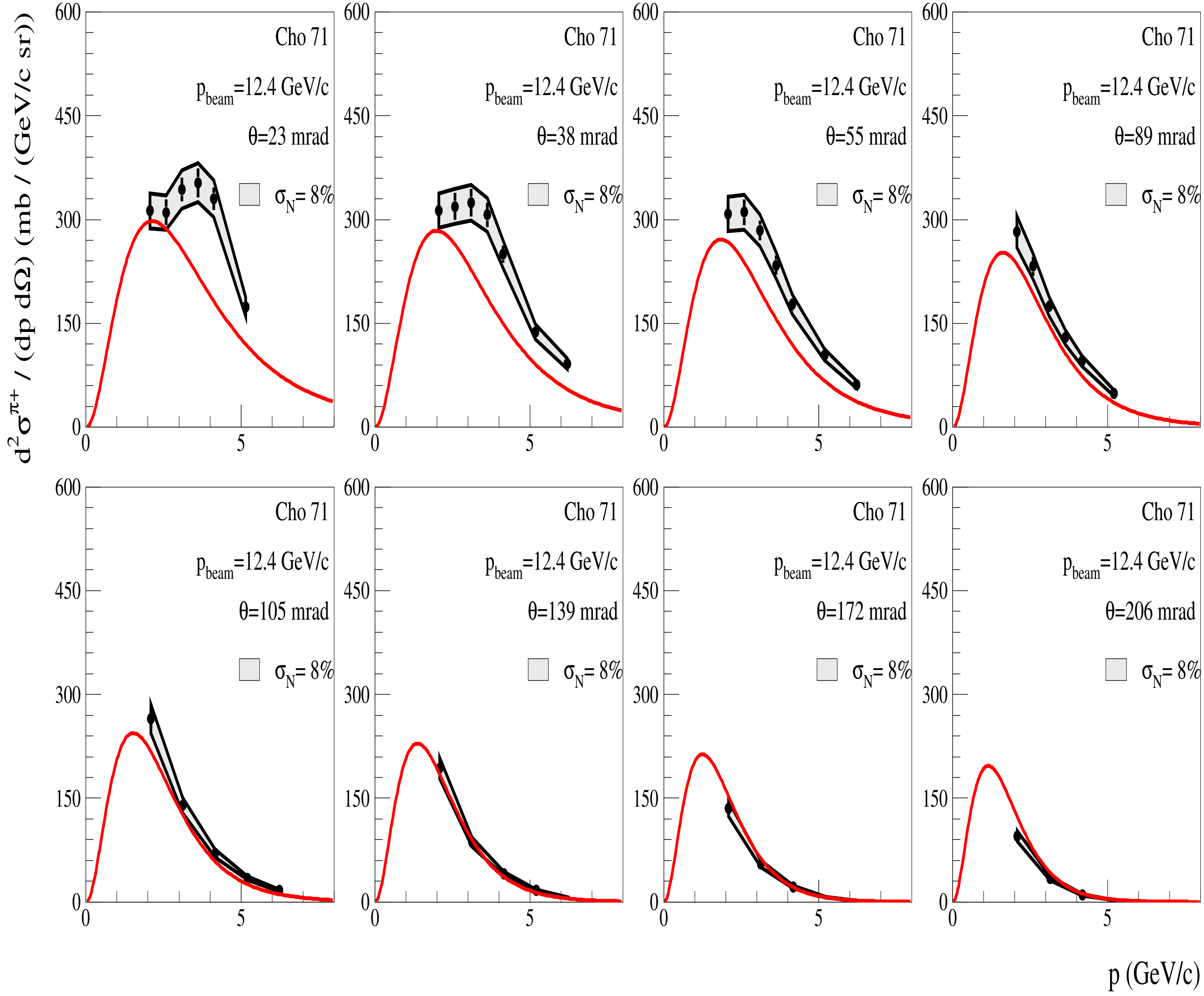
- p_{beam}: $10 \div 15$ GeV/c close to MiniBooNE:
- $\theta < 200$ mrad
- —HARP Sanford-Wang param. at 8.9 GeV rescaled to p_{beam} of old experiments



