New Results from the HARP/PS214 experiment at CERN PS

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Outline

- results for conventional neutrino beams
  - HARP for K2K, MINIBoone
- new Harp forward π^{+-} production results: final p-A data, final π-A data (A=Be,C,Al,Cu,Sn,Ta,Pb)
- results for a Neutrino Factory
  - HARP Large Angle Data analysis
  - Comparison with MC simulations
- new LA results for π-A (A=Be,C,Al,Cu,Sn,Ta,Pb)
- new results for long replica targets for ν beams
- results for EAS and atmospheric neutrinos
  - HARP results with incident C, N_2, O_2
- conclusions

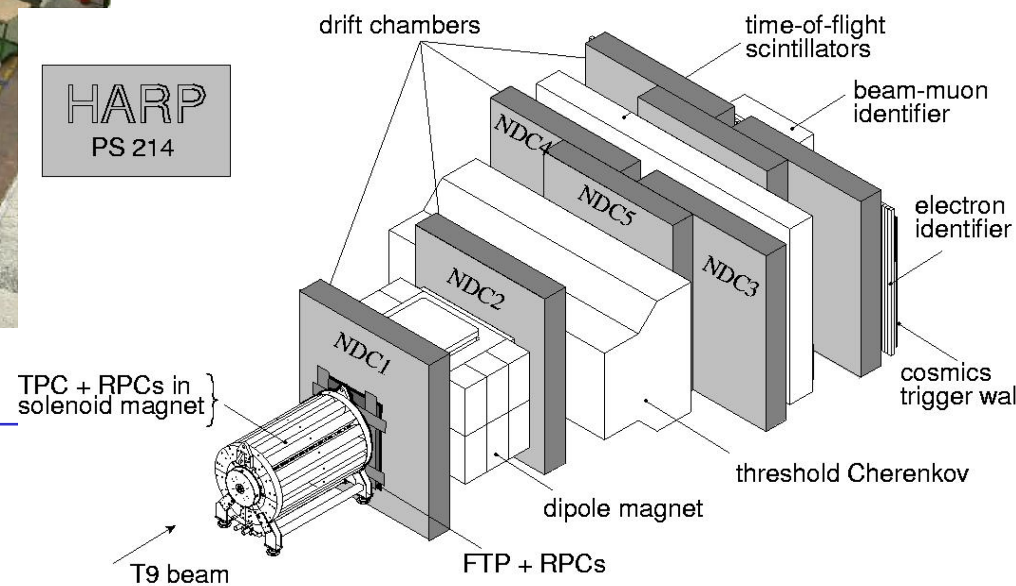
the HARP experiment at CERN PS

2000 – 2001 Installation

2001- 2002 Data taking

- 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 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
PS 214



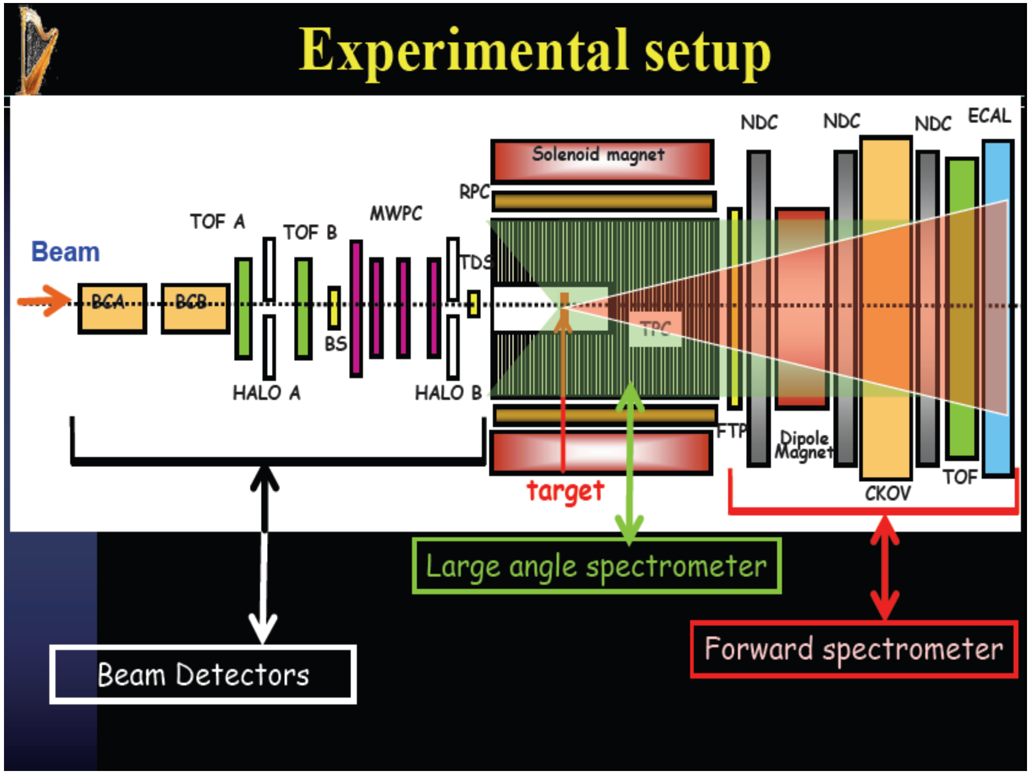
Systematic study of hadron production:

Beam momentum: 3-15 GeV/c

Target: from hydrogen to lead

•Acceptance over full solid angle

•Final state particle identification



Harp detector layout and data taken

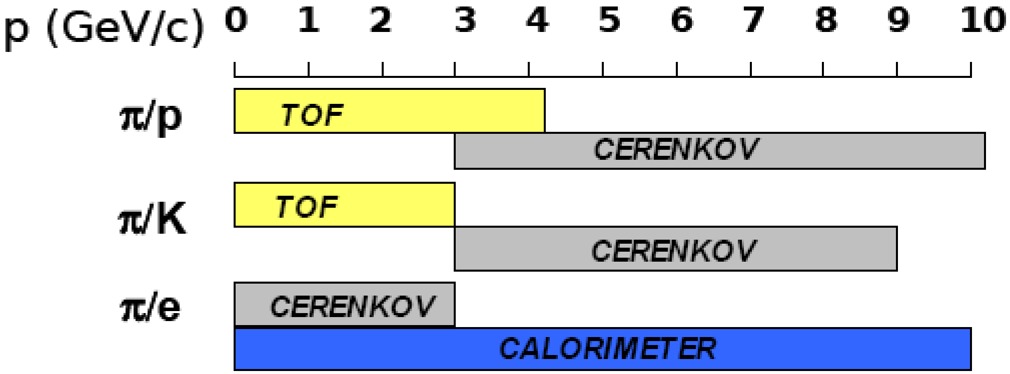
HARP: **barrel spectrometer** (**TPC**) + **forward spectrometer** (**DCs**) to cover the full solid angle, complemented by **PID** detectors

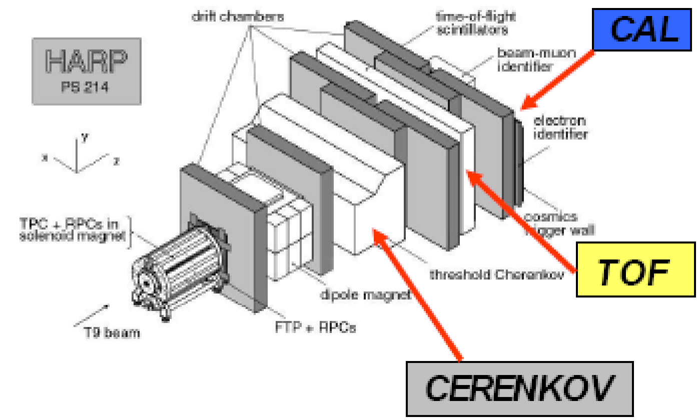
$p = 0.5 - 8.0$ GeV/c $\theta = 25 - 250$ mrad (forward)

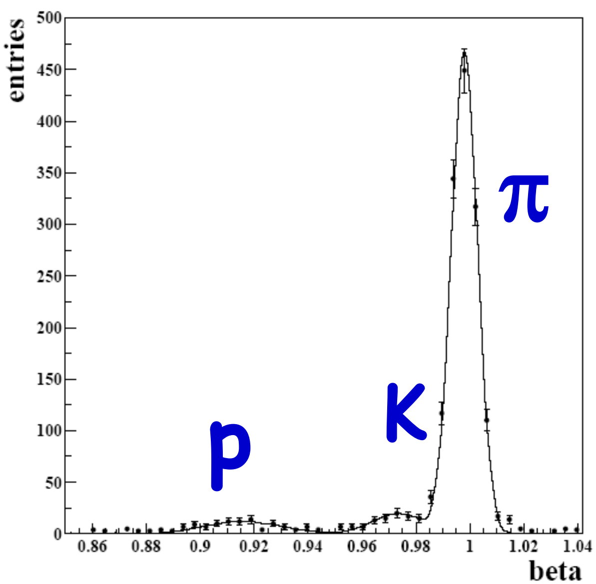
$p = 0.1 - 0.8$ GeV/c $\theta = 350 - 2150$ mrad (large angle)

	Targetl	Target length (λ%)	Beam Momentum (GeV)	#events (Mevts)
Solid targets	Be	2 (2001) 5 100	±3 ± 5 ± 8 ± 12 ± 15 For negative polarity, only 2% and 5%	233.16
	C			
	Al			
	Cu			
	Sn			
	Ta			
	Pb			
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 ± 5 ± 8 ± 12 ± 15	58.43
	0_8			
	D_1			
	H_1			
	H_2	18 cm	±3, ±8, ±14.5	13.83
Water	H_20	10, 100	+1.5, +8(10%)	9.6

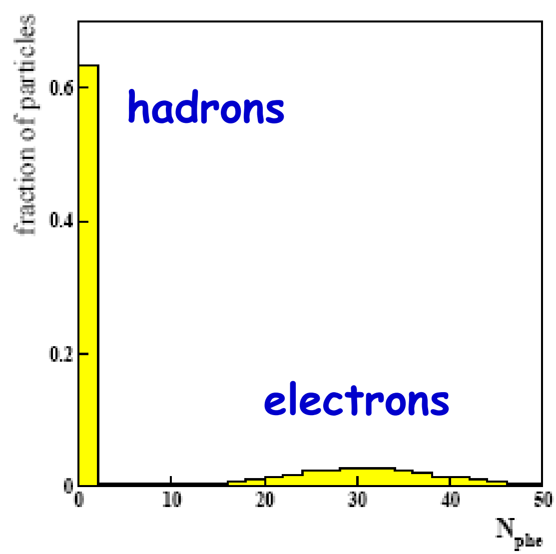
1. HARP forward analysis: particle identification



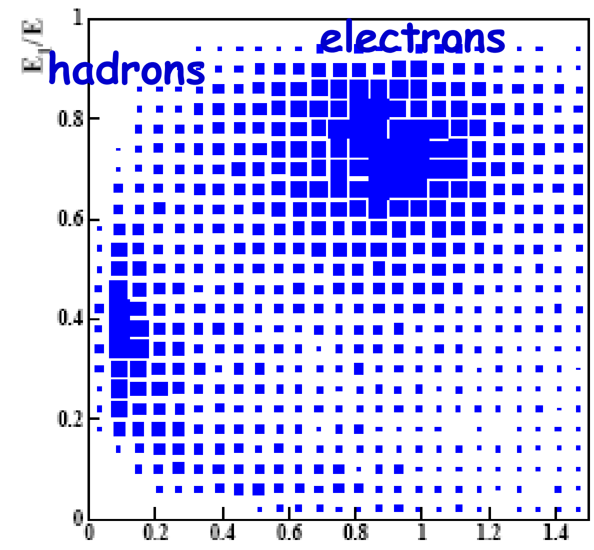




TOF for p=2+-0.25



$N_{cherenkov}$
for p below pion threshold



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

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

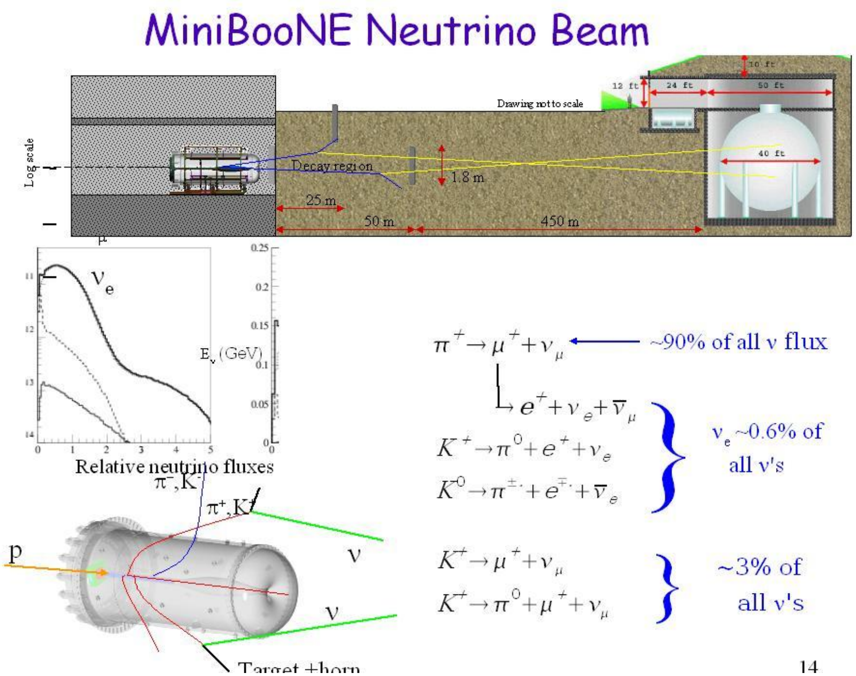
eff. & mig.

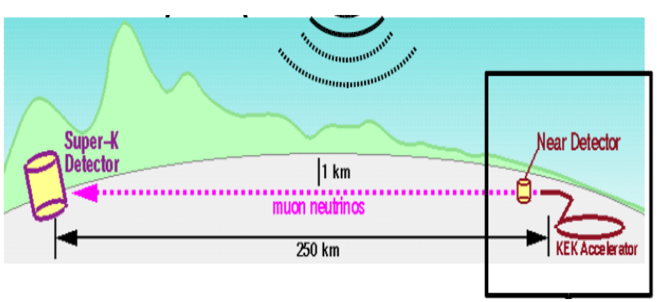
- Apply corrections for reconstructed-to-true pion yield conversion:
  - Momentum resolution
  - Spectrometer angular acceptance
  - Track reconstruction efficiency
  - Efficiency and purity of pion identification
  - Other

norm.

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

Why dedicated Hadroproduction expts: conventional neutrino beams





Oscillation probability at 250 km from the source for atmospheric parameters: maximum effect at ~1GeV

Ingredients to compute a neutrino flux :

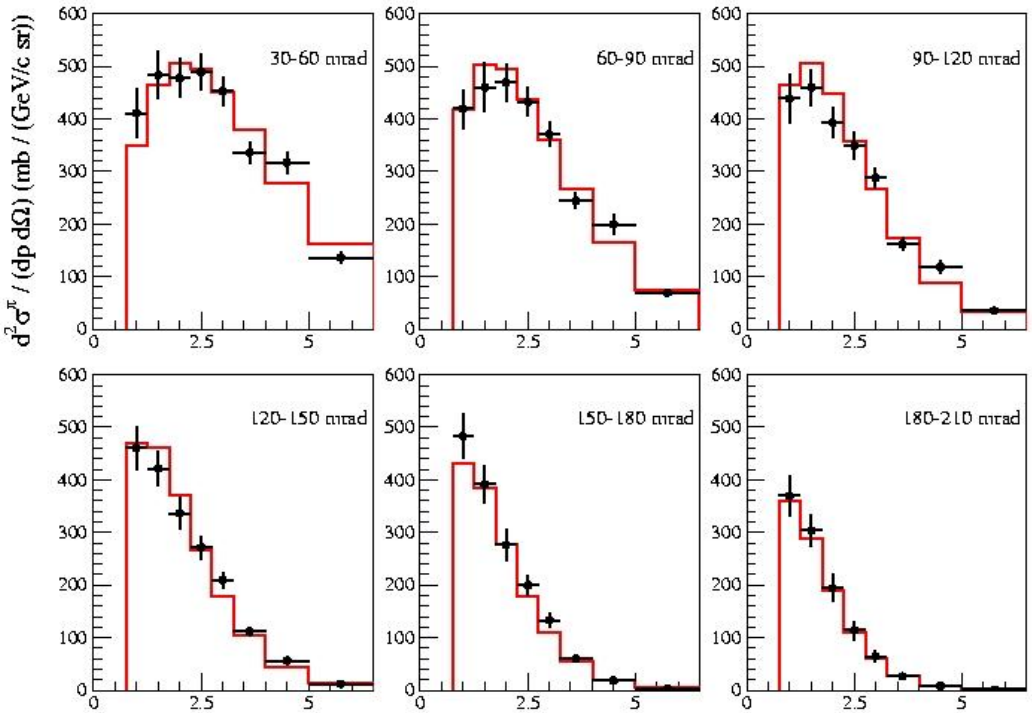
π (and k) production cross section (use same target and proton energy than proton driver of the experiment)

Reinteractions (take data with thin and thick target)

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

K2K: Disappearance experiment to confirm atmospheric osc.

