MOST LIKELY PATH (MLP)

Most likely path of protons inside a patient – Exisiting methods and studies

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Bergen pCT - Workshop

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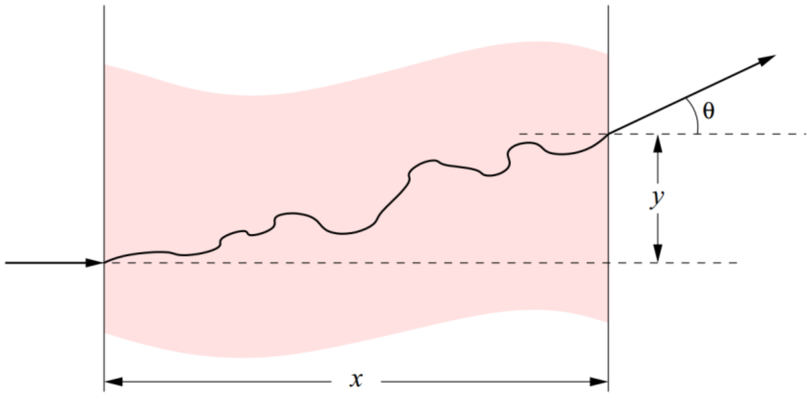
How mlp benefits proton CT



- Protons are affected by multiple Coulomb scattering
- Challenging reconstruction, which voxels are hit?
- In proton CT, individual protons can be distinguished
- Predict the protons most likely path inside the patient using MLP methods
  - Proton path predictions should be accurate enough to help reach the goal of 1 mm spacial granularity and 1% electron density resolution accuracy along the trajectory (Schulte et al 2003).

R. Schulte et al, 2003, *"Design of a Proton Computed Tomography System for Applications in Proton Radiation Therapy"*

Typical proton CT setup, with trackers

- Two trackers in the front of the patient/phantom and two behind
- Phantom is assumed to be homogeneous in current MLP methods

