Recent hadronic physics highlights

J.P. Wellisch
CERN/EP/SFT

Outline

- Neutron spectra from pre-equilibrium decay.
- qgs model for pion and kaon (and gamma) induced reactions
- Neutrons and doppler broadening on the fly
- Internal conversion, and the new photon evaporation data-base
- Gamma nuclear reaction cross-sections
- Chiral invariant phase-space decay
- The cascade codes
- A propagation test for quantum molecular dynamics

Swapping to show a few transparencies on pre-compound neutron yields.

J.P. Wellisch,
CERN/EP/SFT

Low energy neutrons: G4NDL0.2, 3.7

- Are granular selections of data from (alphabetic)
  - Brond 2.1
  - CENDL 2.2
  - EFF-3
  - ENDF/B (VI.0, VI.1, VI.5)
  - ENSDF
  - FENDL/E2.0
  - JEF 2.2
  - JENDL (3.1, 3.2, FF, 3.3 currently under study)
  - MENDL-2(P)
- Large parts of the selection is guided by the FENDL-2 selection
- G4NDL0.2 for non-thermal application

The neutron_hp transport models

- Simulate the cross-sections and interactions of neutrons with kinetic energies below 20 MeV down to thermal energies .
- The upper limit is set only by the evaluated data libraries the code is based on.
- We consider elastic scattering, fission, capture and inelastic scattering as separate models
- Neutron_hp sampling codes for the ENDF/B-VI derived data formats are completely generic (not including general R-matrix for the time being)
- Note that for fission there is a quite competitive theory driven alternative model, G4ParaFissionModel.

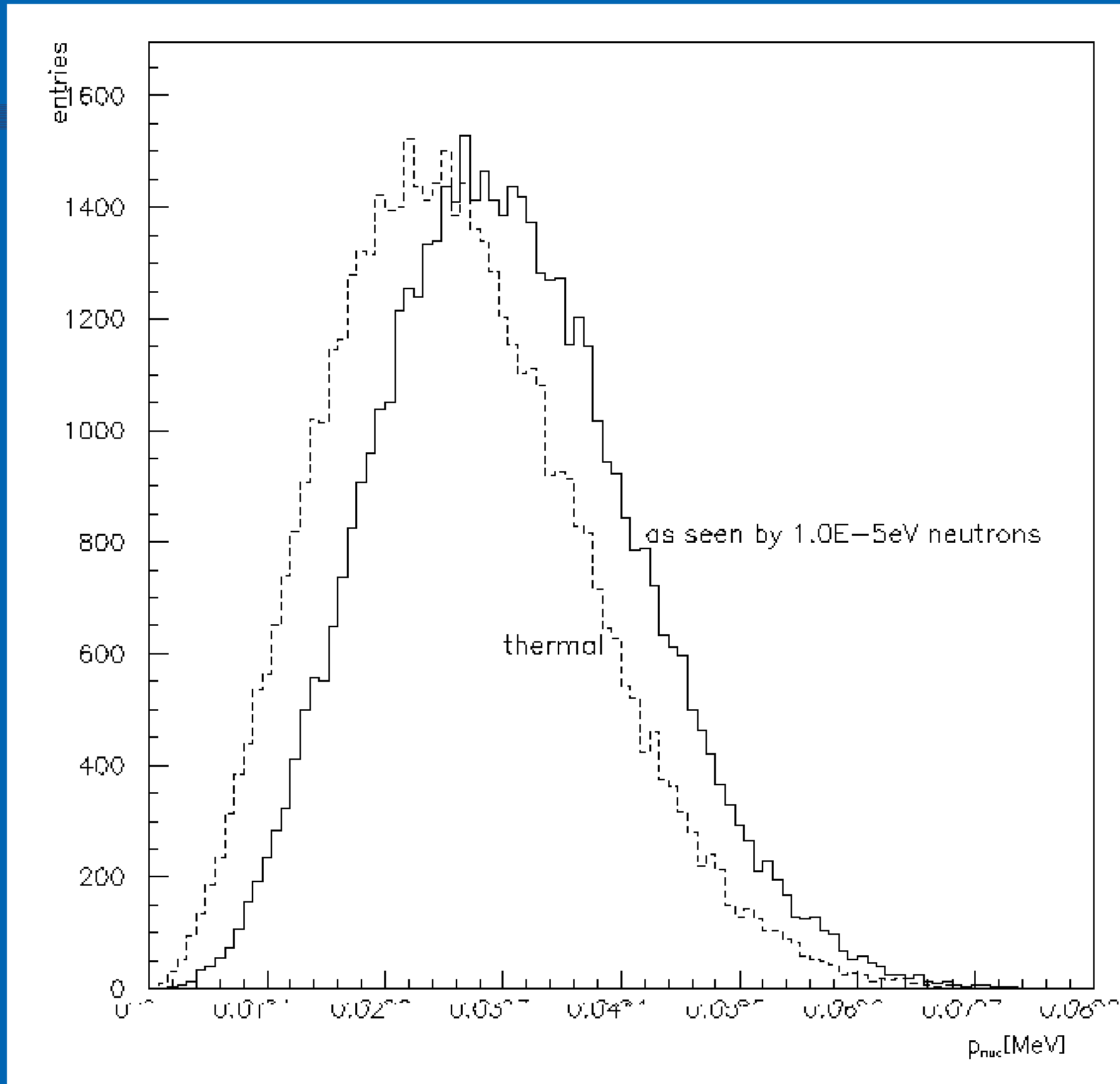
Models for neutron interaction and thermalization.

- neutron_hp models and cross-sections:
  - Uses the unix file-system to ensure granular and transparent access/usage of data sets.
  - More than 10^10 events run.
  - Uses point-wise cross-sections → no artifacts due to multi-group structure.

Doppler broadening

- Does exact doppler broadening on the fly, based on 0K data → no pre-formatting of data to fixed temperatures, and easy simulation of set-ups with mixed temperatures.
- Adds the doppler bias to the nuclear momentum distribution
- Point one is to the best of our knowledge not available from any other transport code (the second is also in MCNP).