HARP 12.9 GeV/c p+Al Results



HARP in black,
Sanford-Wang parametrization in red

HARP p-Al data 12.9 GeV/c:
M. G. Catanesi et al., HARP, Nucl. Phys. **B732** (2006)1

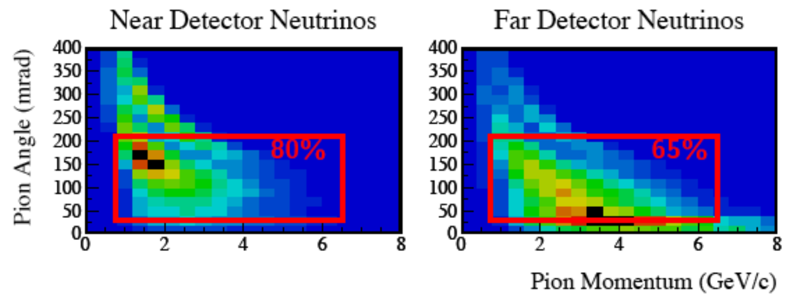
HARP data on inclusive pion production fitted to **Sanford-Wang** parametrization:

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

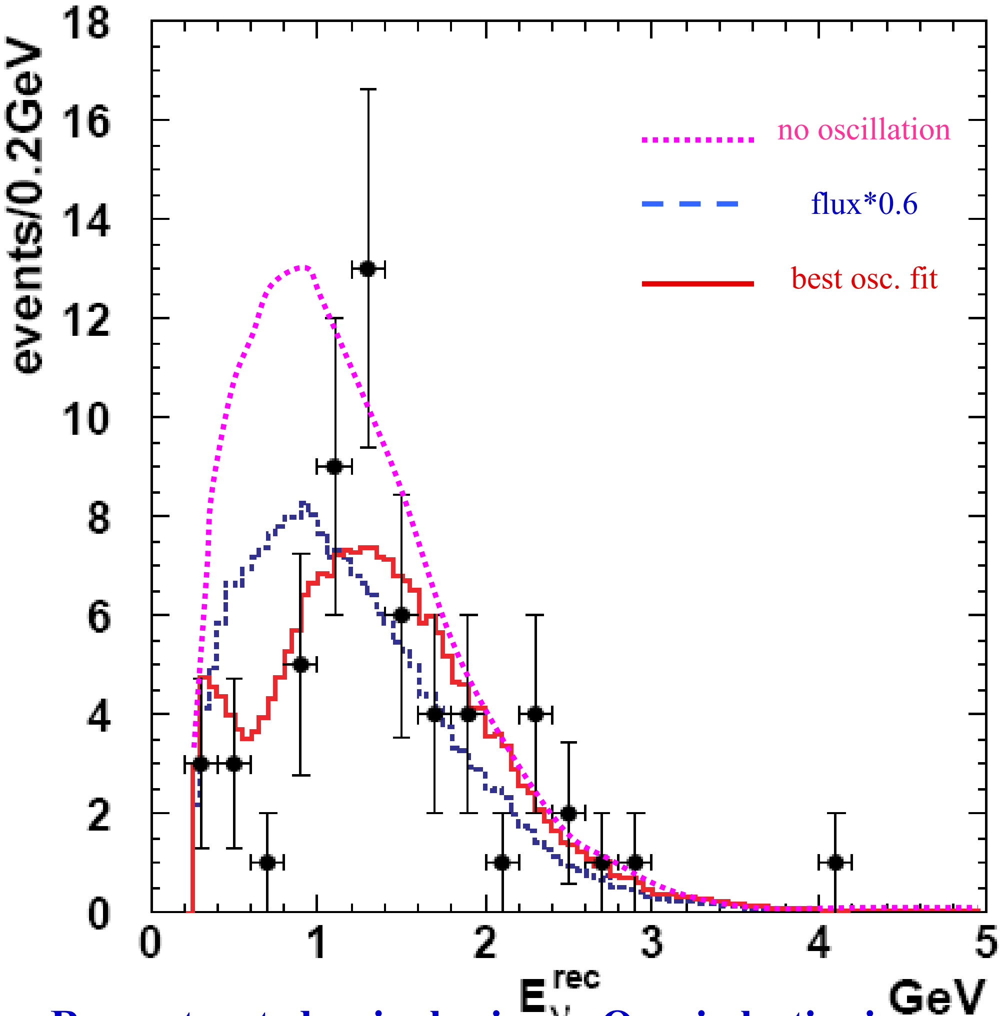
where:

- 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

- Good coverage of phase space of relevance to K2K flux predictions:

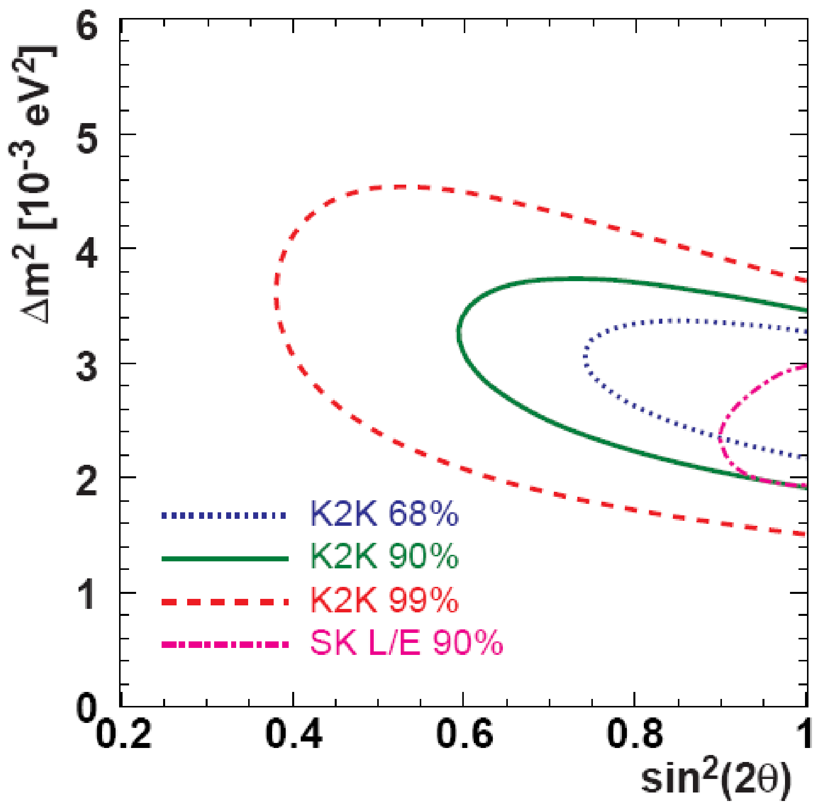


K2K final results (incl. HARP)



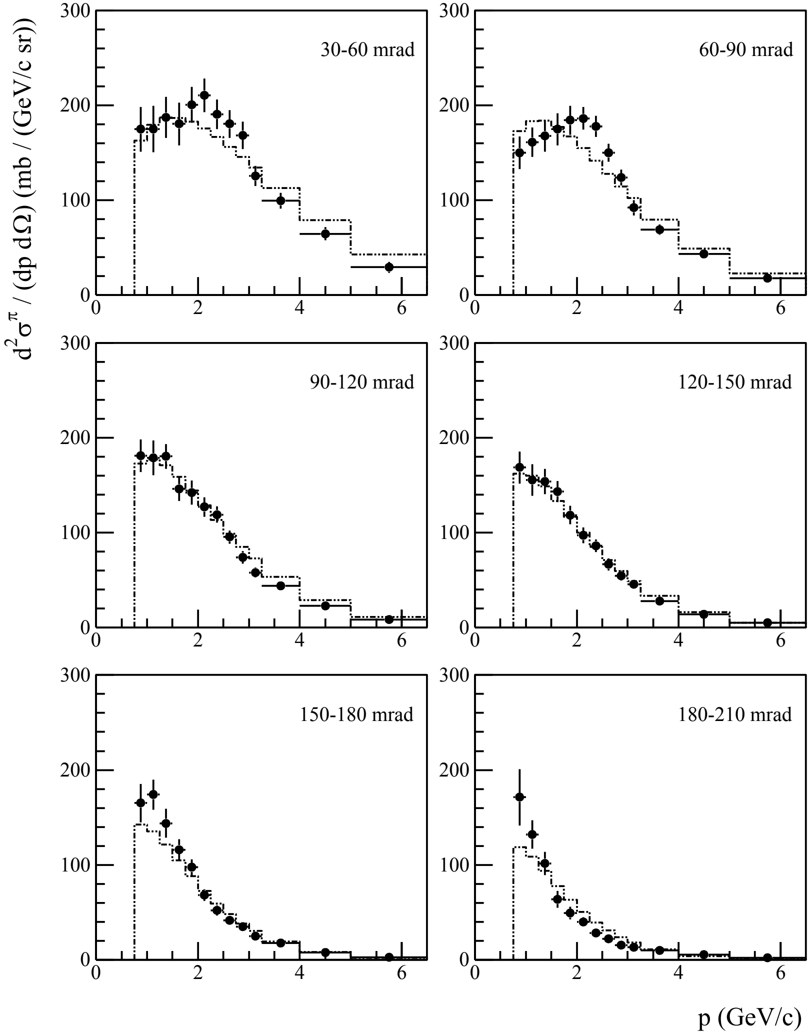
Reconstructed « single ring » Quasi-elastics in SuperKamiokande ==> spectral shape + normalization show oscillation (no oscillation curve for demonstration only)

K2K final results (using HARP input, 4.1 -> 4.4 σ C.L. improved by factor 3)



M. H. Ahn et al. [K2K Collaboration] Phys. Rev. D74 (2006) 072003

HARP Be 5% 8.9 GeV/c Results



Error Analysis: Overall error ~ 5%

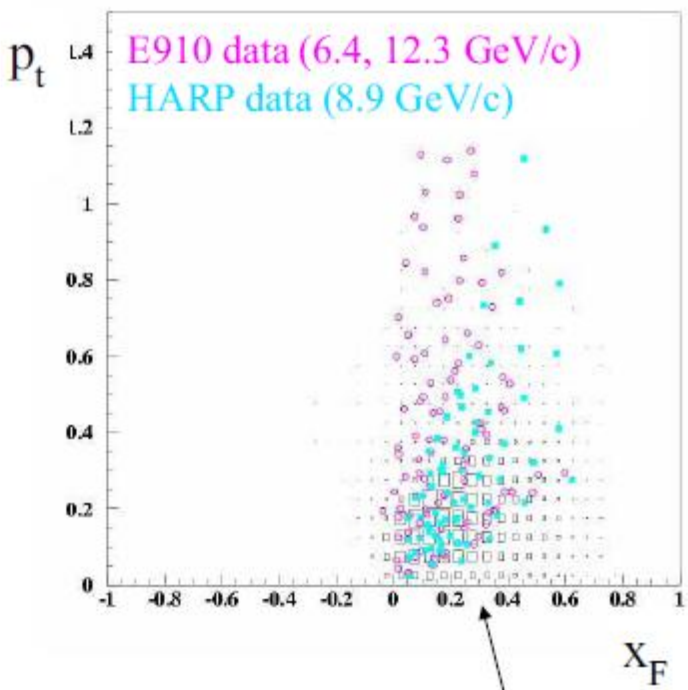
5% λ Be target

$$\delta_{\text{diff}} \equiv \frac{\sum_i (\delta[\Delta^2\sigma^\pi/(\Delta p \Delta\Omega)])_i}{\sum_i (\Delta^2\sigma^\pi/(\Delta p \Delta\Omega))_i} \qquad \delta_{\text{int}} \equiv \frac{\sqrt{\sum_{i,j}(\Delta p \Delta\Omega)_i C_{ij} (\Delta p \Delta\Omega)_j}}{\sum_i (\Delta^2\sigma^\pi)_i}$$

Error Category	Error Source	$\delta^{\pi}_{\text{diff}}$ (%)	$\delta^{\pi}_{\text{int}}$ (%)
Statistical	Be target statistics	4.2	0.6
	Empty target subtraction (stat.)	4.6	0.6
	Sub-total	**6.3**	**0.8**
Track yield corrections	Reconstruction efficiency	1.3	0.8
	Pion, proton absorption	3.6	3.7
	Tertiary subtraction	1.8	1.8
	Empty target subtraction (syst.)	1.3	1.2
	Sub-total	**4.6**	**4.3**
Particle Identification	Electron veto	0.2	<0.1
	Pion, proton ID correction	0.4	0.1
	Sub-total	**0.5**	**0.1**
Momentum reconstruction	Momentum scale	3.6	0.1
	Momentum resolution	3.4	1.0
	Sub-total	**5.2**	**1.0**
Overall normalization	**Sub-total**	**2.0**	**2.0**
All	**Total**	**9.8**	**4.9**

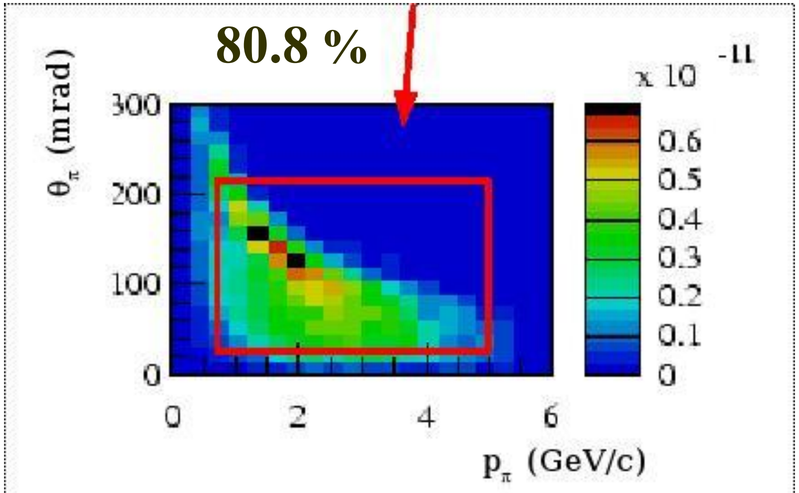
HARP results (data points), Sanford-Wang parametrization of HARP results (histogram)

MiniBoone ν flux predictions



- 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

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

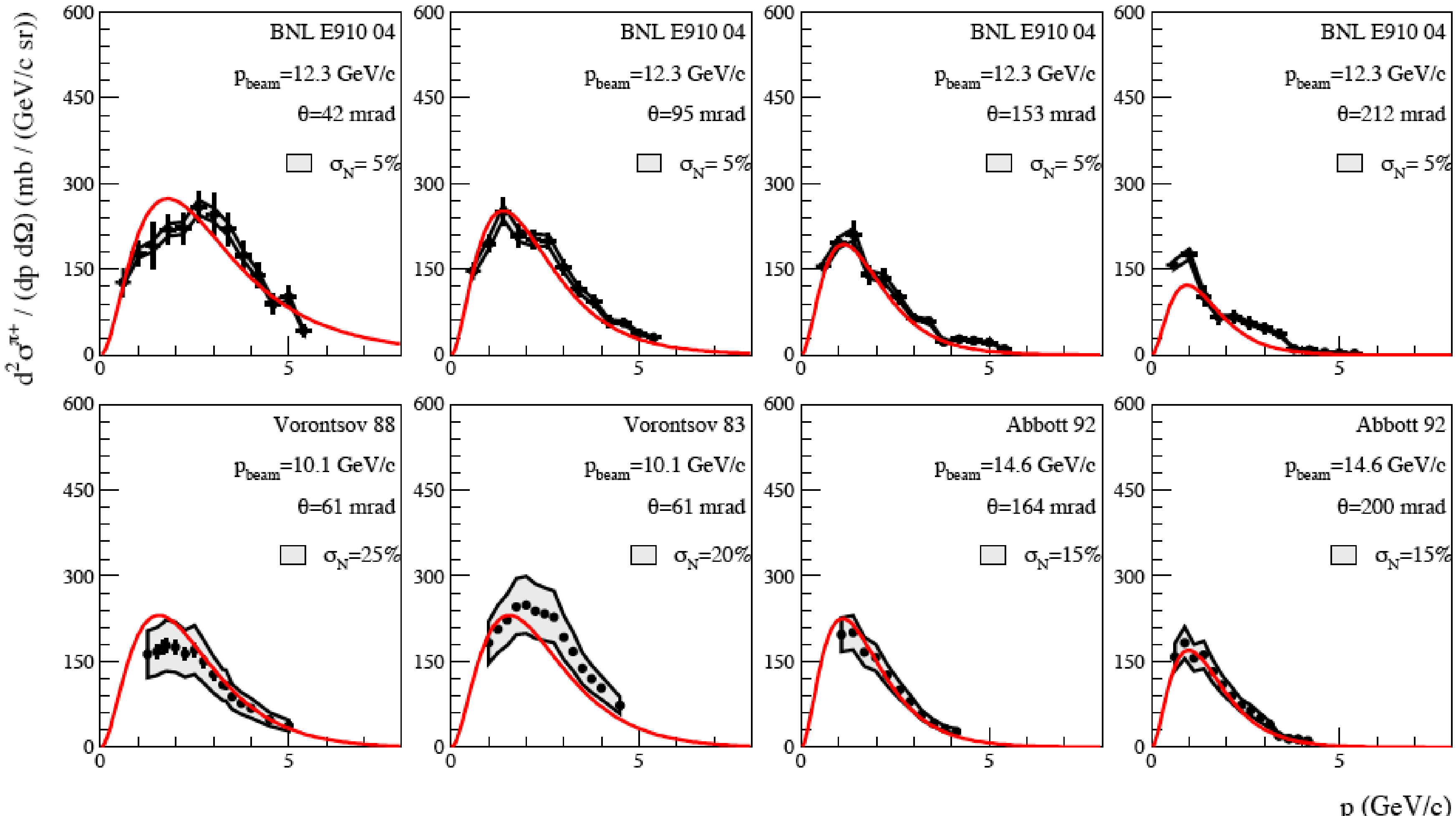


Momentum and Angular distribution of pions decaying to a neutrino that passes through the MB detector.

