Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

BNL Long Strip Results 2022

Chris Madrid

Testbeam Meeting

June 27, 2022

Overview

- Introduction
- Significant analysis updates
- Sensor properties
- Timing measurement
- Position measurement
- Summary/Paper style plots

Introduction

- Large sensors: interesting challenge for test beam
  - Collected large datasets with MANY more sensors & variants than planned—enabled good understanding of signal properties.
  - 15 AC-LGADs in 2 weeks
- Strong team enabled continuous operation!
  - Ohannes Koseyan, René Ríos, Claudio San Martín
  - Chris, Ryan; Artur, Cristián, Si, Zhenyu
- Key insights for larger sensors
  - Gain uniformity is increasingly important
  - Large channel size (capacitance) flattens signal shape
  - Metal vs. pitch size is important for position reconstruction

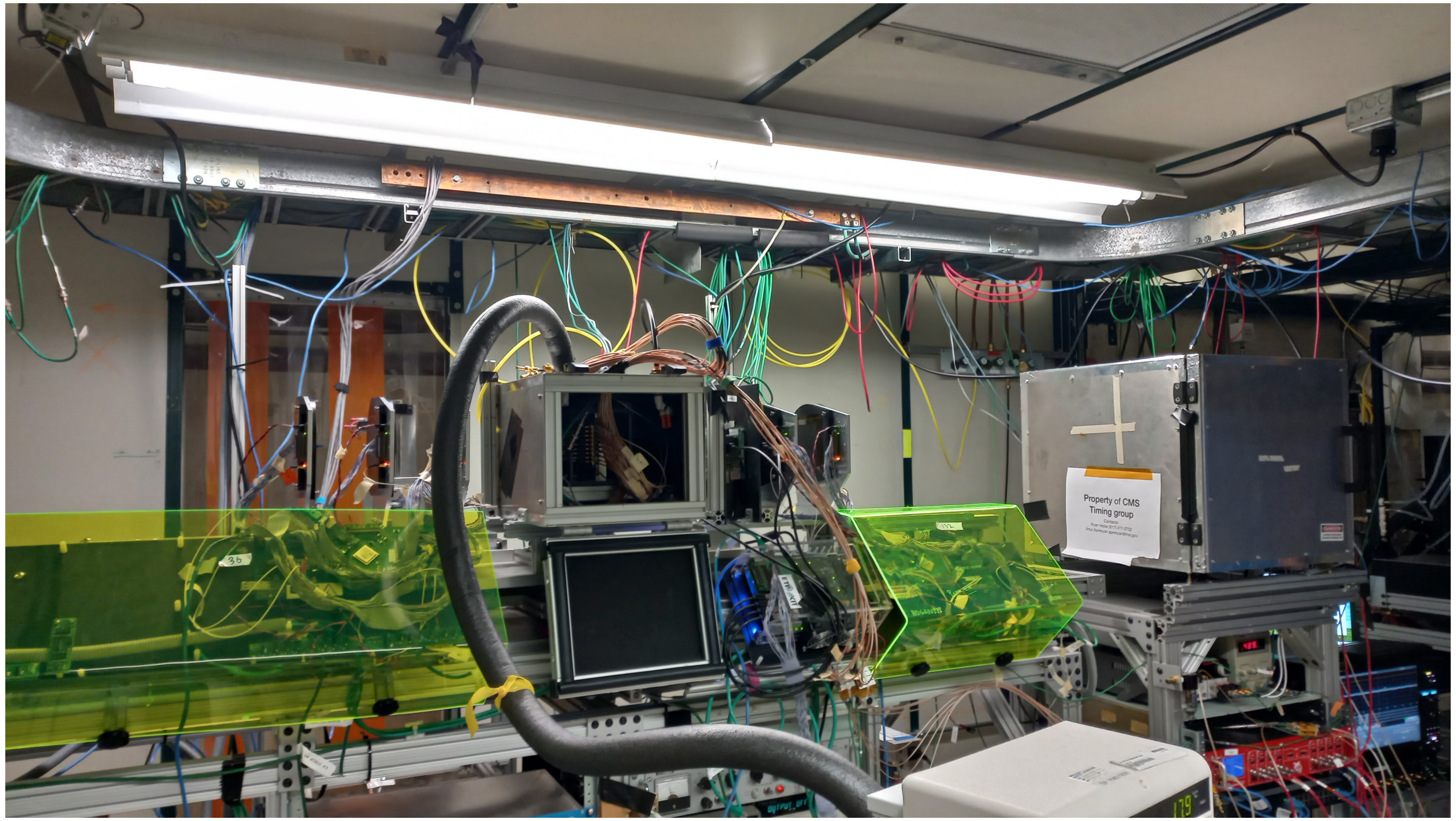
Collected datasets

BNL long strips	Notes
1 cm x 500 um, 300 um gaps, W1	
1 cm x 500 um, 200 um gaps, W2	From Wei Li. Died after ~ 1hr in beam
1 cm x 500 um, 400 um gaps, W2	Backup copy— first one not biasable
2.5 cm x 500 um, 300 um gaps, W1	From UCSC
2.5 cm x 500 um, 300 um gaps, W2	
0.5 cm x 500 um, 300 um gaps, W1	
0.5 cm x 500 um, 300 um gaps, W1	
1 cm multipitch (100, 200, 300 um), 50% gap, W1	

Collected datasets

Other sensors	Notes
HPK 1 cm strips, 80 um pitch, Eb type 30 and 45 um metal	
BNL 500 um pads, 4x4, squares 250 um metal	
BNL 500 um pads, 4x4, circles 150 um diameter metal	
BNL 2021 strips, 150 um pitch	repeat of 2021 measurement to study setup improvements

FTBF setup notes



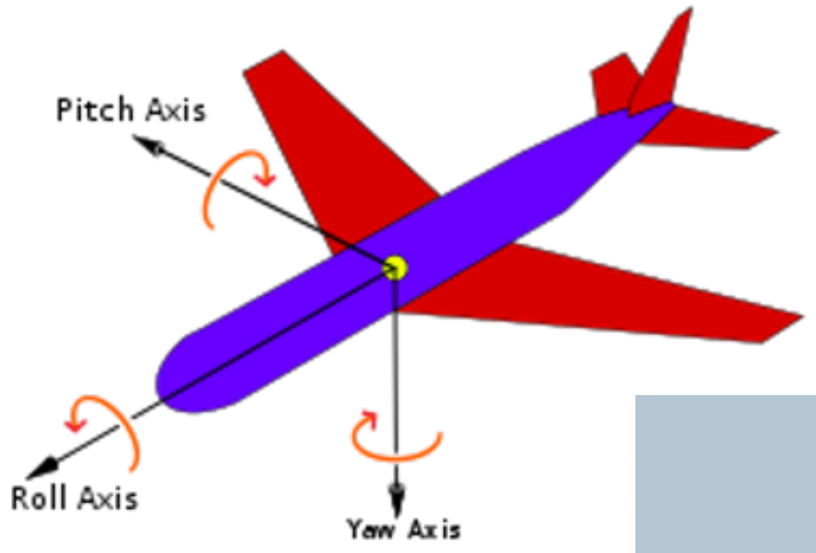
- LGAD readout: same as 2021
  - Upgraded 16-ch boards (better S/N)
  - 8-channel oscilloscope

