A short review of hadroproduction data for neutrino beams

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Talk outline

- High energy conventional neutrino beams
- Available datasets for neutrino beams calculations
  - low, medium and high-energy data
  - an example: the NA56/SPY experiment
- Existing parametrizations of secondary particle yields at high energy:
  - Atherton, Malensek
- A new parametrization of high energy data: the BMPT parametrization
  - the parametrization of cross sections
  - a simple simulation of neutrino beamlines
  - a check with Charm II data
  - applications to WANF, CNGS, NuMI
- What is next :
  - parametrization of secondary particle yields at low energy
  - HARP , E907
- Conclusions

High energy conventional neutrino beams

- Wide band ν beams at the SPS
  - Optics + decay kinematics known

    WANF

$$p \cong 75\text{GeV/c}, \qquad p_T/p \leq 8\text{mrad}$$

CNGS (ref beam)

$$p \cong 40\ \text{GeV/c}; \qquad p_T/p \leq 10\text{mrad}$$

about 50% of ν_μ from secondaries below 60 GeV/c -> data needed

- Minority components -> needs better knowledge of secondary production in target

Available datasets for neutrino beams calculations

- Mainly from old, non dedicated experiments to study hadroproduction (sixties)

- usually single-arm spectrometer experiments
- low statistics, high systematics
- low energy (p_{inc}<30 GeV/c)
- sometimes data are not on nuclear targets but on protons (" nuclear effects")

- I will show a useful selection

1. Low energy data

- J. Allaby et al., CERN-70-12
  - p-nuclei (B_4C, Be, Al, Cu, Pb) and p-p collisions at 19.2 GeV/c
  - Single arm spectrometer
- G. Eichten et al.,Nucl. Phys. B44(1972) 333
  - π,K prod in p-nuclei collisions (Be, B_4C,Al, Cu, Pb targets) at 24 GeV/c
  - single arm magnetic CERN-Rome spectrometer
- All datasets useful, but suffer from low statistics and high systematics (15 % on cross sections)

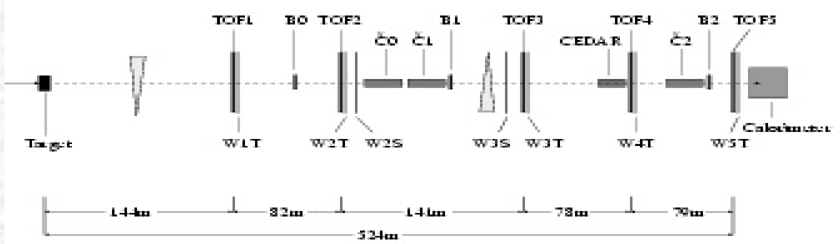
2.Medium energy data

- Barton et al., Phys. ReVD27(1983),2580
  - Study of inclusive production of π, K, p, pbar in 100 GeV/c π^+,K^+,p collisions with C,Al,Cu,Ag,Pb targets
  - Single arm M6E Fermilab spectrometer
- Skubic et al., Phys. ReV. D18 (1978), 3115
  - Strange particle production in 300 GeV/c p collisions with Be,Cu,Pb

3.High energy data by 400-450 GeV/c protons on Beryllium

- H.W. Atherton et al. (NA20), CERN 80-07, 1980
  - p = 60, 120, 200, 300 GeV/c
  - p_t = 0, 500 MeV/c
  - target plate length = 40, 100, 300, 500 mm
- G. Ambrosini et al. (NA56/SPY), Eur. Phys. J. C10 (1999) 605
  - p = 7, 10, 15, 20, 30, 40, 67.5, 135 GeV/c (at p_t = 0)
  - p_t = 0, ±75, ±150, ±225, ±337, ±450, +600 MeV/c (for p = ±15, ±40 GeV)
  - target plate length = 100, 200, 300 mm
  - WANF "T9-like" target (3 rods 10 cm long, 3 mm thick)

An example: the Na56/SPY experiment



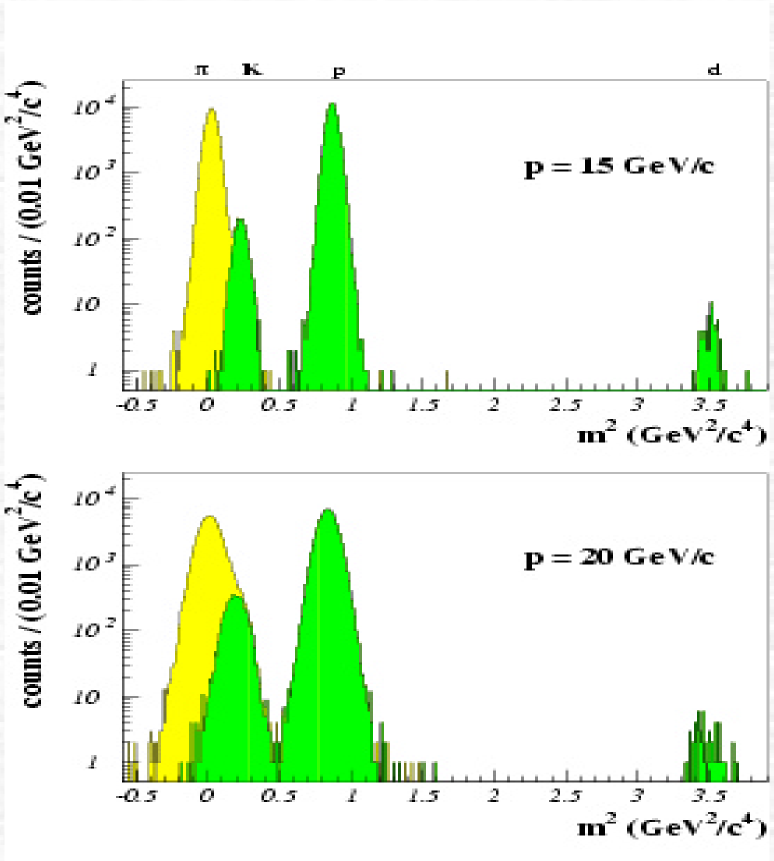
- Measure π, kaon fluxes by 450 GeV/c p on Be (5% precision) -> knowledge of neutrino spectra
- Measure k/π ratio (3% precision) -> knowledge ν_e/ν_μ ratio

- Equipped H6 beamline from NA52 experiment in North Area
- Primary p flux measured by SEM
- Different Be targets (shapes, L)
- PID by TOF counters (low momentum) and Cerenkov (high momenta)

The NA56/SPY experiment

- Critical points for such an experiment
- beamline simulation (spectrometer acceptance) (5 – 10 % precision)
- other systematic errors
- Particle misidentification (< 1%)
- Subtraction of long lifetime particles decaying outside the target (K^0_s -> ππ, ...) (< 2%)
- Beam momentum determination and K lifetime->uncertainty on K decay correction (1 %)
- Protons on target (2 %)

Pid in the NA56/SPY experiment

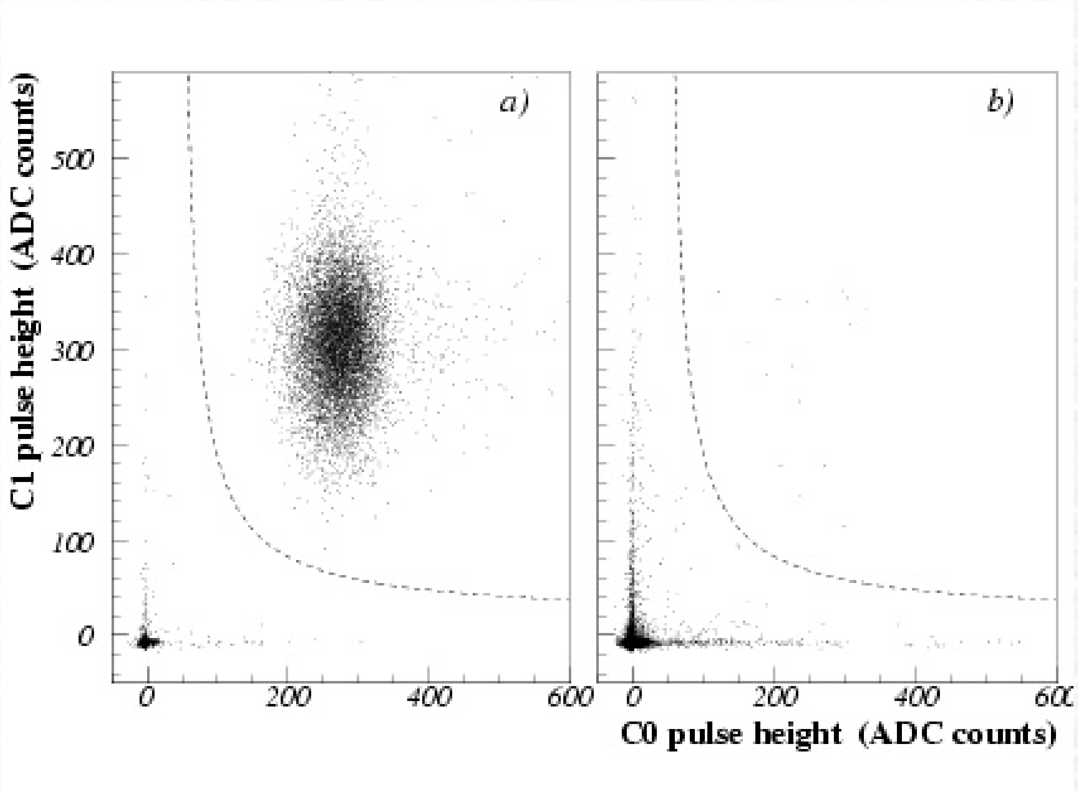


- TOF1-TOF5 scintillator hodoscopes (resolution 70-100 ps)
- C0-C1(N2)/C2(H2)

  threshold Cerenkov counters π/K up to/above 20 GeV/c
- CEDAR differential Cerenkov counter (He) flags π above 15 GeV

