Particle production vs energy

M. Bonesini

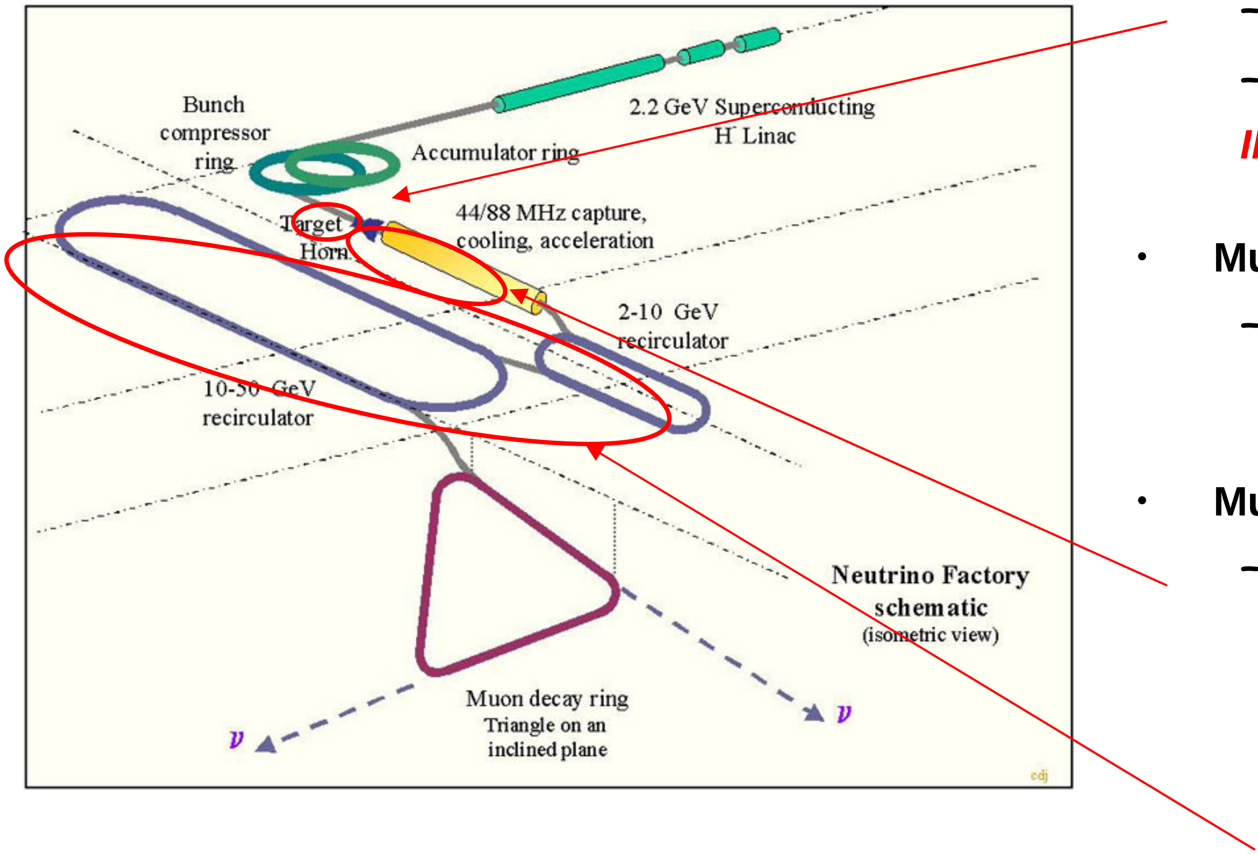
Sezione INFN Milano Bicocca,

Dipartimento di Fisica G. Occhialini

Outline

- Targetry for Nufact
  - HARP
    - Large Angle Data analysis
    - Comparison with MC simulations
- Targetry for conventional neutrino beams
  - HARP for K2K, MINIBoone
  - NA56/SPY for WANF,CNGS, NuMI
- Targetry for EAS and atmospheric neutrino
- Future experiments
- Conclusions

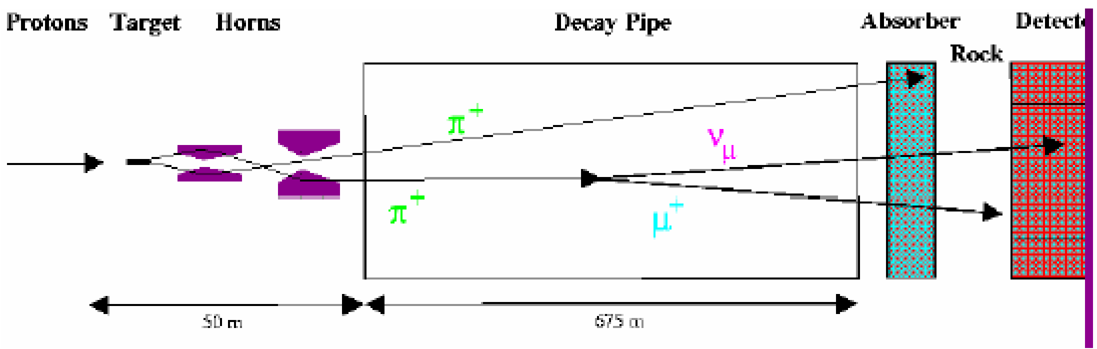
Towards a Neutrino Factory: the challenges

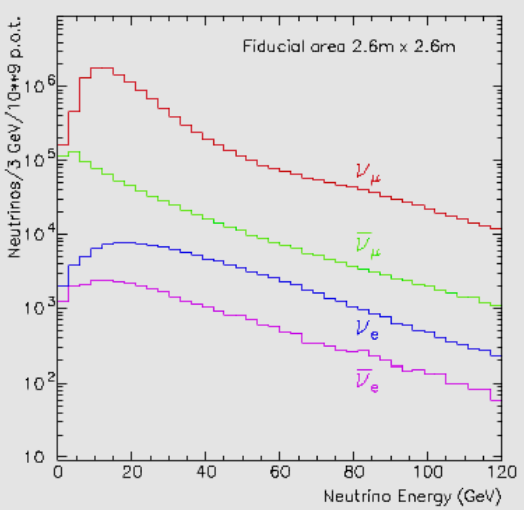


- Target and collection (HARP/MERIT)
  - Maximize π^+ and π^- production
  - Sustain high power (MW driver)
  - Optimize pion capture

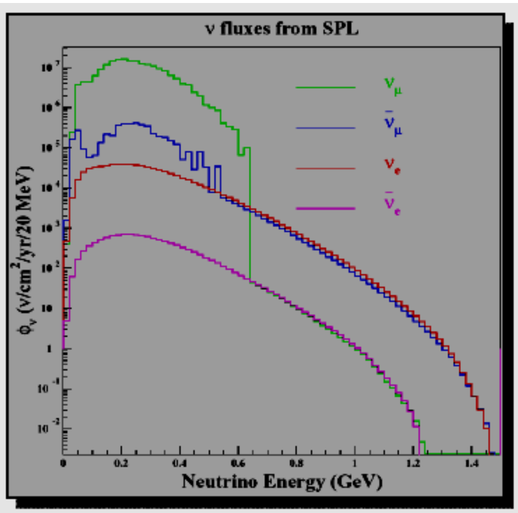
  INTENSE PROTON SOURCE (MW); GOOD COLLECTION SCHEME
- Muon cooling (MICE)
  - Reduce $\mu+/\mu-$ phase space to capture as many muons as possible in an accelerator
- Muon acceleration
  - Has to be fast, because muons are short-lived !

Why dedicated Hadroproduction expts: conventional neutrino beams





NOMAD



SPL

Ingredients to compute a neutrino flux :

π (and k) production cross section (use same target and proton energy than proton driver of the experiment)

Reinteractions (take data with thin and thick target))

All the rest: Simulation of the neutrino line: An “easy” problem.

Simulation of neutrino beams

1. Primary target production → **2. re-interactions in target** → **3. re-interactions in beamline**

Full Montecarlo simulation (MARS, FLUKA, Geant 3 or 4) — **Good for study of systematics**

Fast simulation (parametrization of hadron production data, re-int models) — **Good for beamline optimization**

Available data for simulations of ν beamlines

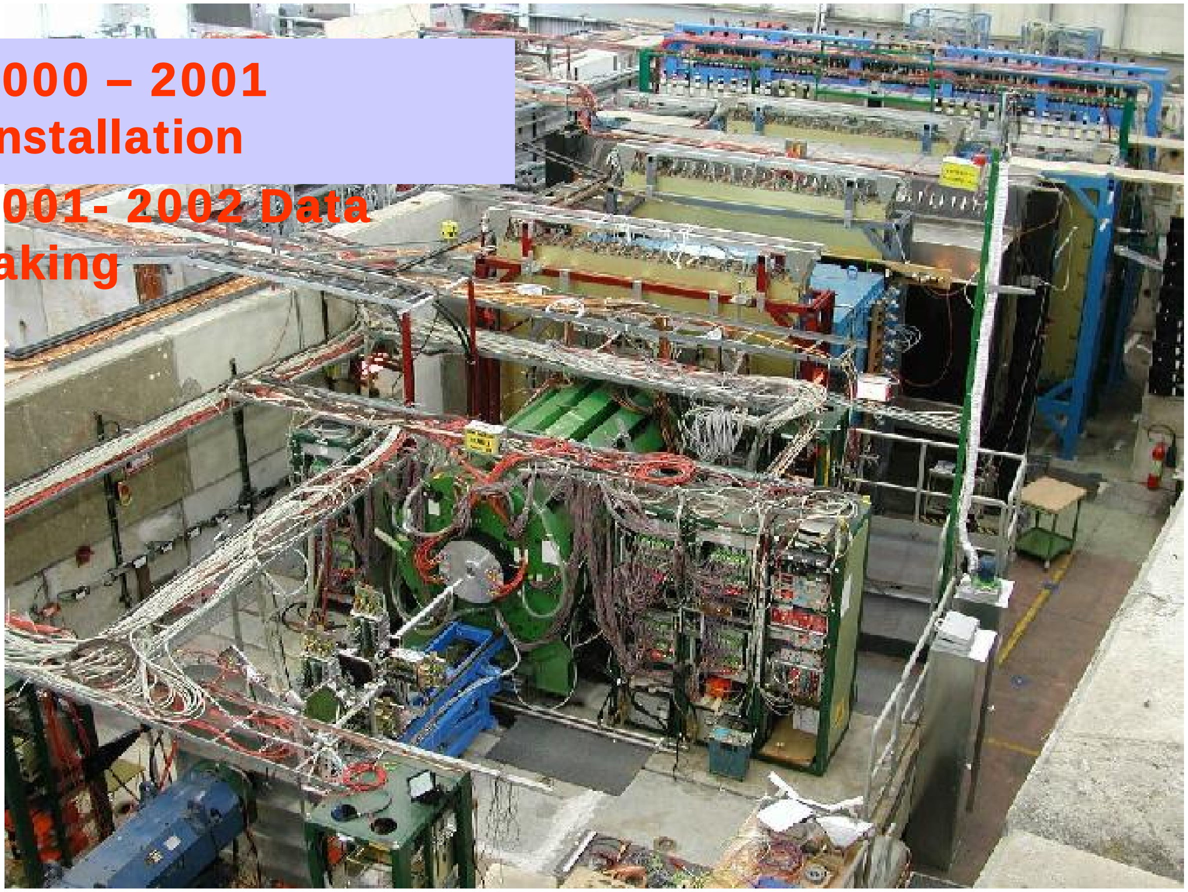
- **Low energy beams (NuFact, K2K, MiniBOONE …); mainly HARP**
- **High energy beams (WANF, CNGS, NuMI, …): NA20, NA56/SPY and coming soon MIPP, NA61/SHINE**
- **In addition a lot of old not-dedicated hadron production experiments, mainly with big systematic errors and poor statistics**

❑ **I will speak mainly of HARP (with an detour on NA56/SPY): see M.G. Catanesi's talk for the others**

Physics goals of HARP

2000 – 2001 Installation

2001- 2002 Data taking



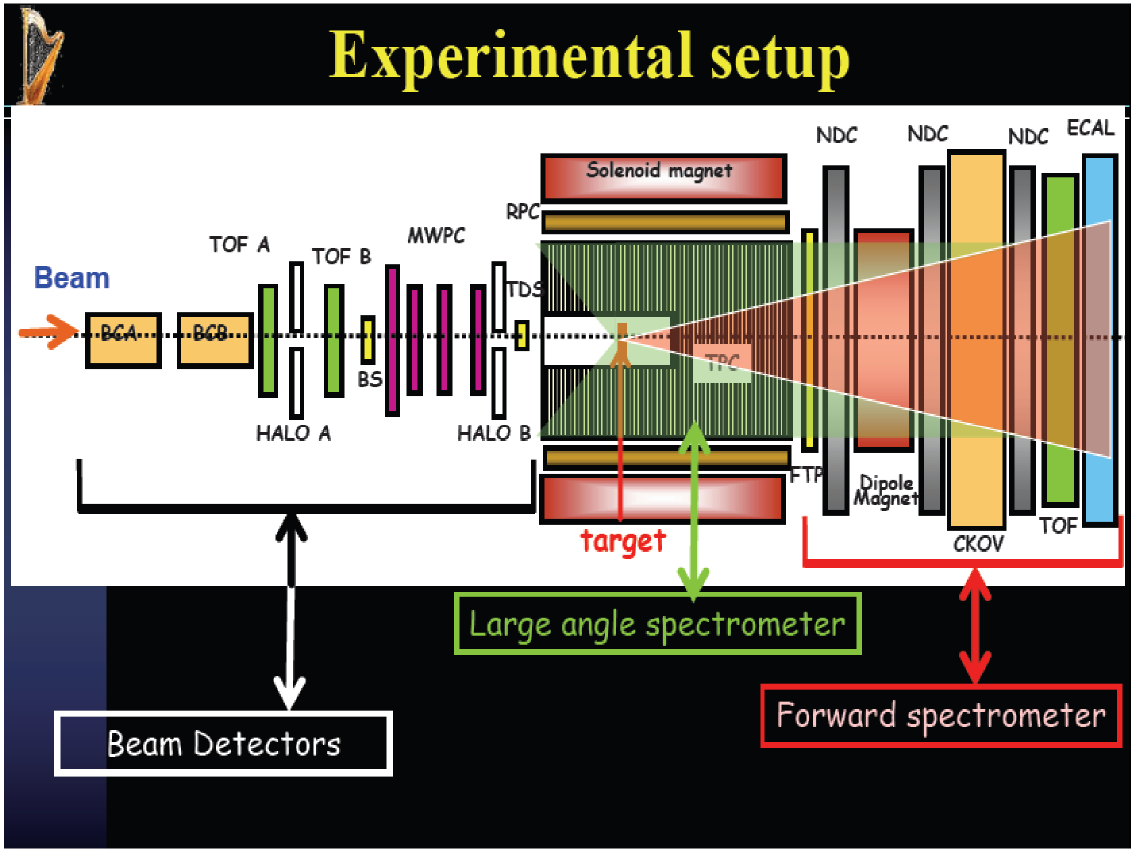
Systematic study of hadron production:

Beam momentum: 3-15 GeV/*c*

Target: from hydrogen to lead

- **Acceptance over full solid angle**
- **Final state particle identification**

- **Input for prediction of neutrino fluxes for the MiniBooNE and K2K experiments**
- **Pion/Kaon yield for the design of the proton driver of neutrino factories and SPL- based super-beams**
- **Input for precise calculation of the atmospheric neutrino flux and EAS**
- **Input for Monte Carlo generators (GEANT4, e.g. for LHC or space applications)**



Harp detector layout and data taken .

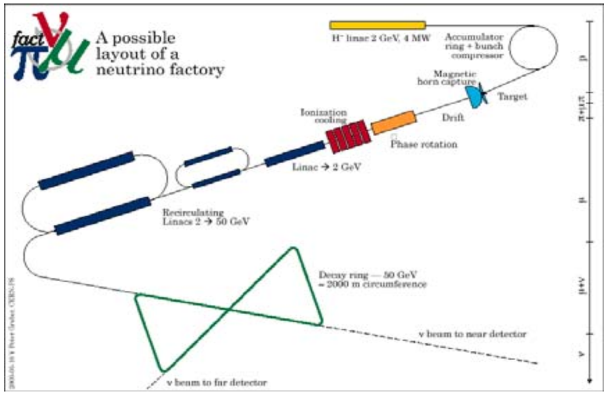
Barrel spectrometer (TPC) + forward spectrometer (DCs) to cover the full solid angle, complemented by PID detectors

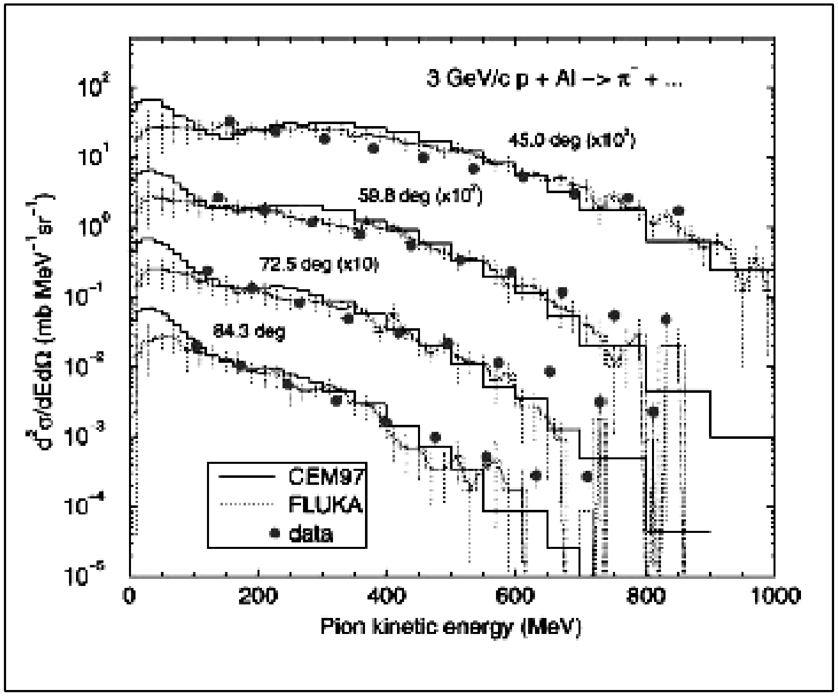
	Targetl	Target length (λ%)	Beam Momentum (GeV)	#events (Mevts)
Solid targets	Be			
	C	2	±3	
	Al	(2001)	± 5	
	Cu		± 8	
	Sn	5	± 12	
	Ta		± 15	233.16
	Pb	100	For negative polarity, only 2% and 5%	
K2K	Al	5, 50, 100, replica	+12.9	15.27
MiniBooNE	Be		+8.9	22.56
Cu "button"	Cu		+12.9, +15	1.71
Cu "skew"	Cu	2	+12	1.69
Cryogenic targets	N_7	6 cm	±3	58.43
	0_8		± 5	
	D_1		± 8	
	H_1		± 12	
			± 15	
	H_2	18 cm	±3, ±8, ±14.5	13.83
Water	$H_2 0$	10, 100	+1.5, +8(10%)	9.6

