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Potential use of combined ToF-tracking sensors for Proton Computer Tomography

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Why Proton CT?

- In proton therapy normally accurate alignment of the accelerator with the patient is done using parallel X-Rays imaging.
  - The use of X-rays:
    - increases the dose on the patient.
    - increases the complexity of the setup.
- The possibility of imaging based on images from proton CT might:
  - reduce the patient dose.
  - improve the imaging.
  - simplify the alignment process (already done with the protons).

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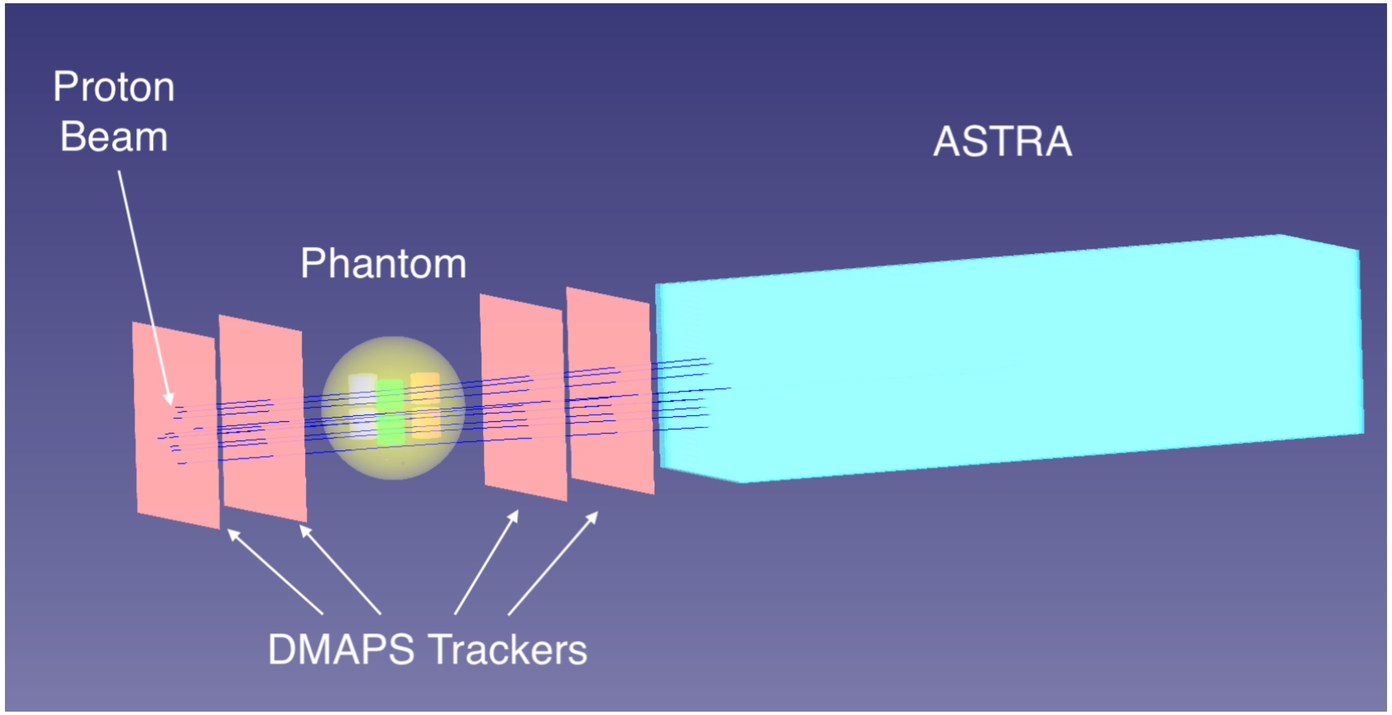
Proton CT concept

- Use the same accelerator to do imaging.
- measurement of proton track input and output directions (DMAPS).
  - might require a reduced proton flux to facilitate the proton reconstruction.
- measurement of the proton energy after the patient/phantom (ASTRA).



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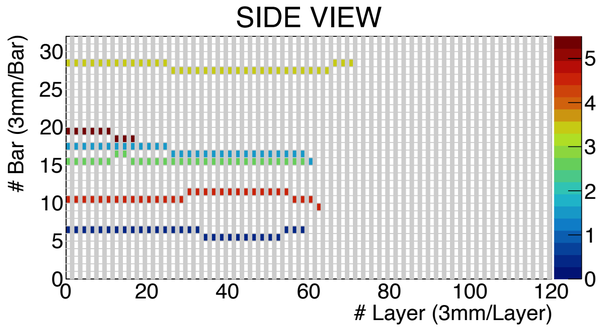
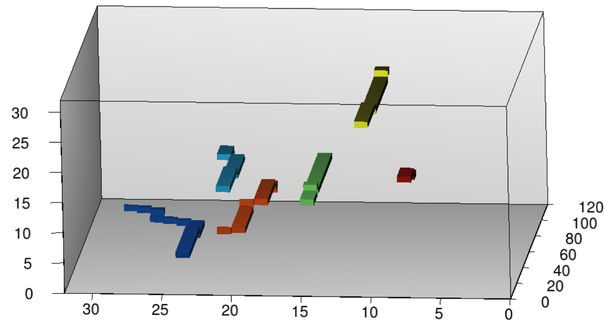
Actual proposal