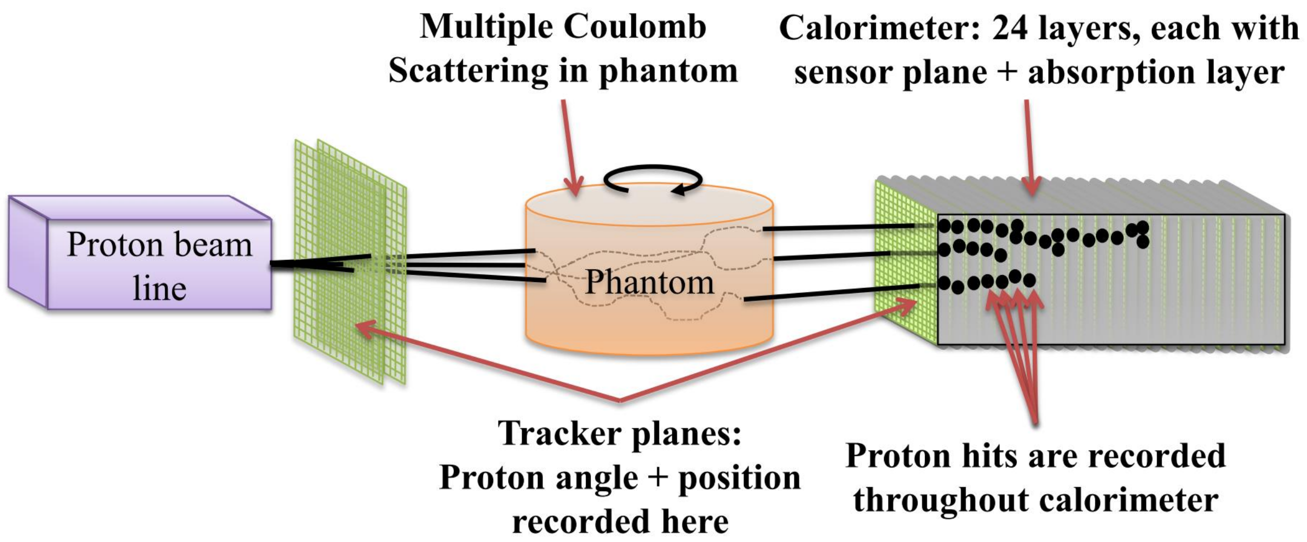


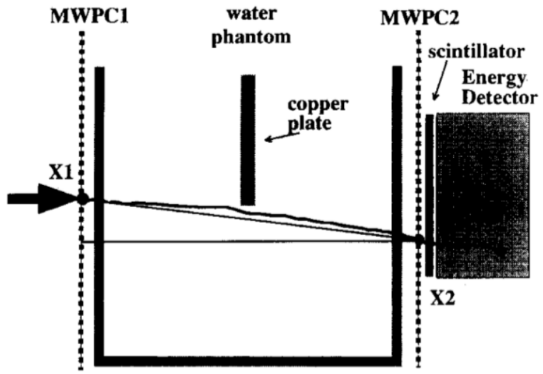
Figure from: H.E.S. Pettersen , 2018, "*A Digital Tracking Calorimeter for Proton Computed Tomography*"

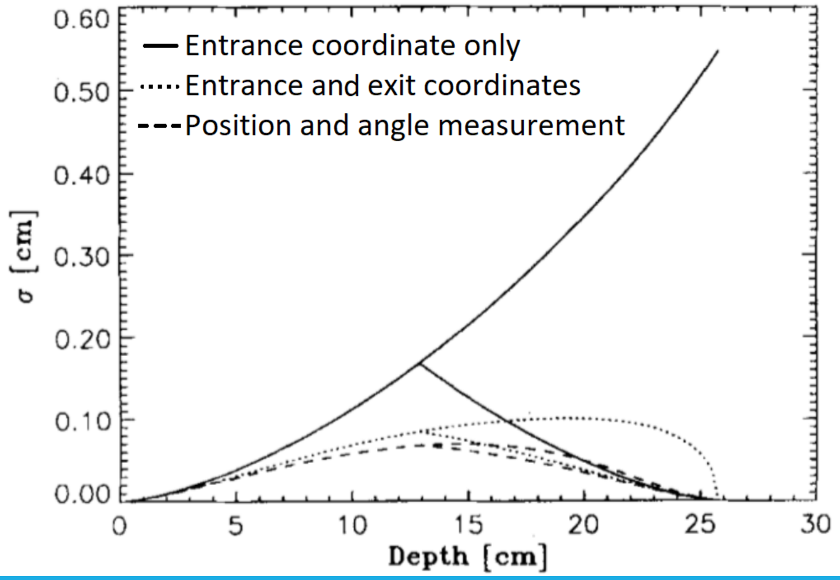
Multiple Coulomb scattering and spatial resolution in proton radiography

Uwe Schneider and Eros Pedroni
Department of Radiation Medicine, Paul-Scherrer-Institut, 5232 Villigen-PSI, Switzerland

(Received 22 June 1993; resubmitted 27 December 1993; accepted for publication 23 June 1994)

- Earliest results deriving protons internal path between two points
- Analytical formulas account for energy loss in the material
  - Based on generalized Fermi-Eyges theory of scattering
  - Gaussian distribution of scattering angles
  - Derive projected distribution function (mlp)
  - Compared with experimental results
- Calculates spatial resolution of 200 MeV protons in water using varying amount of parameters

