How precise can Geant4 be for protontherapy, without G4QGSP_BIC_HP

P. Arce[1], A. Viñals[2], J.D. Azcona[2]

(1) Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

(2) Clínica Universidad de Navarra

Index

- Monte Carlo vs. Treatment Planning System precision
- To simulate or not to simulate nozzle?
- Position-direction distribution for each beam energy (Transversal profiles in air)
- Energy distribution for each beam energy (Integrated Depth Dose profiles)
- Transversal profiles in water: check Geant4 scattering and position-direction distribution
- Absolute dose
- More complex checks
  - SOBP in water
  - SOBP different materials
  - SOBP oblique
  - SOBP with peculiar shapes
  - patients

Index

- To simulate or not to simulate nozzle?
- Position-direction distribution for each beam energy (Transversal profiles in air)
- Energy distribution for each beam energy (Integrated Depth Dose profiles)
- Transversal profiles in water: check Geant4 scattering and position-direction distribution
- Absolute dose
- More complex checks
  - SOBP in water
  - SOBP different materials
  - SOBP oblique
  - Fields of peculiar shapes
  - Patients

Geant4 vs TPS simulation

- In protontherapy Monte Carlo commissioning it is common that fit to experimental data reaches **a few mm and a few % precision**
- But today Treatment Planning systems are improving
  - They use what they call Monte Carlo simulation
  - Can also reach **a few mm and a few % precision**
- **Geant4 simulation precision should improve if it wants to be an alternative to TPS "Monte Carlo" simulation**

Fast Monte Carlo (RayStation MC)

➢ Based on the Monte Carlo technique of propagating particles in matter

Energy Loss:

❖ Energy loss and straggling is computed **on density and voxel specific material composition**

- **Bethe-Bloch formula** to calculate absolute energy loss
- Discretized energy spectra with adaptive energy bin sizes, which provide an **accurate, within 0.2 mm, estimation of the range** as predicted by the continuous slowing down approximation (CSDA)

Multiple scattering:

❖ Elastic multiple and plural scattering is included through the **Goudsmit-Saunderson theory**

  ❖ Based on voxel specific elemental compositions

❖ Elastic proton-hydrogen scattering and inelastic nuclear reactions leading to secondary protons, deuterons, tritons and alphas particles are **modelled based on voxel specific elemental compositions**

Fast Monte Carlo (RayStation MC)

GAMOS

Secondary particle transport:

- **Secondary protons** are transported **like primary protons**
- **Heavier secondaries** are transported taking **only energy loss** into account
- Neutral reaction products (**neutrons and gammas) are not transported**, but given fractions of the absorbed energy are considered
- **Delta electrons are not considered**

Optimizes the beam model based on measured IDDs

To simulate or not to simulate nozzle?

There are two common ways to simulate a protontherapy treament:

1. With phase space files after nozzle (one for each beam energy)
   a) Fit position-direction distribution before nozzle
   b) For the optimised distribution store phase space file after nozzle with protons (and other particles)
   c) Read back phase space files to simulate the patient dose

2. With proton energy distribution after nozzle (one for each beam energy)
   a) Fit position-direction distribution after nozzle
   b) Simulate nozzle and get the energy distribution of protons after it
      - Fit the beam energy + energy sigma
   c) Simulate beam after nozzle with energy distribution after nozzle and fitted position-direction distribution

Do not simulate nozzle

- We opted for option 2
  - ✓ Much easier to simulate postion-direction distribution after nozzle (only in air)
  - ✓ Faster simulate only protons with a given energy distribution than reading phase space files
  - ✓ Avoid huge disk space needs to store phase space files

But we have then to guarantee two things:

1. **Contributions of ther particles than protons after nozzle are negligible:**

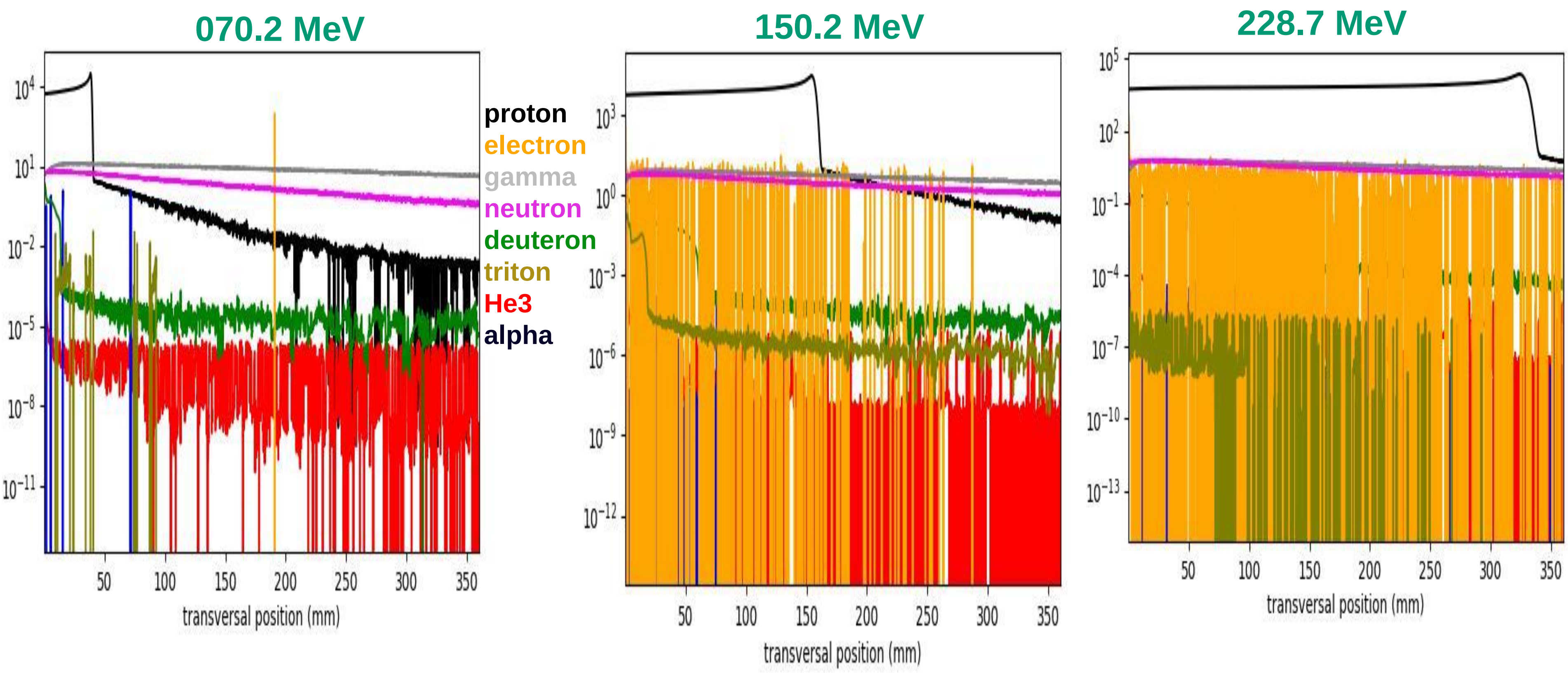
NPARTICLES	70.2	150.2	228.7
proton	1	1	1
e-	0.030606	0.0242768	0.0236784
gamma	0.000431289	0.000301094	0.000280263
neutron	0.00021727	0.000222505	0.000256866
deuteron	8.50657e-05	8.14682e-05	7.06914e-05
triton	4.06365e-06	6.63259e-06	6.75635e-06
He3	8.66912e-06	1.1388e-05	1.01345e-05
alpha	3.98238e-05	4.41755e-05	4.12888e-05

N particles after nozzle

Do not simulate nozzle

1. **Contributions of ther particles than protons after nozzle are negligible:**

Dose from each particle type reading phase space files

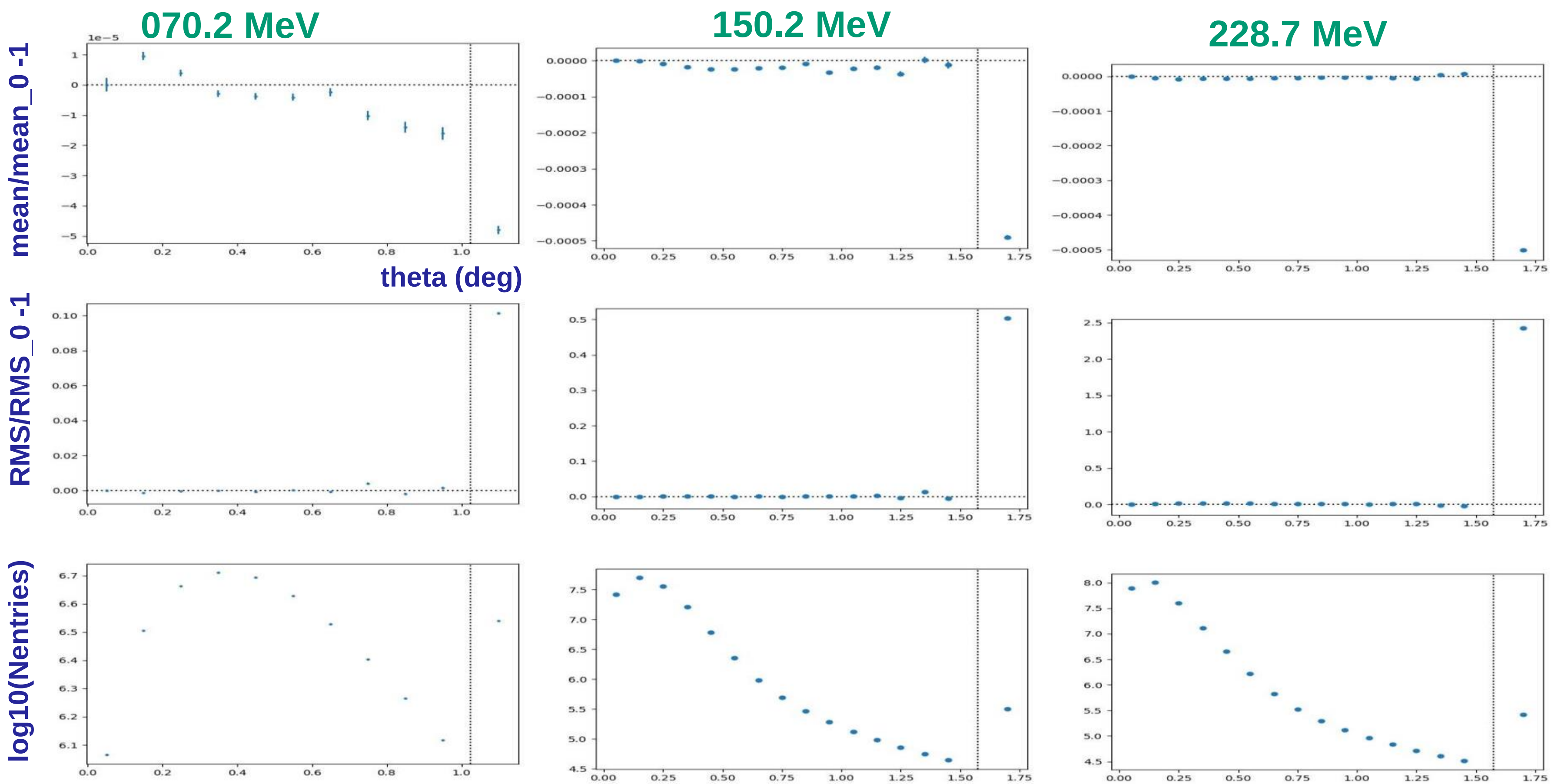


Do not simulate nozzle

2. Angle and position dependence with energy is negligible:

- Simulate nozzle with approximate position/direction distribution and get the dependency of proton energy with the position and direction angle

