Hokkaido 2023

Geant4 Collaboration meeting

Validation of helium radiotherapy

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GEANT4

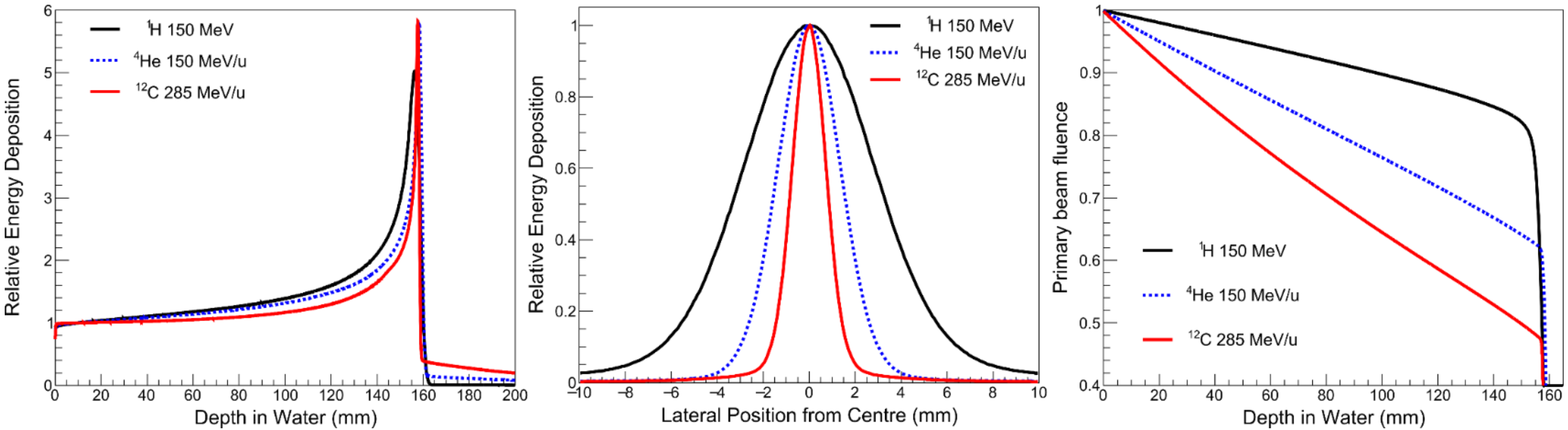
A SIMULATION TOOLKIT

Helium radiotherapy

- Growing interest in helium ion therapy in recent years
  - Patients treated at GSI
- Presents middle ground between proton and carbon ion therapy
- Carbon compared to proton
  - very conformal and can perform efficient damage to cancer (and healthy) cells but produces significant amount of fragments
- Monte Carlo becoming more widely used in medical physics including treatment dose planning verification
- Critical to know the behaviour of models used for medical physics applications

Particle type	Patients treated by 2021
Proton	~280,000
Carbon	~42,000
Helium	2,054

https://www.ptcog.ch

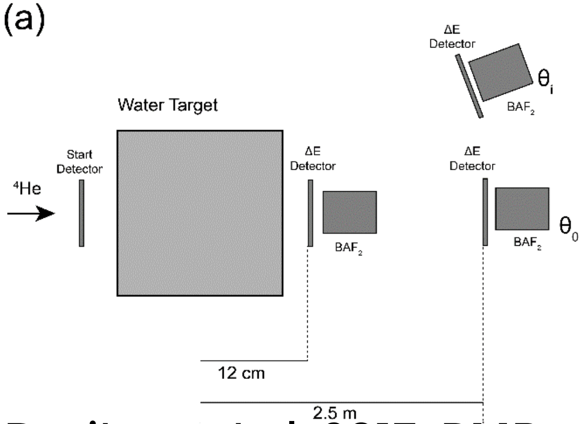


Experimental data for validation

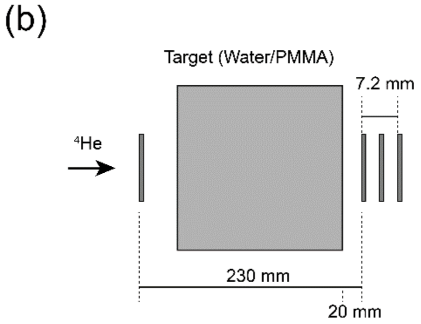
- Comparisons performed using version 11.00 of Geant4 using hadronic models most relevant for medical physics applications
  - BIC
  - QMD
  - INCL

BERT has been tested limitedly, it performed similar to somewhere between BIC and QMD

Publication	Beam energy (MeV/u)	Target	Measurement	Bragg peak position (mm)	Angular acceptance
Rovituso et al. 2017, PMB	120/200	Water	Fragment build up curve, angular and energy distributions	104/260	38, 1.79, 1.79
Arico et al. 2017, PMB	220.5	Water/ PMMA	Fragment build up curve	308	3.4
Marafini et al. 2017, PMB	102/125/145	PMMA	Angular and energy distributions	81/115/150	1.15, 1.15



Rovituso et al. 2017, PMB



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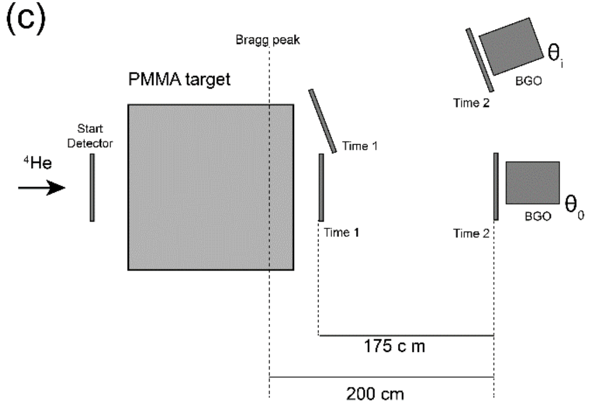
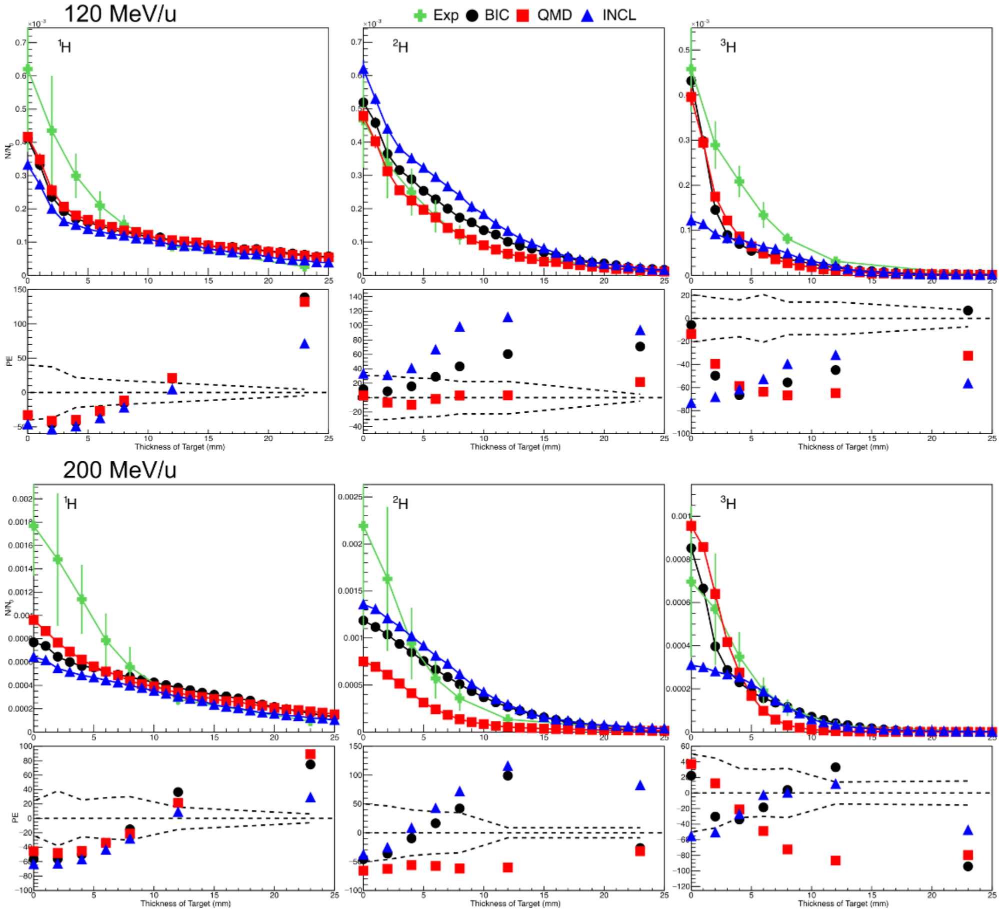