... reasonable agreement, differencies for $\theta > 150$ mrad

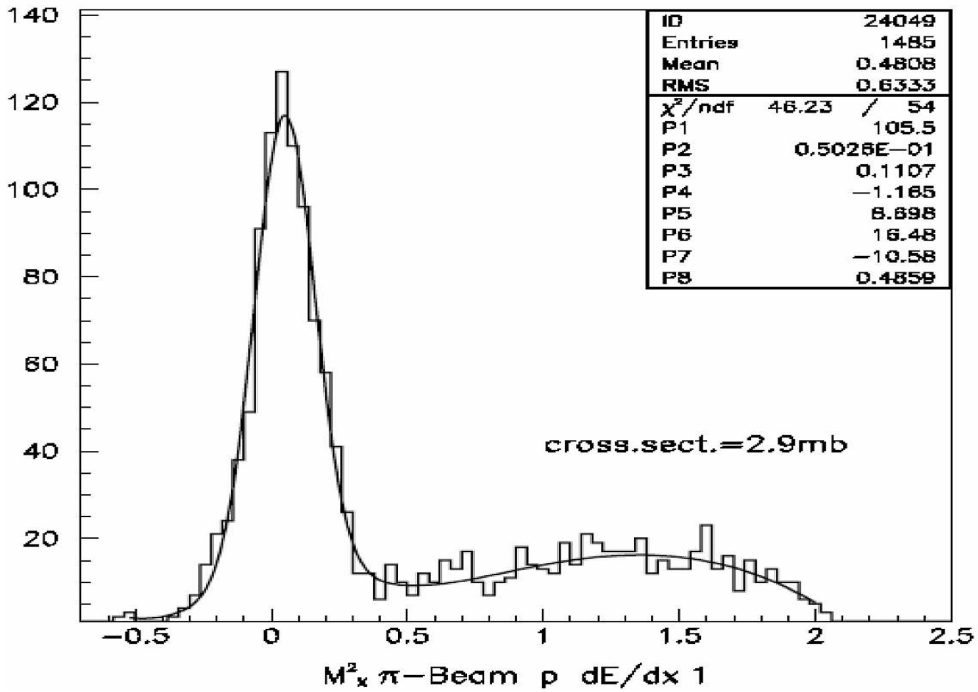
HARP PRELIMINARY results vs. previous data on $p + Be \rightarrow \pi^+ + X$ (Continued)

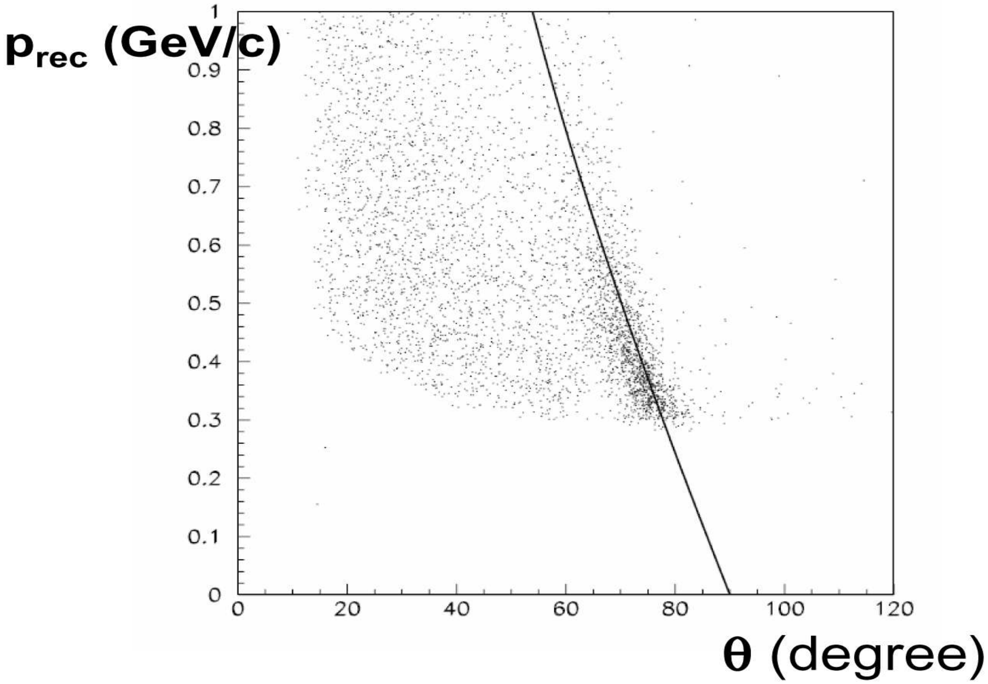
... important variations w.r.t. Cho71 old data (Cho71 data are in disagrement also with BNL E910 ...)



