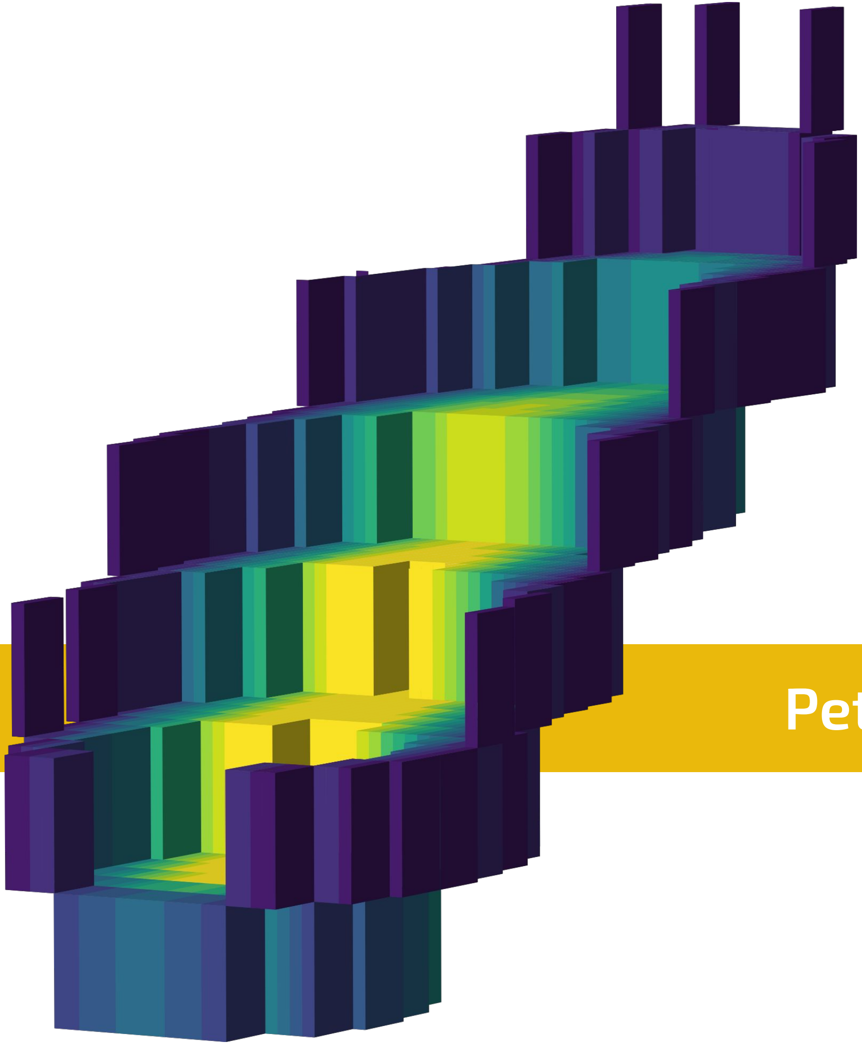


Vector tracking in low-energy nuclear recoils

Peter Mandeville Lewis | 18 March 2021

UNIVERSITÄT BONN

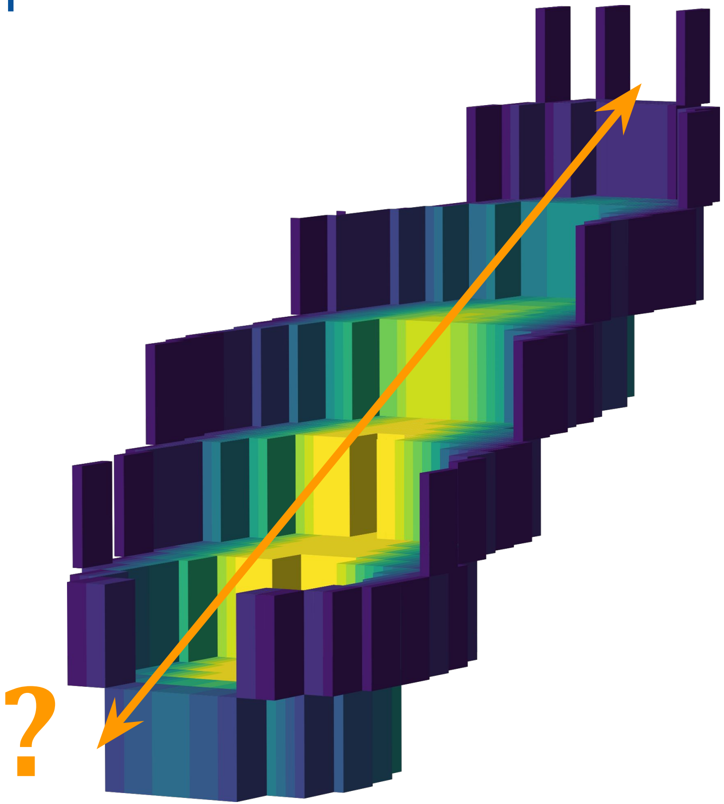
Vector tracking at low energies

HD TPCs for Directional Dark Matter

(see Sven’s talk)

- *Goal*: achieve **vector directionality** at lowest possible energies
    - “HD TPCs”
- This talk:
    - *New algorithm*: primary track recovery (**`ptr`**)
    - Implications for future detectors (briefly)

Using the BEAST TPCs as a model...



The BEAST TPCs

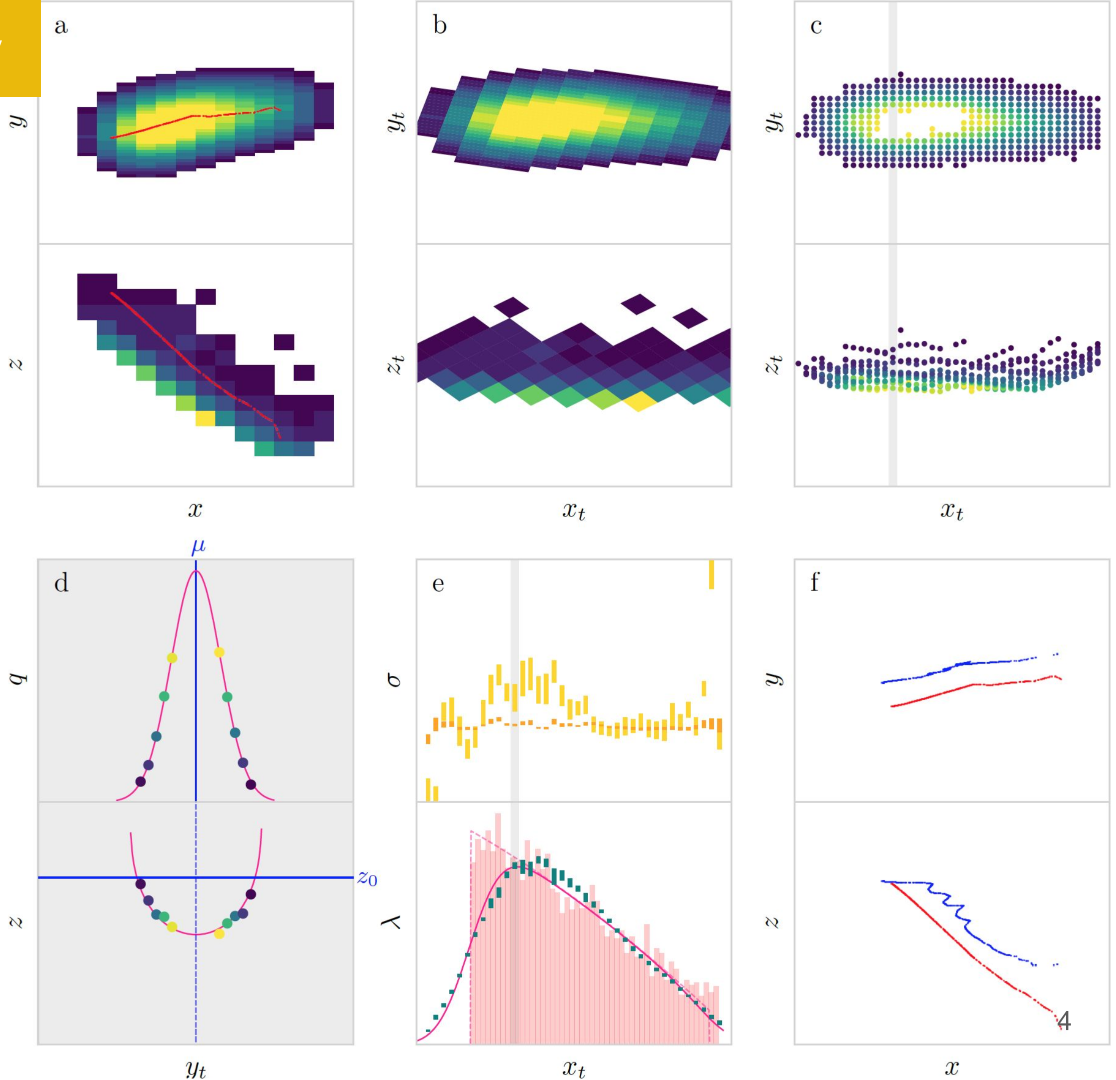
"Micro" HD TPCs

- DDM technology demonstrators
- Used in fast neutron tracking applications
- *Size*: ~**2**x**2**x**10**cm^3 sensitive volume
- *Gas*: 70:30 **He**:CO_2 at 1 atm
    - Principal recoils are He nuclei (**alphas**)
    - Electron drift gas
- *Amplification*: two gas electron multipliers (GEMs)
- *Readout*: ATLAS FE-I4B pixel chip:
    - **50**x**250** μm pitch
    - 4-bit time-over-threshold (TOT)
    - Hit-trigger timing resolution: 25 ns (→ **250 μm**)

Approach

"Effective deconvolution"

- **Model** all physics+detector effects
- **Fit** tracks with model, using primary track properties as free parameters
- **Deconvolve** to obtain recovered primary track

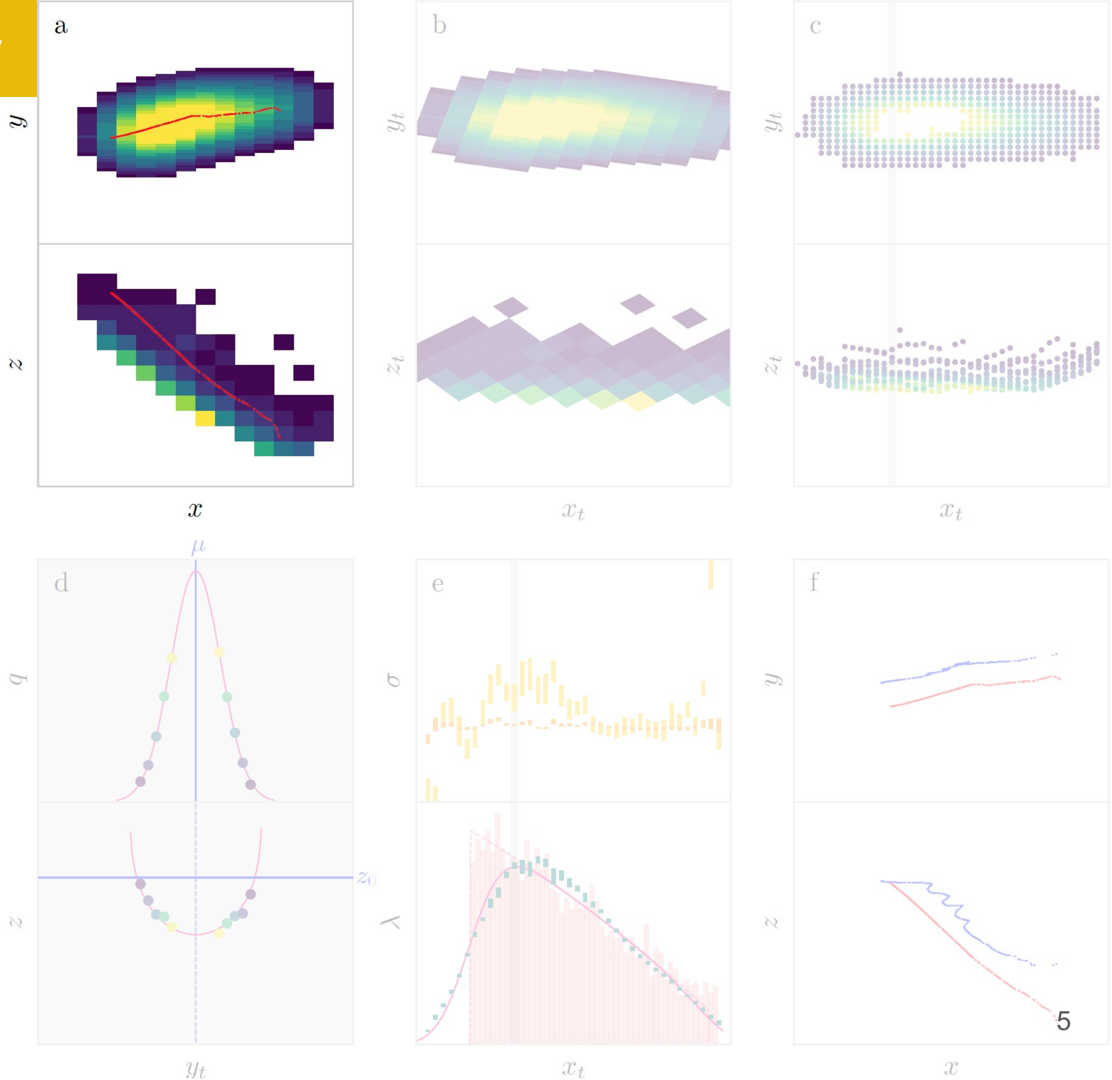


Primary track recovery

a. Model

Track development

Why does a track look like this?