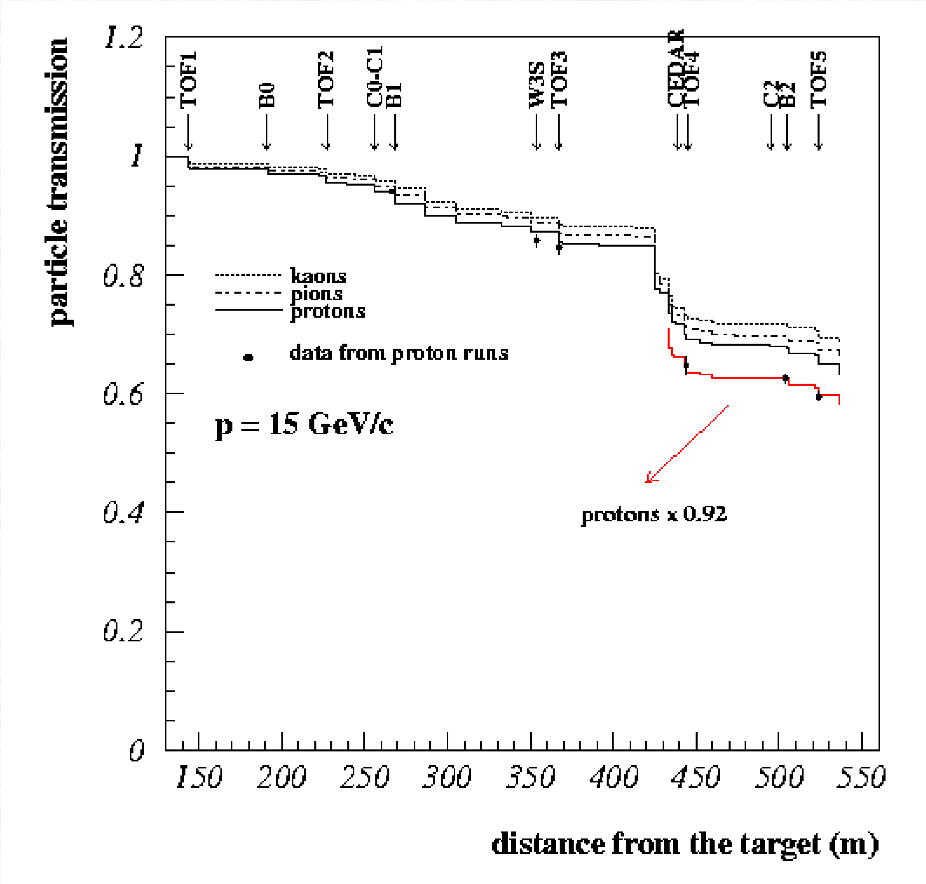
- Low momenta: TOF's up to TOF3
- Intermediate: TOF's and Cerenkov's
- High momenta: Cerenkov's

K/π separation with C counters at 15 GeV/c



- π/K rejection with Cherenkov counters is better than 10^{-5}
- K to π misid probability is at 10^{-3} level, due to particles pileup

Beamline simulation for NA56/SPY



- Multiple scattering + beam OPTICS (TURTLE) + nuclear collisions
- Comparison to data -> simulation reliable in the first part of the beamline (up to TOF3)
- Discrepancies downstream of TOF3 (correct TURTLE predictions, quote residual discrepancy as systematic error max 8 %)

NA56/SPY monitor of primary p intensity

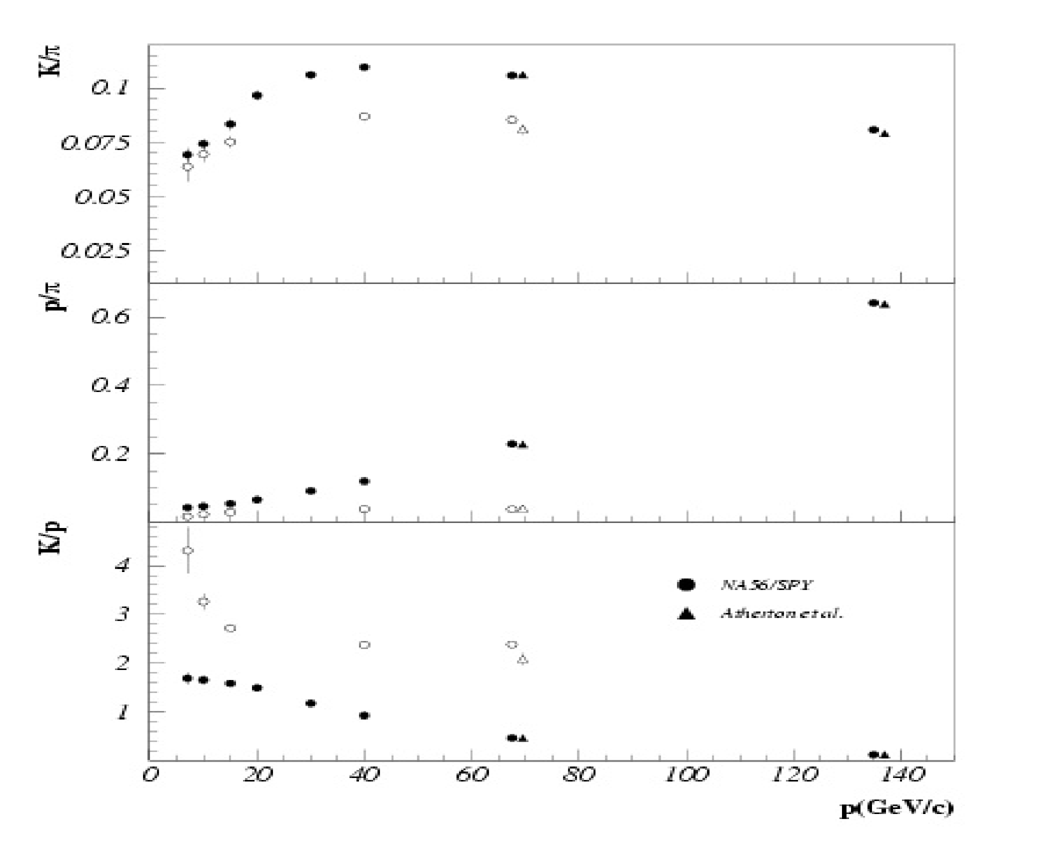
SEM: secondary emission of electrons from Al/Ti foils monitor the beam intensity

- Complete foils (BSI) -> absolute intensity
- Thin strips (BBST V-H) -> spot size

Al foil activation calibrated in the WANF with proton intensity measured by BCT

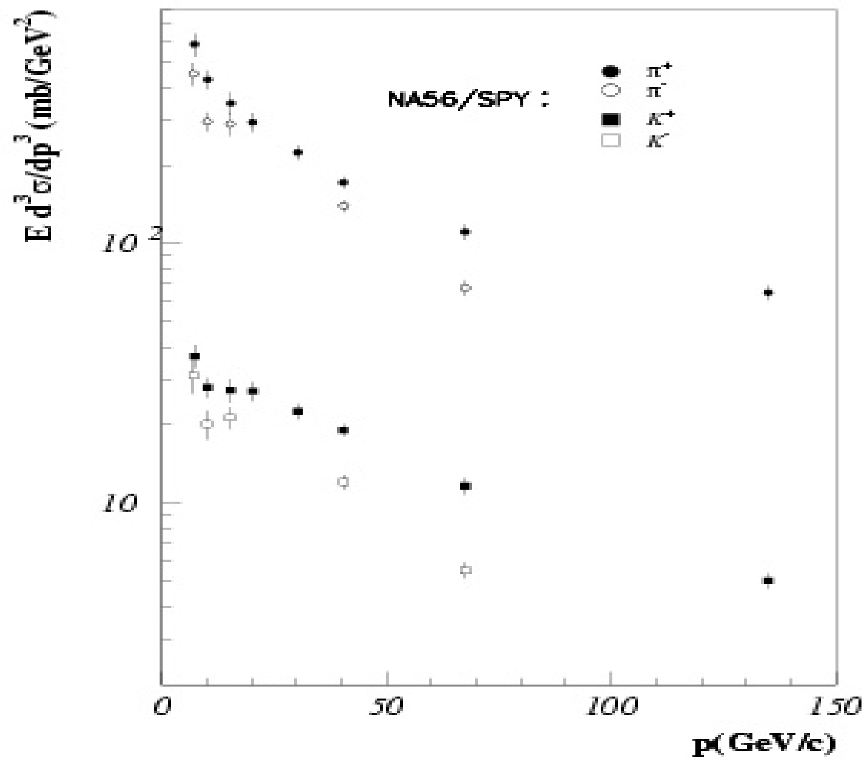
- Precision 1.3 %
- Long term stability +- 1%

Some NA56/SPY results: the K/π ratio



- Solid points negatives, open points positives
- Errors 3 %
- K content (depleted by decays) enriched by trigger prescaling
- 2 samples (one trigger natural composition, the other heavy particles K,p,..)
- $K/\pi = (K/p)_{heavy\ sample}(p/\pi)_{natural}$

Some NA56/SPY results:π/K/p inclusive invariant cross sections



- Forward invariant cross sections
- Model independent extrapolation to zero target thickness with data itself (L=100,200, 300 mm targets)
- Total error 10%

