SPY

A. Marchionni, Fermilab

Flux Measurement and Determination in the Intensity Frontier Era Neutrino Beams, Pittsburgh, December 2012

- **Secondary Particle Yield (SPY) from 450 GeV/c protons on beryllium targets**
  - almost 15 year old experiment!
  - motivations, experimental strategy
  - no details on instrumentation, analysis procedures…
- **Direct use of the SPY data**
  - flux predictions for WANF and CNGS neutrino beams at CERN
- **x_F, p_T parameterization of the hadronic invariant cross section based on SPY and Atherton *et al* data (BMPT)**
- **Use and limitations of the BMPT parameterization**

Some history....

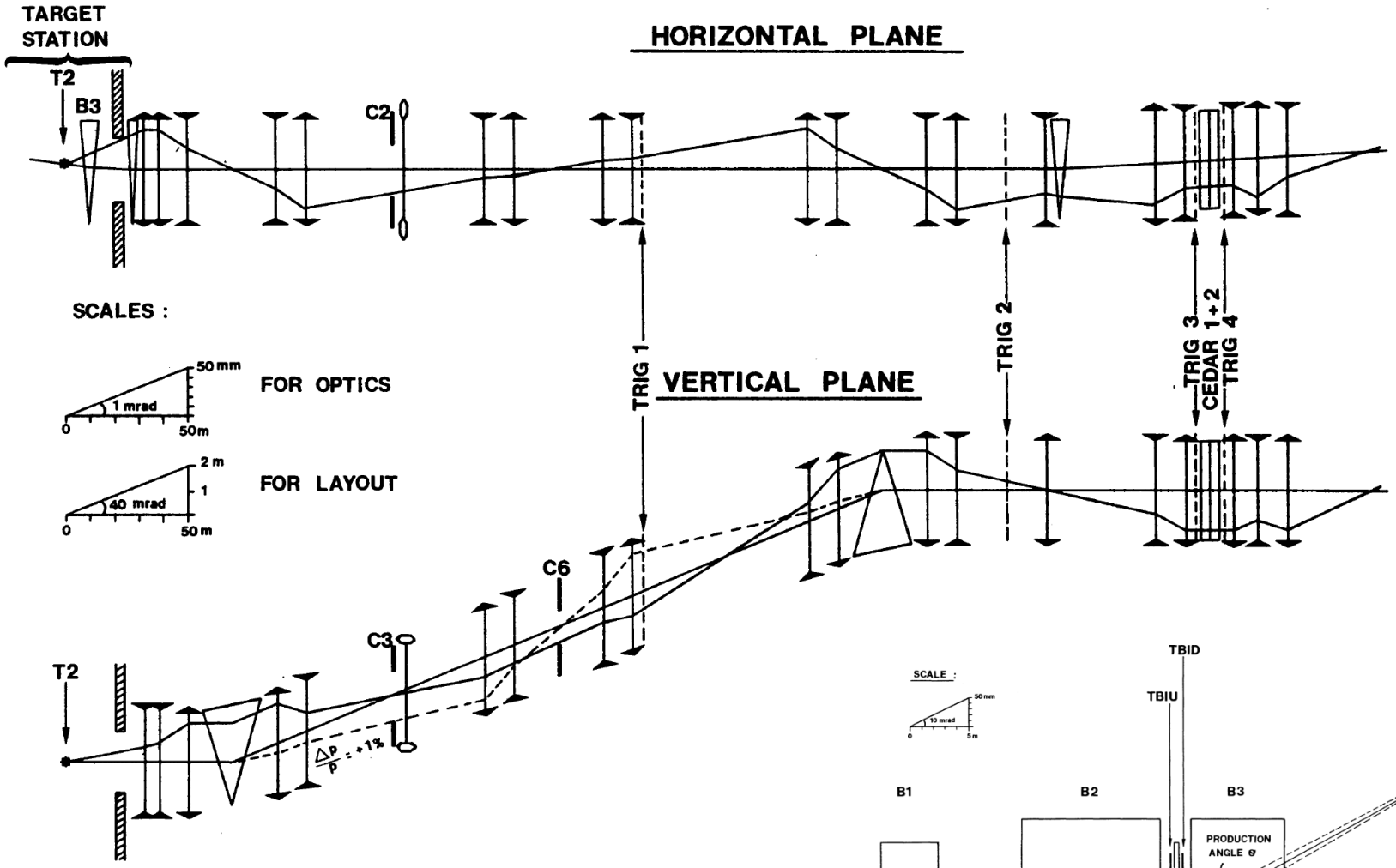
CERN 80-07
Super Proton
Synchrotron Division
22 August 1980

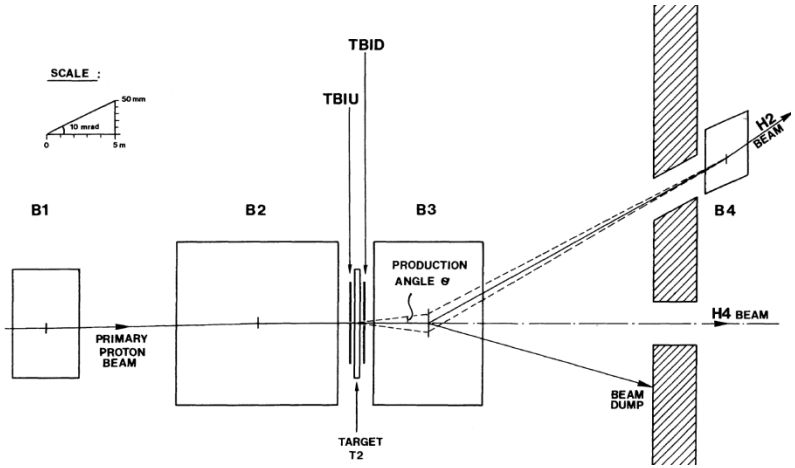
PRECISE MEASUREMENTS OF PARTICLE PRODUCTION
BY 400 GeV/c PROTONS ON BERYLLIUM TARGETS

H.W. Atherton, C. Bovet, N. Doble, G. von Holtey, L. Piemontese,
A. Placci, M. Placidi, D.E. Plane, M. Reinharz and E. Rossa

In addition to the intrinsic interest of particle production measurements, a good knowledge of the production of secondary hadrons by 400 GeV/c protons striking beryllium targets is needed in order to calculate, with high precision, the shape of the CERN neutrino-beam spectra. In particular, a good measurement of the K/π ratio of production cross-sections at various energies and production angles is essential[1)].

Single arm spectrometer on the H2 line



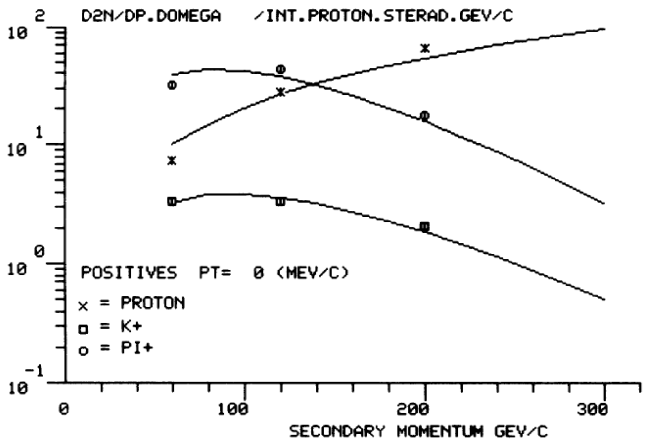


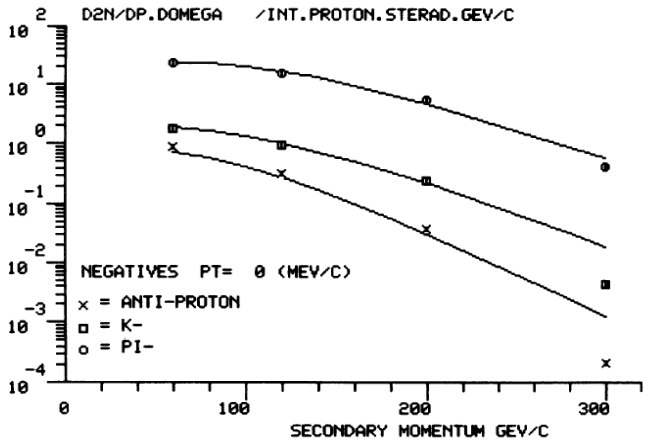
H.W. Atherton et al, CERN 80-07

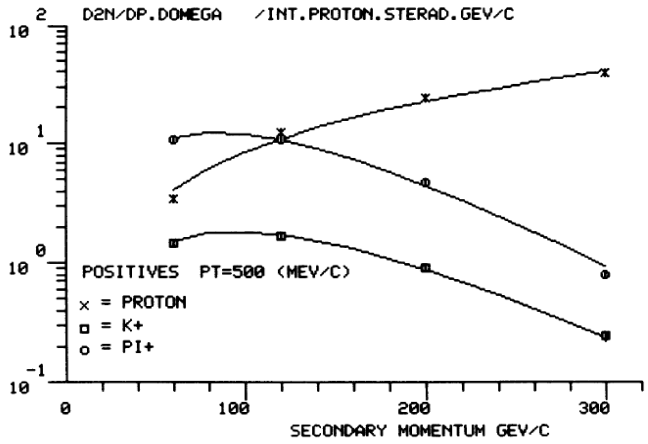
ABSTRACT

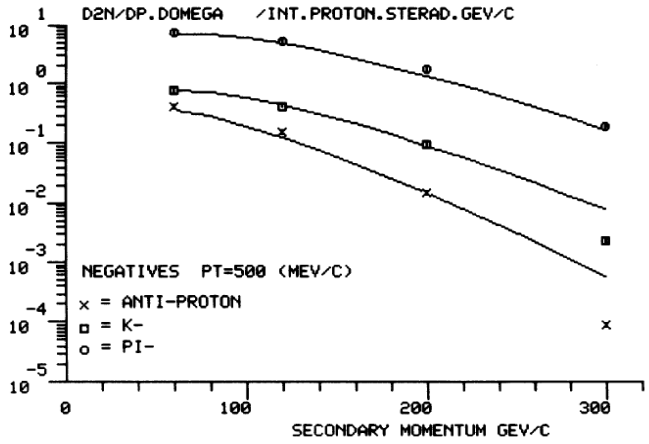
Results are given for beam composition and absolute production cross-sections in proton-beryllium collisions at 400 GeV/c. Measurements have been made on positive and negative particles at four momenta (60, 120, 200, and 300 GeV/c), two transverse momenta (0 and 500 MeV/c), and for three target lengths (100, 300, and 500 mm). Production cross-sections are derived from measurements on a short (40 mm) target.

