Neutron Benchmarks - TARC

1. **TARC Experiment (recap)**
2. **Energy-time (recap)**
3. **Fluence (revised and corrected)**
4. **Thin target (recap)**
5. **Radial Fluence distributions (new)**
6. **Future work**
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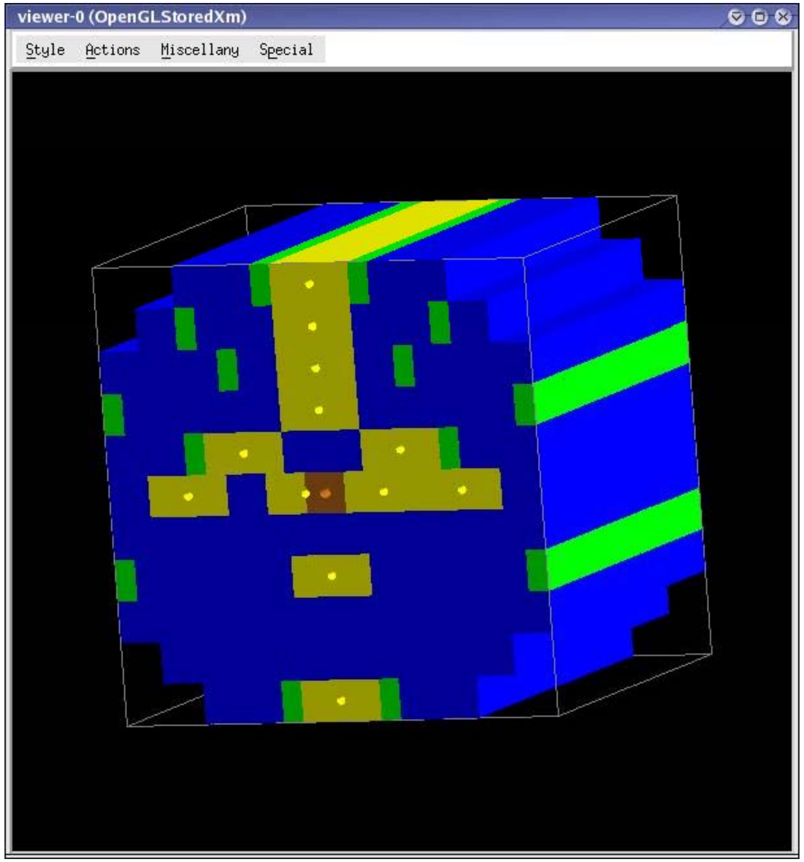
Alex Howard, CERN

Neutron Benchmarks - TARC

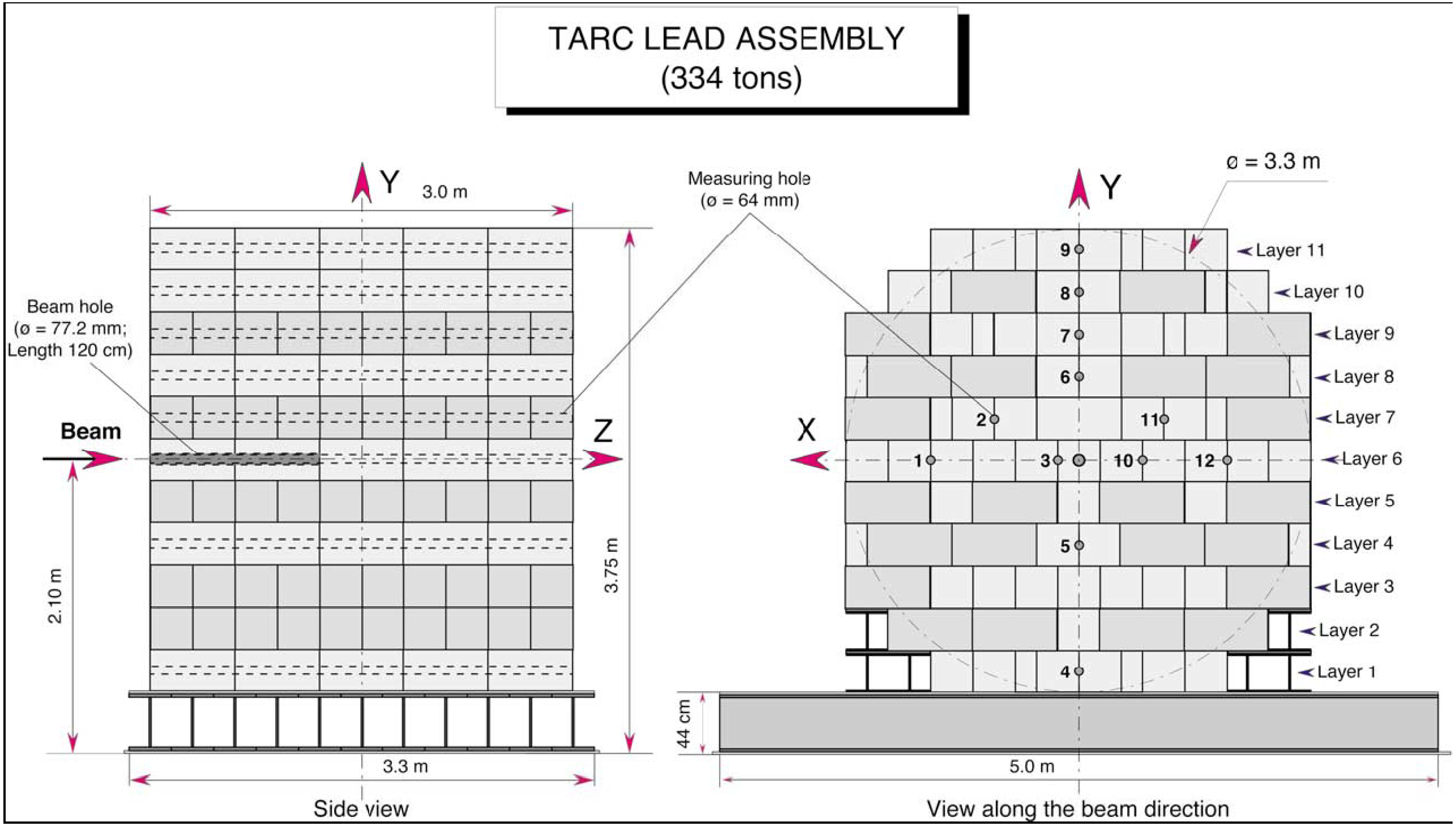
Geant4 Users Workshop Hebden Bridge 17th September 2007

The TARC Experiment

- Neutron Driven Nuclear **T**ransmutation by **A**diabatic **R**esonance **C**rossing (Cern 96-97)
- 2.5 or 3.5 GeV/c proton beam.
- 334 tons of Pb in cylindrical 3.3m x 3.3m x 3m block.
- The lead is 99.99% pure.
- Beam enters through a 77.2mm diameter blind hole, 1.2m long.
- 12 sample holes are located inside the volume to measure capture cross-sections on some isotopes.