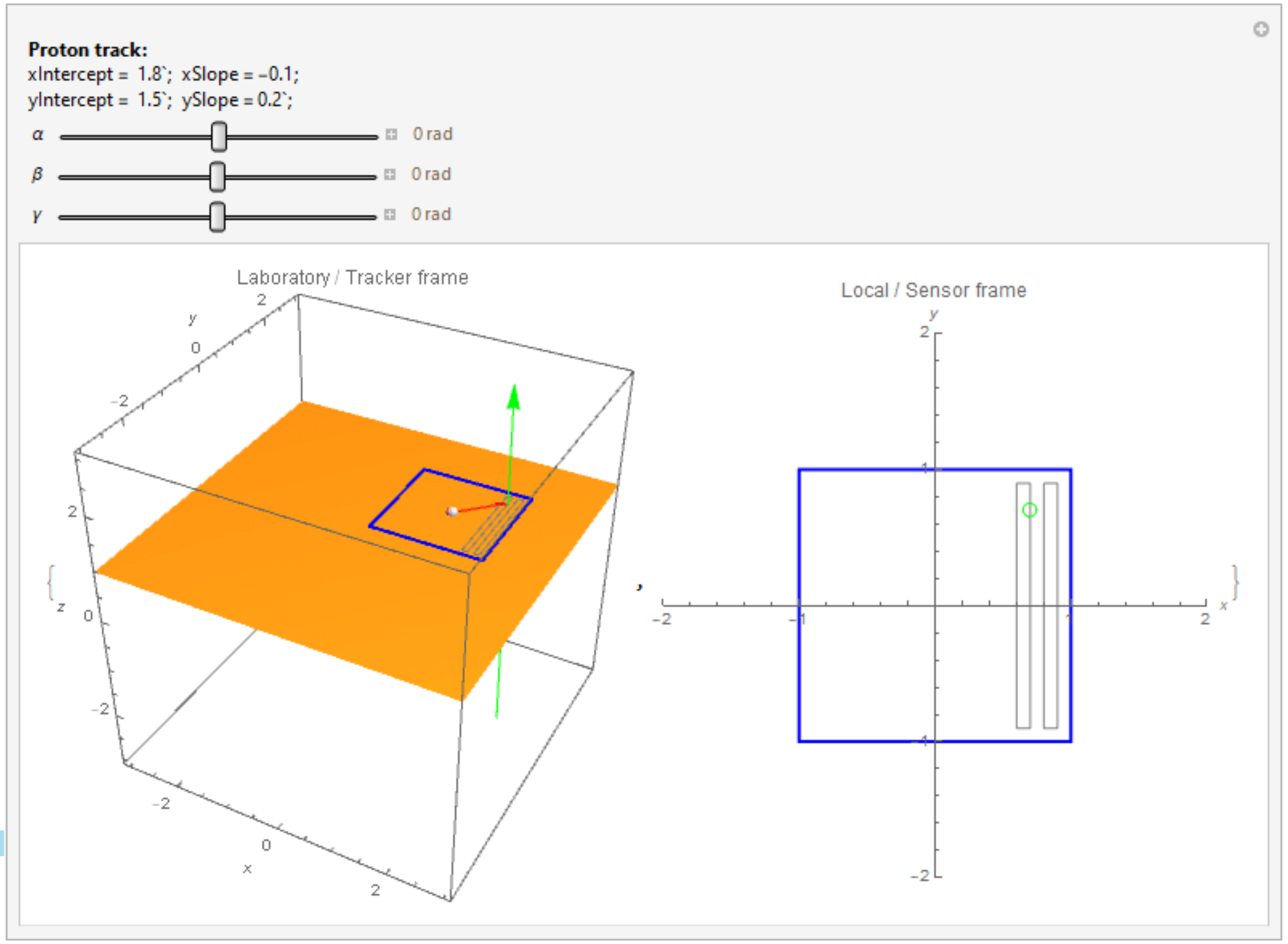
- Slightly improved tracker w.r.t 2021
  - Pixels: 4 layers of 25 x 100 um (CMS Phase II with RD53A)
  - Strips: 60 um—same as before
  - May give small improvement in resolution (reach 4–5 um). Likely limited by material
    - Telescope resolution is much less than AC-LGAD resolution this year