Mean and RMS of direction theta distribution after nozzle

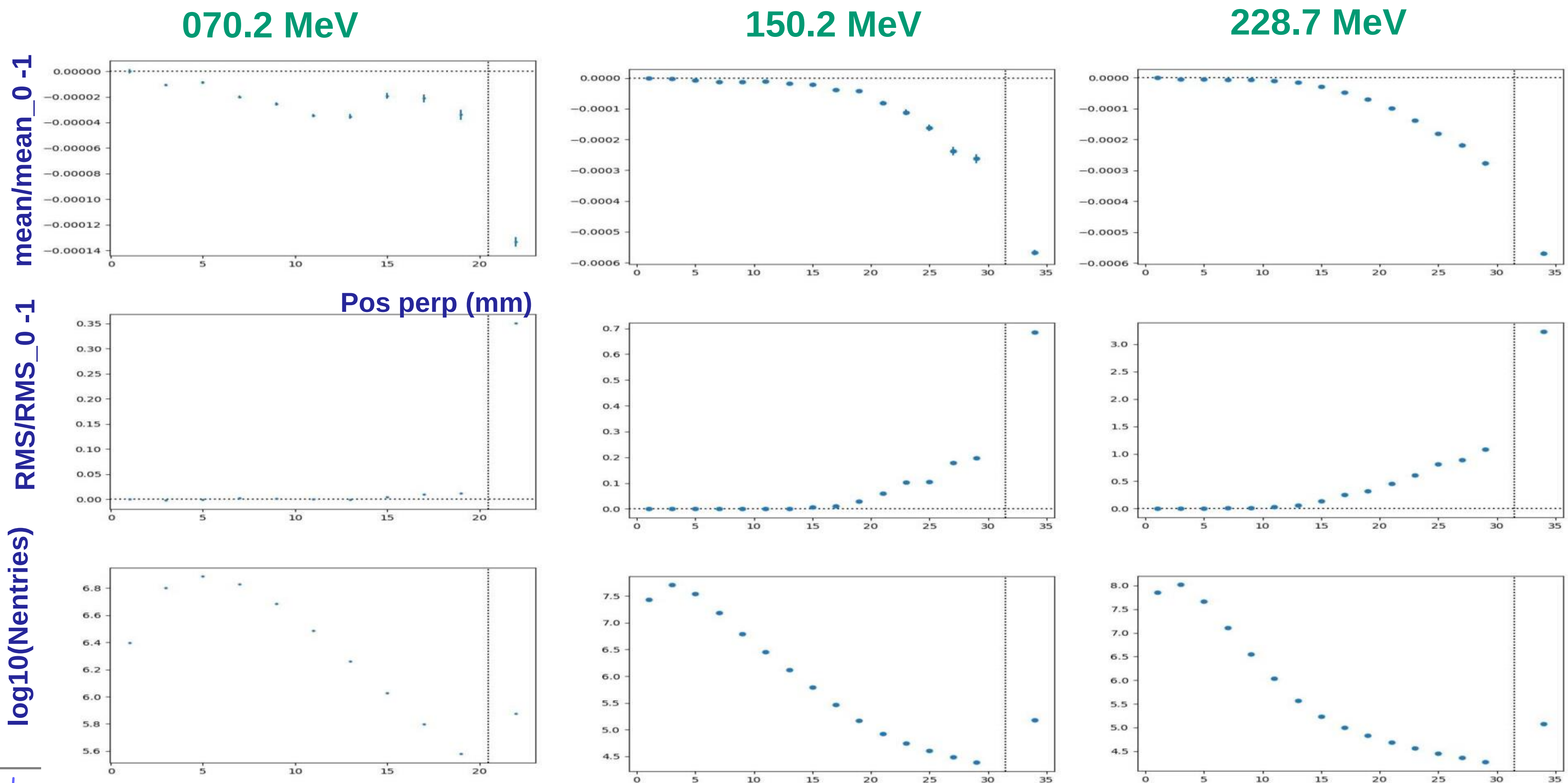


Do not simulate nozzle

2. Angle and position dependence with energy is negligible:

- **Simulate nozzle with approximate position/direction distribution and get the dependency of proton energy with the position and direction angle**

Mean and RMS of perpendicular postion sqrt(x*x+y*y) distribution after nozzle



Position-direction: Transversal profiles in air

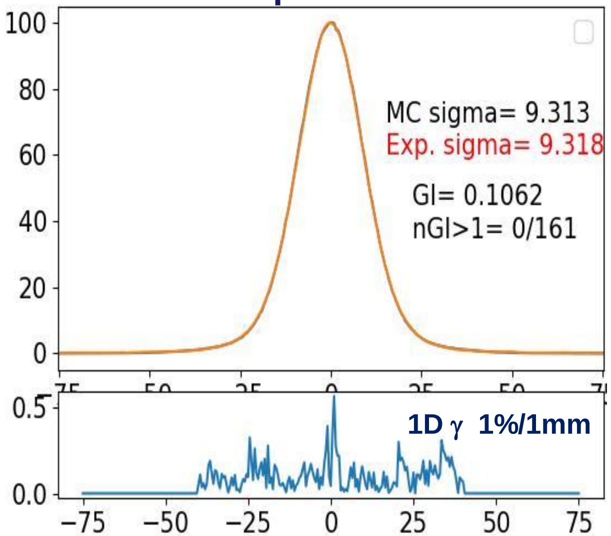
- Hitachi provides Twiss parameters to describe transverse profiles
  - ☹ They only give an approximate distribution

- We have simulated transversal profiles using the initial Twiss parameters to define a **double 2D Gaussian with position-angle and 1st Gaussian-2nd Gaussian correlation, plus XY phase rotation**

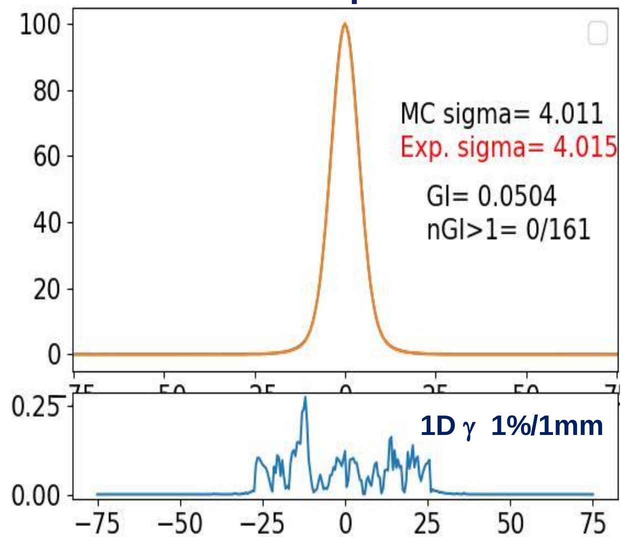
- We have defined an **automatic method to adjust the 16 parameters** with a few iterations
  - ✓ For each of the **98 energies**
  - ✓ Request **a difference in sigma $\lesssim$ 50 μm**
  - ✓ Request a **1D γ index 1%/1mm $\lesssim$ 0.25**

Transversal profiles in air

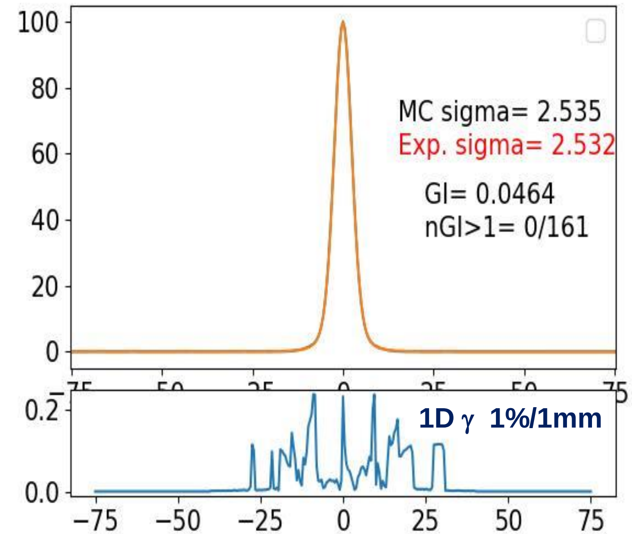
70.2 MeV X profile isoc+200mm



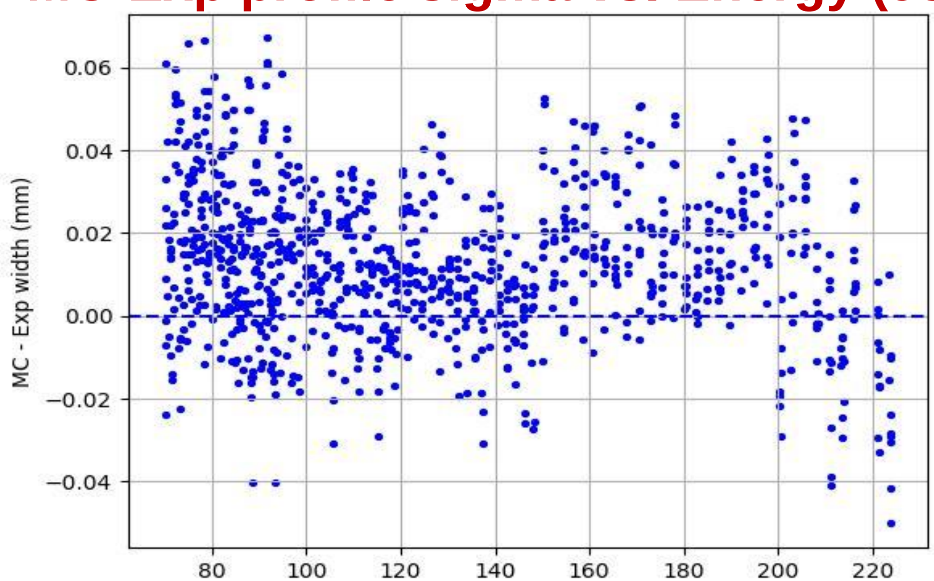
150.2 MeV Y profile isoc



228.7 MeV X profile isoc-200mm



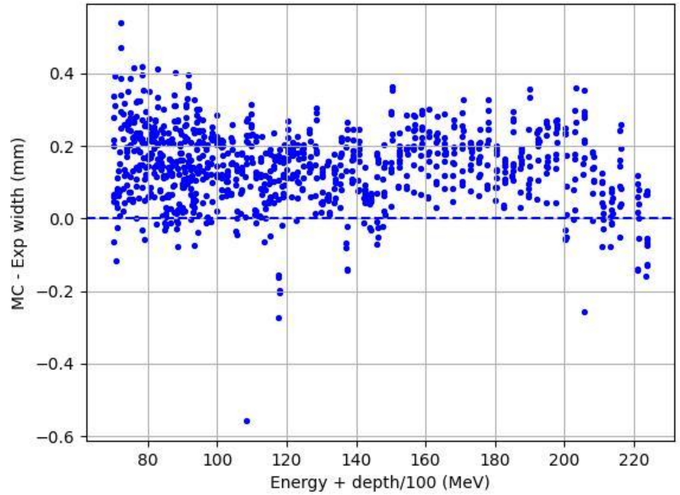
MC-Exp profile sigma vs. Energy (980 fits)



