



Istituto Nazionale di Fisica Nucleare

Interest on the $p(11\text{B},\alpha)\text{X}$ reaction in clinical hadrontherapy

GAP Cirrone, G Petringa , D Chiappara
for the proton-Boron INFN Collaboration

D.-K. Yoon et al.

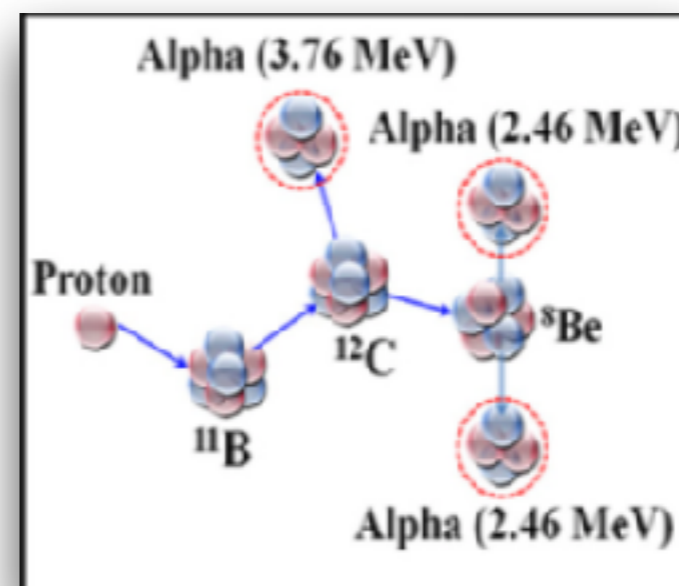
Application of proton boron fusion reaction to radiation therapy: A Monte Carlo simulation study

Applied Physics Letters 105, 223507 (2014);

$p(11\text{B},ee)8\text{Be}$

$p(11\text{B},\alpha)8\text{Be}^*$

$p(11\text{B},2\alpha)\alpha$



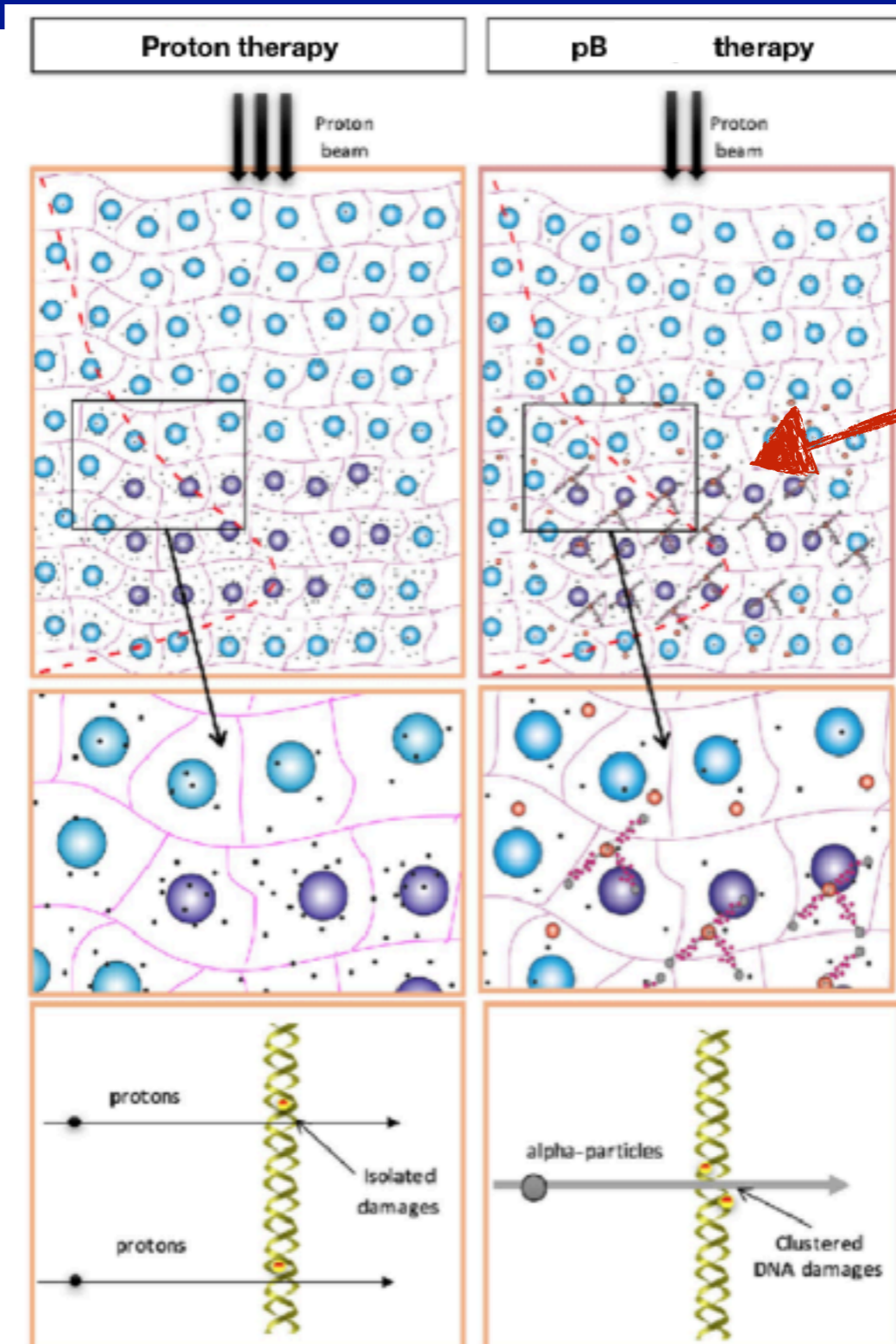
Potential advantages: low-energy/high-LET particles show higher RBE;
If ^{11}B is injected in cancer cells an augmented killing capacity can be observed


The pB and pF nuclear reactions

3

Incident low LET particles 

Potential advantages: low-energy/high-LET particles show higher RBE;
 If ^{11}B is injected in cancer cells an augmented killing capacity can be observed



Local Emission of particles with high LET 



Article | OPEN | Published: 18 January 2018

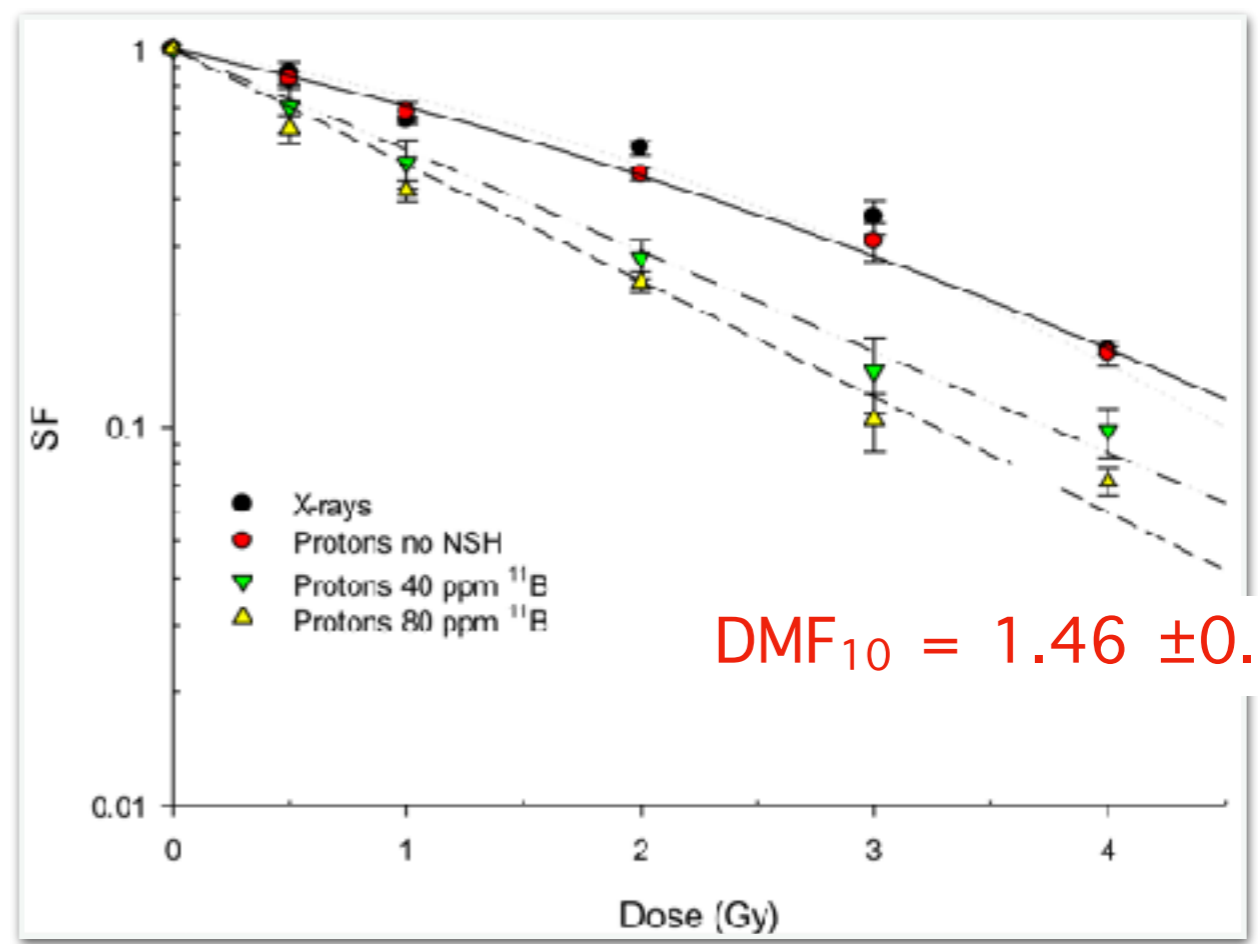
First experimental proof of Proton Boron Capture Therapy (PBCT) to enhance protontherapy effectiveness

G. A. P. Cirrone, L. Manti, D. Margarone, G. Petringa, L. Giuffrida, A. Minopoli, A. Picciotto, G. Russo, F. Cammarata, P. Pisciotto, F. M. Perozziello, F. Romano, V. Marchese, G. Milluzzo, V. Scuderi, G. Cuttone & G. Korn

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DU145 prostate cancer cells irradiated along a proton clinical Bragg peak

