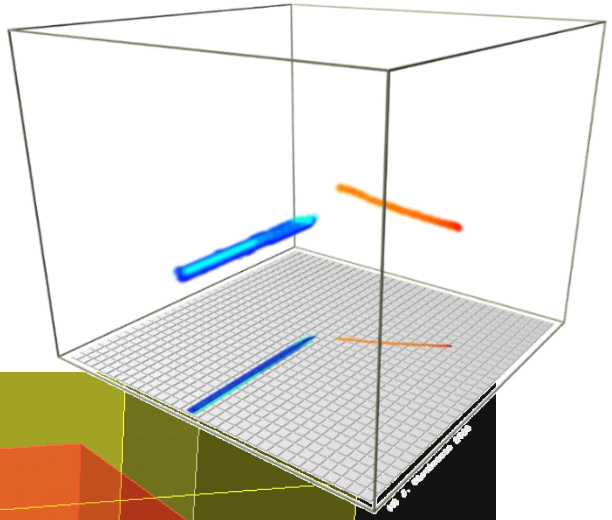
Réseau R&D Détecteurs à Gaz

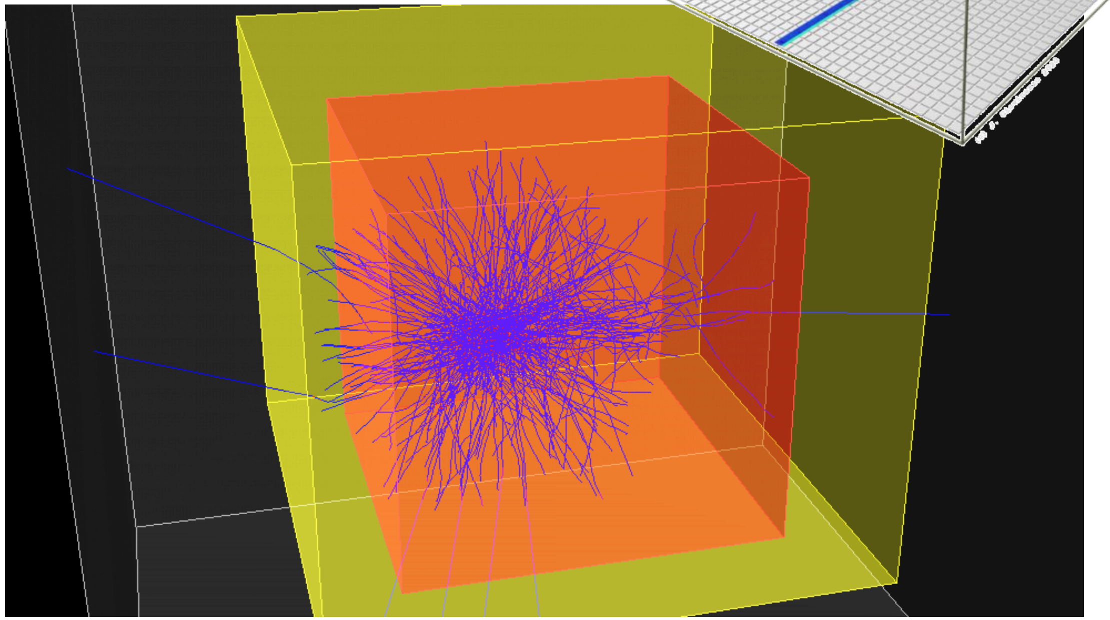
March 31th –April 1st 2025 – Saclay

simulations for ACTAR TPC decay experiments

J. Giovinazzo – LP2iB (former CENBG) – Bordeaux

- decay experiments with ACTAR TPC
- simulations for detection efficiency
- decay simulation principles
- application to tracks analysis





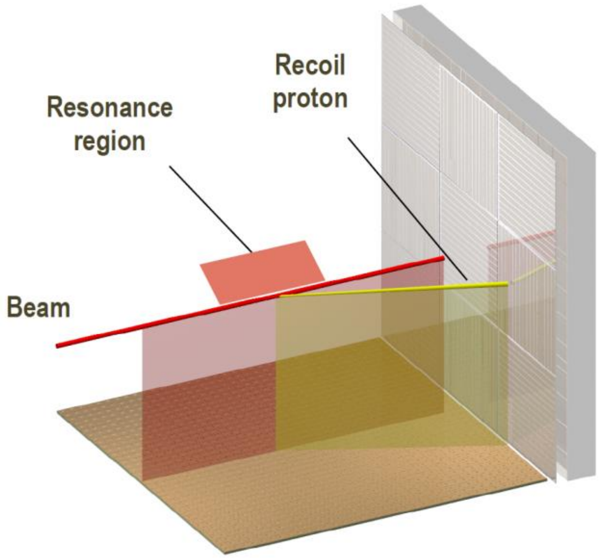
decay experiments with ACTAR TPC

designed as "active target"…
high efficiency, thick target, vertex, tracking, good energy resolution…

inverse kinematic reactions

unbound resonances, highly excited states

transfer & charge exchange reactions

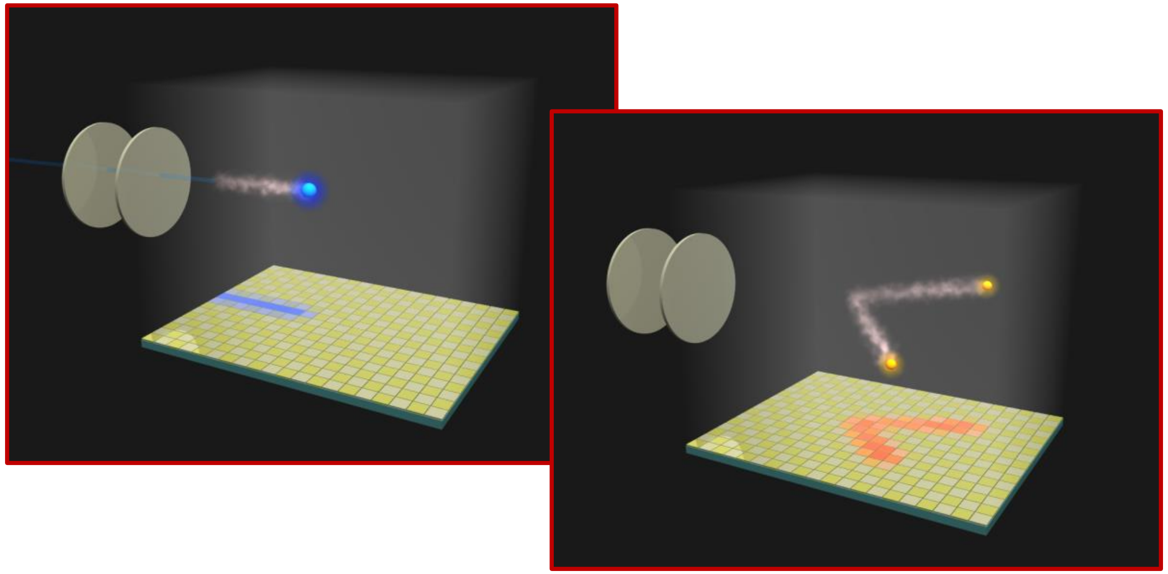


…and implantation/decay TPC
high efficiency, transp. to beta, low threshold
multi-particle tracking…

charged particles / exotic decay modes

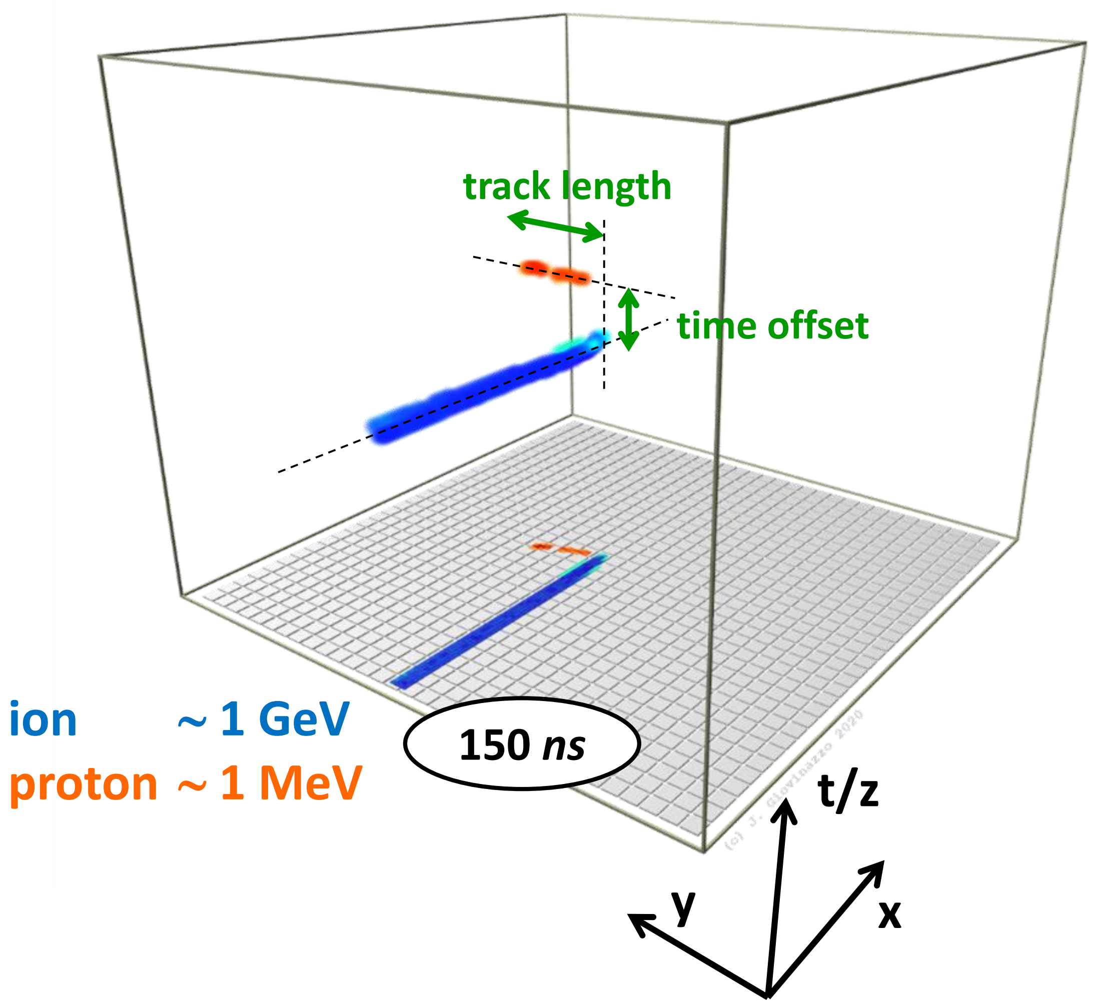
beta-delayed (multi-)proton

particle decay of excited states



decay experiments with ACTAR TPC

E690 (GANIL, 2019): proton decay of ^{54m}Ni



decay experiments with ACTAR TPC

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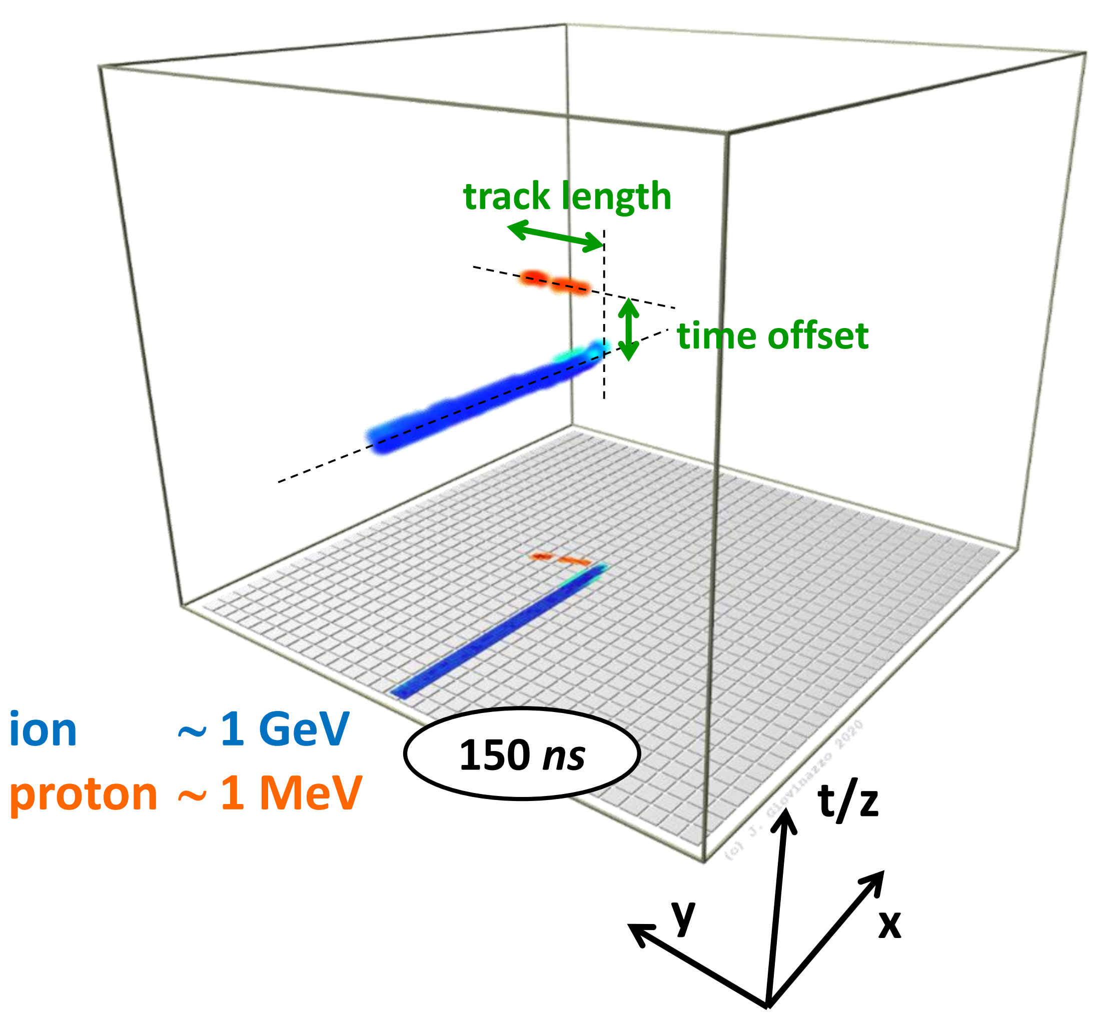
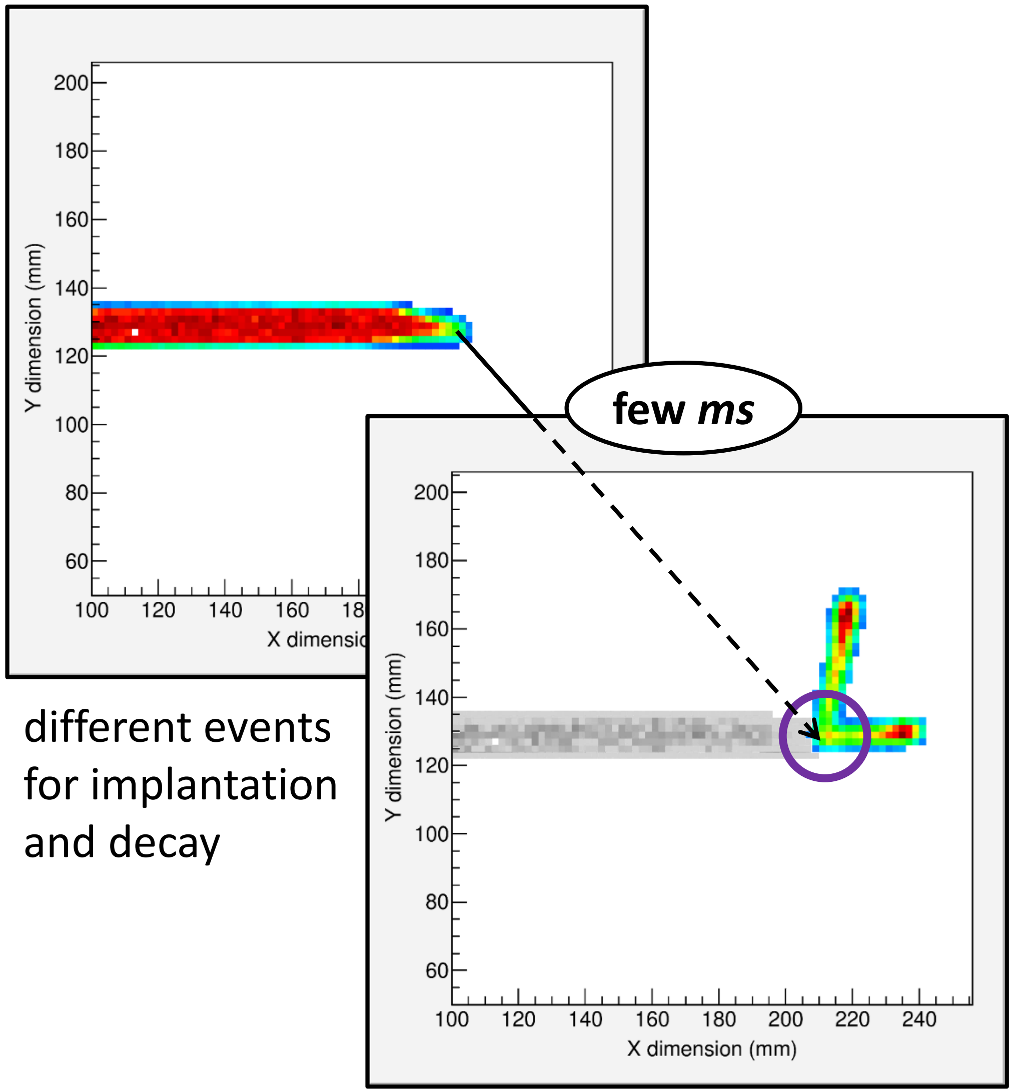


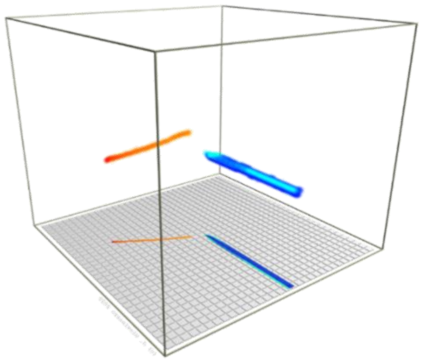
E791 (GANIL, 2021): 2p radioactivity of ^{45}Fe & ^{48}Ni



simulations for detection efficiency

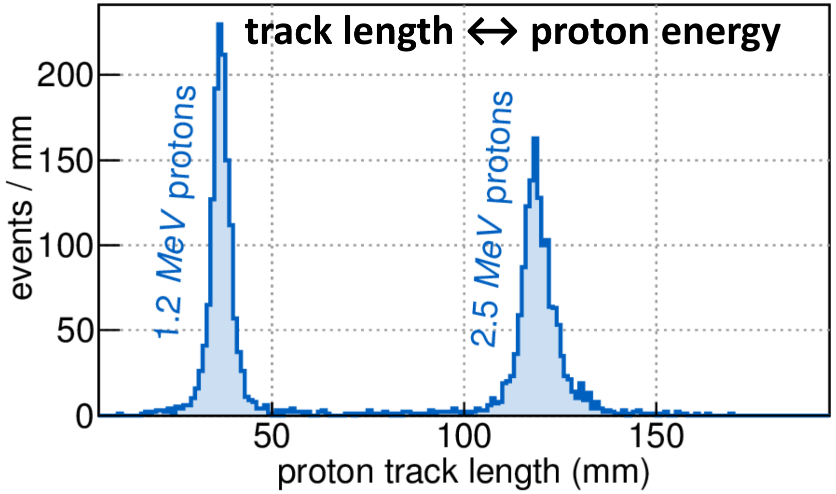
need for simulations: escape probability

E690



2 proton energies
→ relative decay branches intensity ?

