23rd iWoRiD International Workshop on Radiation Imaging Detectors

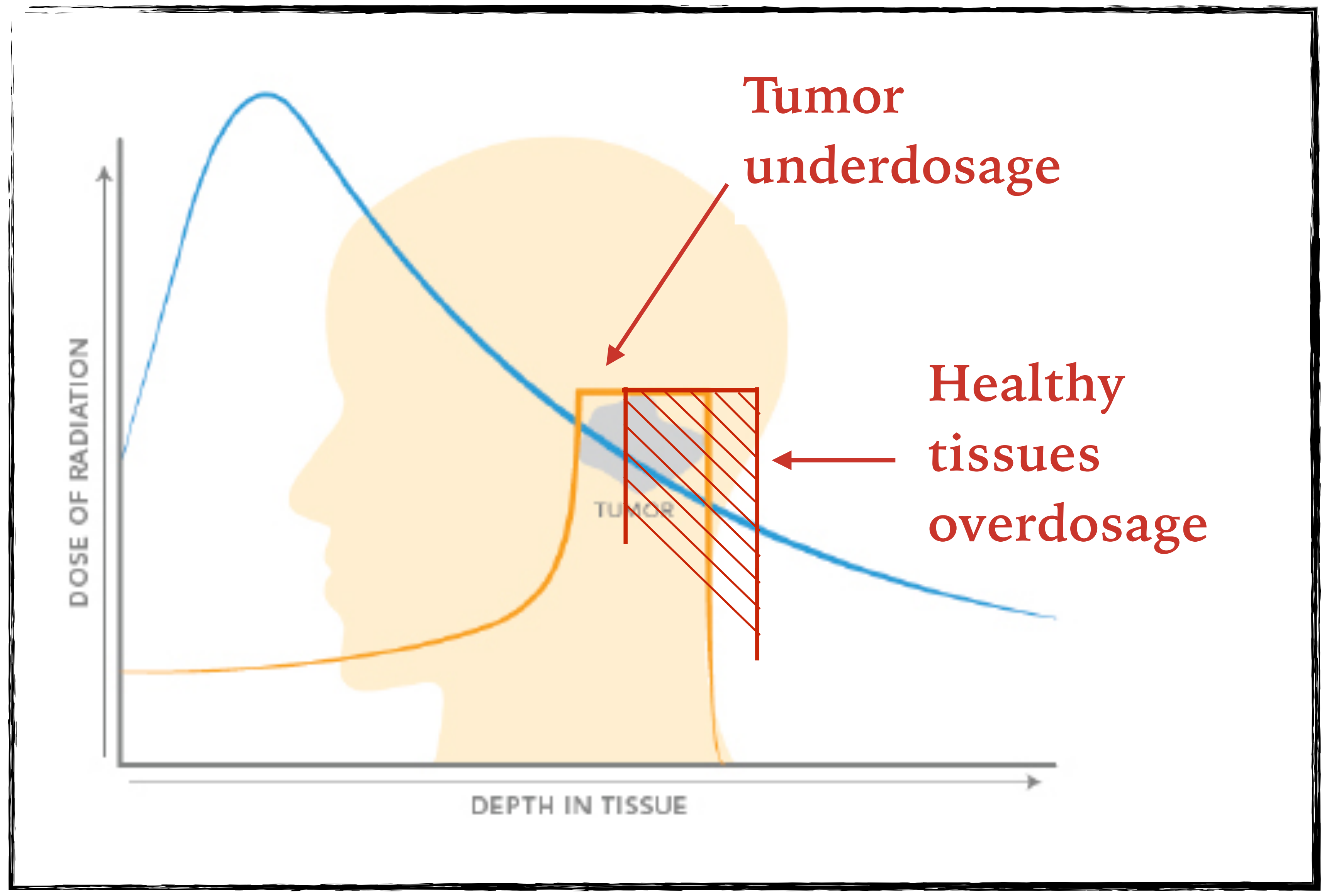
MEASUREMENT OF THE ENERGY LOSS DURING PROTON THERAPY: A NEW TREATMENT VERIFICATION TECHNIQUE

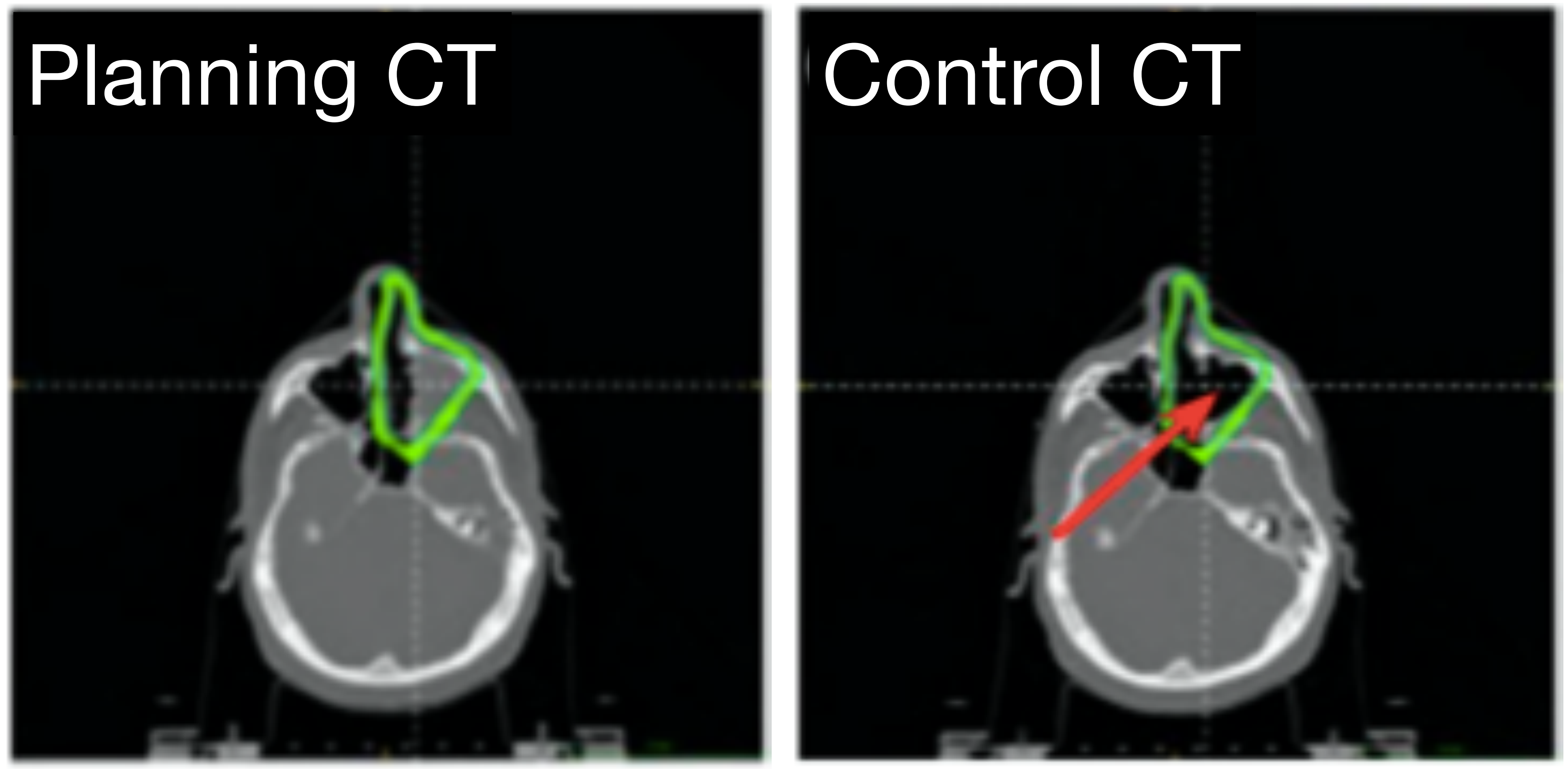
V. Ferrero, M. Aglietta, P. Cerello, E. Fiorina, M. Rafecas, A. Vignati, J. Werner and F. Pennazio

Istituto Nazionale di Fisica Nucleare

26-30 June 2022, Riva del Garda

TREATMENT VERIFICATION



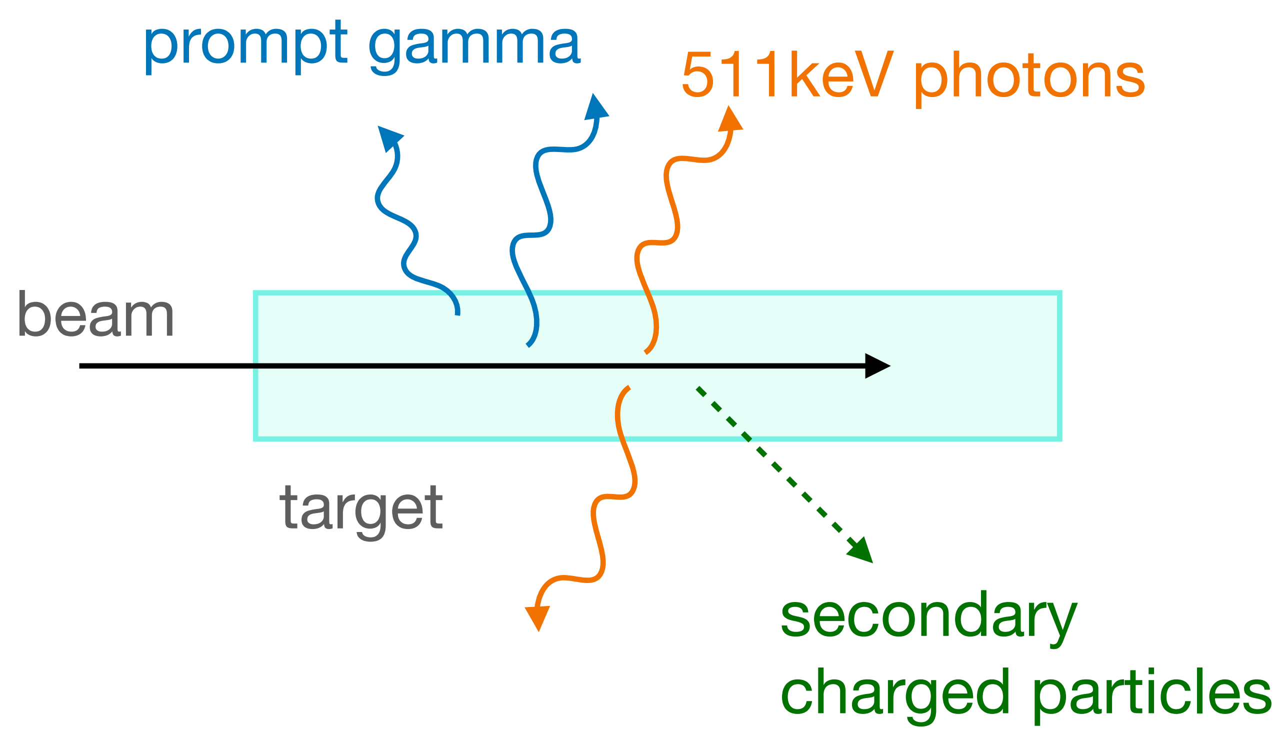


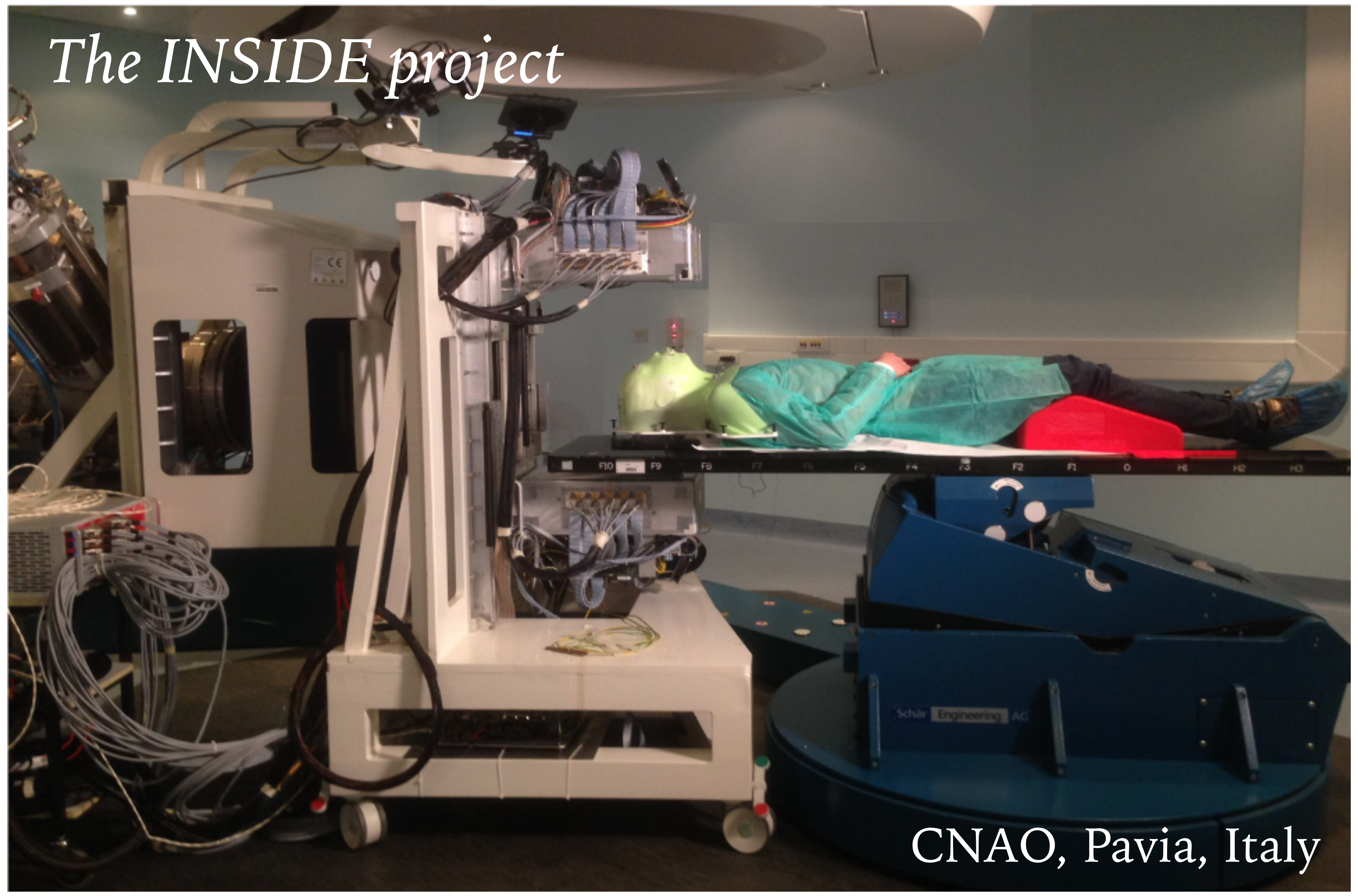
Fiorina E., Ferrero V, et al. Frontiers in Physics 2021

Dose uncertainties:

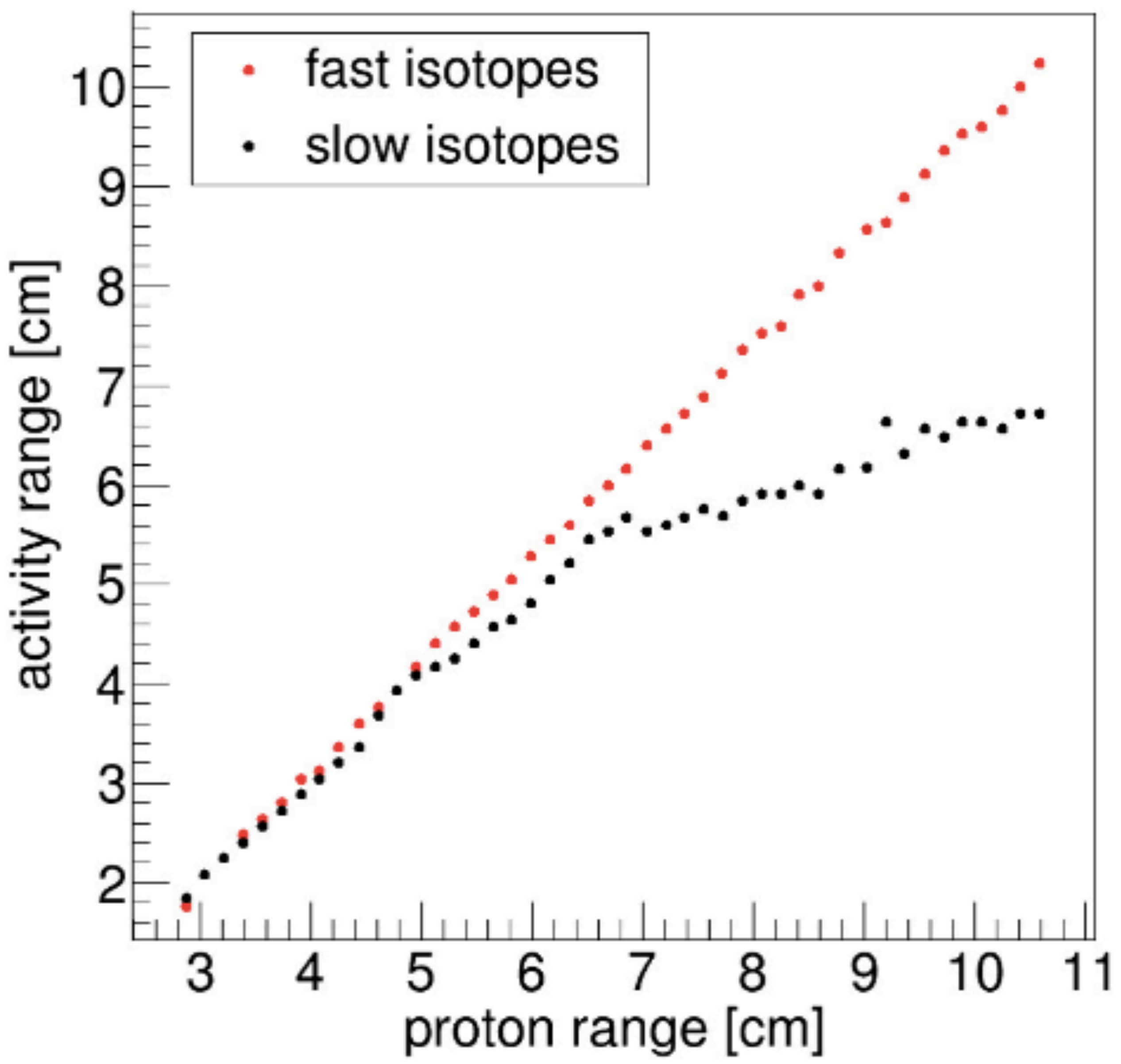
- Patient setup
- Dose calculation
- Anatomical changes

~ 100 proton therapy facilities all over the word (PTCOG)

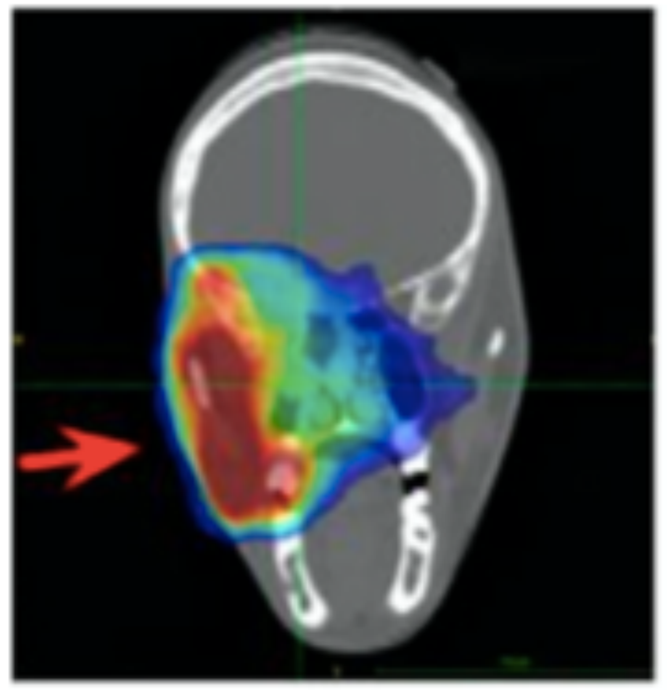




SECONDARY PARTICLES FOR RANGE MONITORING



Ferrero V et al. NIM A 2019

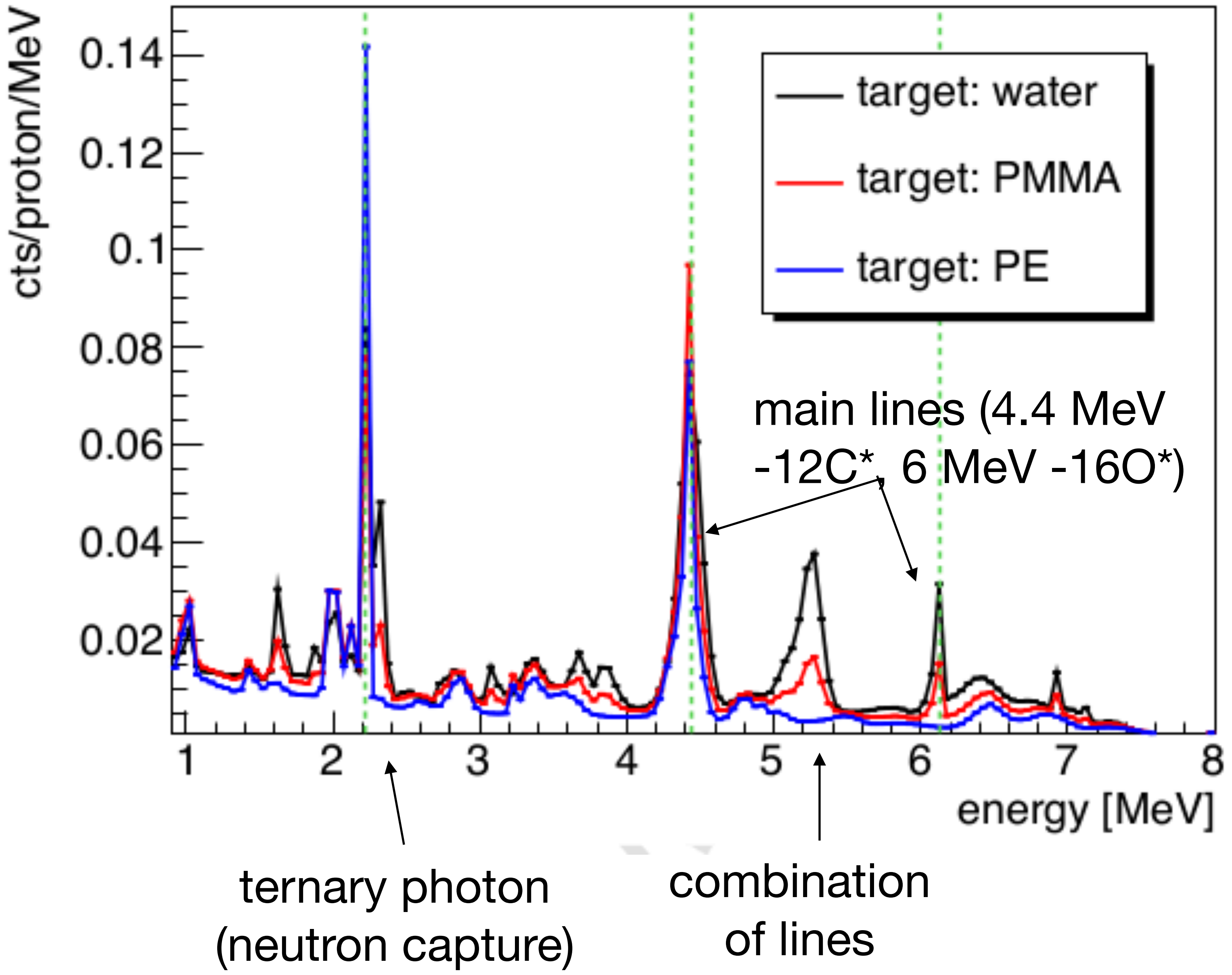


PET signal (MLEM)

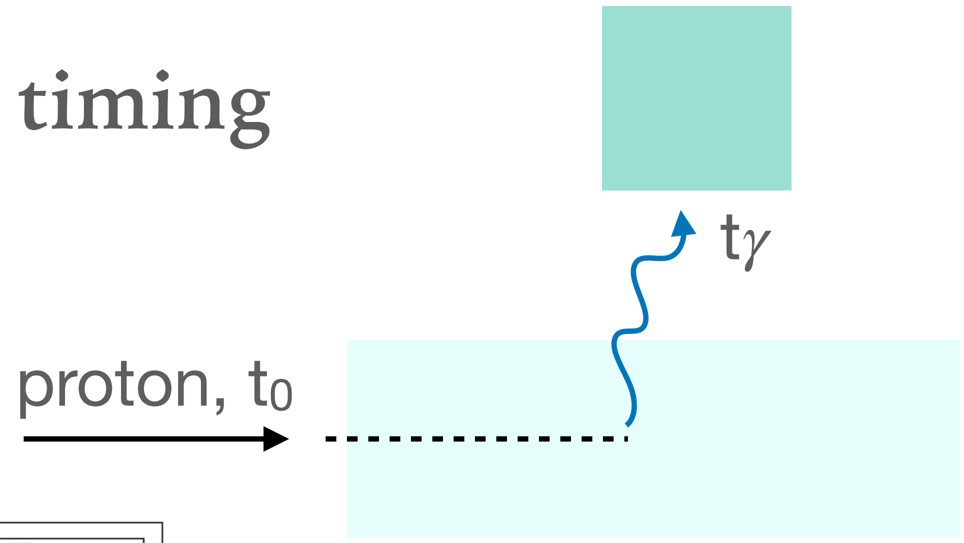
Prompt gamma: commercial interest

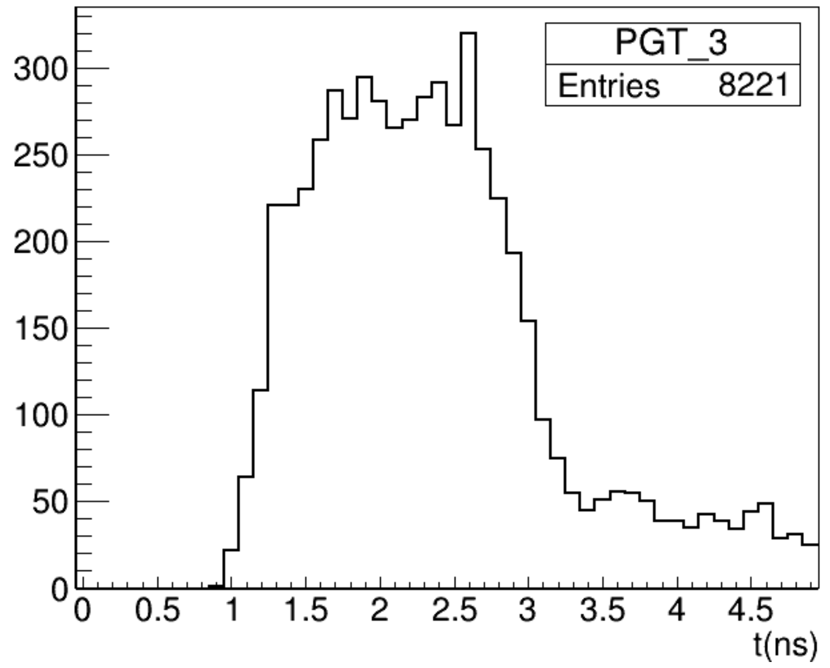
IBA Knife-Edge Slit Camera (collimator): Head-and-neck, brain tumors (range shifts 1-2mm)