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

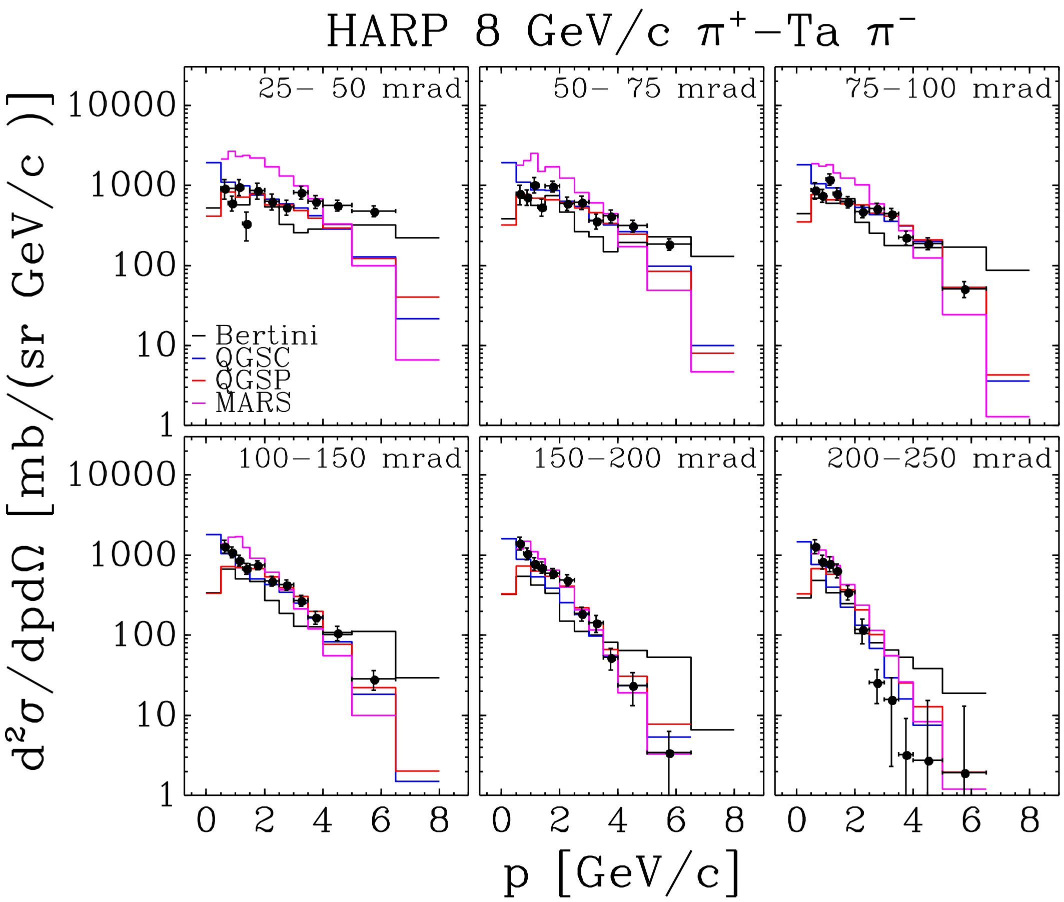
HARP p-Be-> π^+-X data 8.9 GeV/c:
M. G. Catanesi et al., Eur. Phys. J. **C52** (2007) 29
MiniBooNE with Harp input ,
A.A.Aguilar-Arevalo et al., Phys. ReV. Lett. **98** (2007)

Comparison with older p+Be data



albeit, different beam momenta

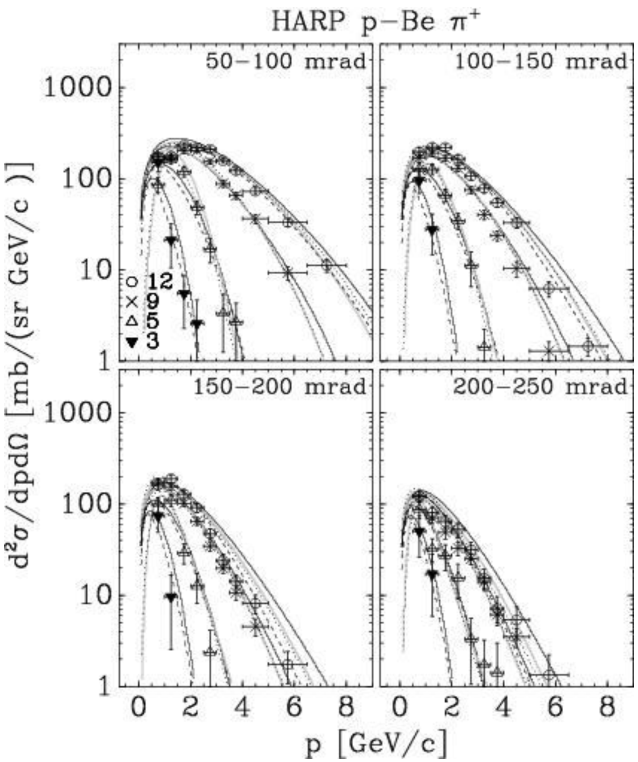
New HARP results: FW data with incident π^+/π^-

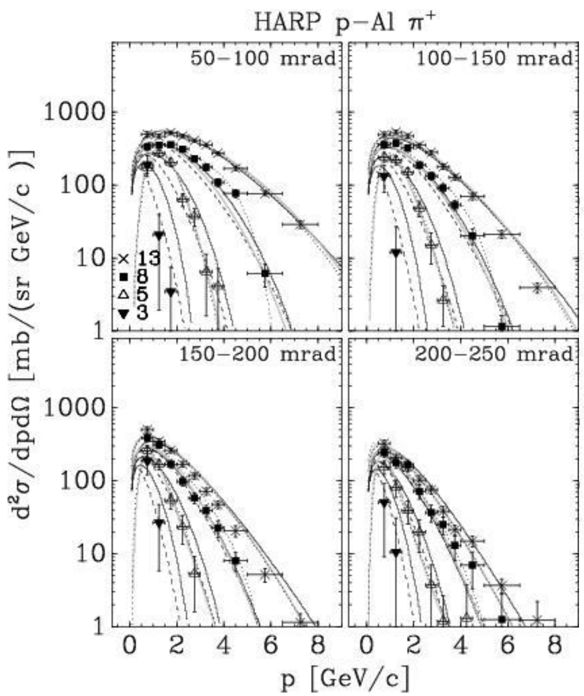


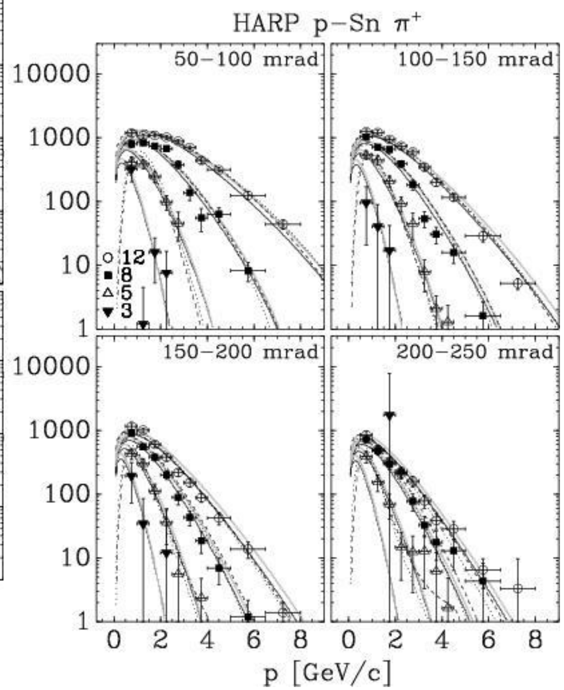
- An example for FW production
- Model comparisons
- Data on thin Be,Al,C,Cu,Sn,Ta,Pb targets with 3-12.9 GeV/c protons

- All FW data taken in pion beams have been published on NP A 801 (2009) 118
- Bad agreement data montecarlo (GEANT4/MARS)
- **Interesting to tune models for re-interactions (and shower calculations in calorimeters etc.)**

New Harp results: final FW results p-A



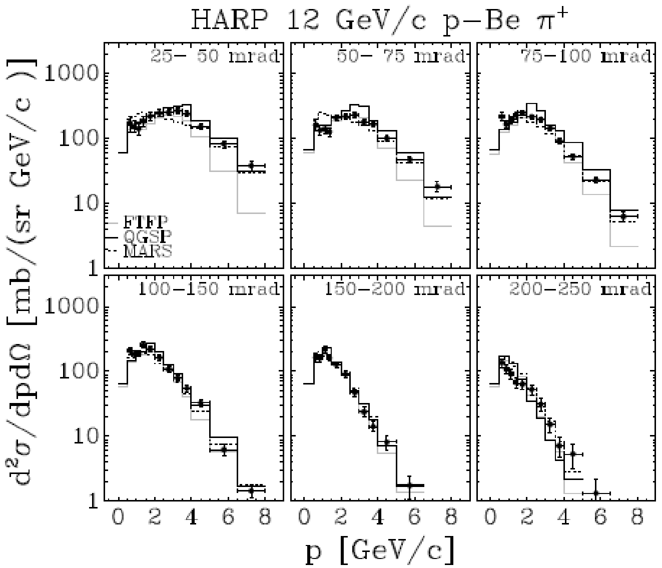




- ❑Final FW results on p-A (A =Be,C,Al,Sn,Cu,Ta,Pb)
- ❑ SW parametrization of all data, comparison with MC
- ❑ submitted to PRC

Comparison of FW p-A->π X with MC

	3 GeV		5 GeV		8 GeV		12 GeV	
	π^+	π^-	π^+	π^-	π^+	π^-	π^+	π^-
ndof	16	16	32	32	36	36	40	40
model	Beryllium							
Bertini	181.1	156.8	340.6	375.8	517.4	342.6	762.7	347.9
Binary	180.8	196.9	272.6	474.5	284.6	401.7		
LHEP	149.8	43.2	115.6	283.5	128.2	118.5	153.7	160.5
QGSP					112.2	210.6	124.9	154.3
FTFP						323.2	55.7	172.1
MARS	9.4	46.2	23.1	13.9	26.3	52.7	24.2	26.2
model	Tantalum							
Bertini	113.8	110.8	165.2	377.8	328.0	193.9	540.5	248.7
Binary	147.8	145.4	197.9	435.1	224.3	284.4		
LHEP	116.1	22.0	94.9	255.8	91.8	76.0	73.2	109.1
QGSP					163.3	169.2	38.8	82.9
FTFP						96.4	69.0	55.6
MARS	44.9	25.9	83.4	65.8	48.8	20.7	26.6	15.9



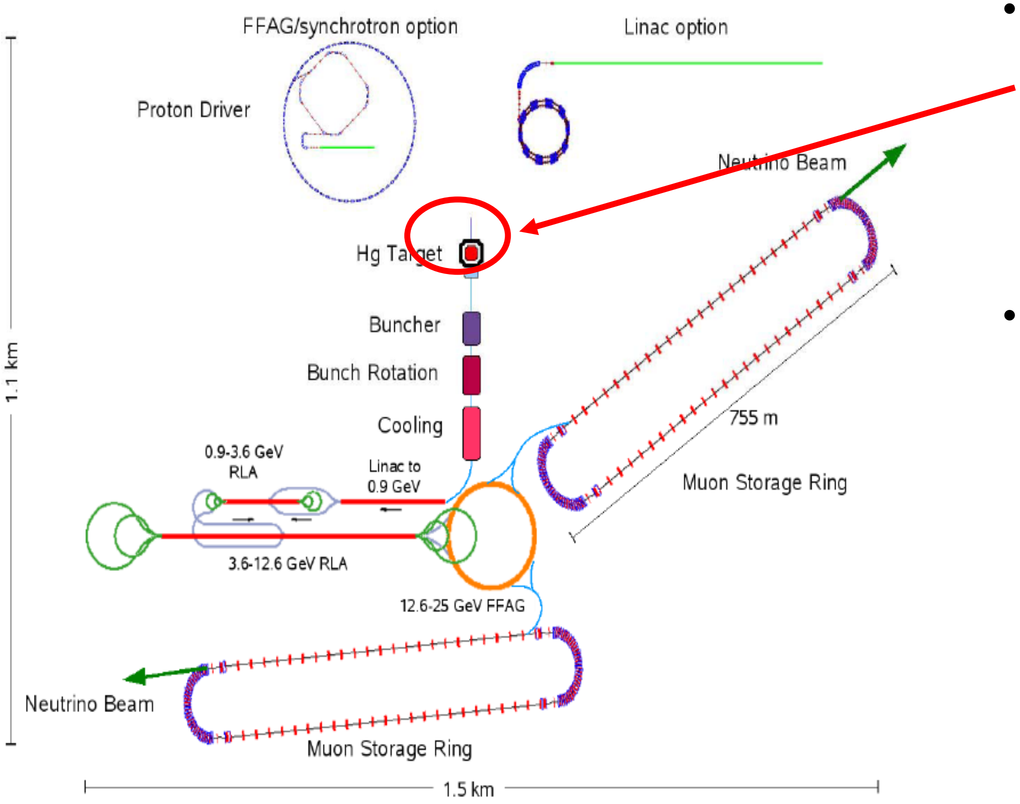
χ^2 assuming a 20% error on MC

Just one example

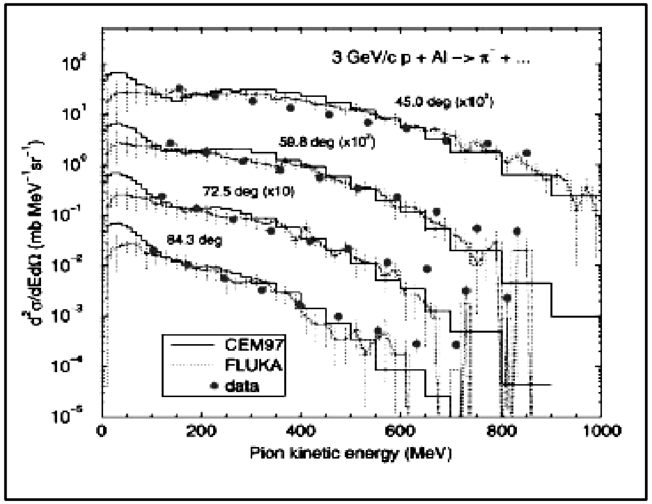
Table 10: Normalization factors data-simulation.

model	Be 3 GeV		Ta 3 GeV		Be 5 GeV		Ta 5 GeV		Be 8 GeV		Ta 8 GeV		Be 12 GeV		Ta 12 GeV	
	π^+	π^-	π^+	π^-	π^+	π^-	π^+	π^-	π^+	π^-	π^+	π^-	π^+	π^-	π^+	π^-
Bertini	0.35	1.02	0.45	0.53	0.70	1.12	0.29	0.35	1.22	1.54	0.84	1.08	1.75	1.81	1.27	1.50
Binary	0.36	0.75	0.28	0.34	0.73	0.88	0.16	0.23	0.99	1.05	0.50	0.56				
LHEP	0.40	0.86	0.81	0.91	0.76	0.98	0.36	0.45	0.78	0.91	0.58	0.66	0.75	0.82	0.54	0.59
QGSP									1.40	1.43	0.80	0.75	0.80	0.88	0.64	0.67
FTFP											0.46	0.65	1.00	1.10	0.63	0.77
MARS	0.83	1.29	1.10	1.16	1.21	1.38	1.17	1.35	1.10	1.21	0.90	0.85	1.02	1.02	0.92	0.82

Neutrino factory design

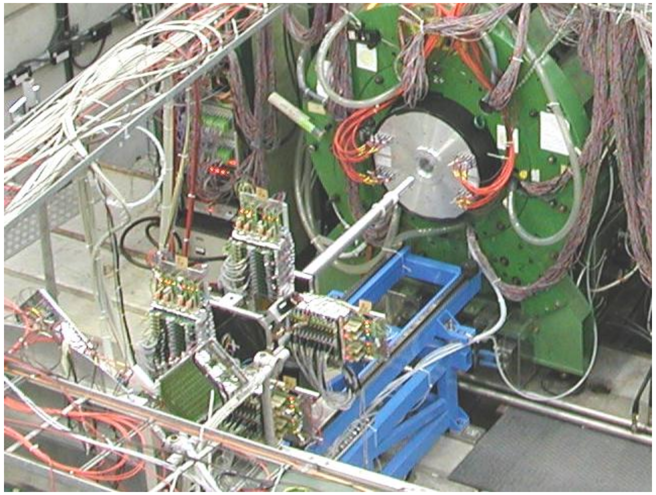


- **maximize $\pi^+(\pi^-)$ production yield as a function of:**
  - **proton energy**
  - **target material**
  - **geometry**
  - **collection efficiency (p_L,p_T)**
- **but different simulations show large discrepancies for π production distributions, both in shape and normalization. Experimental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



$\Rightarrow$ ***Aim: measure p_T distribution with high precision for high Z targets***

2. HARP Large Angle Analysis

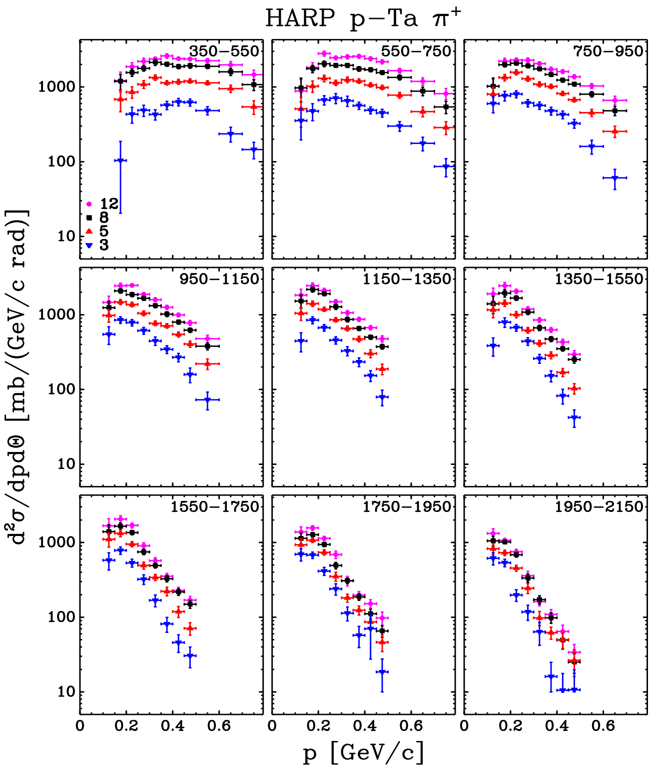


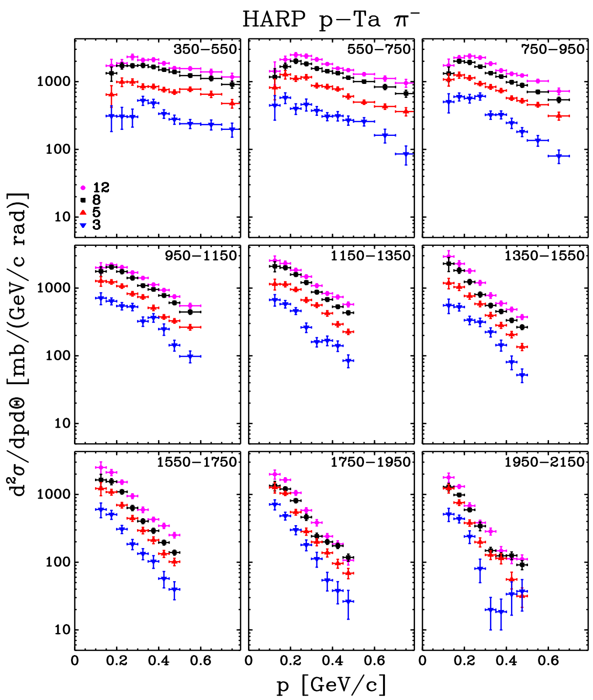
Beam momenta:
3, 5, 8, 12 GeV/c
Data:
5% λ_I targets Be,C,Al,Cu,Sn,Ta,Pb
TPC tracks:
>11 points and momentum measured and track originating in target
PID selection
Corrections:
Efficiency, absorption, PID, momentum and angle smearing by unfolding method
Backgrounds:
secondary interactions (simulated)
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).