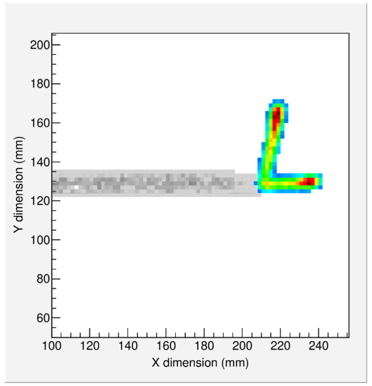
$$N_{emit}(E_p) = \frac{N_{obs}(E_p)}{\varepsilon(E_p)}$$



- **different track energy / length**
  ↔ different escape probabilities
- **proton track hidden in ion track**
- **missing regions in the pad plane**
  (+ analysis procedure and cuts)

need for simulations: escape probability

E791



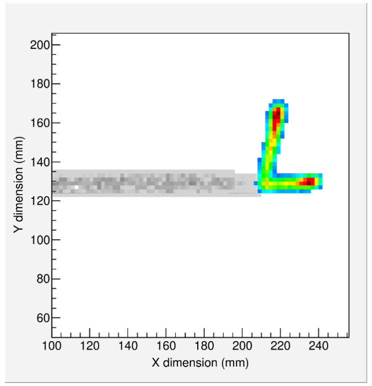
2-proton radioactivity

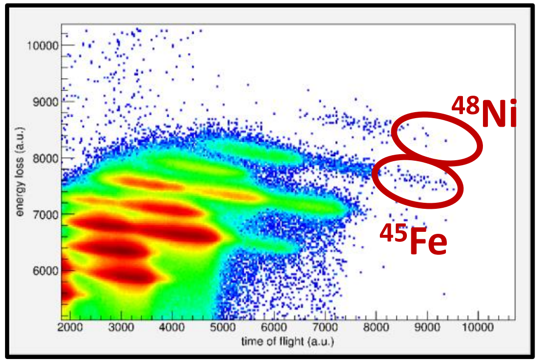
single decay branch

event by event analysis (counting)

need for simulations: escape probability

E791





2-proton radioactivity

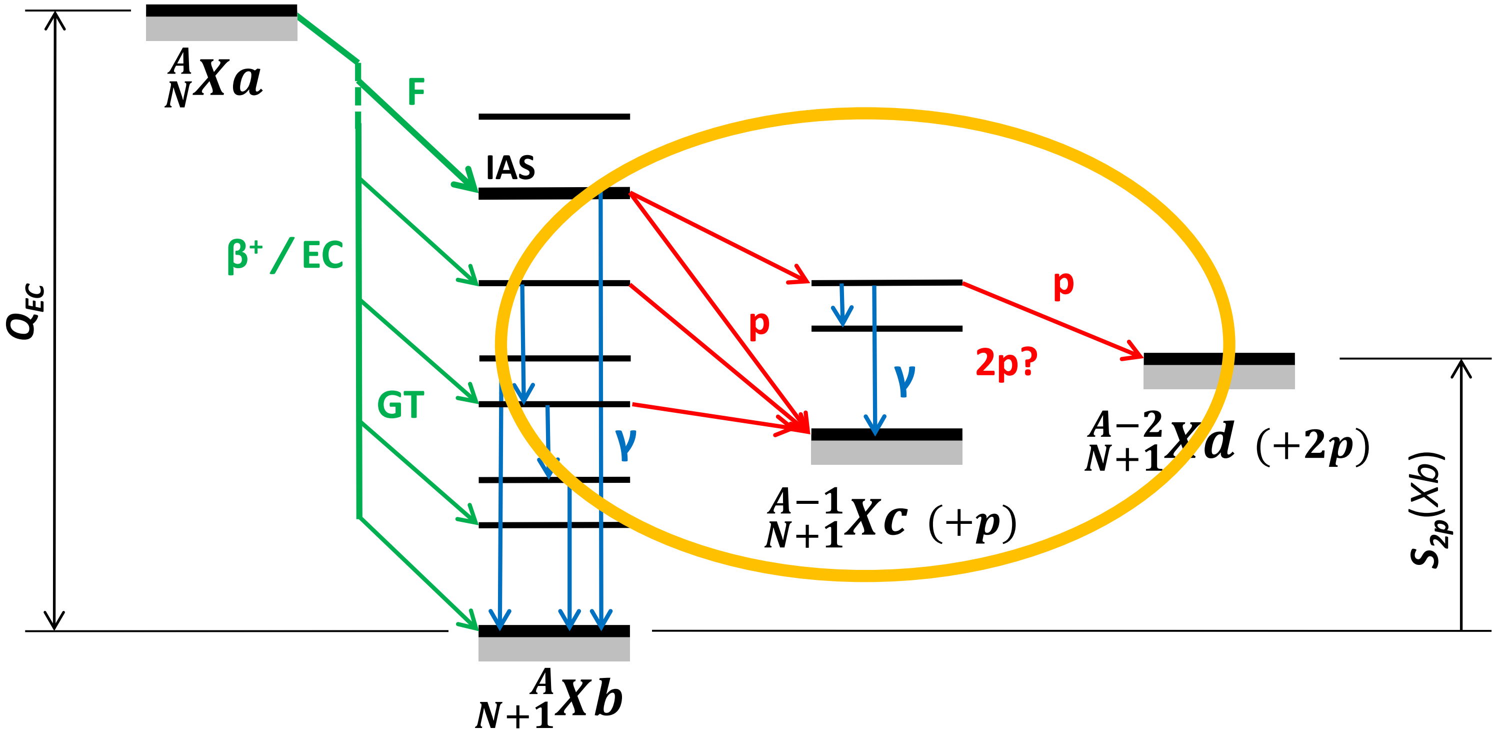
single decay branch

event by event analysis (counting)

beta-delayed 1,2,3-proton(s)

→ from **several nuclei** (cocktail beam)

→ decay scheme



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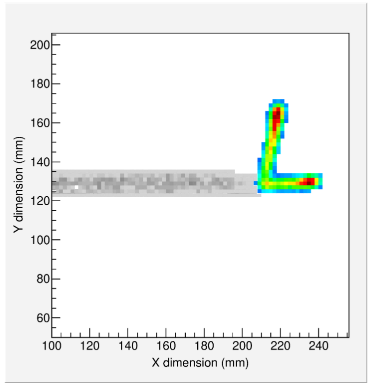
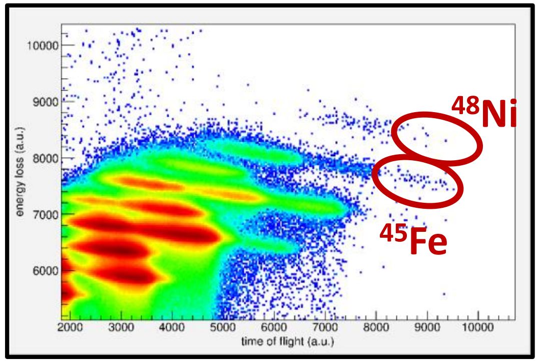
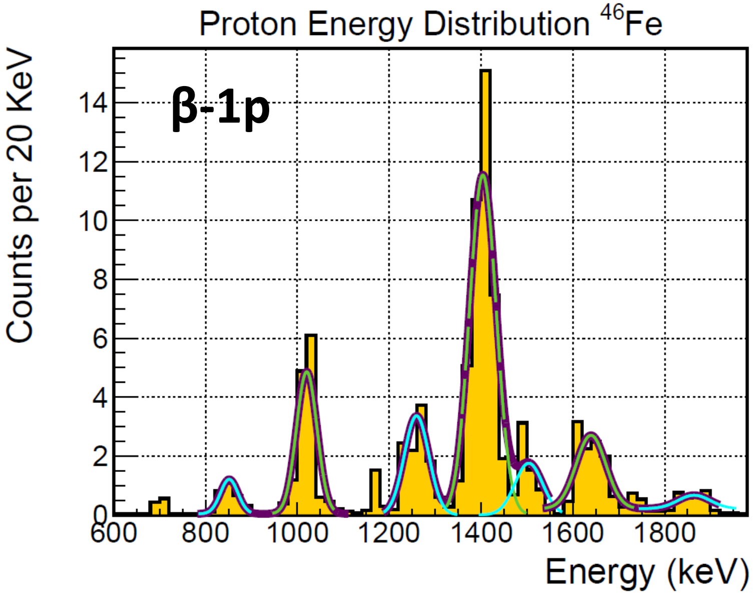


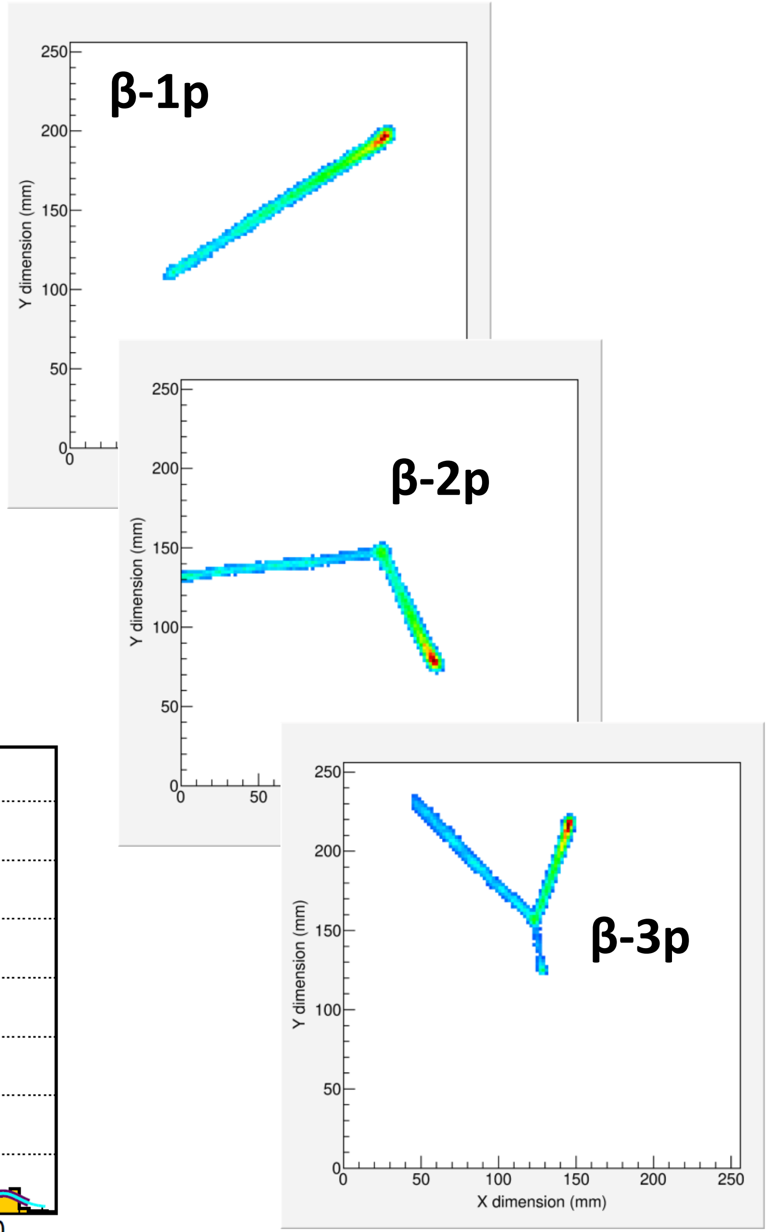


2-proton radioactivity
single decay branch
event by event analysis (counting)

beta-delayed 1,2,3-proton(s)
→ from **several nuclei** (cocktail beam)
→ decay scheme
absolute transitions intensities
→ function of transition energy

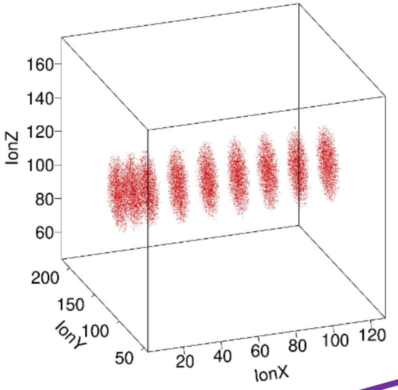
$$I_Y(E_p) = \frac{N_p^{(mes)}(E_p)}{N_Y^{(impl)} \cdot \varepsilon_Y(E_p)}$$