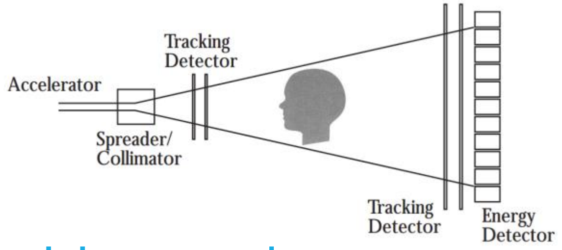




The Most Likely Path of an Energetic Charged Particle Through a Uniform Medium

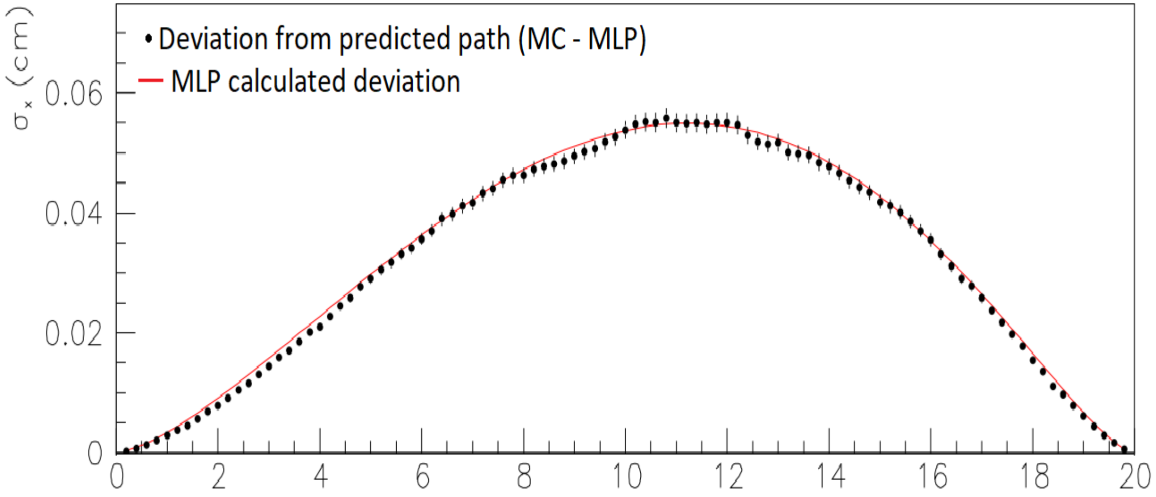
D.C. Williams

Santa Cruz Institute for Particle Physics, Santa Cruz, CA 95064, USA



- Calculation of the most likely path with known entrance and exit positions and angles, along with a probability envelope
  - Verified using Monte Carlo simulations (geant4)
- Closely follows the work by Schneider and Pedroni (1994), but simplifies it with a χ^2 formalism
- MLP predicted path is accurate to < 1 mm
- Observe good agreement between calculation and Monte Carlo simulation

200 MeV protons in water



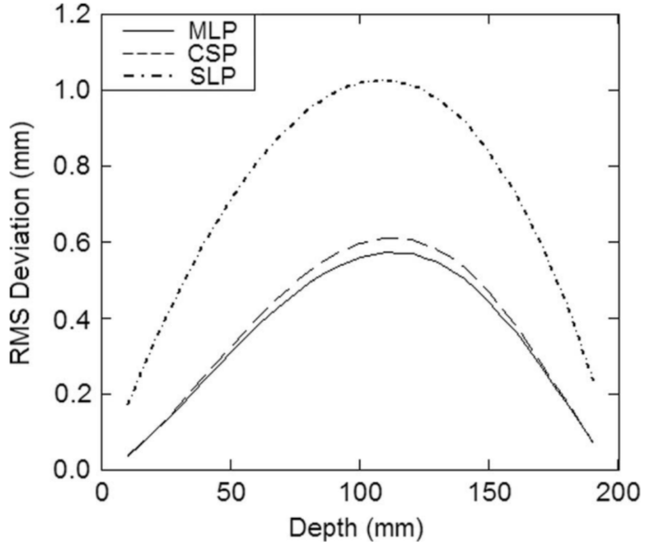
Reconstruction for proton computed tomography by tracing proton trajectories: A Monte Carlo study