X -Y profile width difference ~ 0.1 mm

Transversal profiles in air

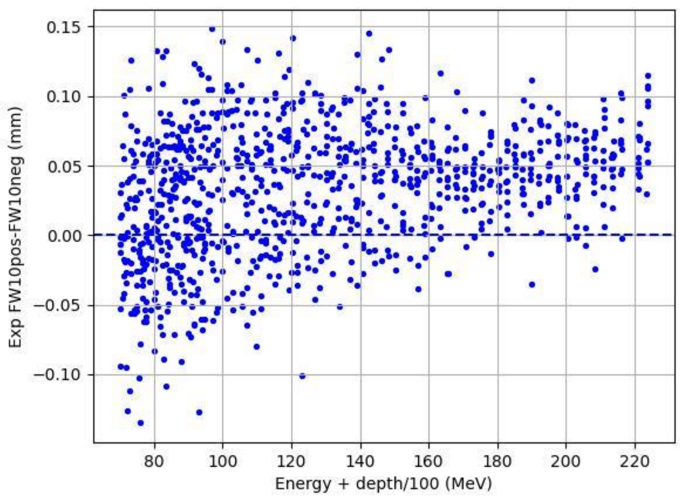
MC-Exp profile FW10 vs. Energy (980 fits)



Tails should be improved for some energies!

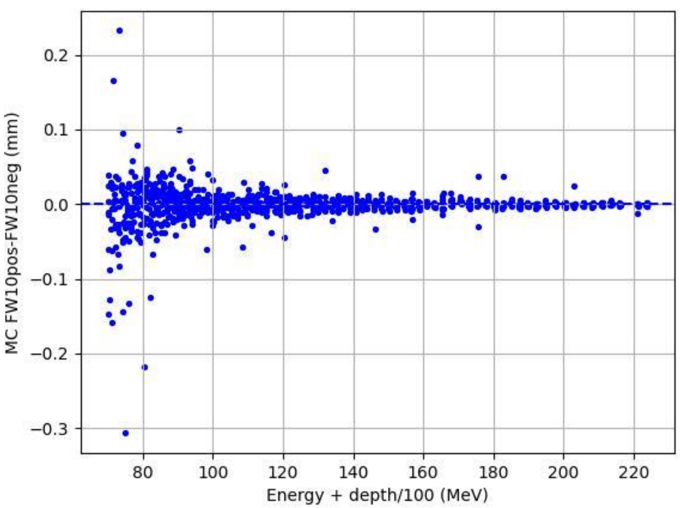
Compare 10% in positive and negative X:

- **Exper: 0.15*sqrt(2) can be due to measurement errors**



Compare 10% in positive and negative X:

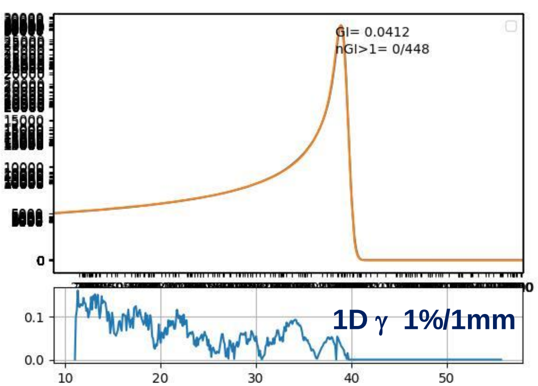
- **MC: 0.2*sqrt(2) can be due to MC statistics**



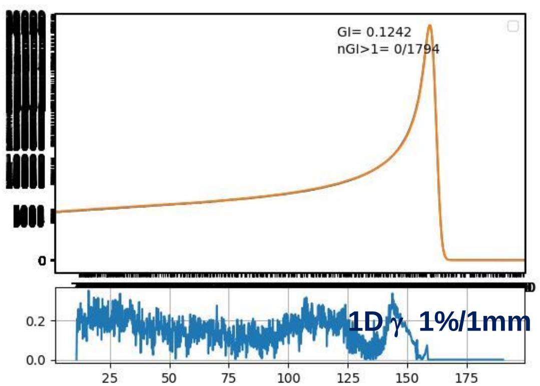
Energy+energy sigma: Integrated Depth Dose (IDD)

- We have adjusted the IDD range (R80) and width (at 80%) for the 98 energies
  - Optimize energy and energy sigma (%) to fit RANGE80, RANGE9010 (difference 90% and 10% after peak) and WIDTH80
  - Allow not best RANGE80 if average GI improves
- Optimal energies are slightly different than nominal ones (also for the Raystation TPS)

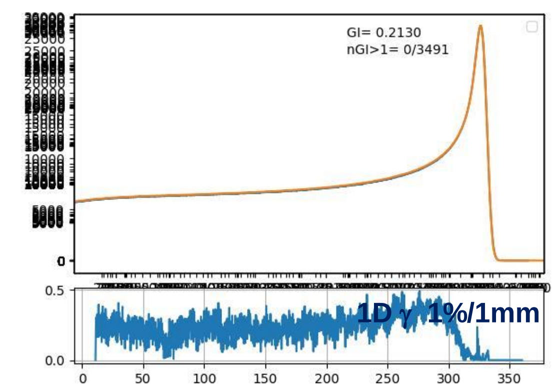
IDD 70.2 MeV E fit = 069.7 s=0.2)



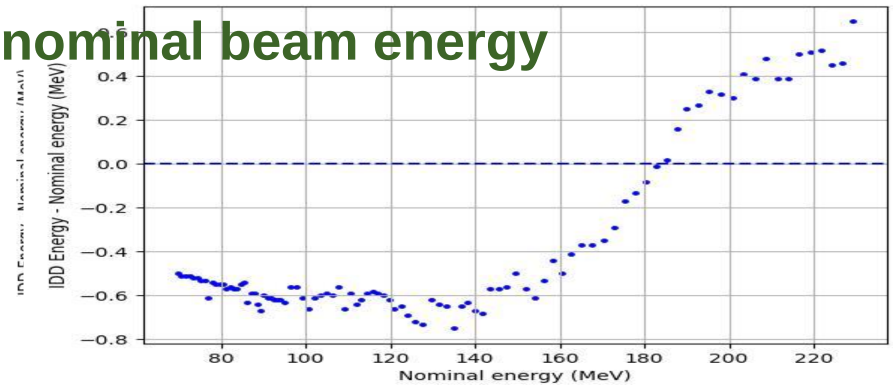
IDD 150.2 MeV E_fit = 149.7, s=0.0)



IDD 228.7 MeV E_fit = 229.35, s=0.0)

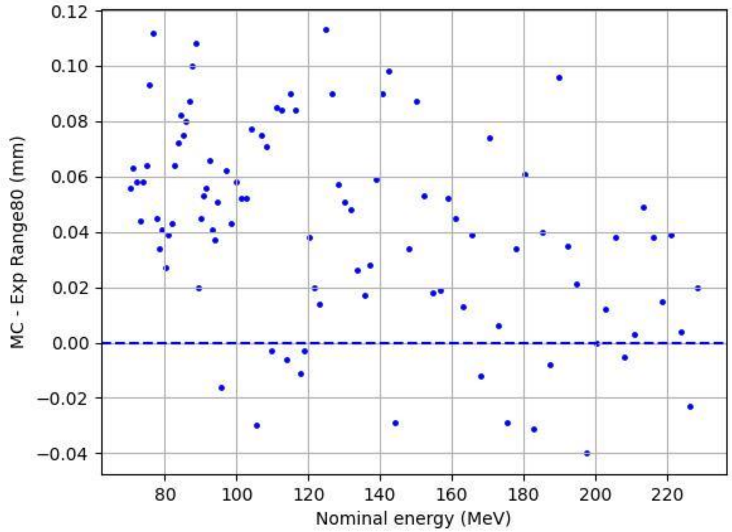


MC-nominal beam energy

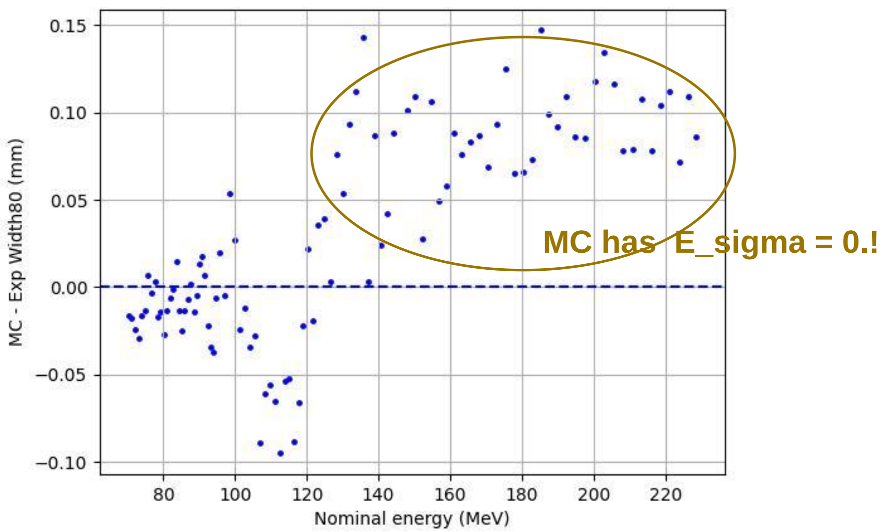


Integrated Depth Dose (IDD)