H.W. Atherton et al, CERN 80-07









$$\frac{d^2N}{dpd\Omega} = A\left[\frac{B}{p_0}\, e^{-Bp/p_0}\right]\left[\frac{2Cp^2}{2\pi}\, e^{-C(p\theta)^2}\right]$$

	A	B	C
π^+	1.2	9.5	5.0
π^-	0.8	11.5	5.0
K^+	0.16	8.5	3.0
K^-	0.10	13.0	3.5
$\bar{p}$	0.06	16.0	3.0

$$\frac{d^2N}{dpd\Omega} = A\left[\frac{(B+1)}{p_0}\left(\frac{p}{p_0}\right)^B\right]\left[\frac{2Cp^2}{2\pi}\, e^{-C(p\theta)^2}\right]$$

	A	B	C
p	0.8	−0.6	3.5

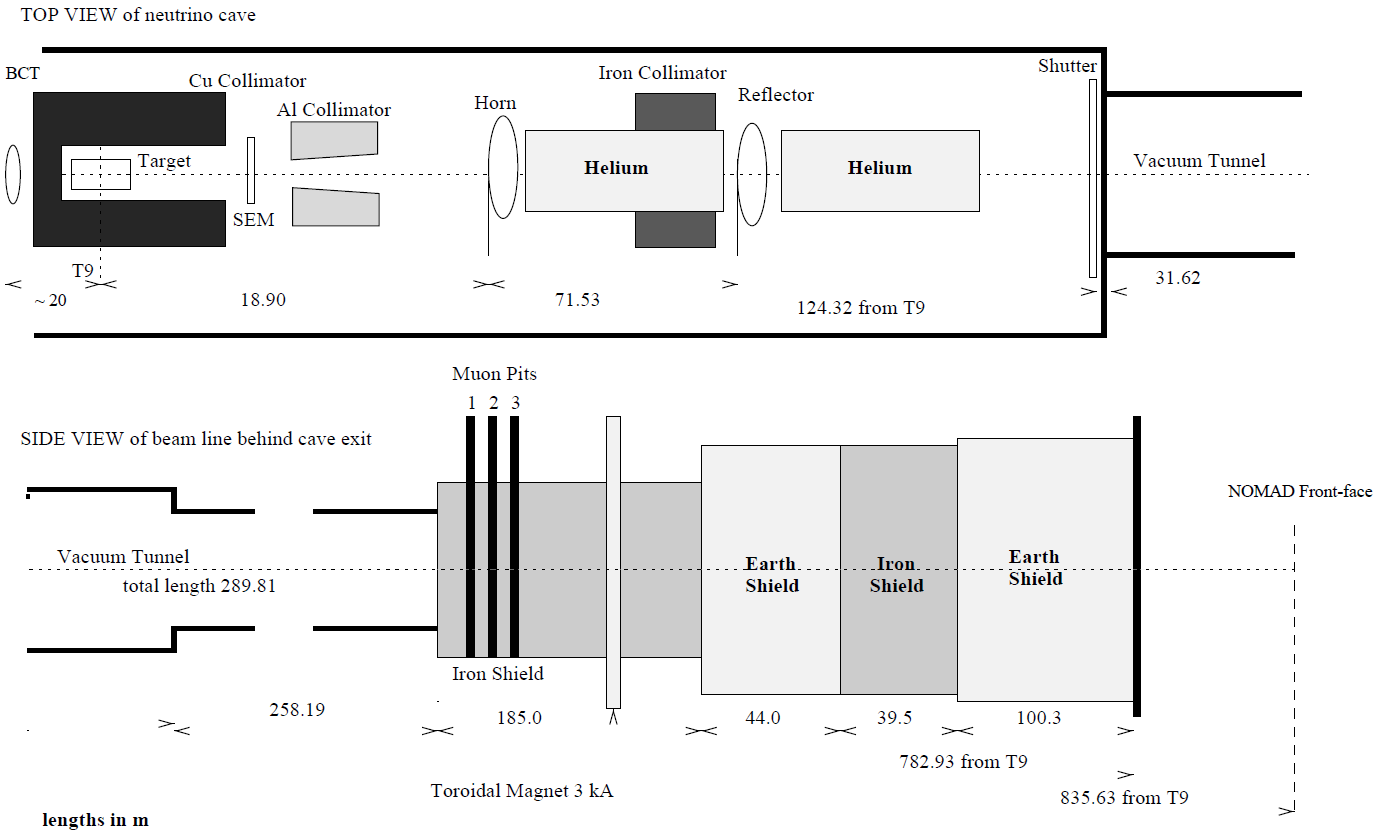
SPY

- **In the second half of 90's**
  - to cover the lower momentum range of secondary particles
  - in support of neutrino flux prediction of the reconfigured WANF for the NOMAD & CHORUS experiments
  - also motivated by an idea of a lower energy neutrino beam (E_ν~6 GeV) with a LAr TPC detector for a short baseline $\nu_\mu \rightarrow \nu_\tau$ and $\nu_\mu \rightarrow \nu_e$ oscillation experiment (M. Bonesini et al, SPSLC/I205)

Eur. Phys. J. C 10, 605–627 (1999)

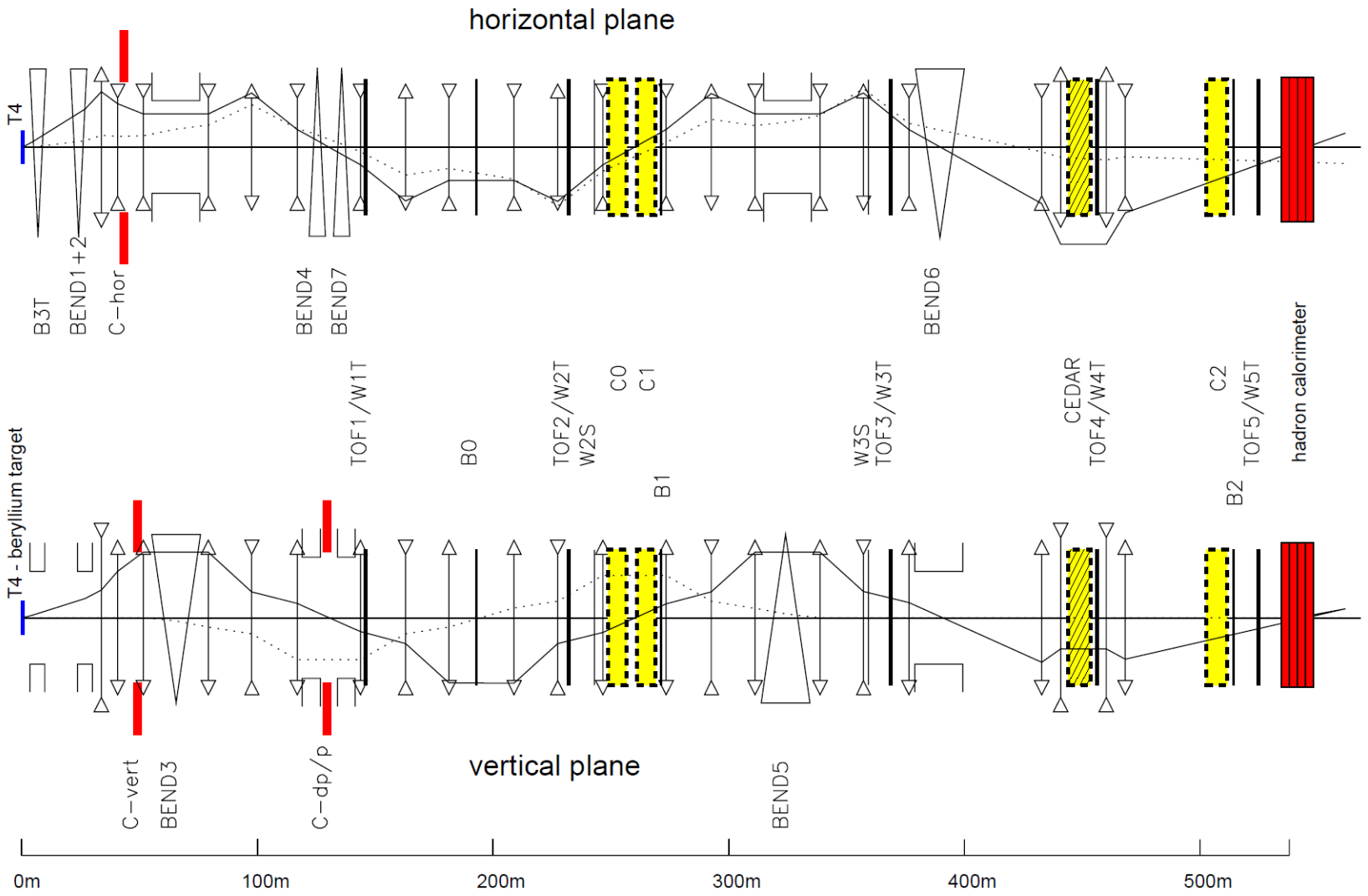
Abstract. This paper presents the results on charged particle yields and production ratios as measured by the NA56/SPY experiment for 450 GeV/c proton interactions on beryllium targets. The data cover a secondary momentum range from 7 GeV/c to 135 GeV/c and p_T values up to 600 MeV/c. An experimental accuracy on the measured yields in the range from 5% to 10%, depending on the beam momentum, and around 3% for the particle production ratios has been achieved. These measurements are relevant for a precise evaluation of fluxes and composition of neutrino beams at accelerators. Results on the target thickness and shape dependence are also reported. Inclusive invariant cross sections in the forward direction have been derived.