Marafini et al. 2017, PMB

Results

Angular distributions

- Rovituso measurements are for a water target with thickness ~half the beam range
  - Models have significant under-production of fragments in the forward direction (smaller angles) with the exception of ^{3}H for 200 MeV/u
  - Differences grow with higher energy, max difference for ^{1}H goes from ~50% to -300%
  - No clear "better" model



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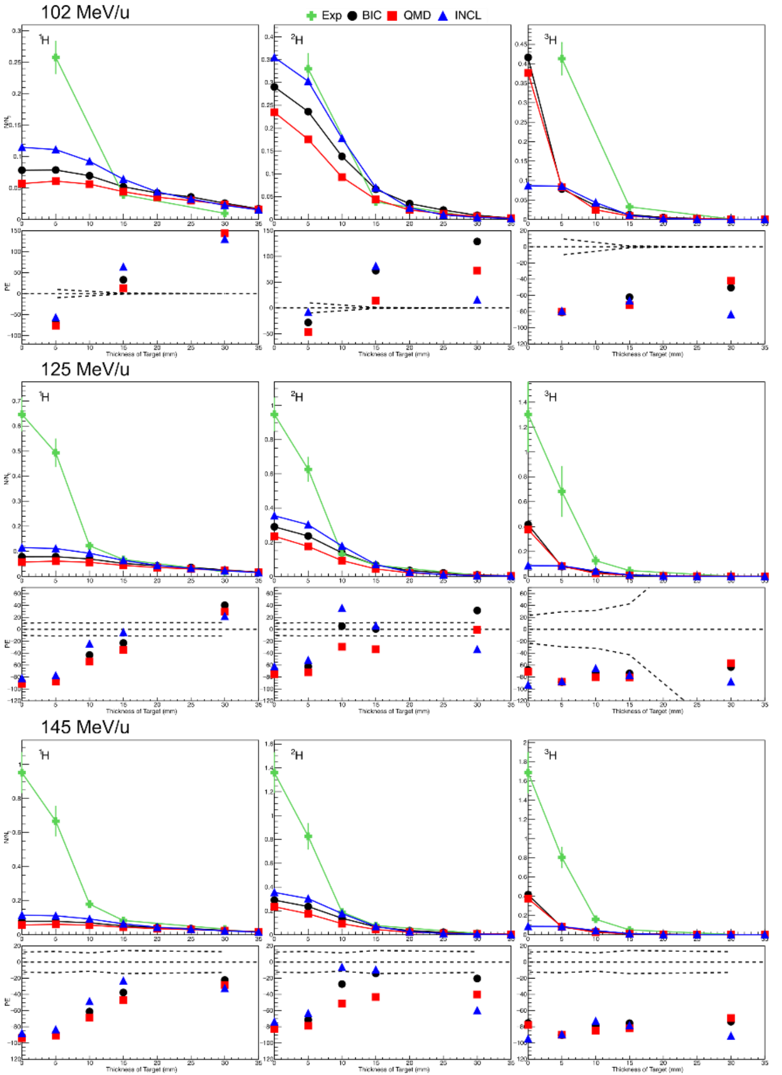
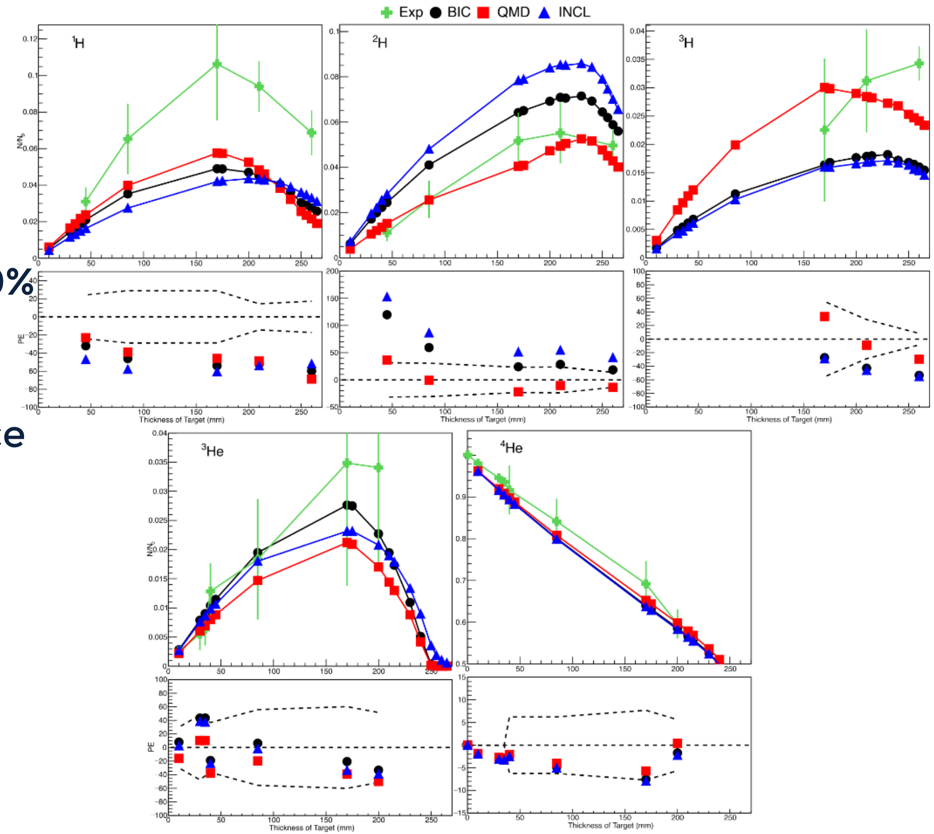
- Marafini measurements done for PMMA with thickness slightly larger than beam’s range
  - Much smaller errors gives a clearer picture of Geant4
  - Compounding effects of model produces larger differences with experiment
  - Up to ~10x difference between experiment and models for ^{1}H fragments (most abundant) at 145 MeV/u
  - INCL gives better agreement at forward/smaller angles



Fragment yields

- Rovituso measurements are collected within an angle of acceptance of 38 degrees
- All models significantly under produce ^{1}H fragments (most abundant fragment) by ~20-60%
- QMD produces noticeably better results for ^{2}H and reproduces ^{1}H and ^{3}H slightly better
- BIC and INCL over produce ^{2}H but under produce ^{3}H



200 MeV/u

Data	σ_{in} (mb)
Experiment	650 (636*) ± 17
Geant4 BIC	760 ± 2
Geant4 QMD	726 ± 2
Geant4 INCL	768 ± 2
Geant4 primary only	786 ± 1
Hybrid Kurotama	392
Tripathi99	585
Tripathi96	756
Kox-Shen	832
Kox	891
Shen	903

