High energy probes

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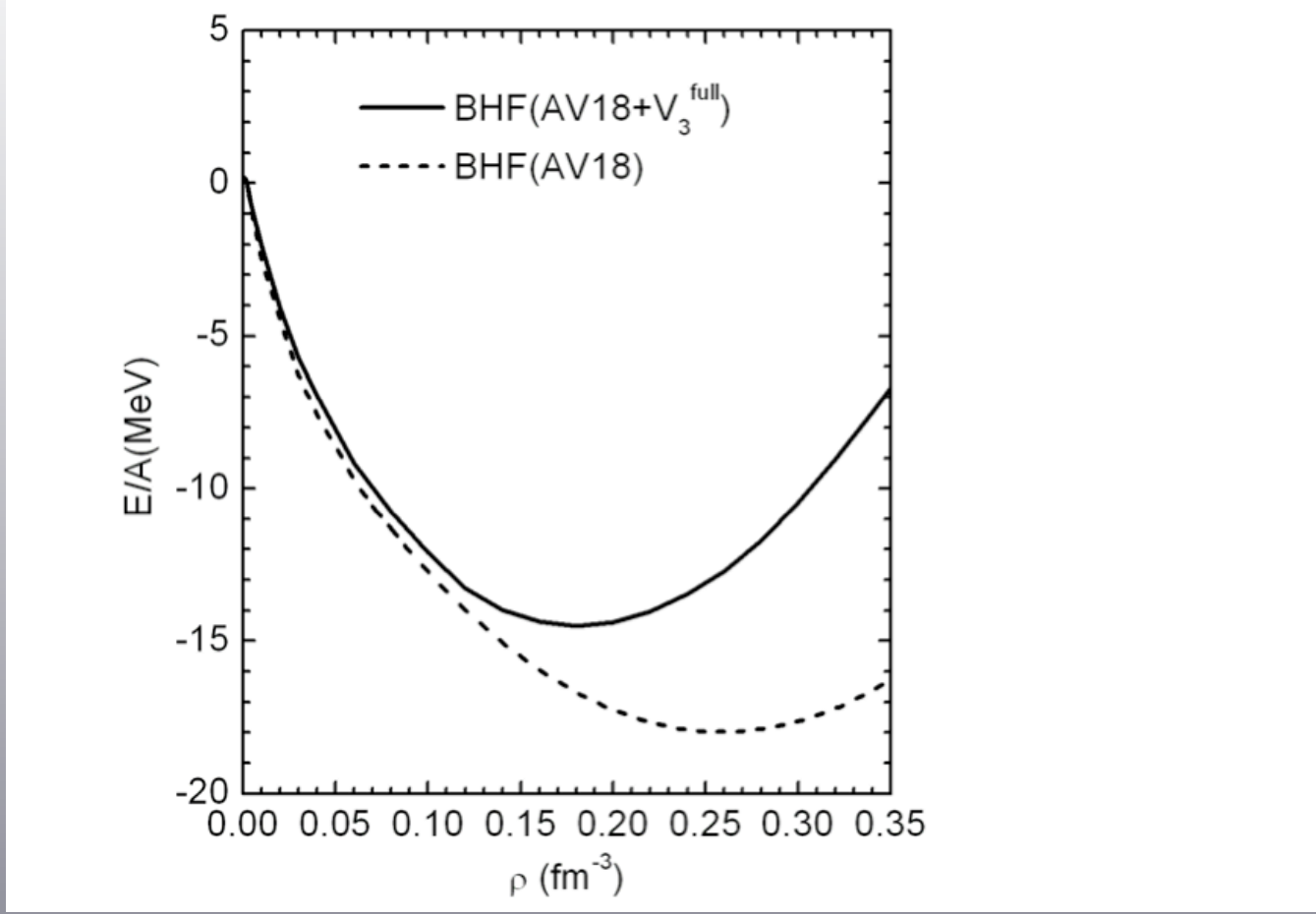
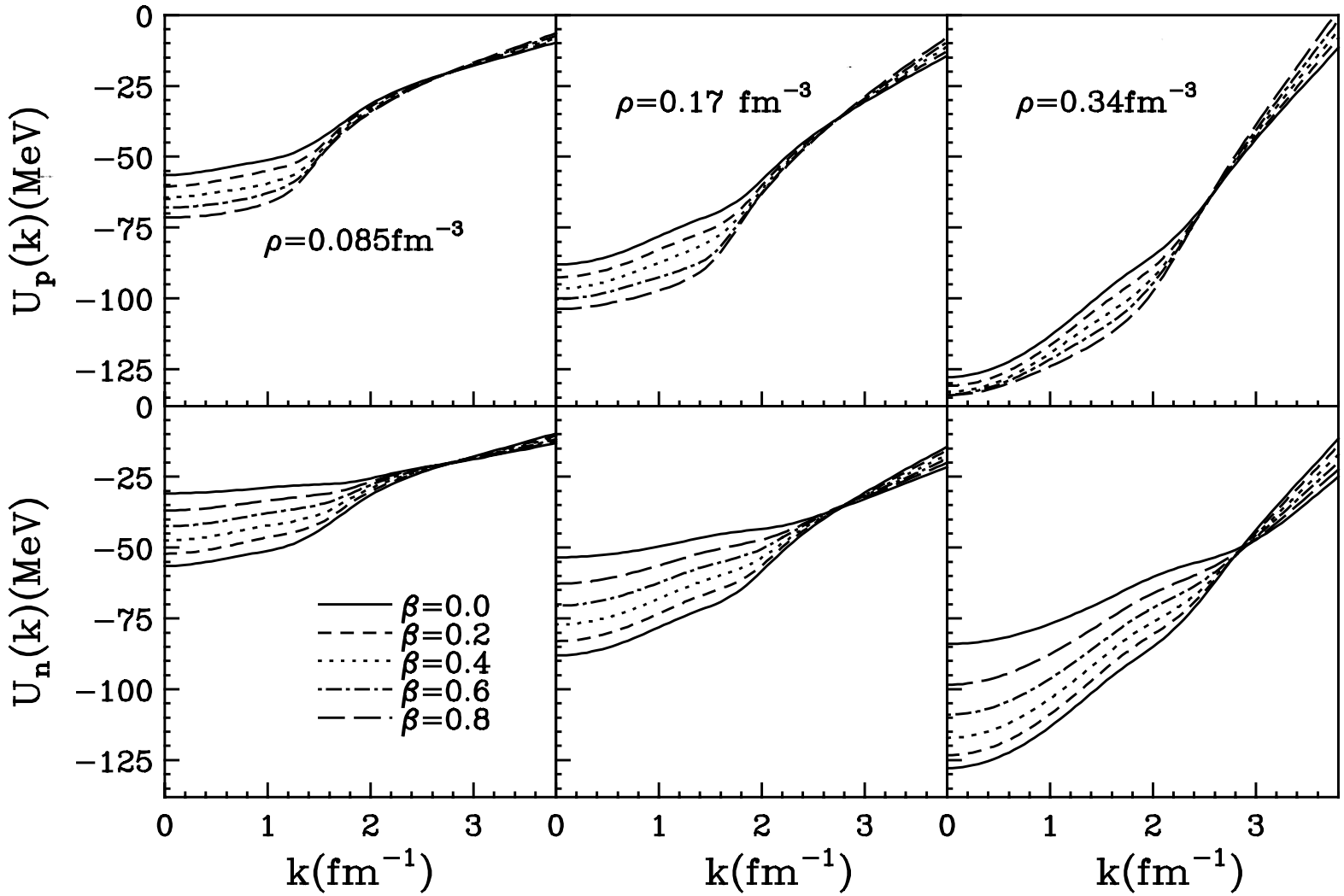
- Introduction
- Why is it important to detect and study energetic particles?
- Which particles: nucleons, photons, pions etc…
- Are those particles sensitive to the EOS? Cooperative effects?
- What have we learned so far?
- What else is left both from theory and experiments to be done?