Pion production yields

9 angular bins: p-Ta π^+/π^-



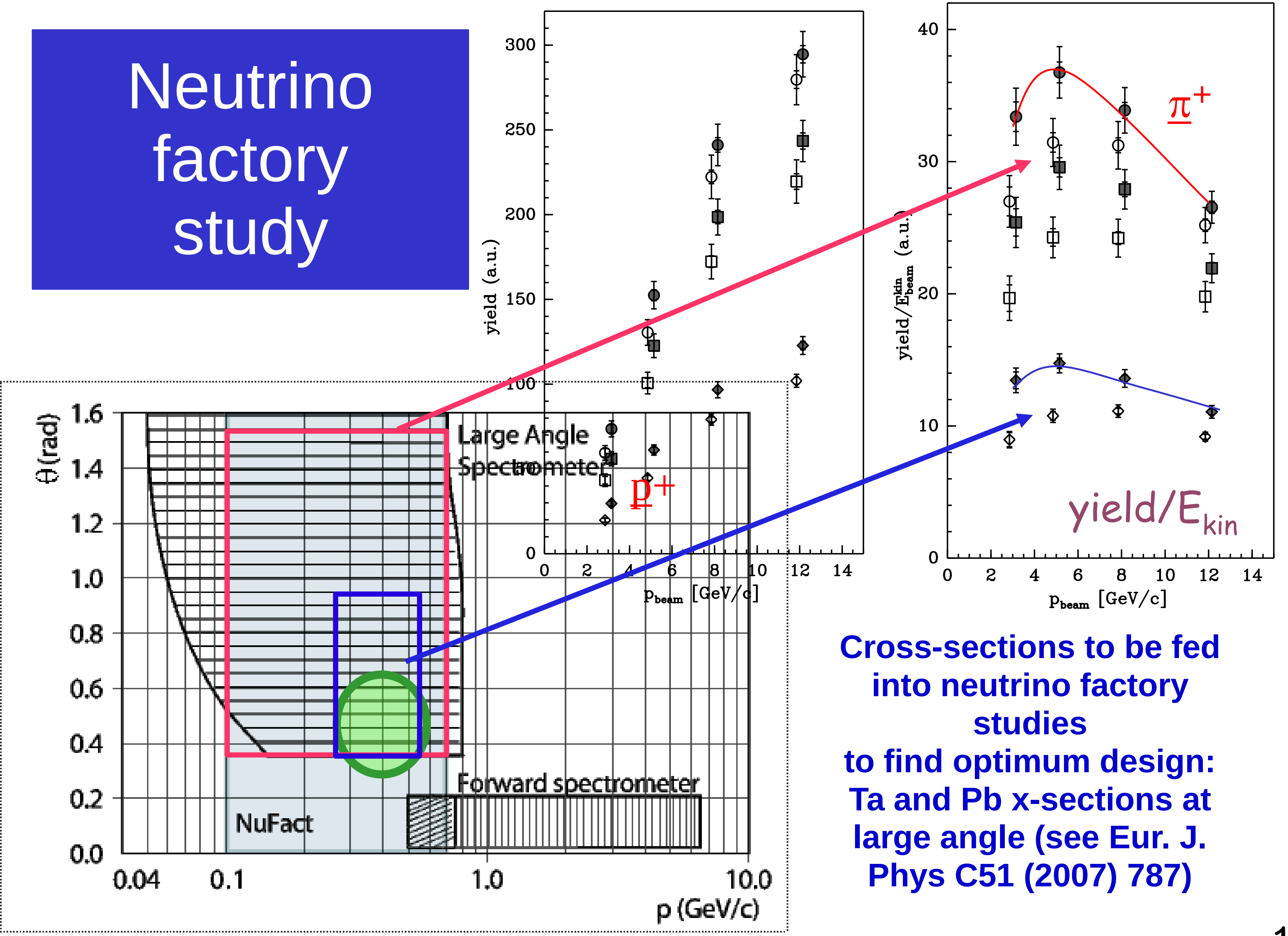


forward
$0.35 < \theta < 1.55$

backward
$1.55 < \theta < 2.15$

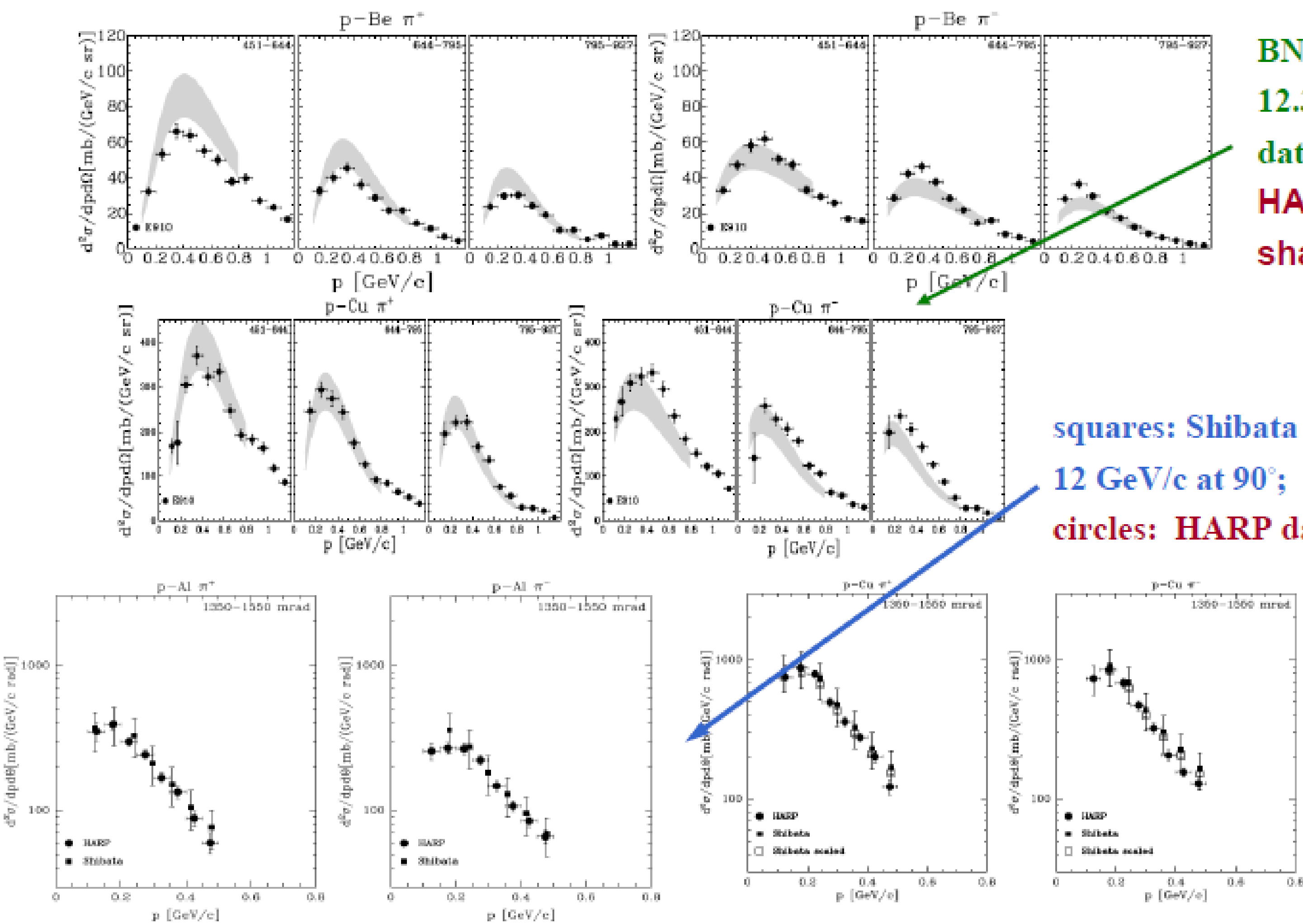
p

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 available data…



BNL E910 at 12.3 GeV/c: data points;

HARP: shaded region

squares: Shibata et al. (KEK), 12 GeV/c at 90°;

circles: HARP data

Comparisons with MC

Many comparisons with models from GEANT4 and MARS to the GiBUU model have been done

Only some examples will be shown here for C and Ta for the GEANT4 and MARS packages

- Binary cascade
- Bertini cascade
- Quark-Gluon string models (QGSP)
- Frittiof (FTFP)
- LHEP
- MARS

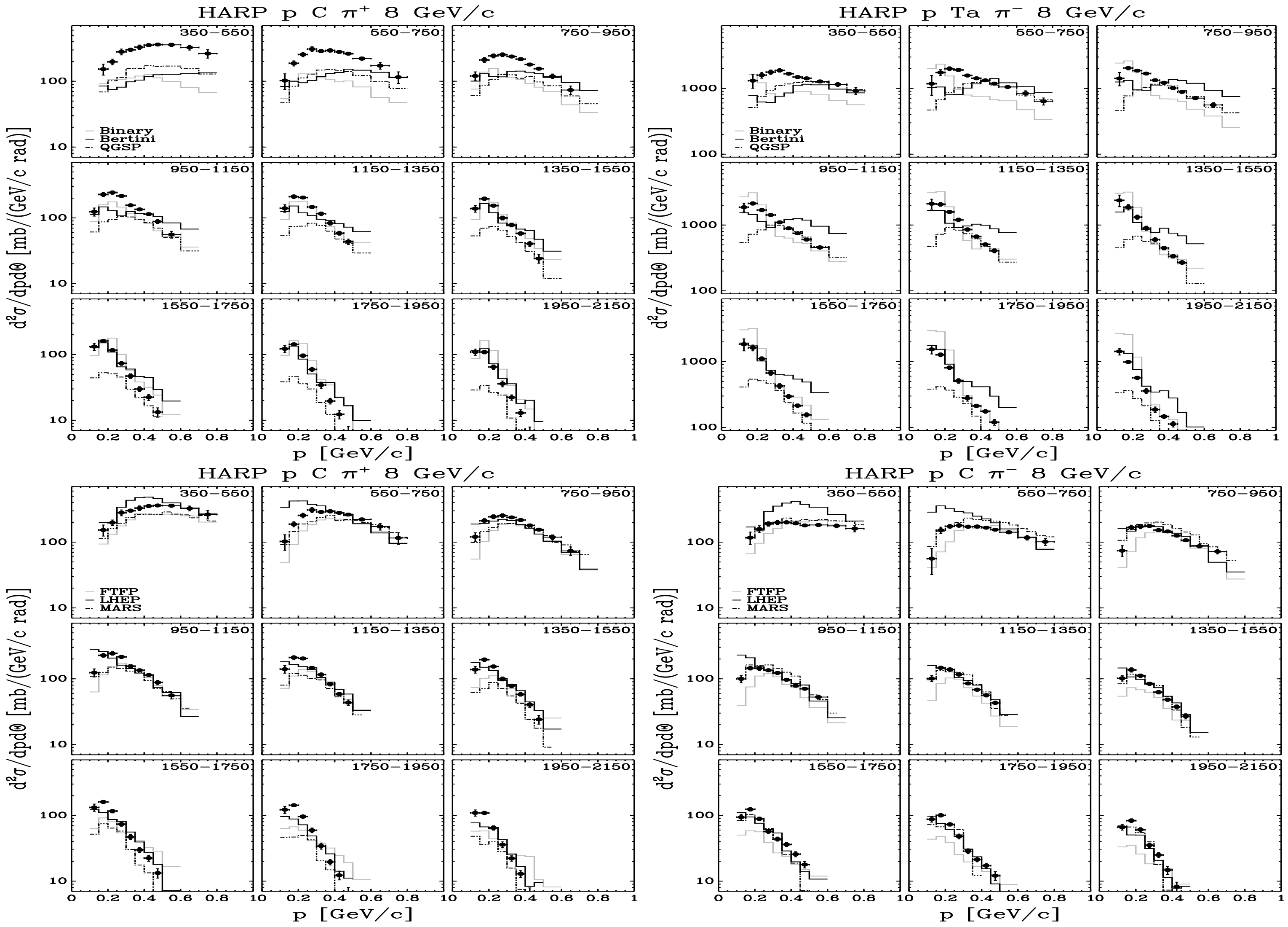
Some models (inside MARS/GEANT4) do a good job in some regions,

but there is no model that describes all aspects of the data. GiBUU seems a little better in the region covered by HARP.

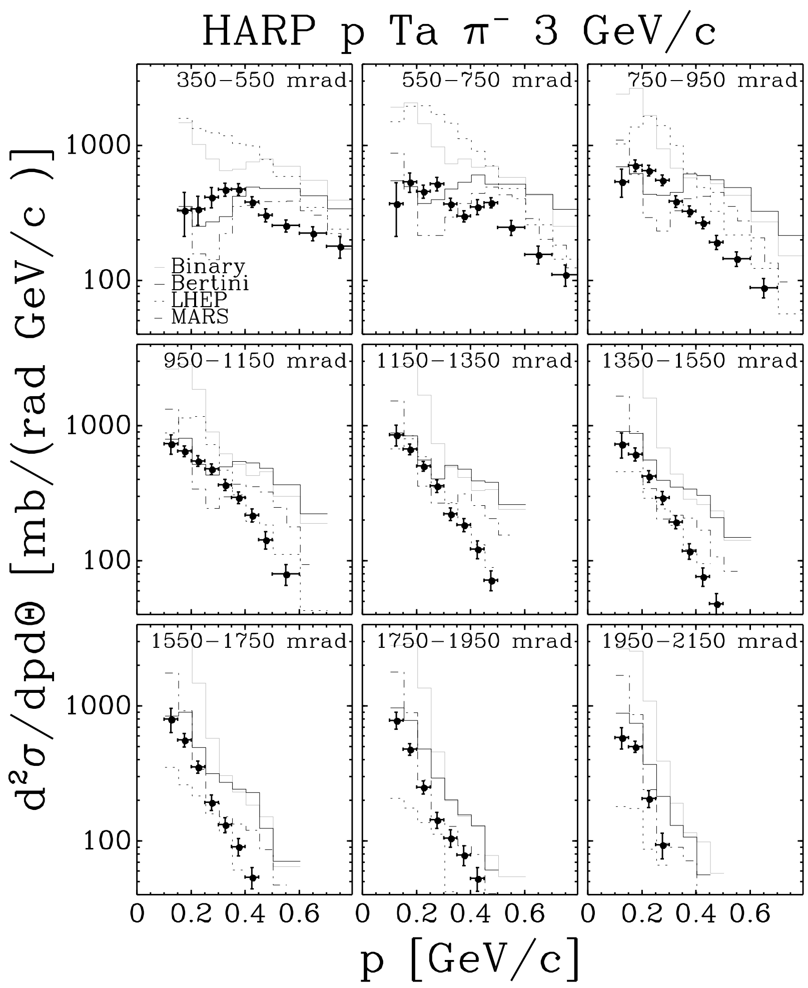
8 GeV/c p-C $\pi^{+/-}$

MODELS

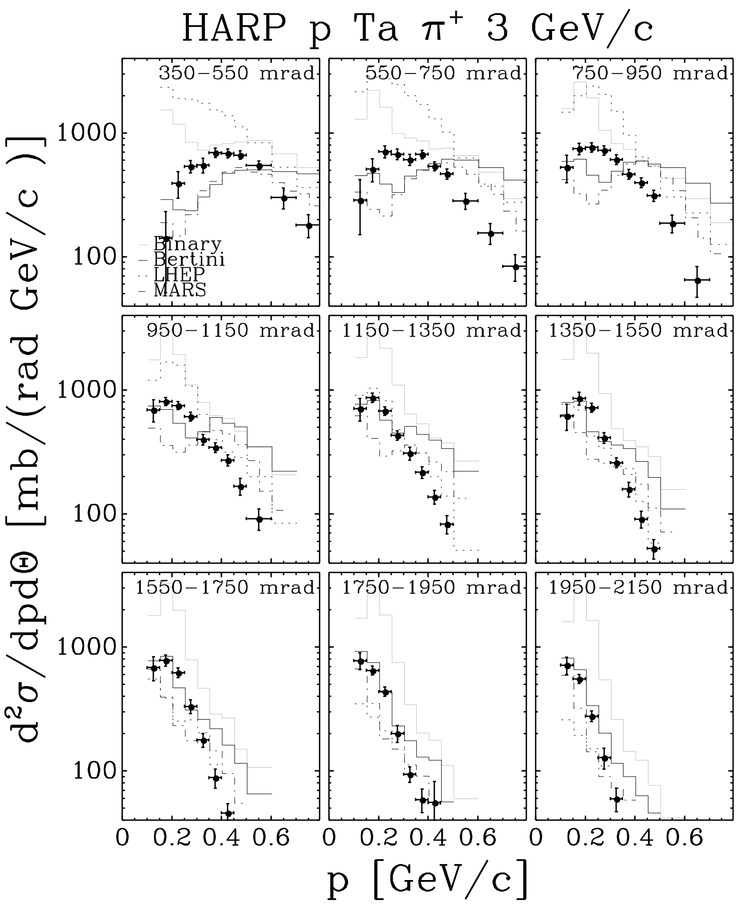
5% λ target



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

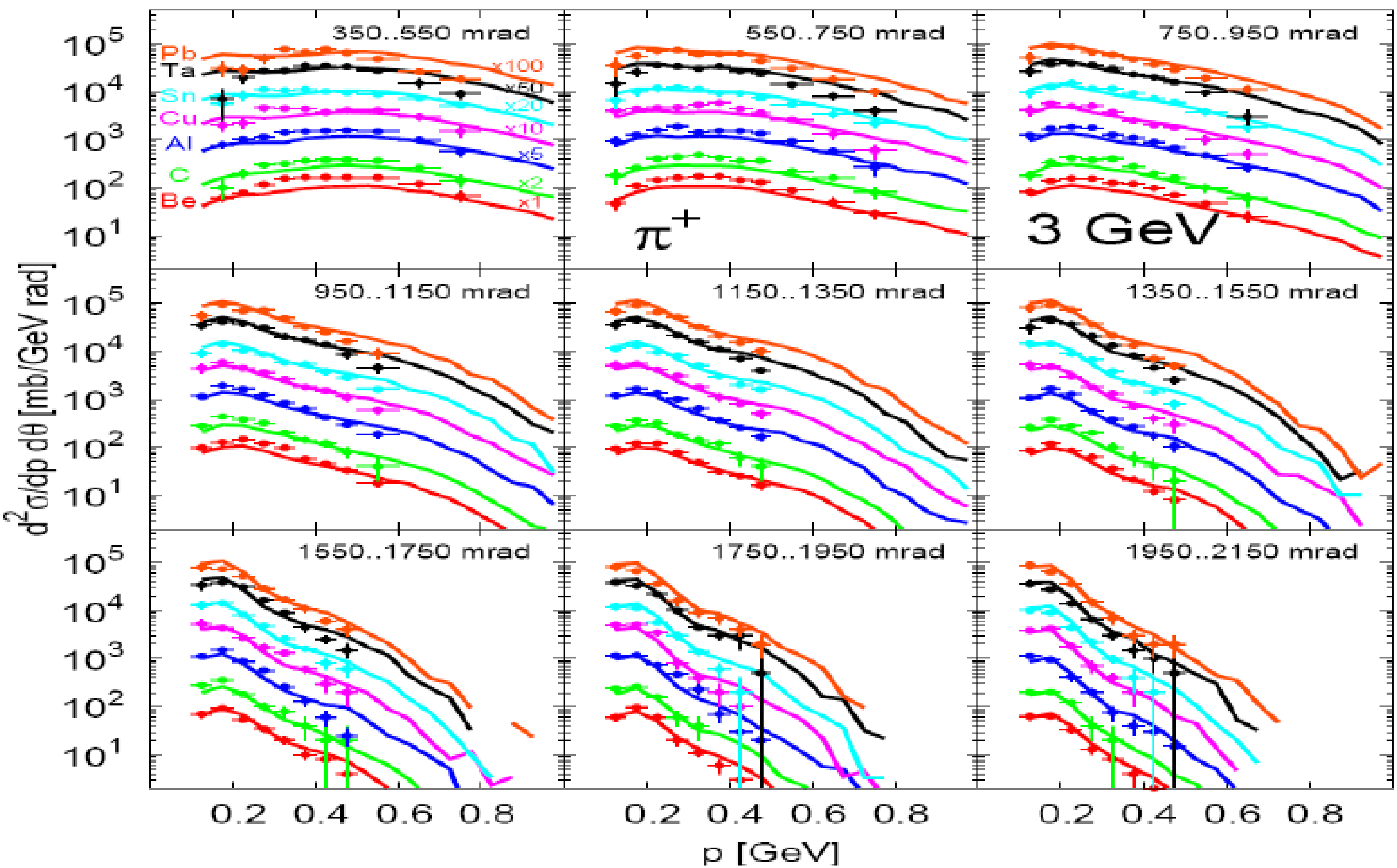


HARP p Ta π⁻ 3 GeV/c
350−550 mrad
550−750 mrad
750−950 mrad
950−1150 mrad
1150−1350 mrad
1350−1550 mrad
1550−1750 mrad
1750−1950 mrad
1950−2150 mrad
Binary
Bertini
LHEP
MARS
d²σ/dpdΘ [mb/(rad GeV/c)]
p [GeV/c]