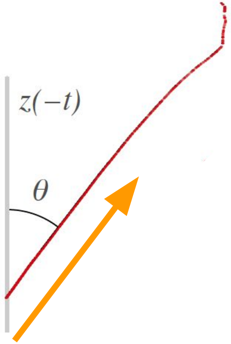


Primary track recovery

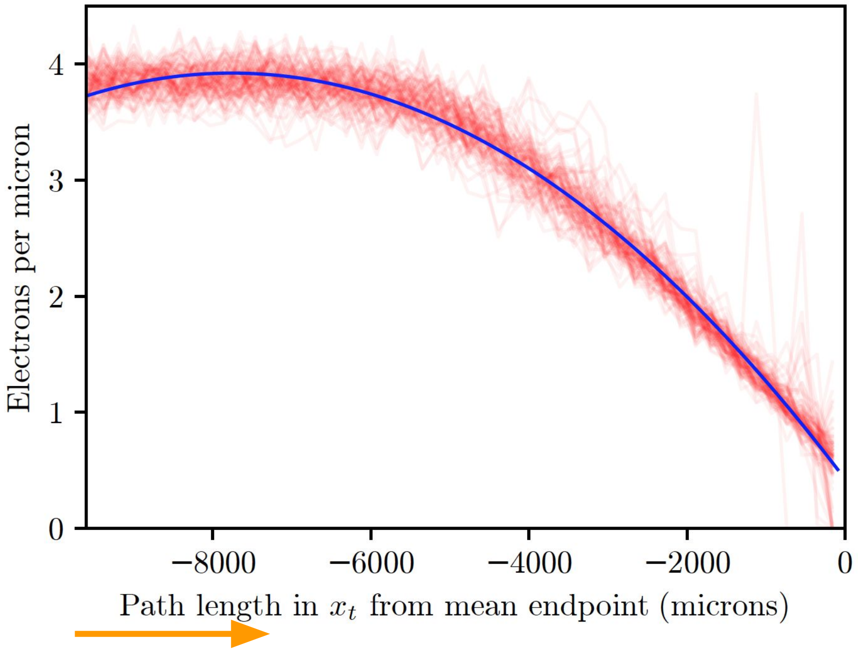
a. Model

Track development

$$\lambda_{\mathrm{B}}(x_t) = \begin{cases} aT_0(x_t) + bT_1(x_t) + cT_2(x_t) \\ 0 \end{cases} \quad \mathrm{i}$$



- **i**: ionization charge deposited (**Bragg**)



Primary track recovery

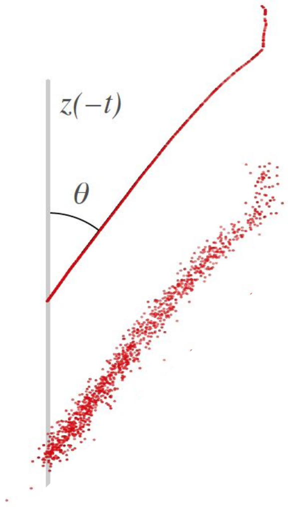
a. Model

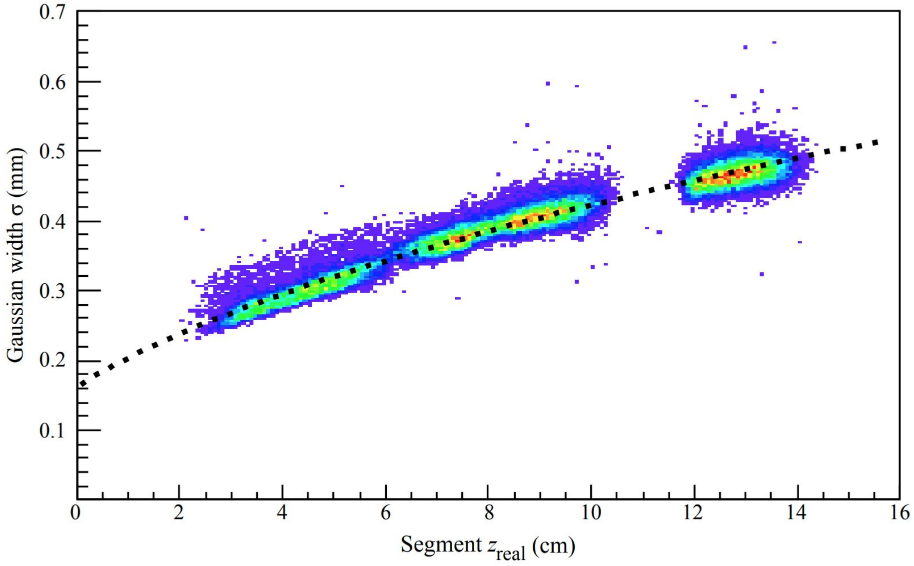
Track development

$$\lambda_B(x_t) = \begin{cases} aT_0(x_t) + bT_1(x_t) + cT_2(x_t) \\ 0 \end{cases} \quad \text{i}$$

- **i**: ionization charge deposited
- **ii**: thermal drift diffusion (**random walk**)

$$\sigma_T^{ii} = B_T\sqrt{z_d}, \quad \sigma_L^{ii} = B_L\sqrt{z_d}, \quad \text{ii}$$





Primary track recovery

a. Model

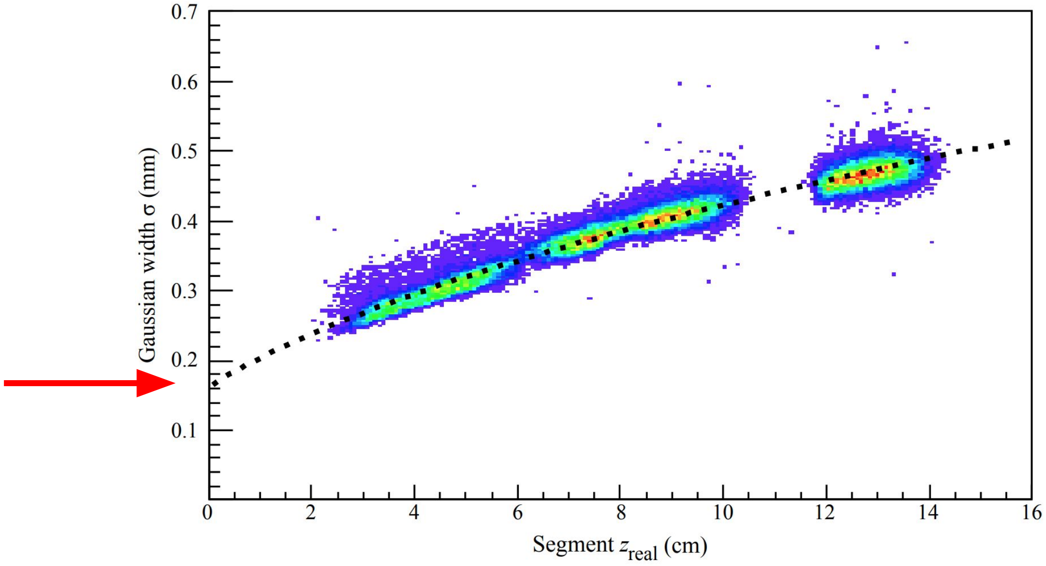
Track development

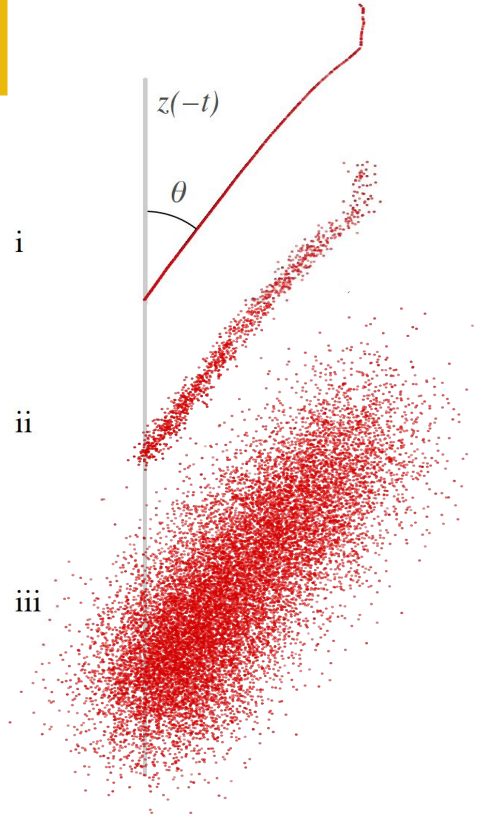
$$\lambda_B(x_t) = \begin{cases} aT_0(x_t) + bT_1(x_t) + cT_2(x_t) \\ 0 \end{cases}$$ i

$$\sigma_T^{ii} = B_T\sqrt{z_d}, \quad \sigma_L^{ii} = B_L\sqrt{z_d},$$ ii

$$\sigma_T^{iii} = \sqrt{A_T^2 + B_T^2 z_d}, \quad \sigma_L^{iii} = \sqrt{A_L^2 + B_L^2 z_d}.$$ iii

- **i**: ionization charge deposited
- **ii**: thermal drift diffusion
- **iii**: amplification dispersion (**Gaussian smearing**)





Primary track recovery

a. Model

Track development

$$\lambda_{\mathrm{B}}(x_t) = \begin{cases} aT_0(x_t) + bT_1(x_t) + cT_2(x_t) \\ 0 \end{cases}$$

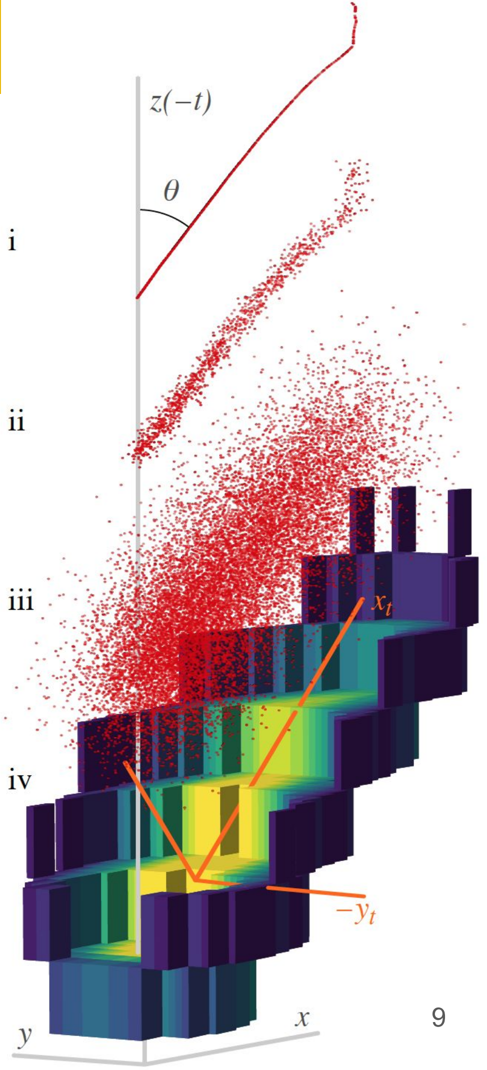
$$\sigma_T^{ii} = B_T\sqrt{z_d}, \quad \sigma_L^{ii} = B_L\sqrt{z_d},$$

$$\sigma_T^{iii} = \sqrt{A_T^2 + B_T^2 z_d}, \quad \sigma_L^{iii} = \sqrt{A_L^2 + B_L^2 z_d}.$$

?