The doppler bias illustrated for Carbon



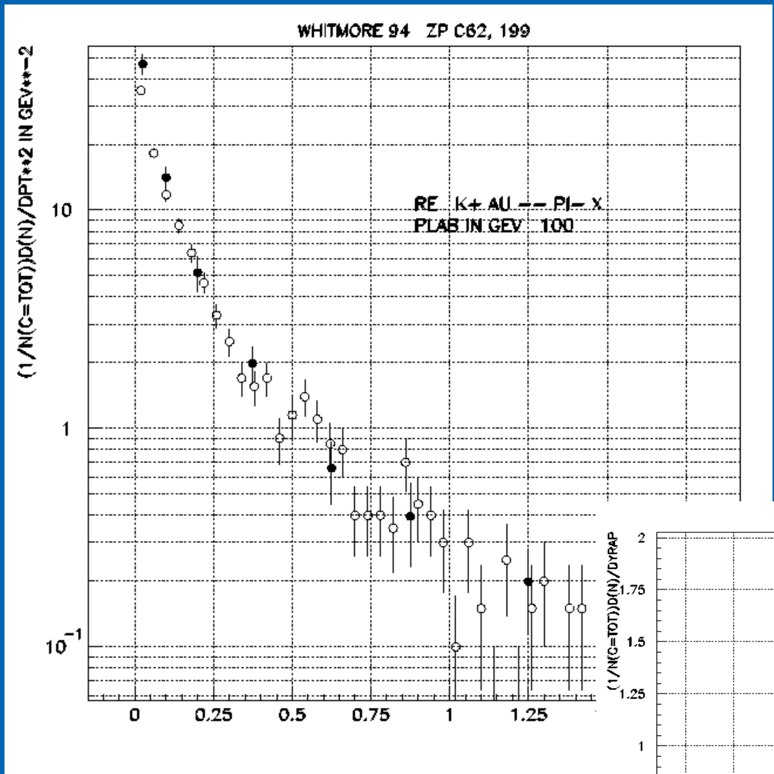
J.P. Wellisch,
CERN/EP/SFT

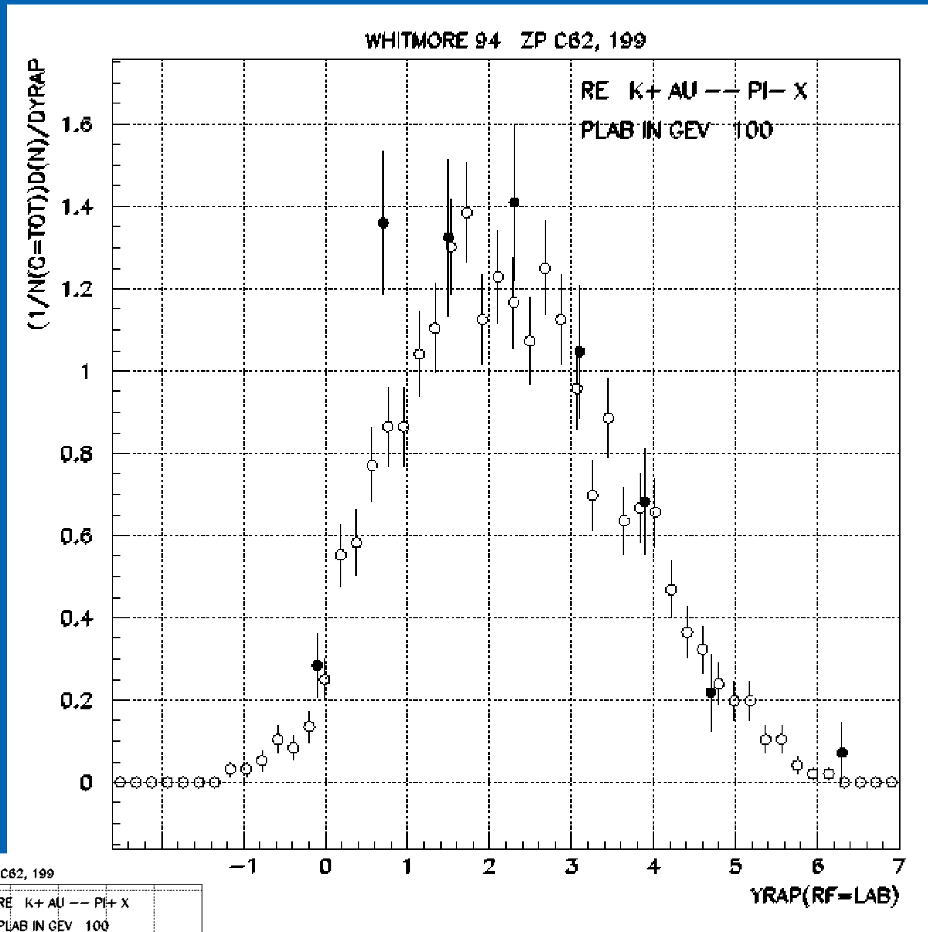
qgs model for π and K induced reactions

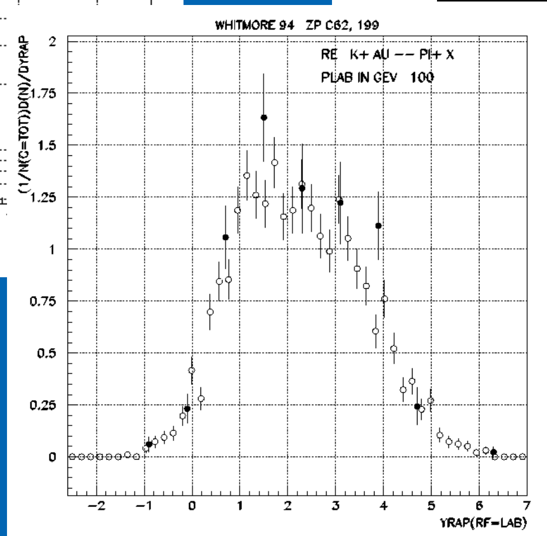
- Pomeron trajectory and vertex parameters tuned to describe elastic, total and diffractive (6% assumed) cross-sections for kaon and pion scattering off nucleons.
- No tuning on final state distributions.
- A few plots to illustrate the quality of prediction

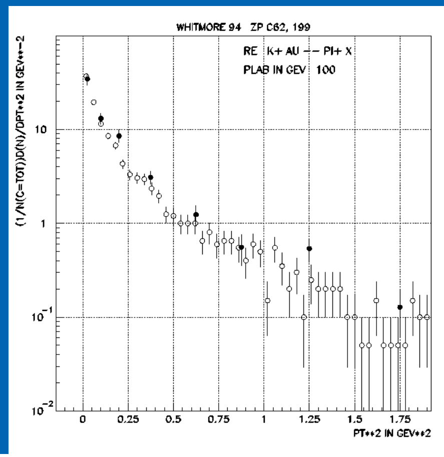
J.P. Wellisch,
CERN/EP/SFT

K-, scattering off Au





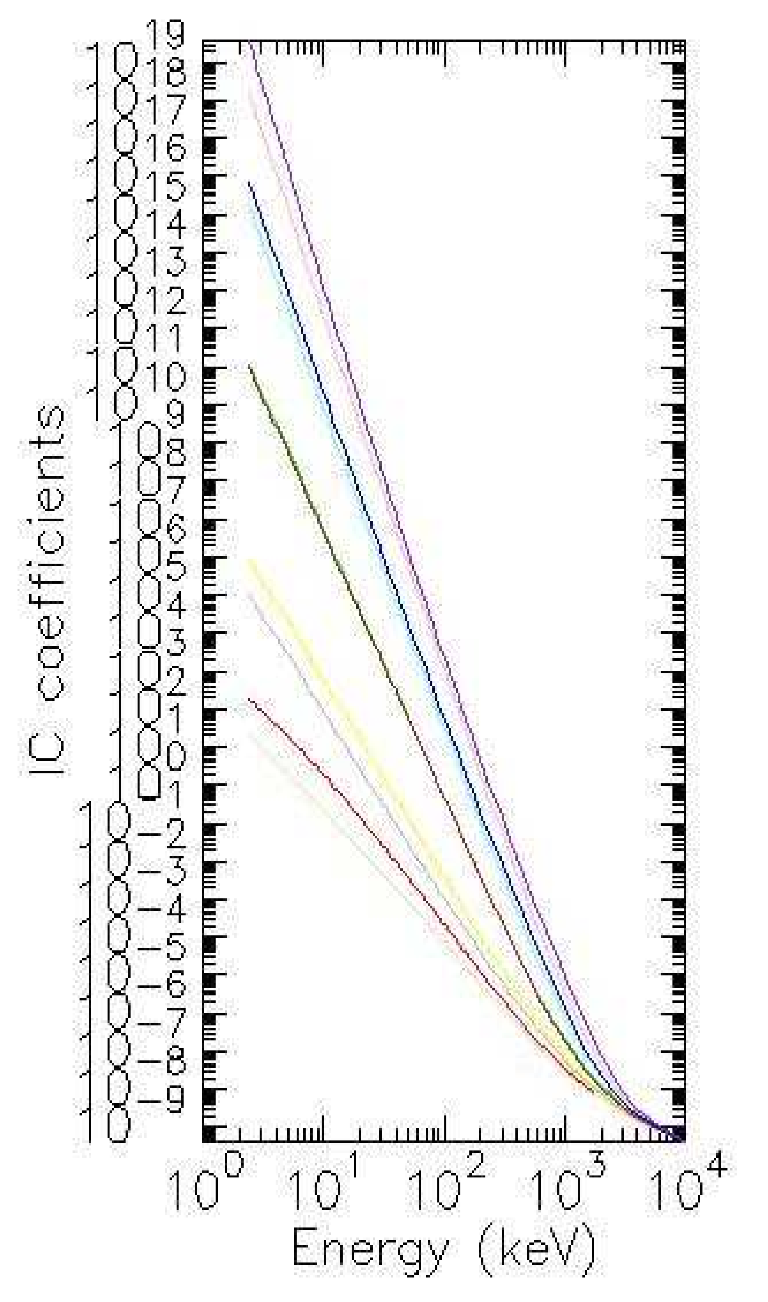




J.P. Wellisch,
CERN/EP/SFT

Photon Evaporation data base

- Originally containing adopted level and gamma-ray transition energies, photon intensity, multi-polarity, half-life and spin parity for isotopes up to Z=94, A=240
- Expanded to include probability of internal conversion and internal conversion coefficients (ICC) from shells K, L1, L2, L3, M1, M2, M3, M4, M5 and N+
- Based on ENSDF data from LBNL and tabulated theoretical ICC data from Band *et. al.* (used for Z ≤ 80) and Rösel *et . al.* (used 80 ≤ Z ≤ 96)



- ICCs are calculated by cubic spline interpolation using above tables at the required gamma-ray energy
- ICC calculated for Mixed multipolarity M1+E2 if mixing ratio available
- Some changes were introduced in the format of the data base entries to keep the size of the files down (data base is now 4.5 times larger)

Comparisons with the RADLIST program from BNL

- ENSDF decay data processed with RADLIST (BNL code) and Geant4 (for 2000 decays)

^{137}Cs

	RADLIST (BNL)		Geant4	
Radiation	Energy (keV)	Intensity (100dks)	Energy (keV)	Intensity (100dks)
CE K	624.216	7.66 (0.23)	624.216	8.70 (0.66)
CE L	655.668	1.39 (0.05)	655.668	1.15 (0.24)
γ	283.500	0.00058		
γ	661.657	85.1 (0.20)	661.657	84.15 (2.05)

^{57}Co

	RADLIST (BNL)		Geant4	
Radiation	Energy (keV)	Intensity (100dks)	Energy (keV)	Intensity (100dks)
CE K	7.301	71.00 (6.0)	7.301	70.55 (1.88)
CE			12.899	10.00 (0.70)
CE L	13.567	7.40 (0.6)	13.562	5.95 (0.54)
CE			13.687	0.35 (0.13)
CE			14.315	0.85 (0.21)
CE			14.405	0.45 (0.19)
CE K	114.949	1.83 (0.14)	114.949	1.95 (0.31)
CE			120.497	5.70 (0.53)
CE L	121.215	0.19 (0.020)		
CE M+	121.968	0.03 (0.005)		
CE K	129.361	1.30 (0.16)	129.362	1.25 (0.25)
CE			134.910	0.25 (0.11)
γ	14.413	9.16 (0.15)	14.413	10.05 (0.71)
γ	122.061	85.60 (0.17)	122.061	86.05 (2.07)
γ	136.474	10.68 (0.08)	136.474	10.05 (0.71)
γ	692.410	0.15 (0.01)	692.030	0.15 (0.09)

Chiral Invariant Phase-space Decay.