Microscopic Equation of State

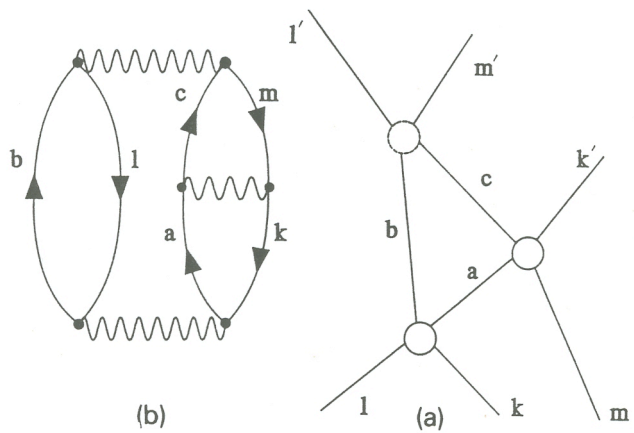


U. Lombardo et al. (2005)

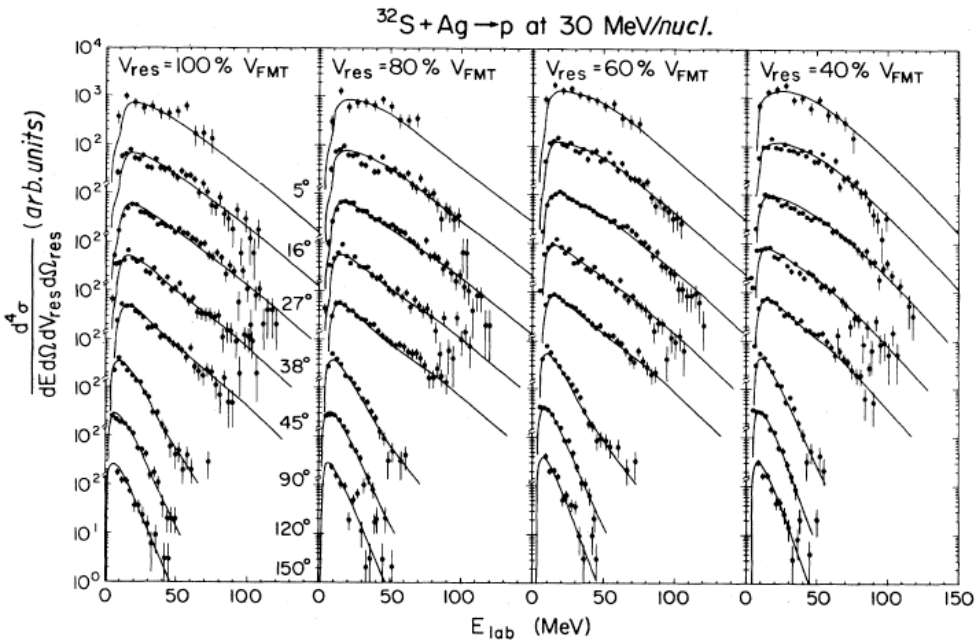


U.Lombardo et al. PRC60 (1999) 024605

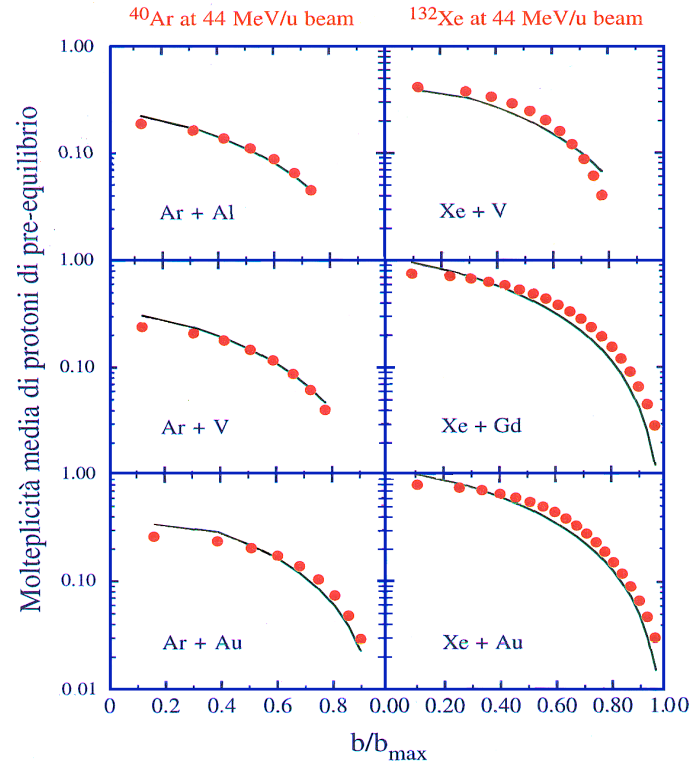
Viscosity: 2+3 body collisions



High energy proton: source selection and b dependence



Proton energy spectra observed in coincdence with residues in different velocity windows for ^{32}S+Ag. Solid lines represent a moving source fit with three sources