- **i**: ionization charge deposited
- **ii**: thermal drift diffusion
- **iii**: amplification dispersion
- **iv**: digitization:
  - *x*, *y* position from pixel center
  - *relative z* position from **threshold-crossing time**
  - *charge* from time-over-threshold (TOT)

→ Charge structure in ***z*** is **integrated out** in each pixel

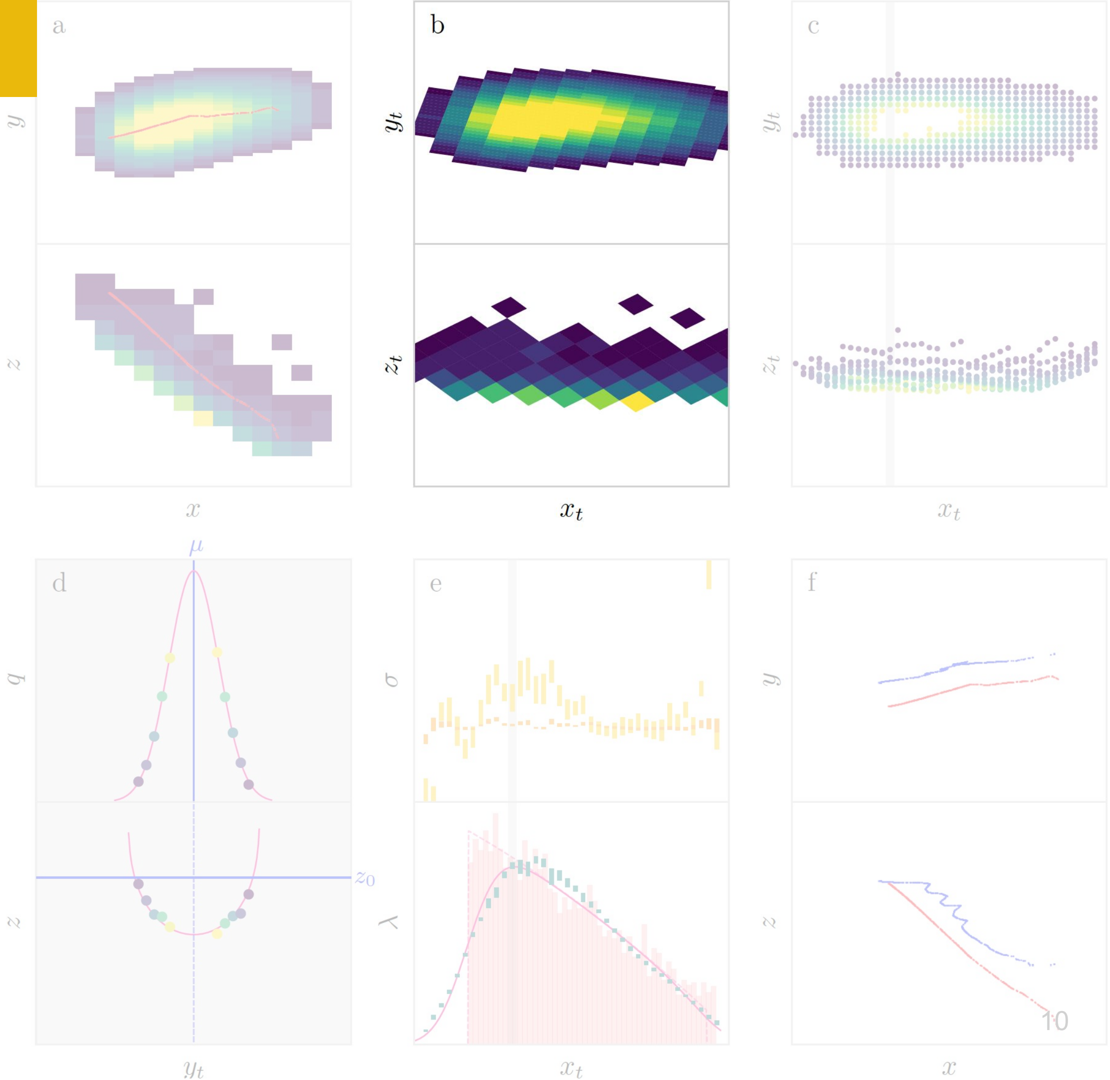


Primary track recovery

b. Prefit

Singular value decomposition of hits

- **Get ϕ/θ**

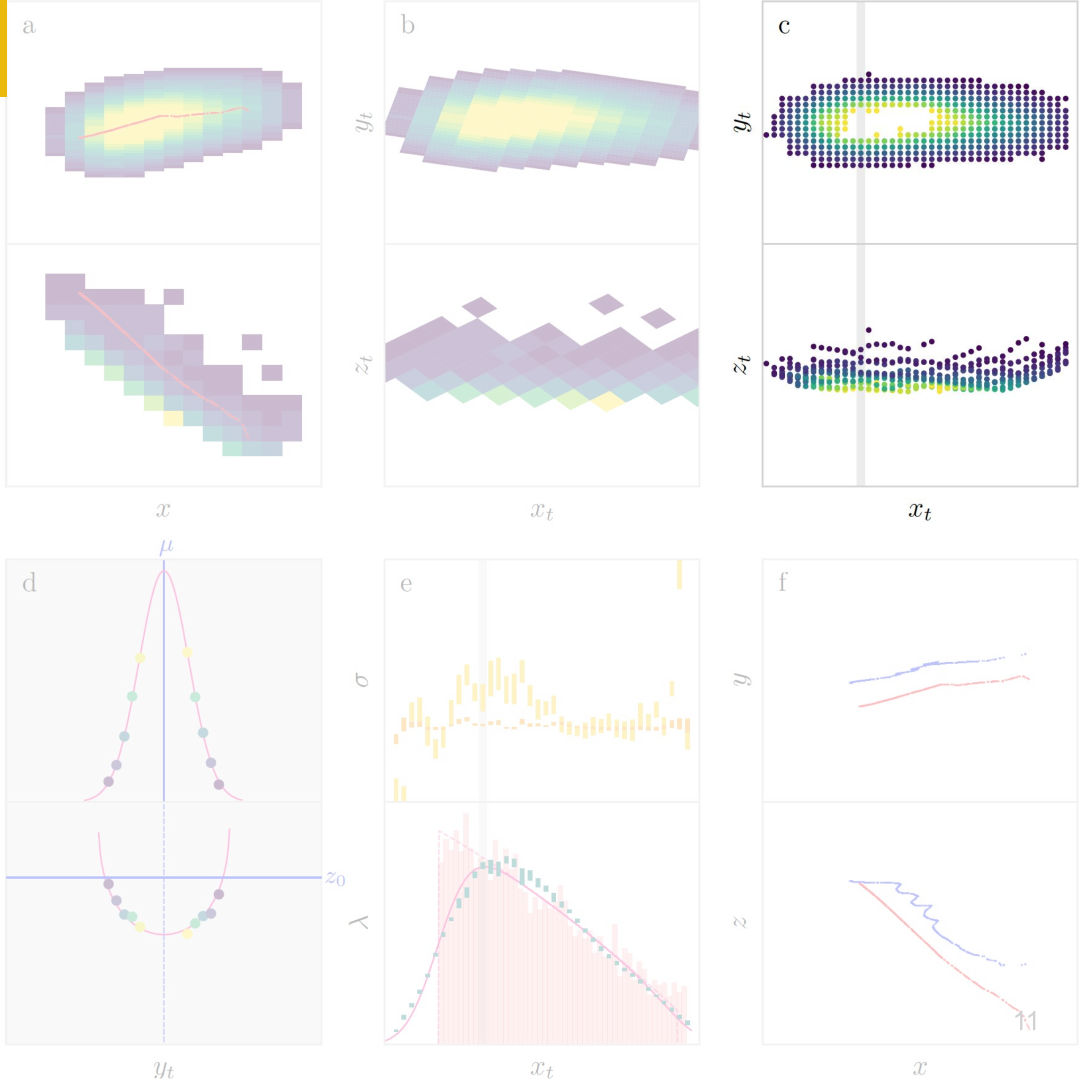


Primary track recovery

c. Slice/sample

Bilinear interpolation between hits

- Estimate ***z***, ***q*** at points transverse to track (***slice***)

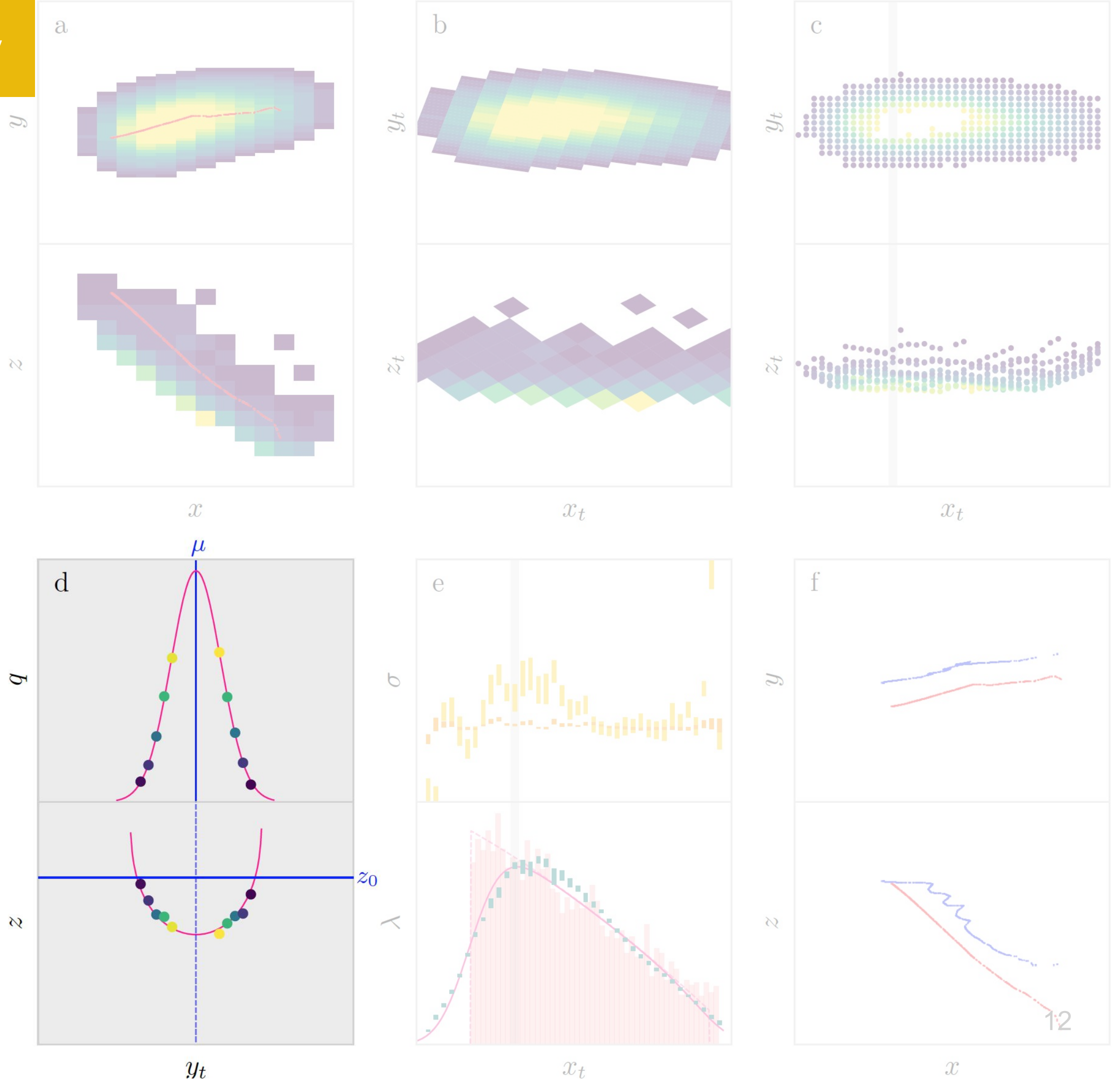


Primary track recovery

d. Slice fits

Charge profile and shell

- This is where the (**unknown**) **digitization model** comes in



Primary track recovery

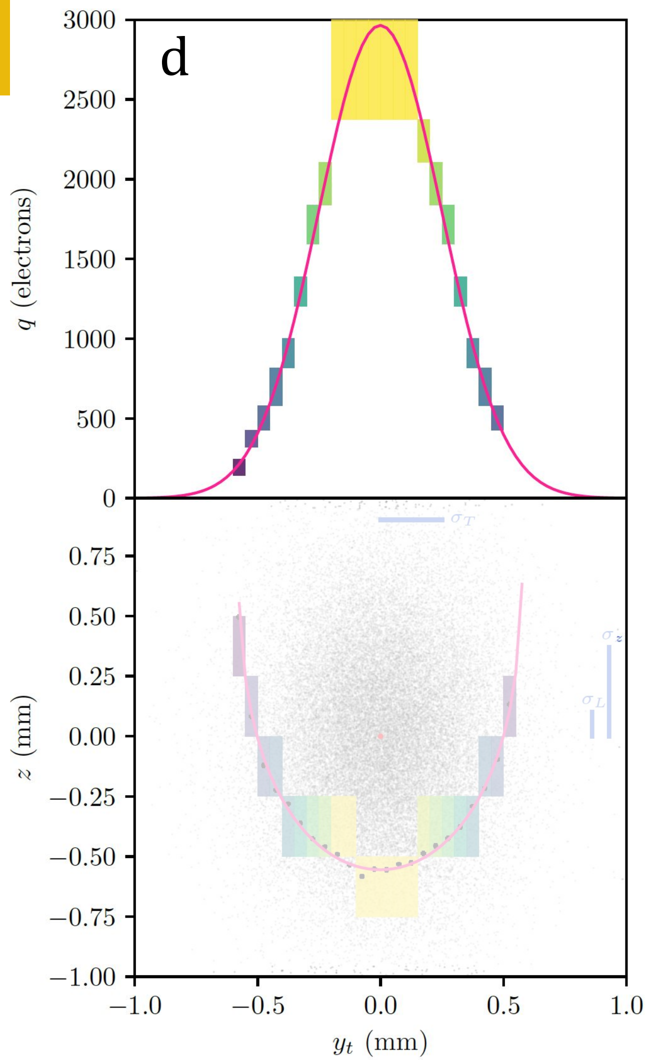
d. Slice fits

Charge **profile**

- The *transverse* charge profile should be Gaussian:

$$q^s(y_t) = h^s g(y_t; \mu_y^s, \sigma_T^s)$$

- Free parameters → track properties
  - h → linear charge density
  - μ → transverse straggling
  - σ_T → transverse diffusion
- (corrections for resolution effects not shown)
- The **shell fit** (bottom) I'll leave for additional slides
  - Model **timewalk** and charge structure in z
  - Fit to get track center position in z and σ_L