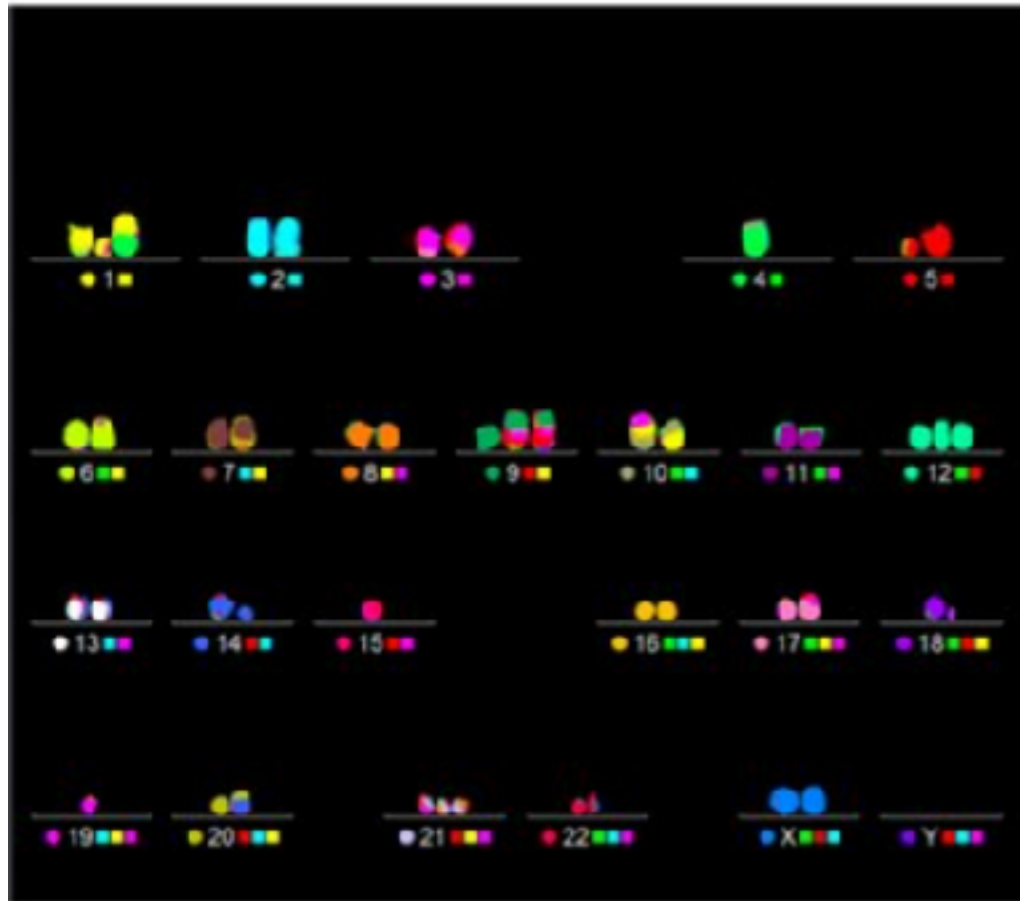
Clonogenic curves



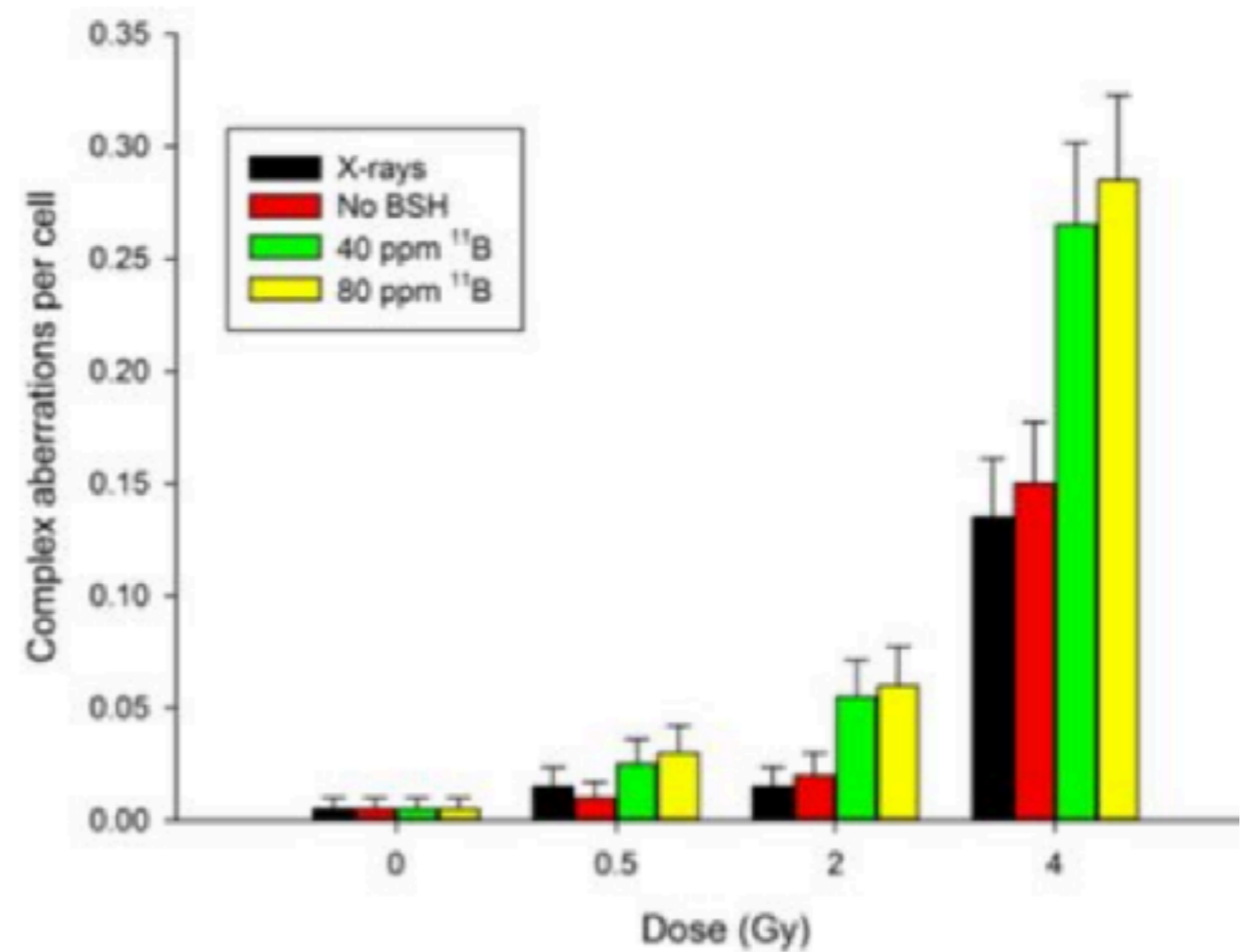
DMF₁₀ = 1.46 ± 0.12

Chromosomal aberrations

5



Chromosomal aberrations



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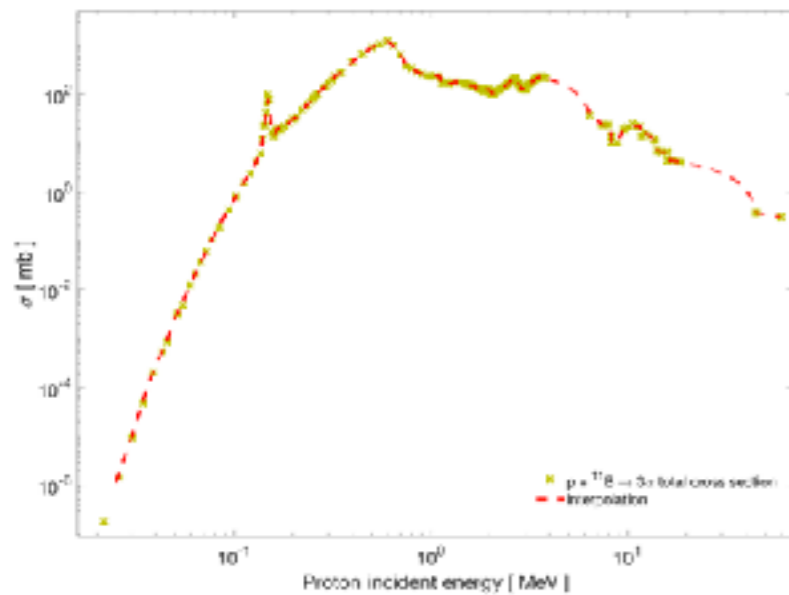
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.....but

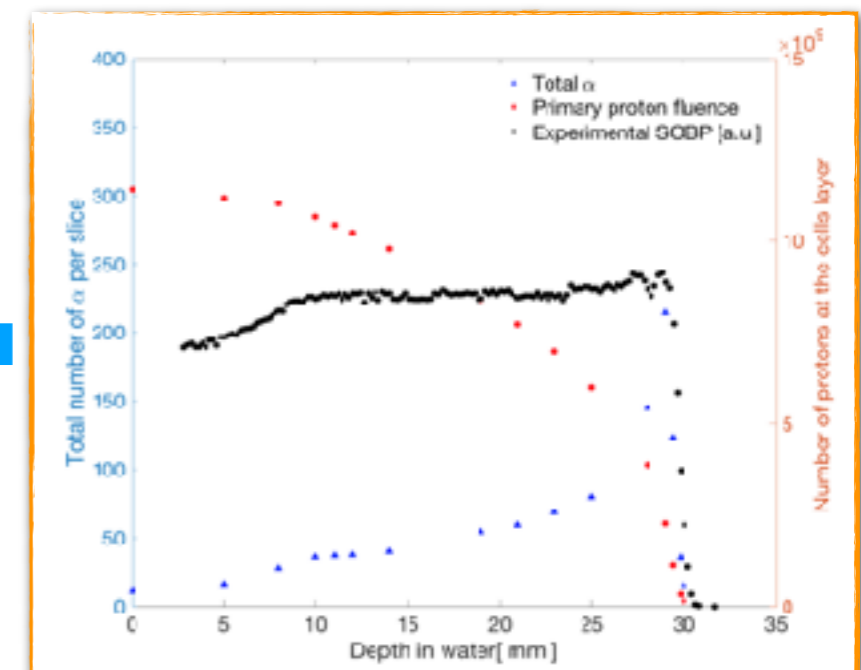
Observed radiobiological effectiveness seems not be justified from the expected number of produced alphas



Experimental cross section
For $p(11B, \alpha)8Be$

Radiobiological model

At least 10^3 α are missed to provide a classical radiobiological interpretation

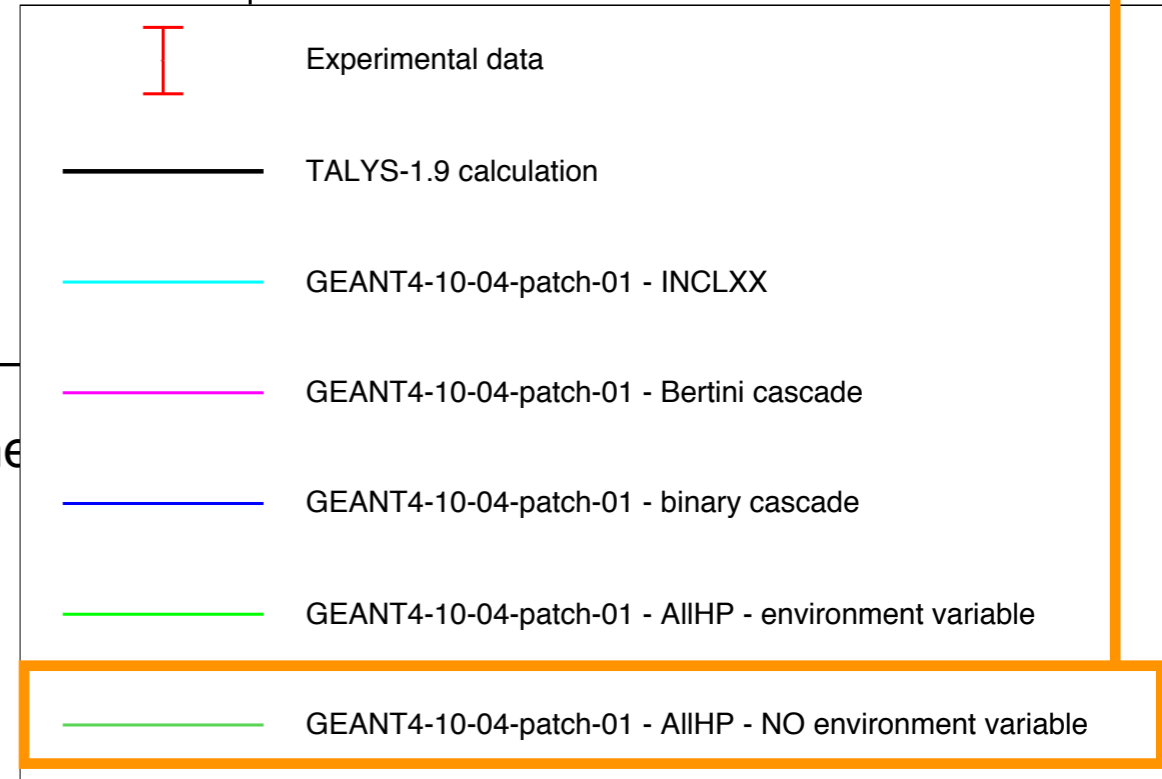
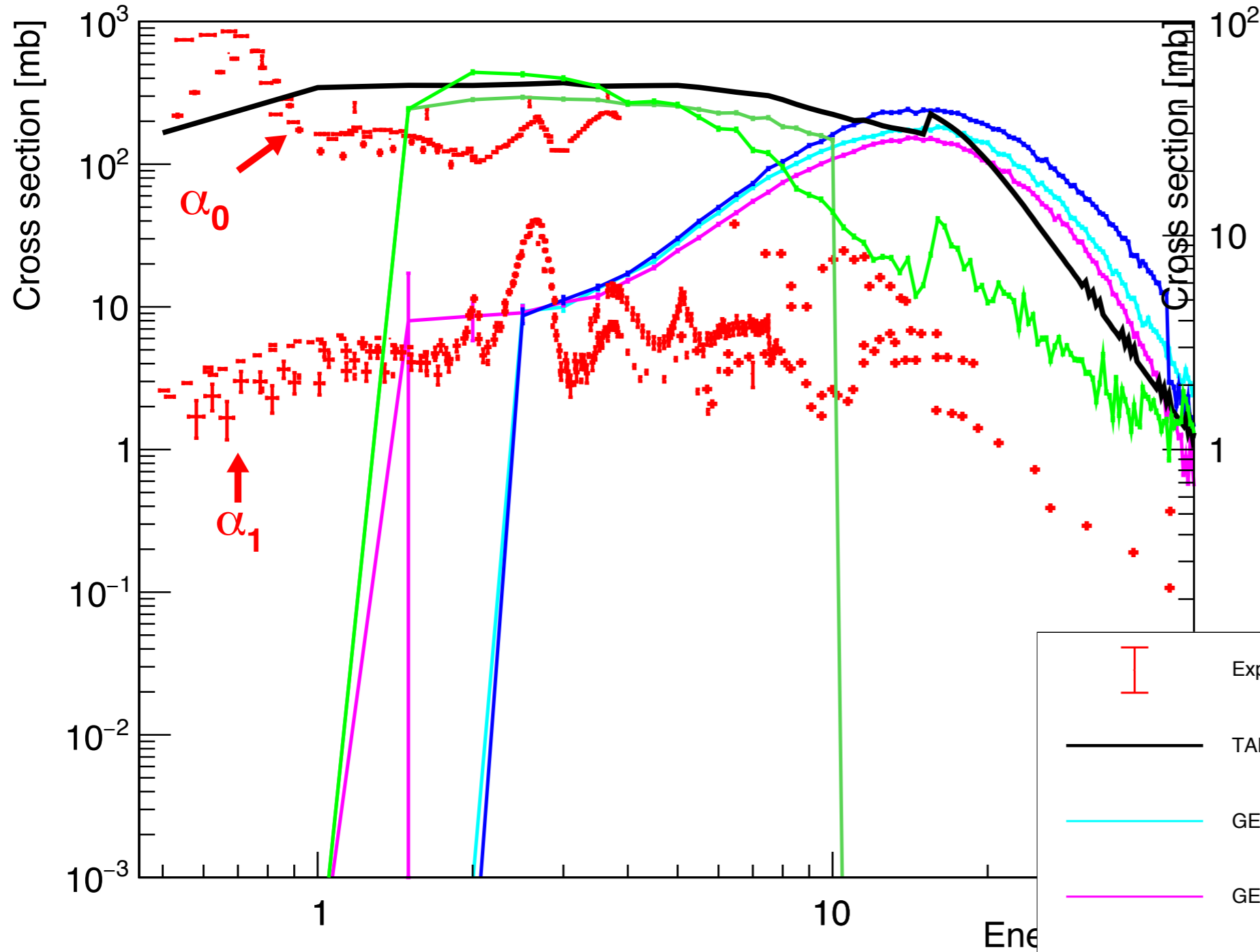


Be sure, at the best of our knowledges, of the correct number of alphas produced also by other reaction channels

- Evaluation of the Geant4 physics models
- Comparison with (when available) experimental data
- Comparison with FLUKA (Collaboration with R Versaci (ELI-beamlines) and P Sala (CERN))

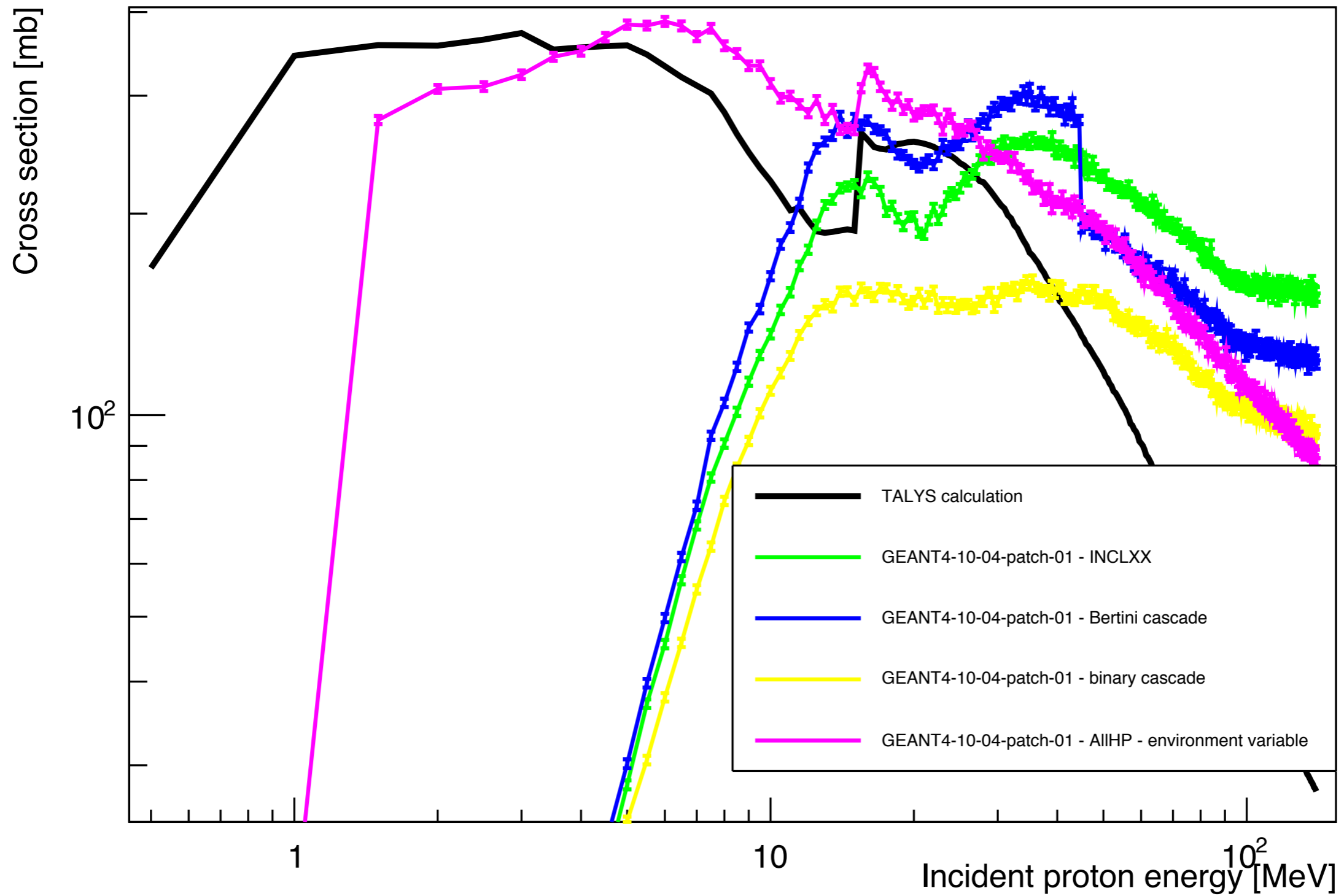
Different approaches at the micro and nano-scale