detection efficiency

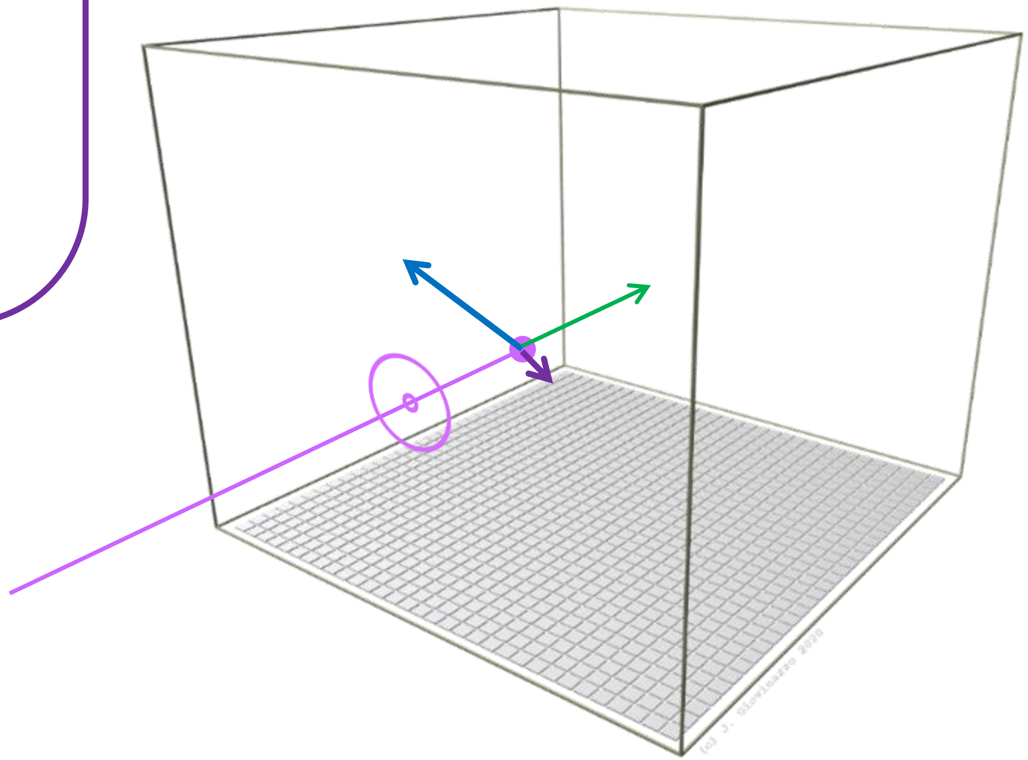
simulation run
$[\vec{r}_i, E_i]$



simulation of decay events
→ **scan of simulation space**

- **emission point ($\vec{r}$)**
- **decay energy (E)**

simulation is only the first step



detection efficiency

intrinsic efficiency…

$\varepsilon_p(\vec{r}, E_p)$

simulation run $[\vec{r}_i, E_i]$

analysis
- **pads mult.**
- **X-Y escape**
- **Z escape**

result
$N_{sim}[\vec{r}_i, E_i]$
$N_{det}[\vec{r}_i, E_i]$

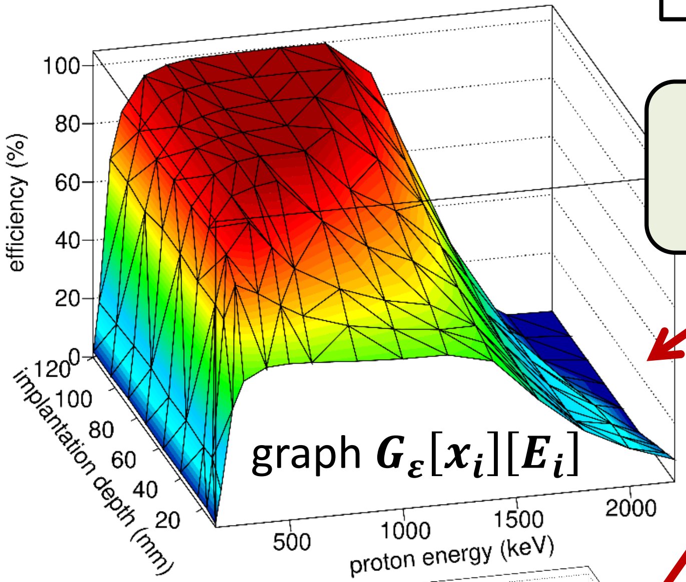
stat. confidence intervals

$\vec{r}_i, E_i, \varepsilon_i, \Delta\varepsilon_{i\pm}$

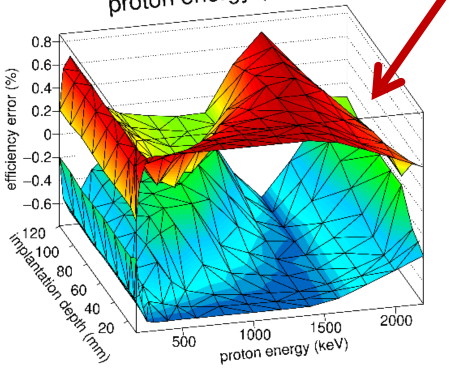
interpolation

$\varepsilon(\vec{r}, E), \Delta\varepsilon_\pm(\vec{r}, E)$

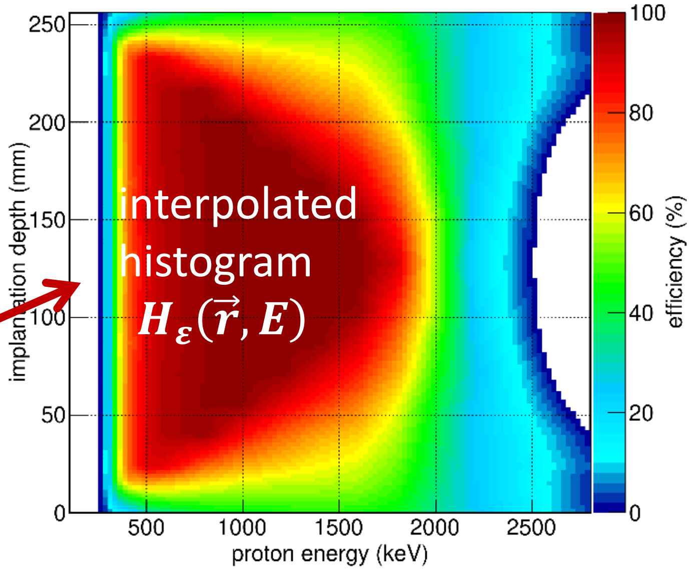
probability of full detection of a proton emitted with energy E_p



graph $G_\varepsilon[x_i][E_i]$



$G_{\Delta\varepsilon}[x_i][E_i]$ (binomial uncertainty)

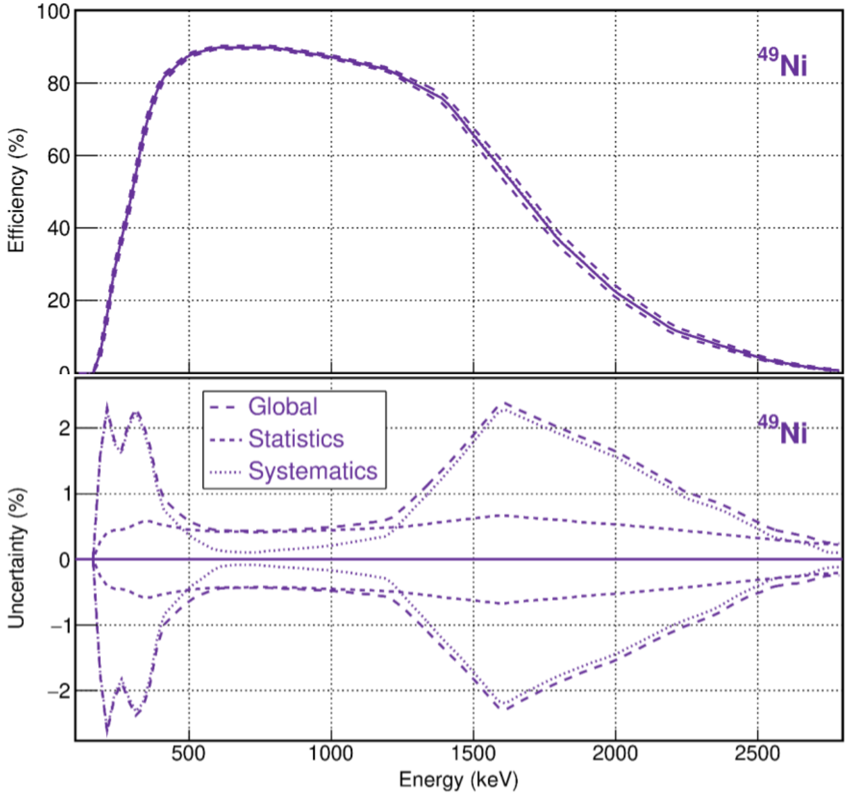


detection efficiency

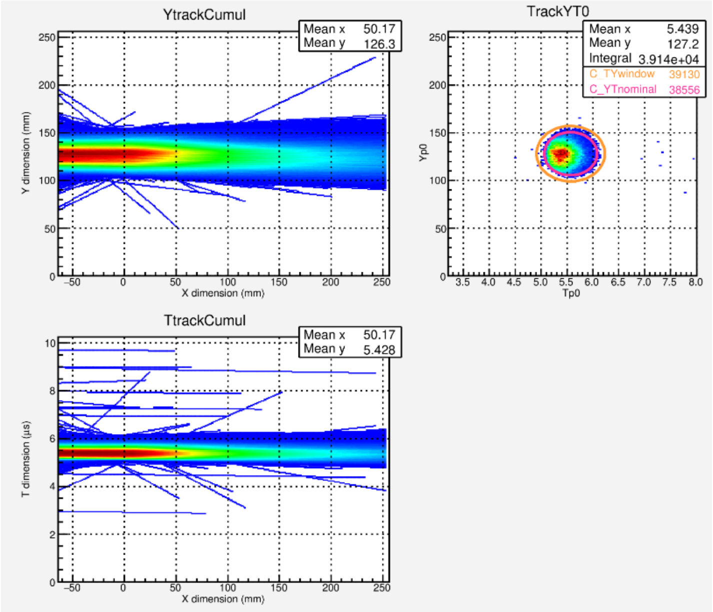
intrinsic efficiency…

…convoluted with experimental implantation distribution for nucleus Y

$$\varepsilon_Y(E_p) = \varepsilon_p(\vec{r}_Y, E_p) \otimes \mathcal{P}_Y(\vec{r}_Y)$$



beam parallel to X axis: $\vec{r} \leftrightarrow x$



uncertainty:

- **statistics**
  number of sim. events
- **systematics**
  + simul. param.: *pressure, ampl., disp., noise, TZ profile…*
  + analysis param.: *threshold, escape cuts*
  (see further)

ACTAR TPC simulations main lines

simulation

purpose is not the full reproduction of the experiments

(unlike particle physics)

estimate the number of protons escaping full detection

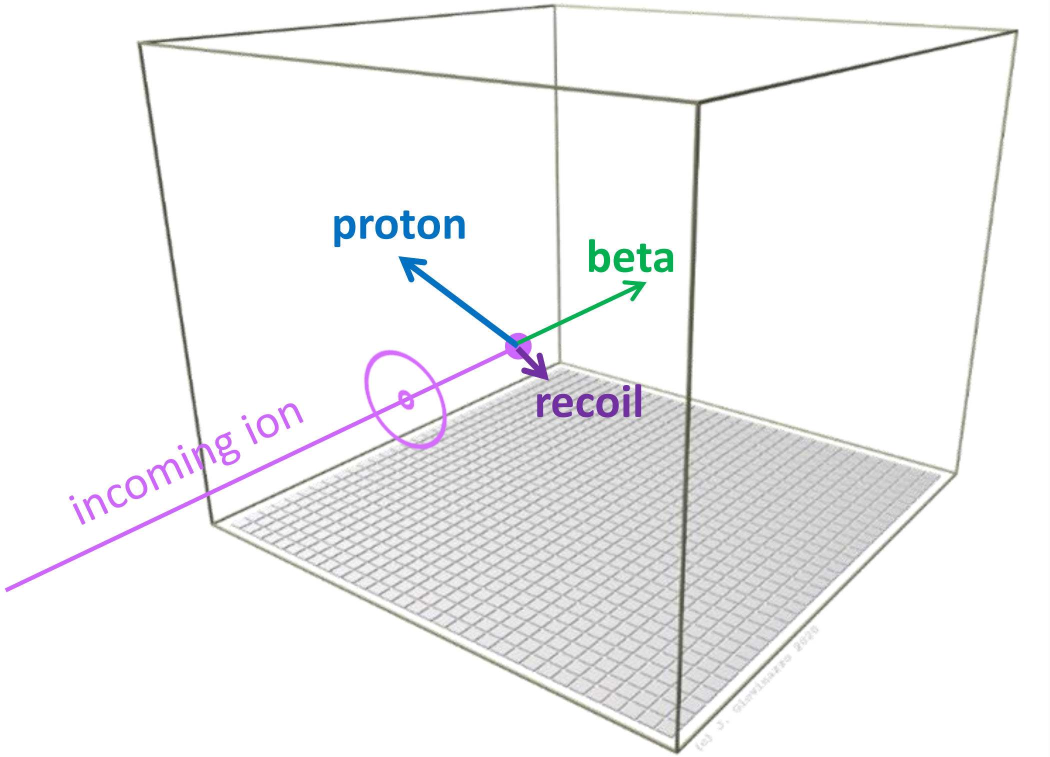
simulation: event generator

event generator

simple *ad hoc* generator

implantation basically not needed
(but backward tracking for E690 – see further…)

generate primary particles at any (implantation) point
→ direction
→ energy



simulation: tracking

event generator

↓

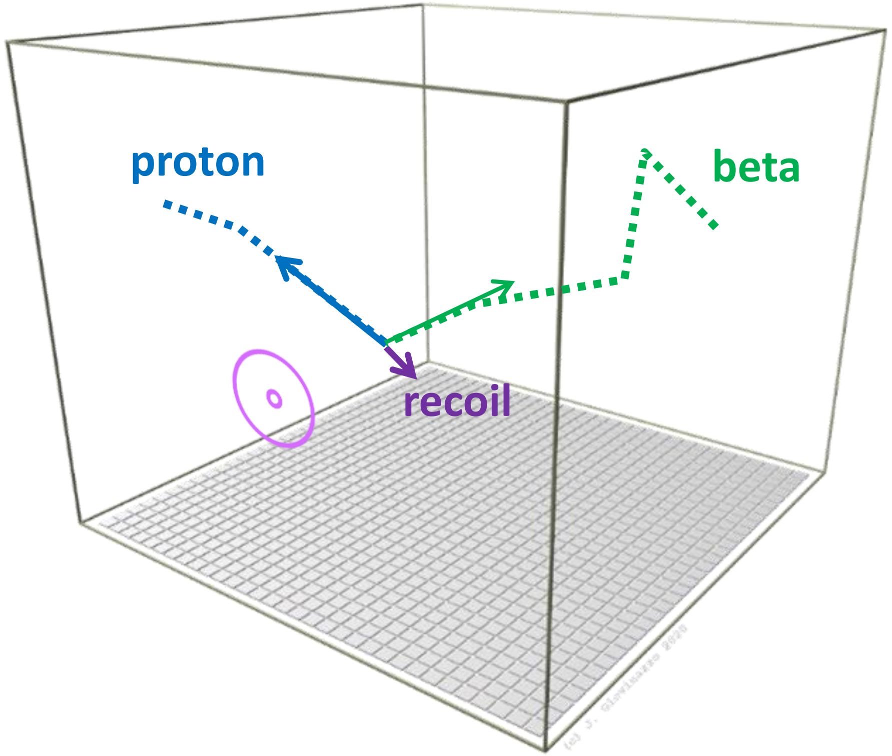
tracking

tracking with Geant4

basically a simple gas volume
with particles travelling inside

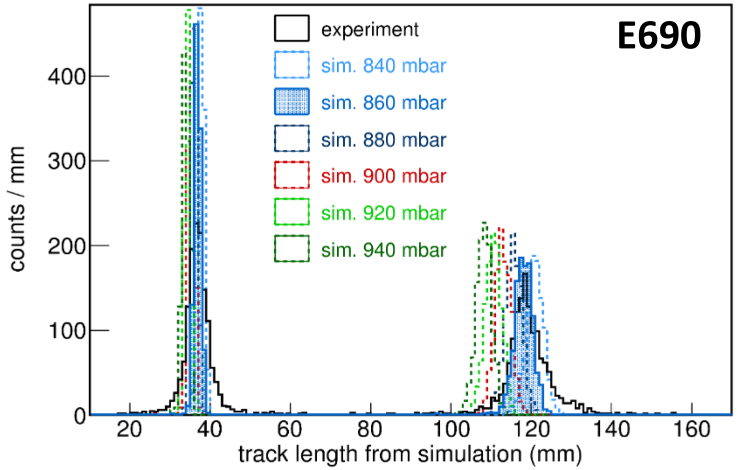
- **primary vertex**
- **tracking of primary particle recording all steps / hits**

→ **energy loss along the particles path**



tracking parameters

- **gas pressure**
- **physics list** (processes)

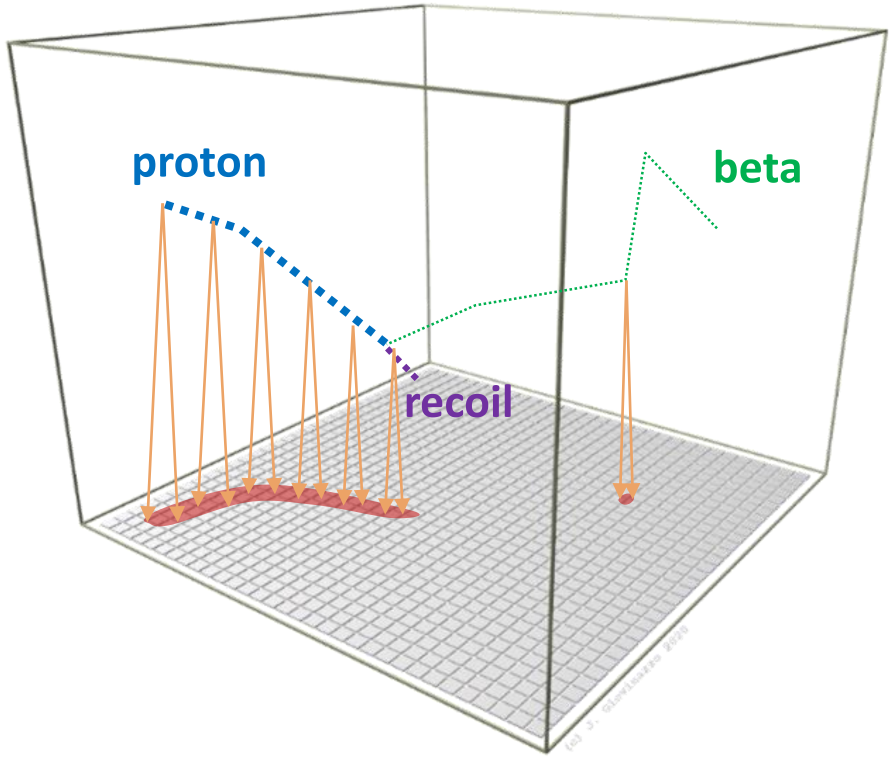


simulation: signal collection

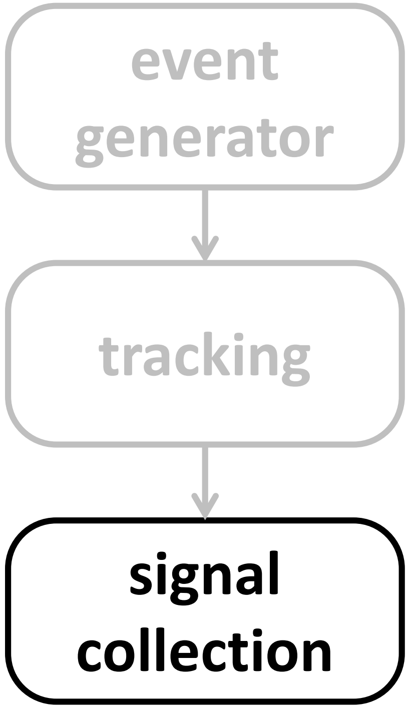
event generator → tracking → **signal collection**

drift of ionization signal

- **from tracking steps energy loss**
- **parameter: drift velocity** (from exp. data)
  → Z to T conversion