The existing parameterizations of secondary particle yield at high energy

- Simple formulas fitting the yield of charged secondary particles from 400 GeV/c protons on Be targets:
  - Data above 60 GeV/c (x ~ 0.15) at p_t = 0 and 500 MeV/c
  - H.W. Atherton et al., CERN 80-07, 1980: thin target approximation

$$\frac{d^2 N_{Be}}{dp\, d\Omega} = A p_{\max} (B e^{-Bx}) \left(\frac{2C}{2p} x^2 e^{-C p_t^2} \right)$$

  - A.J. Malensek, FN-341,1981: thick target approximation (500 mm)

$$\frac{d^2 N_{Be}}{dp\, d\Omega} = Bx \frac{(1-x)^A}{(1+p_t^2/M^2)^4} (1+5e^{-Dx})$$

- *Both fail at low x*

A new parameterization of secondary particle yield from thick targets: the BMPT parametrization

- Goal: improvement with respect to previous models at low x (and p_T ® 0). H.W. Atherton et al., CERN 80-07, 1980, A.J. Malensek, FN-341,1981
- Secondary yield from fit of:
  - π^+ and K^+ invariant cross-section data derived from Atherton et al. & NA56/SPY Collaboration data (Be target),
  - π^-/π^+ and K^-/K^+ data
  - K^0_L evaluation from simple parton model.
- Evaluation of tertiary particles production:
  - Comparison of secondary production from targets of different thickness (100, 200, 300 mm and T9) in Na56/SPY.
- Extrapolation to other target material and incident p energy:
  - Known invariant cross-section dependence on Atomic Number.
  - Comparison with other available data at different proton energy.

The invariant cross section

for secondary production of π^+ and K^+

- Empirical formula based on general physical arguments.

$$\left(E\frac{d^3 s}{dp^3}\right)_{Be} = A(1 - x_R)^a \left(1 + \frac{a}{x_R^?} p_t + \frac{a^2}{2x_R^d} p_t^2\right) e^{-\left(\frac{a}{x_R^?} p_t\right)} (1 + Bx_R) x_R^{-ß}$$

  - Approximate factorization in x and p_t
  - $(1-x)^a$ behavior in the forward direction for $x \rightarrow 1$ (quark counting rule)
  - x^{-b} behavior in for $x \rightarrow 0$ (non direct hadron formation mechanism)
  - Exponential fall in p_t for soft interaction
- $x_R = E^*/E^*_{max}$ (greatly extends scaling to sub-asymptotic energies, Yen Phys. ReV. D10 (1974) 836)

The invariant cross section for secondary production of π^- and K^- and K^0_L

- Empirical formula describing π^+/π^- and K^+/K^- ratios:

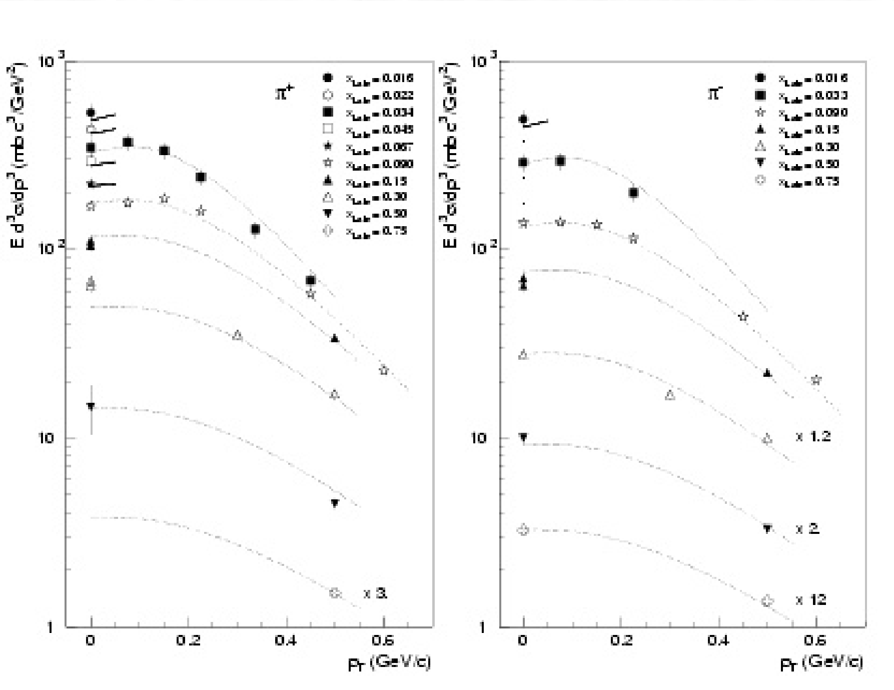
$$R(p(= r_0(1+x_R)^{r1}; R(K) = r_0(1-x_R)^{r1}$$

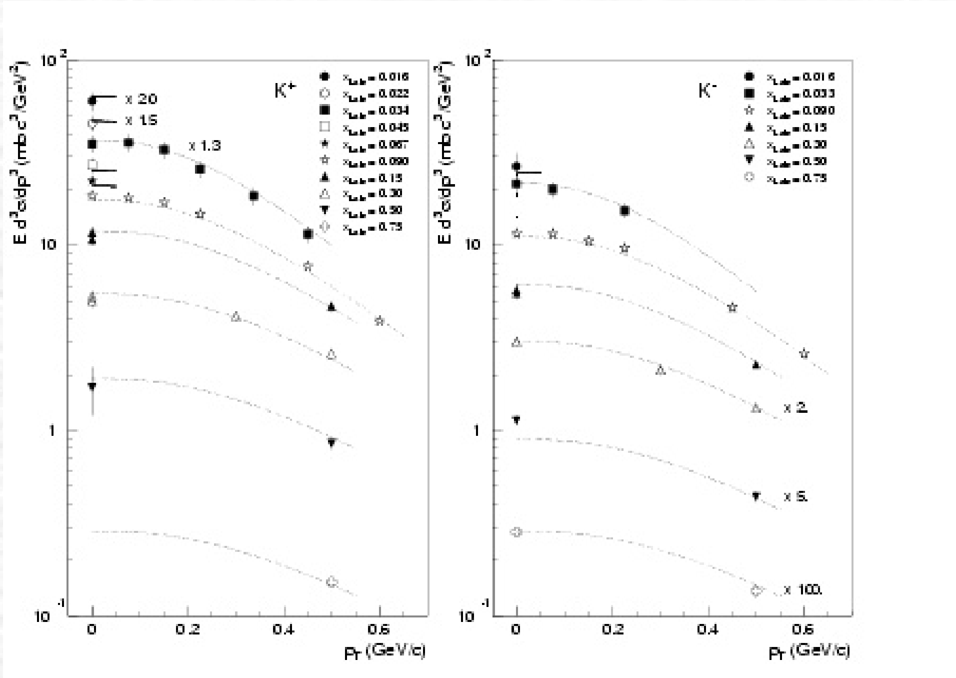
  - function of x only
  - R(p) and R(K) shapes supported by analysis of pp data by Ochs (Nucl. Phys. B118 (1977) 397)
    - R(p) ® 1 for x ® 0; R(p) ® 5 for x ® 1;
    - R(K) $(1\text{-}x)^{-3}$ for x ® 1;
- K^0_L production evaluated from simple parton model

$$N(K^0_L) = \frac{N(K^+) + (2n-1)N(K-)}{2n} \approx \frac{1}{4}(N(K^+) + 3N(K^-))$$

(n = u/d ˜ 2 assuming isospin symmetry)

Invariant cross sections: a) pions, b) kaons





Parametrization extrapolations

- Extension to other target material:

$$\left(E\frac{d^3s}{dp^3}\right)_{A1} = \left(\frac{A_1}{A_2}\right)^a \left(E\frac{d^3s}{dp^3}\right)_{A2}$$

  - From data on several nuclei:
  - Known dependence of the invariant cross section on atomic number A:

  $\alpha(x)$ ˜ $(0.74- 0.55\ x + 0.26\ x^{2)}).(0.98+0.21\ p^2_T)$

  (D.S. Barton et al., Phys. Rev. D35 (1987) 35, Skubic et al., Phys. ReV. D18(1978) 3115)

  = 5% systematic error from Be to C

- Comparison with data at different incident proton energy:
  - 100 GeV/c proton on Carbon (D.S. Barton et al., Phys. Rev. D27 (1983) 2580)
  - 24 GeV/c proton on Beryllium (T.Eichten et al., Nucl. Phys. B44 (1972) 333)

The fit of the experimental data (Atherton et al. & SPY)

- To compare data with different proton energy:
  - from experimental secondary yield to invariant cross section

