# Neutron Interactions

1. Neutron high energy cross-section
2. Elastic scattering – see next talk (M.Kosov)
3. Neutron HP
4. The TARC Discrepancy
5. Cascade neutron production
6. Pre-compound evaporation neutrons
7. Low energy isotope production
8. Cascade isotope production
9. Summary and Conclusions

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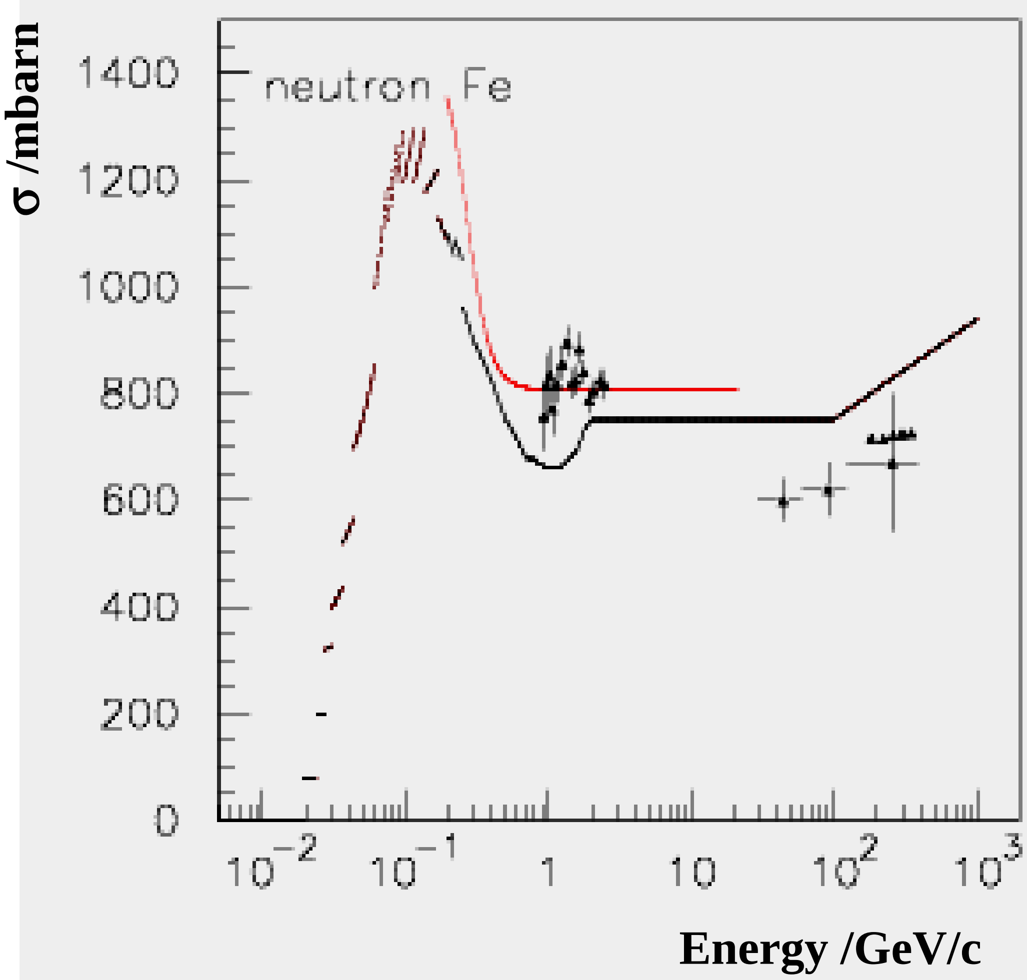
Geant4 Workshop, Lisbon 11th October 2006

# High energy neutron physics

- **Parameterized models**
  - LEP 0~30 GeV
  - HEP ~15 GeV up to 15 TeV
  - a re-engineered version of GHEISHA
  - Elastic, Inelastic, Capture and Fission
- **Theory driven models**
  - Cascade Models
    - Binary Cascade < 3 GeV
    - Bertini Cascade < 10 GeV
  - High Energy Models ~15GeV < E < ~15 TeV
    - Quark-Gluon String (QGS)
    - Fritiof fragmentation (FTF)

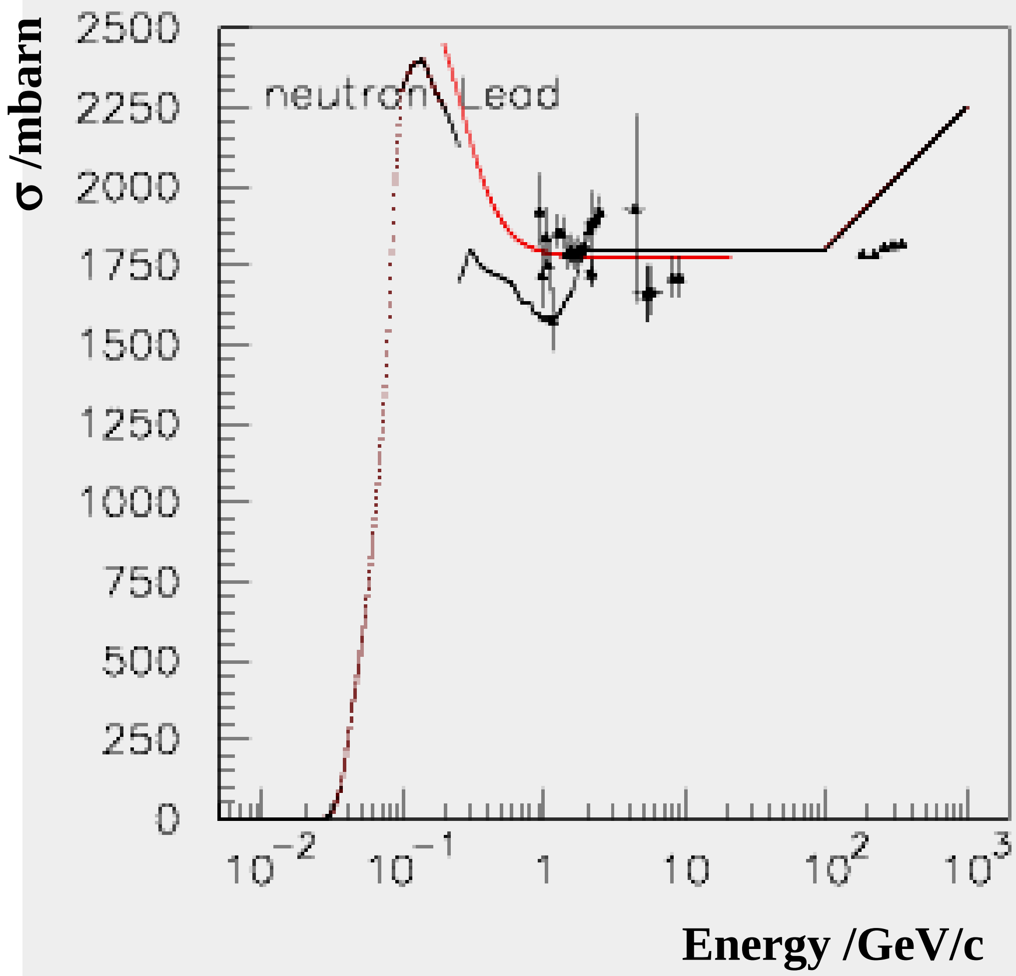
# Neutron on Iron Inelastic Cross-Section

- **Cross-section vs. neutron momentum in GeV/c**



# Neutron on Lead Inelastic Cross-Section

- **Cross-section vs. neutron momentum in GeV/c**



# Low Energy (<20MeV) Neutron Transportation

- **High Precision Neutron Model and Data Sets**
  - G4NDL v3.x
    - Add and replaced data files (Sb, Hf, Sm, Nd, Gd,,,,)
  - Model and data sets
    - Many debugs and several new implementations
- **Thermal Neutron Transportation**
  - Based on thermal neutron scattering files from the ENDF/B-VI, Release2
- **New Data Files**
  - G4NDL v4 ?
  - Produced from ENDF and JENDL
  - Several isotopes are ready and under testing

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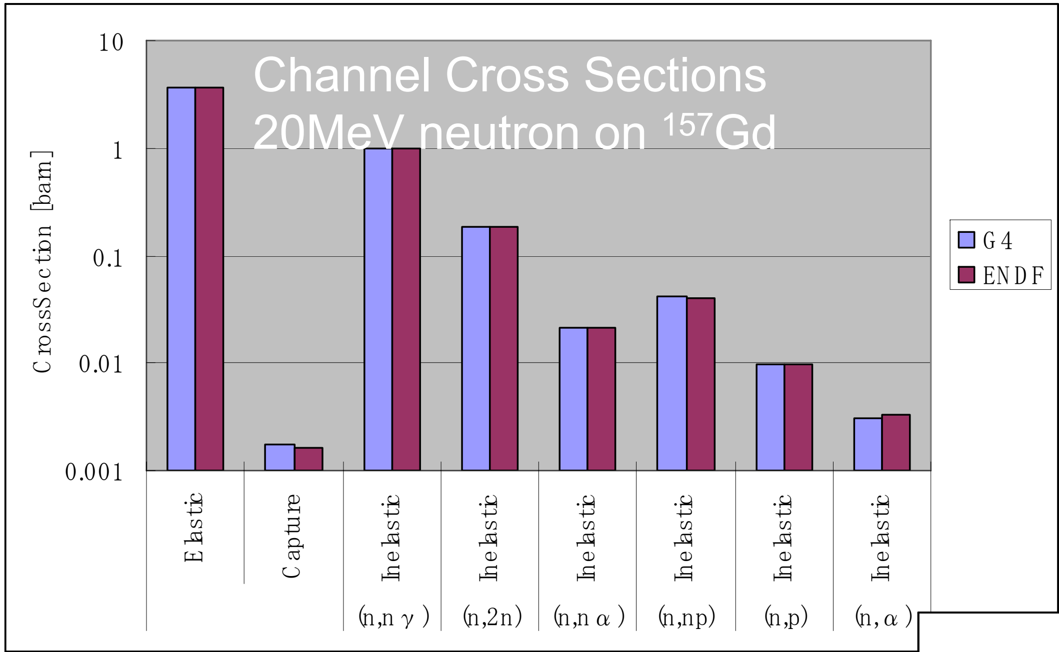
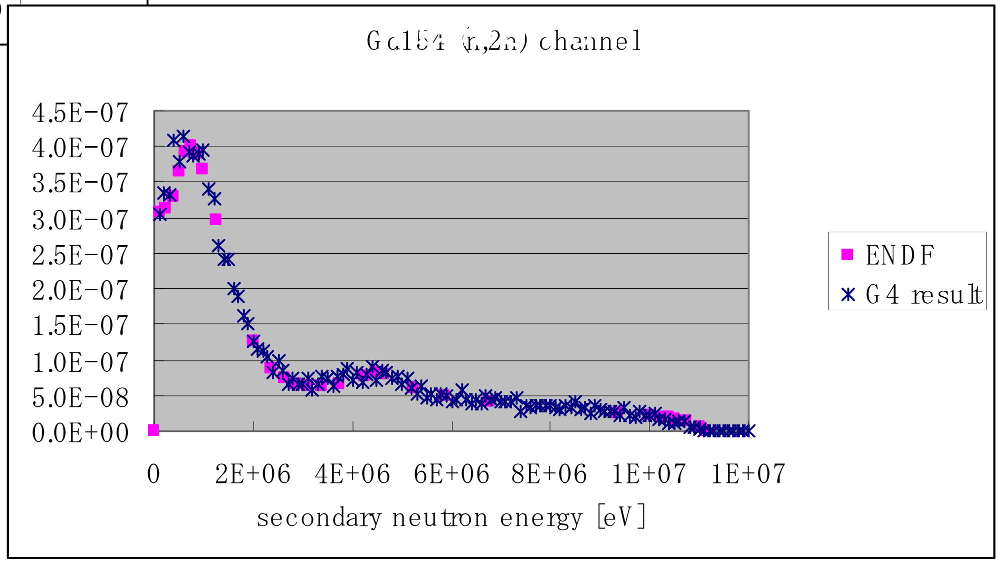
# Verification of High Precision Neutron models