Significant Analysis Changes

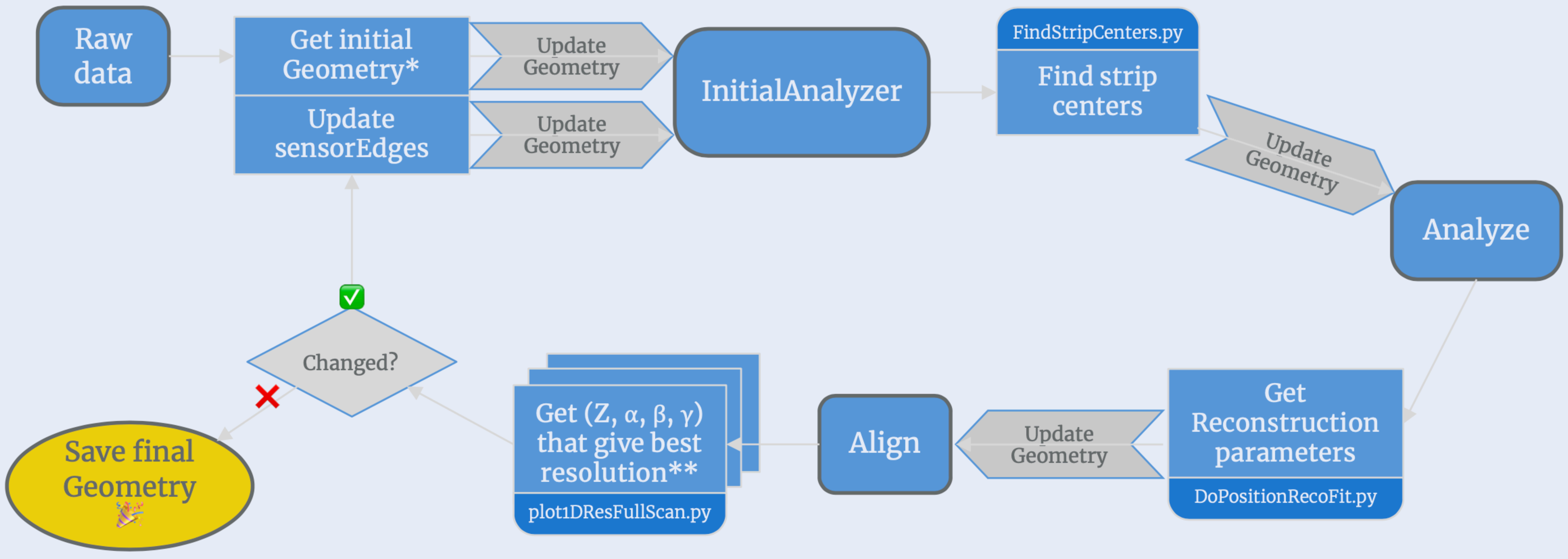
Track alignment correction

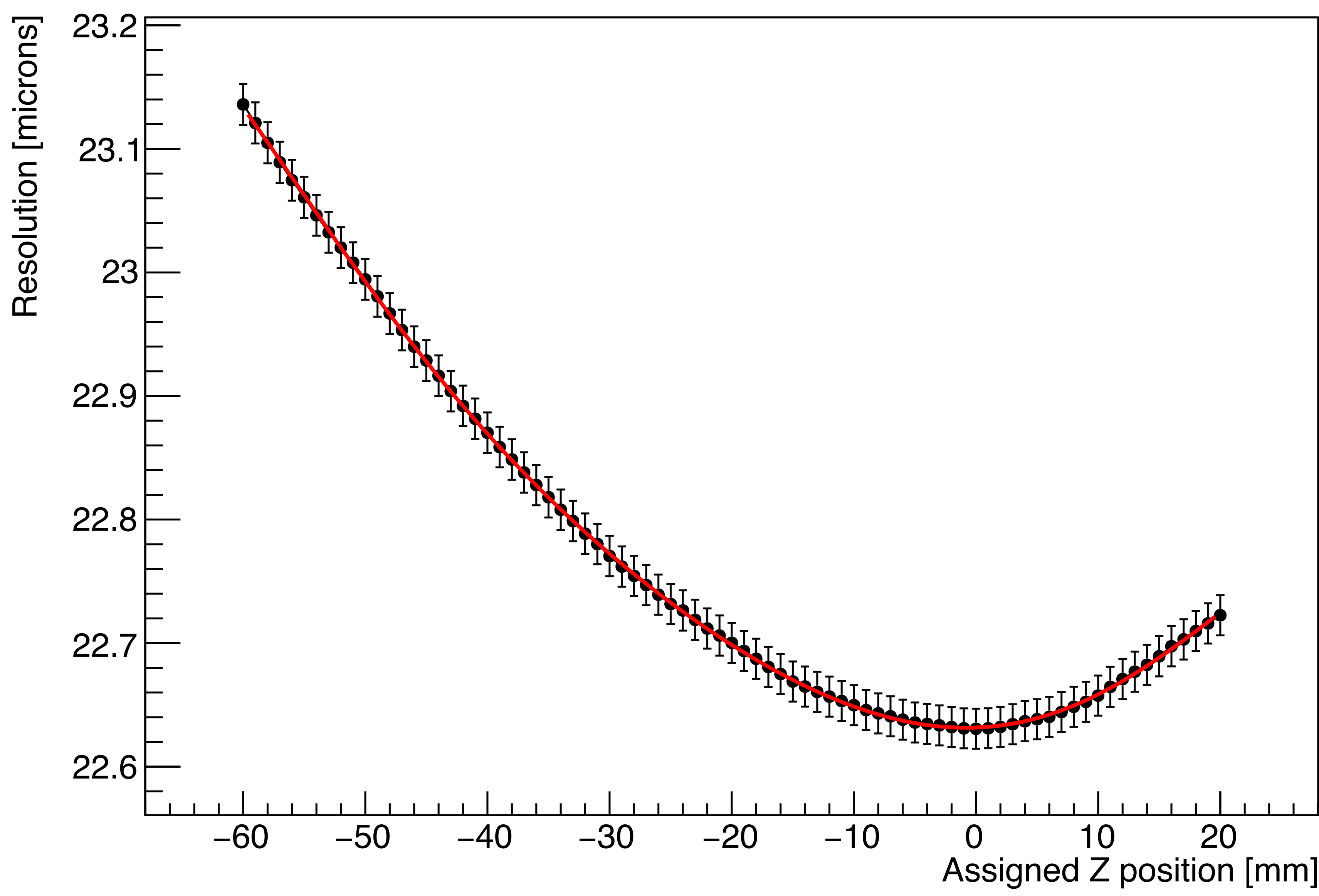
- For each proton the telescope provides a line in 3D w.r.t. the telescope coordinates
  - **Usual procedure assumes the sensor is a plane along telescope x-z and we solve for the line-plane intersection**
  - We would then transform the proton hit position from the telescope frame to sensor frame (trivial shits)
  - Last years paper had the extra step of correcting sensor rotations along the x-z plane
- **Current setup utilizes a full correction for all possible rotation of the sensor w.r.t. the beam**
  - Using three angles defined from the sensor frame axis
  - Similar to pitch, roll, and yaw (Tait-Bryan Angles)
- Then we varied the rotations angles to determine the **minimum position resolution**





Track alignment correction





** The best way of perform this is by iterating 4 to 5 times:

1. Start with (0, 0, 0, 0) → Get best $\alpha=\alpha_1$
2. Start with (0, α_1, 0, 0) → Get best $Z=Z_2$, and check that α has **not** changed (if so, update $\alpha=\alpha_2$)
3. Start with (Z_2, α_2, 0, 0) → Get best $\beta=\beta_3$, and check Z and α (update if necessary)
4. Start with (Z_3, α_3, β_3, 0) → Get best $\gamma=\gamma_4$ (if seems constant, keep $\gamma_4=0$), and check Z, α, and β
5. Start with (Z_4, α_4, β_4, γ_4) → Check parameters don't vary too much

- Defined an iterative procedure for finding the **correct angle and position in z (tracker frame)**
- Minimized the measured position resolution
- Overall impact depends on how bad sensors are align when measured
  - **Expect improvement to measured resolution to be around 10 microns at best**