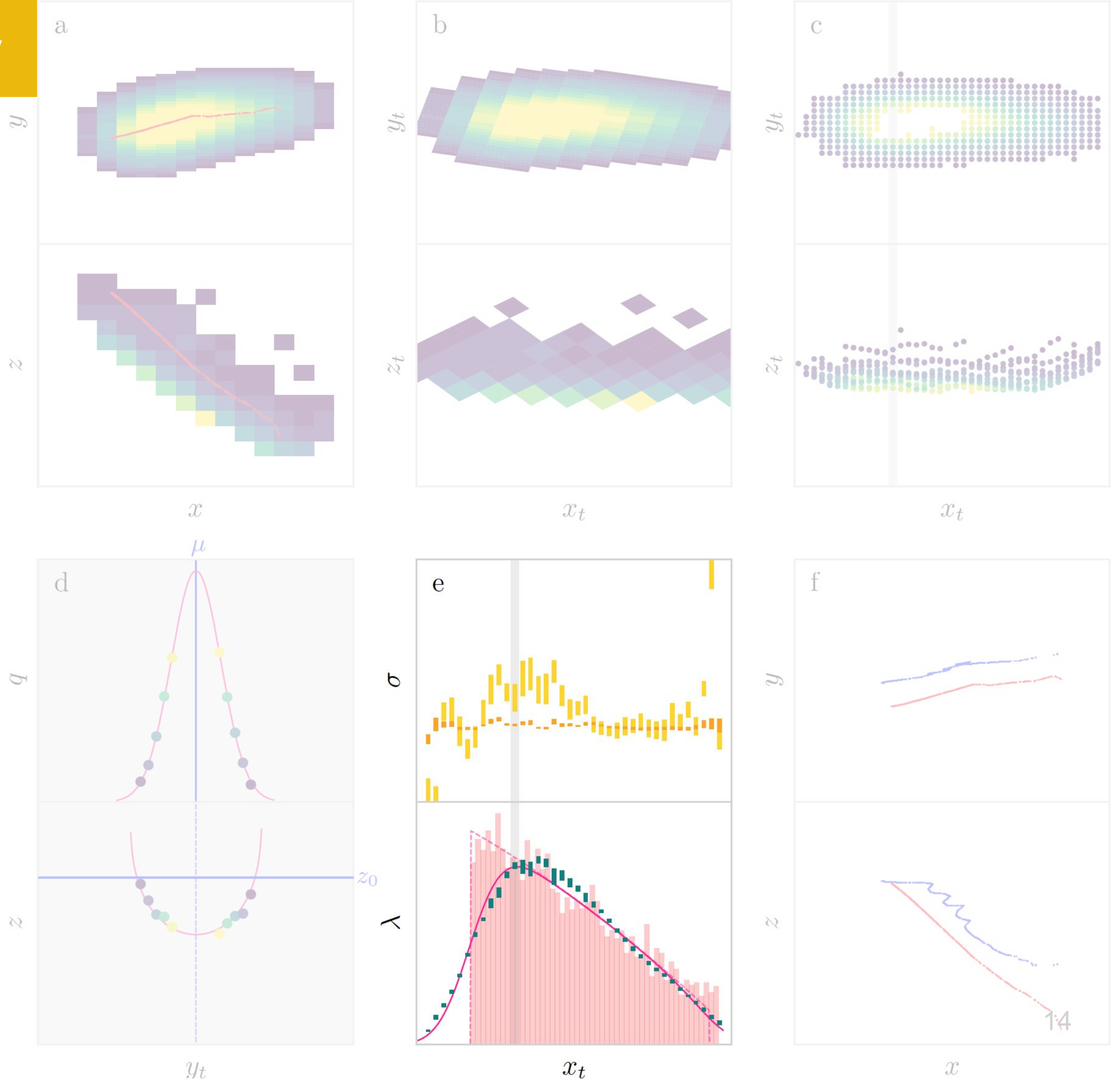


e. Smeared Bragg fit

Deconvolve diffusion+detector effects

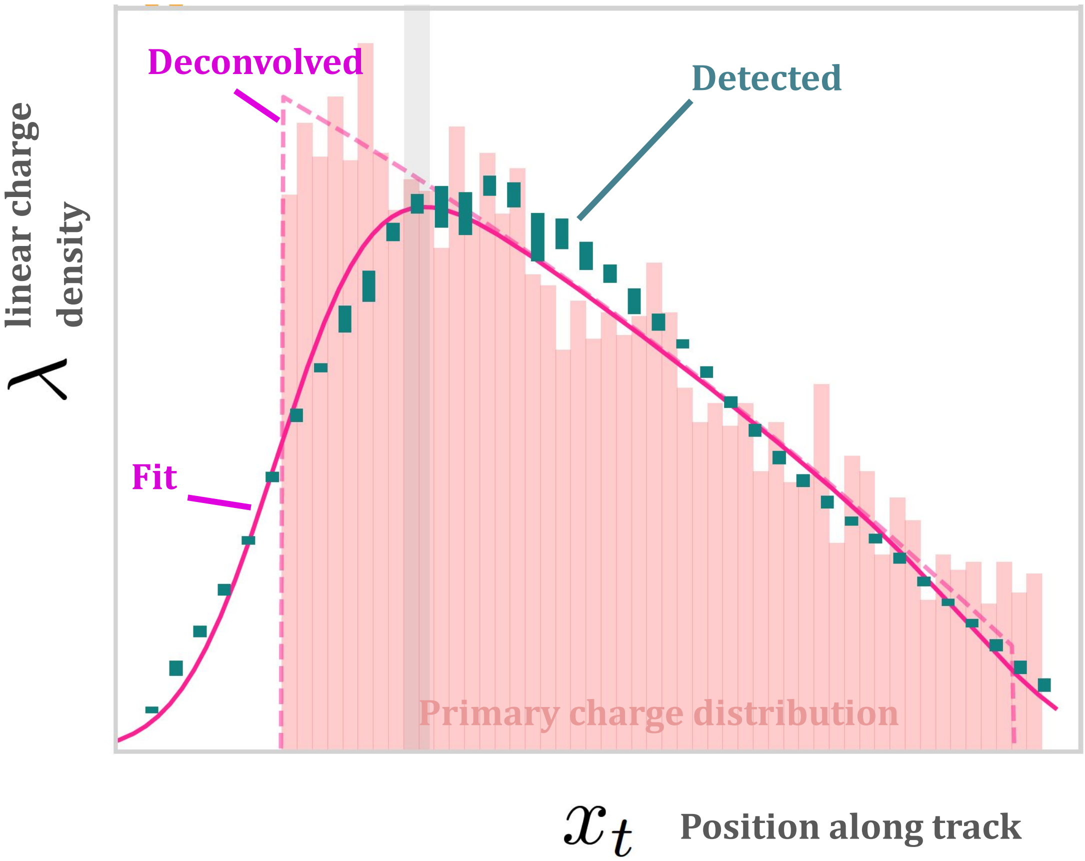
- Fit the **Bragg parameterization** convolved with diffusion+digitization effects determined by slice fits

→ Let's take a closer look...



Primary track recovery

e. Smeared Bragg fit



Free parameters are primary track properties:

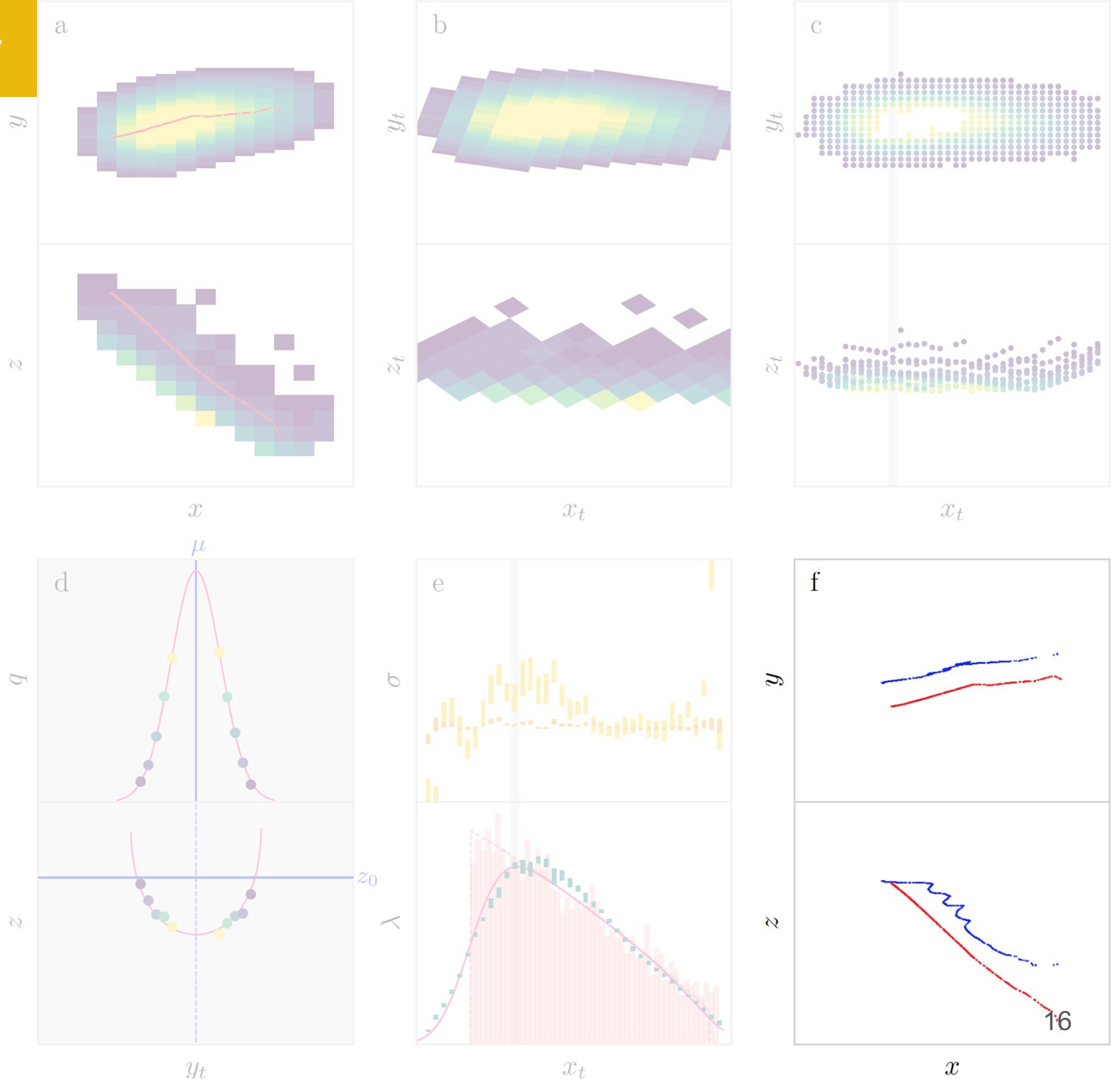
- True length
- True charge
- **Vector direction** (via χ^2 hypothesis testing)

Primary track recovery

f. Recover primary

Deconvolved

- **Distribute charge in 3D** according to *unsmeared* Bragg and including transverse straggling
- **Refit** to get improved ϕ/θ