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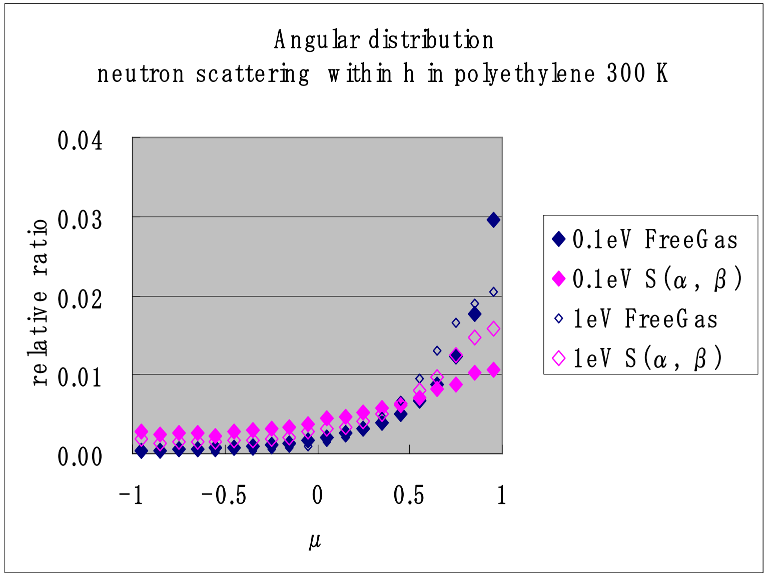
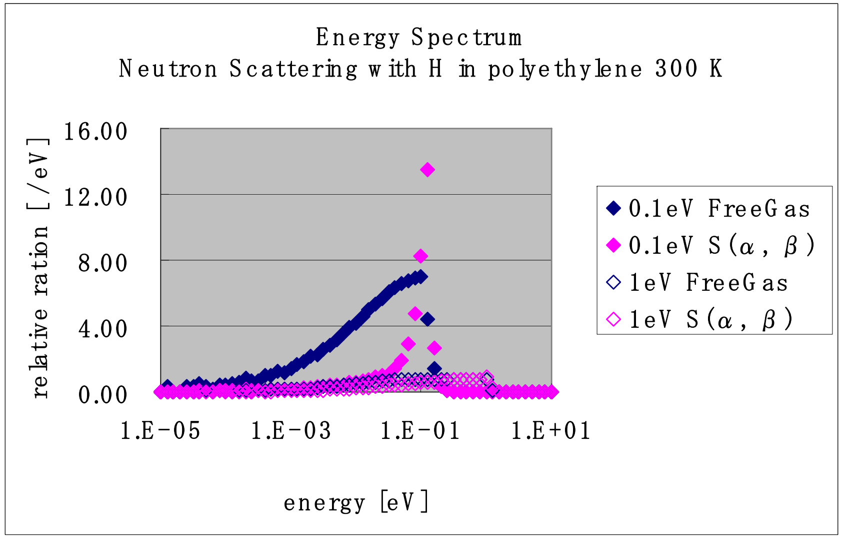
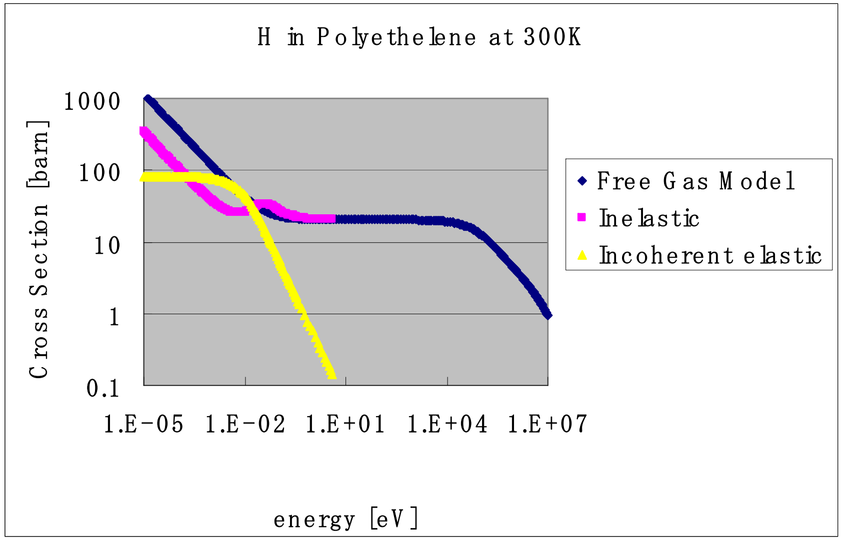
# Cross section and Secondary Neutron Distributions of S(α, β) model

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# Known Problems and Themes

- **Computing Speed**
  - Slow; caused by on flight Doppler broadening
- **Several Disagreements**
  - Some of them are Model Specifications and some of them are bugs
  - Detected in
    - Reaction Q values
    - Flame Transportations
    - Others
- **Correlated Final States**
  - OK for binary products
  - Higher multiple products only treated statistically
    - Non conservation of energy and momentum in each single reaction

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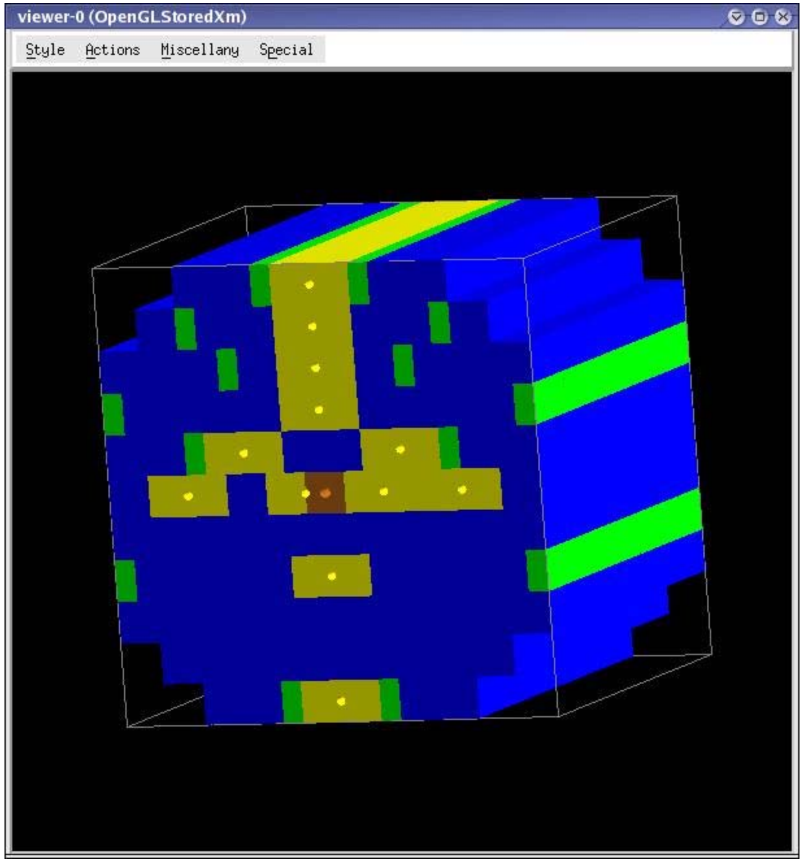
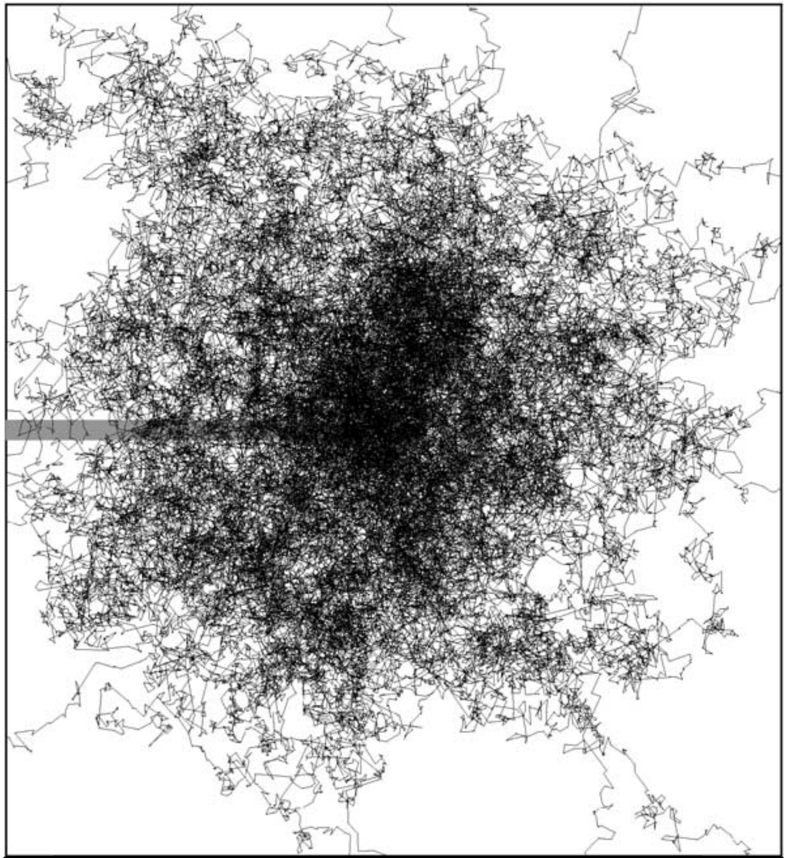
# Simulation of the TARC experiment

