Different energy detectors for single-event helium ion imaging

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Loma Linda workshop 2021

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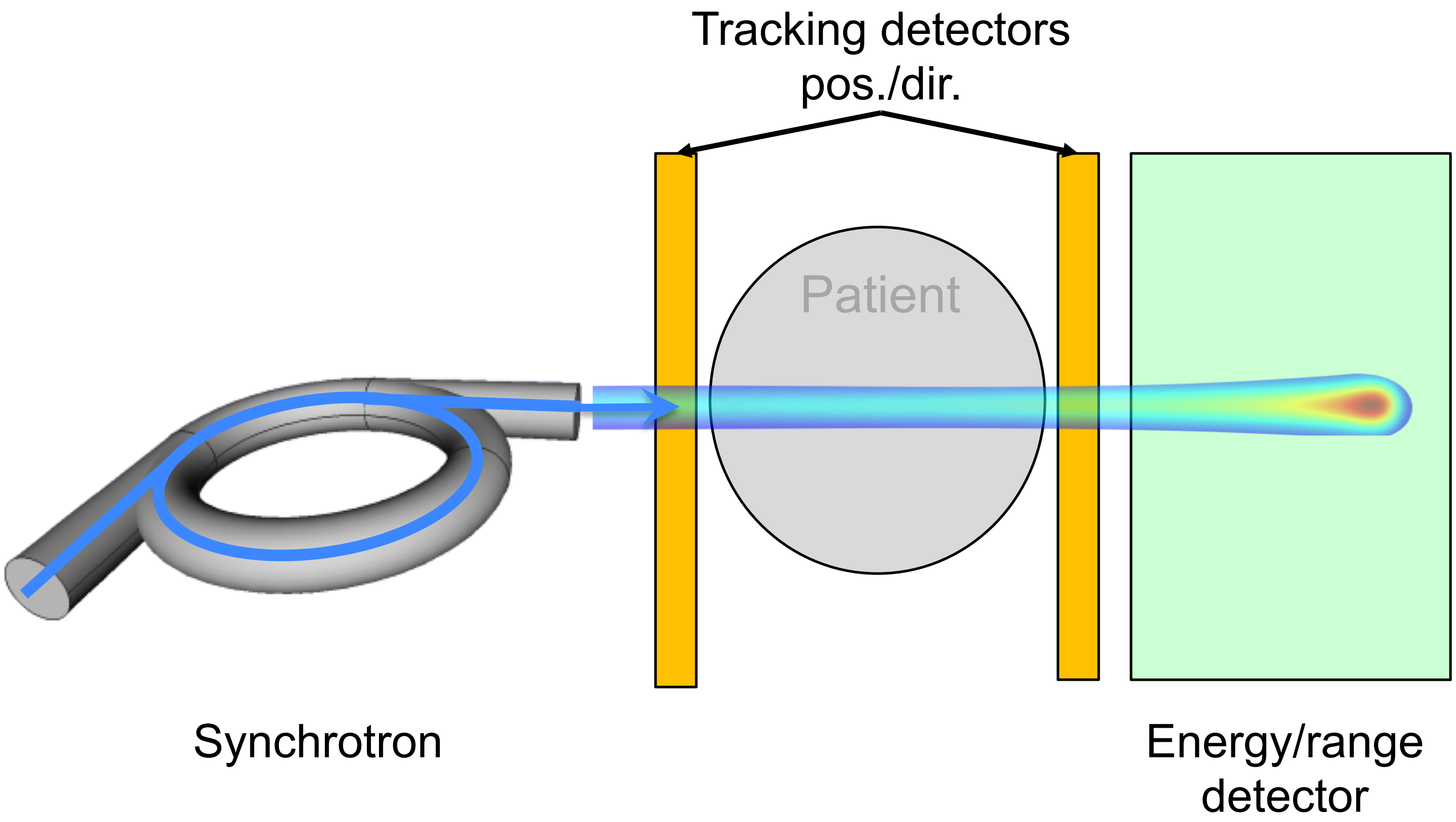
Setup



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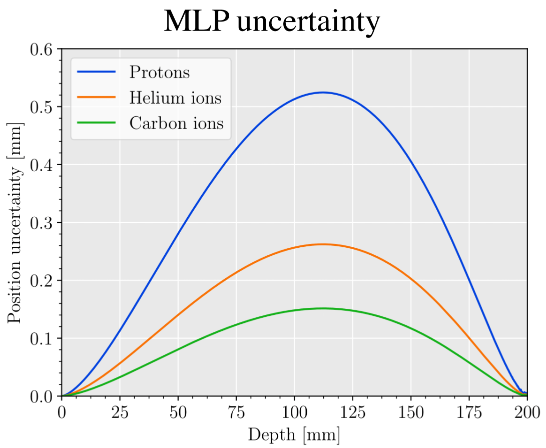
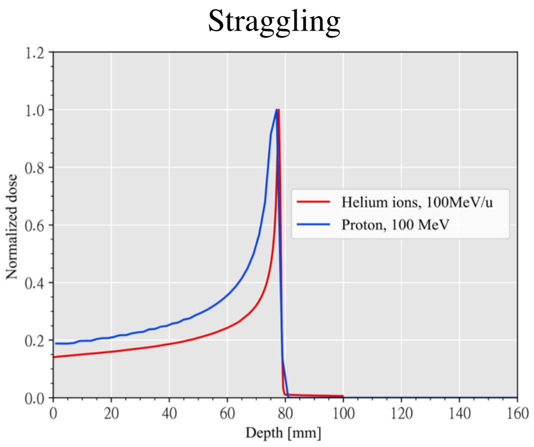
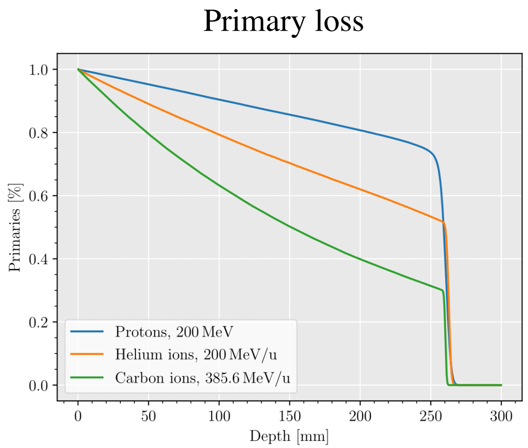
Why helium ion imaging?







- Factor 2 less scattering than protons
- Factor 2 less straggling than protons
- Lower loss of primaries than heavier ions

- Possibly best balance for imaging[1]