CERN WANF beam



- 450 GeV protons impinging on a beryllium target
- protons are extracted in two 4 ms long spills separated by 2.6 s
- the target is made up by 11 beryllium rods, 10 cm long and 3 mm in diameter, separated by 9 cm gaps

H6 beam spectrometer



Using NA52 spectrometer in the H6 beam line of North Area at CERN

Collected data on Beryllium targets

p/z (GeV/c)	Target	Angles (mrad)
+135	100,200,300 mm,T9	0
+67.5	100 mm	0
+40	100 mm	$-15, \pm 11.25, \pm 5.625, +3.75, +1.875, 0$
	T9	$-15, +5.625, 0$
	200,300 mm	0
+30	100 mm,T9	0
+20	100 mm,T9	0
+15	100 mm	$+30, +22.5, \pm 15, \pm 10, +5, 0$
	T9	$-15, +5, 0$
	200,300 mm	0
+10	100,200,300 mm,T9	0
+7	100 mm,T9	0
-67.5	100 mm,T9	0
-40	100 mm	$-15, -11.25, -5.625, \pm 3.75, \pm 1.875, 0$
	200,300 mm, T9	0
-15	100 mm	$-15, -5, 0$
	300 mm,T9	0
-10	100 mm	0
-7	100 mm,T9	0

T9: a 300mm thick target consisting of three Be rods of 100mm length and 3mm diameter interleaved by 90 mm of air

Experimental strategy

- **Trigger**
  - The trigger is based on two independent trigger signals formed at 268 m (trigger A=TOF2B1) and 505 m (trigger B=TOF4B2) downstream of the target. In addition, the information of the threshold Cherenkov counters are used in anti-coincidence to veto or downscale particles above threshold
- **Acceptance and transmission evaluation**

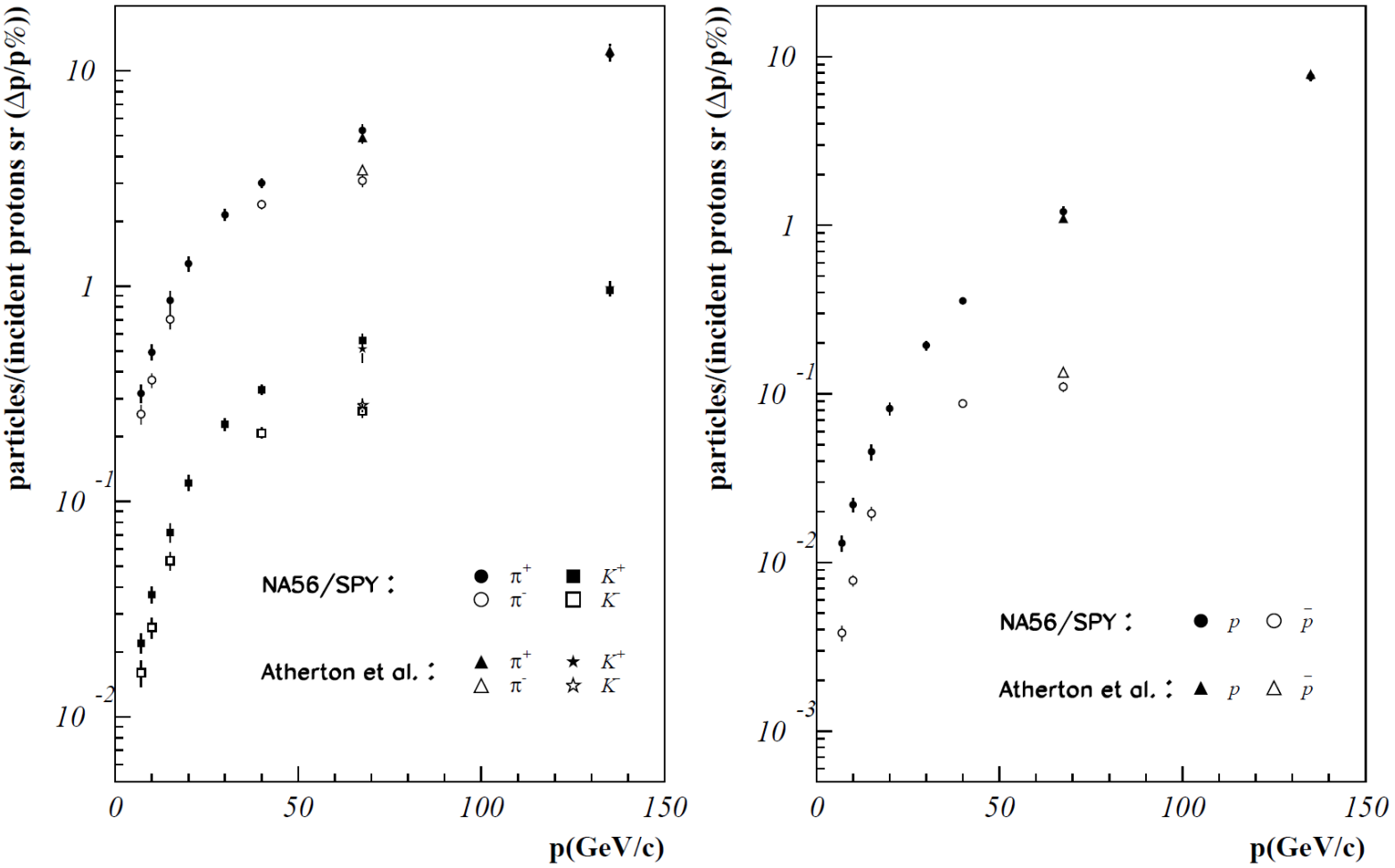
$$\mathcal{A} = \Delta\Omega \cdot (\frac{\Delta p}{p}) \cdot \mathcal{T}$$

  - the spectrometer acceptance has been derived with an accuracy between 5% and 10% depending on the beam momentum, dominated by the accuracy of the phase-space acceptance at high momenta and of the beam line transmission at low momenta
- **Correction for particle decay and determination of the beam momentum**
  - raw yields of secondary mesons are multiplied by a factor given by