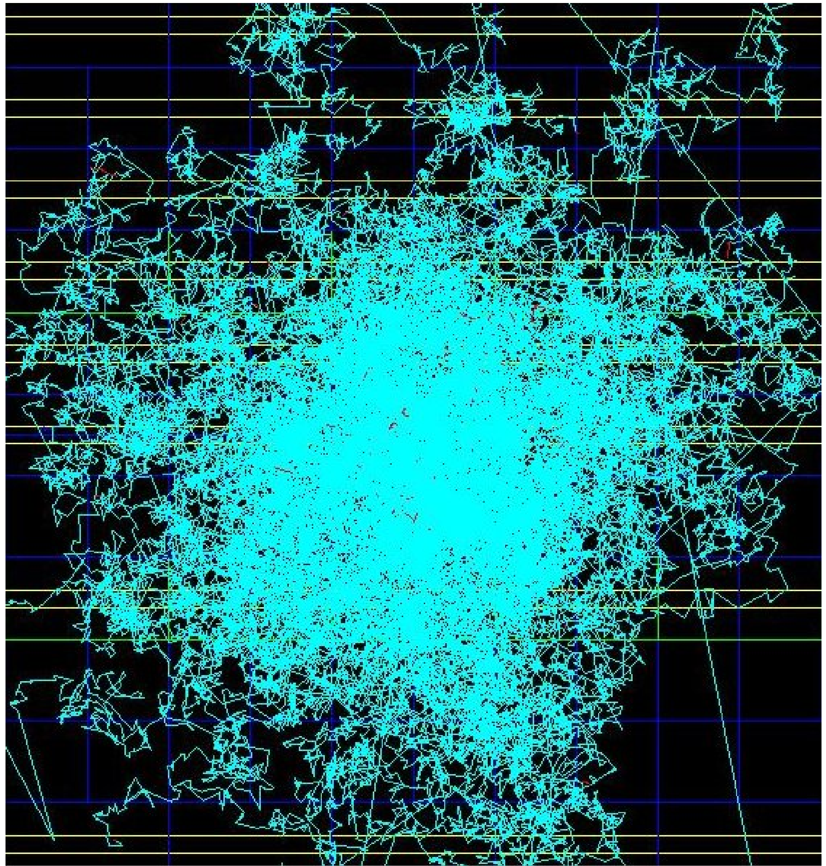
- Neutron Driven Nuclear Transmutation by Adiabatic Resonance Crossing (Cern 96-97)
- 334 tons of pure Pb in cylindrical 3.3m x 3.3m x 3m block.
- 12 sample holes are located inside the volume to measure capture cross-sections on some isotopes.
- 2.5 or 3.5 GeV/c proton beam.



# TARC simulation – single event 3.5 GeV/c proton on natural lead



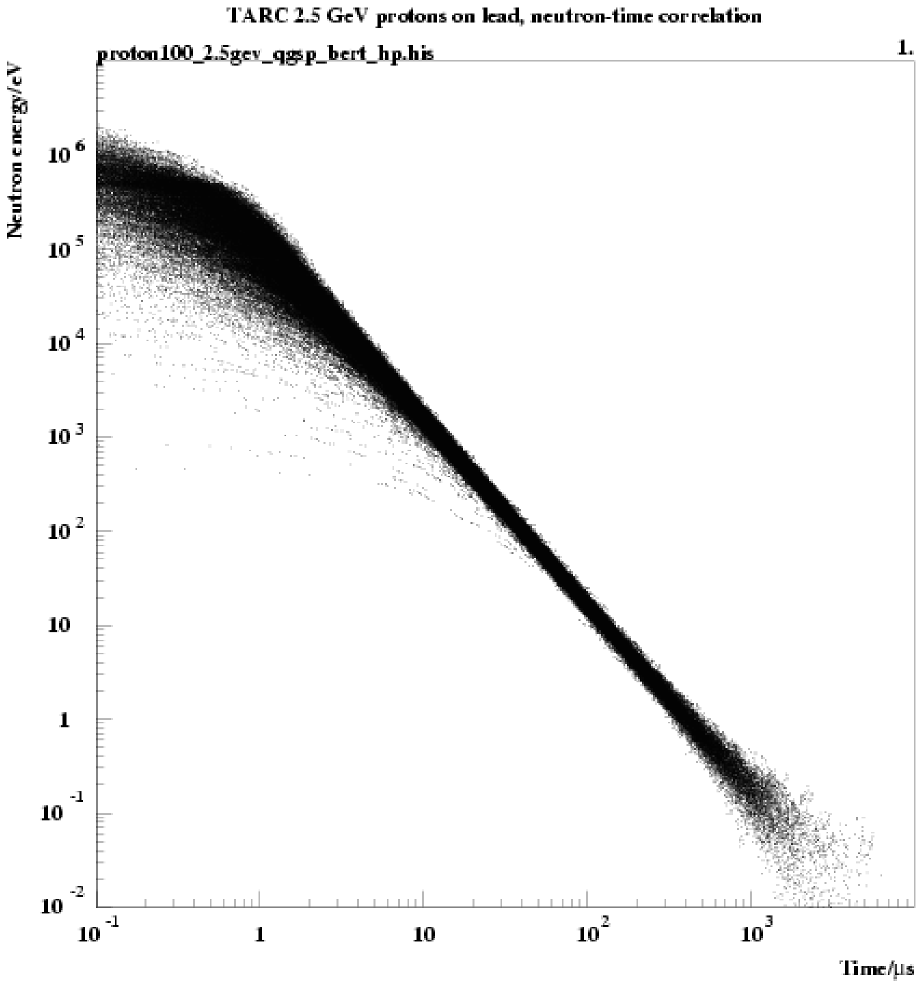
TARC original simulation



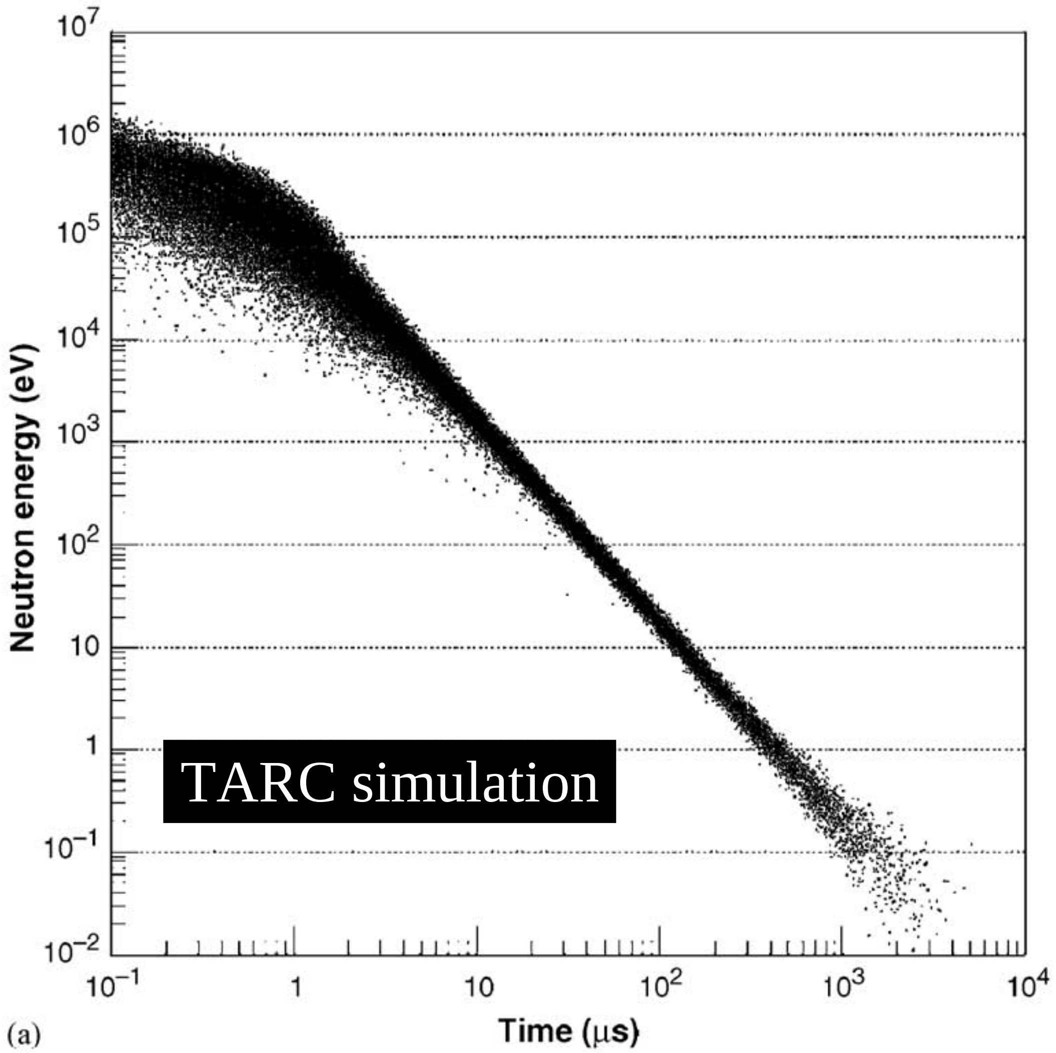
Geant4

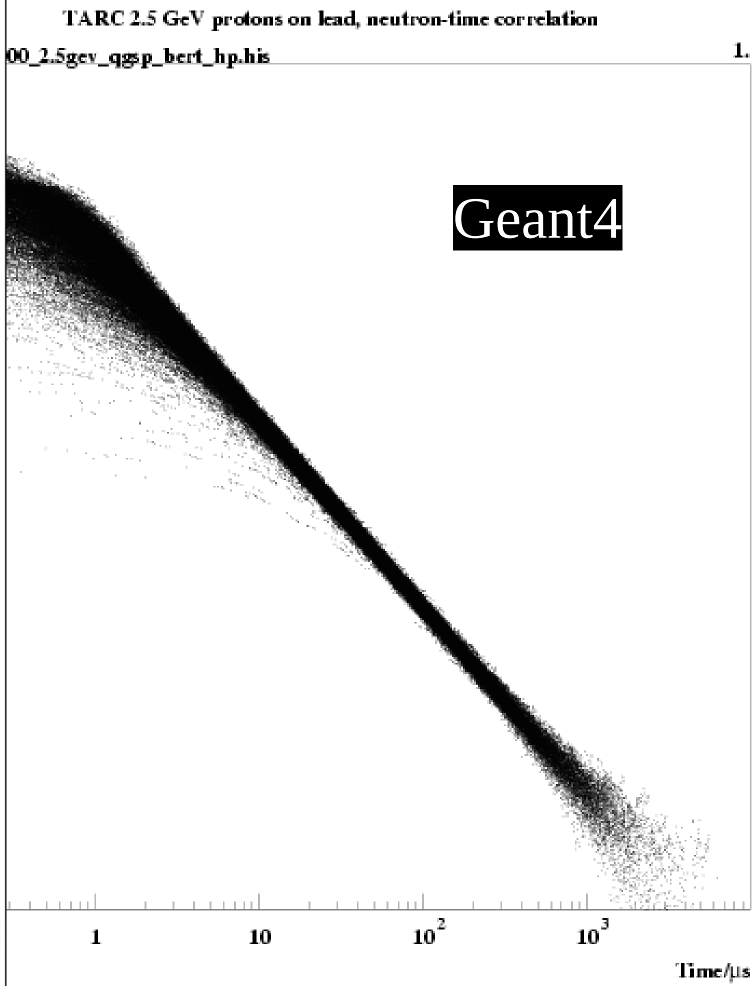
# Neutron Energy-Time Correlation

- Neutron energy and time are stored for the flux through a given radial shell
- Reasonable agreement with expectation, although the low energy population is quite different between physics list (as expected)