[1] Collins-Fekete et al. (2021) PMB

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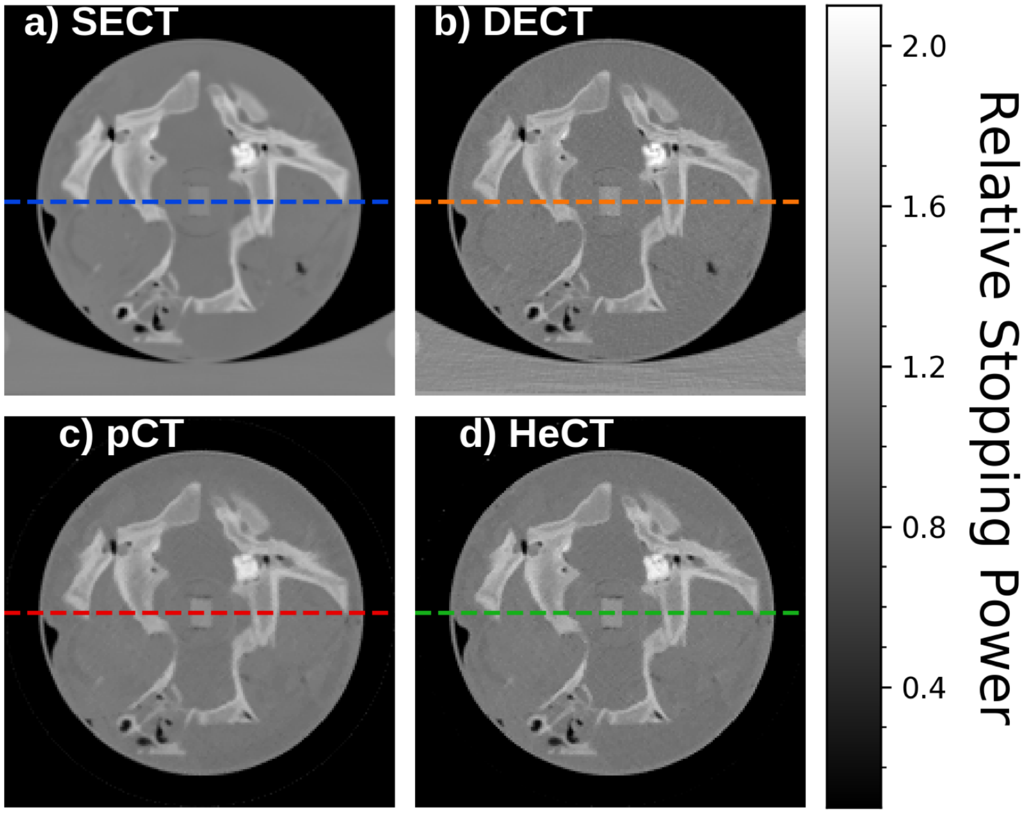
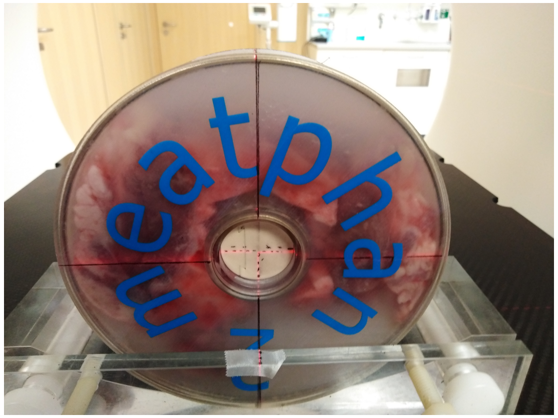
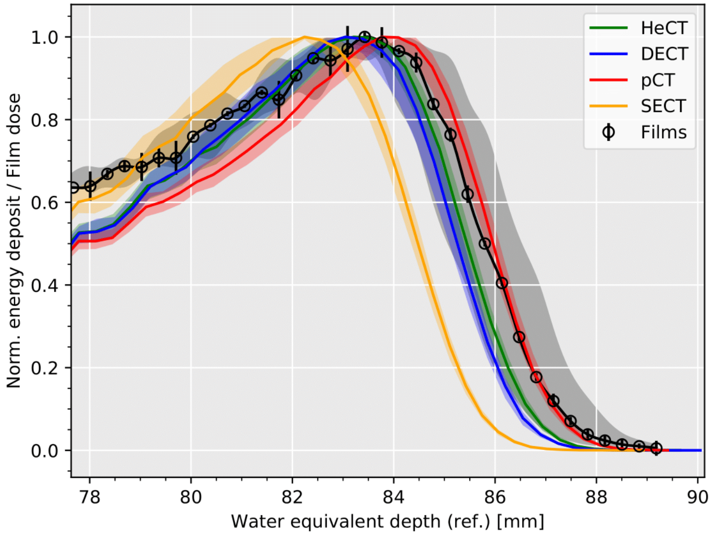
Helium CT with US pCT collaboration prototype







→ PTCOG59 Talk

- Volz, Bär, Collins-Fekete et al. In Preparation

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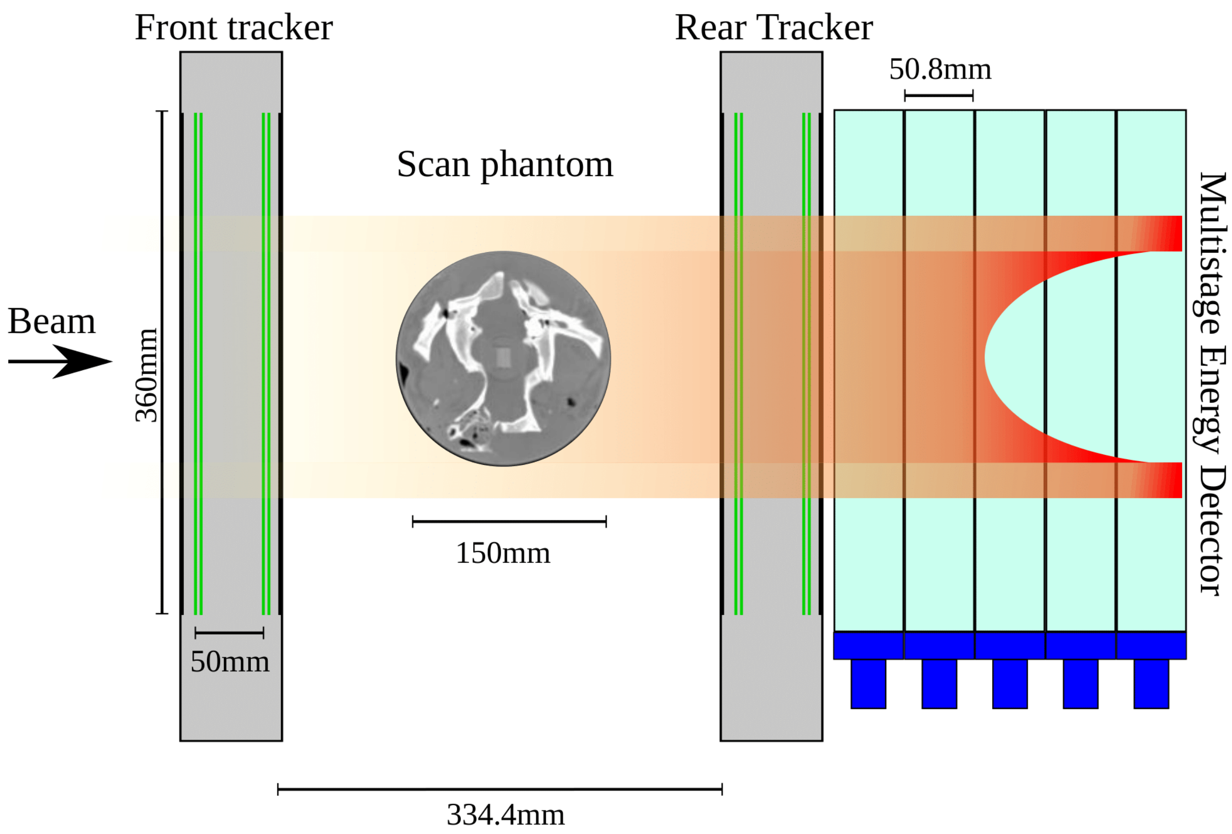
Helium CT with US pCT collaboration prototype



Optimized for proton imaging (Bashkirov et al. (2016) Med. Phys.)

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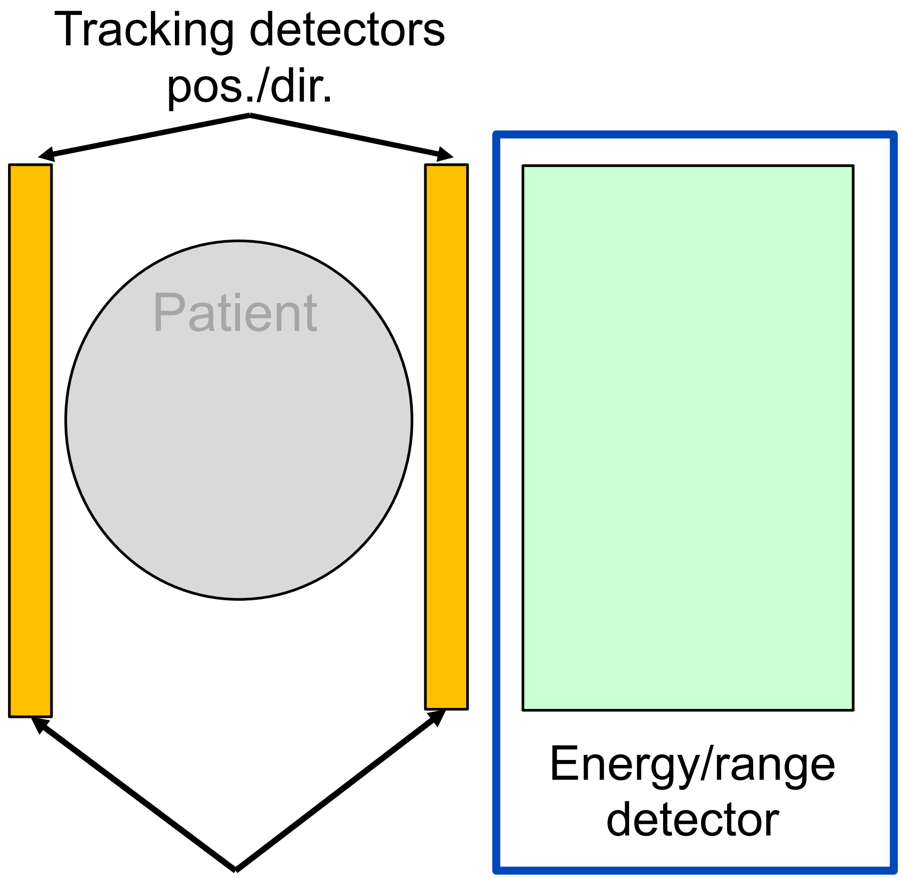
Can we improve the setup for helium ion imaging?