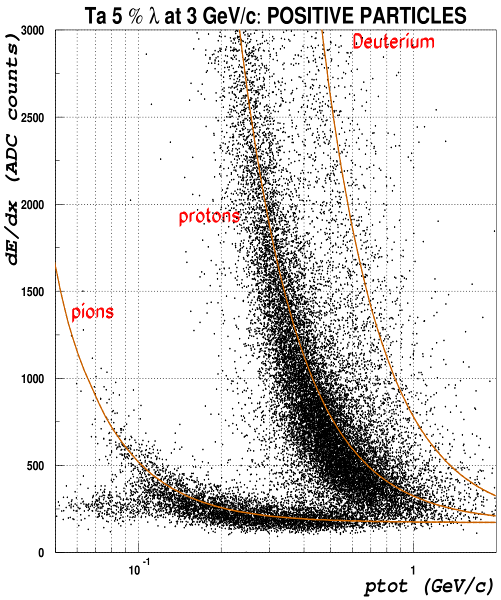
Large angle analysis: the NuFact case

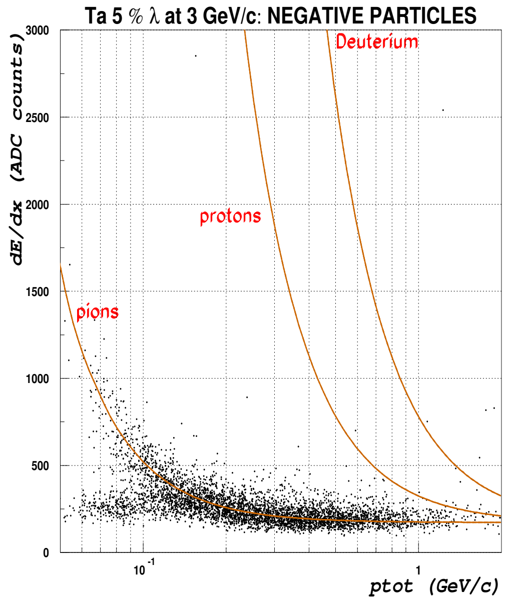
- *Neutrino Factory design require the precise (< 5 %) measurement of p_t distribution of the pion yields from low energy protons on selected targets*
- *TPC response has been calibrated by pion, proton elastic scattering at 3 GeV/c*

