Forschungszentrum Jülich
in der Helmholtz-Gemeinschaft

The Physics of Spallation Processes
Theory and Experiments

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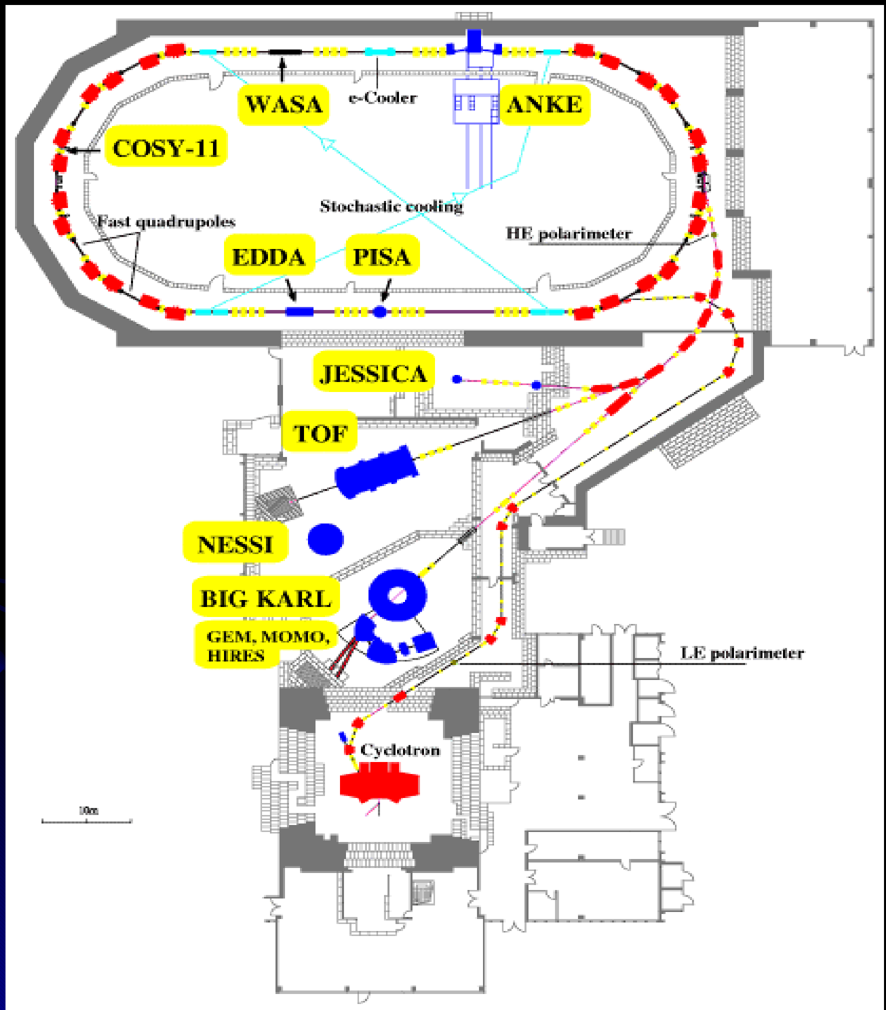
- What is spallation?
- Why are spallation reactions of interest? (applications, fund. physics)
- Theoretical models describing spallation reactions (INC and evap. model)
  - Limits and constraints
  - validation
- **Experimental investigations (here: NESSI, PISA & JESSICA at COSY)**
- **Comparison between models and experiments**
- Conclusion

Physical observables and deduced quantities of interest

most important parameters

- survival probabilities/reaction rates
- average ejectile multiplicities per incident proton and per nuclear reaction
- ejectile (n,p,d,t,He,Li,…,π,γ,) multiplicity distribution
  concerning transport in complex geometries note
  - difference thin/thick target scenarios
  - not only one nucl.reac., further multiplication in multiplying medium
  - particles originate from both: **inter/intra** nuclear cascade
- angular and energy distributions of neutrons and charged particles (π,n,p,d,t,^{3}He, ^{4}He, Li, Be, …, IMF, remnants)
- excitation energy distributions
- energy deposition, dpa
- …

COSY (COoler SYnchrotron) 150 MeV- 2.5 GeV



JESSICA (Jülich Experimental Spallation Target Setup in COSY Area)
external beam

NESSI (Neutron Scintillator and SIlicium detector)
external beam

PISA (Proton Induced SpAllation)
- internal beam
- luminosity: $6.6*10^{+34}$ $cm^{-2}s^{-1}$
- low absorption and small energy loss of ejectiles due to target thicknesses (down to 50 $\mu g/cm^2$

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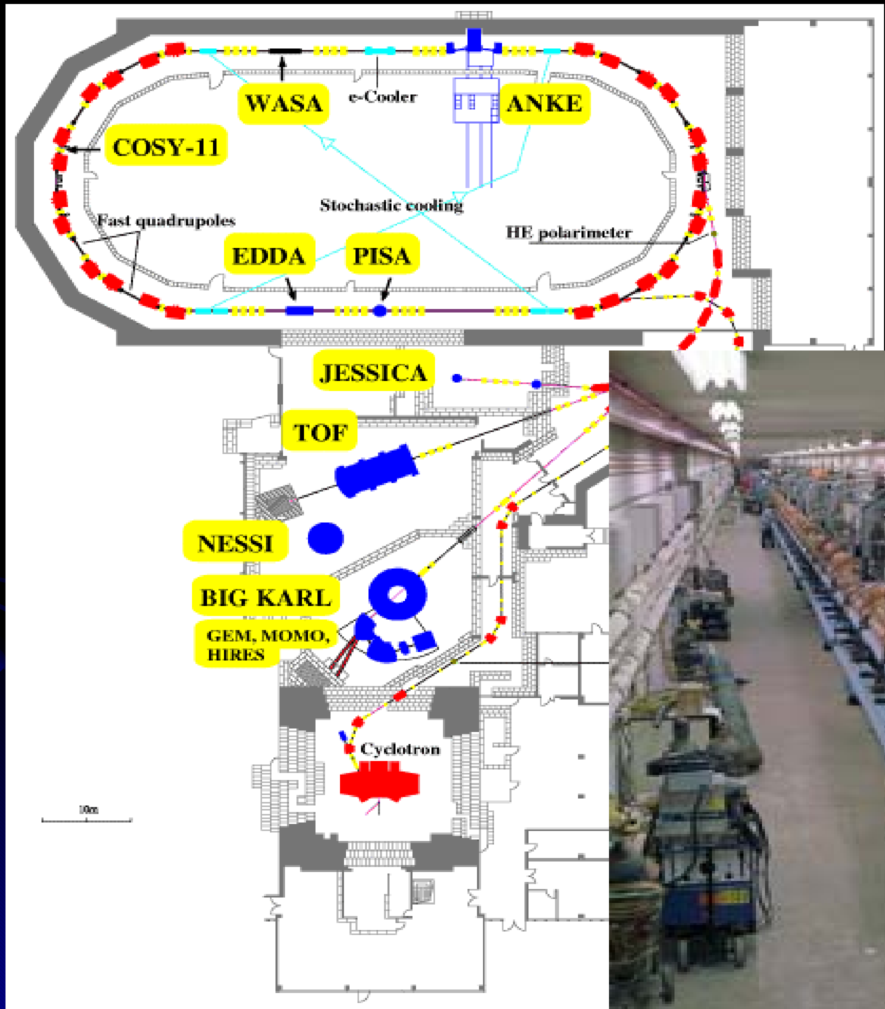