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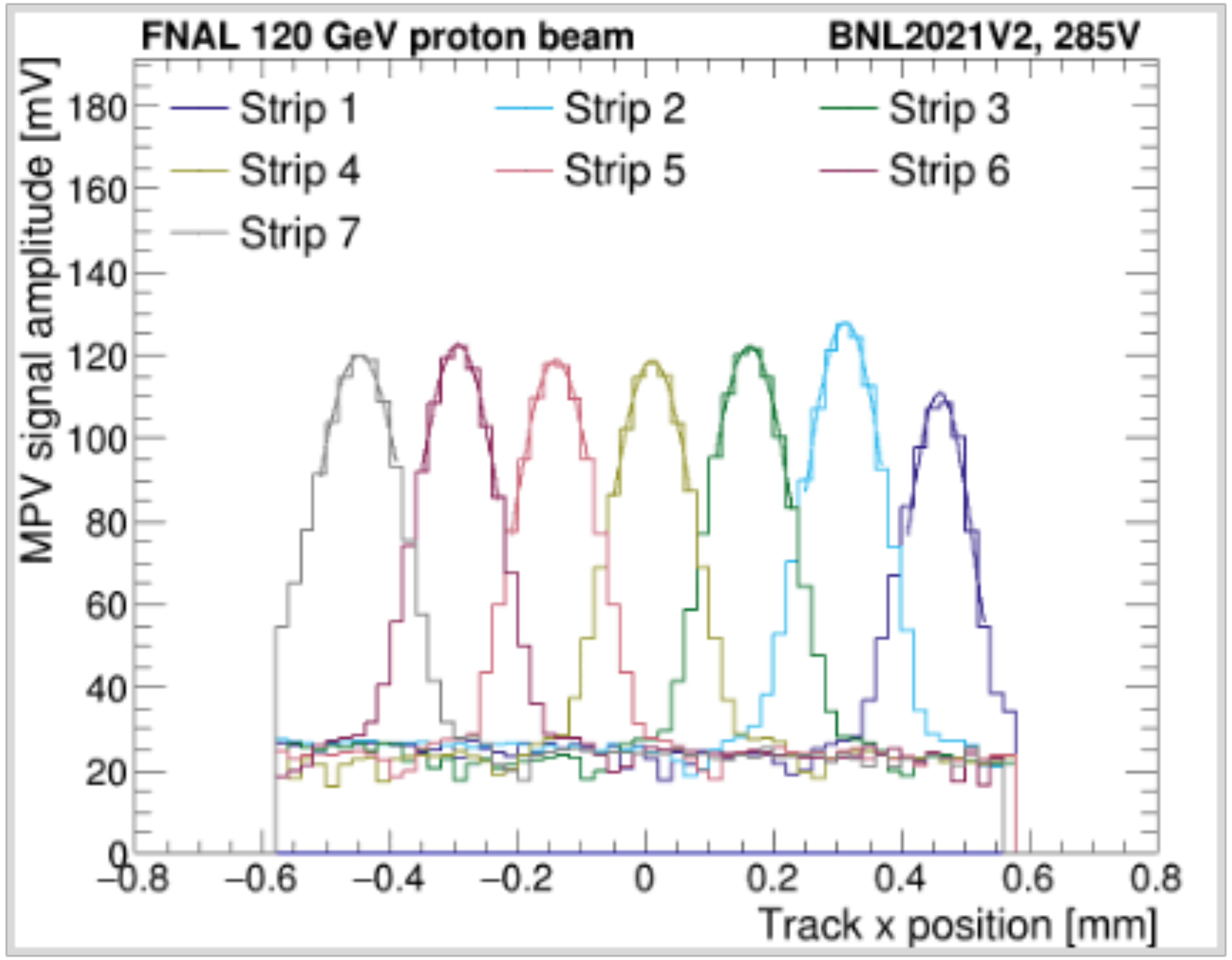
Sensor Center Position

- **Major input to position reconstruction is the location of each strips centers**
  - In the past would determine this by hand and force the difference between positions to equal the pitch

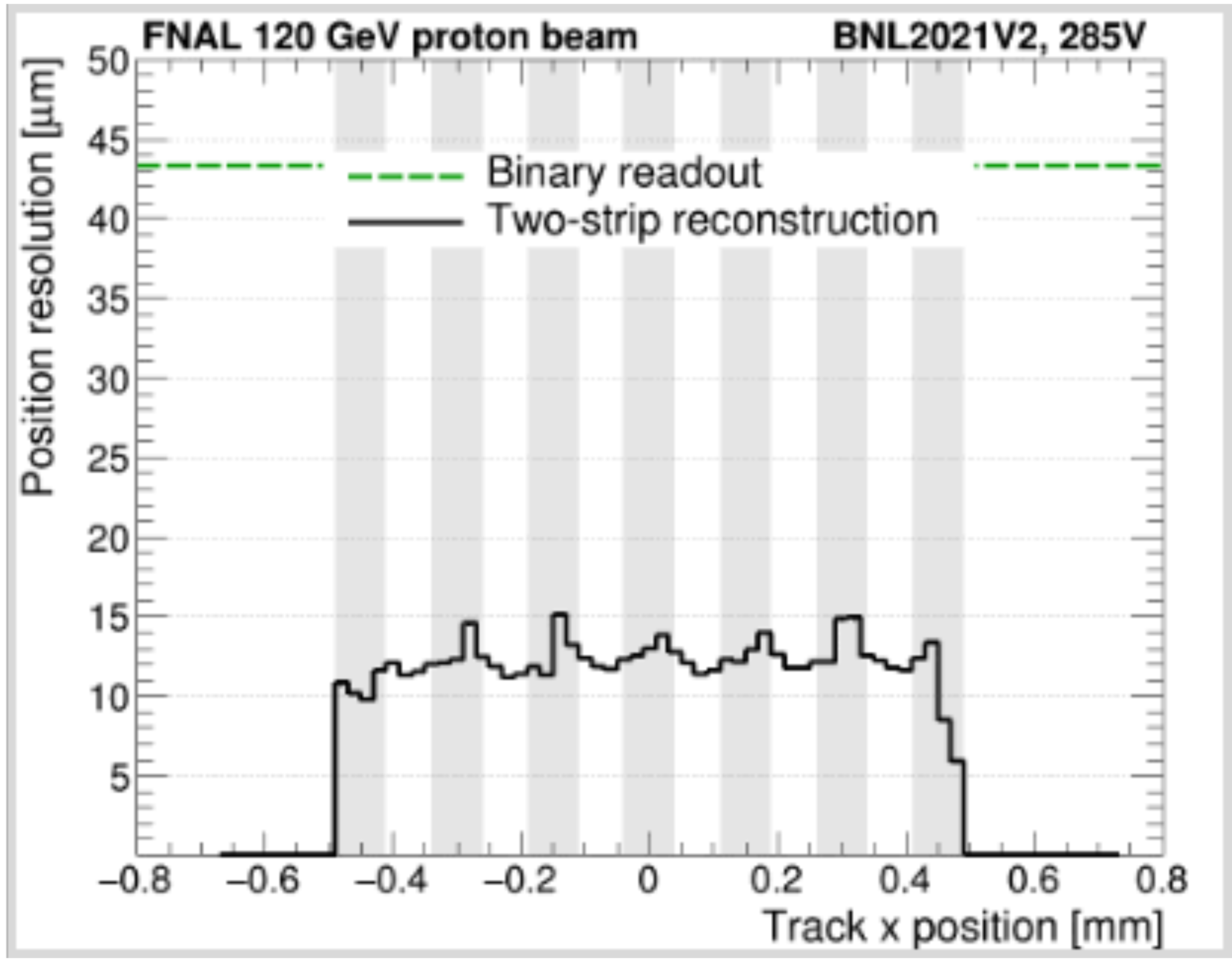
- Now we determine their positions by performing fits to the amplitude vs. x position plots