Comparison of inelastic cross-section

*636 mb is the reported experimental cross-section, 650 mb from refitting data

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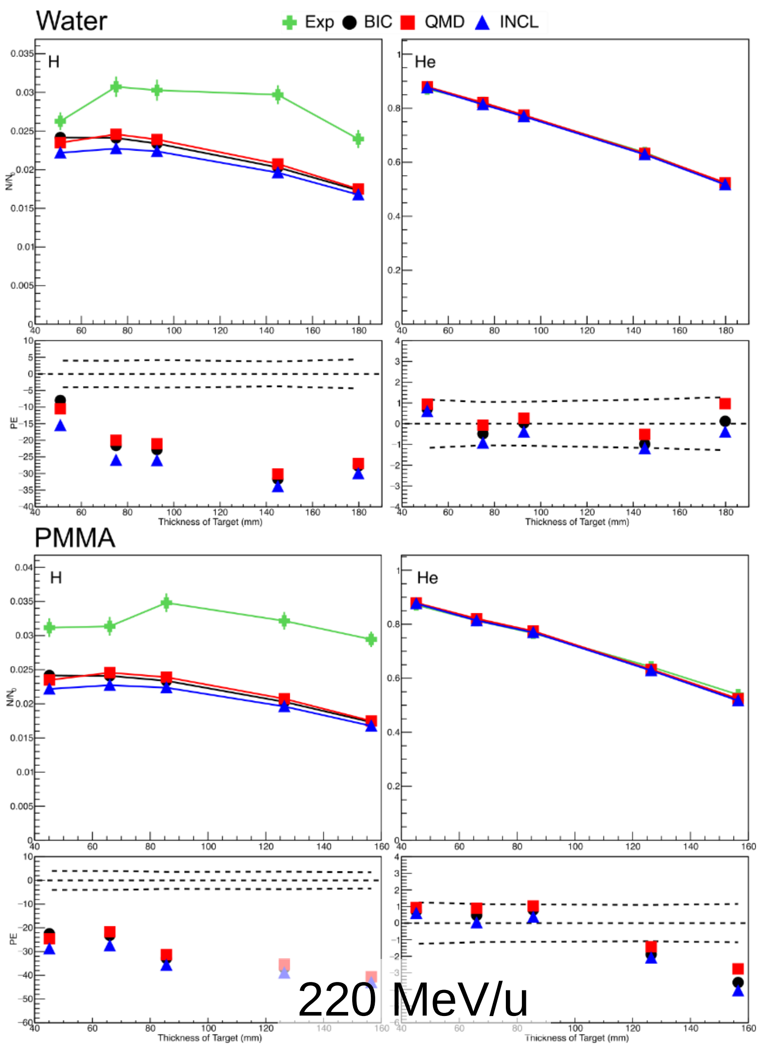
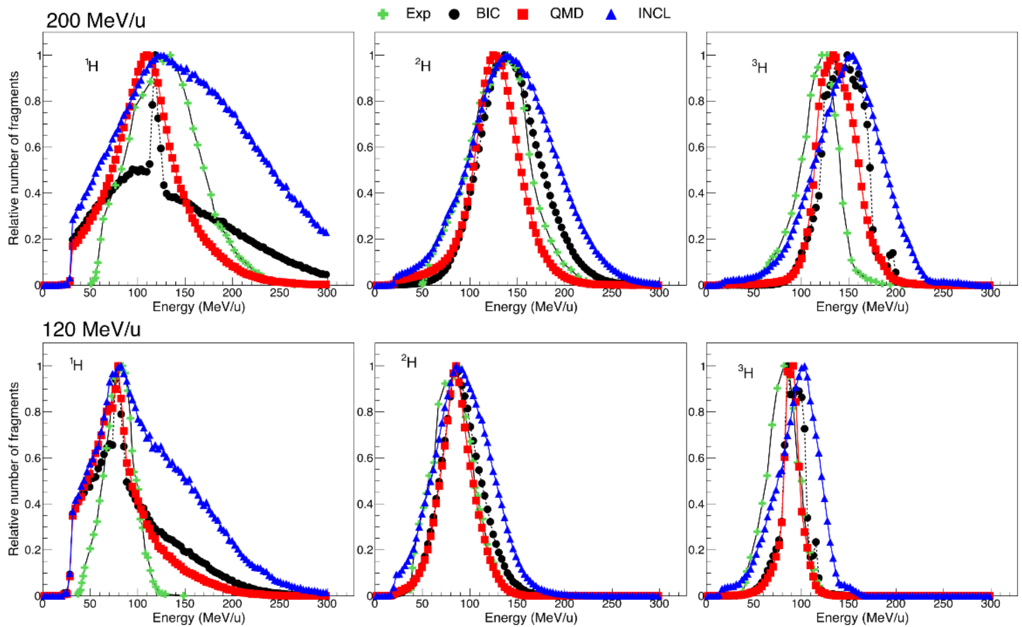
- Arico measurements are taken with an angle of acceptance of 3.4 degrees, measurements don't include BP (308 mm)
- All models perform very similar, QMD slightly better
- Arico, does not distinguish isotopes
  - under and over-production of certain isotopes are average out
- Due to small angle of acceptance (where models reproduce fragment direction the worst), simulation significantly under produces fragment yields ~20-40%



Energy distributions

- Energy distributions are compared in terms of maximum difference of cumulative distributions
- Rovituso (target = 1/2 beam range)
  - Comparing only 6x distributions
  - QMD reproduces distributions best
  - INCL the worst

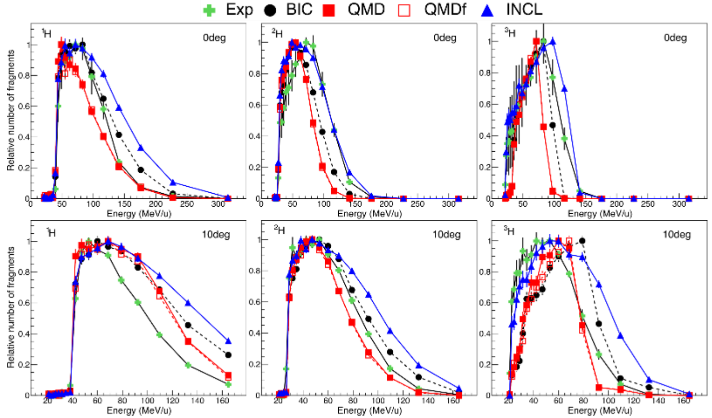


Target thickness ~ 1/2 range of beam
Angle = 6 deg

Data	Peak (MeV)	Max diff ^{1}H	Peak (MeV)	Max diff ^{2}H	Peak (MeV)	Max diff ^{3}H
200 MeV/u						
Exp	134.2	-	139.3	-	121.7	-
BIC	118.5	0.14	136.5	0.19	148.5	0.51
QMD	109.5	0.23	124.5	0.10	133.5	0.39
INCL	121.5	0.26	139.5	0.26	154.5	0.52
120 MeV/u						
Exp	84.0	-	86.4	-	81.8	-
BIC	79.5	0.29	85.5	0.14	85.5	0.31
QMD	79.5	0.18	85.5	0.11	91.5	0.32
INCL	82.5	0.45	85.5	0.19	103.5	0.34

Energy distributions

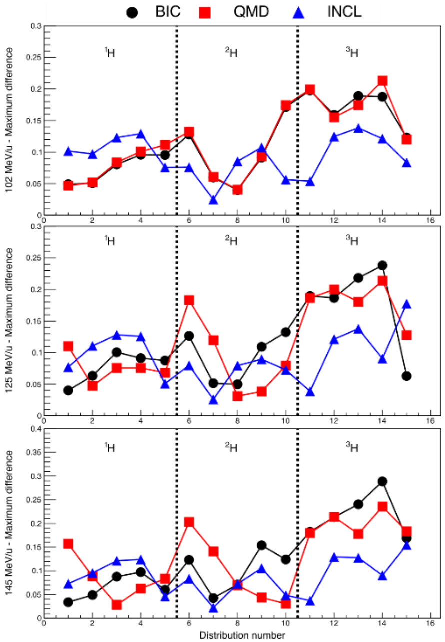
- Energy distributions are compared in terms of maximum difference of cumulative distributions
- Rovituso (target = 1/2 beam range)
  - Comparing only 6x distributions
  - QMD reproduces distributions best
  - INCL the worst
- Marafini (target = beam range)
  - Comparing 15x distributions
  - INCL reproduces ^{3}H distributions the best
  - ^{1}H BIC/QMD best
  - ^{2}H INCL for forward angles the best, QMD for larger angles