- Burker et al. (2020) arXiv
- Krah et al. (2018) PMB

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Wish list

1. Accurate

2. Precise

3. Fast

4. Robust

5. Inexpensive

6. Flexible

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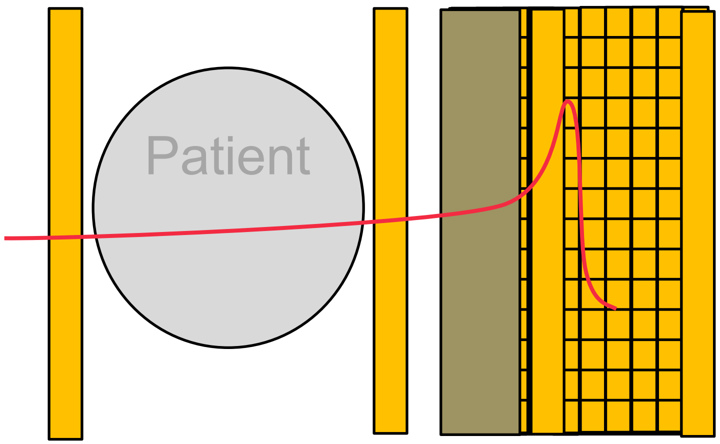
Candidate technology?

- Single stage calorimeters
  - Civinini et al. (2020) PMB
  - ProtonVDA Inc.
- Multistage calorimeters
  - Bashkirov et al. (2016) Med. Phys.
- Range telescopes
  - Sadrozinsky et al. (2013) Med. Phys.
- Tracking telescopes
  - Pettersen et al (2019) Phys. Med.
  - Esposito et al. (2018) Phys. Med.
- Time-of-Flight
  - Worstell et al. (2019) SPIE
- Single plane detector
  - Gehrke et al. (2017/2018) PMB



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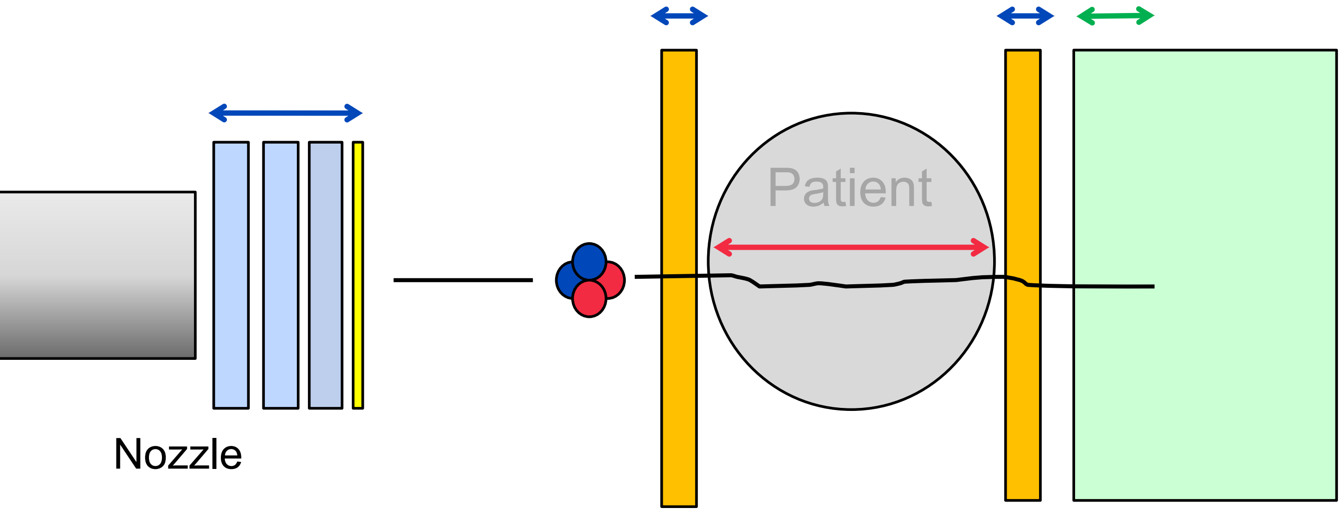
Intrinsic noise properties

Following Bashkirov et al. (2016) Med. Phys.



$$\sigma_{WEPL} = \sqrt{\left(\frac{\sigma_r}{R_0}(WEPL + W_0)\right)^2 + \sigma^2_{Rres}}$$

$$\sigma_{WET} = \frac{\sigma_{WEPL}}{\sqrt{N}}$$

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Intrinsic noise properties

Following Bashkirov et al. (2016) Med. Phys.

- SS-Calorimeter:

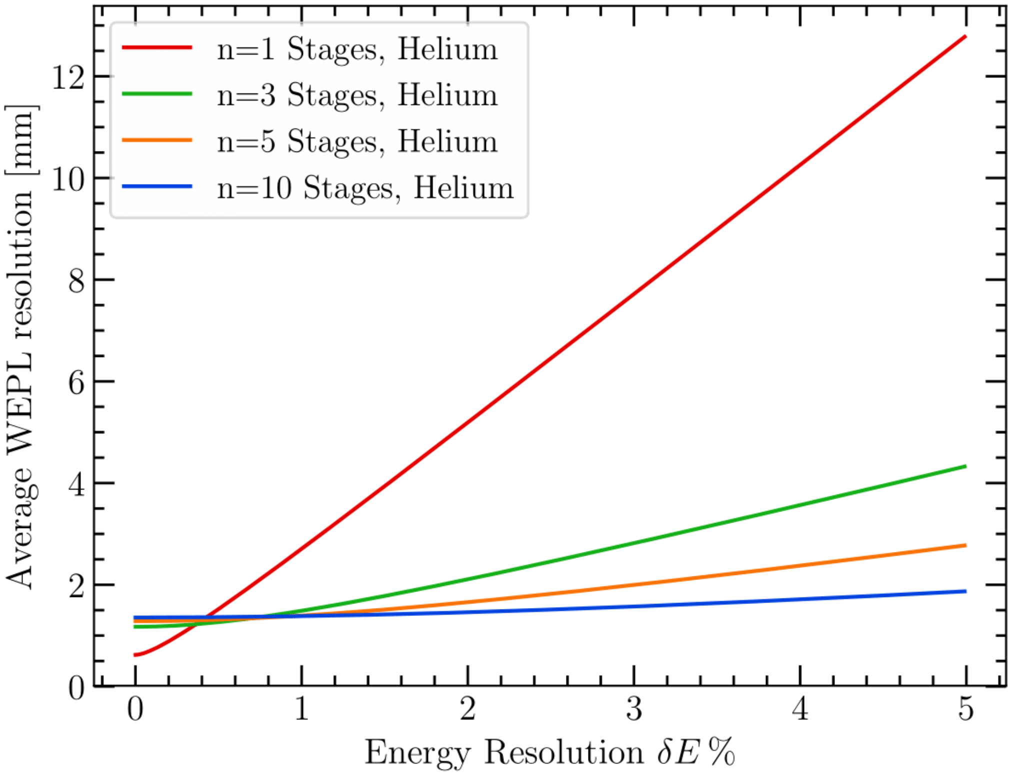
$$R_{res} = aEp$$

$$\sigma_{Rres} = p\,\frac{\sigma_E}{E}\,Rr_{es}$$

- MS-Calorimeter:
  Stages crossed add to *W_0*

- Range telescope:

$$\sigma_{Rres} = \Delta Slab/\sqrt{12}$$



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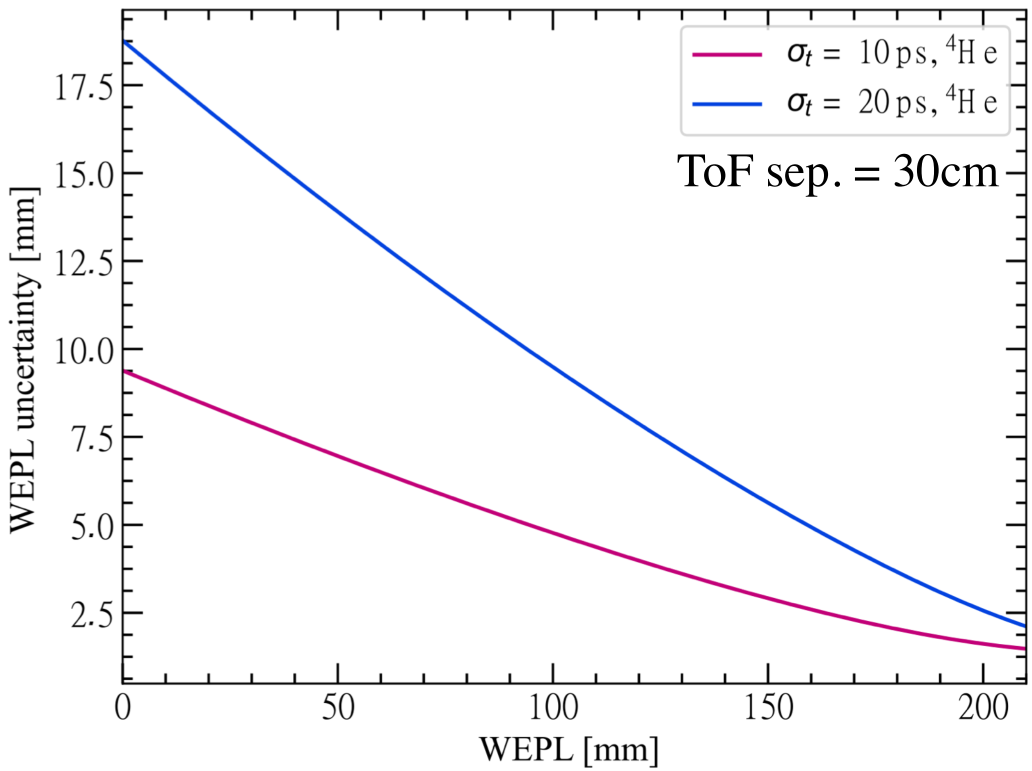
Intrinsic noise properties: Time of Flight detector

- ToF:

$$R_{res} = aEp$$

$$\sigma_{Rres} = p\,\frac{\sigma_E}{E}\,Rr_{es}$$

$$\frac{\sigma_E}{E} = \frac{\gamma^3 m v^2}{t}\frac{\sqrt{2}\sigma_t}{E}$$



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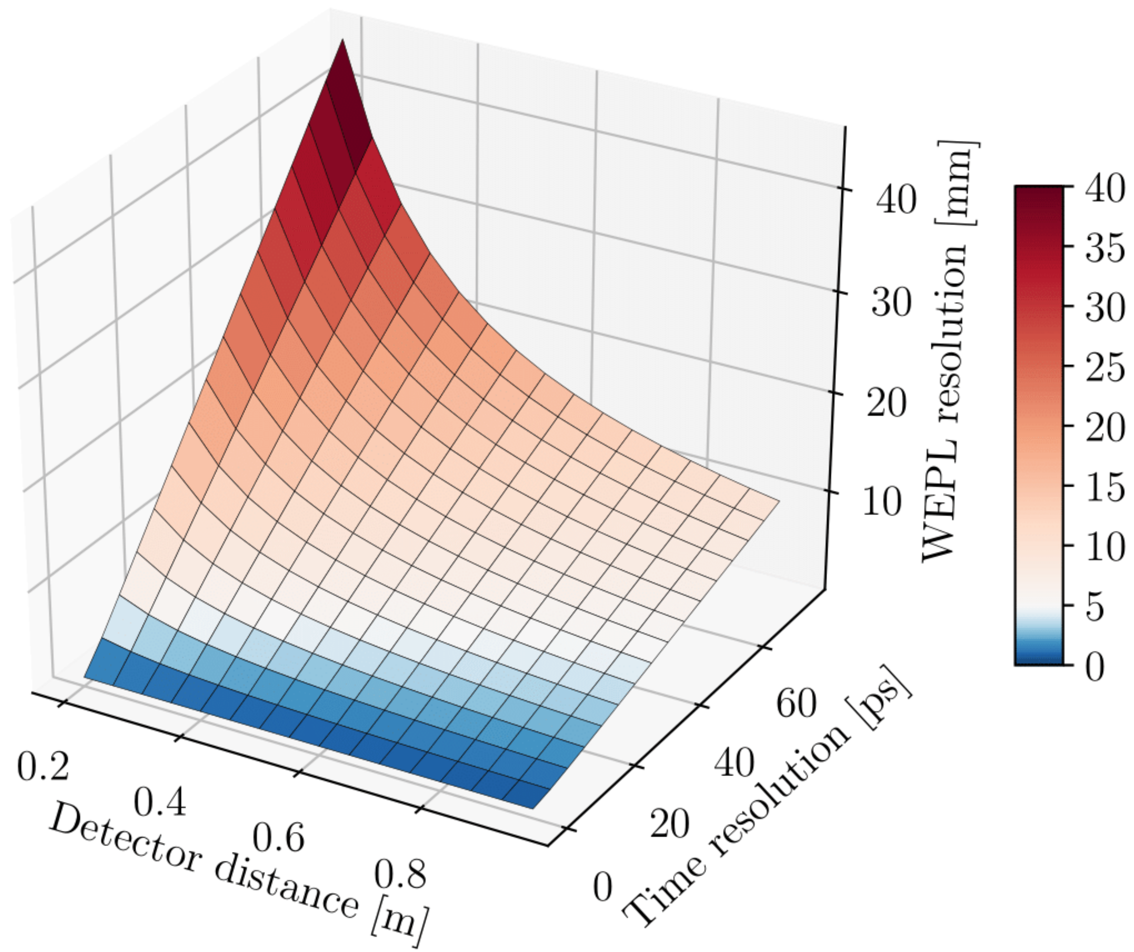
Intrinsic noise properties: Time of Flight detector



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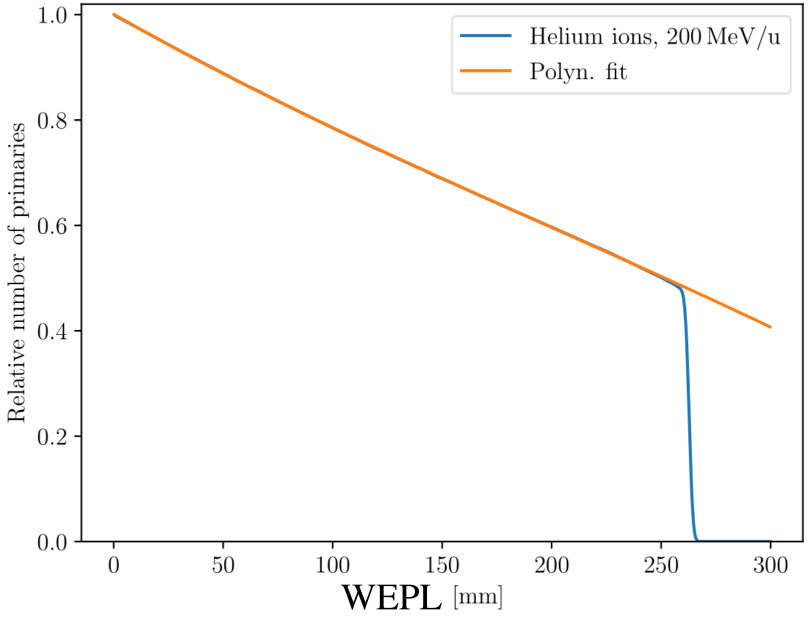
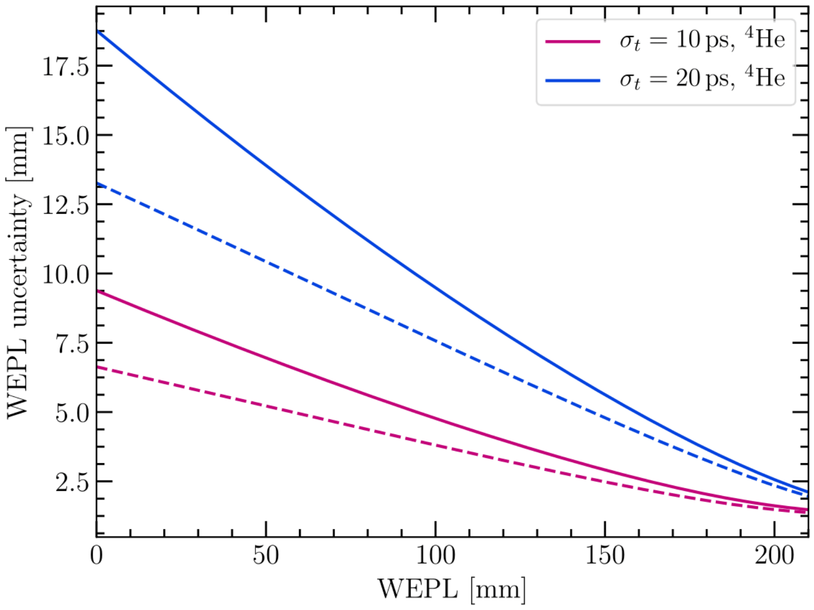
Intrinsic noise properties: Time of Flight detector