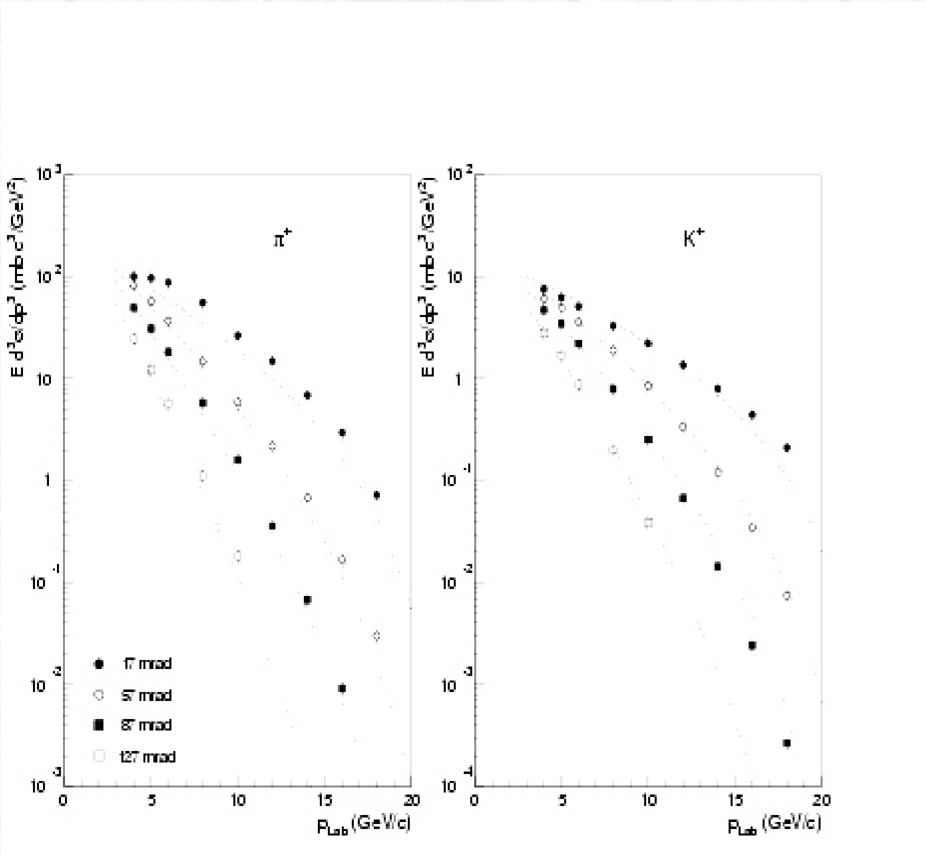
$$\frac{d^2 N_{Be}}{dp \big/ p\, d\Omega} = \left(E \frac{d^3 s}{dp^3}\right)_{Be} \frac{p^3}{E} \frac{N_0 \, r\, l_p f(L)}{A} \qquad f(L) = \frac{e^{-L/l_s} - e^{-L/l_p}}{1 - l_p \big/ l_s}$$

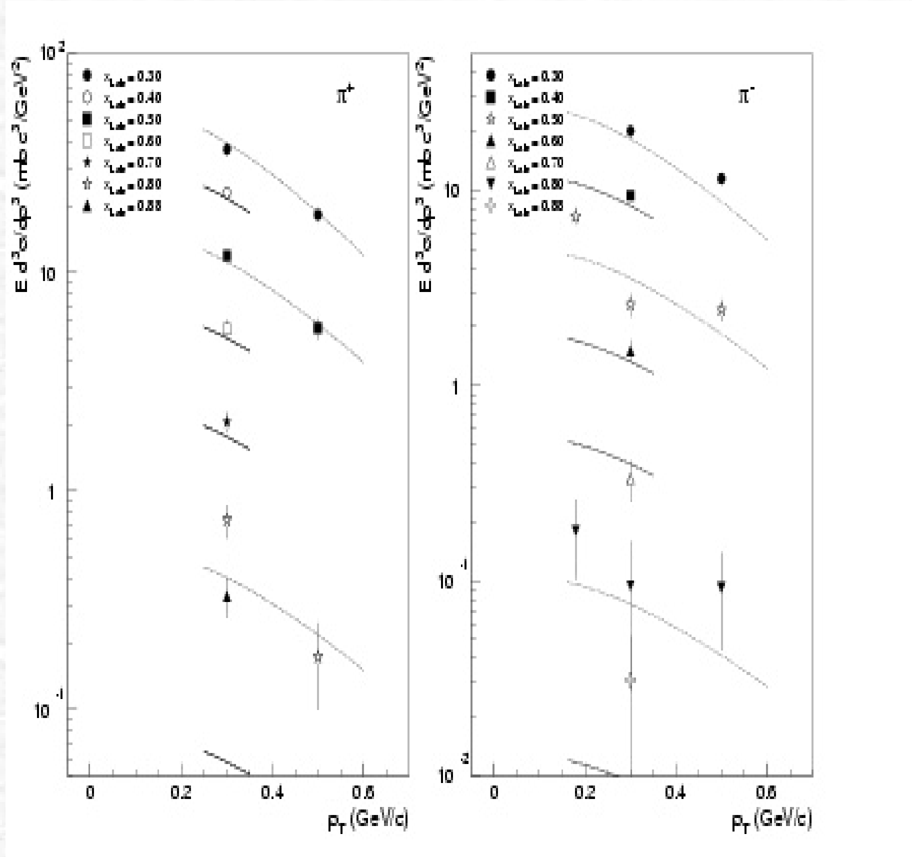
  - f(L) = naive absorption model (100 mm target) (secondaries reabsorbed without producing tertiares)
  - tertiary production taken into account (extrapolation to zero thickness from thicker targets)

- Fit parameters (10% error on data points assumed)

	A	α	β	B	a	γ	δ	r_0	r_1
π	62.3	3.45	0.517	1.57	6.10	0.153	0.478	1.05	2.05
K	7.74	2.45	0.444	-	5.04	0.121	2γ	1.15	–3.17

Comparison with other energies
a)Eichten et al. (24 GeV/c) b)Barton et al. (100 GeV/c)





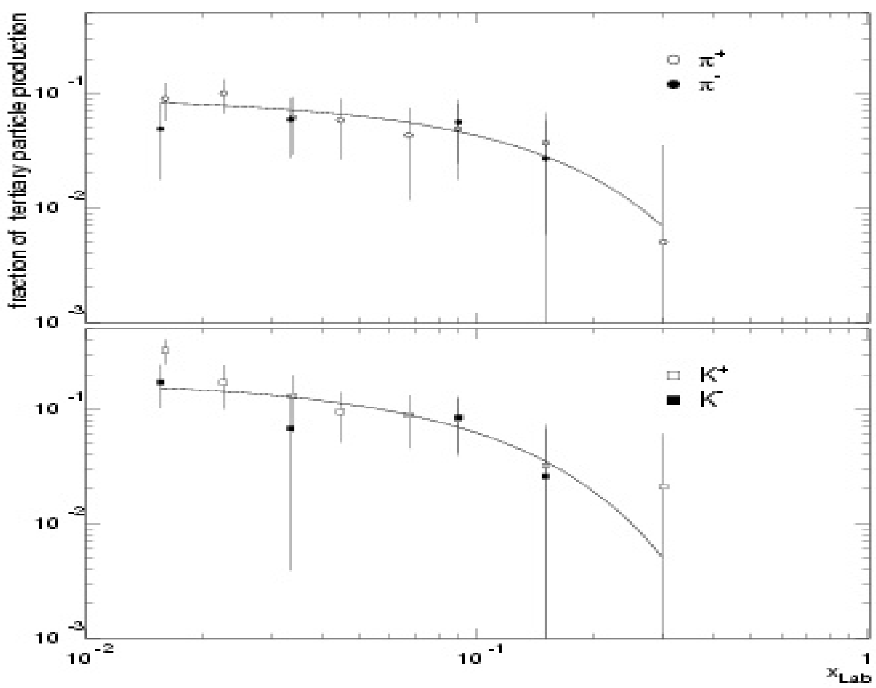
Empirical model for tertiary particles production on thick targets (SPY data)

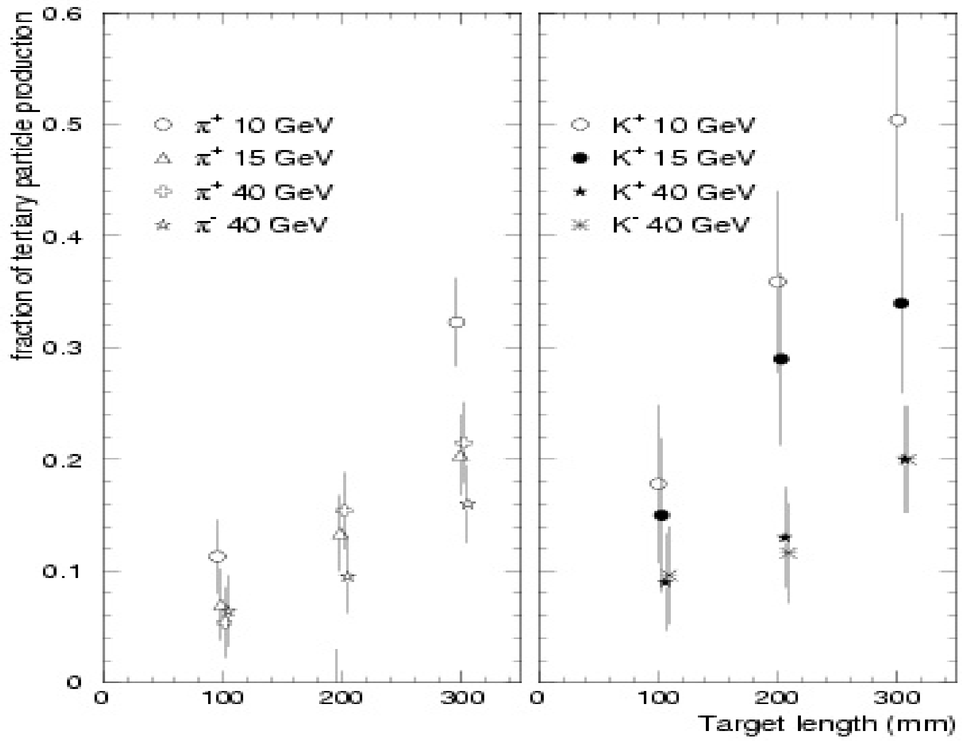
- Experimental evidences:
  - Comparison of secondary production from targets of different thickness (100, 200, 300 mm and T9) in SPY.
    - Naive absorption model inadequate at large thickness
- Empirical assumptions (for long “needle-like” targets):
  - Tertiary particles produced mostly by re-interaction of leading secondary particle in the forward direction -> model to reproduce NA56/SPY data

Secondary particle yield from WANF and CNGS targets

- Simple description of target layout & proton beam:
  - WANF Beryllium target: 11x(10cm-rods + 9cm-air); 3 mm diameter
  - CNGS Graphite target: 8x(10cm-rods + 9cm-air) + 48cm-rod; 4 mm diameter
  - Proton beam with nominal energy (CNGS: 400 GeV, WANF: 450 GeV), width and divergence.
- Proton interactions in target:
  - Secondary production ($\pi^\pm$, $K^\pm$ and K^0_L) from parameterization.
    - Simple exponential distribution along target bars.
    - Attenuation due to re-interactions along path length in target included.
  - Tertiary contribution from empirical model.