102 MeV/u

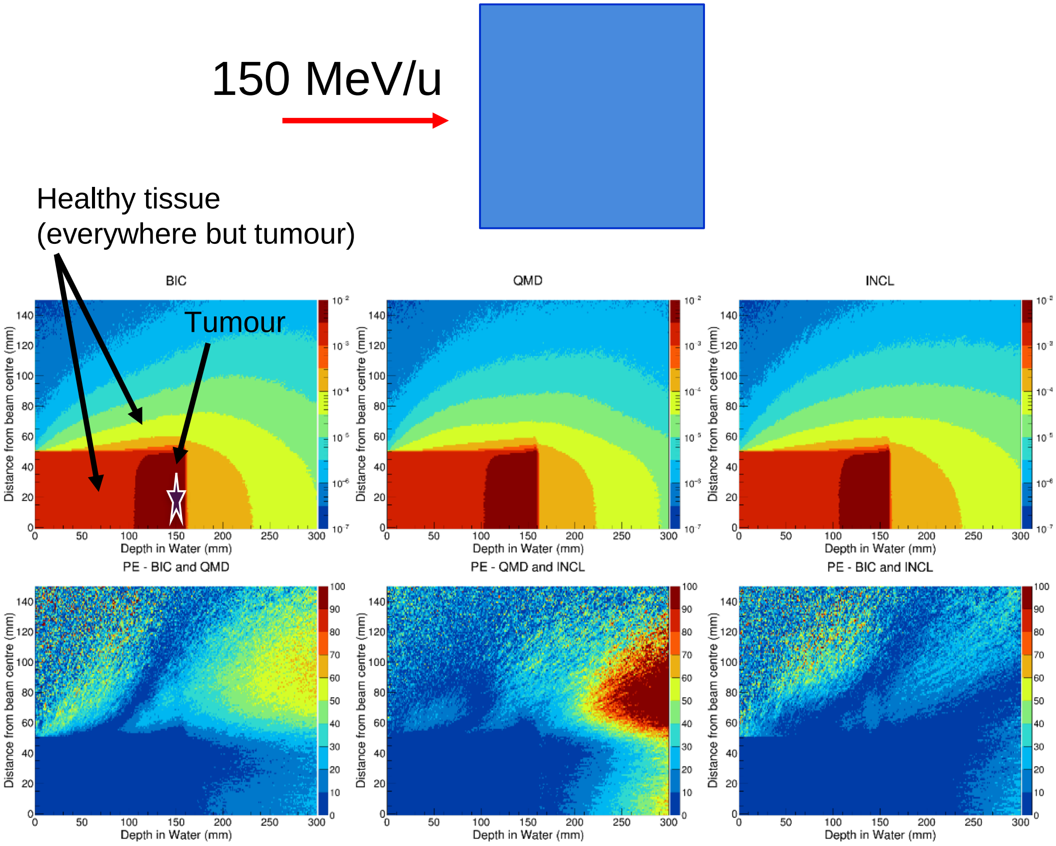
125 MeV/u

145 MeV/u



Impact of model differences on dose

- 10x10 cm^2 square helium beams with 150 MeV/u energy were incident upon a 30 cm water cube
- Largest differences are seen laterally downstream of the beam
- QMD and INCL have the largest differences of up to ~100%
- BIC and INCL have the smallest differences



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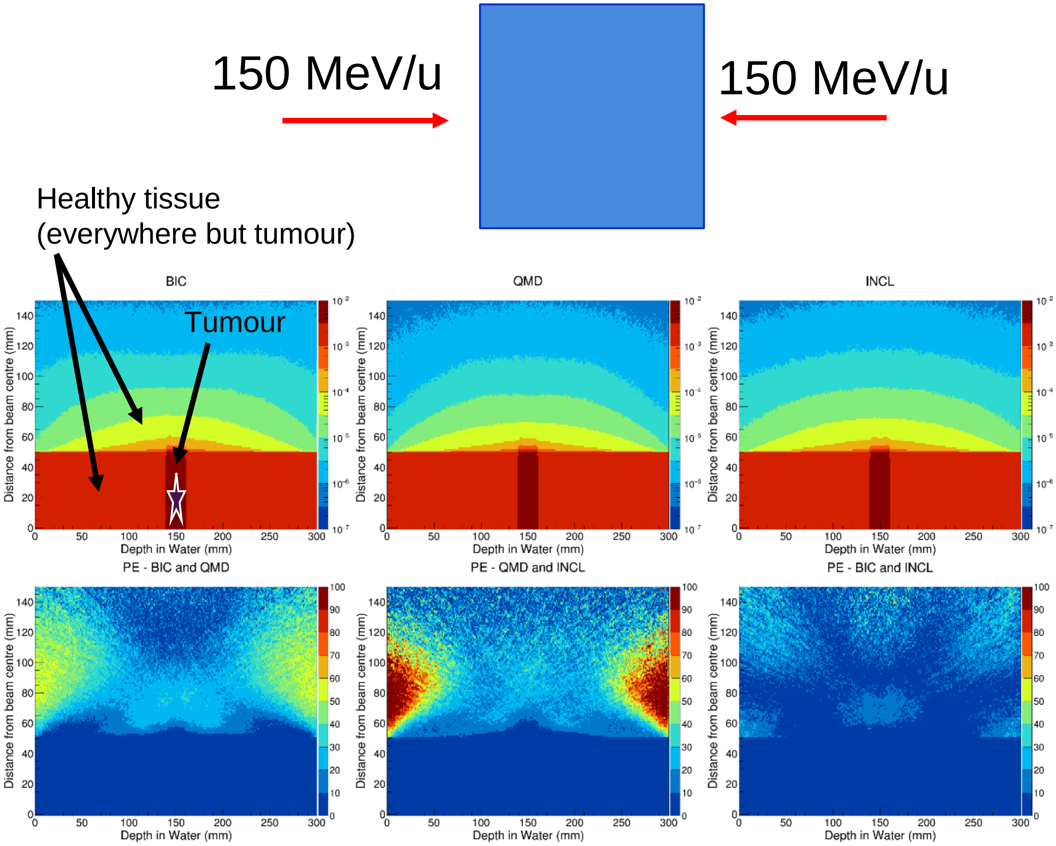
- Comparing more realistic therapeutic setup of two opposing beams
  - Forward angles don't matter as much
  - Differences are similar
  - Regions where dose is most different (away from incident beam) are of interest for calculating dose to healthy tissue to optimise plan and estimate risk of secondary cancer for healthy tissue
- Models typically only differ by <20% between themselves compared to with experiment where usually >20%
  - Differences between experiment and simulation out-of-field doses would then be expected to be even more significant



Summary

- Angular distributions
  - All three models evaluated in Geant4 give very poor agreement with experiment, simulation has large deficiency of forward fragments
  - ^{1}H at 0deg
    - half thickness target : 50% under for 120 MeV/u, 300% for 200 MeV/u
    - target thickness equal to beam range 1000% at 145 MeV/u
  - Improvements to models desirable!

- Fragment yields
  - Must be very careful when comparing fragment yields
    - QMD gives best agreement (when distinguishing isotopes) but doesn't mean that they are being distributed the best
  - Comparisons should ideally include angular data when possible-yield may be good, but distribute them poorly, angle of acceptance
  - Without isotope information differences may be averaged out and skew