ν factory design

- **maximize $\pi^+(\pi^-)$ production yield as a function of:**
    - **proton energy**
    - **target material**
    - **geometry**
    - **collection efficiency (p_L,p_T)**
- **but different simulations show large discrepancies for π production distributions, both in shape and normalization. Experimental knowledge is rather poor (large errors: poor acceptance, few materials studied)**

⇒ aim: measure p_T distribution with high precision for high Z targets





HARP Large Angle Analysis

Beam momenta:

3, 5, 8, 12 GeV/c

Data:

5% λ_I targets Be,C,Al,Cu,Sn,Ta,Pb

TPC tracks:

>11 points and momentum measured and track originating in target

PID selection

Corrections:

Efficiency, absorption, PID, momentum and angle smearing by unfolding method

Backgrounds:

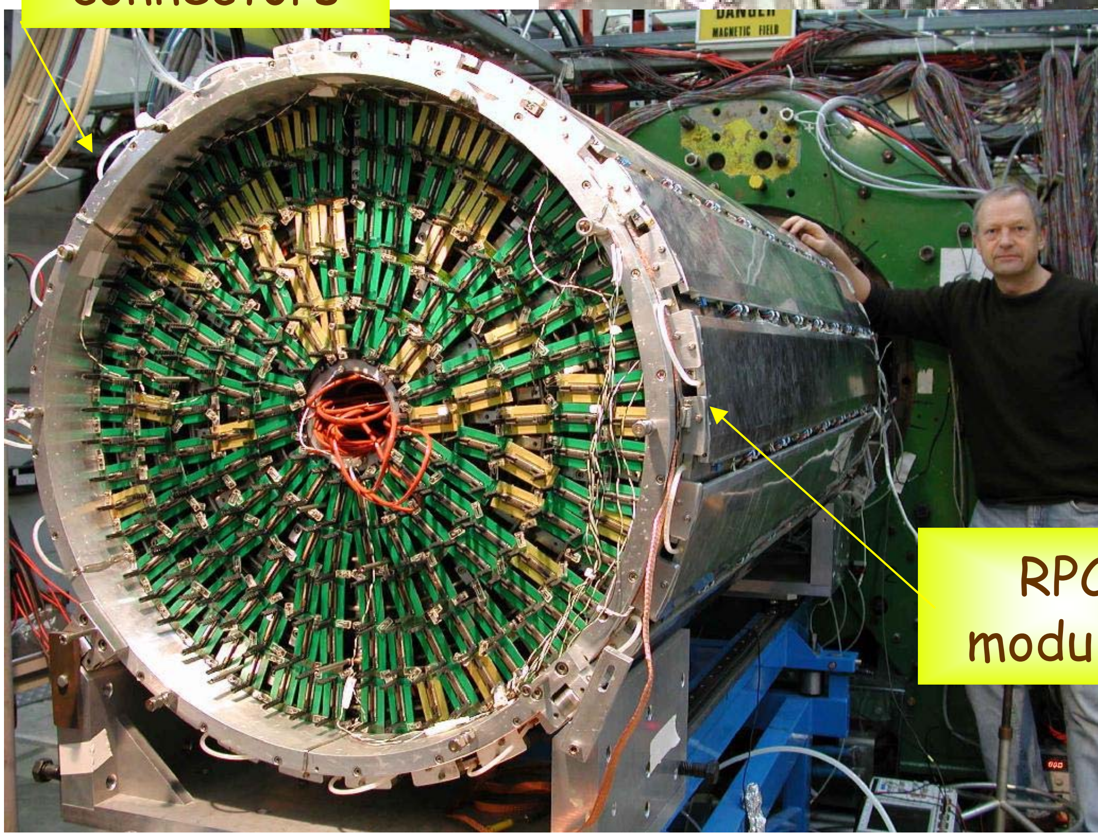
secondary interactions (simulated)

low energy electrons and positrons (all from π^0)

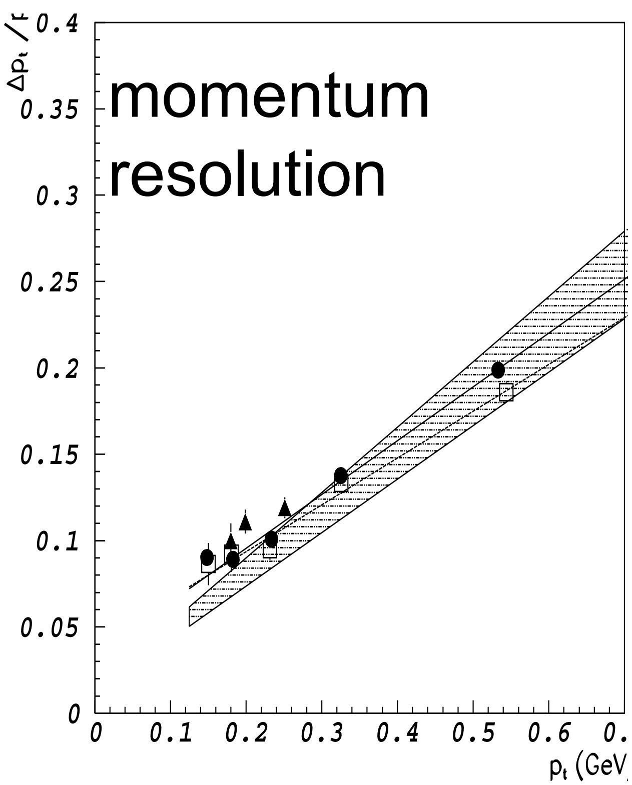
predicted from π^+ and π^- spectra (iterative) and normalized to identified e^{+-}.

Full statistics analysed ("full spill data" with dynamic distortion corrections) although no significant difference is observed with the first analysis of the partial data (first 100-150 events in the spill).

The Target/TPC Region



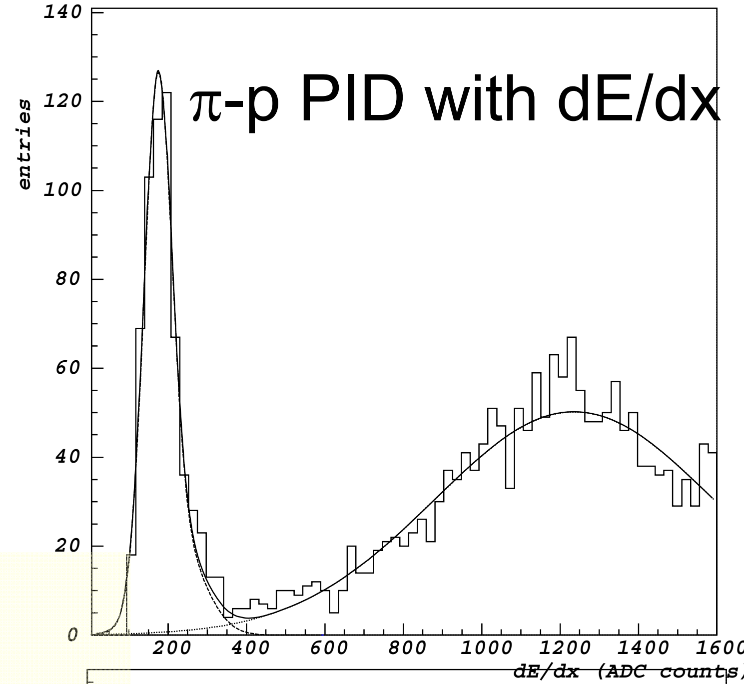
Spectrometer performance

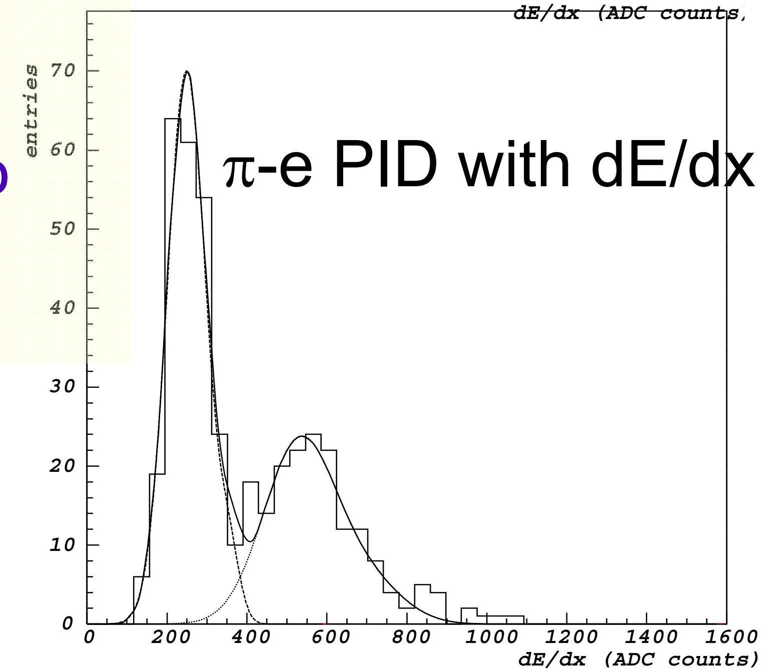


momentum calibration:
cosmic rays
elastic scattering

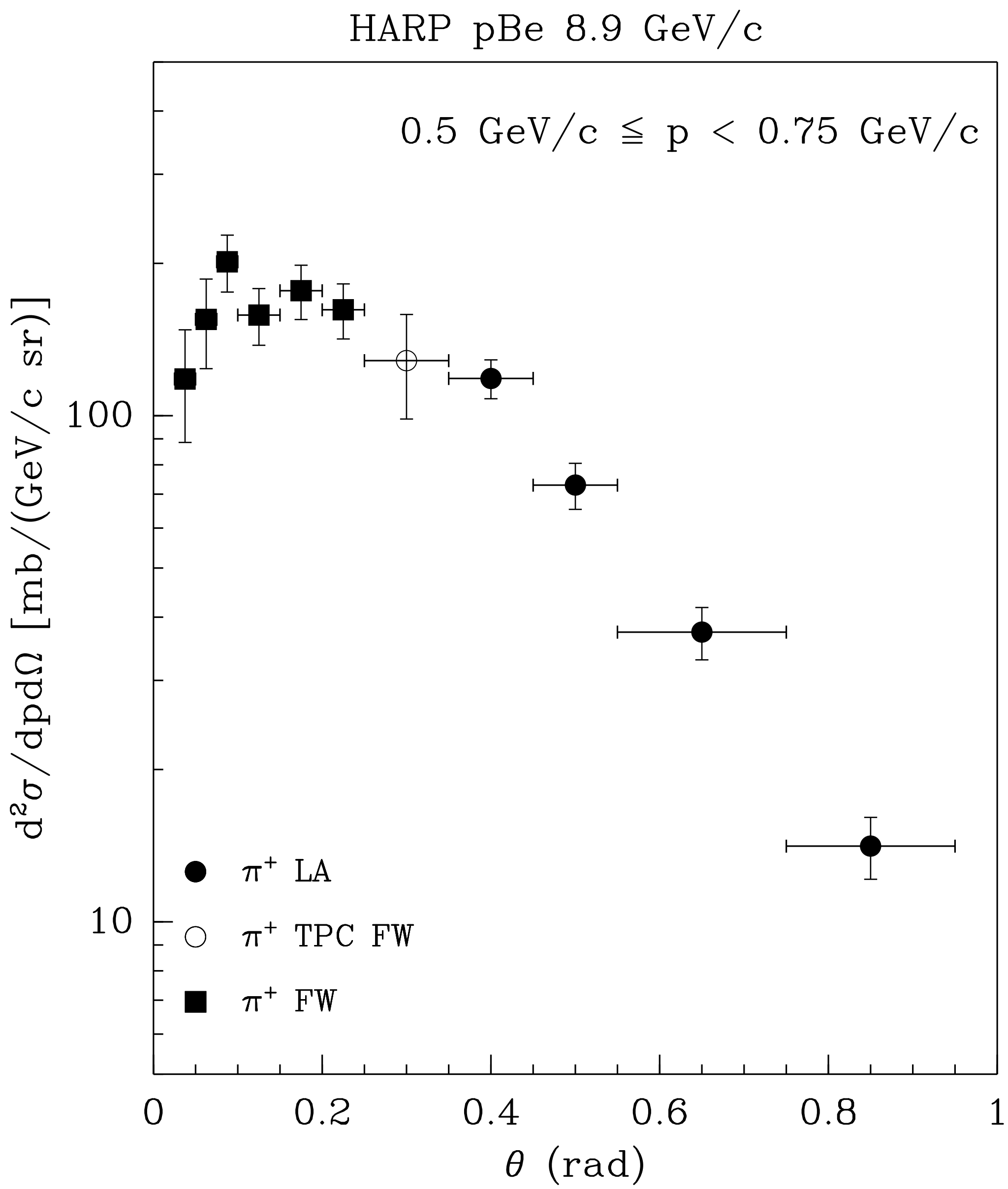
elastic scattering:
absolute calibration of
efficiency
momentum
angle
(two spectrometers!)