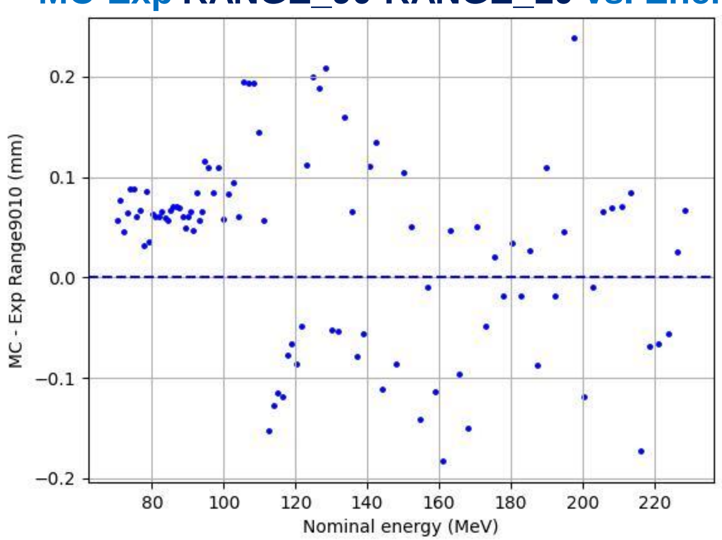
MC-Exp **RANGE_80** vs. Energy



MC-Exp **WIDTH_80** vs. Energy



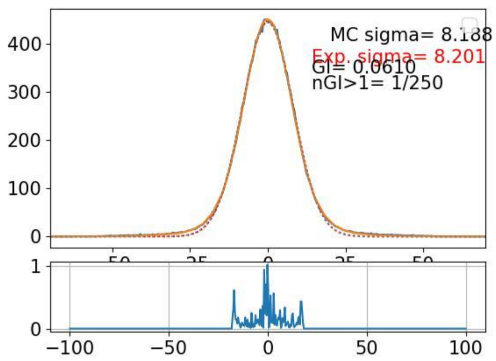
MC-Exp **RANGE_90-RANGE_10** vs. Energy



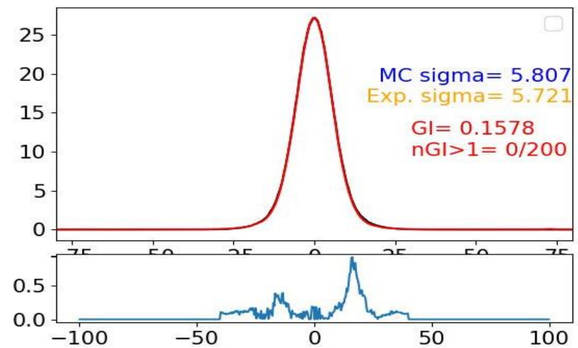
Transversal profiles in water

- Measurements of X and Y dose profiles in water for 3 beam energies at 3 dephts each

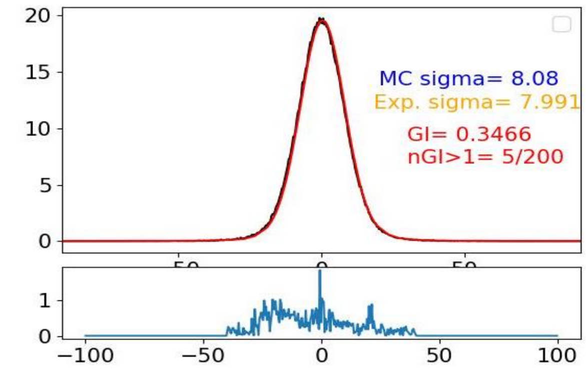
70.2 MeV X profile at 23.28 mm



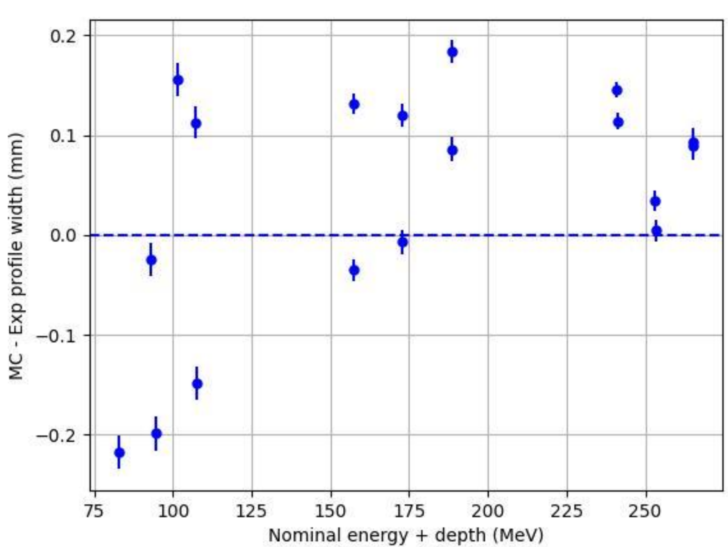
142.5 MeV Y profile at 140 mm



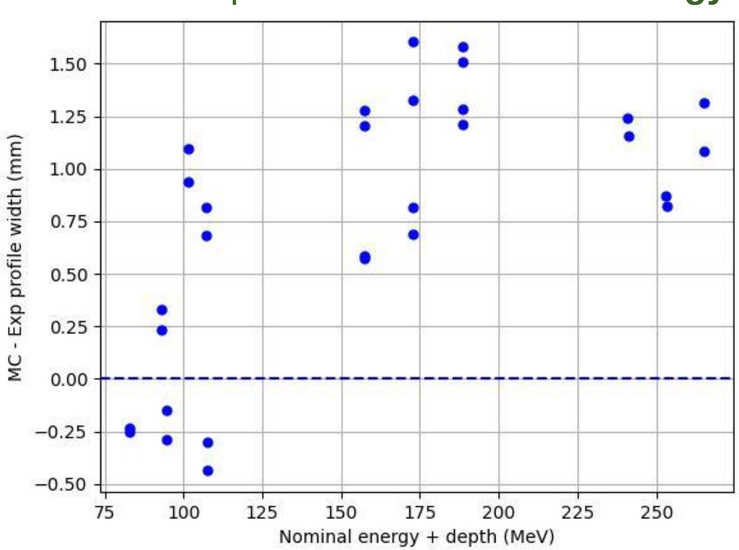
228.7 MeV X profile at 324 mm



MC-Exper. Profile: **sigma vs. Energy**



MC-Exper. Profile: **FW10 vs. Energy**

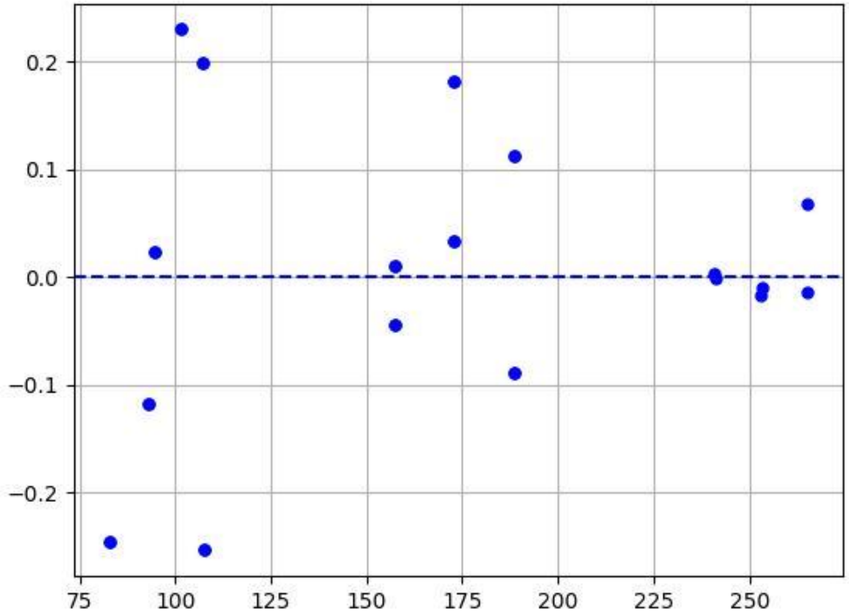


Transversal profiles in water: FW10

Diff FW10 >1. mm cannot be explained by errors in measurements or MC

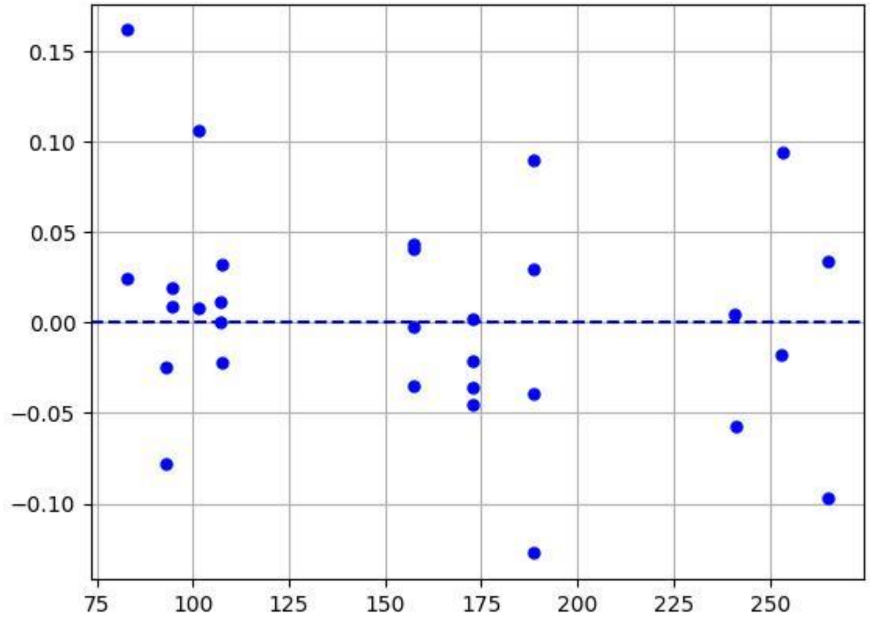
FW10: Compare 10% in positive and negative X:

- **Exper: 0.25 mm can be due to measurement errors**



FW10: Compare 10% in positive and negative X:

- **MC: 0.1 mm can be due to MC statistics**



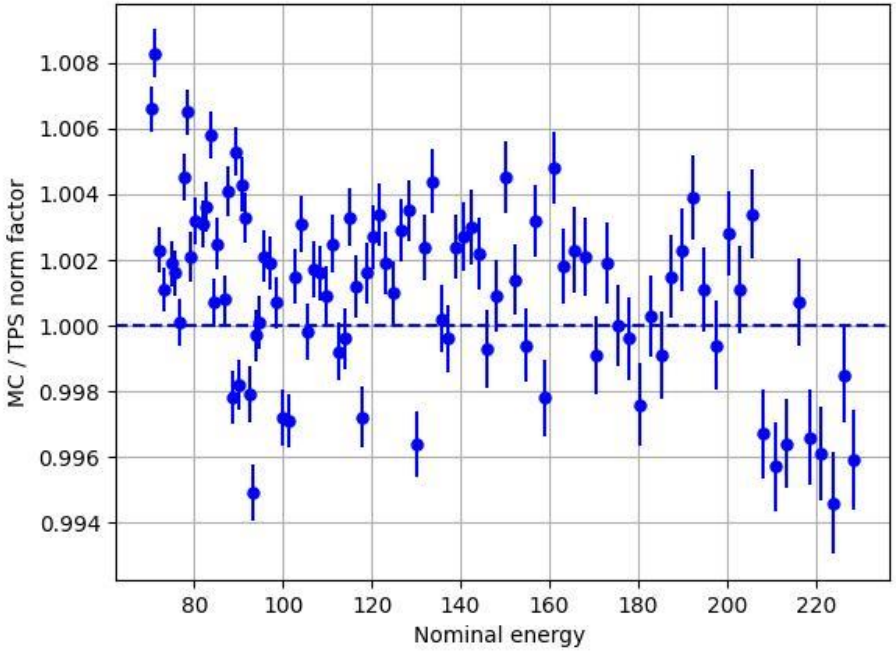
Tails should be improved (specially for high energies)!