- A quark level 3-dimensional event generator for fragmentation of excited hadronic systems into hadrons.
- Based on the QCD idea of asymptotic freedom
- Local chiral invariance restoration lets us consider quark partons massless, and we can integrate the invariant phase-space distribution of quark partons and quark exchange (fusion) mechanism of hadronization
- The only non-kinematical concept used is that of a temperature of the hadronic system (quasmon).

Gamma nuclear reaction cross-sections

- New to geant, see the slides.

Vacuum CHIPS

- This allows to calculate the decay of free excited hadronic systems:
- In an finite thermalized system of N partons with total mass M, the invariant phase-space integral is proportional to M^{2N-4} , and the statistical density of states is proportional to $e^{-M/T}$. Hence we can write the probability to find N partons with temperature T in a state with mass M as

  $$dW \propto M^{2N-4} e^{-M/T} dM$$

- Note that for this distribution, the mean mass square is $\langle M^2 \rangle = 2N(2N-2)T^2$

Vacuum CHIPS

- We use this formula to calculate the number of partons in an excited thermalized hadronic system, and obtain the parton spectrum

$$\frac{dW}{kdk} \propto \left(1 - \frac{2k}{M}\right)^{N-3}$$

- To obtain the probability for quark fusion into hadrons, we can now compute the probability to find two partons with momenta q and k with the invariant mass μ.

$$P(k, M, \mu) = \int \left(1 - \frac{2q}{M\sqrt{1 - 2k/M}}\right)^{N-4} \times \delta\left(\mu^2 - \frac{2kq(1-\cos\theta)}{\sqrt{1-2k/M}}\right) qdqd\cos\theta$$

J.P. Wellisch,
CERN/EP/SFT

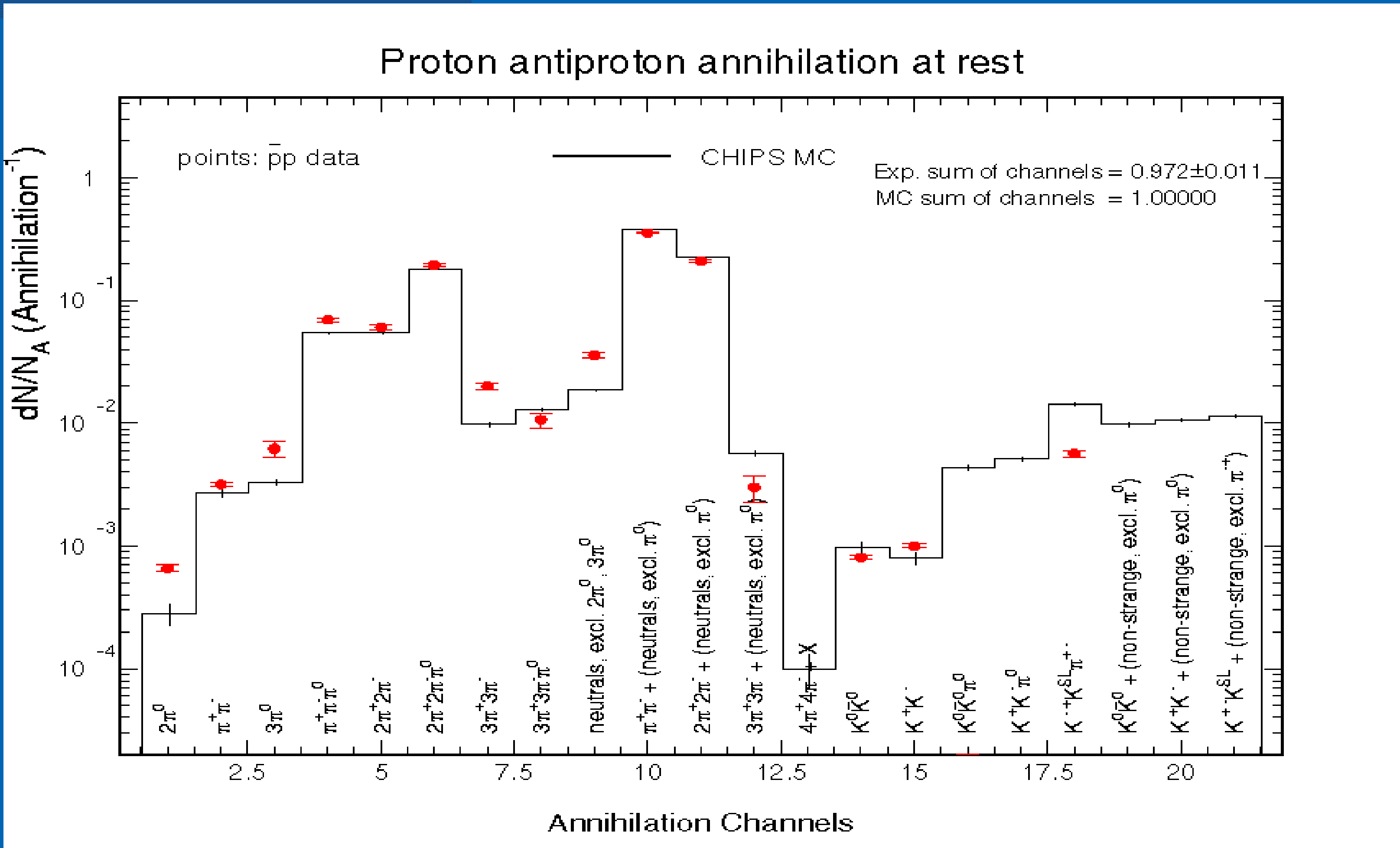
Vacuum CHIPS

- Using the delta function to perform the integration and the mass constraint, we find the total kinematical probability of hadronization of a parton with momentum k into a hadron with mass μ:

$$\frac{M-2k}{4k(N-3)}\left(1-\mu^2/2kM\right)^{N-3}$$

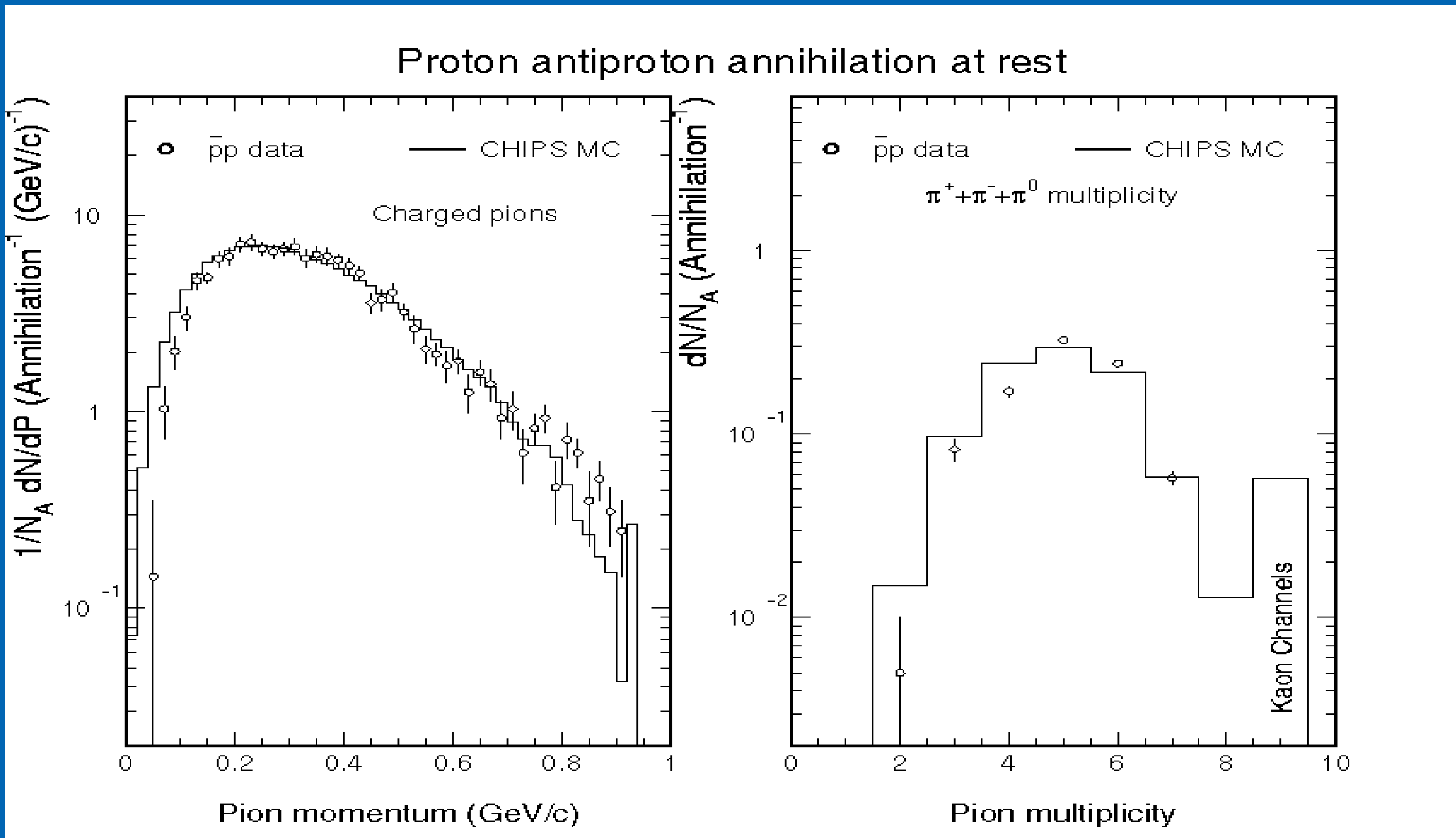
- Accounting for spin and quark content of the final state hadron adds (2s+1) and a combinatorial factor.
- At this level of the language, CHIPS can be applied to p-pbar annihilation

