RD51 collaboration meeting

December 5th 2023

Model-assisted measurement of dE/dx in T2K's near detector High-Angle TPCs

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T2K

ND280 UPGRADE

1. Context
2. Modelization
3. Results with data

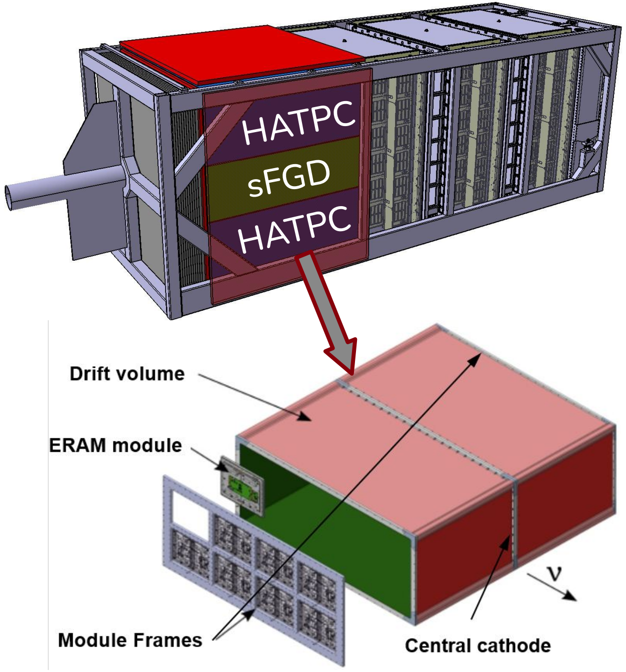
The T2K experiment

Goals

- Study ν_e appearance in ν_μ beam => need e/μ separation
- Measurement of Δm^2_{23}, θ_{23} & δ_{CP} from PMNS matrix

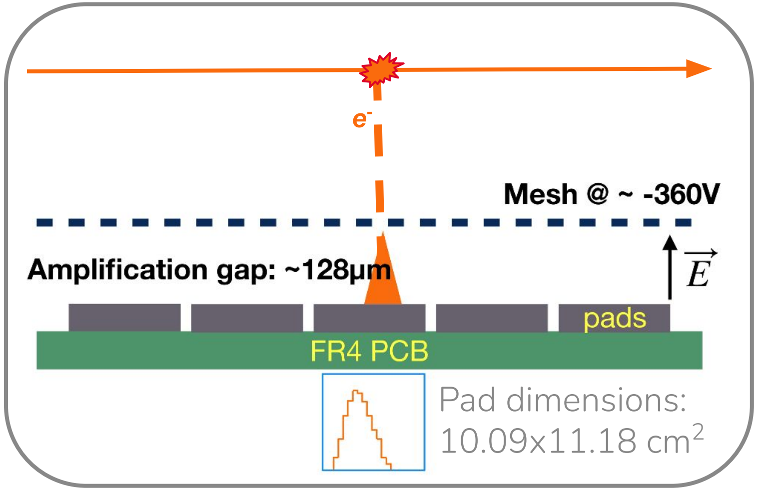
How?

- Far detector:
  - Cherenkov effect
  - 50 ktons of water
- Near detectors:
  - characterize beam
  - constrain systematics
- Upgrade ND280:
  - more active target (Super FGD)
  - 2 High-Angle TPCs (HATPCs)



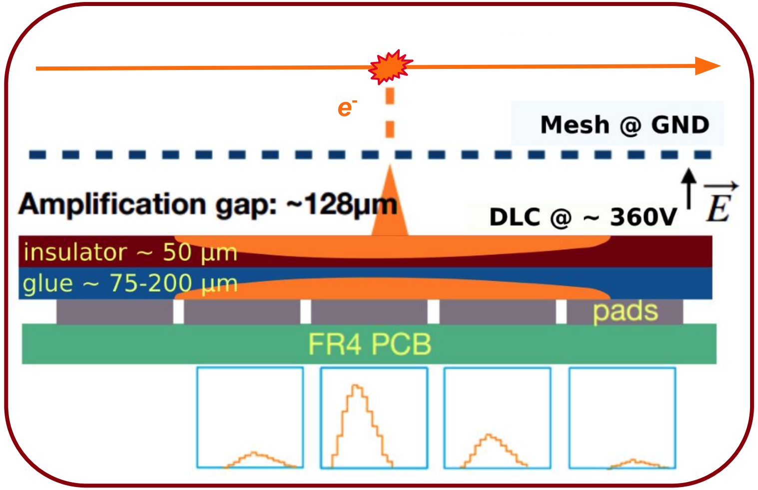
Encapsulated Resistive Anode bulk Micromegas (ERAM)

Bulk Micromegas
Metallic anode



- Spatial constraints to avoid sparks
- Precision ~ pad size
- Implemented in vertical TPCs in ND280

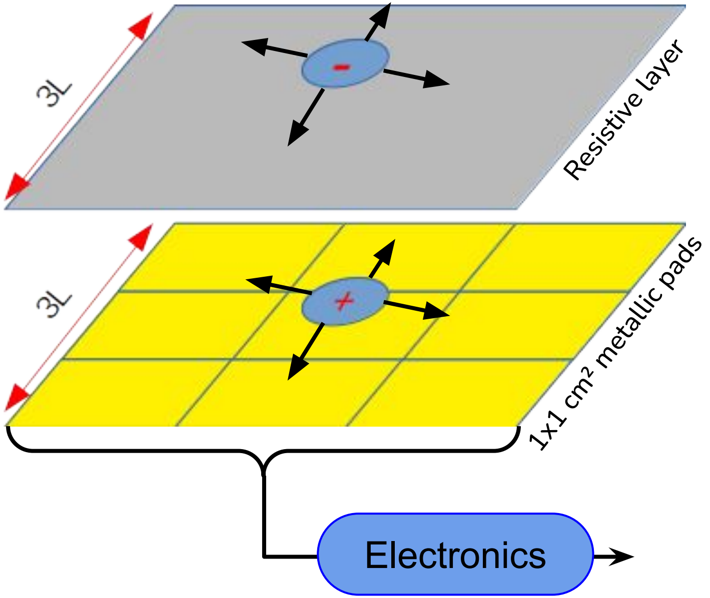
ERAM
Resistive anode



- Prevents sparks & protects the electronics
- Charge spreading gives more precise information about the charge position

➢ Sub-pad precision tracking

Converting an electronic response to a real charge

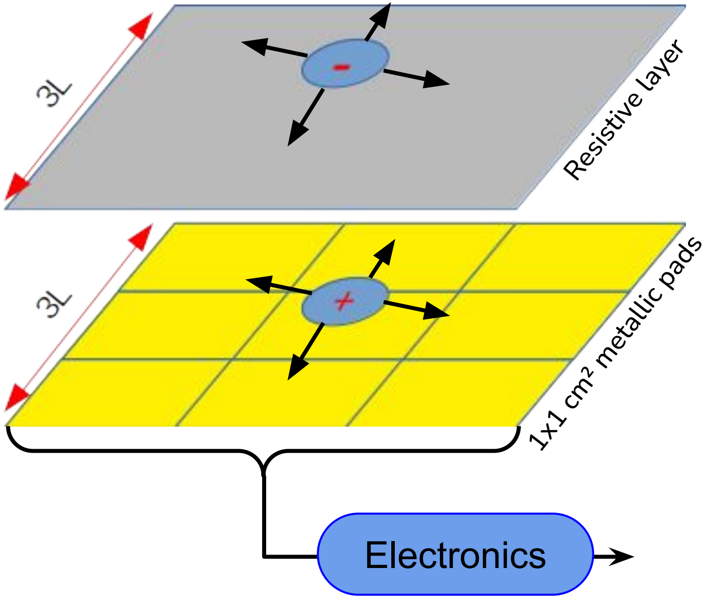


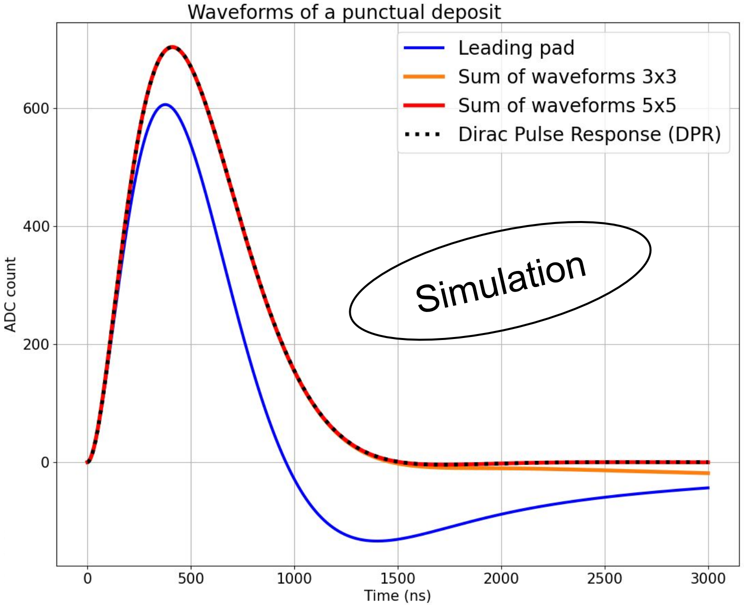
Signal in a pad:

$$S(t) = Q_{\text{pad}}(t) \otimes \frac{\mathrm{d}}{\mathrm{d}t} f_{\text{electronics}}(t)$$

- If the charge escapes the pad during the integration, it is not fully reconstructed by the recorded signal
- But we want the charge to escape, to have a better precision on the position!
- How to meet these contradictory conditions?
  - ➢ Integrate over a larger surface

Converting an electronic response to a real charge





Signal in a pad:

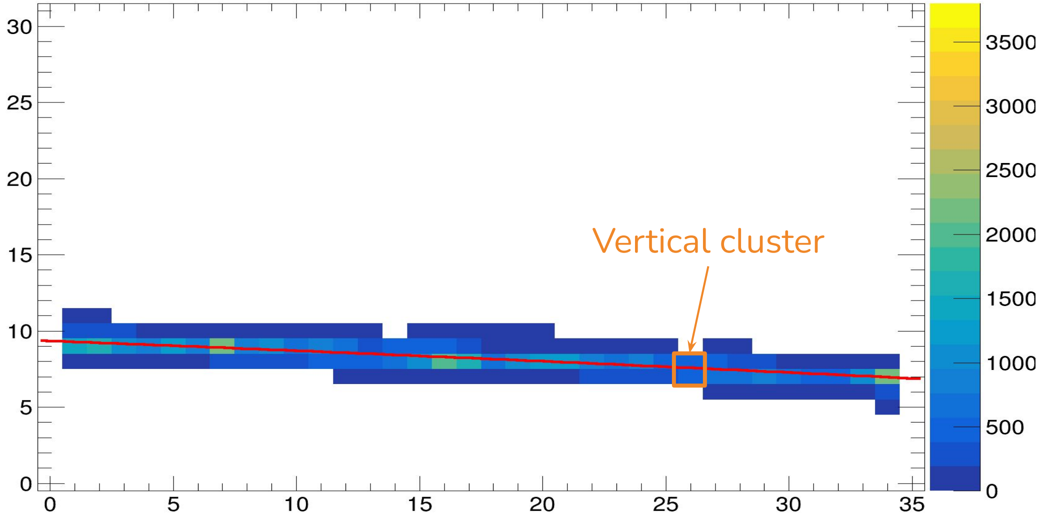
$$S(t) = Q_{\mathrm{pad}}(t) \otimes \frac{\mathrm{d}}{\mathrm{d}t} f_{\mathrm{electronics}}(t)$$