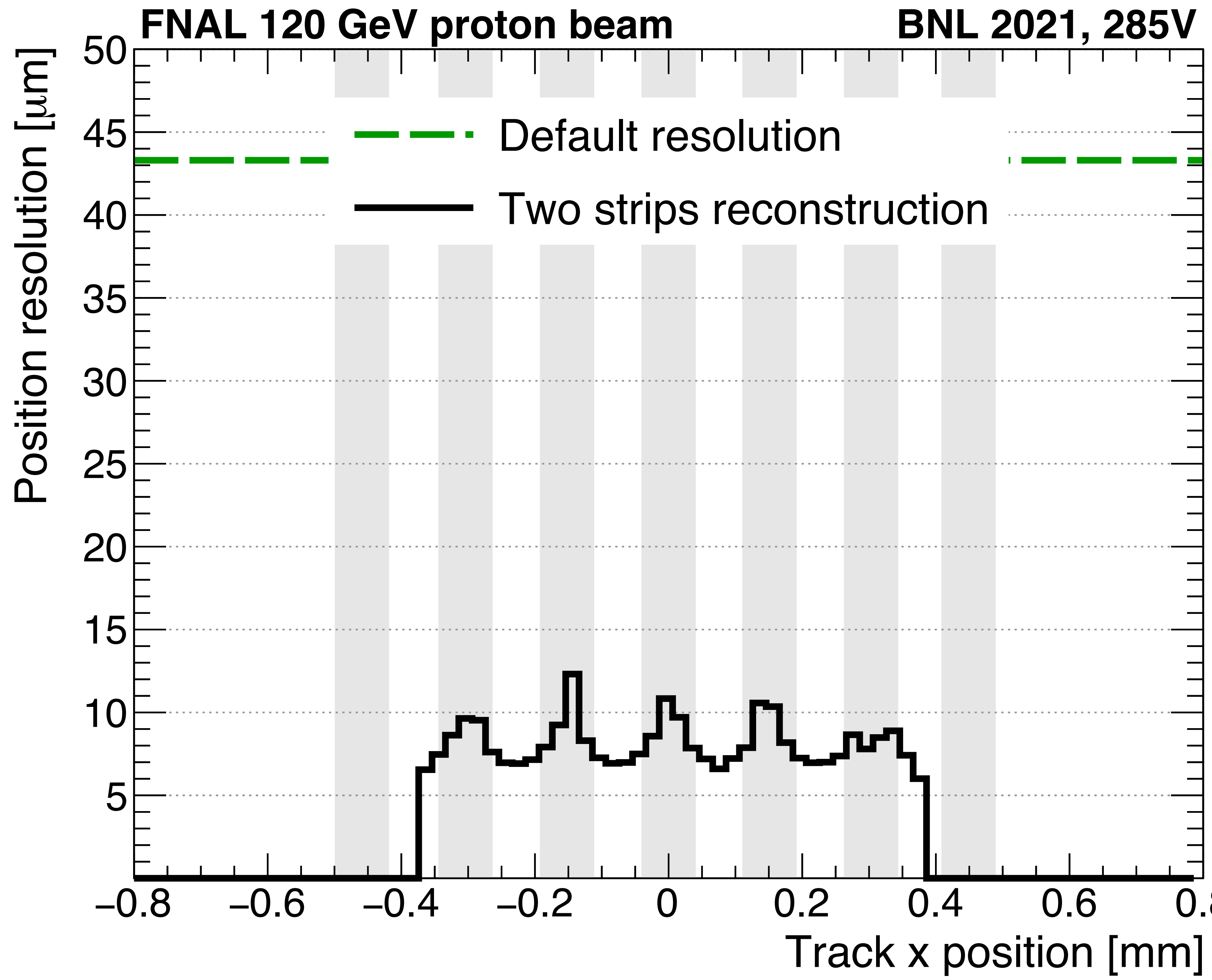
- Now an **automated procedure and part of the alignment workflow**

- More of a quality of life improvement
  - **No major impact on overall performance**



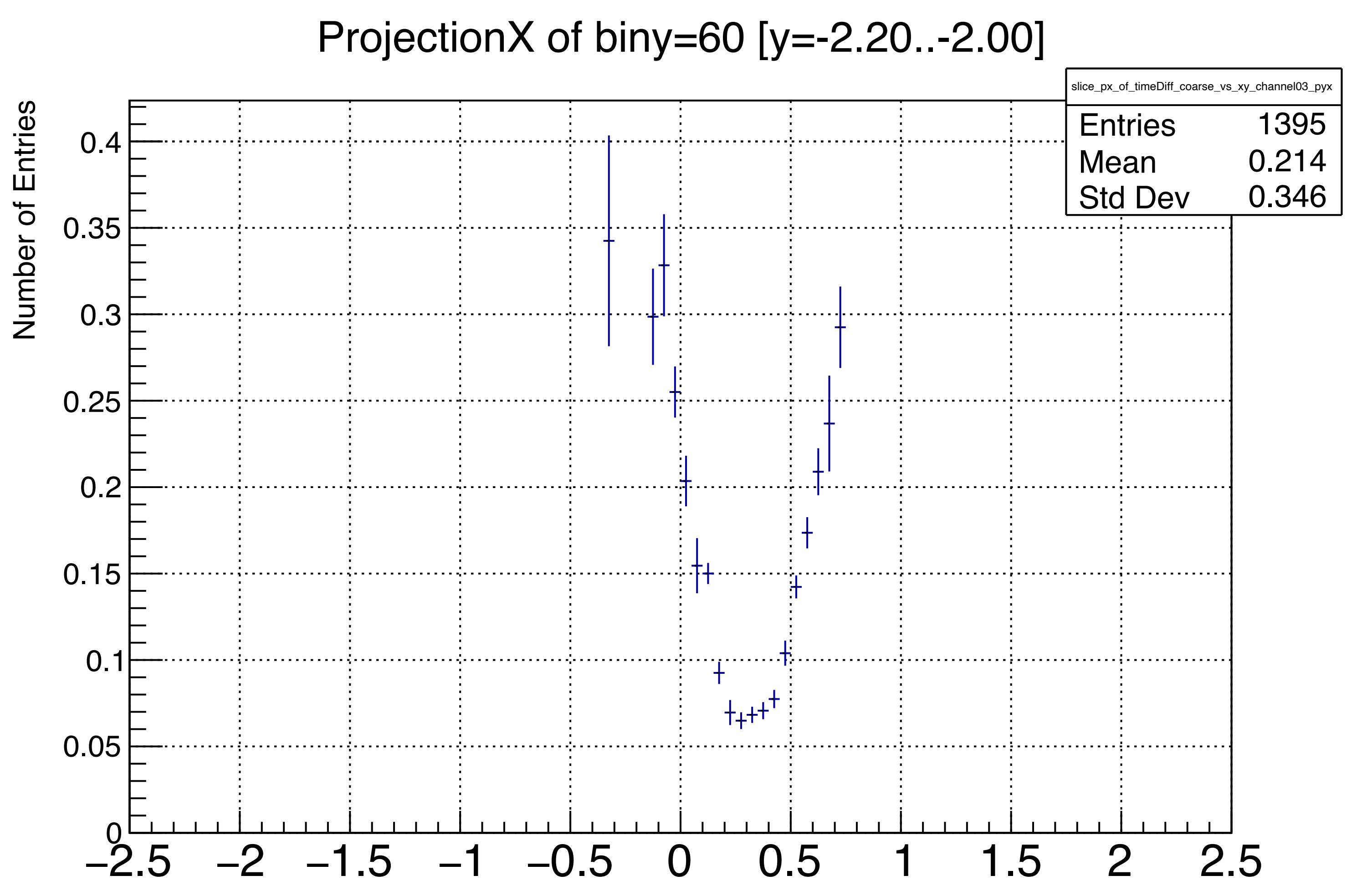
Overall improvement to resolution: BNL 2021