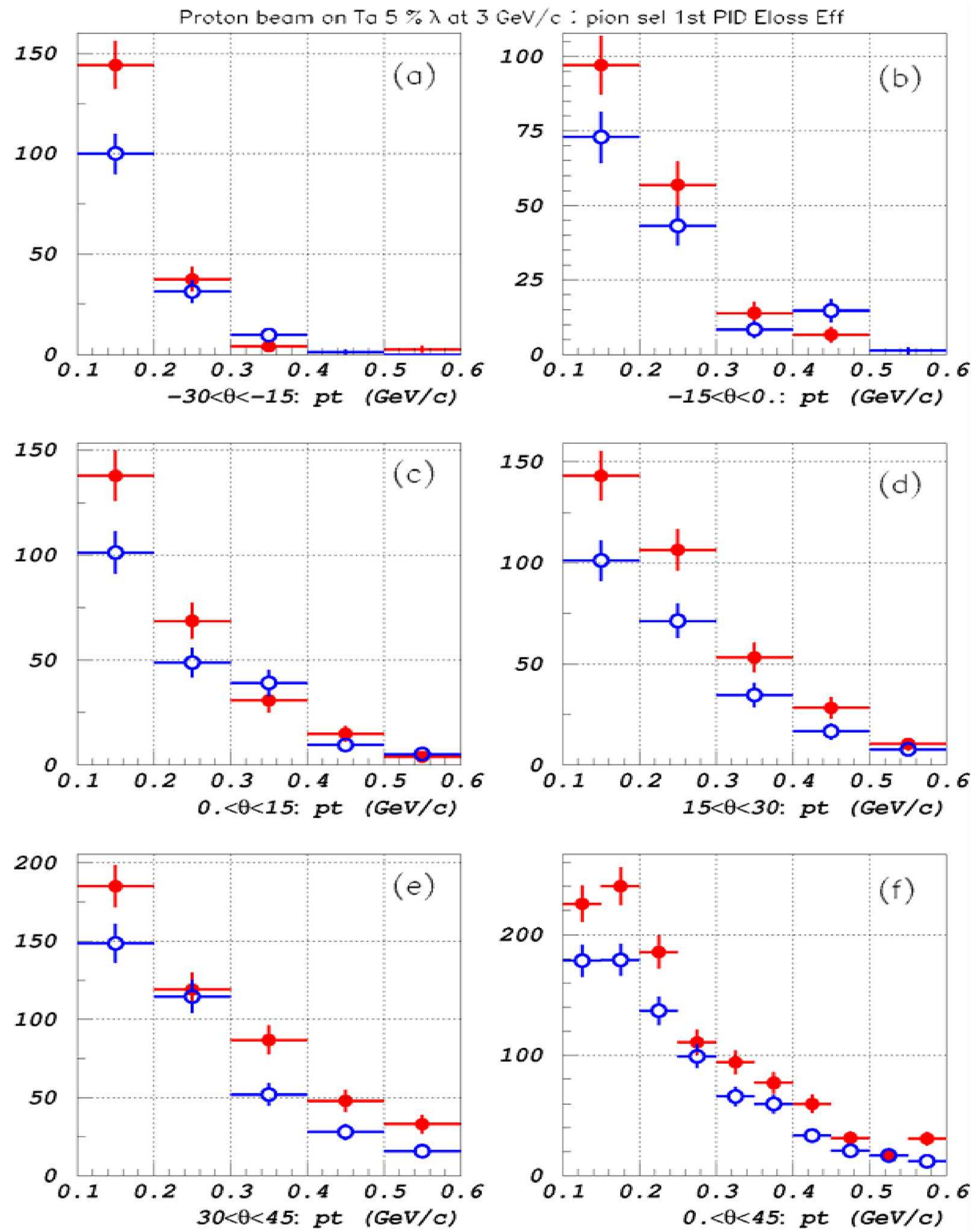




Ta $\pi^{\pm}$ yield analysis, $p_{beam} = 3$ GeV/c, $5\%\lambda$ - PRELIMINARY







- *only one beam particle identified as proton by MWPC + TOF beam counters*
- *event selection: large angle interaction by ITC ($\epsilon_{ITC} = 99$ %)*
- *cuts on the event spill to reject events strongly affected by the dynamic distorsions*

$\rightarrow p_t$ *scan of* π^+ *(–) and* π^- *(–) yields for different production angle* θ *(15 degree bins)*

Conclusions

- *HARP at CERN PS collected data over a wide range of targets and beam momenta to measure π and K production cross sections, relevant for the present K2K and MiniBooNE neutrino beams and for future SuperBeams and Neutrino Factories.*
- *completed the thin target analysis of forward π^+ production for Al (@ 12.9 GeV/c, K2K) and Be (@ 8.9 GeV/c, MiniBooNE): cross sections, measured with 6 % integral and 8.2 % differential uncertainty, are compatible with and more precise than older data available for Be and Al.*

  $\rightarrow$ physics impact in K2K: strong reduction of systematics of Far to Near neutrino flux ratio associated to secondary particle production!

- *on-going studies. Thick and replica K2K and MiniBooNE targets. Study of A and energy dependence. Inclusion of C data expected to be a relevant contribution to the understanding of atmospheric neutrino fluxes.*
- *large angle analysis already produced very promising results. The elastic scattering provides a clean way to calibrate the momentum scale of the detector. Preliminary π^+/π^- yields have been obtained for Ta, that can be used for NuFact. The goal is to give an experimental input to choose the proton driver energy of the Neutrino Factory.*

Correction Factors

Correction Type	Impact On Cross Section	Method
Momentum Resolution	Shape	MC
Particle Efficiency	15% up	Data
Geometric Acceptance	$\sim 100 - 160\%$ up	MC/Analytic
Pion ID	Efficiency: 5-10% up	Data
Pion ID	π-proton migration:$< 5\%$ down	Data
Absorption/decay	10-30% up	MC
Tertiary Production	$< 5\%$ down	MC
Electron Veto eff.	5-10% up	MC
Kaon Subtraction	1-3% down	Data/MC
Target-out Subtraction	$\sim 20\%$	Data