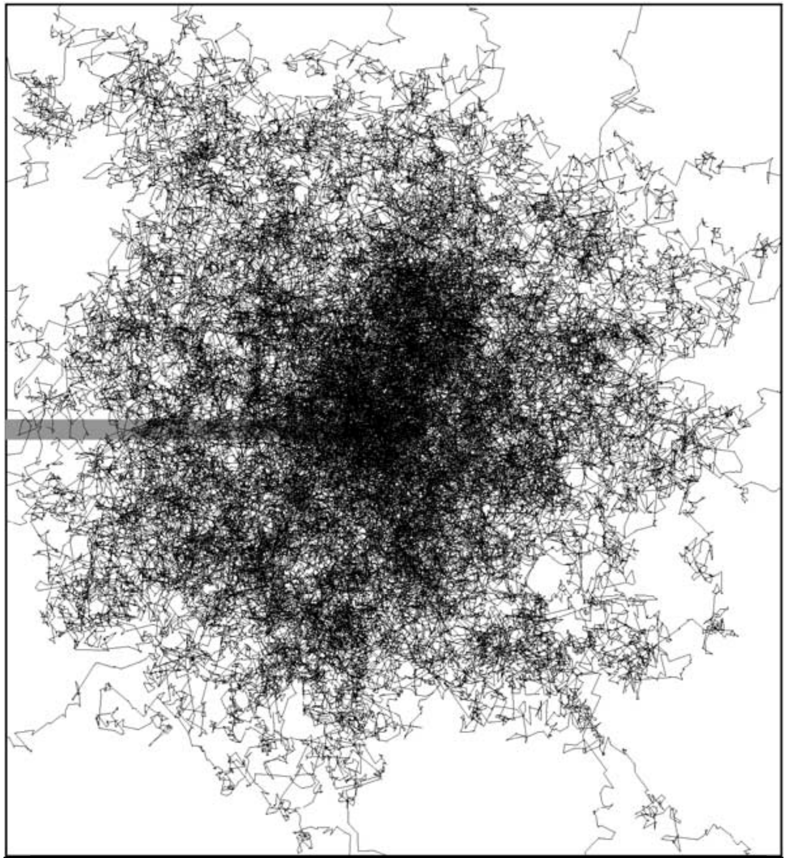
TARC – experimental set-up



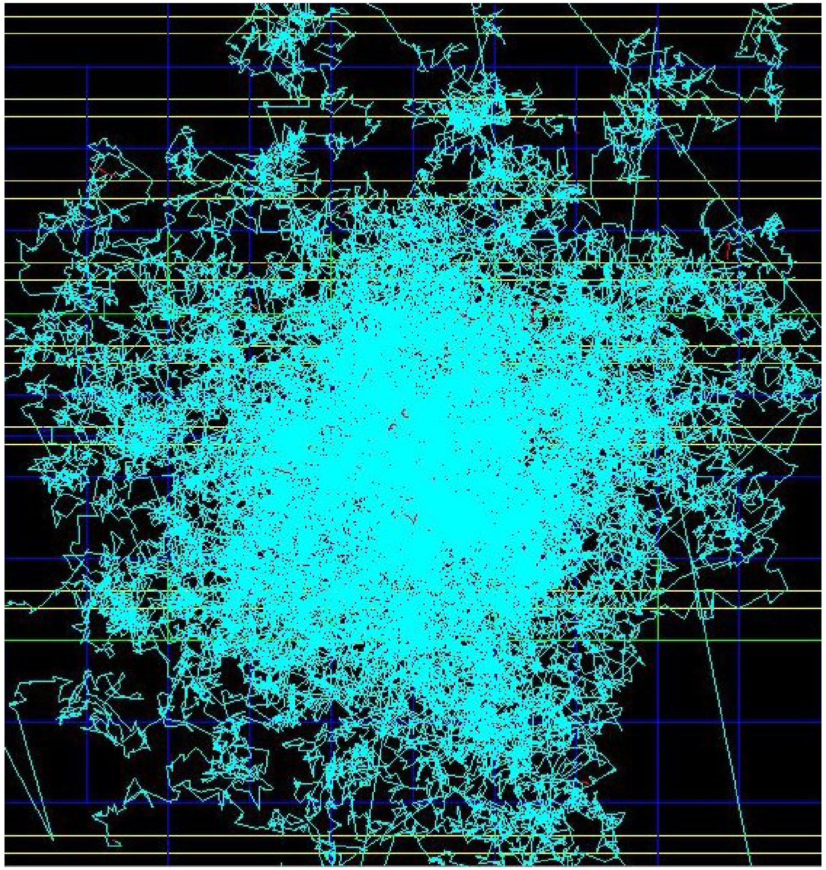
Geant4 Physics Modelling

- The Geant4 BERTINI and BINARY cascade physics models were chosen for simulating hadron production
  - Both of these include nuclear de-excitation models
- The low energy neutron_hp package was used below 20 MeV
  - Neutron interaction
  - Transportation
  - Elastic scattering
  - Capture
- Other "standard" Geant4 processes are included for elastic, electromagnetic, stopping
- Using physics lists QGSP_BERT_HP and QGSP_BIC_HP

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



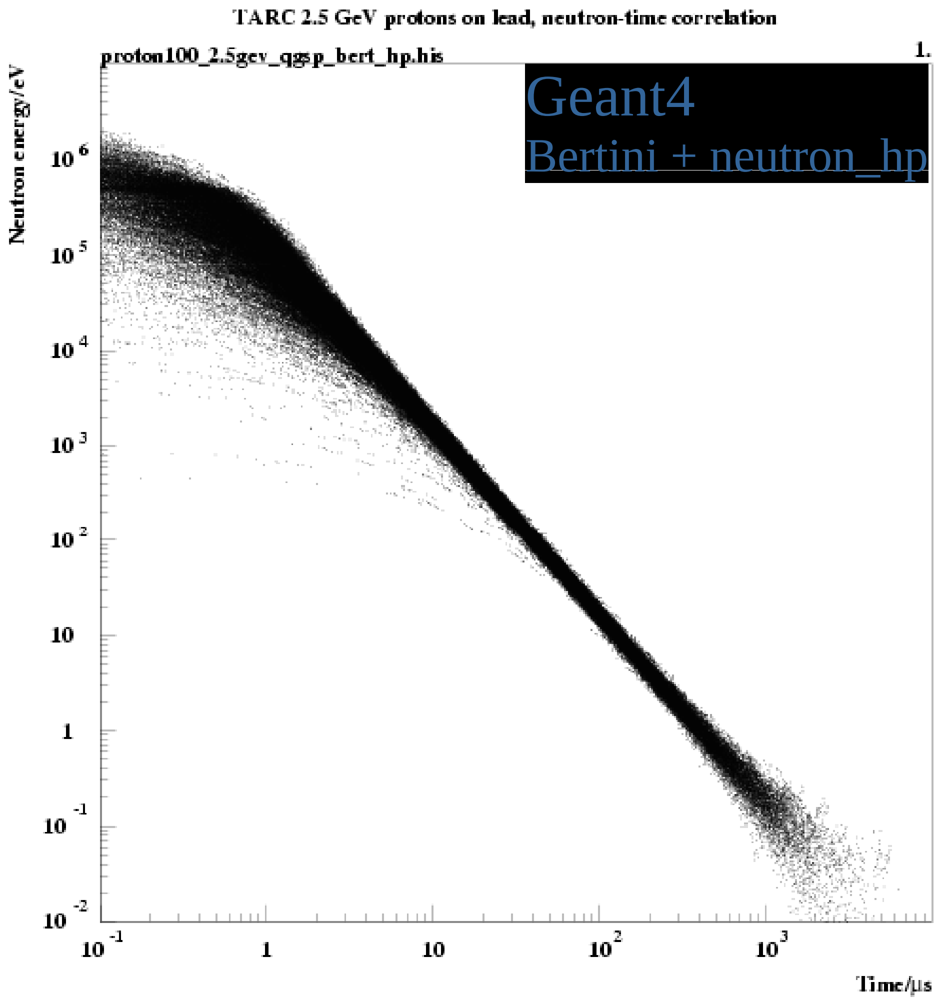
TARC original simulation
FLUKA and custom transport



Geant4 – Bertini Cascade
neutron_hp

Neutron Energy-Time Correlation

- A first test of neutron transportation in Geant4 is to look at energy-time correlation
- This relies heavily on the high precision neutron_hp model for neutrons < 20 MeV
- 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)



Fluence Calculation

- **In the TARC analysis they use a definition of fluence as follows:**
  - For monoenergetic neutrons of velocity *V* and density *n*, the neutron flux is defined as $\phi = Vn$ *and is a quantity that upon multiplying by the macroscopic cross-section (Σ), one obtains the neutron reaction rate per unit volume*
  - *Should not be confused with the rate of particles crossing a surface element, which is a 'current' and depends on the orientation of the direction of the particles*
- **Three procedures were used to determine the fluence:**

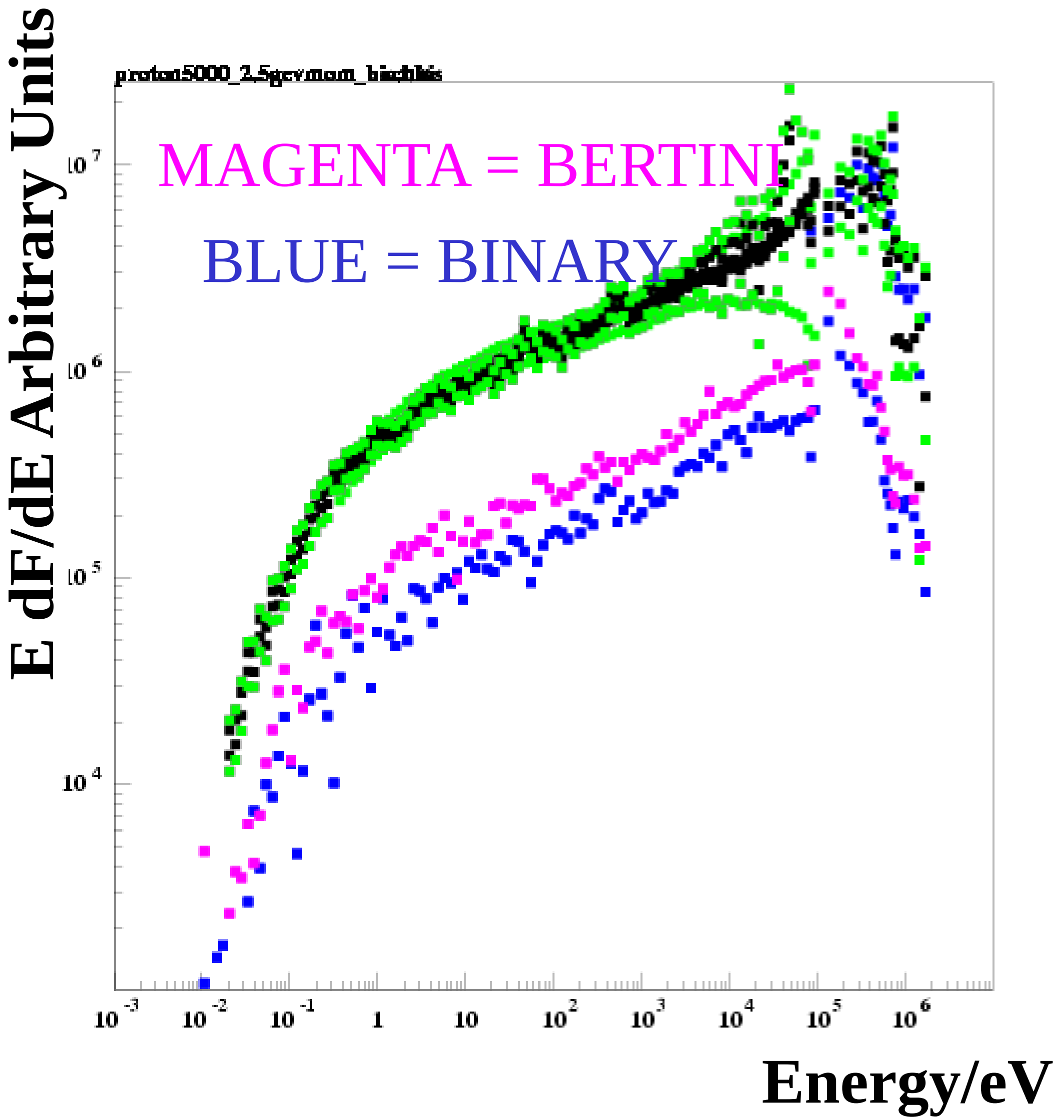
  1) dN/dS_{perp} is the number of neutrons crossing a surface element dS, with $dS_{perp} = dS\cos\theta$ where θ is the neutron angle to the normal