PID:
dE/dx used for analysis
TOF used to determine efficiency



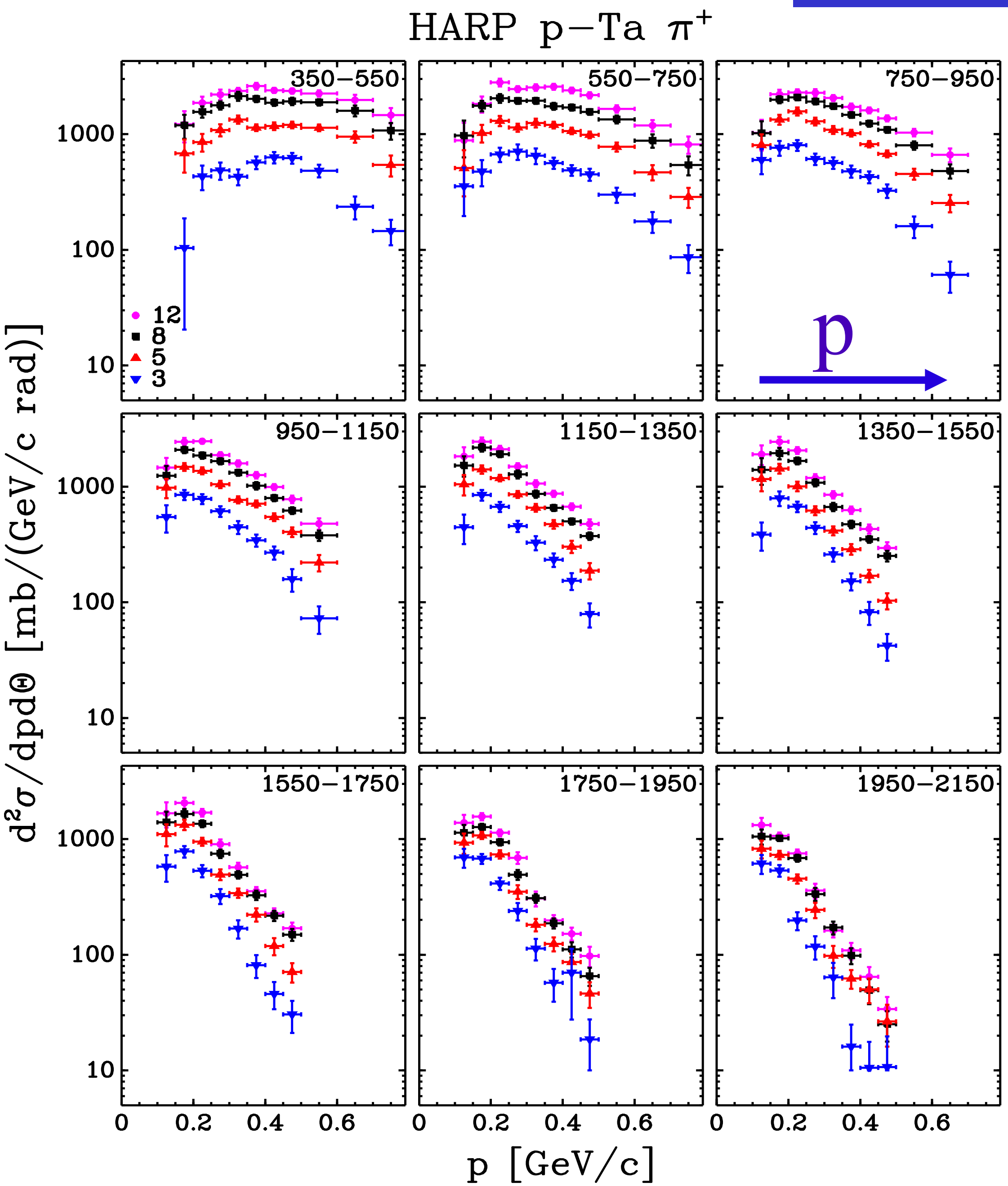


The two spectrometers match each other



9 angular bins: p-Ta π^+

Pion production yields

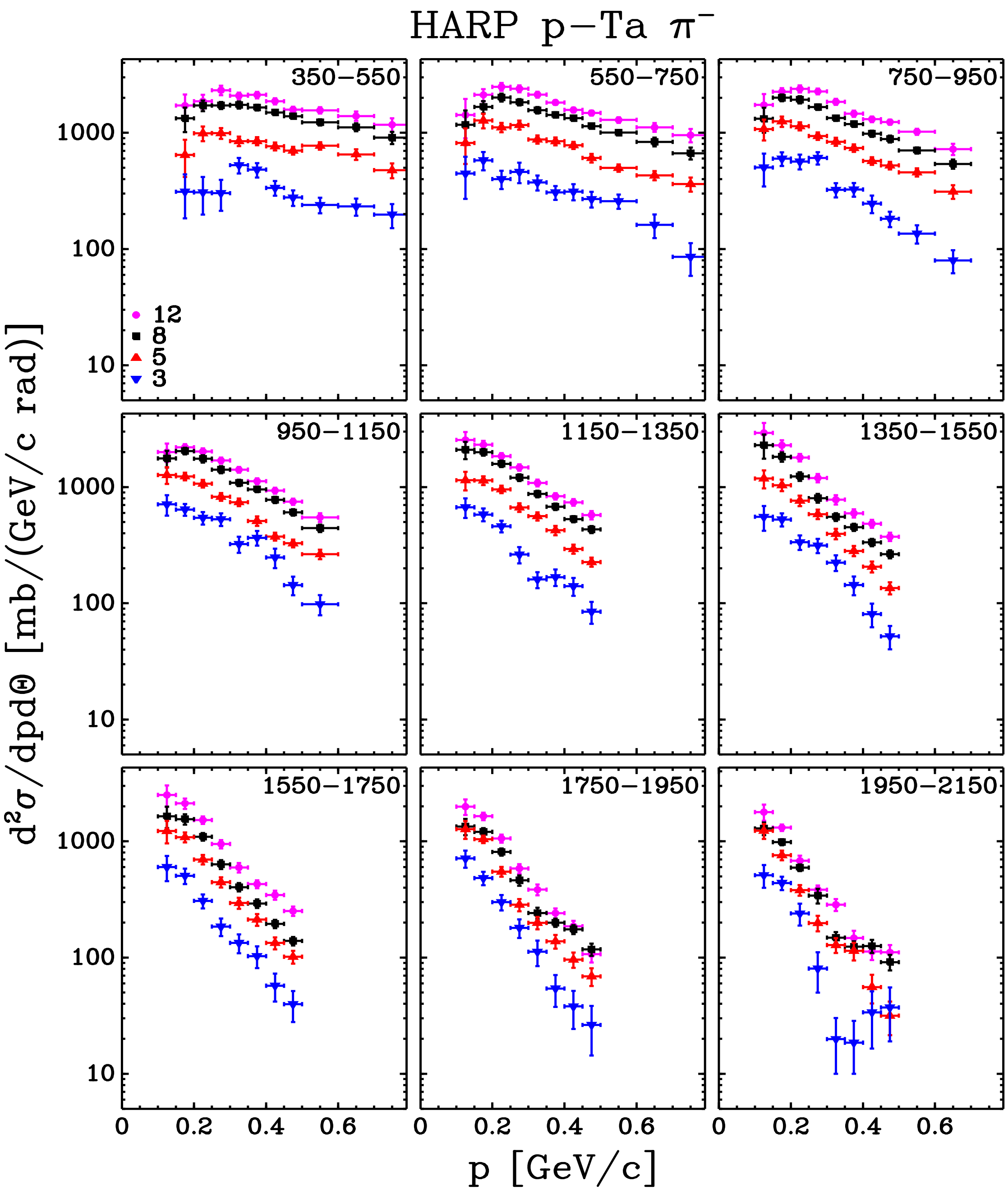


forward
$0.35 < \theta < 1.55$

backward
$1.55 < \theta < 2.15$

Pion production yields

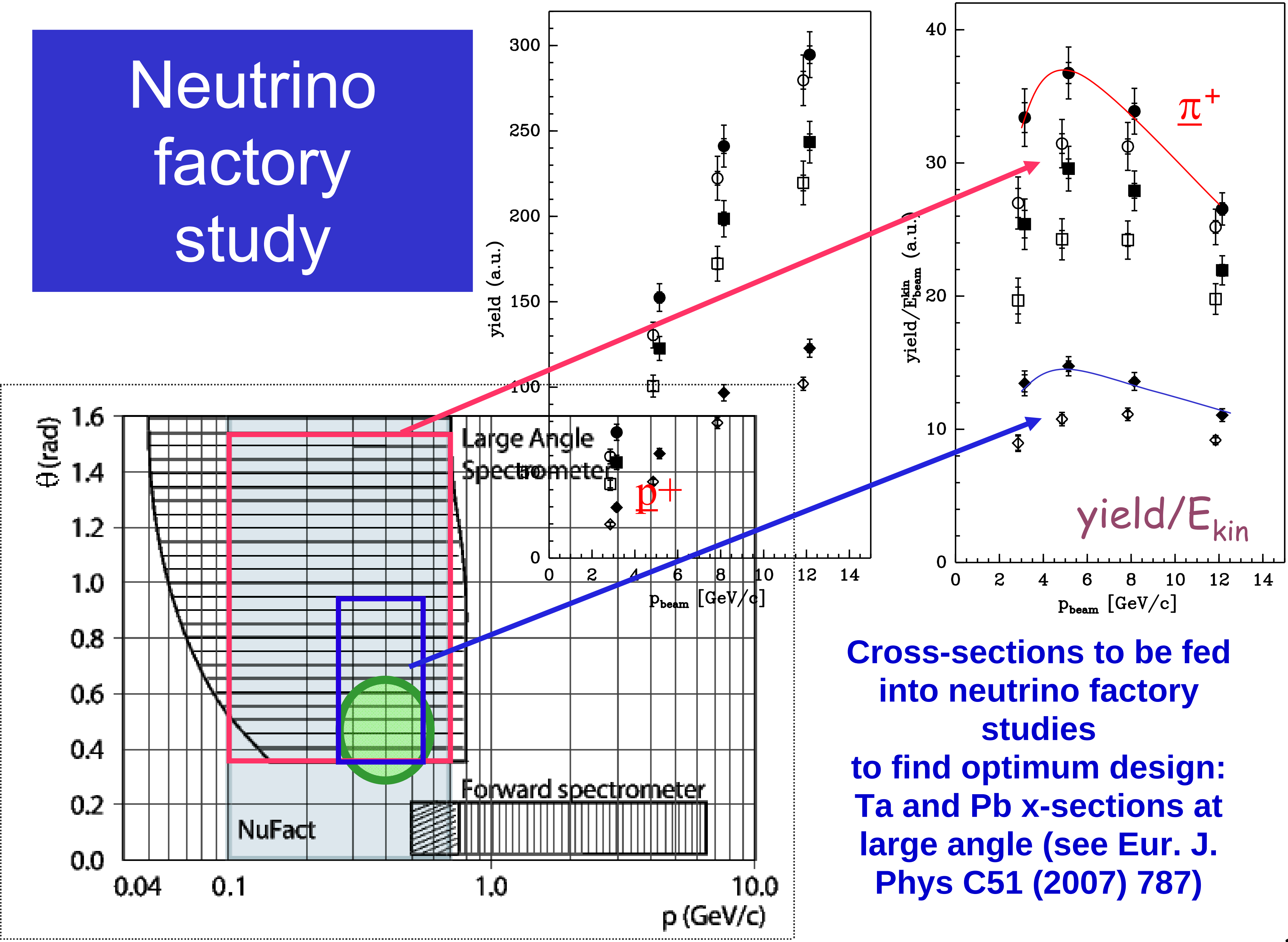
p-Ta π^-



forward
$0.35 < \theta < 1.55$

backward
$1.55 < \theta < 2.15$

Neutrino factory study



Cross-sections to be fed into neutrino factory studies to find optimum design: Ta and Pb x-sections at large angle (see Eur. J. Phys C51 (2007) 787)

Comparisons with MC

Many comparisons with models from GEANT4 and MARS are being done, starting with C and Ta

Some examples will be shown for C and Ta

Binary cascade

Bertini cascade

Quark-Gluon string models (QGSP)

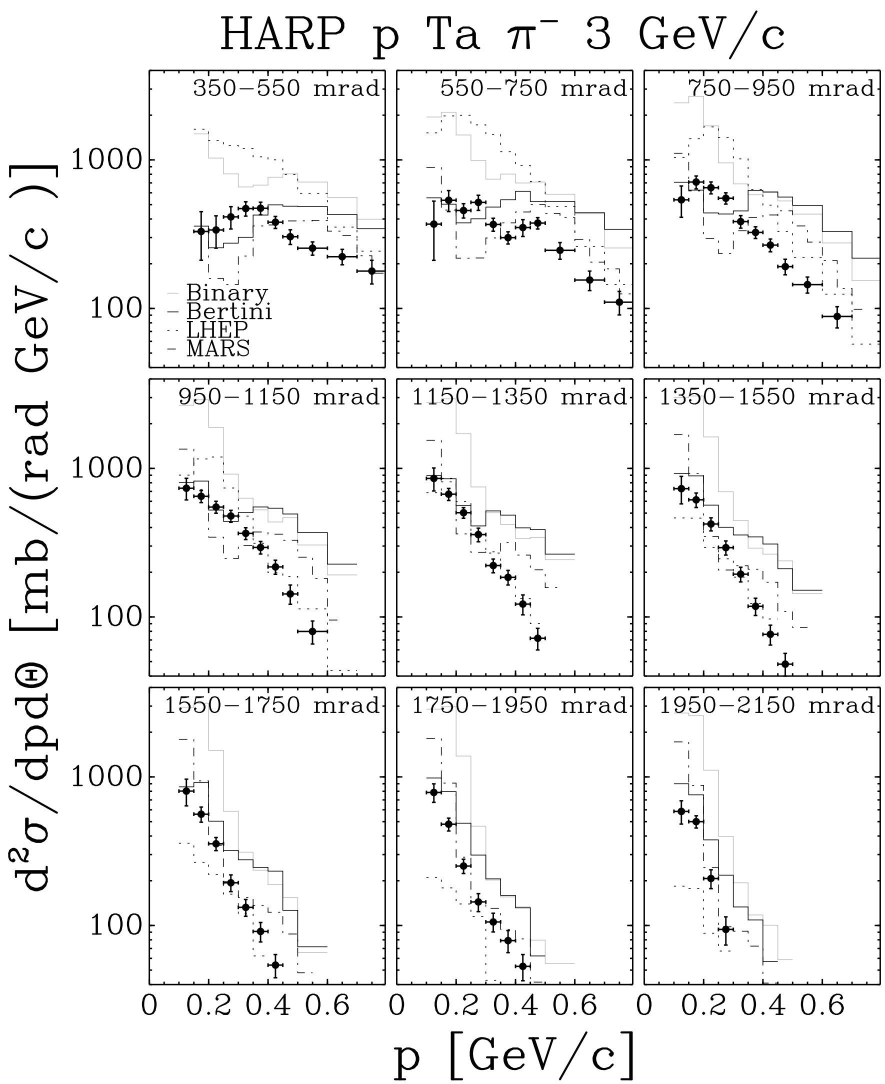
Frittiof (FTFP)

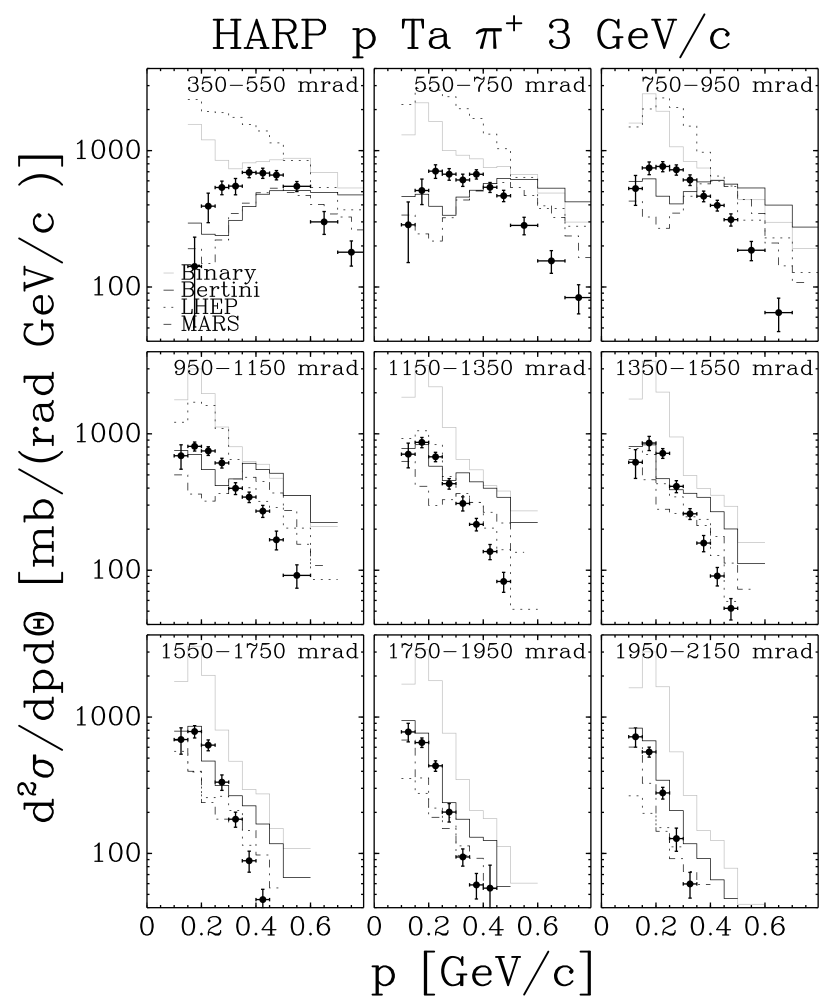
LHEP

MARS

Some models do a good job in some regions, but there is no model that describes all aspects of the data

3 GeV/c p-Ta $\pi^{+/-}$

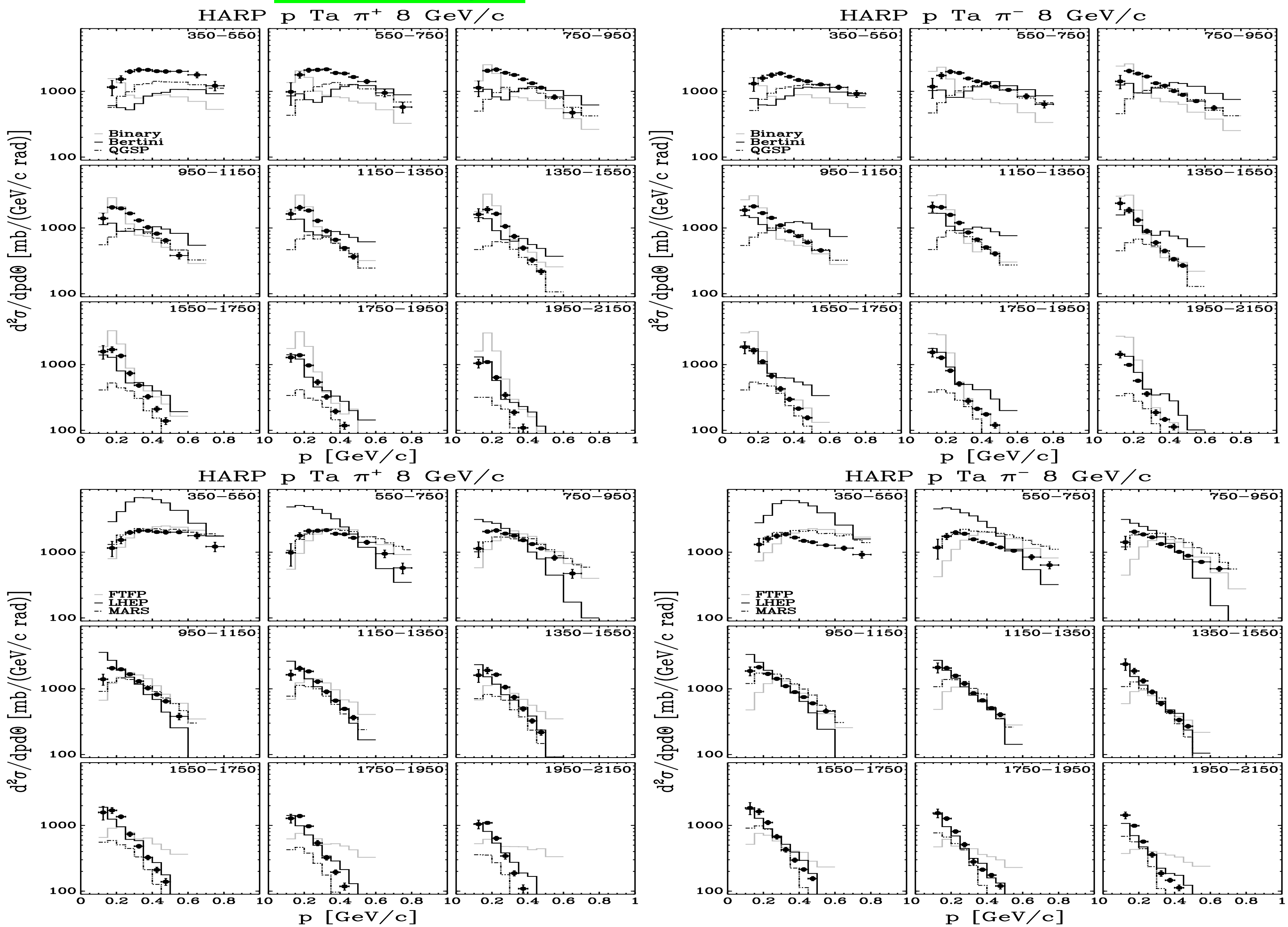

HARP p Ta π⁻ 3 GeV/c
350−550 mrad
550−750 mrad
750−950 mrad
950−1150 mrad
1150−1350 mrad
1350−1550 mrad
1550−1750 mrad
1750−1950 mrad
1950−2150 mrad
Binary
Bertini
LHEP
MARS
d²σ/dpdΘ [mb/(rad GeV/c)]
p [GeV/c]


HARP p Ta π⁺ 3 GeV/c
350−550 mrad
550−750 mrad
750−950 mrad
950−1150 mrad
1150−1350 mrad
1350−1550 mrad
1550−1750 mrad
1750−1950 mrad
1950−2150 mrad
Binary
Bertini
LHEP
MARS
d²σ/dpdΘ [mb/(rad GeV/c)]
p [GeV/c]

8 GeV/c p-Ta $\pi^{+/-}$

5% λ target

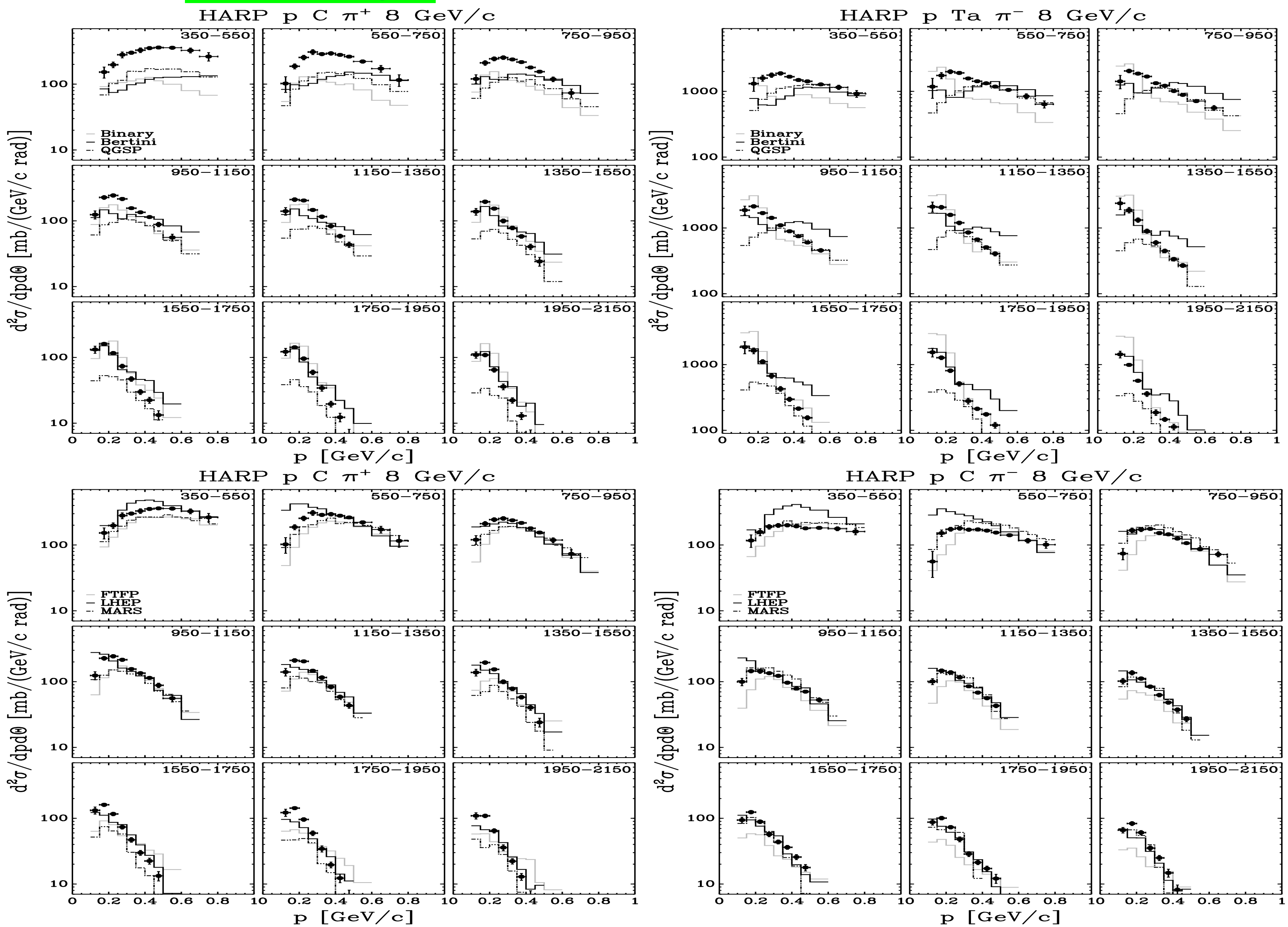
MODELS



8 GeV/c p-C $\pi^{+/-}$

5% λ target

MODELS



Comparison with MC at Large Angle

1. **Data available on many thin (5%) targets from light nuclei (Be) to heavy ones (Ta)**
2. **Comparisons with GEANT4 and MARS15 MonteCarlo show large discrepancies both in normalization and shape**
   - **Backward or central region production seems described better than more forward production**
   - **In general π^+ production is better described than π^- production**
   - **At higher energies FTP models (from GEANT4) and MARS look better, at lower energies this is true for Bertini and binary cascade models (from GEANT4)**
   - **Parametrized models (such as LHEP) have big discrepancies**