$$f_\tau = \exp\left(\frac{L}{pc}\frac{mc^2}{c\tau}\right)$$

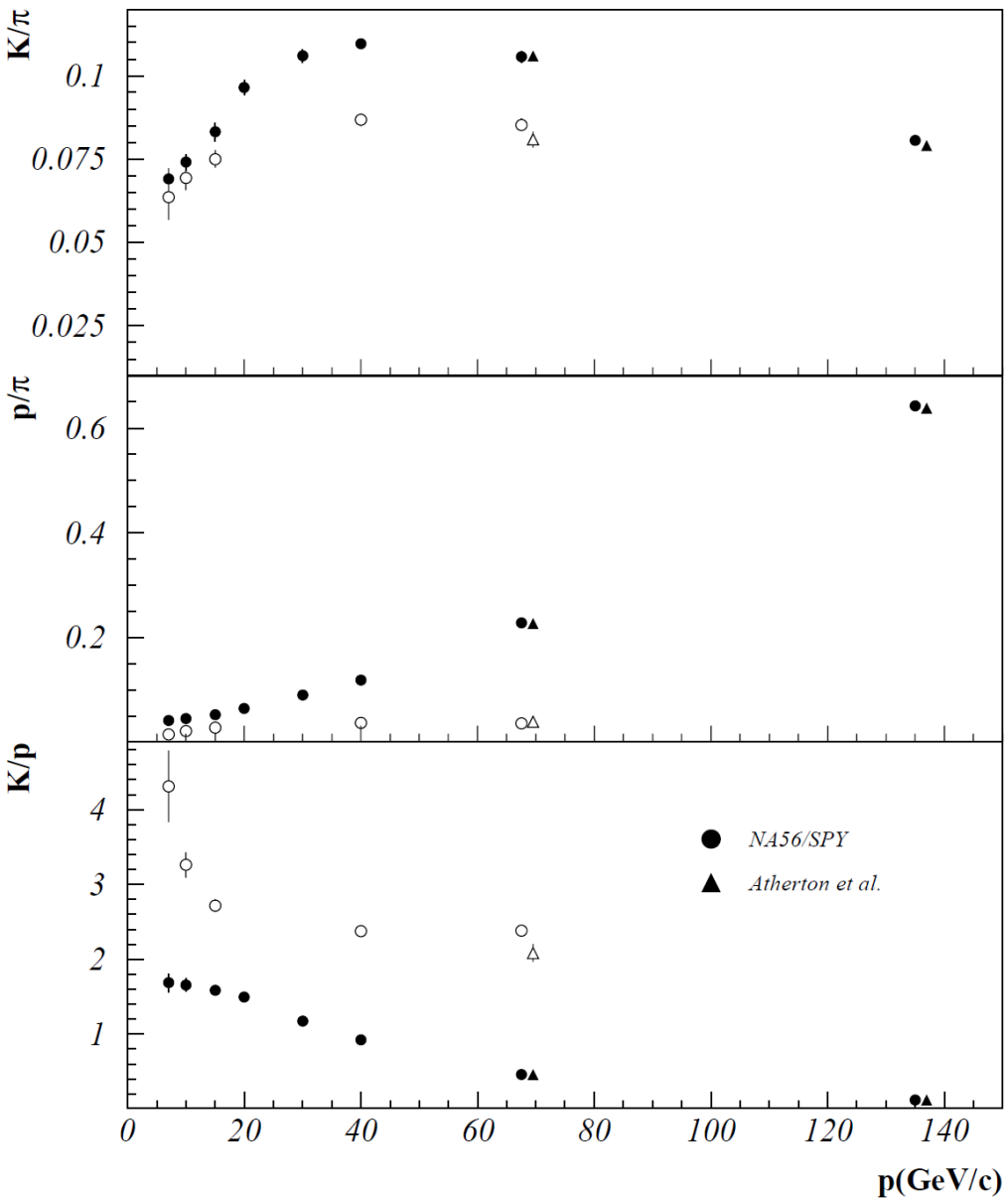
  - beam momentum determination by TOF

Particle yields



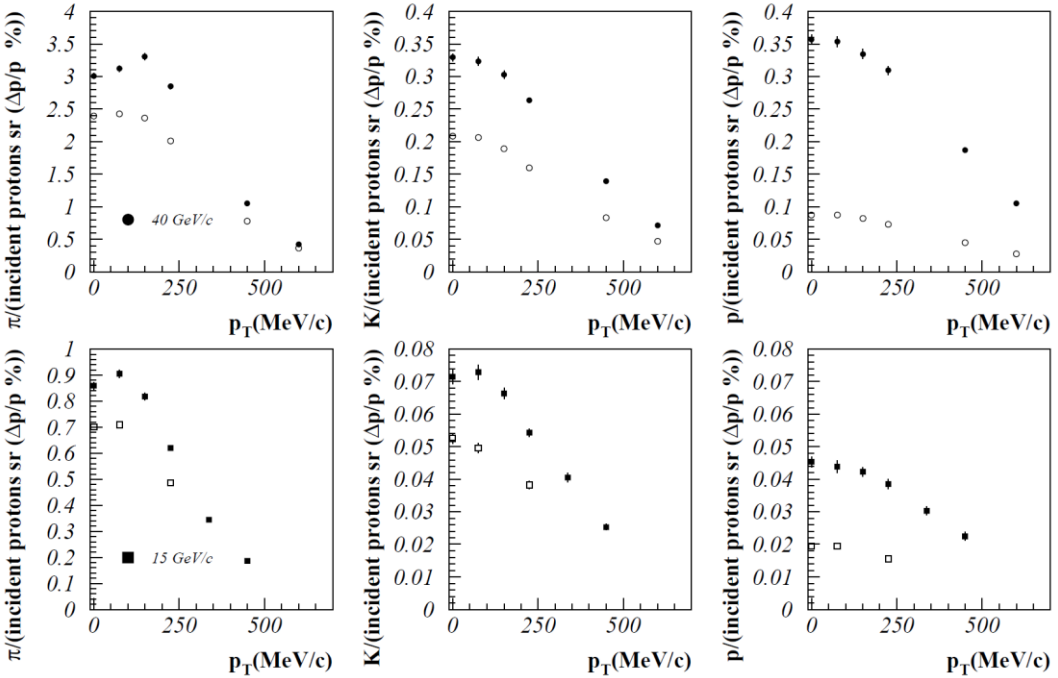
- particle yields in the forward direction for the 100mm Be target
- data are corrected for the contribution of strange particle decays
- Atherton et al. particle yields have been rescaled by $(450/400)^2$, see relation between invariant cross-section and yields

Particle ratios

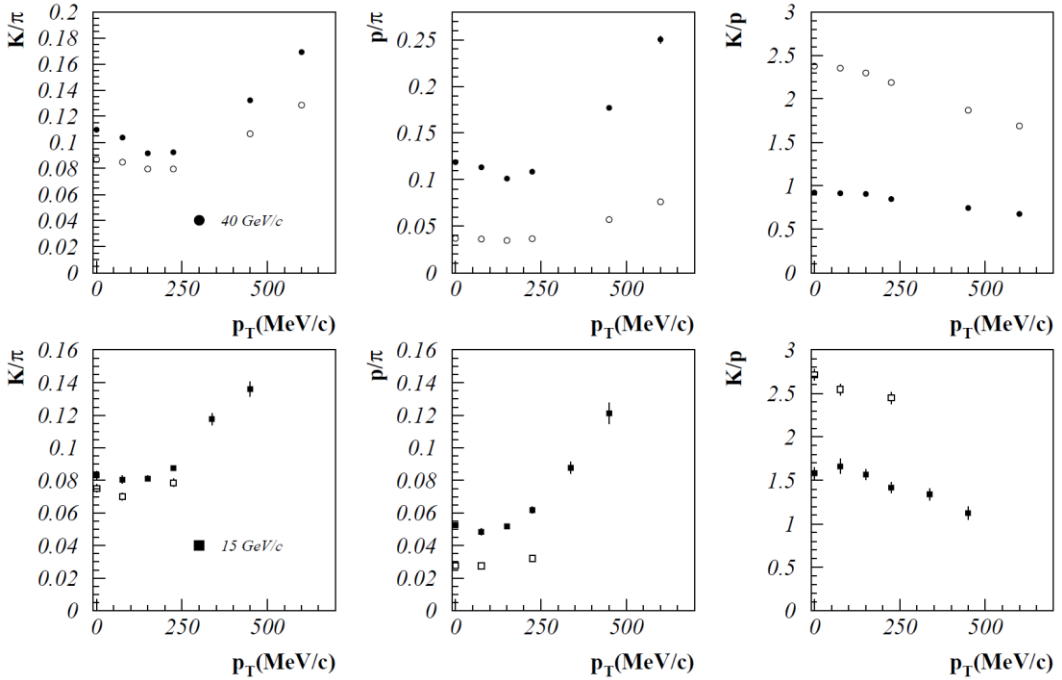


- particle production ratios for the 100mm Be target in the forward direction
- open (full) dots refer to negative (positive) particles

Angular dependance

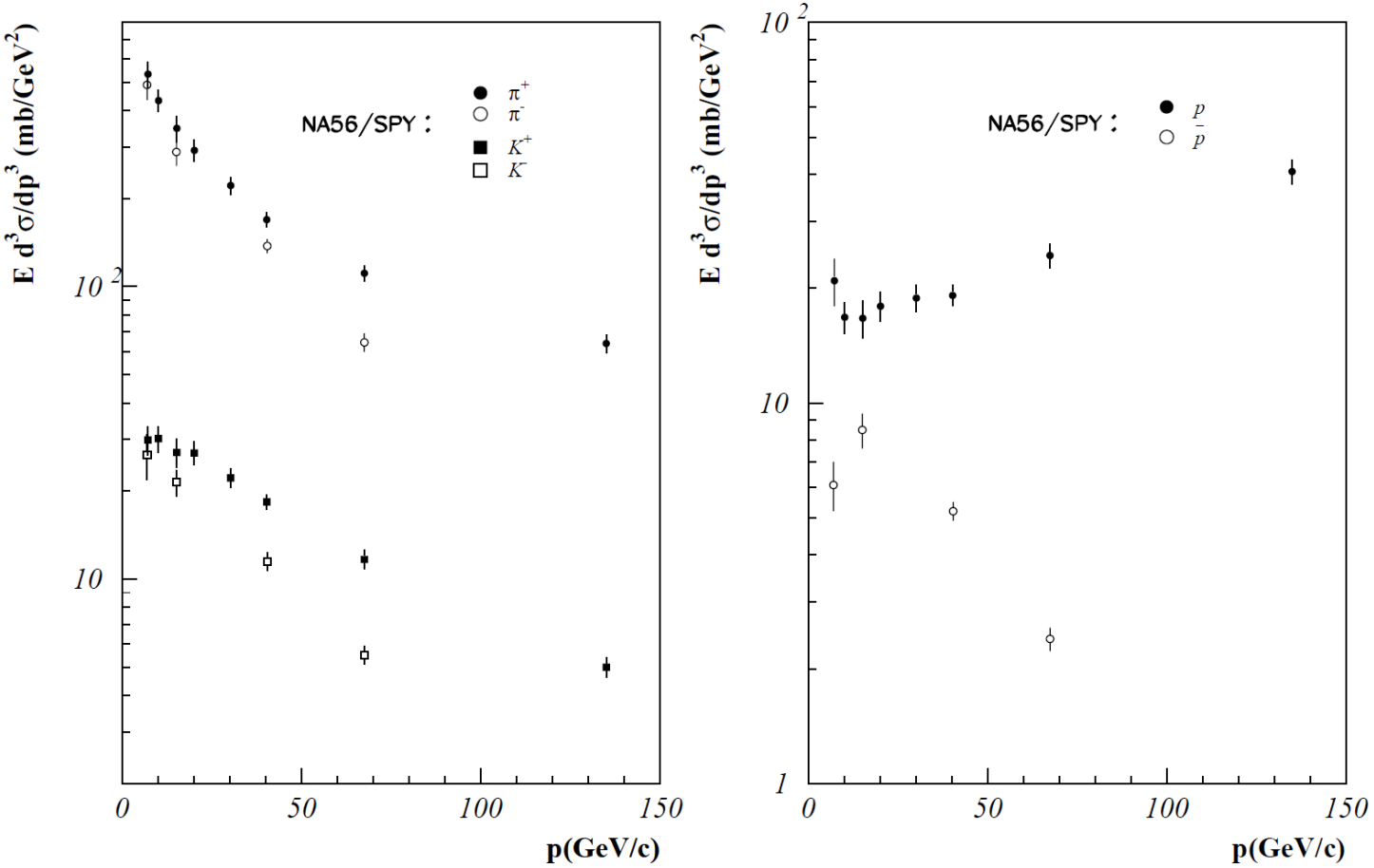


- particle yields at 40 and 15 GeV/c for the 100mm Be target
- open (full) dots refer to negative (positive) particles
- data corrected for contribution of strange particle decays



- particle production ratios at 40 and 15 GeV/c for the 100mm Be target
- open (full) dots refer to negative (positive) particles
- data corrected for contribution of strange particle decays