  2) the average fluence in a volume element dV as dl/dV, where dl is the total track length of neutrons in dV

  3) Number of interactions in a detector and computing fluence as $(1/\Sigma)dN/dV$, where dN is the number of interactions in dV
- **The first two were used in simulation**

TARC Fluence – old (circa Lisbon 2006)

- Spectral fluence is determined from the energy-time correlation with cross-checks (lithium activation and He3 ionisation detectors)
- The BERTINI cascade gives most simulated neutrons
- The spectral shape looks reasonable and similar between two cascades
- Normalisation in progress (how many neutrons produced with higher energy – off-scale)

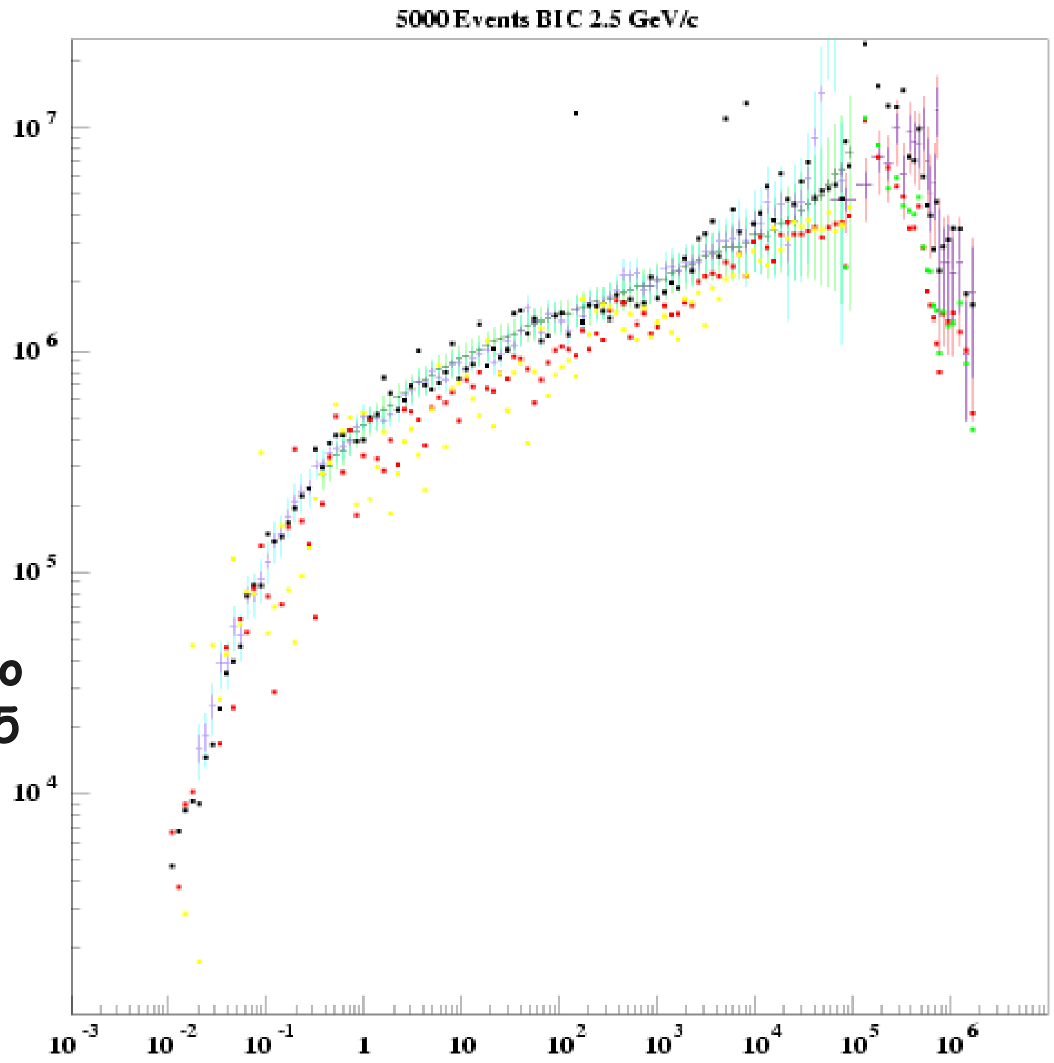


Fluence Revision

TARC data are unbinned

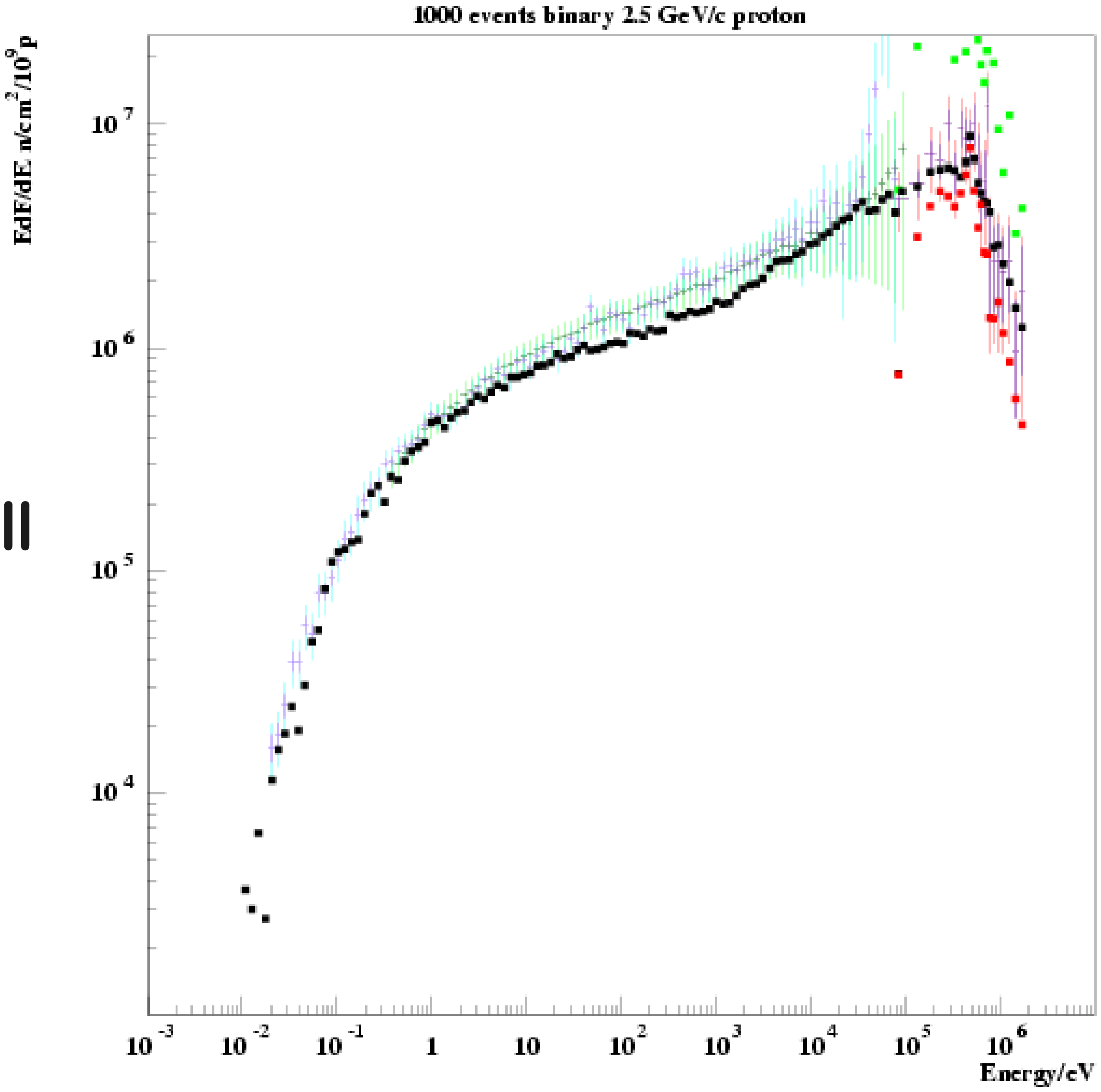
- E dF/dE
- Measure counts in bin
  - divide by bin width
  - multiply by mean energy