Krimmer et al NIM A 2018



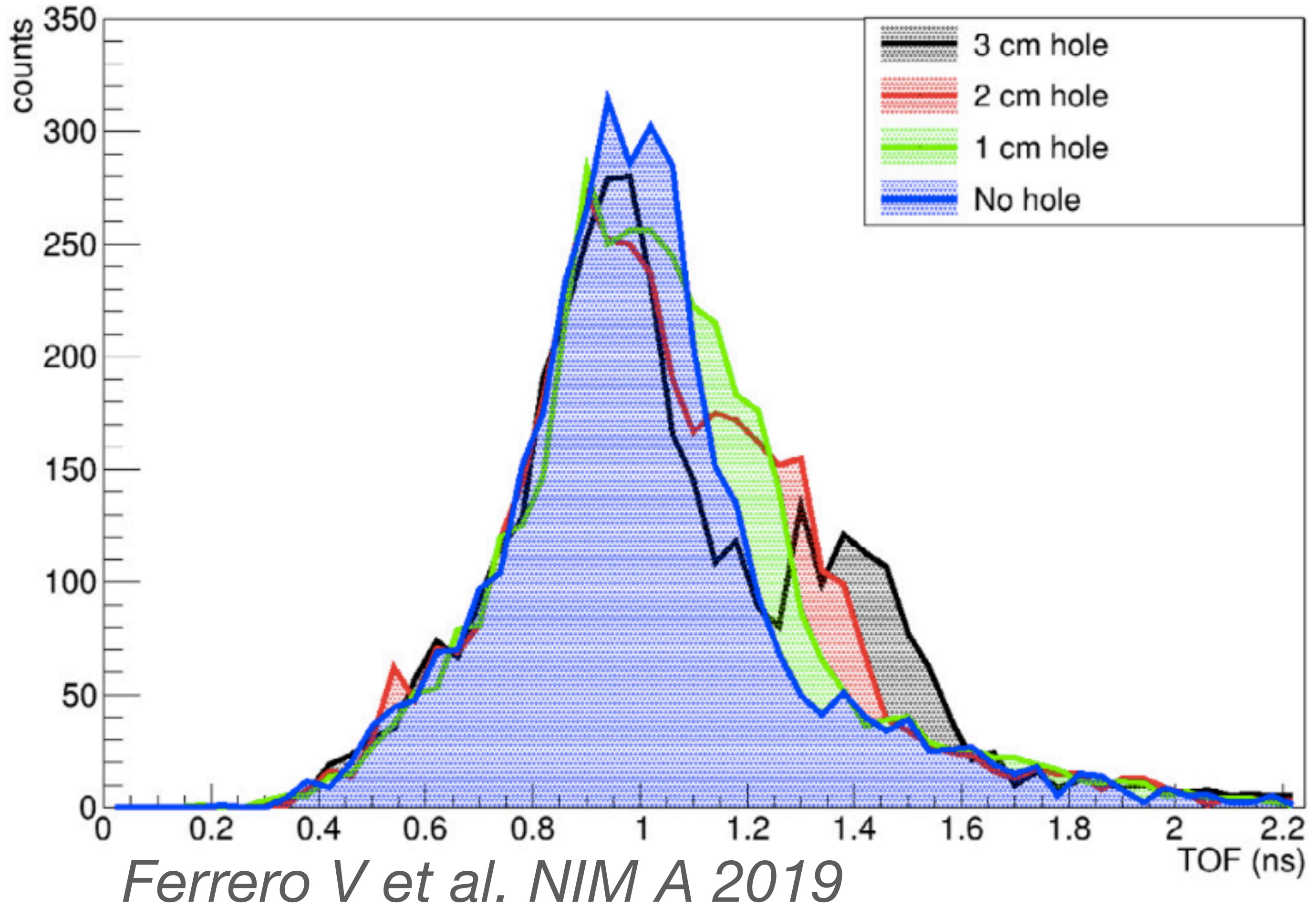
Prompt gamma timing (PGT)





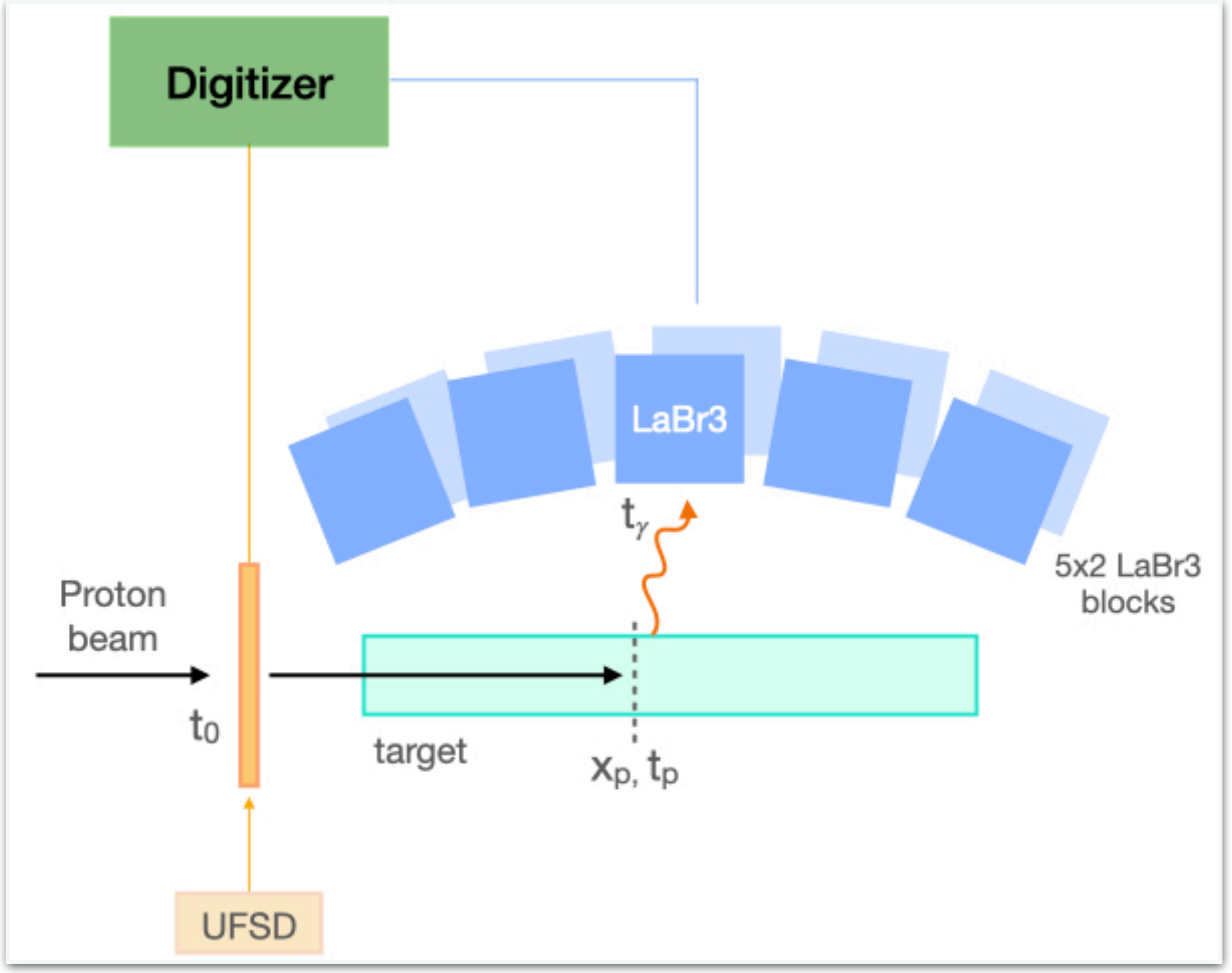
$TOF = t_\gamma(z_p) - t_0$

PGT for range monitoring



Ferrero V et al. NIM A 2019

SPATIO-TEMPORAL EMISSION RECONSTRUCTION



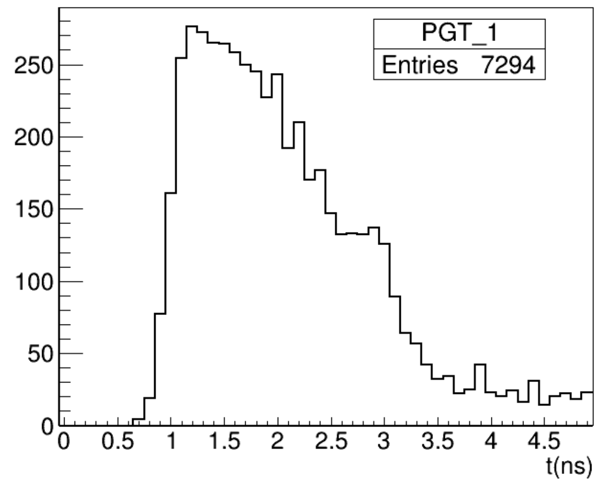
PGT MULTI-DETECTOR SYSTEM

Setup with N detectors

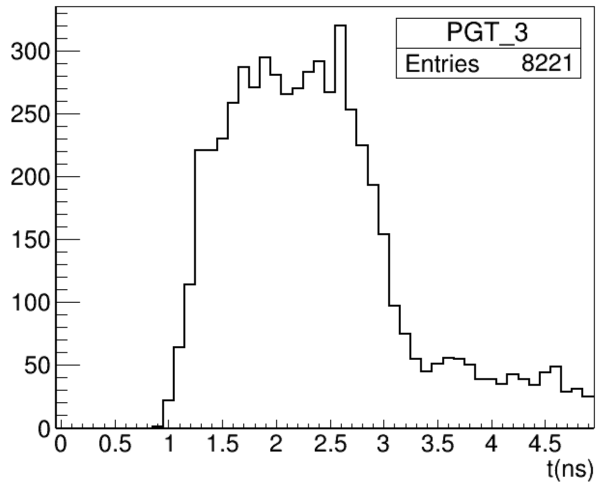
LaBr3:Ce for the prompt gamma detection (t_γ)

UFSD for the primary proton detection (t_0)

TOF = $t_\gamma - t_0$



det 1



det 3

… *det N*

Pennazio F. et al PMB 2022

$$m_{jp}^{k+1} = \frac{m_{jp}^{k}}{S_{jp}} \sum_i \sum_d \frac{n*_{id}}{\sum_l \sum_t f_{idlt} m_{lt}^{k}} f_{idjp}$$

data

prompt photon

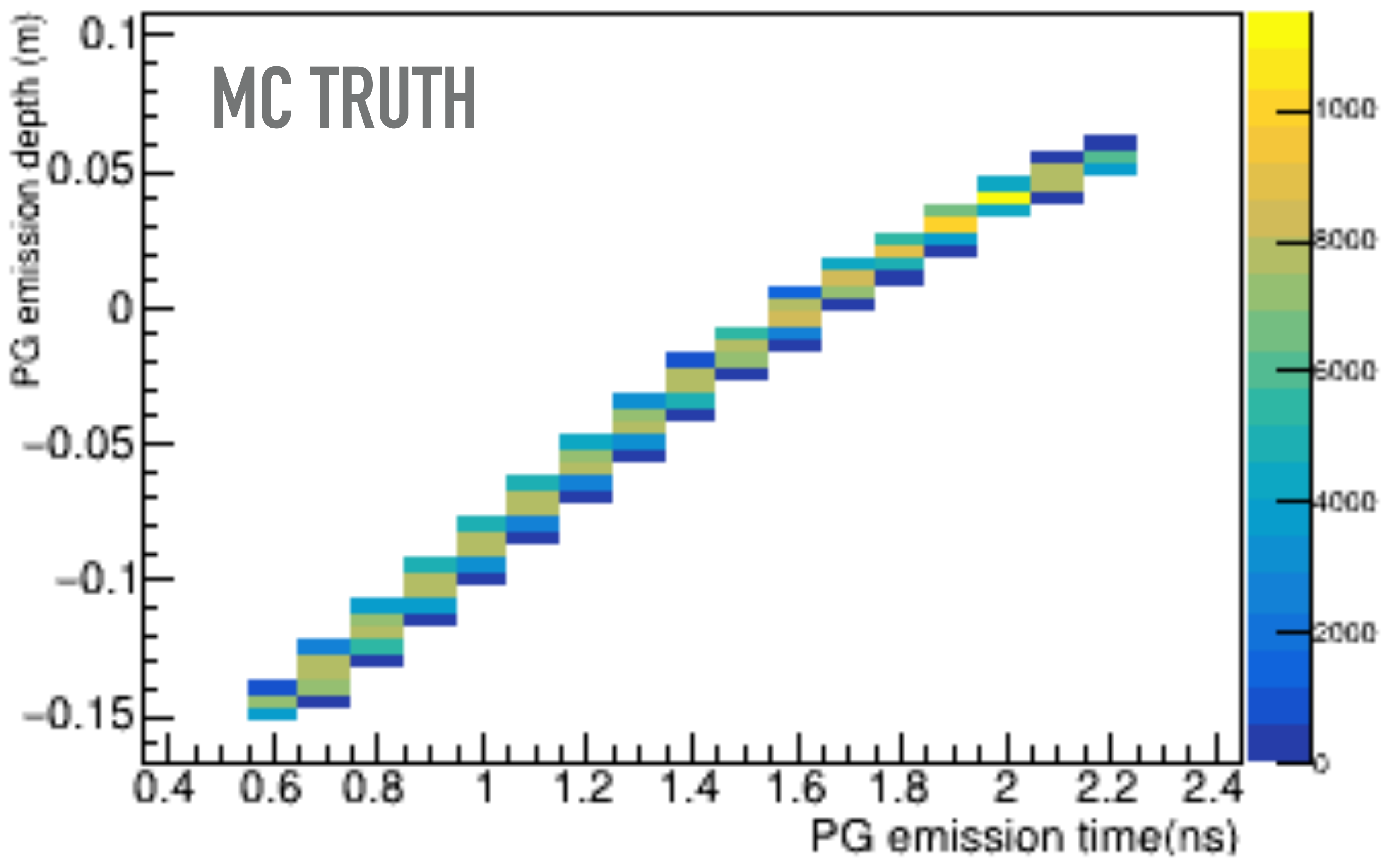
sensitivity

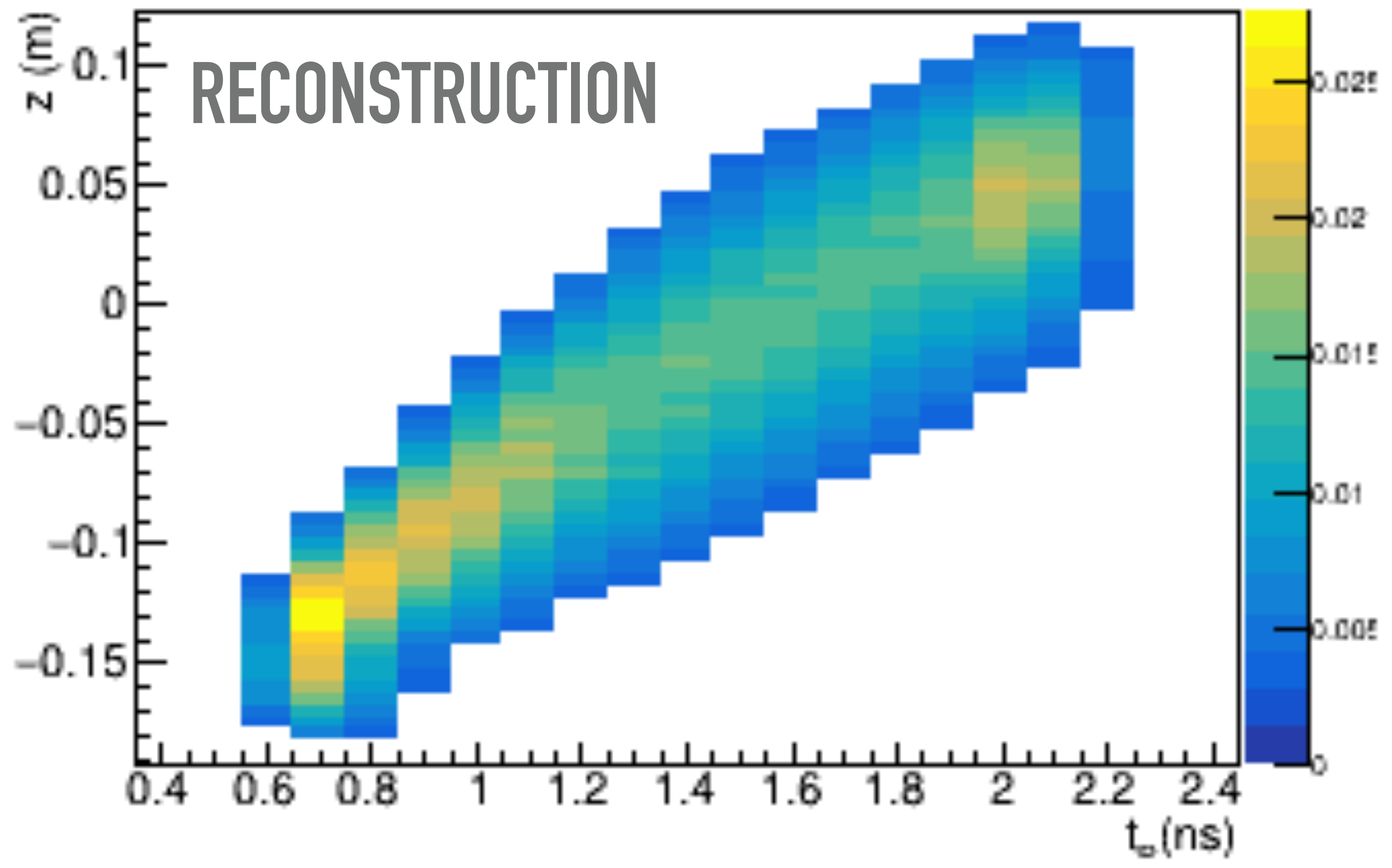
SM

p: time bin (emission)
j: space bin (emission)
i: time bin (detection)
d: detector

MLEM disentangles the directional information comprised in the multiple TOF to reconstruct the position and time of emission of prompt gammas

SPATIO-TEMPORAL EMISSION RECONSTRUCTION





10^8 protons, 189MeV

10^7 produced photons in 4π

Time resolution=100 ps σ

Energy cut 1MeV-7MeV

$\sim 10^4$ events per detector

110 detectors (clinical scenario)

5 simulation runs

FLUKA MC tool

$$m_{jp}^{k+1} = \frac{m_{jp}^{k}}{S_{jp}} \sum_i \sum_d \frac{n*_{id}}{\sum_l \sum_t f_{idlt} m_{lt}^{k}} f_{idjp}$$

data

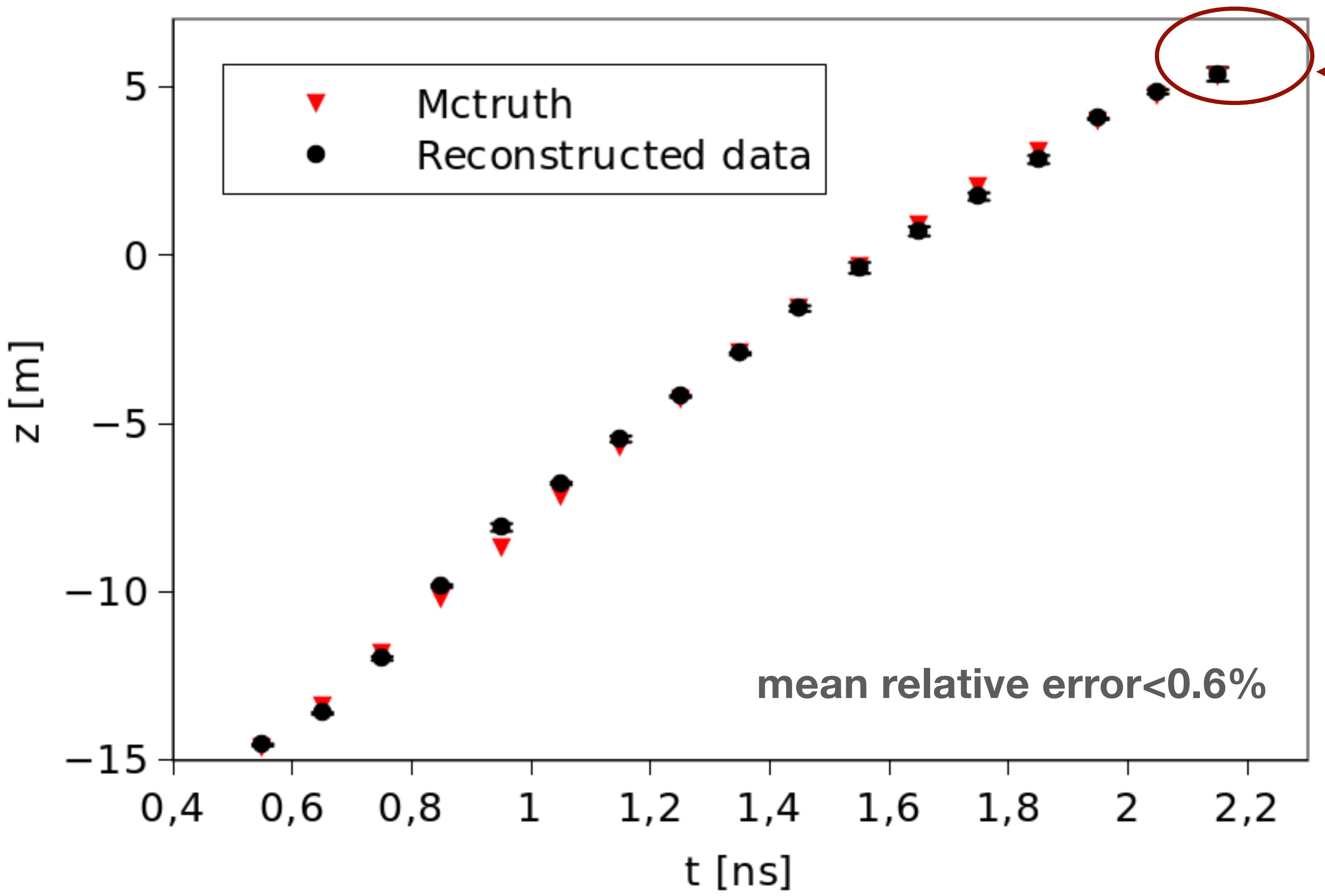
prompt photon

sensitivity

SM

p: time bin (emission)
j: space bin (emission)
i: time bin (detection)
d: detector

mean z at fixed t



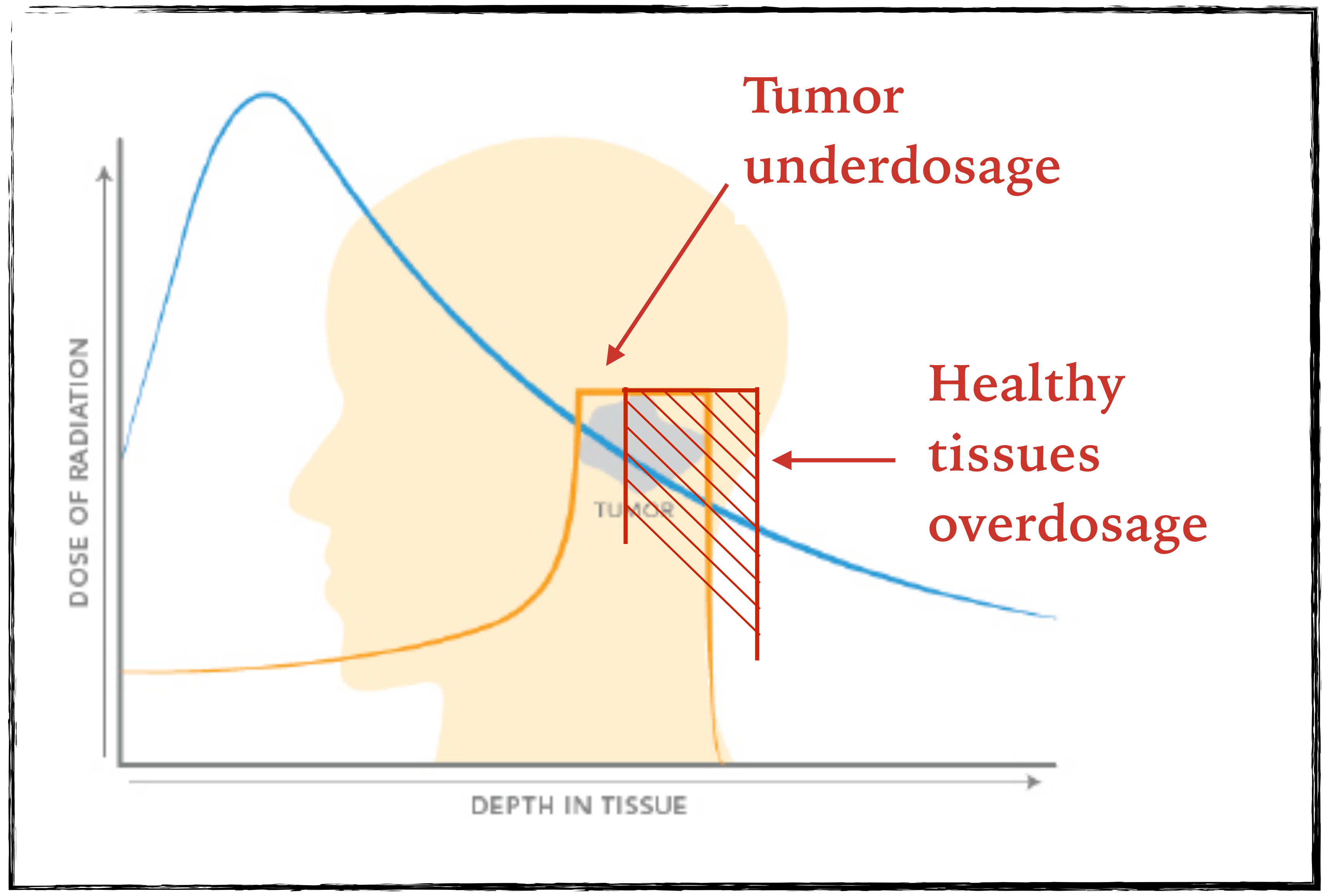
particle range

... but we have the whole (z,t) distribution: proton motion study

↓

stopping power evaluation

STOPPING POWER AS TREATMENT VERIFICATION METHOD

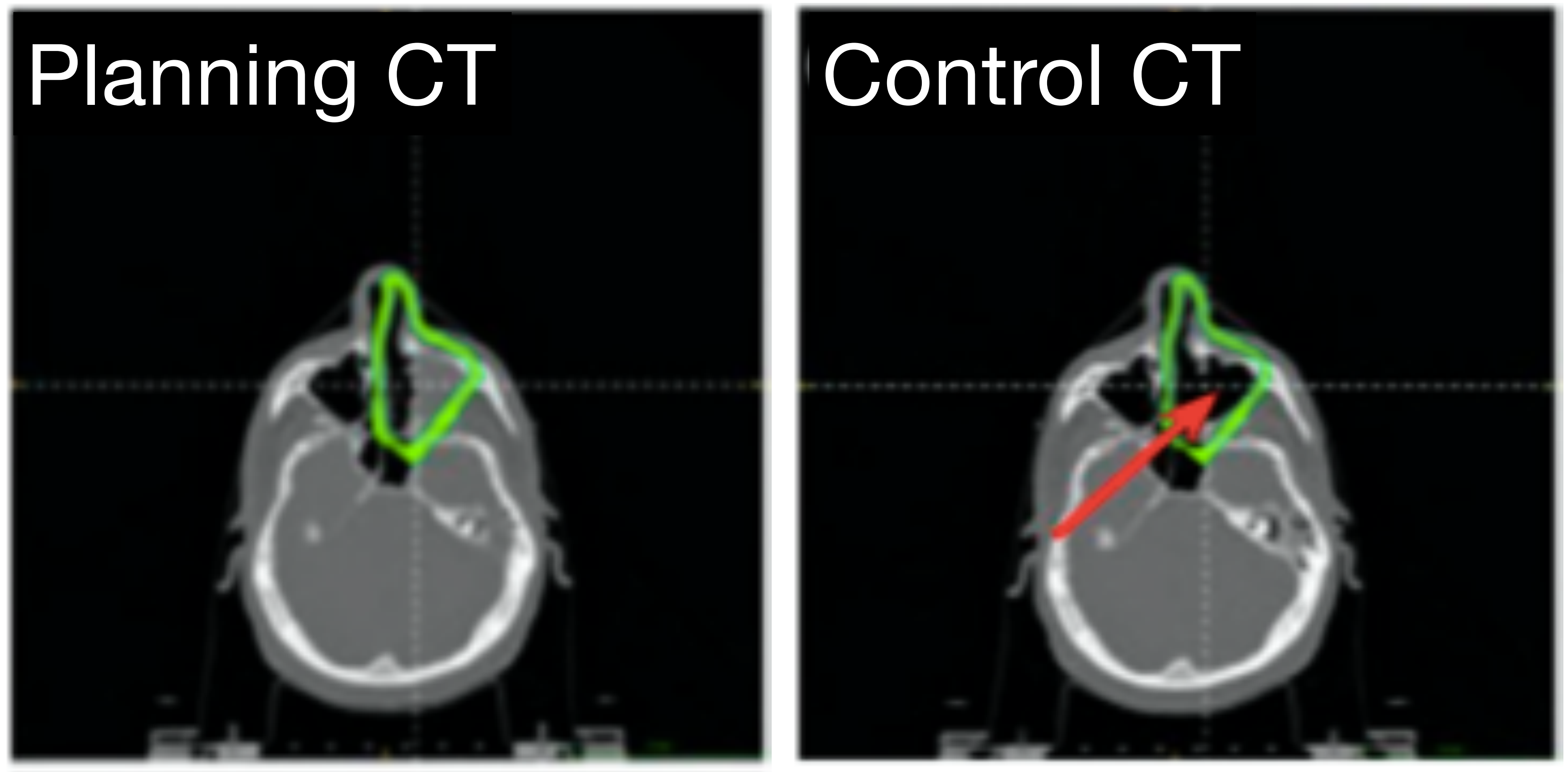


Strong clinical motivations:

- ➡ Model approximations
- ➡ HU to Stopping Power ratio conversion uncertainties
- ➡ Change of morphology

STOPPING POWER INFORMATION

1. TREATMENT VERIFICATION AND OPTIMIZATION
2. STOICHIOMETRIC APPROACH VERIFICATION (TPS)



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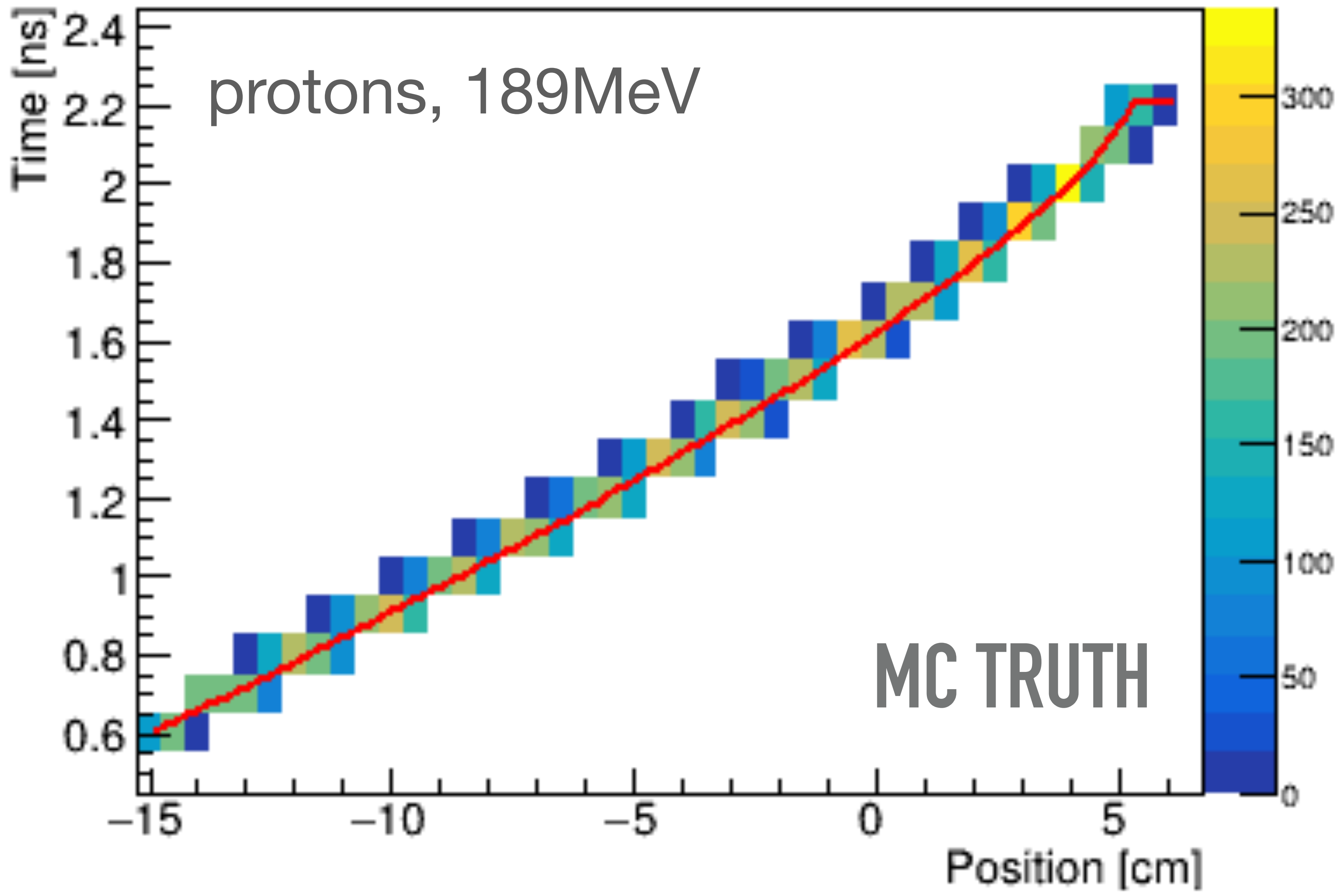
Measurement of the EneRgy Loss for IN-vivo Optimization in particle therapy (MERLINO)

INFN Istituto Nazionale di Fisica Nucleare

From the measurement of **prompt gamma**… to the **beam stopping power**

FORMULATION OF THE PROBLEM



$$v(E(\hat{z})) = c\sqrt{1 - \left(\frac{m_0c^2}{E(\hat{z}) + m_0c^2}\right)^2} = c\sqrt{1 - \left(\frac{m_0c^2}{\sqrt[p]{\frac{R_0-\hat{z}}{\alpha}} + m_0c^2}\right)^2}$$

$$t(z) = \int_{z_0}^{z} \frac{dz'}{v(E(z'-z_0))} + t_0 = \int_0^{z-z_0} \frac{d\hat{z}'}{v(E(\hat{z}'))} + t_0$$

$$\int \frac{d\hat{z}}{v(E(\hat{z}))} = \frac{-p\,(R_0-\hat{z})}{c\,(4p^2-1)\sqrt{\frac{2m_0c^2}{E(\hat{z})}+1}}\left[(p-1)\sqrt{\frac{2E(\hat{z})}{m_0c^2}+4}\;{}_2F_1\left(\frac{1}{2}, p+\frac{1}{2}; p+\frac{3}{2}; -\frac{E(\hat{z})}{2m_0c^2}\right) + \left(\frac{2m_0c^2}{E(\hat{z})}+1\right)(2p+1)\right]$$

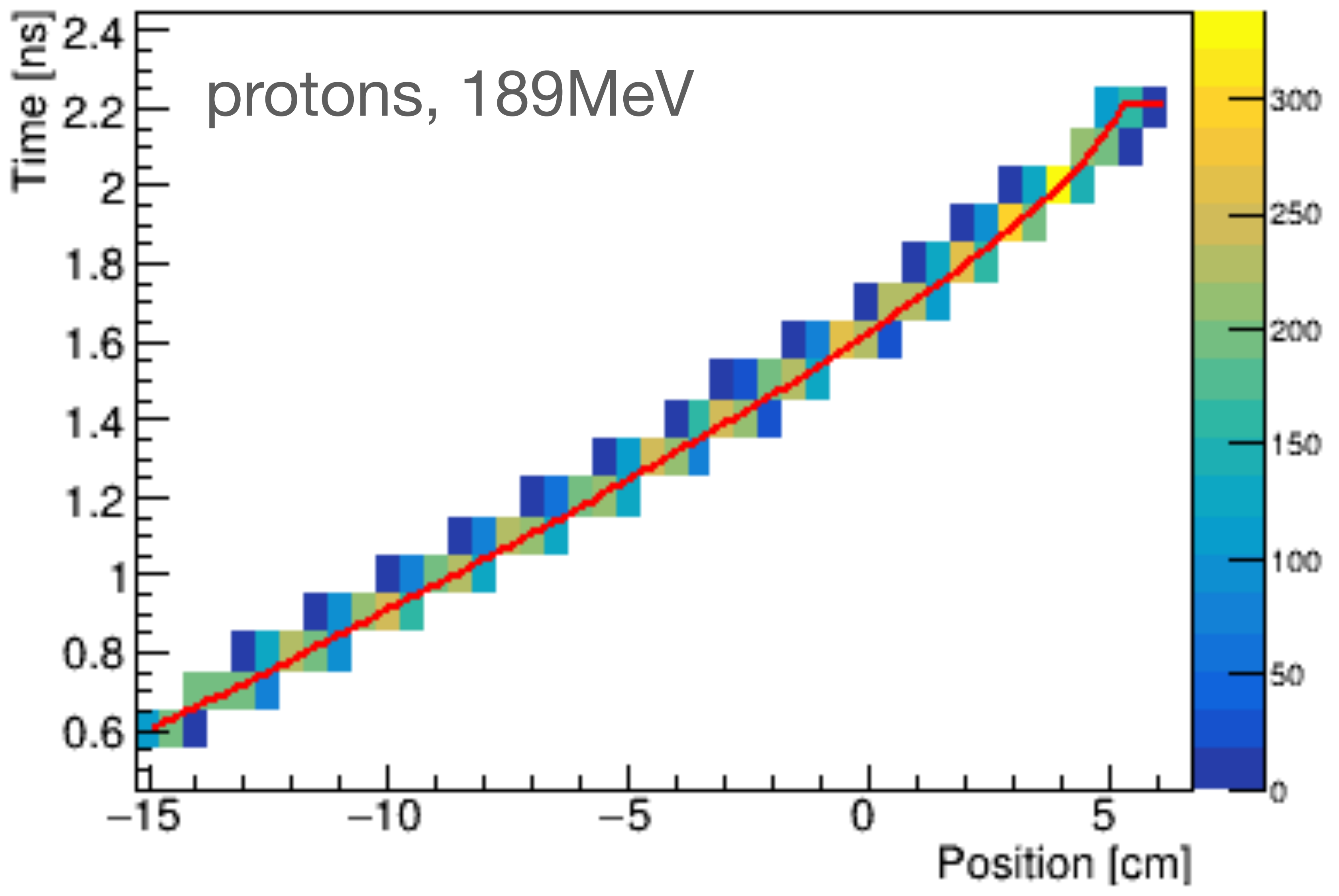
PHYSICAL DESCRIPTION t(z)
(based on Bortfeld formulation)

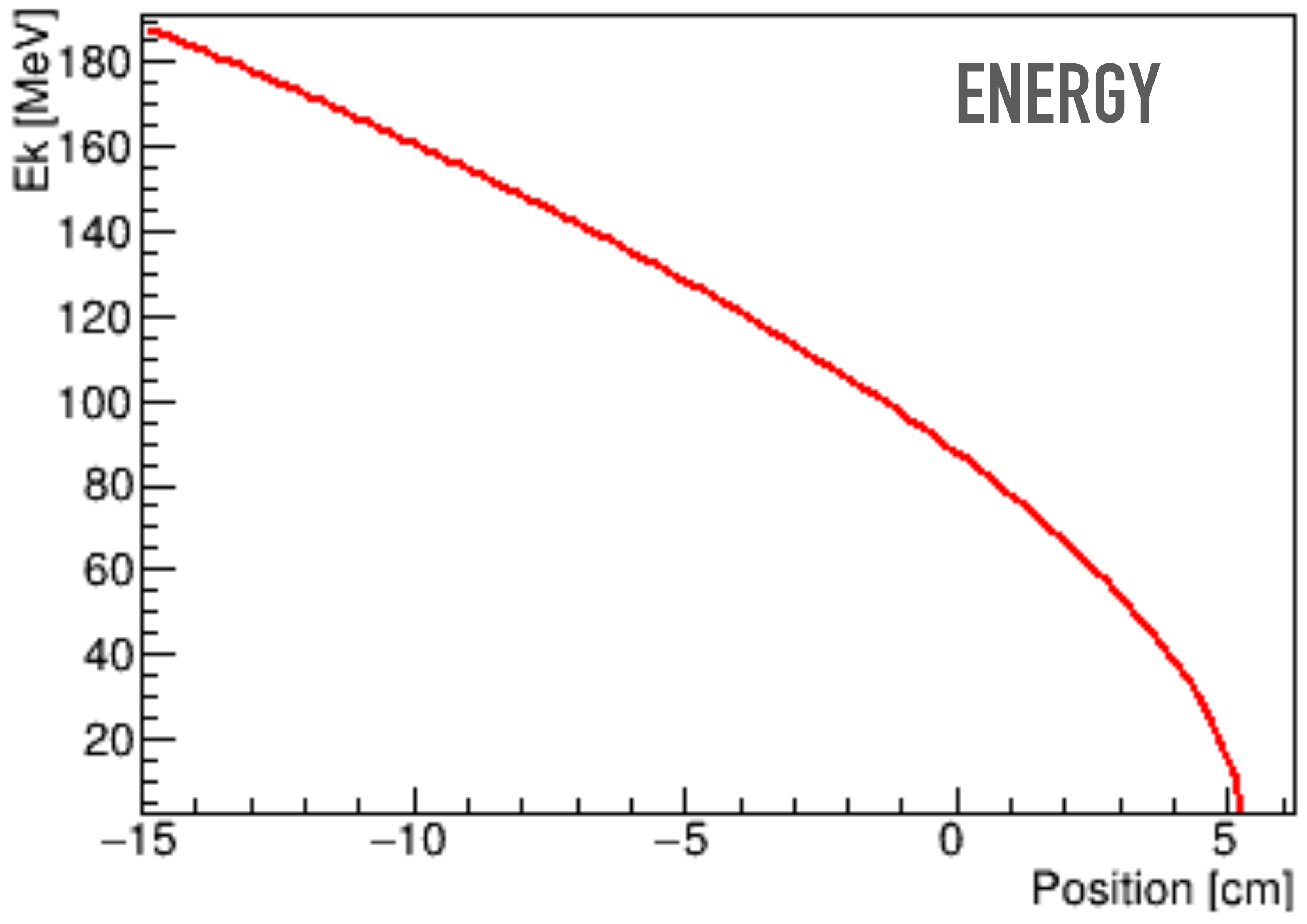
$$R_0 = \alpha E_0^p, \quad E(\hat{z}) = \sqrt[p]{\frac{R_0-\hat{z}}{\alpha}}$$

$$S(\hat{z}) = -\frac{dE}{dz} = \frac{1}{p\sqrt[p]{\alpha}}(R_0-\hat{z})^{1/p-1}$$

Bortfeld Med Phys 1997

PRELIMINARY WORK: MC TRUTH





PHYSICAL DESCRIPTION t(z)
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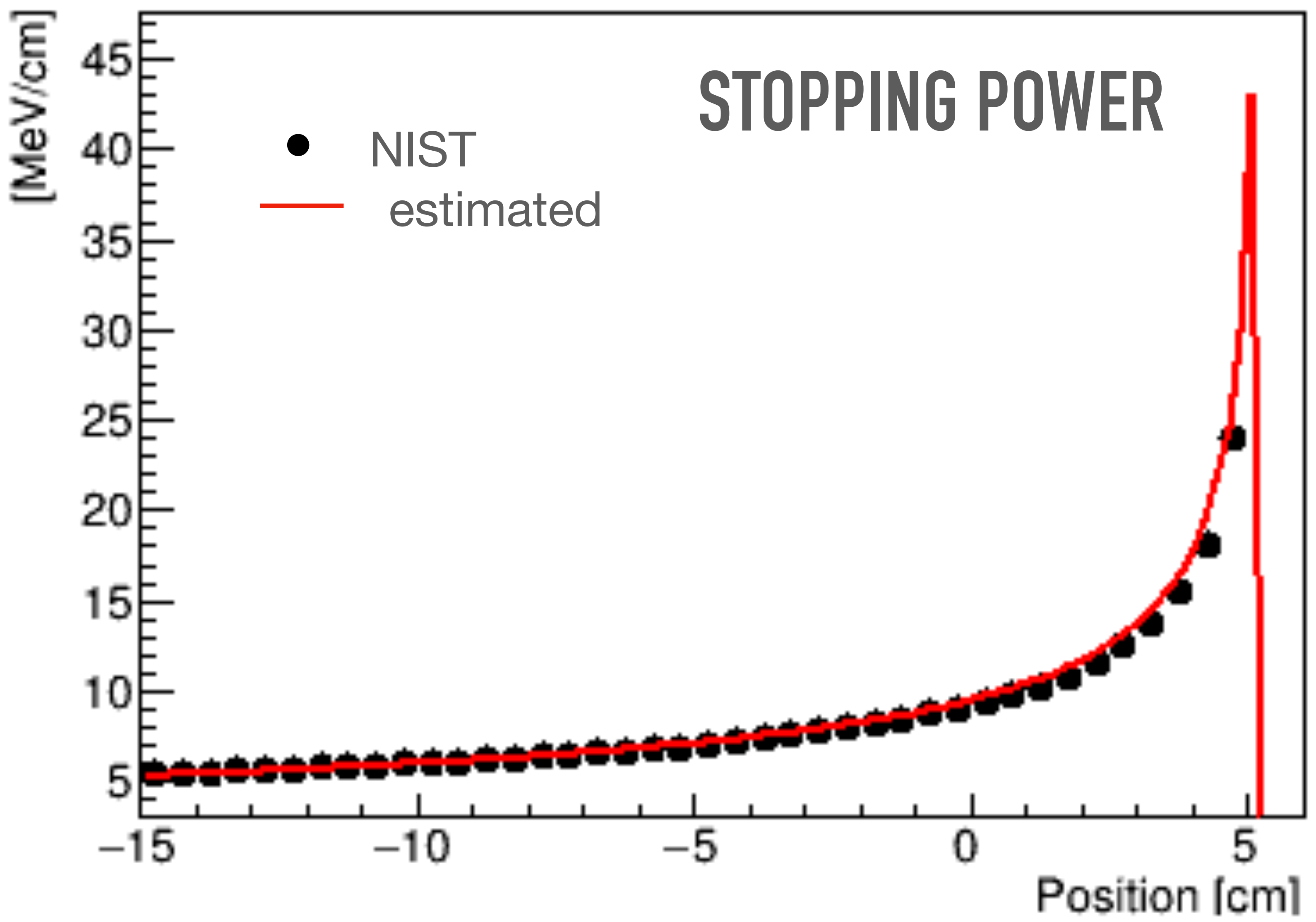
$$S(\hat{z}) = -\frac{dE}{dz} = \frac{1}{p\sqrt[p]{\alpha}}(R_0 - \hat{z})^{1/p-1}$$