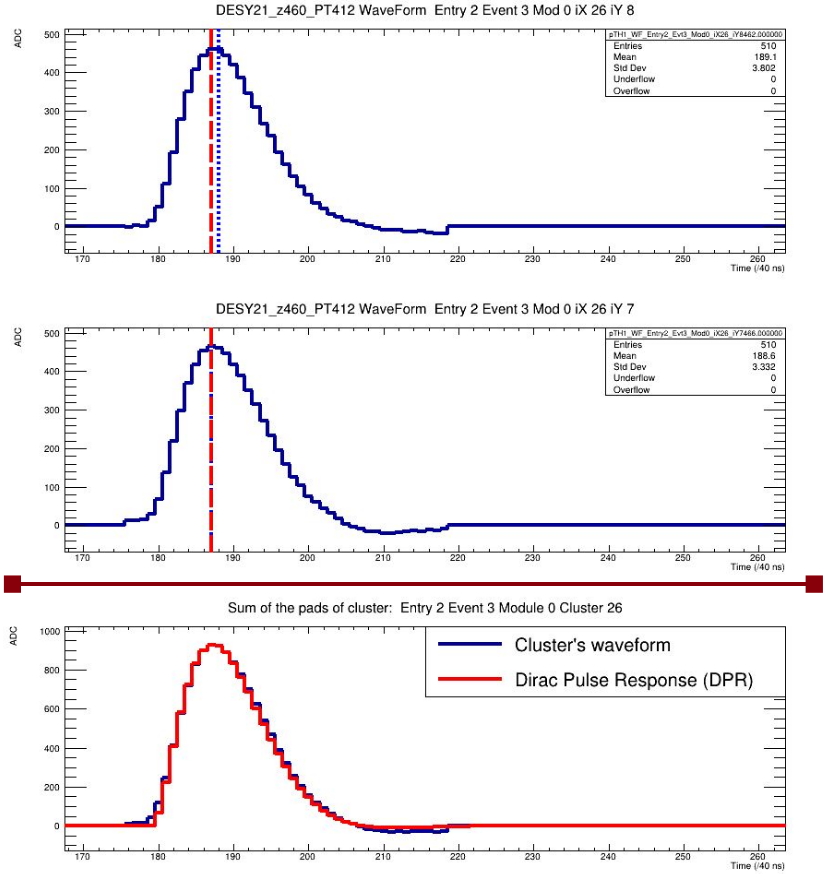
- 1 pad => unsatisfactory
- 3 pads => good
- 5 pads => excellent

dE/dx by summing waveforms: WF_{sum} method

Horizontal tracks

- Charge Q spreads as a wavefront ⊥ to the track
- Regroup pads into vertical clusters
- Good Q reconstruction

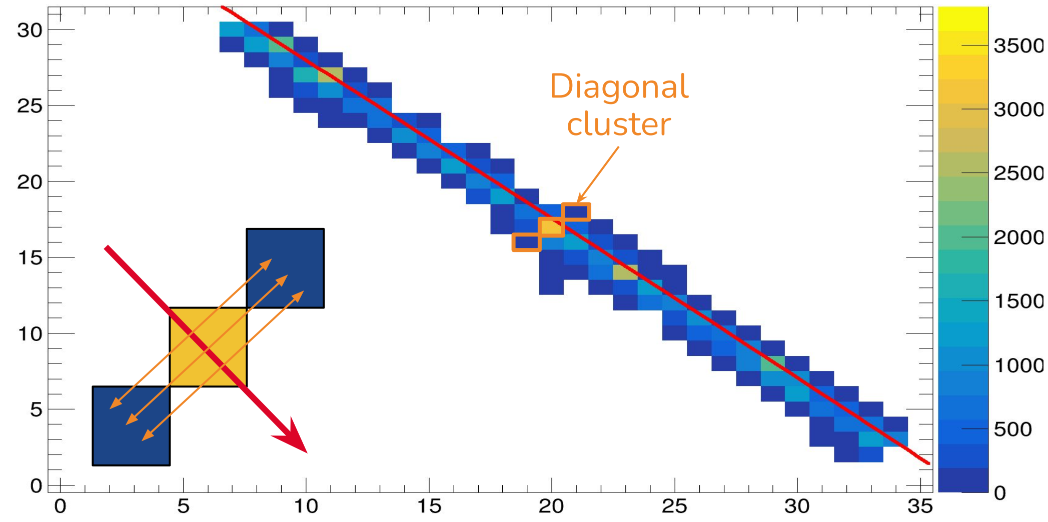


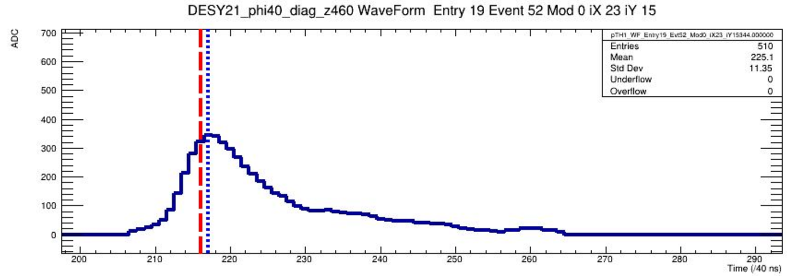


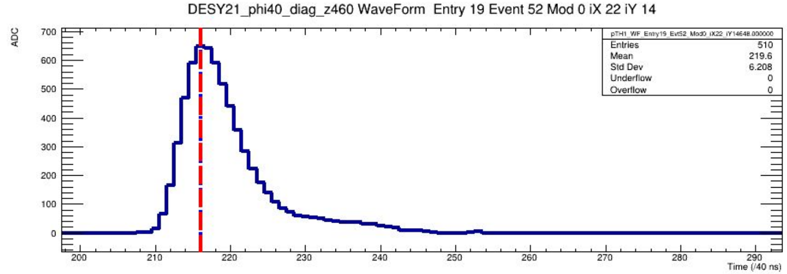
dE/dx by summing waveforms: WF_{sum} method

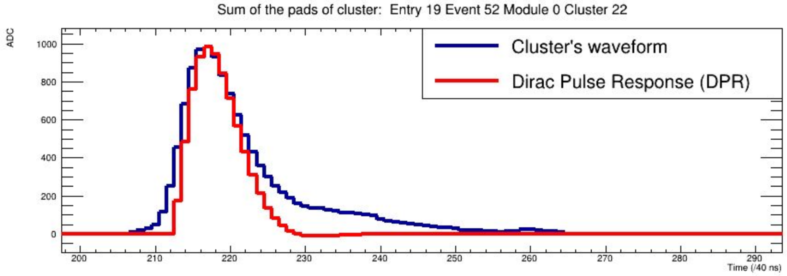
Diagonal tracks

- Charge Q spreads as a wavefront ⊥ to the track
- Regroup pads into diagonal clusters
- Poor Q reconstruction because of improper clustering









ND280 UPGRADE

Problem:

- Clustering is not trustworthy for inclined tracks (relies on too many approximations)

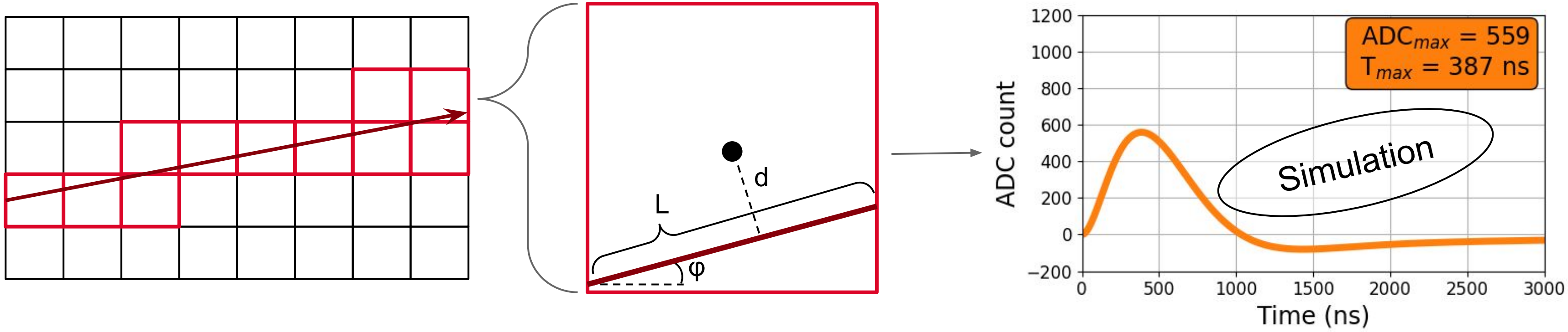
Solution:

- Modelize the detector's response
- Rely on this modelization to reconstruct the deposited charge without clusters

ND280 UPGRADE

1. Context
2. Modelization
3. Results with data

modelization: the idea



A modelization of the charge spreading allows to:

- Simulate every track configuration
- Retrieve the deposited charge in a pad just with its waveform & the track fit
- Overlook neighbour pads (i.e. not crossed by the track)

➢ dE/dx can be obtained without clusters

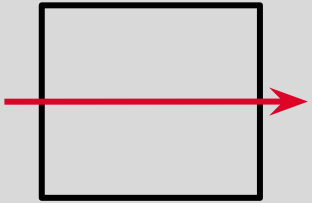
➢ Only needs A_{max}, T_{max} & track information

modelization: the mathematics

What was known:

1. Linear charge spread for horizontal track:

$$Q_{pad}(t) = \frac{\lambda}{2}[x_{\text{right}} - x_{\text{left}}]\left[\text{erf}\left(\frac{y_{\text{high}} - y_c}{\sqrt{2}\sigma(t)}\right) - \text{erf}\left(\frac{y_{\text{low}} - y_c}{\sqrt{2}\sigma(t)}\right)\right]$$



2. Pad signal depending on Q(t) and the electronics:

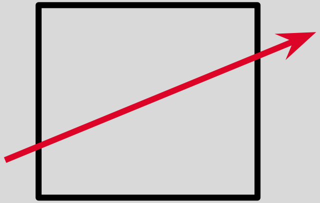
$$S(t) = Q_{\text{pad}}(t) \otimes \frac{\text{d}}{\text{d}t} f_{\text{electronics}}(t)$$

What is new: Linear charge spread for inclined tracks

$$Q_{pad}(t) = \frac{\lambda\sqrt{1+m^2}}{2m}\left(\sqrt{\frac{2(1+m^2)}{\pi}}\sigma\left(-e^{-\frac{(-c+am+q)^2}{2(1+m^2)\sigma^2}} + e^{-\frac{(-c+bm+q)^2}{2(1+m^2)\sigma^2}} + e^{-\frac{(-d+am+q)^2}{2(1+m^2)\sigma^2}} - e^{-\frac{(-d+bm+q)^2}{2(1+m^2)\sigma^2}}\right)\right.$$

$$+ (c - am - q)\,\text{Erf}\left[\frac{-c+am+q}{\sqrt{2(1+m^2)}\sigma}\right] - (d - am - q)\,\text{Erf}\left[\frac{-d+am+q}{\sqrt{2(1+m^2)}\sigma}\right]$$

$$\left. +(-c+bm+q)\,\text{Erf}\left[\frac{-c+bm+q}{\sqrt{2(1+m^2)}\sigma}\right] + (d - bm - q)\,\text{Erf}\left[\frac{-d+bm+q}{\sqrt{2(1+m^2)}\sigma}\right]\right)$$