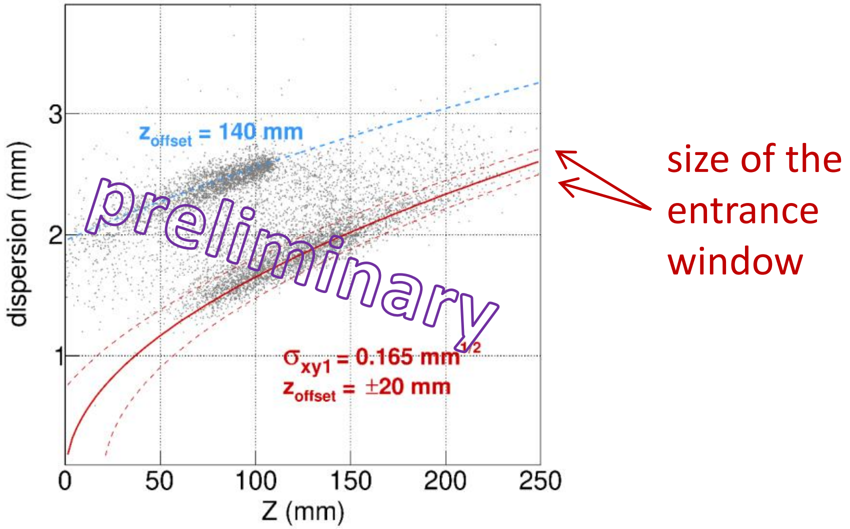


simulation: signal collection



drift of ionization signal

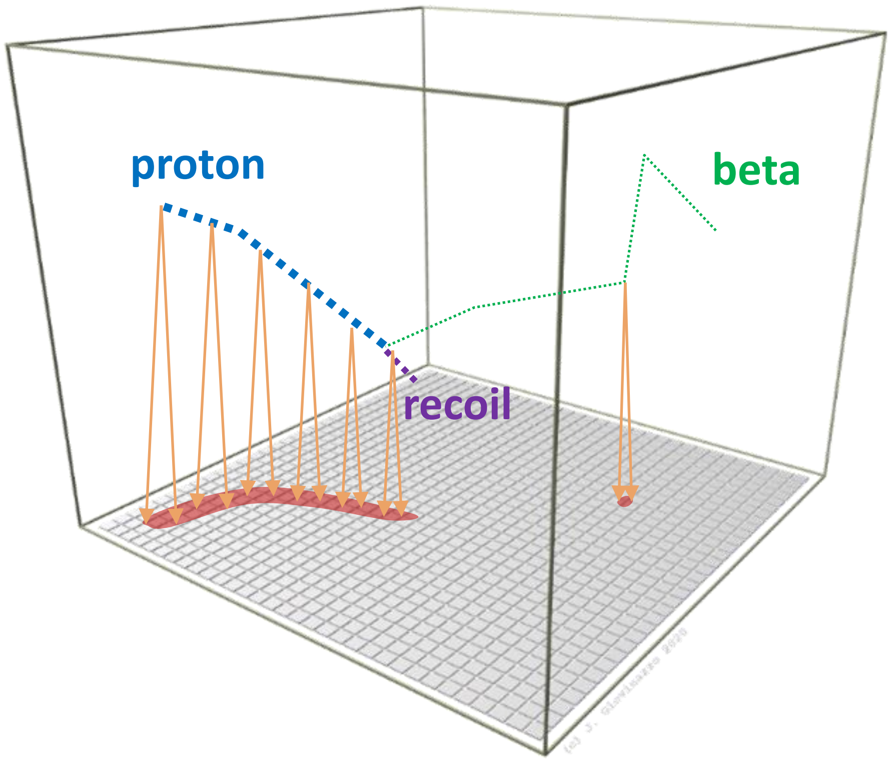
- from tracking steps energy loss
- parameter: **drift velocity** (from exp. data)
  → Z to T conversion



signal dispersion

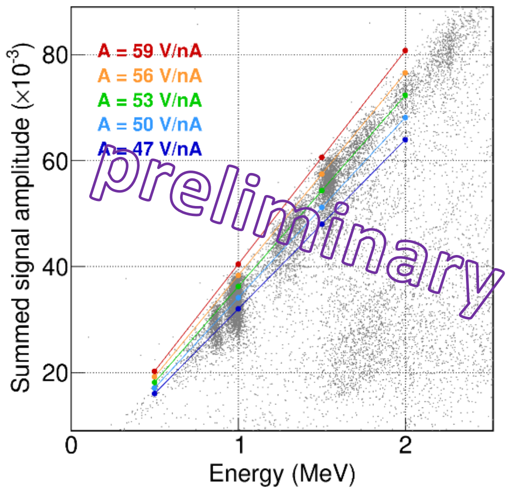
- 3D Gaussian dispersion (XY & Z/T)
- dependence with drift path:

$$\sigma_{XY/T}(z) = \sigma_{0_{XY/T}} + \sigma_{1_{XY/T}} \cdot \sqrt{z}$$



simulation: signal collection

event generator
↓
tracking
↓
signal collection



drift of ionization signal

- **from tracking steps energy loss**
- **parameter: drift velocity** (from exp. data)
  → Z to T conversion

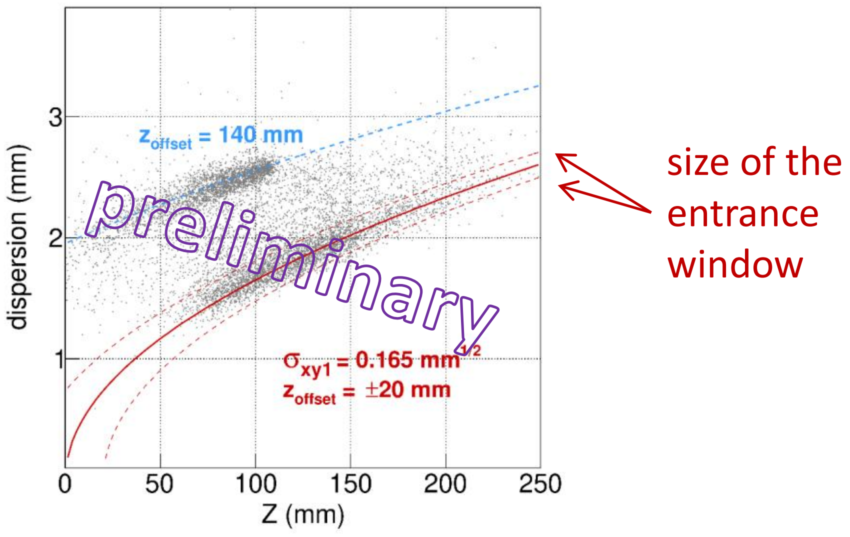
signal dispersion

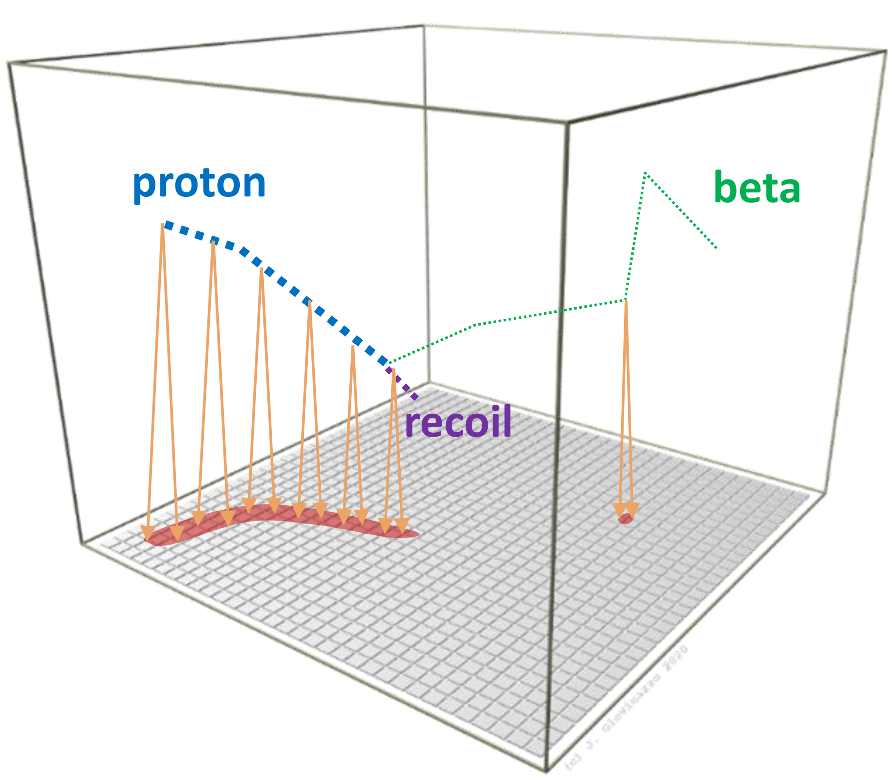
- **3D Gaussian dispersion** (**XY** & **Z/T**)
- **dependence with drift path:**

$$\sigma_{XY/T}(z) = \boldsymbol{\sigma_{0_{XY/T}}} + \boldsymbol{\sigma_{1_{XY/T}}} \cdot \sqrt{z}$$

amplification

- **collection gain from micromesh**
- **adjusted from known proton energies**
  (after processing…)



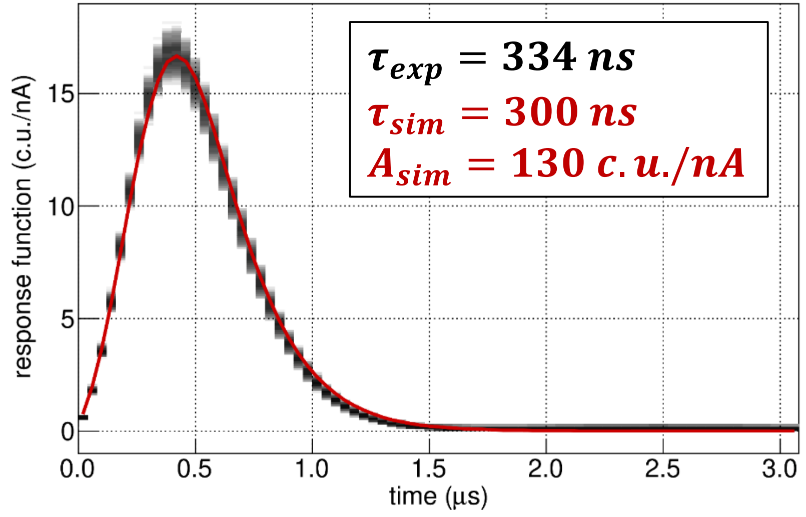


simulation: signal processing

event generator → tracking → signal collection → **signal processing**

electronics response function

charge preamp. + shaper from GET electronics



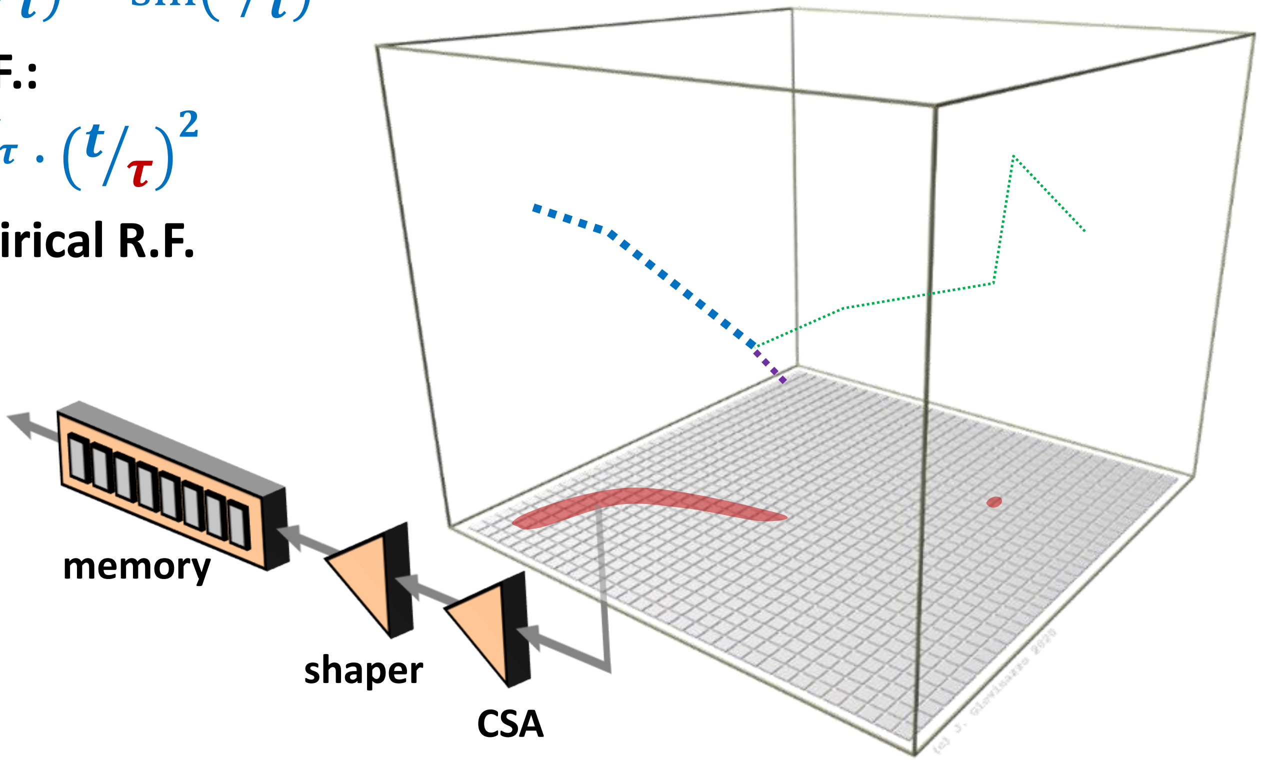
- **theoretical R.F. (P. Baron):**

$$H(t) = A \cdot e^{-3 t/\tau} \cdot \left(t/\tau\right)^3 \cdot \sin\left(t/\tau\right)$$

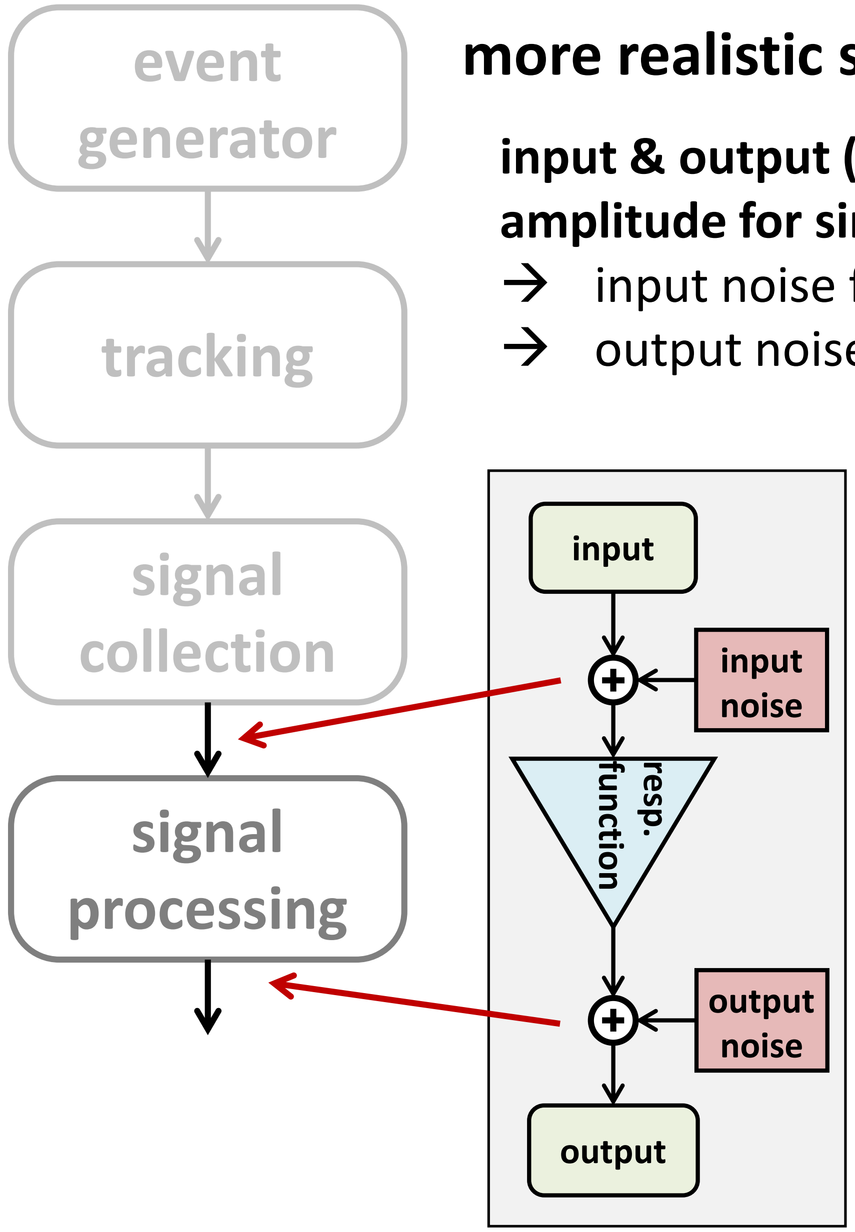
- **effective analytical R.F.:**

$$H(t) = A \cdot e^{-2 t/\tau} \cdot \left(t/\tau\right)^2$$

- **comparison with empirical R.F.**
  2 parameters:
  → amplification (A)
  → shaping time (τ)



simulation: fluctuations and noise

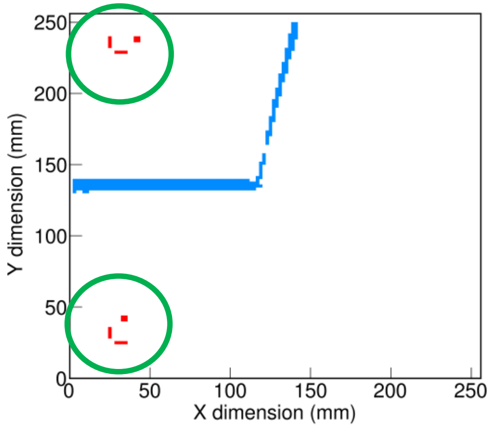


more realistic signals ?