$^{11}\text{B}(p,\alpha)^8\text{Be}$ channel comparison



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G4PHP_DO_NOT_ADJUST_FINAL_STATE=1

Total cross section for reactions producing at least one alpha



DO_NOT_SET_PHP_AS_HP=1
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Baryonic number is not conserved

10

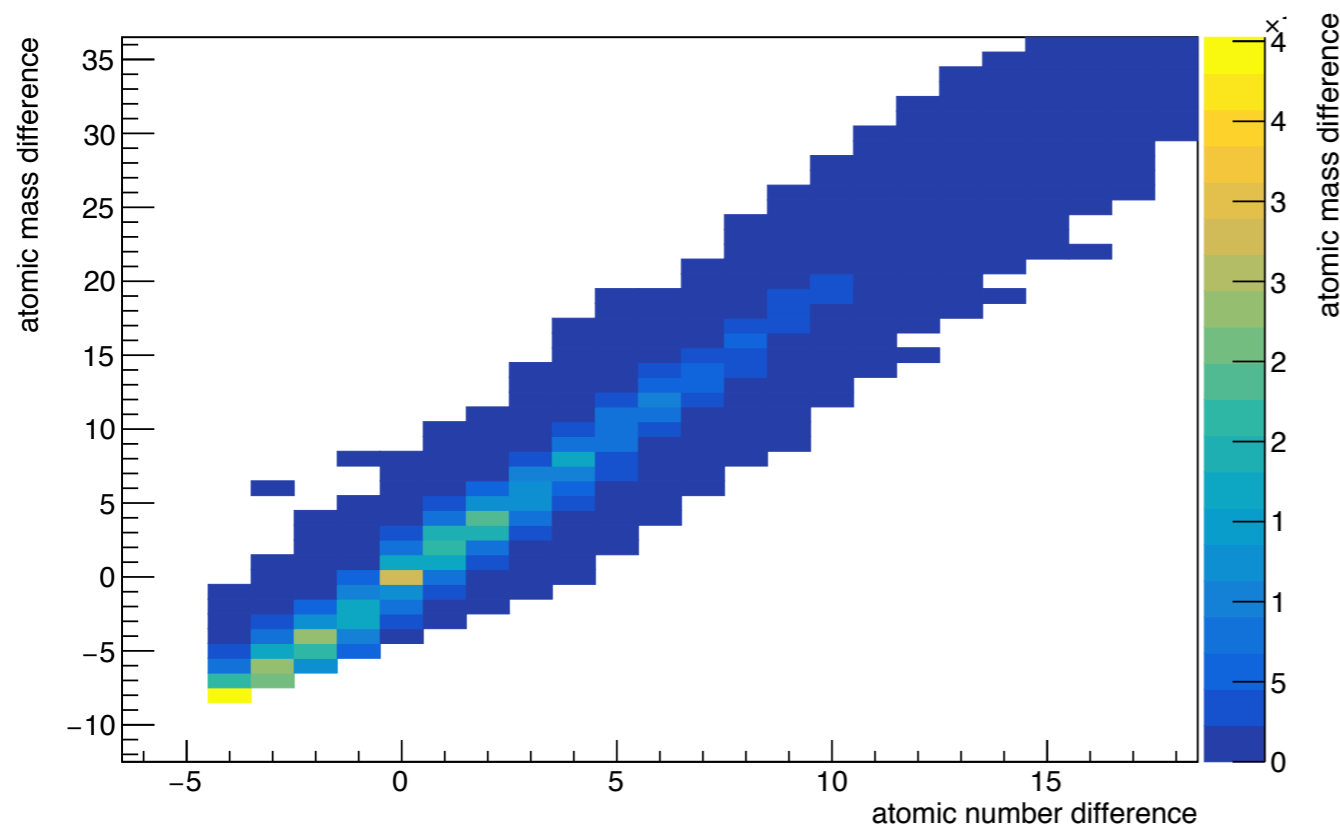
G4HadronPhysicsQGSP_BIC_AllHP

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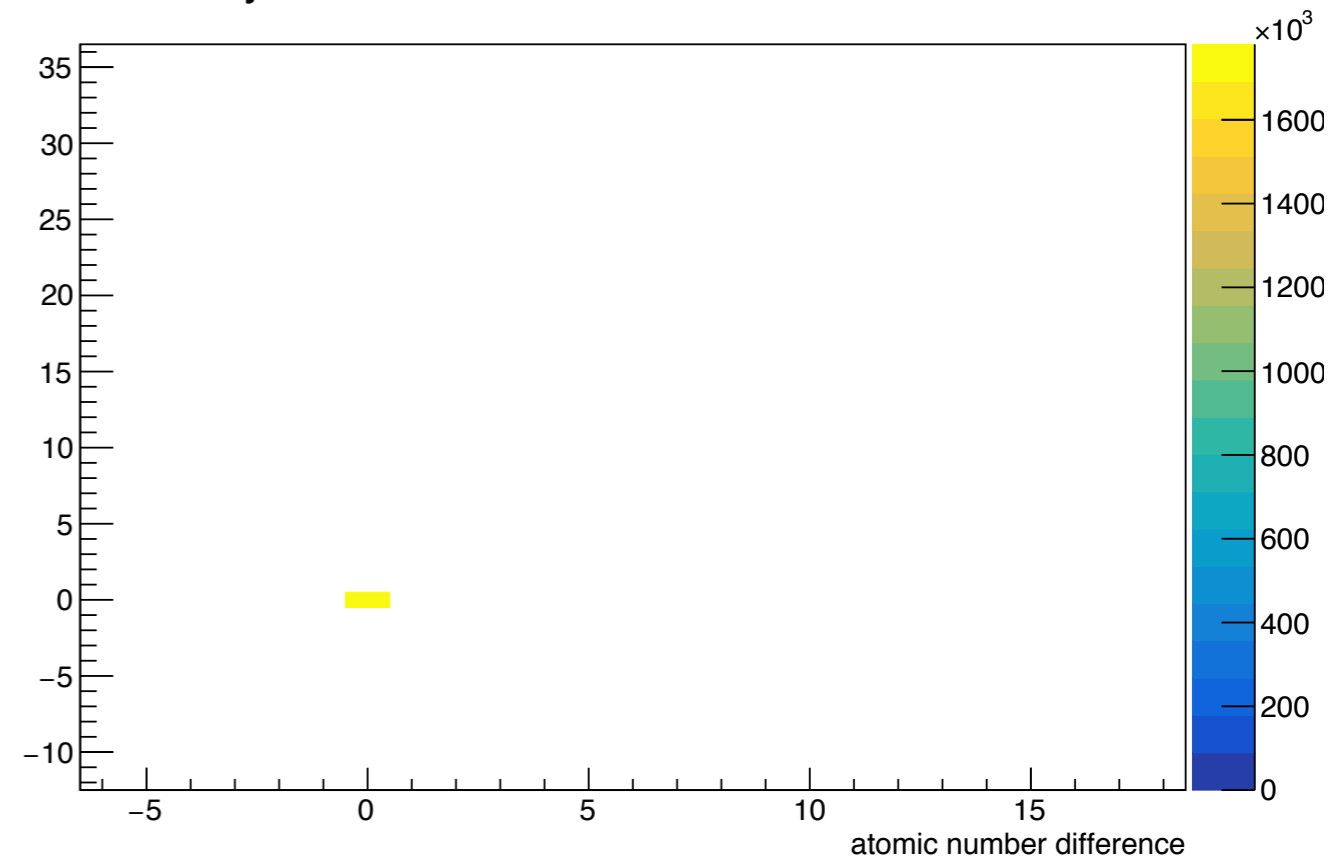
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G4HadronPhysicsFTF_BIC

Baryon Number Difference in reactions simulated



Baryon Number Difference in reactions simulated



All reaction producing at least one alpha in the 0.5 - 140 MeV range

```

ENERGY = 30.0 MeV
Total alpha creation: 208.99918
proton + 11 B -->
proton + 11 B --> alpha + Be8 15.505300
proton + 11 B --> 3 alpha 1.3237200
proton + 11 B --> He3 + alpha + He5 6.4591500
proton + 11 B --> tritium + alpha + Li5 4.1789600
proton + 11 B --> deuteron + alpha + Li6 43.014100
proton + 11 B --> proton + alpha + Li7 34.605400
proton + 11 B --> proton + 2 alpha + tritium 0.0047790900
proton + 11 B --> proton + tritium + 2 alpha 0.0095769100
proton + 11 B --> proton + deuteron + alpha + He5 1.4490500
proton + 11 B --> 2 proton + alpha + He6 0.070320900
proton + 11 B --> neutron + alpha + Be7 25.832800
proton + 11 B --> neutron + deuteron + alpha + Li5 0.47945300
proton + 11 B --> neutron + proton + alpha + Li6 75.993600
proton + 11 B --> neutron + 2 proton + alpha + He5 0.064278900
proton + 11 B --> 2 neutron + proton + alpha + Li5 0.0086889500
    
```

Same for AllHP

Total alpha production cross sections:

proton + B11 → 2 alpha + Be8	0.327364
proton + B11 → alpha + Be8	2.17183
proton + B11 → 2 alpha	2.63893
proton + B11 → alpha	0.5664
proton + B11 → 2 alpha + 2 Be8	0.0517103
proton + B11 → alpha + 2 Be8	0.258551
proton + B11 → 3 alpha	0.413082
proton + B11 → 4 alpha	0.0517103
proton + B11 → proton + 2 alpha	1.08905
proton + B11 → proton + 2 alpha + 2 Be8	0.0517103
proton + B11 → proton + alpha	0.02575
proton + B11 → proton + 3 alpha	0.103421
proton + B11 → alpha + B11	0.072233
proton + B11 → alpha + B11 + Be8	0.0517103
proton + B11 → 2 alpha + D11	0.155131
proton + B11 → proton + alpha + Be8	1.34447
proton + B11 → proton + 4 alpha	0.103421
proton + B11 → proton + alpha + B11	0.361972
proton + B11 → proton + alpha + 2 Be8	0.155131
proton + B11 → proton + 2 alpha + Be8	0.566013
proton + B11 → proton + 3 alpha + Be8	0.0517103
proton + B11 → proton + 2 alpha + D11	0.0517103
proton + B11 → proton + alpha + B11	0.0517103
proton + B11 → proton + alpha + 4 Be8	0.0517103
proton + B11 → proton + alpha + 3 Be8	0.0517103
proton + B11 → proton + alpha + B11 + Be8	0.0517103
proton + B11 → neutron + alpha + Be8	1.34447
proton + B11 → neutron + alpha + B11	0.0517103
proton + B11 → 2 proton + 3 alpha	0.155131
proton + B11 → neutron + alpha	5.42950
proton + B11 → neutron + 2 alpha + Be8	0.258551
proton + B11 → alpha + C11	0.0517103
proton + B11 → 2 alpha + C11	0.0517103
proton + B11 → neutron + 2 alpha	1.10934
proton + B11 → 3 neutron + alpha	0.206841
proton + B11 → neutron + alpha + 2 Be8	0.155131
proton + B11 → 2 neutron + alpha + Be8	0.258551
proton + B11 → neutron + 3 alpha	0.0517103
proton + B11 → 2 neutron + alpha	1.13763
proton + B11 → neutron + alpha + C11	0.0517103
proton + B11 → proton + neutron + alpha + Be8	0.566813
proton + B11 → neutron + 4 alpha	0.0517103
proton + B11 → 2 proton + 2 alpha	0.079074
proton + B11 → proton + neutron + 2 alpha + Be8	0.206841
proton + B11 → proton + neutron + alpha	3.15433
proton + B11 → 2 proton + alpha	2.58551
proton + B11 → 2 proton + alpha + Be8	0.723944
proton + B11 → proton + 2 neutron + alpha + Be8	0.155131
proton + B11 → 2 neutron + 2 alpha + Be8	0.103421
proton + B11 → 2 neutron + alpha + 2 Be8	0.103421
proton + B11 → proton + neutron + 2 alpha	0.723944
proton + B11 → 2 neutron + alpha + B11	0.0517103
proton + B11 → 2 neutron + 2 alpha	0.310262
proton + B11 → neutron + 2 alpha + B11	0.103421
proton + B11 → 4 neutron + alpha	0.0517103
proton + B11 → 2 neutron + 3 alpha	0.103421
proton + B11 → 2 proton + 2 alpha + Be8	0.0517103
proton + B11 → proton + neutron + alpha + B11	0.103421
proton + B11 → proton + 2 neutron + 2 alpha	0.310262
proton + B11 → proton + neutron + 2 alpha + C11	0.0517103
proton + B11 → proton + neutron + 2 alpha + 2 Be8	0.103421
proton + B11 → 2 proton + neutron + alpha + Be8	0.155131
proton + B11 → proton + 2 neutron + alpha + 2 Be8	0.0517103
proton + B11 → 3 neutron + 2 alpha	0.103421
proton + B11 → 3 proton + 2 alpha	0.103421
proton + B11 → 3 neutron + 2 alpha + Be8	0.0517103
proton + B11 → proton + 2 neutron + alpha + B11	0.155131
proton + B11 → proton + 2 neutron + 2 alpha + Be8	0.0517103
proton + B11 → 2 proton + neutron + alpha	1.08905
proton + B11 → proton + 2 neutron + alpha	0.020523
proton + B11 → 2 proton + alpha + B11	0.103421
proton + B11 → 2 proton + 2 neutron + alpha	0.155131
proton + B11 → proton + 2 neutron + 3 alpha	0.103421
proton + B11 → 2 proton + neutron + alpha + B11	0.0517103
proton + B11 → 2 proton + neutron + 2 alpha + Be8	0.0517103
proton + B11 → 2 proton + neutron + 2 alpha	0.155131
proton + B11 → 3 proton + alpha + Be8	0.0517103