- **CONCLUSIONS: MCs need tuning with HARP data for p_{inc}<15 GeV/c**

ν beams flux prediction

- ***Energy, composition, geometry of a neutrino beam is determined by the development of the hadron interaction and cascade ⇒ needs to know π spectra, K/ π ratios***

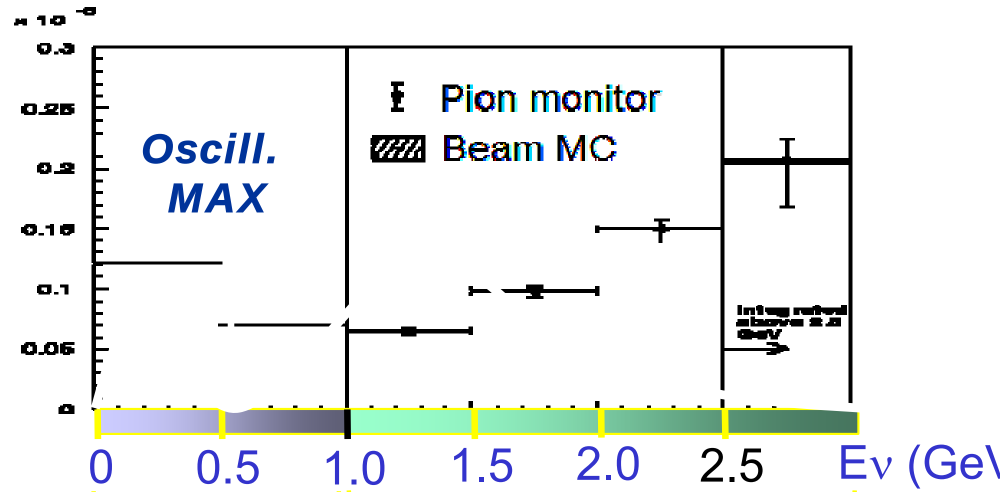
- K2K : **Al target, 12.9 GeV/c**

Al targets 5%, 50%, 100% λ (all p_{beam}), K2K target replica (12.9 GeV/c)

➔ **special program with K2K replica target**

M.G. Catanesi et al., HARP, Nucl. Phys. B732 (2006)1

M. H. Ahn et al., K2K, Phys. Rev. D74 (2006) 072003.



Beam MC

Beam MC confirmed by Pion Monitor

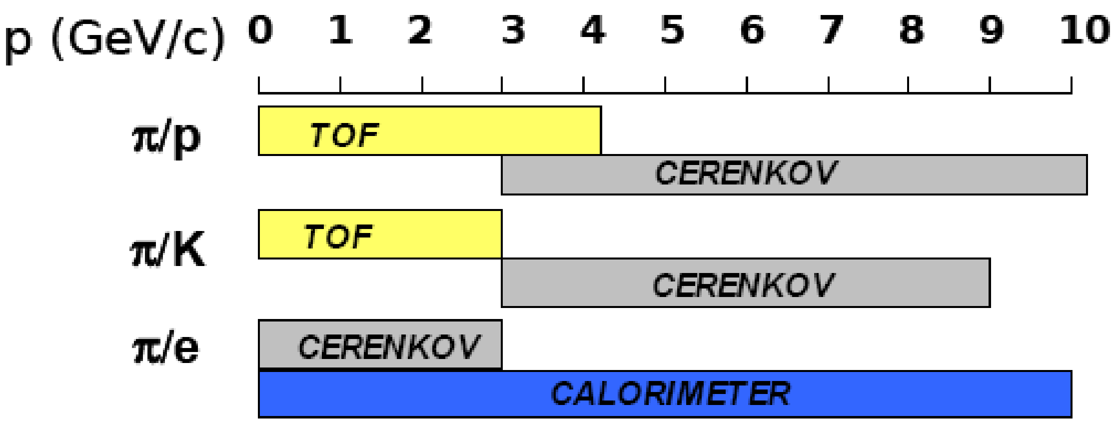
- MiniBooNE: Be target 8.9 GeV/c

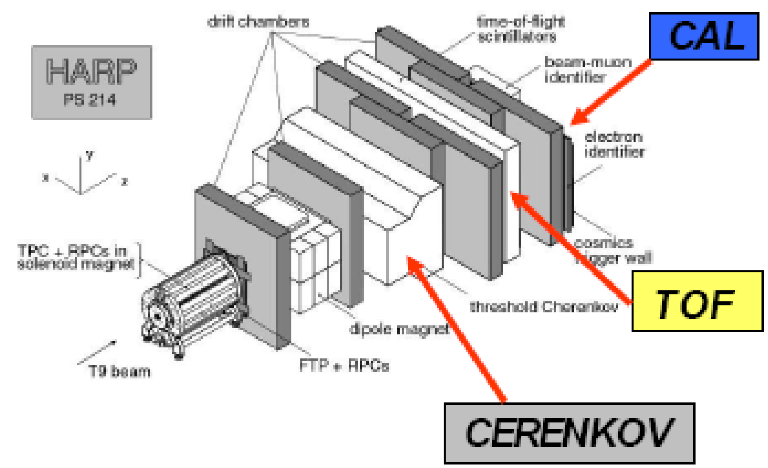
M.G. Catanesi et al., HARP, Eur. Phys. J. C52(2007) 29

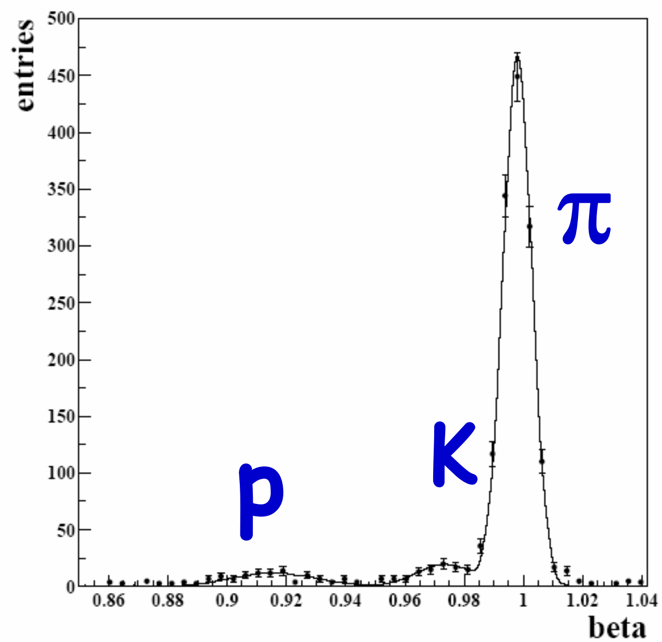
Be targets: 5%, 50%, 100% λ, MiniBoone target replica

Precise p_T and p_L spectra for extrapolation to far detectors and comparison between near and far detectors

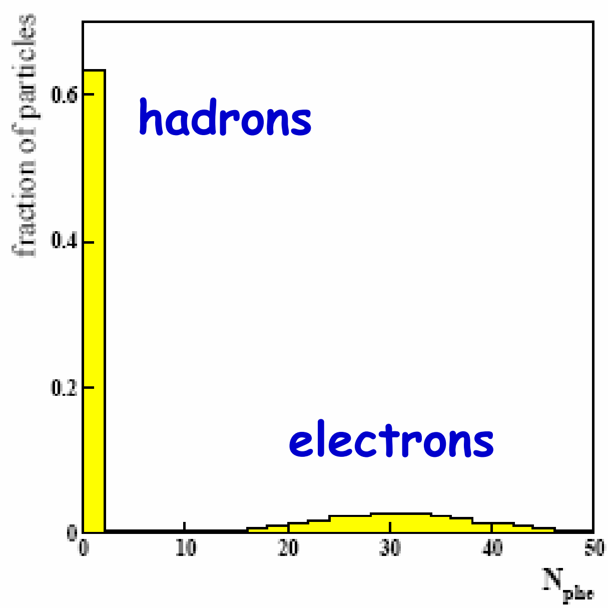
HARP forward Particle identification



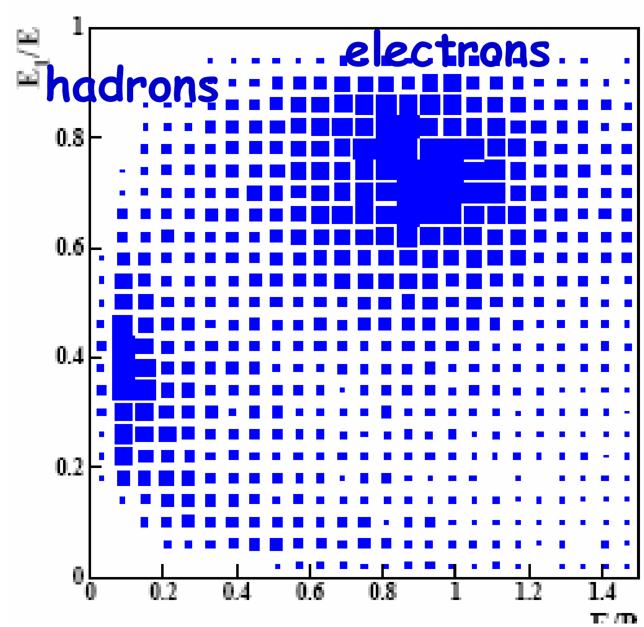




TOF for p=2+-0.25

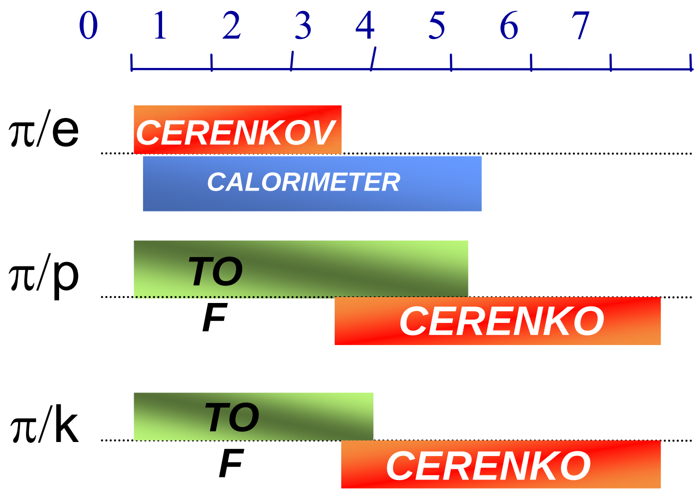


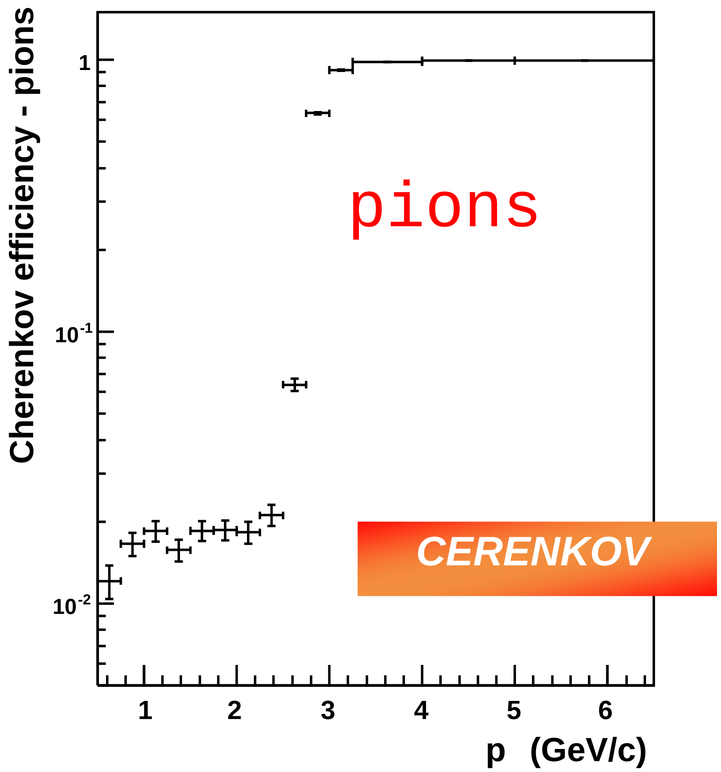
$N_{cherenkov}$
for p below pion threshold

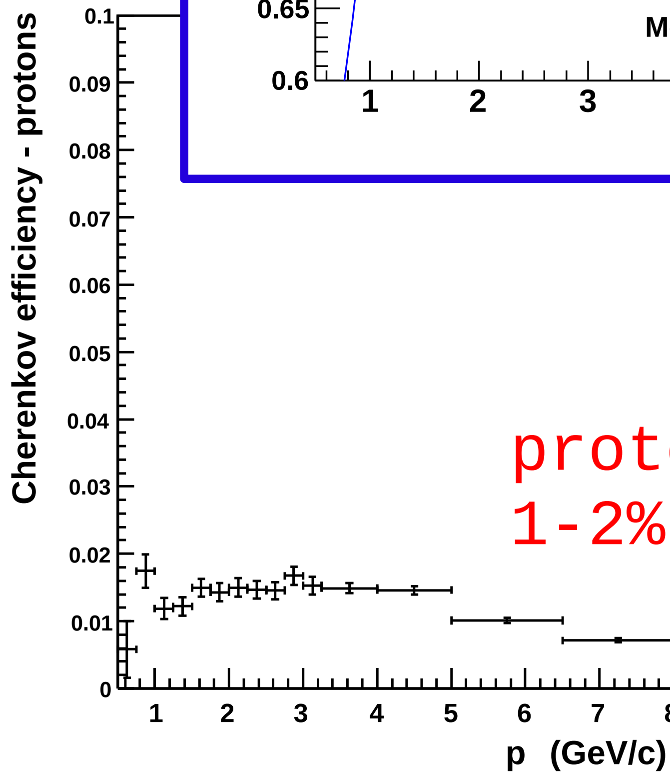


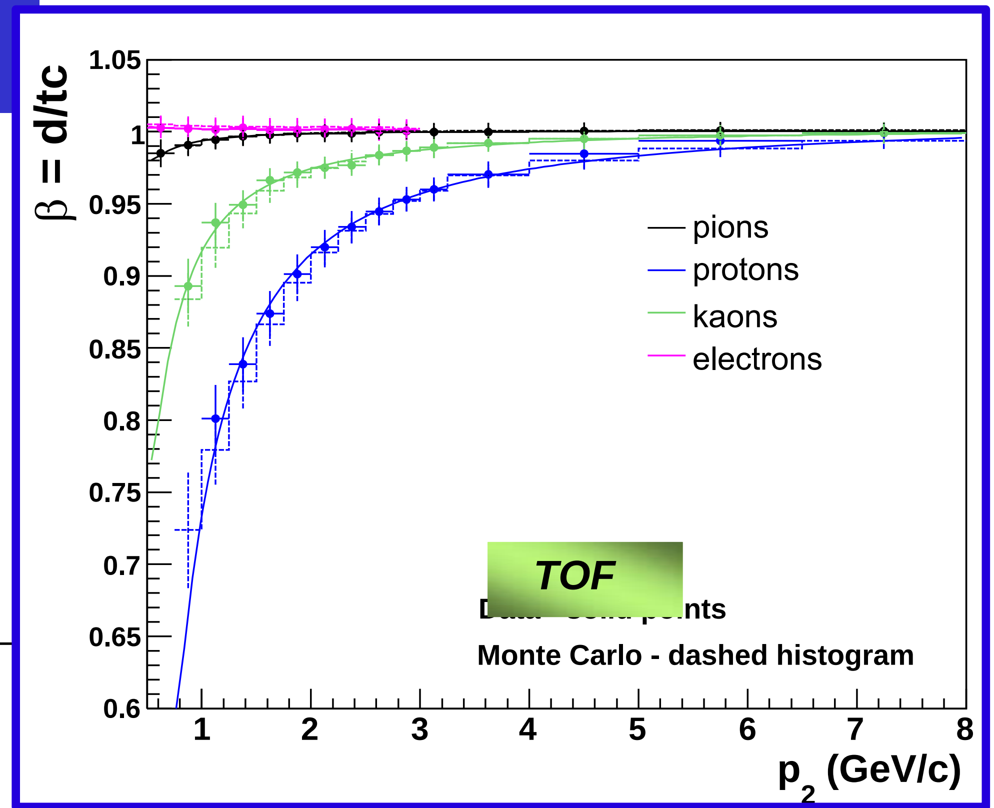
Calorimeter
E/p and E(1st layer)/E
for p above pion threshold