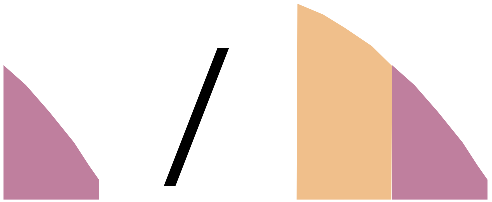


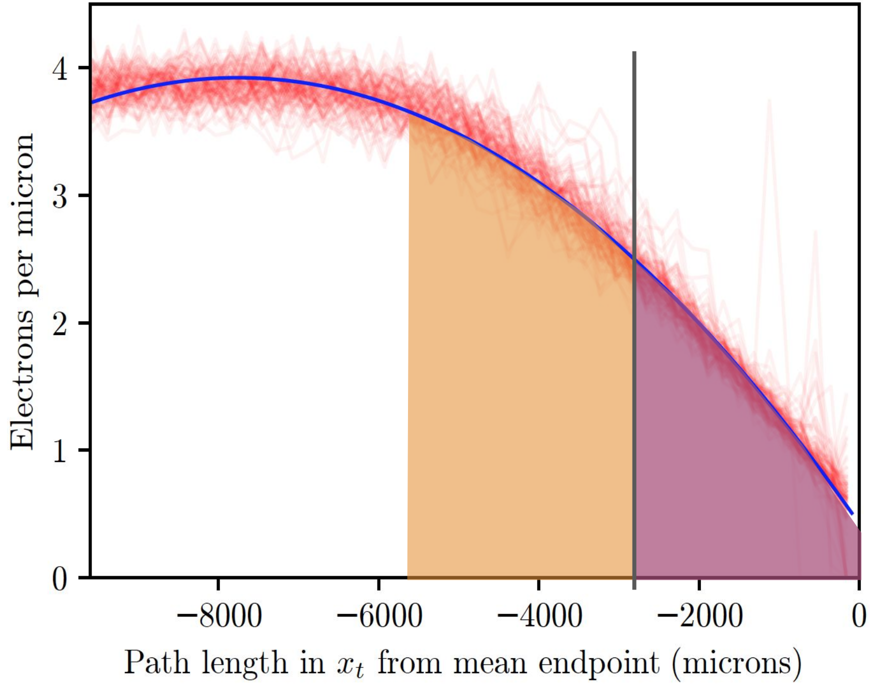
Performance

Focus on ***vector directionality***

- Compare to *head charge fraction (HCF)*
  - Recently demonstrated
  - Use **charge imbalance** along track to determine vector direction

HCF (correct assignment) < **0.5**:





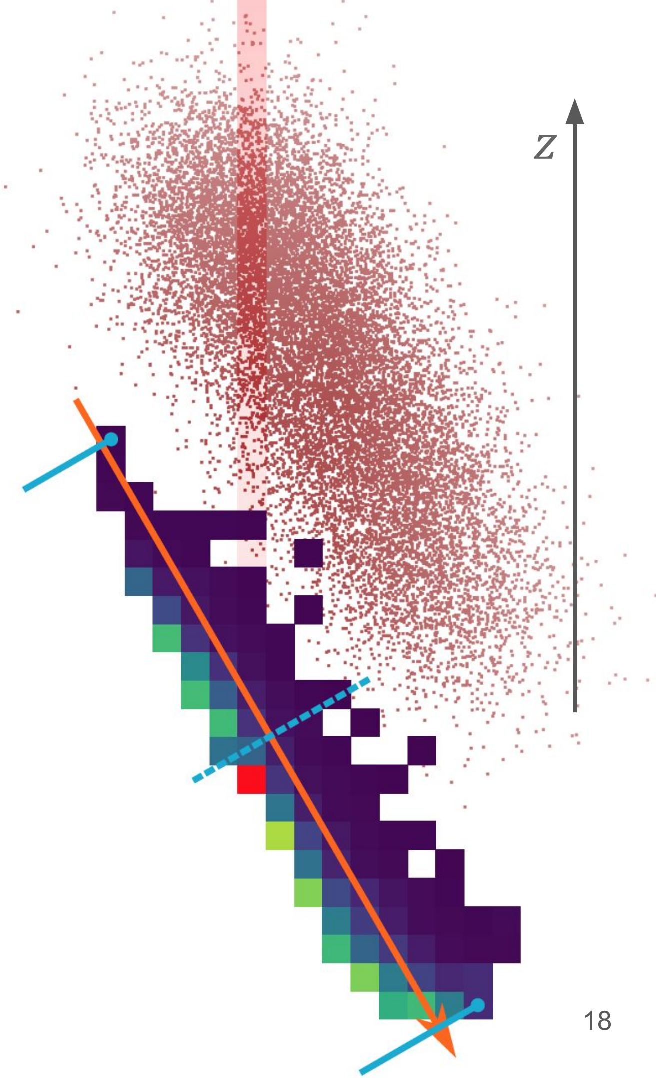
But a digitization effect limits performance of this...

Primary track recovery

Performance

Head charge fraction (HCF)

- **Integration effects** limit traditional reconstruction
- For HCF, *inclined* tracks have **biased charge distributions**



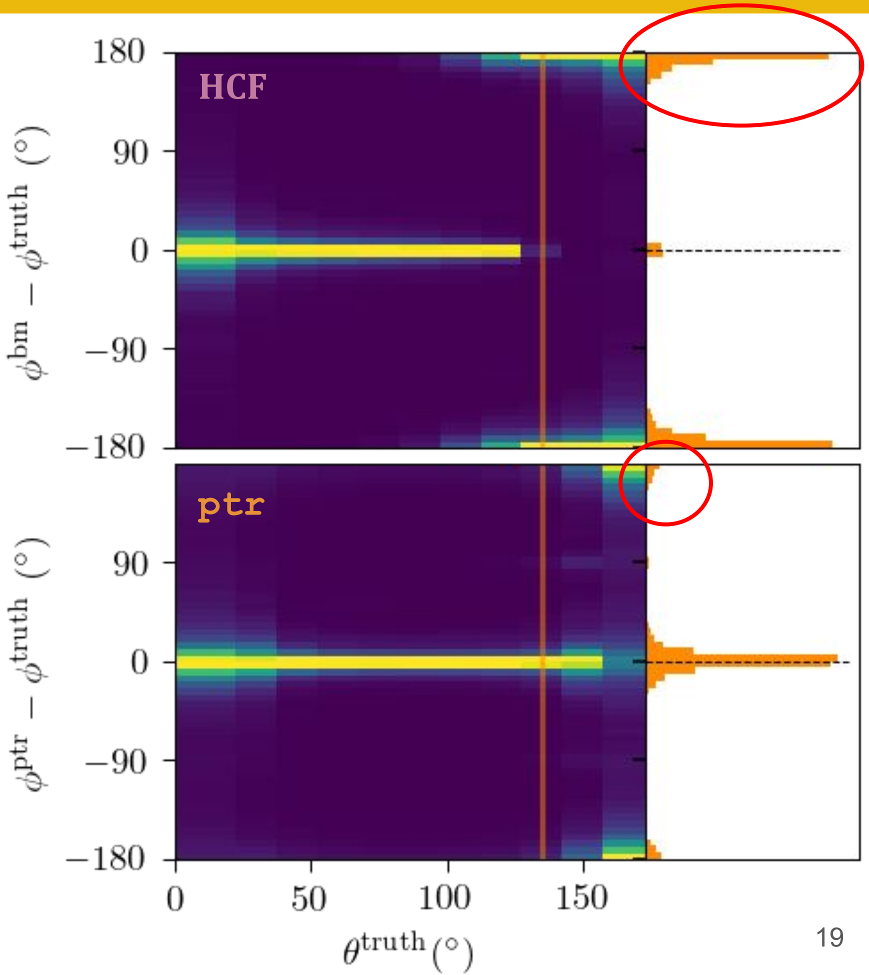
Primary track recovery

Performance

Vector directionality vs ***θ***

- (using 1M simulated, digitized recoils)
- **HCF** (top) is compromised by **integration effects**
- **`ptr`** (bottom) is robust against these effects

But improvement is most important at *low energies*...

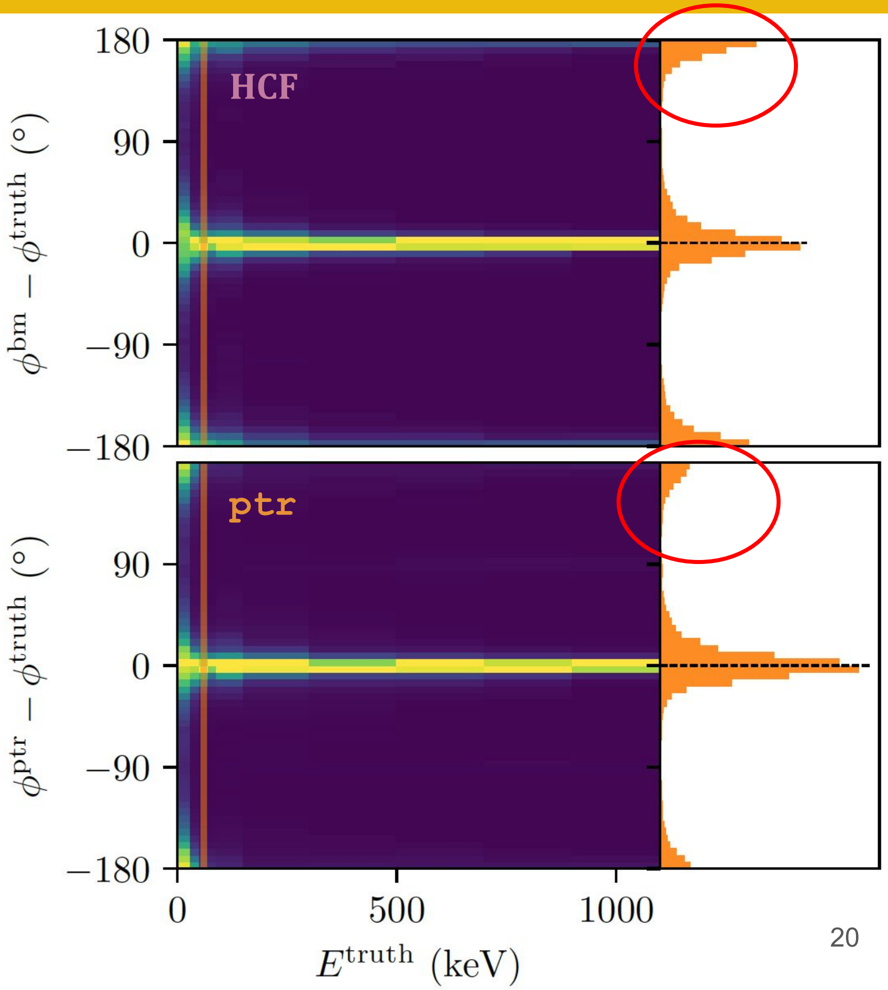


Primary track recovery

Performance

Vector directionality vs ***E***

- Significant improvement at **low energies**
  - At **60 keV**, right, where $L/\sigma_T \sim 4$



...but does it work on data?