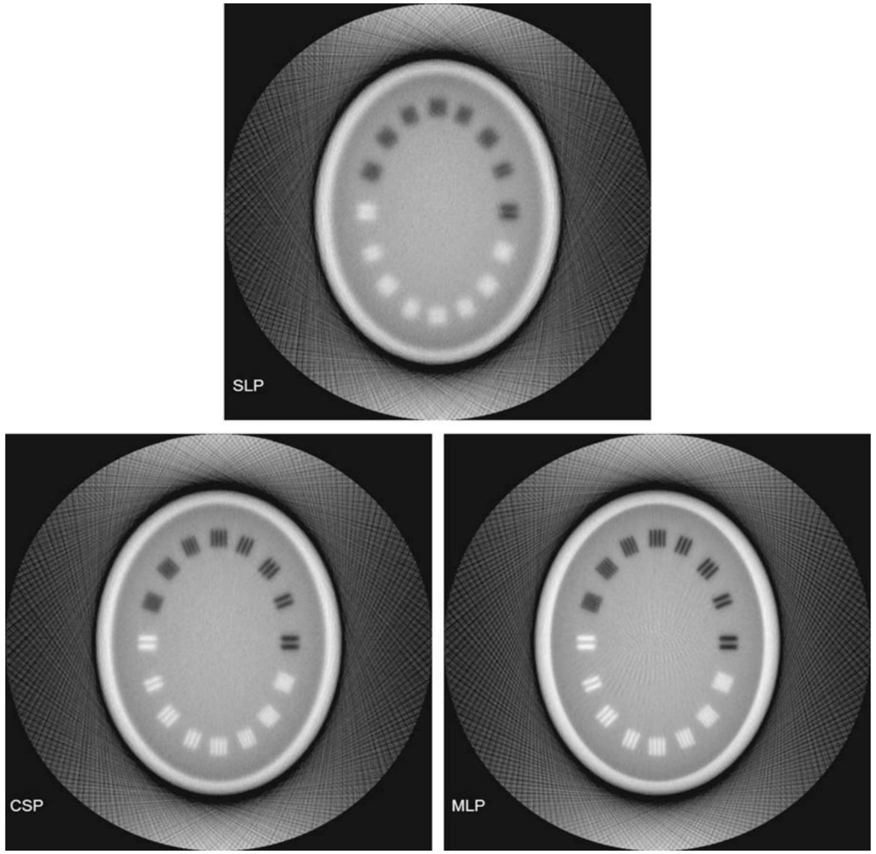
Tianfang Li and Zhengrong Liang[a)]
Departments of Radiology, Computer Science, and Physics and Astronomy, State University of New York at Stony Brook, Stony Brook, New York 11794

- Compares three different path-estimation methods used in proton CT
  - Straight Line Path (SLP)
  - Cubic Spline Path (CSP)
  - Most Likely Path (MLP) <- D.C. Williams

- RMS difference between MLP and CSP is no more than 10%

RMS deviation of the displacement between each path estimate method and MC path

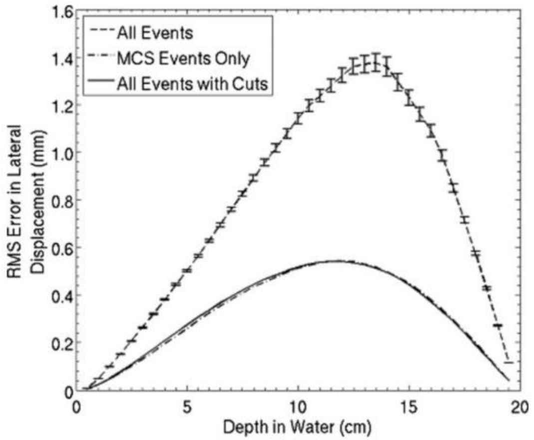




A maximum likelihood proton path formalism for application in proton computed tomography