$y = mx + q$ the track equation

$(a, b, c, d) = (x_{\text{left}}, x_{\text{right}}, y_{\text{low}}, y_{\text{high}})$

with $\sigma(t) = \sqrt{\frac{2t}{RC} + zD^2}$

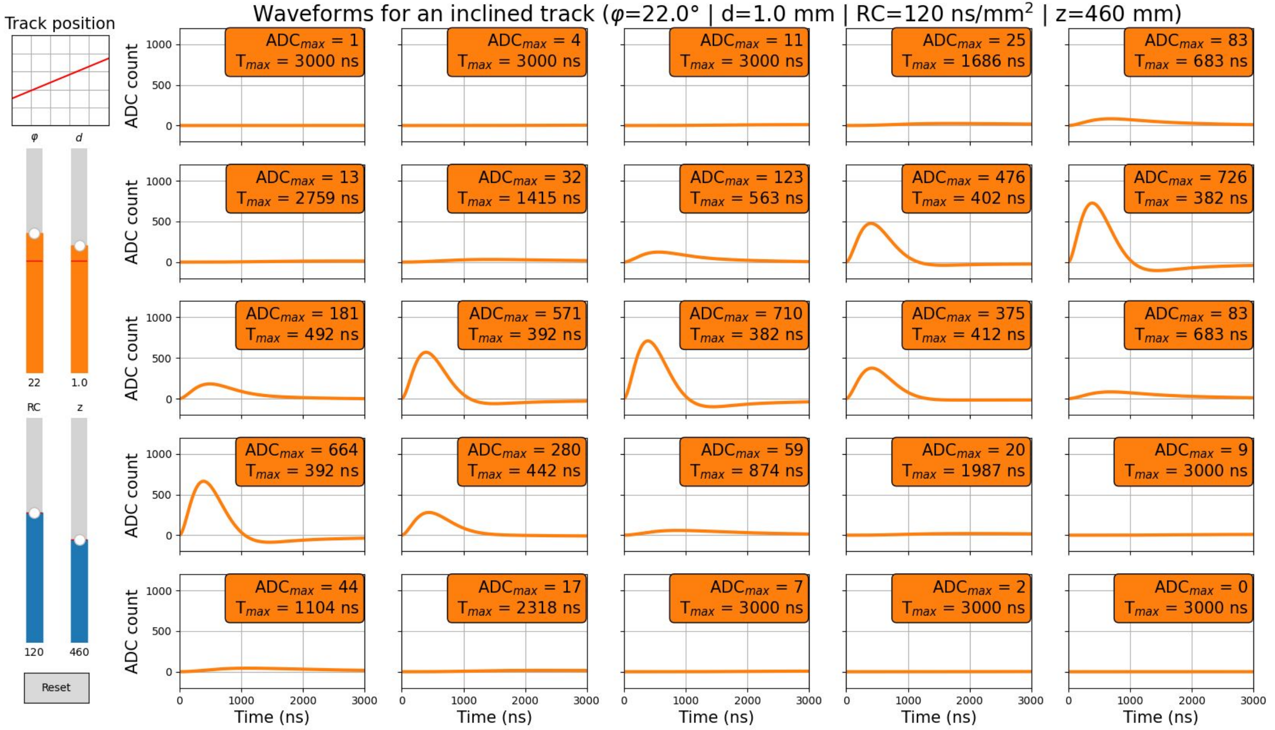
modelization: the simulation

modelization depends on:

- Track angle φ
- Impact parameter d
- Drift distance Z_{drift}
- Diffusion coefficient of the pad 1/RC

For a given configuration, a pad has:

- a real charge deposited Q_{anode}
- which corresponds to a waveform with a maximum amplitude A_{max}



➢ Store in Look-Up Tables (LUT) a scaling factor for all track configurations to retrieve Q_{anode}

modelization: the Crossed Pads (XP) method

1. Make a model of the detector
Estimate the scaling factor for all possible track configurations

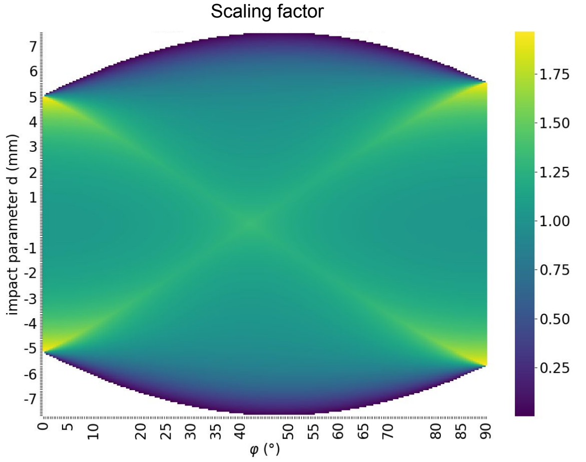
2. Get the track's fit
- List the pads crossed by the track
- Get φ, d & the length of the track L in each of them

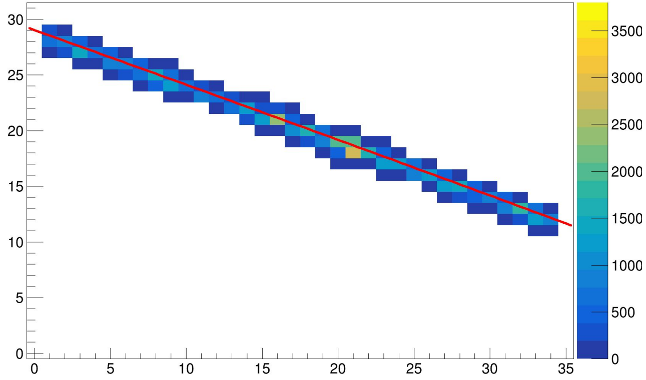
3. Reconstruct Q^{anode}
- Apply to the ADC count of each of crossed pad the ratio estimated in step 1. based on its (φ, d)
- Get a reconstructed Q^{anode} (in ADC count)

4. Truncate
- Gain equalization
- Order these pads with respect to Q^{anode}/L
- Only keep the 70% lowest

5. Get a dE/dx estimator
Sum the Q^{anode} & divide it by the sum of L

4D Lookup Tables (LUTs) :
1. Impact parameter d
2. Angle φ
3. Drift distance Z_{drift}
4. RC





modelization: the Crossed Pads (XP) method

1. Make a model of the detector

Estimate the ratio Q^{anod}…

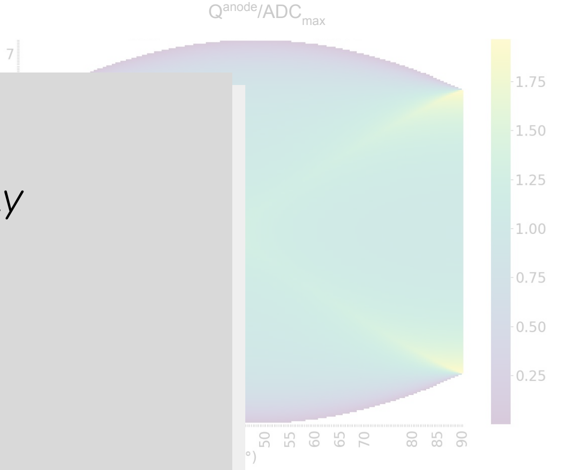
for all possible track con…

What is used:

- A_{max} & T_{max} of the pads crossed by the track *only*
- The track fit
- The modelization of the detector response

What is not used:

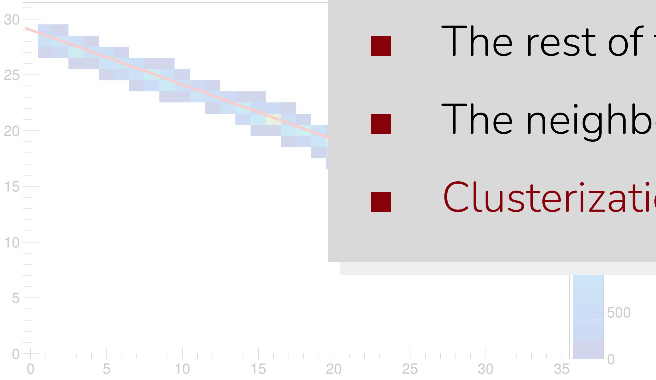
- The rest of the waveform of crossed pads
- The neighbour pads (i.e. not crossed by the track)
- Clusterization



Q^{anode}/L

…dE/dx estimator

Sum the Q^{anode} & divide it by the sum of L



T2K ND280 UPGRADE

1. Context
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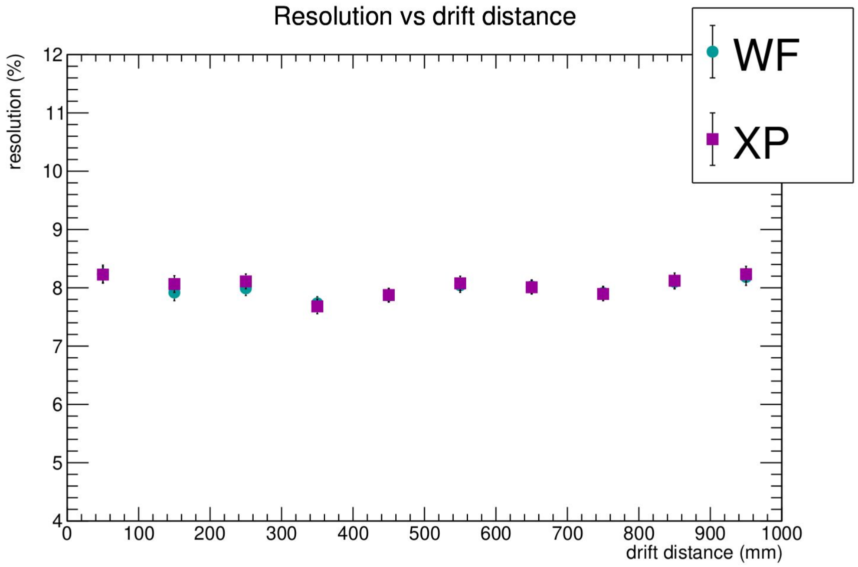
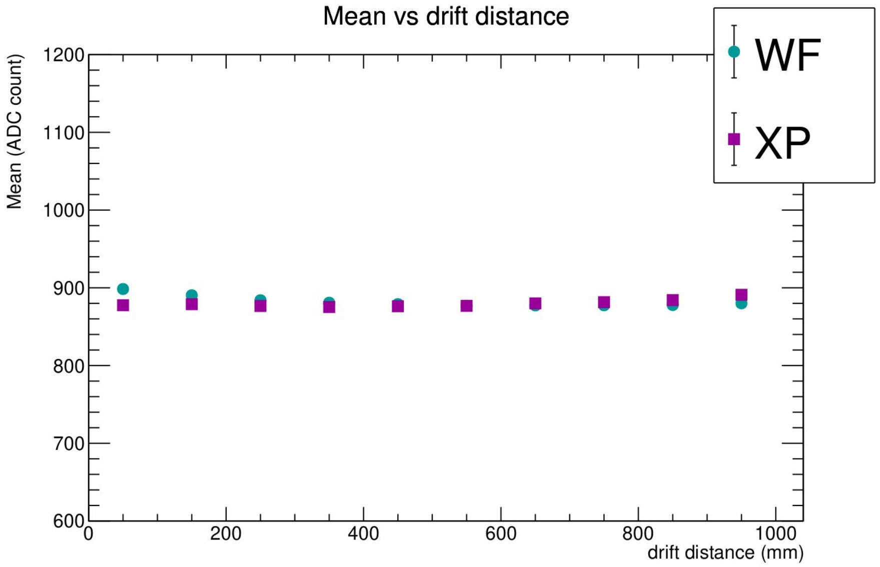
3. Results with data

Drift distance scan (test beam e^- 4 GeV @ DESY)