PID performance

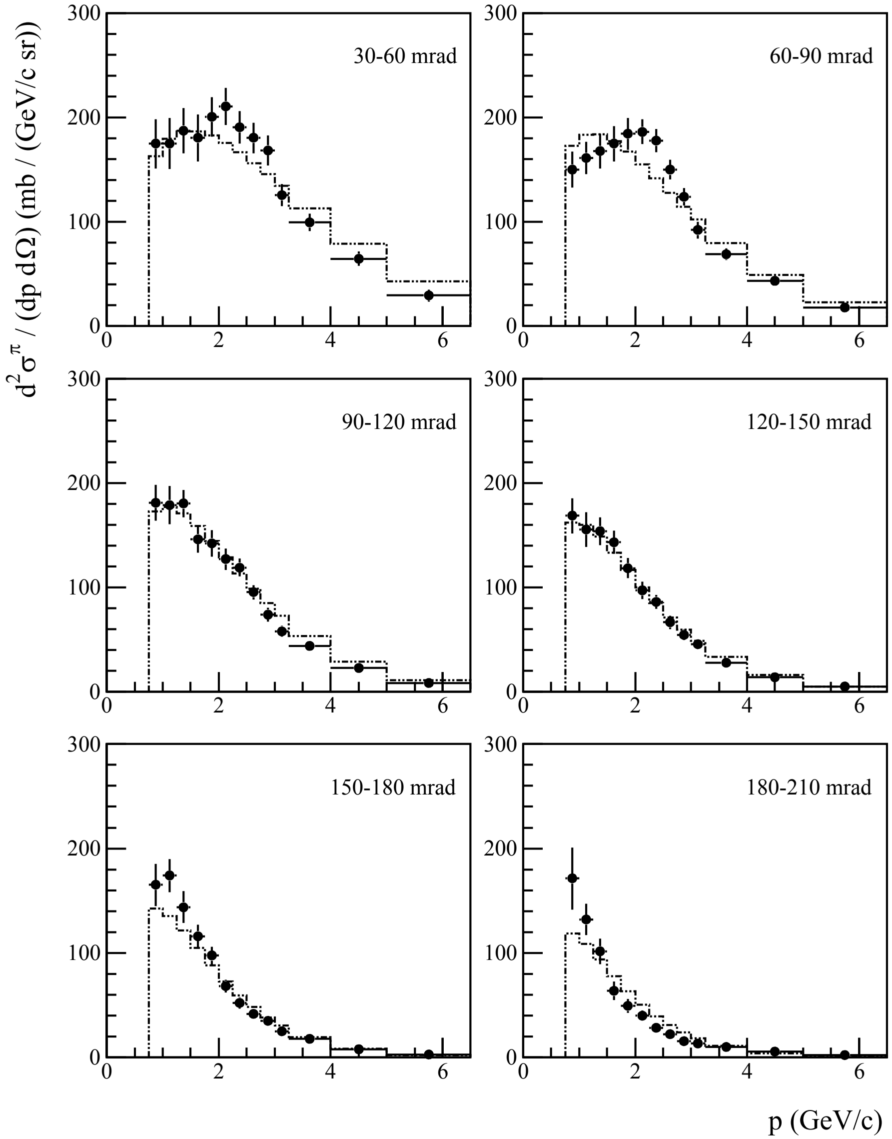




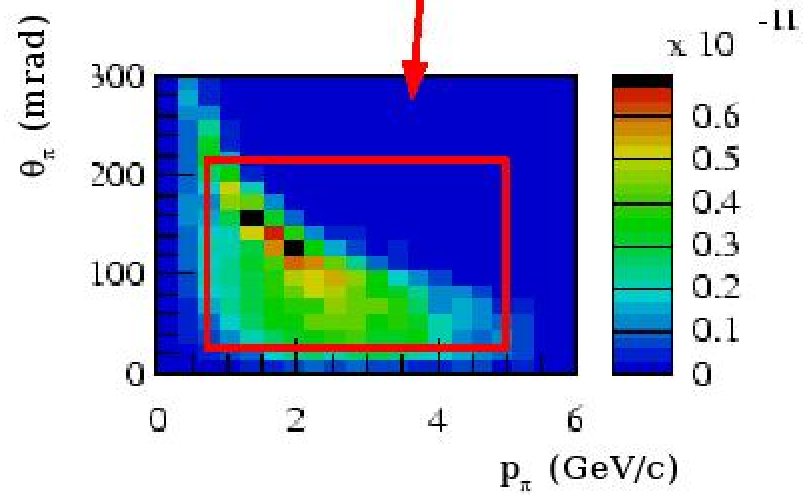




HARP Be 5% 8.9 GeV/c Results



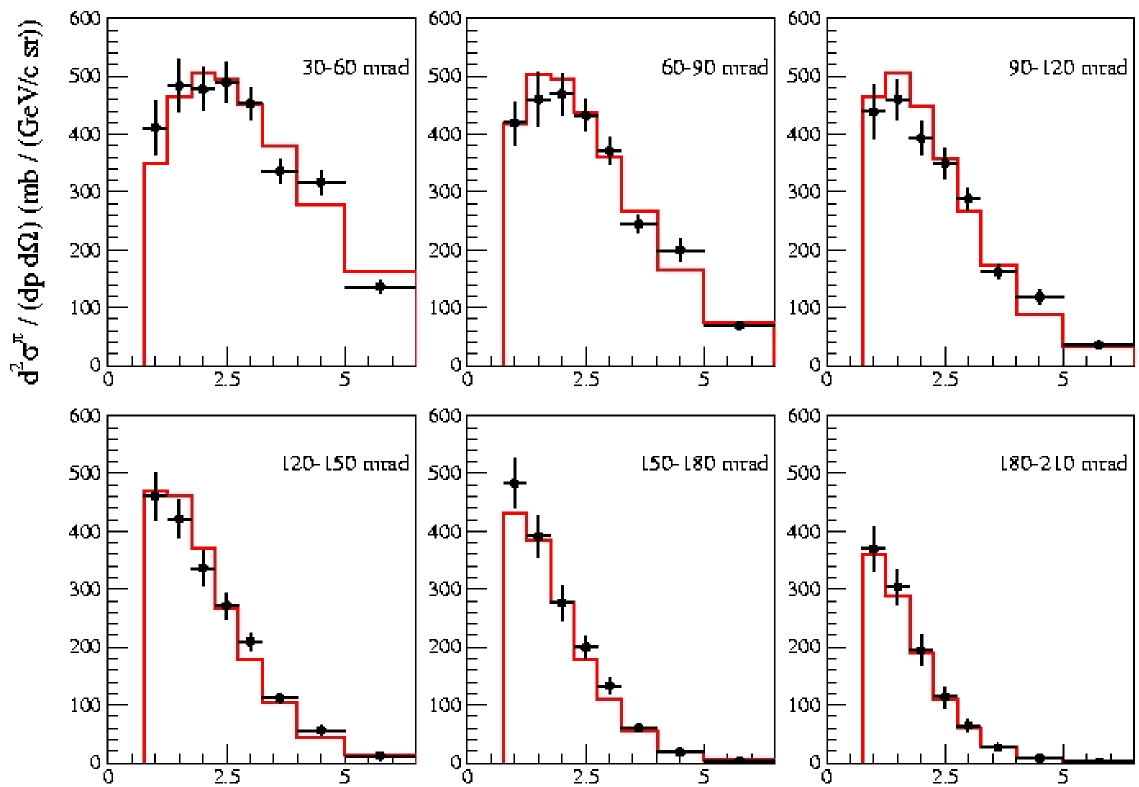
0.75<p<5 GeV/c
30<theta<210 mrad
relevance for MiniBooNE



Momentum and Angular distribution of pions decaying to a neutrino that passes through the MB detector.

HARP results (data points), Sanford-Wang parametrization of HARP results (histogram)

HARP 12.9 GeV/c p+Al Results



HARP data on inclusive pion production fitted to **Sanford-Wang** parametrization:

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

where:

X: any other final state particle

$p_{beam}=12.9$: proton beam momentum (GeV/c)

$p,\ \theta$: π^+ momentum(GeV/c), angle(rad)

$d^2\sigma/(dp\,d\Omega)$ units: mb/(GeV/c sr), where $d\Omega\equiv 2\pi\, d(\cos\theta)$

$c_1,\ldots,c_8$: emprical fit parameters

HARP in black,

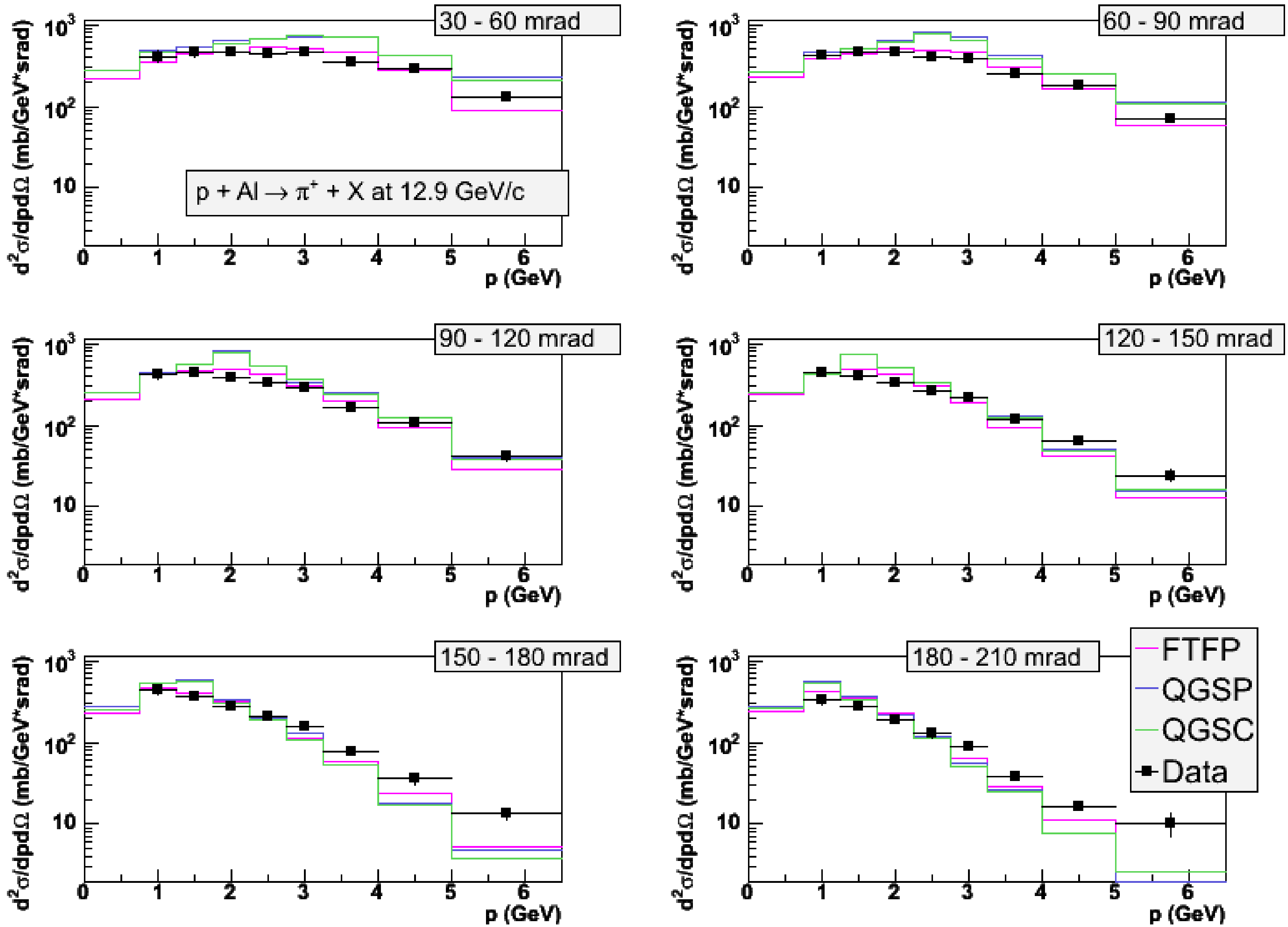
Sanford-Wang parametrization in red

Sanford-Wang parametrization

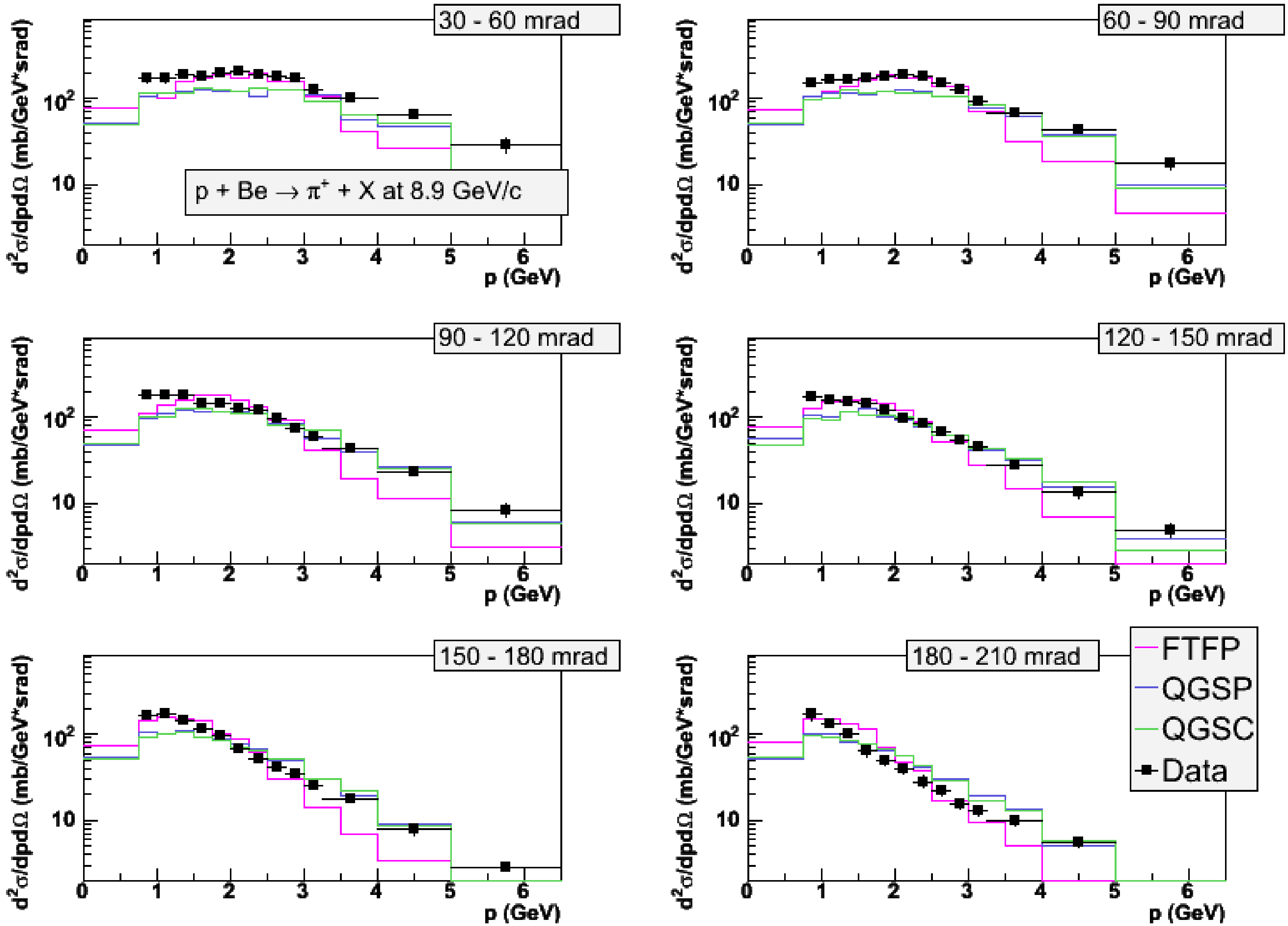
HARP data used to:

- in K2K and MiniBooNE beam MC
- Translate HARP pion production uncertainties into flux uncertainties
- Compare HARP results with previous results

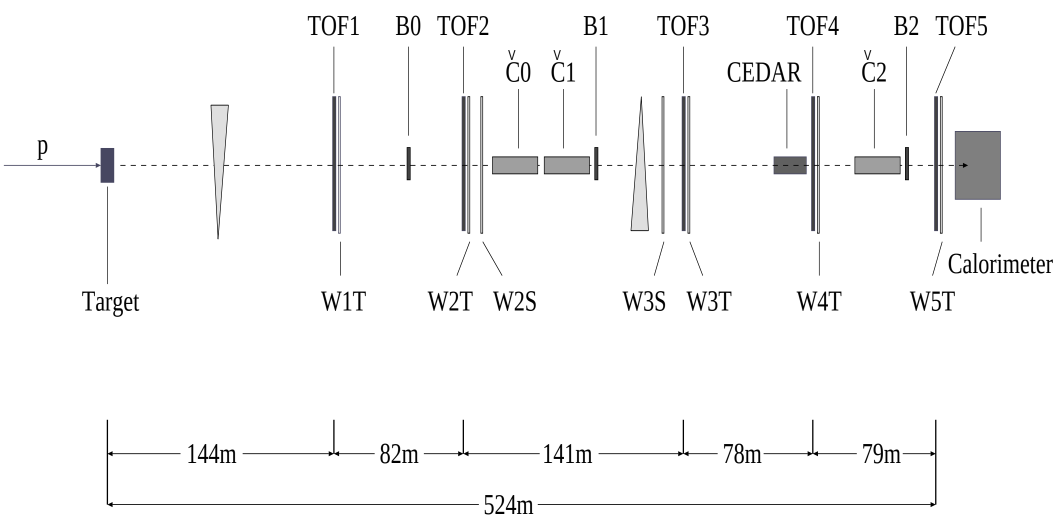
p+Al versus GEANT4



p+Be versus GEANT4



A small detour: the NA56/SPY experiment at SPS

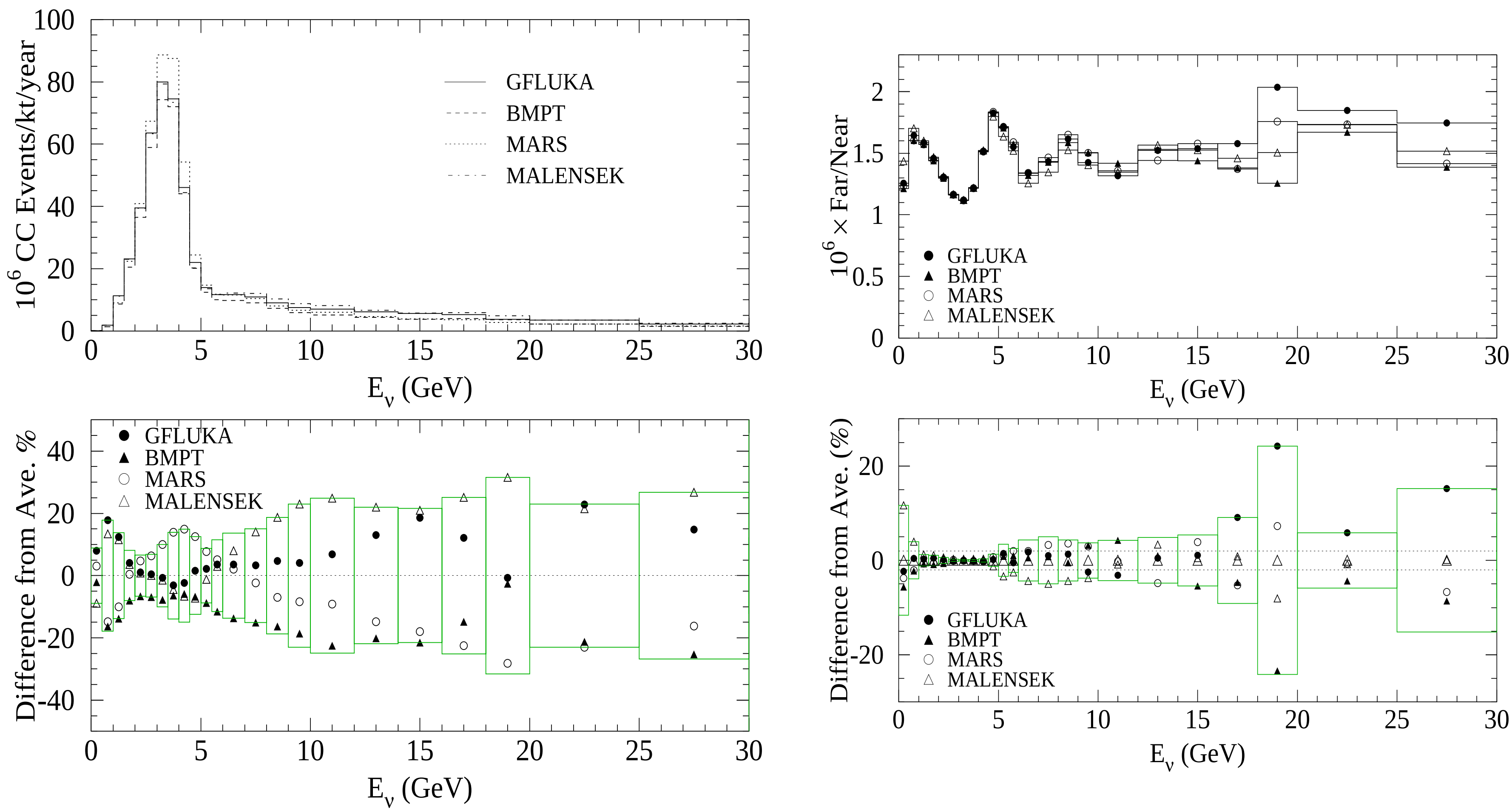


- Measure p, kaon fluxes by 450 GeV/c p on Be (5% precision)
  ->knowledge of neutrino spectra
- Measure k/p ratio (3% precision) ->
  knowledge n_e/n_m ratio
- Equipped H6 beam from NA52 experiment in North Area
- Primary p flux measured by SEM
- Different Be targets (shapes, L)
- PID by TOF counters (low momenta) and Cerenkov (high momenta)