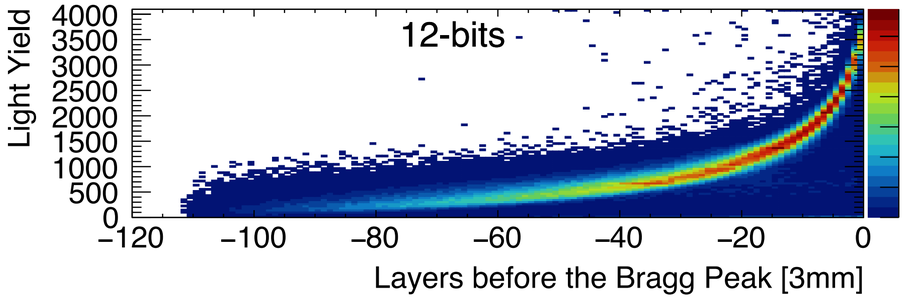
Phys.Med.Biol. 67 (2022) 3, 035013

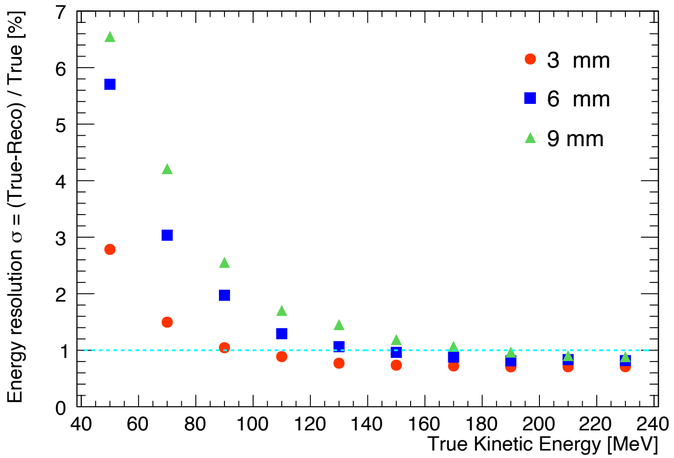
Birmingham, Barcelona, Geneva

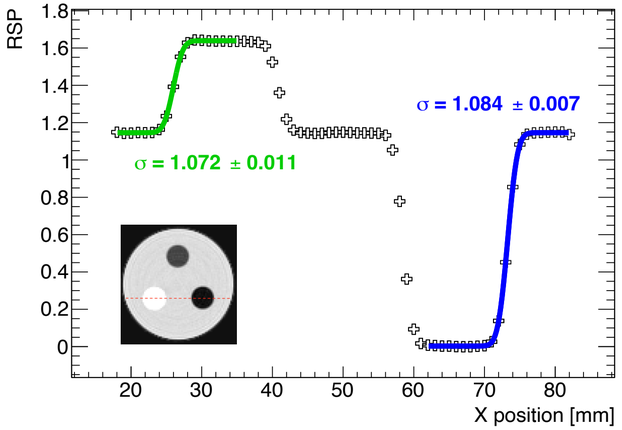




- Use a tracking calorimeter (ASTRA) to perform proton kinematic reconstruction.
  - fibre read scintillator bars aligned in X and Y.
- Excellent energy reconstruction (σ_E< 1%)
  - combination of range and Bragg peak measurement. **New concept**
- Excellent imaging performance (σ_x< 10 μm)