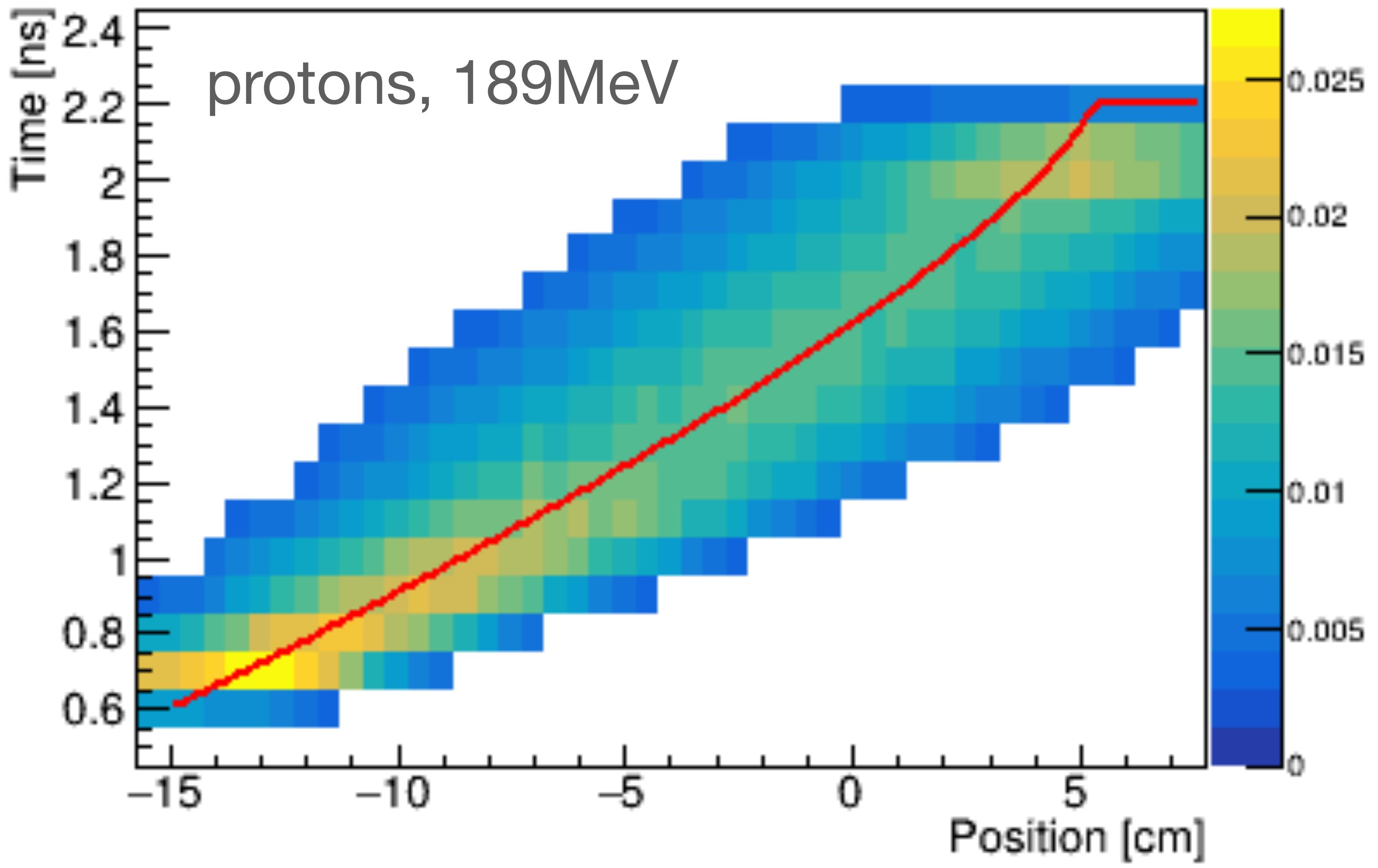
Bortfeld Med Phys 1997

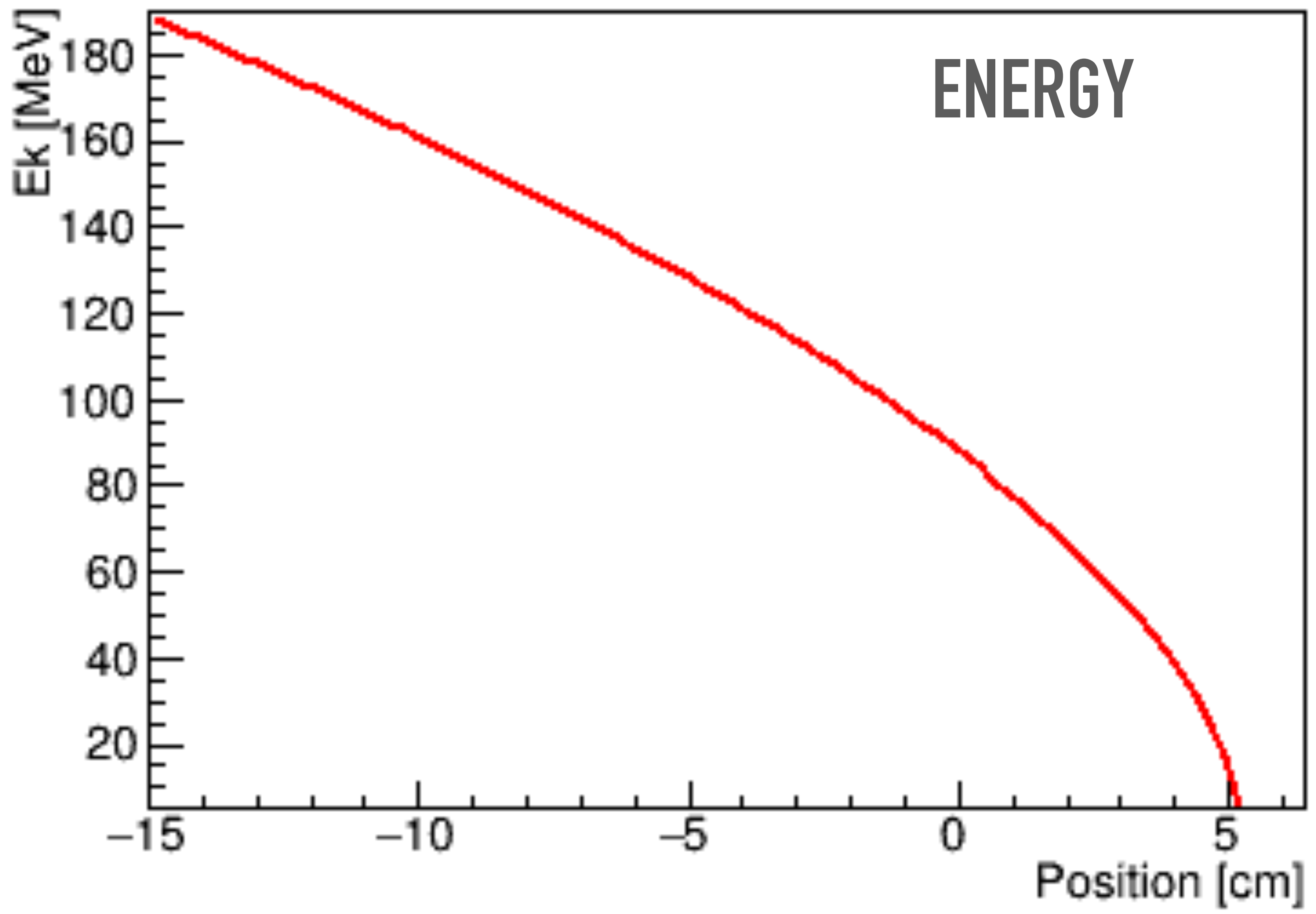


Mean relative error: 0.4 [MeV/cm] ⇒ 2.8%

PCC=0.9

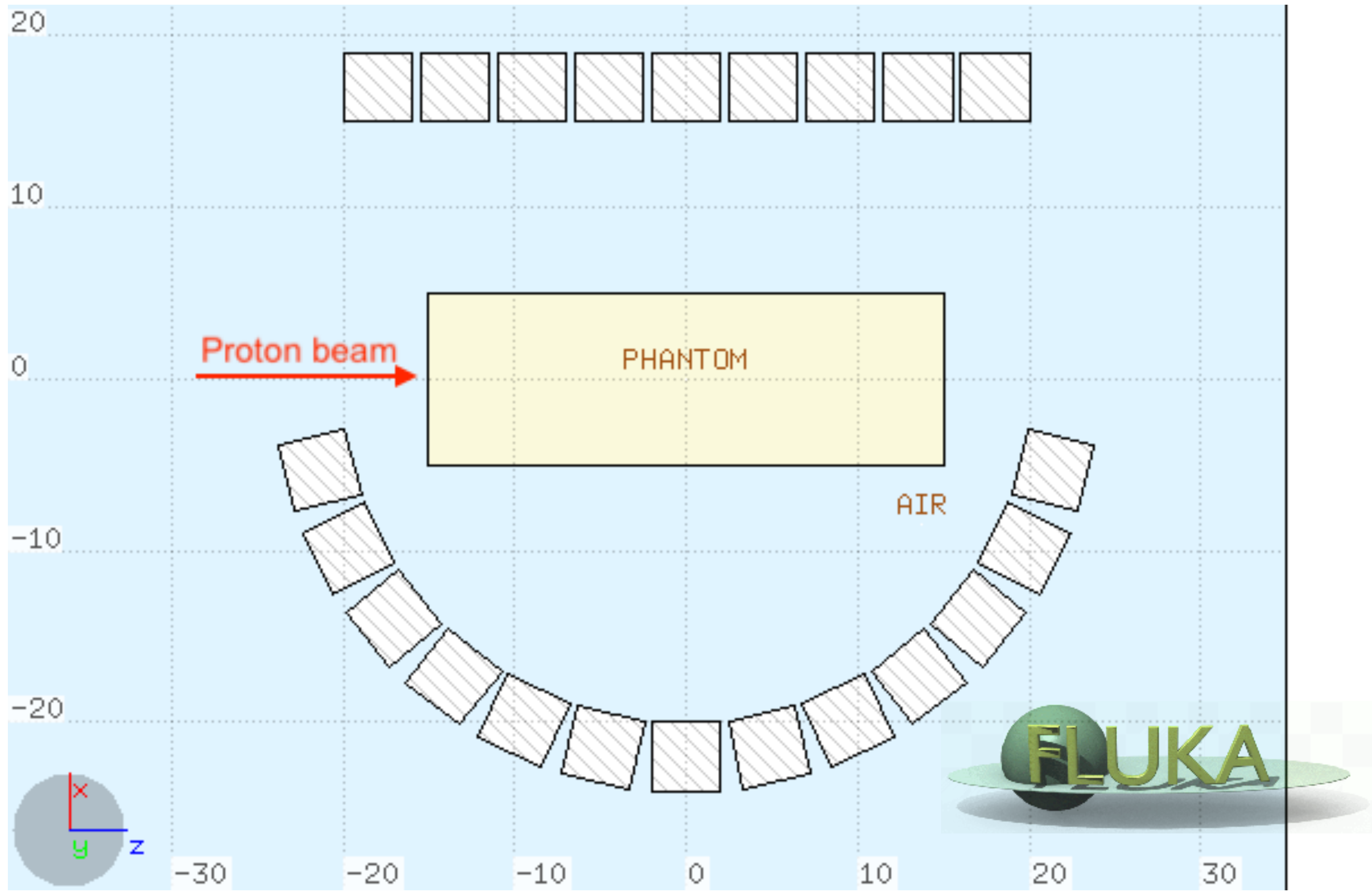
PRELIMINARY WORK: RECONSTRUCTION

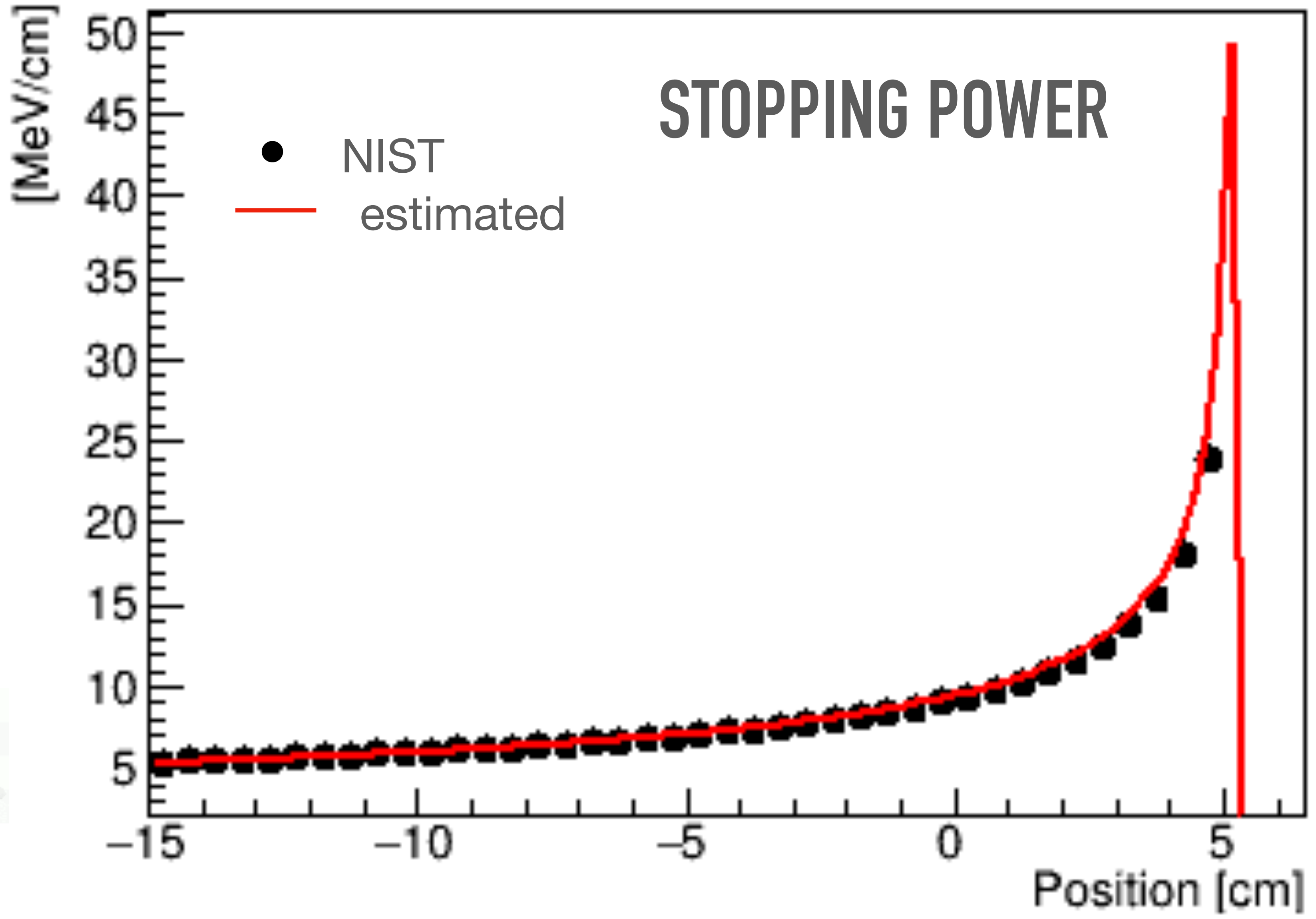




10^8 protons, 189MeV
10^7 produced photons in 4π

~**10^4 events** per detector
Energy cut 1MeV-7MeV
Time resolution=**100 ps σ**
110 detectors (clinical scenario)

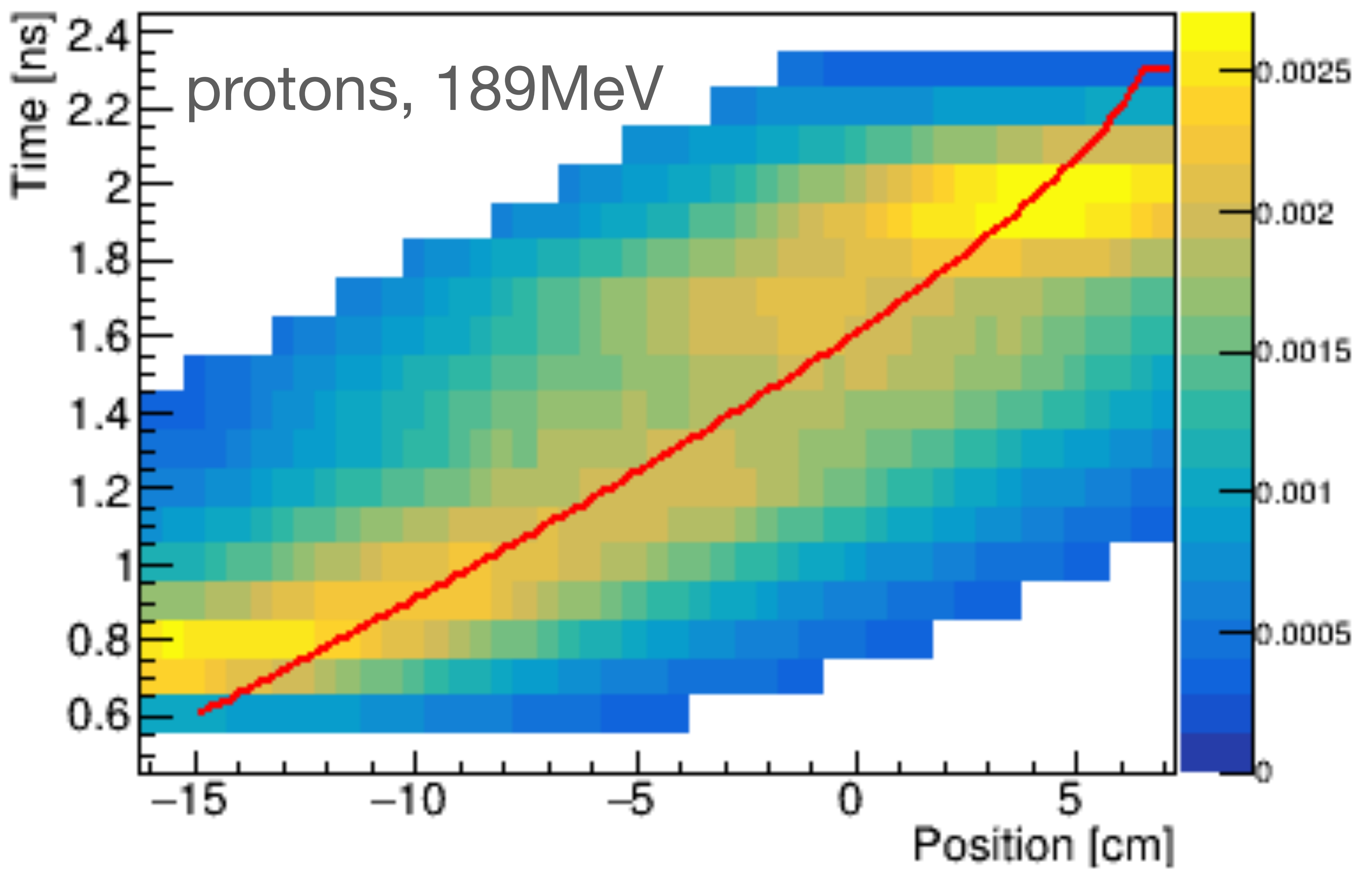


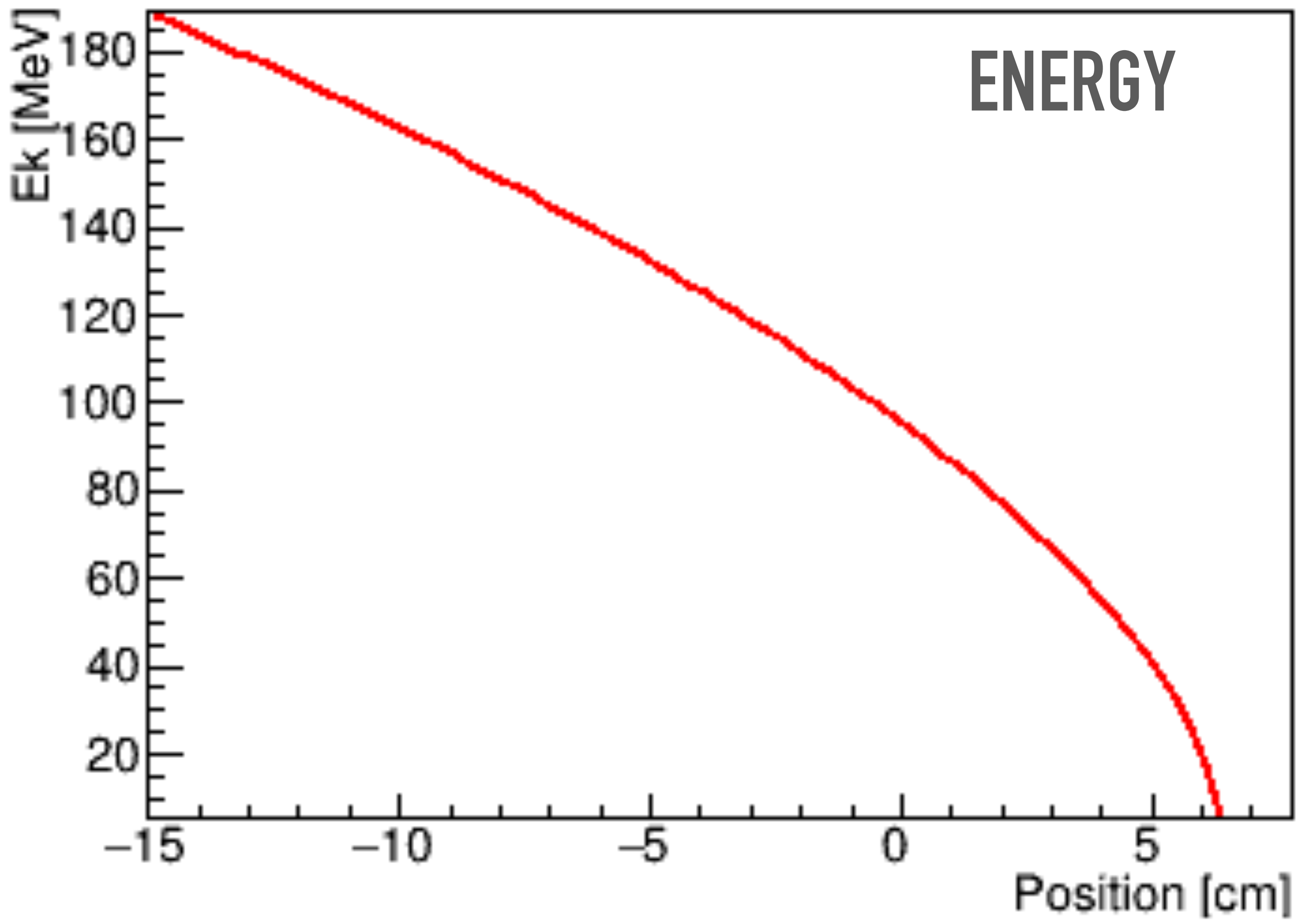


Mean relative error: 0.4 [MeV/cm] ⇒ 2.8%

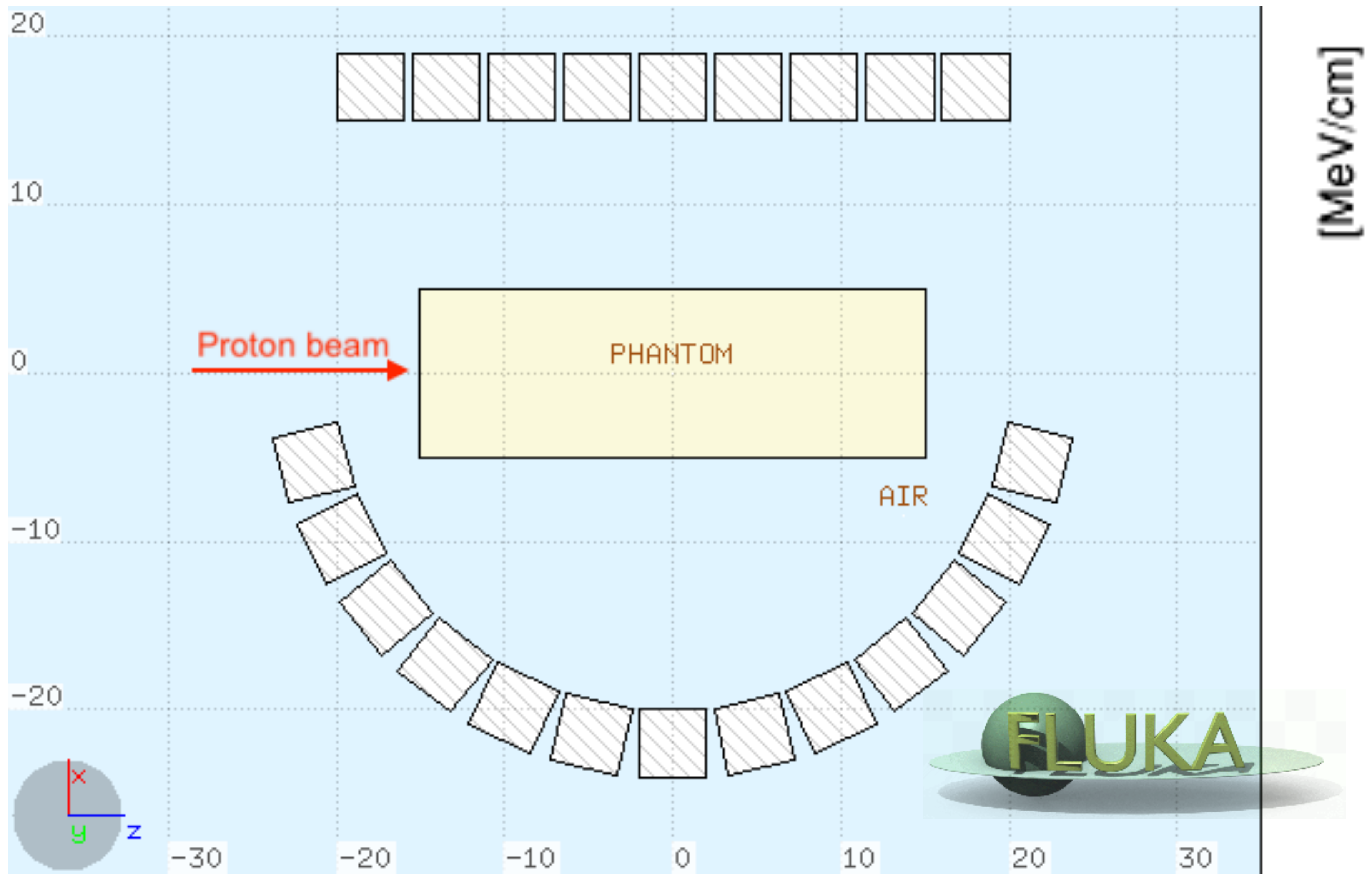
PCC=0.9

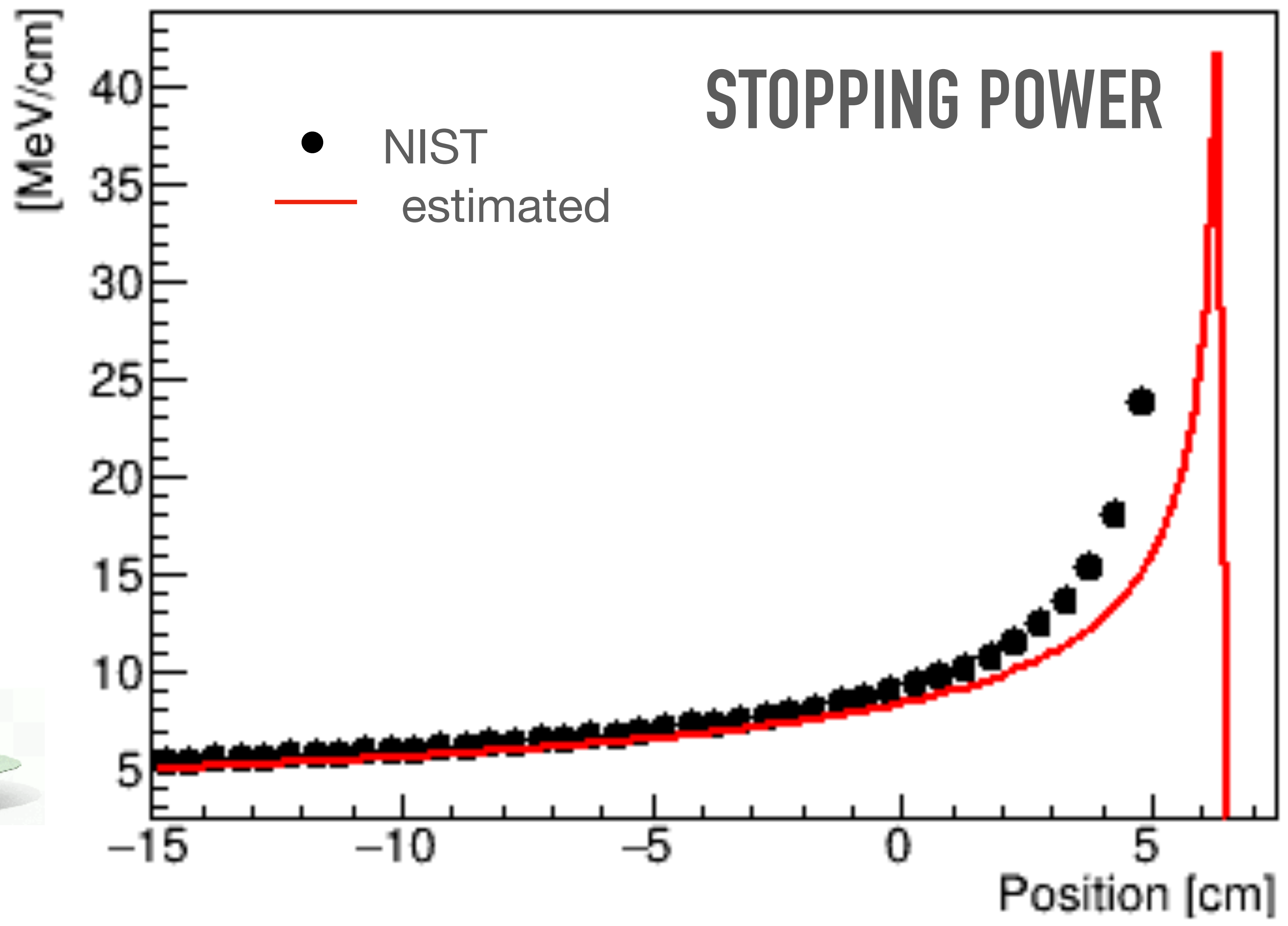
PRELIMINARY WORK: RECONSTRUCTION





10^8 protons, 189MeV
10^7 produced photons in 4π
~**10^4 events** per detector
Energy cut 1MeV-7MeV
Time resolution=**100 ps σ**
110 detectors (clinical scenario)
UFSD ε=0.2
10^8 pps, RF=2.13MHz
Random events inclusion
10% true coinc, 90% random evts