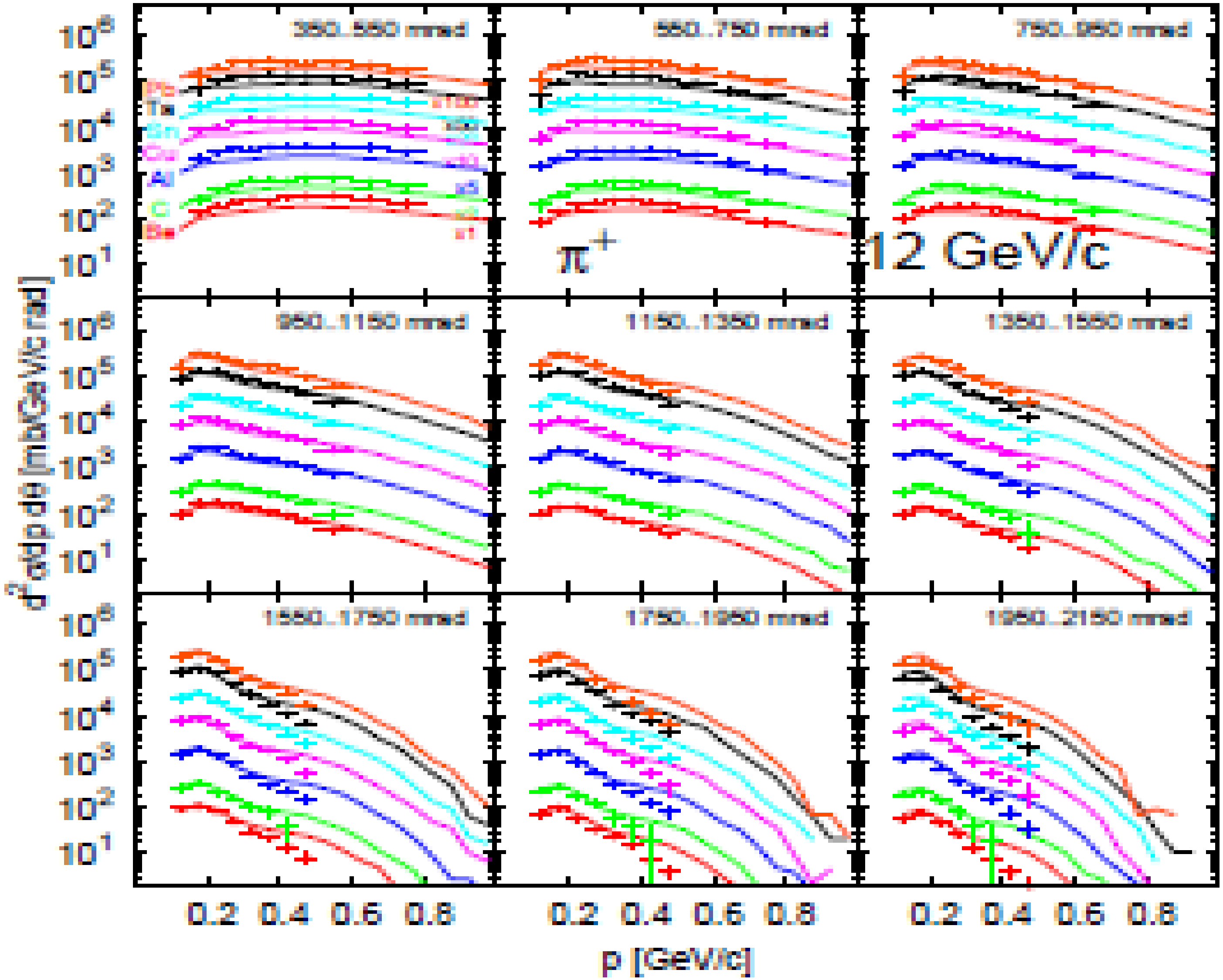
HARP p Ta π⁺ 3 GeV/c
350−550 mrad
550−750 mrad
750−950 mrad
950−1150 mrad
1150−1350 mrad
1350−1550 mrad
1550−1750 mrad
1750−1950 mrad
1950−2150 mrad
Binary
Bertini
LHEP
MARS
d²σ/dpdΘ [mb/(rad GeV/c)]
p [GeV/c]

3 GeV/c π^+ HARP LA data vs GiBUU



GiBUU (arXiv:0901.1770 [hep-ex])

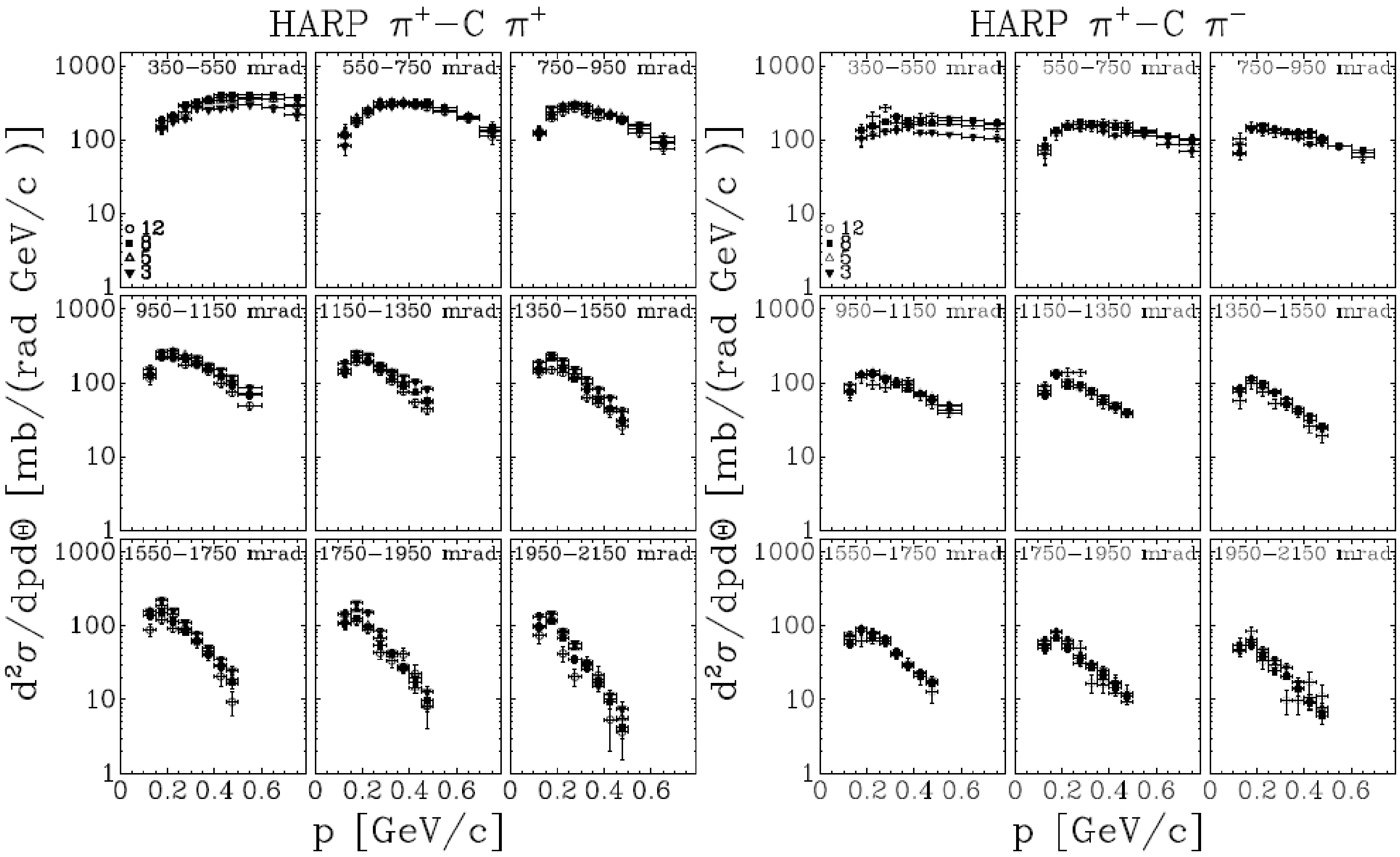
12 GeV/c π^+ HARP LA data vs GiBUU

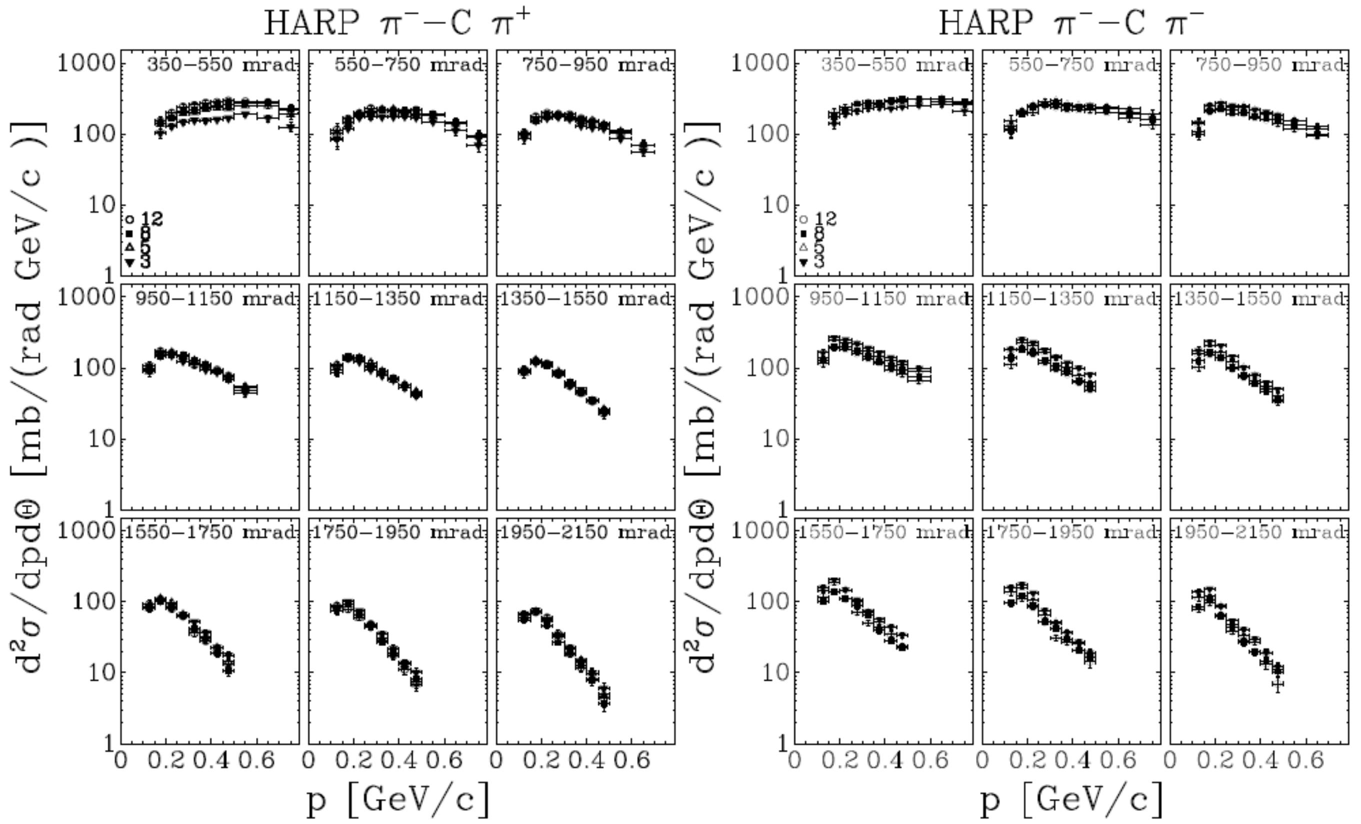


Comparison with MC at Large Angle

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\
3. Comparison with GiBUU seems better

New LA data with incident π^{+-}





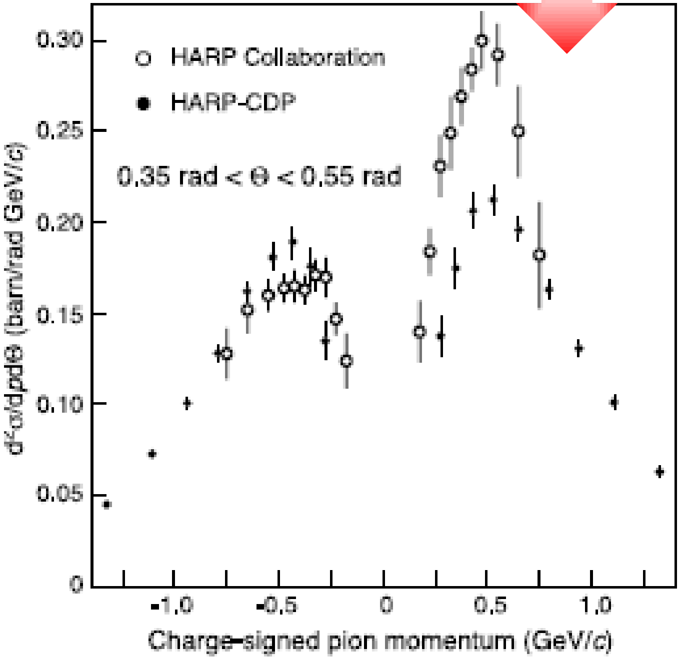
- ❑ π^{+-} A-> π^{+-} X data published for A=Be,C,Al,Sn,Cu,Ta,Pb
- ❑ comparisons with GEANT4/MARS MC
- ❑ for more details see HARP Collaboration, arXiv 0907.1428

HARP-CDP splinter group (F.Dydak et al.)

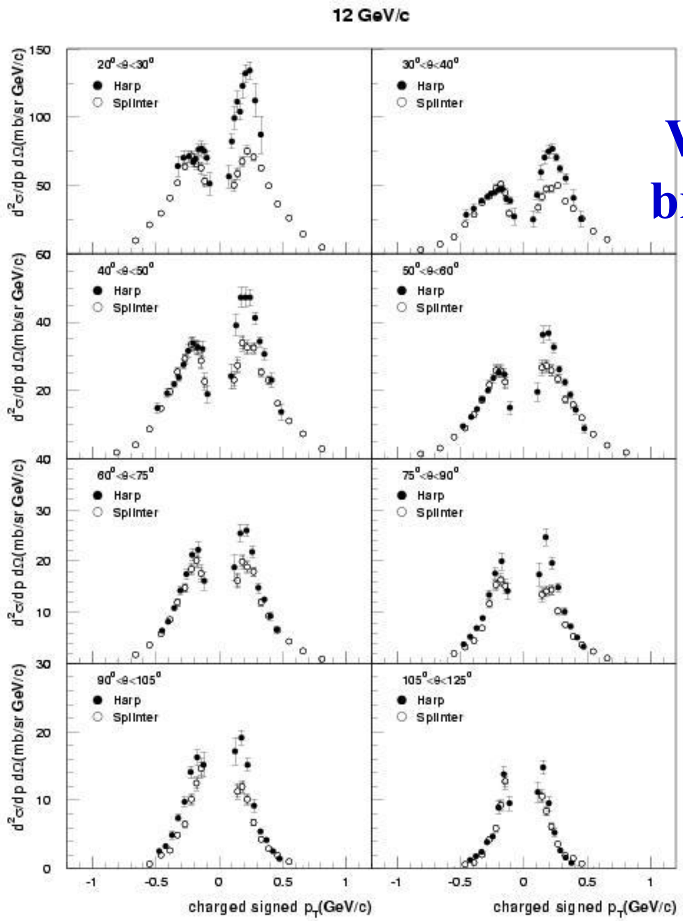
The systematic precision of our inclusive cross-sections is at the few-per-cent level, from errors in the normalization, in the momentum measurement, in particle identification, and in the corrections applied to the data.

Houston we have a problem (from WEB: originally reporting of a life threatening fault. Now humorously used to report ANY problem

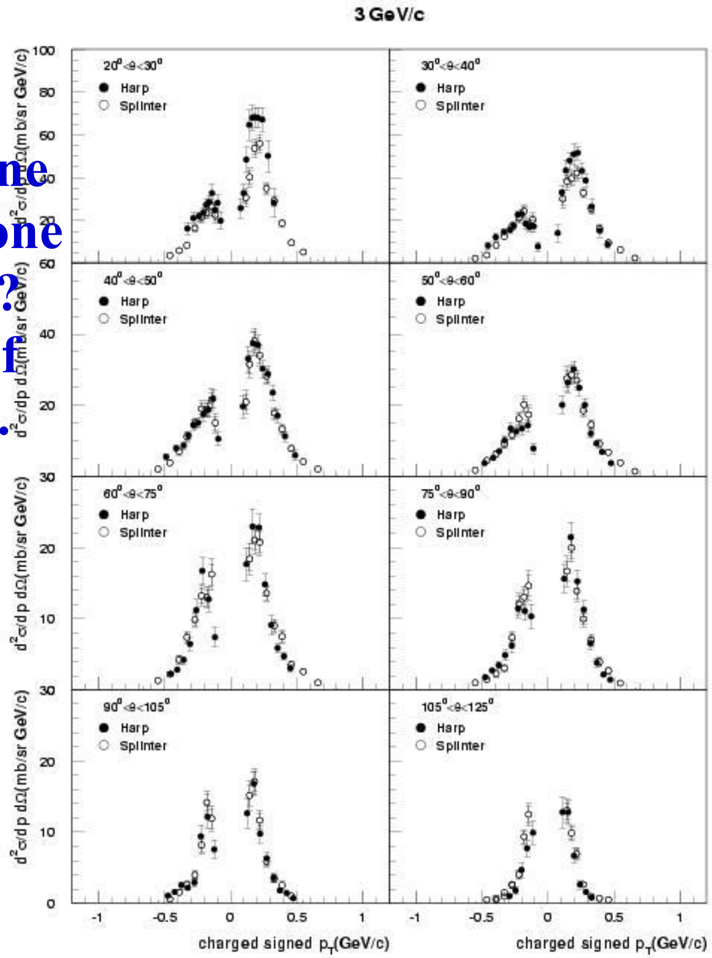
We conclude that claims and results published by OH [5–8, 25, 32–34, 36–38] suffer from systematic biases and shortcomings that are absent in our analyses presented in this and forthcoming papers.