- Because the bins are isolethargic my error lead to a constant scaling of 6.1975



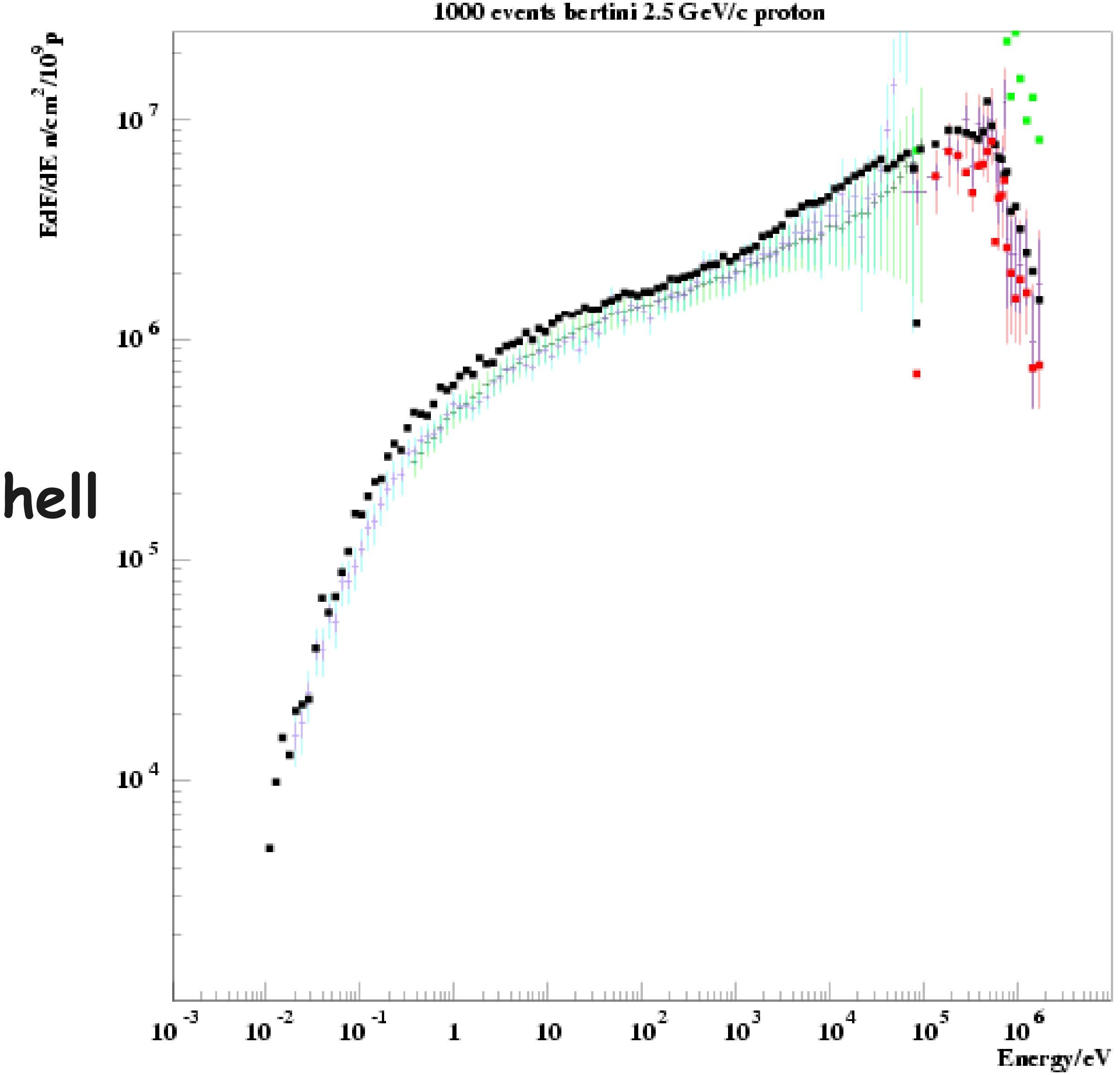
Fluence Binary cascade

- Yellow: sphere
- Red: cylinder
- Black: Full 4π shell



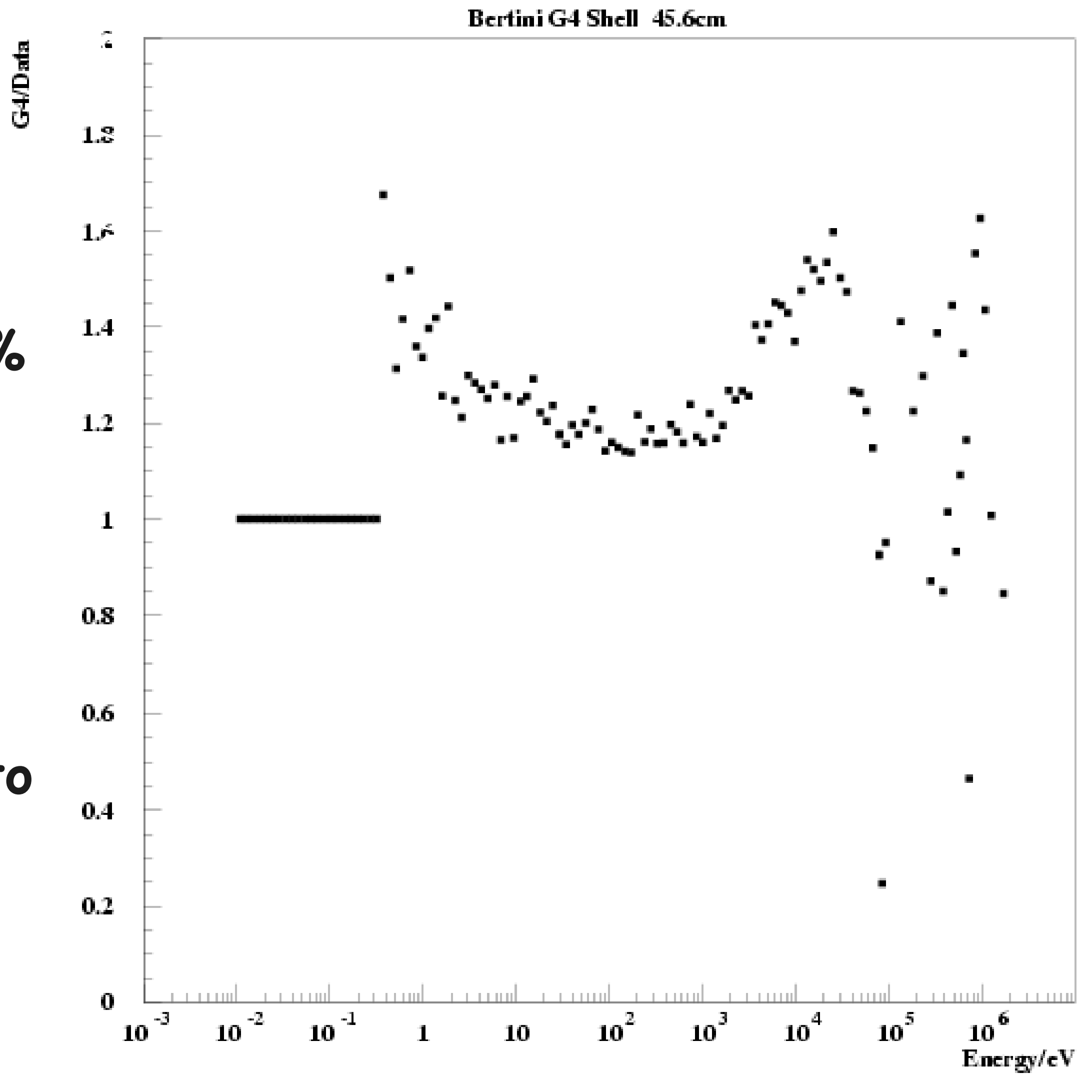
Fluence Bertini cascade

- Yellow: sphere
- Red: cylinder
- Black: Full 4π shell



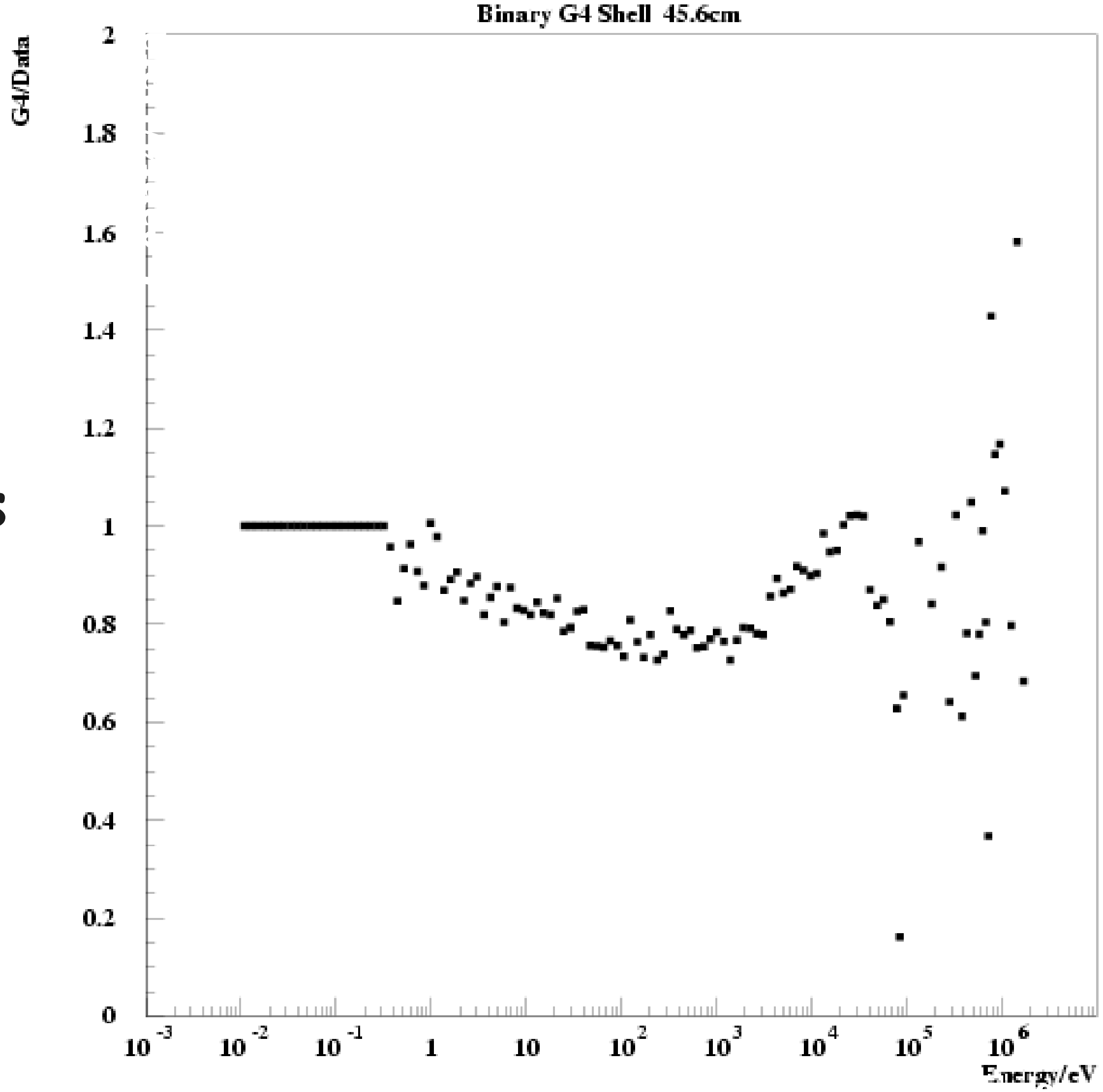
Ratio Plots of fluence G4/Data – Bertini

- Ratio of
  4π shell : Data
- Two-sets of data
- Approximately 50-60% overestimated
- Dominated by systematic errors of experiment
- Shell approach better
- Sub-structure – due to bertini?



Ratio Plots of fluence G4/Data – Binary

- Ratio of
  4π Shell : Data
- Approximately agrees (~15% under-estimated)
- Dominated by systematic errors of experiment

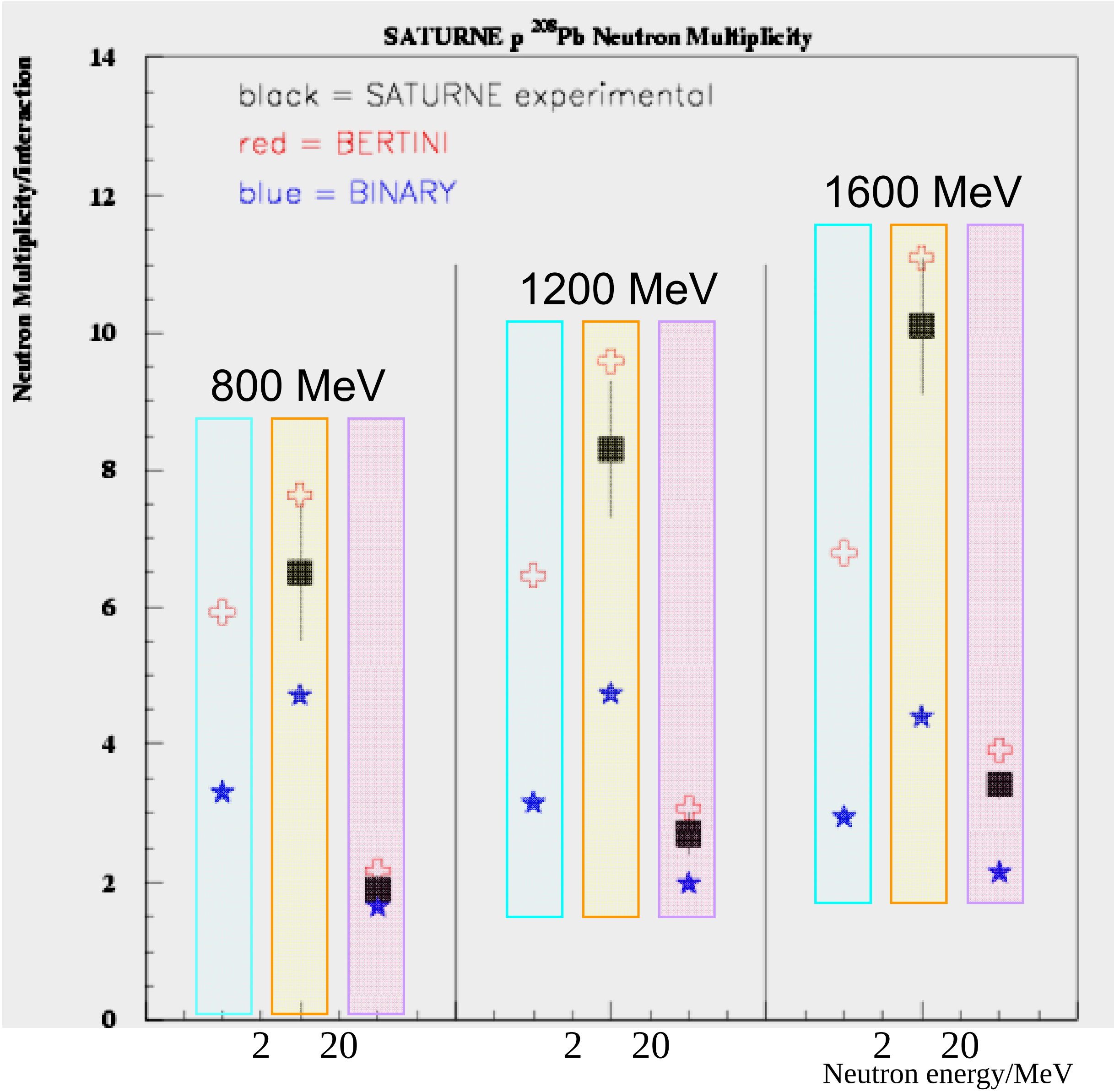


Thin Target Comparisons – Lisbon 2006

- **To understand the normalisation new tests involving thin target data were looked at within the relevant energy range**
- **SATURNE data exist for 800MeV, 1200MeV, 1600MeV protons on lead (Leray *et al* PRC 65, 044621)**
  - neutron multiplicity and energy imparted to neutrons
- **Geant4 cascades had not been tested before above 800MeV**
- Isomer gamma measurements for protons on ^{208}Pb producing ^{207}Pb or ^{206}Pb **(used to estimate # of neutrons)**
  - Kawakami *et al* (Nucl. Phys. A262, 52-60) gives data for protons incident on lead at 52, 44, 36, 28, 24 MeV
  - **To compare with Geant4 requires scaling with the number of isomeric states (normalisation)**
- **Precompound tests at these low energies were also limited**

SATURNE Neutron multiplicity (2006)