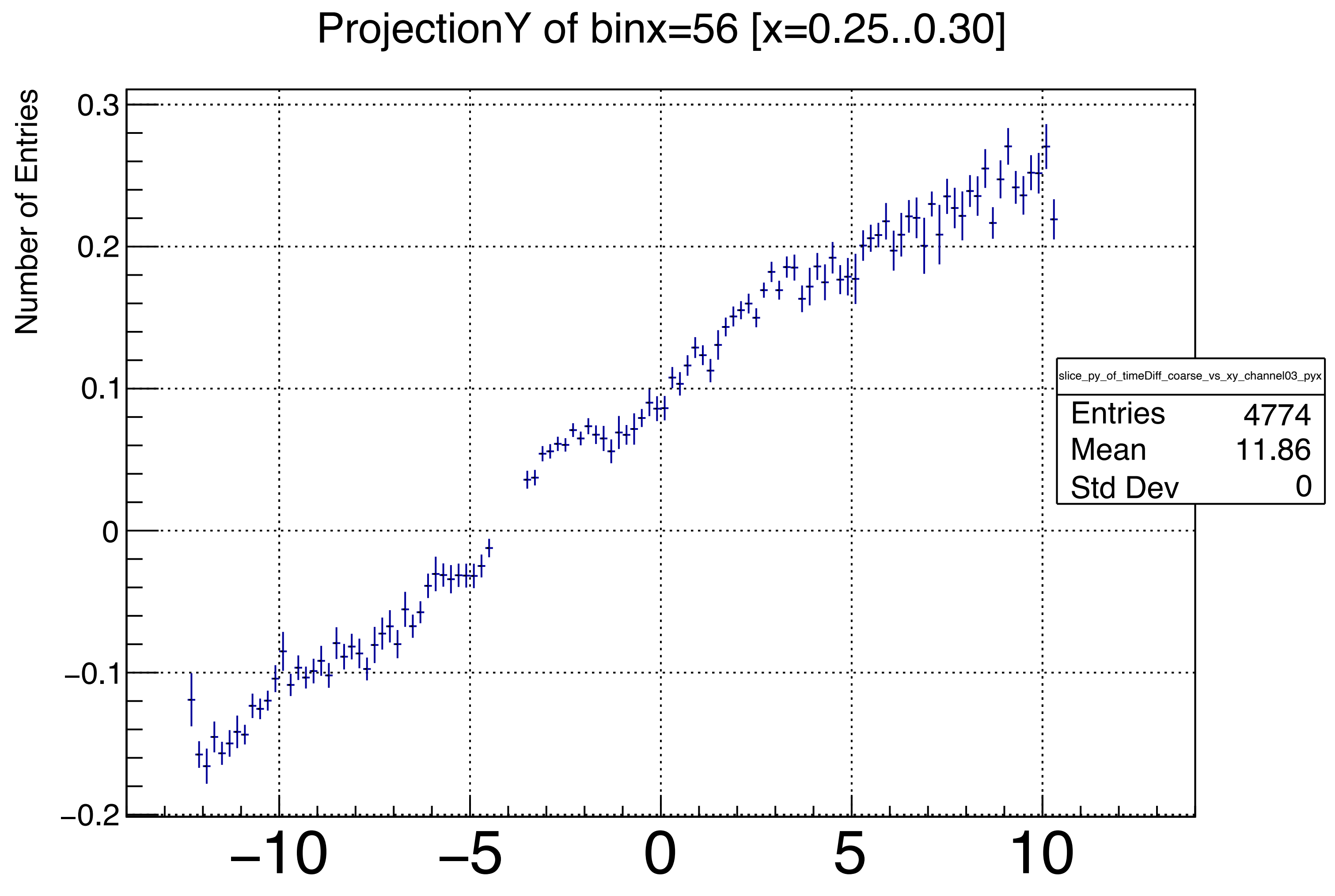


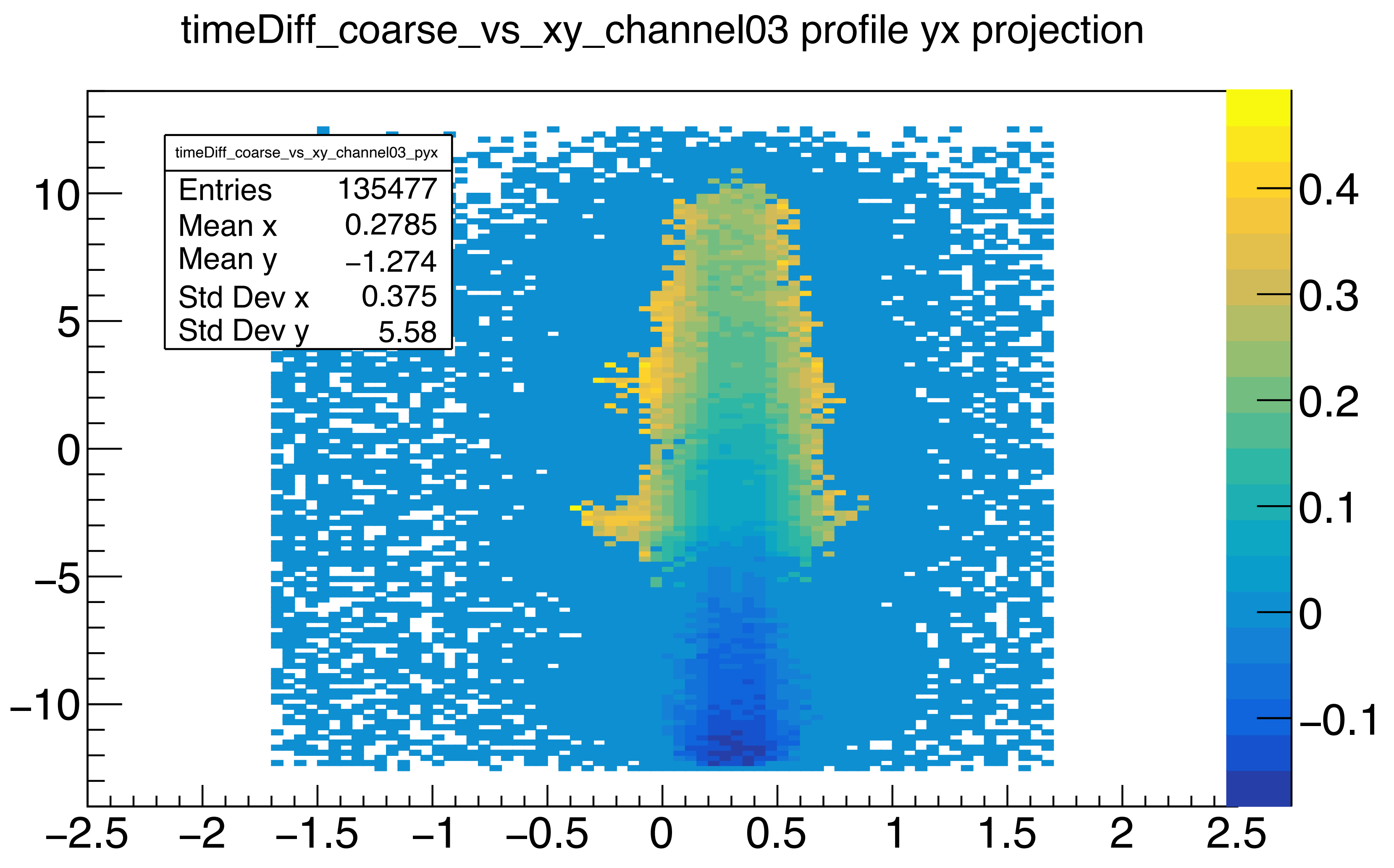


- We see a good improvement to the measured resolution for the BNL 2021 sensor from last years paper
  - Note: we retook data for this sensor this year with more stats
- Overall resolution went from ~13 um -> ~8 um
  - We published 11 um for this sensor last year (after subtracting tracker component)
- **However, we do not expect this to have a large impact on the large sensors measured this year**

Time delay corrections







- Last year the only corrections made to measured time was a **constant offset per channel** meant to account for different cable lengths