Absolute dose

❖ For each energy, adjust number of events in MC to get dose in a point equal to measurement of an Advanced Markus chamber in water => number of protons per MU for each E

❖ Instead of using point where measurement is taken, correct it by differences in peak MC/Exper (as IDD's are adjusted at peak)

MC norm factor / TPS norm factor

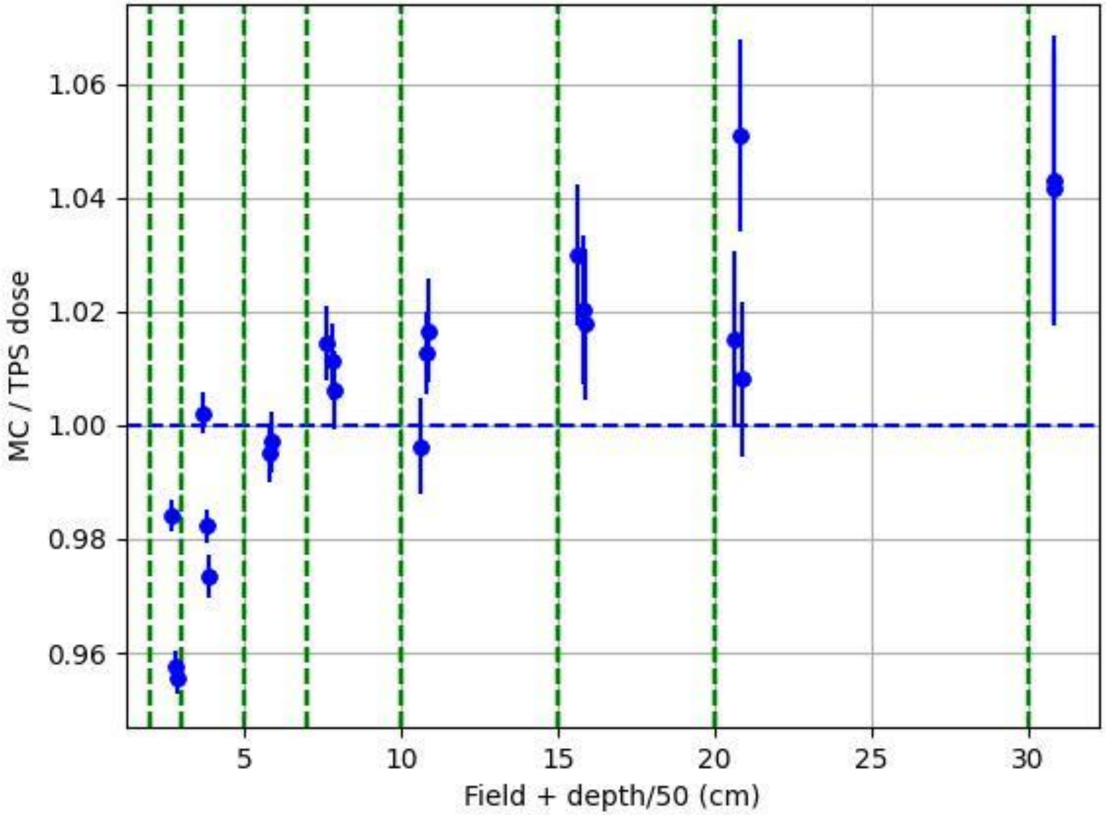


❖ Differences w.r.t. values provided by vendor: > 0.5-1.8%

SOBP measurements in water

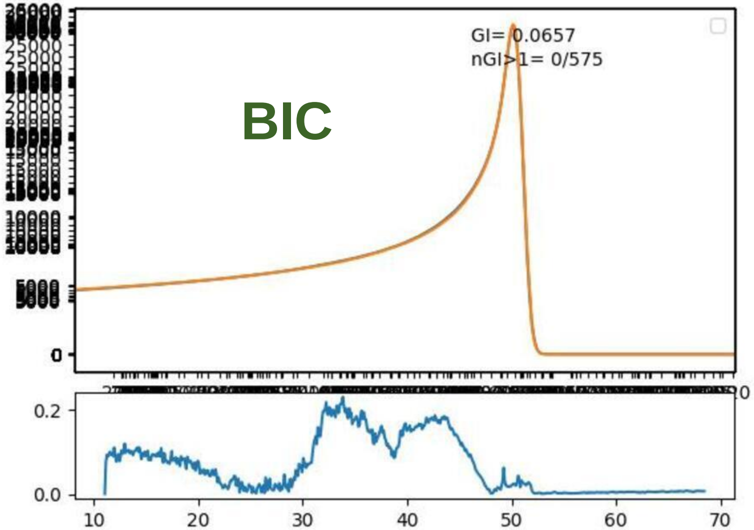
- SOBP for different fields (2x2 cm^2 to 30x30 cm^2)
- Compare GAMOS with dose measurements at some points along the central line

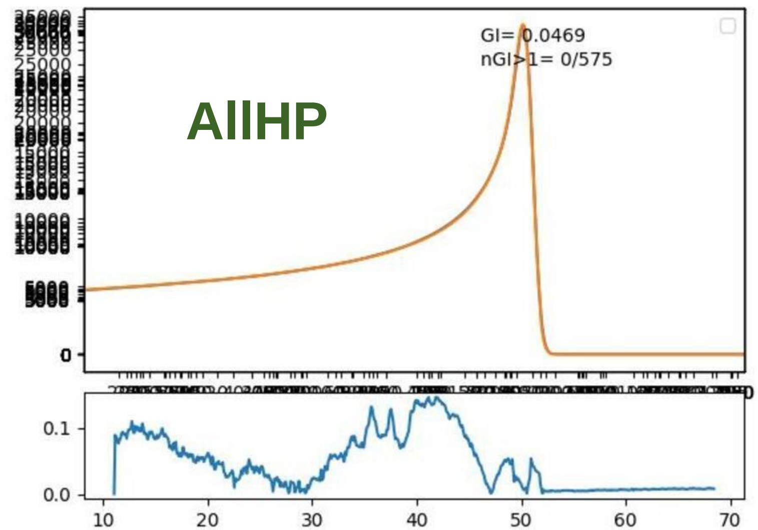
MC / Exper. dose at SOBP point vs field width

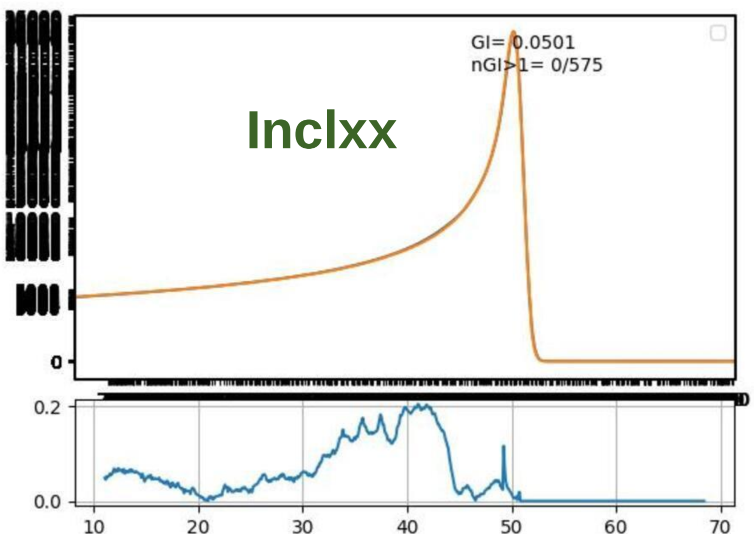


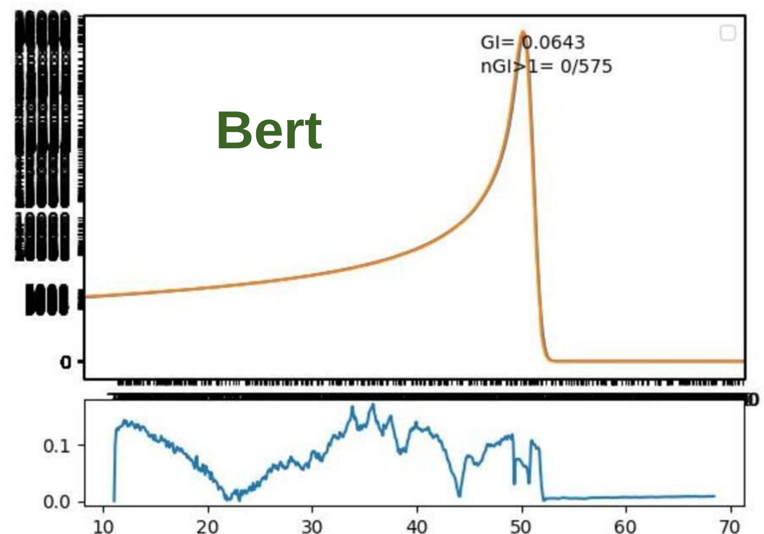
Best physics list: is it QGSP_BIC_HP?