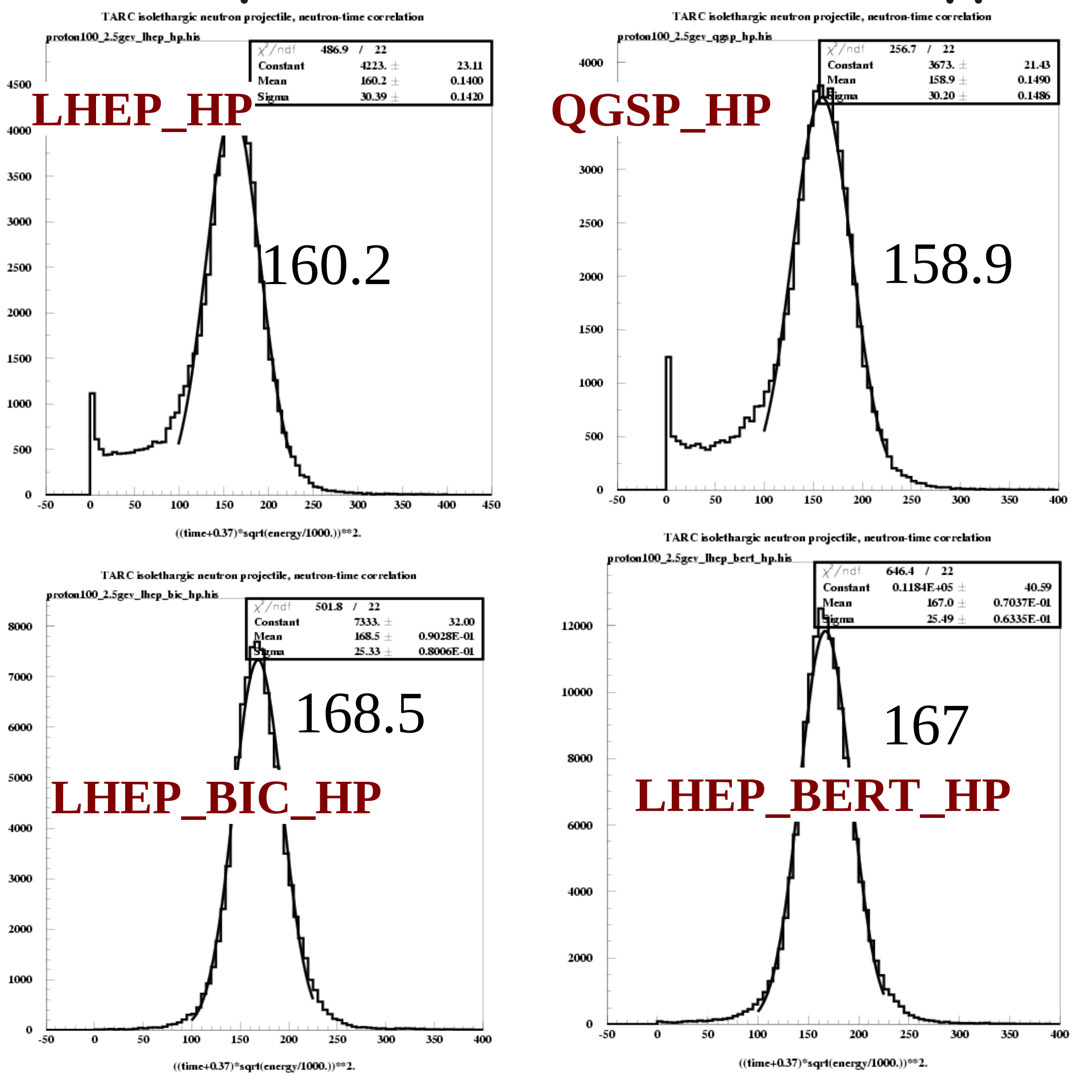
# Neutron Energy-Time Correlation



# Neutron Energy-Time Correlation

- **The slope of the correlation can approximate a Gaussian distribution**




Experiment and TARC simulation gave 173±2

- Bertini and Binary cascades are close to agreement with experiment

Minuit errors on the mean are between 0.03 and 0.08

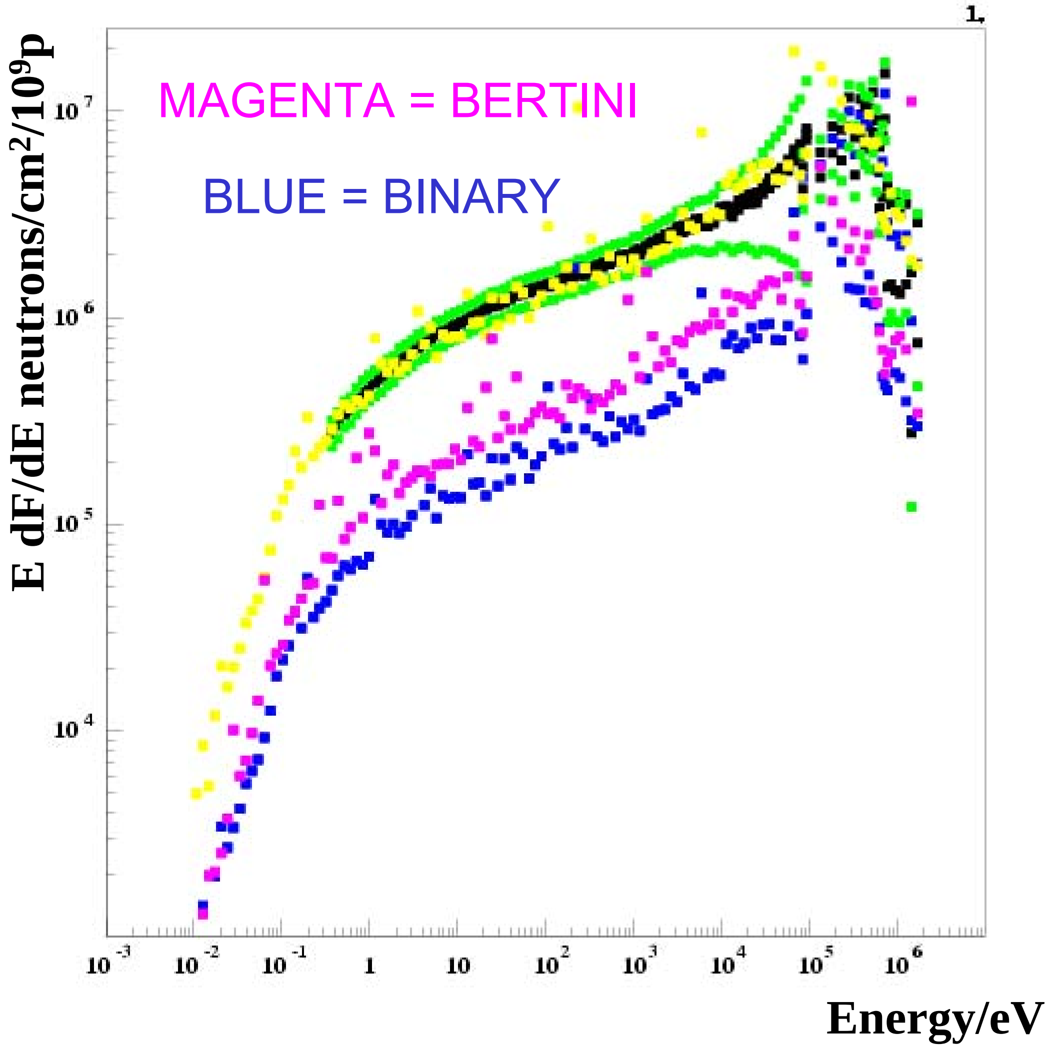
# Number of neutrons exiting

- TARC determined the number of neutrons exiting their set-up as 30% of those produced. This is primarily based on the FLUKA neutron production code with their own transportation
- Geant4 can be used to compare the difference energy spectra and multiplicities of the cascade models
- So far initial numbers are:

  - BERTINI gives 32.5% exiting
  - BINARY gives 32.34% exiting

# TARC Fluence

- Spectral fluence is determined from the energy-time correlation with cross-checks (lithium activation and He3 ionisation detectors)
- The simulated fluence is still below measurement
- The bertini cascade gets closest to the data
- The spectral shape looks reasonable
- Yellow curve is ~ 4xBERTINI or ~ 6xBINARY

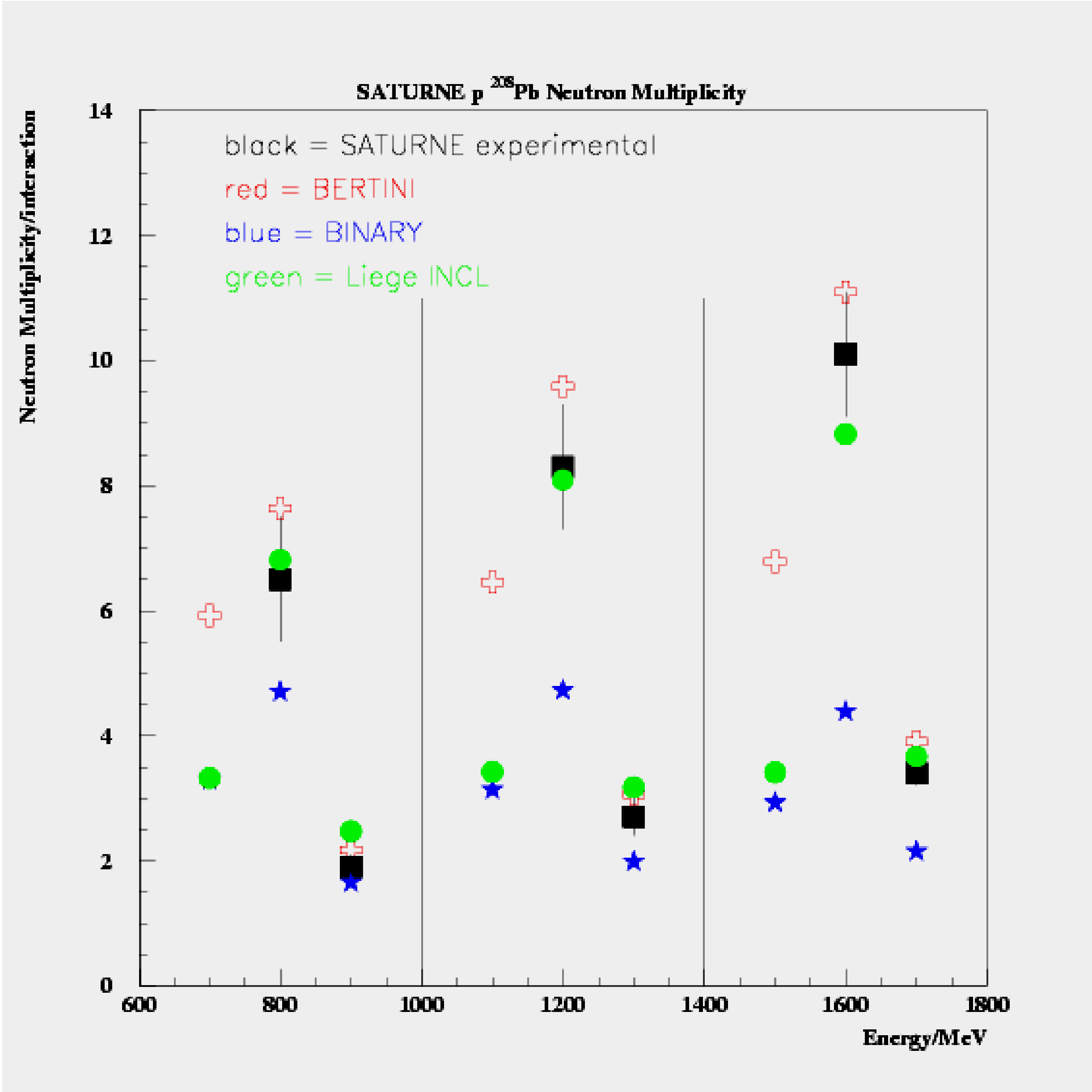


# Neutrons in Cascades

- Clearly the TARC fluence is severely underestimated by a factor of 4 (bertini) → 6 (binary)
- It was decided to look at thin target data across the relevant energy range
- SATURNE data exist for 800MeV, 1200MeV, 1600MeV → neutron multiplicity, and E x $M_n$
- Isomer gamma measurements for proton on $^{208}$Pb producing $^{207}$Pb or $^{206}$Pb
- To compare with Geant4 requires scaling with the number of isomeric states *(or use RDM → future)*
- At low energy (<100 MeV) the ratio of states can be considered approximately fixed vs. energy
- Data for 52, 44, 36, 28, 24 MeV
- Comparison made between data, bertini, binary and the Liege INCL/ABLA code