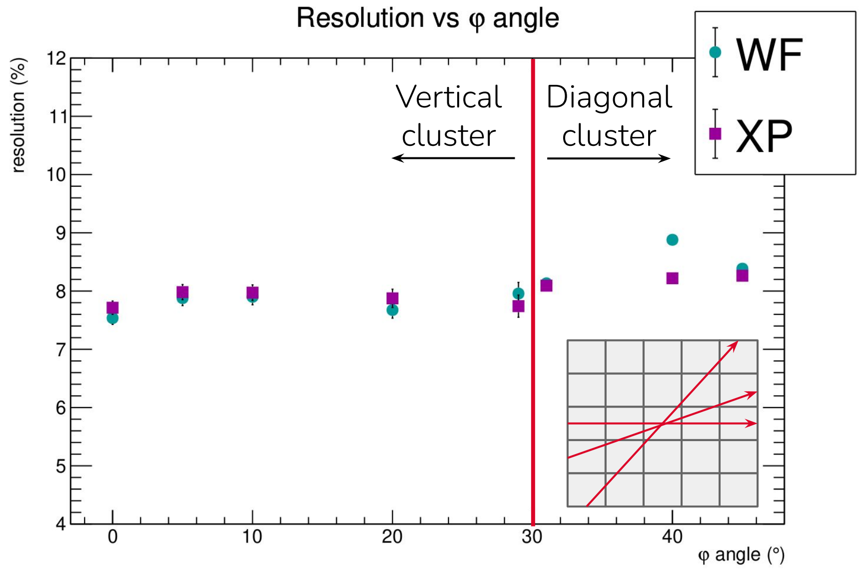


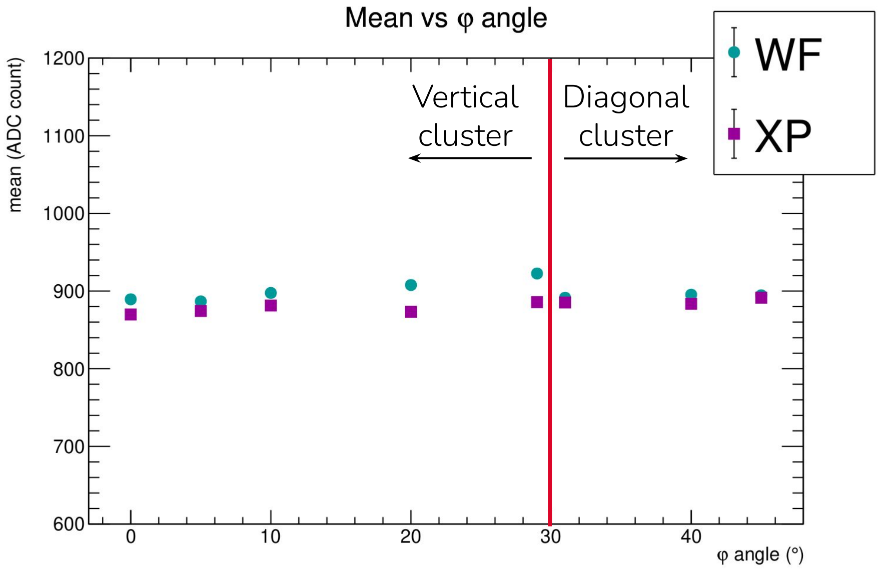


- Horizontal tracks
- Resolution σ/μ ~ 8% and stable
- Methods are almost indistinguishable

- Rather flat distribution for both methods
- Shows consistency of WF_{sum} & XP with horizontal tracks

Angle scan (test beam e⁻ 4 GeV @ DESY)

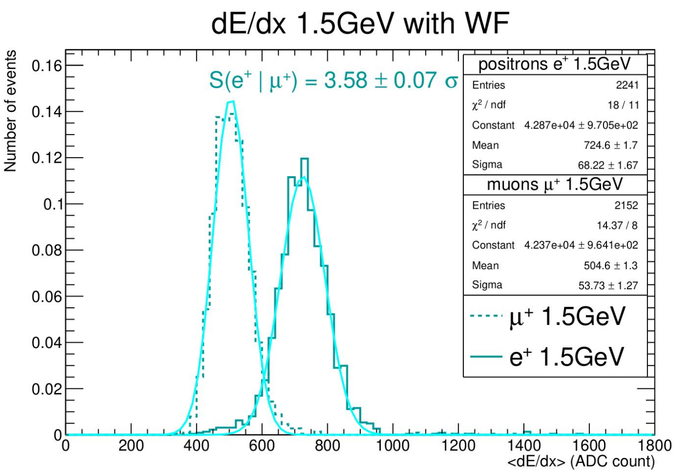


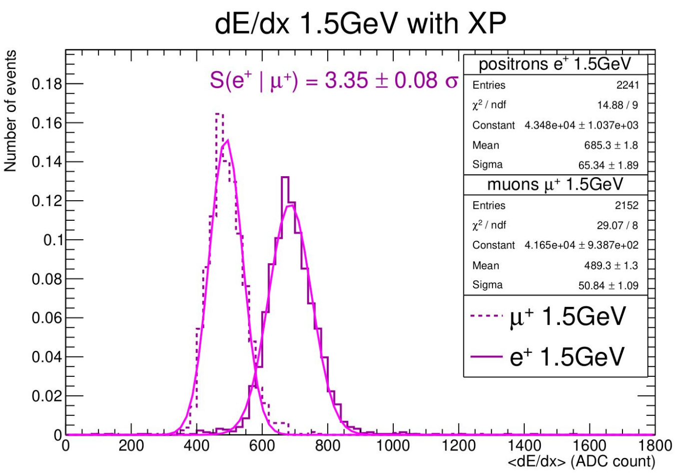


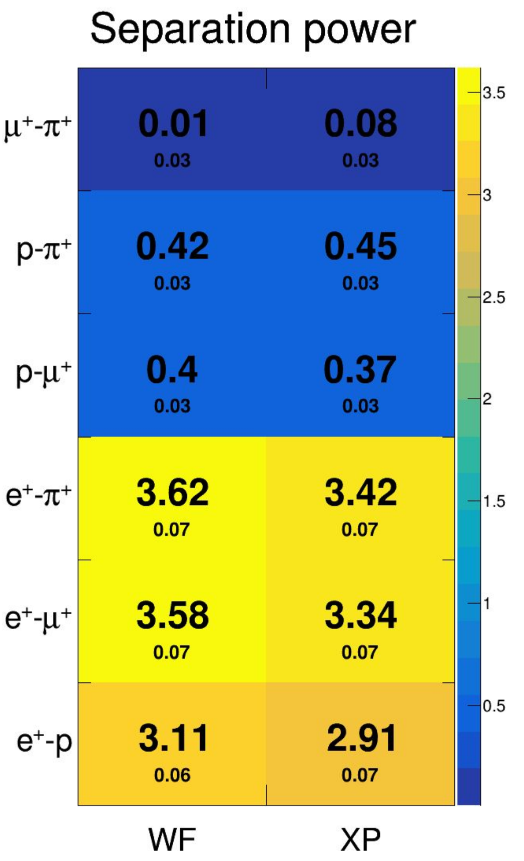
- Inclined tracks
- Resolution σ/μ ~ 8% and stable
- XP gives better results at high angle

- XP is remarkably constant across φ
- WF_{sum} needs an *ad hoc* parameterized correction to achieve a relative dE/dx flatness

Separation power with 1 detector (1.5 GeV @ CERN)



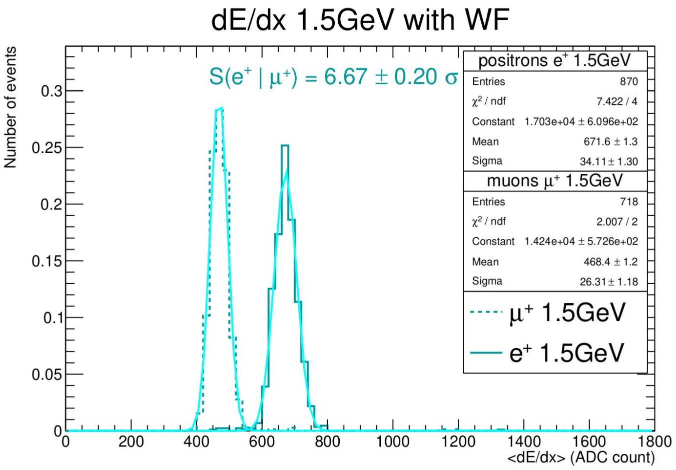


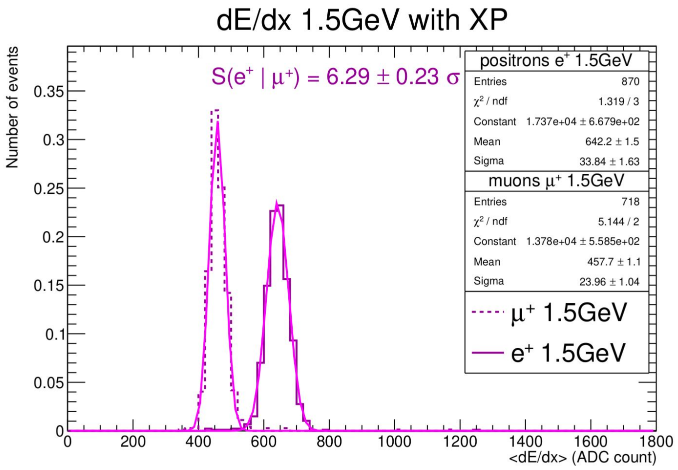


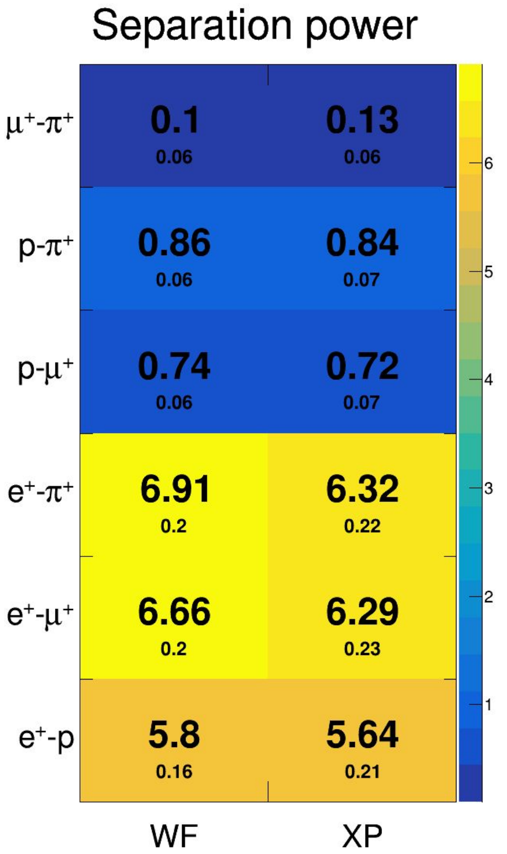
- μ^+ & e^+ split by more than 3σ
- Expect P ~ 0.5 GeV in Japan

$$S(e^+,\mu^+) = \frac{|\mu_{e^+} - \mu_{\mu^+}|}{\sqrt{\left(\sigma^2_{e^+} + \sigma^2_{\mu^+}\right)/2}}$$

Separation power with 4 detectors (1.5 GeV @ CERN)