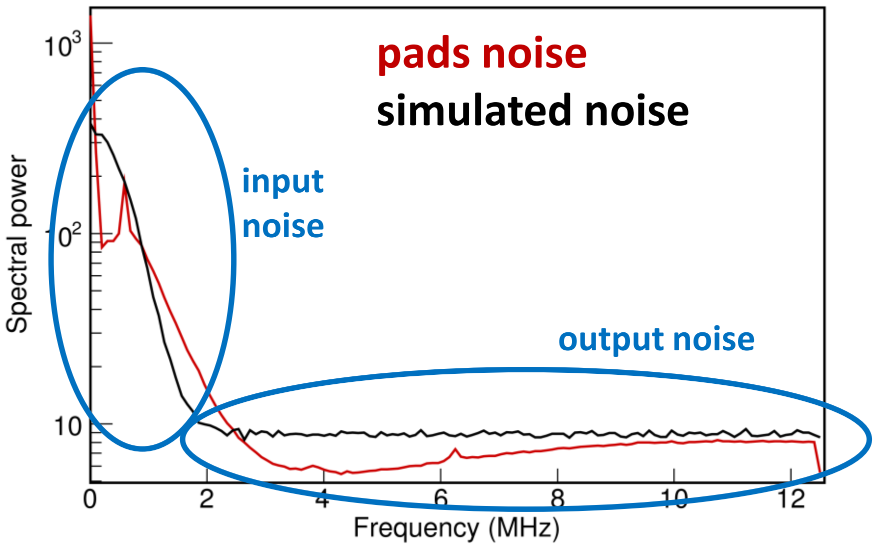
input & output (Gaussian) noise amplitude for simulation
→ input noise filtered by resp. function
→ output noise not modified

chip architecture
effects no reproduced

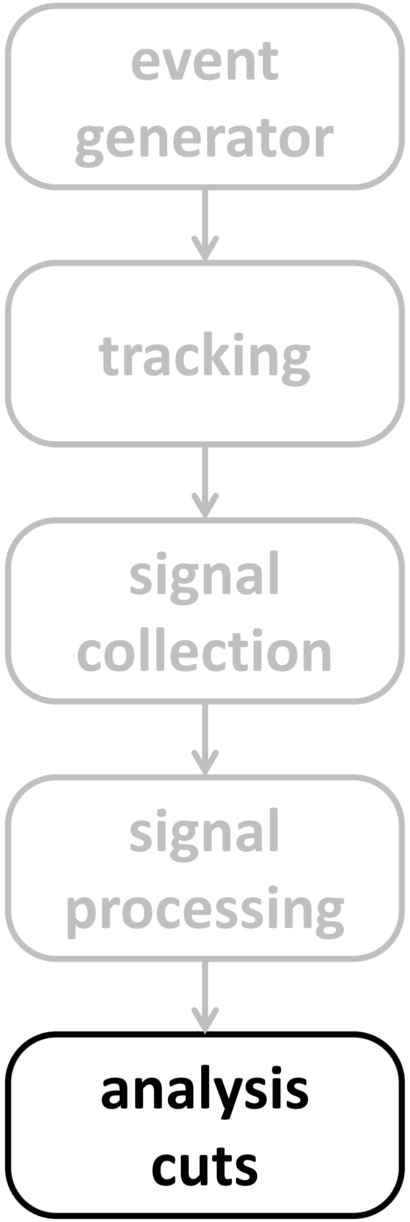
input noise constraints:
power vs filtering (shaper)



analysis of spectral power distribution
adjust noise on experimental S.P.D.
→ from pads in “read always” pads (if no signal)
→ from events with no signal



analysis cuts



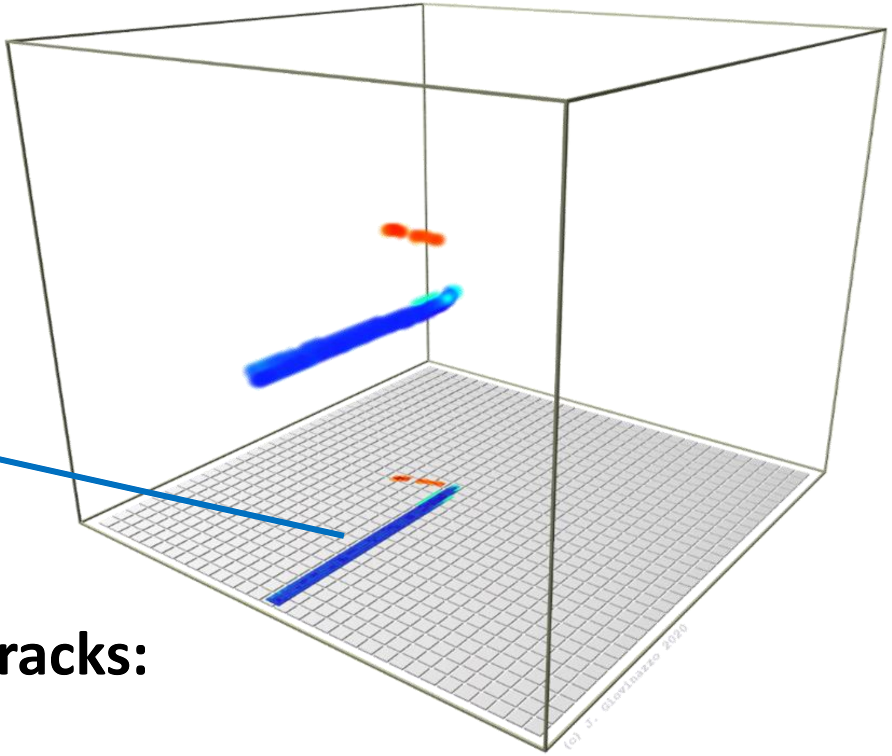
simulation → tracks signal on each pad

include exp. data analysis parameters

- → **bad pads suppression**
- → **pad validation from signal threshold**
- → **global trigger multiplicity**
- → **number of border pads for for escape condition**

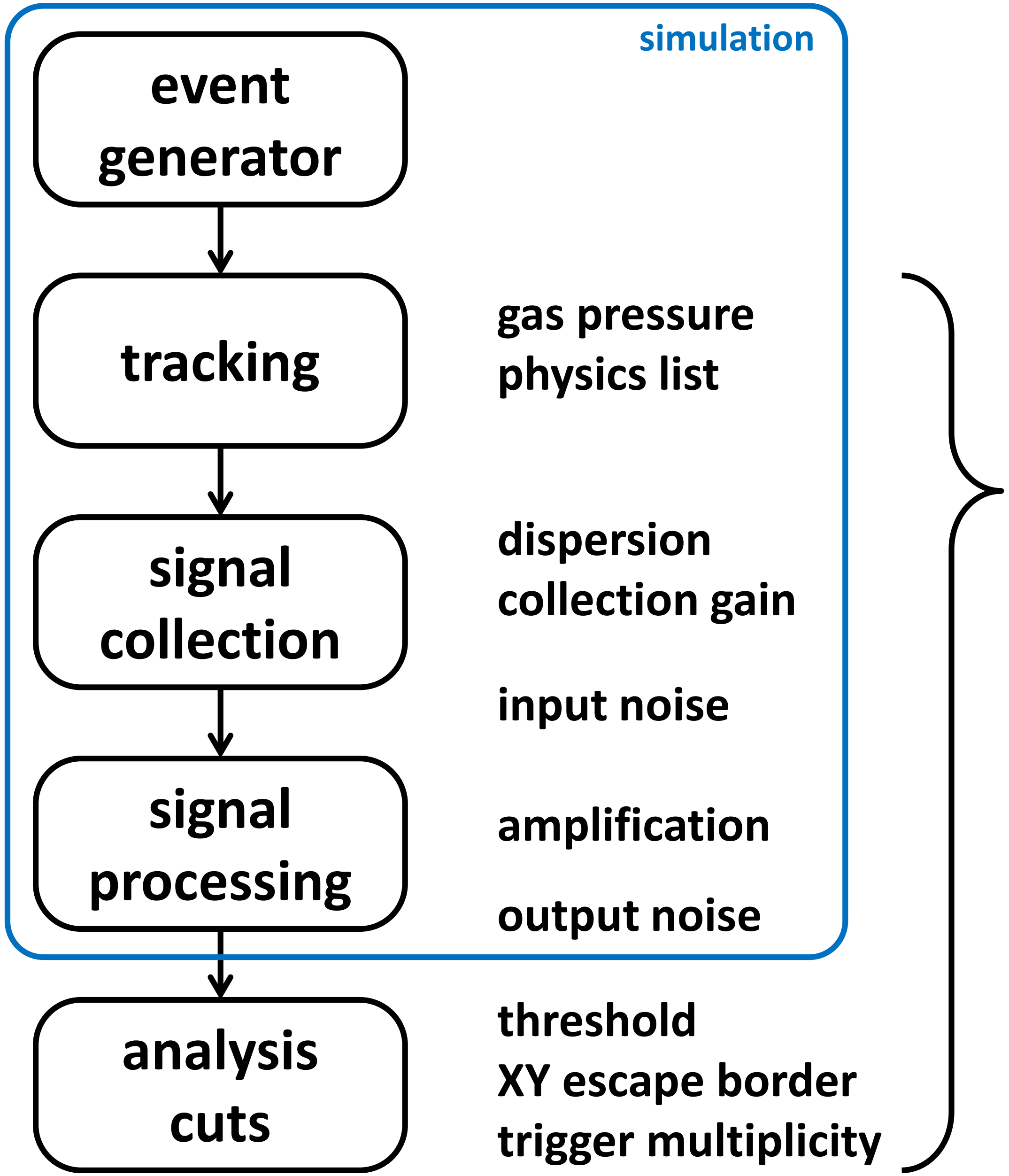
for E690

- → **suppression of pads “hidden” by implantation signal**
  ion track back-traced according to experiment directions distribution for ion pads suppression



⇨ **number of fully reconstructed tracks: detection efficiency**

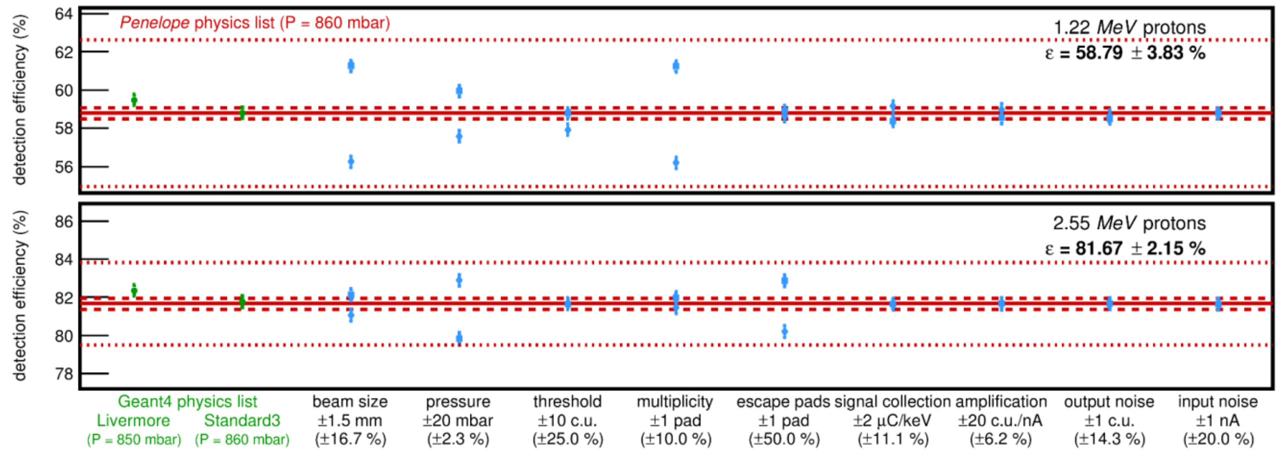
efficiency uncertainties



all parameters need to be considered in resulting efficiency error budget

some correlated parameters
heavy to take into account (not difficult)
($\boldsymbol{N_{par}}^{\mathbf{2}}$ × computing time)

E690



simulations for tracks analysis

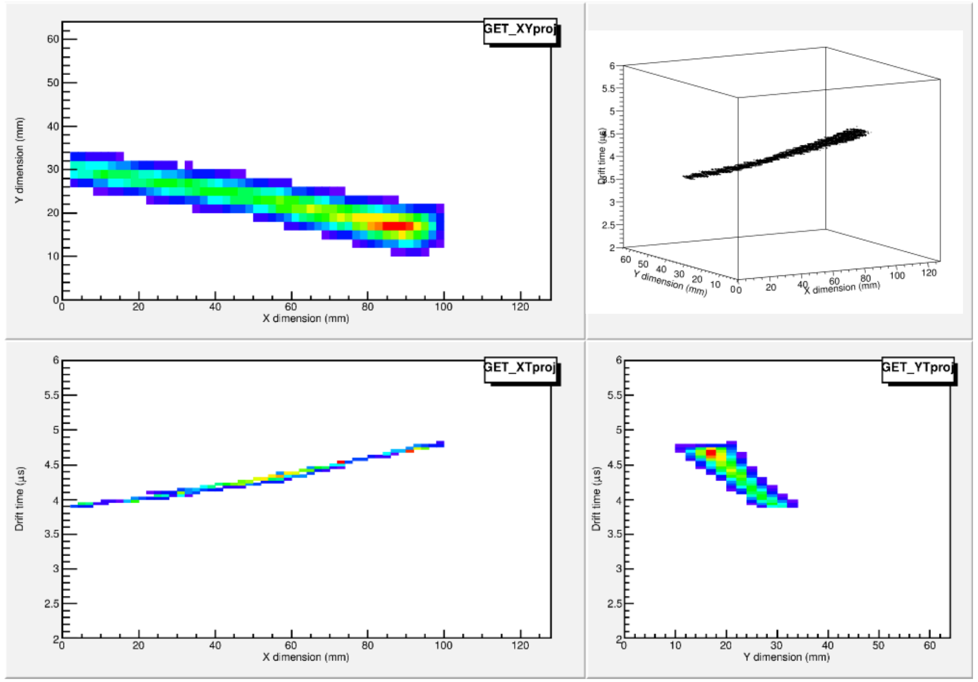
tracks analysis

“standard” analysis

signal amplitude + CFD timing

2D (X,Y) A & T

→ 2 × 16k = 32k data



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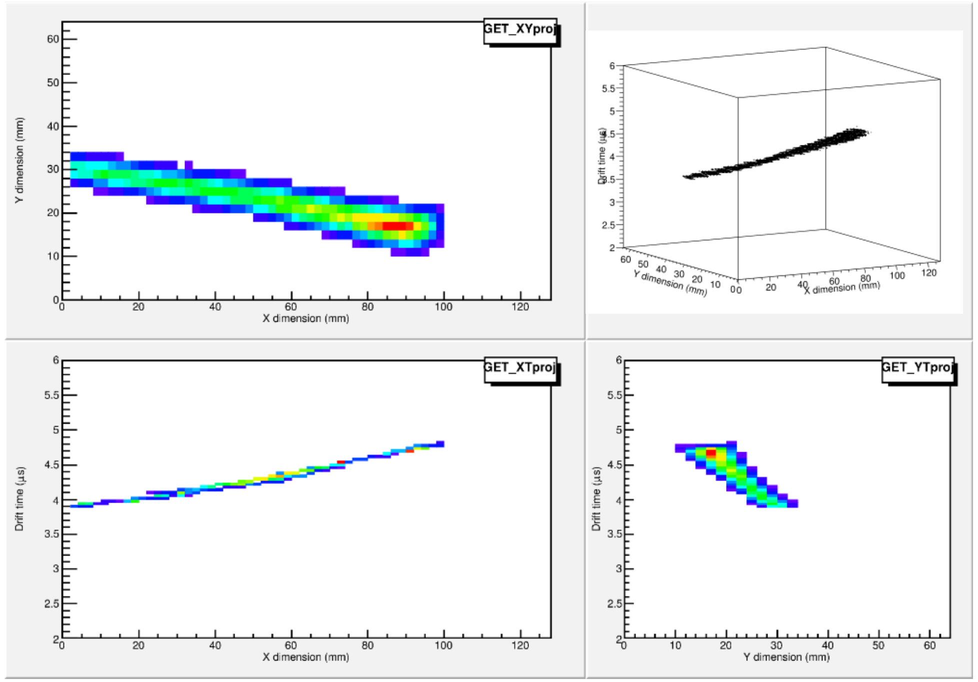


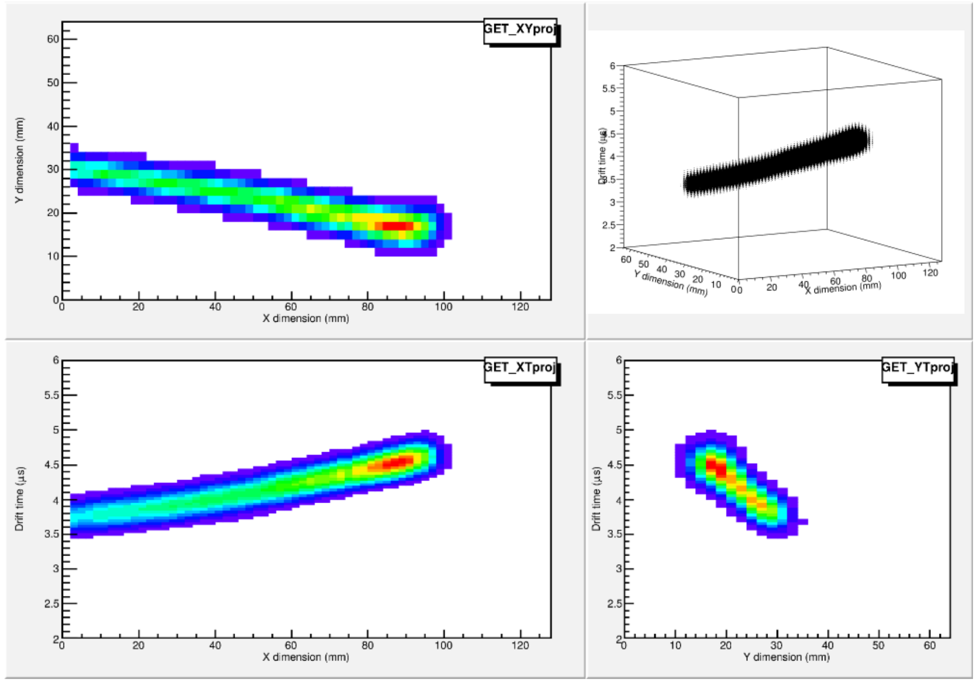
deconvolution analysis

→ response functions for each channel

full 3D (X,Y,T) signal distribution (from FFT)