Page 1

proton + B11 → 3 proton + alpha + Be8	0.0517103
proton + B11 → 2 proton + neutron + 2 alpha + C11	0.0517103
proton + B11 → proton + 3 neutron + alpha	0.206841
proton + B11 → 2 proton + 2 alpha + B11	0.0517103
proton + B11 → 3 proton + alpha	0.517103
proton + B11 → 2 proton + neutron + alpha + B11 + Be8	0.0517103
proton + B11 → 3 proton + alpha + B11	0.0517103
proton + B11 → 2 proton + 2 neutron + 2 alpha + B11	0.0517103
proton + B11 → 3 proton + neutron + alpha	0.310262
proton + B11 → 3 proton + 2 neutron + alpha	0.0517103
proton + B11 → 3 neutron + 2 alpha + B11	0.0517103
proton + B11 → 4 proton + 2 alpha	0.103421
proton + B11 → alpha + B10	1.65473
proton + B11 → neutron + 2 alpha + deuteron	0.206841
proton + B11 → 2 alpha + deuteron + Be8	0.206841
proton + B11 → proton + alpha + B10	1.39618
proton + B11 → neutron + alpha + Be8 + B10	0.258551
proton + B11 → proton + alpha + Be8 + B10	0.510262
proton + B11 → 3 alpha + deuteron	0.0517103
proton + B11 → alpha + deuteron	3.67143
proton + B11 → proton + neutron + alpha + Be8 + B10	0.103421
proton + B11 → neutron + alpha + deuteron	1.08086
proton + B11 → alpha + Be8 + B10	0.517103
proton + B11 → 2 alpha + D10	0.413082
proton + B11 → alpha + deuteron + Be8	0.775654
proton + B11 → alpha + deuteron + 2 Be8	0.206841
proton + B11 → 4 proton + alpha	0.0517103
proton + B11 → 2 proton + 2 neutron + 2 alpha	0.0517103
proton + B11 → proton + alpha + deuteron	2.94748
proton + B11 → proton + 2 neutron + alpha + deuteron + C11	0.0517103
proton + B11 → alpha + deuteron + D11 + 2 Be8	0.0517103
proton + B11 → neutron + alpha + B10	1.08502
proton + B11 → alpha + deuteron + B11	0.103421
proton + B11 → alpha + B11 + D10	0.0517103
proton + B11 → alpha + 2 Be8 + B10	0.0517103
proton + B11 → proton + alpha + deuteron + D11	0.155131
proton + B11 → proton + neutron + alpha + B10	0.465392
proton + B11 → alpha + B10 + C11	0.0517103
proton + B11 → proton + neutron + alpha + deuteron	1.29276
proton + B11 → proton + neutron + alpha + deuteron + Be8	0.0517103
proton + B11 → 2 proton + neutron + alpha + deuteron	0.517103
proton + B11 → neutron + alpha + deuteron + Be8	0.566813
proton + B11 → 2 alpha + deuteron + B11	0.0517103
proton + B11 → proton + 2 alpha + deuteron + Be8	0.103421
proton + B11 → neutron + alpha + deuteron + 2 Be8	0.0517103
proton + B11 → proton + 2 alpha + D10	0.206841
proton + B11 → neutron + alpha + 2 deuteron + Be8	0.155131
proton + B11 → 2 proton + alpha + deuteron + Be8	0.206841
proton + B11 → alpha + deuteron + B11 + Be8	0.0517103
proton + B11 → alpha + 2 deuteron	0.775654
proton + B11 → 3 alpha + deuteron + Be8	0.0517103
proton + B11 → neutron + alpha + deuteron + B11	0.103421
proton + B11 → proton + alpha + deuteron + Be8	0.723944
proton + B11 → neutron + alpha + B11 + B10	0.0517103
proton + B11 → proton + neutron + alpha + deuteron + B11	0.103421
proton + B11 → neutron + 2 alpha + D10	0.206841
proton + B11 → alpha + 2 deuteron + B11	0.0517103
proton + B11 → 2 proton + alpha + deuteron	0.079074
proton + B11 → 2 neutron + alpha + deuteron	0.775654
proton + B11 → proton + neutron + 2 alpha + deuteron	0.103421
proton + B11 → 2 alpha + deuteron	0.723944
proton + B11 → proton + 2 neutron + alpha + deuteron	0.361972
proton + B11 → alpha + deuteron + D10	0.020523
proton + B11 → 2 proton + neutron + alpha + B10	0.103421
proton + B11 → proton + 2 neutron + alpha + B10	0.258551
proton + B11 → proton + neutron + 2 alpha + deuteron + Be8	0.0517103
proton + B11 → 2 proton + alpha + Be8 + B10	0.103421
proton + B11 → proton + alpha + 2 D10	0.0517103
proton + B11 → 2 neutron + 2 alpha + B10	0.0517103
proton + B11 → 2 neutron + 2 alpha + deuteron + Be8	0.0517103
proton + B11 → alpha + deuteron + Be8 + B10	0.103421
proton + B11 → 2 proton + alpha + deuteron + B11	0.103421
proton + B11 → neutron + alpha + deuteron + Be8 + B10	0.0517103
proton + B11 → alpha + B11 + 2 B10	0.0517103
proton + B11 → neutron + alpha + 2 B10	0.0517103

Page 2

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proton + B11 --> neutron + alpha + 2 B10 0.0517103
proton + B11 --> proton + alpha + deuteron + B10 0.465392
proton + B11 --> proton + alpha + deuteron + B11 + B10 0.0517103
proton + B11 --> proton + neutron + alpha + 2 deuteron 0.258551
proton + B11 --> proton + 2 alpha + deuteron 0.079074
proton + B11 --> 2 neutron + alpha + B10 0.155131
proton + B11 --> 3 alpha + B10 0.155131
proton + B11 --> proton + alpha + 2 deuteron 0.723944
proton + B11 --> 2 alpha + Be8 + Be9 0.155131
proton + B11 --> neutron + alpha + deuteron + B10 0.258551
proton + B11 --> alpha + 2 deuteron + Be8 0.206841
proton + B11 --> proton + 2 neutron + alpha + Be8 + B10 0.0517103
proton + B11 --> neutron + alpha + 2 deuteron 0.465392
proton + B11 --> proton + alpha + 2 deuteron + B11 0.0517103
proton + B11 --> alpha + Be9 1.29276
proton + B11 --> 2 alpha + 2 deuteron + B10 0.0517103
proton + B11 --> alpha + He3 0.258551
proton + B11 --> proton + alpha + deuteron + 2 Be8 + B10 0.0517103
proton + B11 --> proton + alpha + He3 0.206841
proton + B11 --> neutron + alpha + Be9 0.775654
proton + B11 --> neutron + alpha + Be7 0.155131
proton + B11 --> 2 proton + alpha + B10 0.413682
proton + B11 --> proton + alpha + Be8 + Be9 0.258551
proton + B11 --> alpha + Be7 0.775654
proton + B11 --> 2 proton + alpha + 2 deuteron + B11 0.0517103
proton + B11 --> alpha + He3 + B10 0.155131
proton + B11 --> proton + neutron + alpha + He3 0.103421
proton + B11 --> proton + alpha + He3 + B10 0.103421
proton + B11 --> 2 proton + neutron + alpha + Be8 + B10 0.103421
proton + B11 --> alpha + 2 B10 0.0517103
proton + B11 --> 2 alpha + Be9 0.103421
proton + B11 --> proton + neutron + alpha + triton 0.155131
proton + B11 --> neutron + alpha + Be8 + Be9 0.310262
proton + B11 --> proton + alpha + deuteron + Be9 0.413682
proton + B11 --> 2 proton + neutron + 2 alpha + deuteron 0.206841
proton + B11 --> proton + 3 alpha + deuteron 0.155131
proton + B11 --> 2 alpha + Be8 + B10 0.0517103
proton + B11 --> 2 neutron + alpha + deuteron + 2 Be8 0.0517103
proton + B11 --> proton + neutron + alpha + deuteron + B10 0.206841
proton + B11 --> alpha + triton 0.517103
proton + B11 --> proton + 2 neutron + alpha + He3 0.0517103
proton + B11 --> proton + 2 alpha + He3 0.103421
proton + B11 --> alpha + Be7 + Be8 0.206841
proton + B11 --> neutron + alpha + deuteron + B11 + Be8 0.0517103
proton + B11 --> alpha + deuteron + He3 0.258551
proton + B11 --> alpha + deuteron + Be9 0.517103
proton + B11 --> neutron + alpha + Be7 + Be8 0.0517103
proton + B11 --> 3 neutron + alpha + Be8 + B10 0.0517103
proton + B11 --> 2 proton + alpha + Be9 0.155131
proton + B11 --> alpha + Be8 + Be9 0.155131
proton + B11 --> 2 proton + alpha + deuteron + B10 0.361972
proton + B11 --> proton + alpha + Be7 + B10 0.103421
proton + B11 --> alpha + B9 0.361972
proton + B11 --> neutron + alpha + deuteron + B11 + Be8 + B10 0.0517103
proton + B11 --> alpha + Be9 + B10 0.206841
proton + B11 --> proton + alpha + He3 + Be8 0.103421
proton + B11 --> 2 proton + neutron + alpha + Be8 + Be9 0.0517103
proton + B11 --> neutron + alpha + triton 0.206841
proton + B11 --> neutron + 2 alpha + B9 0.0517103
proton + B11 --> alpha + Be8 + B9 0.0517103
proton + B11 --> proton + neutron + alpha + Be7 + Be8 0.0517103
proton + B11 --> proton + 2 alpha + Be9 0.103421
proton + B11 --> 2 proton + neutron + alpha + deuteron + 2 Be8 0.0517103
proton + B11 --> proton + alpha + Be9 0.775654
proton + B11 --> 2 proton + alpha + B11 + Be9 0.0517103
proton + B11 --> 2 proton + alpha + Be7 + Be8 0.0517103
proton + B11 --> 2 neutron + alpha + deuteron + B10 0.103421
proton + B11 --> alpha + deuteron + Be7 0.103421
proton + B11 --> proton + 2 alpha + triton 0.103421
proton + B11 --> neutron + alpha + B9 0.258551
proton + B11 --> 2 neutron + alpha + Be9 0.103421
proton + B11 --> proton + 2 alpha + B9 0.0517103
proton + B11 --> 2 alpha + triton + Be8 0.0517103
proton + B11 --> neutron + alpha + He3 0.258551
proton + B11 --> proton + alpha + 2 Be8 + B10 0.0517103
proton + B11 --> proton + neutron + 2 alpha + B9 0.0517103
proton + B11 --> 2 proton + alpha + B9 0.0517103