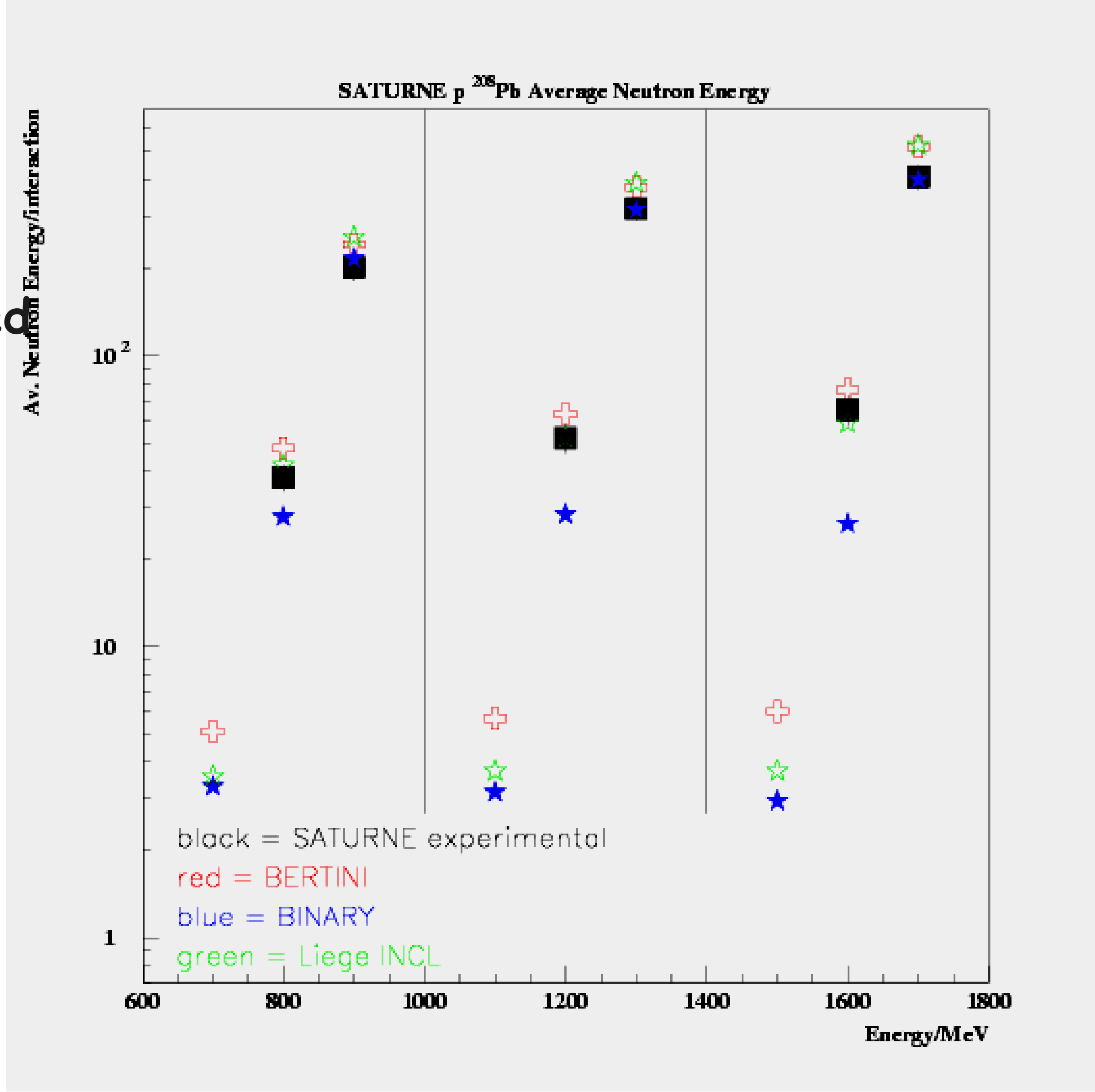
# SATURNE Neutron multiplicity

- First point is 0-2MeV Neutron Energy Bin
- Second is 2-20MeV
- Third is >20MeV



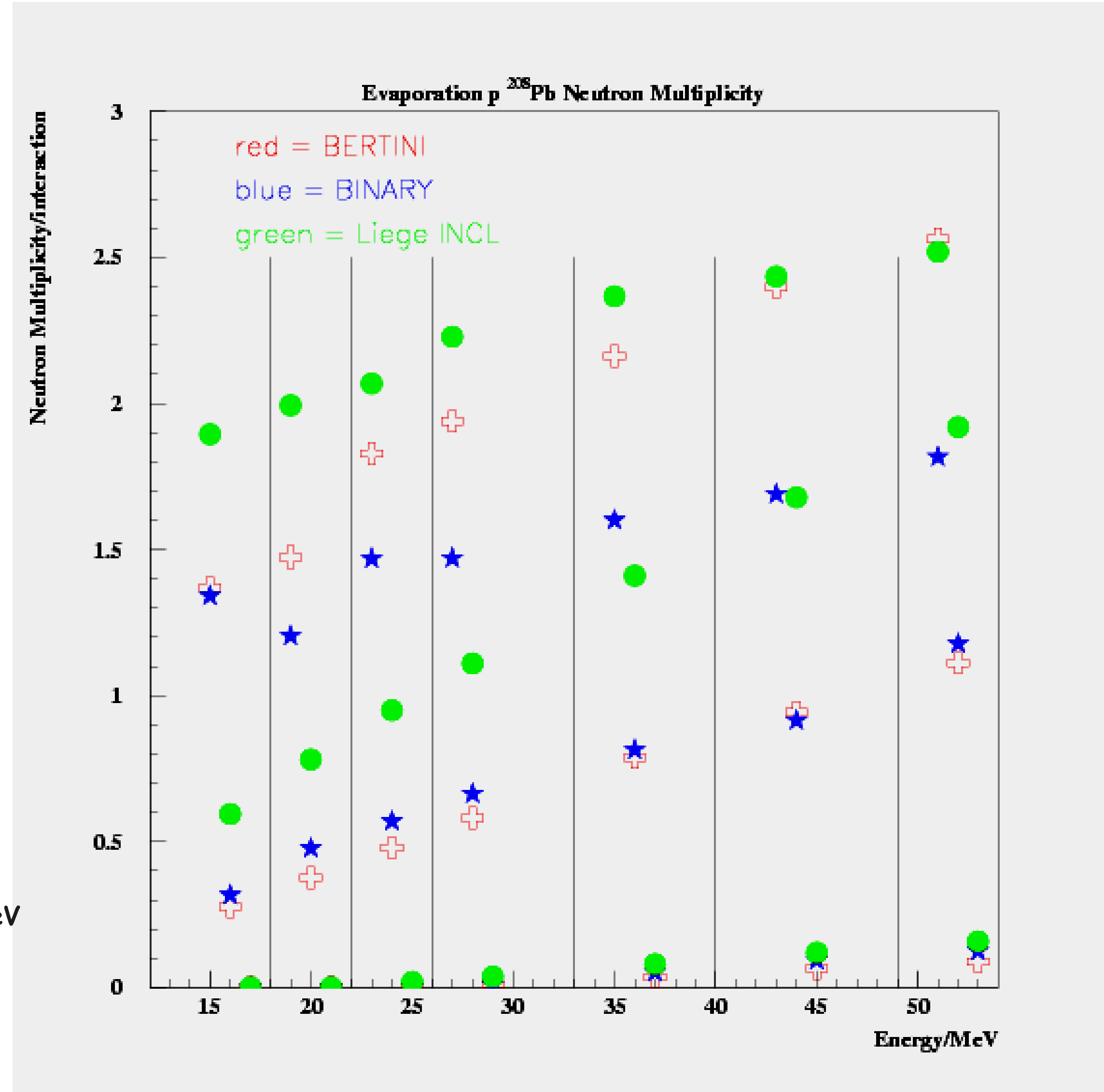
# SATURNE Av. Neutron Energy

- Average energy carried by neutrons per interaction
- NOT average energy of each neutron