→ 512 × 16k = 8000k data

JG, NIM A 2020



analysis / computing cost ×200 !!

tracks analysis

“standard” analysis
signal amplitude + CFD timing
2D (X,Y) A & T

→ **2 × 16k = 32k data**

problem at large vertical angles

deconvolution analysis
→ **response functions for each channel**
full 3D (X,Y,T) signal distribution (from FFT)

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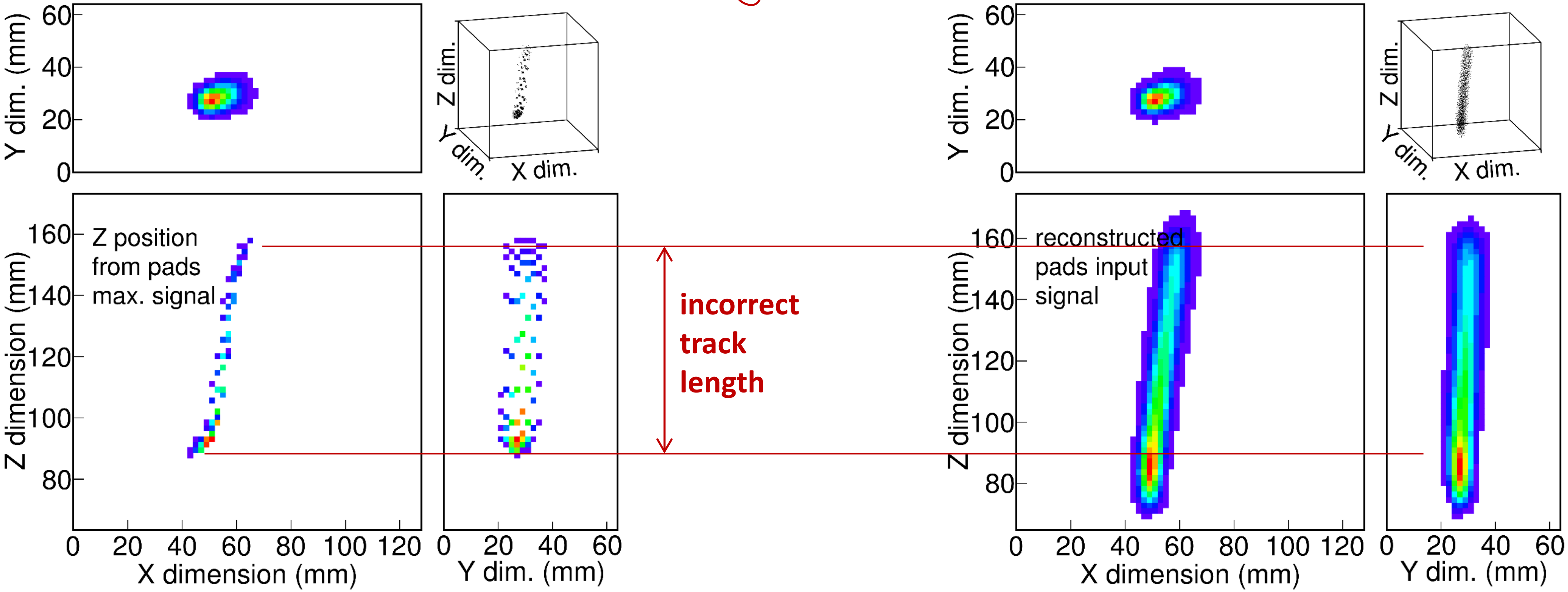

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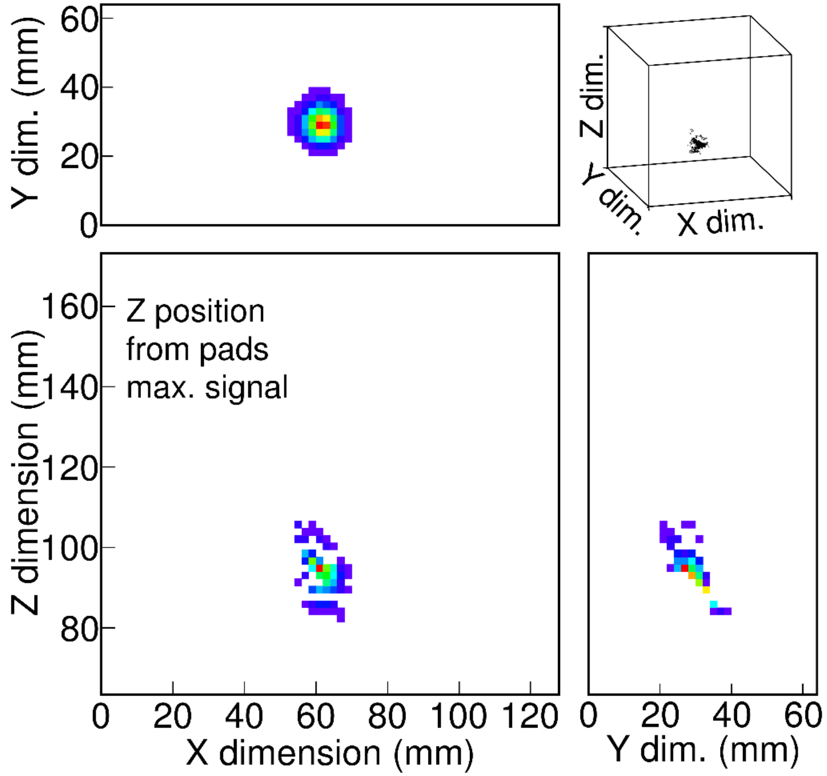

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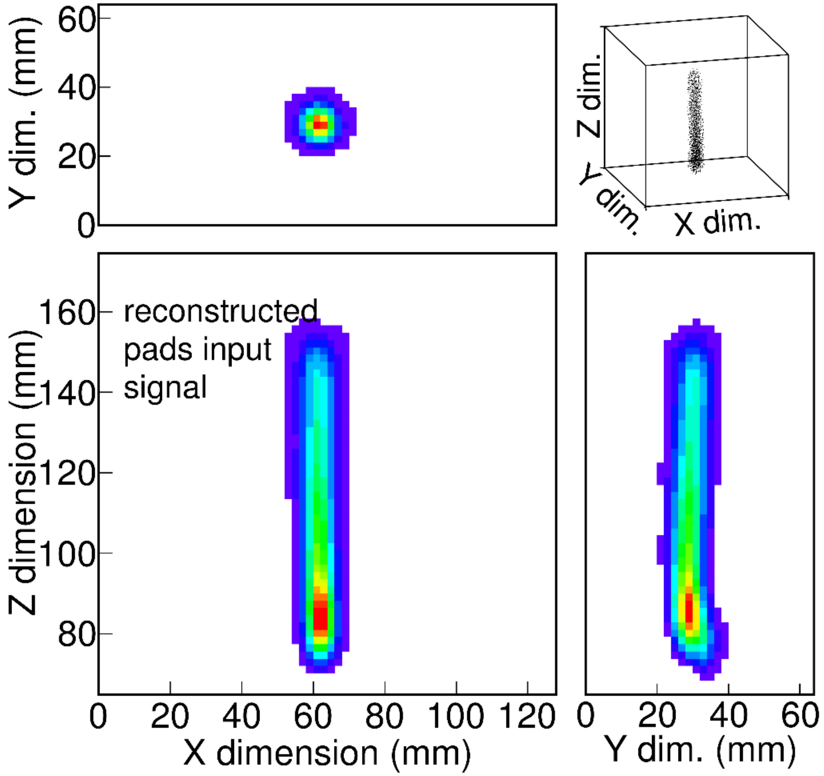
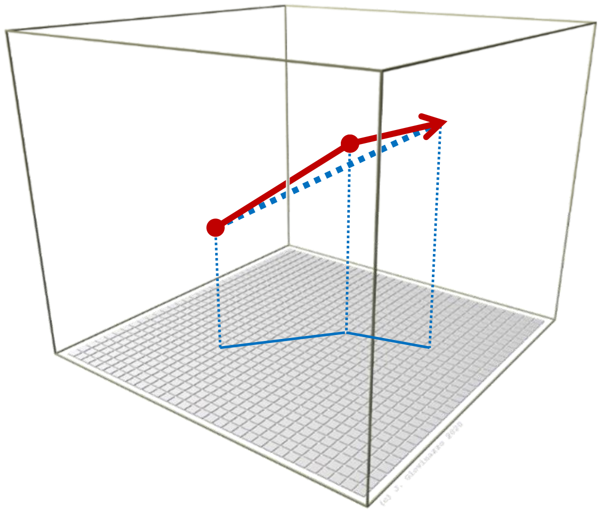


tracks fitting

- **2D ampl. + time** → **2×16k pads** (A+T)
- **full 3D rec. charge** → **512×16k voxels**
  (deconvolution from R.F.)



- **trajectory (geometrical) definition**
  start and **stop** 3D points
  (+ additional control points for segments
  or Bézier curves)
  → 3 param. (x, y, t) per point

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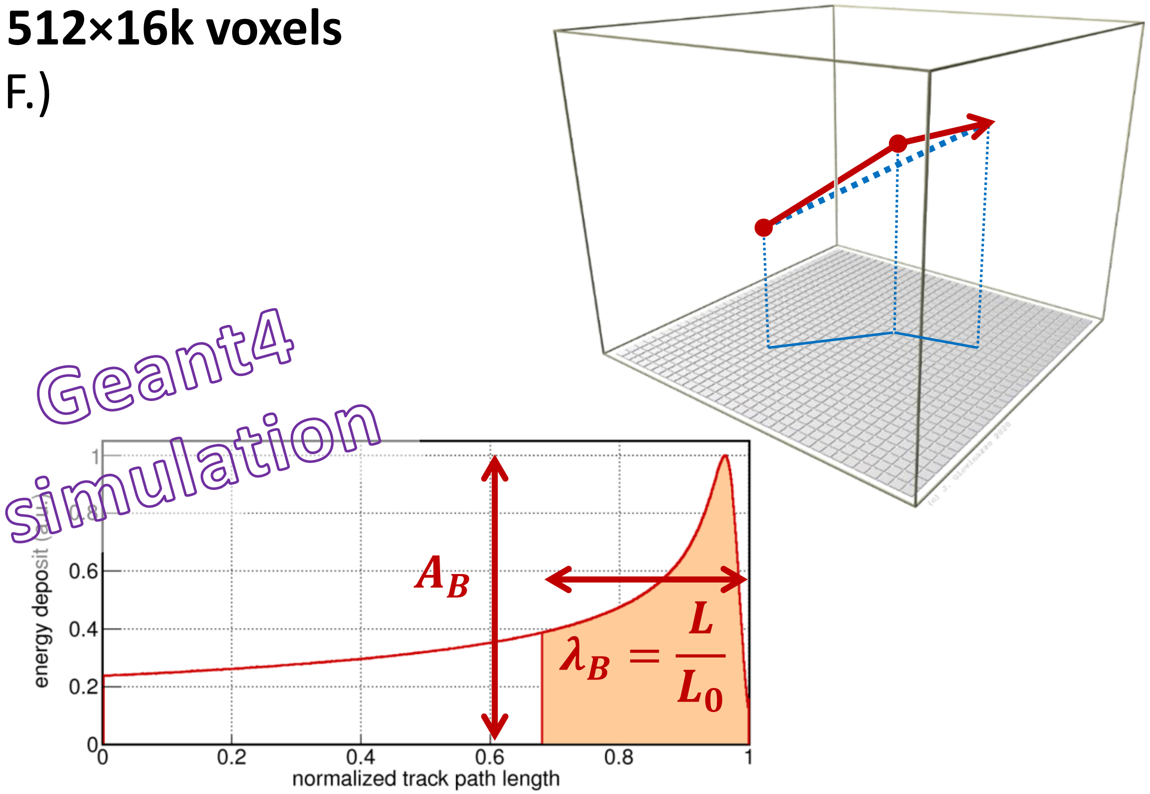
- **Bragg peak model (energy loss)**
  projected along the trajectory
  amplitude factor (A_B) & length fraction (λ_B)



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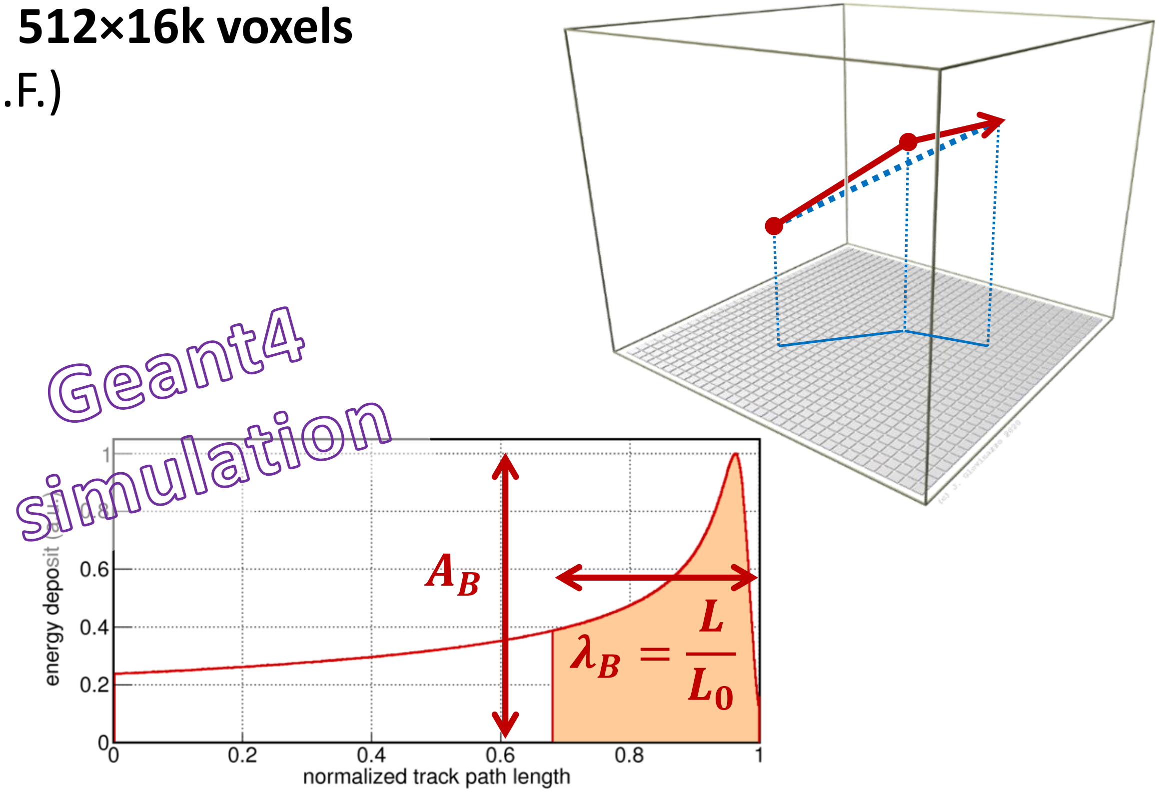

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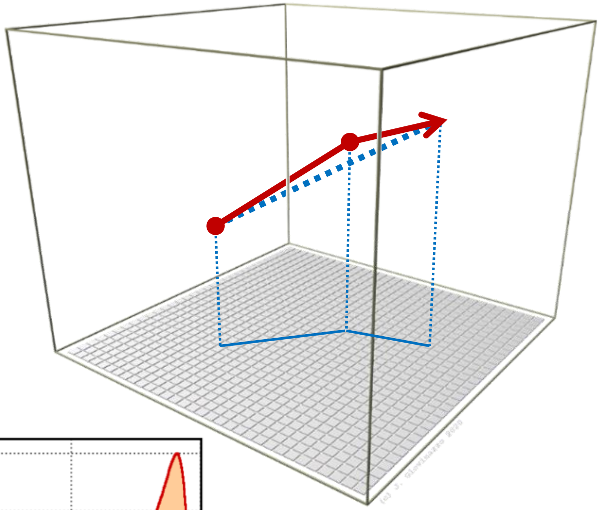
  start and **stop** 3D points
  (+ additional control points for segments
  or Bézier curves)
  → 3 param. (x, y, t) per point

- **Bragg peak model (energy loss)**
  projected along the trajectory
  amplitude factor (A_B) & length fraction (λ_B)

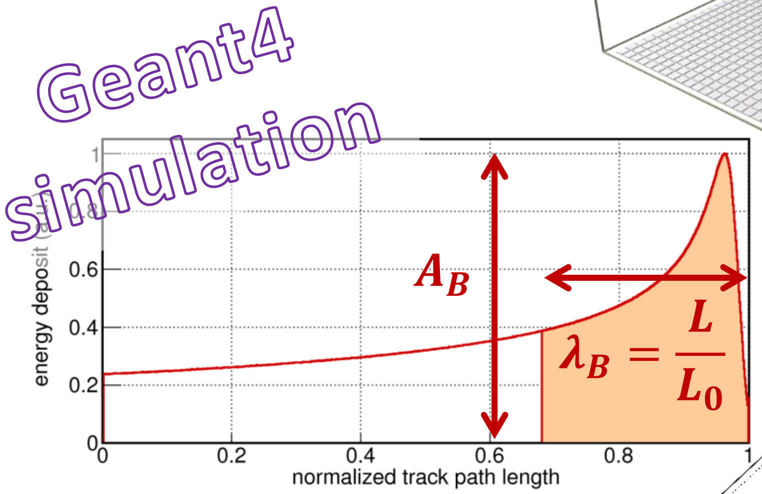
- **dispersion along drift**
  $\sigma_{XY/T}(t) = \sigma_{0,XY/T} + \sigma_{1,XY/T} \cdot \sqrt{z(t)}$

tracks fitting

- 2D ampl. + time → **2×16k pads** (A+T)
- **full 3D rec. charge** → **512×16k voxels** (deconvolution from R.F.)