Ep>40 MeV, θ>40

Wada et al. PRC 39(1989) -> source selection vs centrality

J. Peter et al. PLB 237(1990)187 -> M_p vs b

R. Alba et al. PLB 322 (1994) 38 -> MEDEA data M_p vs b

E. Plagnol et al. PRC 61 (2000) 014606 ->INDRA data

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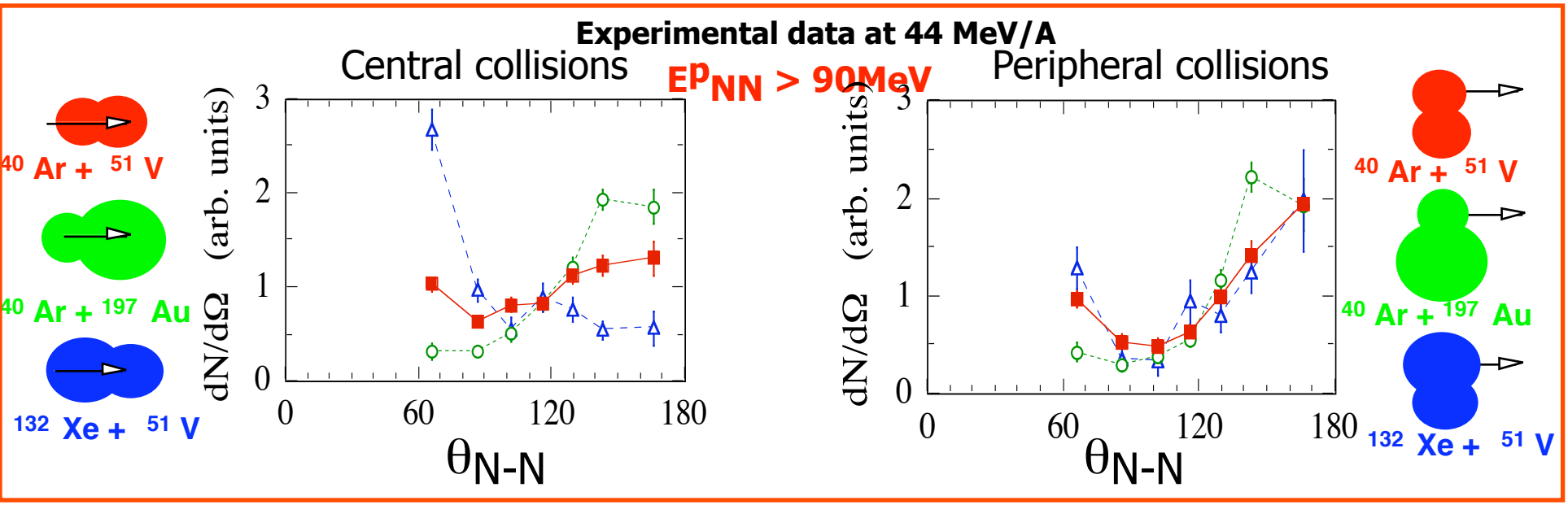
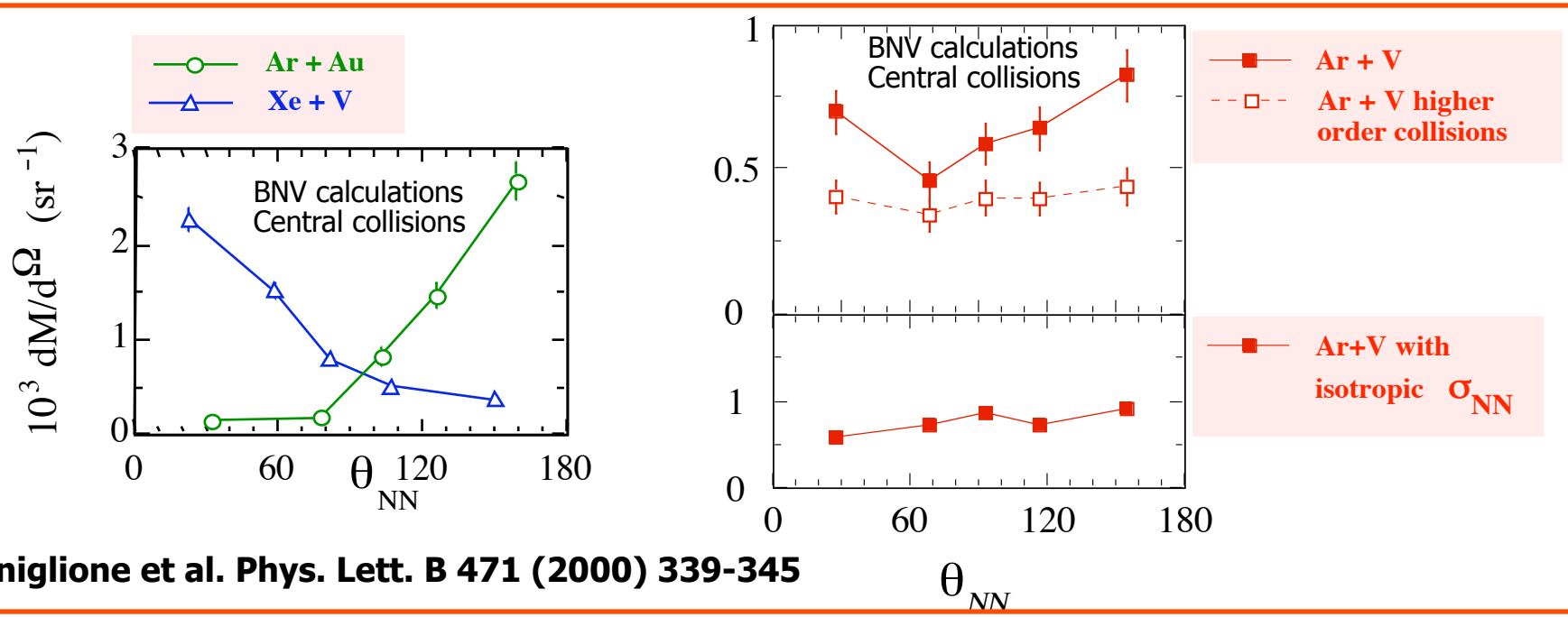
High energy proton angular distribution: sensitivity to σ_{NN}

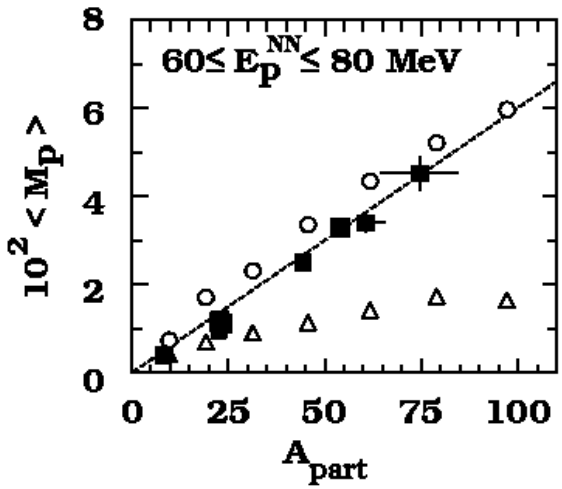




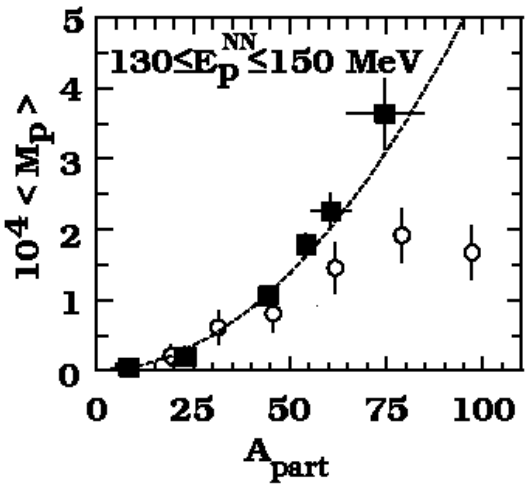
R. Coniglione et al. Phys. Lett. B 471 (2000) 339-345

Extremely energetic protons: cooperative processes ?

Ni+Ni 30MeV/A



■ data
○ BNV with GBD MDI
✕ BNV using a local Skyrme



Deviation from linear dependence

P. Sapienza et al. PRL 87 (2001) 072701- MEDEA data

On extremely energetic protons see M.Germain et al. PLB437(1998)19 ->inclusive data - no collective effects