R. W. Schulte[a)]
Department of Radiation Medicine, Loma Linda University Medical Center, Loma Linda, California 92354

- Matrix based MLP method employing Bayesian statistics
  - Equivalent to MLP formalism by D.C. Williams, but more compact and adaptable
  - Applied to scenarios with incomplete proton track information (D.C. Williams's require information about entrance, exit and angle)
- Able to predict MC tracks of 200 MeV protons in water to within 0.6 mm, using a 3σ cut on the relative exit angle



$$y=\begin{pmatrix} t_1 \\ \theta_1 \end{pmatrix}$$

t_1 = lateral coordinate
θ_1 = angle relative to reference axis

y_d = parameter vector at depth d

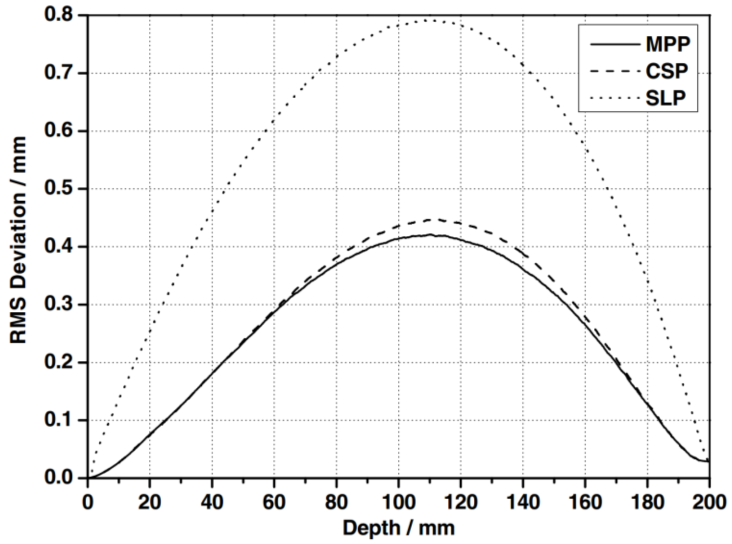
Bayes' theorem relates the prior and posterior likelihood, L

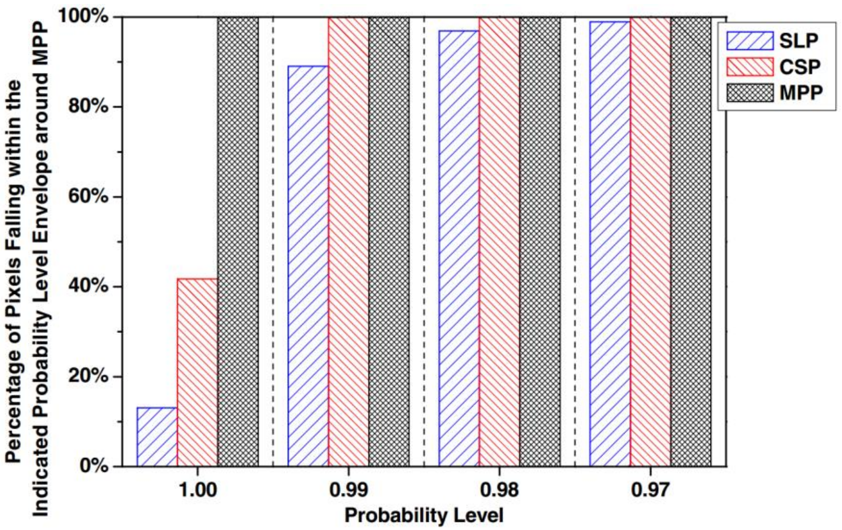
$$L(y_d|exit\ data)=L(exit\ data|y_d)L(y_d|entry\ data)$$