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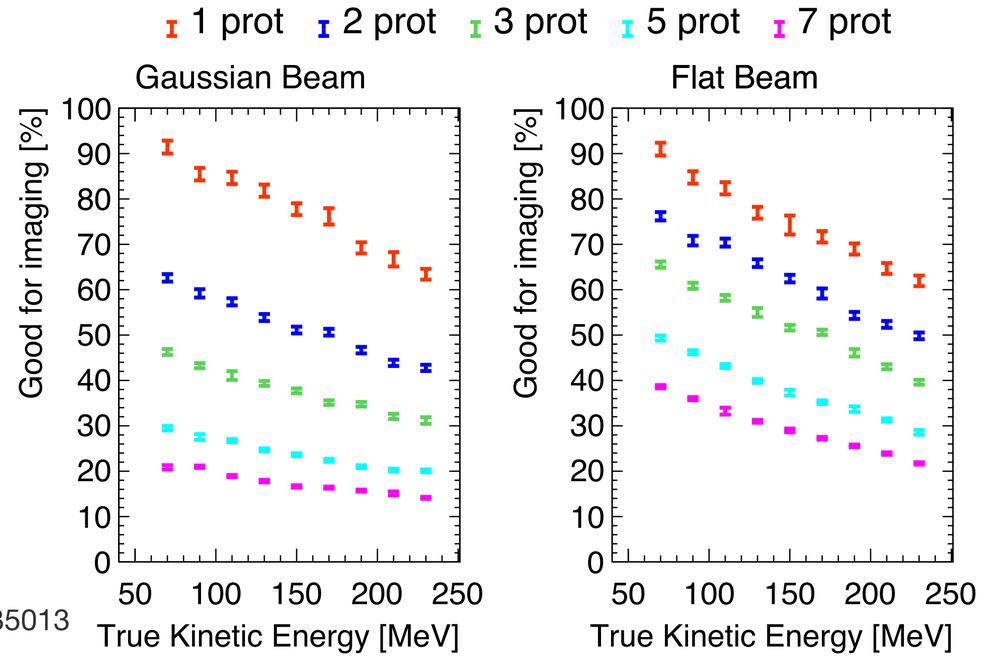
Problems with ASTRA idea

- Coarse position resolution in ASTRA —> proton track superposition —> low proton intensity.
- The fraction of usable protons decreases with the number of protons/acquisition window.
- Beam's are normally providing a minimum of 1proton/10ns. Coarse position detectors such as ASTRA requires fast electronics.



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Impressive performance versus other alternative proposals.

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Additional problems

- The typical proton accelerators show a large dispersion of momentum of protons before entering the patient (mainly @ low energies).

arXiv:2111.02712v1

Beam Energy [MeV]	70	100	150	200	245
Beam Energy Spread	1.1%	1.1%	0.9%	0.6%	0.3%
Beam Energy Spread [MeV]	0.8	1.1	1.3	1.2	0.8
0.2% of Beam Energy [MeV]	0.1	0.2	0.3	0.4	0.5

TABLE I: *Beam energy spreads of the PSI treatment beam, and the 0.2% available on the same machine at lower currents, for e.g. pCT scanning.*

The resolution will be very bad with low momentum protons both for the calorimetric approach and the beam spread.

- There might be also issues in the track association before and after the patient when proton intensity is large.

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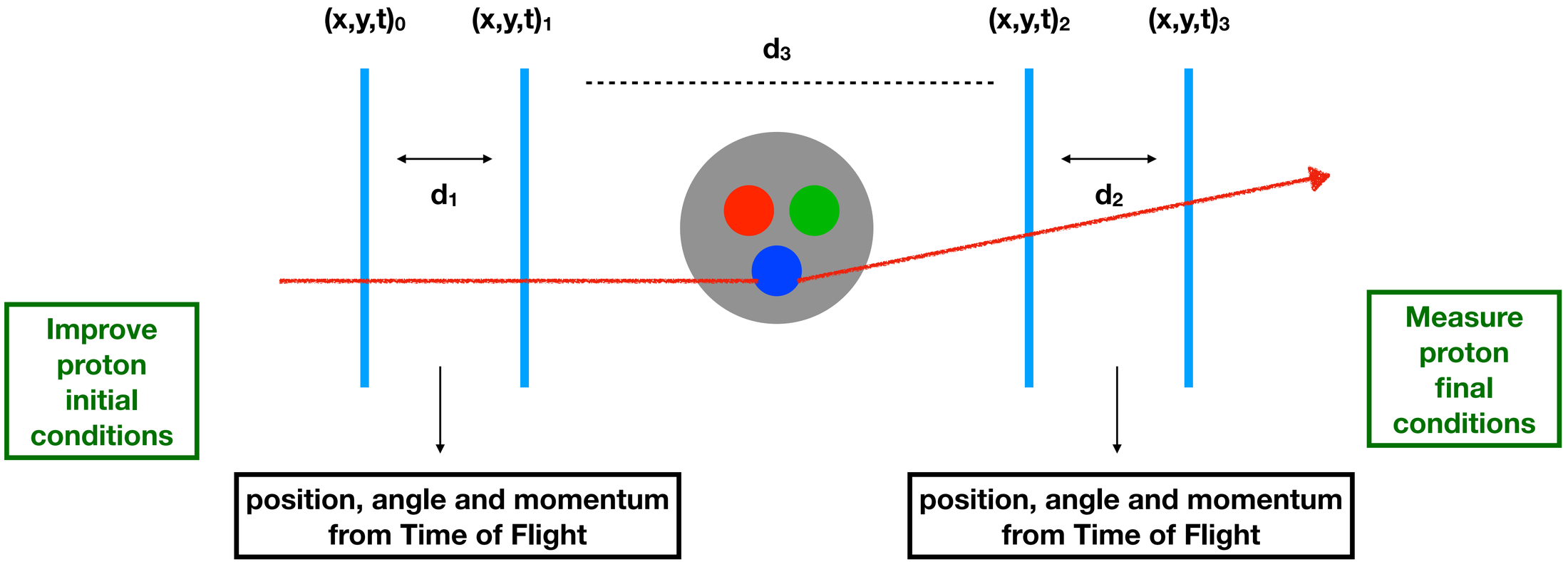
How to overcome the problems?: Track and time