$$N_{ToF} = NP_{rim} \times f(WEPL)$$

$$N_{others} \cong N_{Prim} \times 0.5$$

$$\rightarrow NTo_F = 2f(WEPL)N_{others}$$

$$\sigma_{WET} = \frac{\sigma_{WEPL}}{\sqrt{N}}$$

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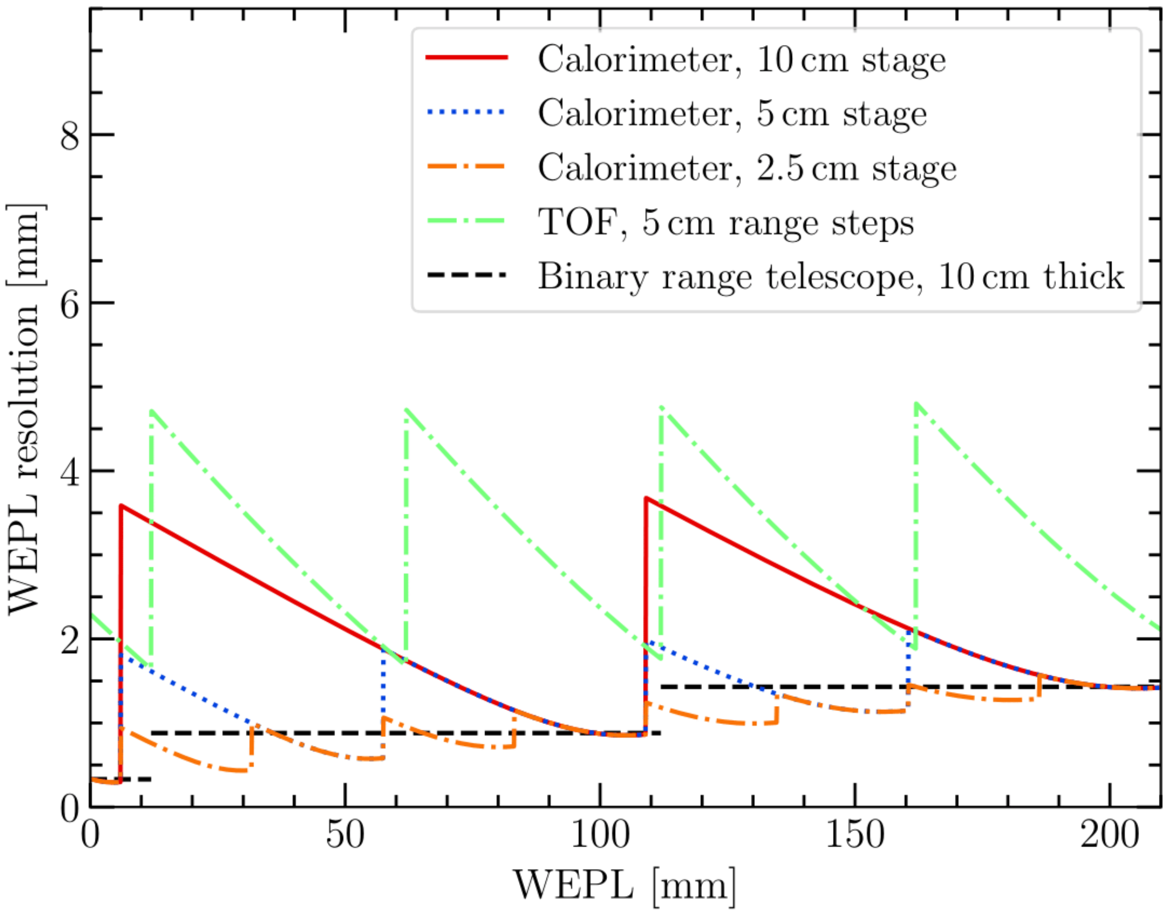
Intrinsic noise properties: Energy modulation



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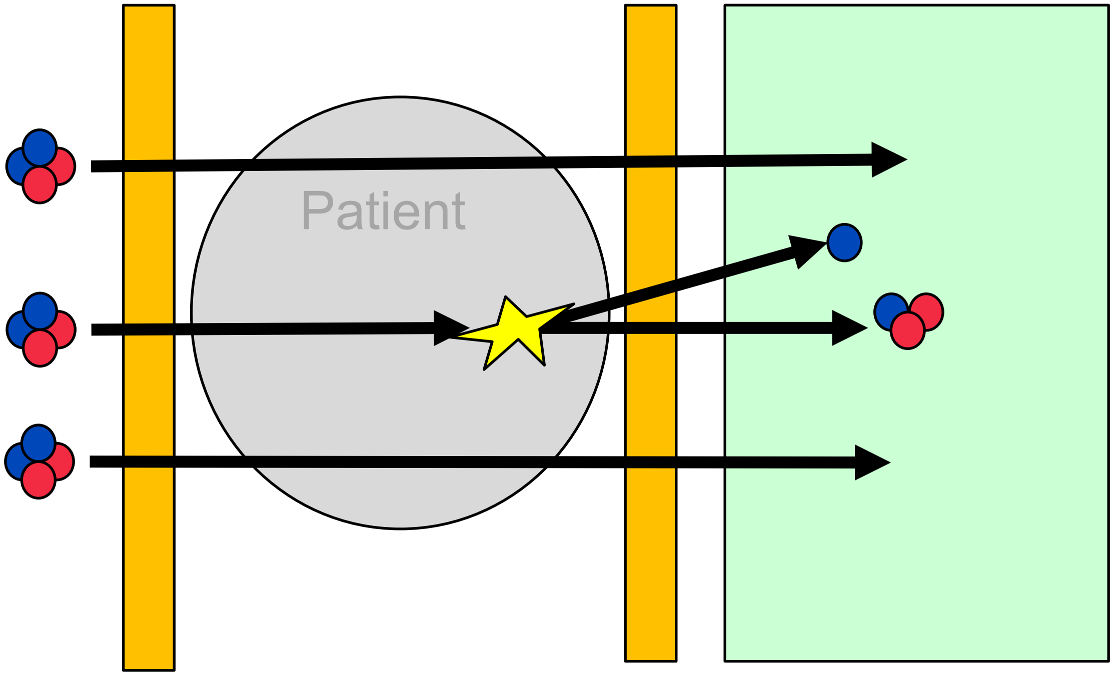
Fragment filtering