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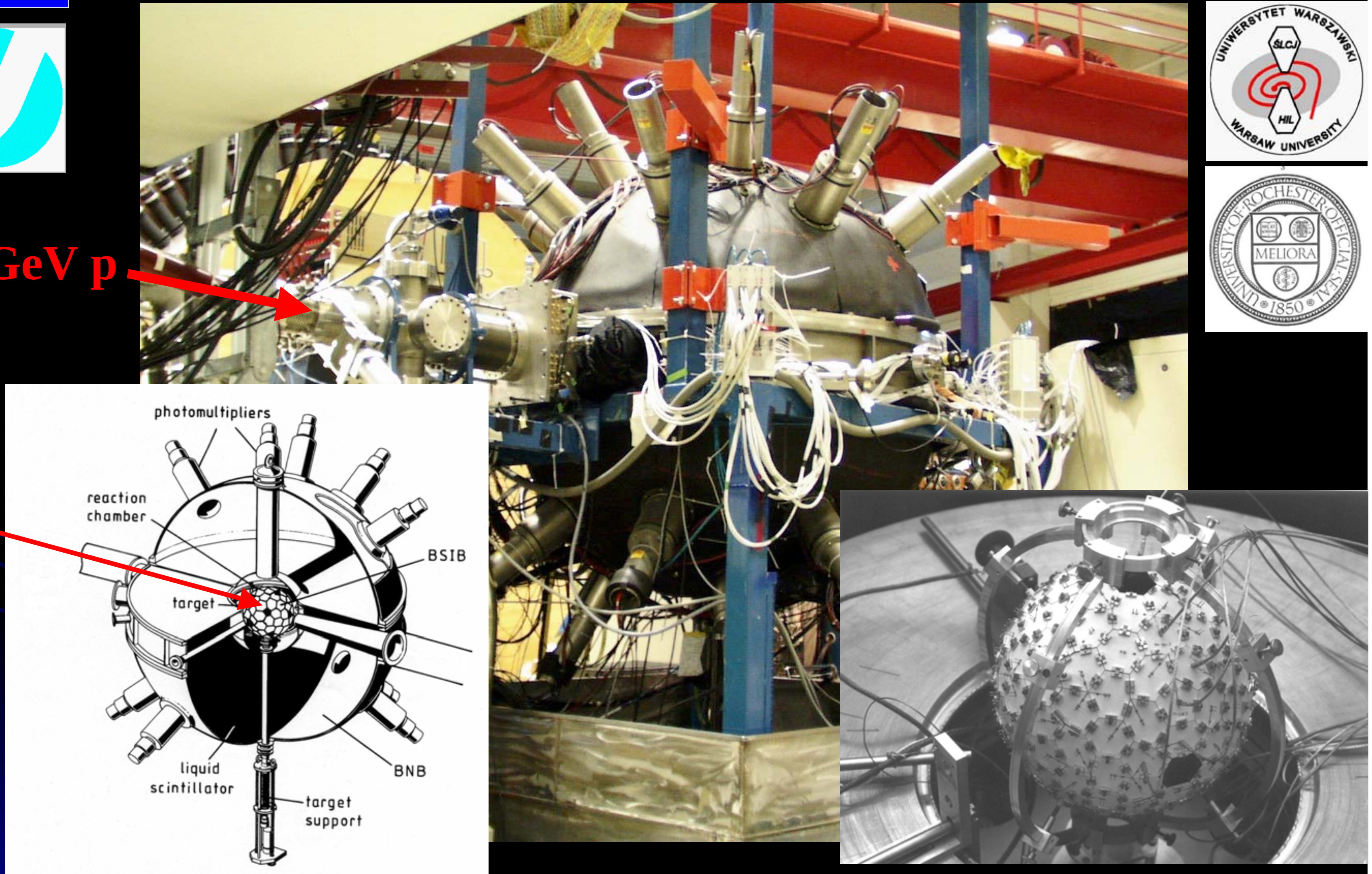
NESSI @ COSY

Forschungszentrum Jülich

in der Helm

GeV p

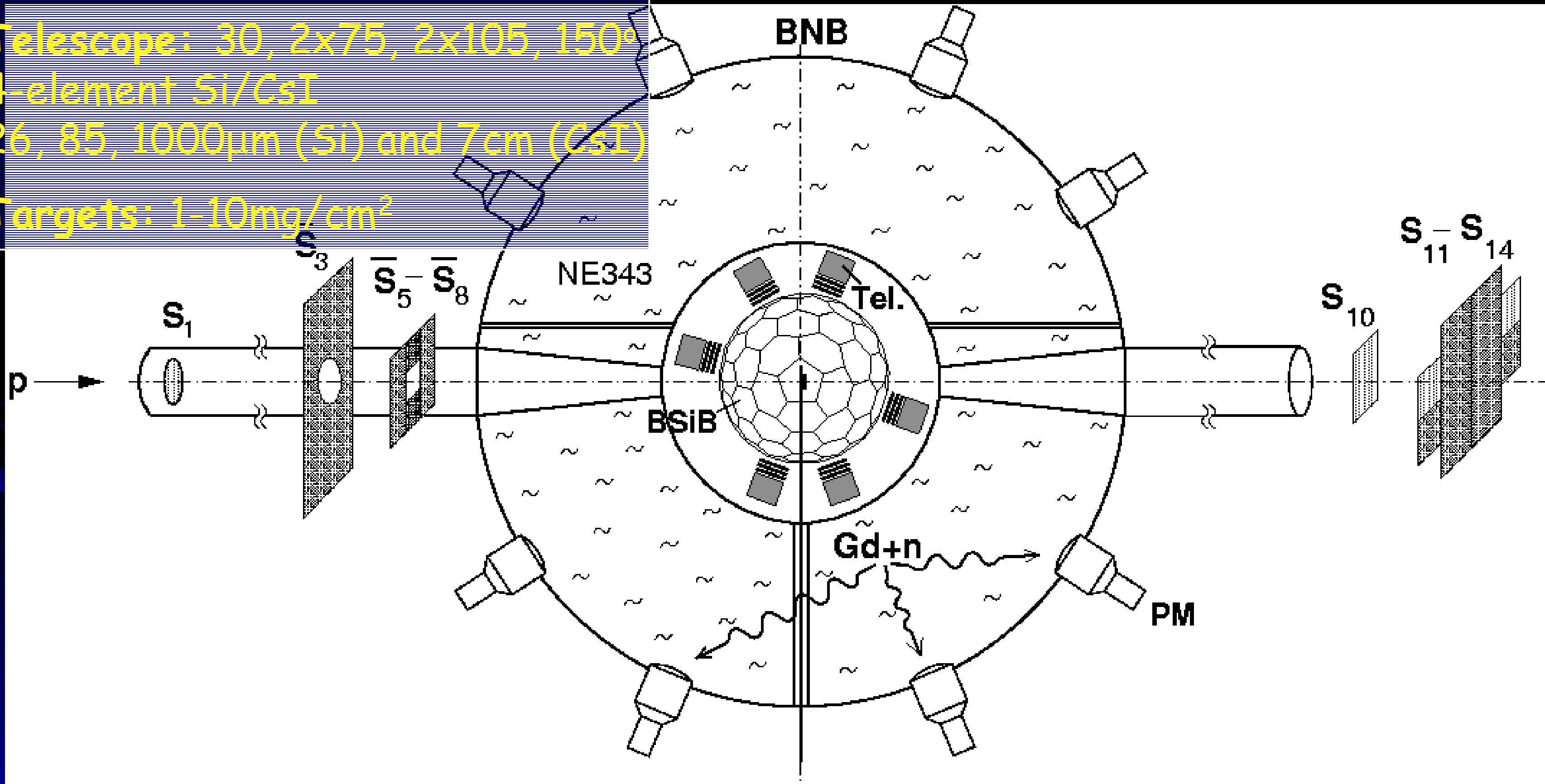


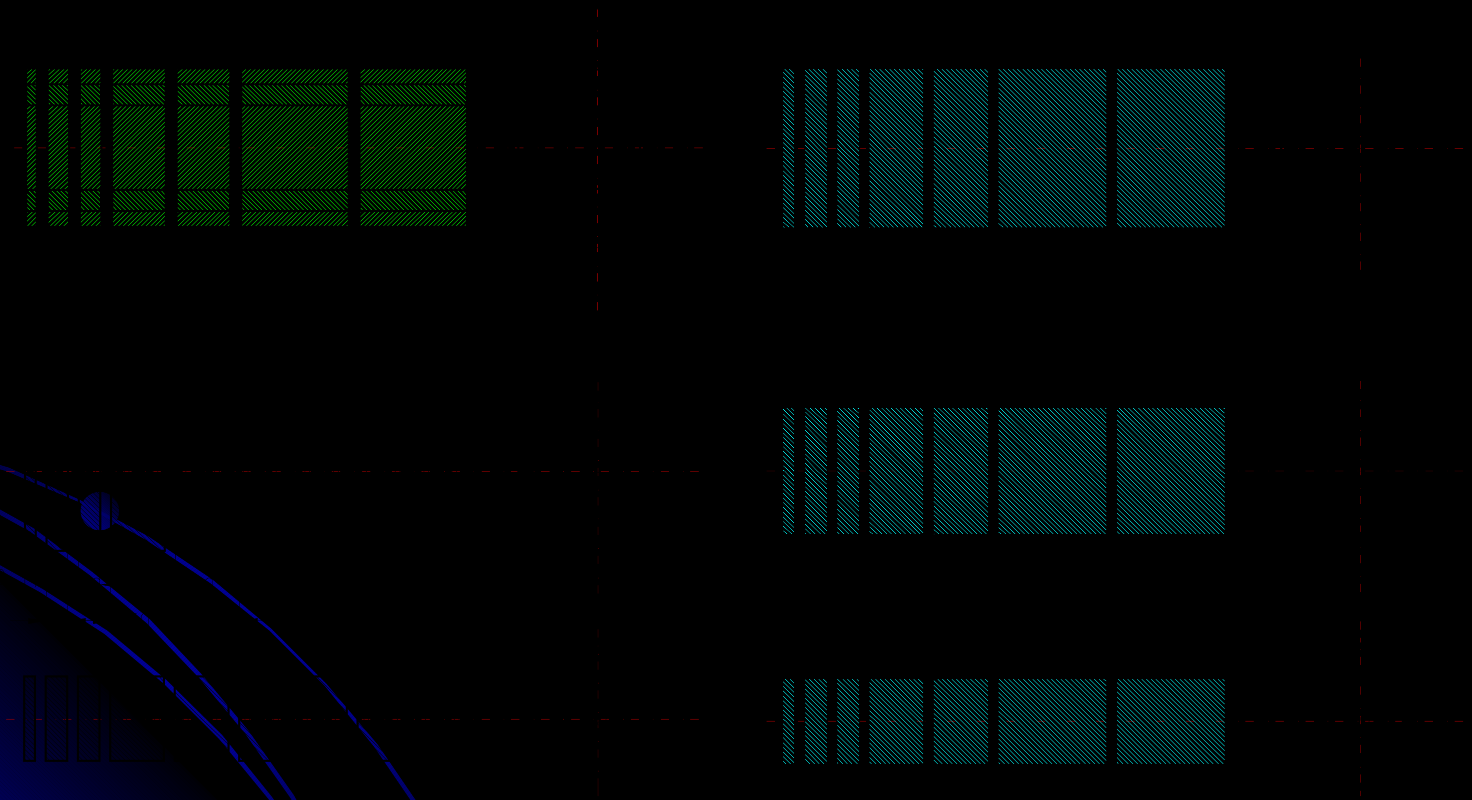
Light charged particle and cluster production in 1.2 GeV p-induced reactions on Al-Th