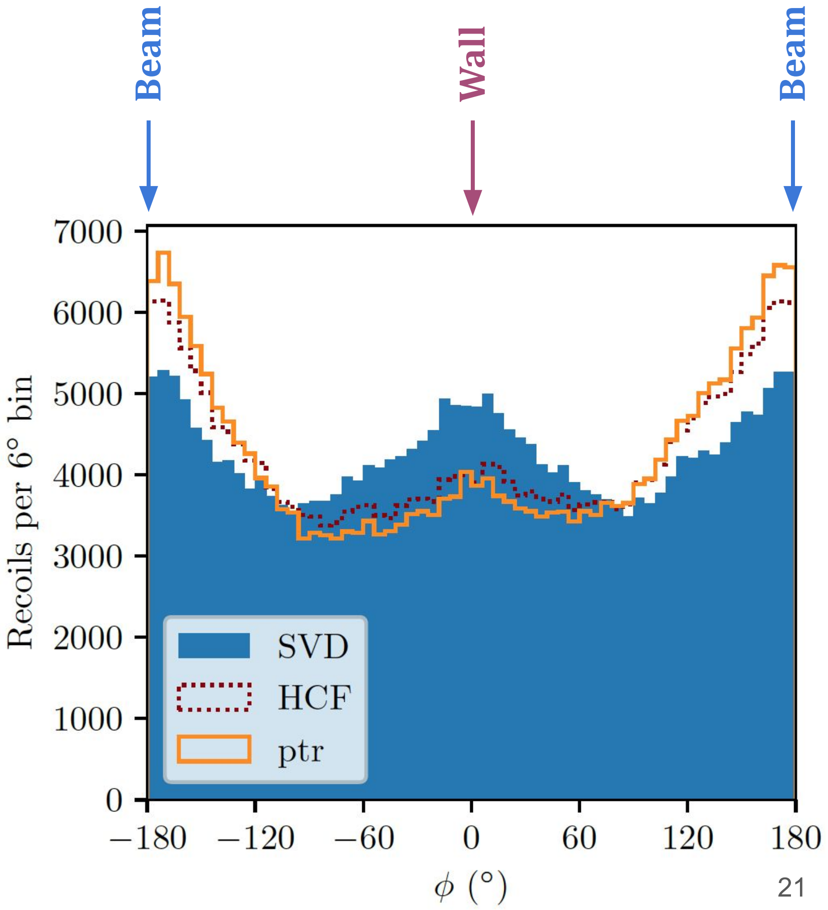
Primary track recovery

Performance

Data validation

- Use BEAST TPC beam background monitor at SuperKEKB
  - (fast neutron recoils)
  - Beam parallel to *z* axis: point source in ϕ, smeared by recoil angle
- **SVD** prefit assigns track direction randomly
- **HCF** assigns correct direction usually
- **ptr** assigns correct direction more frequently
  - Improvement due to **proper modeling of physics and detector dynamics**

(similar improvements in other variables…)

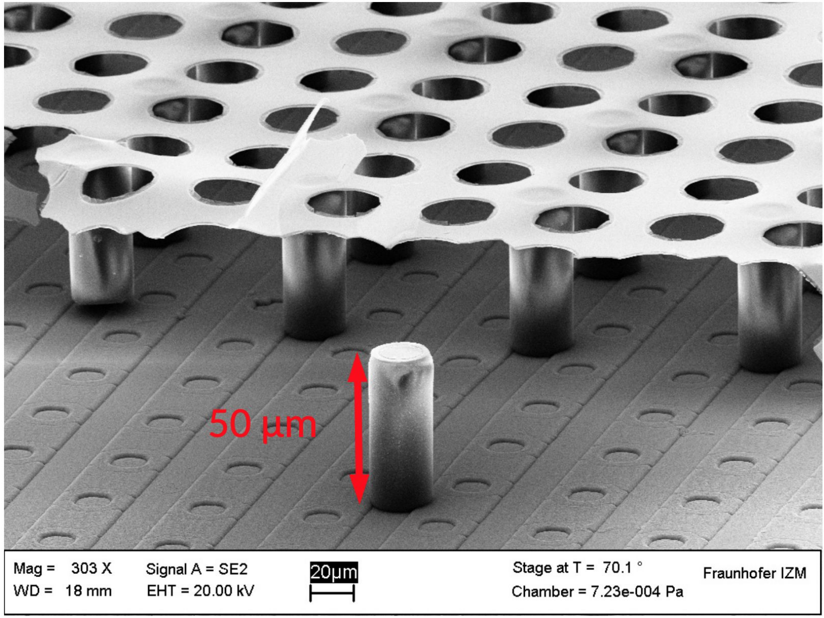


Implications for future detectors

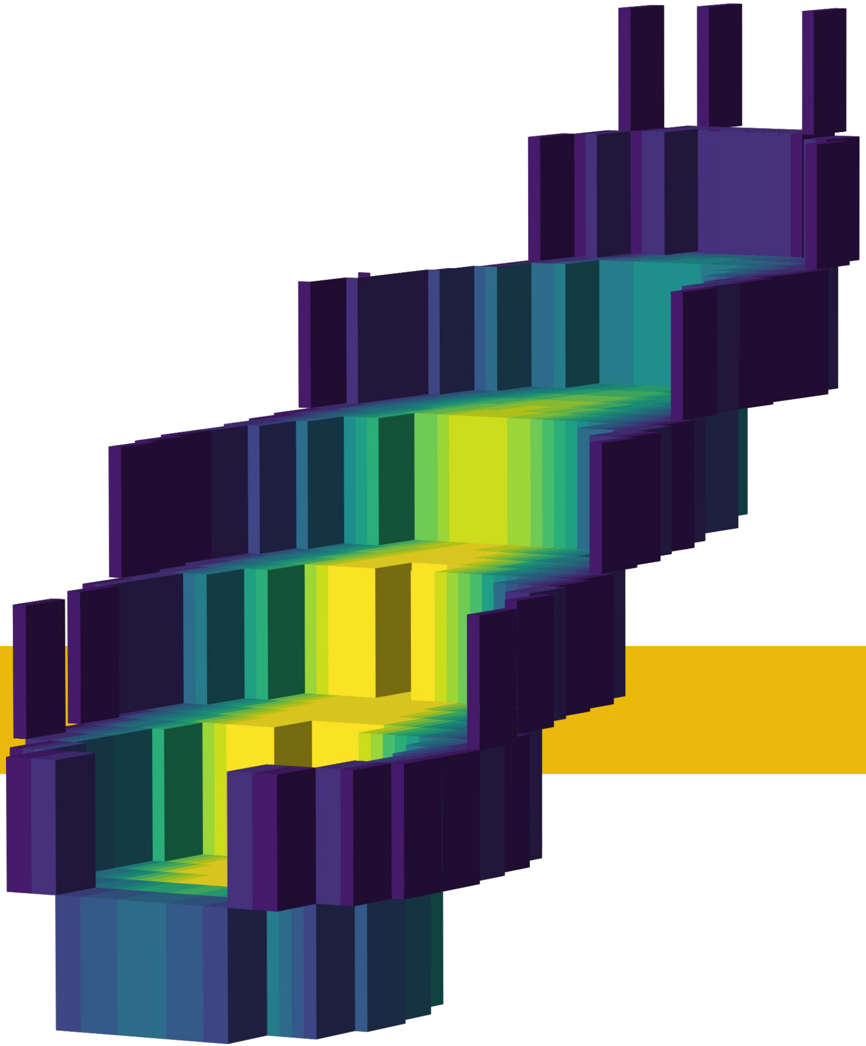
HD TPCs with InGrid readout

- Even with **`ptr`**, performance is limited by:
  - Integration effects
  - Amplification dispersion
  - Drift diffusion
- **All** of these are mitigated by combining **InGrid readout** with **negative ion drift**
  - The ultimate HD TPC
  - Such a TPC was demonstrated last year

The low-E frontier for vector tracking will continue to demand the most of **detector technology** *and* **reconstruction algorithms**

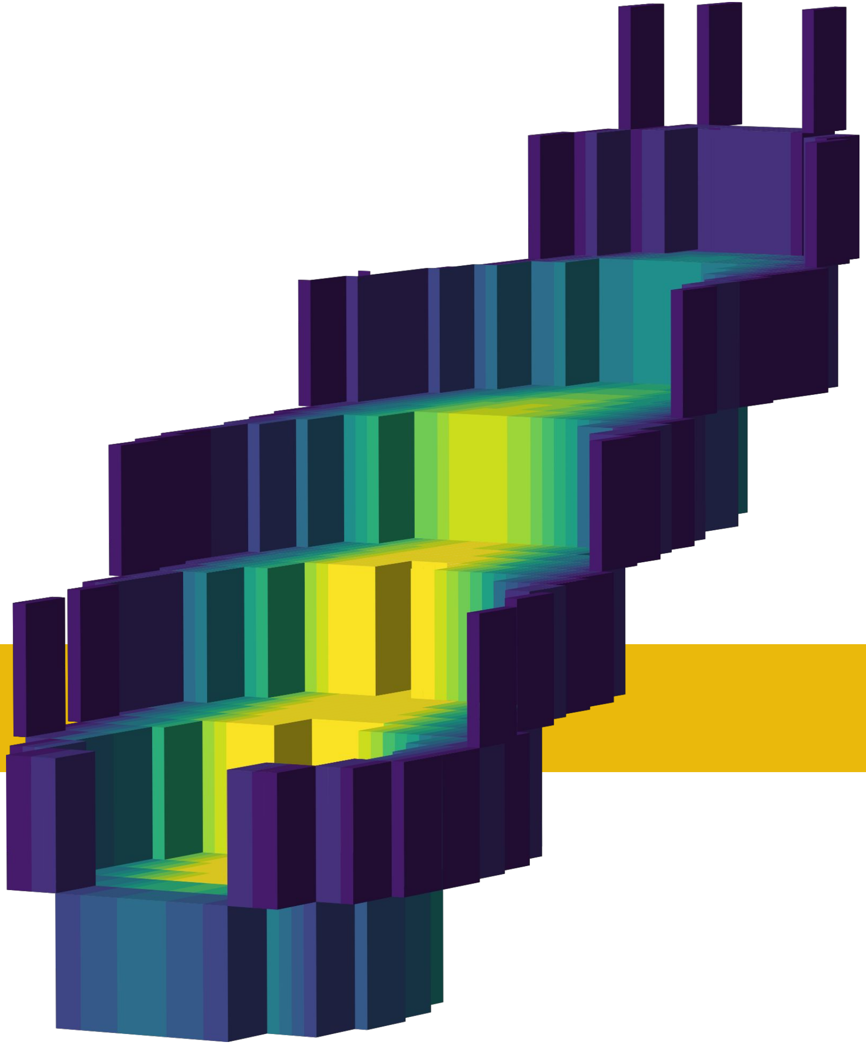


Ligtenberg, 2020



Thank you!

(watch for our paper coming soon!)



Additional slides

Primary track recovery

d. Slice fits

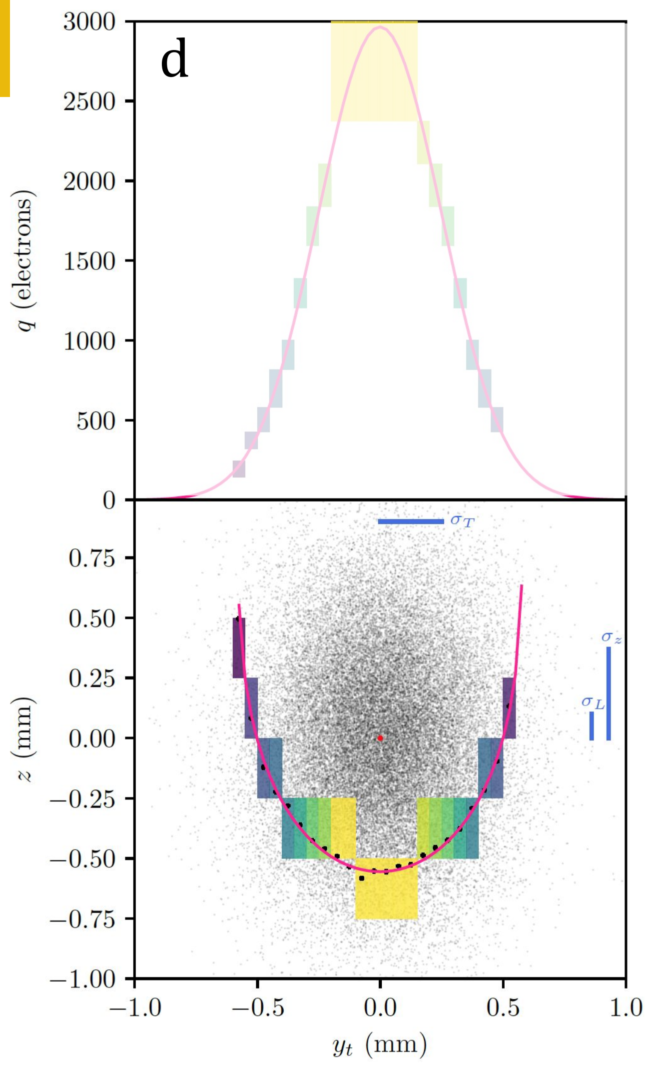
Charge **shell**

- First parameterization:

$$z^h(y^h) = z_0 + \sqrt{2}\sigma_z \mathrm{erf}^{-1}\left[\frac{2q_{\mathrm{th}}}{h^s g(y^h;\mu_y,\sigma_T)} - 1\right]$$

$$\sigma_z^2 = \sigma_L^2 + \frac{\sigma_T^2}{\tan^2\theta}$$

- Incorporates **timewalk** and **charge structure**
- Free parameters ⟶ track properties
- **3D is recoverable!** (from relationship between **neighboring hits**)