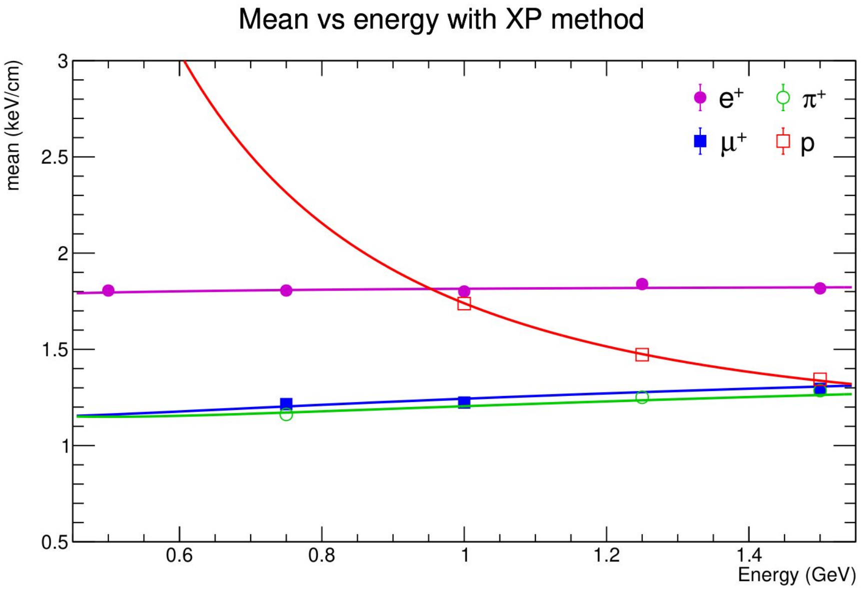


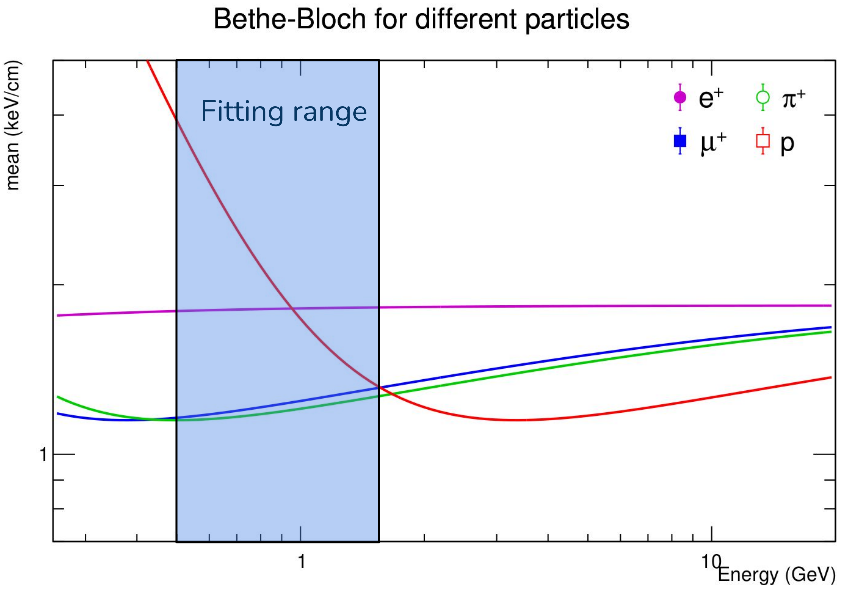


- μ^+ & e^+ split by more than 6σ
- Tracks will not fully cross 4 detectors so the effective separation power will be lower

$$S(e^+,\mu^+) = \frac{|\mu_{e^+} - \mu_{\mu^+}|}{\sqrt{\left(\sigma^2_{e^+} + \sigma^2_{\mu^+}\right)/2}}$$

dE/dx & Bethe-Bloch curve with 4 detectors (@ CERN)





$$\left\langle -\frac{dE}{dx} \right\rangle = \frac{\mathrm{P1}}{\beta^{\mathrm{P4}}} \left[\mathrm{P2} - \beta^{\mathrm{P4}} - \ln\left(\mathrm{P3} + [\beta\gamma]^{\mathrm{P5}} \right) \right]$$

https://doi.org/10.1007/978-3-540-76684-1

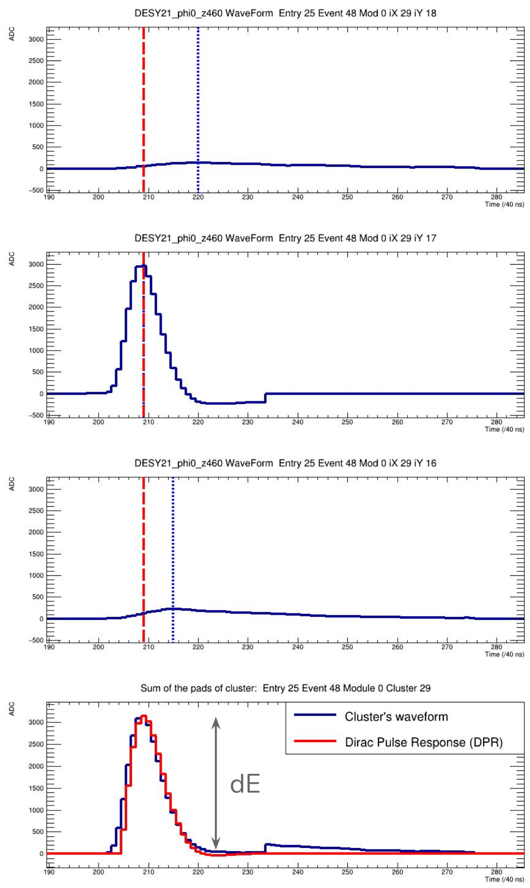
- Particles datasets are coherent with each other
- Values (keV/cm) & fit extrapolation match expectations

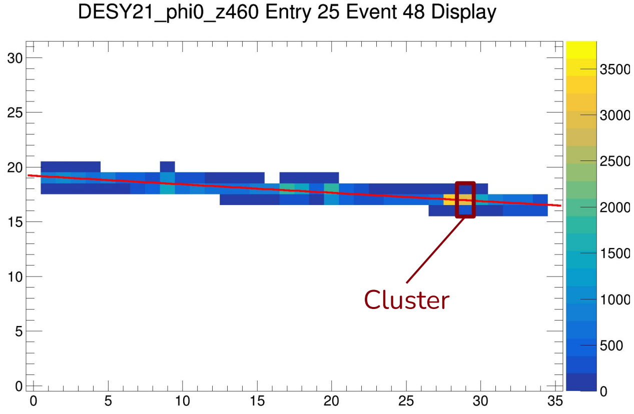
ND280 UPGRADE

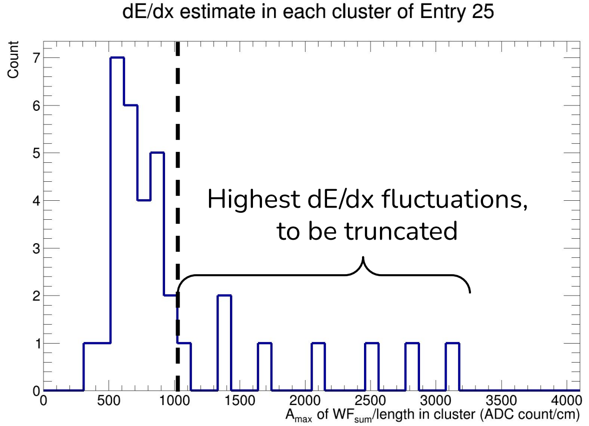
CONCLUSIONS

- A new dE/dx method to overcome clustering issues in presence of charge sharing has been developed
  - Based on a modelization of the ERAM response
  - Demonstrates our complete understanding of the detector
- dE/dx:
  - Resolution as good as the previous method
  - More consistent values for inclined tracks
- XP will now be implemented in the ND280 reconstruction software

Current dE/dx method: sum of waveforms in a cluster WF_{sum}







1. Clusterize the pads into slices and sum the waveforms in each slice to get dE

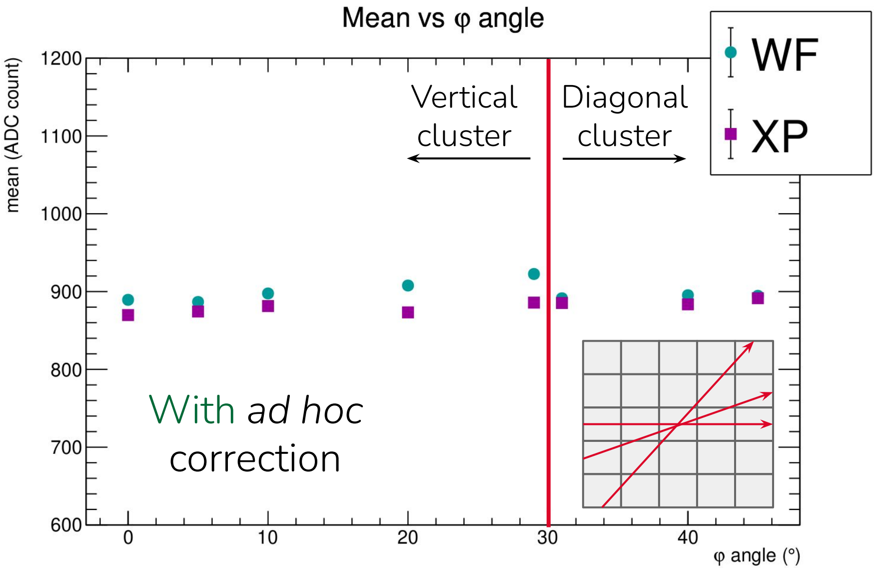
Step modified in the new method

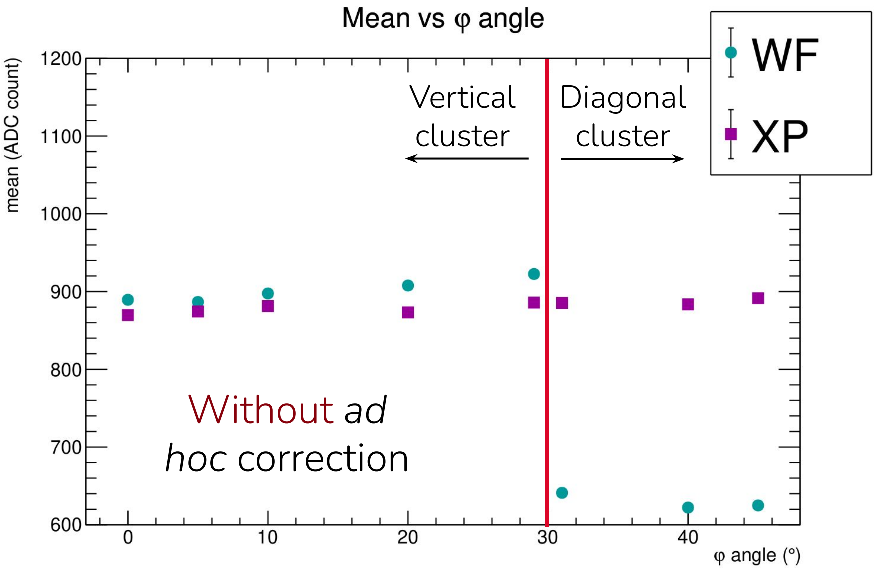
2. Get the track length in each cluster to get dX

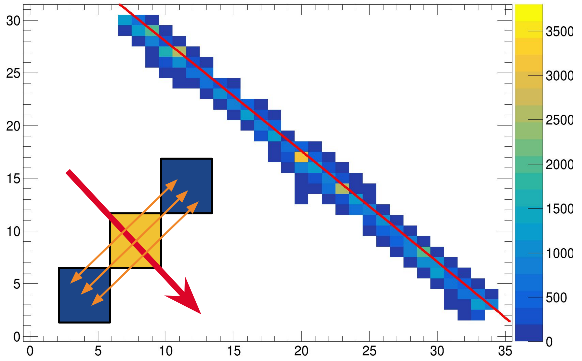
3. Truncate the clusters with the highest dE/dx (top 30%) to get rid of fluctuations