BSiB: 20cm, 151, 500µm Si, 67msr

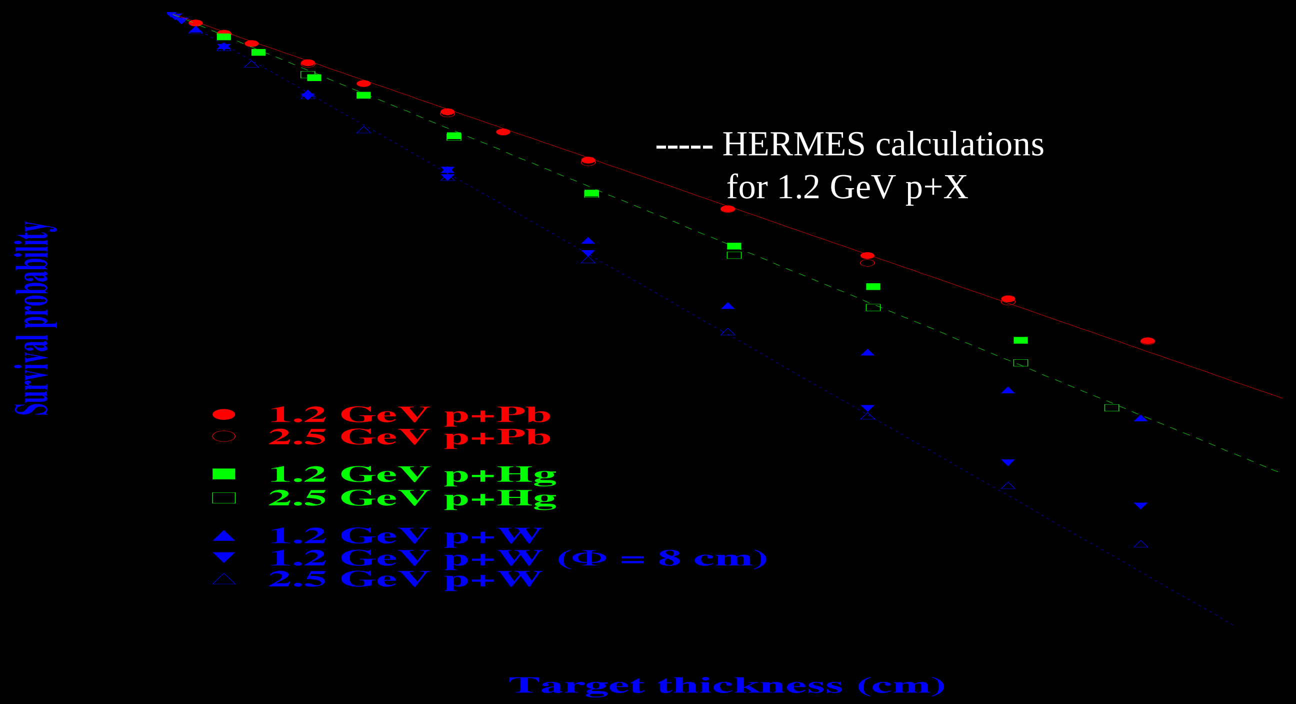
Telescope: 30, 2x75, 2x105, 150°
4-element Si/CsI
26, 85, 1000µm (Si) and 7cm (CsI)

Targets: 1-10mg/cm²

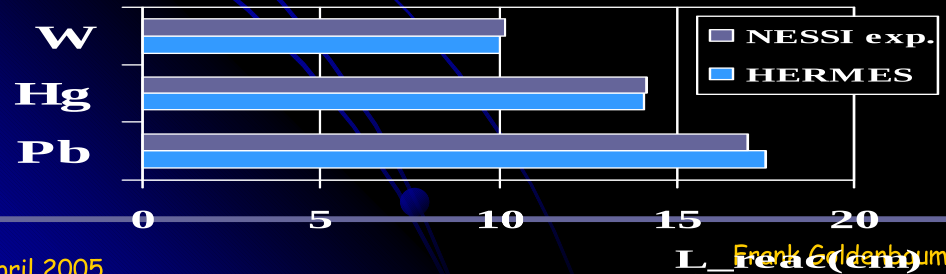


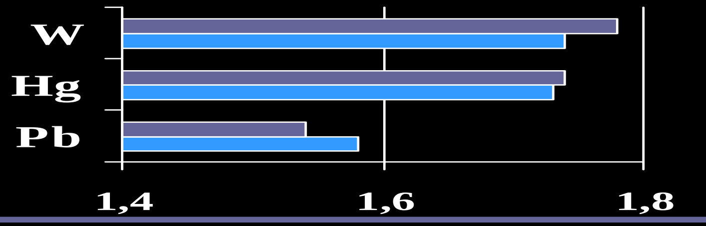


Comparison measured and calculated survival probability



HERMES calculations follow perfectly the exponential law
(1-P_reac)=exp(-L/L_reac)