Primary track recovery

Performance

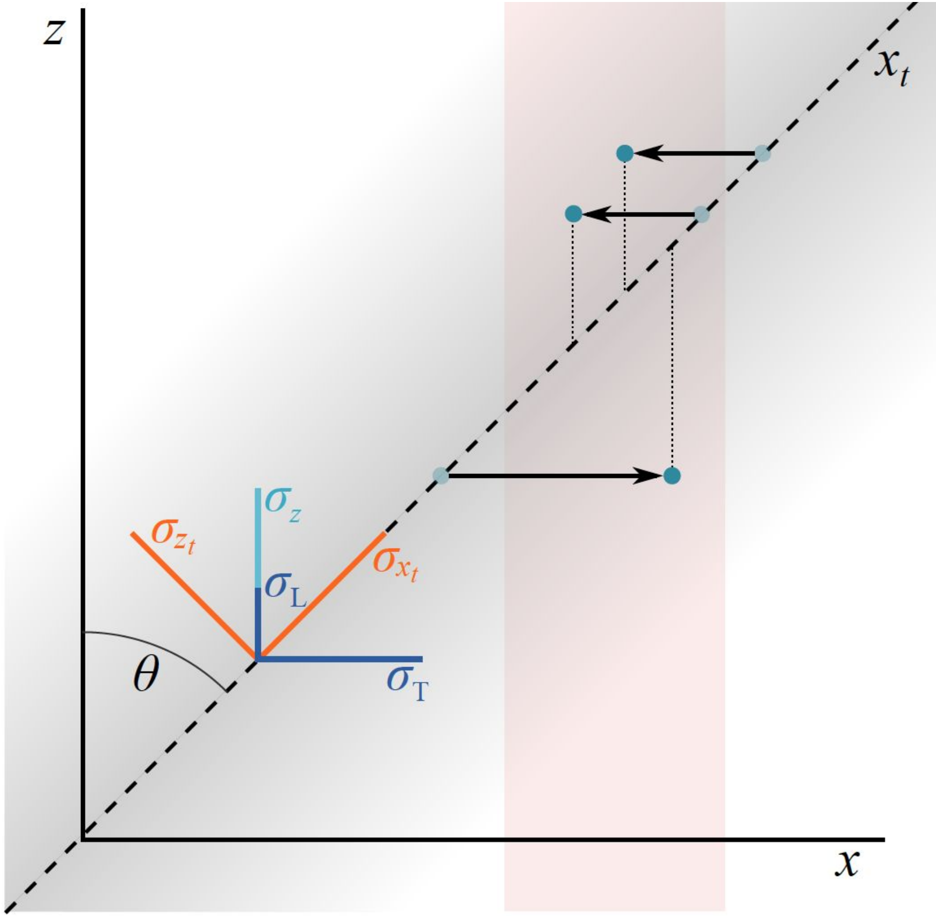
Other results

- Charge recovery
- True length
- Absolute *z* position
- Longitudinal diffusion

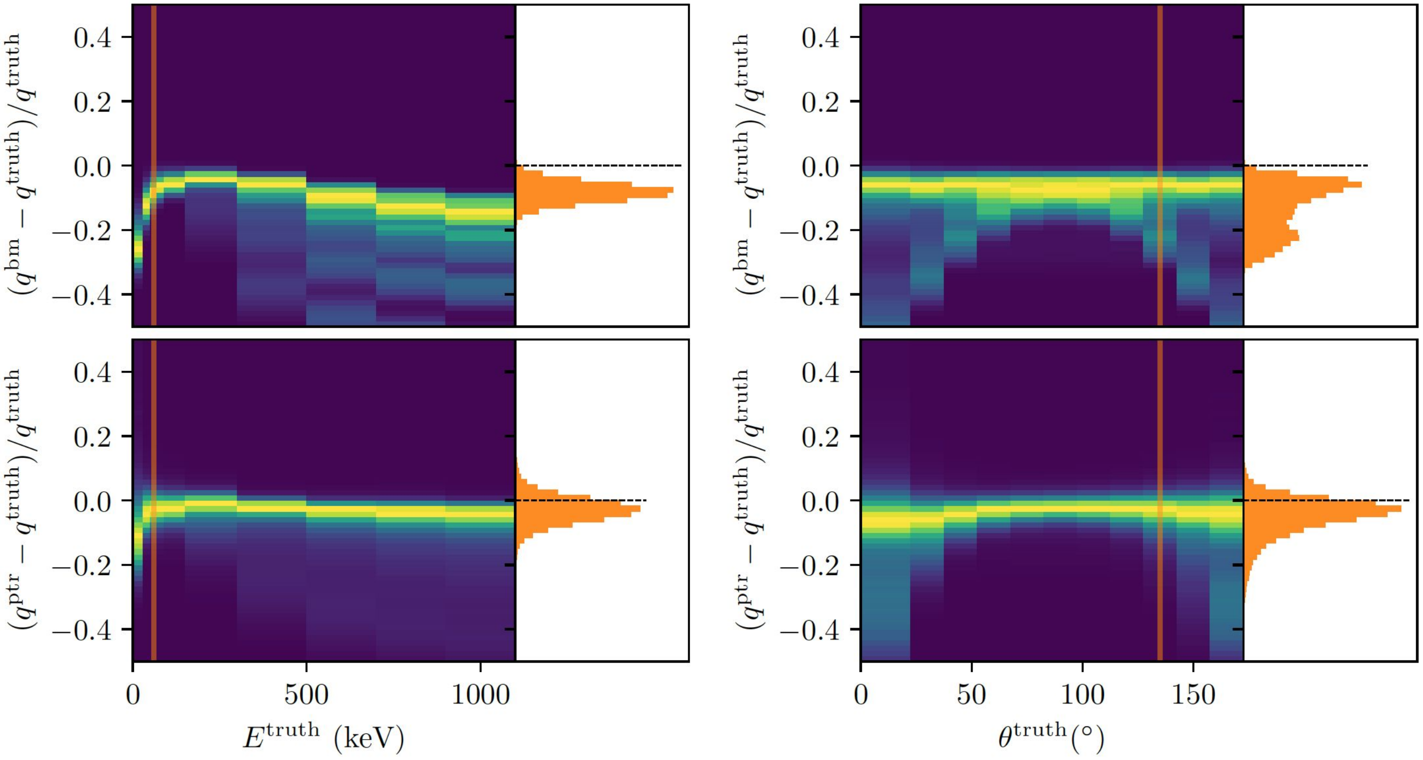
MC performance for θ=135°, E=60 keV

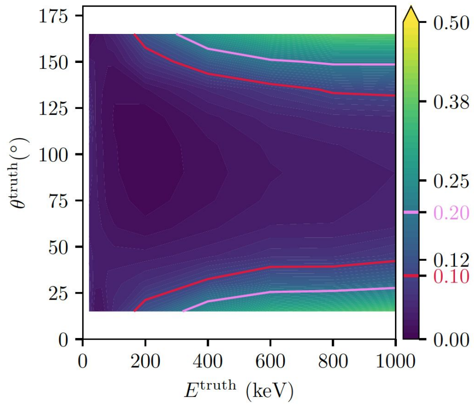
Variable	Type	`ptr`	Benchmark
q	frac. err.	$-\mathbf{0.021} \pm 0.041$	$-0.081 \pm \mathbf{0.029}$
L	frac. err.	$\mathbf{0.00} \pm \mathbf{0.13}$	0.60 ± 0.22
ϕ	abs. err. (°)	$-40 \pm \mathbf{83}$	$\mathbf{12} \pm 176$
ϕ (fold)	abs. err. (°)	1 ± 14	1 ± 14
θ	abs. err. (°)	$-\mathbf{19} \pm \mathbf{44}$	52 ± 118
θ (fold)	abs. err. (°)	$\mathbf{5} \pm 11$	$-16.6 \pm \mathbf{7.8}$
$\varepsilon_{\mathrm{ht}}$	abs.	$\mathbf{0.837} \pm 0.021$	0.504 ± 0.046
σ_T	frac. err.	$-\mathbf{0.019} \pm \mathbf{0.031}$	–
σ_L	frac. err.	$\mathbf{0.15} \pm \mathbf{0.15}$	–
z_{abs}	abs. err. (cm)	$\mathbf{1.6} \pm \mathbf{2.1}$	–