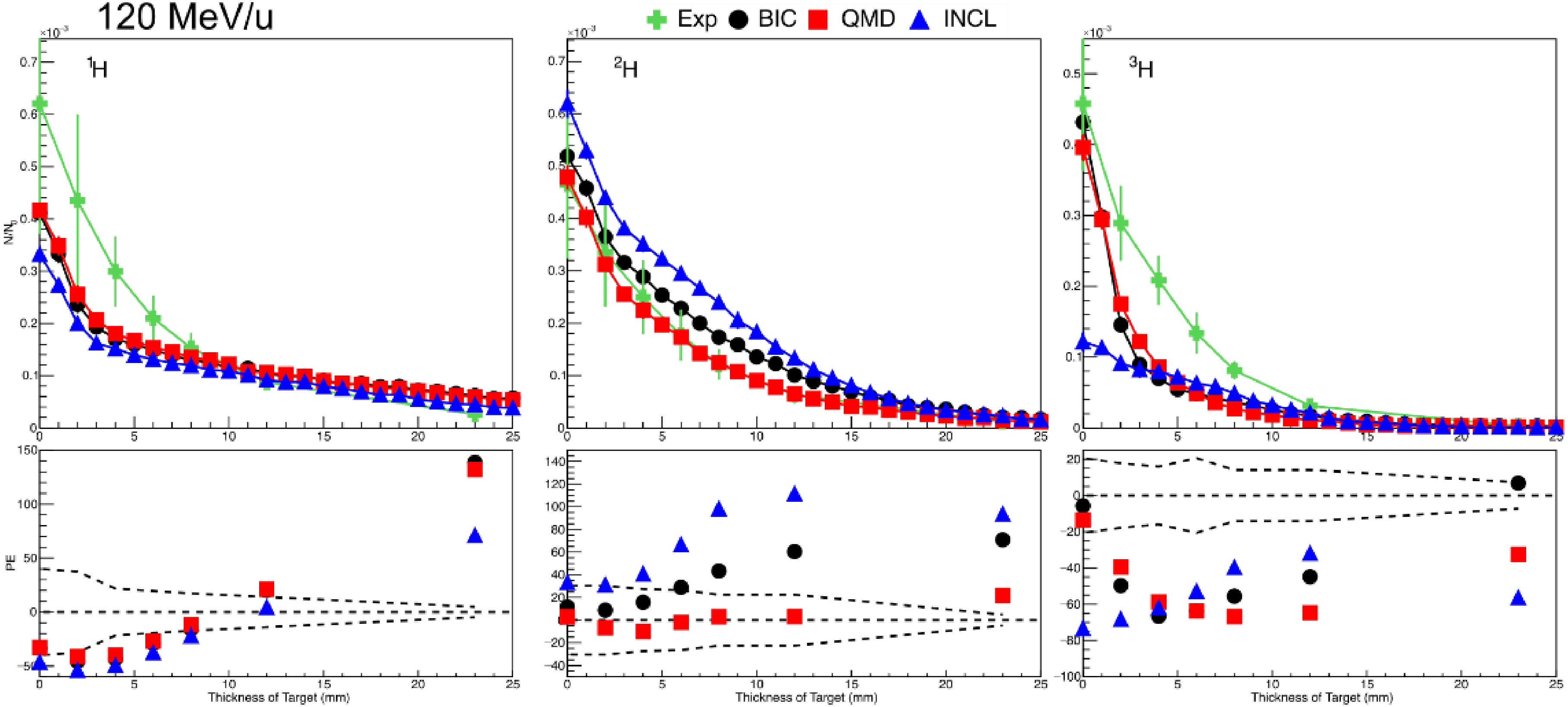
- Energy distributions
  - QMD slightly better overall due to ^{1}H and ^{2}H agreement

- Out of field dose distributions (important for treatment planning and evaluating secondary cancer risk) produced by models differ up to ~100% among the models alone
  - Models typically only differ by ~20% in terms of angular fragment distributions, models differ with experiment much more in general!

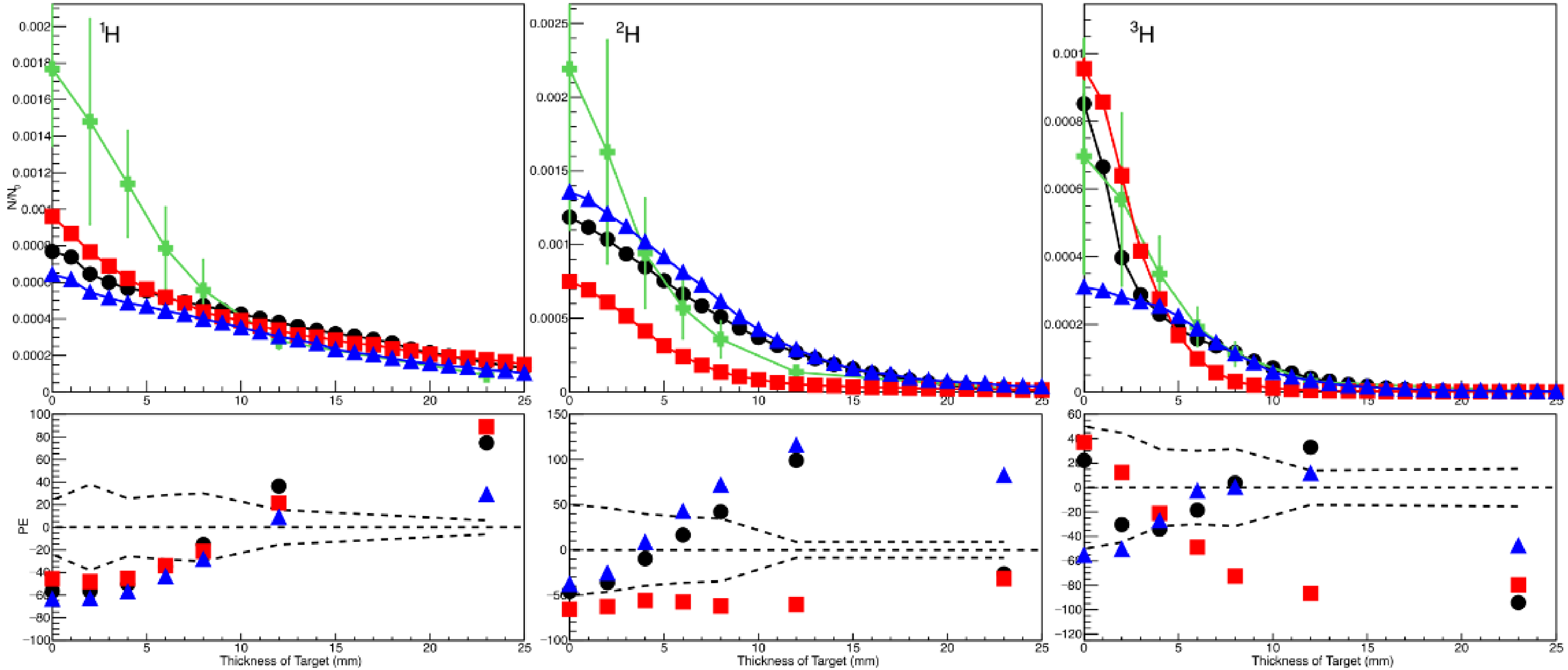
Questions/comments?

Extra slides (larger plots)