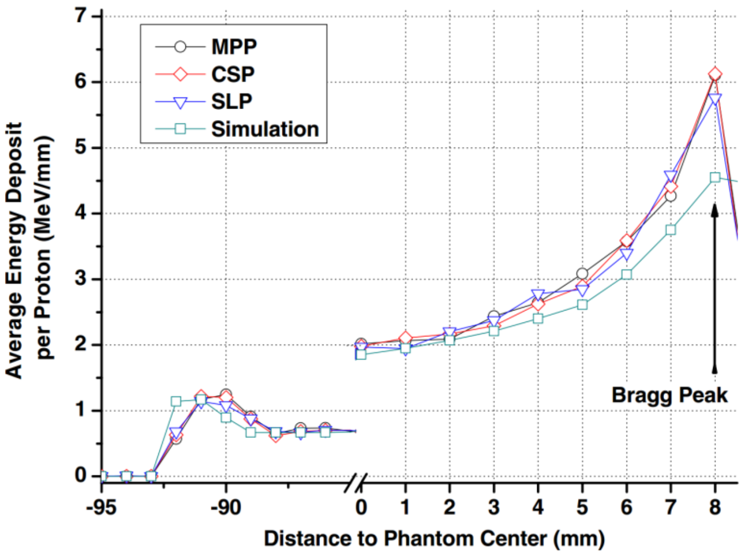
Bragg peak prediction from quantitative proton computed tomography using different path estimates

Dongxu Wang , T Rockwell Mackie and Wolfgang A Tomé

- Compares SLP and CSP performance with MLP and MC
  - Predicting the Bragg peak location
- Employing SLP or CSP may yield lower spatial resolution, but can still accurately predict Bragg peak location





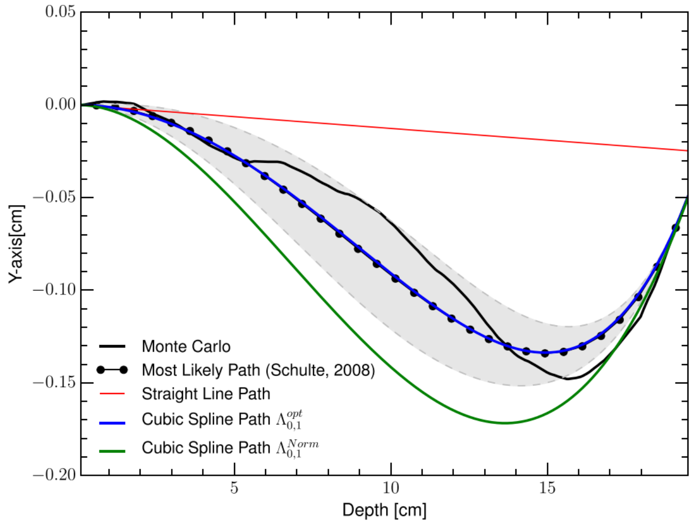


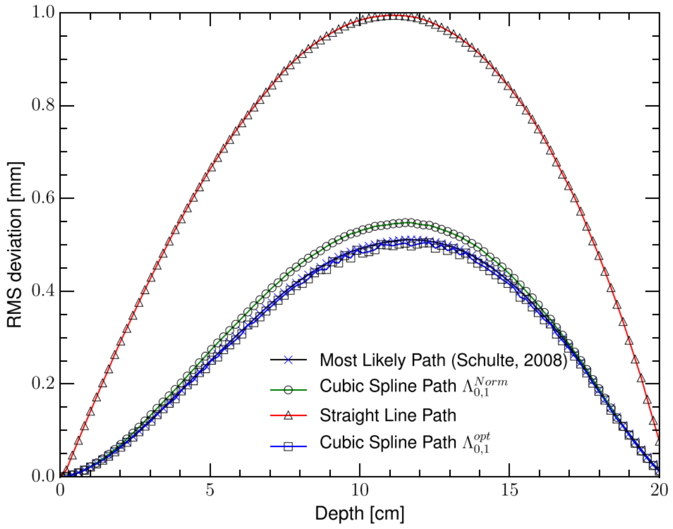
Developing a phenomenological model of the proton trajectory within a heterogeneous medium required for proton imaging