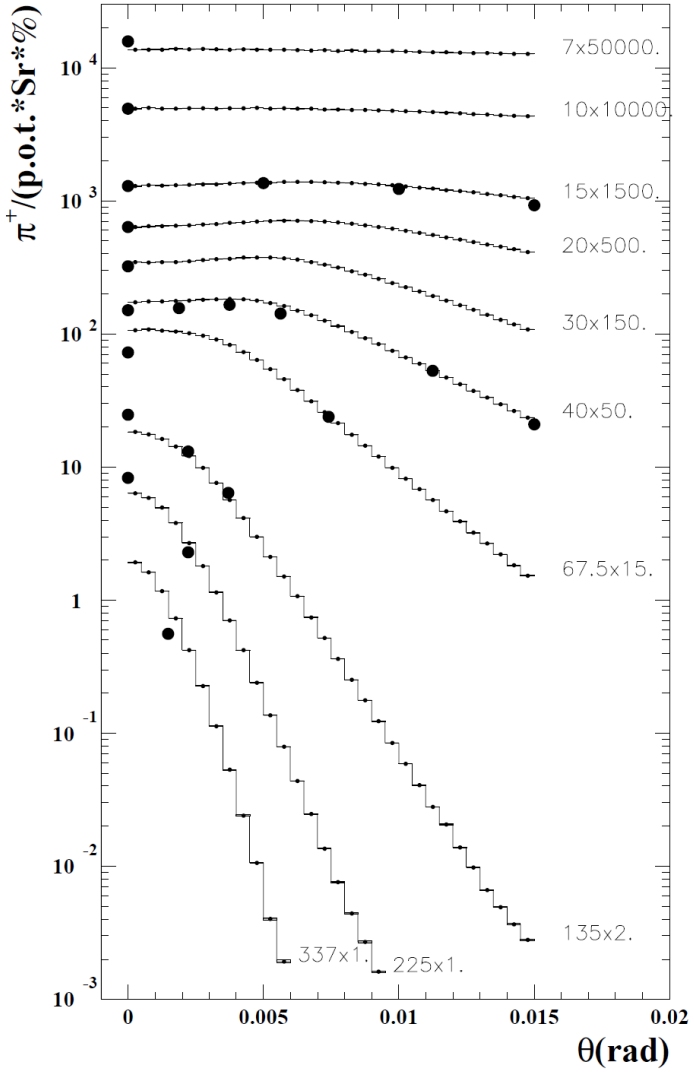
Inclusive invariant cross sections in forward direction

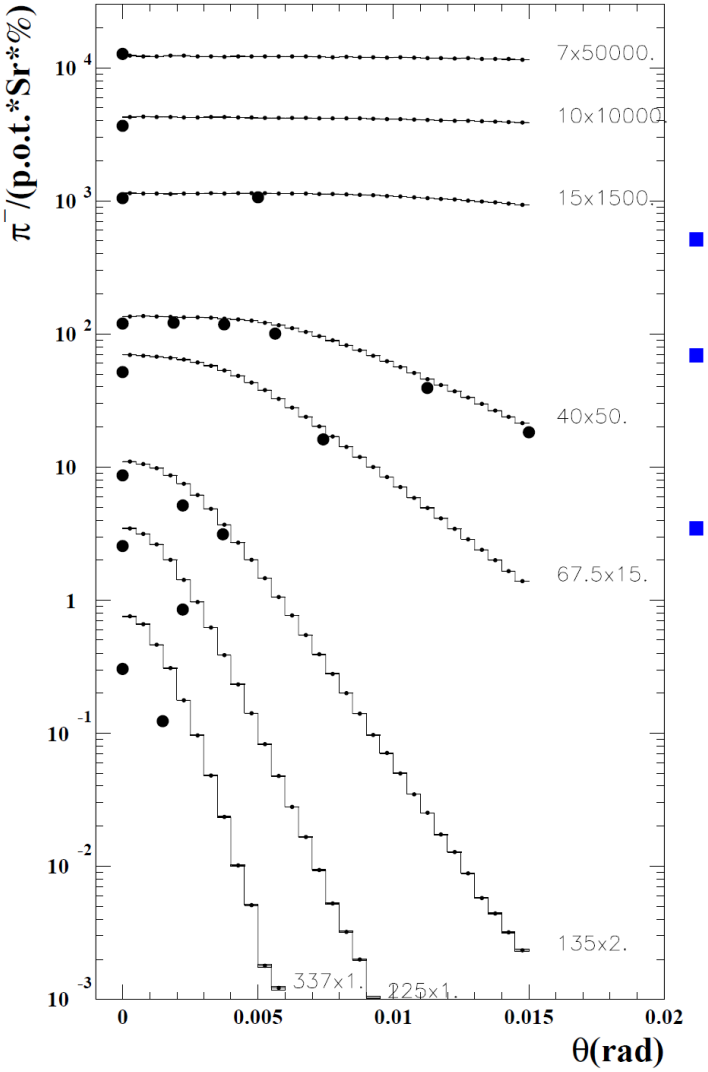


$$E \times \frac{d^3\sigma}{dp^3} = (100 \cdot Y) \cdot \frac{E}{p^3} \cdot \frac{A}{N_0 \cdot \rho \cdot \lambda_p \cdot f(L)}$$

- derived for secondary momenta at which particle yields from targets of at least two different thicknesses have been measured
- tertiary production accounted for by extrapolating the results to zero target thickness

Prediction of ν fluxes in NOMAD I

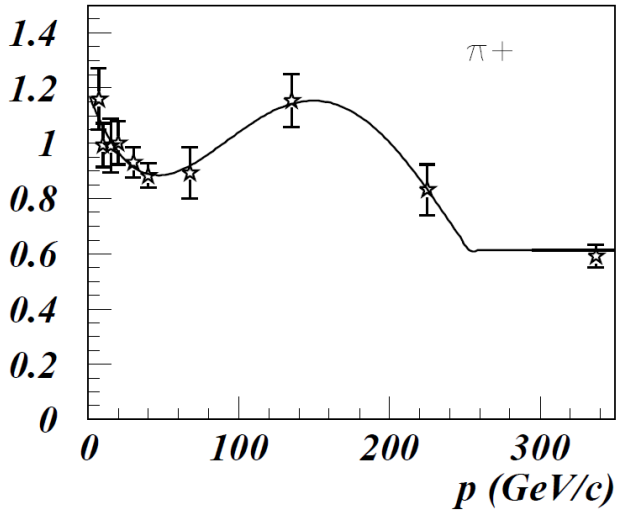


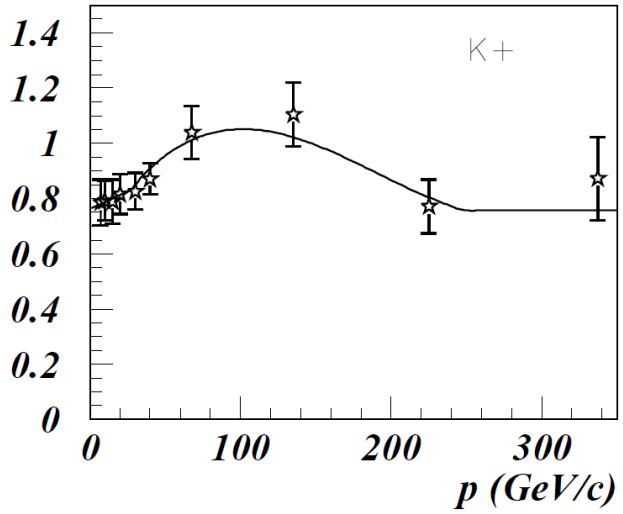


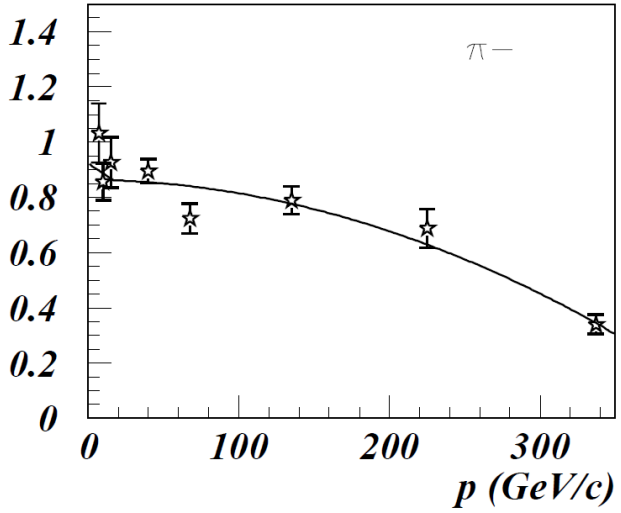
NIM A515 (2003) 800–828

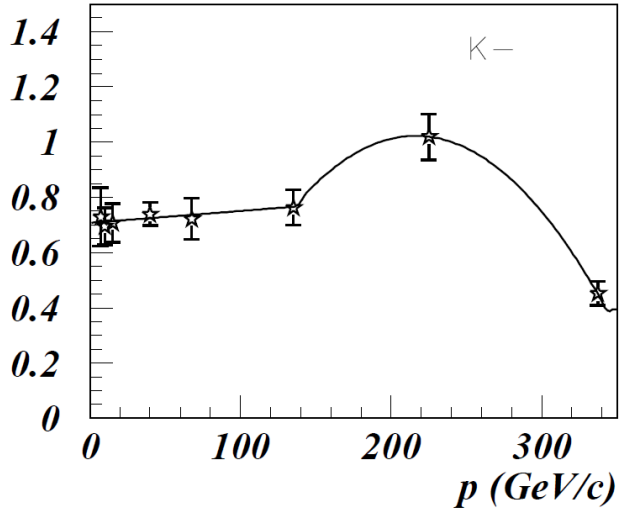
- pion yields from p–Be interactions
- histograms are FLUKA 2000 predictions
- points are SPY and Atherton et al. data

Prediction of ν fluxes in NOMAD II









FLUKA 2000 reweighting functions for NOMAD neutrino flux determination

BMPT

Eur. Phys. J. C 20, 13–27 (2001)