- Let's replace the silicon devices by a tracking with high time resolution:



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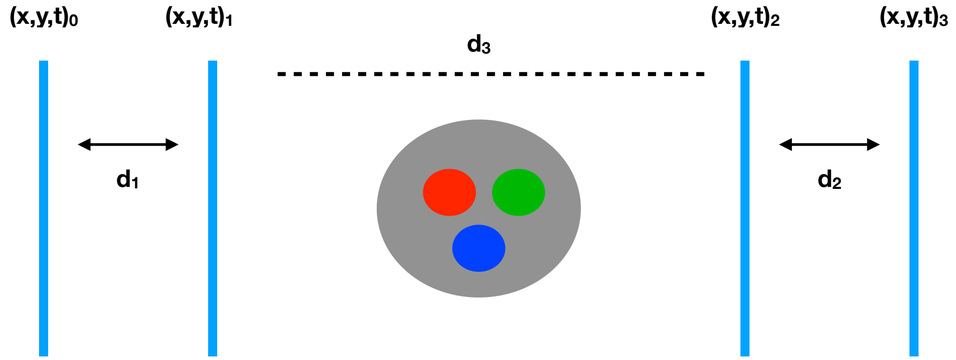
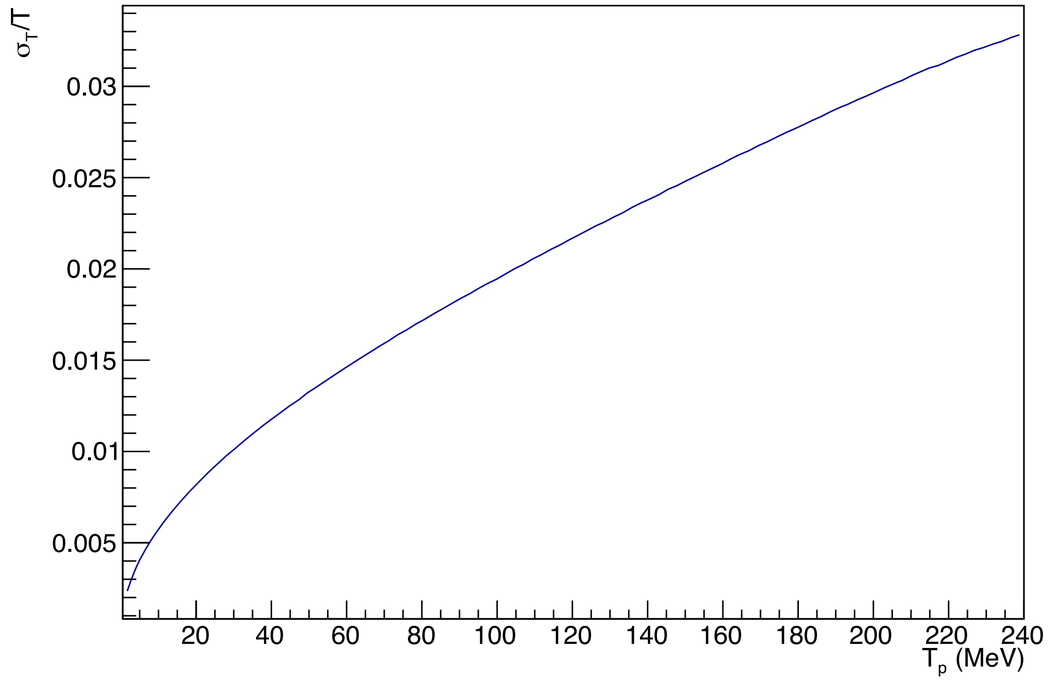
Is it possible?