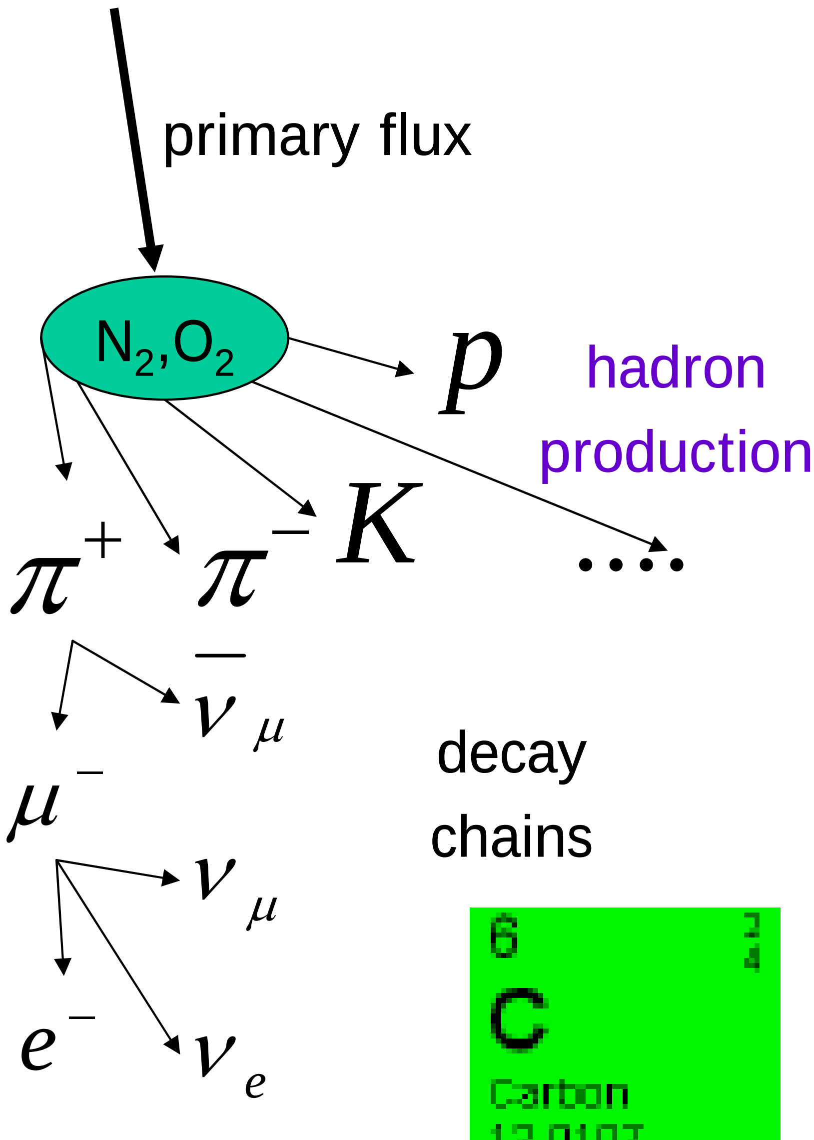
- **Available results were parametrized (BMPT parametrization) or used to tune available MC (such as Fluka). Used for the study of available high-energy neutrino beamlines: WANF at SPS, CNGS, NuMi**

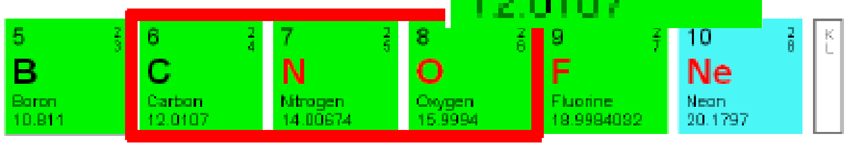
An application to NUMI (from M. Messier et al.)

- Comparison BMPT, Mars, GFLUKA in Minos near/far detecor

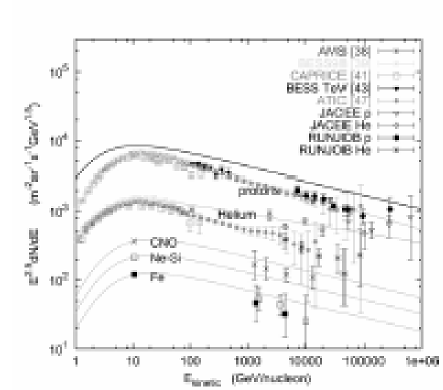


Atmospheric ν flux





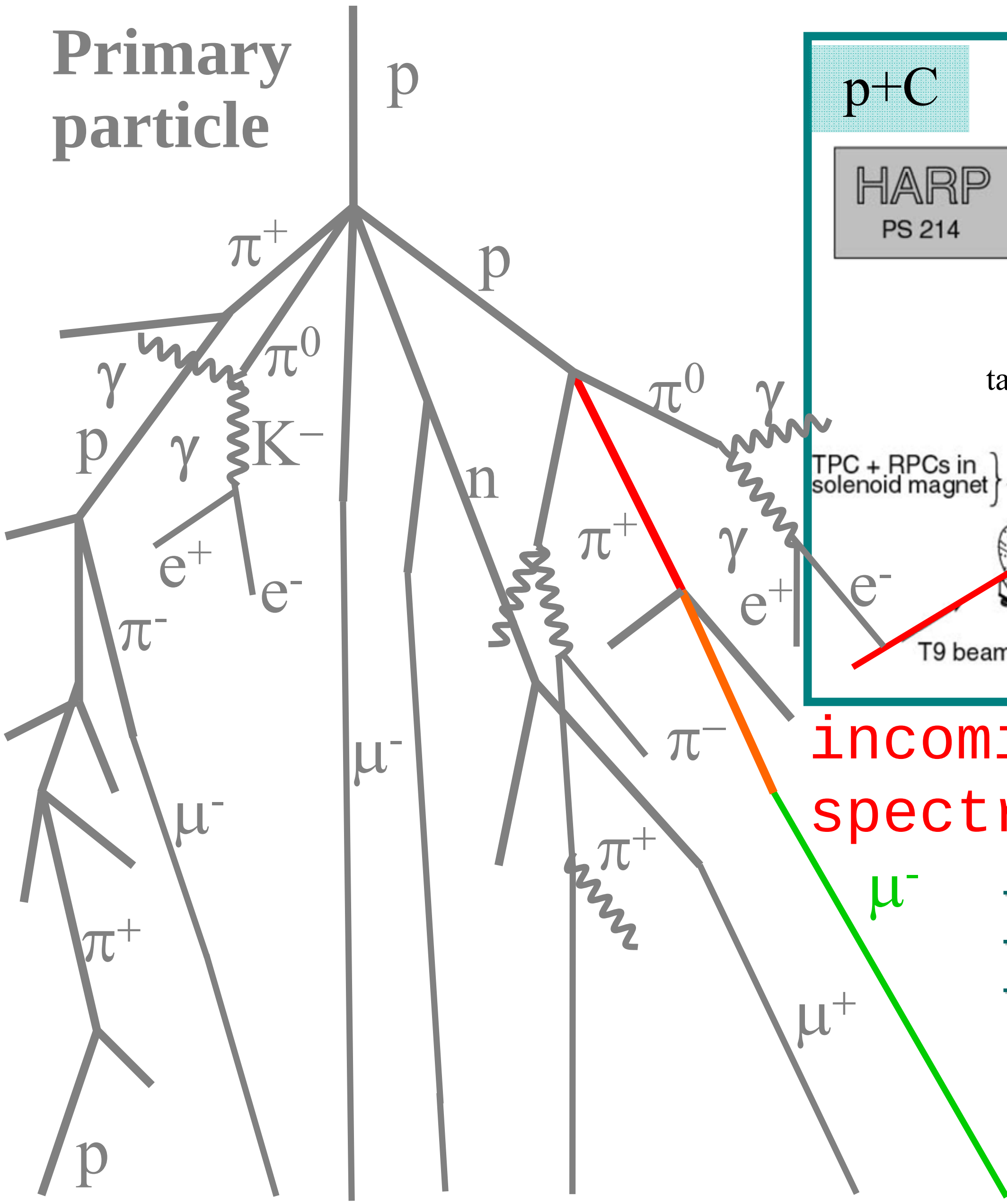
- Primary flux (70% p, 20% He, 10% heavier nuclei) is now considered to be known to better than 15% (AMS, Bess p spectra agree at 5% up to 100 GeV, worse for He)

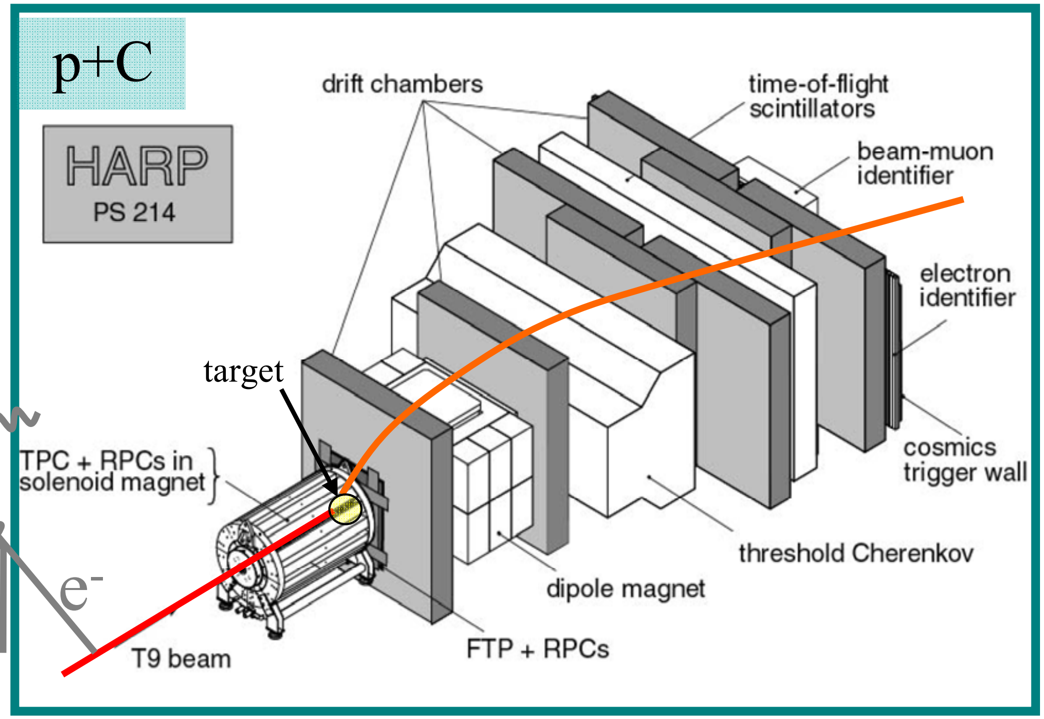


- Most of the uncertainty comes from the lack of data to construct and calibrate a reliable hadron interaction model.
- Model-dependent extrapolations from the limited set of data leads to about 30% uncertainty in atmospheric fluxes
- → cryogenic targets (or at least nearby C target data)

78% nitrogen
21% oxygen

Extended Air Showers

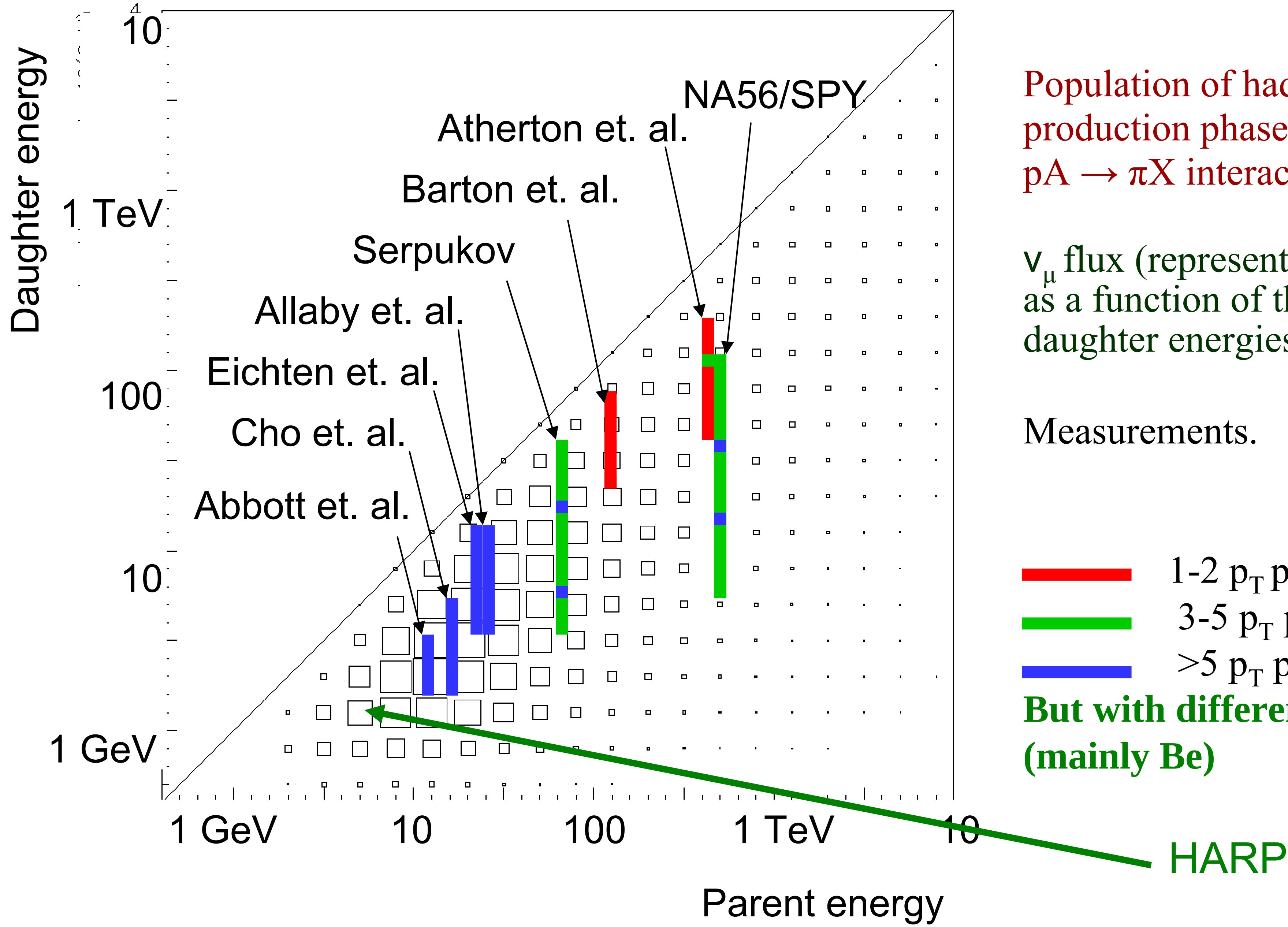




incoming protons and pions spectra: π^+ and π^-

- \+ Several targets
- \+ Forward direction
- \+ Relevant energy range: 10-400 GeV

Hadron production experiments



Population of hadron-production phase-space for $pA \rightarrow \pi X$ interactions.

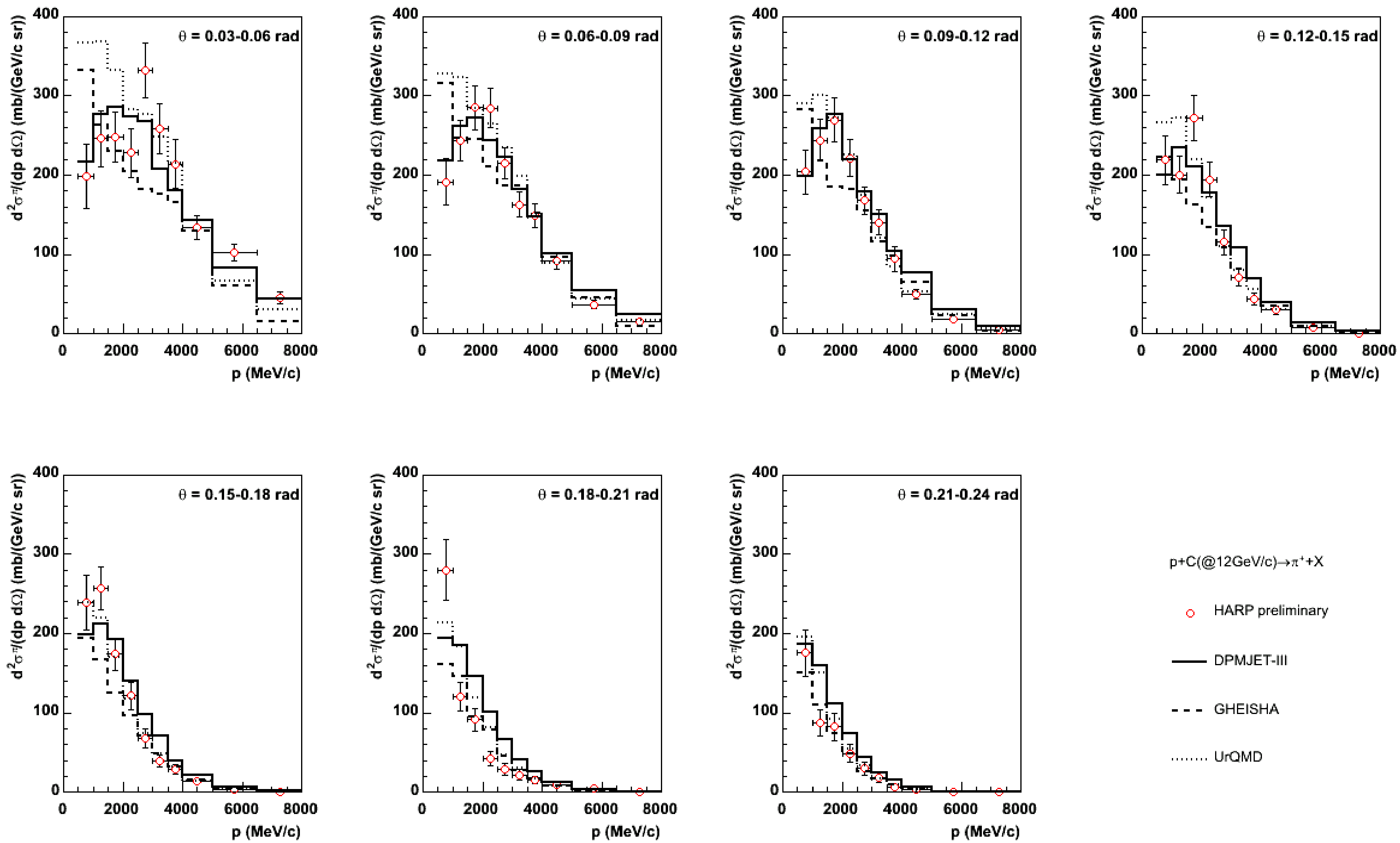
ν_μ flux (represented by boxes) as a function of the parent and daughter energies.