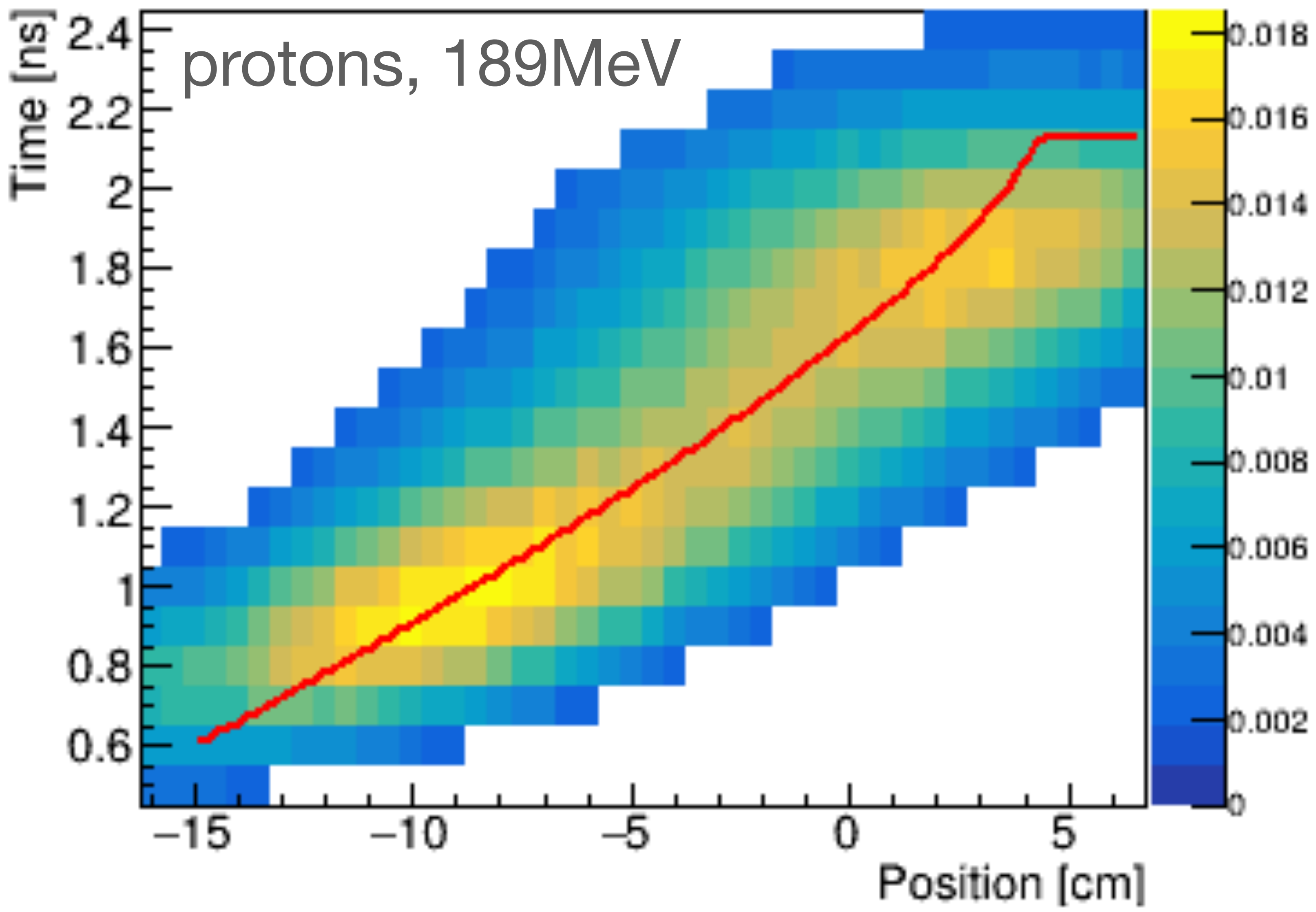


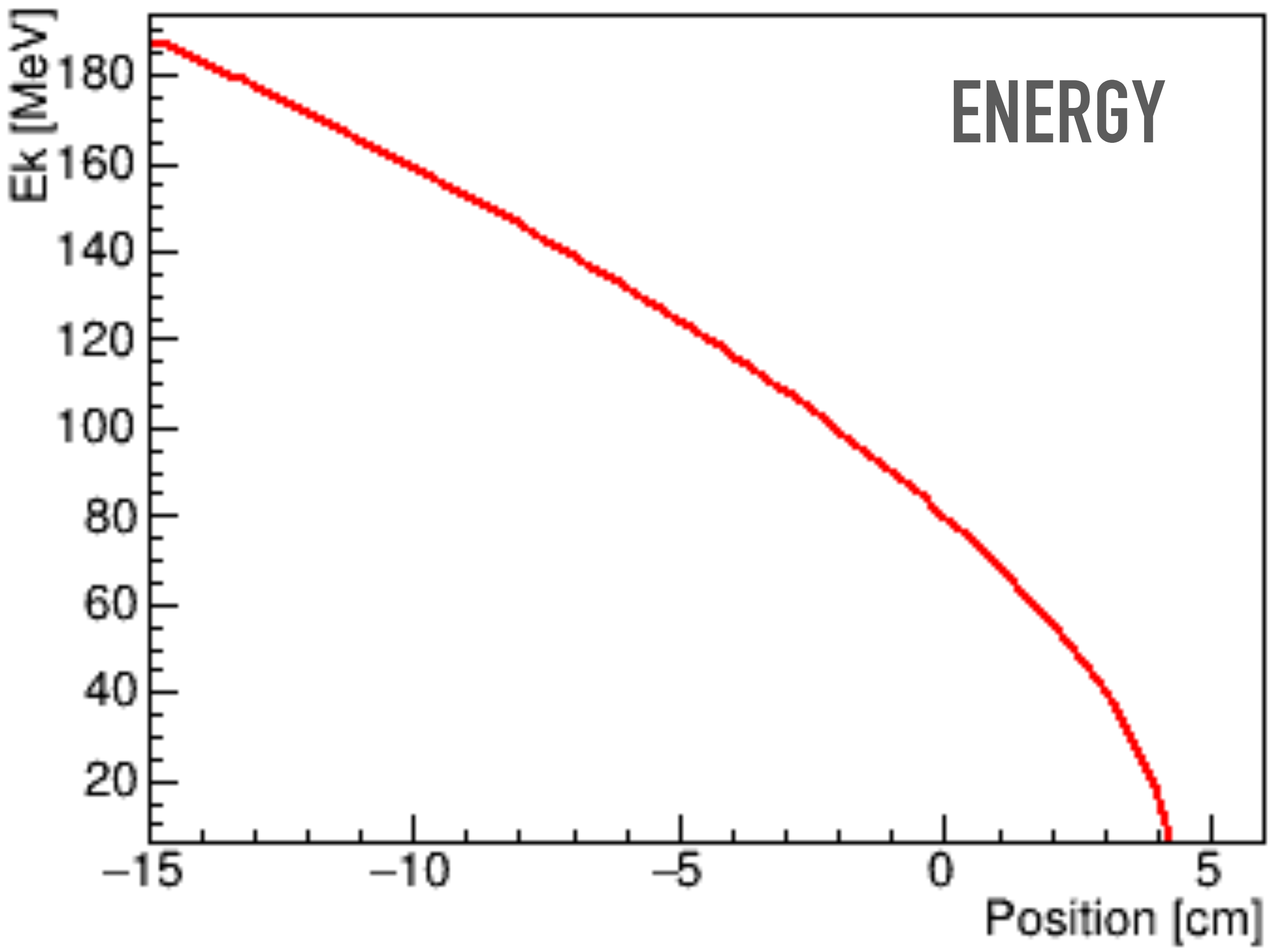


Mean relative error: 1.08 [MeV/cm] ⇒9.23%

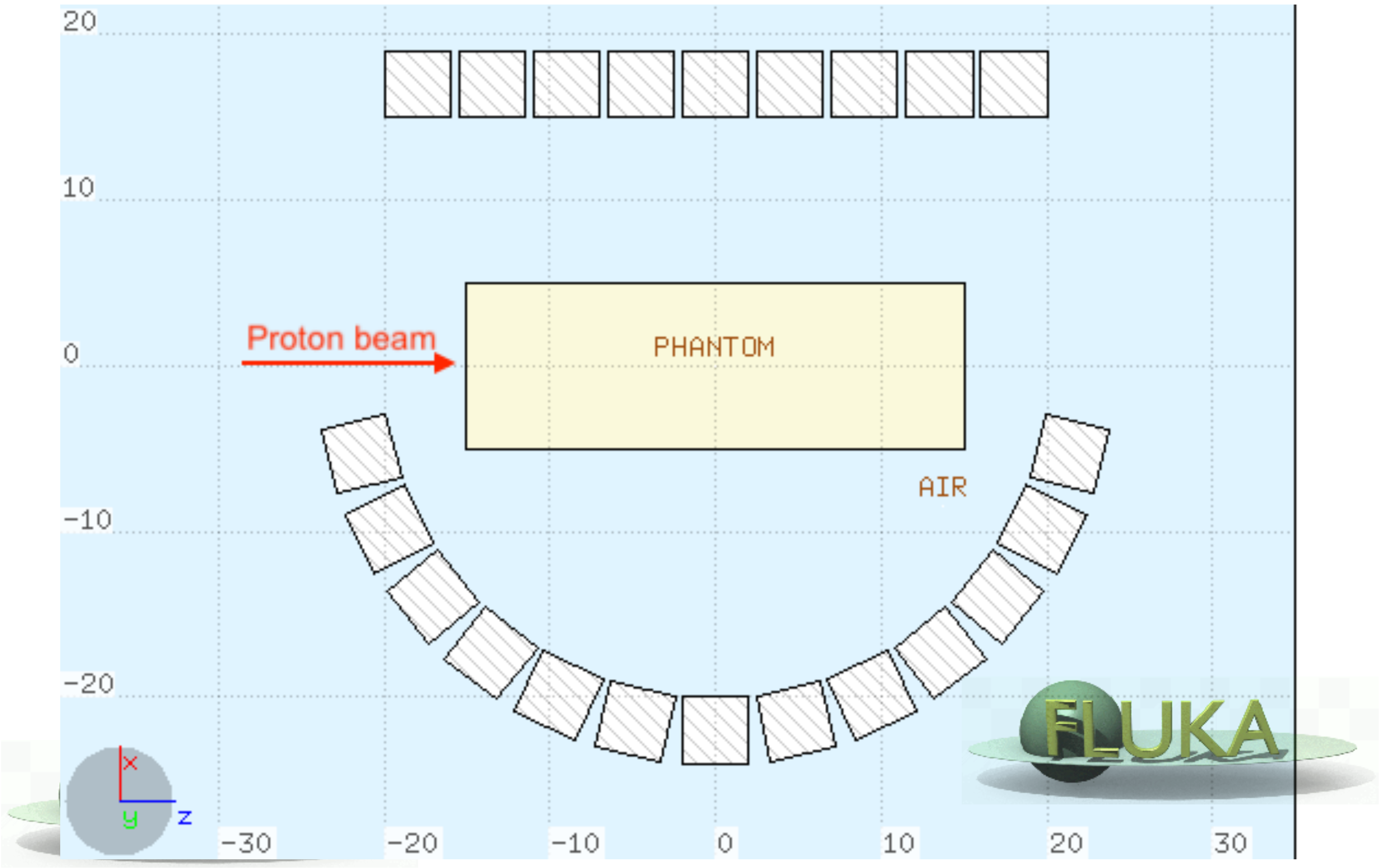
PCC=0.87

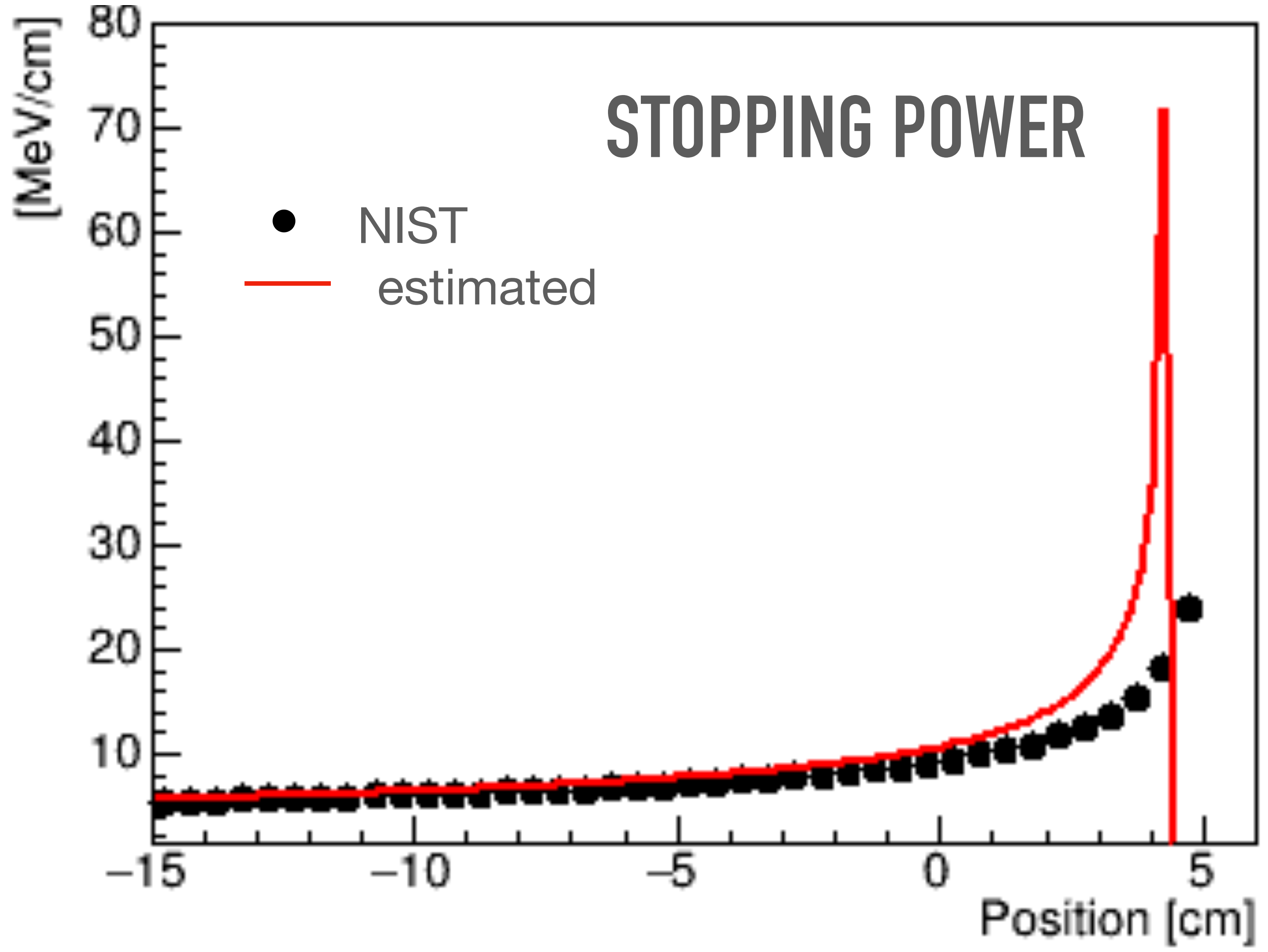
PRELIMINARY WORK: RECONSTRUCTION





10^8 protons, 189MeV
10^7 produced photons in 4π
~**10^4 events** per detector
Energy cut 1MeV-7MeV
Time resolution=**300 ps σ**
110 detectors (clinical scenario)

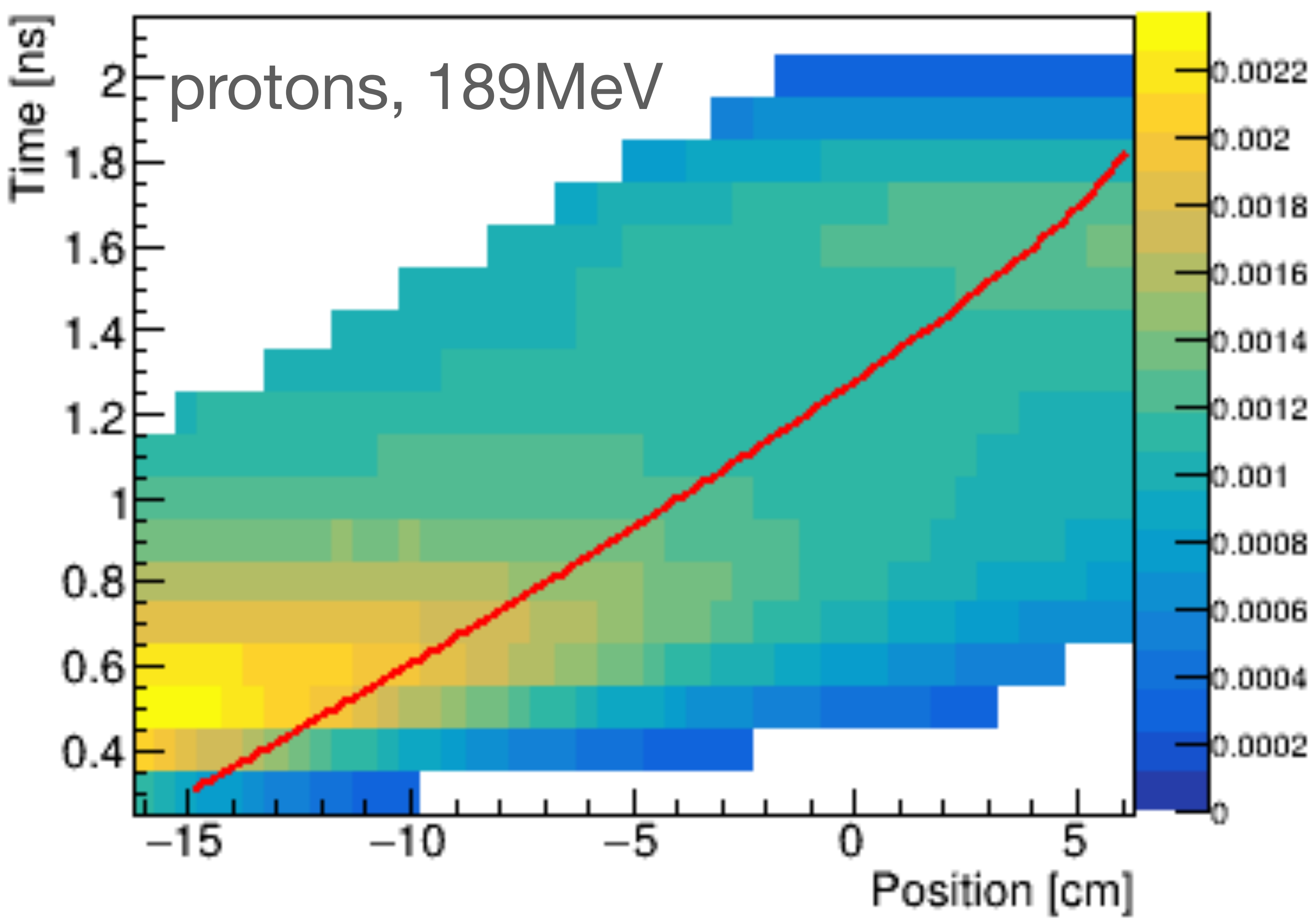


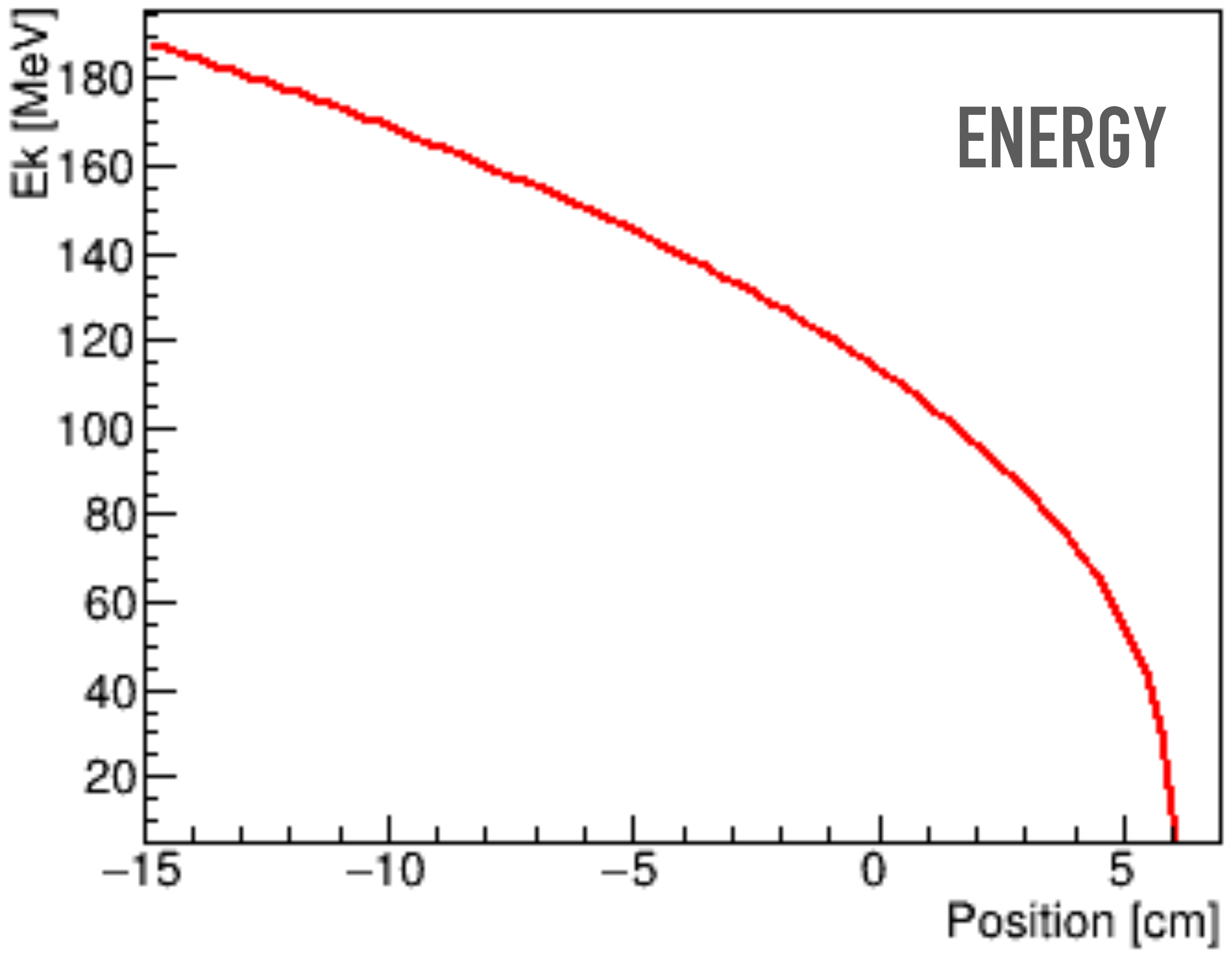


Mean relative error: 2.5 [MeV/cm] ⇒18.2%

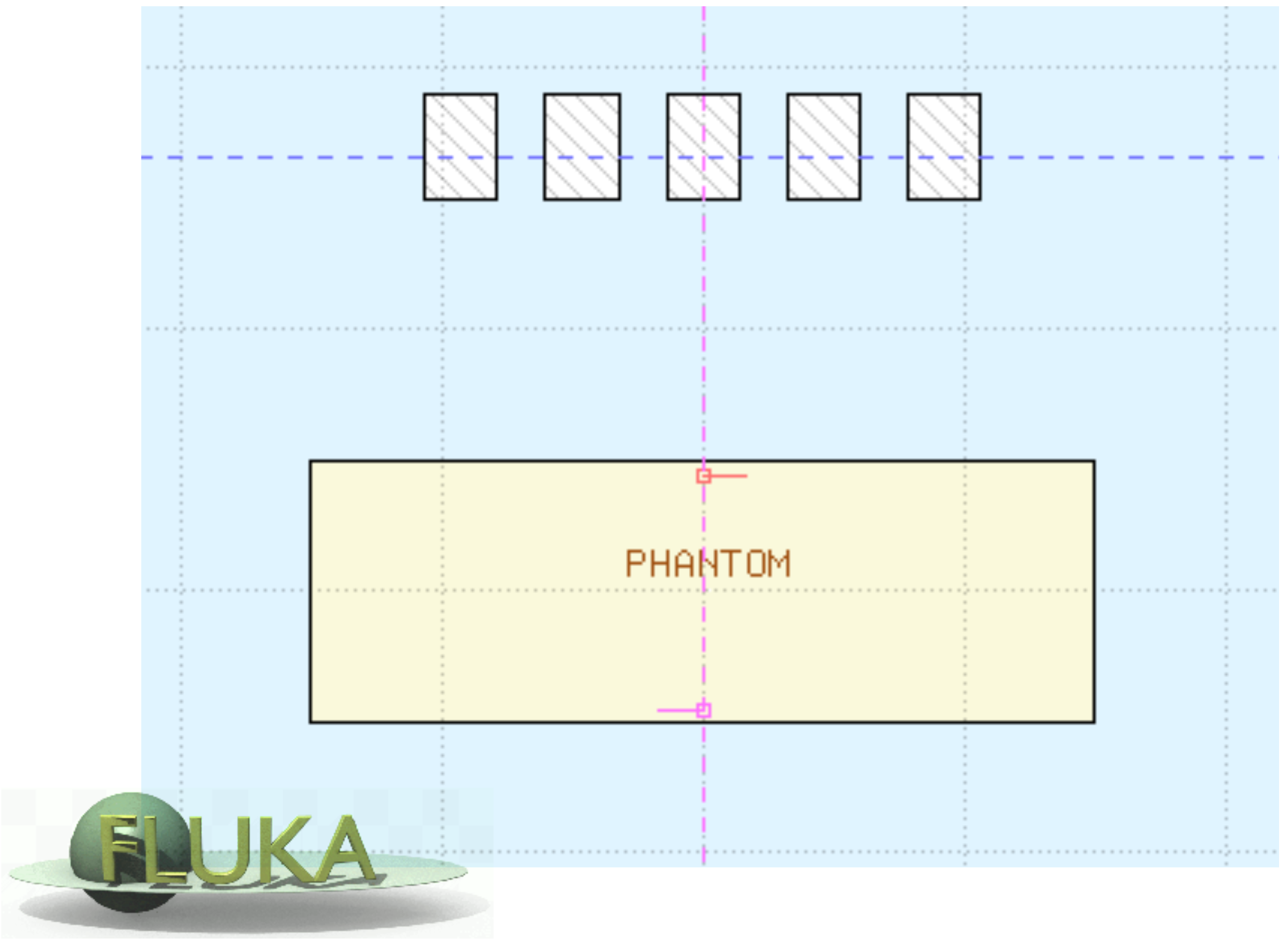
PCC=0.58

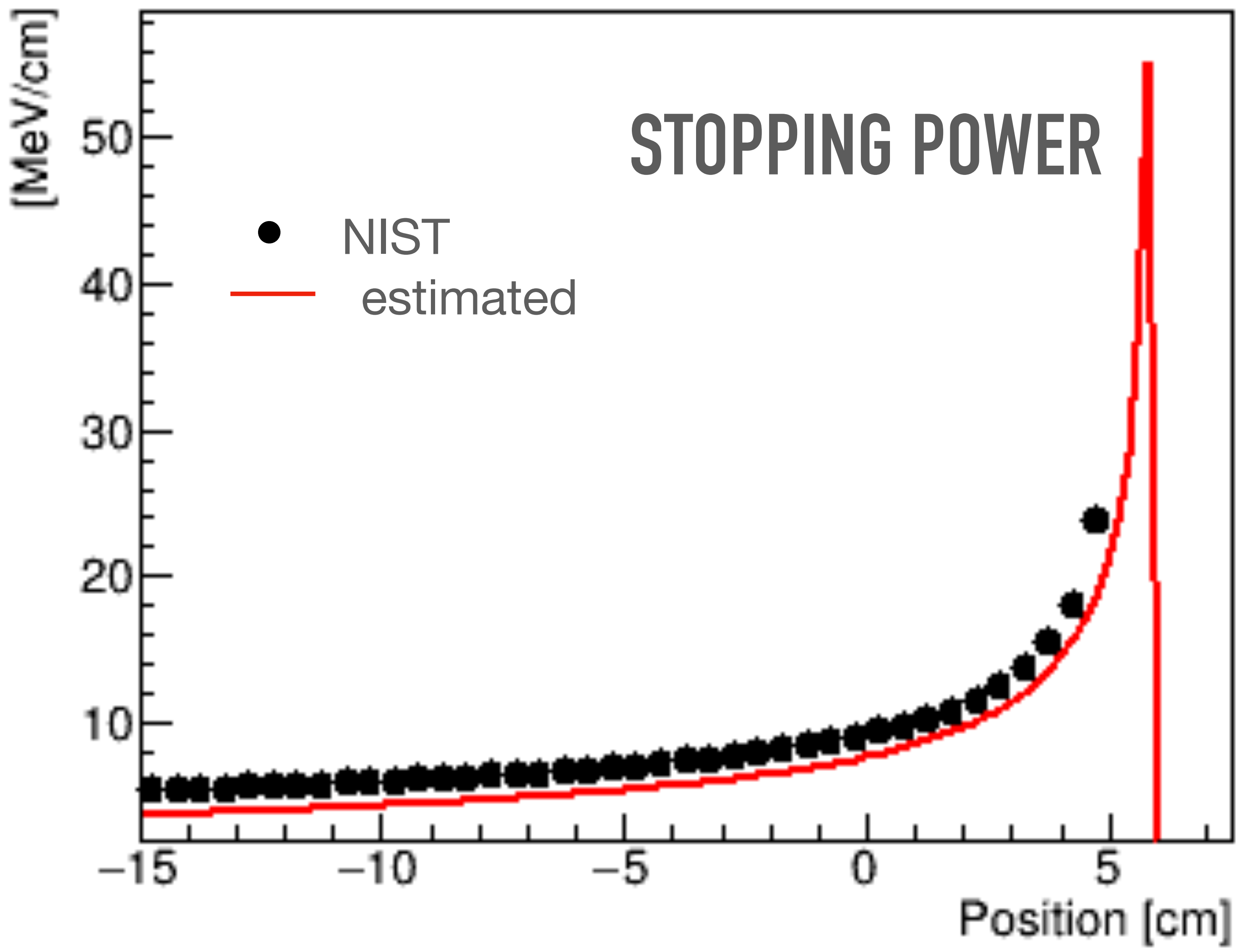
PRELIMINARY WORK: RECONSTRUCTION





10^8 protons, 189MeV
10^7 produced photons in 4π
~$\mathbf{10^4}$ **events** per detector
Energy cut 1MeV-7MeV
Time resolution=**100 ps σ**
10 detectors (proof of concept)