- Let's take the 13 ps resolution obtained by the Geneva group.
- Asume we build a tracker system with 2 layers/plane (4 layers before and 4 layers after the patient).
- Separation of 20cm between the layers (d1 = d2 = 20 cm).





- 3% at 240 MeV (0.7% with ASTRA).
- < 1.5 % below 70 MeV (> 30% with ASTRA)

Not quite competitive…. but not far

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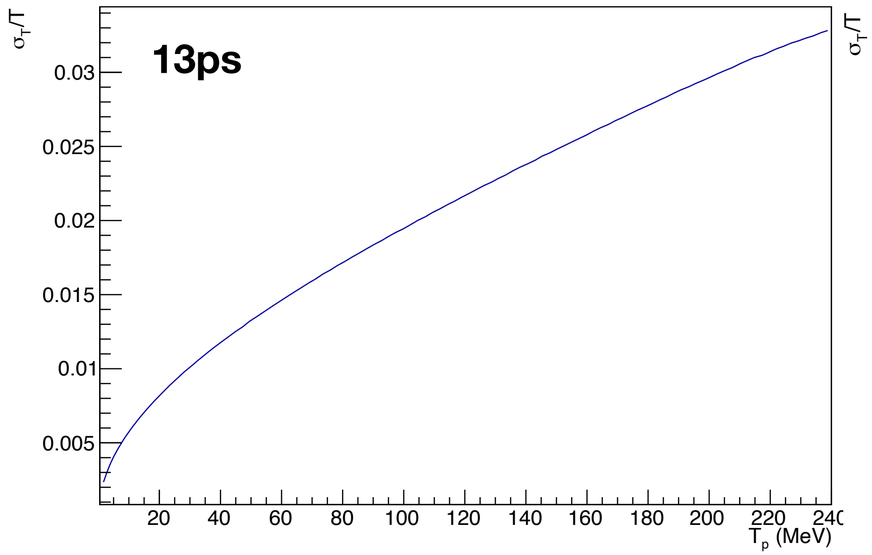
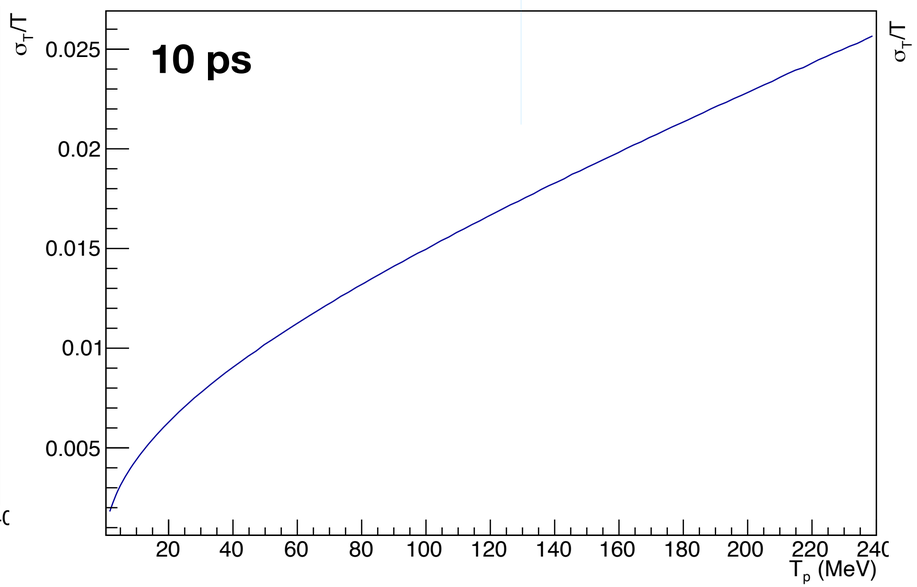
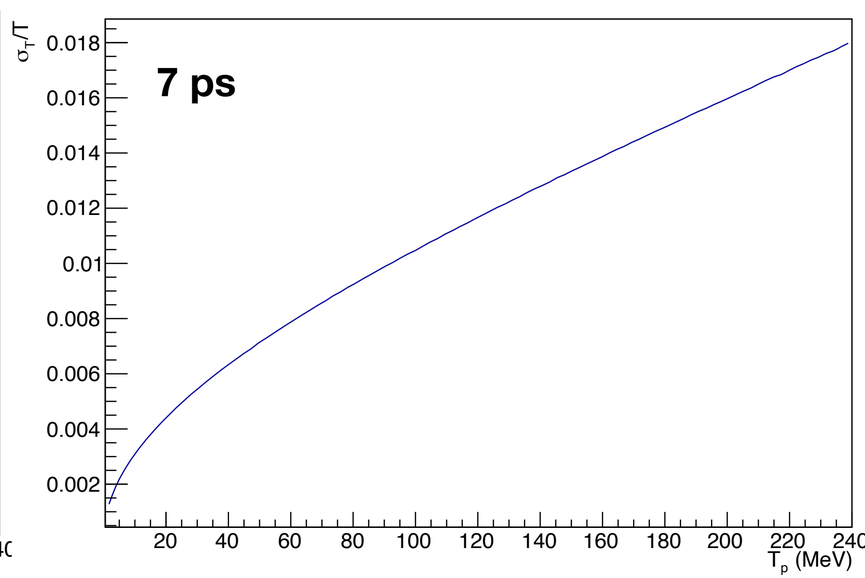
Proton vs MIP's