Charles-Antoine Collins Fekete , Paul Doolan , Marta F Dias , Luc Beaulieu , Joao Seco

- Motivated by the computational burden of MLP, and the reasonably good estimation power of CSP
- Improve the estimation power of CSP by introducing an optimized factor when calculating the direction vector magnitude used in CSP.

$$\Lambda_{0,1}^{opt} = A + B(WET/WEPL)^2$$

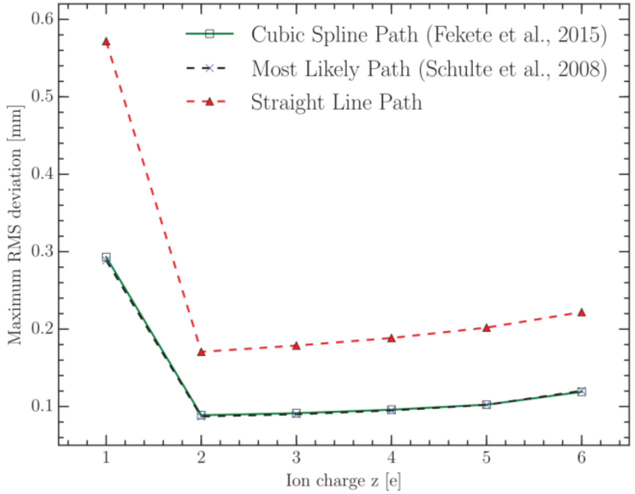


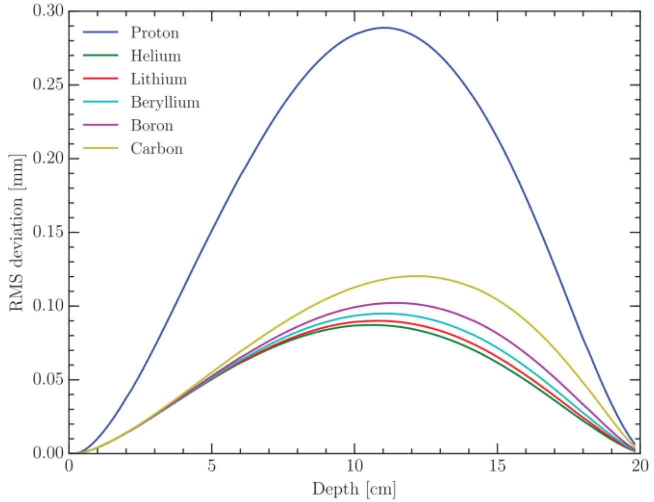


A theoretical framework to predict the most likely ion path in particle imaging

Charles-Antoine Collins-Fekete, Lennart Volz, Stephen K N Portillo, Luc Beaulieu and Joao Seco

- A rigorous Bayesian formalism predicting the MLP of any ion between two points
  - First to extract ions MLP
- Based on the work by Schulte (2008), but more compact
- The optimized CSP is concluded to be an efficient characterization of MLP





Summary

- All studies apply Gaussian approximation of MCS and use the same scattering theory foundation (Fermi-Eyges theory)
- Only homogeneous materials are considered
  - Scattering in two perpendicular planes are treated as uncorrelated and investigated seperately.
- The MLP Bayesian formalism has become more compact (2008-2017)
  - The CSP formalism provides a good and less resource heavy estimation of the proton path
- All methods (except SLP) report a sub-mm deviation from MC

Going forward – Bergen pCT

- MC simulations
  - Four trackers, two on both sides of a homogeneous water phantom
- Implement CSP method
  - Basic and optimized version
- Implement MLP method
  - Williams, χ^2 formalism
  - Fekete, Bayesian formalism
- Investigate the effect of removing the two front trackers.
- Inhomogeneous materials(?)
  - Iteratively update the MLP with density information
  - Take advantage of the information found in MCS