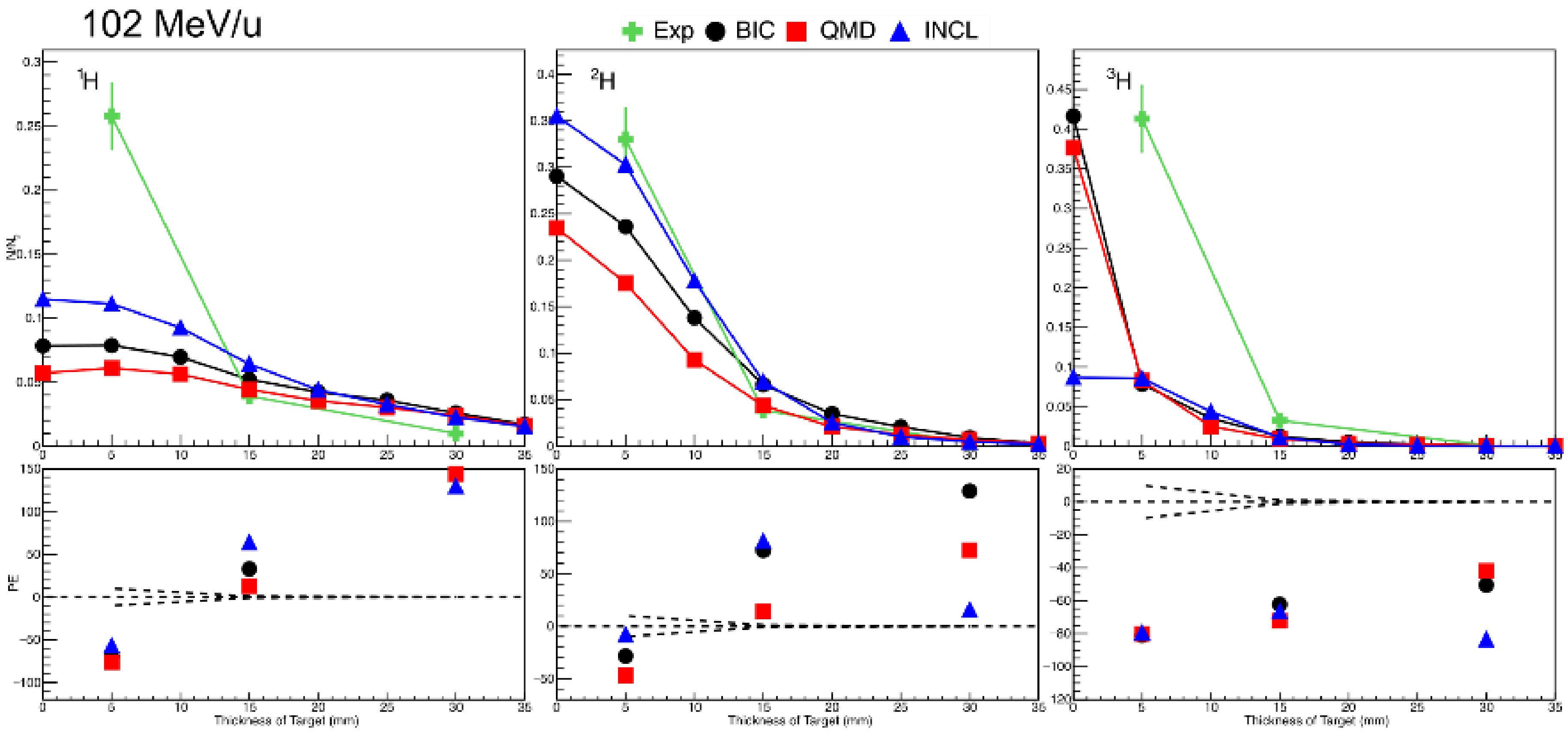
120 MeV/u



200 MeV/u

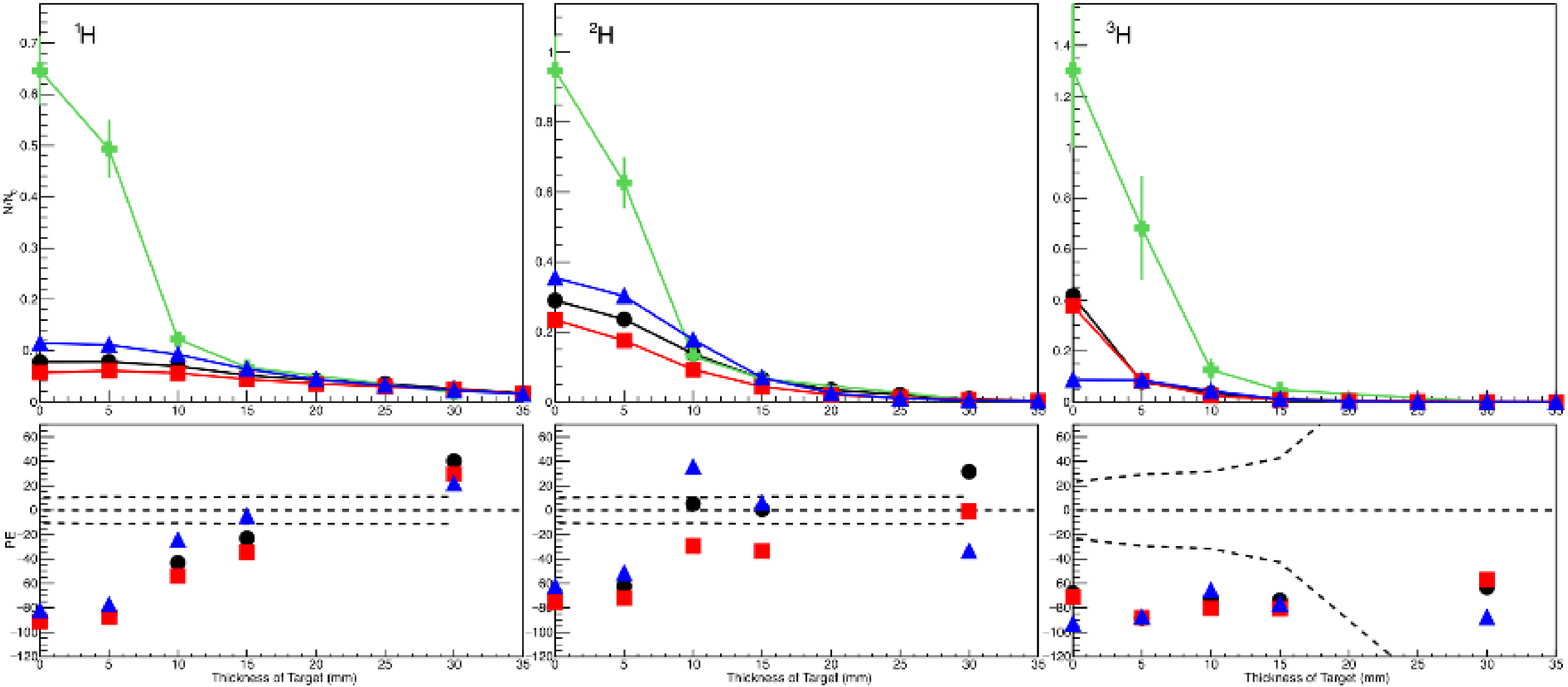


^{1}H
^{2}H
^{3}H
N/N$_0$
PE
Thickness of Target (mm)
Thickness of Target (mm)
Thickness of Target (mm)



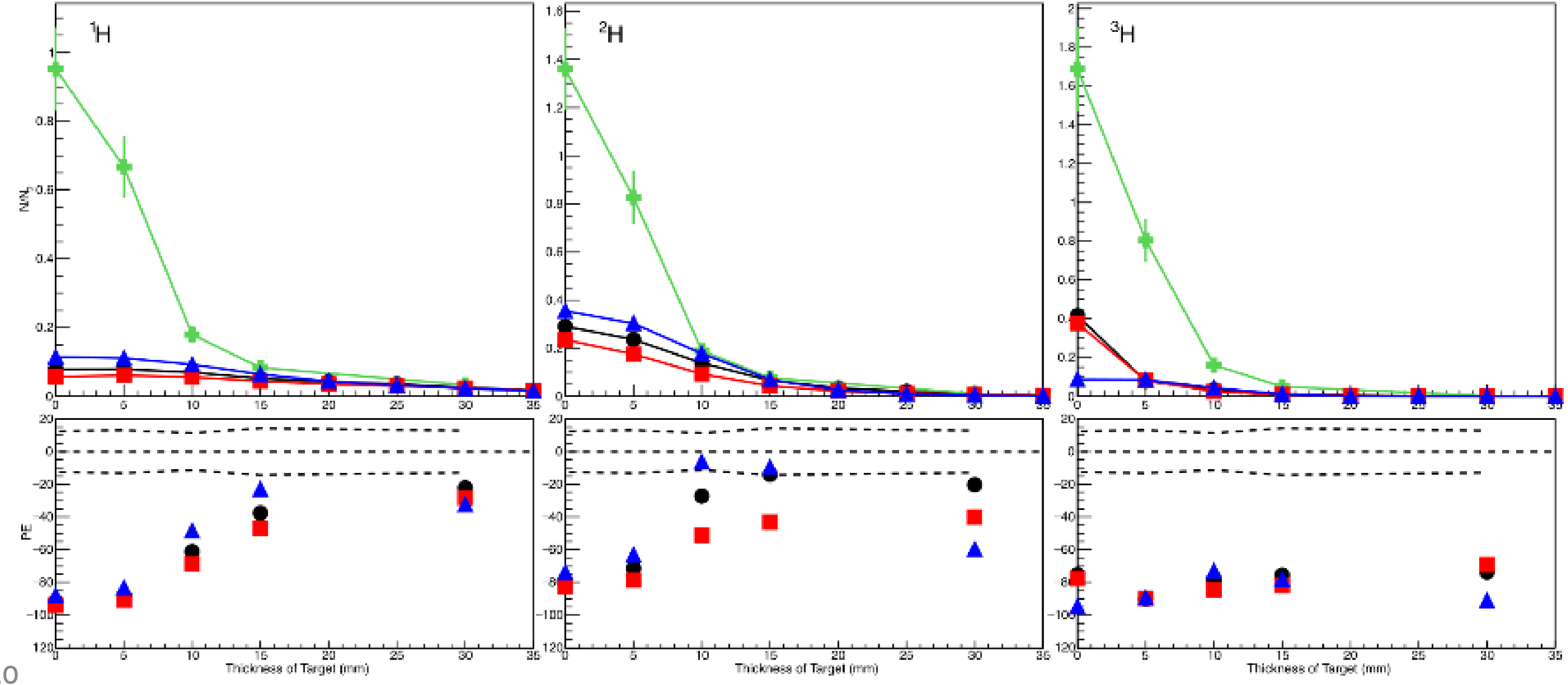
102 MeV/u
Exp
BIC
QMD
INCL
^{1}H
^{2}H
^{3}H
N/N$_0$
PE
Thickness of Target (mm)
Thickness of Target (mm)
Thickness of Target (mm)