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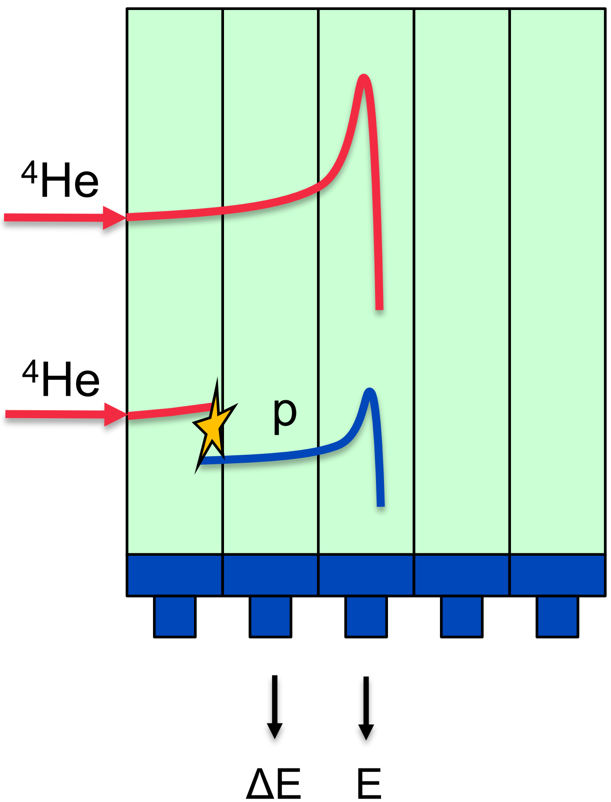
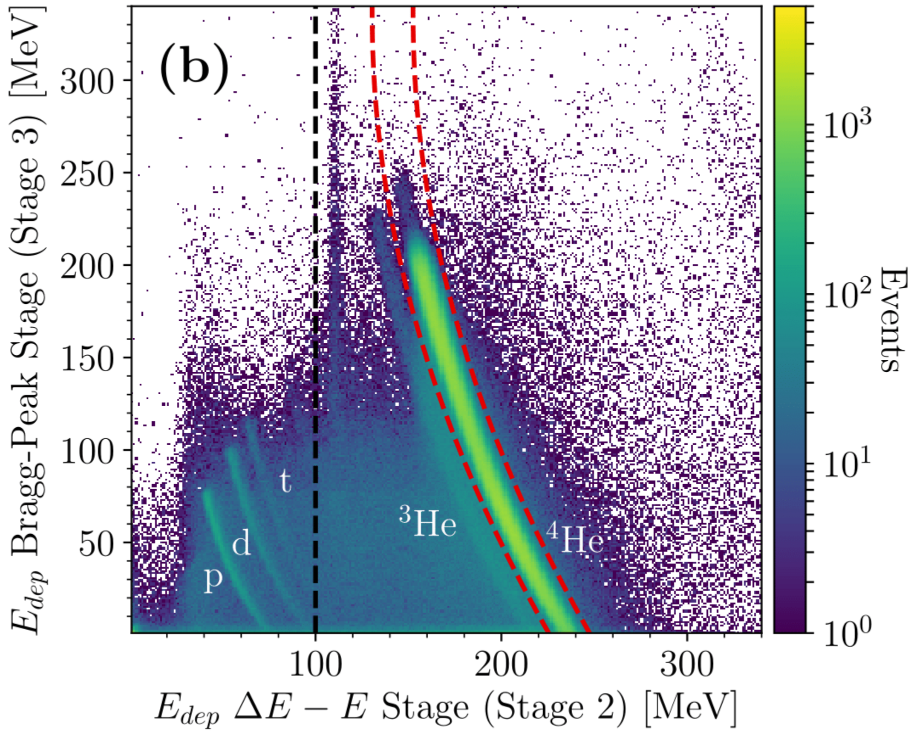
Fragment filtering





- Volz et al. (2018) PMB

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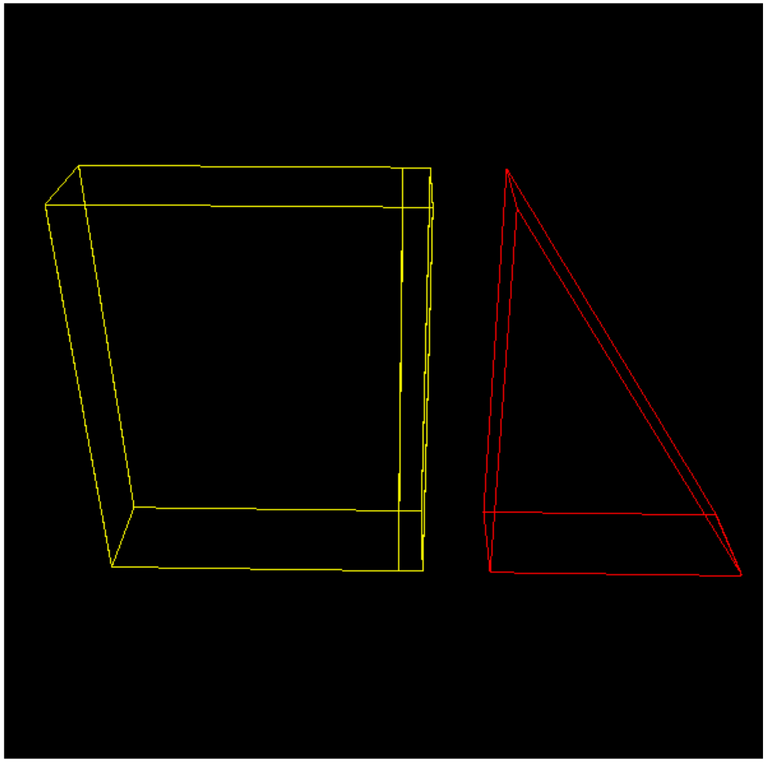
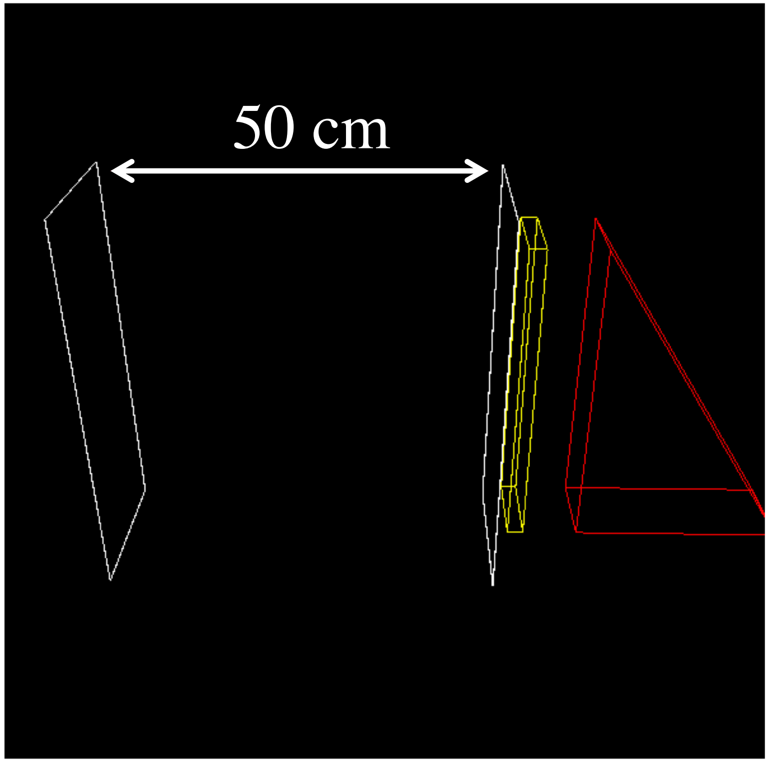
Fragment filtering

- TOPAS MC simulations
- based on Piersimoni et al. (2018) Med. Phys.
- Scintillation light quenching in Sim;
- Energy/time res. post hoc: 2%σ_E; σ_t=64ps
- 5x10^5 primaries, 200 MeV/u, flat field





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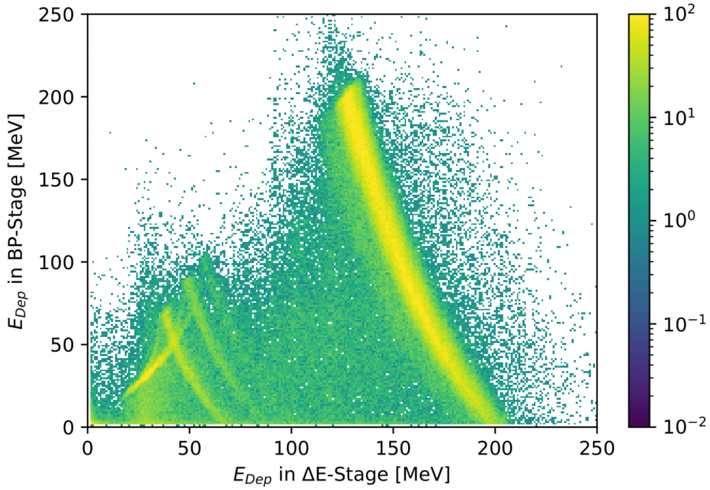
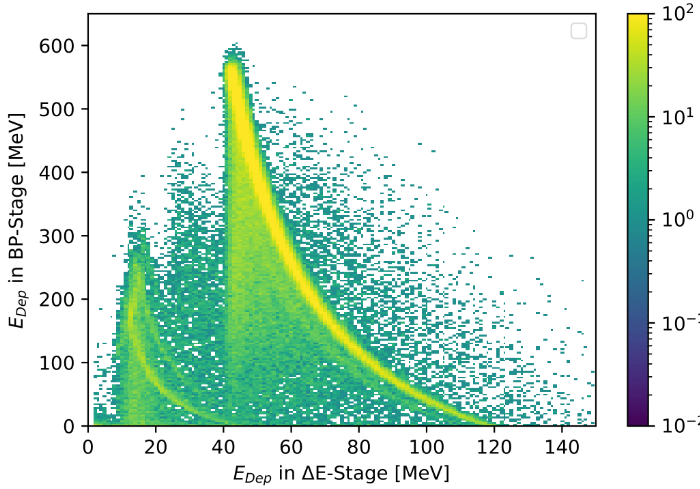
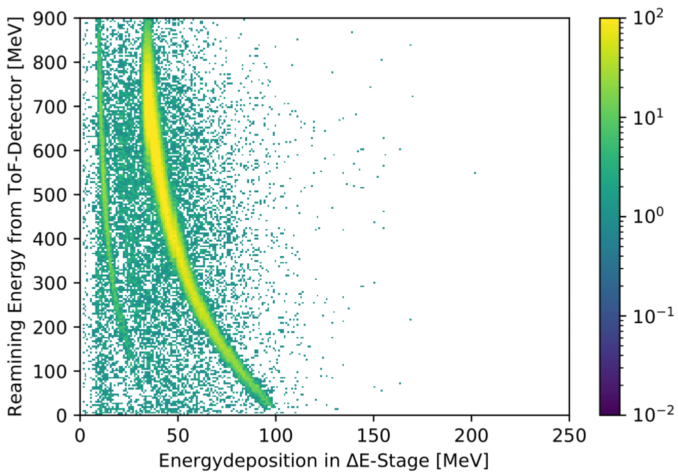
Fragment filtering