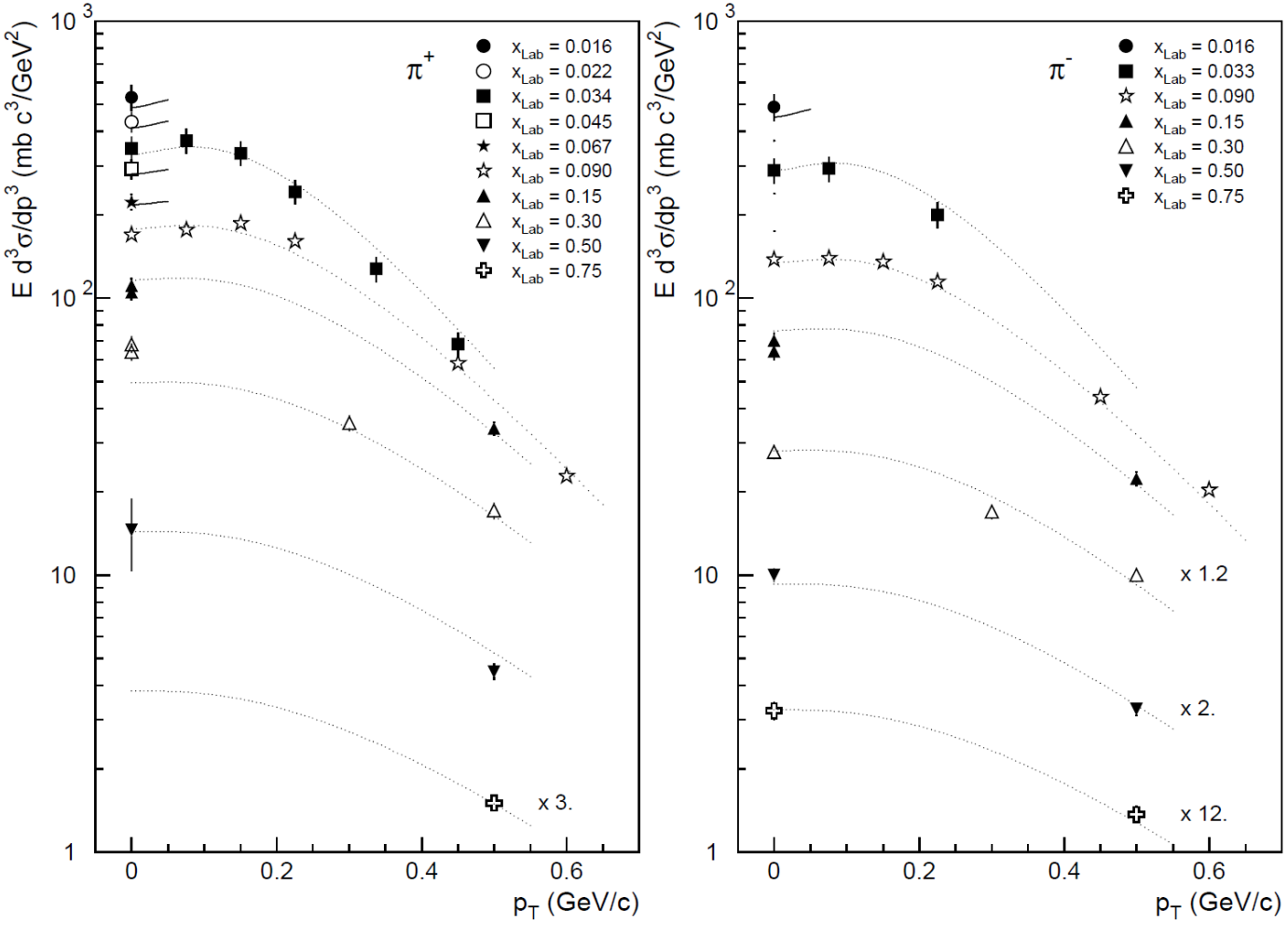
- in order to make SPY and Atherton et al. measurements of general applicability, measured single-particle yields on Beryllium have been converted to single-particle invariant cross sections, correcting for target efficiency and tertiary particle production
- data has been empirically parameterized as a function of the transverse momentum (*pT*) and the scaling variable $x_R = E^*/E^*_{max}$, defined as the ratio of the energy of the detected particle in the centre-of-momentum frame and the maximum energy kinematically available to the detected particle, with a formula based on general physical arguments

$$\left(E \times \frac{d^3\sigma}{dp^3}\right) = A(1-x_R)^{\alpha}(1+Bx_R)x_R^{-\beta} \times$$
$$(1 + a'(x_R)p_T + b'(x_R)p_T^2)e^{-a'(x_R)p_T}$$

$$\text{where } a'(x_R) = a/x_R^{\gamma} \text{ and } b'(x_R) = a^2/2x_R^{\delta}.$$

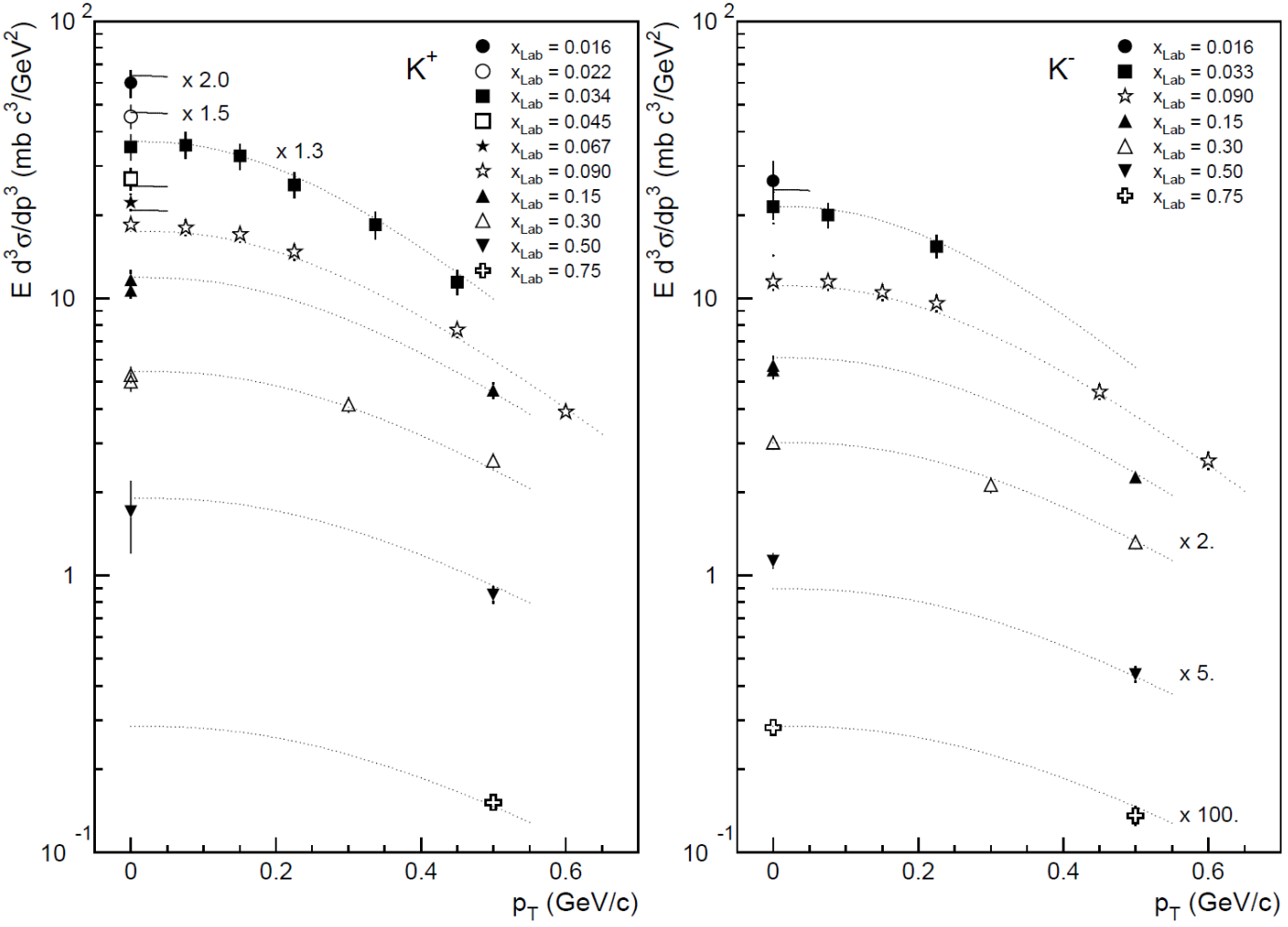
$$r(\pi) = r_0 \cdot (1+x_R)^{r_1}$$
$$r(K) = r_0 \cdot (1-x_R)^{r_1}$$