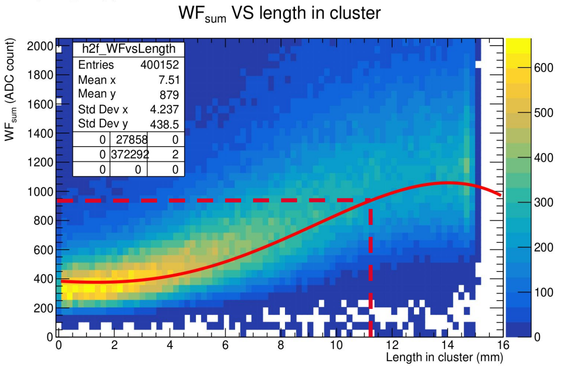
4. Get the mean over remaining estimates dE/dx

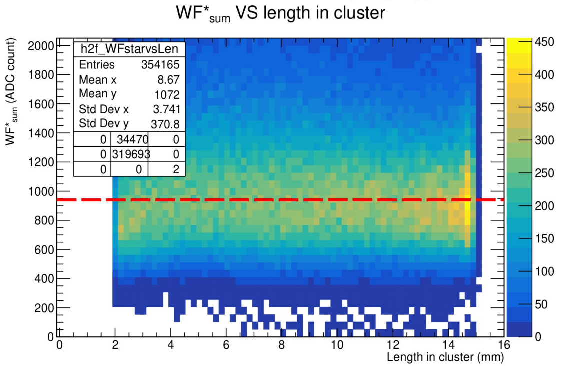
WF_{sum} *ad hoc* mean correction











modelization: complete mathematics

1) **1D linear charge** function in a pad for a linear track, parametrized with an angle φ & an impact parameter d:

$$Q_{pad}(t) = \frac{\lambda\sqrt{1+m^2}}{2m}\left(\sqrt{\frac{2(1+m^2)}{\pi}}\sigma\left(-e^{-\frac{(-c+am+q)^2}{2(1+m^2)\sigma^2}} + e^{-\frac{(-c+bm+q)^2}{2(1+m^2)\sigma^2}} + e^{-\frac{(-d+am+q)^2}{2(1+m^2)\sigma^2}} - e^{-\frac{(-d+bm+q)^2}{2(1+m^2)\sigma^2}}\right)\right.$$
$$+ (c-am-q)\,\mathrm{Erf}\left[\frac{-c+am+q}{\sqrt{2(1+m^2)}\sigma}\right] - (d-am-q)\,\mathrm{Erf}\left[\frac{-d+am+q}{\sqrt{2(1+m^2)}\sigma}\right]$$
$$\left. +(-c+bm+q)\,\mathrm{Erf}\left[\frac{-c+bm+q}{\sqrt{2(1+m^2)}\sigma}\right] + (d-bm-q)\,\mathrm{Erf}\left[\frac{-d+bm+q}{\sqrt{2(1+m^2)}\sigma}\right]\right)$$

$y = mx + q$ the track equation
$(a,\, b,\, c,\, d)$ borders of the pad

with $\sigma(t) = \sqrt{\frac{2t}{RC} + zD^2}$

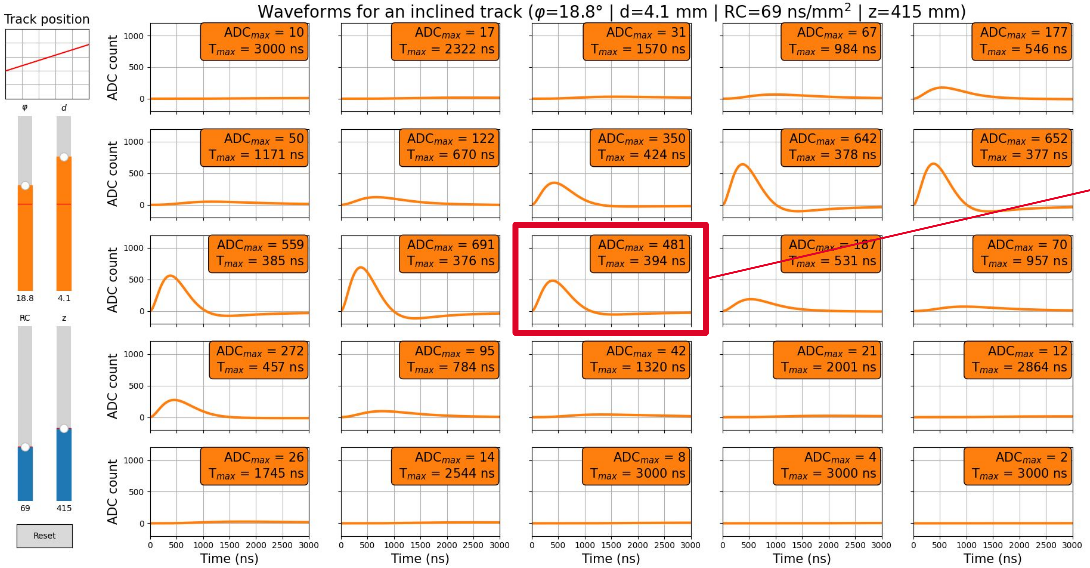
2) **Electronics** function depending on two parameters Q & w_s:

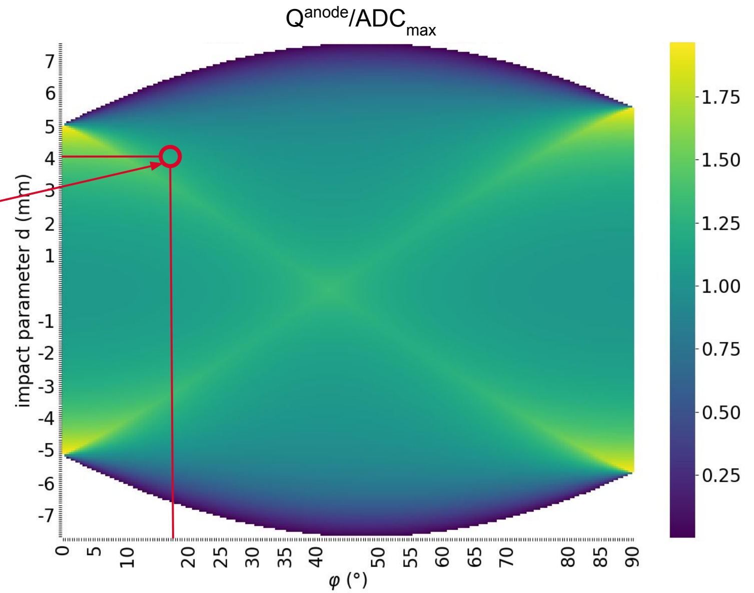
$$ADC_{\text{Dirac}}(t) = \frac{4096}{120fC}\frac{F(t)}{F^{Max}} \text{ with } F(t) = e^{-w_s t} + e^{-\frac{w_s t}{2Q}}\left(\sqrt{\frac{2Q-1}{2Q+1}}\sin\left(\frac{w_s t}{2}\sqrt{4-\frac{1}{Q^2}}\right) - \cos\left(\frac{w_s t}{2}\sqrt{4-\frac{1}{Q^2}}\right)\right)$$

3) Finally, do the **convolution** of the derivative of the charge & the electronics:

$$ADC(t) = \frac{dQ}{dt} \otimes ADC_{\text{Dirac}}$$

modelization: filling the LUTs





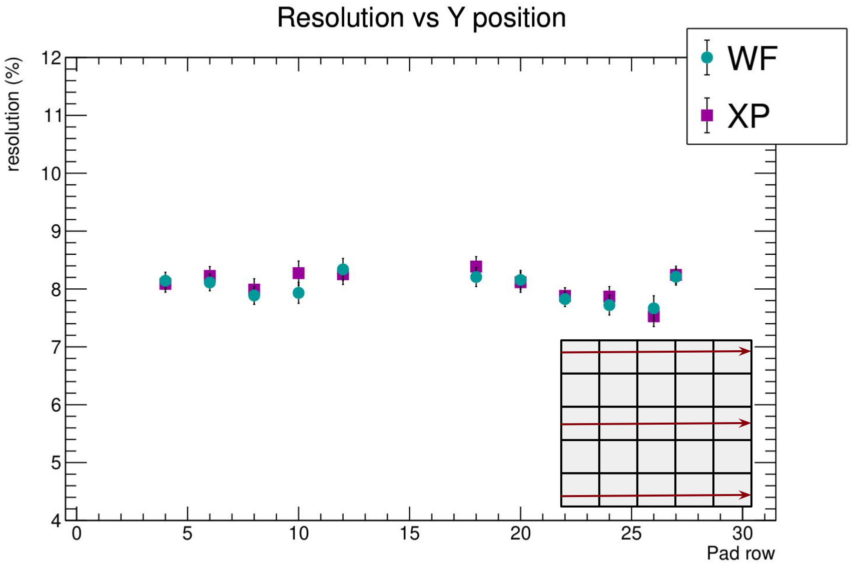
- Based on 1D linear deposit model
- Charge ⊗ Electronics
- Physical characteristics: RC, transverse diffusion, charge sharing

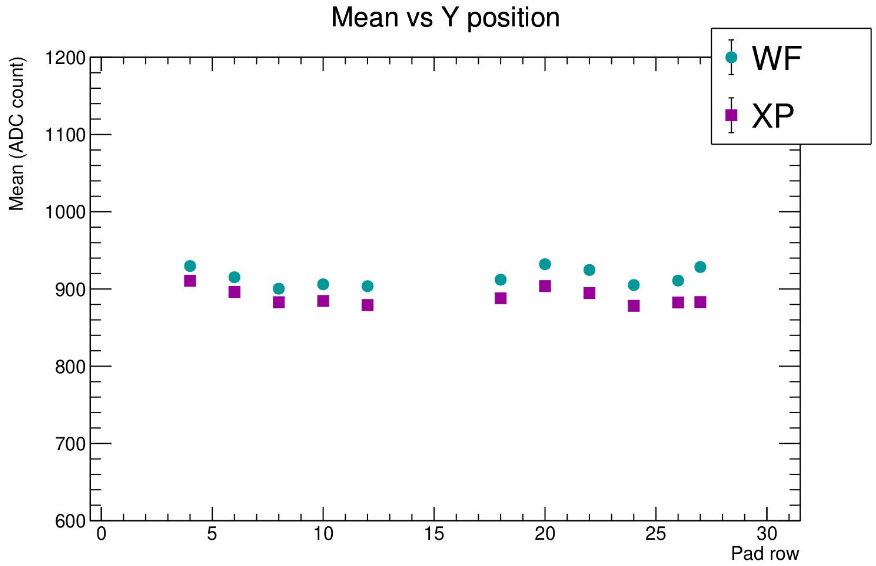
Goal: Resolution < 10% & stable mean

4D Look-Up Table (**LUT**):

- Angle **φ**: 200 steps [0°, 90°]
- Impact parameter: 200 steps [-7.3, +7.3] mm
- Drift distance: 21 steps [0, 1] m
- RC: 21 steps [50, 150] ns/mm²

Row scan (test beam e⁻ 4 GeV @ DESY)