Kinetic energy	$(dE/dx)/(dE/dx)_{MIP}$
50 MeV	~6
250 MeV	~2

- Protons are non-relativistic.
  - The amount of charge per pixel is larger —> better momentum resolution.







already competitive for proton beam measurement

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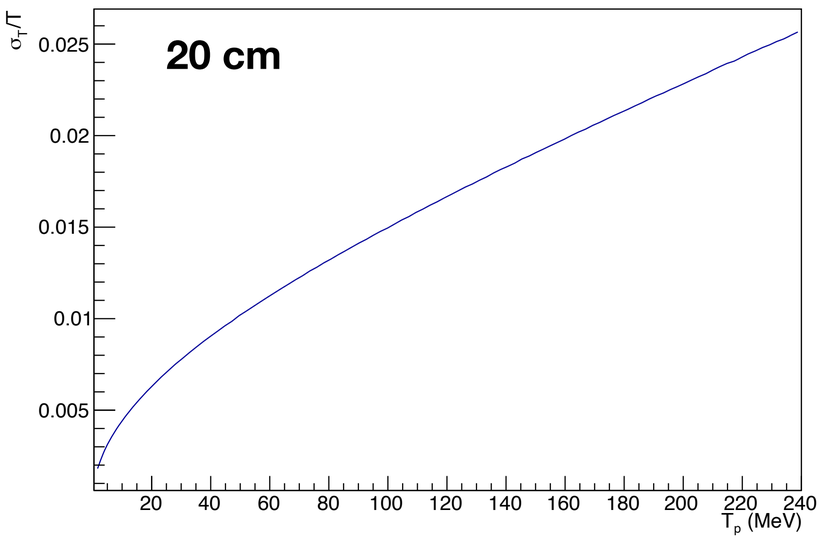
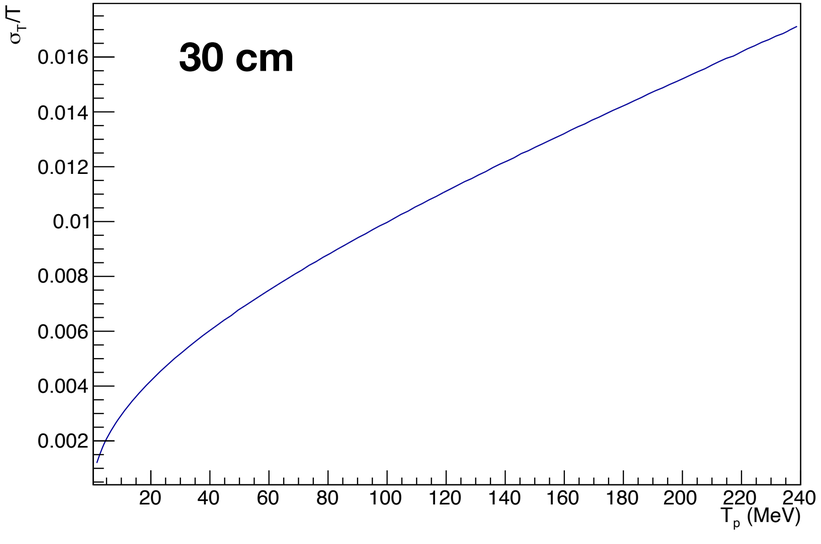
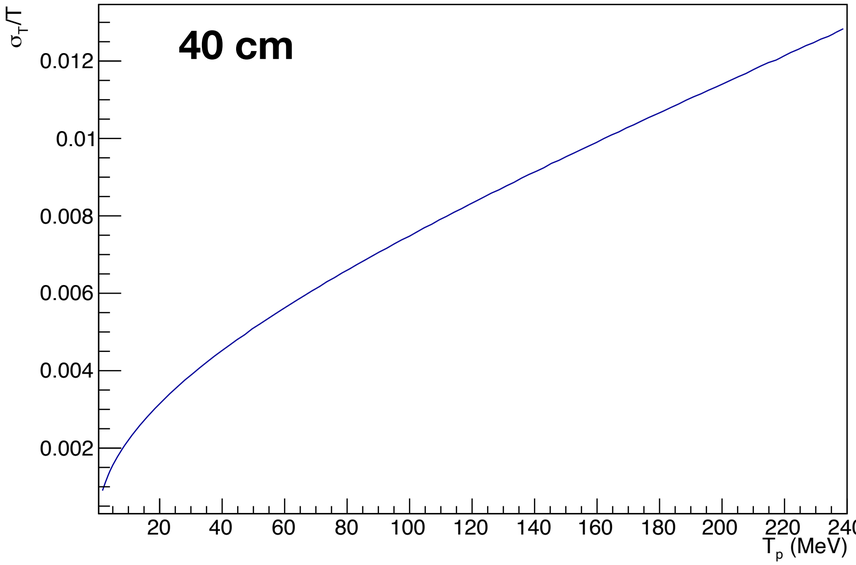
Effect of ToF distance