Well … let’s have a look, take p-Be data



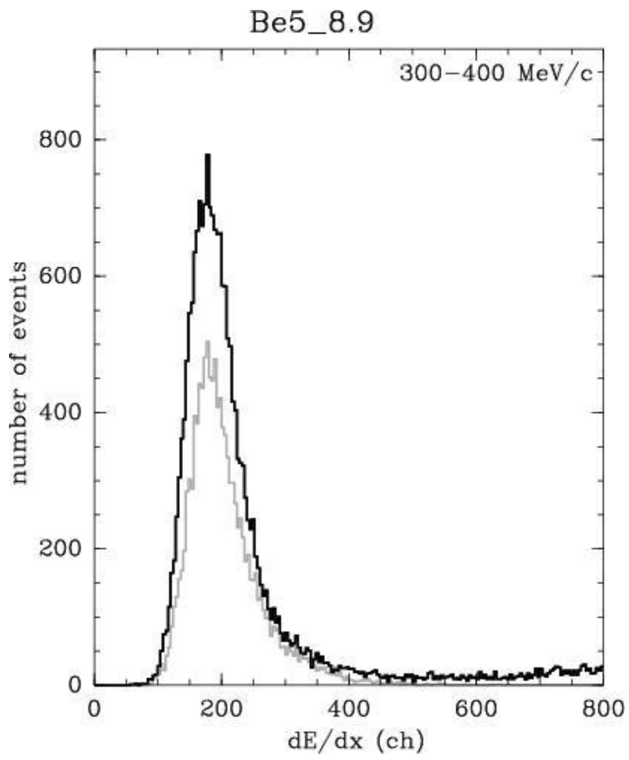
Why only that one bin ? and at the one at high energy ? Other dozens of similar plots …



Just remind: quark’s counting rules

In addition “**a few % systematic error** ,, may be largely underestimated (for a TPC with many problems) …. (we are at ~10%)

And what about raw data ?



- Simple cross-check in the region 300-400 MeV/c (where background are negligible) for thin Be at 8.9 GeV/c
- π/p separation is large (difficult to make errors)
- Momentum resolution ~ 10-15%
- other corrections (efficiences, backgrounds …) similar
- $R_{raw}=N_{\pi+}/N_{\pi-}=1.52+-0.10$

 published HARP results 1.55+- 0.10

Conclusions are left to the reader …

3. Realistic production targets

In practice neutrino beams production targets are not thin:

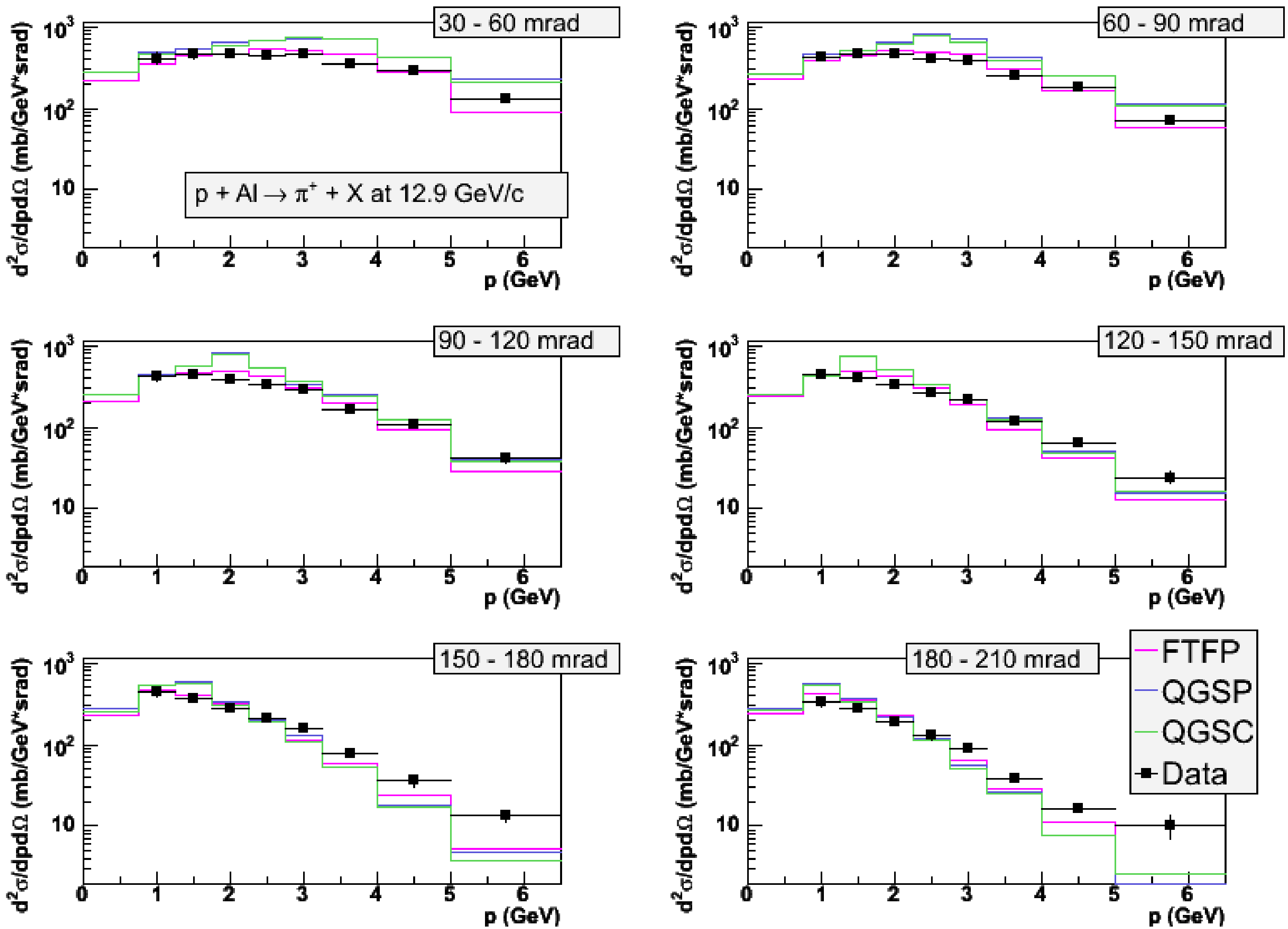
Cascade calculations or dedicated measurements with "replica targets" are needed.

HARP has taken, albeit with somewhat lower statistics, and analysed **p+A, π^++A and π^--A** data at different beam momenta with 100% λ_{int} targets (for K2K and MiniBOONE experiments).

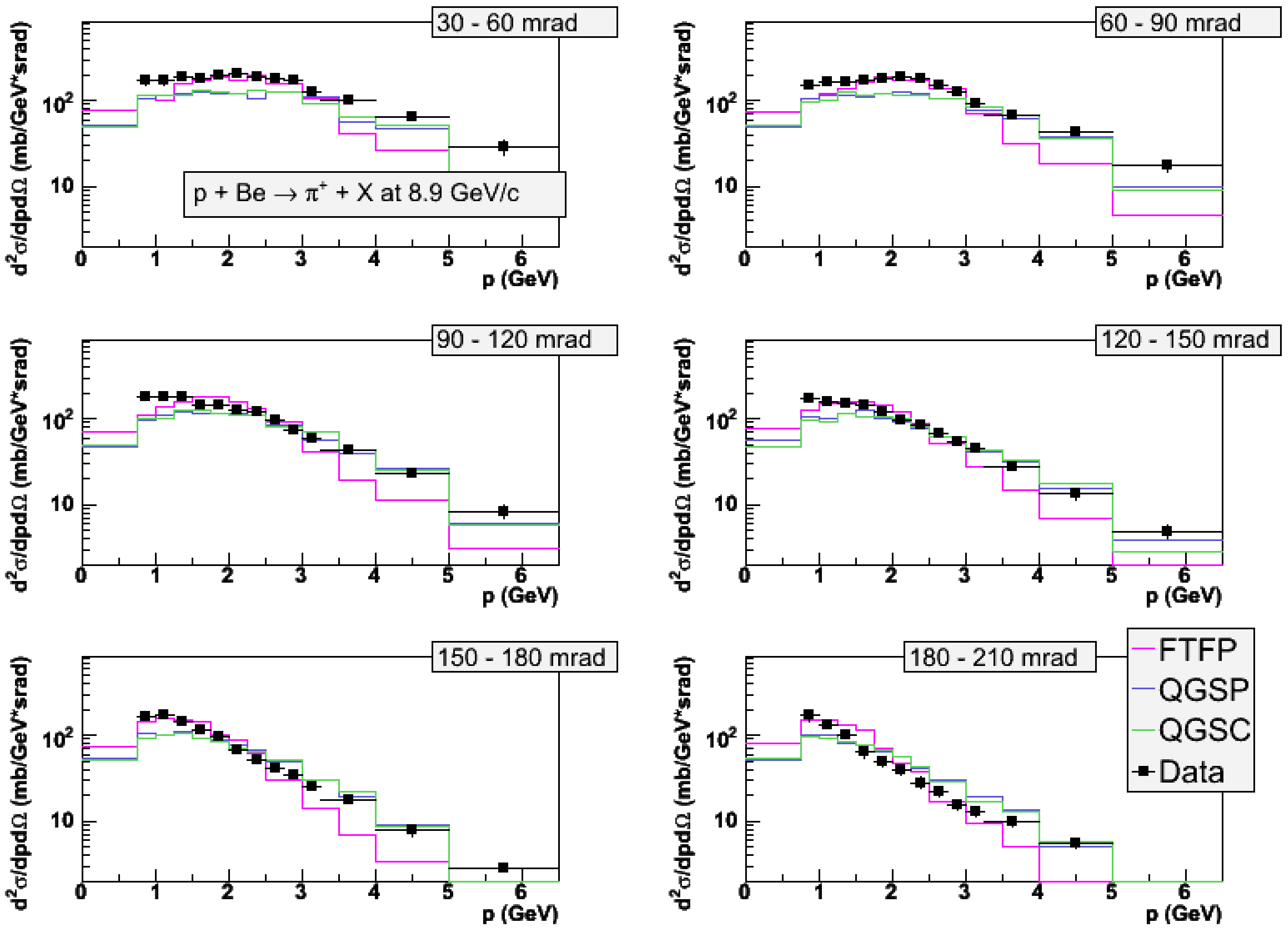
They can be used for complete parametrizations or tuning of models.

Preliminary spectra available

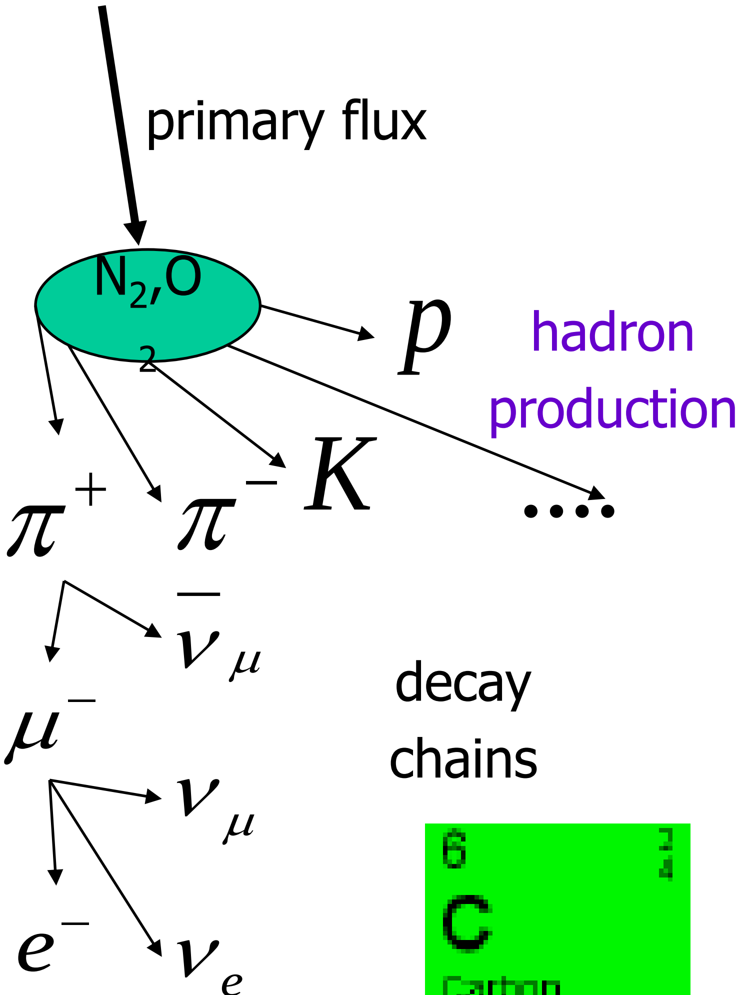
p+Al versus GEANT4

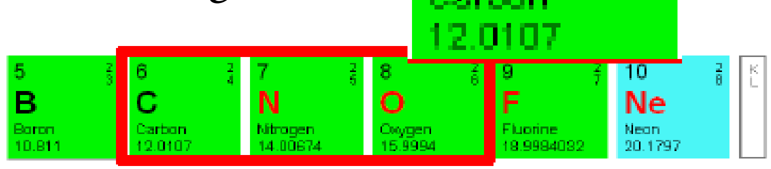


p+Be versus GEANT4

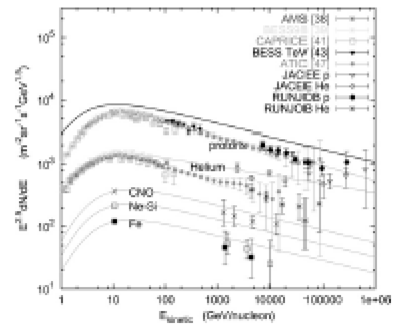


4. Atmospheric ν flux





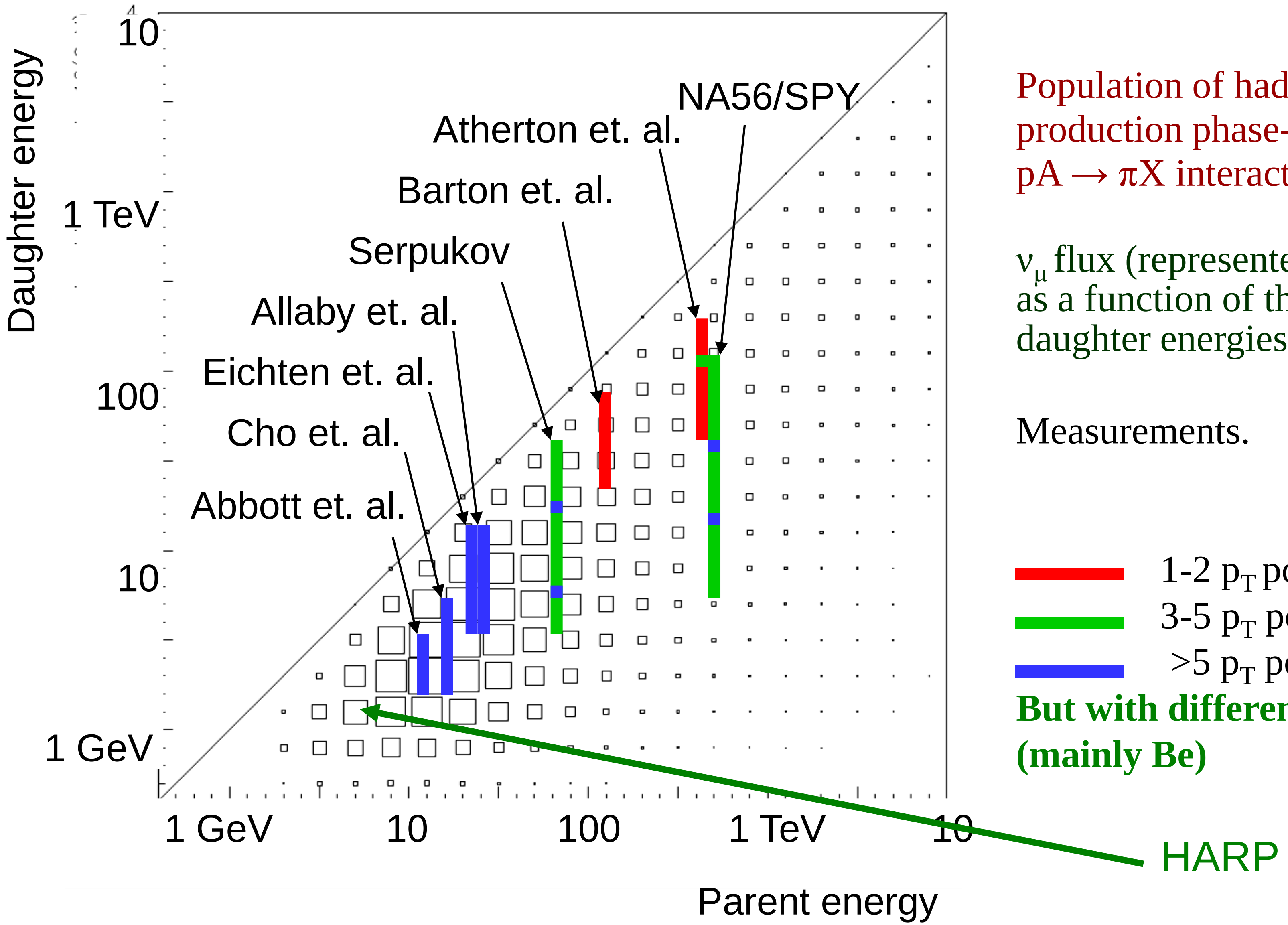
- Primary flux (70% p, 20% He, 10% heavier nuclei) is now considered to be known to better than 15% (AMS, Bess p spectra agree at 5% up to 100 GeV, worse for He)



- 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

Hadron production experiments



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

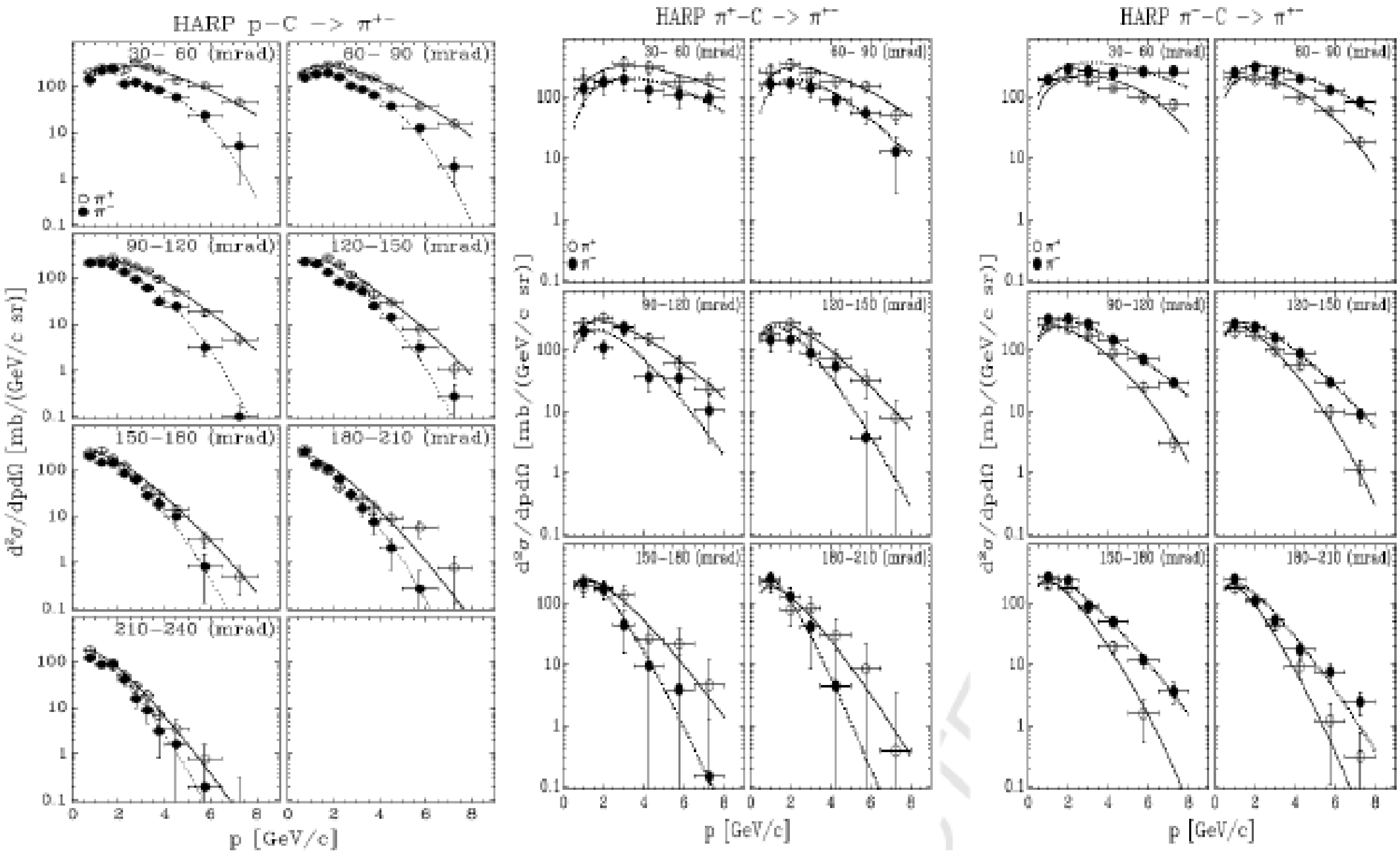
ν_μ flux (represented by boxes) as a function of the parent and daughter energies.