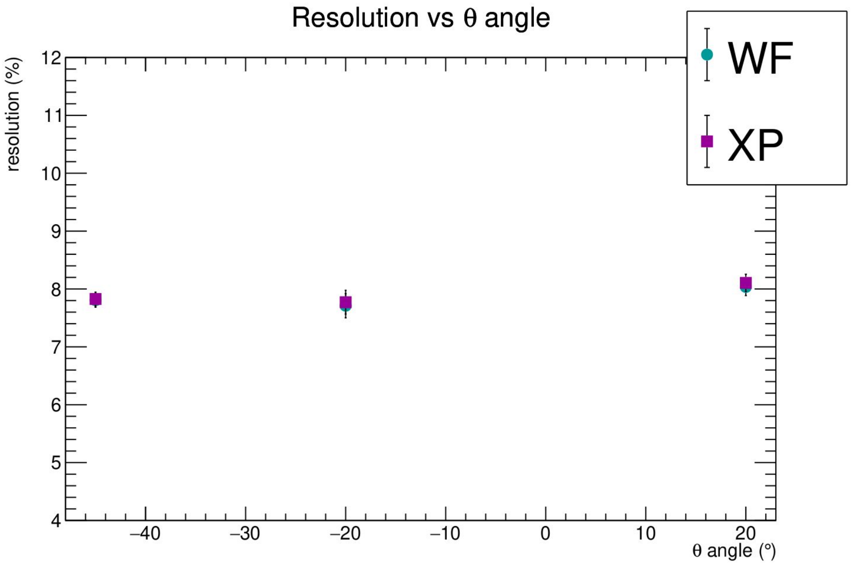


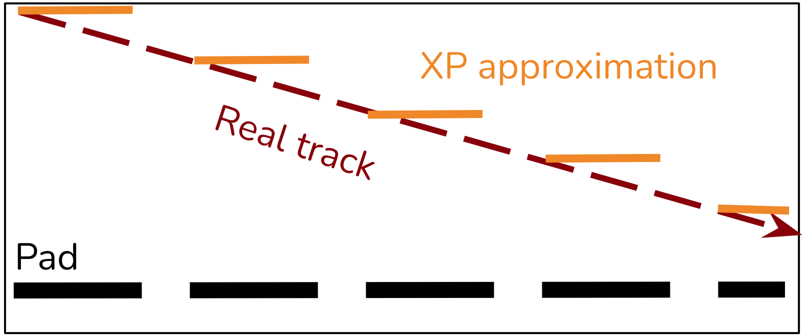


- horizontal tracks over different pad rows
- Resolution σ/μ ~ 8%
- Similar results with XP or WF_{sum}

- XP is quite constant
- Mean difference can come from the track fitting quality at low drift distance

Theta angle (test beam e^- 4 GeV @ DESY)

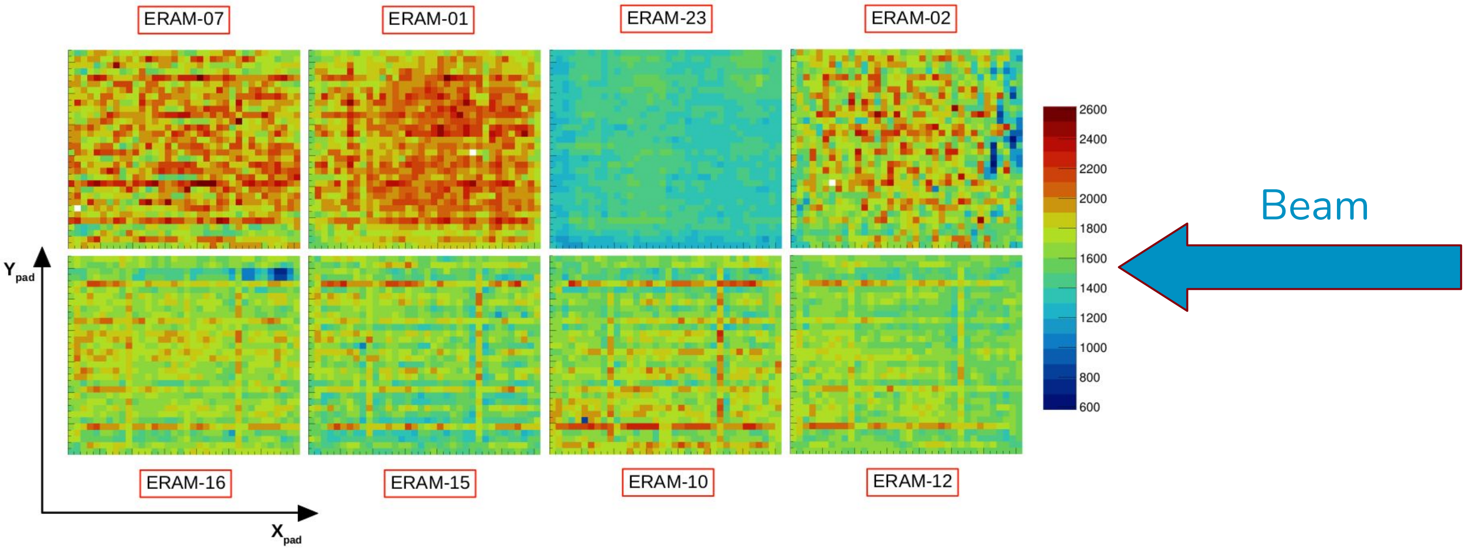




- Tracks inclined towards the ERAMs
- Resolution σ/μ ~ 8%
- Similar results with XP or WF_{sum}

- WF_{sum} has no procedure to handle such tracks
- XP does not directly include theta dependency either
- Can do a reasonable approximation for XP with a “staircase” description

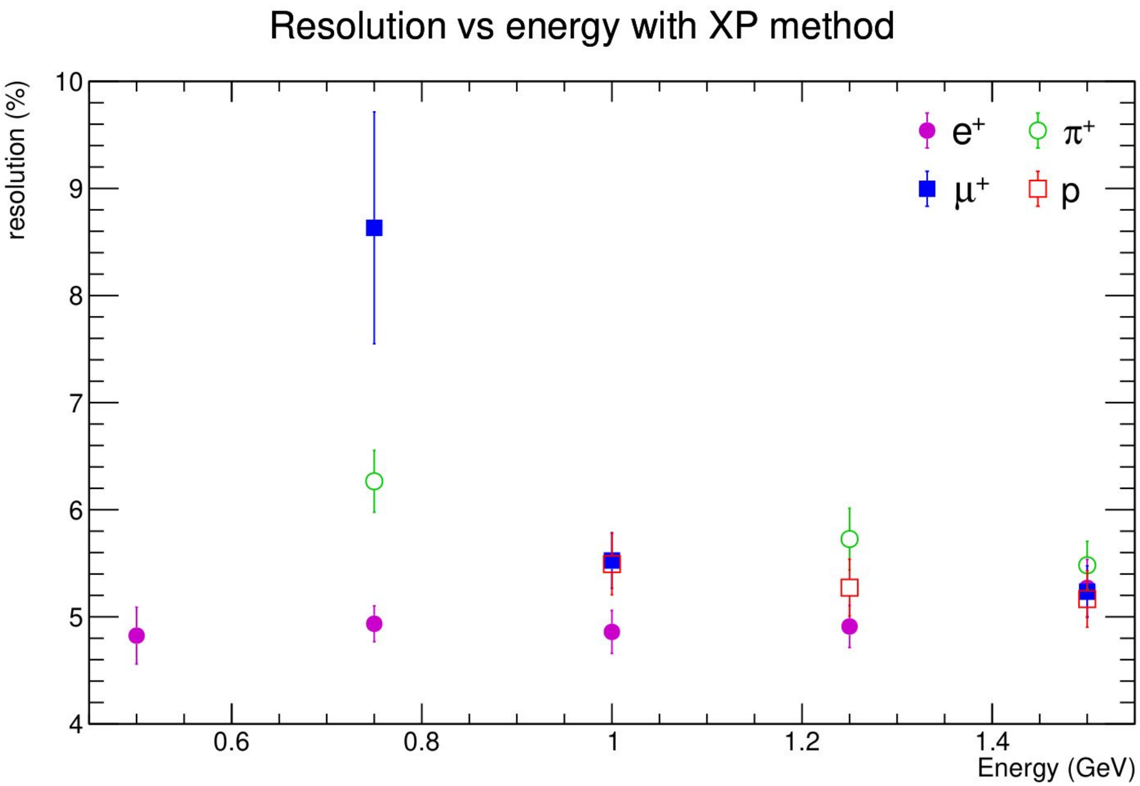
CERN22: Mockup gain maps



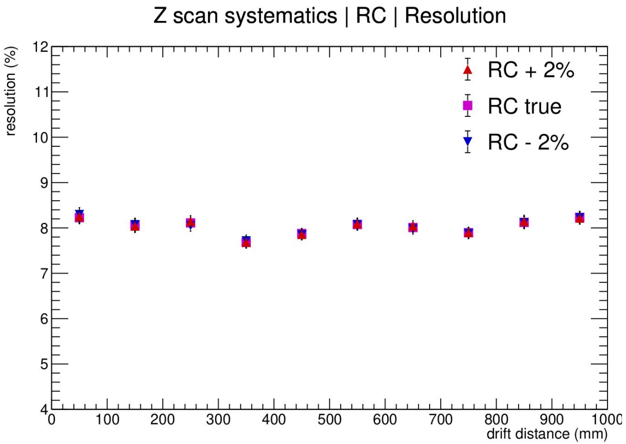
- Truncation across 4 ERAMs requires gain equalisation.
  - Especially because of ERAM23.
- Equalisation done by getting the average gain value across the 4 ERAMs and use it as a scaling factor.

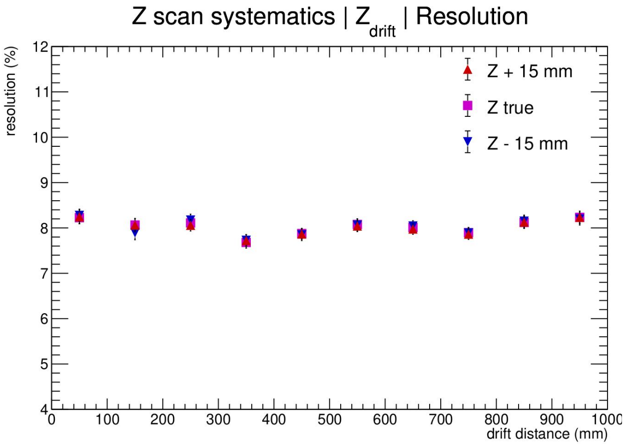
Energy scan with 4 detectors (CERN22)

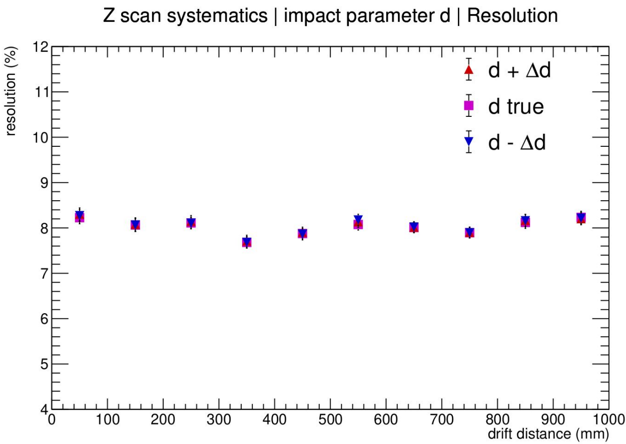
- Resolution < 6.5% (except low stat)
- e^+ stable < 5%
- Satisfies ND280 upgrade requirements



XP systematics - drift distance scan - resolution







RC:

- ΔRC ~ 2% (Shivam's fits)
- Induced systematics < 0.1%
- Constant effect ∀ Z_{drift}