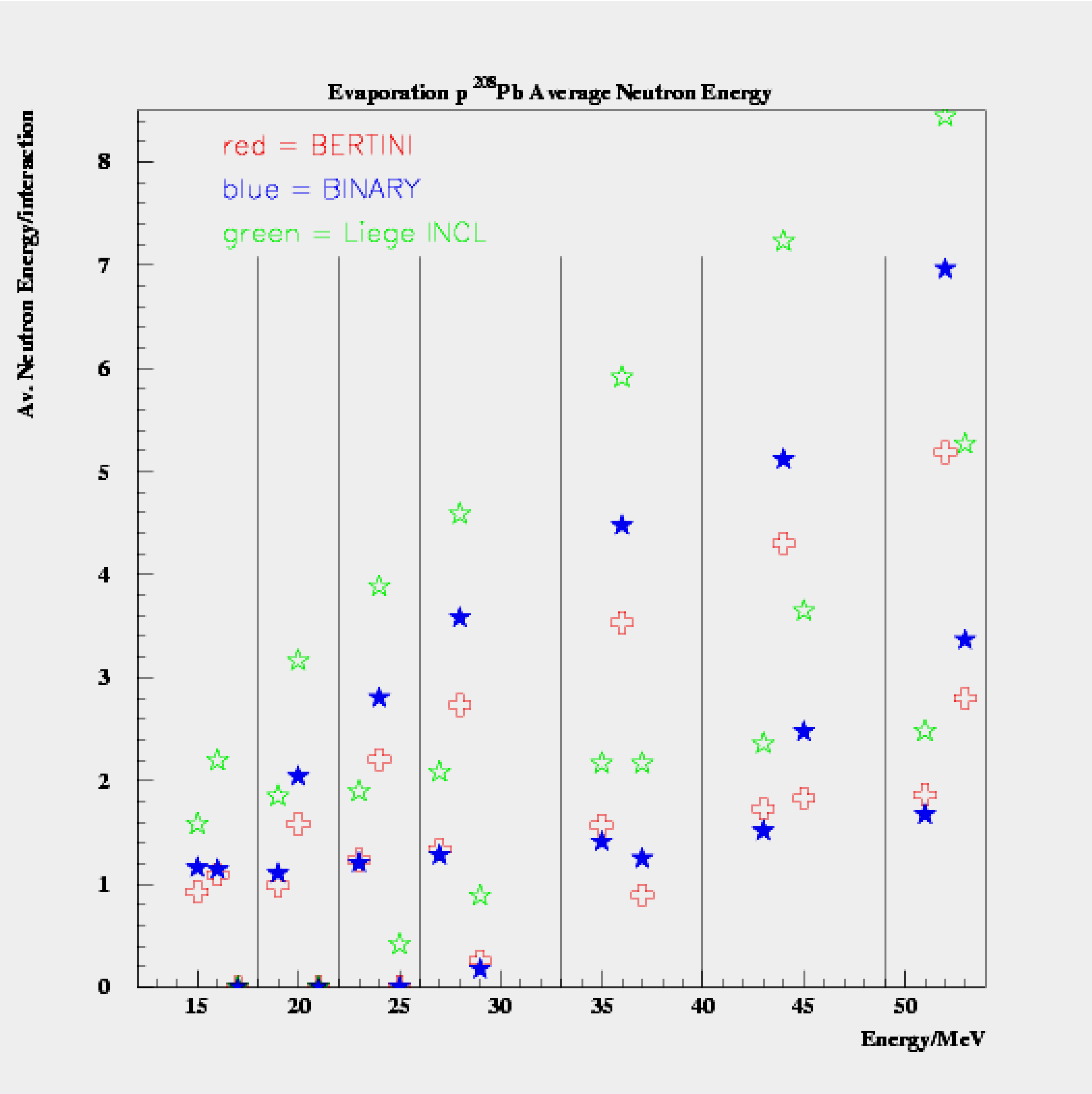

- First point is 0-2MeV Neutron Energy Bin
- Second is 2-20MeV
- Third is >20MeV

# Neutron multiplicity 16-52 MeV




- First point is 0-2MeV Neutron Energy Bin
- Second is 2-20MeV
- Third is >20MeV

# 16-52 MeV Av. Neutron Energy



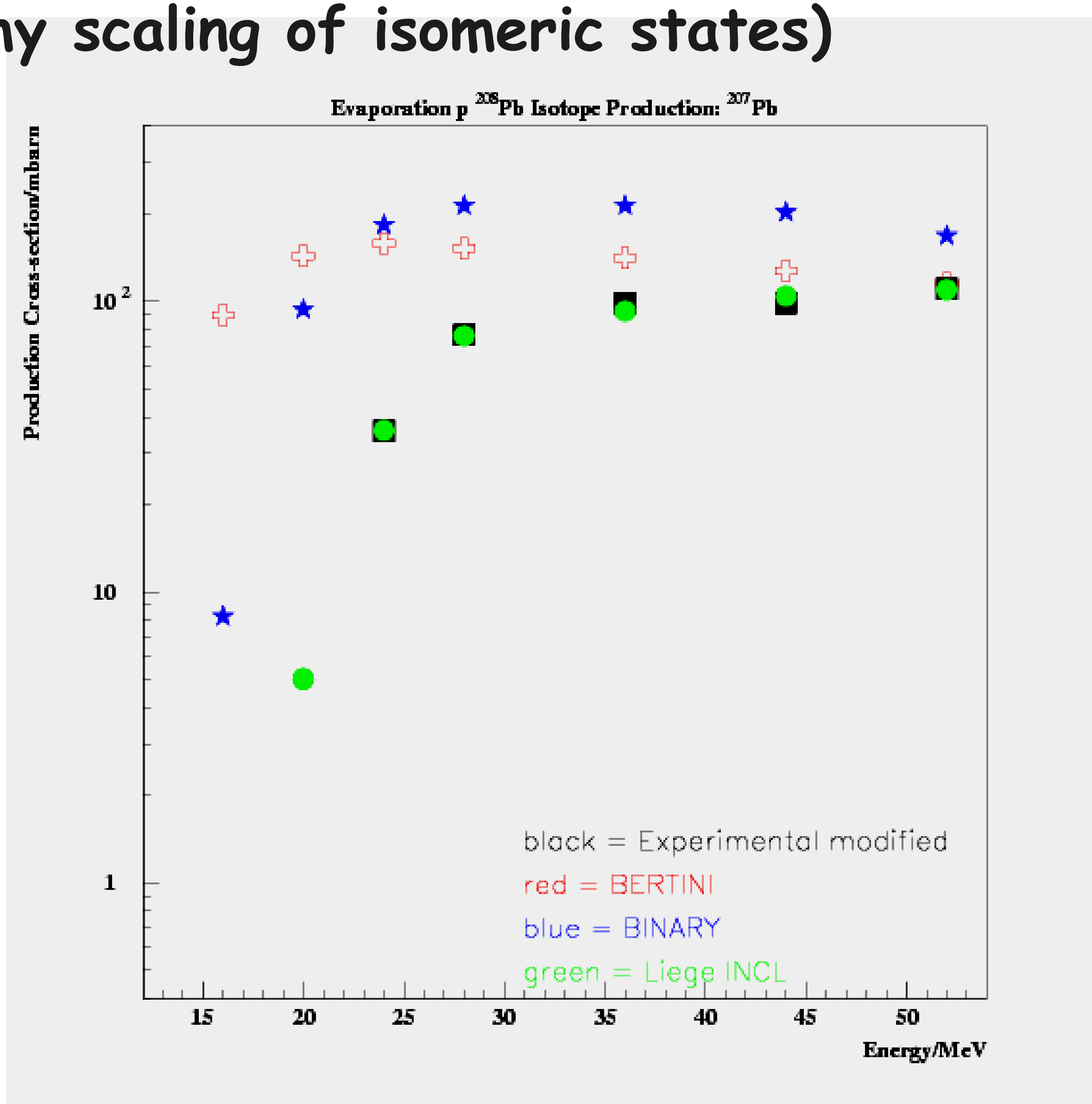

- First point is 0-2MeV Neutron Energy Bin
- Second is 2-20MeV
- Third is >20MeV

# Cross-section comparison – low energy (16-52MeV)

- **Experimental data is purely isomer gamma-line**
- **The measured cross-section was scaled by the number of isomeric states (estimate)**
- **This gives a lower value for the cross-section**
- **Experimental errors were quite large (+/- 25%)**
- **Converting Liege INCL output to cross-section:**
  - Assume ntuple is filled per interaction
  - Scaled number of entries by total and multiplied by cross-section (as given by INCL)
  - The ratio between final states should at least be true

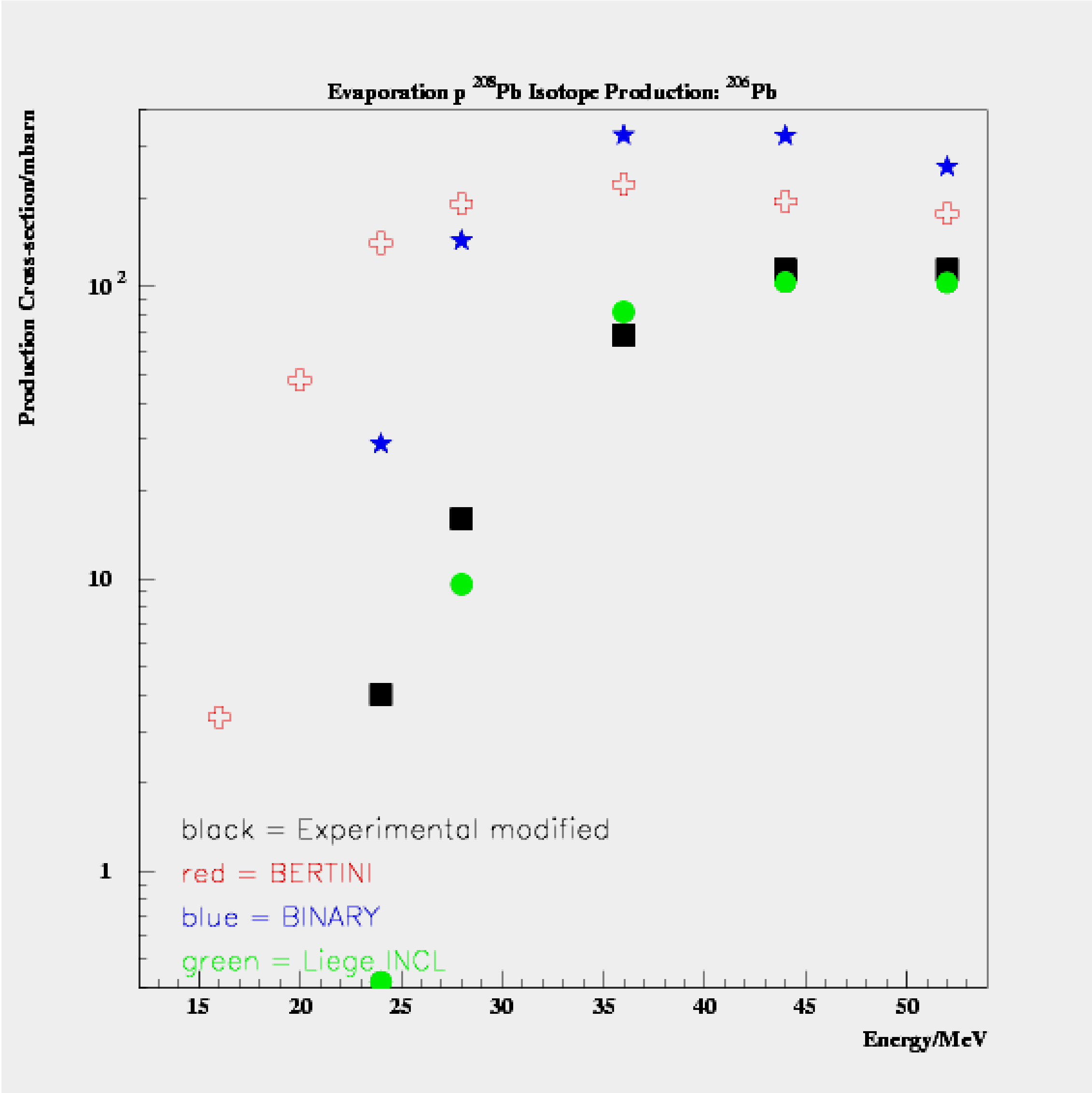
# $^{207}$Pb Production 16-52 MeV

- The agreement between INCL/ABLA is surprising (given my scaling of isomeric states)