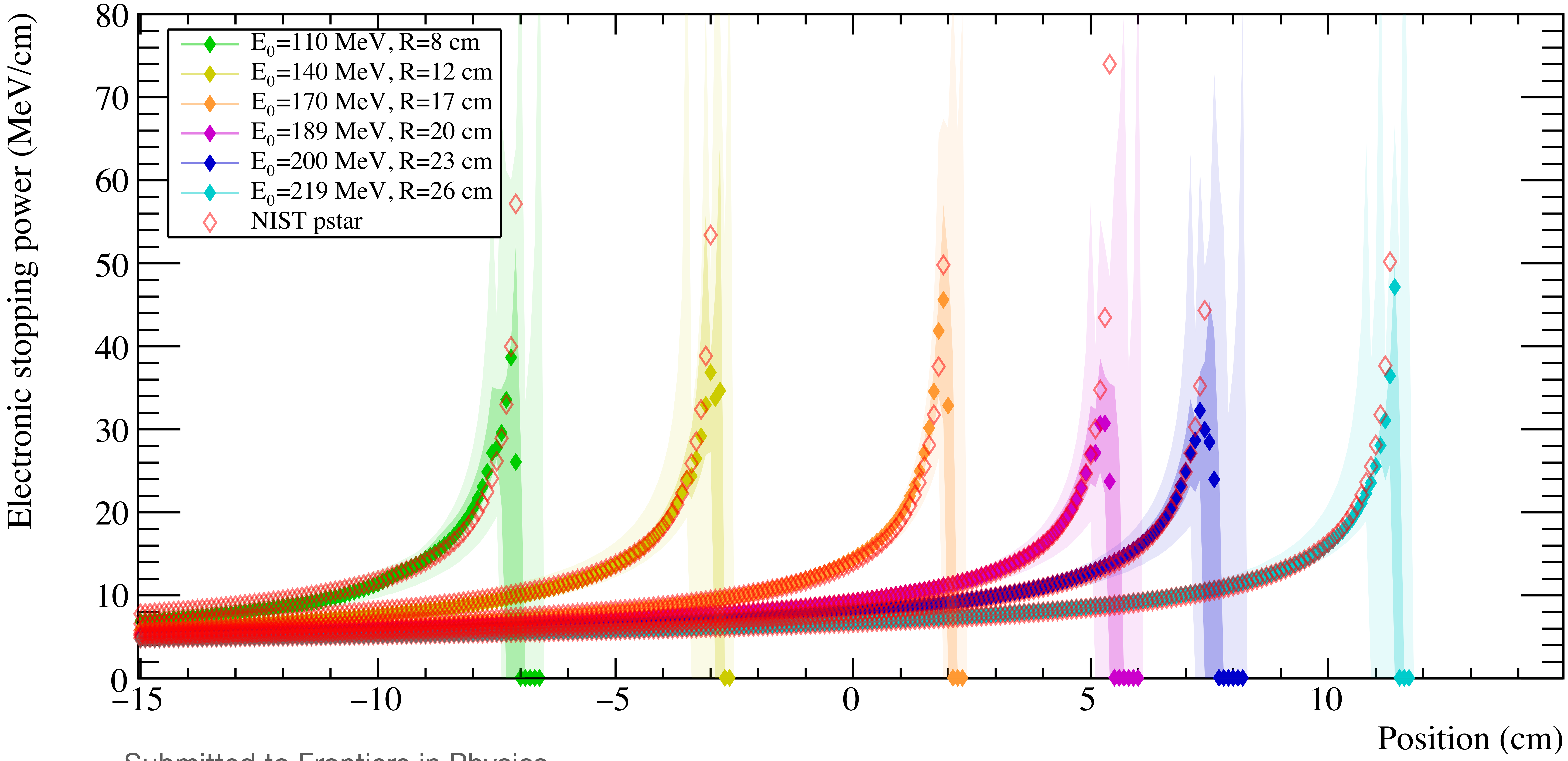




Mean relative error: 1.7 [MeV/cm] ⇒22%

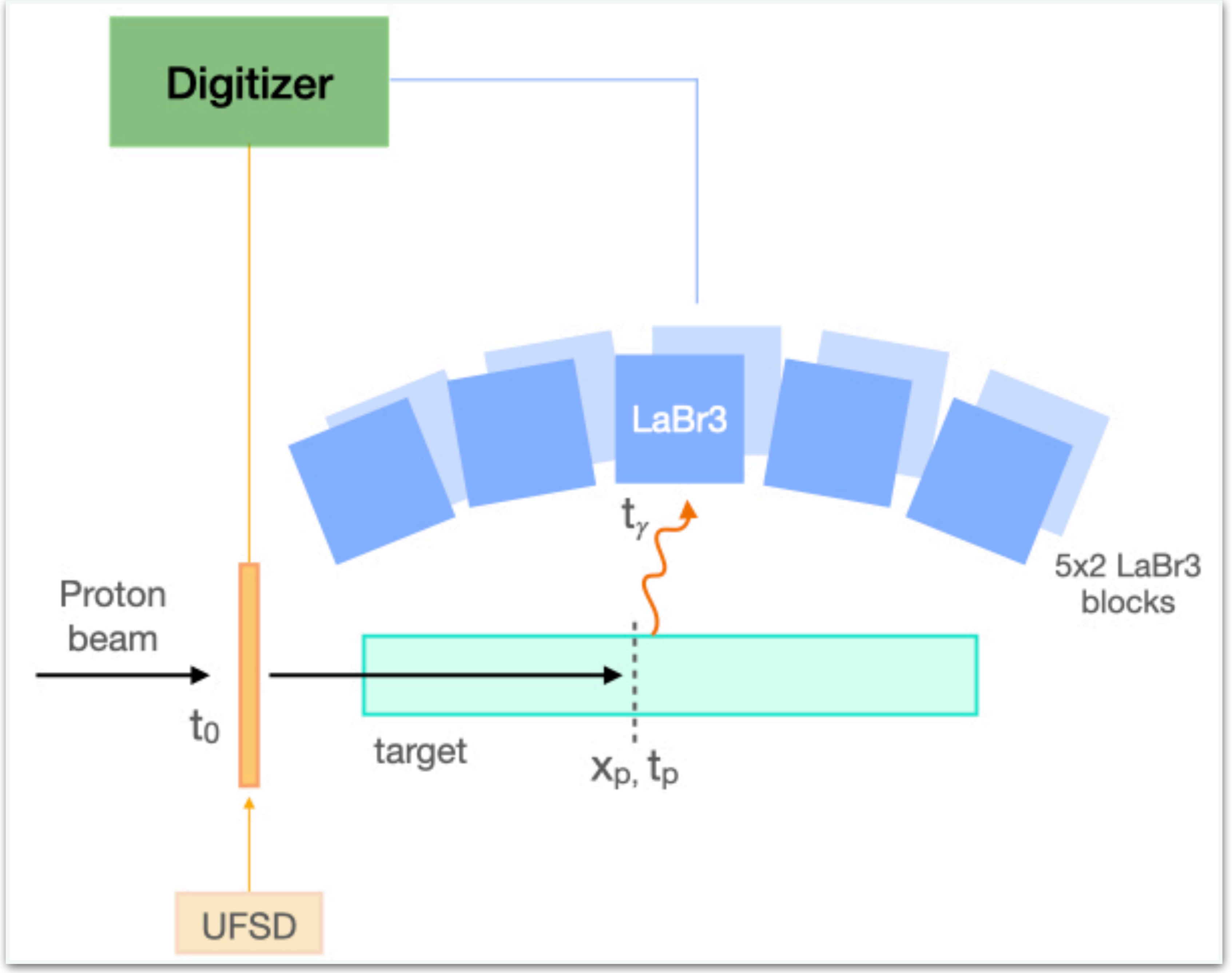
PCC=0.95

PRELIMINARY WORK: RECONSTRUCTION



Submitted to Frontiers in Physics

DETECTOR R&D



PGT MULTI-DETECTOR SYSTEM

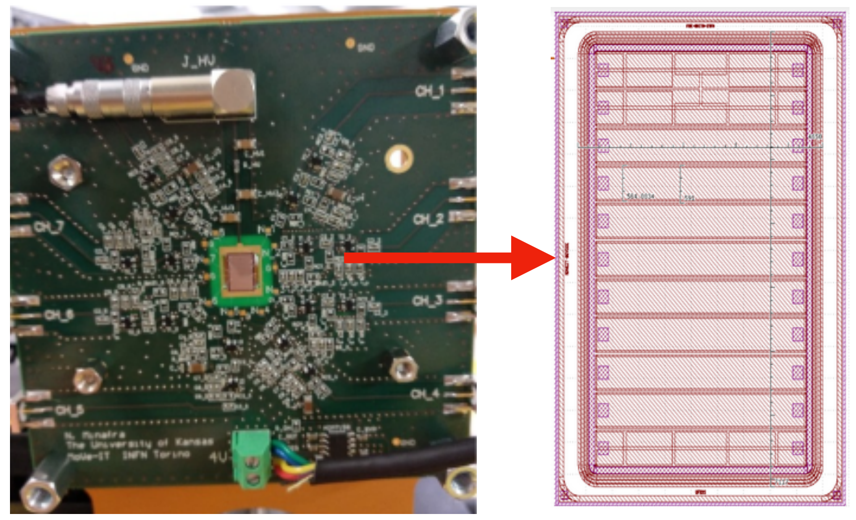
Setup with N detectors

LaBr3:Ce for the prompt gamma detection (t_γ)

UFSD for the primary proton detection (t_0)

UFSD: measure the delivery time of each primary proton

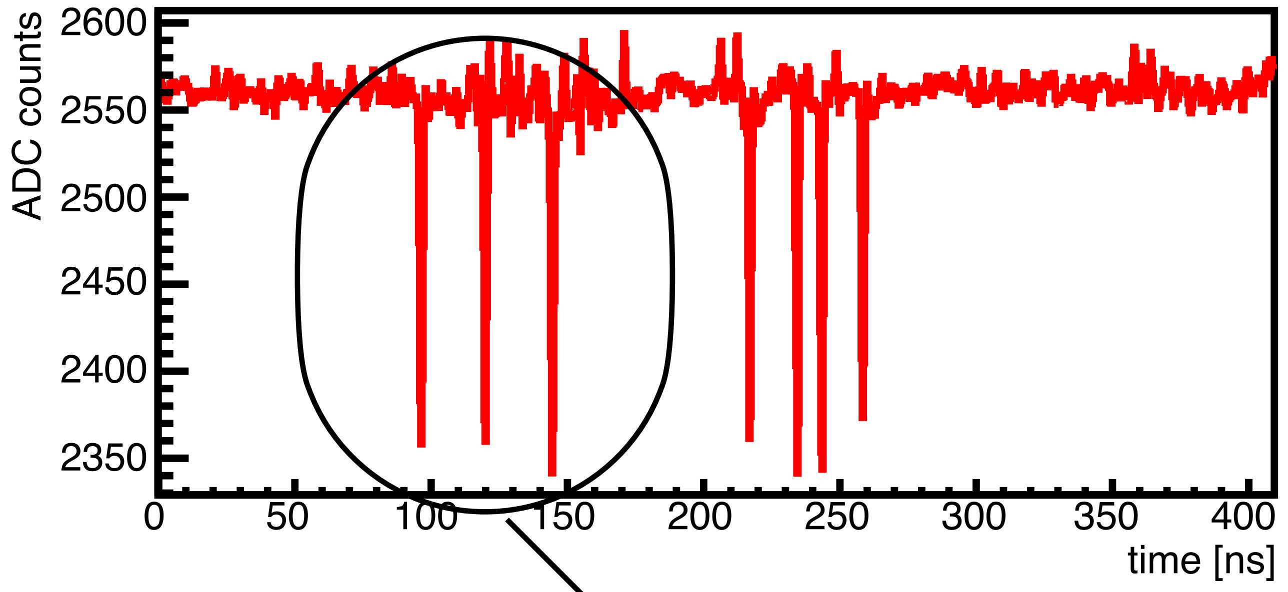
Developed by MoVeIT collaboration



8 ch (2.2 mm^2)

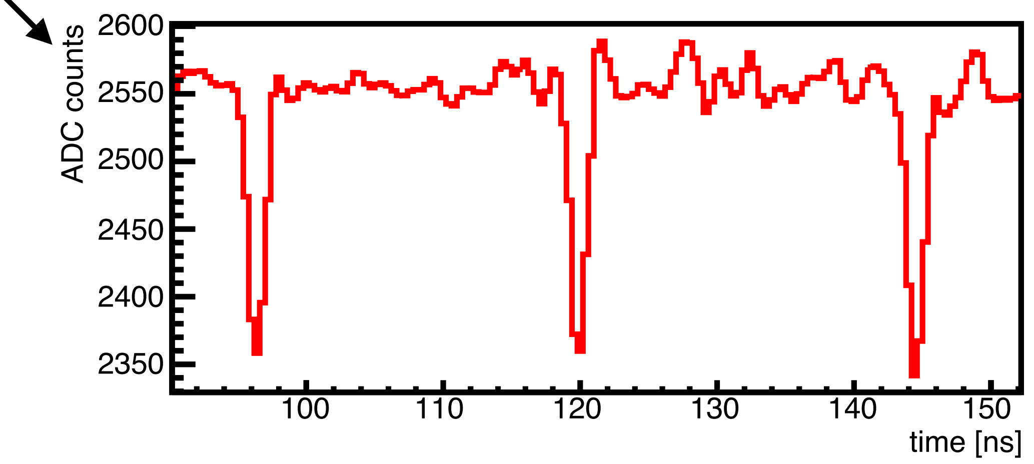
Time resolution ~ **10 ps**

Read by digitizer

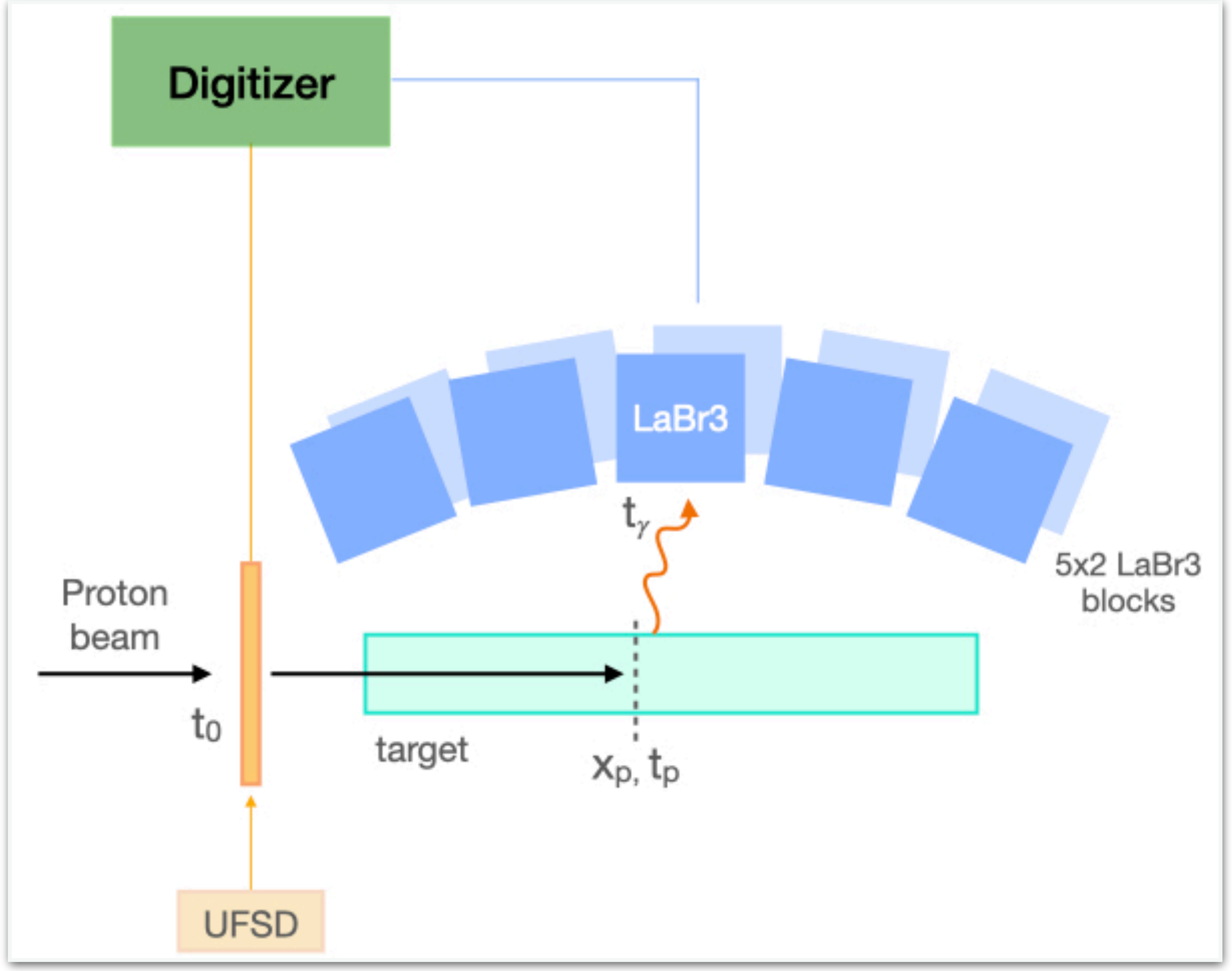


Detection efficiency up to ~27%

Beam Test @ CNAO, Jun 2021
Protons, 227MeV, ~10^5 pps



DETECTOR R&D



PGT MULTI-DETECTOR SYSTEM

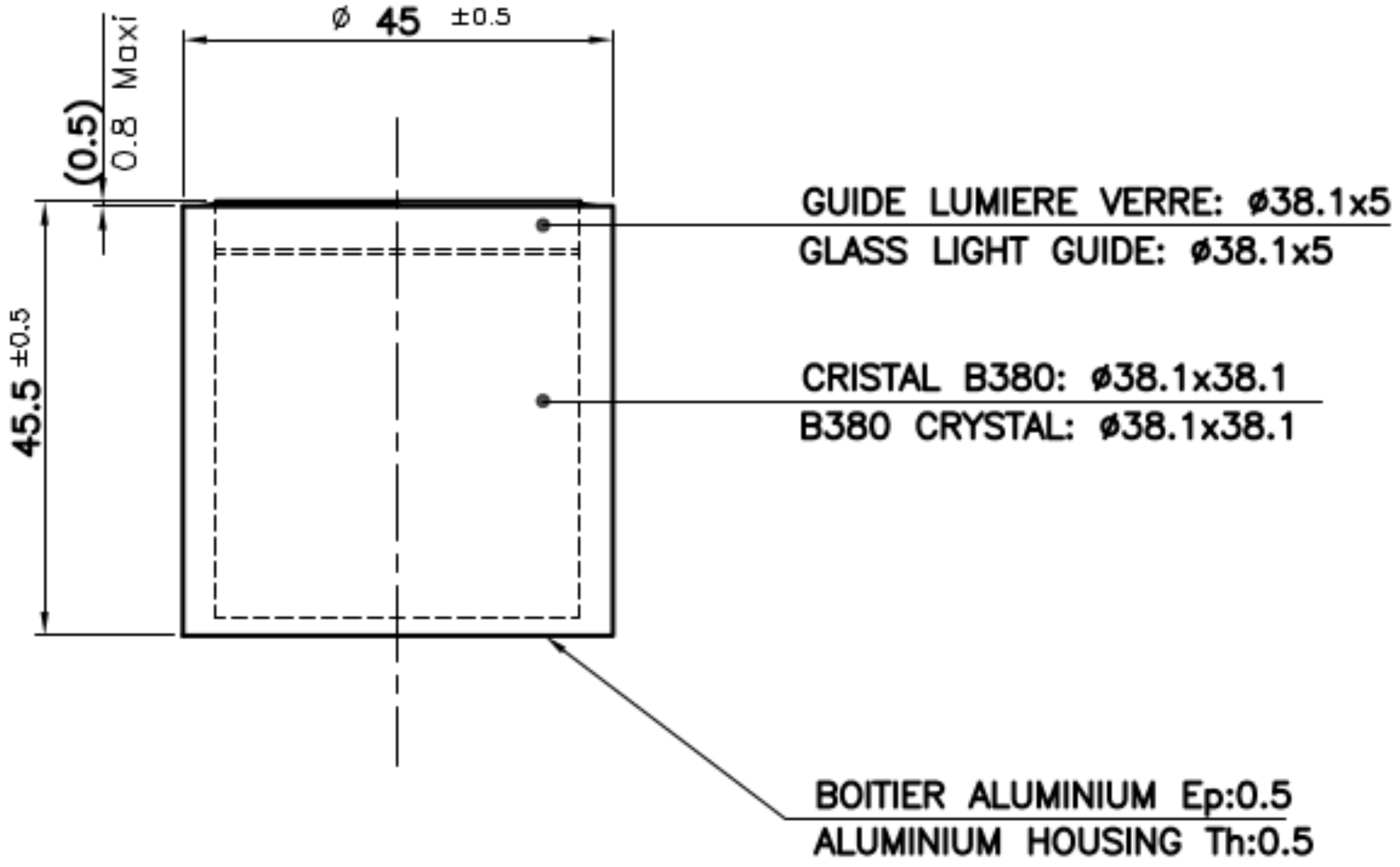
Setup with N detectors

LaBr3:Ce for the prompt gamma detection (t_γ)

UFSD for the primary proton detection (t_0)

$LaBr_3$(Ce): measure the arrival time of the secondary prompt photons

Istituto Nazionale di Fisica Nucleare

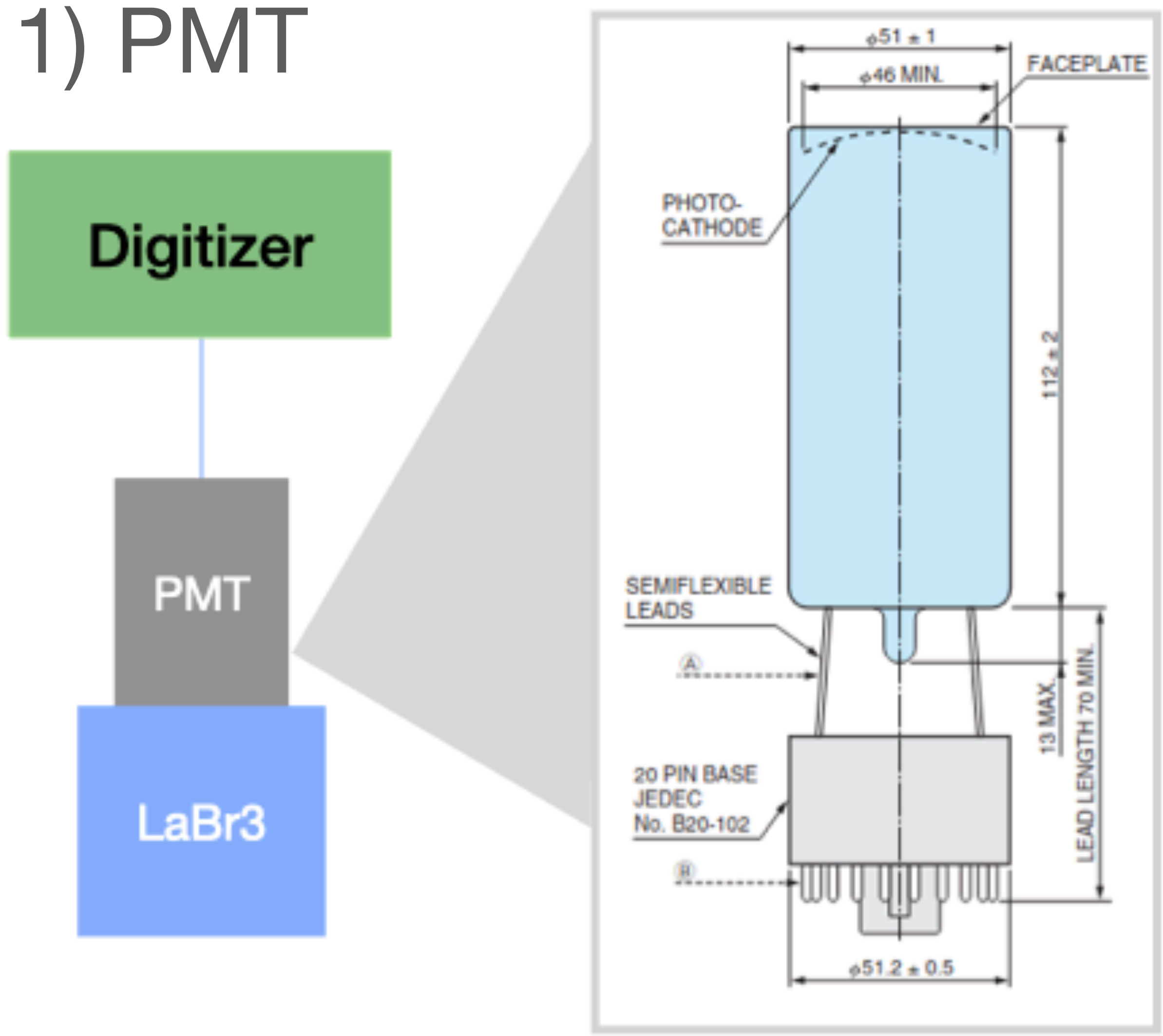


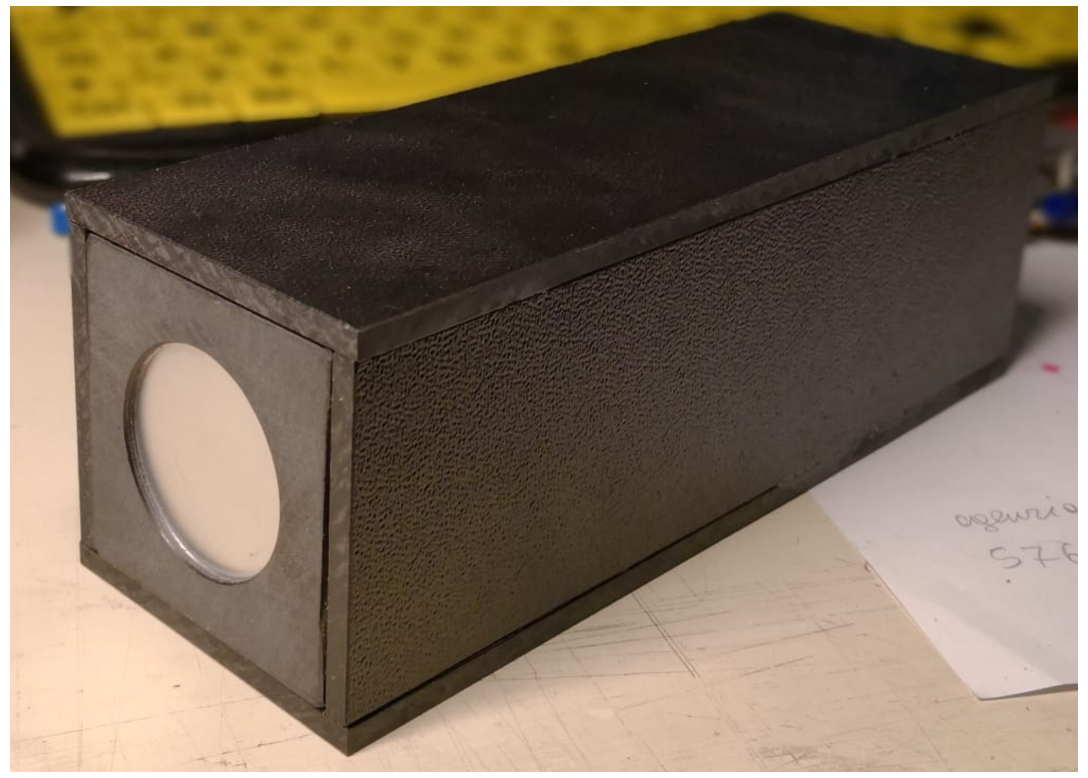
Scintillating crystals, 16 ns decay
Dimension: ⌀38.1 mm, h38.1 mm
Energy resolution 1.3% @ 6.1 MeV
Expected time resolution: **100 ps σ**