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

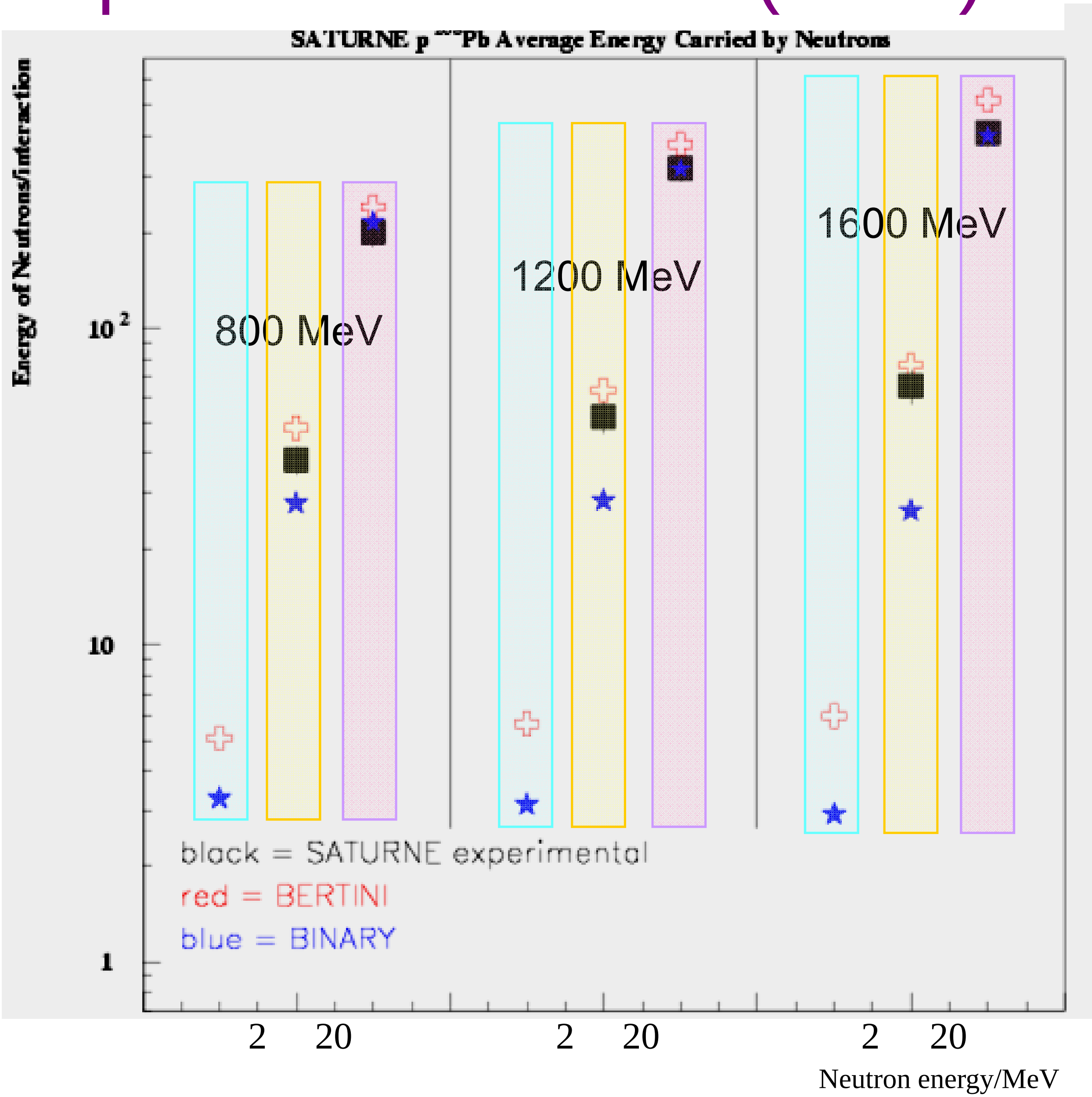


SATURNE Energy imparted to neutrons (2006)

- Sum of kinetic energy carried by neutrons per interaction

- Black = data
  Red = G4 BERTINI
  Blue = G4 BINARY

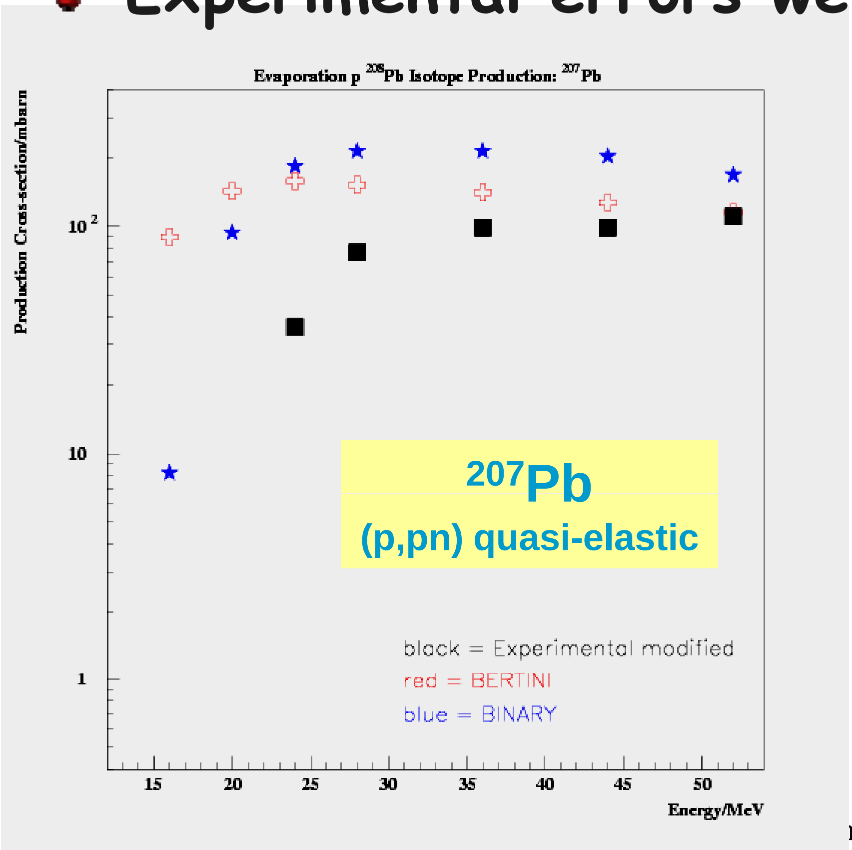
  - First band is 0-2MeV Neutron Energy Bin
  - Second is 2-20MeV
  - Third is >20MeV

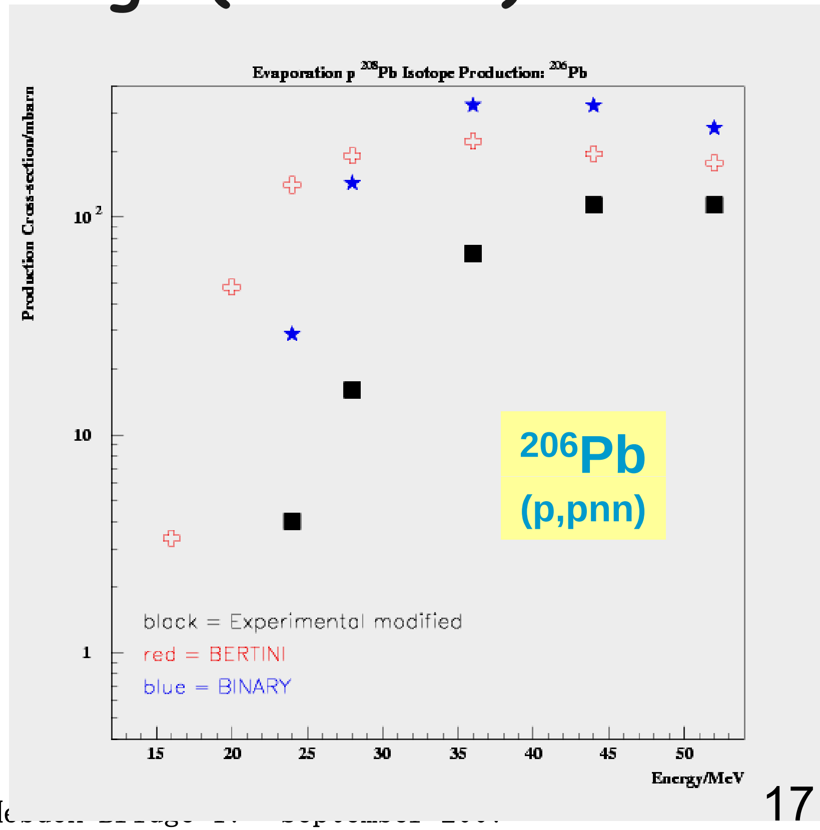


Cross-section isotope production – low energy (16-52MeV) protons on ^{208}Pb

2006

- Experimental data is purely isomer gamma-line
- The measured cross-section was scaled by the number of isomeric states (estimate)
  - Lower limit for cross-section
- Experimental errors were quite large (+/- 25%)