Measurements.

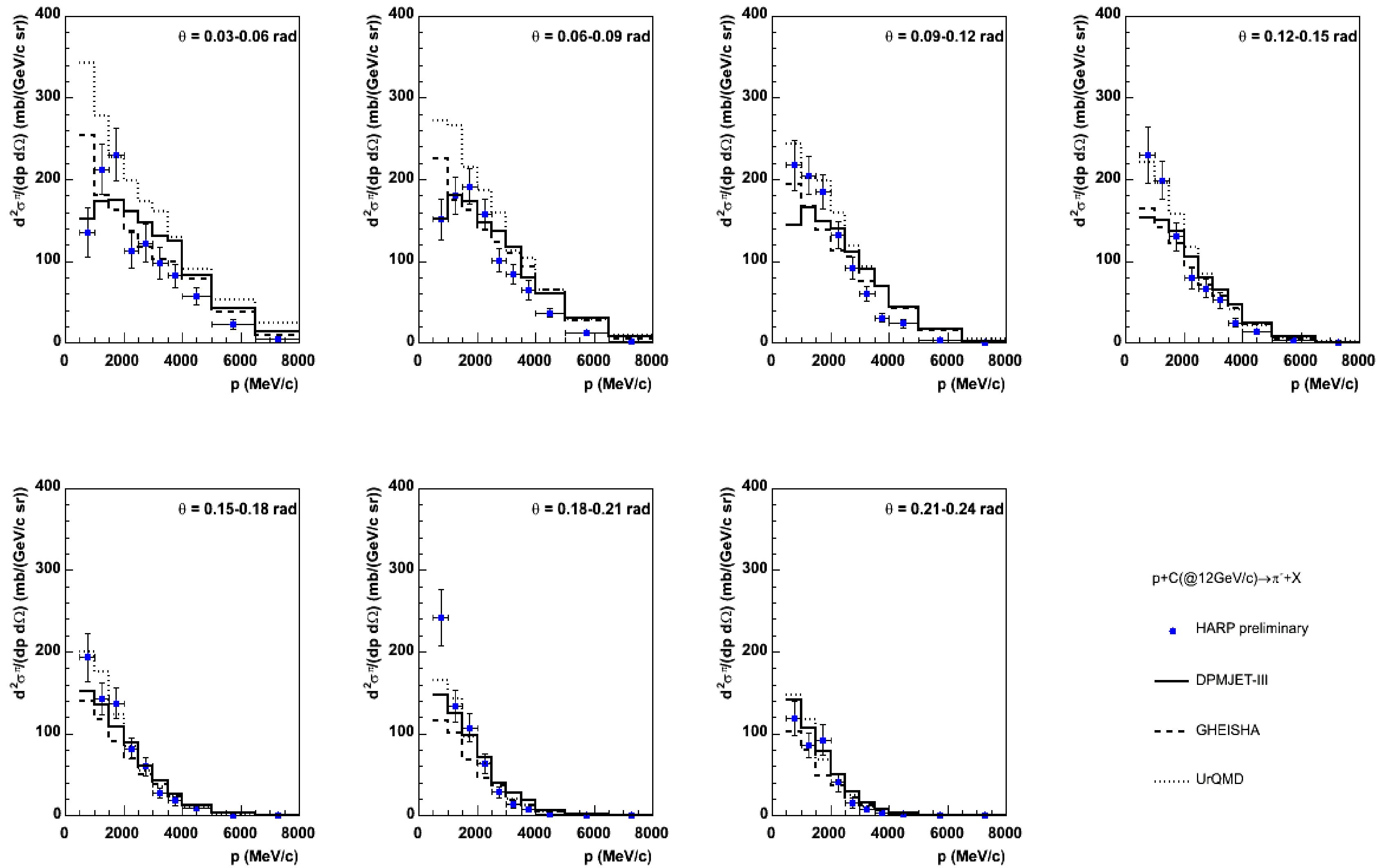
- 1-2 p_T points
- 3-5 p_T points
- >5 p_T points

But with different targets (mainly Be)

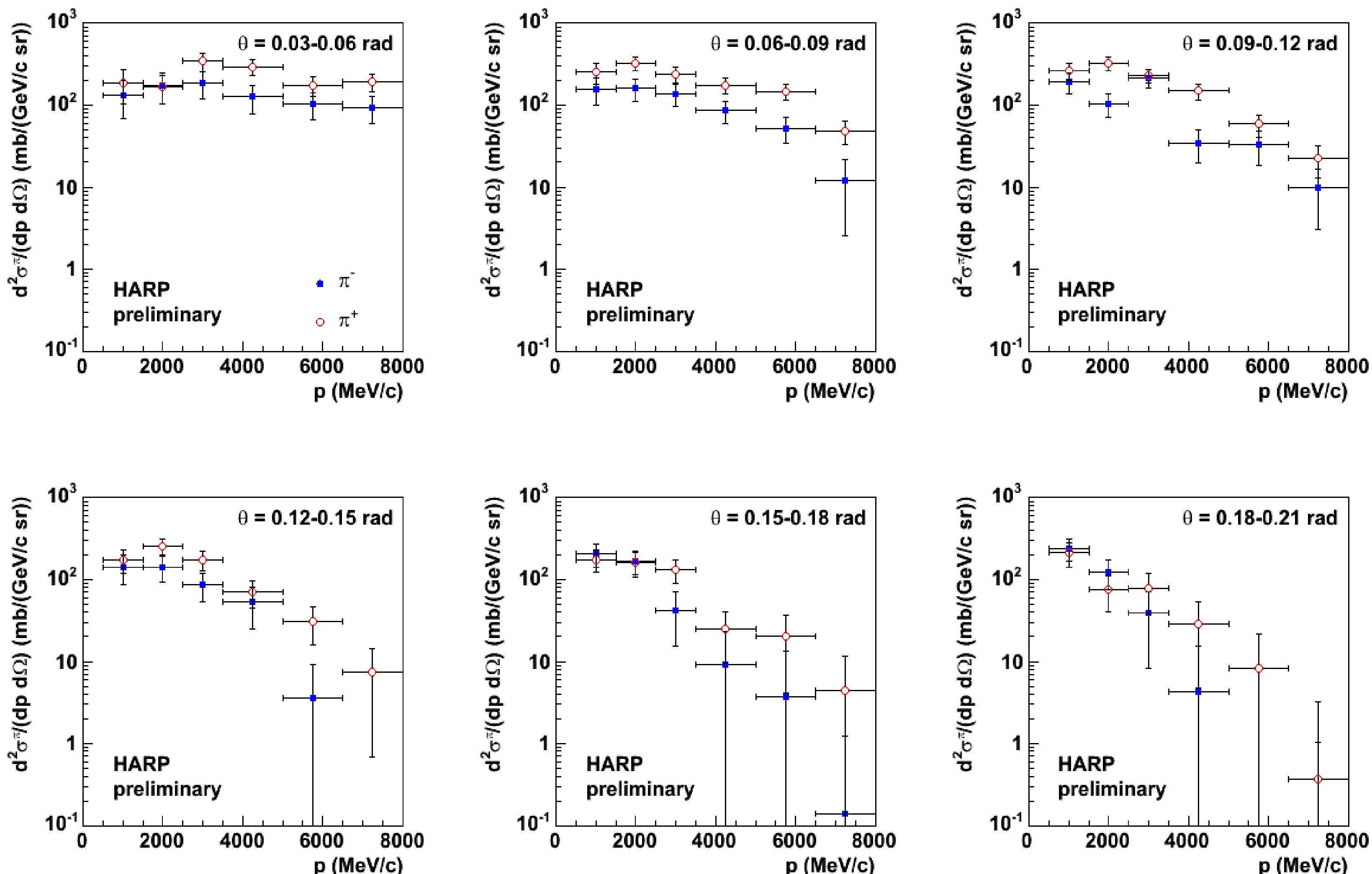
Model comparison: HARP $p+C \rightarrow \pi^{+}+X$



Model comparison: $p+C \rightarrow \pi^{-}+X$

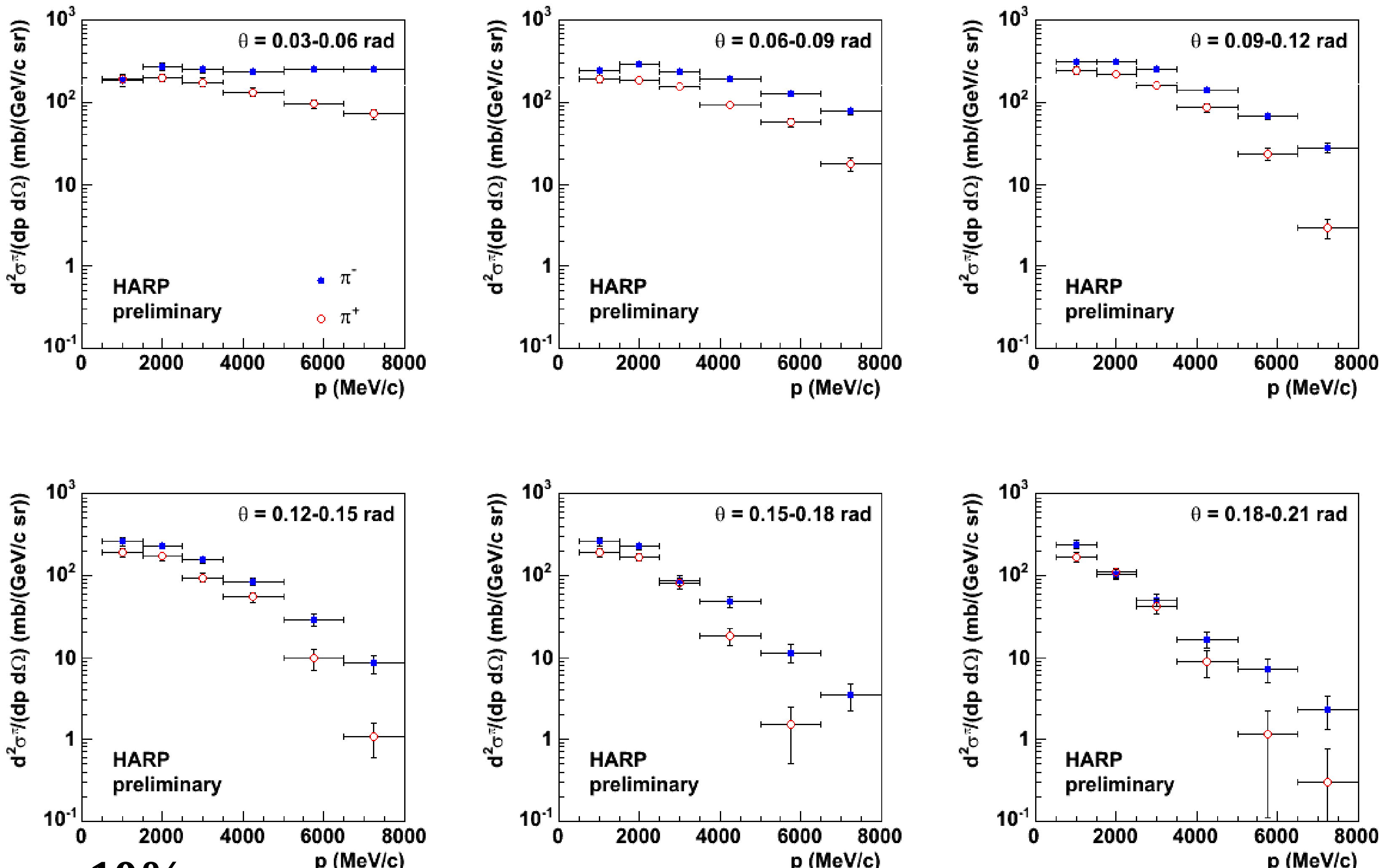


π^++C @ 12 GeV/c
(lower statistics)



- **stat error ~ 30-40 %**
- **syst error ~ 10%**

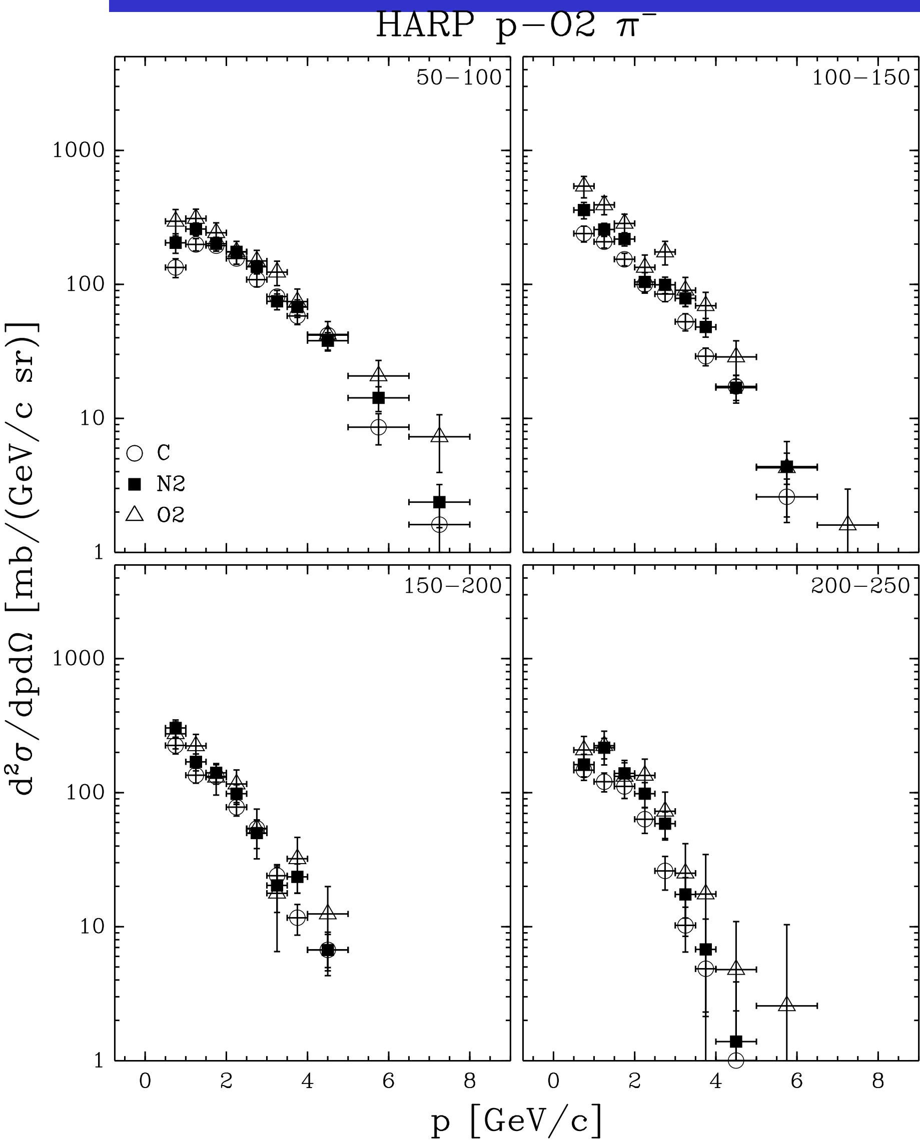
π^-+C @ 12 GeV/c
(high statistics)

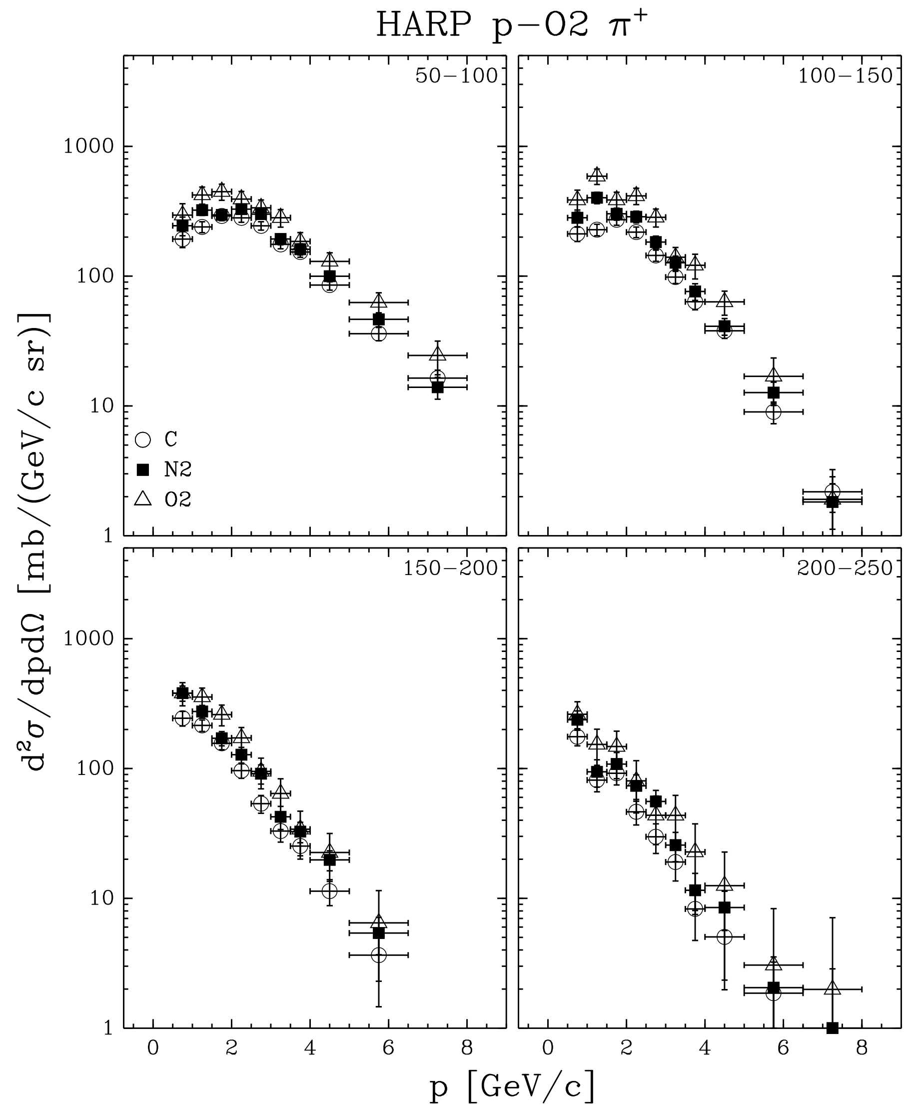


Stat error ~ 10%

Syst error ~ 10%

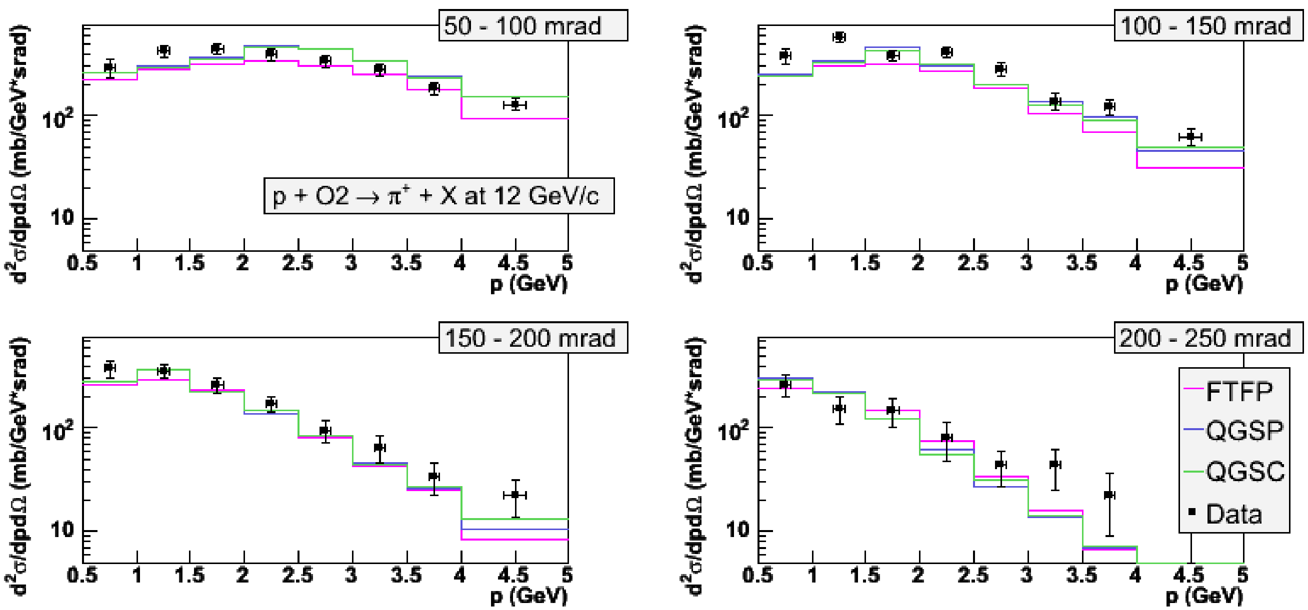
Measurements with N_2,O_2 cryogenic targets