79.6 MeV



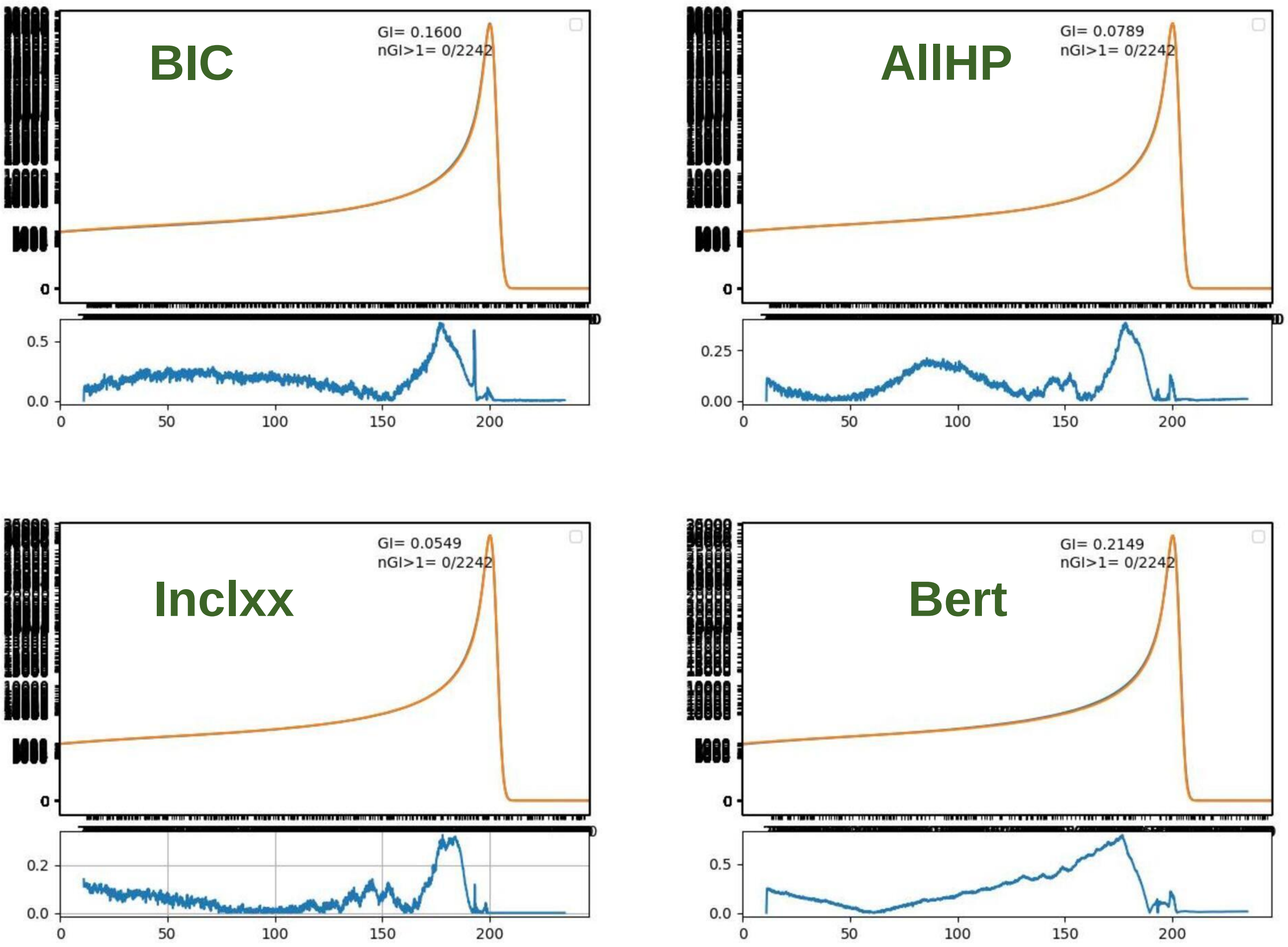






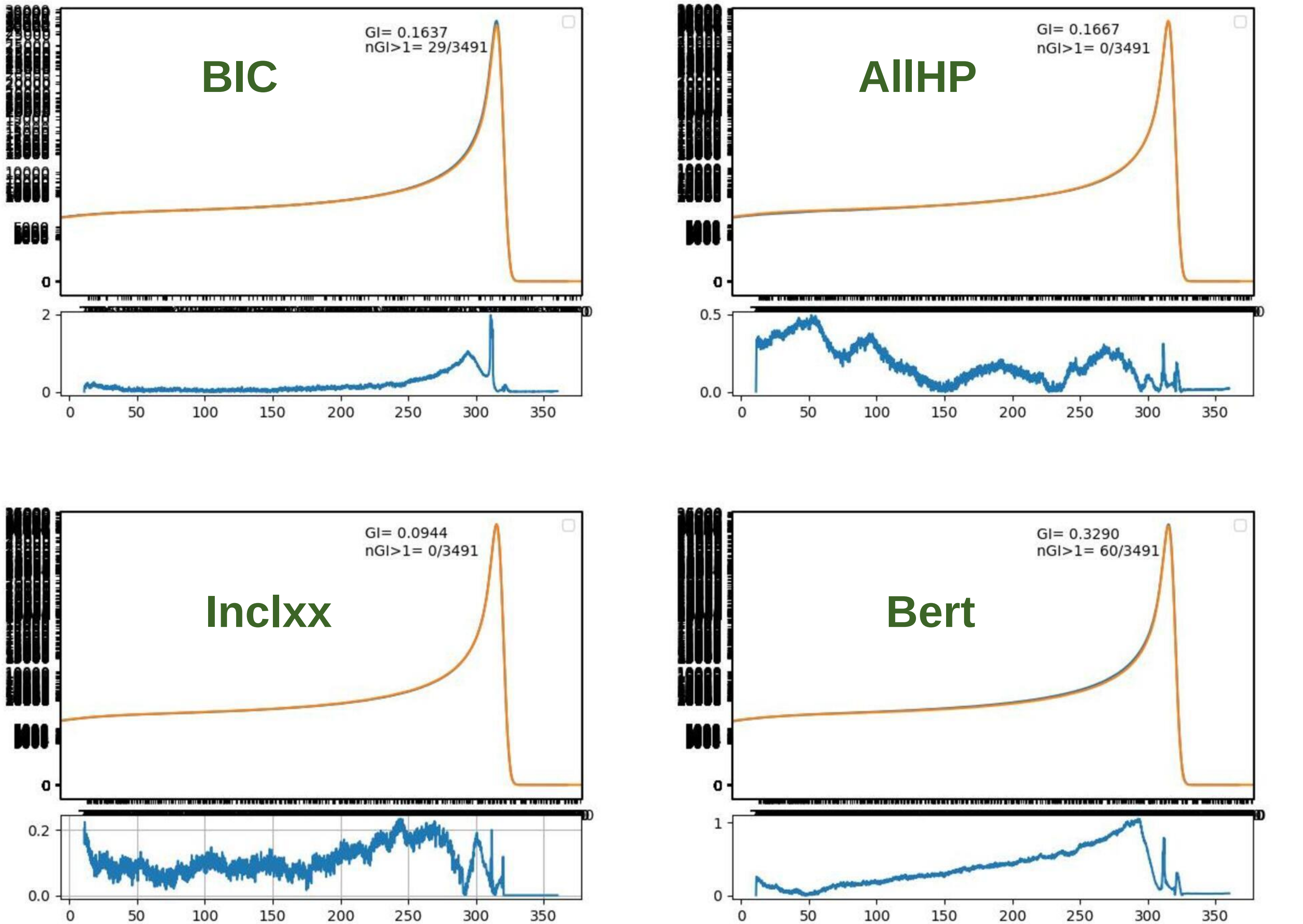
Best physics list

170.2 MeV



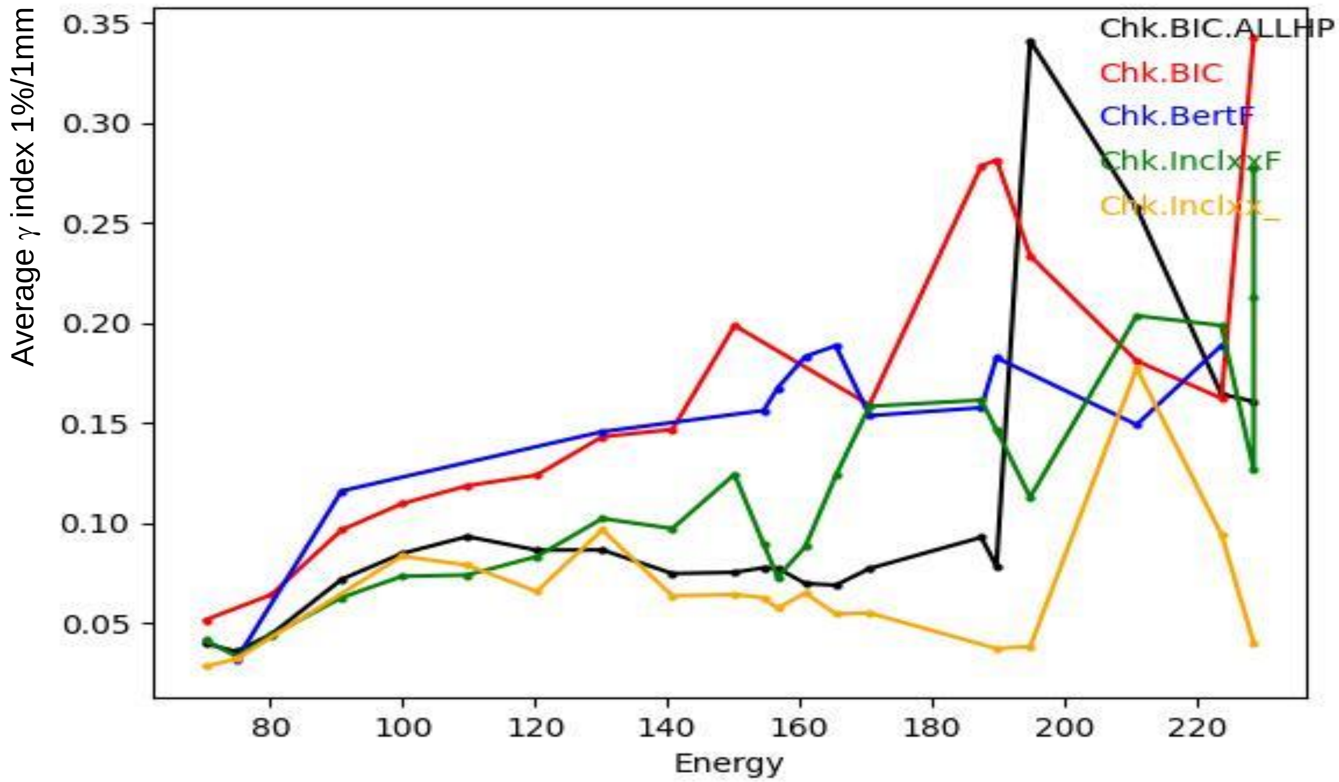
Best physics list

224.2 MeV



Best physics list

Compare IDD for four physics lists: QGSP_BIC_HP, QGSP_BIC_AllHP, QGSP_INCLXX_HP, QGSP_BERT_HP



- INCLXX is best. AllHP is as good, but has problems at E >190 ??