10 crystals, 10 ch
Read by digitizer

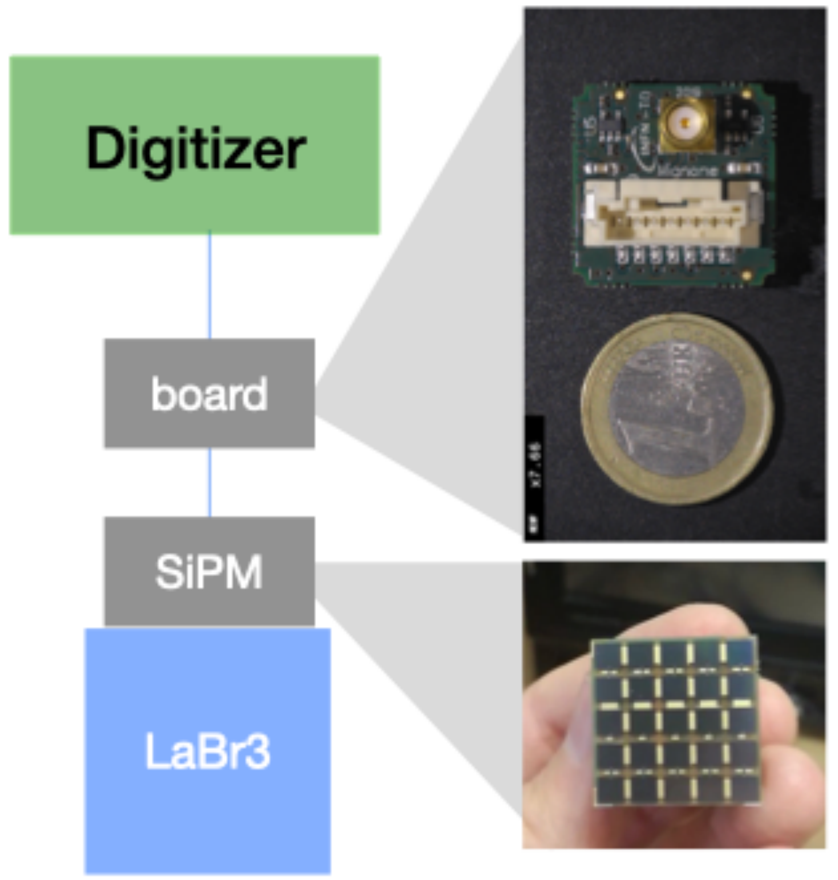
DETECTOR R&D

1) PMT





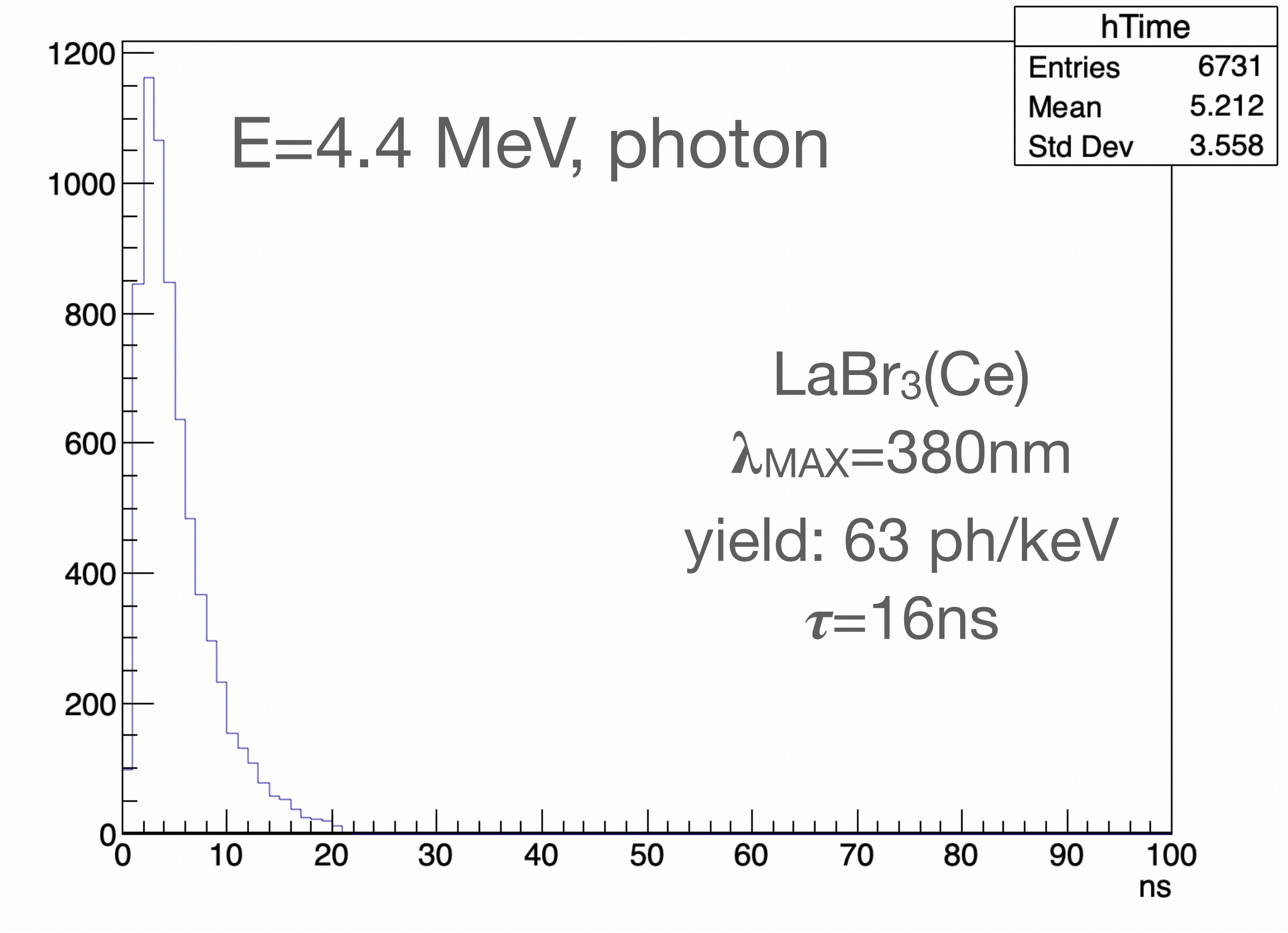
2) SiPM

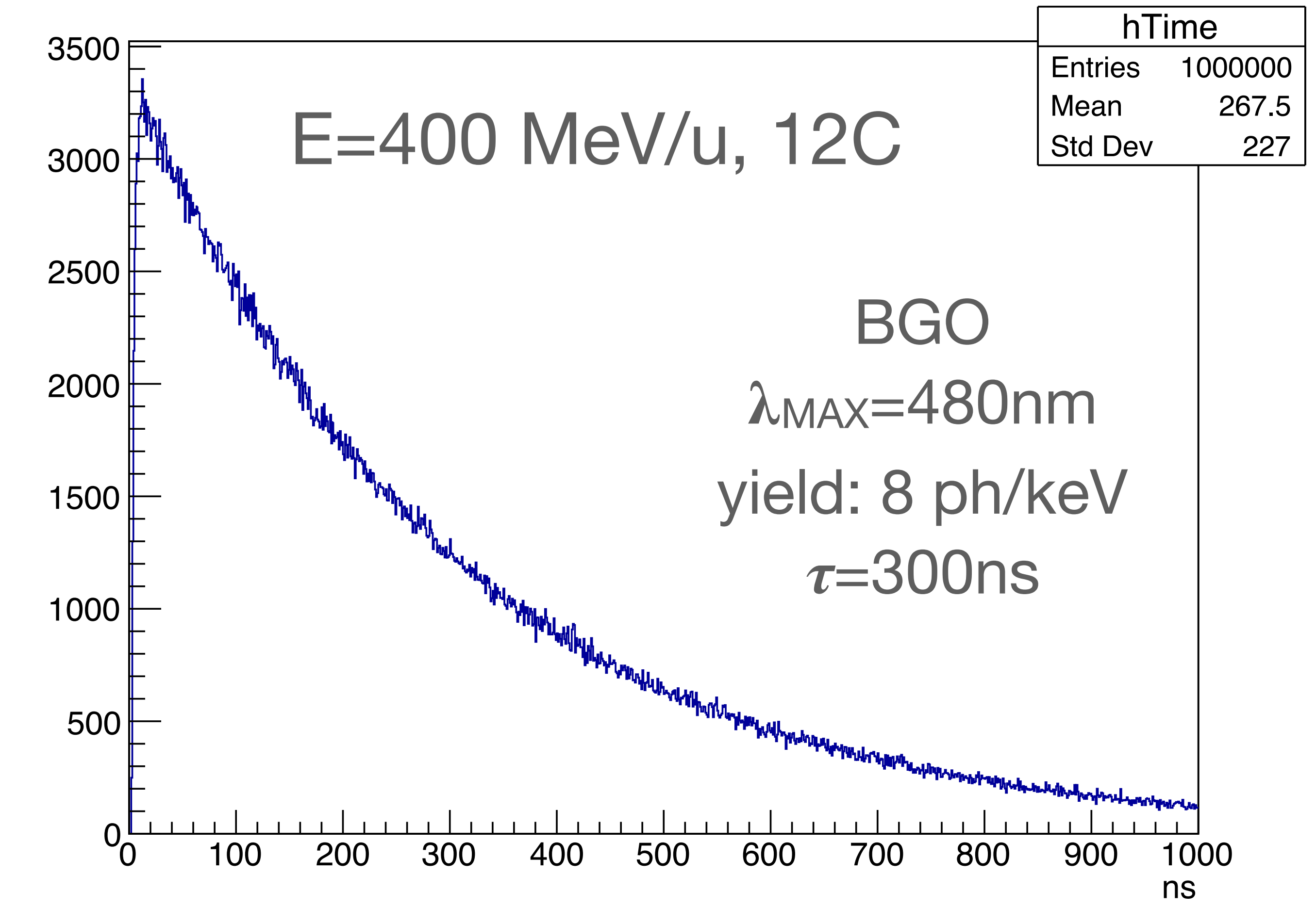


FE board and SiPM tile developed by the FOOT collaboration

SiPM by FBK
5x5 tile
→10^6 microcells per SiPM

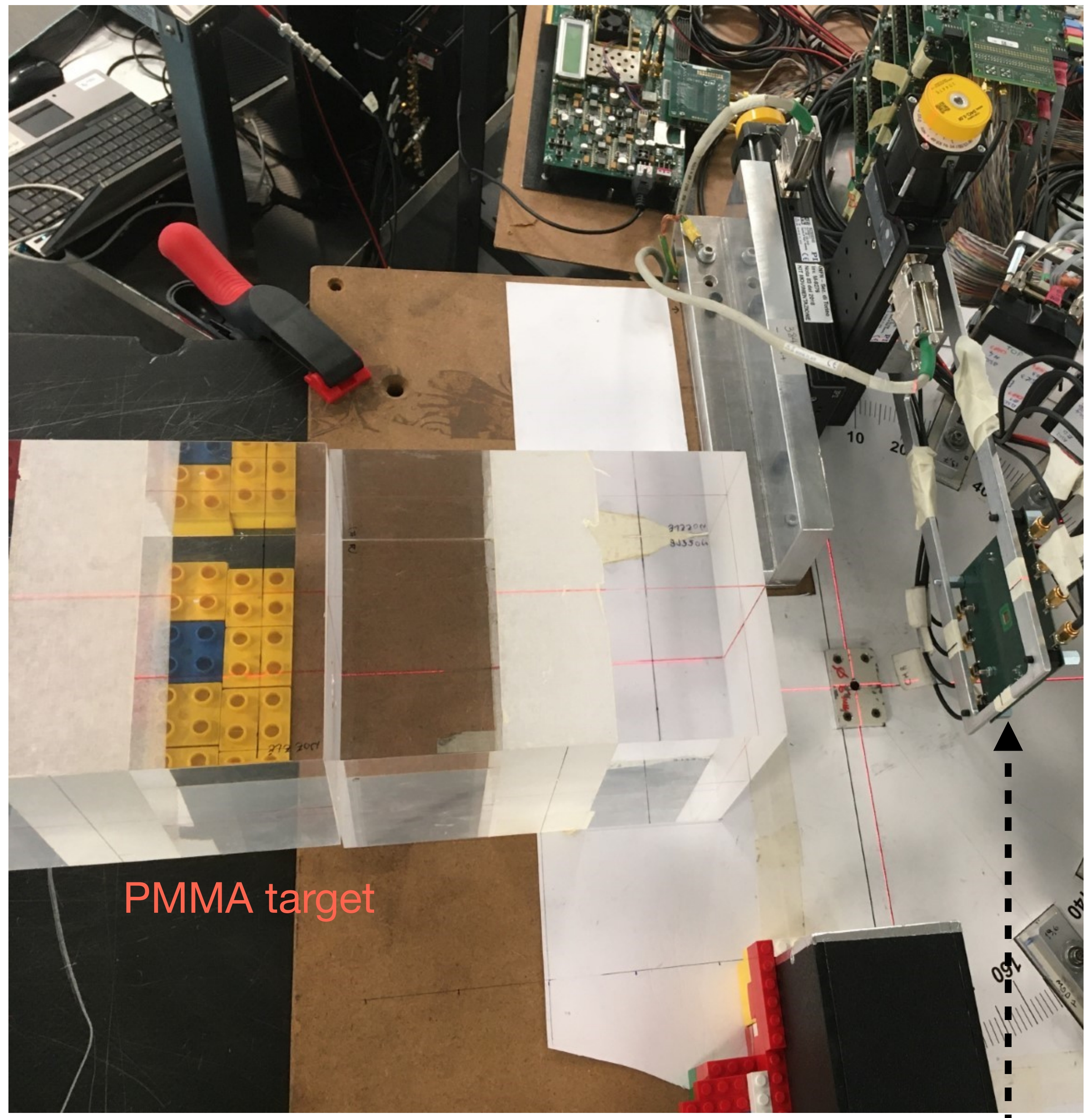
MC simulatons (FLUKA tool)





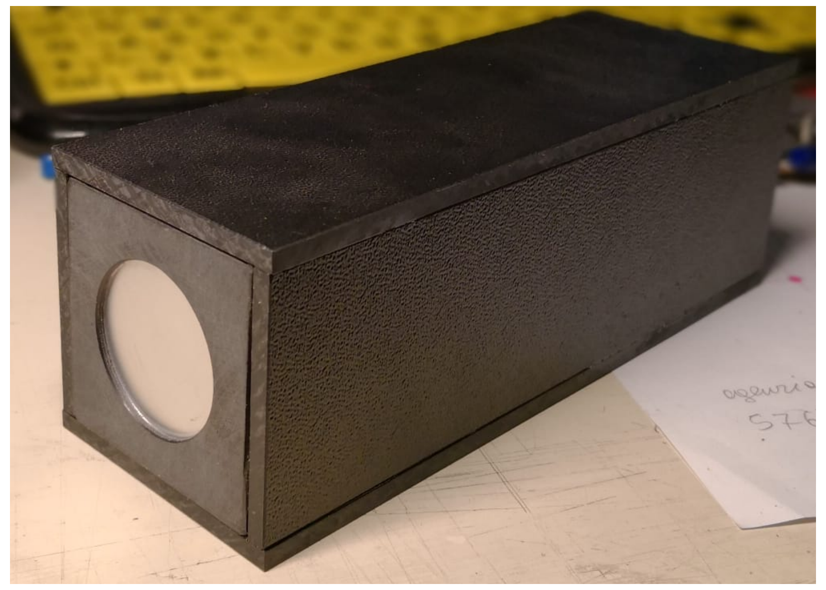
→ experimentally validated

PRELIMINARY TESTS



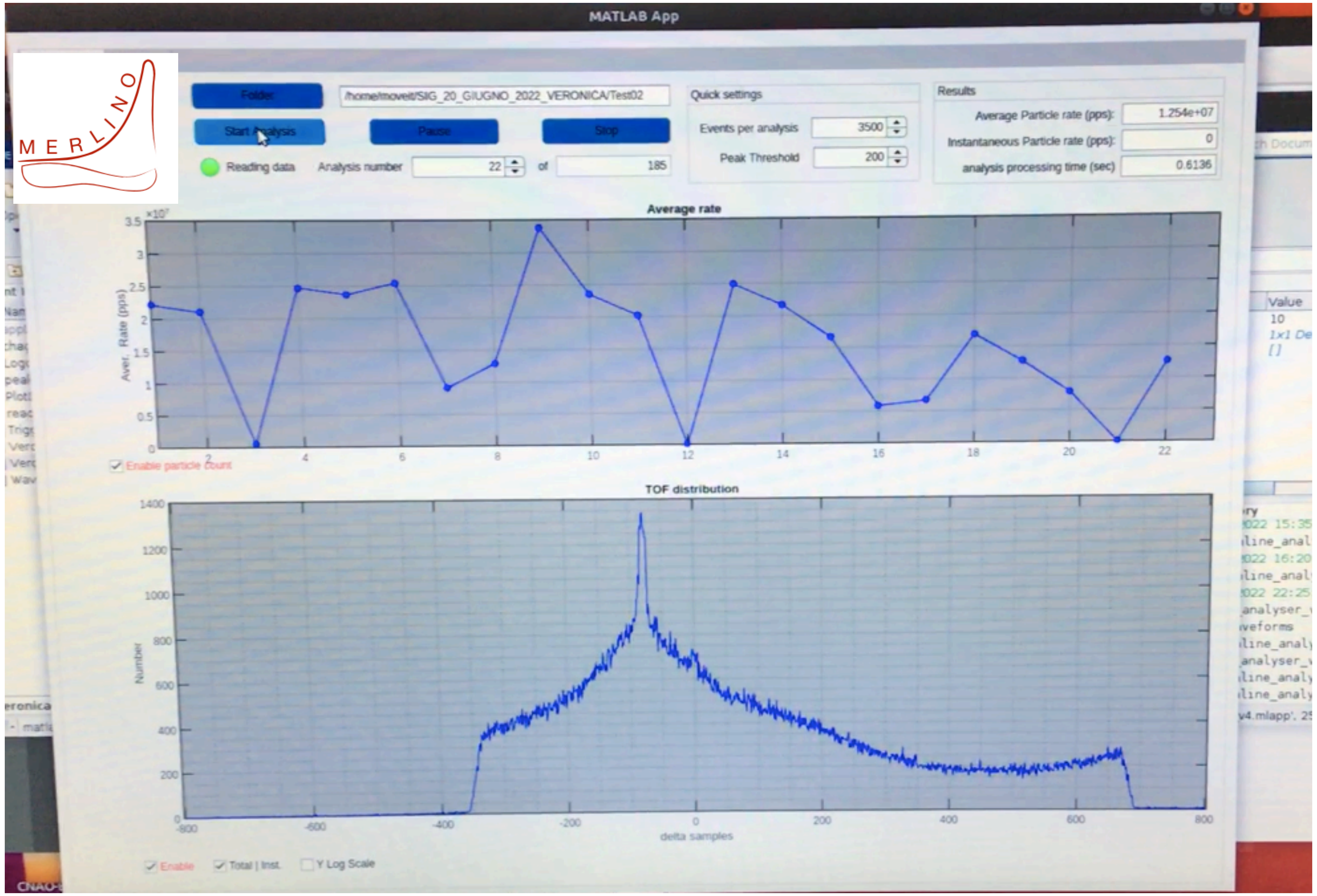
beam

LaBr3+PMT



UFSD
8 strips (2.2 mm^2 active area, 590 um pitch)

ONLINE PGT INTERFACE



Beam test @ CNAO, 21/06/2022

CONCLUSIONS

data

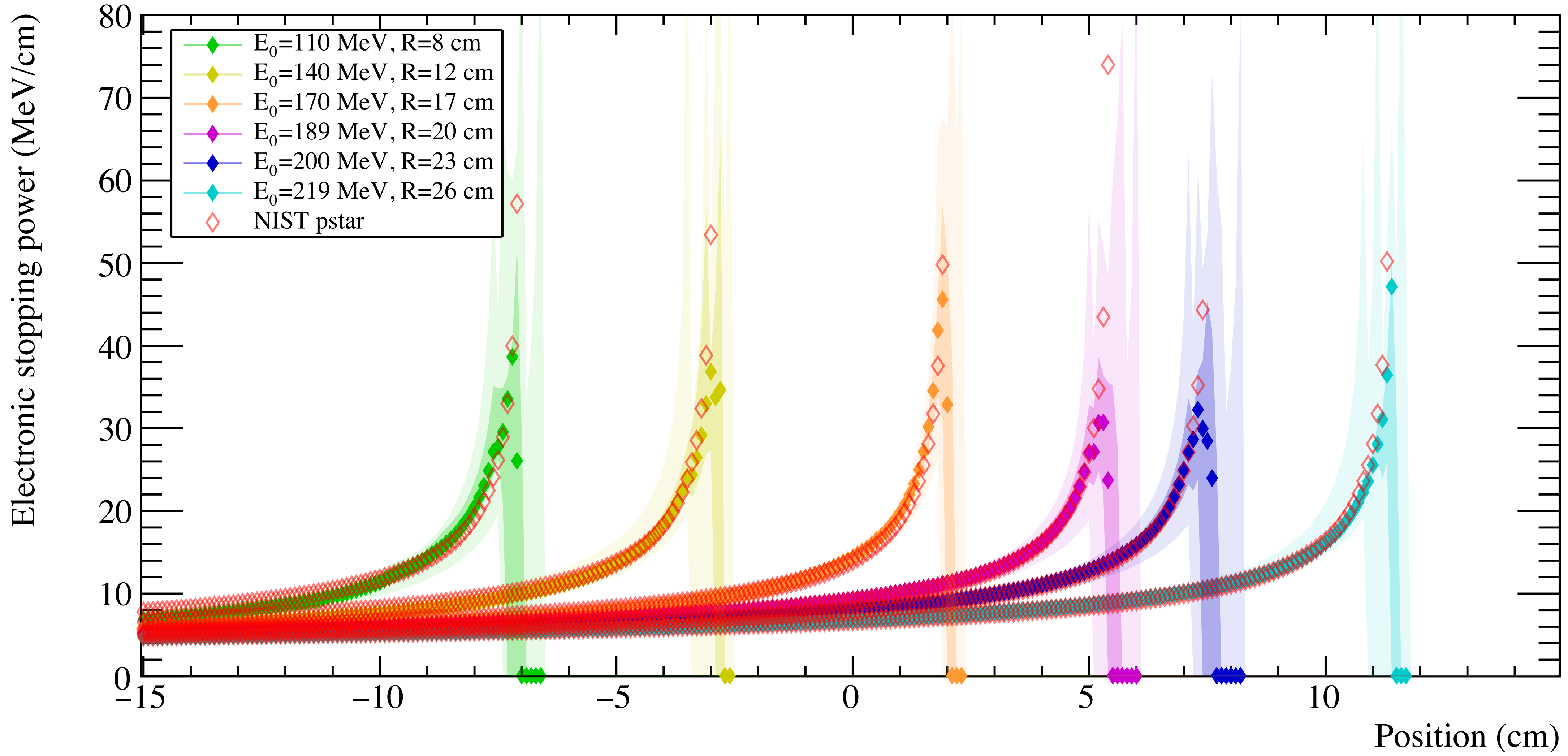
$$m_{jp}^{k+1} = \frac{m_{jp}^{k}}{S_{jp}} \sum_i \sum_d \frac{n*_{id}}{\sum_l \sum_t f_{idlt} m_{lt}^{k}} f_{idjp}$$

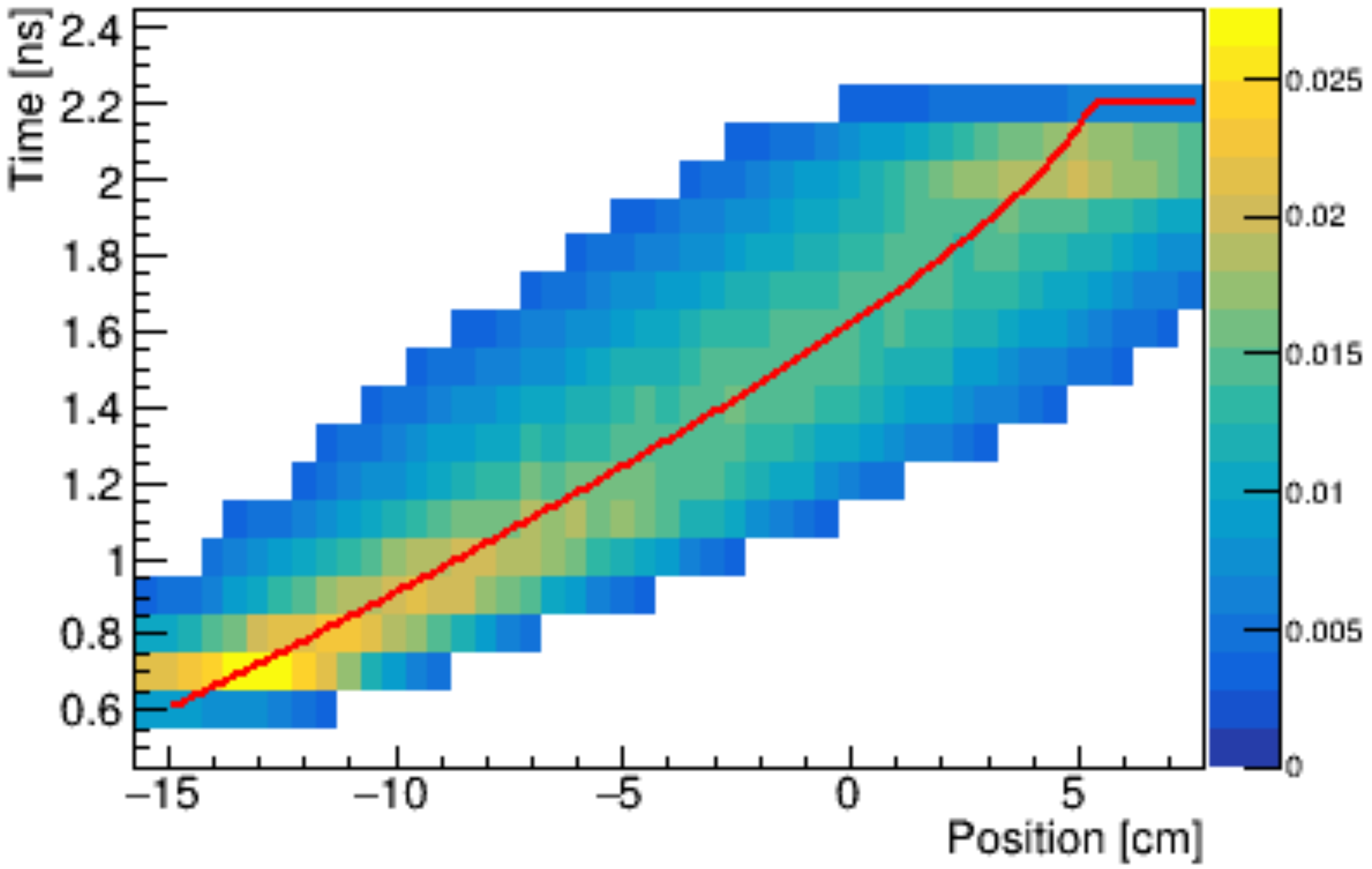
prompt photon

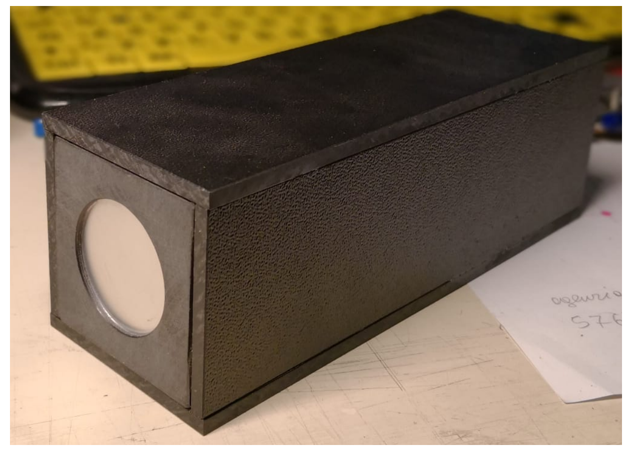
sensitivity

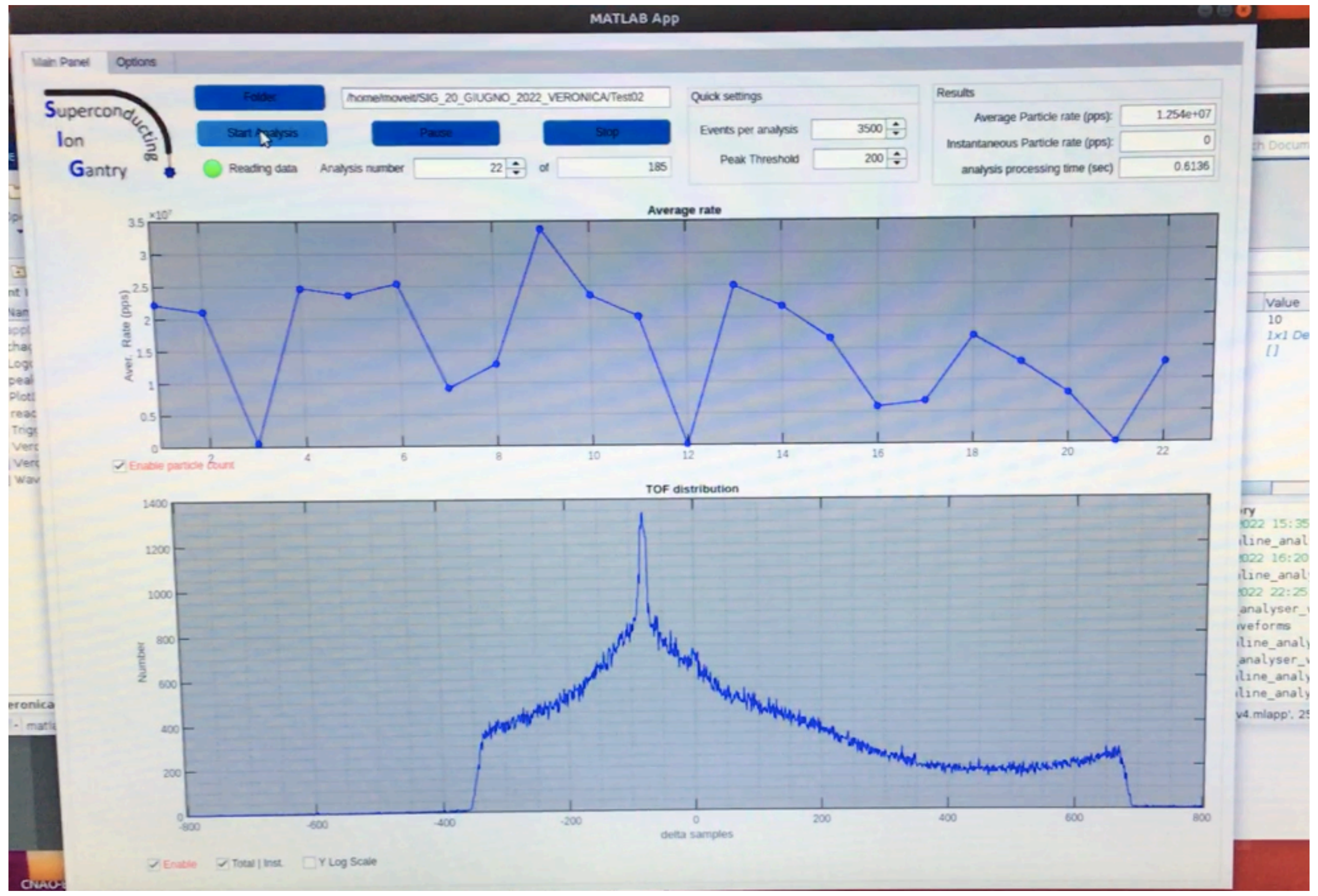
p: time bin (emission)
j: space bin (emission)
i: time bin (detection)
d: detector