Parameterization of pion data



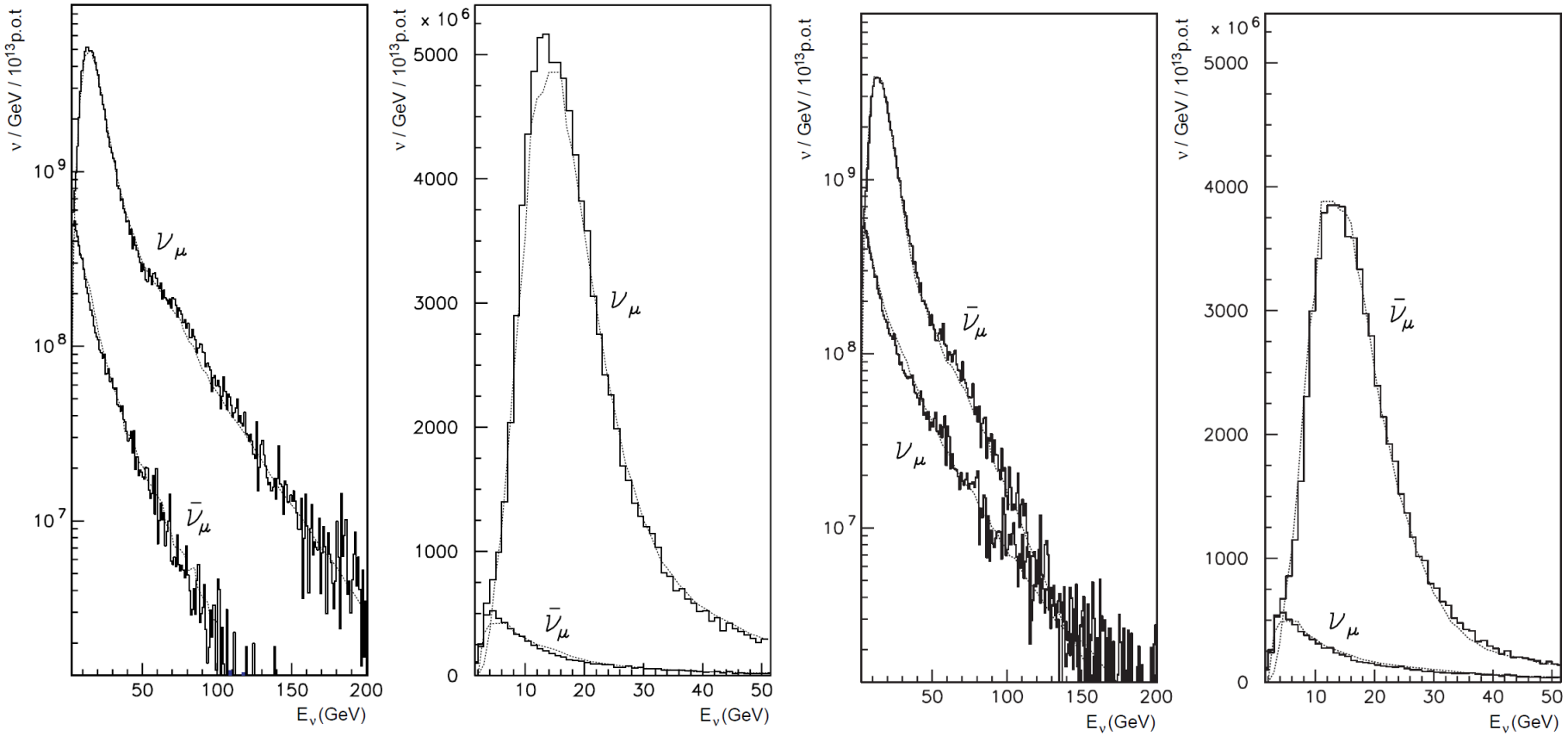
	A (mb/GeV^2)	B	α	β	a (GeV^{-1})	b (GeV^{-2})	γ	δ	r_0	r_1
π	62.3	1.57	3.45	0.517	6.10	–	0.153	0.478	1.05	2.65

Parameterization of Kaon data



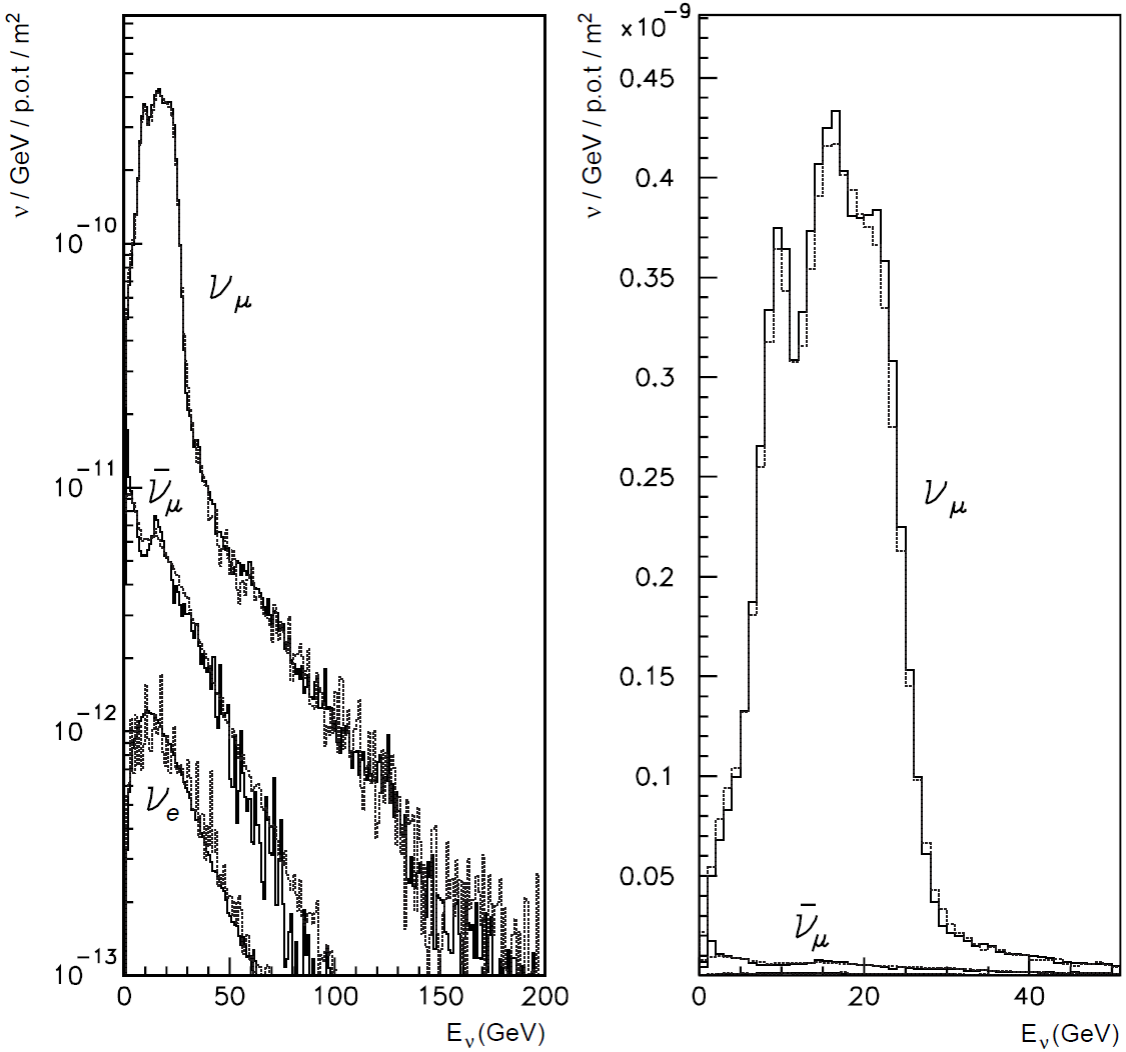
	A (mb/GeV^2)	B	α	β	a (GeV^{-1})	b (GeV^{-2})	γ	δ	r_0	r_1
K	7.74	–	2.45	0.444	5.04	–	0.121	2γ	1.15	-3.17

WANF ν and $\bar{\nu}$ fluxes at the CHARM II detector



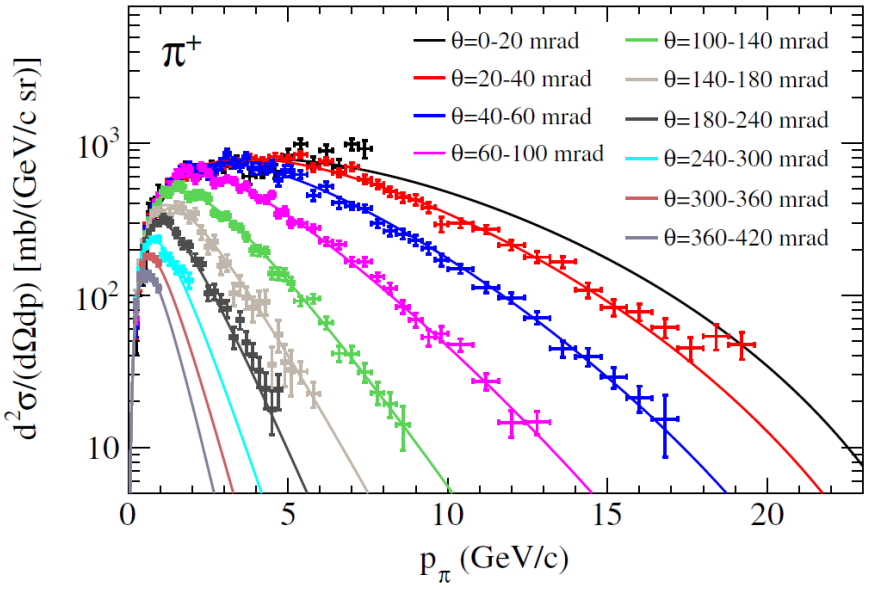
the dotted lines are experimental data from CHARM II, the continuous line is the BMPT based simulation

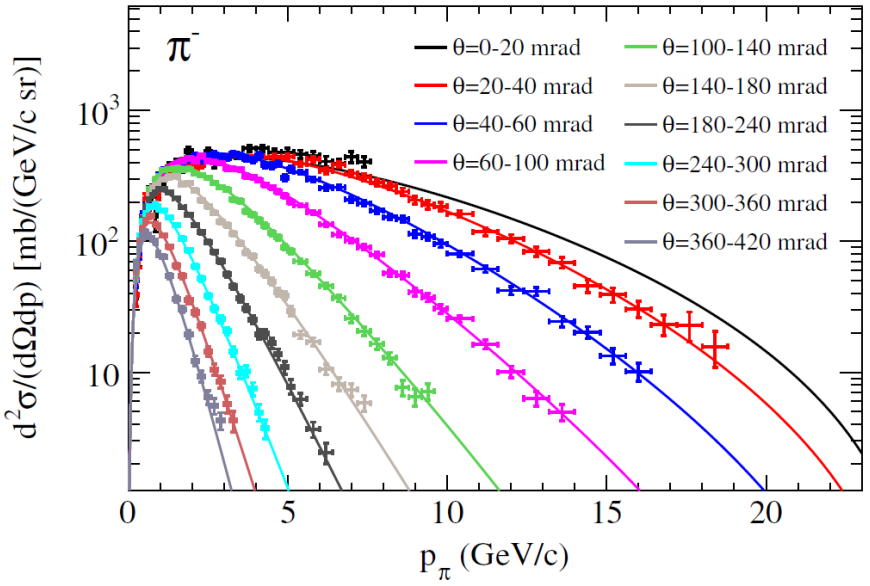
CNGS neutrino fluxes



Comparison between FLUKA/GEANT simulation (dotted lines) and the BMPT based simulation (continuous line)