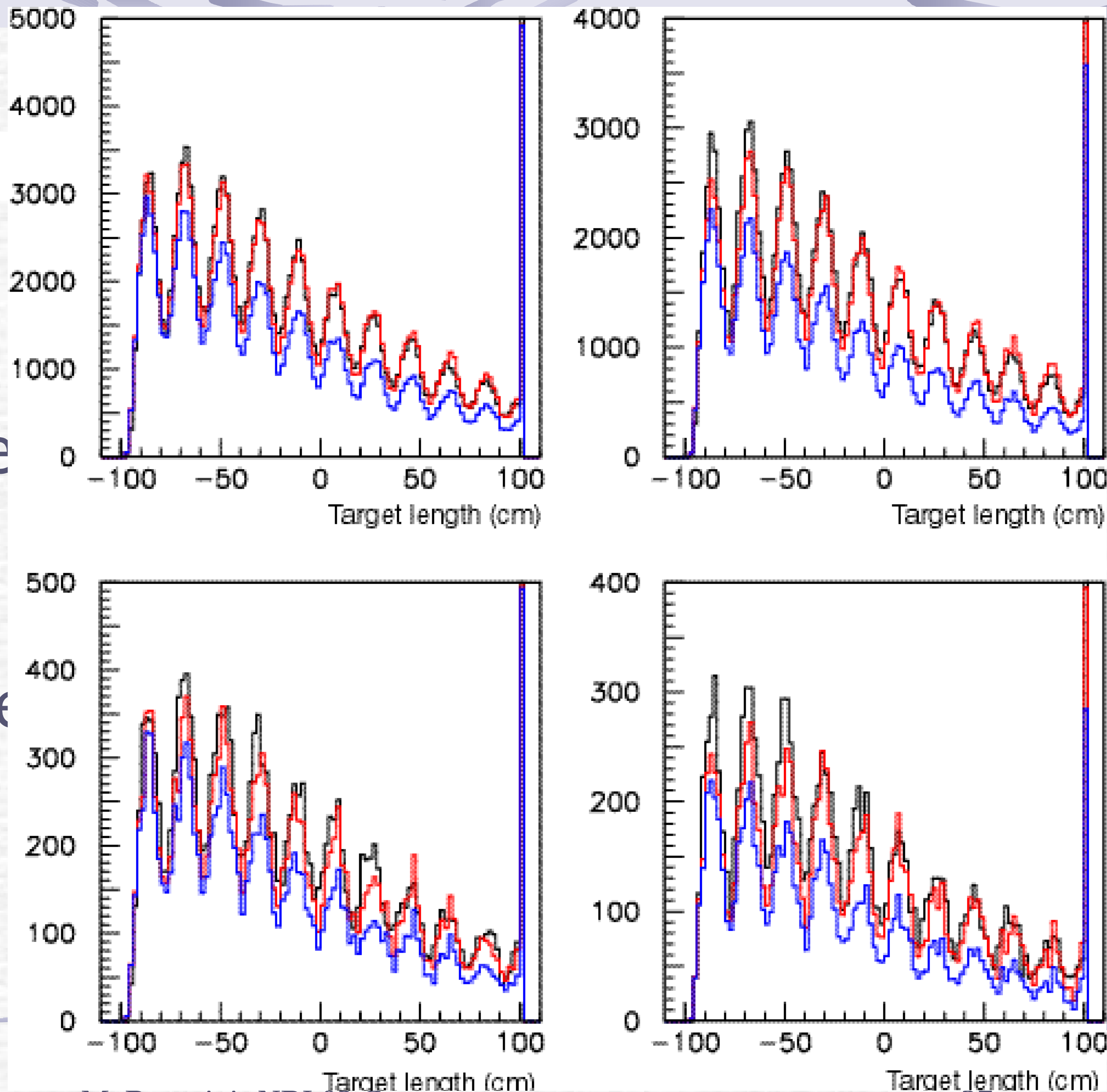
Tertiary production (modelled on NA56/SPY data)





WANF: Proton interactions in target

- 450 GeV protons
- Beryllium target
- 30 mrad acceptance

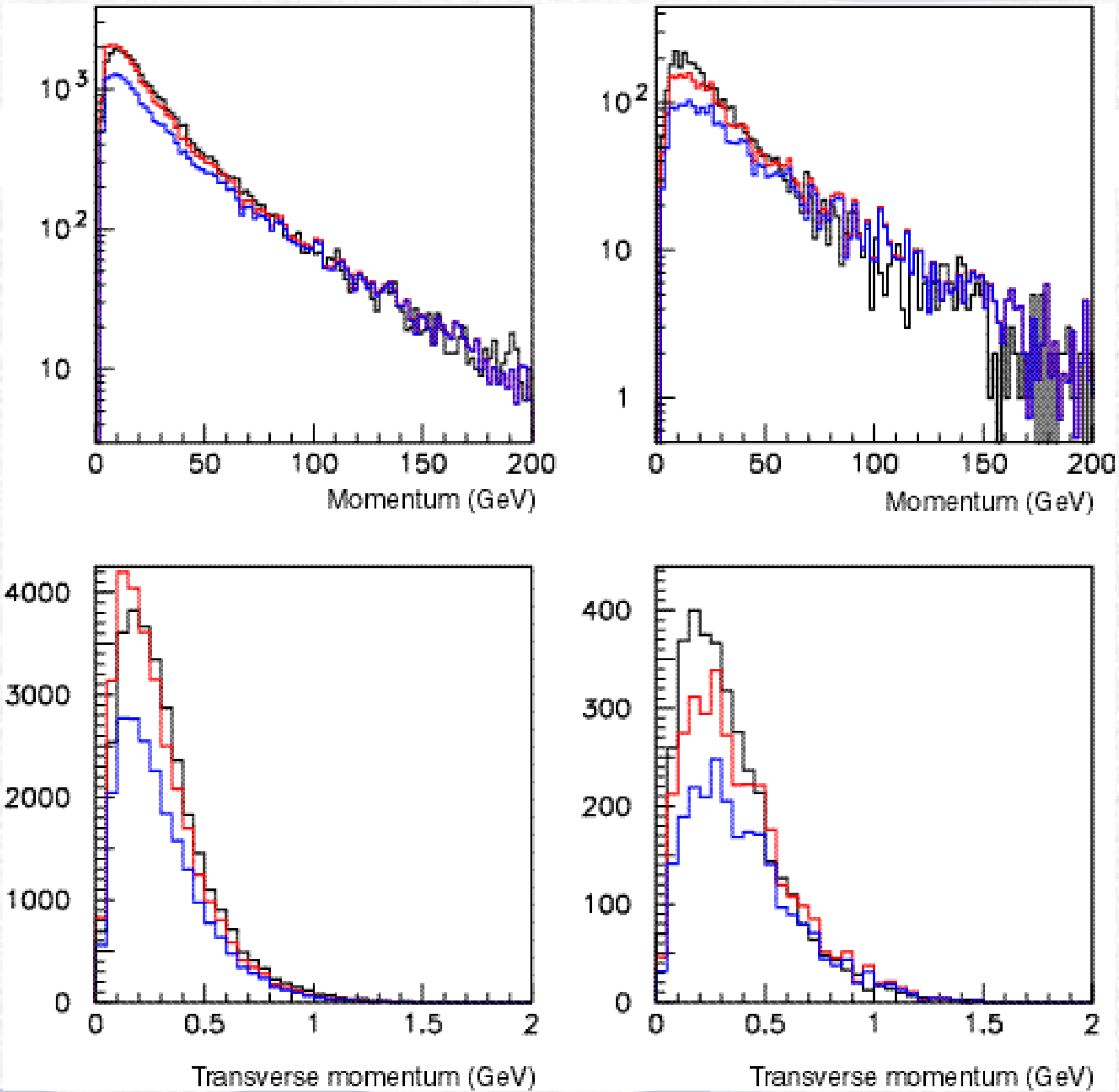


- Exit point from target
  - Black: Fluka
  - Blue: Secondaries only
  - Red: with Tertiaries