Similar trend in π° and η at higher incident energy ...but multistep processes

800 MeV/A

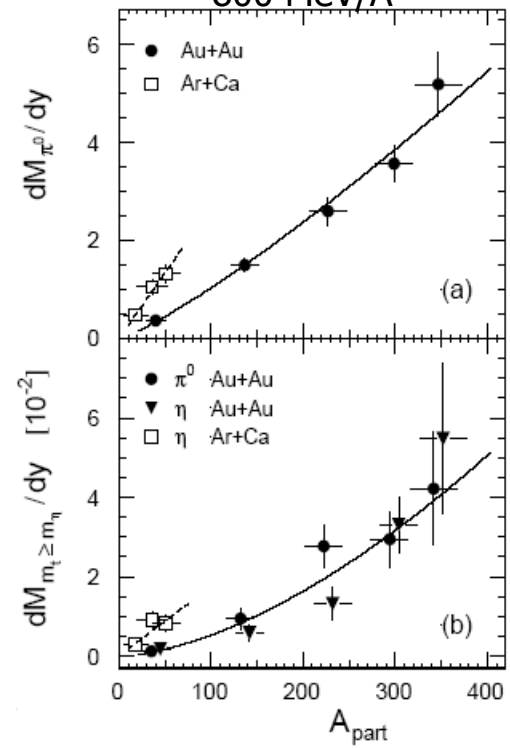


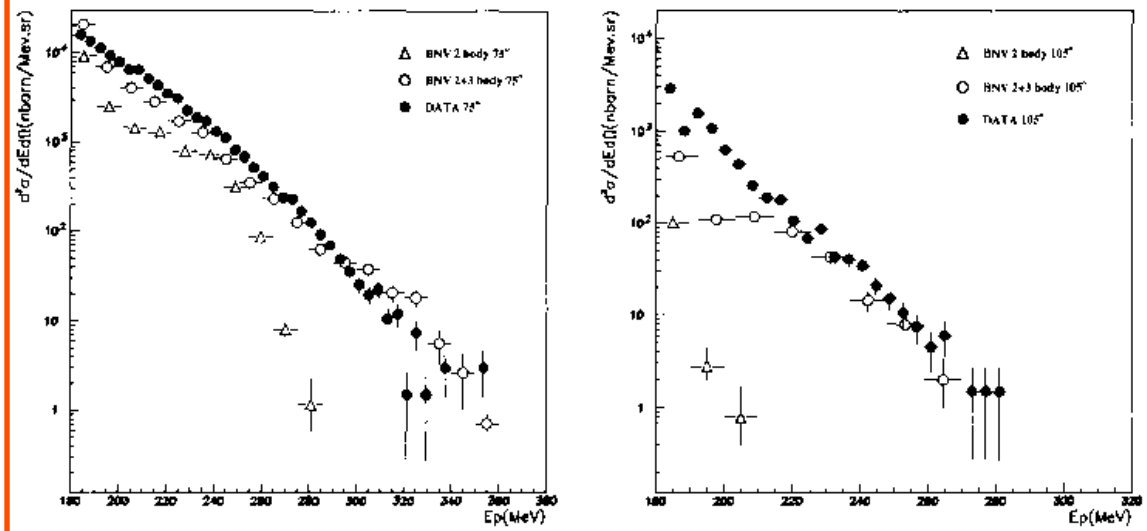
FIG. 3. Differential meson multiplicities near midrapidity as a function of the number of participants for Au + Au and Ar + Ca at 800A MeV. Shown are (a) the gross π^0 multiplicity dM_{π^0}/dy, (b) the multiplicities of η and high-m_t π^0 mesons, jointly denoted by $dM_{m_t \geq m_\eta}/dy$

The Au + Au data are fitted by functions of the form A_{part}^{α} (solid curves), while for Ar + Ca a strictly linear dependence is indicated (dashed lines). The η and high-m_t π^0 data points in Au + Au are displaced by ±5 units in A_{part}.

A.R. Wolf et al. PRL 80 (1998) 5281- TAPS data

Extremely energetic protons: cooperative processes ?

Ar + Ta 94 MeV/A



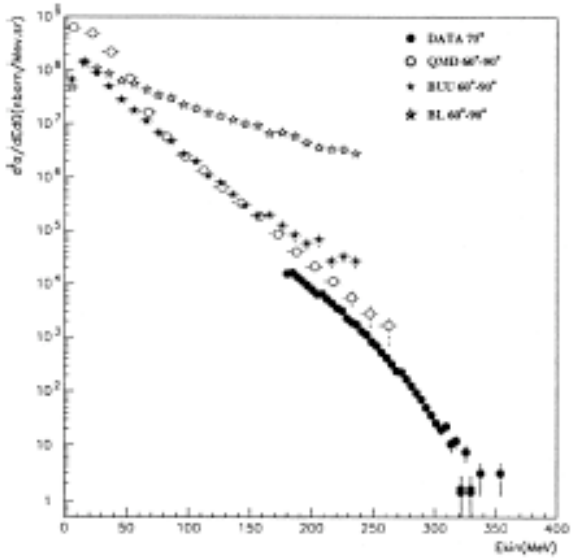
Comparison between experimental and BNV simulated proton energy spectra for 94 MeV/u Ar+Ta interactions at 75° and 105°. The BNV calcualtion is performed over an angular interval of ± 5°.

Conclusions

One needs the cooperation of a third nucleon in BNV transport theory to account for the high energy tail: this provides a link between nucleon–nucleon processes and clusterisation effects which are invoked to account for kaon production in the framework of the cooperative model [5]. The good agreement observed with the three-body BNV simulation leads to an interesting consequence: high transverse momentum protons are emitted at the very beginning of the reaction and characterize the pre-equilibrium phase.

M. Germain et al. NPA620(1997) 81

Ar + Ta 94 MeV/A



Comparison of the measured proton spectra for Ar (92A MeV) to those obtained in QMD using different angular bins.

Conclusions

We can conclude that high energy protons do not call for highly collective effects, contrarily to well below threshold kaons.

M.Germain et al. PLB437(1998)19

Complex particles

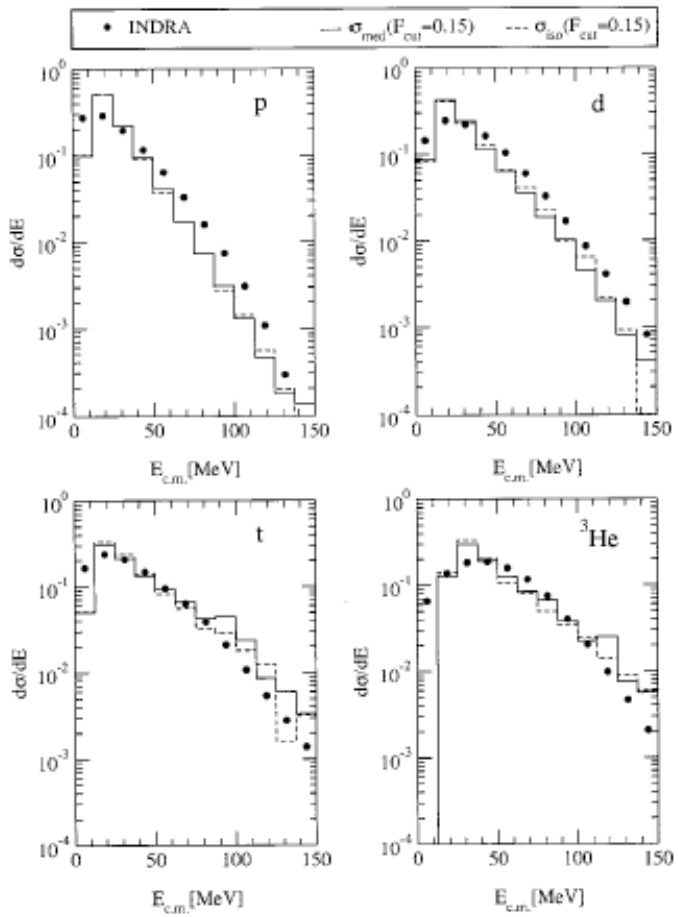


FIG. 5. Renormalized light charged light particle spectra in the center of mass system for the reaction ^{129}Xe+^{119}Sn at 50 MeV/nucleon. The filled circles represent the data of the INDRA Collaboration [21]. The solid line shows the calculations with the in-medium *Nd* reaction rates, while the dashed line shows a calculation using the isolated *Nd* breakup cross section; both with F_{cut}=0.15.