Time of different physics lists

stud.timeCPU.physList/run.patient_MAMA_9991_200_2_1

neutron	HP:	14.070	AllHP:	0.978	Bert:	0.684	Inclxx:	0.991
proton	HP:	401.760	**AllHP:**	**2.888**	Bert:	0.768	Inclxx:	0.767
e-	HP:	858.050	AllHP:	1.147	Bert:	0.187	Inclxx:	0.183
ALL	HP:	1712.830	AllHP:	1.565	Bert:	0.433	Inclxx:	0.430

(similar for other 3 patients tested)

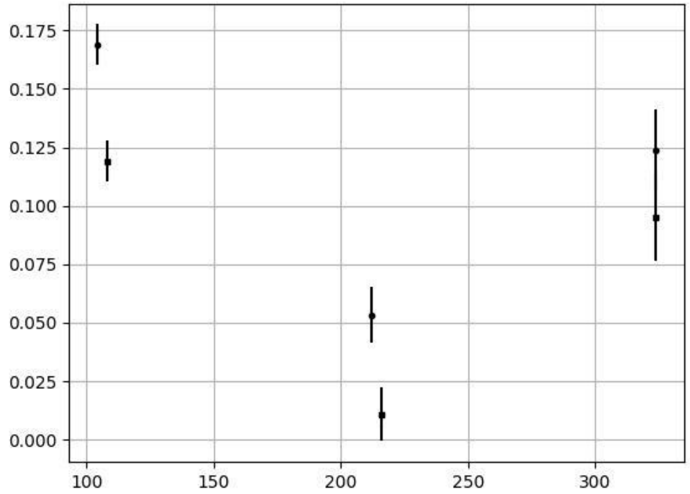
HP/AllHP are EMZ, Bert/Inclxx are EMY, that's why e- time is much bigger and proton time slightly bigger

Cut is 0.05

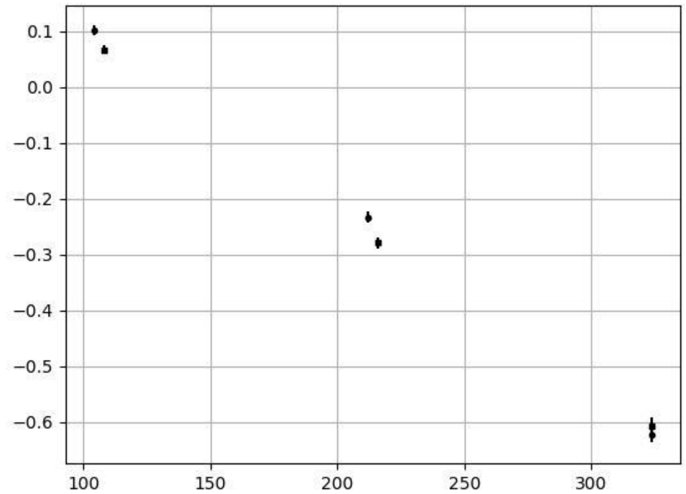
AllHP takes too much time in protons

Optimized physics list: EMY vs EMZ

EMZ: MC-Exper. Sigma of profile in water Energy = 229.35 MeV



EMY: MC-Exper. Sigma of profile in water Energy = 229.35 MeV



- EMY EMZ is ~1.45 slower than EMY, but gives better waterProf

- Get which physics parameters and physics models makes EMZ better, but optimizing the CPU

EMY+ physics models

- Make changes in EMY EMZ is ~45 slower than EMY, but gives better waterProf

PARAMETER	EMY	EMZ	CPU EMY/EMZ	Optim
/process/eLoss/minKinEnergy	10 eV	100 eV	+2%	**100 eV**
/process/msc/RangeFactor	0.03	0.08	+7%	**0.08**
/process/eLoss/StepFunction	0.2 0.1	0.2 0.01	-10%	**0.2 0.1**
/process/eLoss/StepFunctionMuHad	0.2 0.05	0.1 0.05	=	**0.2 0.05**
/process/msc/Skin	1	3	=	**3**

EMY+ physics models

PHYSICS PROCESS	MODEL EMY	MODEL EMZ	CPU EMY/ EMZ	MODELOptim
gamma Compton	KleinNishina	LowEPCompton +KleinNishina	=	**LowEPCompton +KleinNishina**
gamma pair conversion	BetheHeitlerLPM	BetheHeitler5D	=	**BetheHeitler5D**
e-/e+ msc	UrbanMsc	GoudsmitSaund. +WentzelVIUni	+56%	**GoudsmitSaund. +WentzelVIUni**
proton msc	UrbanMsc	WentzelVIUni	=	**WentzelVIUni**
mu & hadron msc	UrbanMsc	WentzelVIUni		**WentzelVIUni**
e-/e+ Coulomb scattering	NO	YES	+21%	**NO**
e-/e+ ionisation	MollerBhabha	PenIoni +MollerBhabha	=	**PenIoni +MollerBhabha**

Optimised physics list:

- **= EMZ**
- ***/process/eLoss/StepFunction 0.2 0.1 (not 0.2 0.01)***
- **No Coulomb scattering**

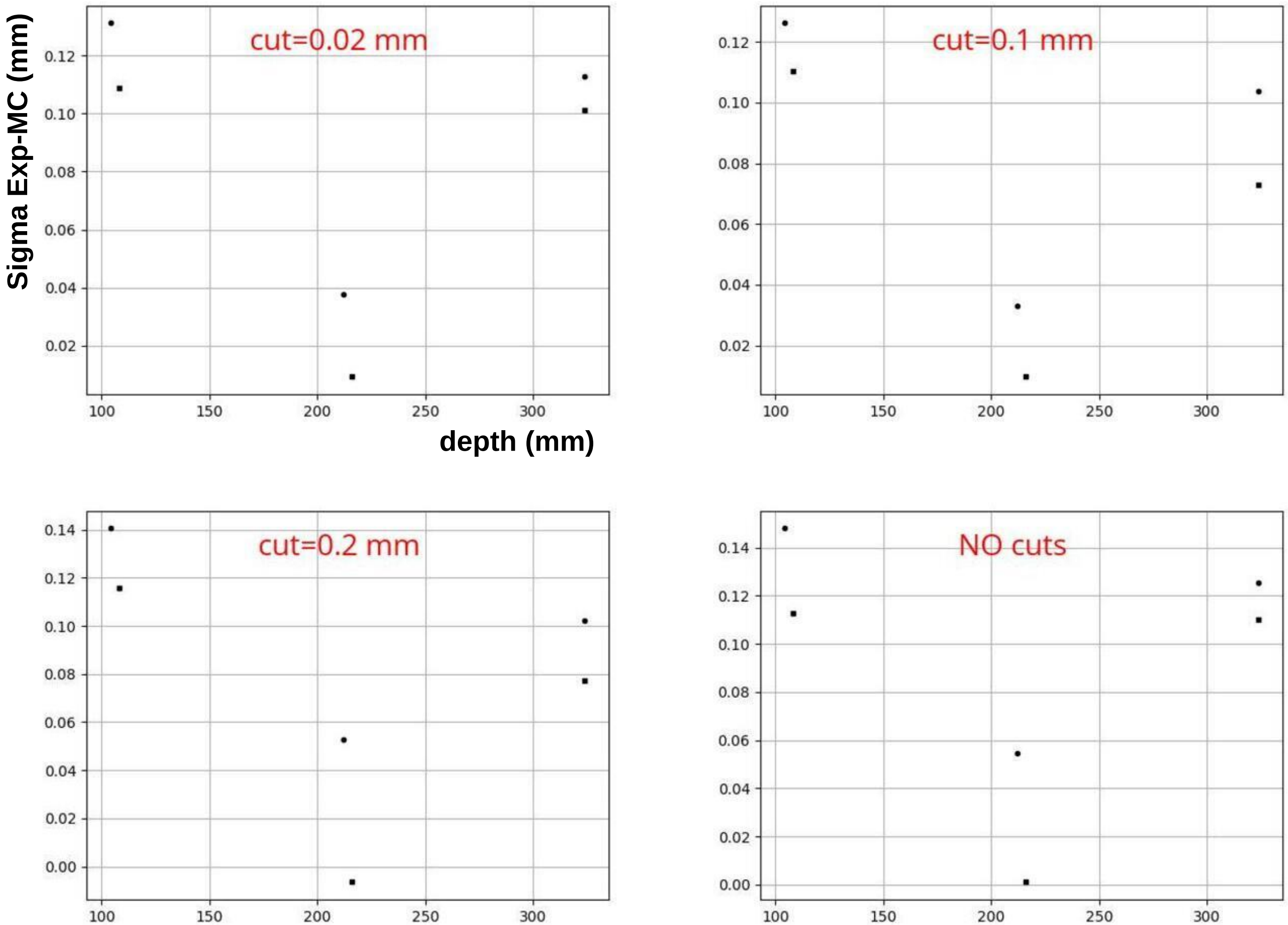
➢ **~ 25% faster than EMZ**

Optimization of production cuts: Time

Production cut	CPU time (s)	Relative Time
INCLXX_EMZ	11,906	1.
0.005 mm	29,530	2.47
0.02 mm	8,833	0.74
0.05 mm	6,285	0.53
0.1 mm	4,737	0.40
0.2 mm	3,692	0.30
NO e-/e+	3,005	0.25

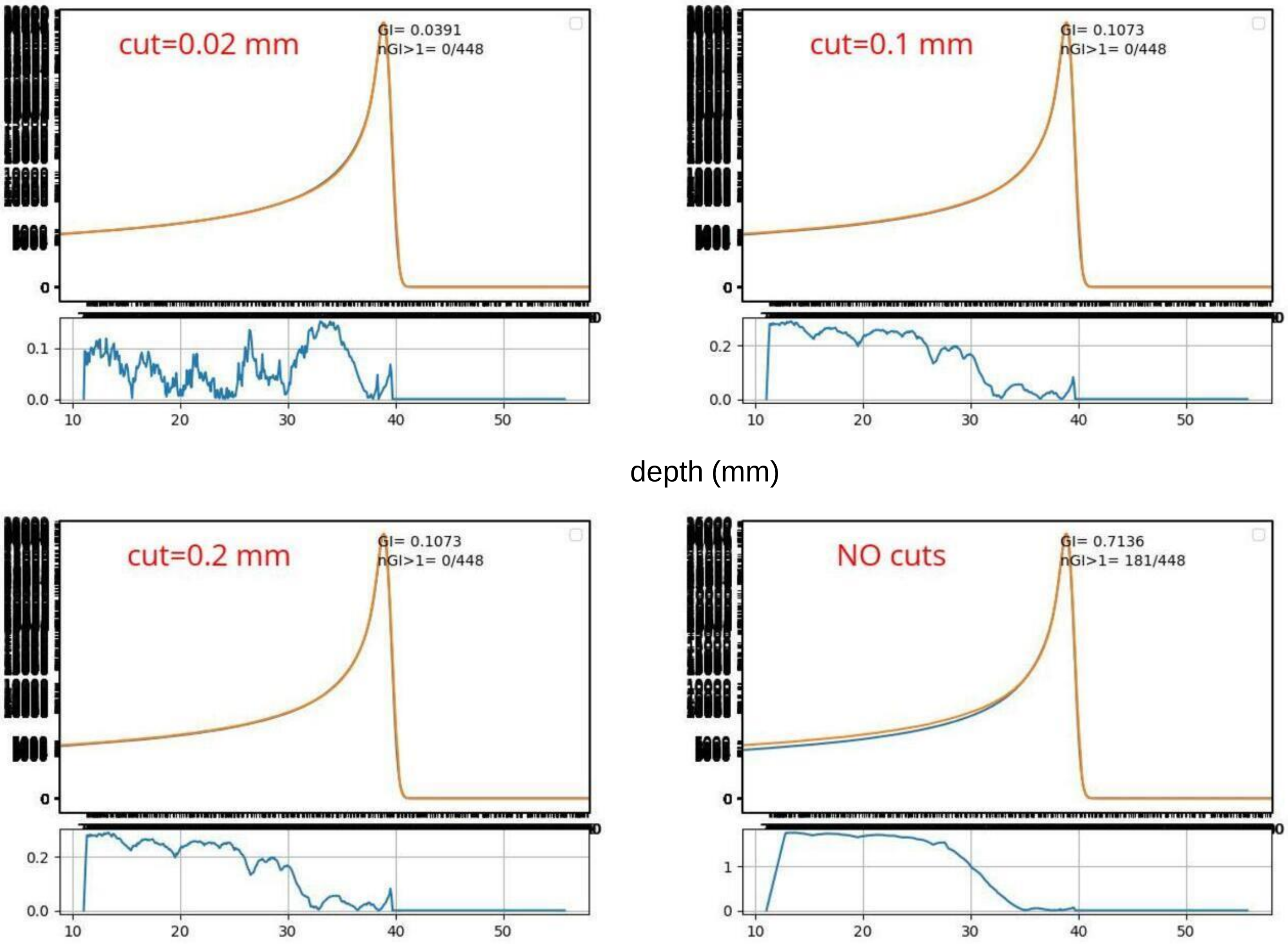
Optimization of production cuts: Transversal profiles