Anti proton annihilation



J.P. Wellisch,
CERN/EP/SFT

Anti proton annihilation



J.P. Wellisch,
CERN/EP/SFT

Nuclear CHIPS

- In order to apply CHIPS for an excited hadronic system within nuclei, we have to add parton exchange with nuclear clusters to the model
- The kinematical picture is, that a color neutral quasmon emits a parton, which is absorbed by a nucleon or a nuclear cluster. This results in a colored residual quasmon, and a colored compound.
- The colored compound then decays into an outgoing nuclear fragment and a 'recoil' quark that is incorporated by the colored quasmon.

Nuclear CHIPS

- Applying mechanisms analogue to vacuum CHIPS, we can write the probability of emission of a nuclear fragment with mass μ as a result of the transition of a parton with momentum k from the quasmon to a fragment with mass μ′ as:

$$P(k,\mu',\mu)=\int\left(1-\frac{2(k-\Delta)}{\mu'+k(1-\cos\theta_{kq})}\right)^{n-3}\frac{\mu'(k-\Delta)}{2\left[\mu'+k(1-\cos\theta_{kq})\right]^{2}}\,d\cos\theta_{kq}$$

- Here, n is the number of quark-partons in the nuclear cluster, and Δ is the covariant binding energy of the cluster, and the integral is over the angle between parton and recoil parton.

Nuclear CHIPS

- To calculate the fragment yields it is necessary to calculate the probability to find a cluster of ν nucleons within a nucleus. We do this using the following assumptions:
  - A fraction ε1 of all nucleons is not clusterising
  - A fraction ε2 of the nucleons in the periphery of the nucleus is clustering into two nucleon clusters
  - There is a single clusterization probability ω
- and find, with a being the number of nucleons involved in clusterization

$$P_\nu = \frac{C_\nu^a \omega^{\nu-1}}{(1+\omega)^{a-1}}$$

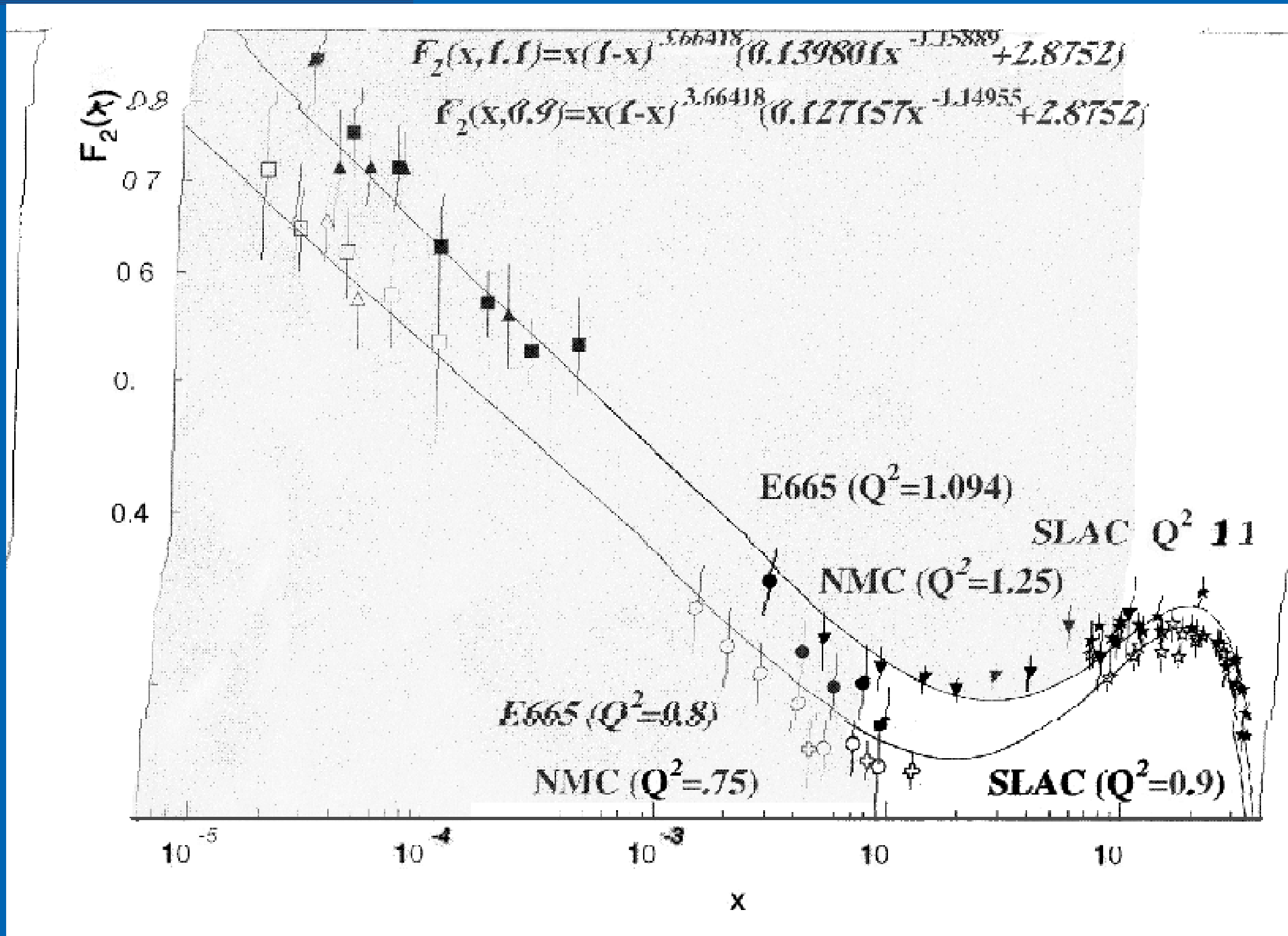
Nuclear CHIPS

- At this level of the language, CHIPS can be applied to capture of pions and photo-nuclear reactions.