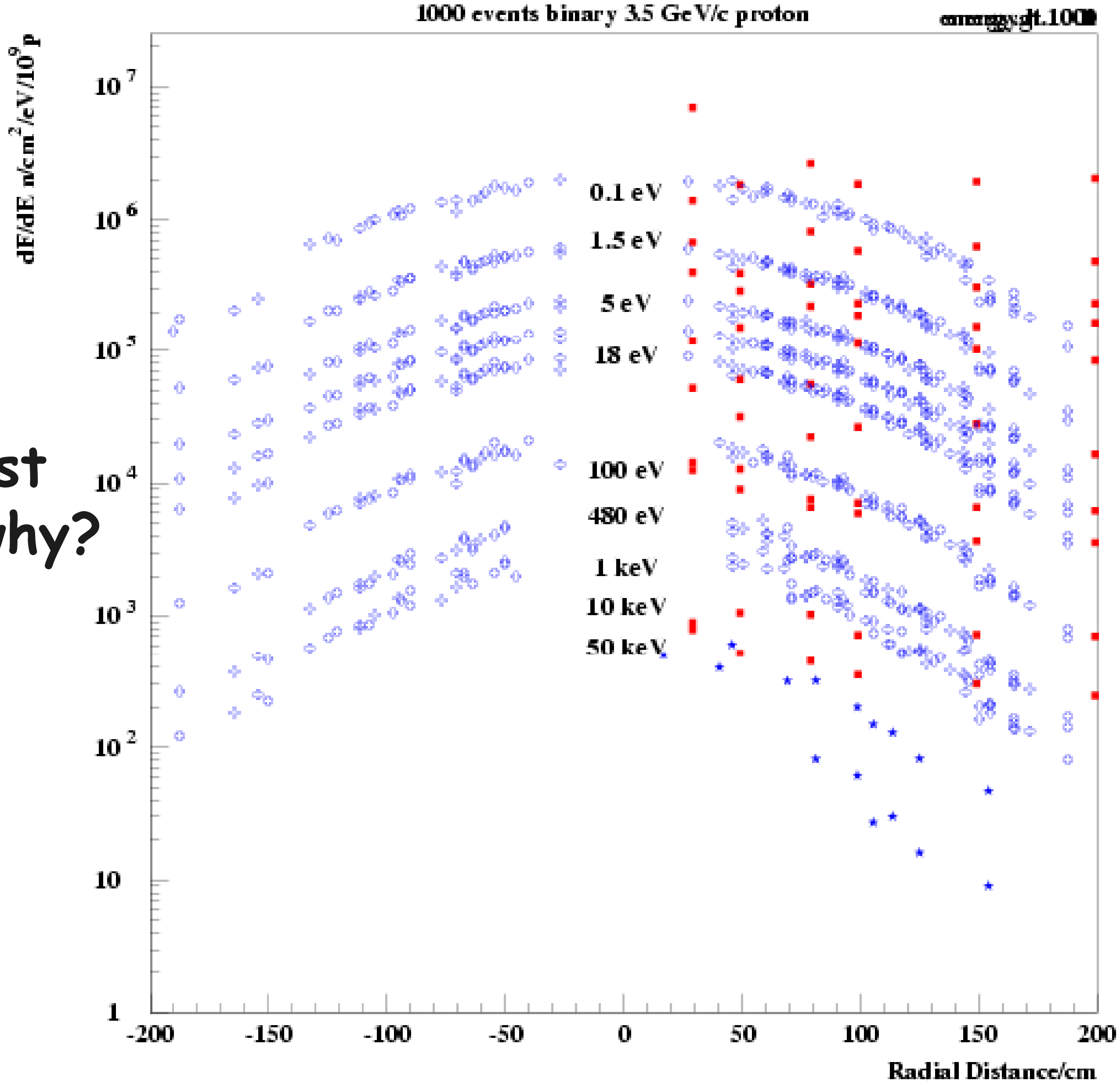


Radial Fluence Distributions

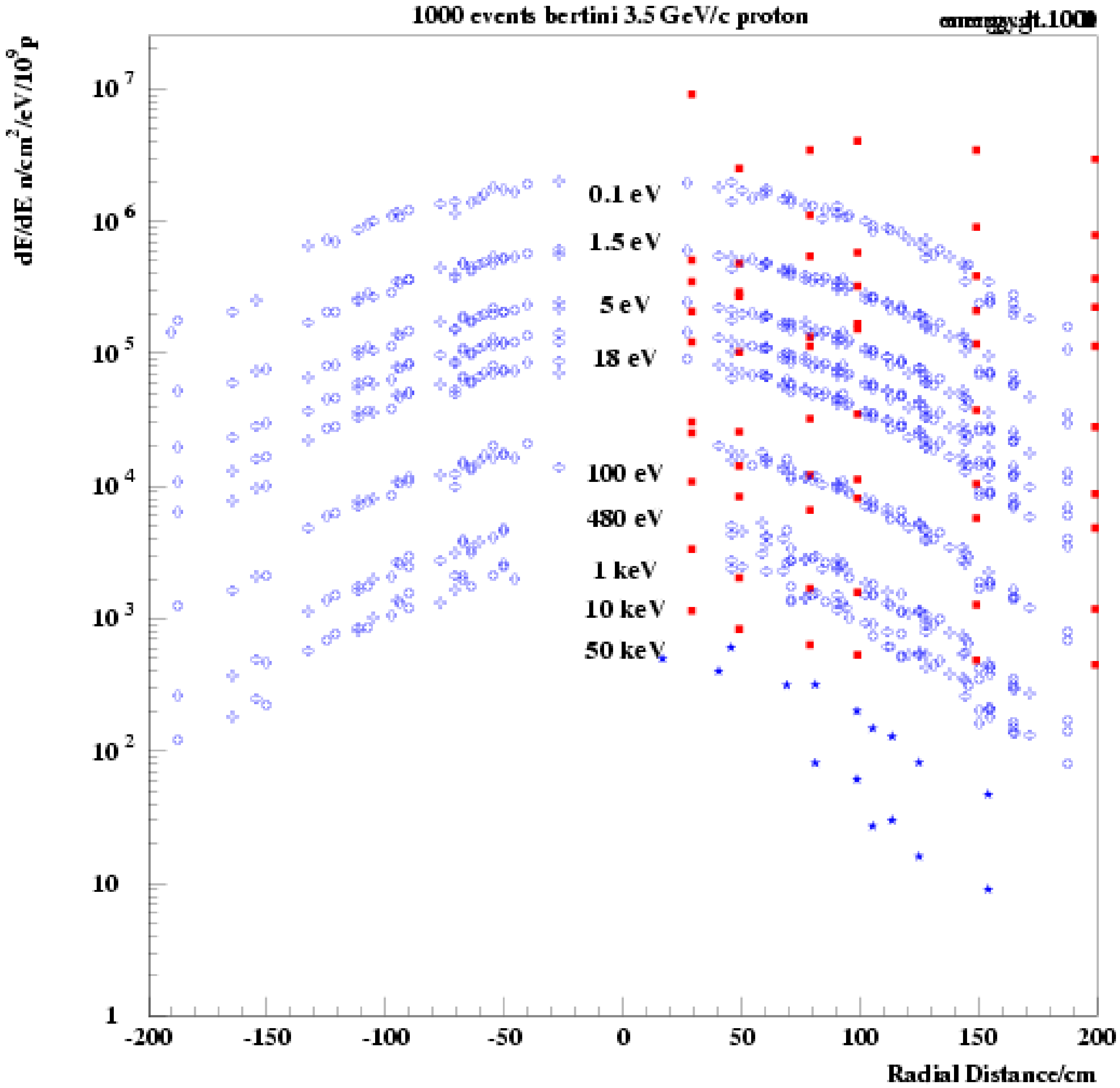
- TARC measured the radial dependence of the neutron fluence in order to measure the slowing down within the lead volume
- By using coupled transportation a series of parallel shell volumes were created at different radii