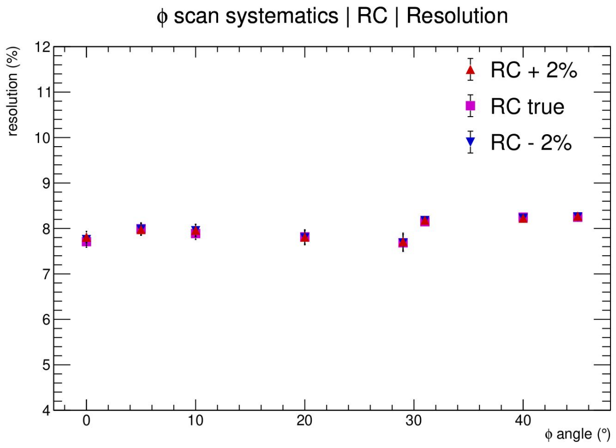
Drift distance:

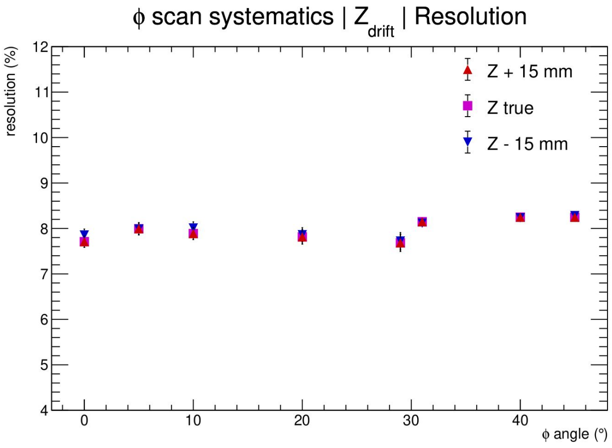
- ΔZ_{drift} ~ 1.5 cm
  - Beam extension ~ 8 mm
  - ΔT_{max} ~ 8 mm
- Induced systematics < 0.1%
- Constant effect ∀ Z_{drift}

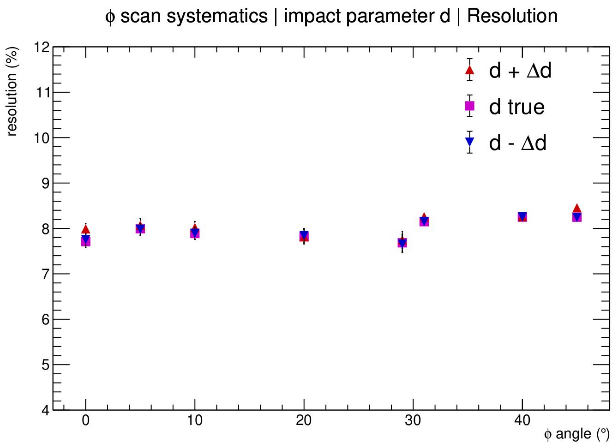
Impact parameter d:

- Δd varies between 0 & 250 μm
- Induced systematics ~0.1%
- Constant effect ∀ Z_{drift}

XP systematics - φ scan - resolution







RC:

- ΔRC ~ 2% (Shivam's fits)
- Induced systematics < 0.1%
- Constant effect ∀ φ

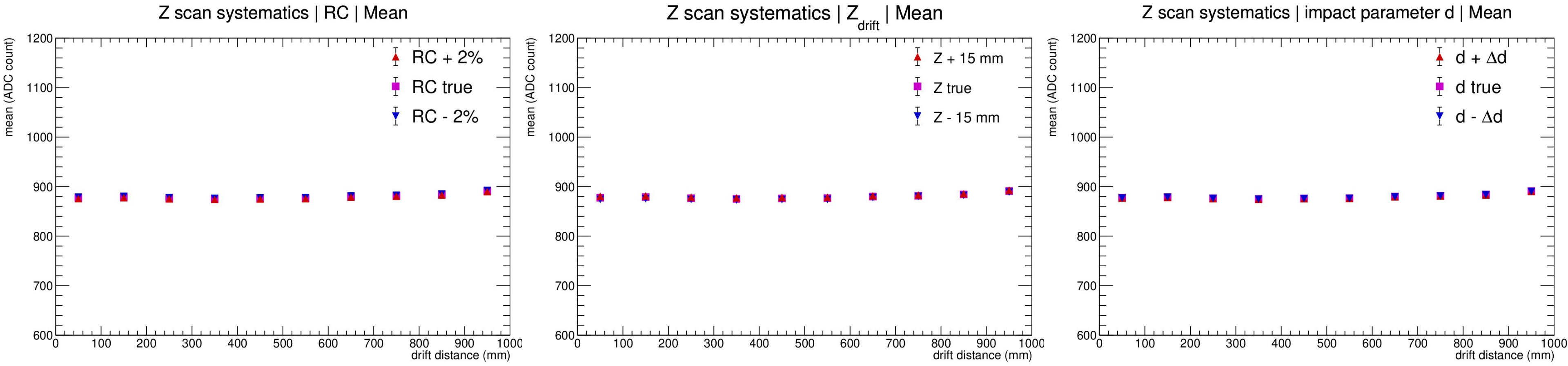
Drift distance:

- ΔZ_{drift} ~ 1.5 cm
  - Beam extension ~ 8 mm
  - ΔT_{max} ~ 8 mm
- Induced systematics < 0.1%
- Constant effect ∀ φ

Impact parameter d:

- Δd varies between 0 & 250 μm
- Induced systematics < 0.2%
- Constant effect ∀ φ

XP systematics - drift distance scan - mean plots



RC:

- $\Delta RC \sim 2\%$ (Shivam's fits)
- Difference < 10 ADC counts
- Constant effect $\forall\ Z_{drift}$

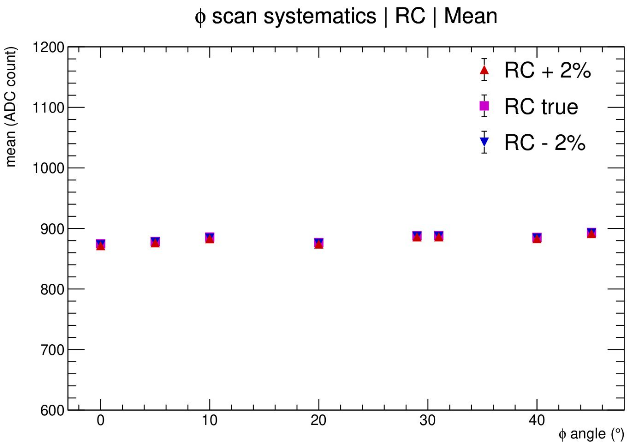
Drift distance:

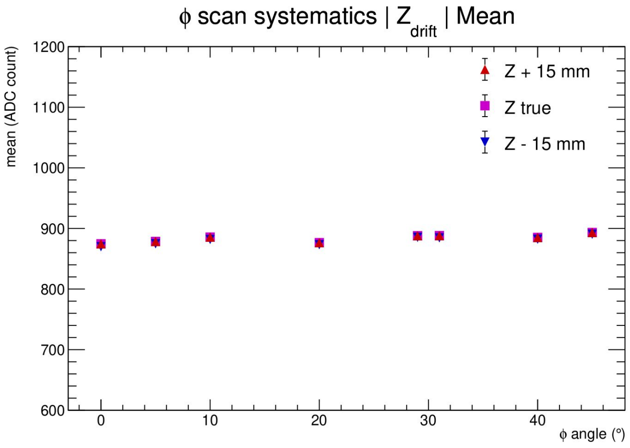
- $\Delta Z_{drift} \sim 1.5$ cm
  - Beam extension ~ 8 mm
  - $\Delta T_{max} \sim 8$ mm
- Difference < 10 ADC counts
- Constant effect $\forall\ Z_{drift}$

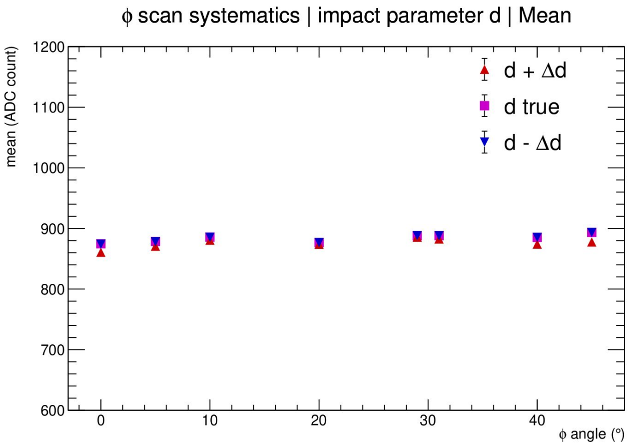
Impact parameter d:

- Δd varies between 0 & >1 mm
- Difference < 10 ADC counts
- Constant effect $\forall\ Z_{drift}$

XP systematics - φ scan - mean plots







RC:

- ΔRC ~ 2% (Shivam's fits)
- Difference < 10 ADC counts
- Constant effect ∀ φ

Drift distance:

- ΔZ_{drift} ~ 1.5 cm
  - Beam extension ~ 8 mm
  - ΔT_{max} ~ 8 mm
- Difference < 10 ADC counts
- Constant effect ∀ φ

Impact parameter d:

- Δd varies between 0 & 250 μm
- Difference < 25 ADC counts

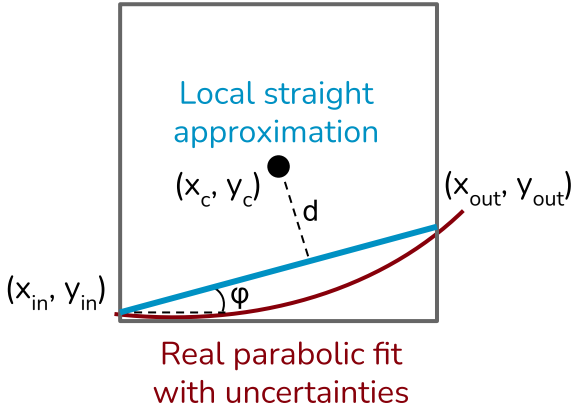
Error propagation for impact parameter

- Parabola parameters are correlated
- Can express the error on d with respect to a, b & c

$$d = \frac{mx_c - y_c + q}{\sqrt{m^2+1}} = \frac{(b + c(x_{out}+x_{in}))x_c - y_c + a - cx_{out}x_{in}}{\sqrt{(b+c(x_{out}+x_{in}))^2+1}}$$

$$y_{curve} = a + bx + cx^2$$
$$y_{line} = mx + q$$

$$\delta d^2 = DCD^T = (\partial_a d \quad \partial_b d \quad \partial_c d)\begin{pmatrix} \delta a^2 & C_{ab} & C_{ac} \\ C_{ab} & \delta b^2 & C_{bc} \\ C_{ac} & C_{bc} & \delta c^2 \end{pmatrix}\begin{pmatrix} \partial_a d \\ \partial_b d \\ \partial_c d \end{pmatrix}$$



$$\partial_a d = \frac{1}{\sqrt{(c(x_{out}-x_{in})+b)^2+1}}$$

$$\partial_b d \quad \frac{x_c}{\sqrt{(b+c(x_{out}+x_{in}))^2+1}} - \frac{(b+c(x_{out}+x_{in}))(x_c b - y_c + c(x_c(x_{out}+x_{in}) - x_{in}x_{out}) + a)}{((b+c(x_{out}+x_{in}))^2+1)^{3/2}}$$

$$\partial_c d = \frac{x_c(x_{out}+x_{in}) - x_{in}x_{out}}{\sqrt{((x_{out}+x_{in})c+b)^2+1}} - \frac{(x_{out}+x_{in})((x_{out}+x_{in})c+b)((x_c(x_{out}+x_{in}) - x_{in}x_{out})c - y_c + bx_c + a)}{(((x_{out}+x_{in})c+b)^2+1)^{3/2}}$$