Water profiles for the highest energy, 228.7 MeV



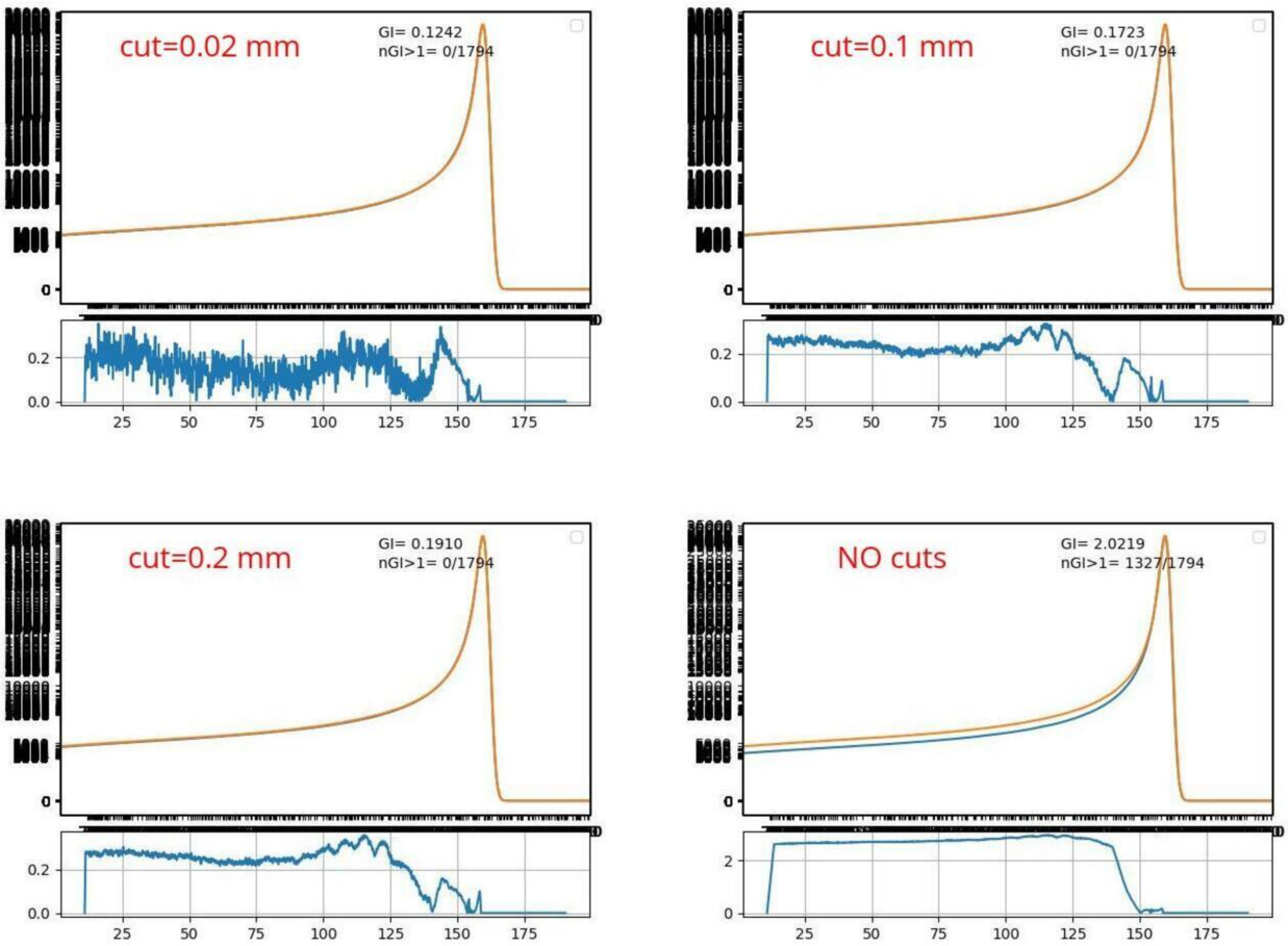
Optimization of production cuts: IDDs

70.2 MeV



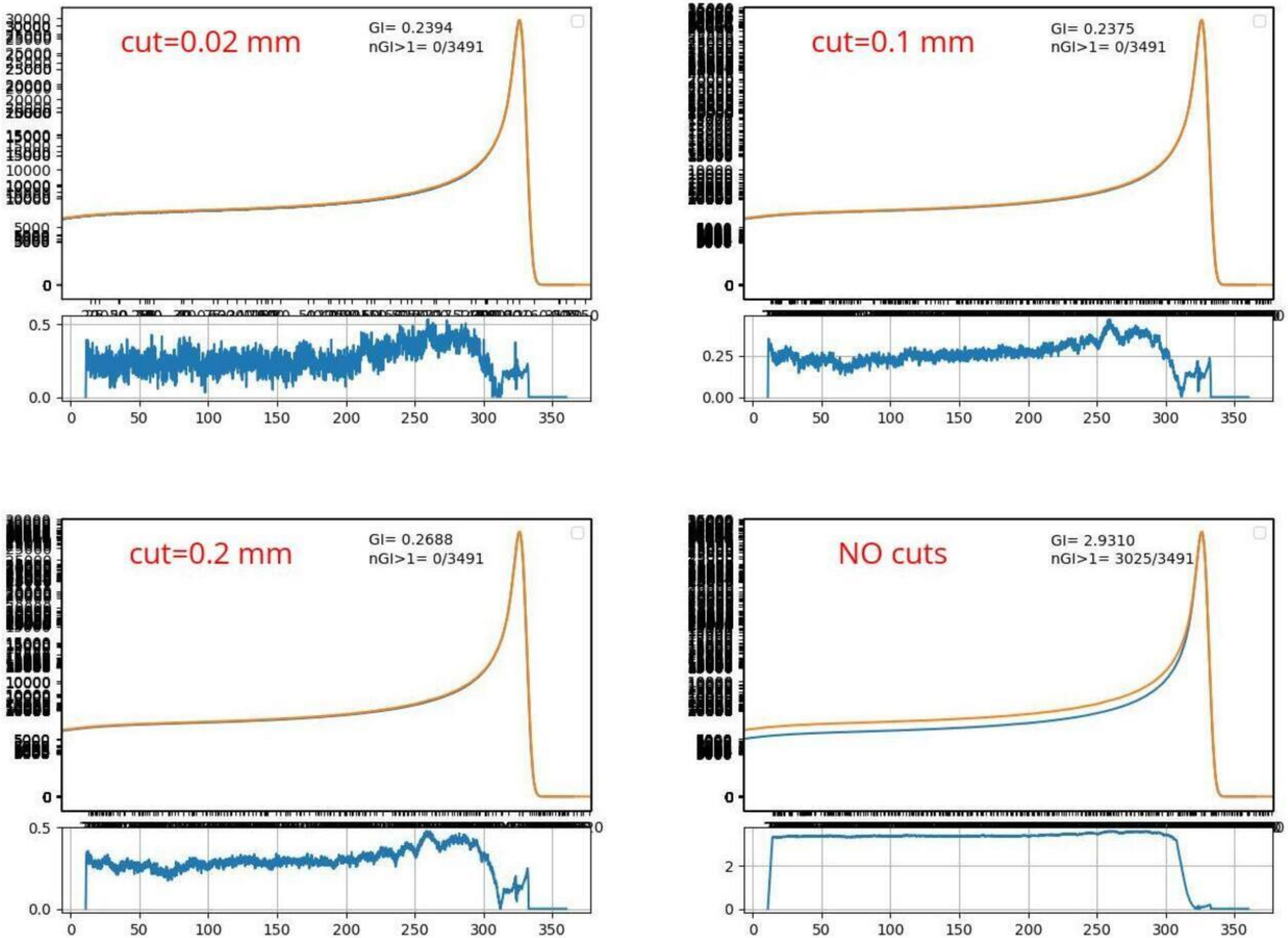
Optimization of production cuts: IDDs

150.2 MeV



Optimization of production cuts: IDDs

228.7 MeV



SUMMARY

- We have made a of detailed fig of GAMOS to cun protontherapy experimental data
  - Profiles in air width < y 1%/1mm 0.25
  - IDD proton range < y 1%/1mm 0.5
  - Profiles in water < y 1%/1mm 0.5
  - Absolute dose
  - SOBP measurements < 5%
  - Patient dose < y 2%/2mm 3
    - HU to material conversion?
- We have compared GAMOS to RayStation v.12 TPS LET_D unrestricted
  - Significant measurements found
- Differences GAMOS – TPS have to be better understood

SUMMARY

- We have made a of detailed fit of GAMOS to CUN protontherapy experimental data
  - Profiles in air width < y 1%/1mm 0.25
  - IDD proton range < y 1%/1mm 0.5
  - Profiles in water < y 1%/1mm 0.5
  - Absolute dose ~= TPS
  - SOBP measurements < 5%

SUMMARY

- We have optimized the Geant4 physics list
  - Hadronic models
    - QGSP_INCLXX_HP_EMZ and QGSP_BIC_AllHP (EMZ) better than QGSP_BIC_HP (EMZ)
    - QGSP_BERT_HP_EMZ better than QGPS_BIC_HP
  - Electromagnetic models
    - EMY not good
    - EMZ but
      - /process/eLoss/StepFunction 0.2 0.1 (not 0.2 0.01)
      - No Coulomb scattering
      - ~ 25% faster than EMZ
  - Production cuts
    - 0.2 60% faster than EMZ

SUMMARY

TO DO:

- ✓ Add tilt in ellipse describing profiles in air
- ✓ Better understand FW10 discrepancies > 1mm
  - Include energy distribution dependence with position and direction?
  - Play with multiple scattering?

- ✓ Modify Mean Excitation Energy of Schneider materials to fit experimental Stopping Power Ratios
- ✓ Adjust VirtualAxisDistance to fit experimental data (instead of nominal value provided by DICOM files)
- ✓ Simulate SOBP of increasing complexity

- ➢ Simulate patients