125 MeV/u

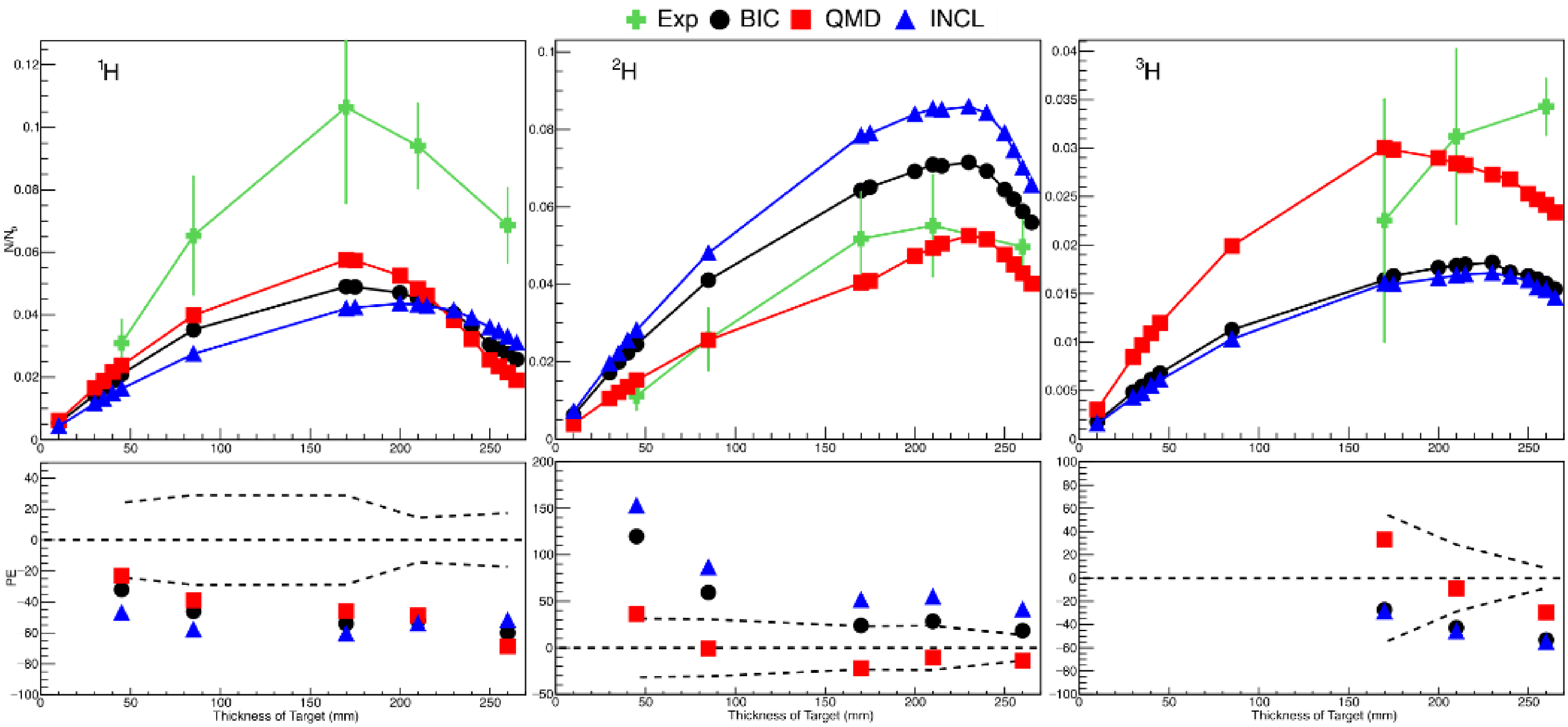


^{1}H
^{2}H
^{3}H
N/N$_0$
PE
Thickness of Target (mm)
Thickness of Target (mm)
Thickness of Target (mm)