Intra-nuclear CHIPS

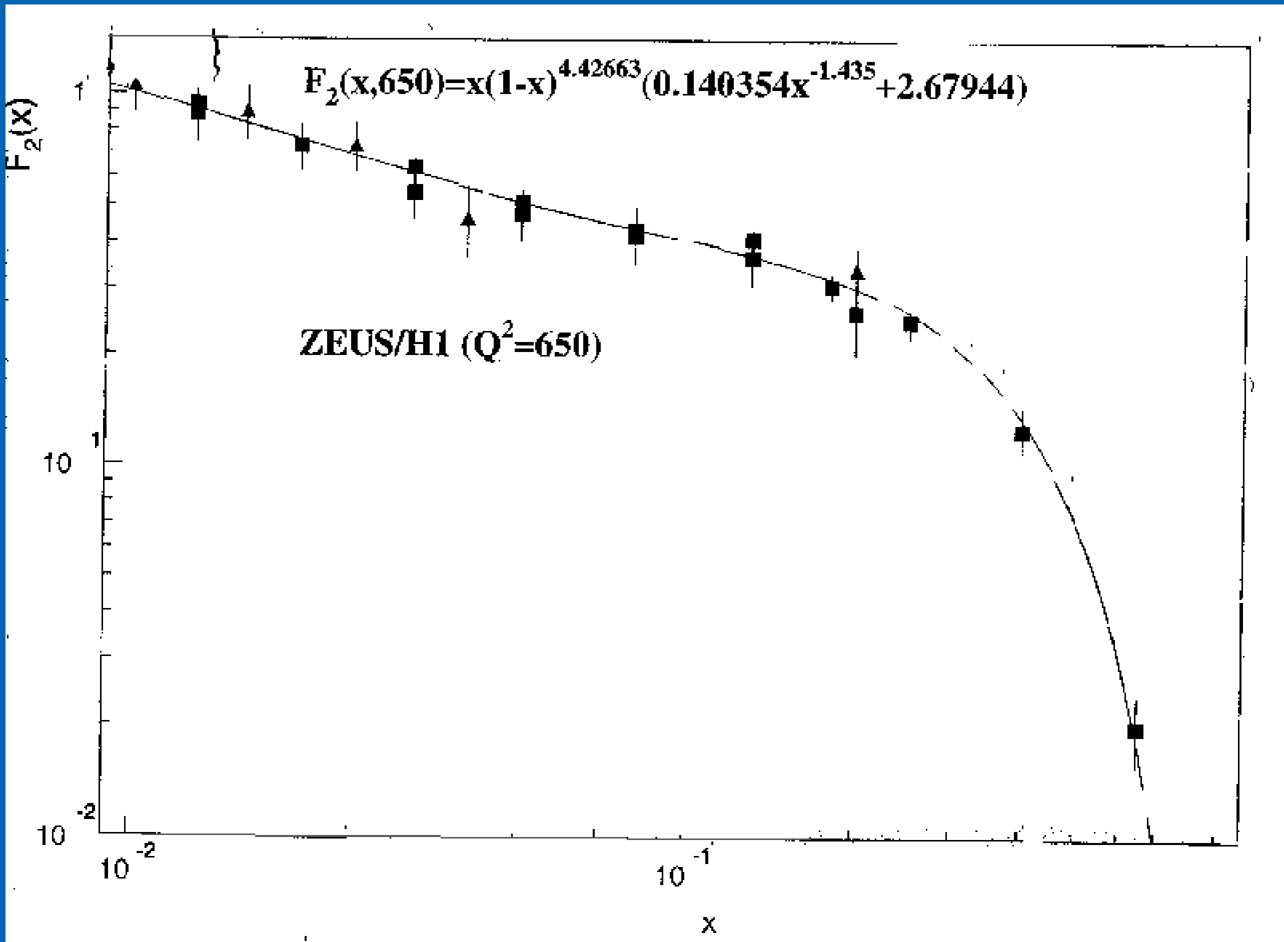
- Extensions to include the behavior of multiple quasmons within one nucleus have been added.

Hard scattering in electro-nuclear



J.P. Wellisch,
CERN/EP/SFT

Hard scattering in electro-nuclear

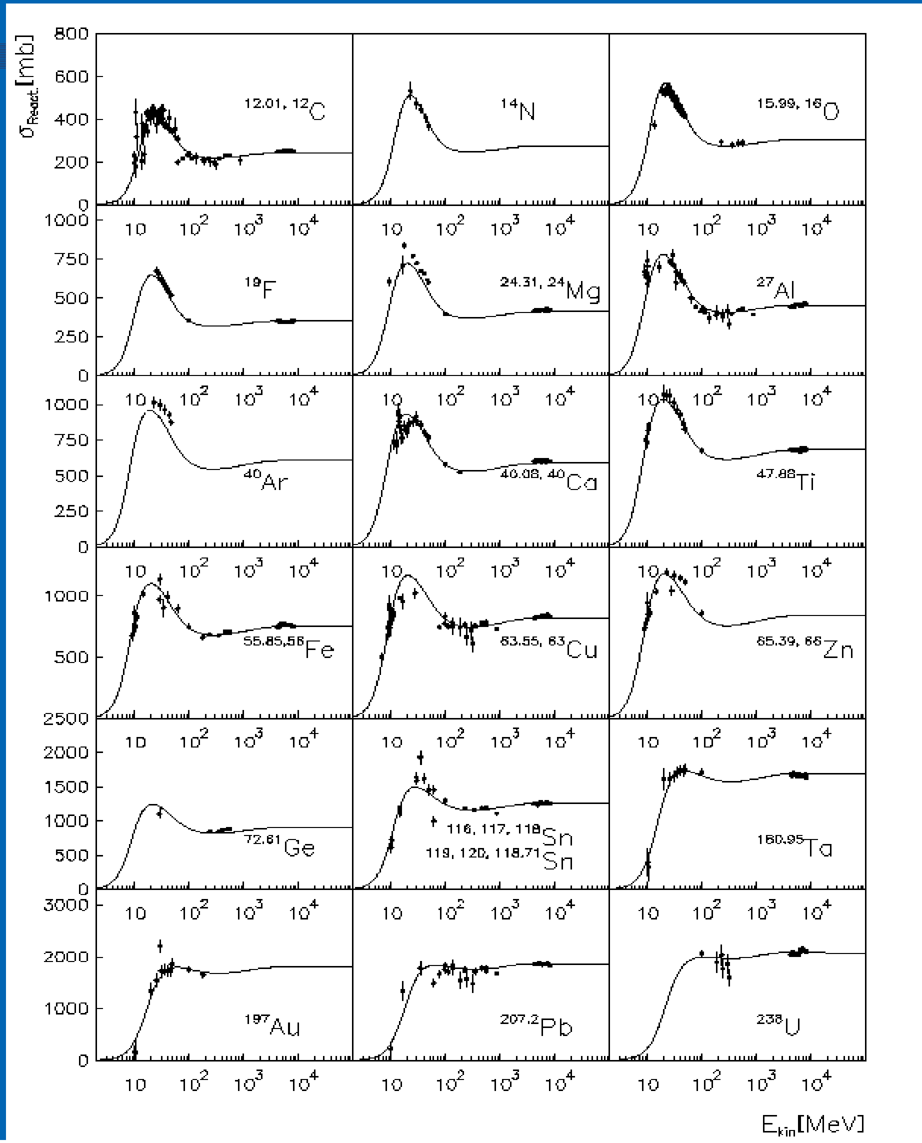


J.P. Wellisch,
CERN/EP/SFT

Final states for proton induced reactions

- Two cascade codes to be released on 5.0 (if all goes well)
  - A kinetic cascade
  - A re-write of HETC