WANF: proton interactions in target

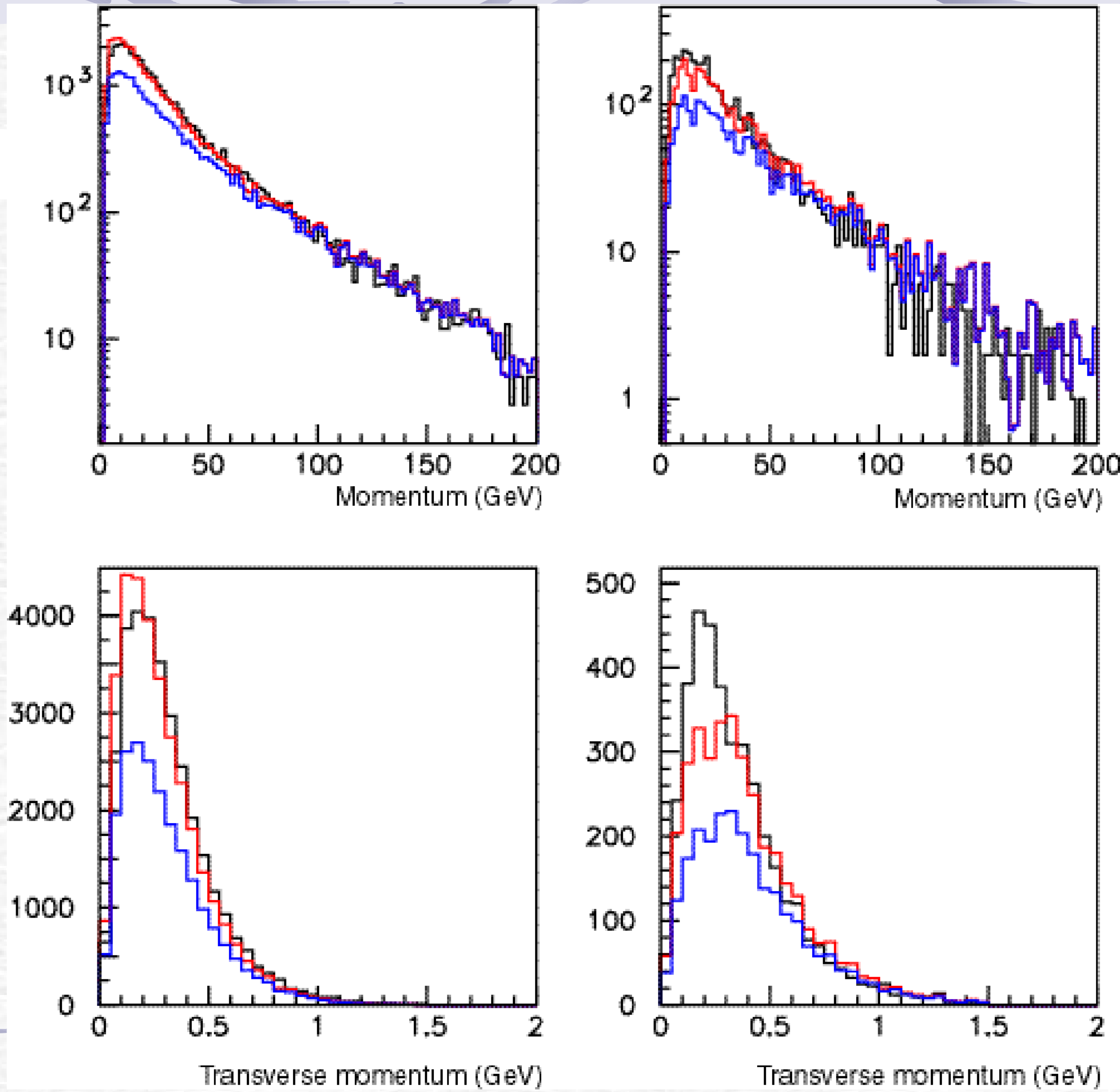
- 450 GeV p on Be target
- 30 mrad acceptance

p, p_T secondary mesons from target



CNGS: Proton interactions in target

- 400 GeV protons
- Graphite target
- 30 mrad acceptance



- p and p_T distributions:
  - Black: Fluka
  - Blue: Secondaries only
  - Red: with Tertiaries

CNGS: Proton interactions in target

- 400 GeV protons
- Graphite target
- 30 mrad acceptance

- Exit point from targe
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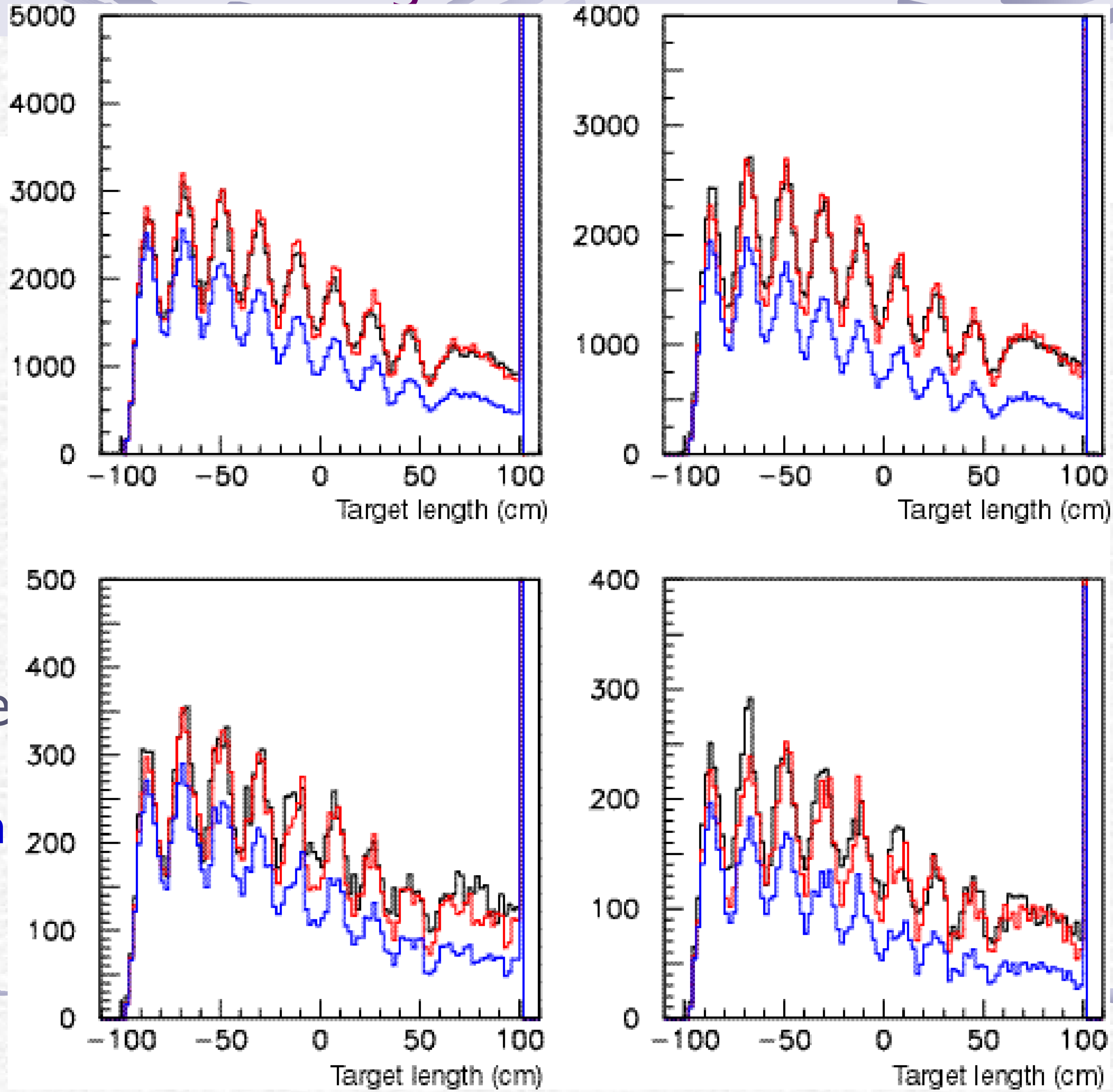


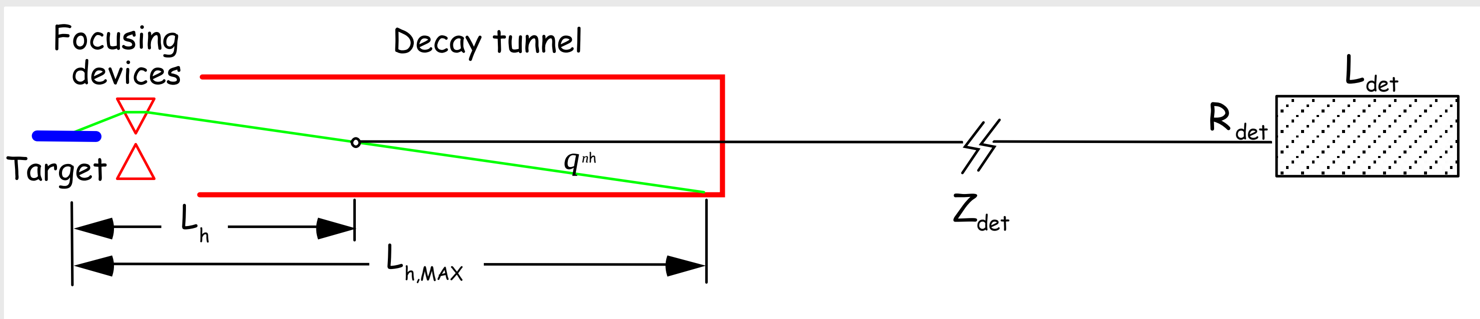
A fast neutrino beam simulation (based on BMPT parametrization)

- Secondary meson production from BMPT parametrization
- 3-dimensional description of all beamline elements
- Tracking of parent mesons
- Neutrino production from parent meson decay (2/3 body decay included)
- Useful to check parametrization, fast simulation tool to “debug” beamlines