BMPT fits to the NA61 π data



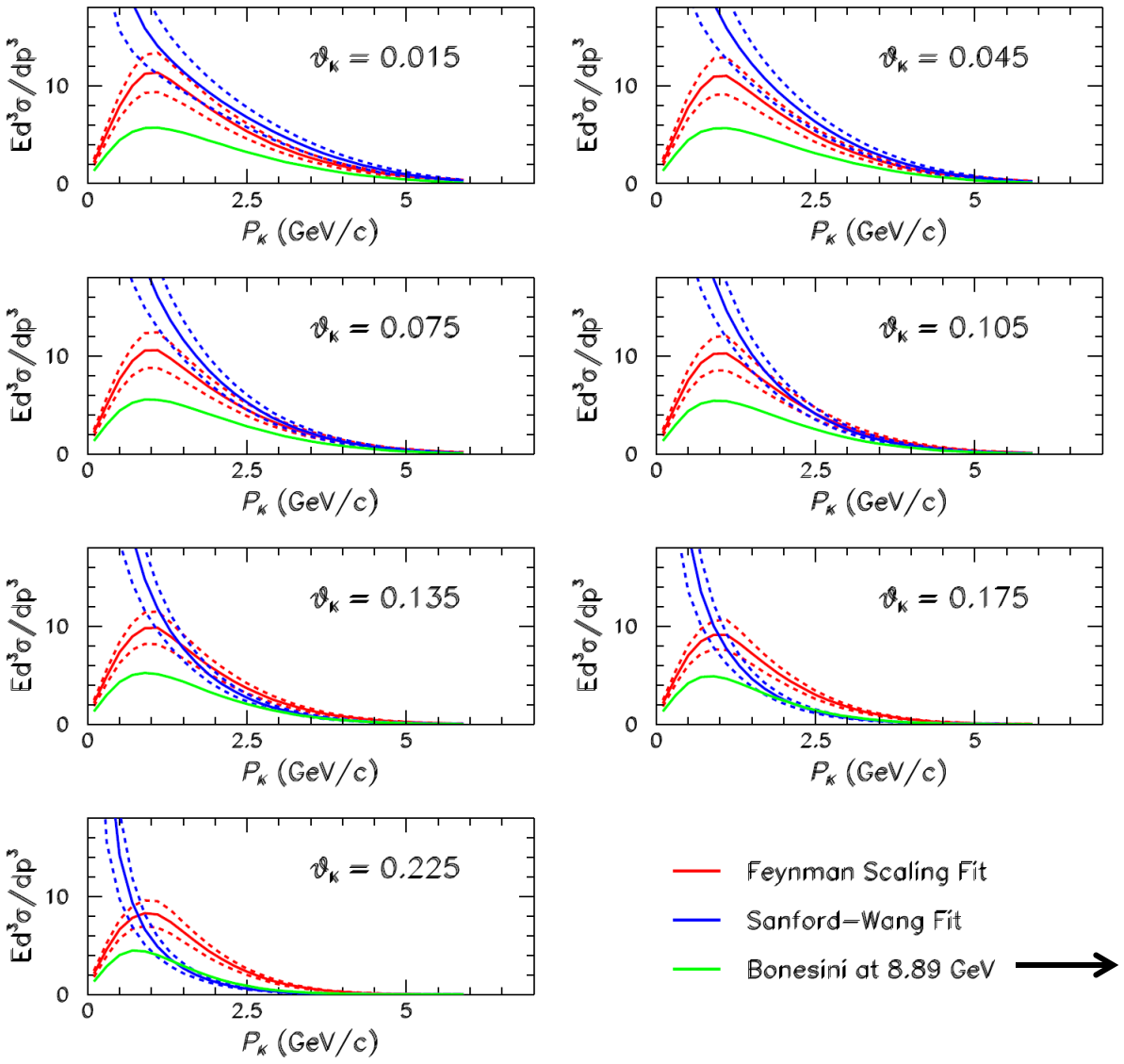


T2K neutrino flux predictions
arXiv:1211.0469 [hep-ex]

BMPT Parameter	π^+	π^-
A (mb/GeV^2)	188 ± 15	90.8 ± 2.7
B	−0.661 ± 0.379	−1.15 ± 0.07
α	3.40 ± 0.35	1.89 ± 0.13
β	0.303 ± 0.029	0.461 ± 0.012
a (GeV^{-1})	5.37 ± 0.14	5.19 ± 0.045
γ	0.245 ± 0.018	0.194 ± 0.005
δ	0.799 ± 0.053	0.783 ± 0.017
r_0	-	1.10 ± 0.031
r_1	-	1.95 ± 0.17

- The BMPT parameterization is used to extrapolate the data into the uncovered region
- The uncertainty in the FLUKA model in the uncovered region is estimated as the change in flux when the production is reweighted by the BMPT fits

Parametrization of K^+ production in p-Be collisions at low energy using Feynman scaling



C. Mariani et al.,
Phys Rev D84, 114021 (2011)

parameterization of secondary K^+ for experiments with primary protons from 8.89 to 24 GeV/c

$$\frac{d^2\sigma}{dpd\Omega} = \frac{p_K^2}{E_K}\left(E_K\frac{d^3\sigma}{dp_K^3}\right)$$
$$= \left(\frac{p_K^2}{E_K}\right)c_1 \times \exp[c_3|x_F|^{c_4} - c_7|p_T \times x_F|^{c_6} - c_2 p_T - c_5 p_T^2].$$

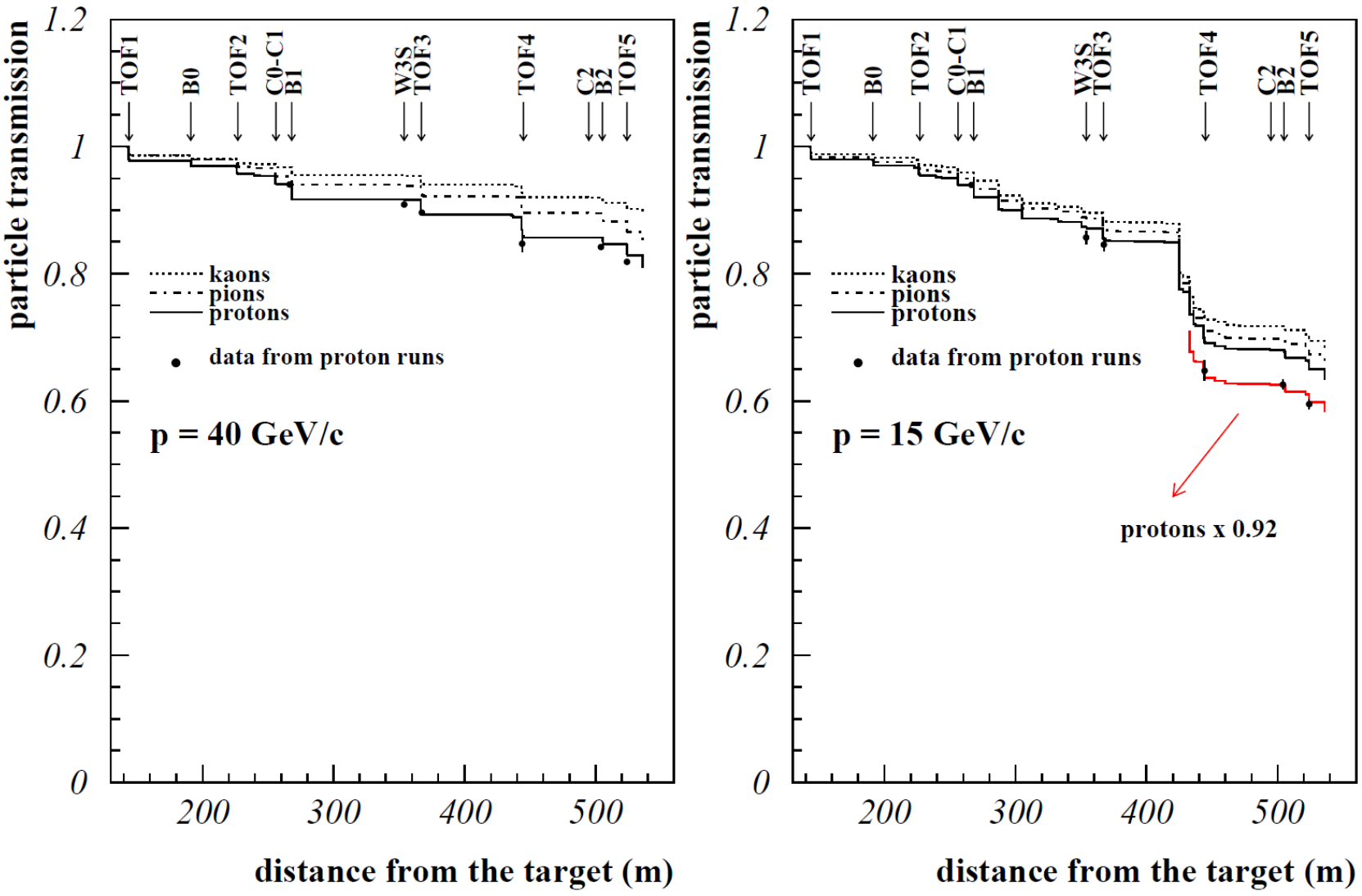
directly extrapolated from 400-450 GeV/c data

Final considerations

- **SPY has provided useful data for the predictions of the WANF and CNGS neutrino beams at CERN**
  - precise measurements for a set of discrete points, 5% to 10% for particle yields, depending on beam momentum, ~3% for particle production ratios
  - the last of the “beam-spectrometer-like” hadro-production experiments?
- **x_F (x_R), p_T parameterization of hadronic invariant cross section production based on the combination of SPY and Atherton *et al.* data (BMPT)**
  - BMPT is not a theoretical model, but a parameterization based on general physical arguments
  - care should be used when extrapolating the original parameterization, derived from 400 and 450 GeV proton data, to considerably lower energies
  - best to refit available experimental data in the energy range of interest (a good tool to combine sparse data)
  - very useful for fast MC approaches

Backup

Particle transmission in SPY



Beam momentum determination in SPY