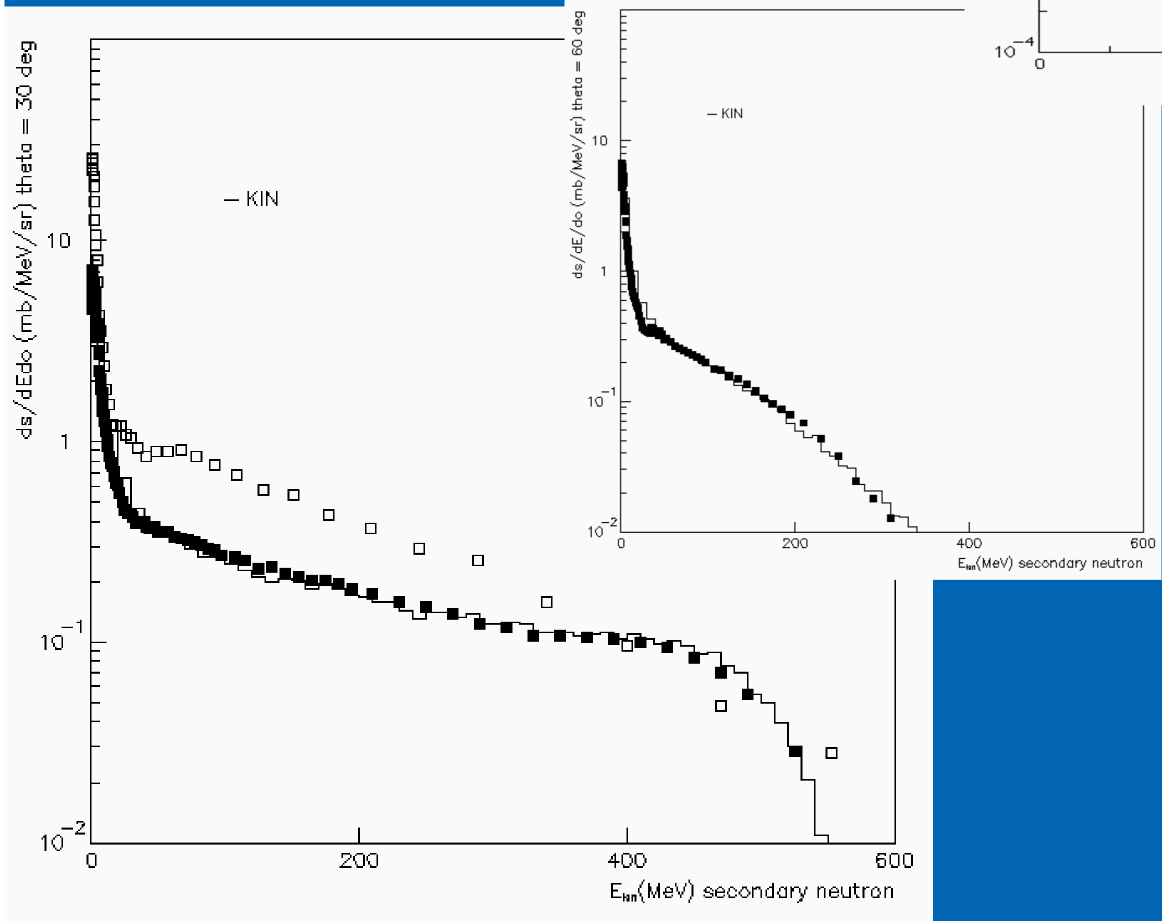
Proton induced reactions

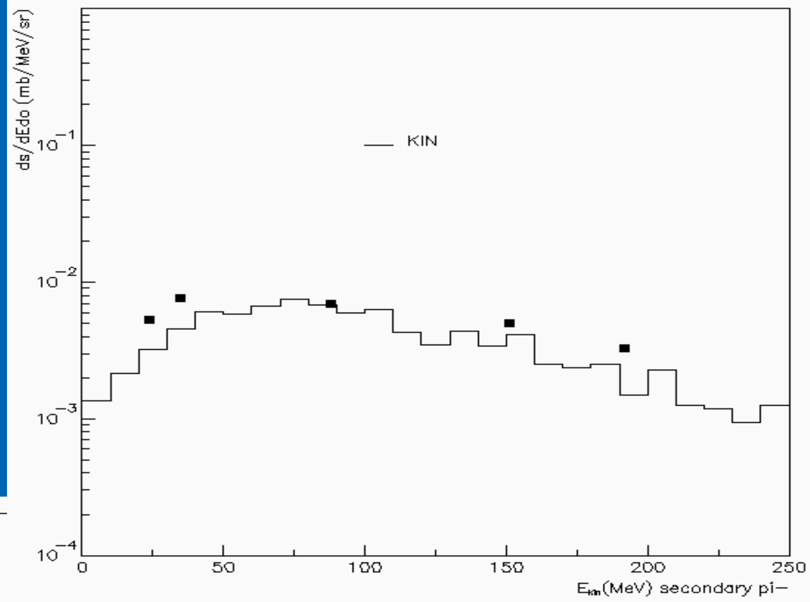


J.P. Wellisch,
CERN/EP/SFT

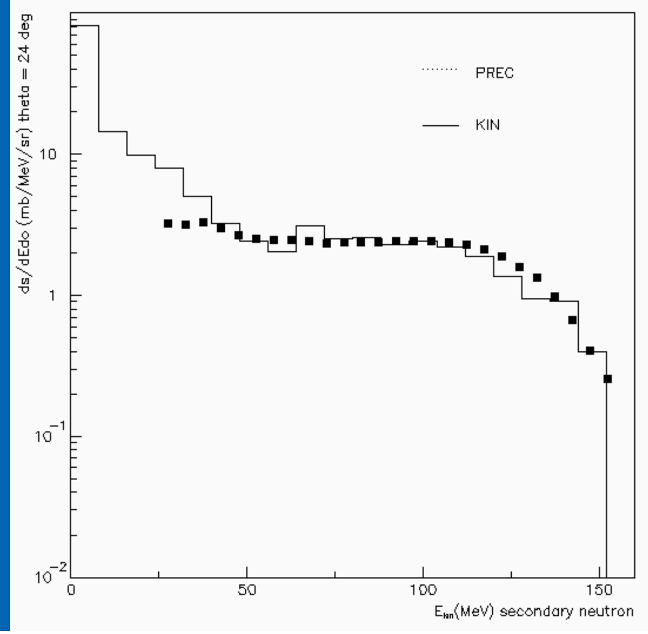
Preview on kinetic cascade

585MeV p on Al, forward
And backward n and π

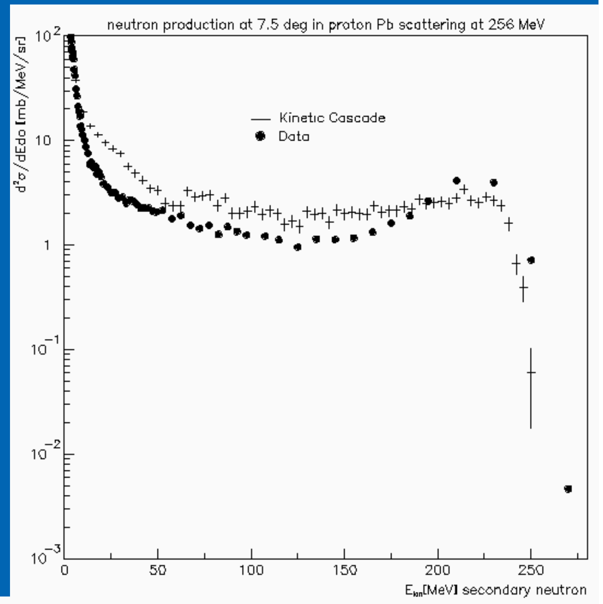


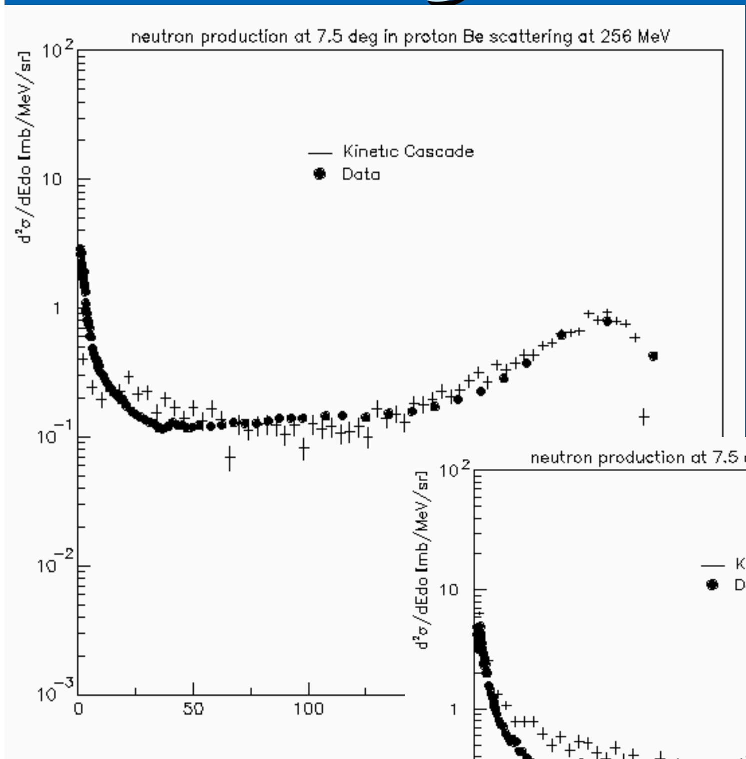


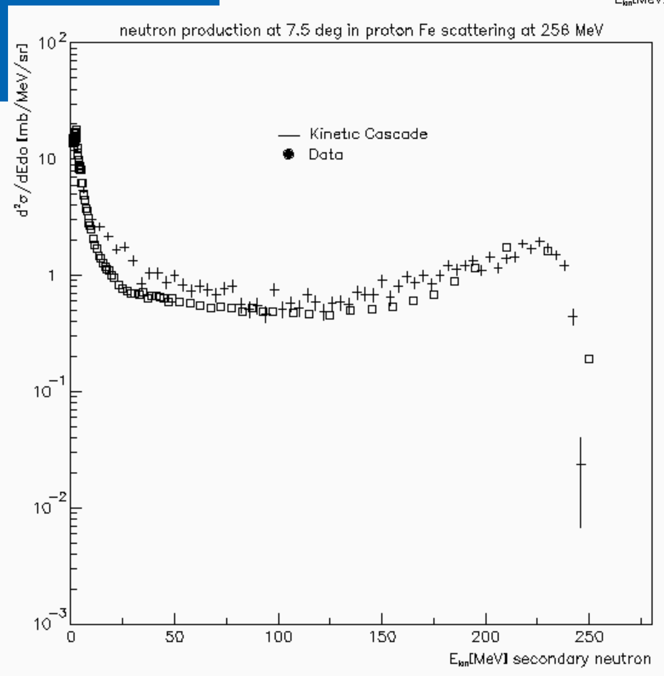
160 MeV p on Pb,
forward neutrons

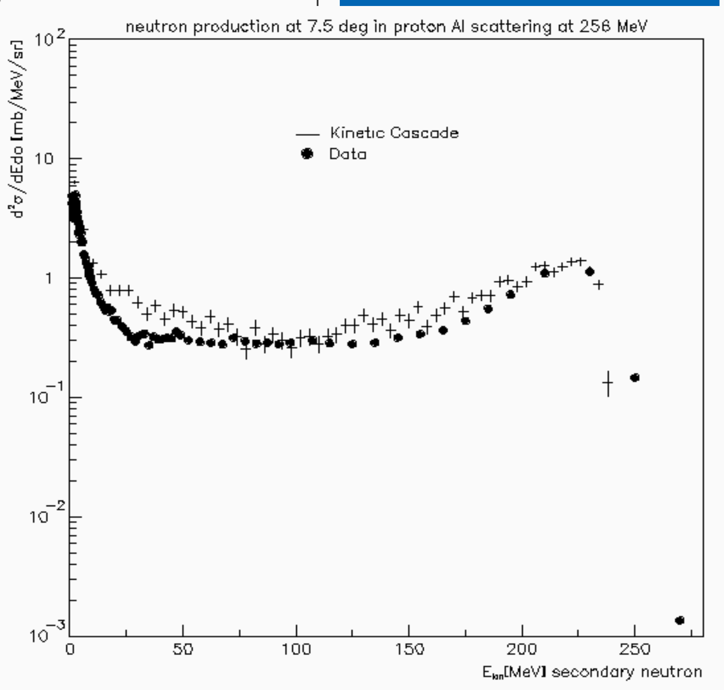


Quasi-elastic peaks in proton scattering (256 MeV)