C. Kuhrts et al. PRC 63 034605
INDRA data

^{64}Zn + ^{92}Mo

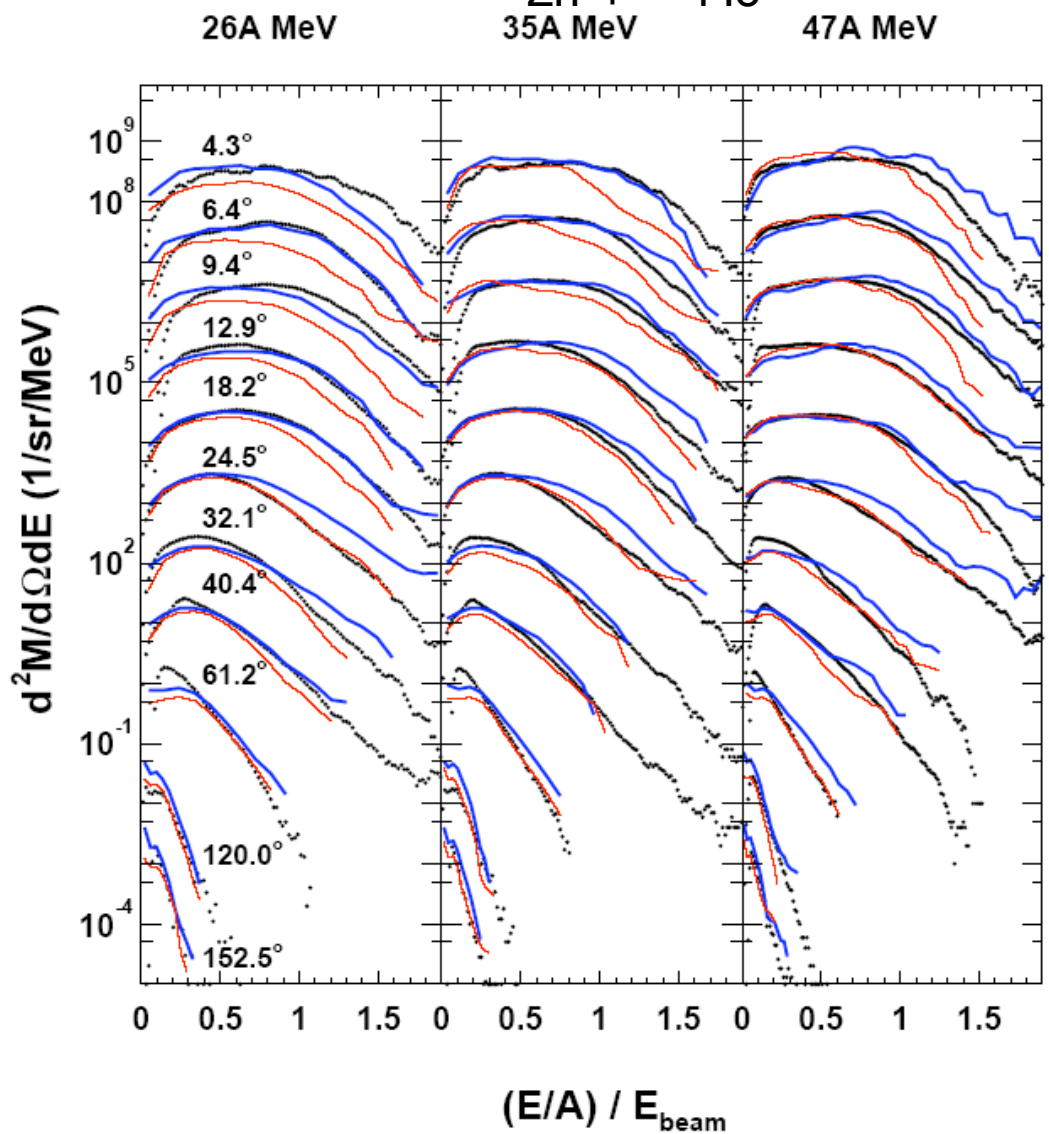


FIG. 20: Similar plots to Fig. 19, but for α particles.

Wada et al. PRC69 (2004) 044610

γ impact parameter dependence and transport model

$^{40}Ar+^{158}Gd$ 44 MeV/a

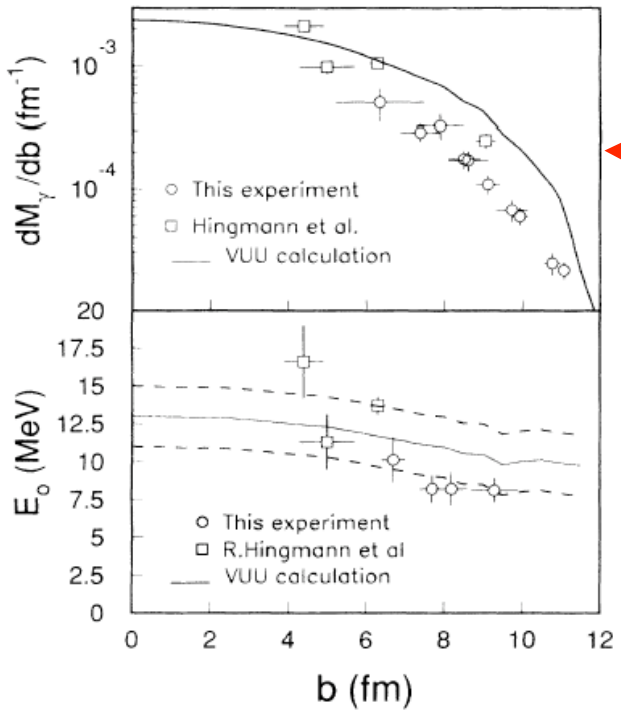


FIG. 3. γ-ray multiplicity above E_γ=25 MeV (top) and inverse slope parameter (bottom) as a function of the deduced impact parameter. The solid curves represent results of the VUU-model calculations and the dashed curve represents the theoretical uncertainties. The vertical and horizontal error bars reflect statistical and systematical errors. The data points taken from Ref. [7] deviate from the originally published values (≈ 10%), since the detector response has now been taken into account in a more refined way.

- M. Kwato Njock et al. NPA489 (1988)
- S. Riess et al. PRL69 (1992)1504 -> TAPS
  Mγ vs b – VUU calculations
- E. Migneco PLB 298 (1993)46 -> MEDEA
  Mγ vs b – BNV calculations
- Cassing et al. Phys.Rep.188(1990)365