- **This year we can see a large delay contribution as a function of the proton hit position due to the size of the sensors**
- We now have a delay correction as a function of tracker x, y position measured by taking the deltaT for each channel w.r.t. the photek time
- This has a **major impact on the measured time resolution** and will be necessary for operation of AC-LGADs

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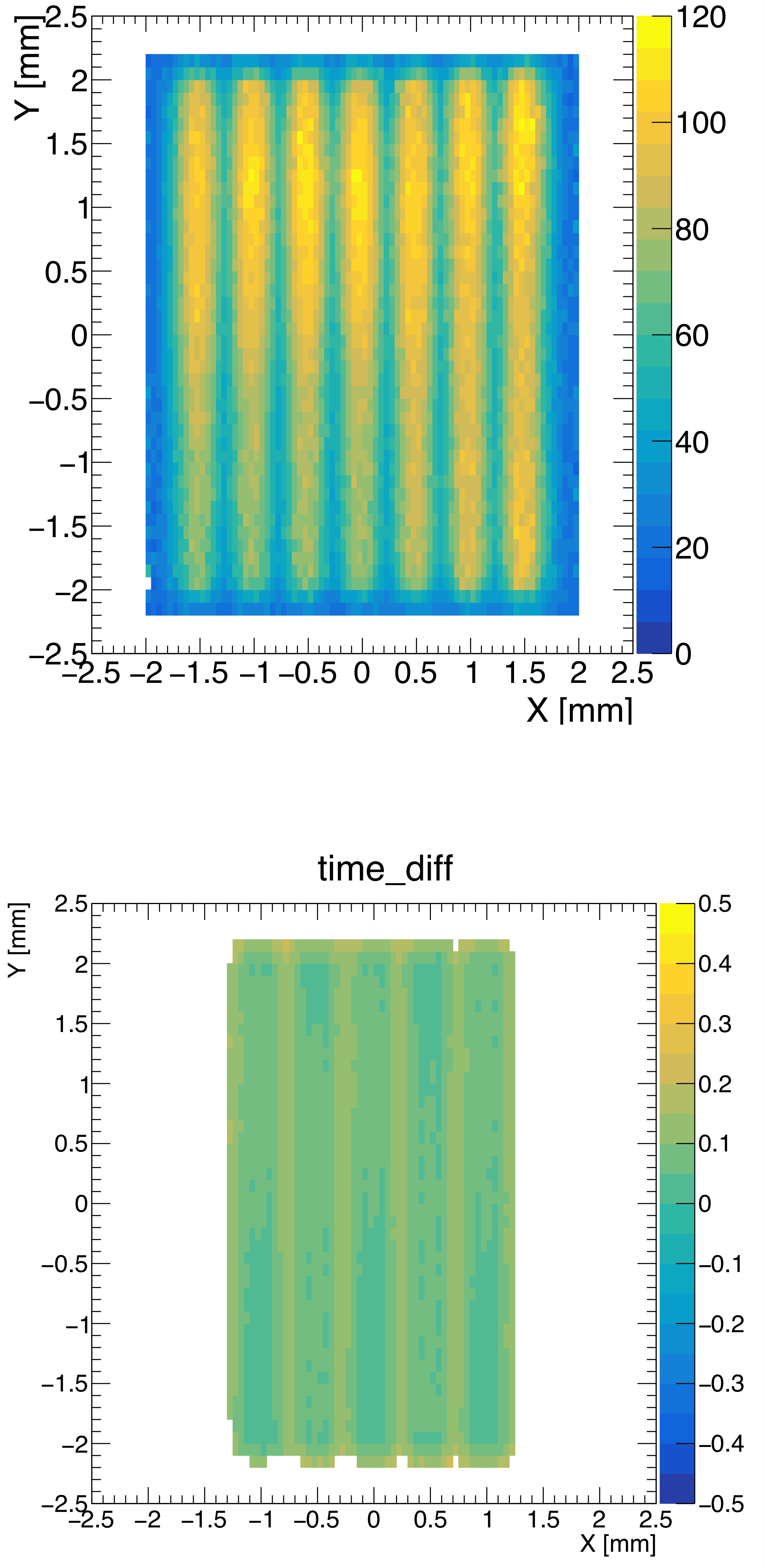
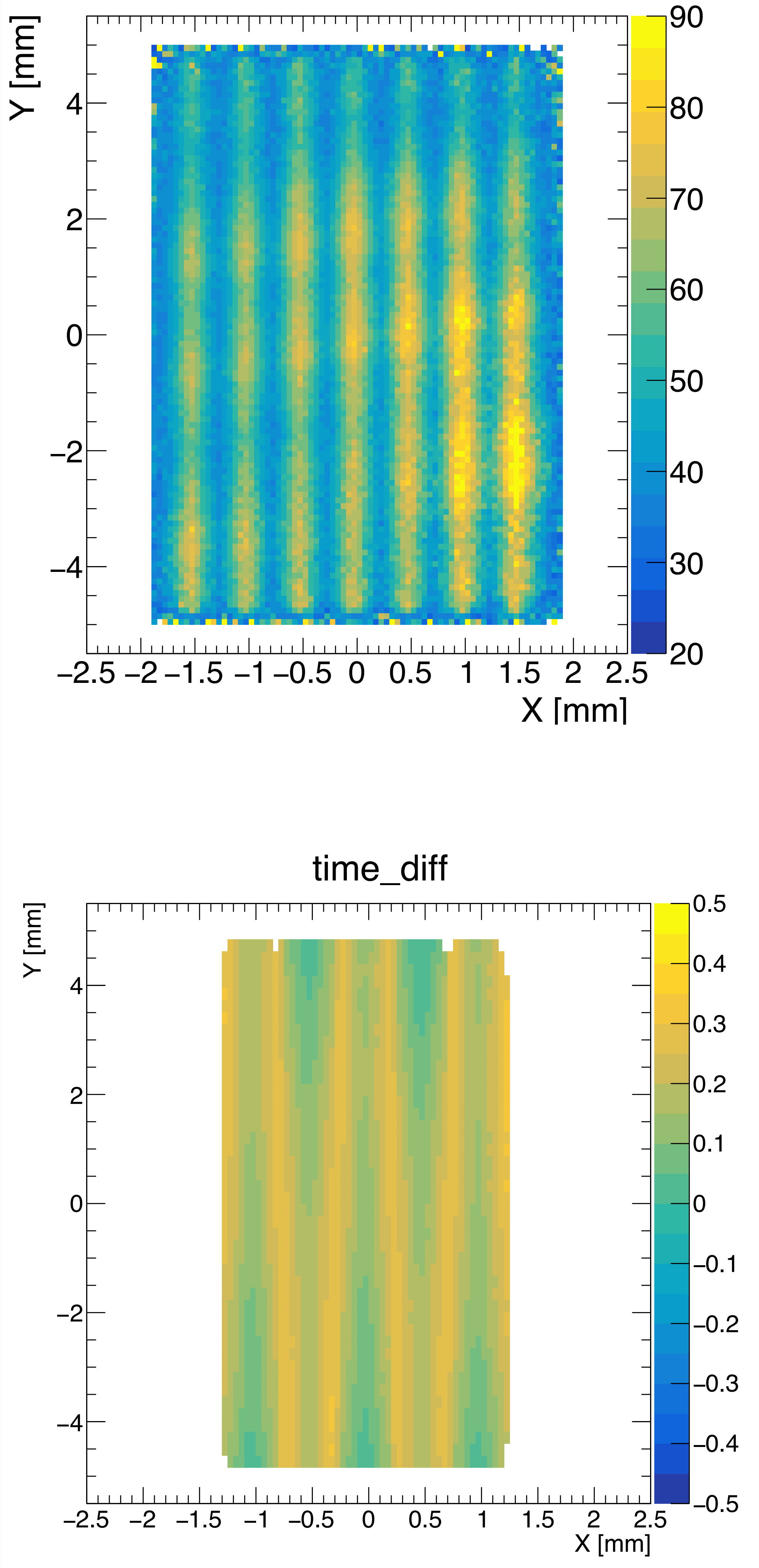
Signal Properties