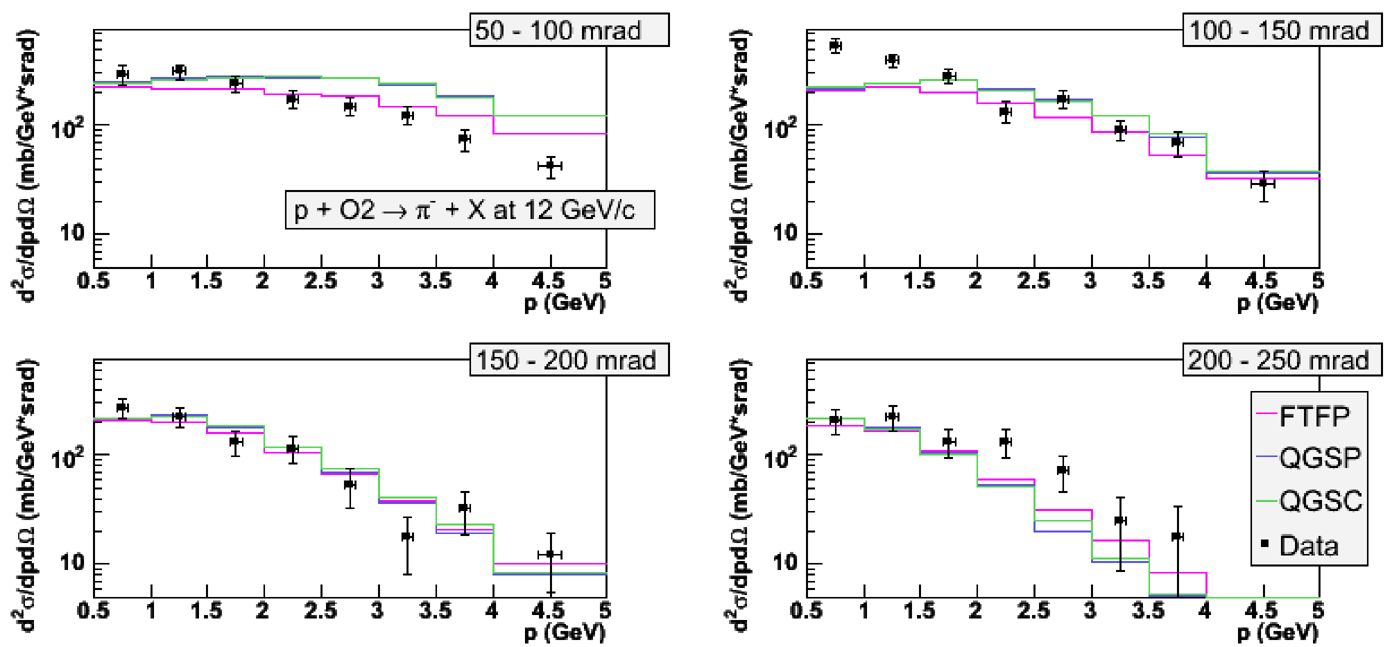




Shape looks similar =>may use simpler C target data (solid, not cryogenic target)

Comparison with GEANT4



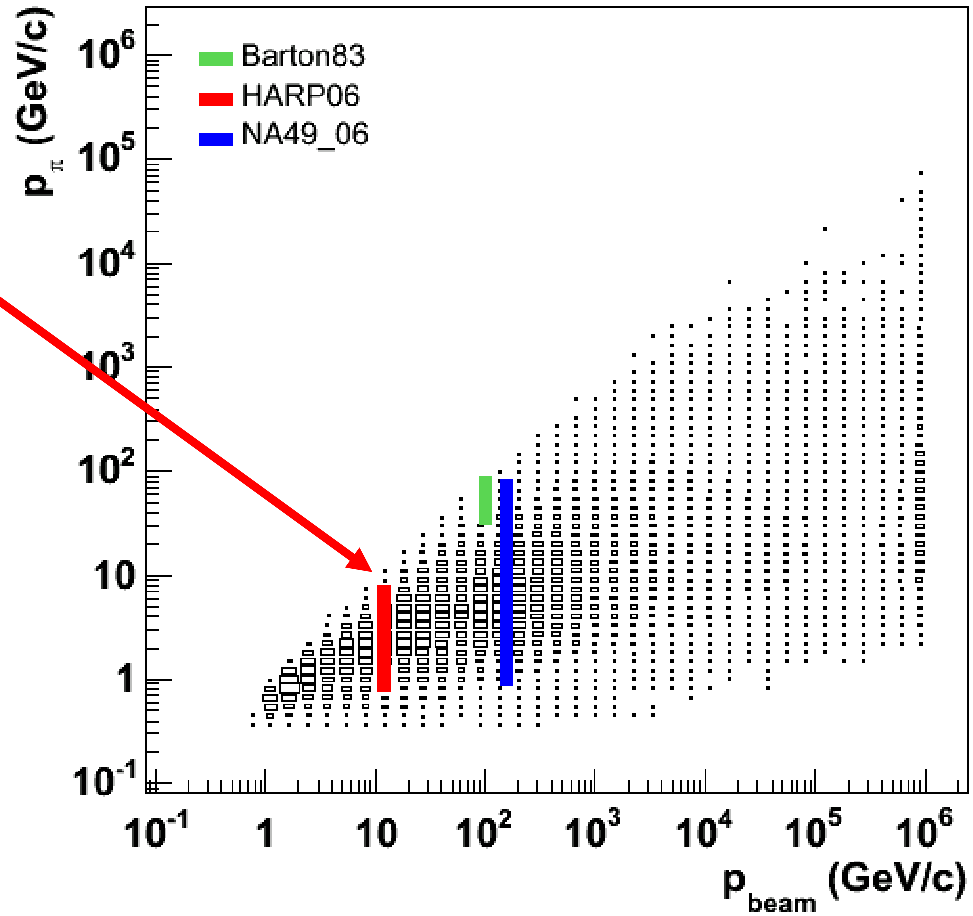


preliminary

Covered phase space region

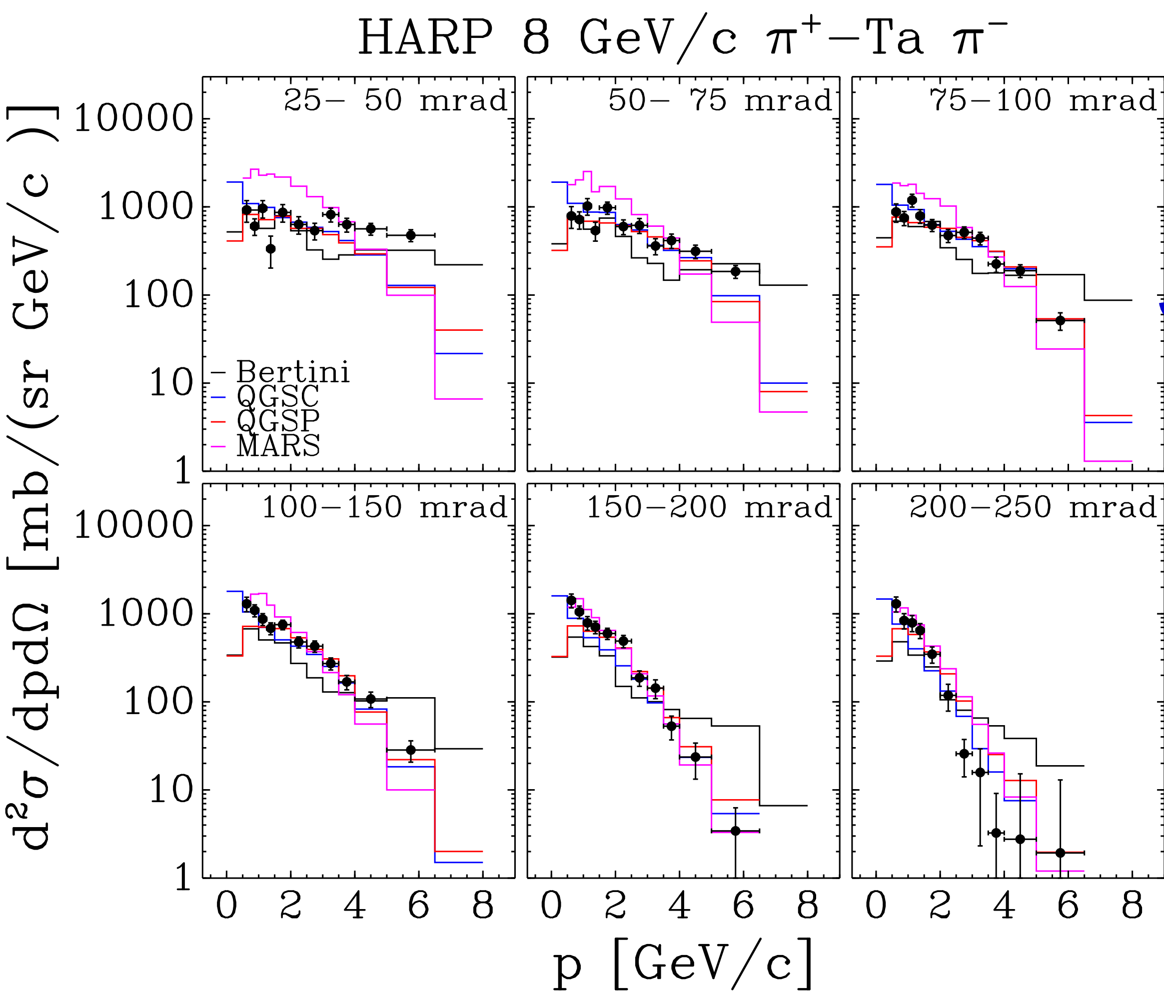
- New data sets

  ($p+C$, $\pi^{+}+C$ and $\pi^{-}+C$, pO_2, pN_2 at 12 GeV/c)
- Important phase space region covered
- Data available for model tuning and simulations
- Results on N2 and O2 data are preliminary



[Barton83]	Phys. Rev. D 27 (1983) 2580	(Fermilab)
[NA49_06]	Eur. J. Phys., hep-ex/0606028	(SPS)
HARP		(PS)

Data with incident π^+/π^-



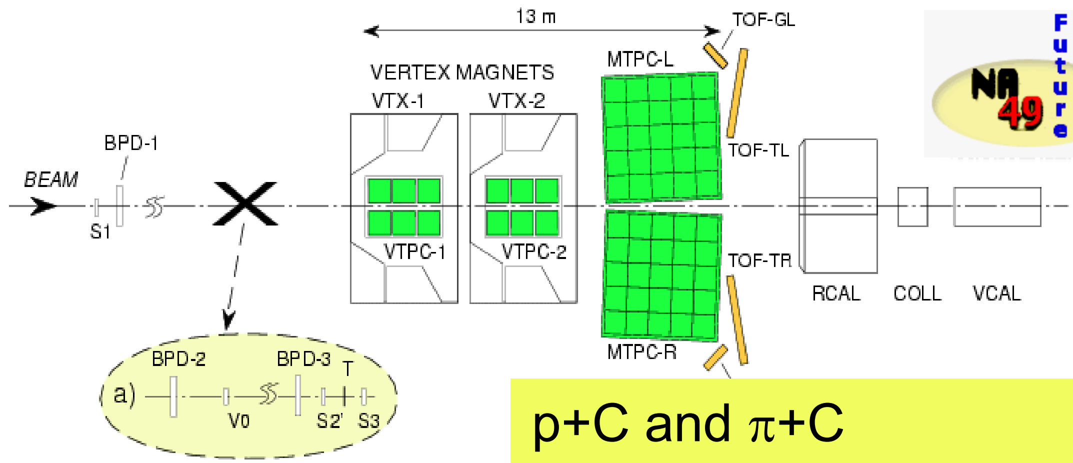
Just an example for FW production

HARP paper in preparation

- All thin target data taken in pion beams also available
- Interesting to tune models for re-interactions (and shower calculations in calorimeters etc.)

Next measurements/analyses

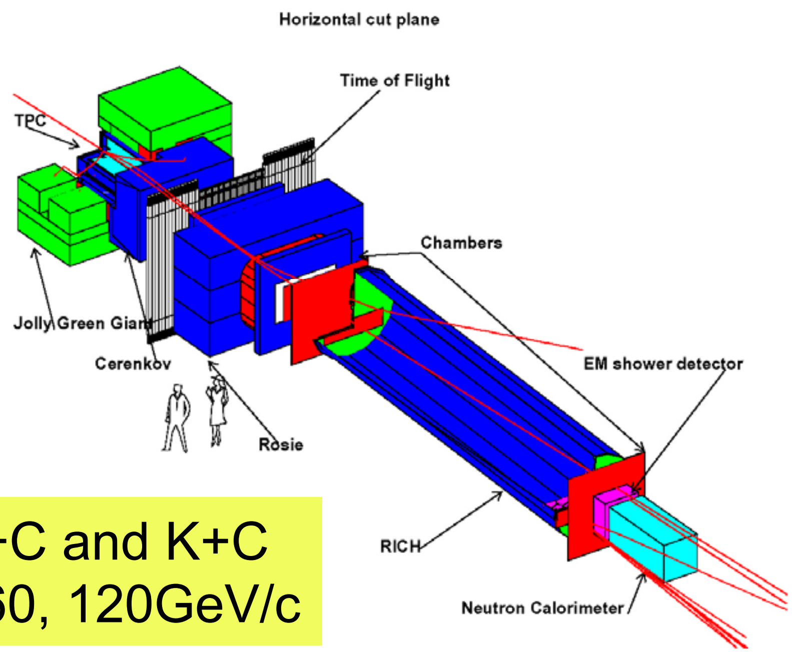
Energy range and phase space of interest	
$\langle E_{beam} \rangle$	8-1000 GeV
p	0.5-11.0 GeV/c
θ	0-300 mrad



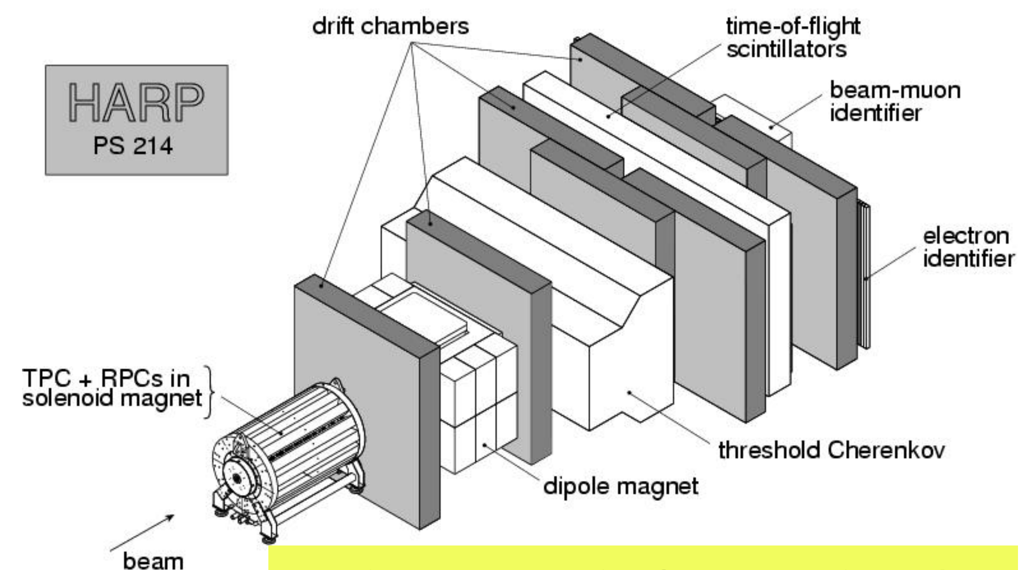
p+C and π+C
@ 30, 40, 50, 158GeV/c

MIPP

Main Injector Particle Production Experiment (FNAL-E907)



p+C, π+C and K+C
@ 20, 60, 120GeV/c



p+C and π+-C @ 3-15 GeV/c
N_2,O_2 targets

Summary

- **HARP has provided results useful for conventional ν beams study, ν factory design, EAS, atmospheric ν studies and in addition for general MC tuning (Geant4, FLUKA …) with full solid angle coverage, good PID identification on targets from Be to Pb at low energies (< 15 GeV) with small total errors (syst+stat < 15 %). About 10 physics paper published or submitted**
- **<u>More HARP results coming</u> : forward production with incident pions, protons on Be to Ta targets; production with long targets, …**
- **Comparison with available MC show some problems**