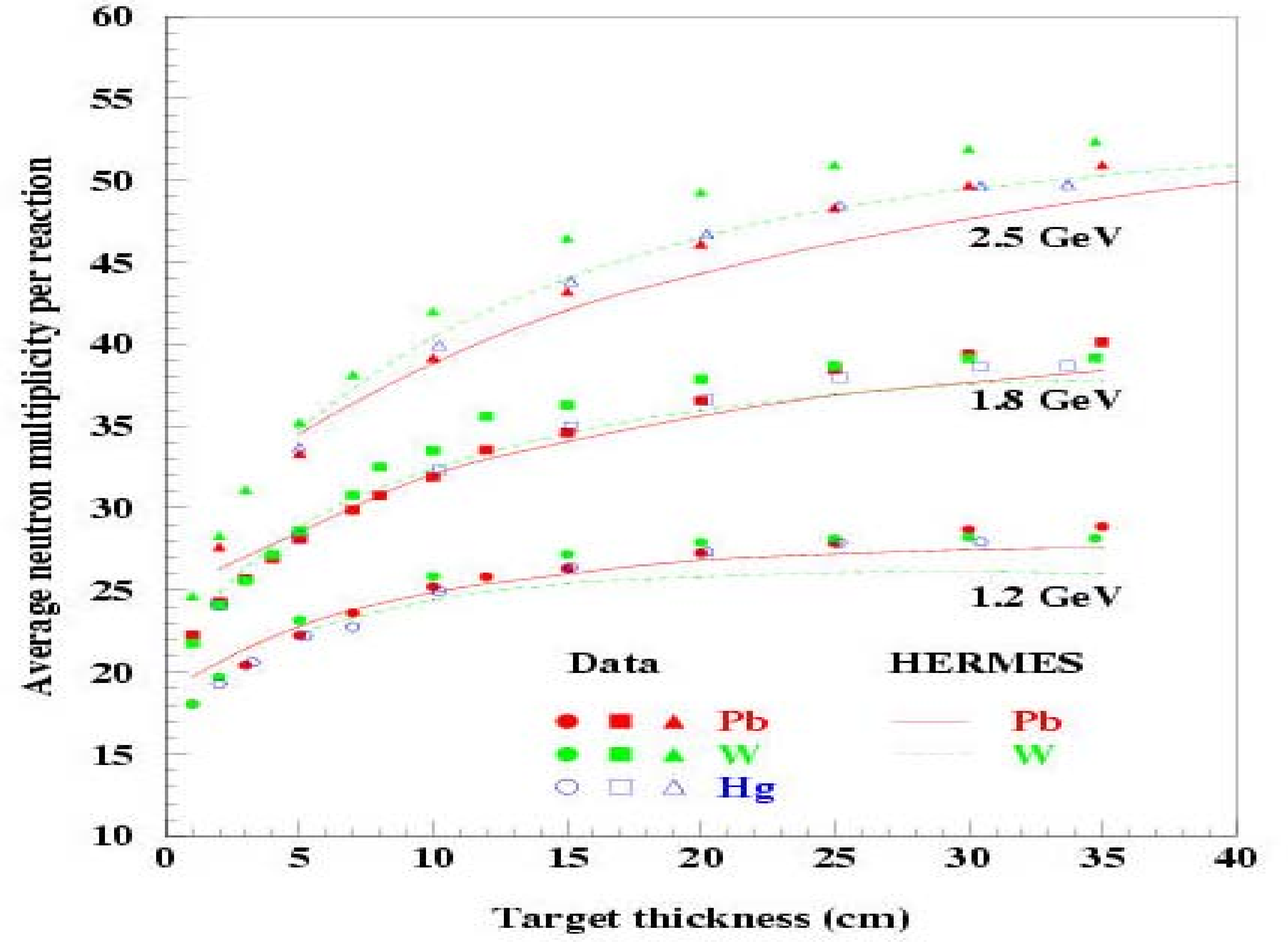




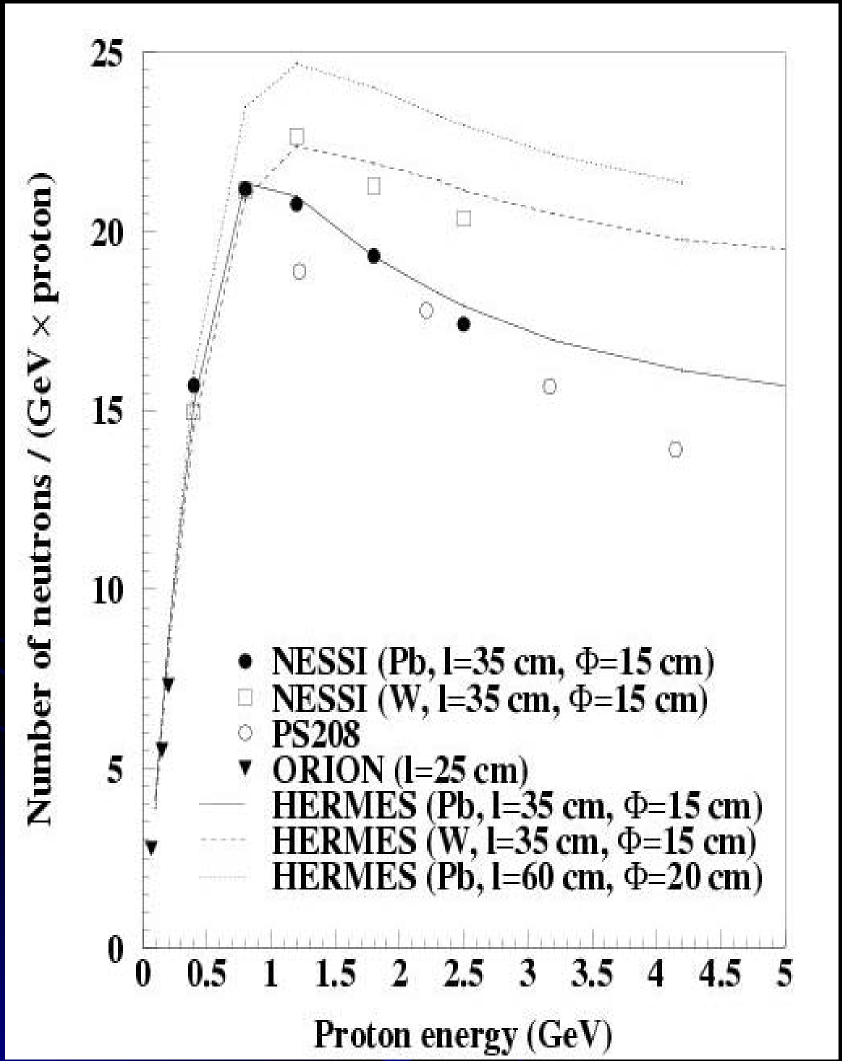
Average neutron multiplicity M_n/p for 1.2 and 2.5 GeV p+Hg, Pb and W

Average…

Neutron multiplicities in thick targets



Neutron multiplicities in thick Pb and W targets



NIM B 170 (2000), 299

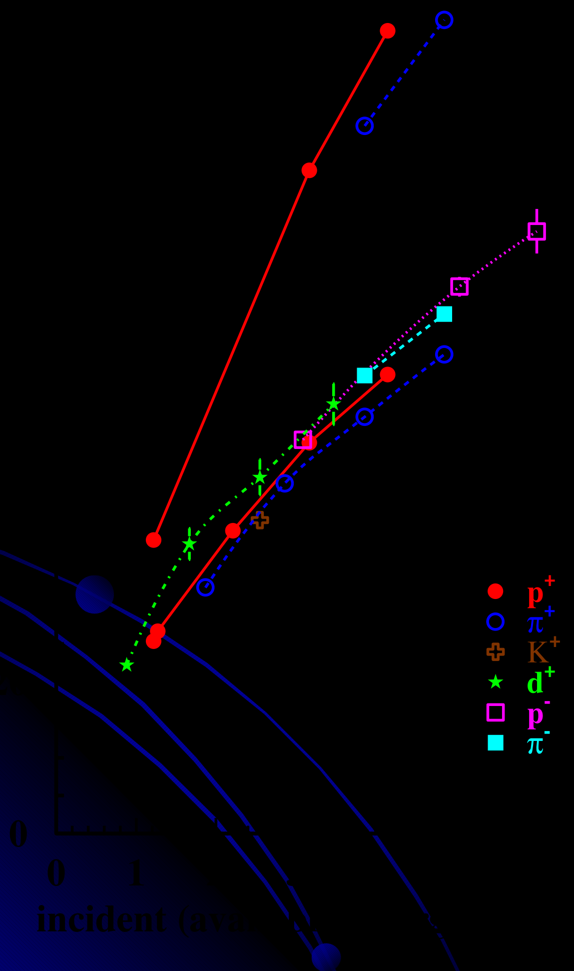
HERMES/MCNPX 1.2 GeV p+Hg

Distributions!

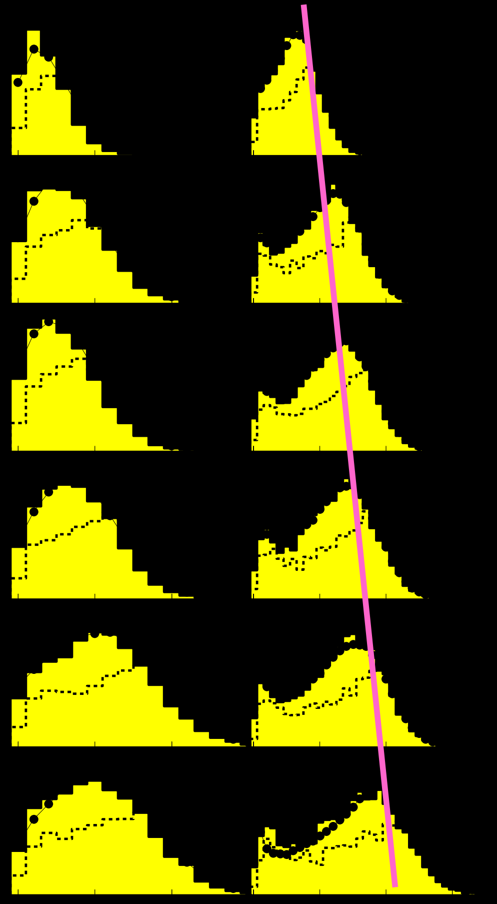
putting much stronger constraints to the models…