A fast neutrino beam simulation: phase-space weighting

$$P = \left[\left(1 - e^{-\frac{L_{h,MAX}}{\lambda_h}}\right) e^{-\frac{L_h}{\lambda_h}} \right] \left[e^{-\frac{L_{mat}}{\lambda_{int}}} \right] \left[BR \rightarrow \frac{\nu_\mu \mu}{\nu_e x} \right] \left[\left(\frac{m_h}{E_h - p_h \cos \theta_{\nu h}} \right)^2 \right] \left[\sigma_0 \frac{m_h^2 - m_{\mu,x}^2}{2 m_h} \frac{m_h}{E_h - p_h \cos \theta_{\nu h}} \right] \left[\frac{\pi R_{det}^2}{4 \pi Z_{det}^2} N_A \rho_{det} L_{det} \right]$$

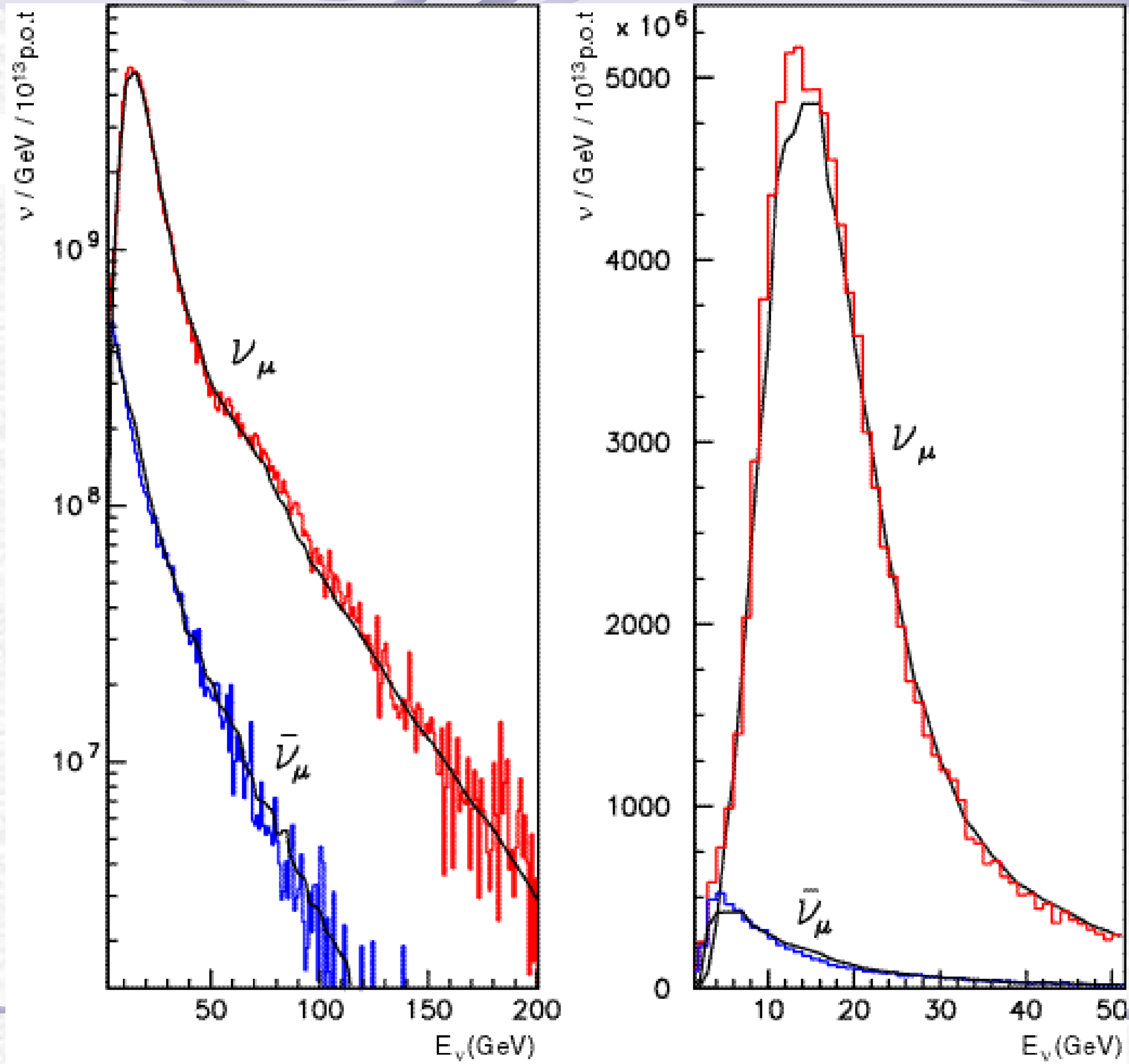
- Hadron decay inside the tunnel
- Interact. in material
- 2/3 body decay
- Probability that the ν is emitted in the detector direction
- ν momentum in lab frame
- Total ν cross-section
- Solid angle
- Nucleon target density in the detector



WANF: Comparison with CHARM II data

The CHARM II collab., Eur. Phys. J. C11 (1999), 18

- 450 GeV p on Be
- 8 mrad acceptance
- Detector at 881 m
- Positive focusing
  - ν_μ beam (10^5 pot)
  - CHARM II data
  - Anti- ν_μ contamination



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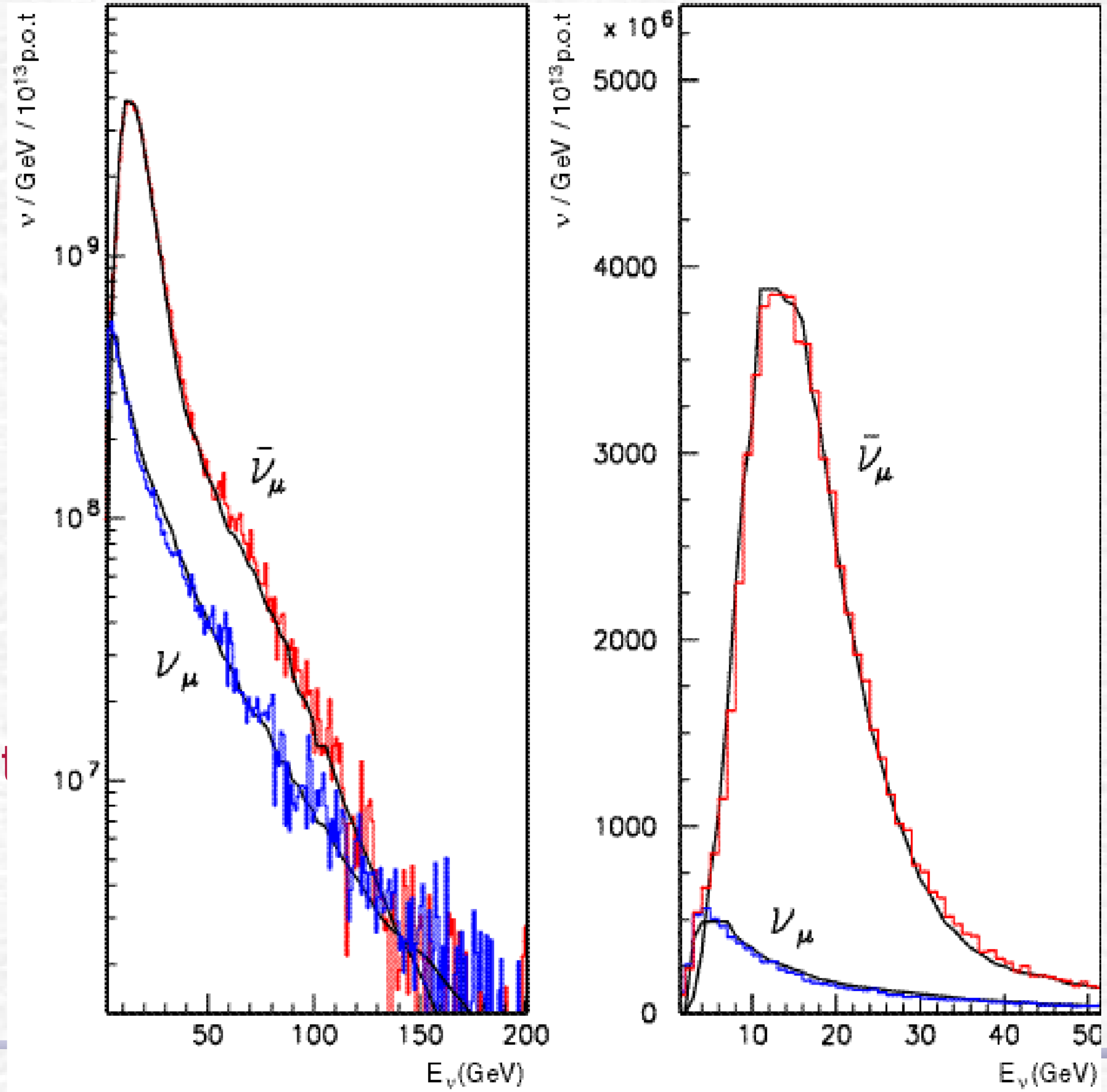
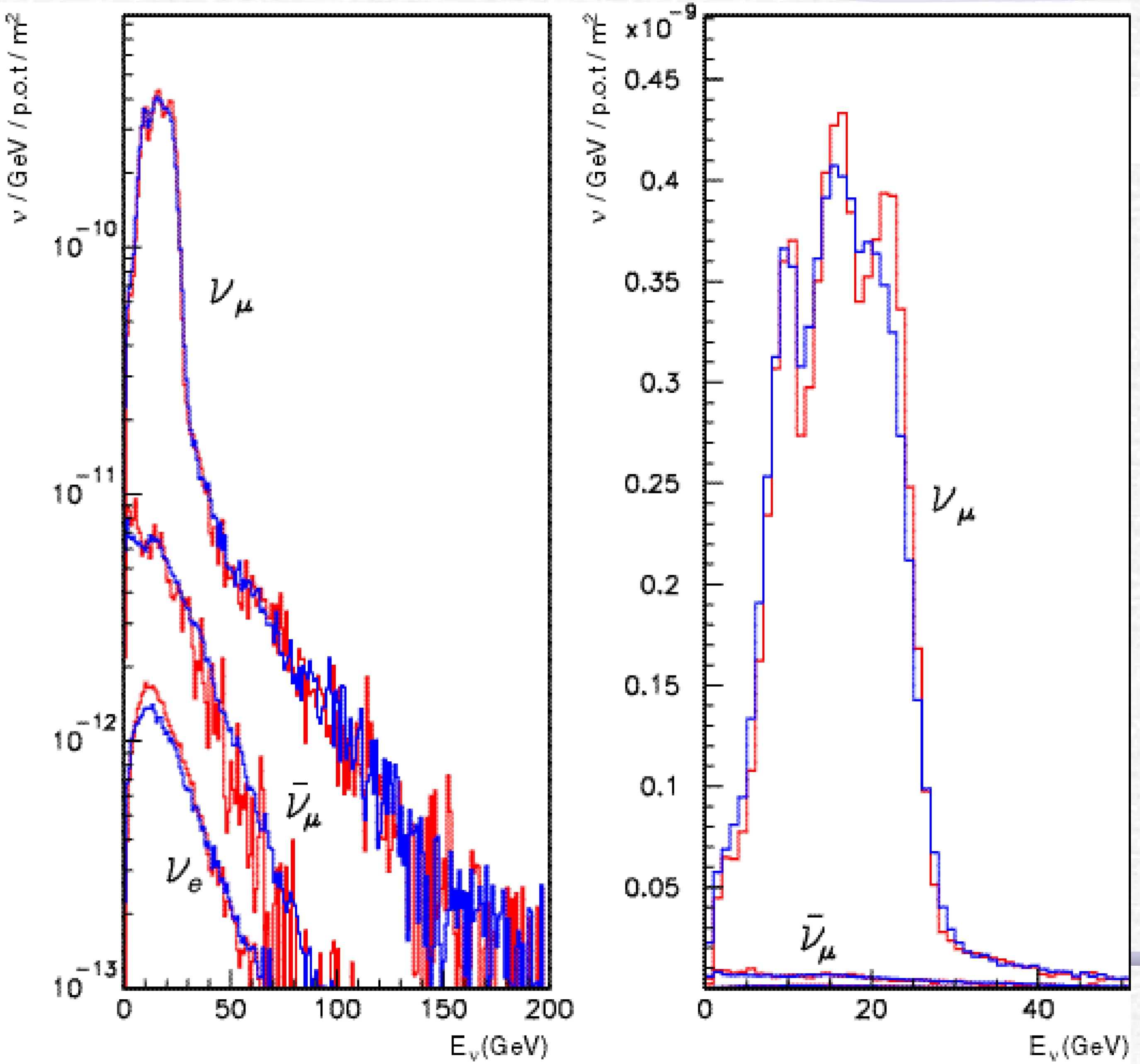