Radial Fluence Distribution - BINARY

- **Agreement best at 45.6cm – why?**



Radial Fluence Distribution - BERTINI



Future Work

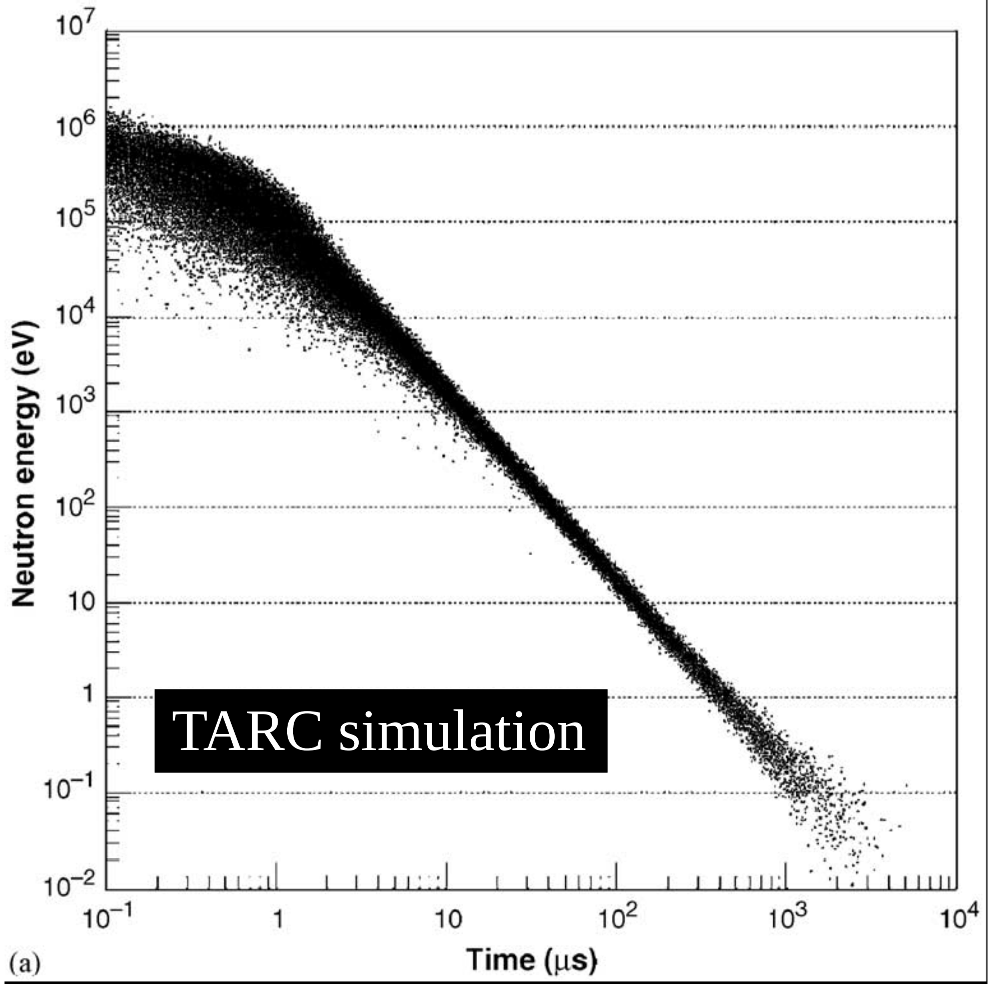
- True Calorimetry
- Capture and transmutation on Tc, I
- Precision runs
- Complete radial distributions
- Sensitivity to lead isotopes and impurities (e.g. silver)

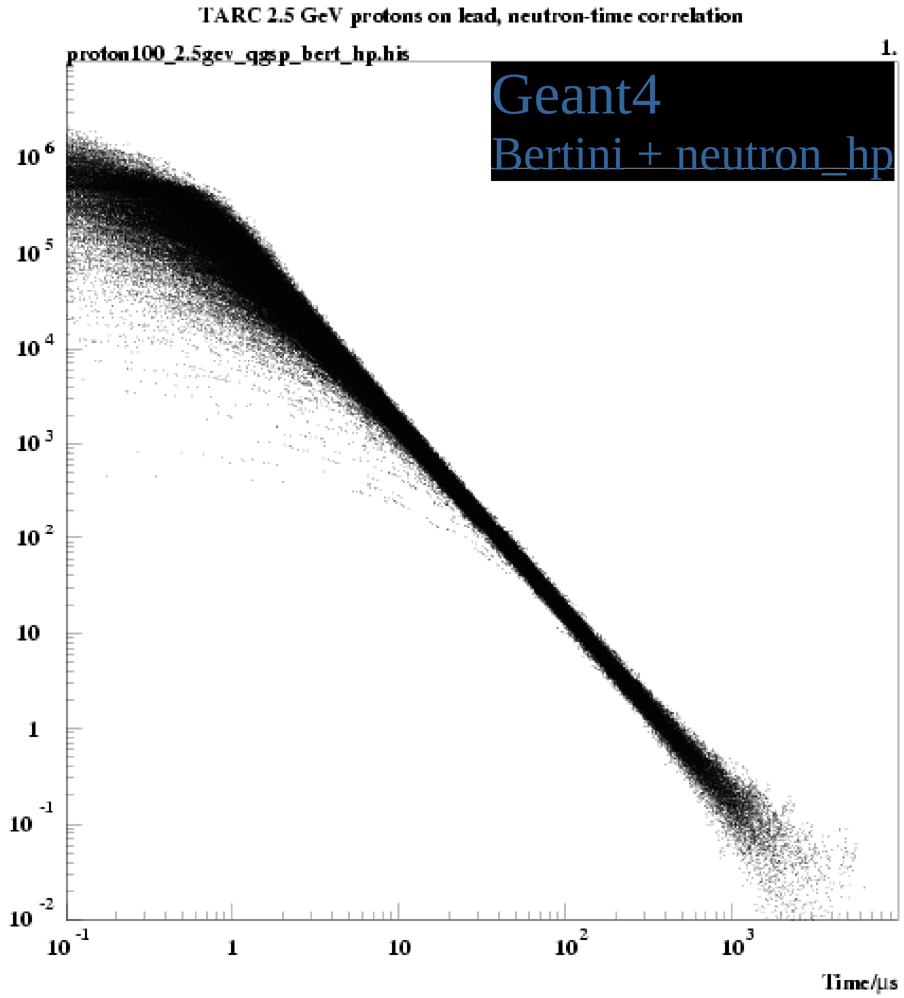
Summary

- The TARC simulation agrees very well with the data
- Neutron energy-time distribution is slightly short, but within the experimental errors
- The fluence vs. energy is now in agreement (including systematic errors)
- There appears extra fine structure due to neutorn_hp?
- The binary and bertini cascades appear either side of the data – as in thin target, but binary is in best agreement (for once)
- Radial distributions – agreement is not perfect, needs further investigation
- Nonetheless fluence agreement at 45.6cm is very encouraging

- **Spare slides**

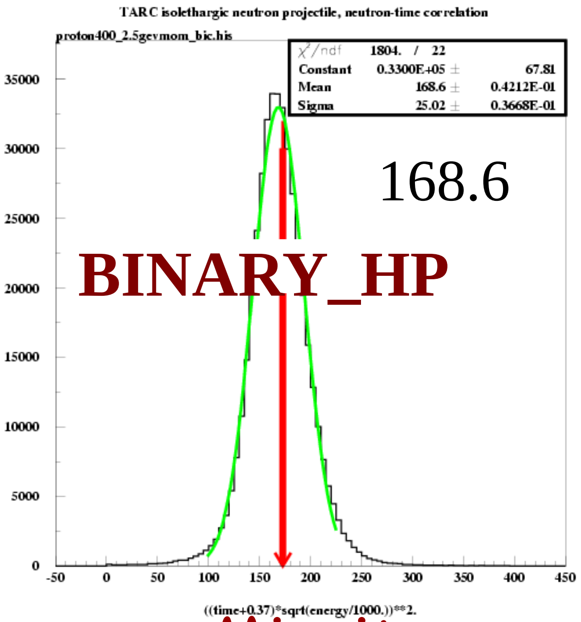
Neutron Energy-Time Correlation

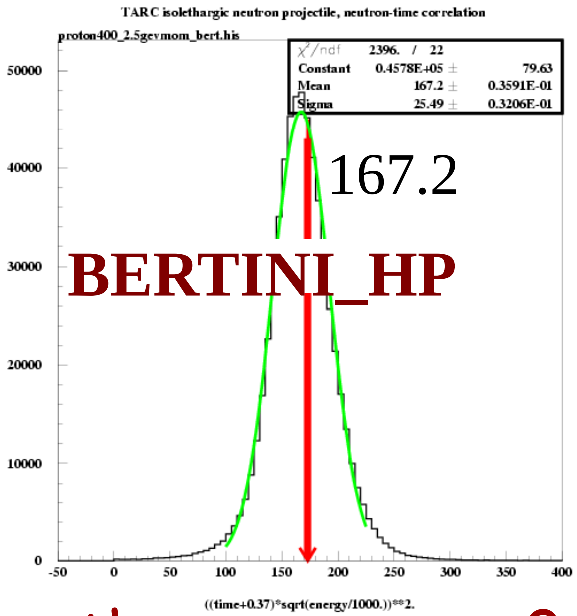




Neutron Energy-Time Correlation

- The slope of the correlation can be approximated by a Gaussian distribution





Experiment and TARC simulation gave 173±2

Minuit errors on the mean are ~0.04

- It is possible to fit the correlation according to:

$$E(t)\,(t+t_0)^2 = \sqrt{K}$$

where t_0 is a correction for non-infinite initial energy

- The (small) difference between BINARY and BERTINI can be attributed to a harder neutron spectrum with BINARY

Motivation

- **The production, interaction and transport of neutrons is important in a number of applications:**
  - Background radiation studies
  - Radiation effects (single event upsets in electronics)
  - Background and spill-over (LHC experiments)

- **Validation with TARC offers testing Geant4 physics over a broad energy and process range**
  - Neutron production from ~GeV protons
  - Secondary neutron production
  - Thermalisation and capture
  - Absolute fluence measurement