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proton + B11 --> 3 proton + neutron + alpha + Li6 + Be10 0.0517103
proton + B11 --> 2 proton + neutron + alpha + deuteron + Be8 + Be10 0.0517103
proton + B11 --> 3 neutron + alpha + 2 Li6 + 2 Li7 0.0517103
proton + B11 --> neutron + alpha + 2 deuteron + Li6 + 2 Be7 0.0517103
proton + B11 --> proton + neutron + alpha + deuteron + He3 + Li6 + B10 0.0517103
proton + B11 --> proton + 2 neutron + alpha + 2 He3 + Be8 + B9 + B10 0.0517103
proton + B11 --> N gamma or e- + 2 alpha + deuteron + He3 + Li6 + Be8 0.0517103
proton + B11 --> proton + alpha + 2 deuteron + 2 Li6 0.0517103
proton + B11 --> 2 neutron + alpha + Li6 + Be7 + Be9 0.0517103
proton + B11 --> alpha + deuteron + Be8 + B9 + 2 B10 0.0517103
proton + B11 --> 2 neutron + 3 alpha + C10 0.0517103
proton + B11 --> proton + neutron + alpha + deuteron + He3 + Li6 + Li7 + 2 Be8 + B10 + C10 0.0517103
proton + B11 --> 2 neutron + 2 alpha + 2 triton + Li6 + Be9 0.0517103
proton + B11 --> N gamma or e- + alpha + Li7 + B10 0.0517103
proton + B11 --> 3 proton + alpha + deuteron + Be7 + Be10 + B9 0.0517103
proton + B11 --> 2 neutron + alpha + Be7 + B9 + 2 B10 0.0517103
proton + B11 --> N gamma or e- + 2 proton + alpha + Li7 0.0517103
proton + B11 --> 2 proton + neutron + alpha + deuteron + triton + Be9 0.0517103
proton + B11 --> 2 proton + neutron + 2 alpha + Be7 + B10 0.0517103
proton + B11 --> N gamma or e- + proton + neutron + alpha + deuteron + B11 0.0517103
proton + B11 --> proton + neutron + alpha + deuteron + triton + Li7 + Be8 0.0517103
proton + B11 --> proton + neutron + alpha + 2 Li6 + Be7 + B10 0.0517103
proton + B11 --> proton + 2 neutron + alpha + Be7 + Be9 + B10 0.0517103
proton + B11 --> proton + 2 alpha + deuteron + Li6 + Be8 + Be10 0.0517103
proton + B11 --> proton + alpha + 2 deuteron + B9 + C11 0.0517103
proton + B11 --> 3 proton + neutron + alpha + 2 deuteron + B9 0.0517103
proton + B11 --> 2 proton + alpha + 2 deuteron + triton + Be7 + Be10 + B10 0.0517103
proton + B11 --> 3 proton + 3 neutron + alpha 0.0517103
proton + B11 --> 2 alpha + Be3 + 2 Li6 0.0517103
proton + B11 --> neutron + alpha + 2 deuteron + B11 + Li7 0.0517103
proton + B11 --> 2 proton + 2 neutron + alpha + deuteron + Li6 + Be7 0.0517103
proton + B11 --> alpha + deuteron + triton + 3 Be8 0.0517103
proton + B11 --> 4 proton + 2 neutron + alpha + Li6 + Be7 0.0517103
proton + B11 --> N gamma or e- + alpha + deuteron + Be9 0.0517103
proton + B11 --> proton + 2 neutron + alpha + deuteron + Be8 + Be10 0.0517103
proton + B11 --> proton + 2 neutron + 4 alpha + deuteron 0.0517103
proton + B11 --> 5 proton + alpha + deuteron + triton + Li6 0.0517103