Measurements.

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

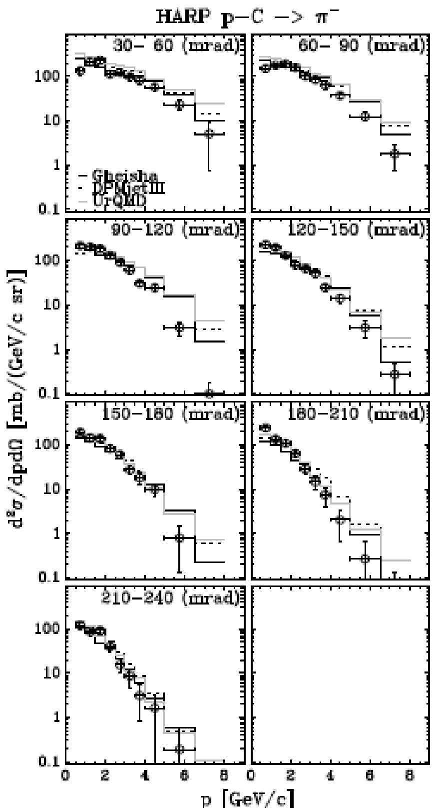
But with different targets (mainly Be)

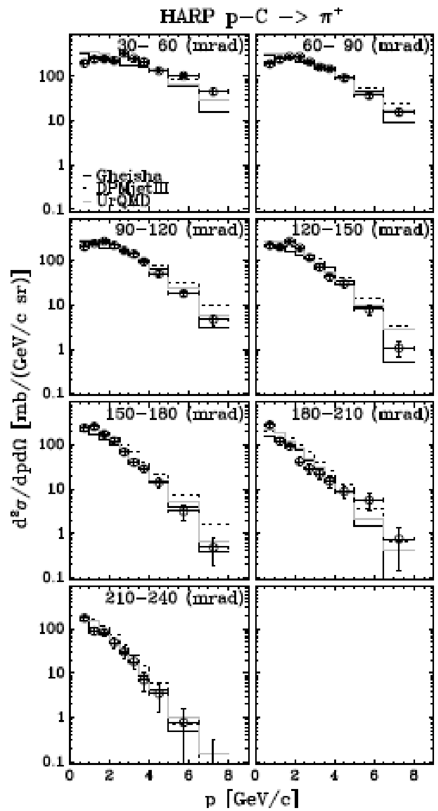
Harp: p,π^{+-}+ C at 12 GeV/c data

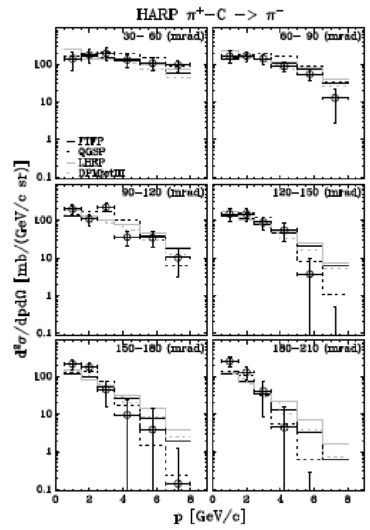


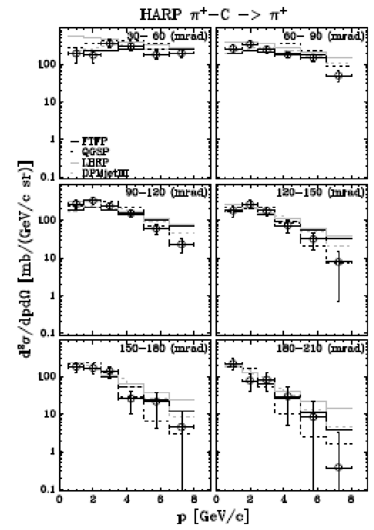
SW parametrization superimposed

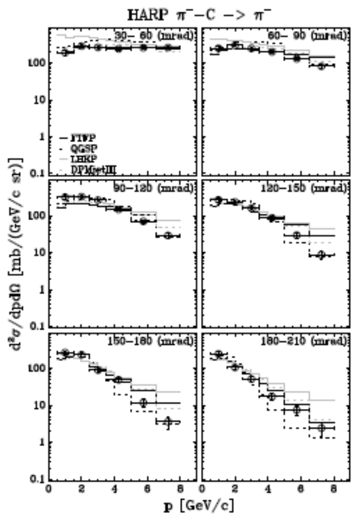
Model comparison

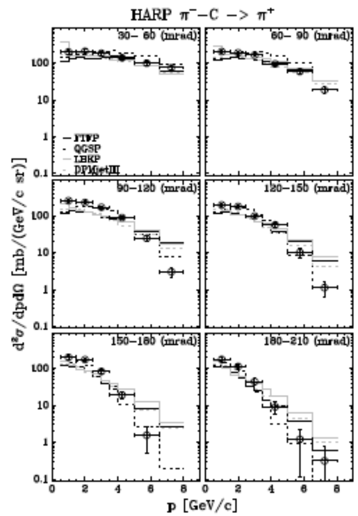




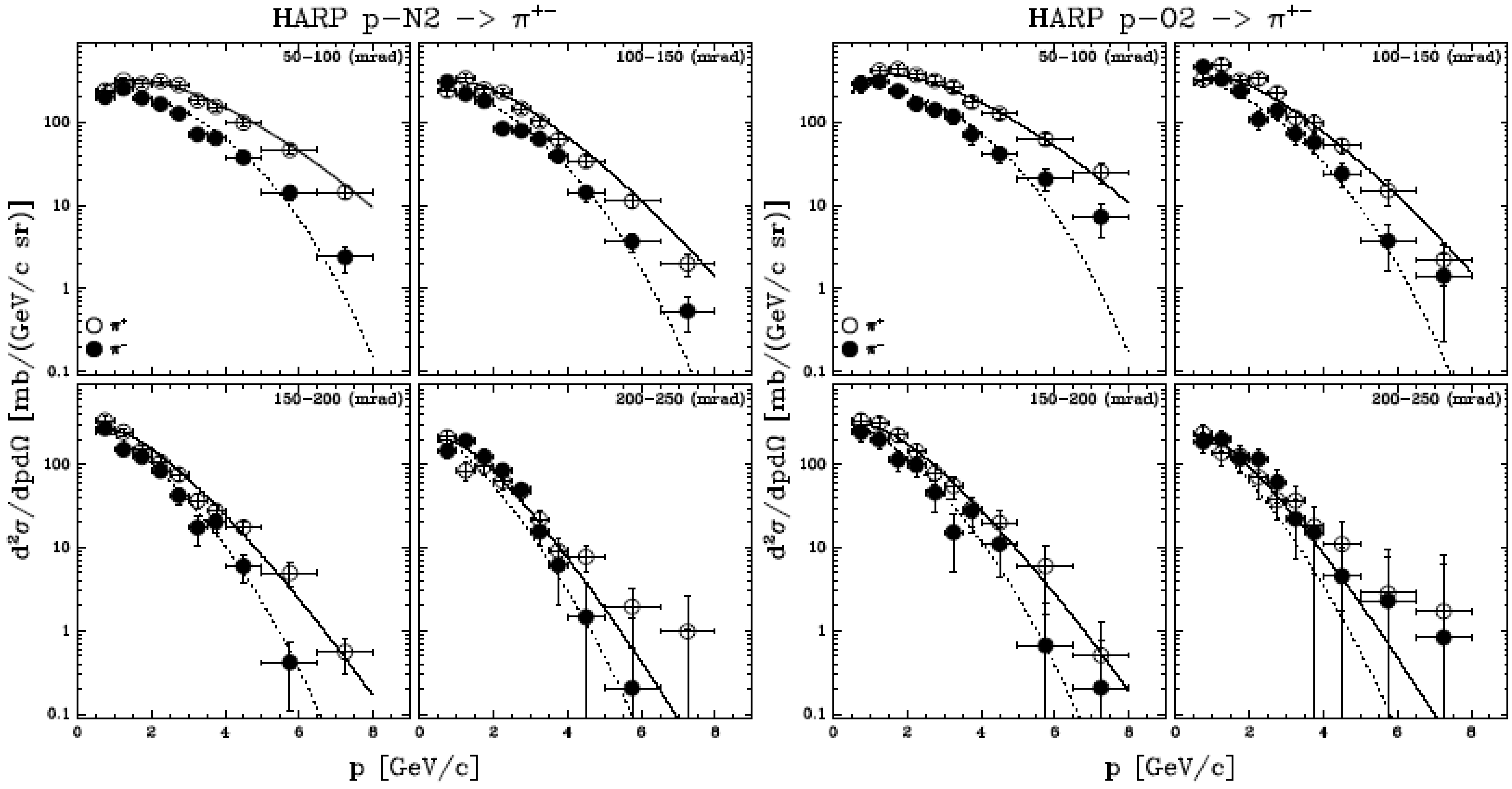






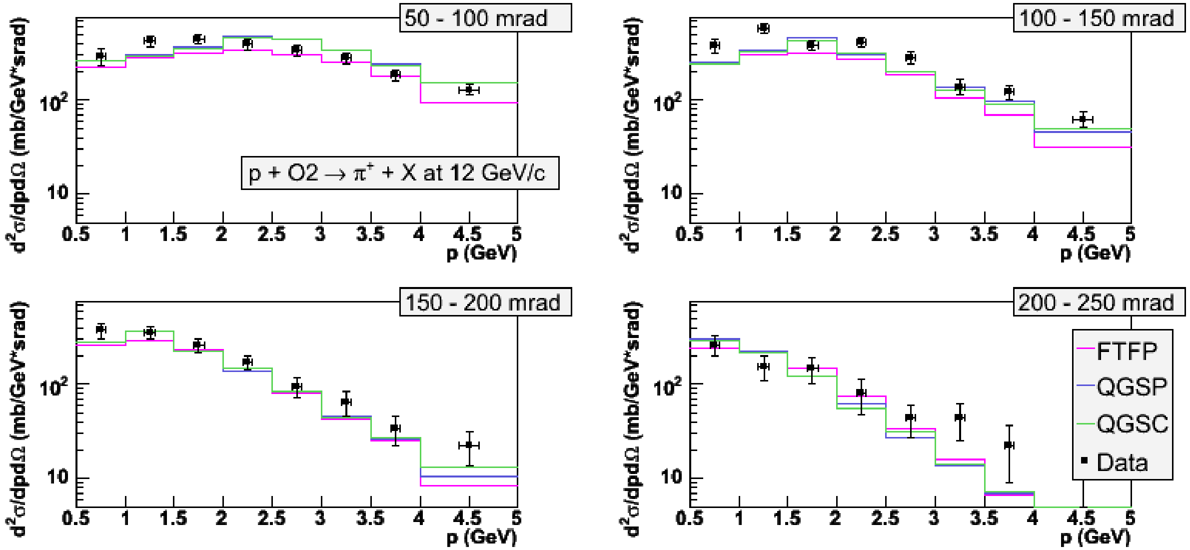


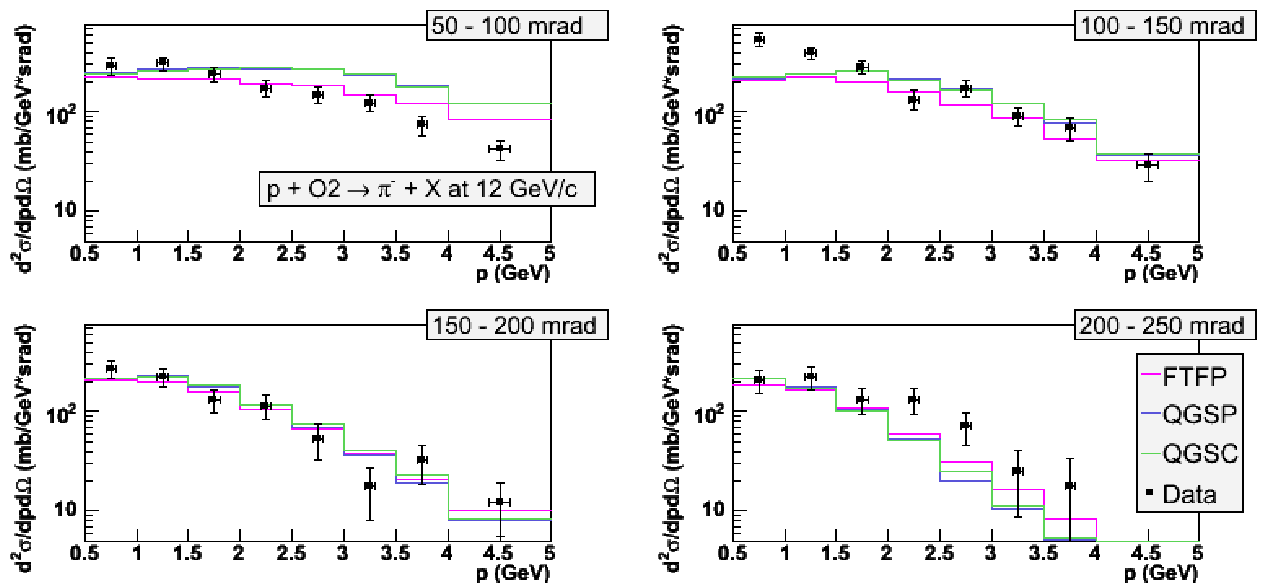
Measurements with N_2,O_2 cryogenic targets



HARP results confirm that p-C data can be used to predict p-N_2 and p-O_2 pion production

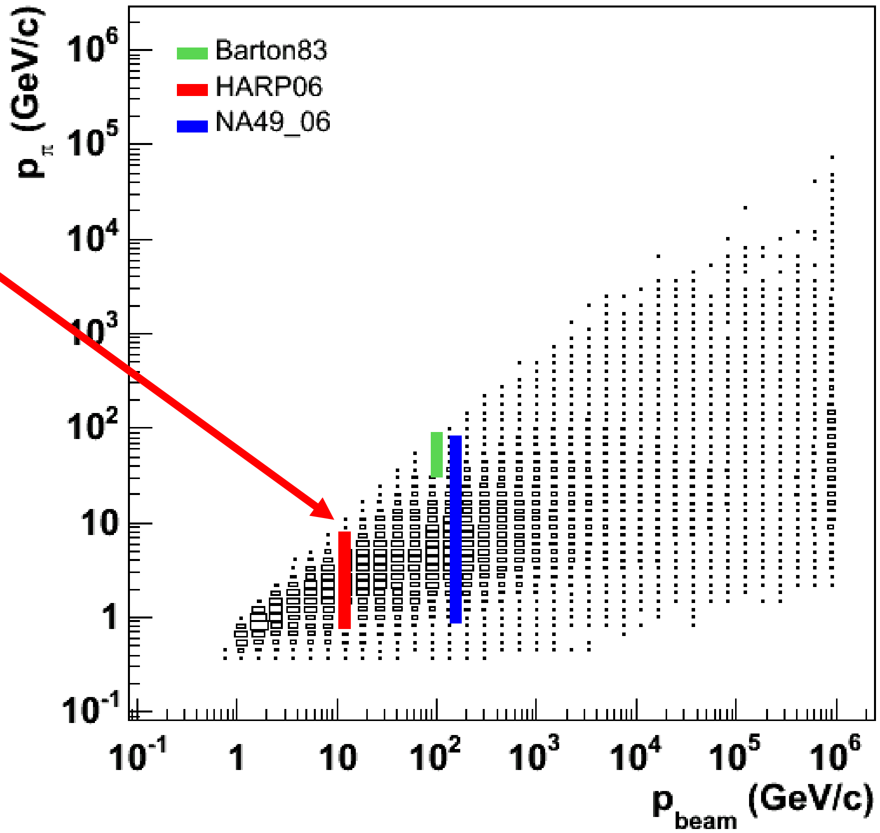
Comparison with GEANT4





Covered phase space region

- New data sets
  (p-C, π^+–C and π^-–C,
  p-O_2, p-N_2 at 12 GeV/c)
- Important phase space region covered
- Data available for model tuning and simulations



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

Harp Published physics results

Measurement of the production cross-section of positive pions in p-Al collisions at 12.9 GeV/c, Nucl.Phys. **B732** (2006) 1

Measurement of the Production of Charged Pions by Protons on a Tantalum Target, Eur. Phys. J. **C51** (2007) 787, [arXiv:0706.1600].

Measurement of the production cross-section of positive pions in the collision of 8.9GeV/c protons on beryllium, Eur. Phys. J. **C52** (2007) 29, [hep-ex/0702024].