- **trajectory (geometrical) definition**
  start and **stop** 3D points
  (+ additional control points for segments or Bézier curves)
  → 3 param. (x, y, t) per point



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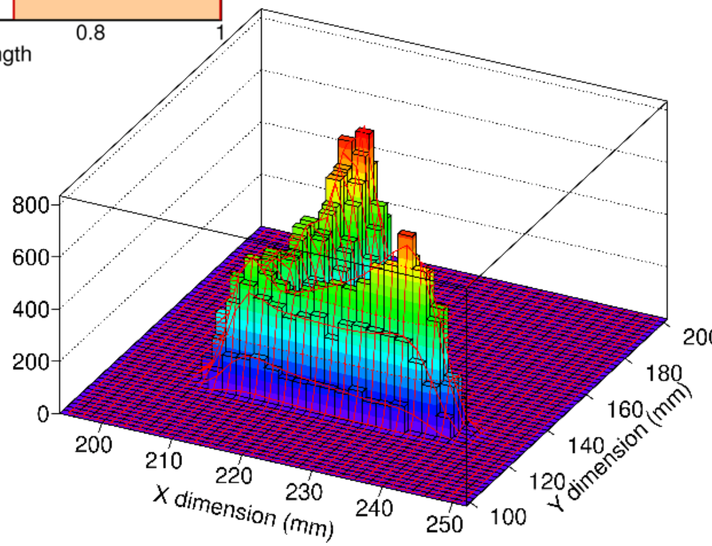
  $$\sigma_{XY/T}(t) = \sigma_{0,XY/T} + \sigma_{1,XY/T} \cdot \sqrt{z(t)}$$

→ **fit signal function** $A_{2D}(x, y|\vec{a})$, $T_{2D}(x, y|\vec{a})$ **or** $S_{3D}(x, y, t|\vec{a})$

→ **comparison to experimental distributions**



from fit: track length (≡ energy), angles (x-p), charge deposit

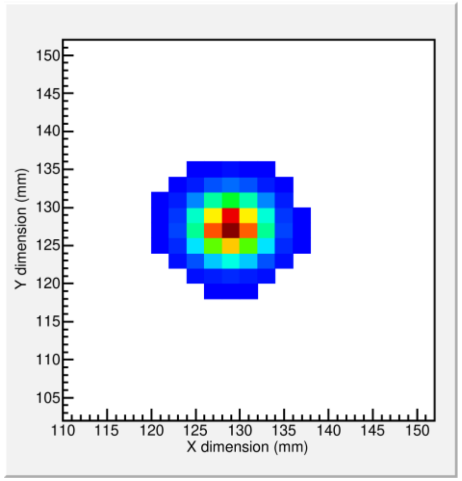
simulation for tracks fit dispersion

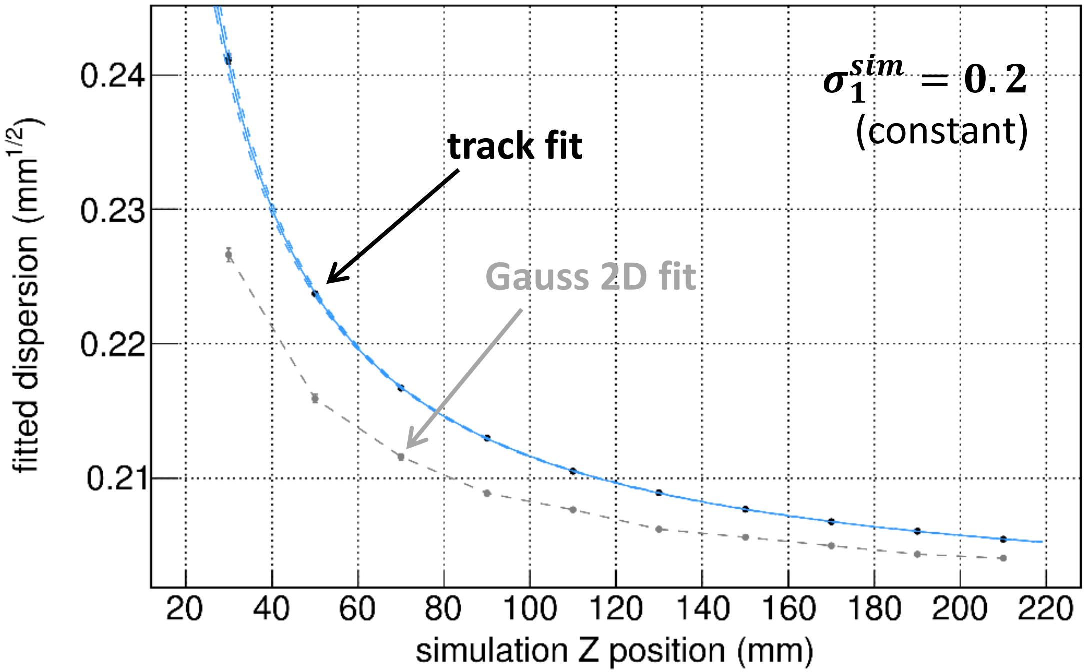
many parameters in fits
dispersion depends on detector conditions, not from events

test fit of “point-like” energy deposit
with $\sigma_{XY} = \sigma_1 \cdot \sqrt{z}$

→ fixed σ_1, variation z of position

→ fixed z position, variation of σ_1





wrong fit output for dispersion parameter !

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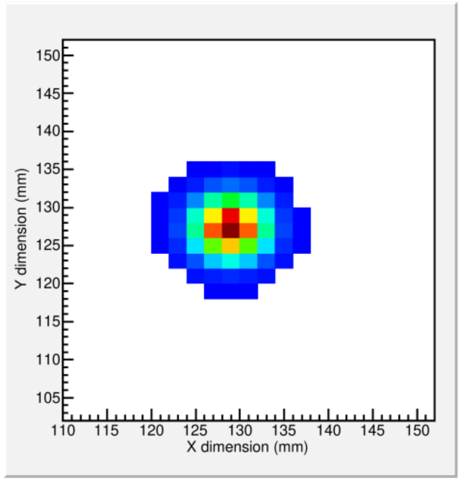

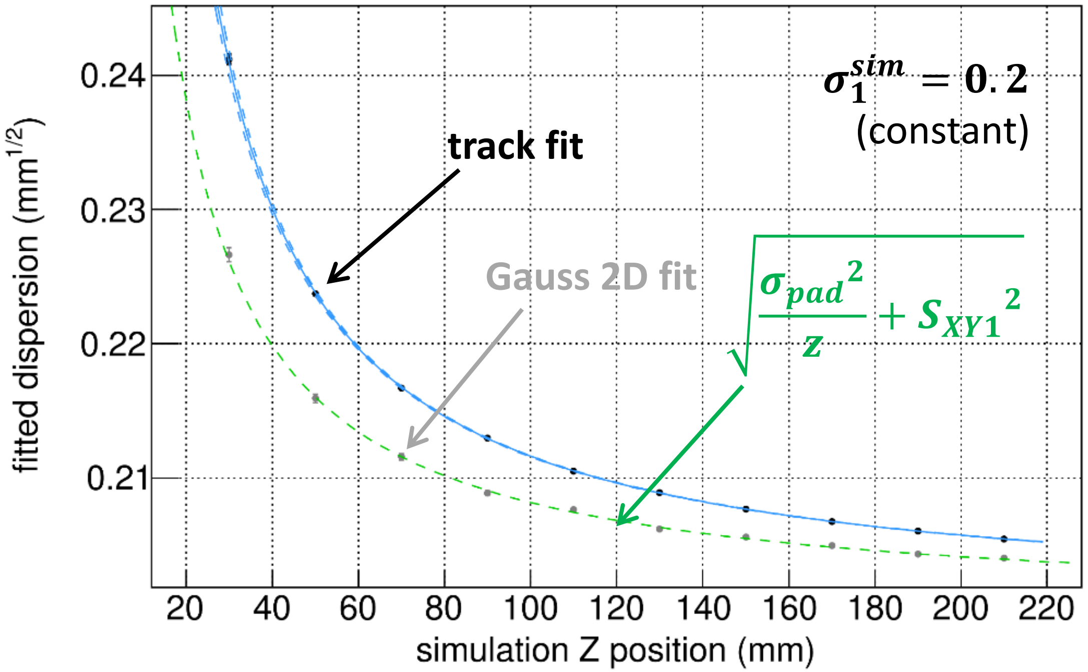

intrinsic dispersion from pad size

$$\frac{\sigma_{pad}}{\sqrt{z}} = \frac{\Delta x}{\sqrt{12 \cdot z}}$$

→ matches simple 2D Gauss fit !!!

simulation for tracks fit dispersion

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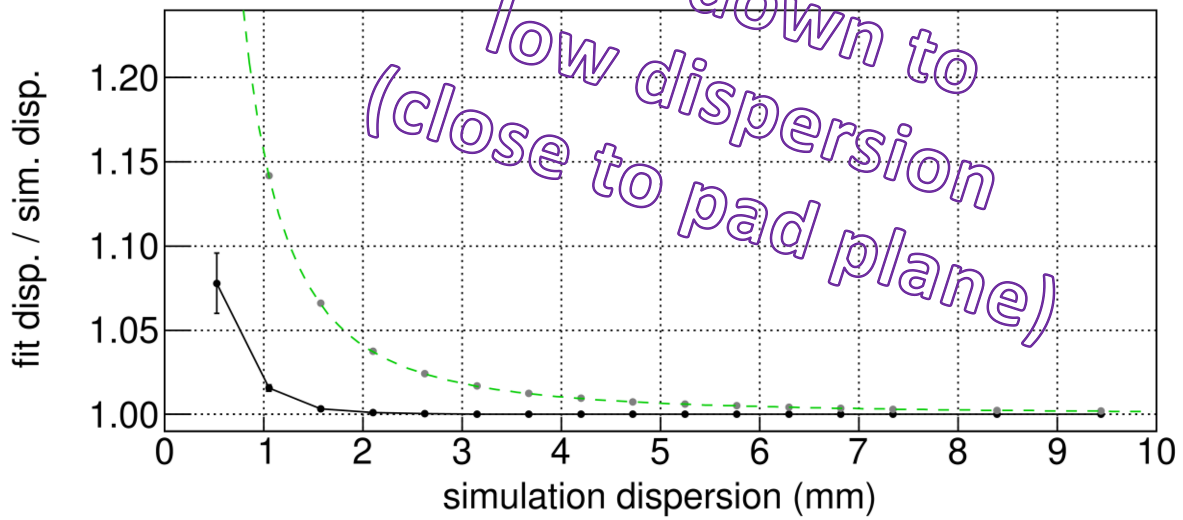

- $\boldsymbol{\sigma_{XY}} = \sqrt{(\boldsymbol{\sigma_{pad}})^2 + (\boldsymbol{\sigma_1} \cdot \sqrt{\boldsymbol{z}})^2}$

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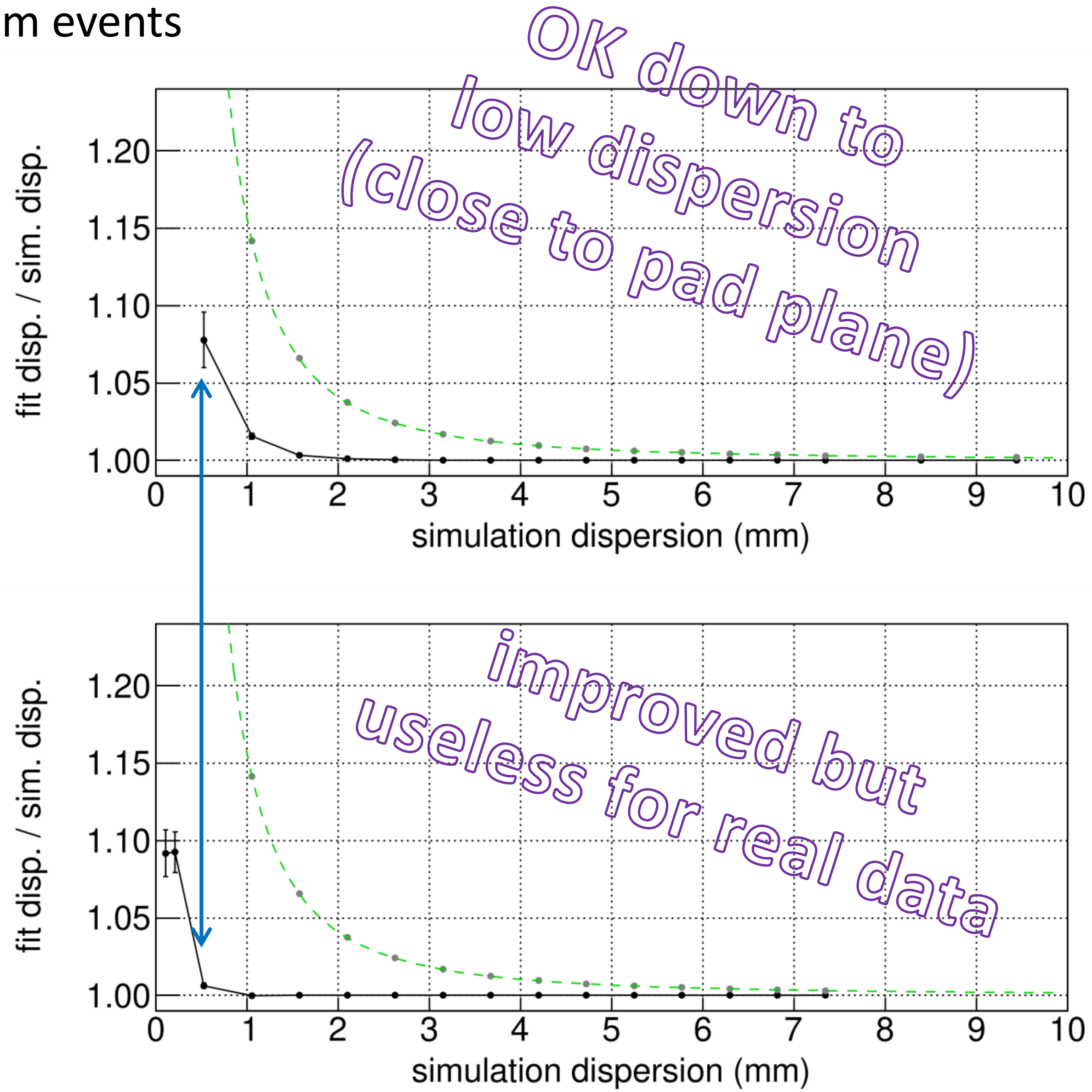
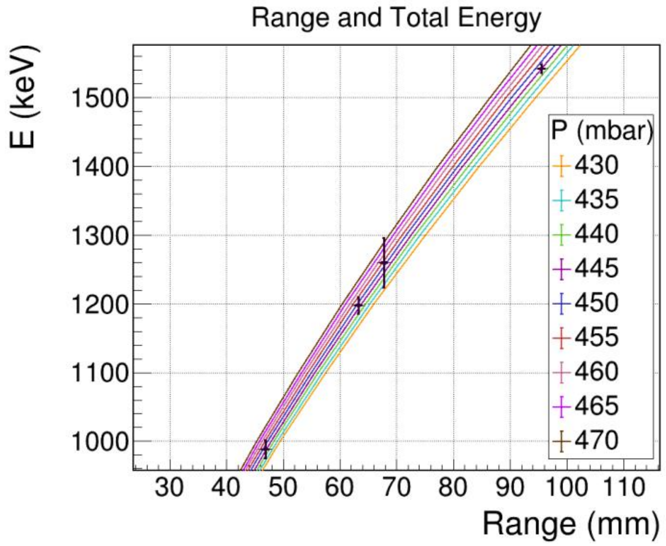
- $\boldsymbol{\sigma_{XY}} = \sqrt{(\boldsymbol{\sigma_{pad}})^2 + (\boldsymbol{\sigma_1} \cdot \sqrt{\boldsymbol{z}})^2}$

- reduced threshold
  (cannot be changed in real data !!!)
- analytical integral over pad signal
  instead of mean/center value
  (4× ***erf*** function instead of 1× ***Gauss***
  → 20× slower fit…)



simulation for effect of recoil nucleus

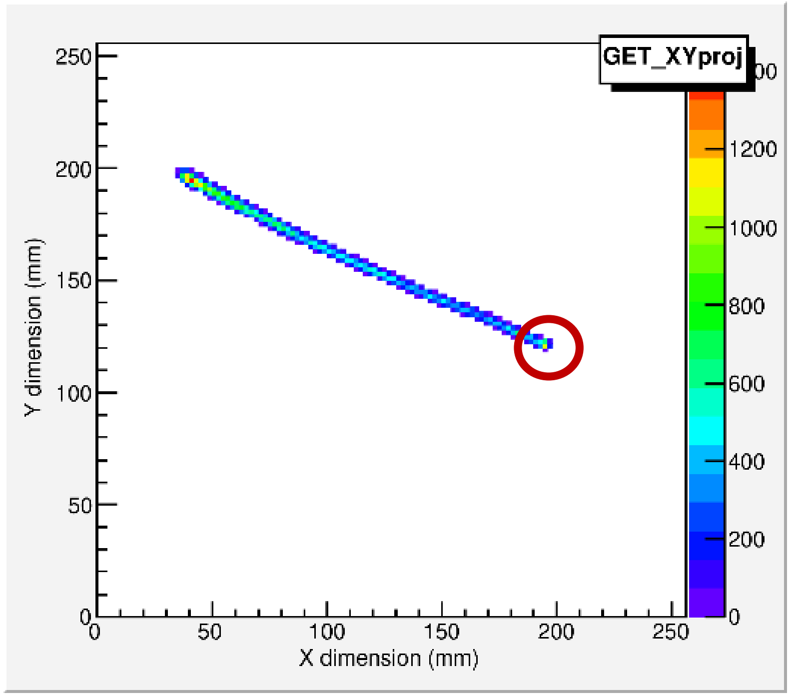
energy calibration (track length ↔ energy conversion) based on known (β-)proton transitions
calibration curve from SRIM at optimal pressure



recoil nucleus (ion):
- ~2-3 % of transition energy (1/A)
- very short range
- most likely quenching
- neutralization

neglected

Ok for β-p decays
(same conditions)