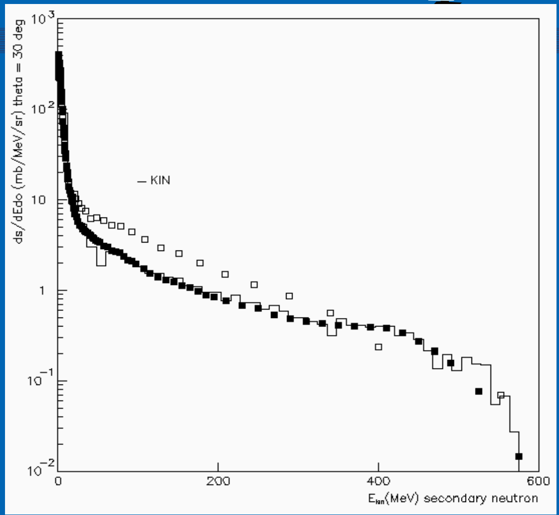


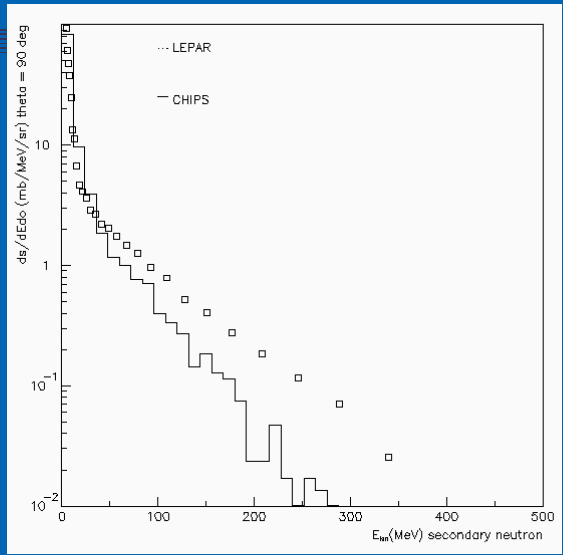
J.P. Wellisch,
CERN/EP/SFT

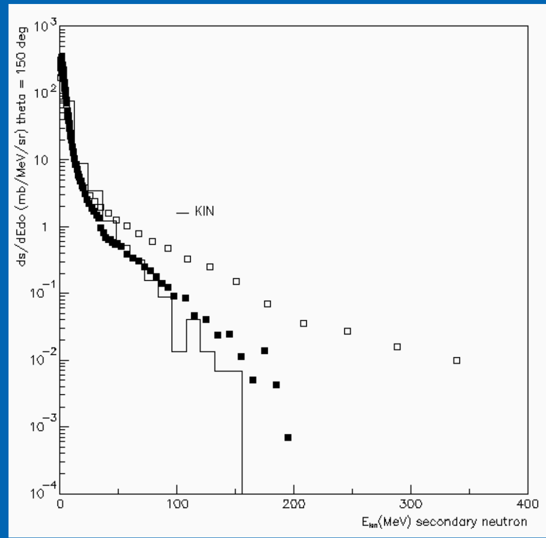
The cascade verification suite (CERN/SLAC)

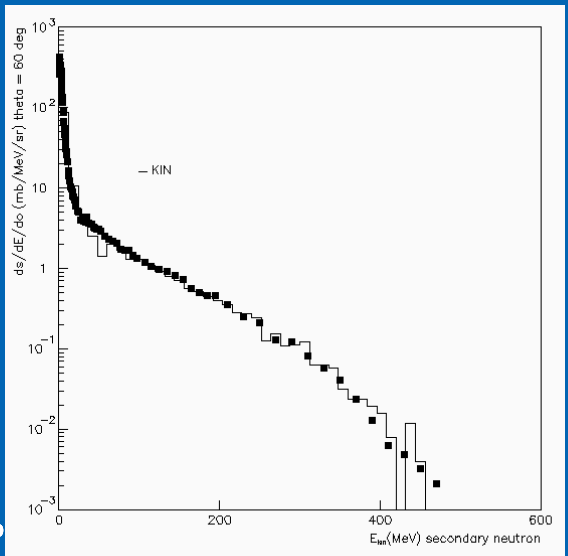
- Materials: H, d, Be, C, Al, Fe, Ni, Zr, Pb.
- Be: 113, 256, 585, 800 MeV
- C: 113, 590, 800 MeV
- Al: 22, 39, 90, 113, 160, 256, 585, 800 MeV
- Fe: 22, 65, 113, 256, 597, 800 MeV
- Ni: 200, 585 MeV (for pion production)
- Zr: 22, 35, 50, 120, 160, 256, 800 MeV
- Pb: 35, 65, 120, 160, 256, 597, 800 MeV
- H, d: pion production at 585 MeV
- More being added as we speak.