In medium γ probability per single p-n collisions

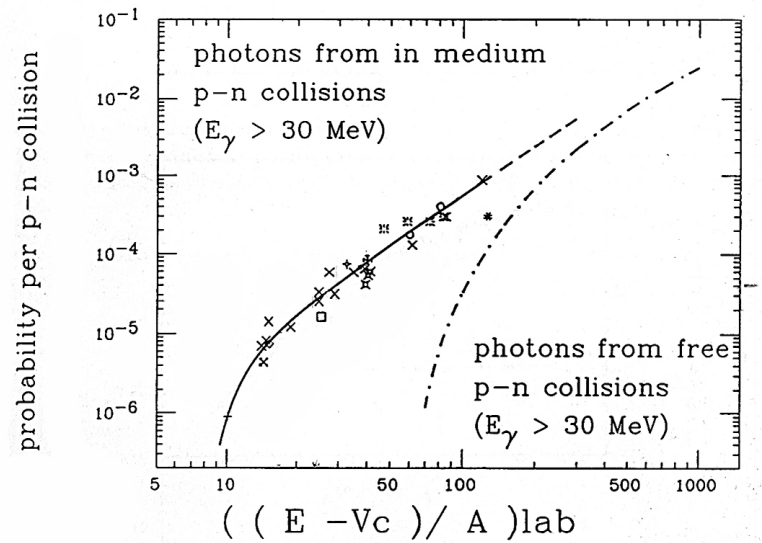


Figure 6: Emission probability for photons with E_γ >30 MeV per in – medium nucleon nucleon collision (see text and eq. (1)). The experimental data are compiled from ref.[1-13] The figure is taken from ref.[14]

$$M_{\tilde{a}}(b) = N_{n-p}(b) \cdot P_{n-p}^{E\tilde{a}>30MeV}$$

γ energy spectra: comparison between experimental data and transport models

$^{41}Ar + ^{51}V$ 65MeV/u $E\gamma > 30$ MeV

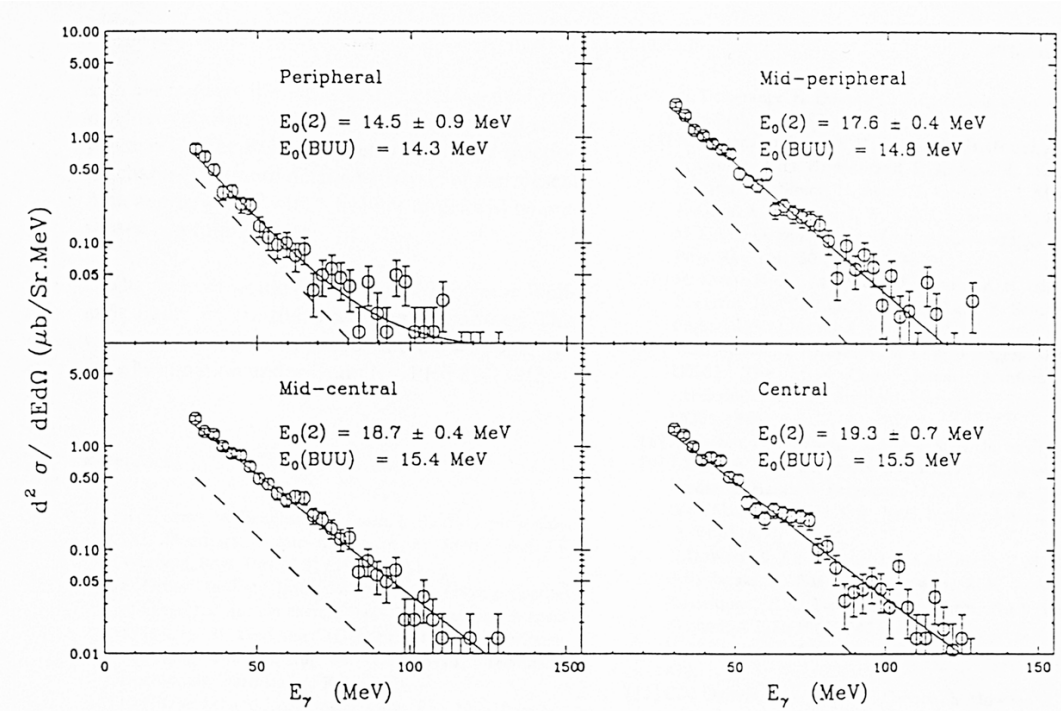


Fig. 3. Laboratory energy spectra for different impact parameters from the detector $BaF_2(2)$ at $\theta_2 = 79.4°$. The full curves are the result of fitting an exponential plus constant background to the data. The dashed curves are the results of the BUU calculation; see the text.

$^{86}Kr + ^{nat}Ni$ 60 MeV/A

$^{181}Ta + ^{197}Au$ 40 MeV/A

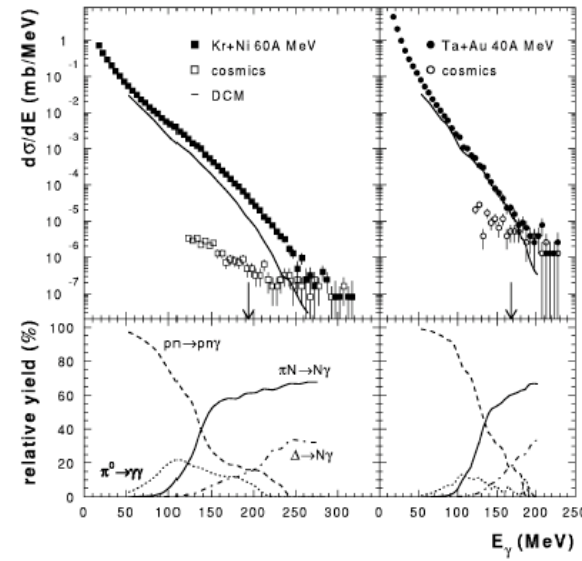


FIG. 1. Measured photon spectrum (full symbols) in the reaction $^{86}Kr + ^{nat}Ni$ at 60*A* MeV (left panel) and $^{181}Ta + ^{197}Au$ at 40*A* MeV (right panel) after subtraction of the cosmic-ray contribution. The level of cosmic-ray background is shown with open symbols. The solid line represents the DCM calculations. In the lower part the calculated spectrum is decomposed into fractions corresponding to the following elementary mechanisms: $p + n \rightarrow p + n + \gamma$, $\pi + N \rightarrow N + \gamma$, $\pi^0 \rightarrow \gamma\gamma$, and $\Delta \rightarrow N\gamma$. The arrows indicate the kinematical limits.

E. Grosse et al. Europhys. Lett. 2 (1987)9 -> first experimental spectra
T. Repouser et al. PL B276 (1992) 418 -> MSU data - BUU comparison
K.K. Gudima et al. PRL 76 (1996) 2412 ->TAPS data – DCM comparison

π° energy spectra comparison between experimental and transport models.