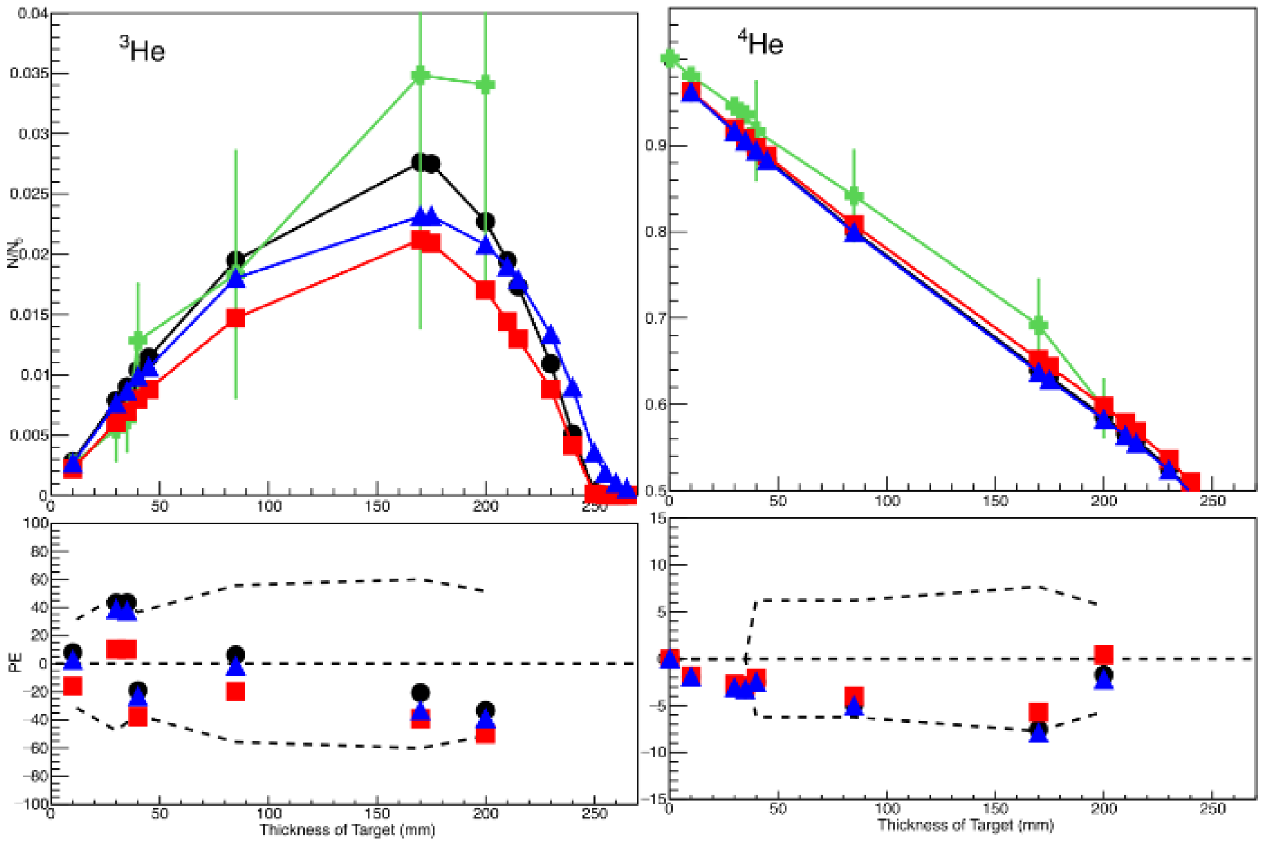
145 MeV/u

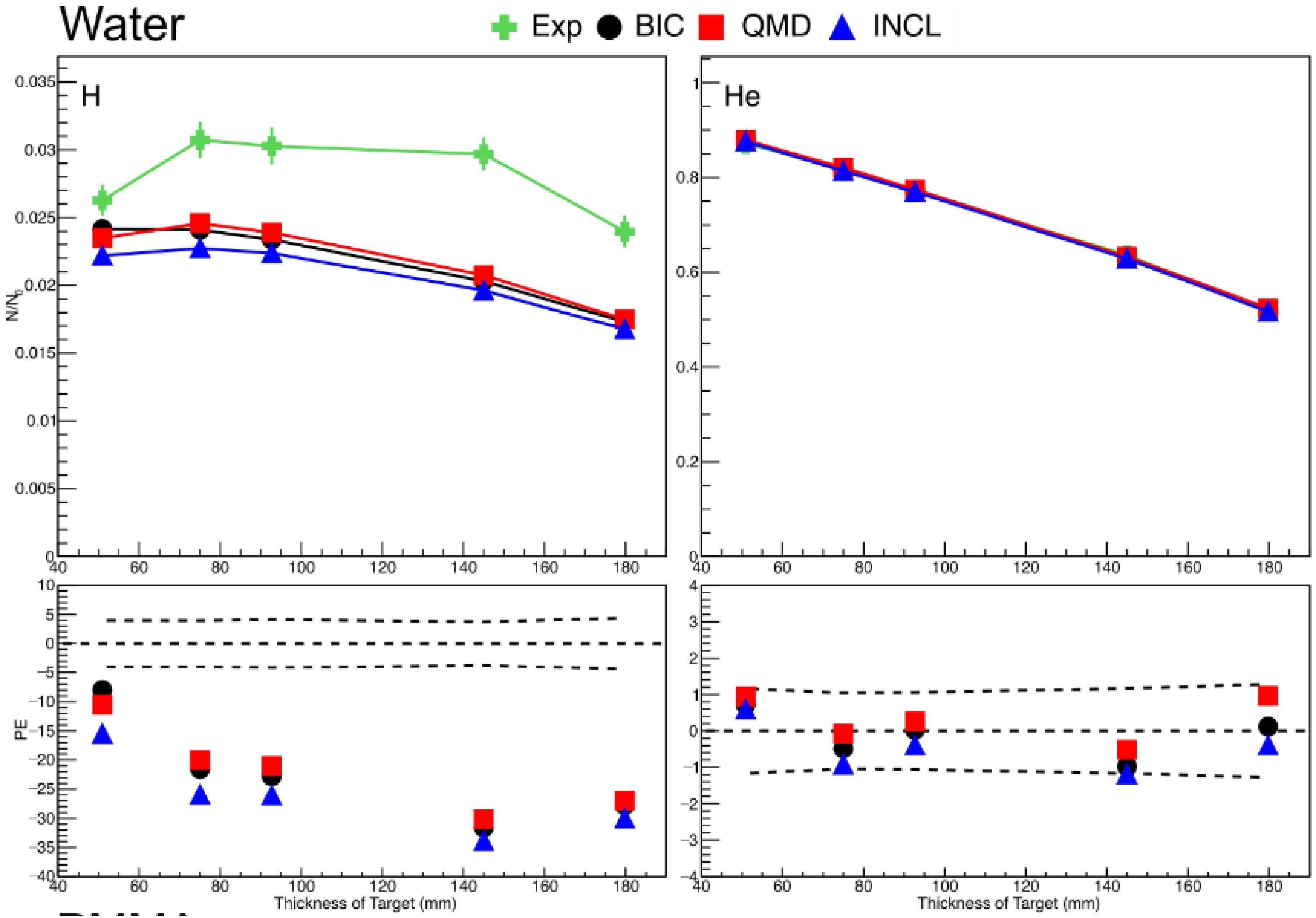


^{1}H
^{2}H
^{3}H
N/N$_0$
PE
Thickness of Target (mm)
Thickness of Target (mm)
Thickness of Target (mm)



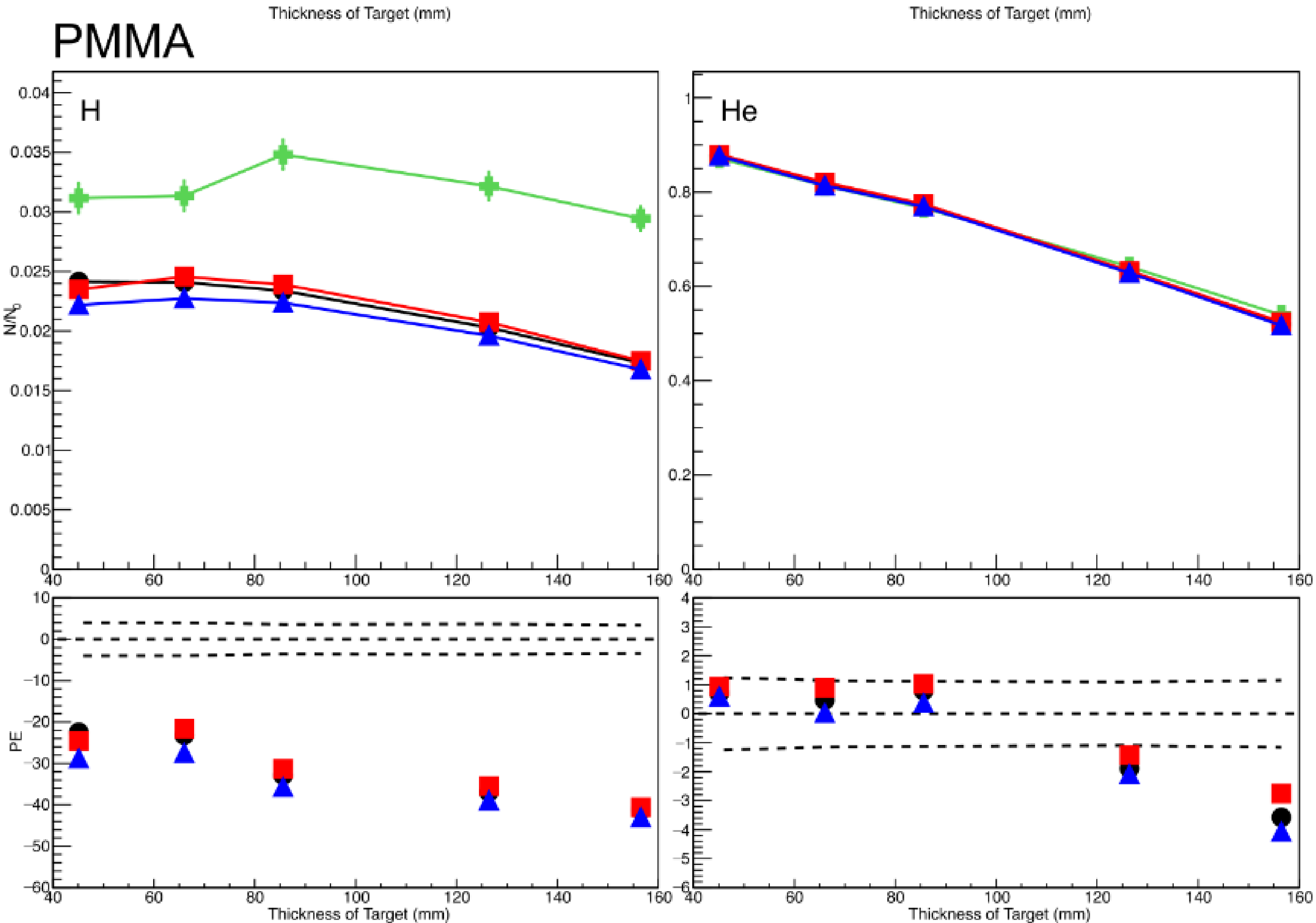
Exp BIC QMD INCL
^{1}H
^{2}H
^{3}H
N/N_0
PE
Thickness of Target (mm)
Thickness of Target (mm)
Thickness of Target (mm)


^{3}He
^{4}He
N/N$_0$
PE
Thickness of Target (mm)
Thickness of Target (mm)



Water
Exp
BIC
QMD
INCL
H
He
N/N0
PE
Thickness of Target (mm)
Thickness of Target (mm)

PMMA


Thickness of Target (mm)
Thickness of Target (mm)
H
He
N/N0
PE
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
1
0.8
0.6
0.4
0.2
0
10
0
−10
−20
−30
−40
−50
−60
4
3
2
1
0
−1
−2
−3
−4
−5
−6
40
60
80
100
120
140
160
Thickness of Target (mm)
Thickness of Target (mm)