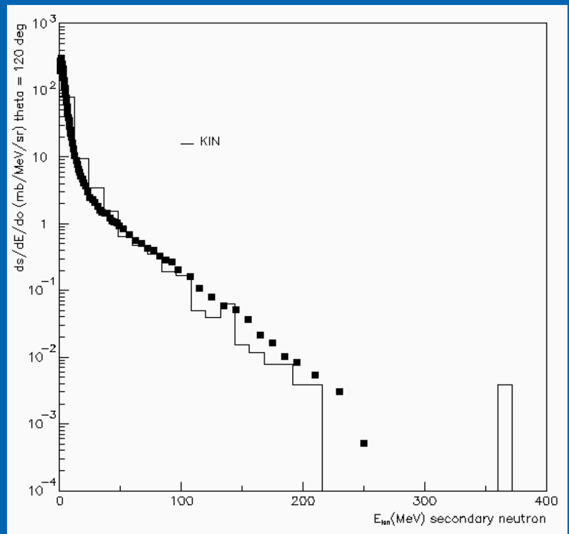
One example:
597 MeV p on Pb





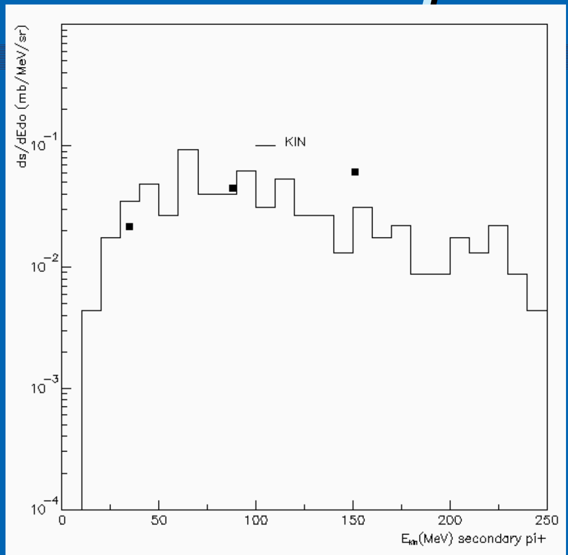


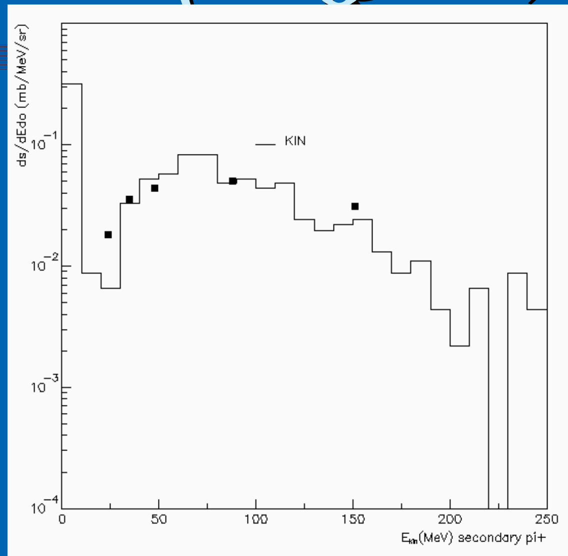


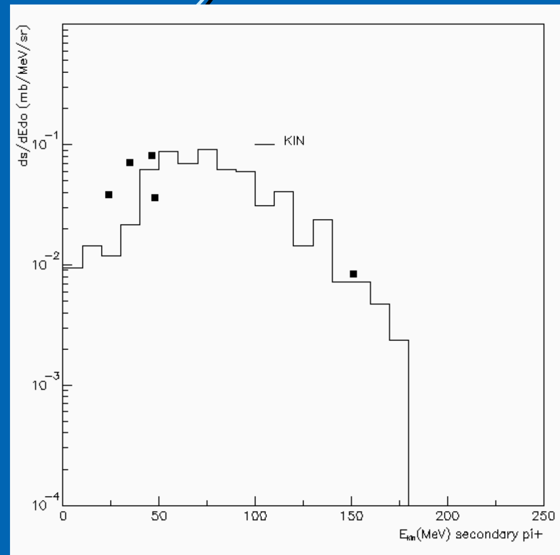


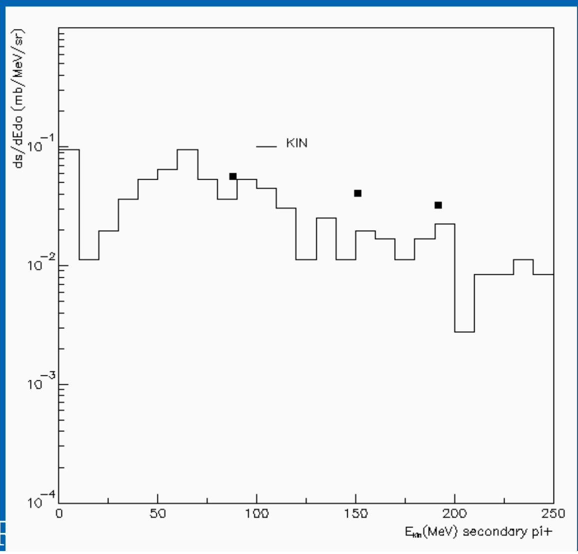
Neutron production
At 30, 60, 90, 120
And 150 degrees

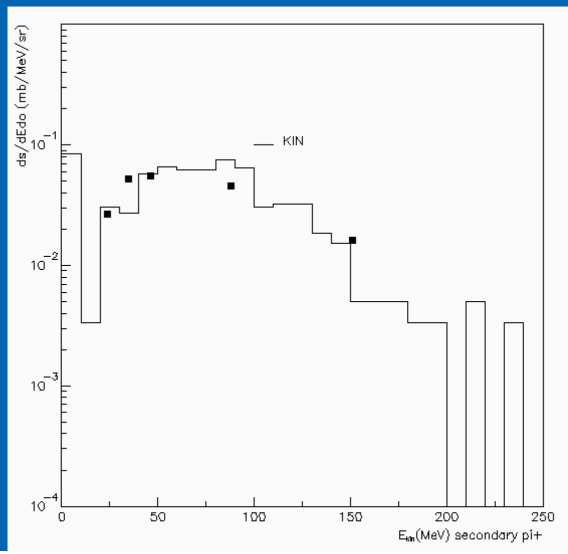
One complete example: 597 MeV p on Pb (PRC 22, p1184)





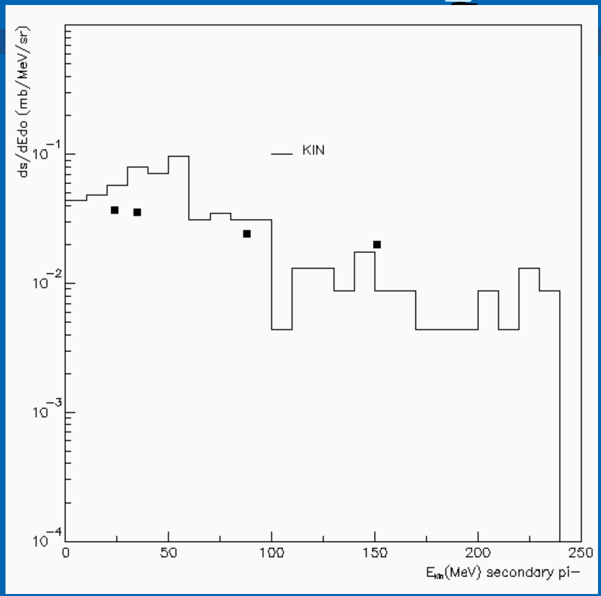


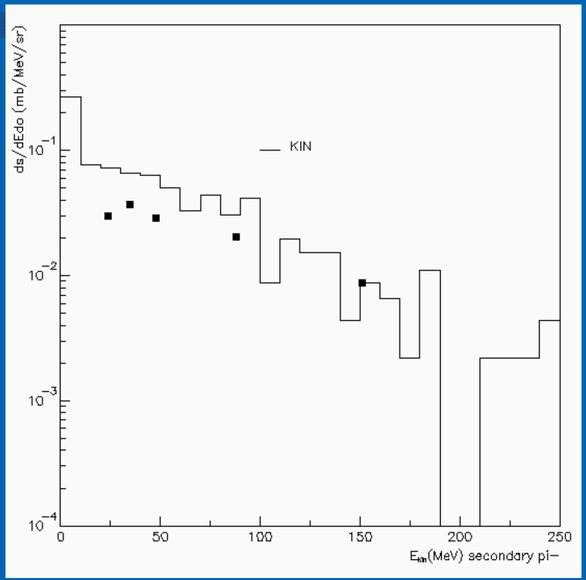


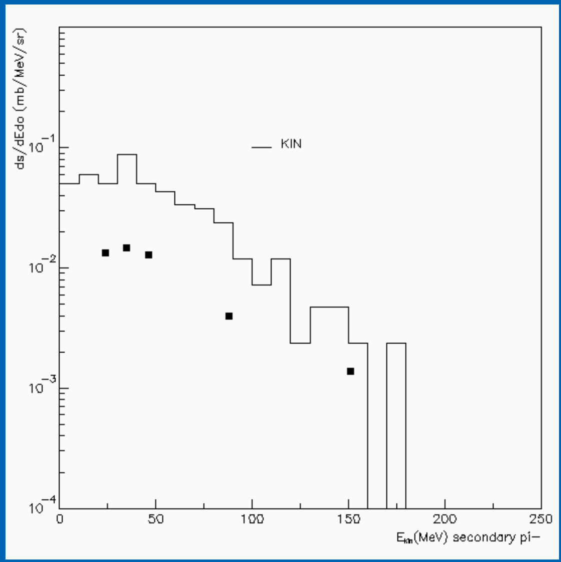


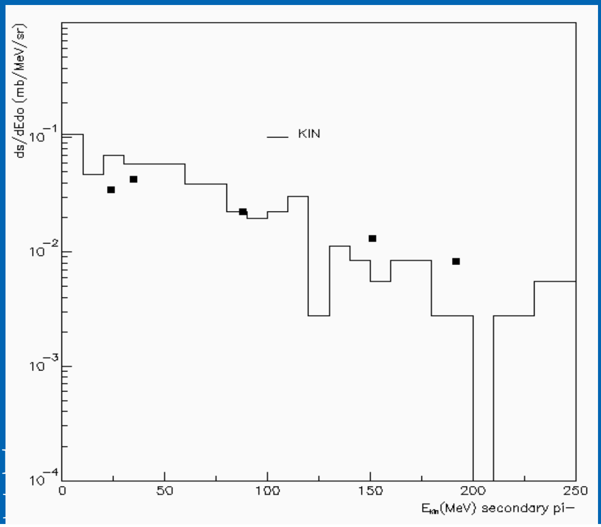
Pi+ production at 22.5, 45, 60, 90, And 130 degrees

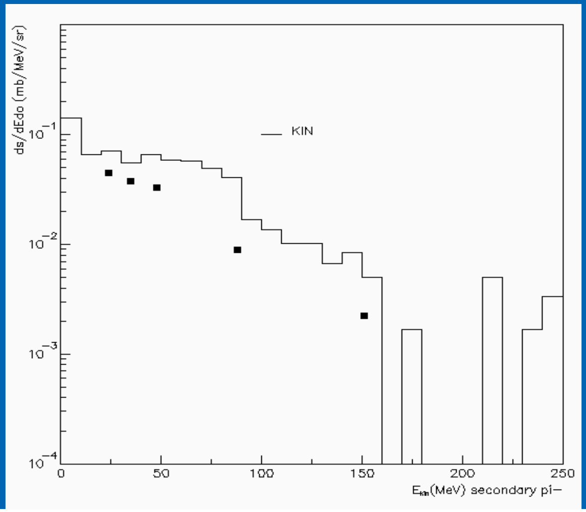
One complete example:
597 MeV p on Pb (PRC 22, p1184)











Pi- production at
22.5, 45, 60, 90,
And 130 degrees

A propagation test for QMD development

- Some characteristics of QDM:
  - A kinematical cascade with detailed modeling of the nucleus.
  - Nuclear Hamiltonian calculated from 2 and 3 body potentials of all hadrons present in the system.
  - Solving the equation of motion by integrating this time-dependent Hamiltonian.
  - Scattering term in terms of localized interactions and decays.
  - Etc..