$^{36}Ar+^{27}Al$ 95 Mev/A

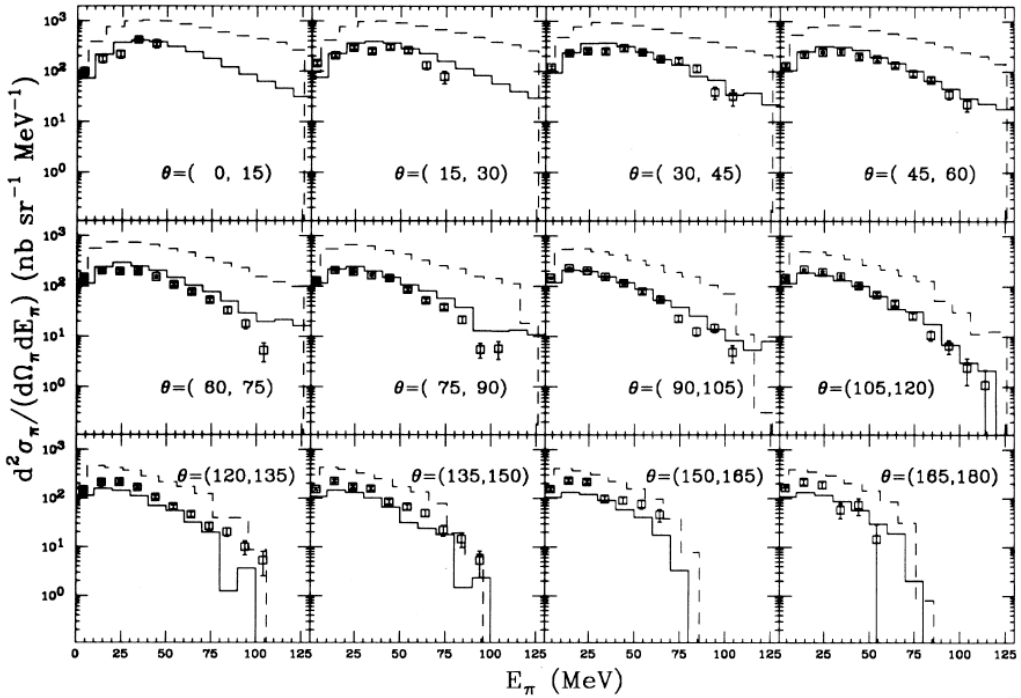
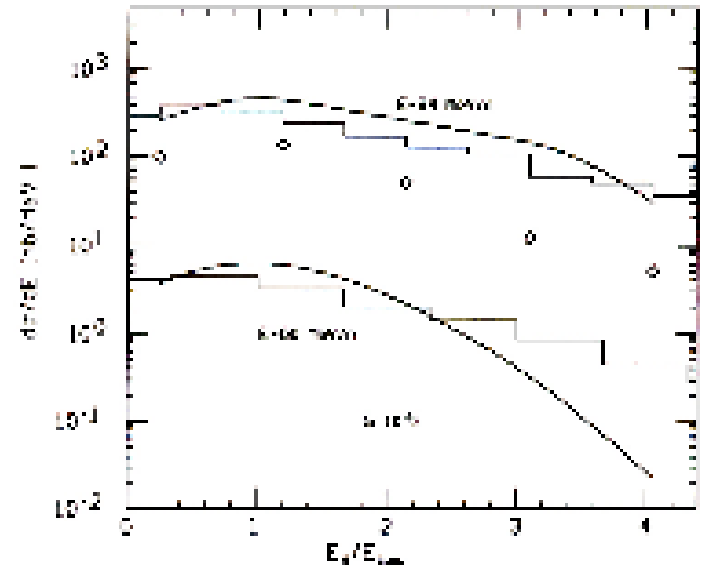


FIG. 2. Comparison between experimental (points) pion energy spectra at different detection angles and the results of a BNV dynamical calculation taking into account the effect of pion reabsorption in the nuclear medium (solid histogram). The dashed histograms represent the BNV calculations without reabsorption effect.

A. Badala et al. PRC 48 (1993) 2350 -> MEDEA data – BNV calculations well reproduce data when re-absorbition is taken into account

C+C at 60 and 84 MeV/A

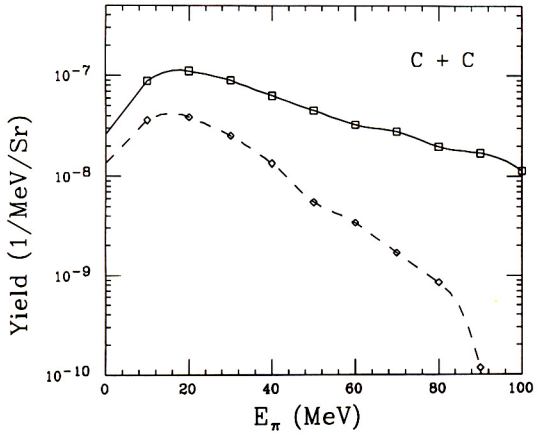


Pion spectra for the system C+C at 60 MeV and 84MeV/nucleon. Histogramss: experimental data. Full line:MBNV model. Dashed line: BNV model

H. Noll et al. PRL 52(1984)1284 -> experimental spectra
Bonasera Gulminelli and Molitoris Phys.Rep.243(1994)
->BNV comparison

R. S. Mayer PRL 70 (1993) 904, K.K. Gudima et al. PRL 76 (1996) 2412 -> TAPS data - DCM comparison (calculations under-estimate data)

pioni



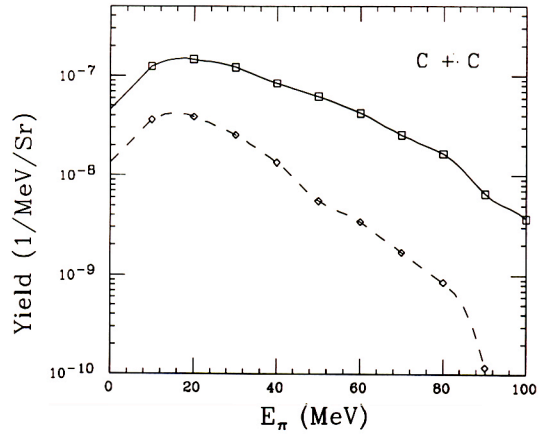


Fig. 7.19. Pion spectra for a C + C collision at 84 MeV/u and $b = 0.5$ fm in a BNV calculation with two body collisions only. Full line: $p_F = 260$ MeV. Dashed line: $p_F = 220$ MeV.

Fig. 7.20. Pion spectra for the same system of Fig. 7.14 with a Fermi momentum $p_F = 220$ MeV. Full line: two and three body collisions. Dashed line: two body collisions only.

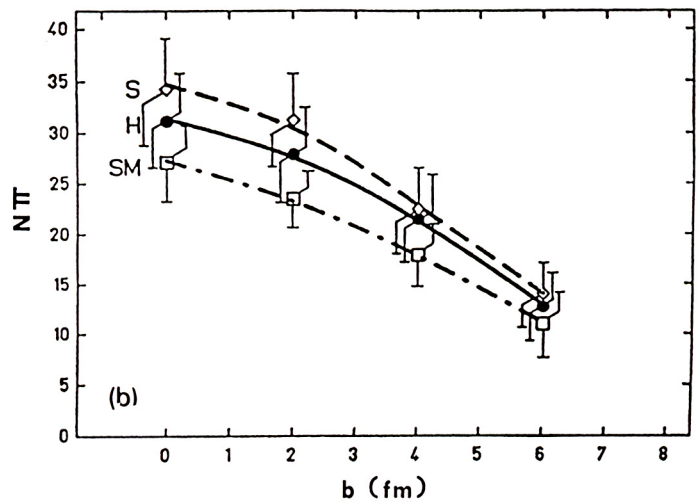
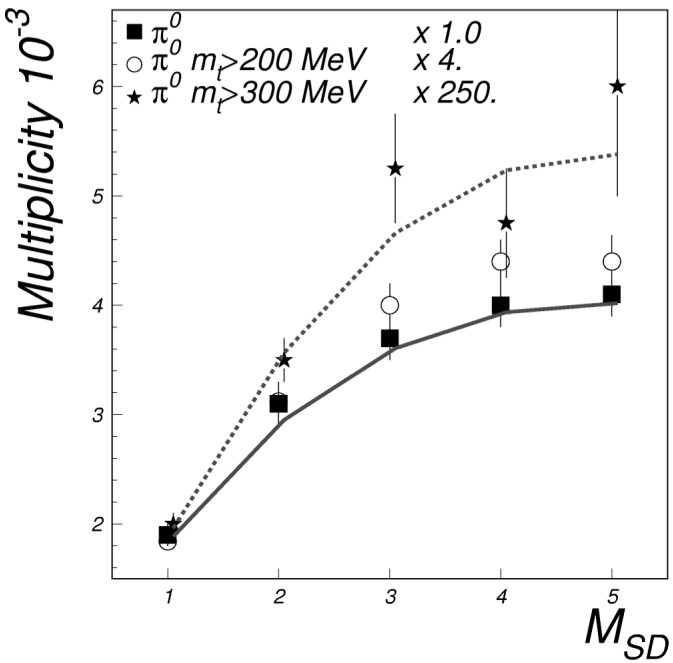


Fig. 7.9. (a) Pion production as a function of incident energy for La + La collisions in the INC (solid line), INC with the inclusion of the Pauli principle (dashed line), VUU (dashed-dotted line), and experimentally (symbols). (b) Pion production as a function of impact parameter in the QMD model. Dashed line: soft equation of state. Full line: hard equation of state. Dashed dotted line: soft equation of state with momentum dependence.