- 5-stage Calorimeter



- Single Calorimeter (+dE)



- ToF (+dE)

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Fragment filtering

	5-stage
TP	47.7%
TN	45.8%
FP	4.2%
FN	2.3%

TP = not filtered, primary
FP = not filtered, secondary
TN = filtered, secondary
FN = filtered, primary

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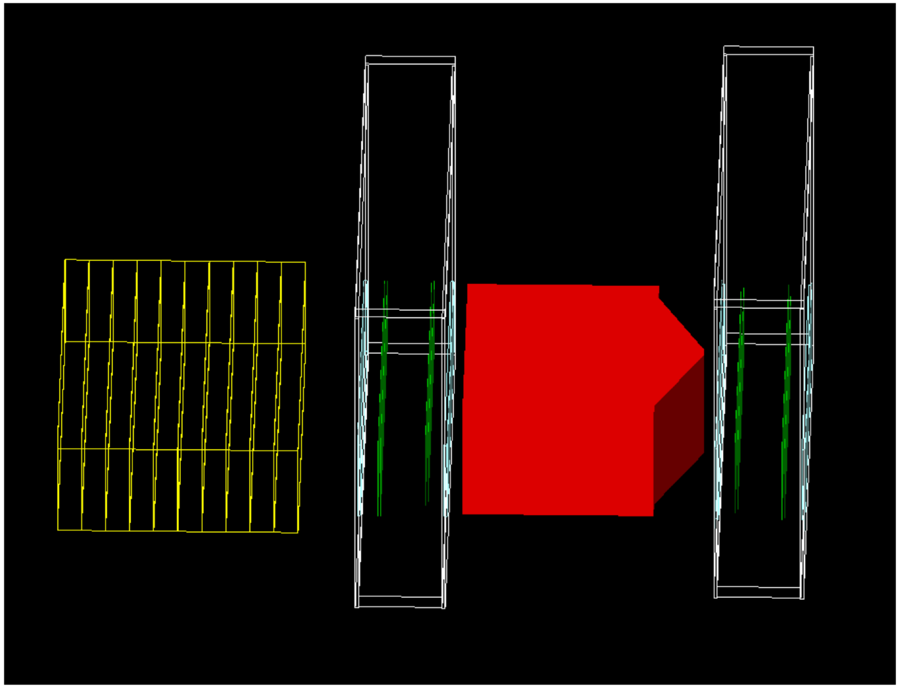
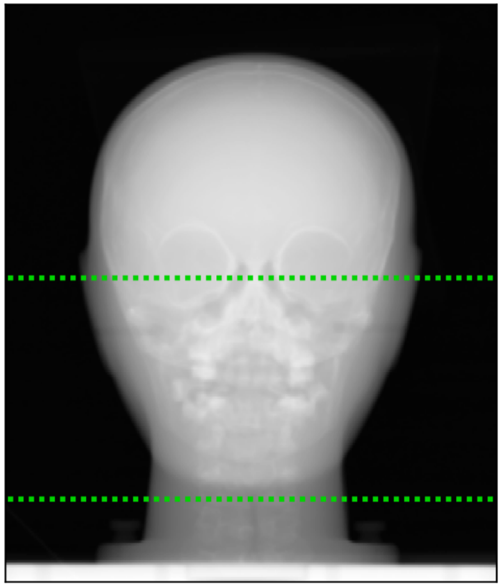
HeRads of head phantom

- Setup based on Piersimoni et al. (2018) Med. Phys.
- Digital ped. head from Giacometti et al. (2017) Med. Phys.
- Calibration following Schultze et al. (2021) IEEE





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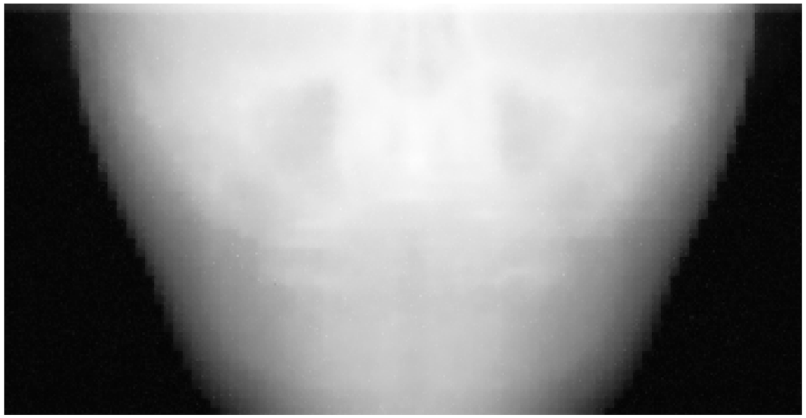
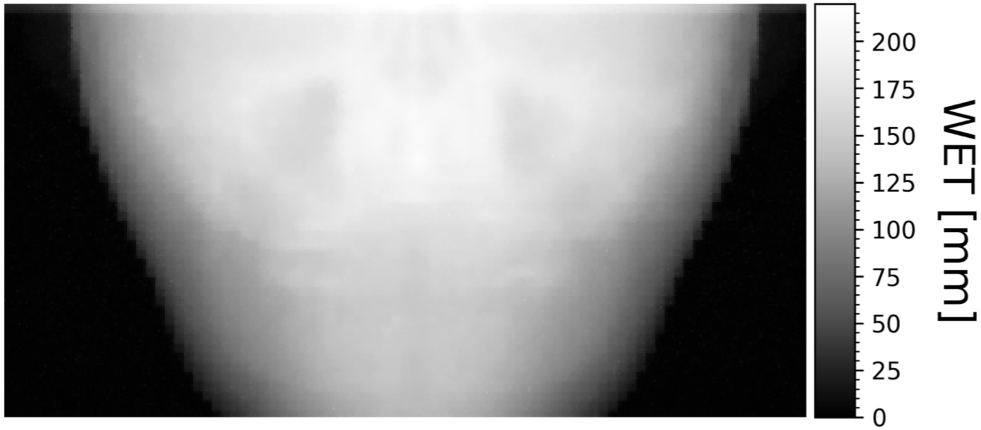
HeRads of head phantom

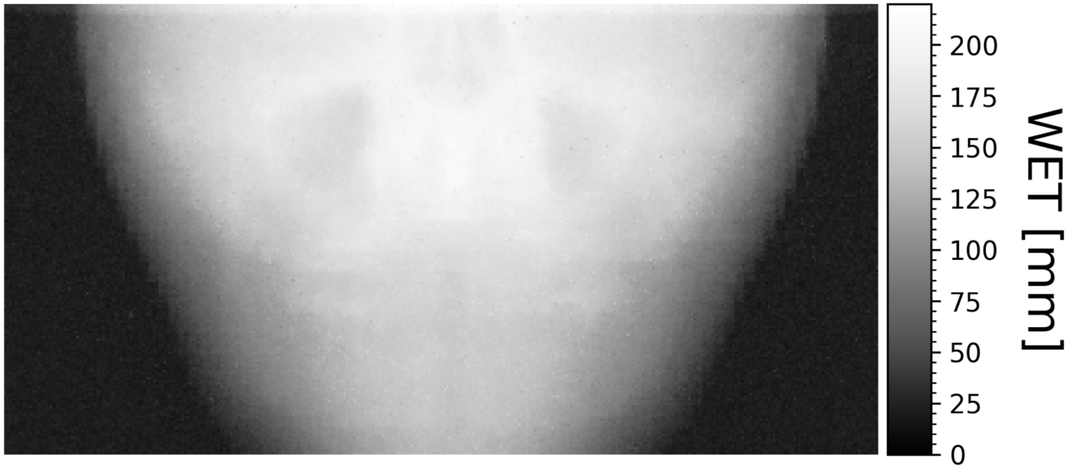
5-stage Cal.