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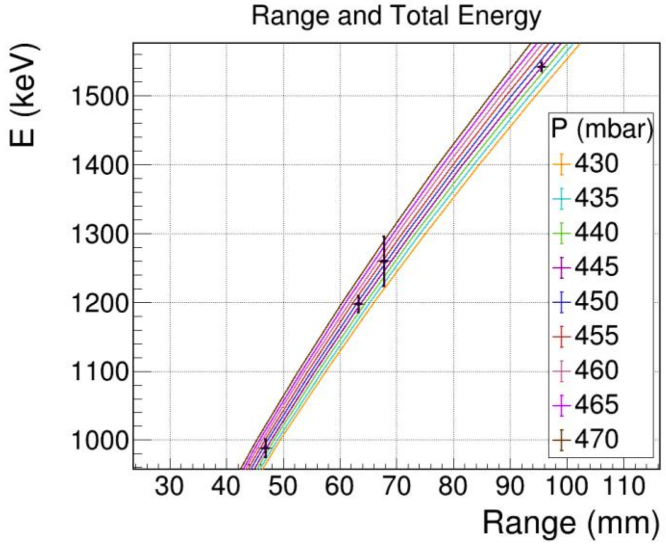

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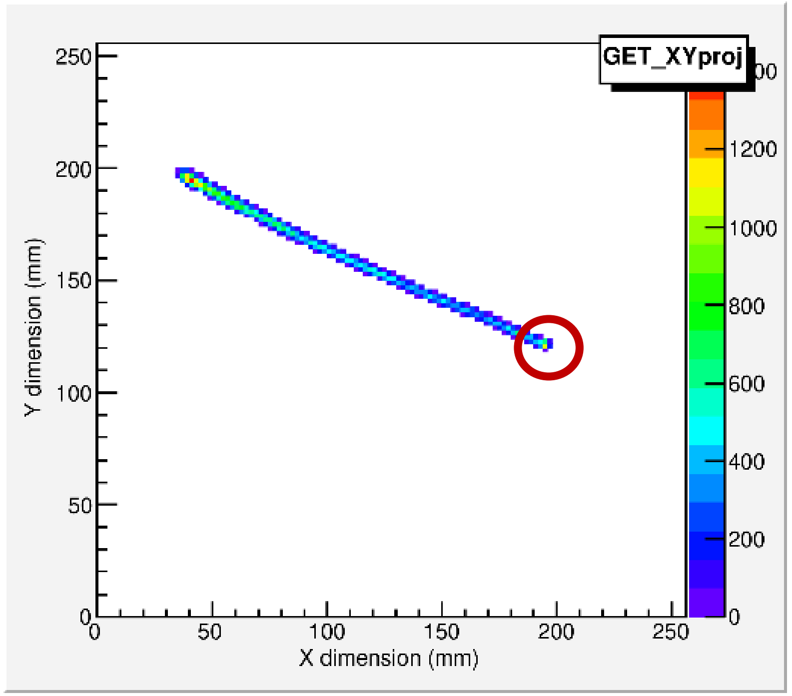

problem for 2p decays
measured Q-value lower than previous measurements

momentum conservation
different contribution of recoil with p-p angle

simulation for effect of recoil nucleus

energy calibration (track length ↔ energy conversion) based on known (β-)proton transitions
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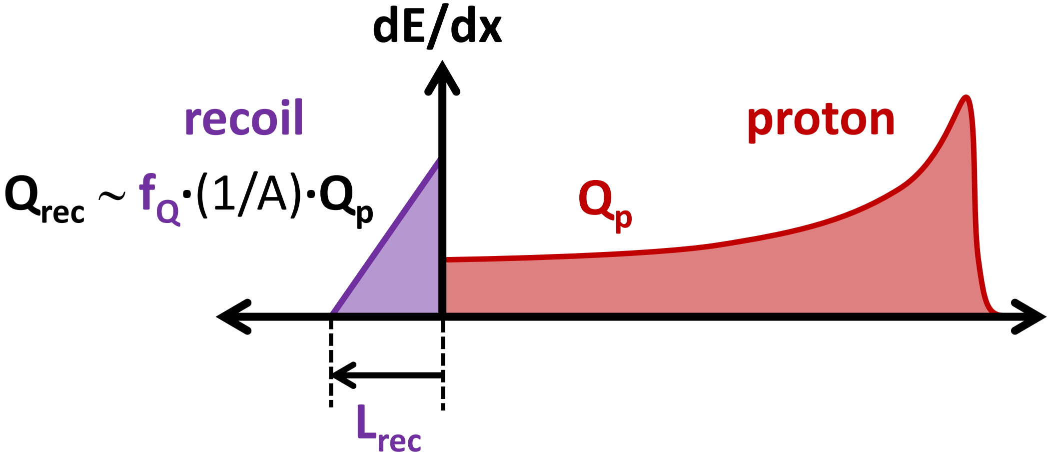
included in fits (param. L_{rec} and f_Q)
of simulated events
(recoil from β neglected)



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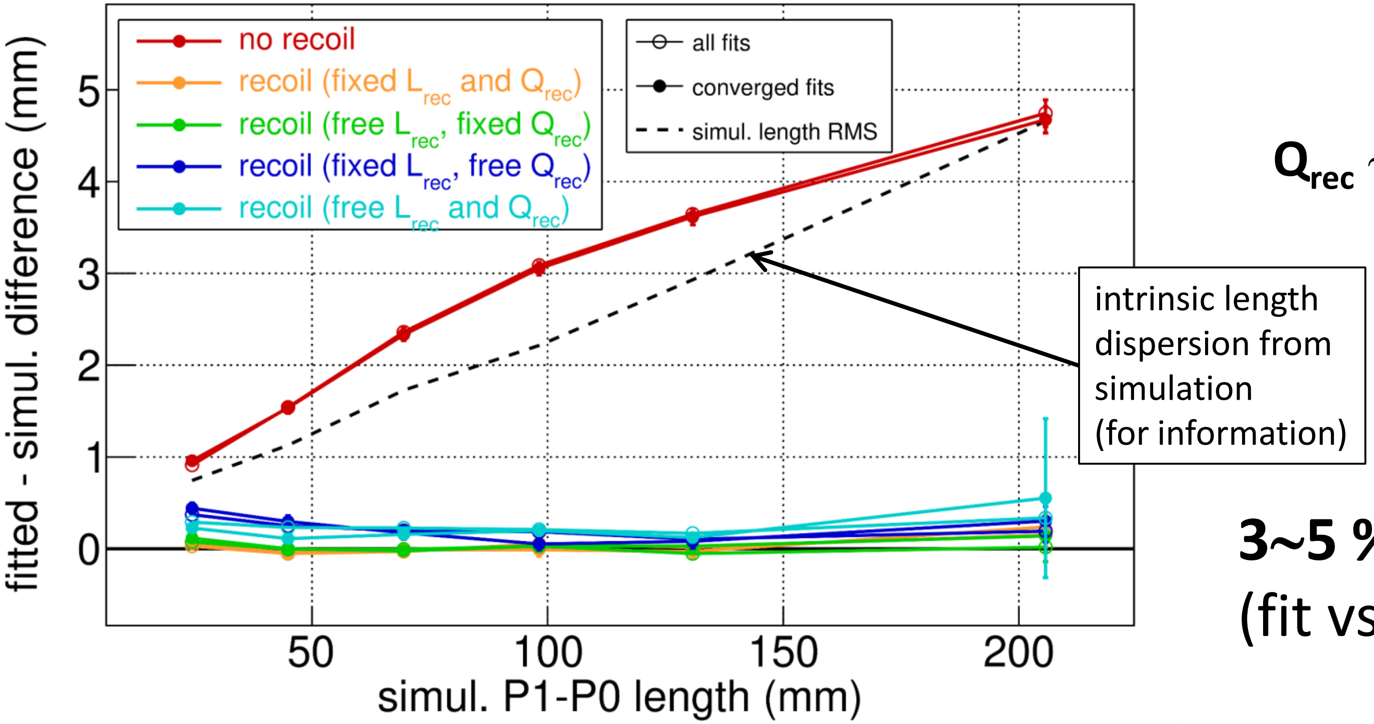

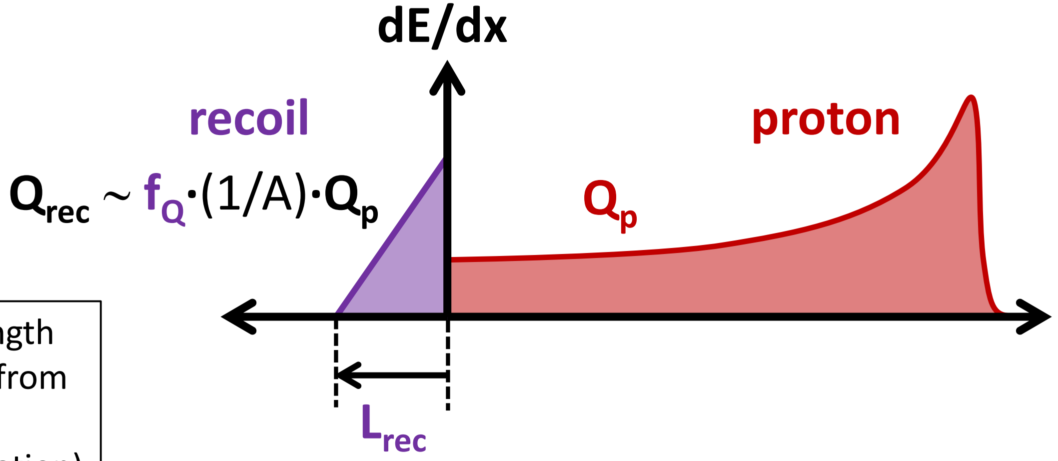

3~5 % length difference
(fit vs simul. length)

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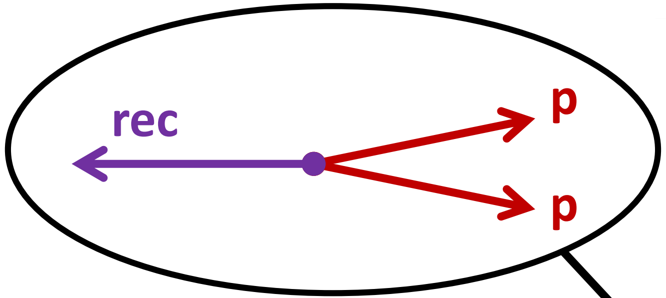

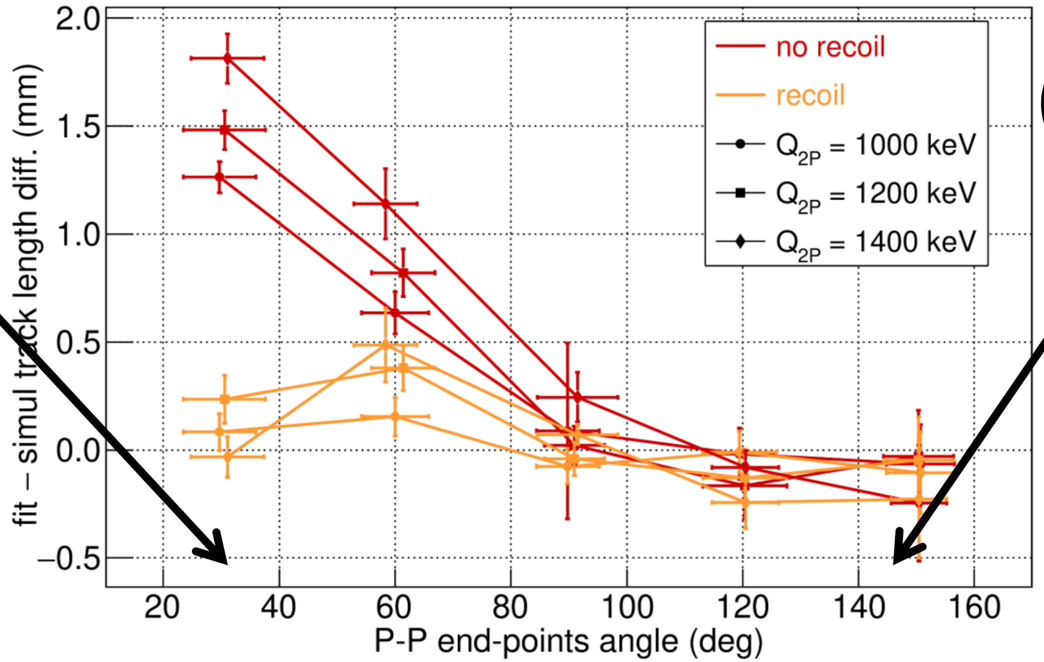

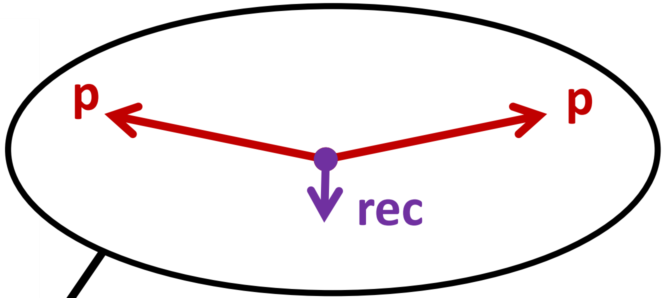

2P decay:
Q-value from fitted length increased by ~2%

concluding remarks

▷ **simulations needed for ACTAR TPC decay detection efficiency**

custom empirical simulation (no need for microscopic description)
parametrization based on experimental data
dominated by systematic uncertainties
slight differences in E690 & E791 procedures

▷ **simulations help tracks analysis and fits**

identification of events topology (not discussed here)
control and correction of fit procedure
→ corrected dispersion
→ included recoil signal

▷ **still some work to be done…**

sorting of decay events types (for now "artisanal" way…)
improve fits (3D fits extremely slow)
control G4 results (problems…)

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thank you for your attention !

▷ **still some work to be done…**

sorting of decay events types (for now “artisanal” way…)

improve fits (3D fits extremely slow)

control G4 results (problems…)

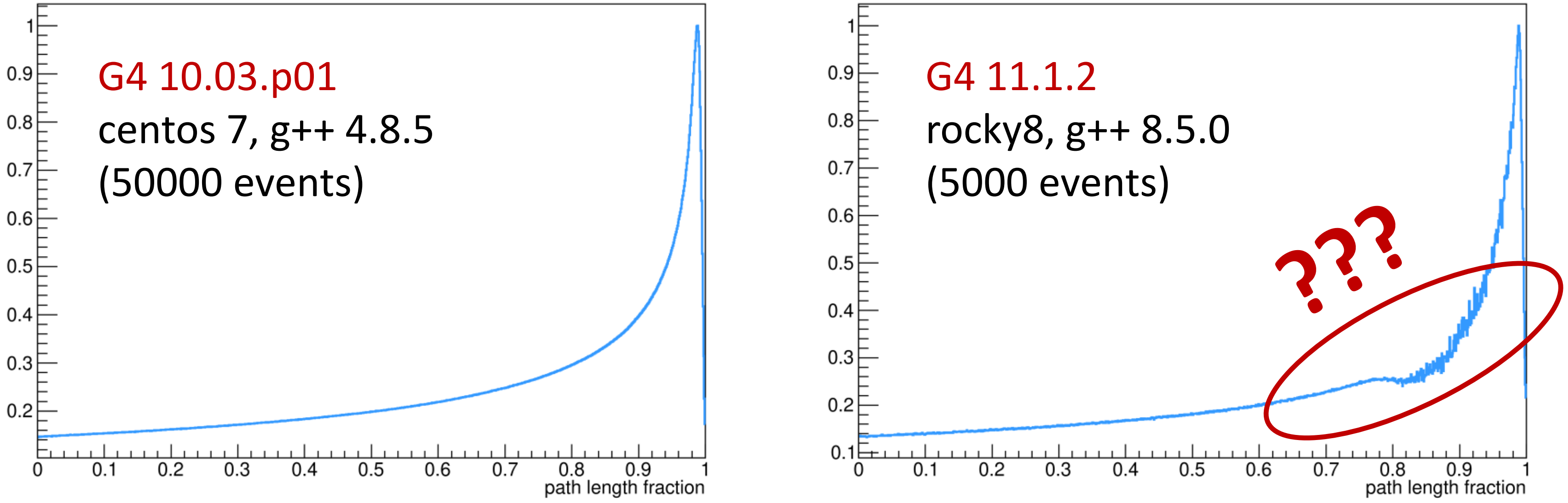
problems

updated SimRange program for GSimTPC 6.0 (for rocky linux 8)

recomputed Bragg peak histograms (fit pattern) for alpha and protons in Ar-C4H10 (90%-10%): 50000 events

- **10 MeV protons, P = 5 bar (file `proton_10MeV_5bar.root`)**
- **10 MeV alpha, P = 1 bar (file `alpha_20MeV_2bar.root`)**

20 MeV **alpha** average energy loss
in Argon-Isobutane (90-10%) gas (P = 2 bar)



average of energy deposit along "**normalized**" track path