π°: impact parameter dependence

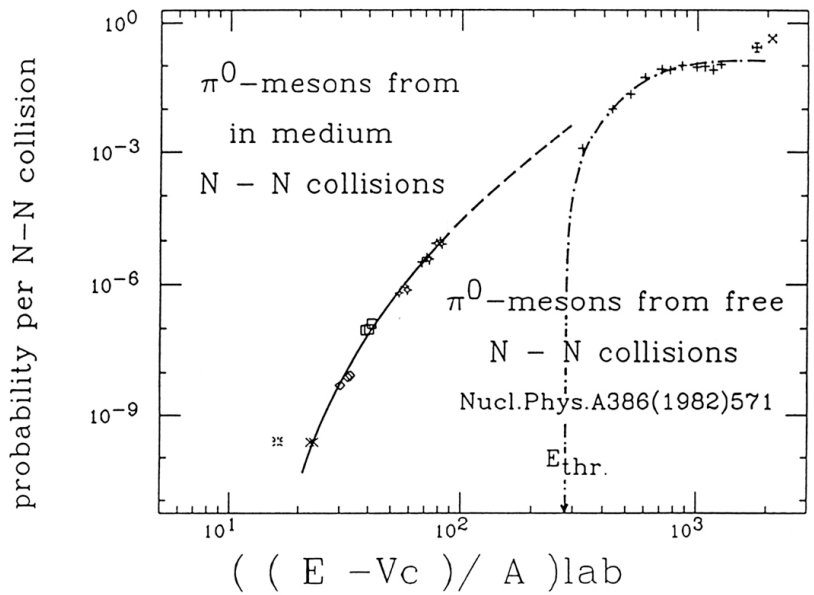
Ar + Ca 180 MeV/A
π°multiplicity vs centrality



Multiplicity of π° and high m_t π° as a function of the number of detected particles in the SD, normalized at M_{SD}=1. The solid line is proportional to A_{part} ant the dashed line proportional to A_{part}^3

G. Martinez et al. PRL 83(1999) 1541

In medium π° probability per single N-N collisions



Emission probability of neutral pions for in medium nucleon-nucleon collisions as a function of the bomberding energy.

- Cassing et al. Phys.Rep.188(1990)365

Conclusions and outlook

- Experimentally situation is rather clear: energetic particles are emitted at the first stages from NN collisions and do not equilibrate.
- Do we need more experimental investigations to put constraints on models?
- Theory: did we put constraints on compressibility, momentum dependence, three body forces etc...?
- Momentum dependent forces seem to work better than local potential, but no comparisons to photon spectra for instance.
- Extremely energetic particles not fitted with two body collisions for any potential. Need higher order correlations or something else.

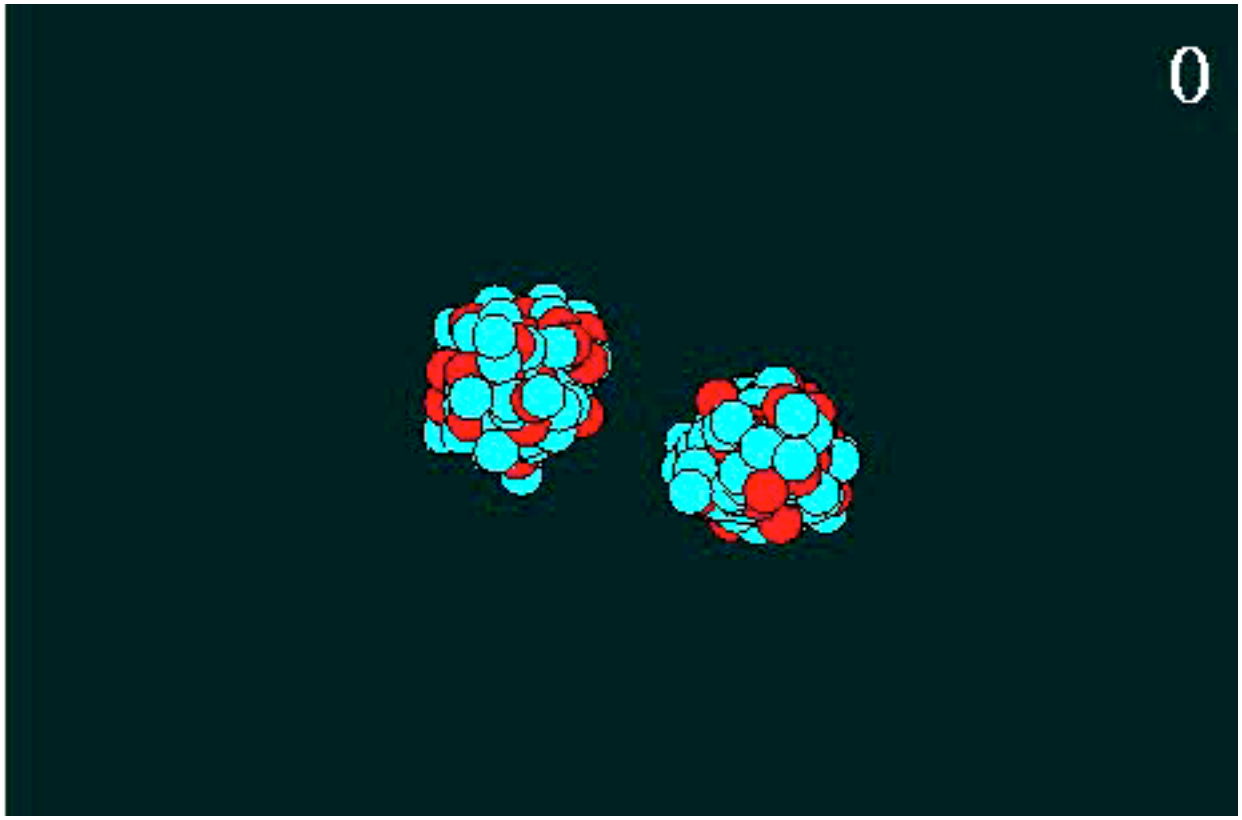
More in detail

- Very energetic protons display a quadratic dependence on the number of participants but effect is small. Is this result in constrast with BHF calculations of NM where 3-body forces are essential to obtain the NM g.s.?

- Pion production displays a non-linear dependence on the participants as well at higher energies. Real 3-body forces through deltas.

- Transport models lack good definition of the g.s. Often in calculations one changes the forces but no minimizations to find the g.s. Role of the surface term not discussed much. Better in AMD, FMD and CoMD where the gs is defined self-consistently.

- Dependence of the results on 'hidden parameters': width of gaussians or delta-functions or triangular functions, Fermi motion included in the width or not etc...?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