Large-angle production of charged pions by 3 GeV/c-12 GeV/c protons on carbon, copper and tin targets , Eur. Phys. J. **C53** (2008) 177, [arXiv:0709.3464]

Large-angle production of charged pions by 3 GeV/c-12.9 GeV/c protons on beryllium, aluminium and lead targets, EPJ **C54** (2008) 37, [arXiv: 0709.3458]

Measurement of the production cross-sections of $\pi^{\pm}$ in p-C and $\pi^{\pm}$ -C interactions at 12 GeV/c, Astr. Phys. 29 (2008) 257, [arXiv: 0802.0657]

Forward $\pi^{\pm}$ production in p-O_2 and p –N_2 interactions at 12 GeV/c, Astr. Phys. 30 (2008) 124, [arXiv: 0807.1025]

*Large-angle production of charged pions with incident protons on nuclear targets as measured in the Harp experiment, Phys. ReV. **C77** (2008)055207*, [arXiv: 0805.2871]

*Forward production of charged pions with incident $\pi^{\pm}$ on nuclear targets as measured at CERN PS, Nucl. Phys. **A821** (2009) 118* [arXiv: 0902.2105]

Conclusions

- 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 (but not negligible) total errors (syst+stat < 15 %).

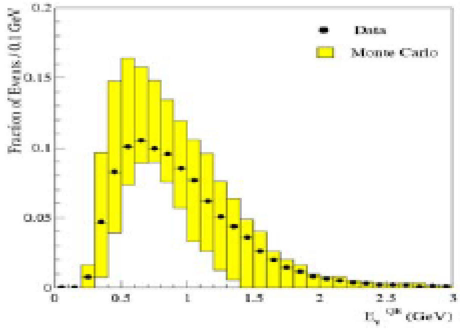
Nine physics paper published plus another two submitted

- <u>More HARP results coming</u> : forward production with incident pions; production with long targets, …

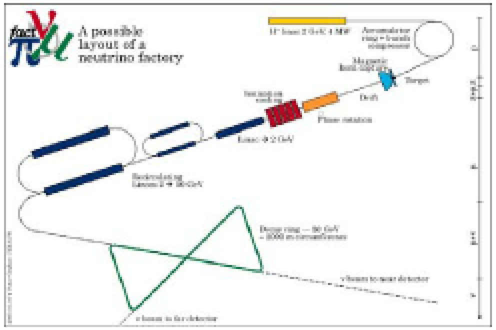
- Comparison with available MC show some problems

Backup material

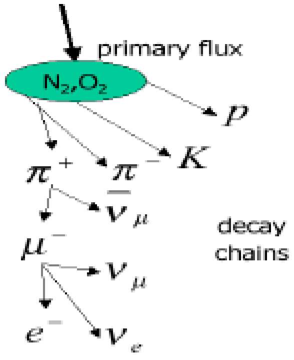
Harp physics goals



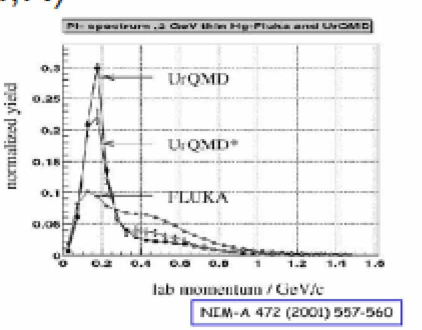
Input for prediction of neutrino fluxes for the **K2K** and **MiniBooNE / SciBooNE** accelerator experiments



Pion/Kaon yield for the design of the proton driver and target system of **Neutrino Factories** and **Super-Beams**

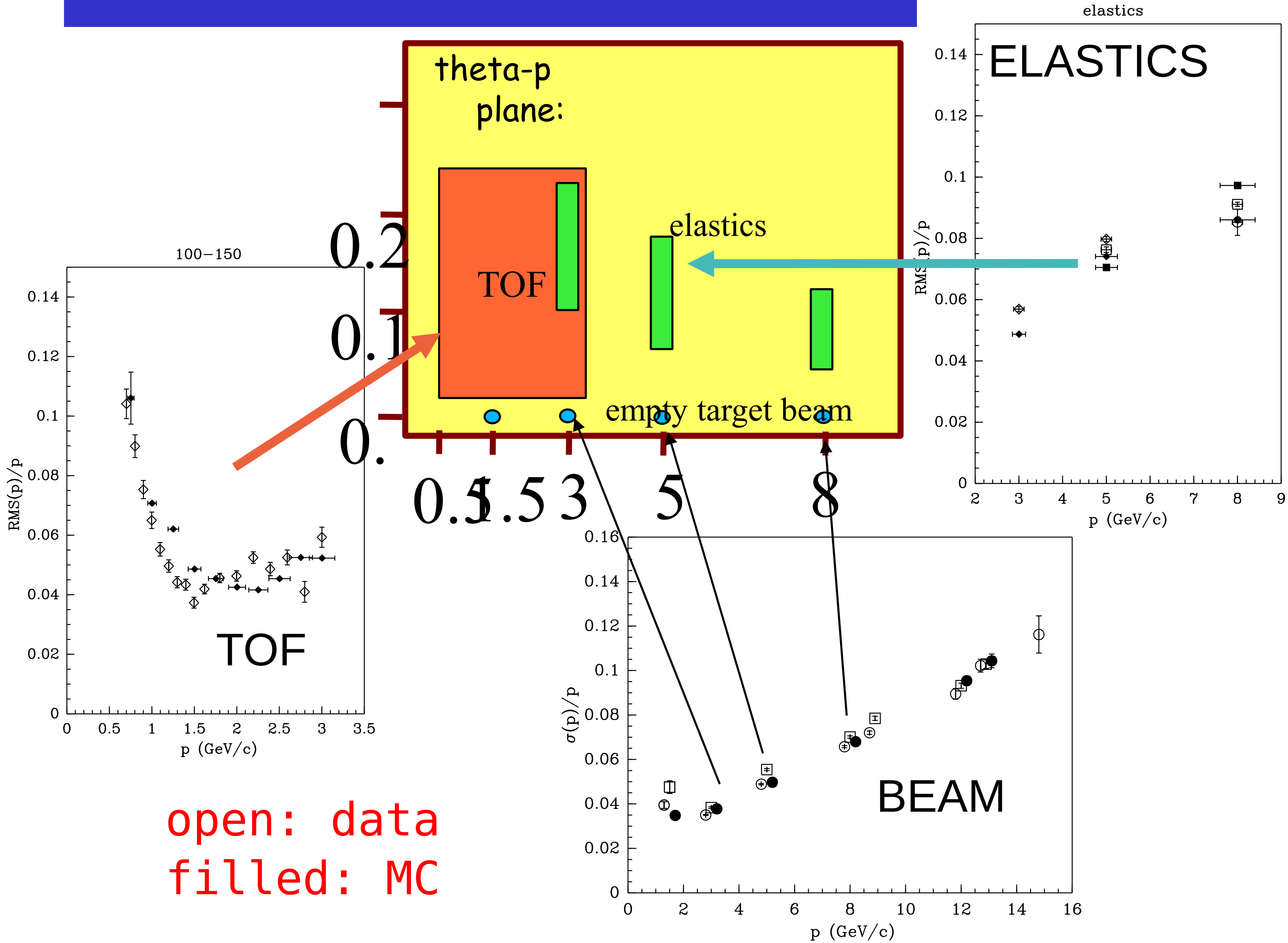


Input for precise calculation of the **atmospheric neutrino** flux (from yields of secondary π,K)



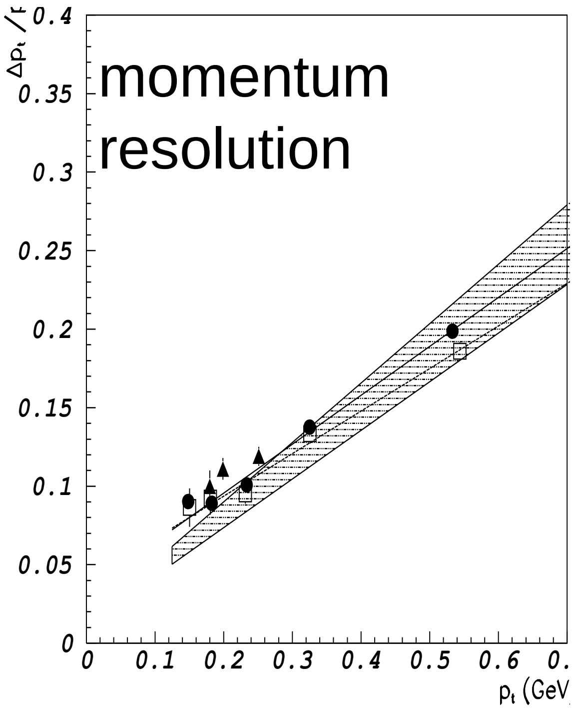
Input for **Monte Carlo** generators (GEANT4 and others)

Momentum Resolution



open: data
filled: MC

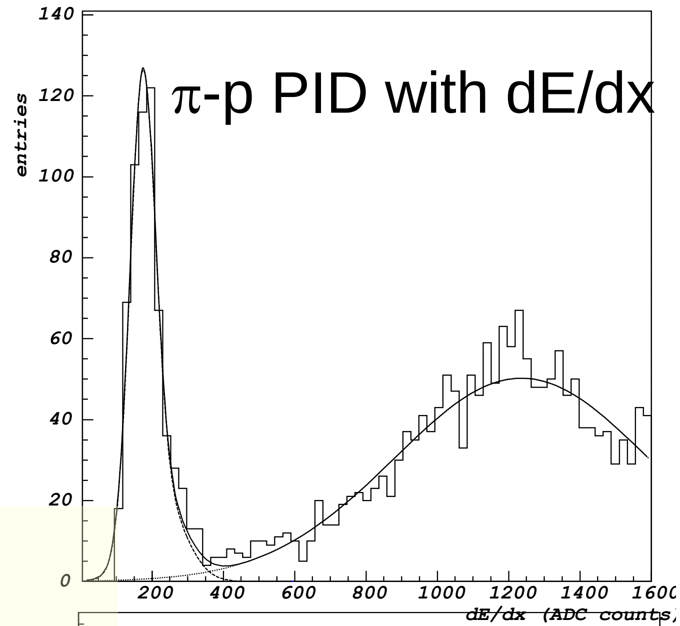
Spectrometer performance

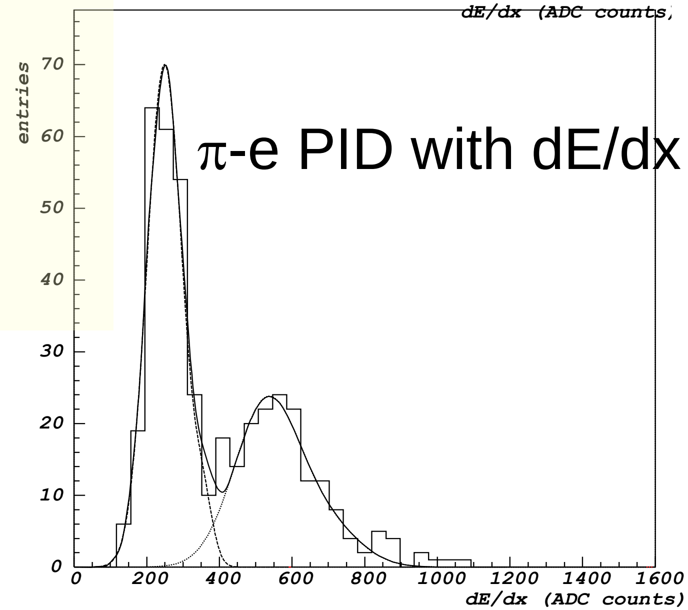


momentum
calibration:
cosmic rays
elastic scattering

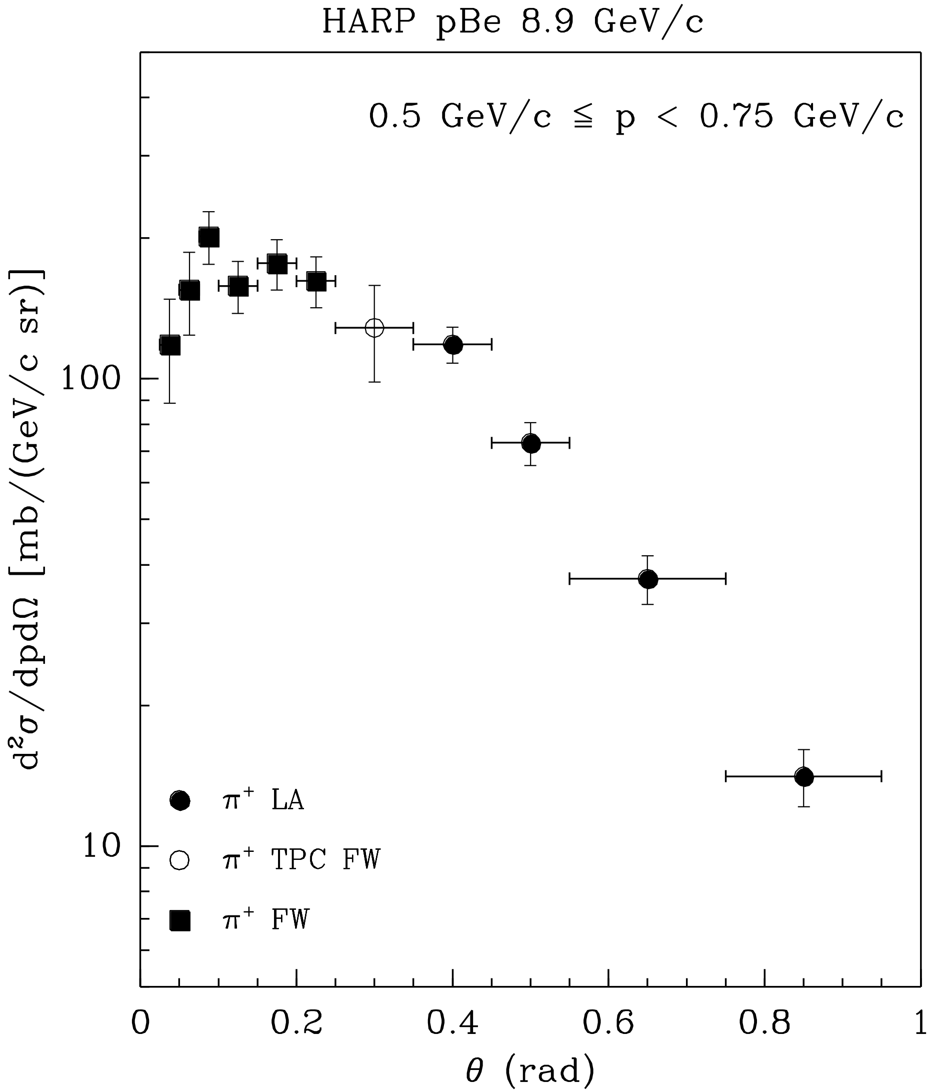
elastic scattering:
absolute calibration of
efficiency
momentum
angle
(two spectrometers!)

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





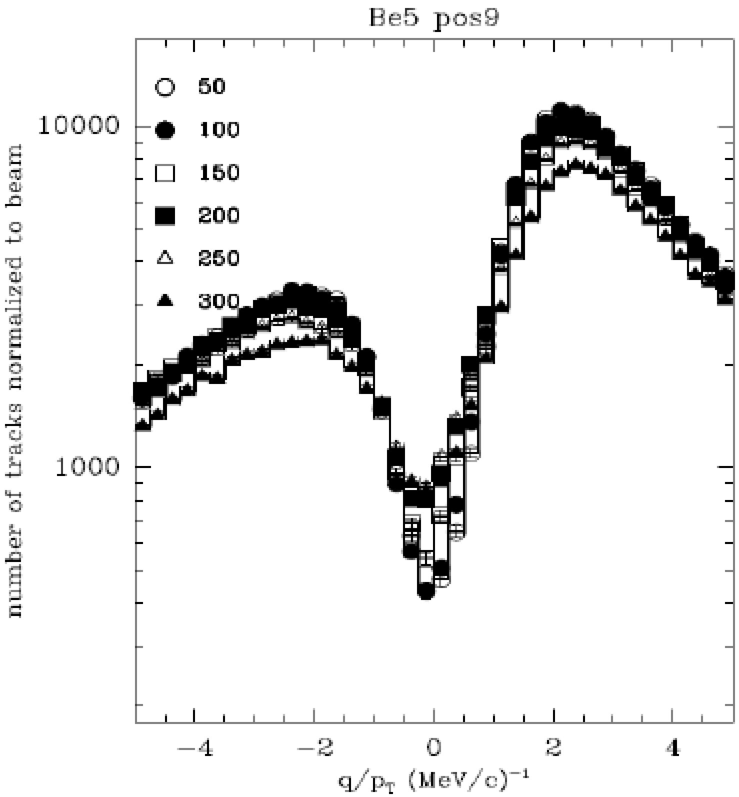
The two spectrometers match each other



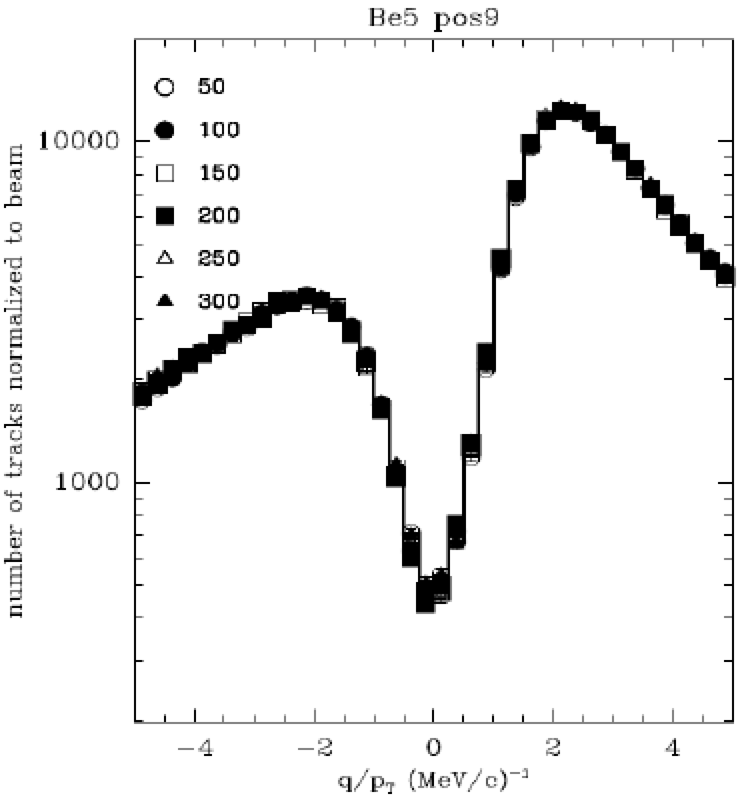
Harp TPC: corrections for dynamic distortions

arXiv:0903.4762 [physics.ins-det]

before



after



Analyses of full data sample

Phys. Rev. C 77 (2008) 055207