Neutron multiplicity distributions for 1.2 GeV p + Al ....U

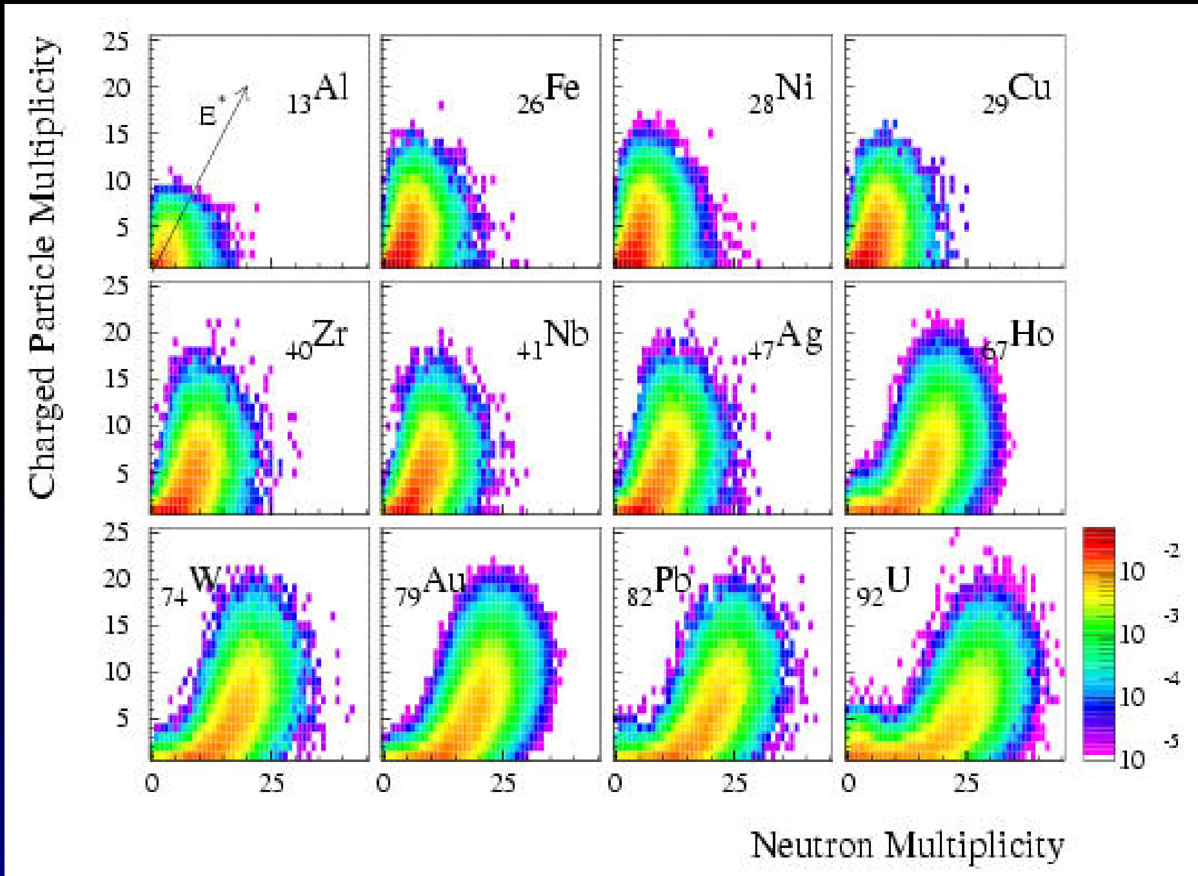
Dickes Target



Thin target 1.2 GeV p + X



Light particle production in spallation reactions induced by protons of 0.8 to 2.5 GeV incident kinetic energy (NESSI)



Correlation of measured LCP-vs. N-multiplicity for 2.5 GeV proton-induced spallation reactions

The color scale gives the relative yield for each target per multiplicity bin

Thermal excitation is following indicated arrow

Distributions of E* for 0.4, 1.2 and 2.5 GeV p+Au induced reactions

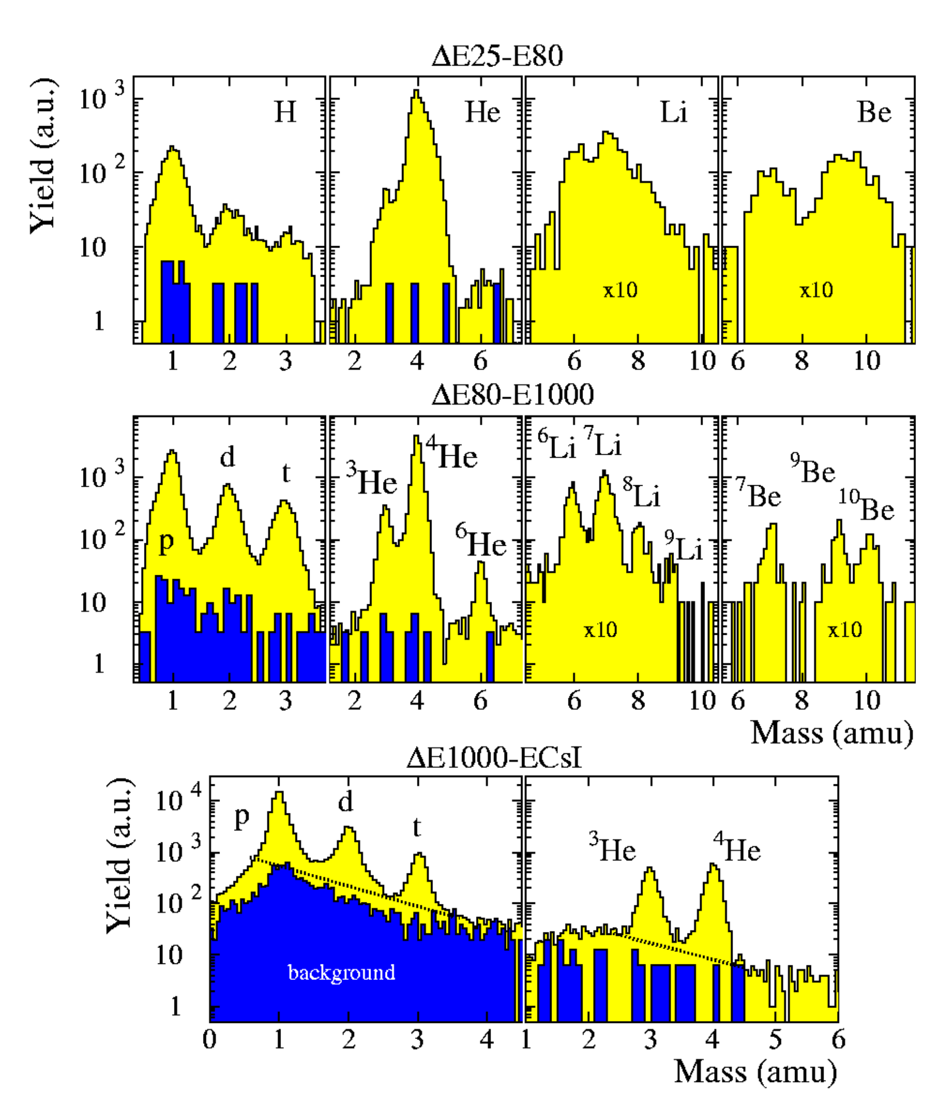
Discrepancy found between the models among themselves...