# $^{206}$Pb Production 16-52 MeV

- INCL/ABLA does a good job, except at threshold



# Isotope Production

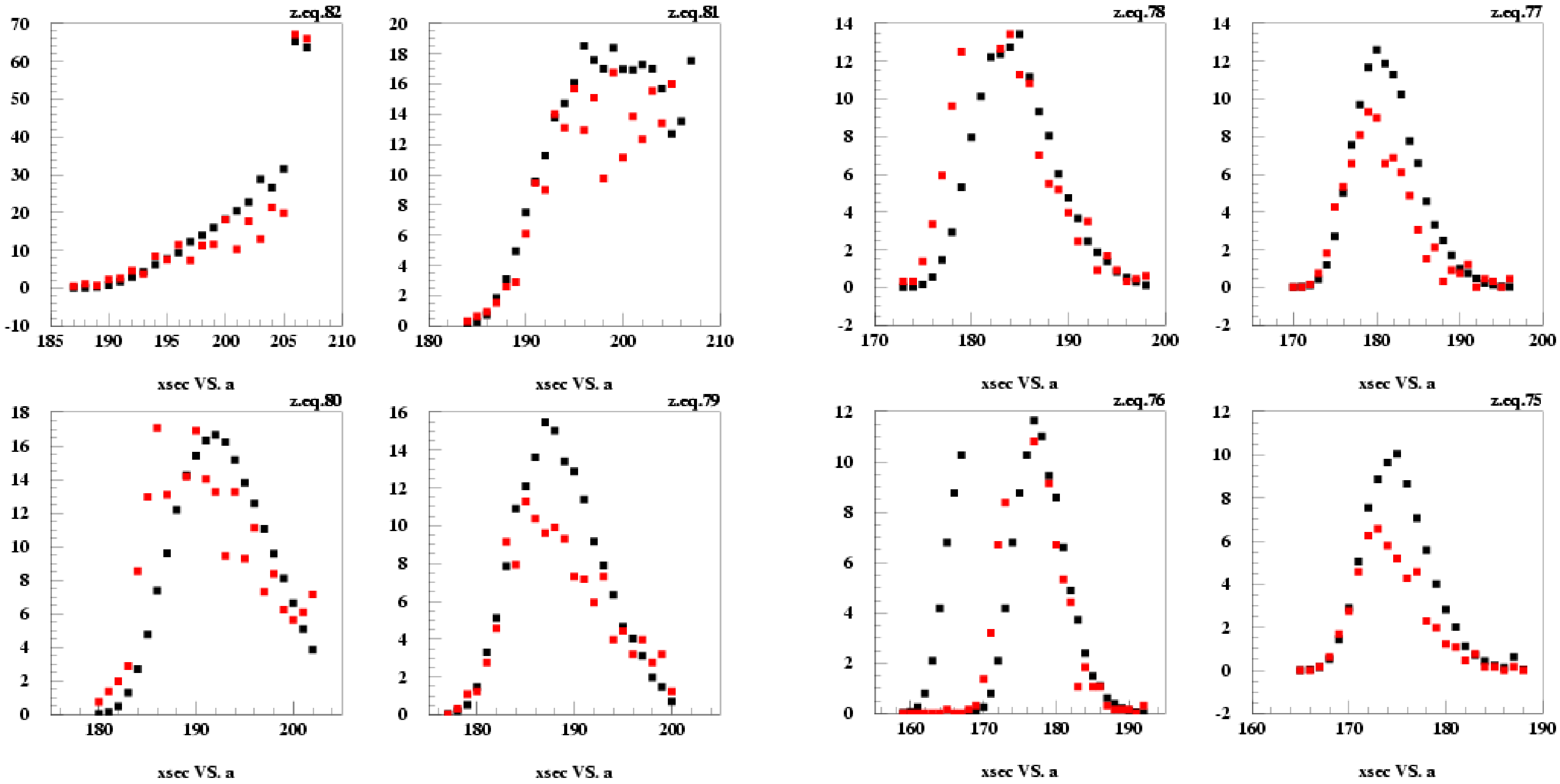
- Data exist for 1GeV/A lead incident on hydrogen target
- Reverse kinematics allow the cross-section of isotope production to be determined
- The production of isotopes will heavily influence the neutron multiplicity and with energy conservation the spectrum

→ Ultimately determining the TARC fluence (at least at a generator level)

- In following data are black, simulation is red

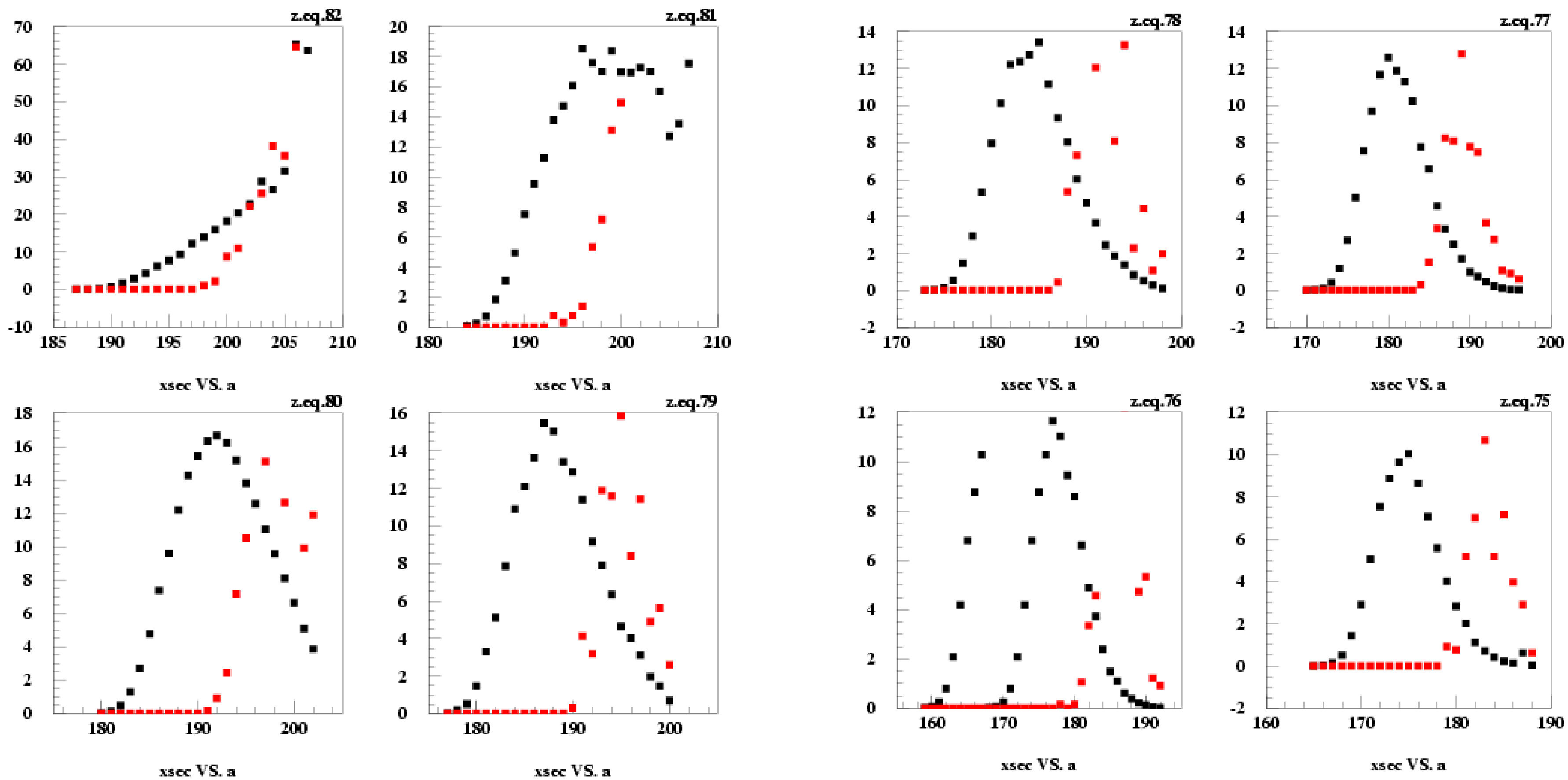
# 1GeV/A Pb on hydrogen – BERTINI z=82-75

- **BERTINI seems to do a (very) good job!**



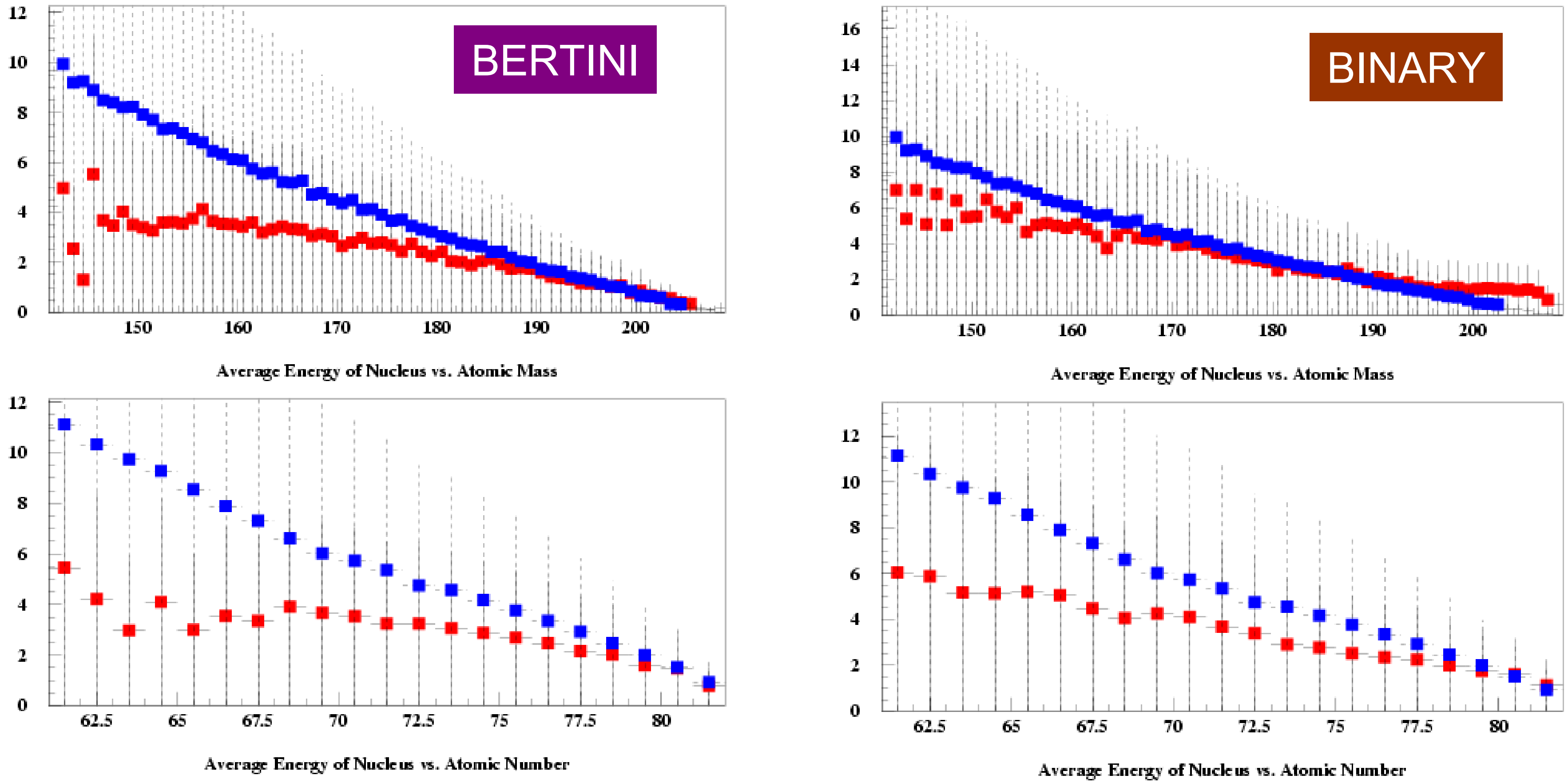
# 1GeV/A Pb on hydrogen – BINARY z=82-75