Primary track recovery

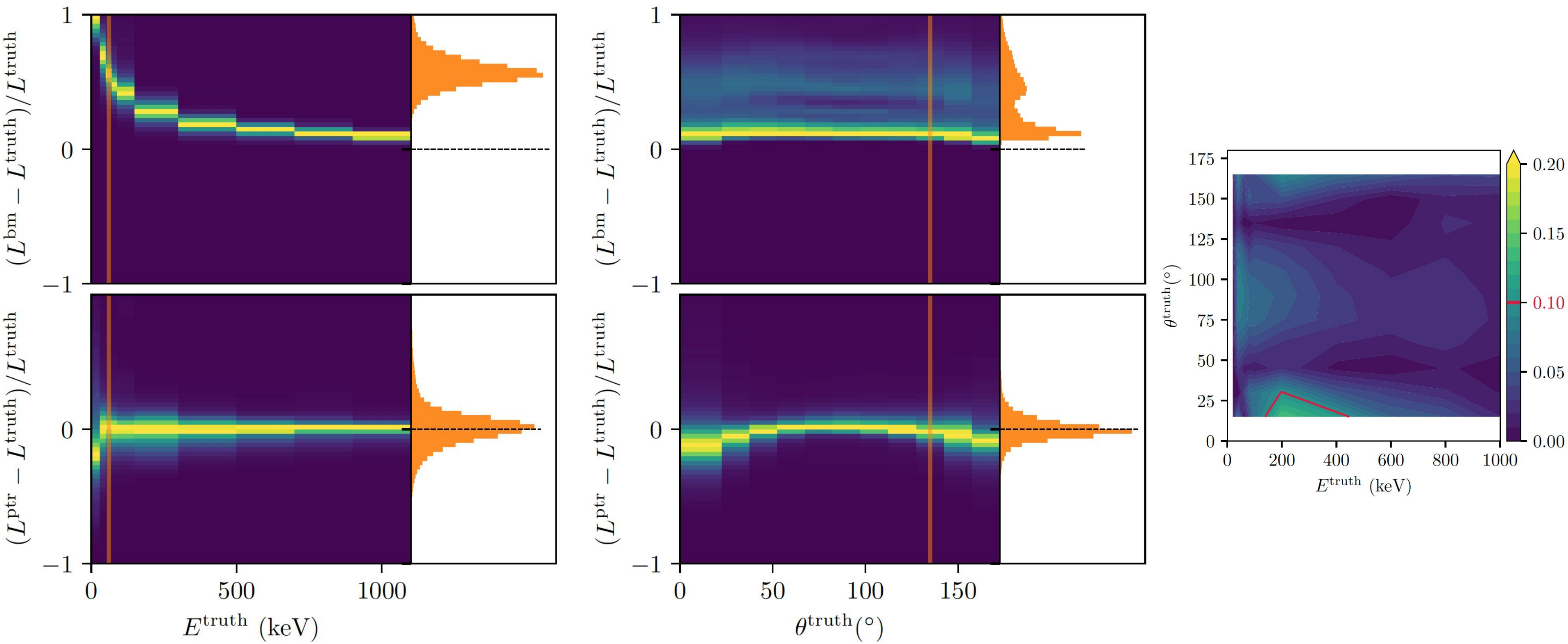


Primary track recovery

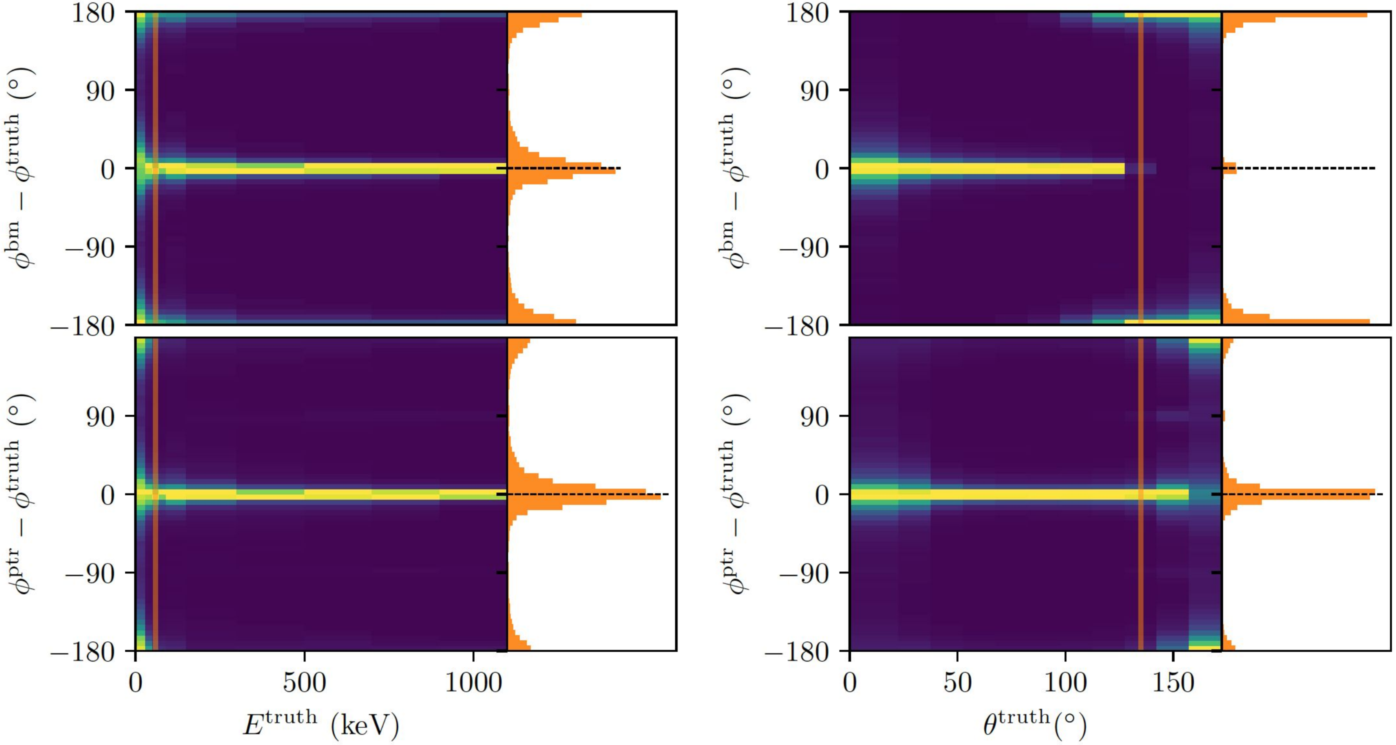


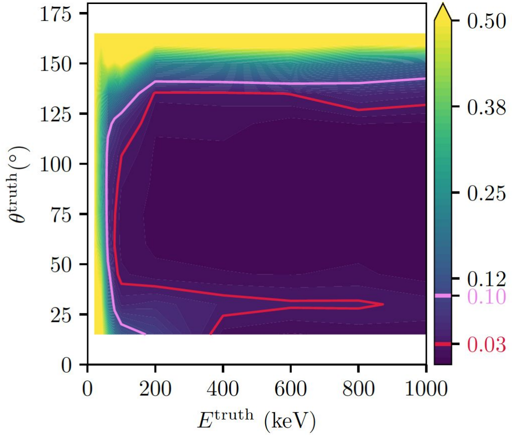


Primary track recovery

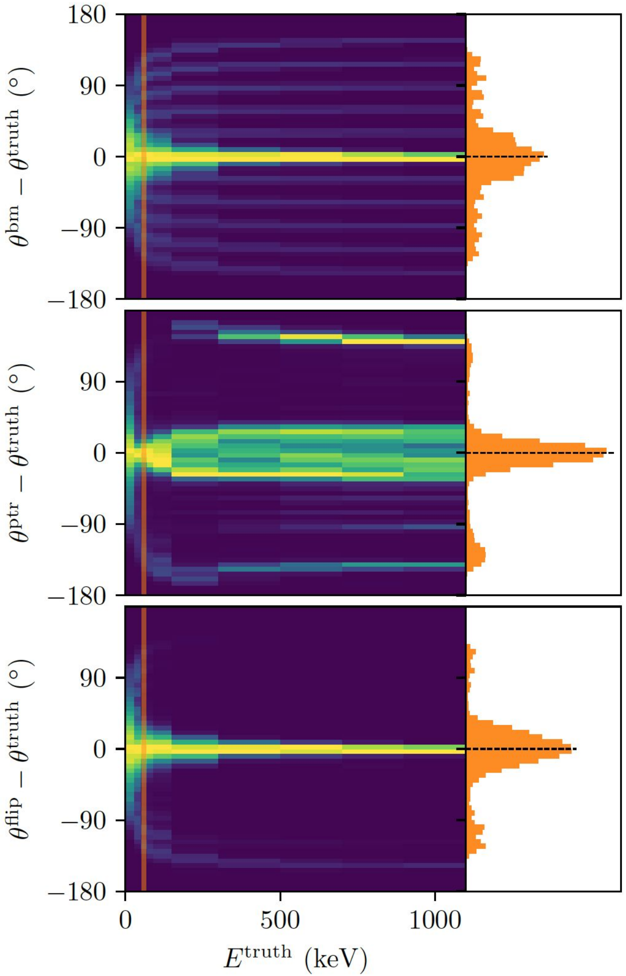


Primary track recovery





Primary track recovery



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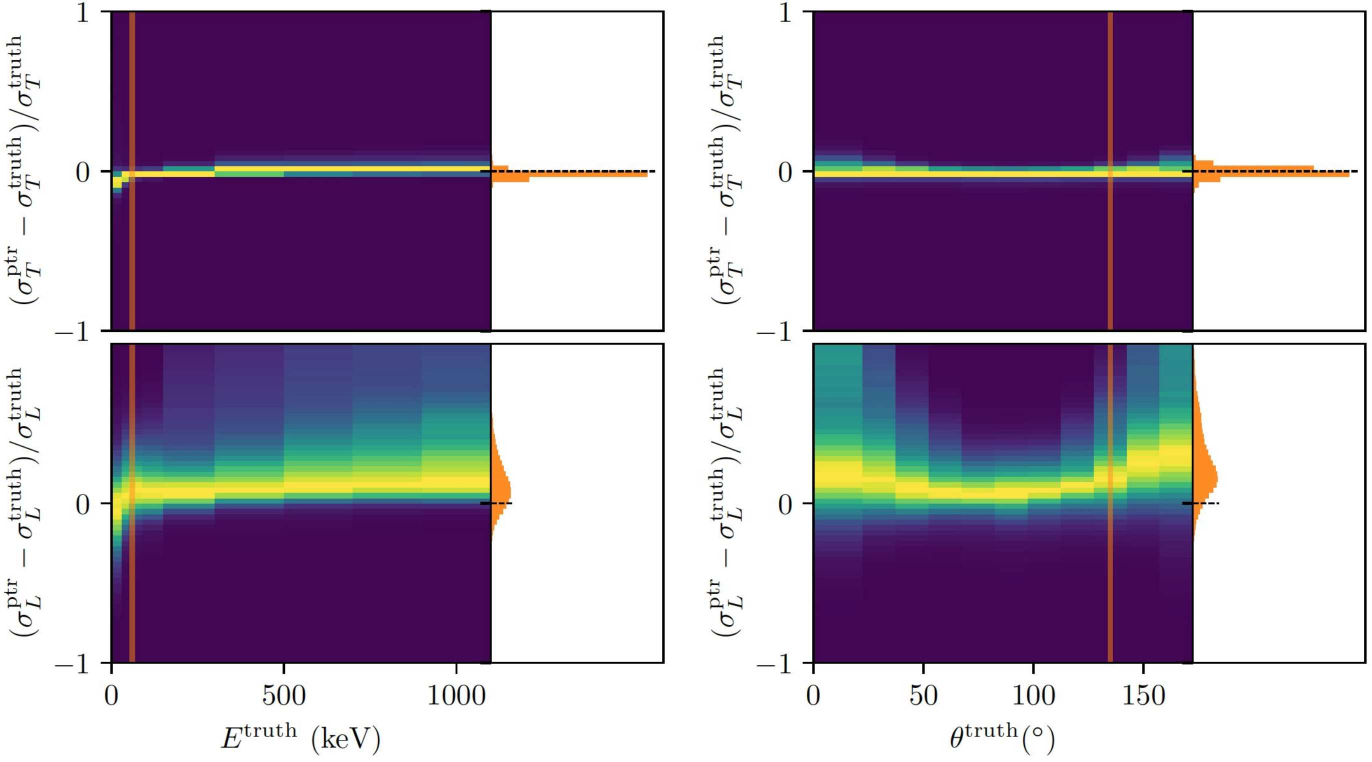
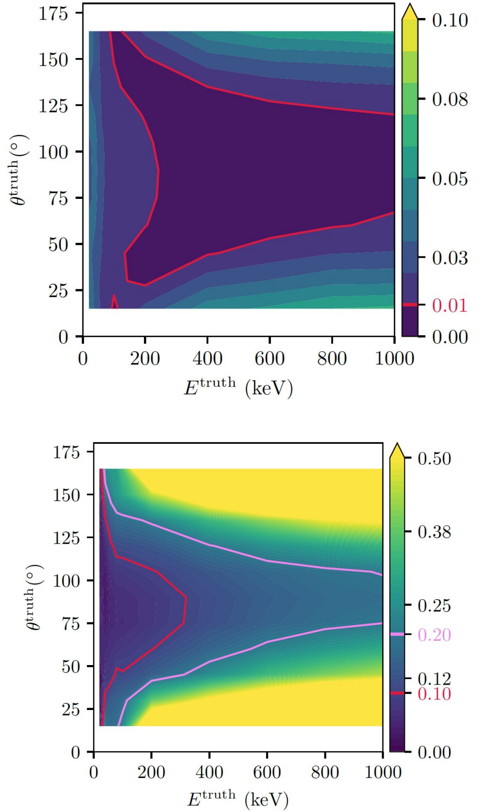
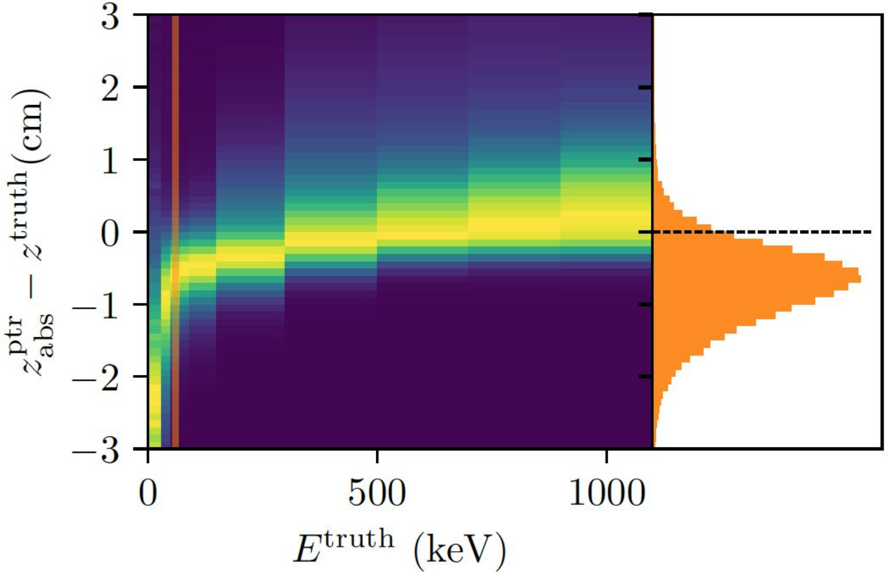
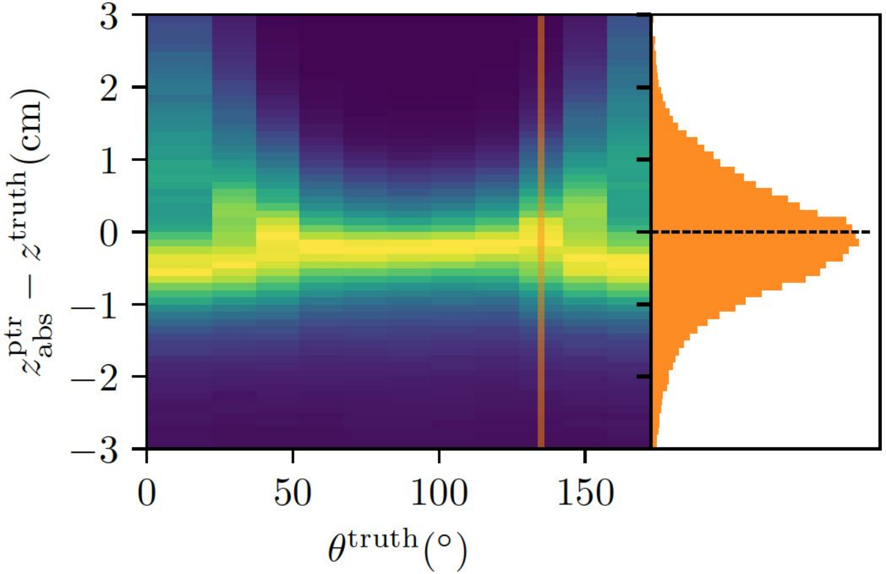
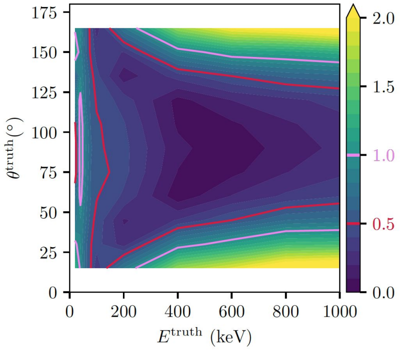


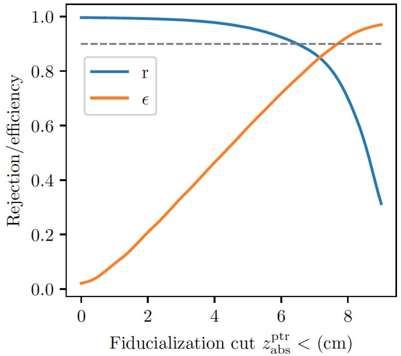


Primary track recovery









Primary track recovery