- Planes can be moved apart.
- Assume 10ps resolution:







already competitive for proton beam measurement

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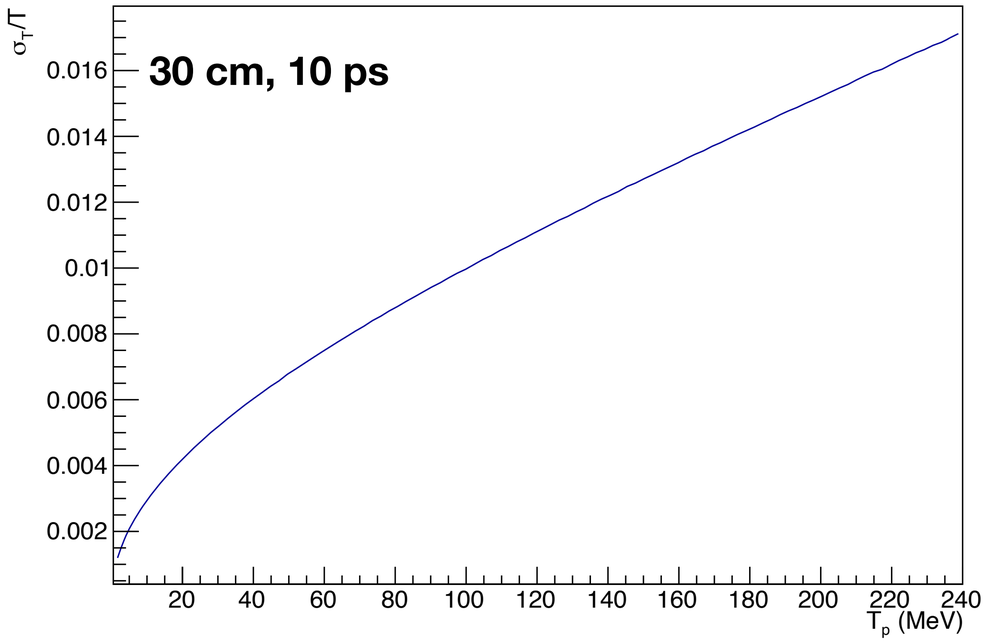
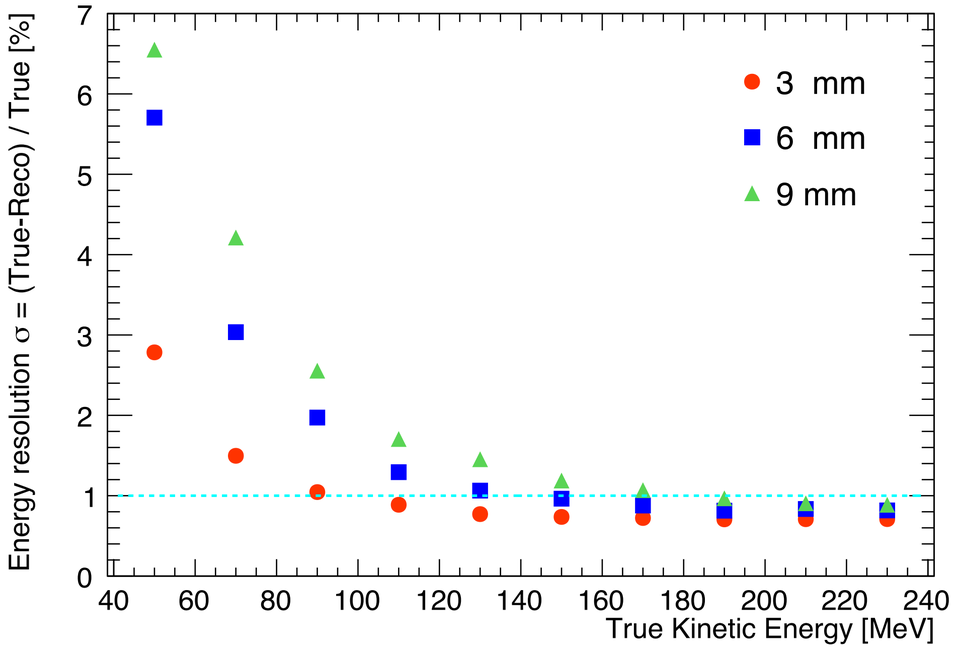
Discussion