- **BINARY significantly under-produces lighter isotopes – therefore less neutrons**



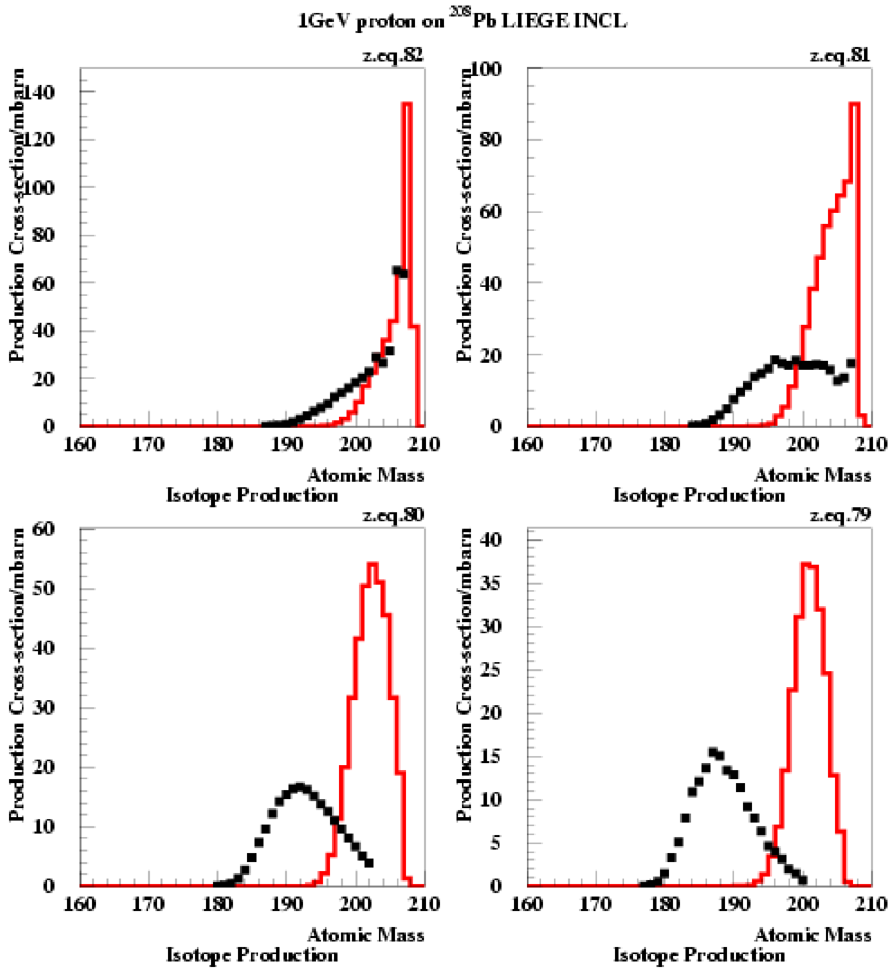
# 1GeV/A Pb on hydrogen – Fragment Energy

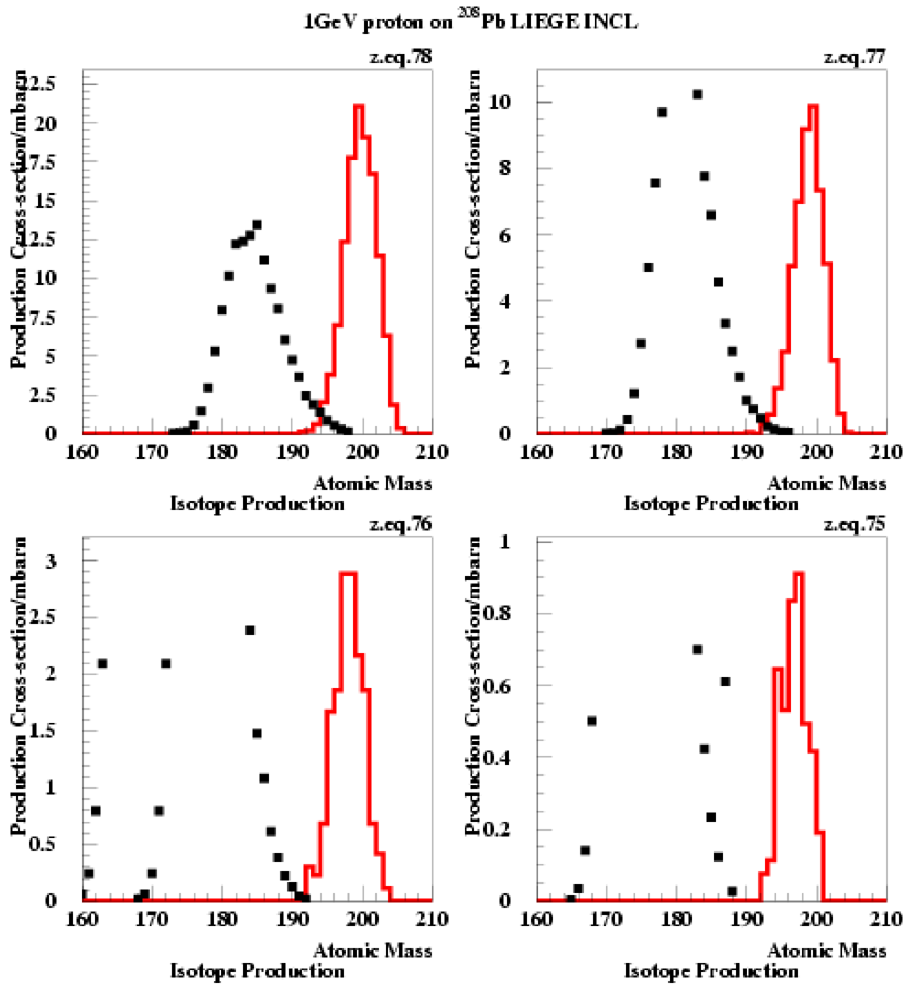
- **Fragment energy is low for both models binary is higher**



# Isotope production – Liege z=82-75

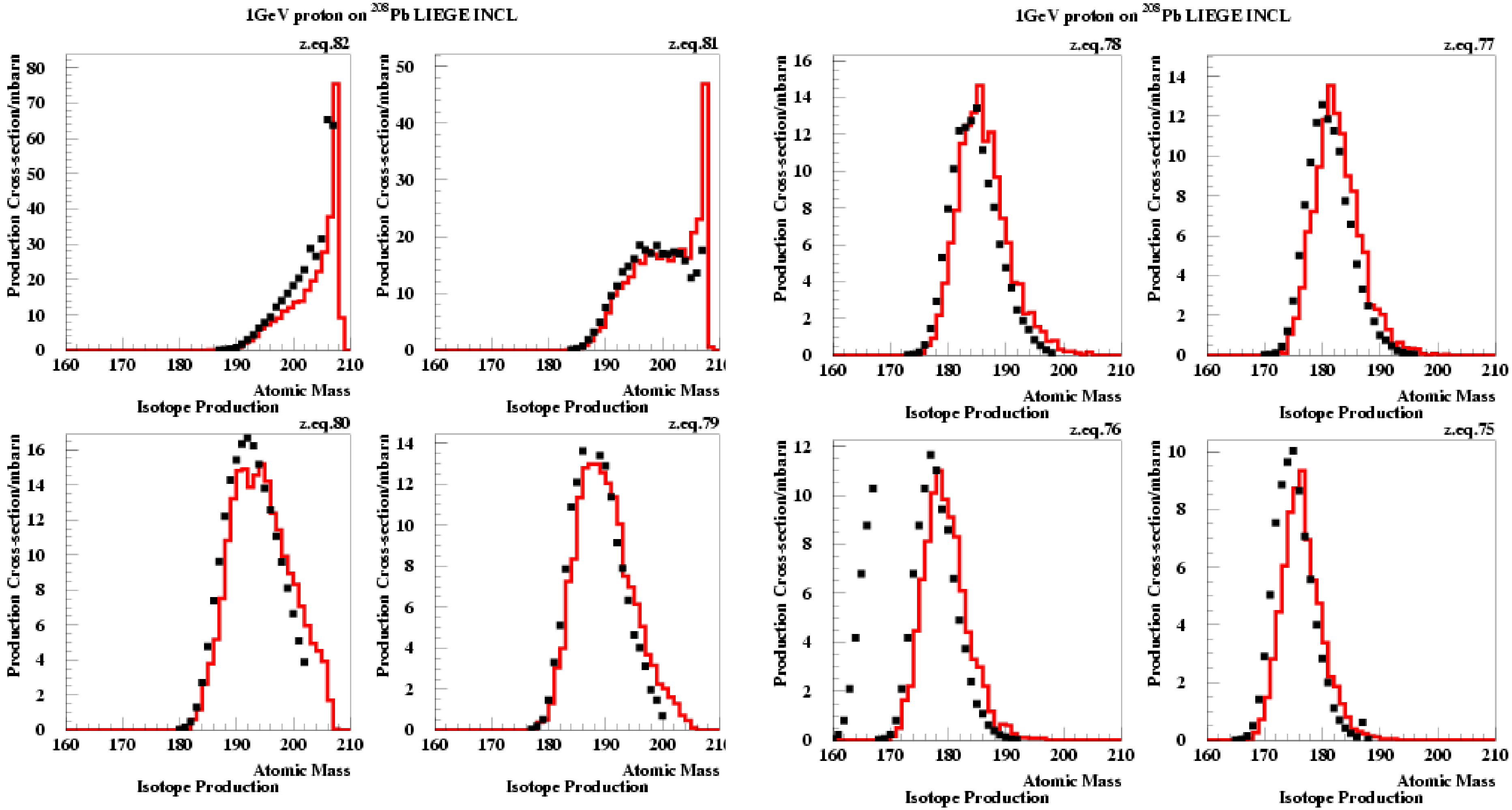
- "Remnant" nucleus distribution from Liege INCL/ABLA



# Isotope production – Liege z=82-75

- Produced isotope distribution from Liege INCL/ABLA
- **The plots here are corrected from the ones shown at Lisbon** 19/10/06



# Summary and Conclusions

- The high energy cross-sections for neutrons show slightly strange systematic behaviour
- Neutron_hp offers high precision cross-sections coming from evaluated data-base
- The S(α,β) model would improve simulation of very low energy neutrons on specific isotopes
- TARC simulation gives good agreement for transportation – energy-time correlation and number of exiting neutrons
- But, TARC fluence is under-estimated by Geant4 (all models)
- BERTINI slightly over-produces neutrons in the cascade region
- BINARY significantly under-produces neutrons
- Data and INCL/ABLA seem to be between binary and bertini
- INCL/ABLA does a very good job even for isotope production
- It is still unclear how we can produce neutrons well, but then lose them from the TARC fluence…
- Suggestions?

# Isotope production – Liege z=82-75

- Produced isotope distribution from Liege INCL/ABLA
- **This was presented but is erroneous – see slide 29 for correct one**