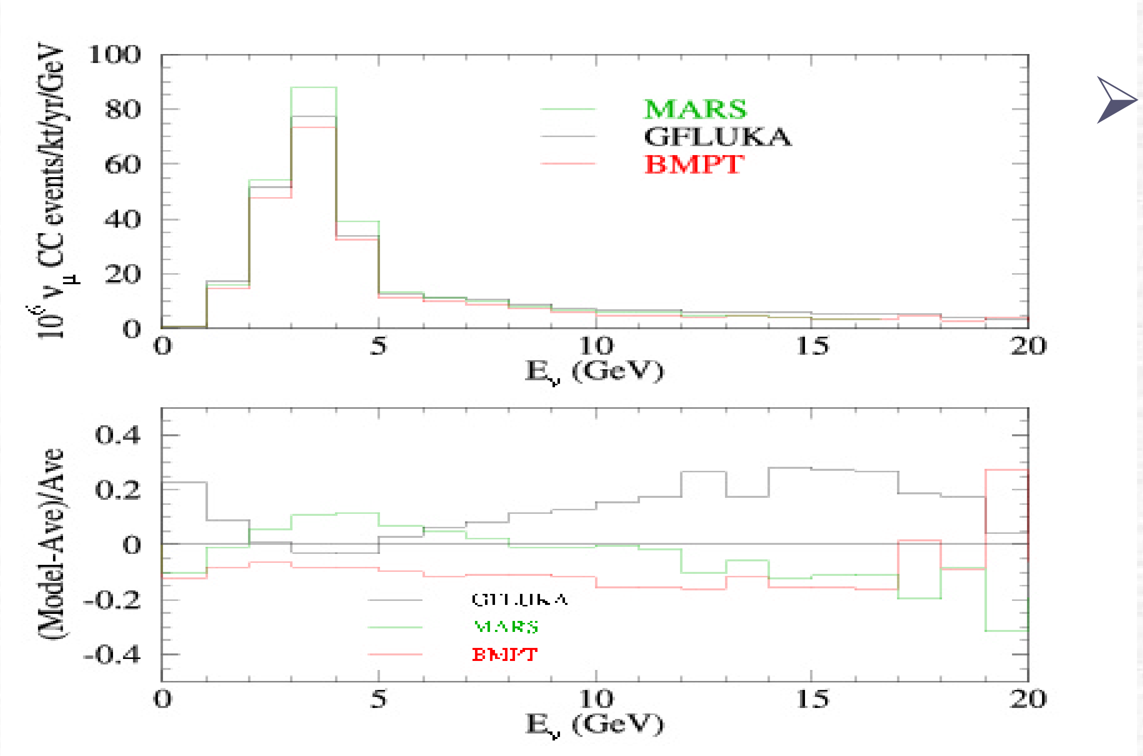
CNGS: Comparison with Fluka+Geant MC

R. Bailey et al., CERN-SL-99-034-DI, 1999

- 400 GeV protons on graphite target
- Positive focusing
- Detector at 732 Km
  - This simulation
  - Fluka+Geant MC



An application to NuMI



- Comparison BMPT, Mars, GFLUKA in Minos near detecor

What is next?

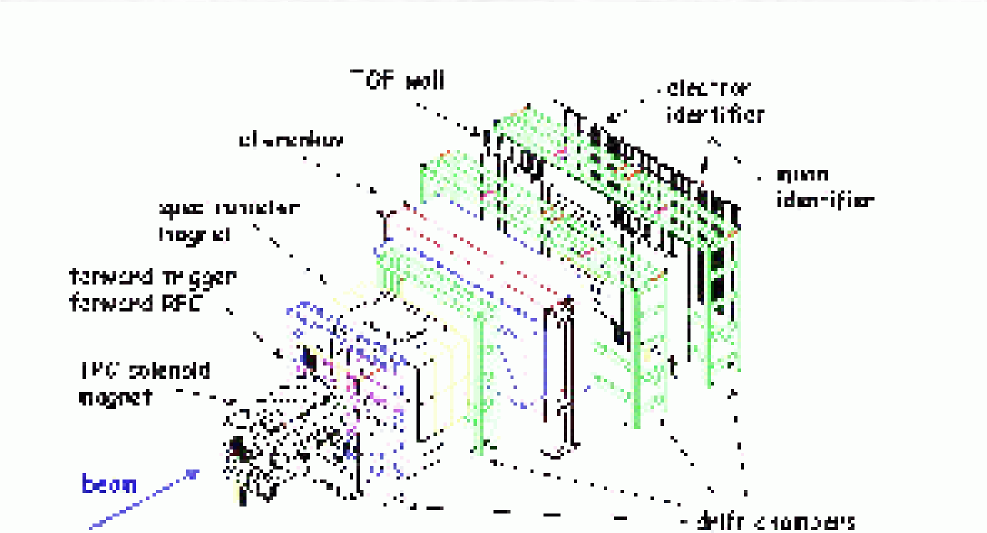
- New neutrino beams (K2K from 12 GeV/c proton synchroton, Miniboone from 8 GeV/c Booster at FNAL) +ν–factory need new hadroproduction data -> new round of experiments at lower energy
- Harp at Cern (2-24 GeV/c, full solid angle acceptance, many nuclear targets)
- P907 at FNAL

The existing "parametrizations" at low energy

- Sanford-Wang, "Empirical Formulas for particle production in p-Be collision between 10 and 35 BeV/c", preprint BNL
- Cocconi, Koester, Perkins, UCRL-10022
- Von Dardel, CERN/NP 62-17

❖ All apply to ν beams from incident protons at 10-30 GeV/c

Harp at the Cern PS



- 2-24 GeV/c incident p beam on nuclear targets (Be, C,Al, Cu, Sn, Ta, Pb, ... + Miniboone & K2K replica)
- Full solid angle acceptance
- PID for π/p separation

Aims: cross sections at a 2% precision

See next talk for details (A. Guglielmi)

Conclusions

- Good quality hadroproduction data available, but mainly in the forward direction. Wait for the next round (Harp, …) for lower energies and full solid angle.
- Parametrization of available high-energy data on particle production on light nuclei (BMPT):
  - Fits satisfactory the 400 & 450 GeV p-Be experimental data over a wide x and p_T range.
  - Can be safely extrapolated to thick target and to different proton momentum (® ˜ 24 GeV/c) and target material .
  - Can be applied to neutrino beam simulations:
    - Efficient (fast) alternative to full hadronic cascade codes
    - Reproduces existing data within ˜ 10% (CHARM II and ...)

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