Kinetic energy spectra of $\pi^{\pm}$ 1.2 GeV p+Au BERTINI/INCL2.0

Explanation for discrepancy…

Bertini:
less pions, lower energetic…

Mass spectra of H, He, Li and Be



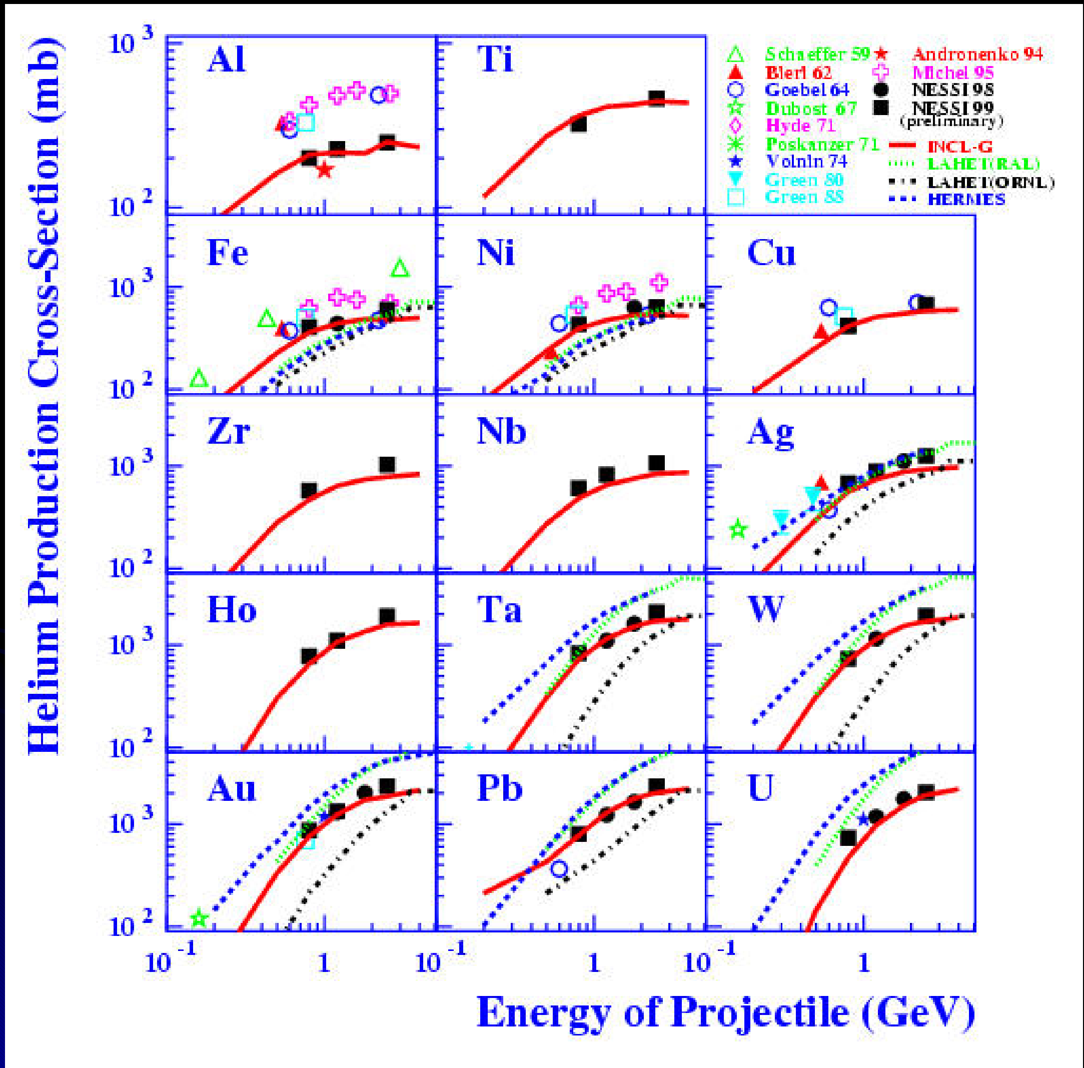
measured with different combinations of ΔE-E telesc.

blue: background empty target frame

For CsI high backround due to sensitivity and high light output for neutrons and gammy rays

Energy calibration of CsI for individual particles by reference to the energy loss in the 1000μm Si detector in front; for high energy H ions CsI punch-through energies were used for calibration (160, 210, 250MeV for p,d,t)

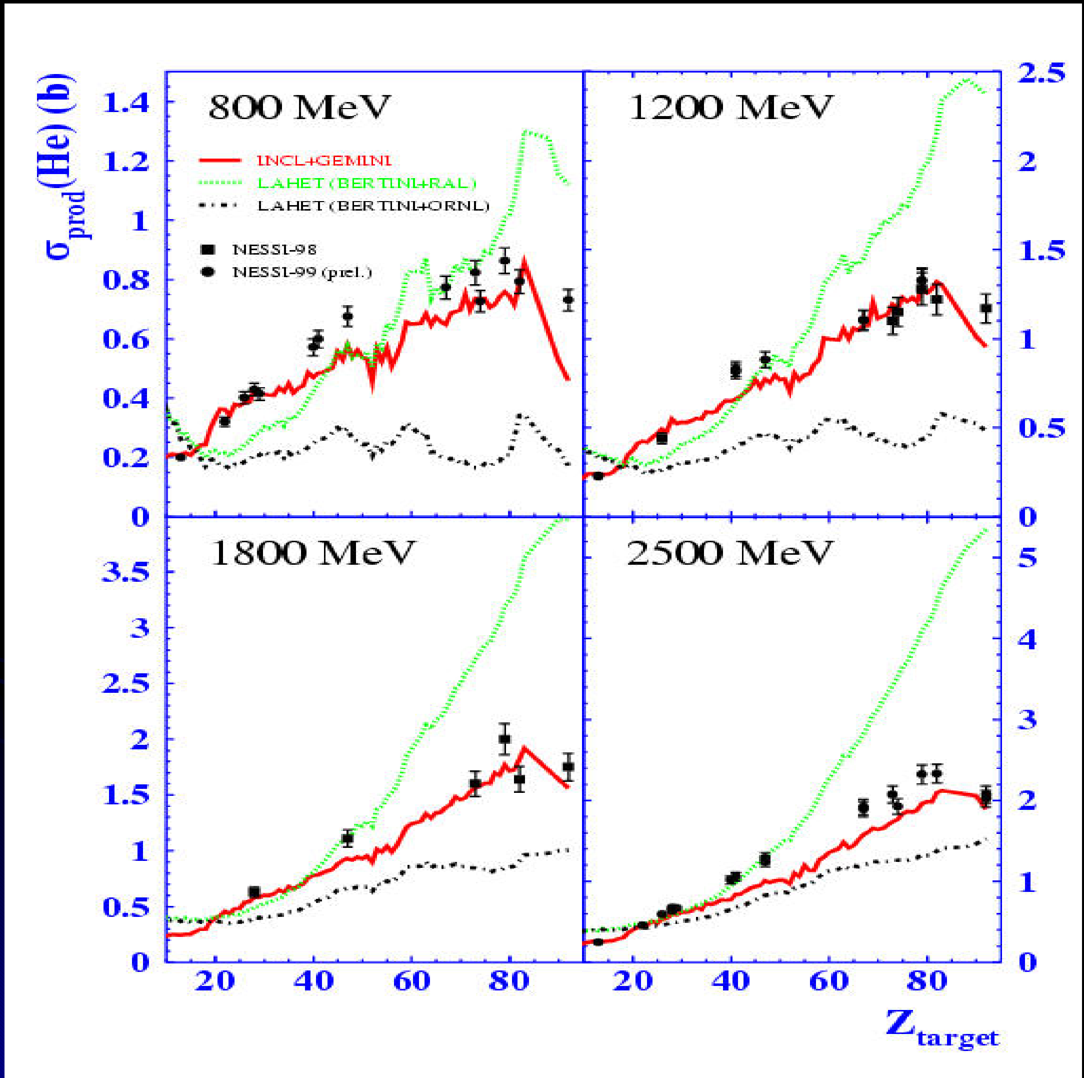
H production cross sections as a function of E_p for p+Al,...,U



Comparison of experimental He production cross sections (symbols) and calculations (INCL, LAHET, HERMES as lines) as a function of proton energy for various targets.