SM





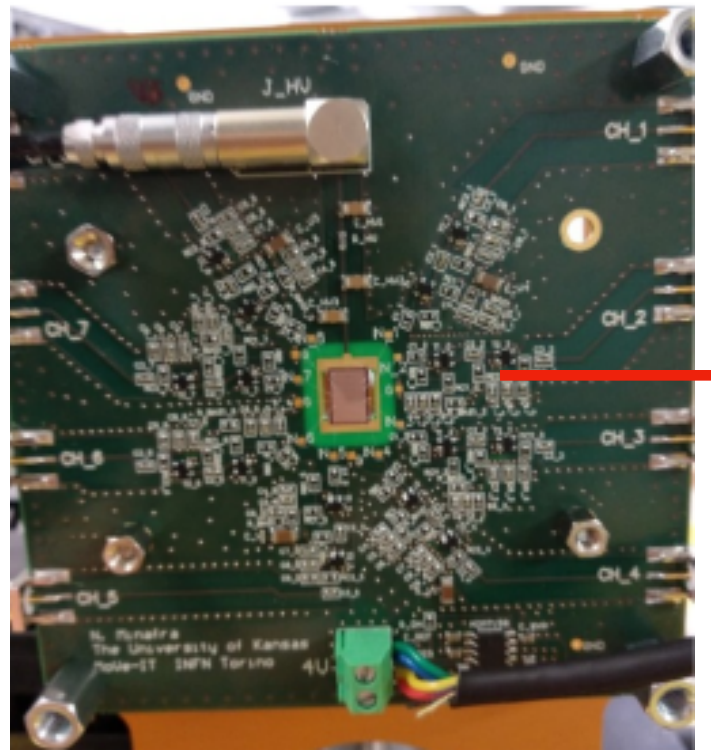


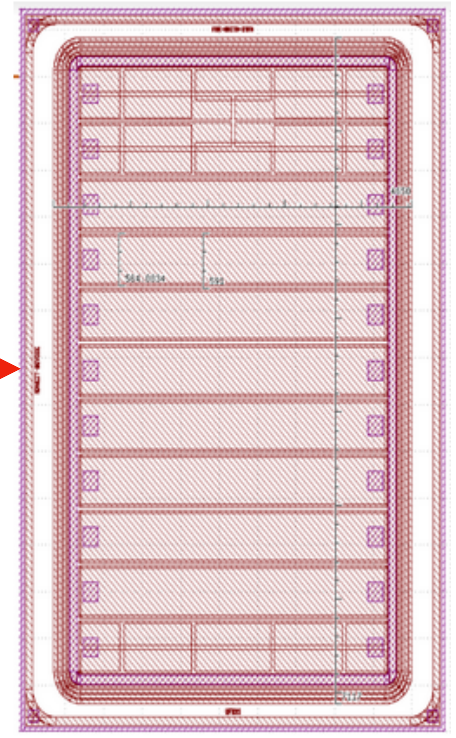


BACKUP SLIDES

ULTRA-FAST SILICON DETECTORS

UFSD for beam monitoring: measure the delivery time of each primary particle
Developed by MoVeIT collaboration (CSN5)

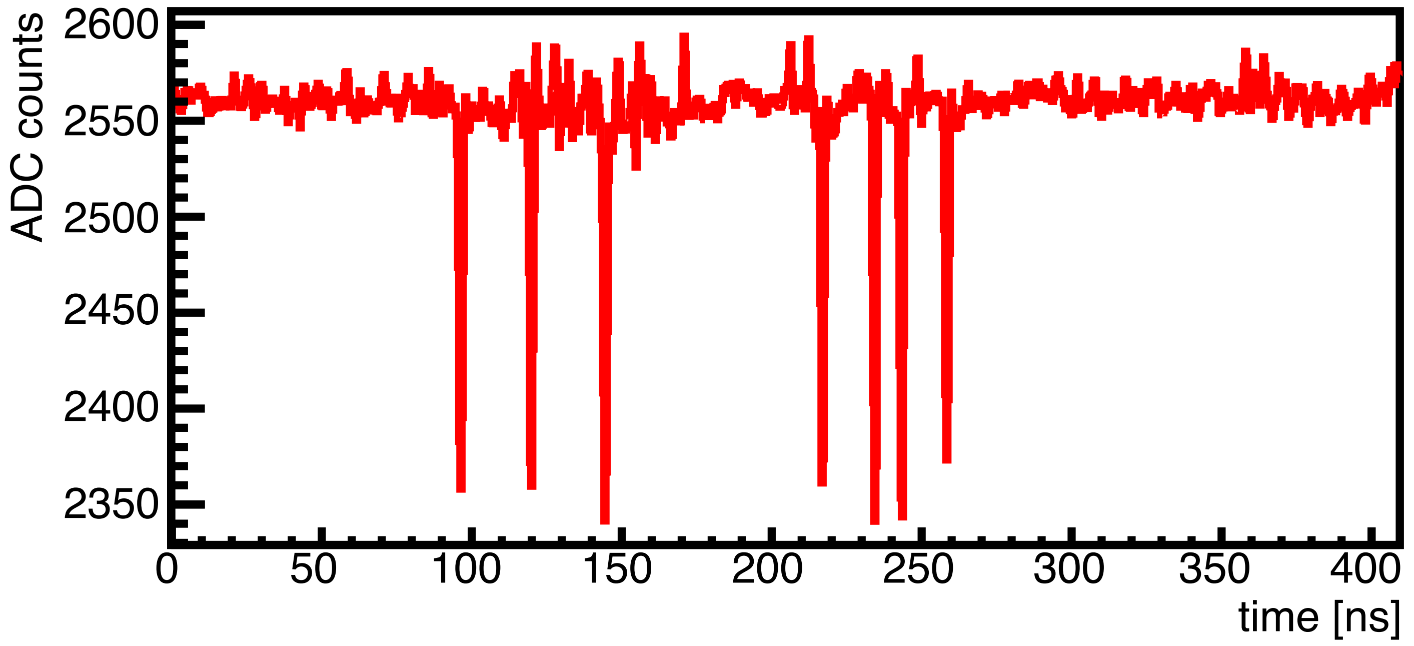




FE board: 8ch, 2 amplification stages (fast analog amplifier)
Optimized for timing measurements at high rates
Dynamic range: 3-150 fC → 60-250MeV protons

Fast signals (∼2ns), single discrimination up to 10^9 $ps^{-1}cm^{-2}$ (> 10 MHz/ch)

Ch specifications: noise < 3 mV, SNR > 25, jitter < 30 ps



8 strips + 3 test strips, 2.2 mm^2 (3393 um x 550 um, pitch 590 um)
Read by a digitizer (16ch, CAEN DT5742)
Time resolution ∼10 ps
Detection efficiency up to ∼27% with clinical beams

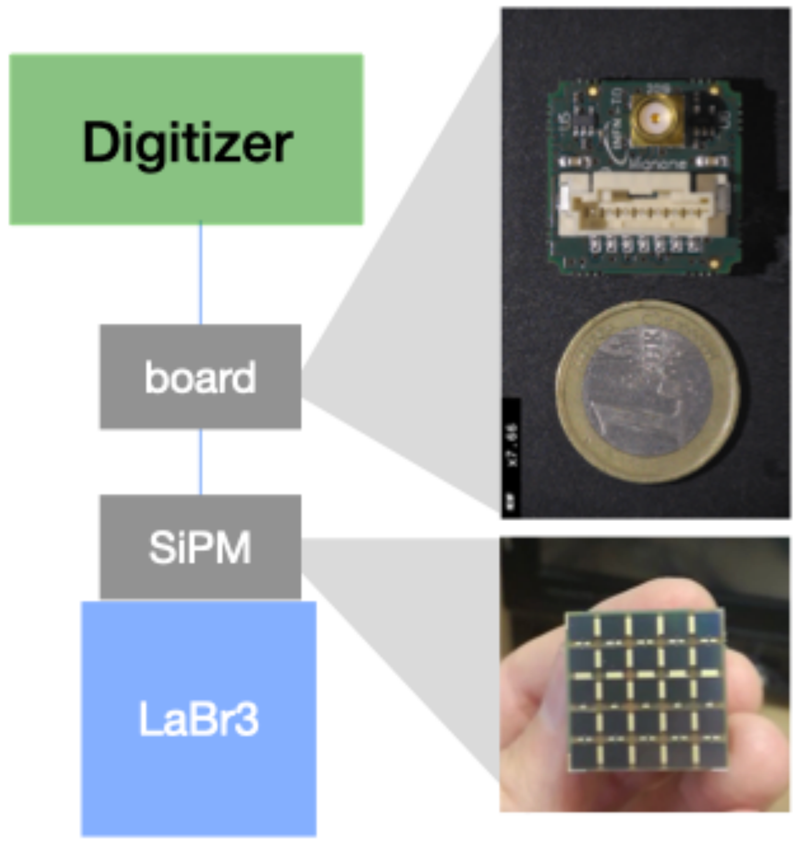
FOOT SIPM TILE

Pausch et al. "Detection systems for range monitoring in proton therapy: needs and challenges" NIM A 2020

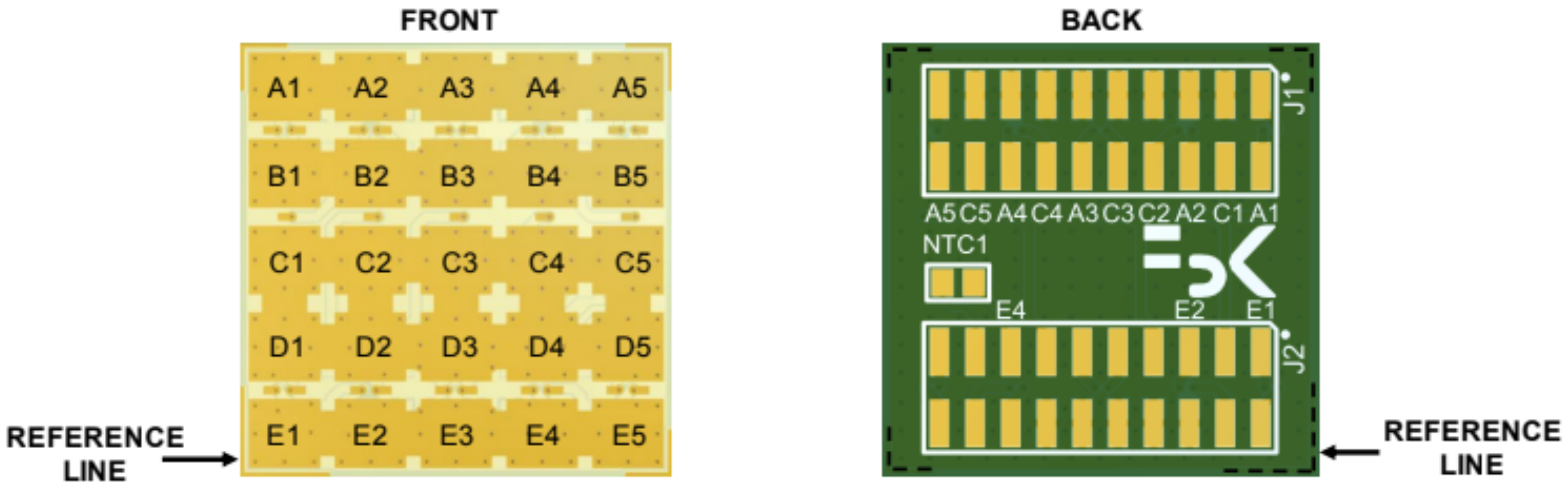
5.6. Challenge and potential approach

It seems an obvious approach to rely on the construction scheme and the SiPM light sensors of recent PET-MR detectors but to replace the LSO or LYSO crystals by $CeBr_3$ or $LaBr_3$:Ce. The high light yield

Readout 2: SiPMs



FOOT (CSN3 INFN) FE board and SiPM tile



SiPM by FBK:

SiPM Type			Tile		
Technology	Cell size (µm)	SiPM size (mm²)	Tile size (mm²)	# SiPMs	Resin
RGB-HD	15	16	24x24	25	Epoxy

→10^6 microcells per SiPM

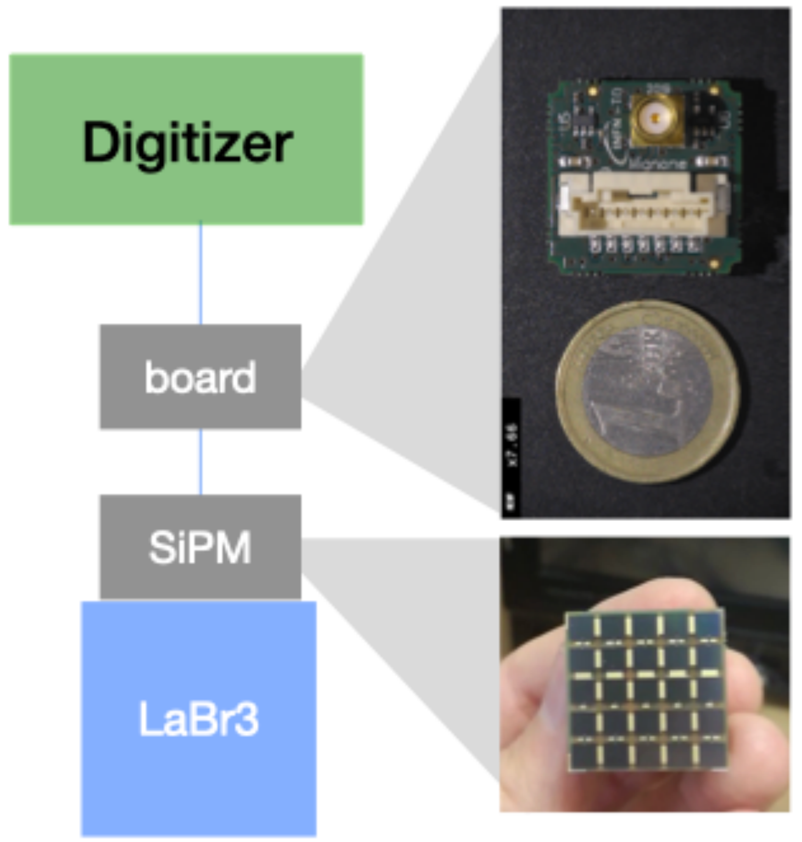
BGO time resolution ~600 ps σ (cosmic rays), τ=300 ns

Digitizer 2.5 Gs/s

→better time res might be achieved with $LaBr_3$(Ce)

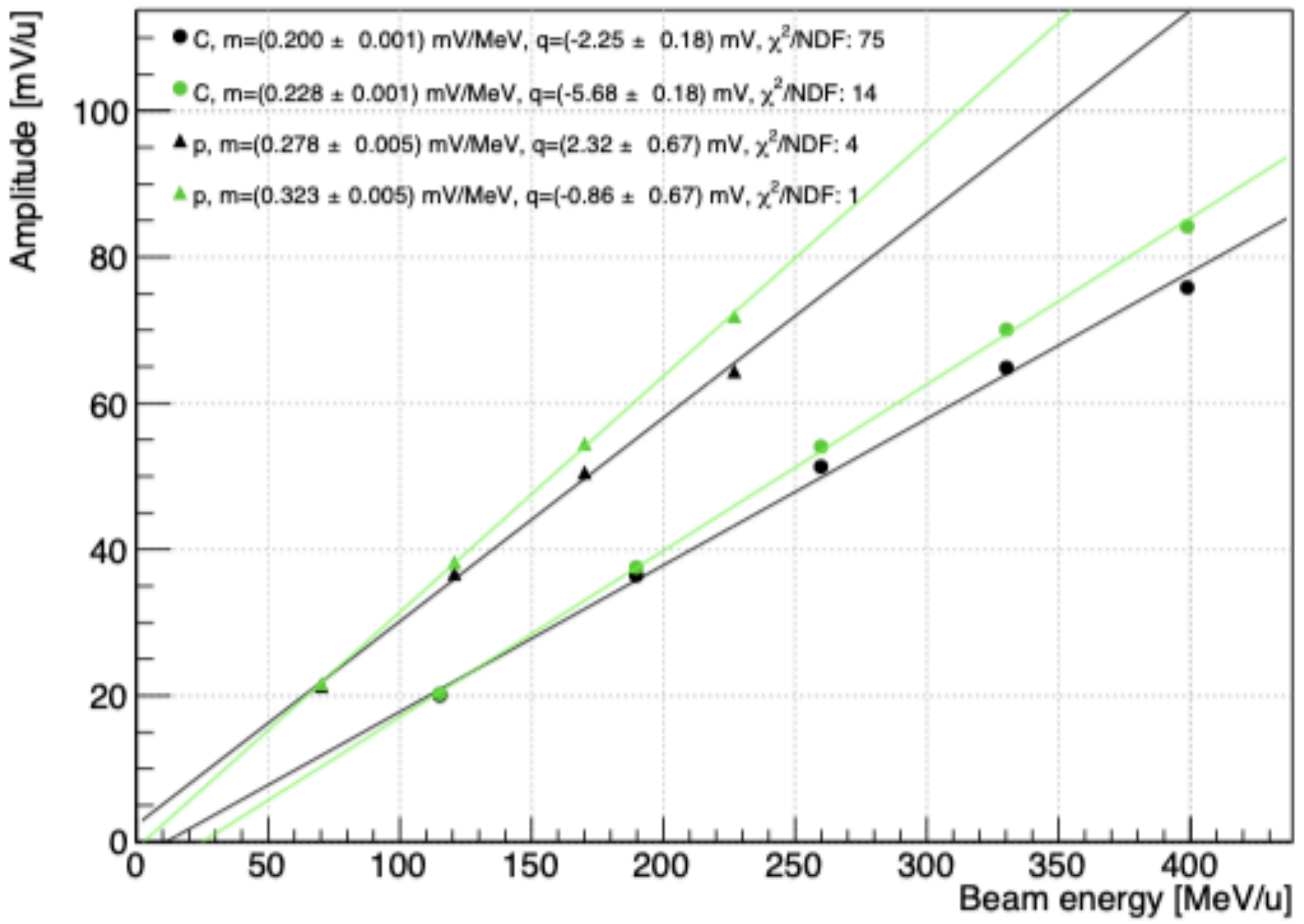
FOOT SIPM TILE

Readout 2: SiPMs

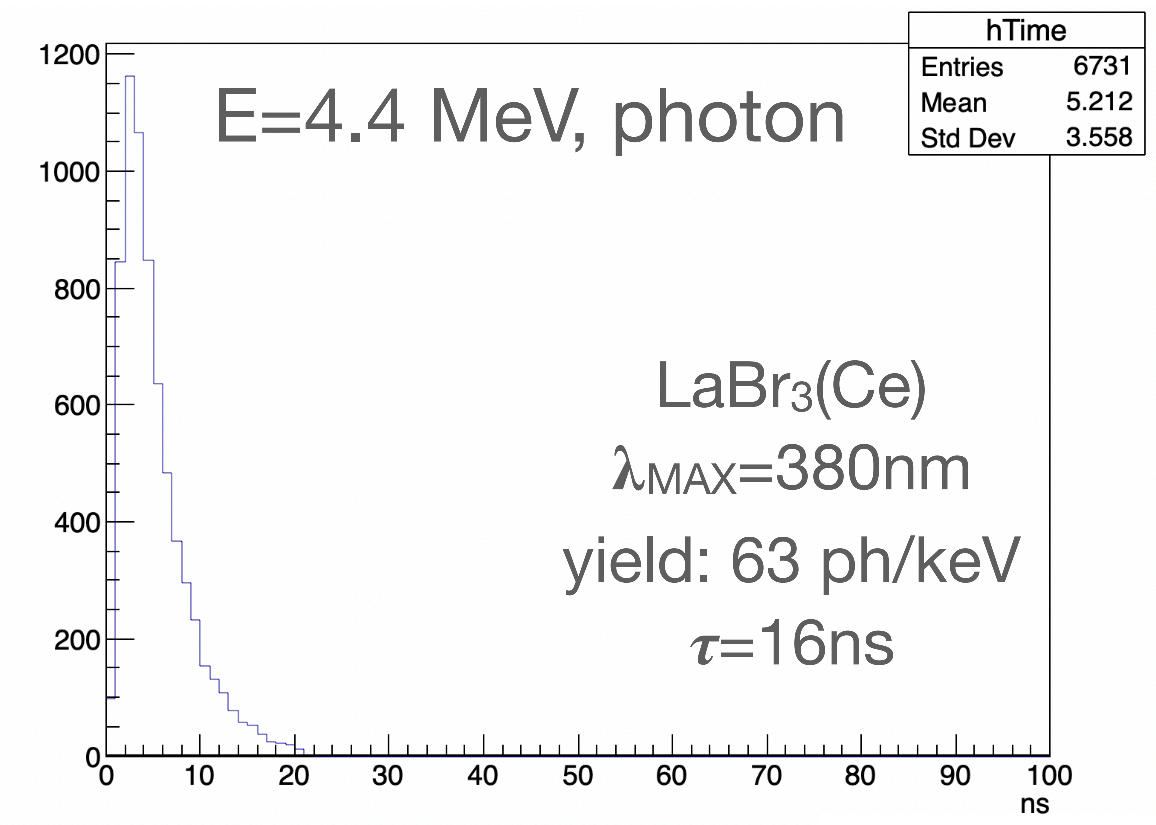


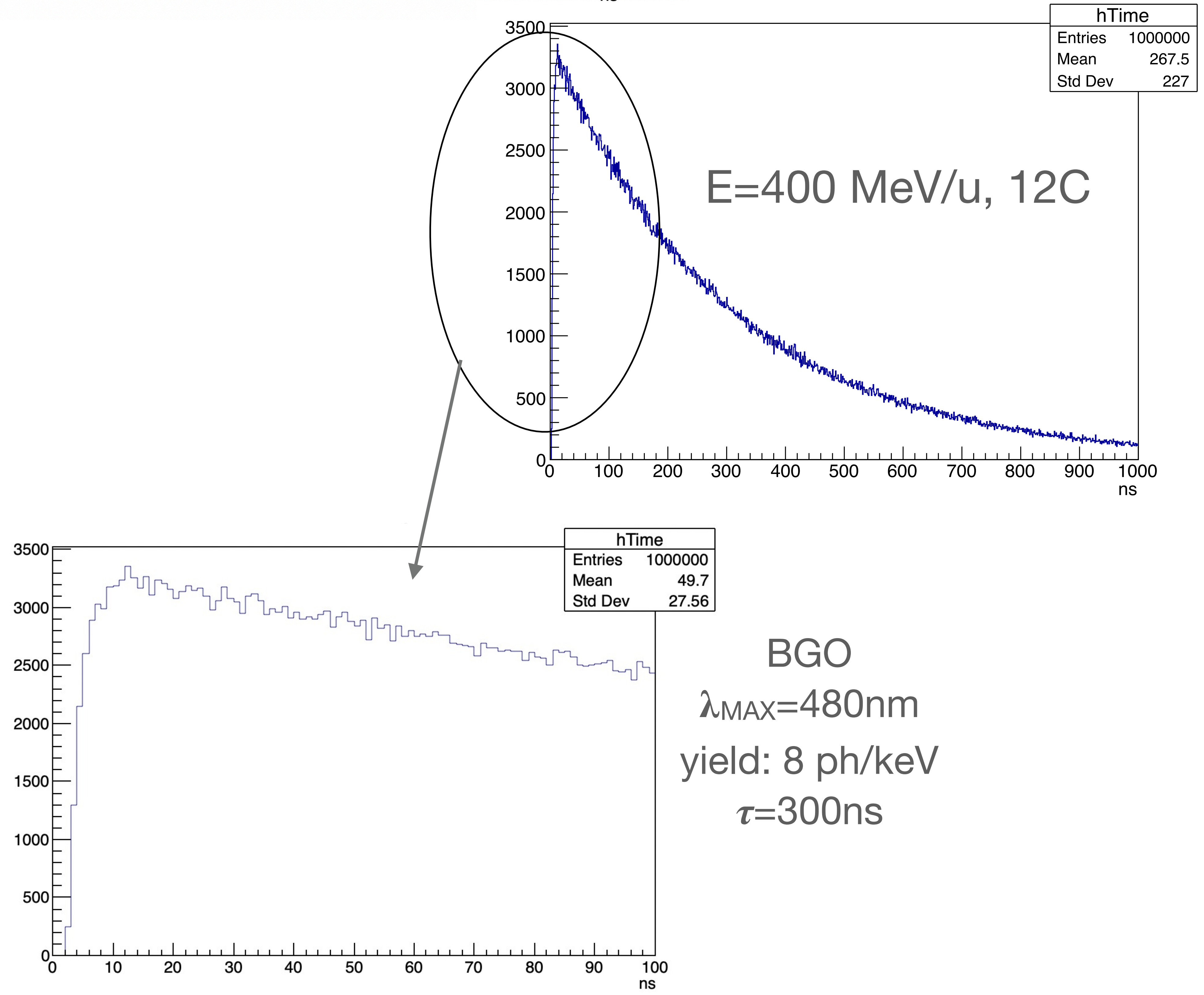
FOOT (CSN3 INFN) FE board and SiPM tile

SiPM response linearity vs beam energy



MC simulations





BGO

λ_{MAX}=480nm

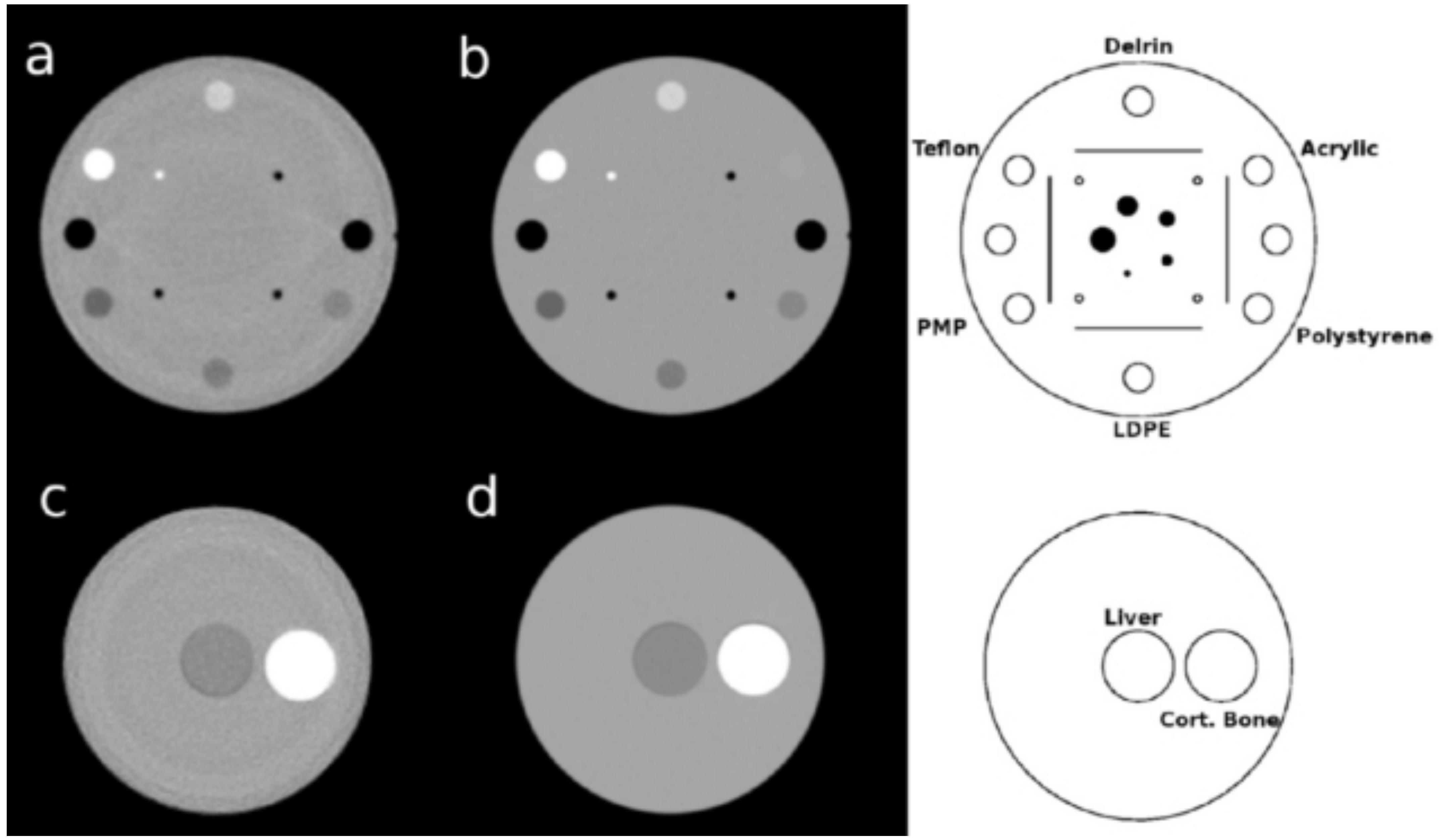
yield: 8 ph/keV

τ=300ns

PROTON CT, DUAL ENERGY CT

→HU to Stopping Power ratio conversion uncertainties

Proton CT Dual Energy CT



PCT: <1.31% measured SP accuracy, 0.55% mean absolute error

DECT: <2.38% measured SP accuracy, 0.67% mean absolute error

PCT: lower doses than DECT

Multiple Coulomb scattering→spatial resolution degradation

Neither PCT nor DECT can be used for treatment verification