10-stage Cal.



TOF



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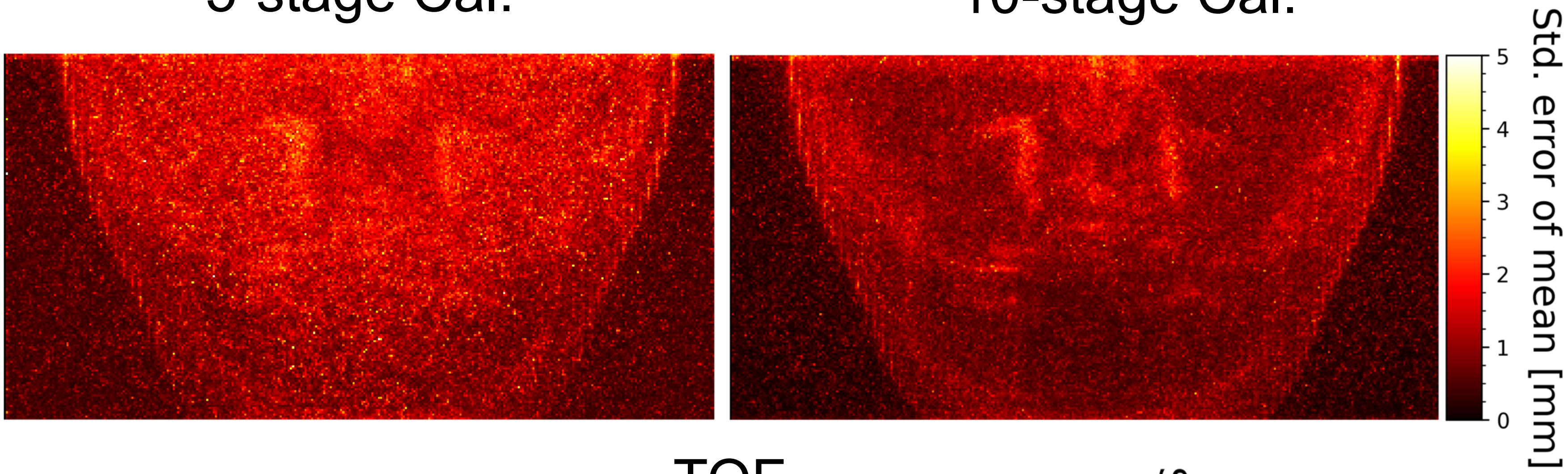
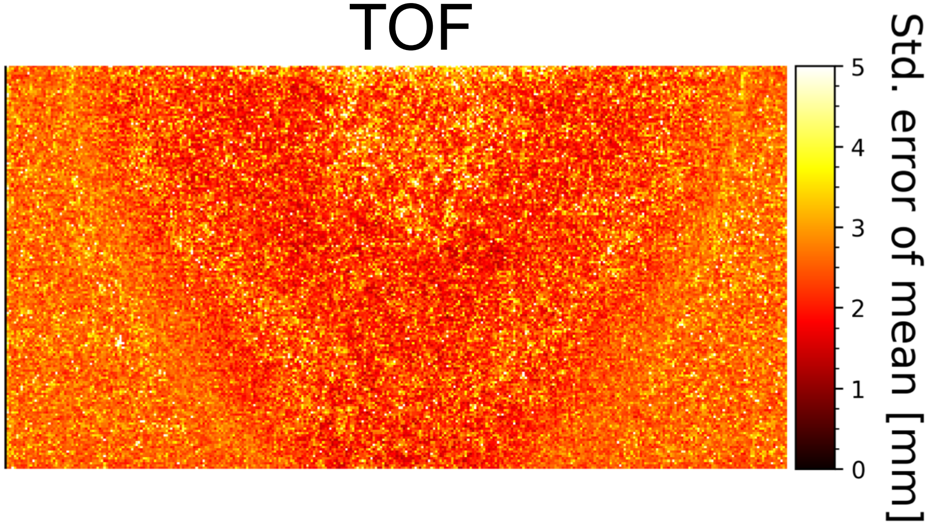
HeRads of head phantom

5-stage Cal. | 10-stage Cal.



TOF



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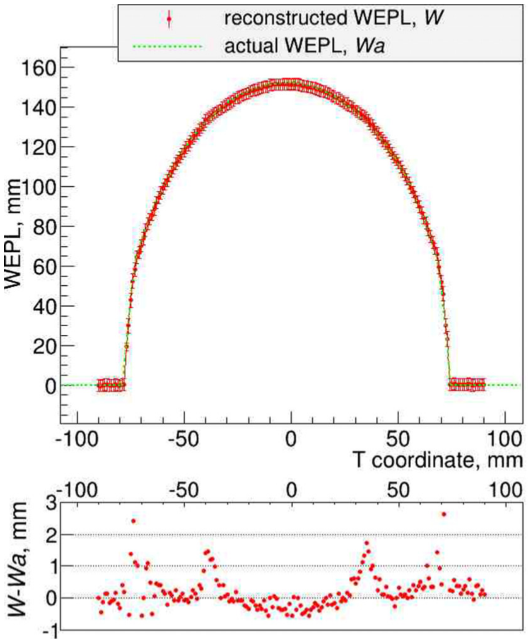
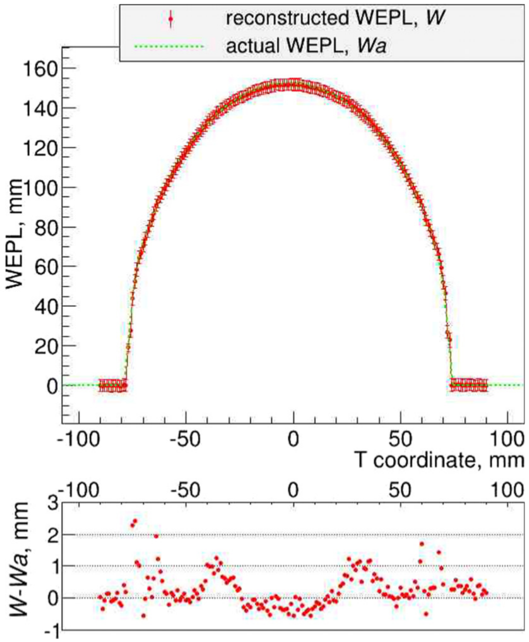
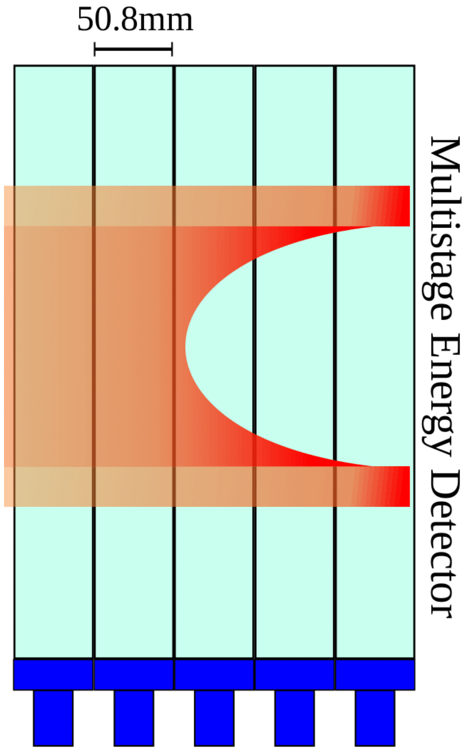
Artifacts for multistage designs







- Simulated and experimental radiograph of a water phantom compared to ground truth.
  Bashkirov et al. (2016) Med. Phys.

Recent improvements by Dickmann et al. (2021) Phys. Med.

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Conclusions

- Multi-stage design offer high precision…
  but suffer artifacts and lack acquisition speed
- Single stage detectors avoid artifacts…
  but lack precision and speed
- Binary range telescopes are precise and accurate…
  but lack intrinsic filtering capabilities
- ToF detectors are fast and reduce primary loss…
  but require very high time resolution

→ A bit inconclusive… Maybe range telescopes?

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Backup

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