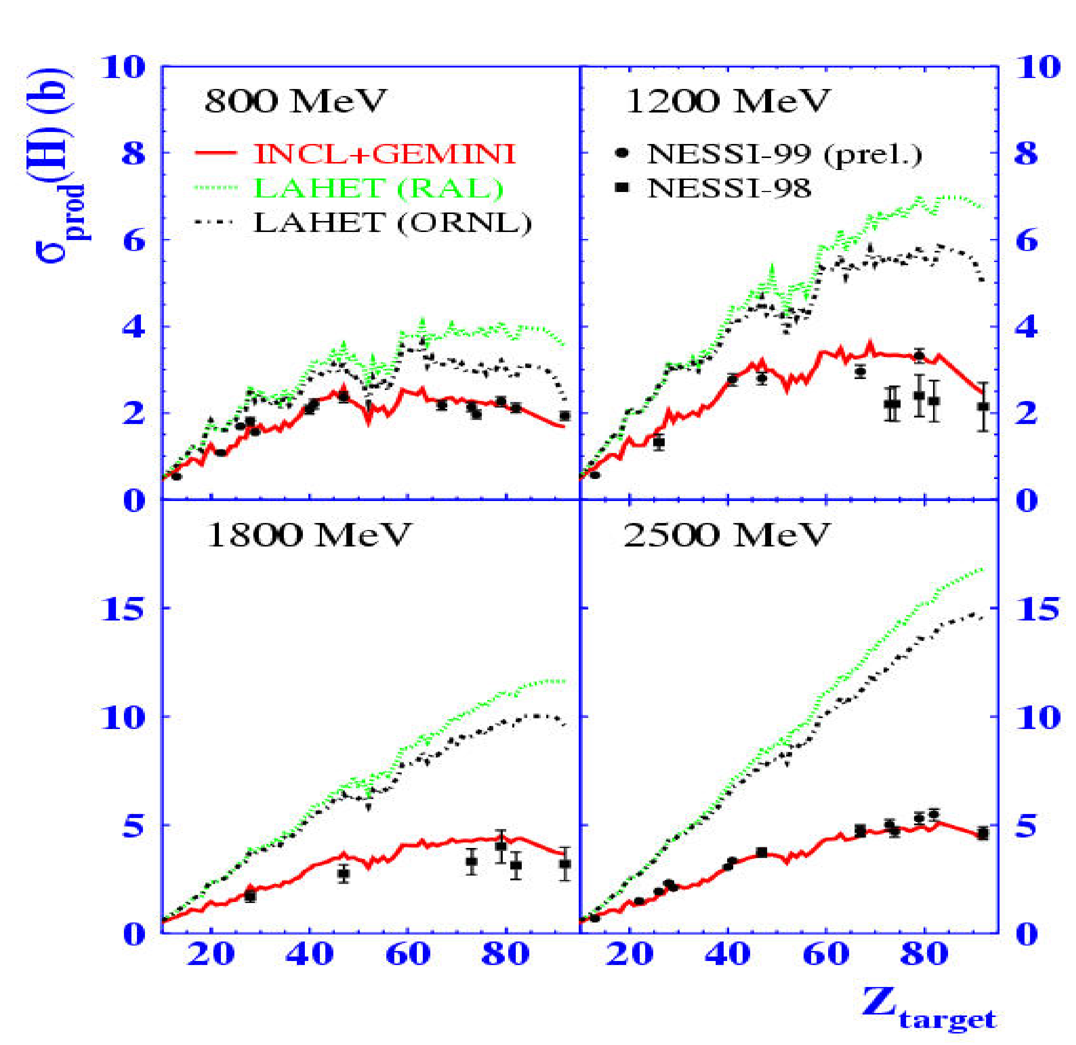
The first authors and year of the publications of previous experiments are also indicated.

He production cross sections (Z, E_p)



Note the different scales of the left and the right panels.

H production cross sections (Z, E_p) for p,d,t with thresholds of 2.2-26,49,76 MeV

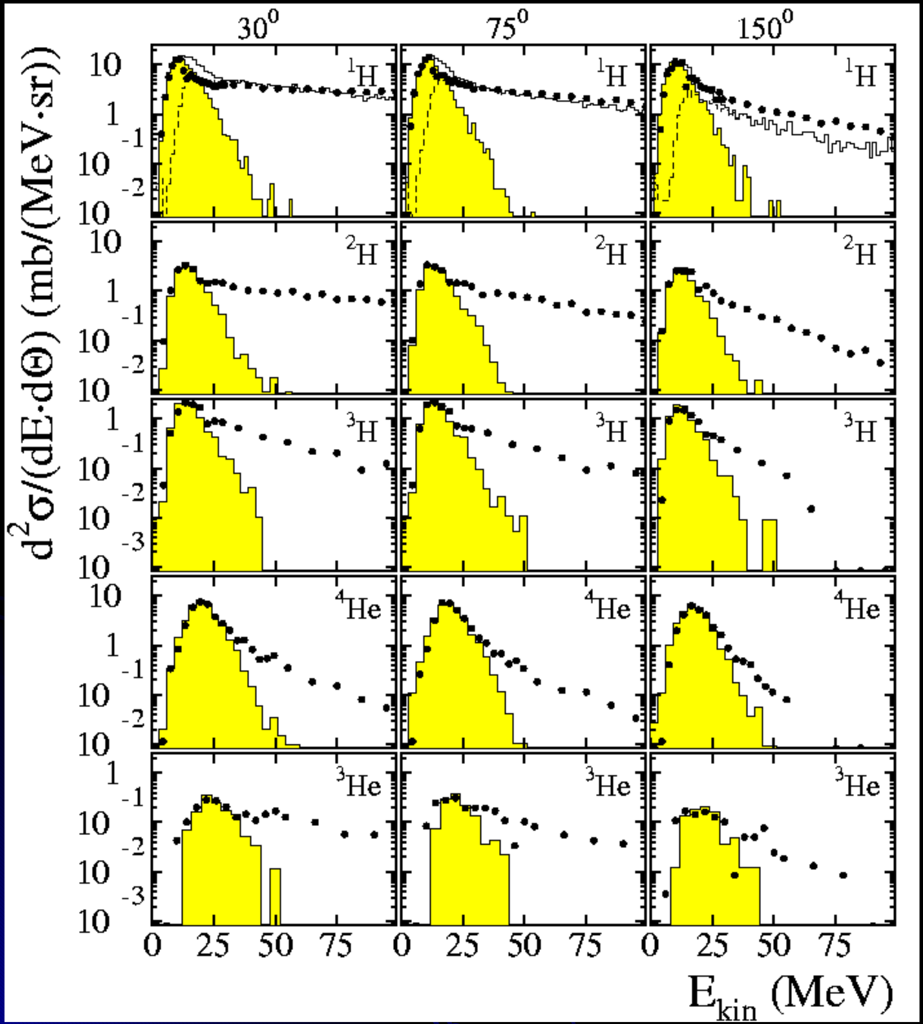


-the INCL code combined with the GEMINI evaporation code describes reasonably well the H- and He- production cross sections for light and heavy nuclei.

-the LAHET code with RAL option overestimates the H production for all Z and the He production for heavy nuclei while for light nuclei and low bombarding energies the He production is underestimated.

-the ORNL option for the evaporation code (no E* dependence of Coulomb barriers underestimates the He production and still overestimates the H-production when compared to the experimental results of NESSI.

Energy spectra of $^{1,2,3}H$ and $^{3,4}He$



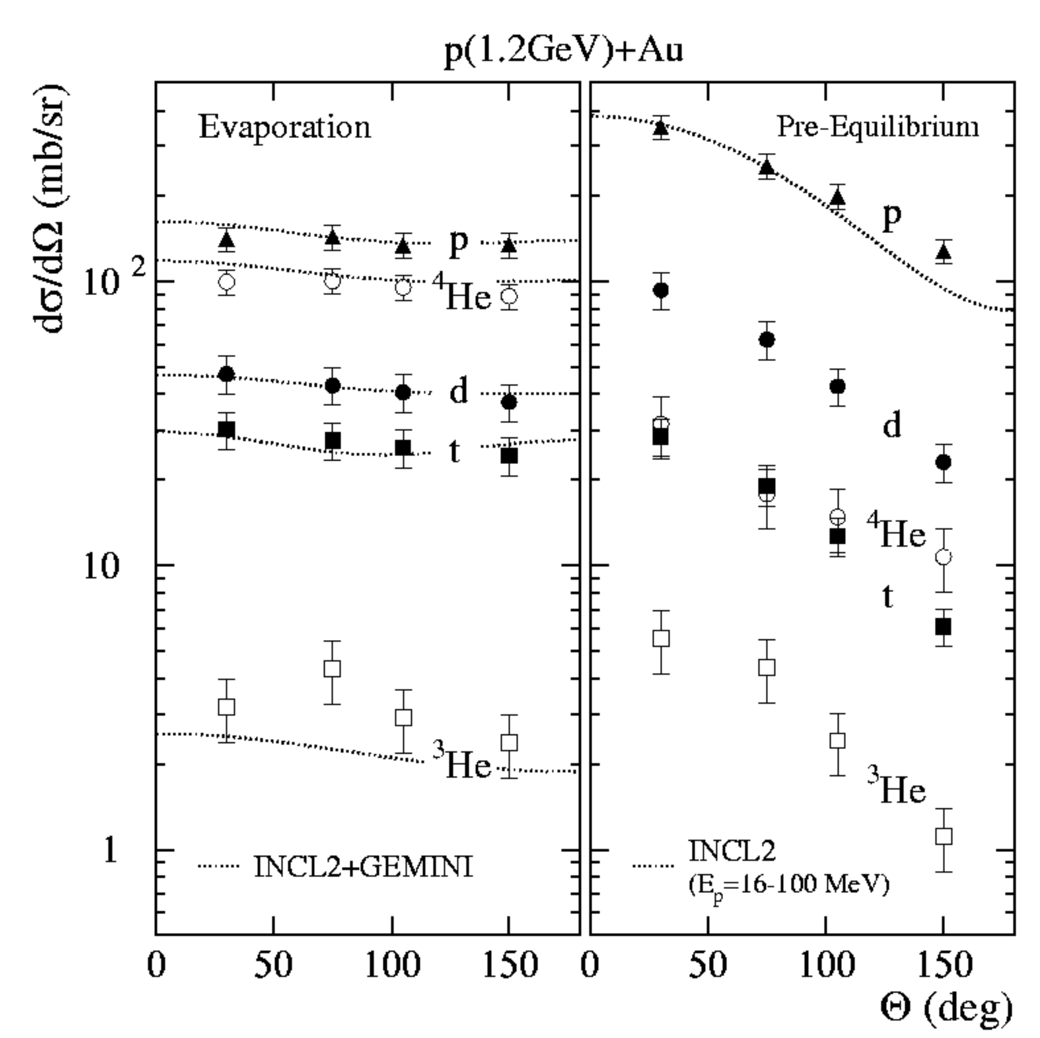
@30, 75 and 150^0 for the reaction 1.2 GeV p +Ta

dots: experimental data
→ clearly feature two components!

shaded histos: calculated evaporation spectra normalized to experimental spectra

dashed histo: INC-protons by INCL2.0

Angular distributions of LCPs in the 1.2 GeV p+Au



Symbols exp.