proton + B11 --> 4 proton + alpha + Be8 + C10 0.0517103
proton + B11 --> neutron + alpha + 2 triton + 2 Be8 0.0517103
proton + B11 --> proton + 5 neutron + alpha + B11 0.0517103
proton + B11 --> neutron + alpha + 2 deuteron + 2 B11 0.0517103
proton + B11 --> proton + 2 alpha + Li6 + Be7 + Be8 + B9 0.0517103
proton + B11 --> 2 alpha + B11 + Li6 + Li7 + Be8 0.0517103
proton + B11 --> 3 proton + 2 neutron + alpha + Be9 + Be10 0.0517103
proton + B11 --> proton + 2 neutron + 3 alpha + Li6 + Be7 0.0517103
proton + B11 --> proton + alpha + Li7 + 2 Be7 0.0517103
proton + B11 --> N gamma or e- + proton + 2 alpha + Li6 + Be8 + B10 + C10 0.0517103
proton + B11 --> 3 alpha + deuteron + 2 Li6 0.0517103
proton + B11 --> proton + neutron + 2 alpha + Li6 + B9 + B10 0.0517103
proton + B11 --> 2 proton + 2 neutron + alpha + 2 deuteron + B10 0.0517103
proton + B11 --> proton + neutron + 2 alpha + triton + B9 + B10 0.0517103
proton + B11 --> 2 proton + neutron + 2 alpha + deuteron + Be9 + B10 0.0517103
proton + B11 --> 4 proton + alpha + deuteron + Li7 + Be7 + B10 0.0517103
proton + B11 --> neutron + alpha + triton + Li6 + Be8 + Be10 0.0517103
proton + B11 --> 2 proton + alpha + 2 deuteron + 2 He3 + Be9 0.0517103
proton + B11 --> proton + 2 alpha + deuteron + Be8 + Be10 0.0517103
proton + B11 --> N gamma or e- + 2 proton + alpha + Be10 + B10 0.0517103
proton + B11 --> proton + 2 neutron + alpha + Be7 + B9 0.0517103
proton + B11 --> 5 proton + alpha + deuteron + B11 + Li6 0.0517103
proton + B11 --> 2 neutron + 2 alpha + B11 + 2 Li6 + Be9 0.0517103
proton + B11 --> proton + neutron + alpha + deuteron + He3 + Li7 0.0517103
proton + B11 --> neutron + 2 alpha + deuteron + Li6 + Be7 + B10 0.0517103

```

proton + B11 --> 2 proton + neutron + alpha + 2 deuteron + Li6 + Be7 + B9 + B10

..... + 7 pages more

TALYS calculations: TALYS-1.9

Geant4 simulation: geant4-10-04-patch-01 (28-February-2018).

In the first graph all lines are referred to the axis on the left but Simulation - AllHP - environment variable.

In baryon number graph reaction producing at least one alpha has been selected.

Environment variables set up are:

DO_NOT_SET_PHP_AS_HP=1

G4PHP_DO_NOT_ADJUST_FINAL_STATE=1

All Geant4 simulations have the problem that below 1 MeV no alphas are produced, also ParticleHP.

Without environment variables:

-a lot of warning: "More than one neutron is required for the balance of baryon number!"

-crashes beyond 10 MeV with error: "G4IonTable::GetIon() : illegal atomic number/mass Z =0 A = 4 E = 0"

-It is similar but not equal to TALYS calculations, why?

With environment variables:

-A lot of nonsense reactions: with 2.8e6 particle simulated found out 84049 different reactions, mostly not conserving baryon number

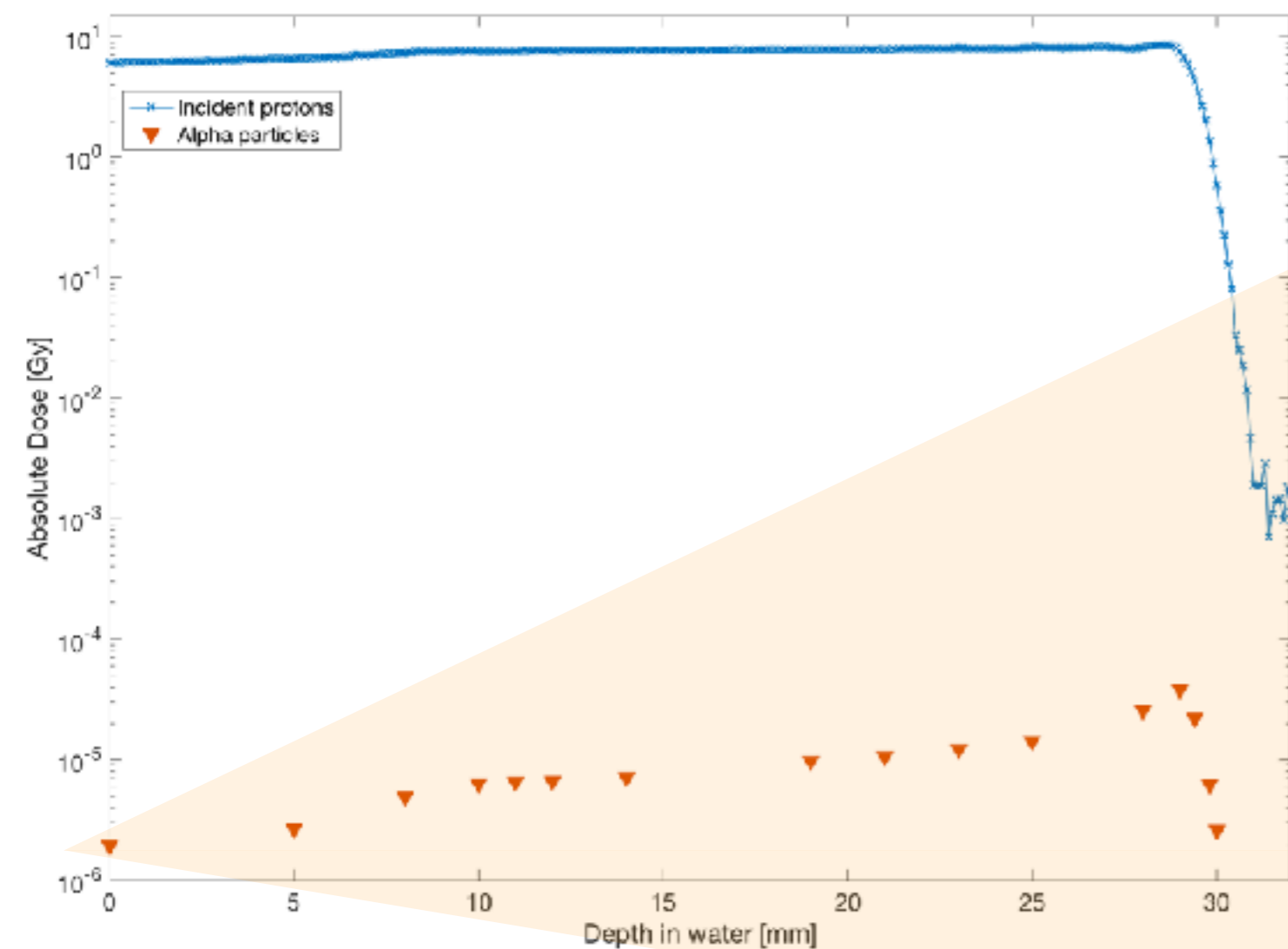
-Example of nonsense reactions:

proton + B11 --> 3 proton + 2 neutron + 3 alpha + Be9 + B9 + B10

proton + B11 --> 3 proton + 3 neutron + Li8 + Be8 + Be9

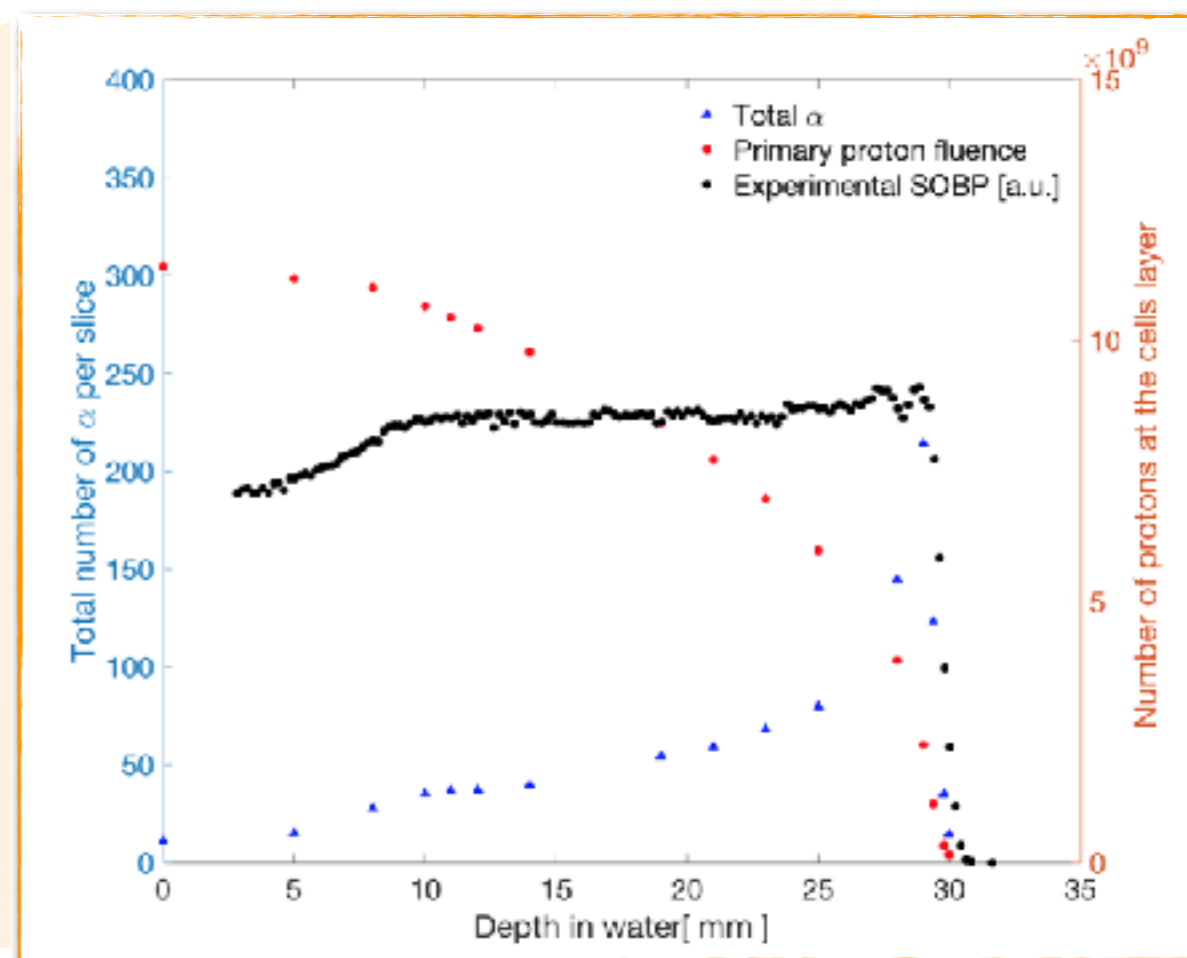
Thank you

Protons and alpha particles doses



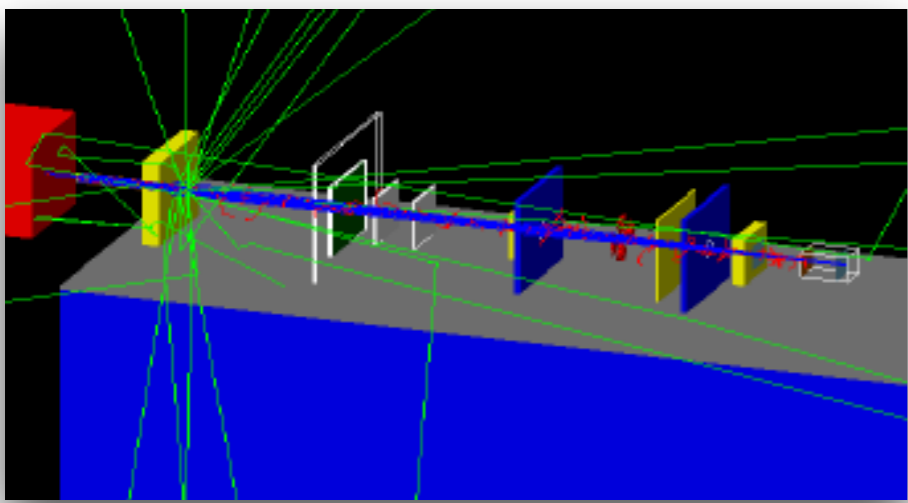
* 10^6 order of magnitude as difference

* almost 200 alpha particles in a T25 flask (25 cm^2)



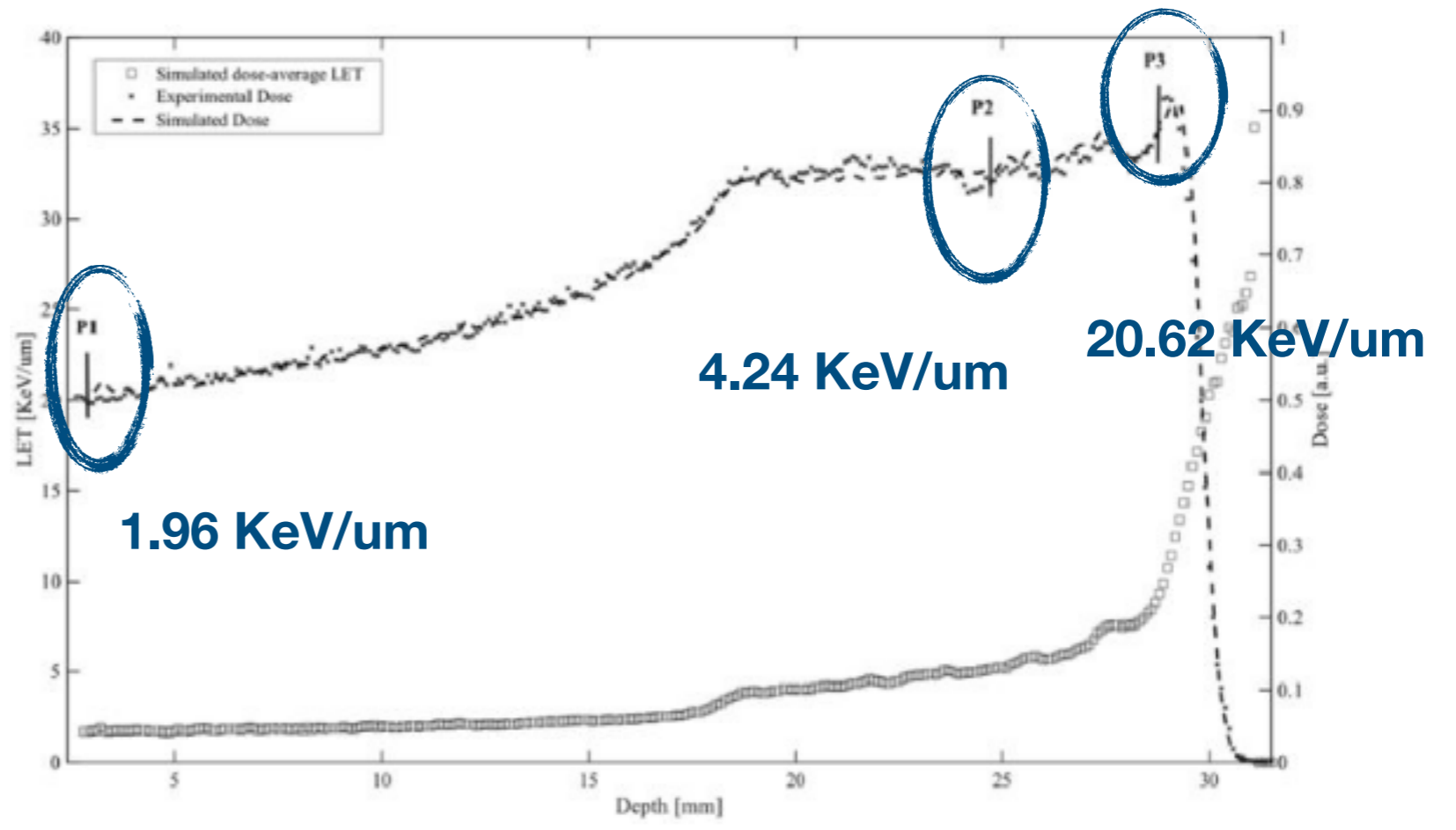


Cuttone et al. EPJ 126 (2011)



G.A.P. Cirrone et al., NST, 207-212 (2011)

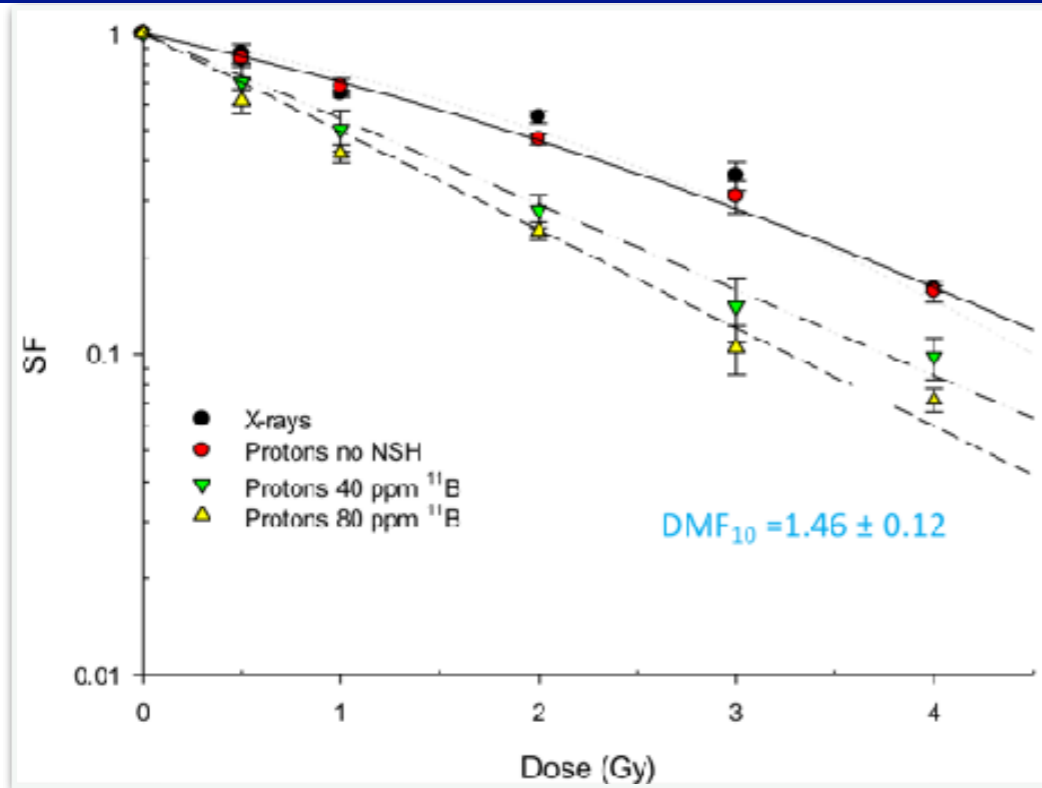
DU145 prostate cancer cells irradiated along a proton clinical Bragg peak



Clonogenic survival curves show an increase in proton killing power

18

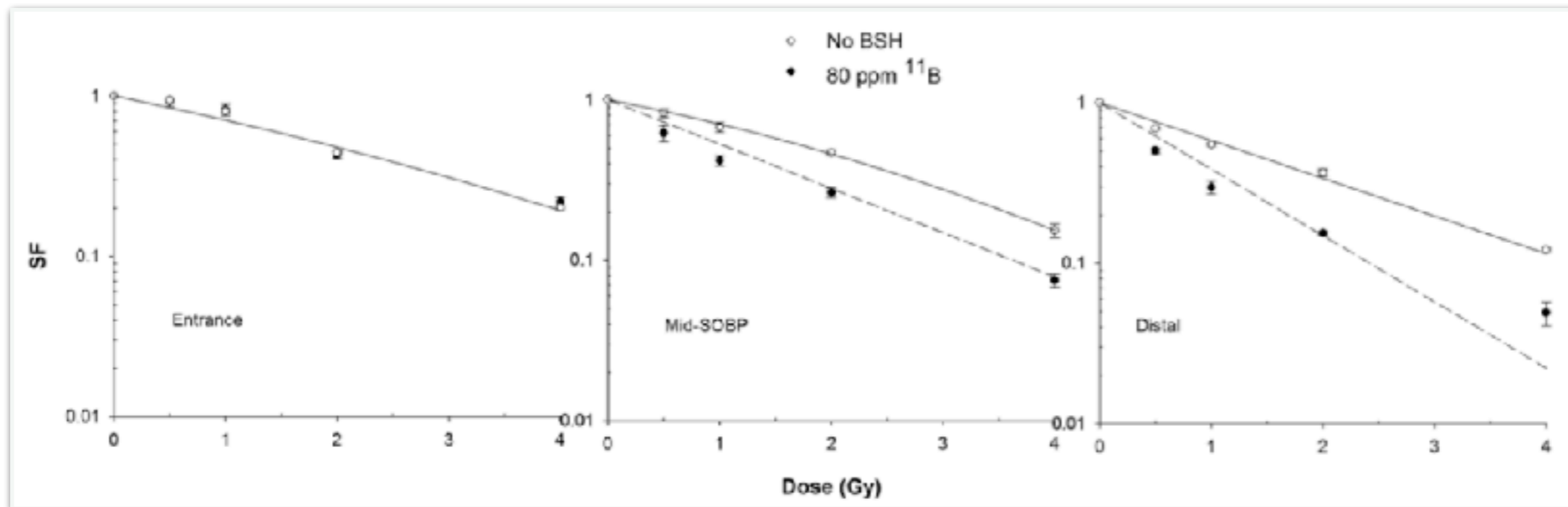
Irradiation @MID-SOBP



	α (Gy^{-1})	β (Gy^{-2})
X ray irradiation	0.222 ± 0.062	0.064 ± 0.014
Proton irradiation in the absence of BSH	0.314 ± 0.022	0.035 ± 0.007
Proton irradiation with 40 ppm ^{11}B	0.614 ± 0.069	—
Proton irradiation with 80 ppm ^{11}B	0.705 ± 0.033	—

$$\text{DMF}_{10} = 1.46 \pm 0.12$$

Irradiation along the SOBPs



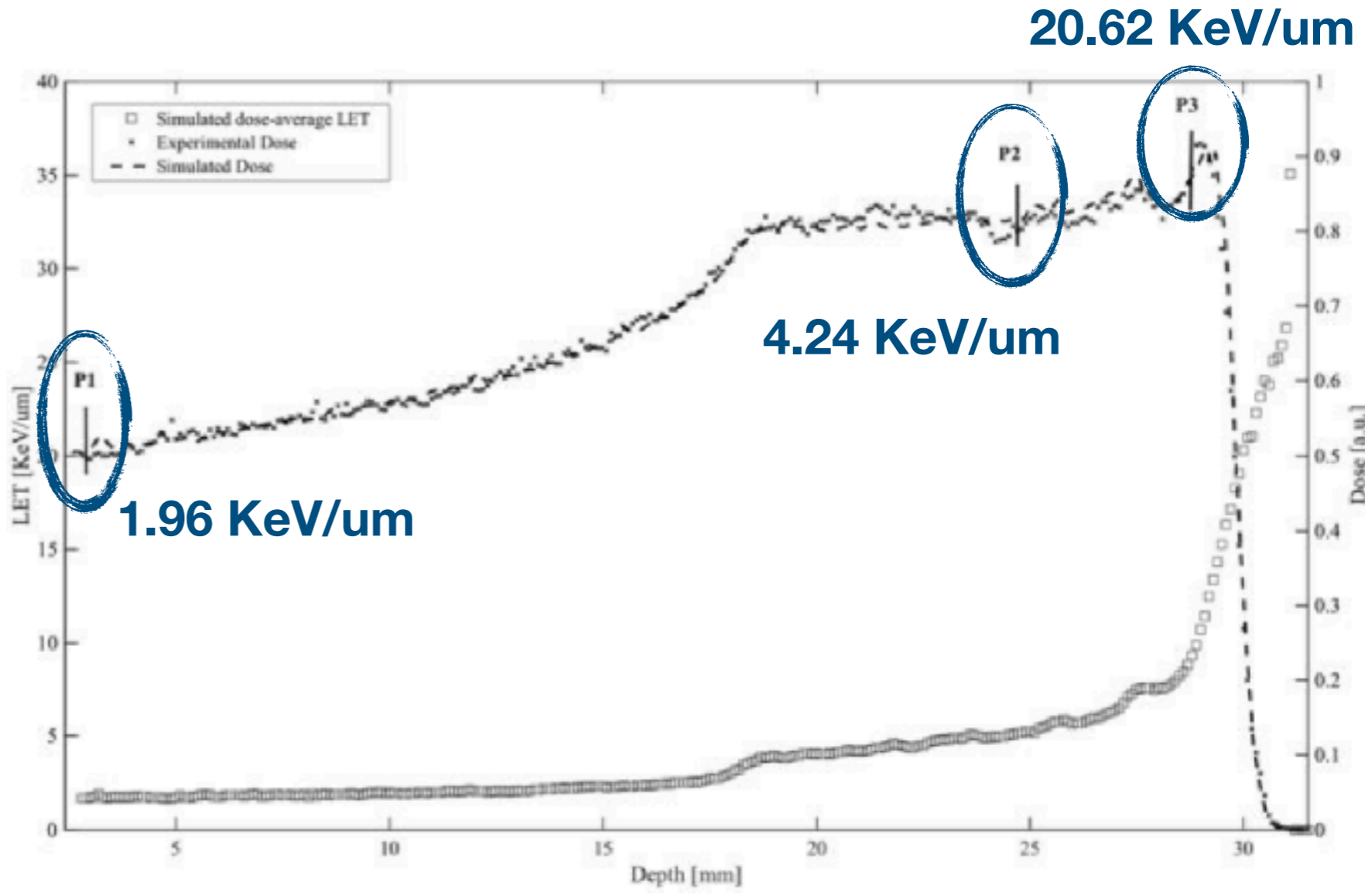
incident proton beam
of 62 MeV

Doses:
0.5 - 1 - 2 - 4 [Gy]

BSH concentration:
80ppm and 40ppm

fluence $\sim 10^{10}$ p/cm²

prostate cancer cell line DU145



G.A.P. Cirrone, et al., "First experimental proof of Proton Boron Capture Therapy (PBCT) to enhance protontherapy effectiveness", Scientific Reports, vol 8: 1141 (2018)

Chromosomal aberrations

20

e

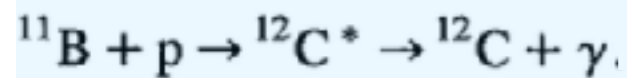
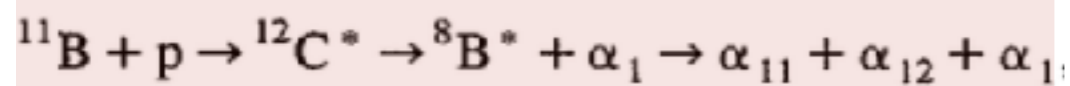
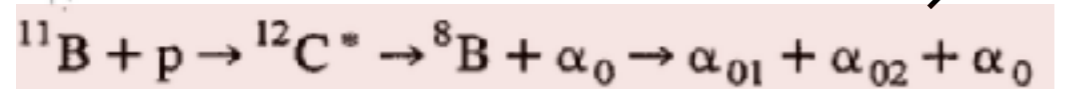
Trying to explain the
effect from a 'classic'
point of view



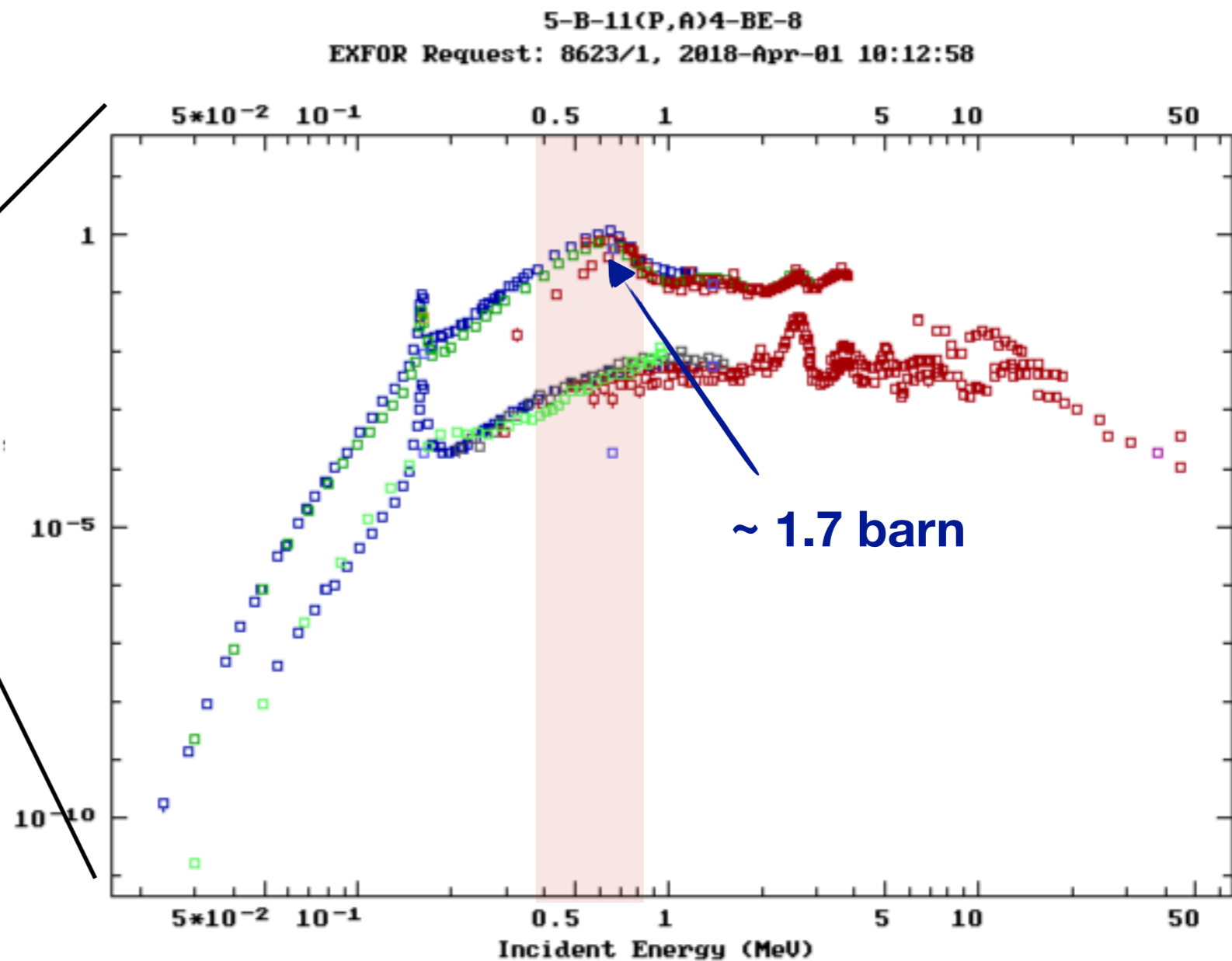
Istituto Nazionale di Fisica Nucleare

The reaction mechanism

Reaction channels

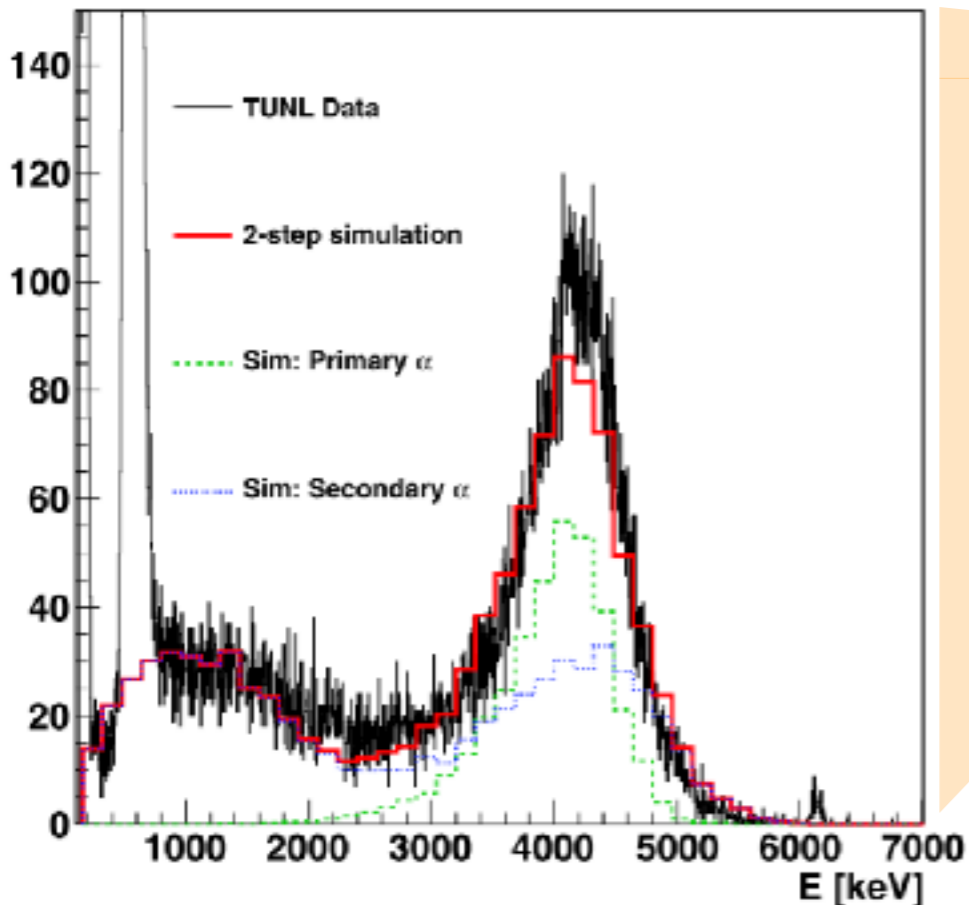


The reaction exit channels have a maximum cross section of 157 μb for incident proton energy under 1 MeV

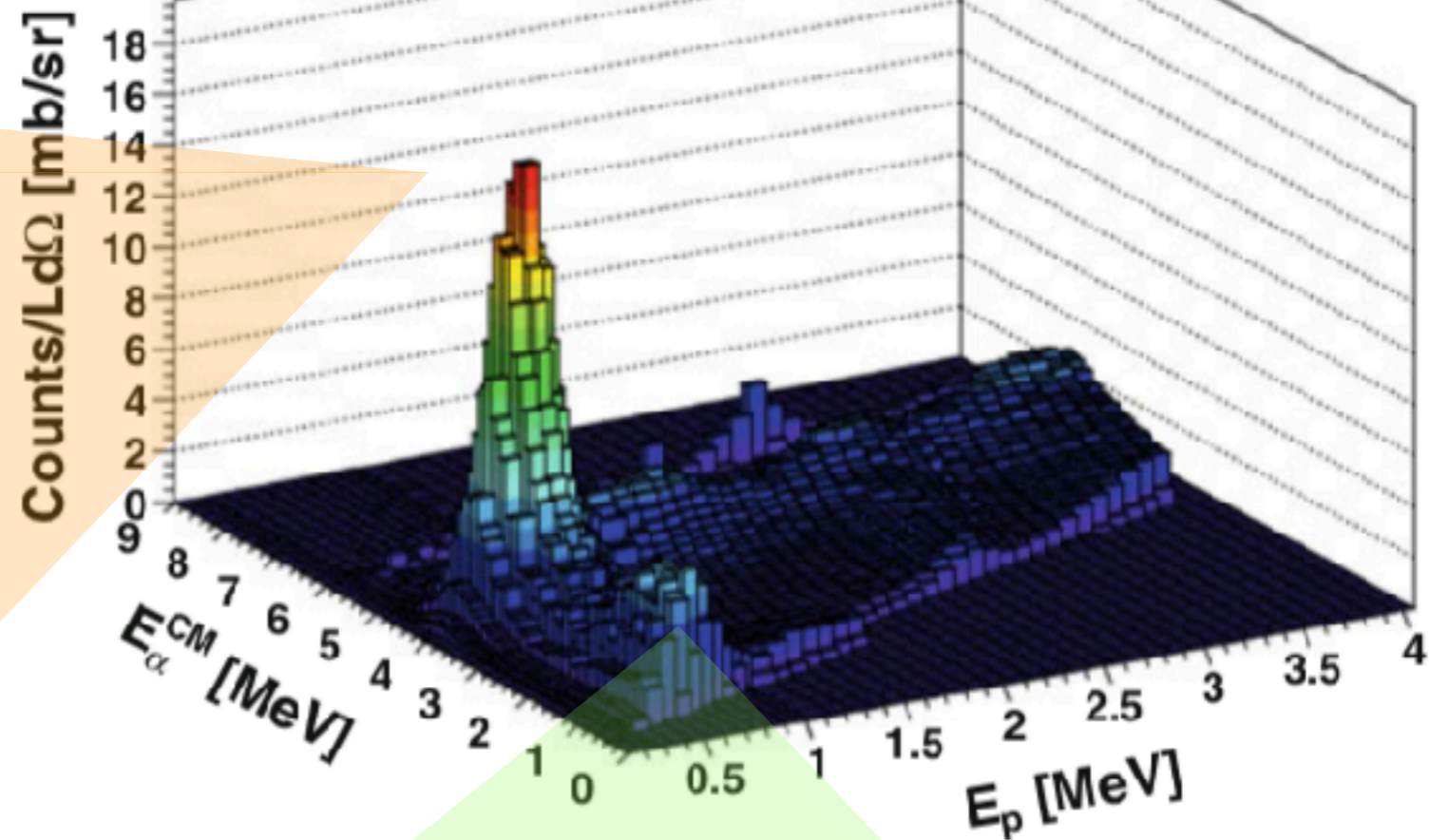


The reaction mechanism

23



M.H.Sikora, H.R.Weller, A new evaluation of the $^{11}\text{B}(p, \alpha)\alpha$ reaction rates, *J. Fusion Energy* (2016) 35:538



Resonances

$$E_p = 0.150 \text{ MeV}$$

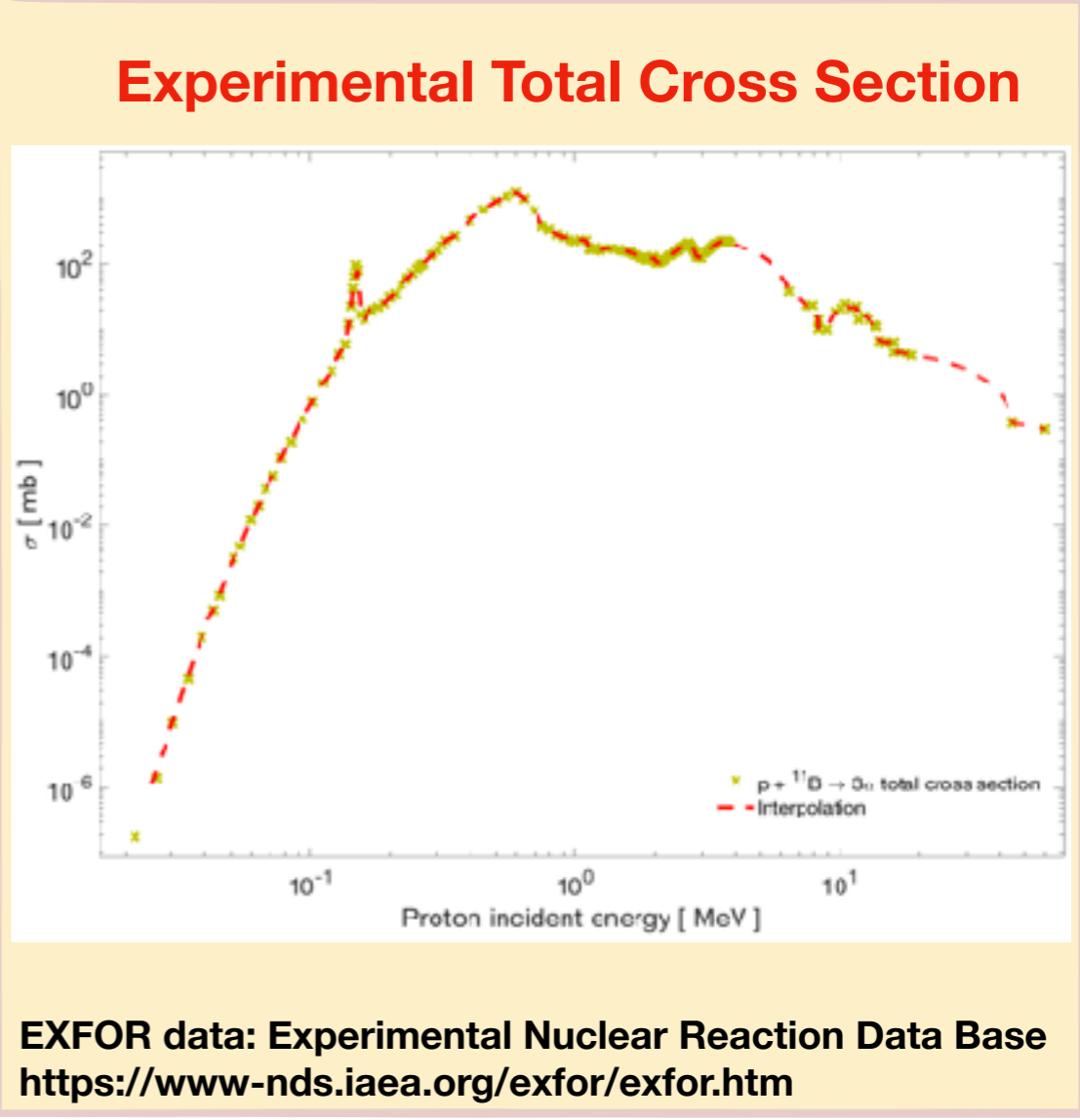
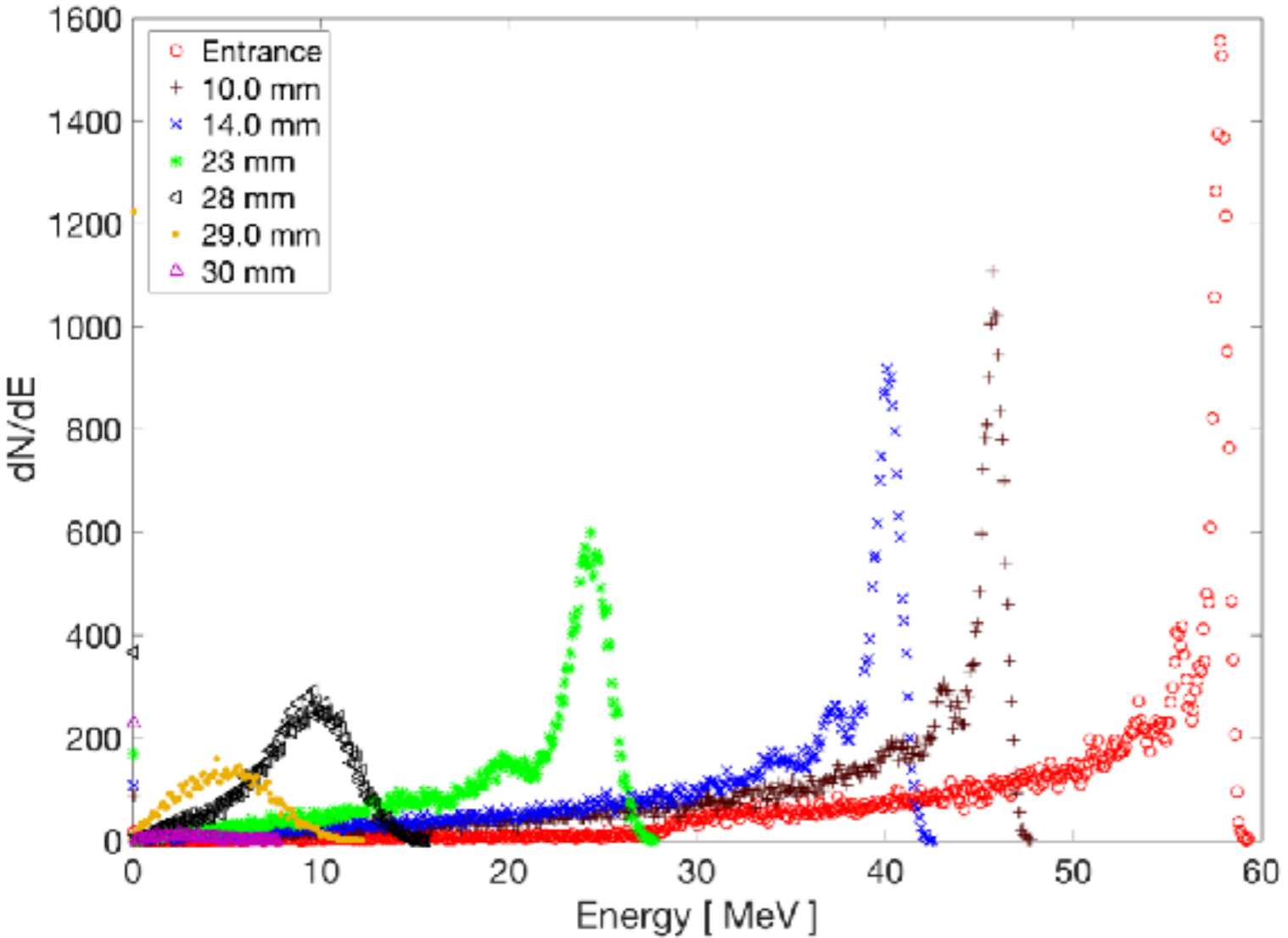
$$E_p = 0.675 \text{ MeV}$$

$$E_p = 2.64 \text{ MeV}$$

Proton energy spectra and analytical counts

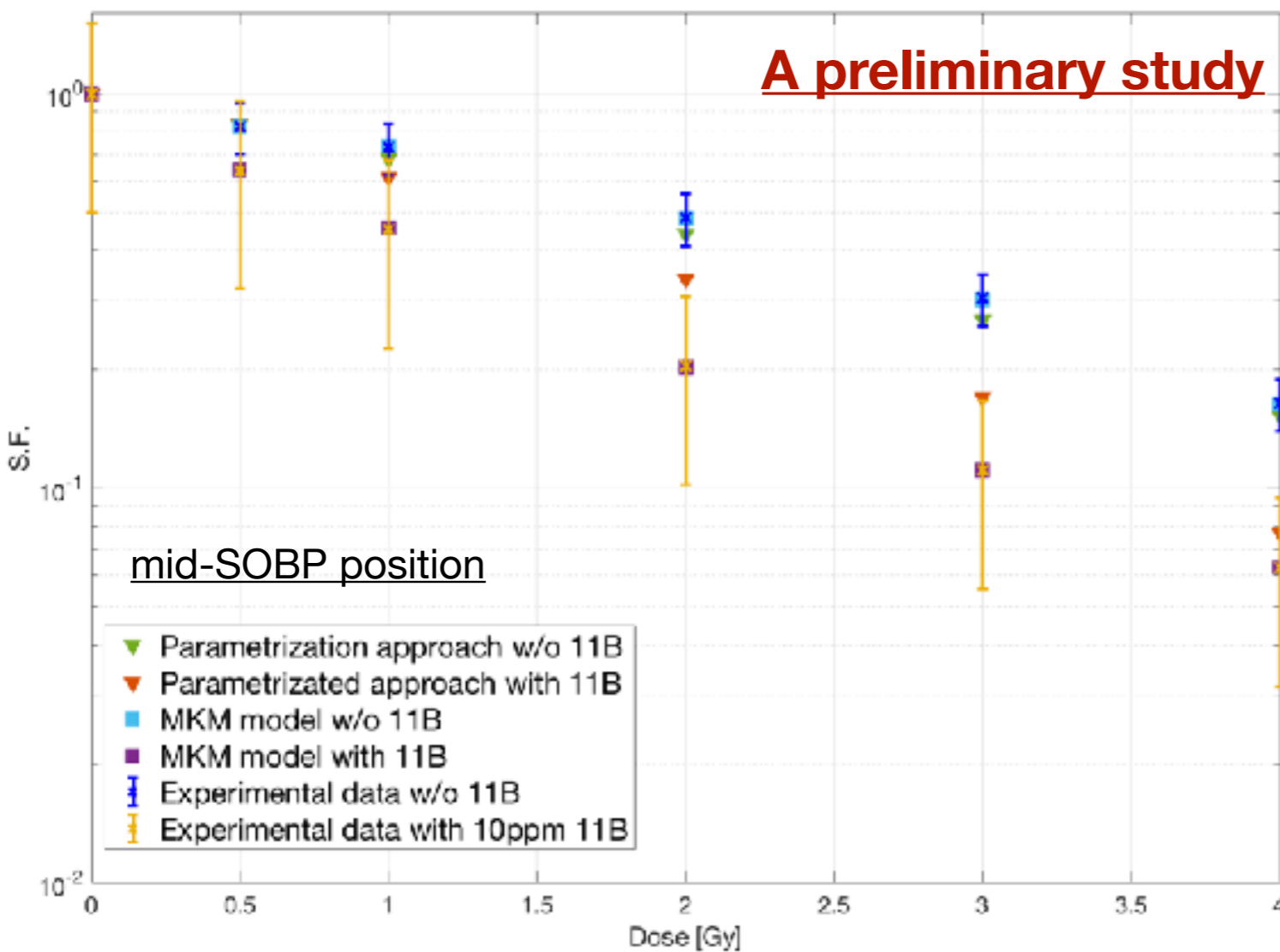
10⁴ events
Modulated Beam
Voxel size: 100um

Simulated proton spectra



11B(p,a)2a

A preliminary study