Complementary



Beam Energy [MeV]	70	100	150	200	245
Beam Energy Spread	1.1%	1.1%	0.9%	0.6%	0.3%

Get proton kinetic energy dispersion to less than 1% in the full region of momentum.
Improve significantly the resolution after patient for < 100 MeV.

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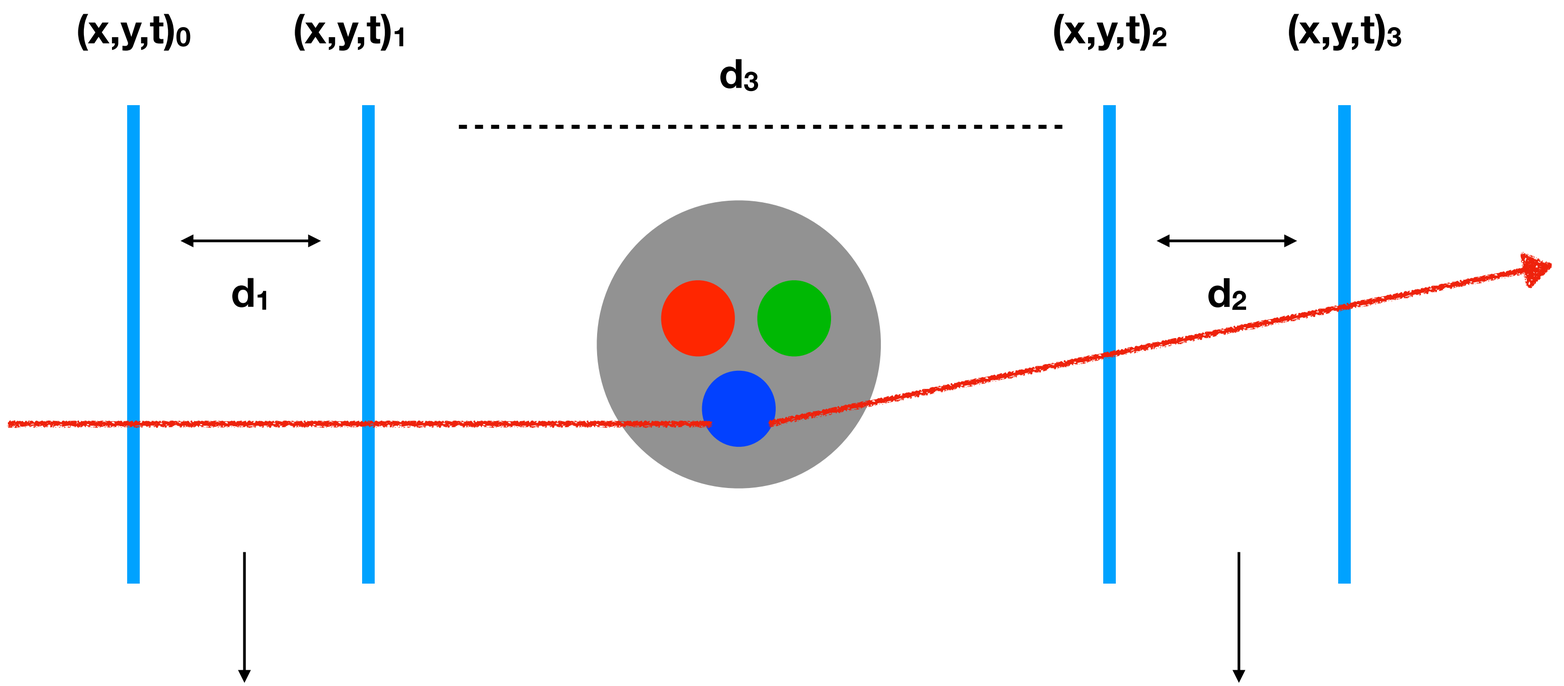
And more ?



position, angle and momentum from Time of Flight

position, angle and momentum from Time of Flight

d_3 can be used to explore the direction along the beam. 3D proton CT?

time can be used to have proper track matching to improve purity

proper time matching might help to use scattered protons

ToF method is better for lower proton momentum: can we do low momentum proton CT?

Compact and single technology.