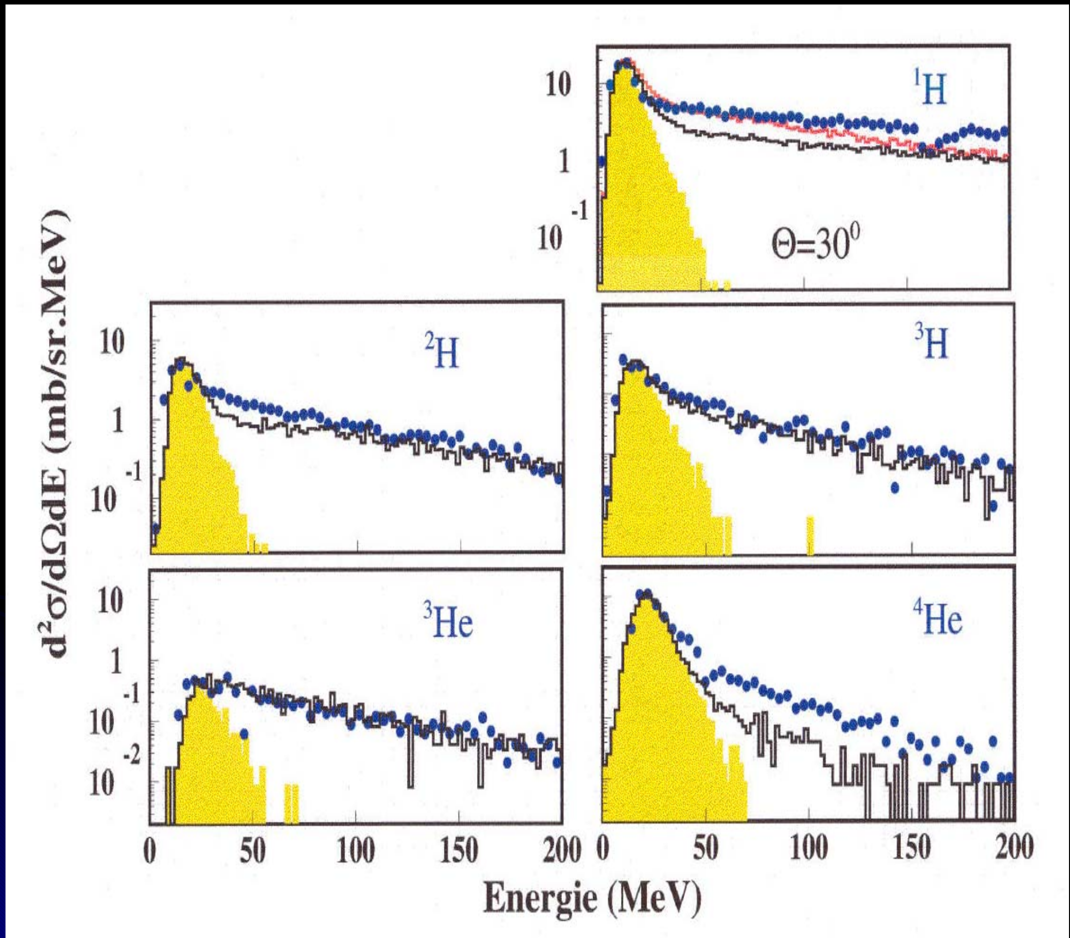
Lines: INCL2.0+GEMINI

Left panel isotropic evap

Right panel: more directly emitted particles exhibit larger forward/backward asymetry;

Protons are well described also in pre-equilibrium process…

^{1,2,3}H and ^{3,4}He spectra for 2.5 GeV p+Au at 30 degree



Kinetic energy spectra for ^{1,2,3}H and ^{3,4}He measured by telescopes for 2.5 GeV p+Au at 30 degree (symbols)

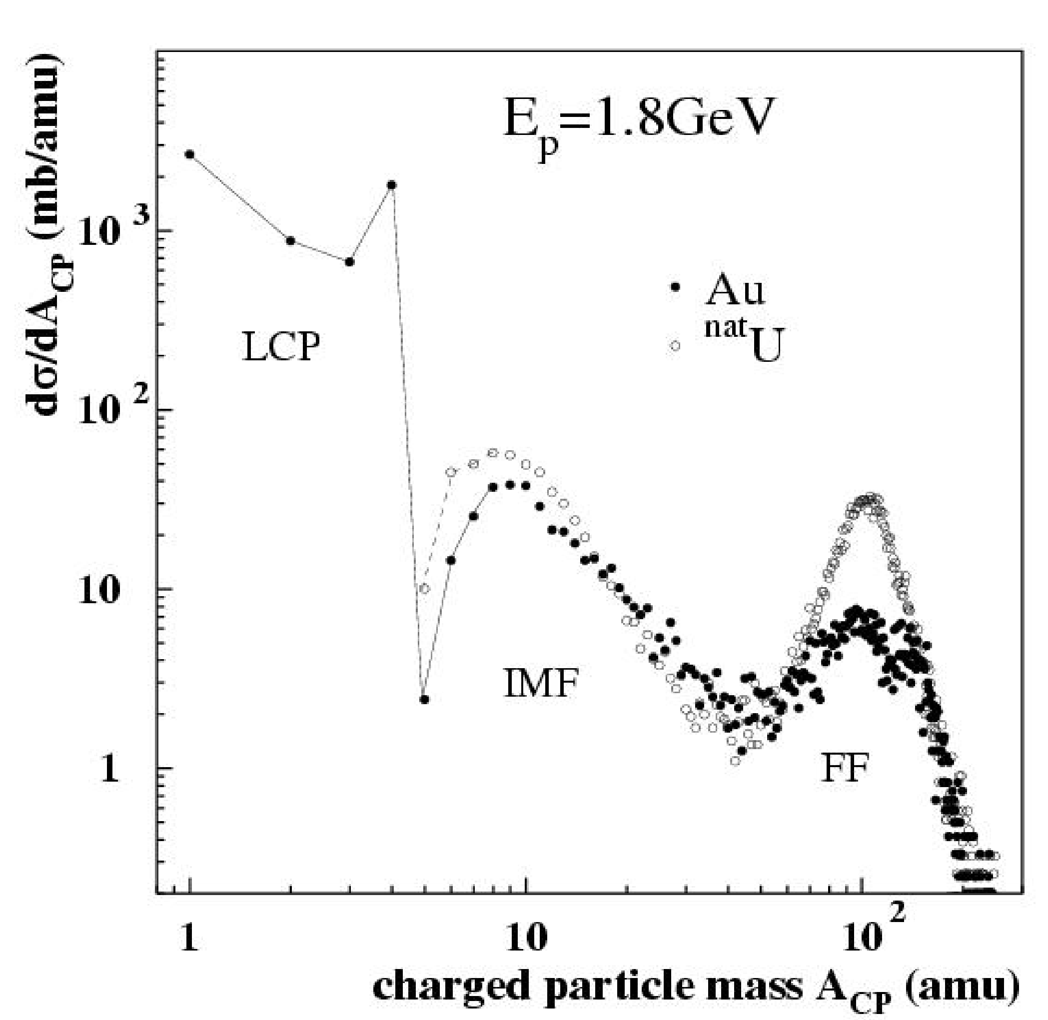
Simulations with INCL including a coalescence model for the pre-equilibrium stage are shown as the black histograms.

The yellow shaded histogams represent the evaporation component.

The red histogram for protons (upper right panel) displays the proton spectra of the original INCL calculations without preequilibrium.

^{4}He mostly evaporative!

Mass distribution for 1.8GeV p+Au,U



M.Enke et al.