Total dose average LET value

$$LET_{protons + \alpha} = \frac{dE_p^1 \frac{dE_p^1}{dx_p^1} + dE_p^2 \frac{dE_p^2}{dx_p^2} + \dots + dE_p^n \frac{dE_p^n}{dx_p^n} + dE_\alpha^1 \frac{dE_\alpha^1}{dx_\alpha^1} + dE_\alpha^2 \frac{dE_\alpha^2}{dx_\alpha^2} + \dots + dE_\alpha^n \frac{dE_\alpha^n}{dx_\alpha^n}}{dE_p^1 + dE_p^2 + \dots + dE_p^n + dE_\alpha^1 + dE_\alpha^2 + \dots + dE_\alpha^n}$$

Position	Depth in water [mm]	Proton dose averaged LET [KeV/um]	Total dose averaged LET [KeV/um]	Dose Modifying Factor (DMF)
Entrance	50	1.96	3.66	1.17 ± 0.37
Mid-SOBP	210	4.24	9.53	1.36 ± 0.44
Distal	298	20.62	33.92	2.04 ± 0.66

An increment of the order of 40% correspond to ~10⁵ alpha particles emitted

McNamarra et al. PMB, November 2015; 60(21)

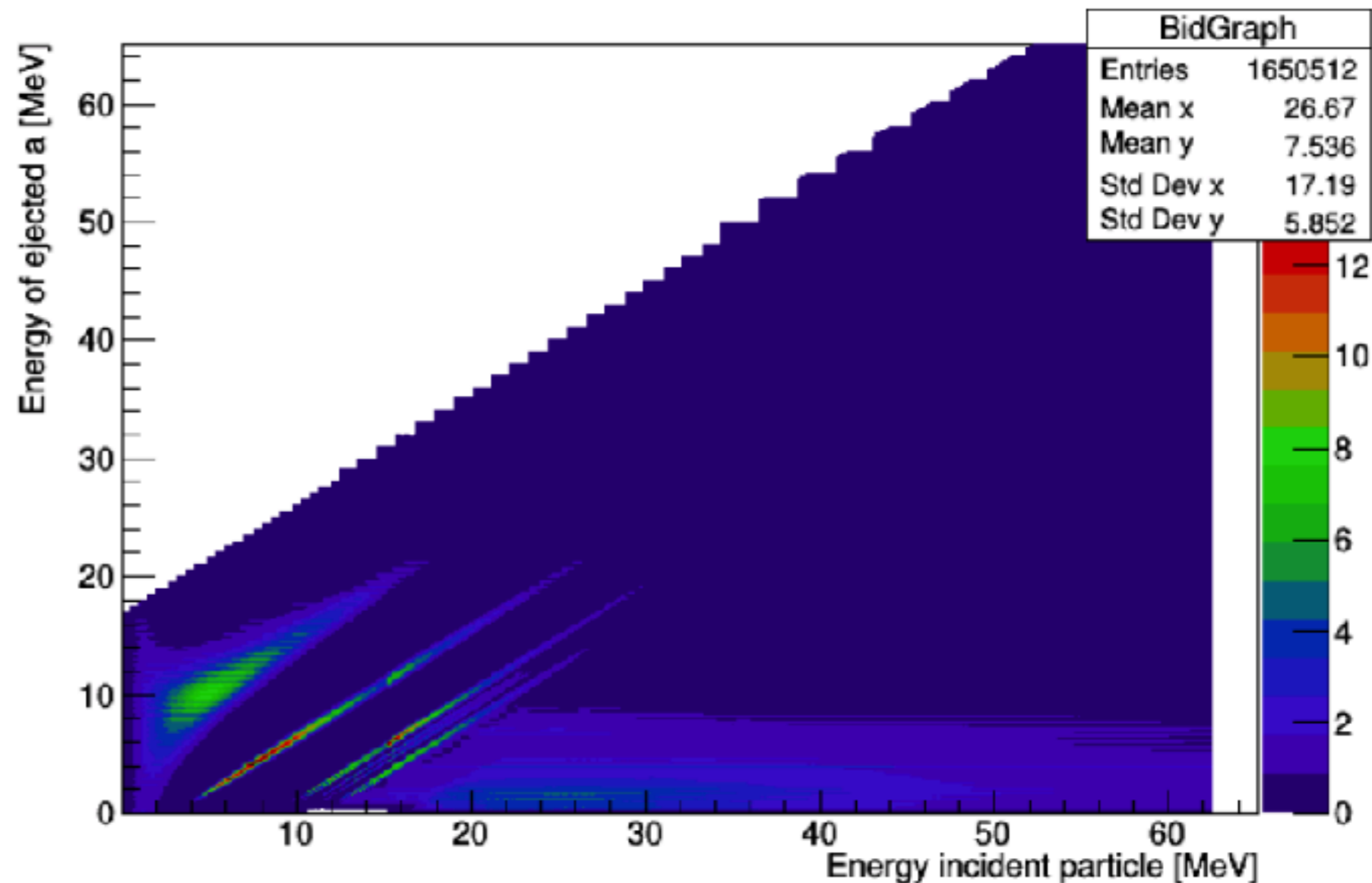
Survival: <https://github.com/batuff/Survival>

Other competing reactions

26

Target: ^{11}B	Maximum Cross Section
$^{11}\text{B}(p,\alpha)^8\text{Be}$	2000 mb at ~ 600 KeV
$^{11}\text{B}(p,n)^{11}\text{C}$	500 mb at ~ 5 MeV
$^{11}\text{B}(n,p)^{11}\text{Be}$	10 mb at ~ 15 MeV
$^{11}\text{B}(n,\alpha)^8\text{Li}$	200 mb at ~ 8 MeV

Target: ^{10}B	Maximum Cross Section
$^{10}\text{B}(p,\alpha)^7\text{Be}$	100 mb at ~ 100 KeV
$^{10}\text{B}(p,n)^{10}\text{C}$	10 mb at ~ 10 MeV
$^{10}\text{B}(n,p)^{10}\text{Be}$	100 mb at ~ 2.5 MeV
$^{10}\text{B}(n,\alpha)^7\text{Li}$	10000 mb at ~ 200 KeV



M.E. Kormaz, "INVESTIGATION OF REACTION CROSS SECTIONS OF $^{10,11}\text{B}$ WITH PROTONS AND NEUTRONS OF 0 - 30 MEV INCOMING ENERGY USING NUCLEAR MODELS "BPL, 20, 201035, pp. 293 - 300 (2012)

- An evident and reproducible radiobiological effect is observed
- Some aspects still need to be investigated in order to modelize correctly the effect

Recently an international collaboration is involved to investigate the effect. The INFN is engaged to study different aspects:

- ▶ INFN-Naples (Radiobiological aspects)
- ▶ INFN-Rome3 & LNS & TIFPA (Simulation and modeling)
- ▶ INFN-Rome1 (Imaging)
- ▶ INFN-Pavia & Legnaro (Microdosimetry)



External Collaborations



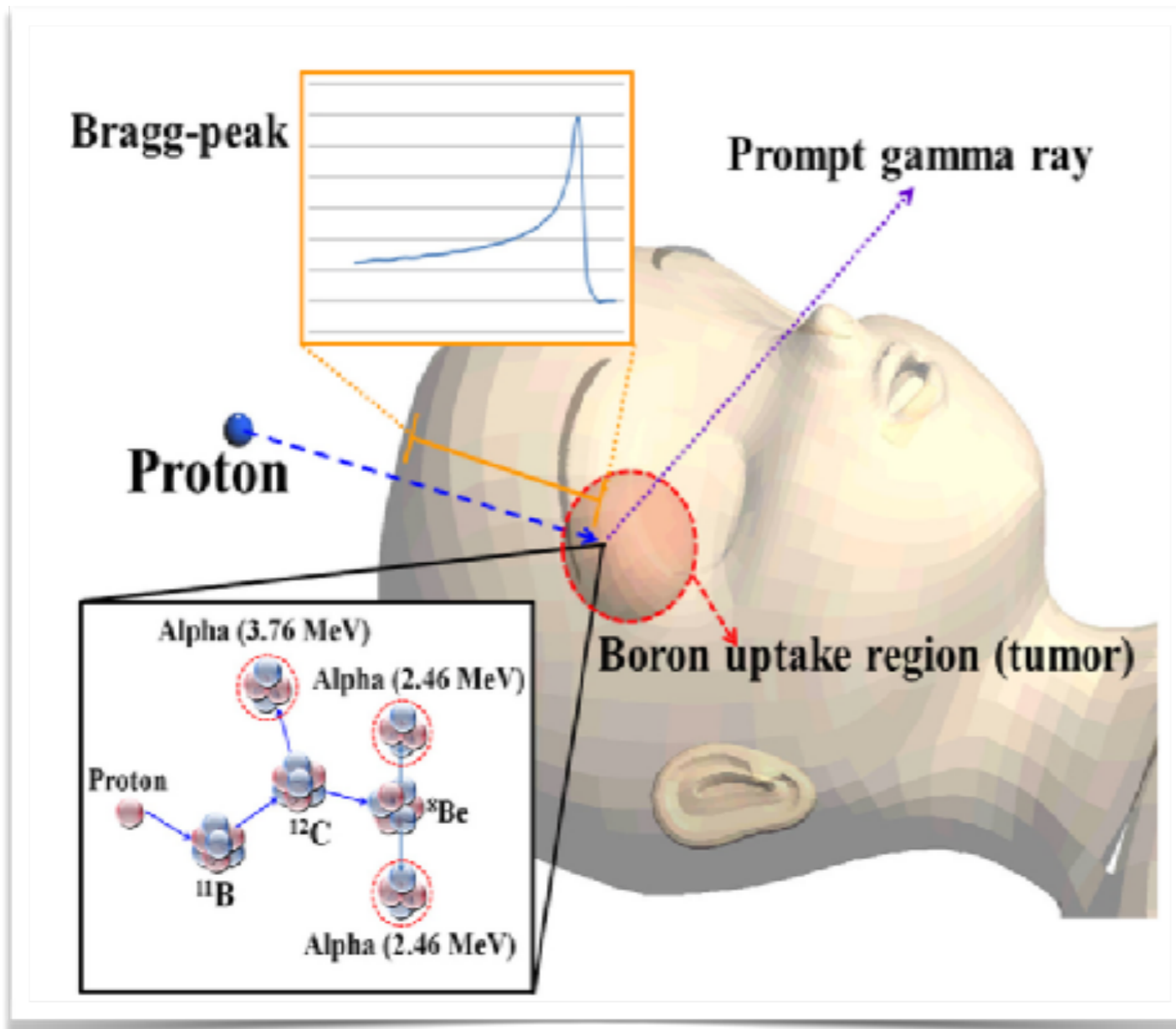
p 1 proton
(hydrogen)

Thank you for your attention



Acknowledgments

Pablo Cirrone (INFN-LNS) - Lorenzo Manti (INFN-NA) - Davide Chiappara (INFN-PD) - Andrea Attili (INFN-RM3)



Proposed approach

D.-K. Yoon et al, “Application of proton boron fusion reaction to radiation therapy: A Monte Carlo simulation study”,
Applied Physics Letters 105, 223507 (2014);

First in-vitro experiment:

G.A.P. Cirrone, et al., “First experimental proof of Proton Boron Capture Therapy (PBCT) to enhance protontherapy effectiveness”,
Scientific Reports, vol 8: 1141(2018)