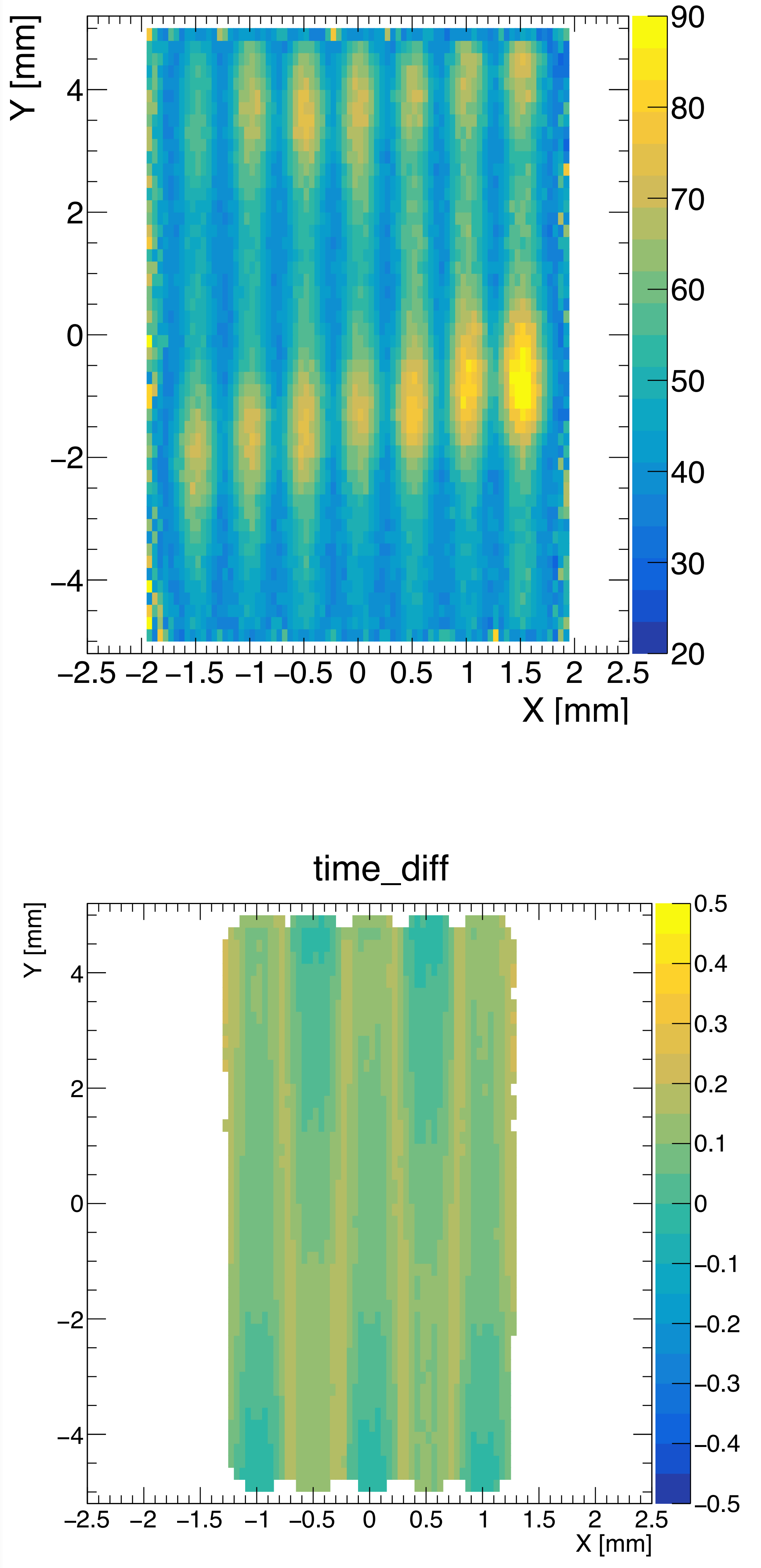
Amplitude MVP and Mean Time



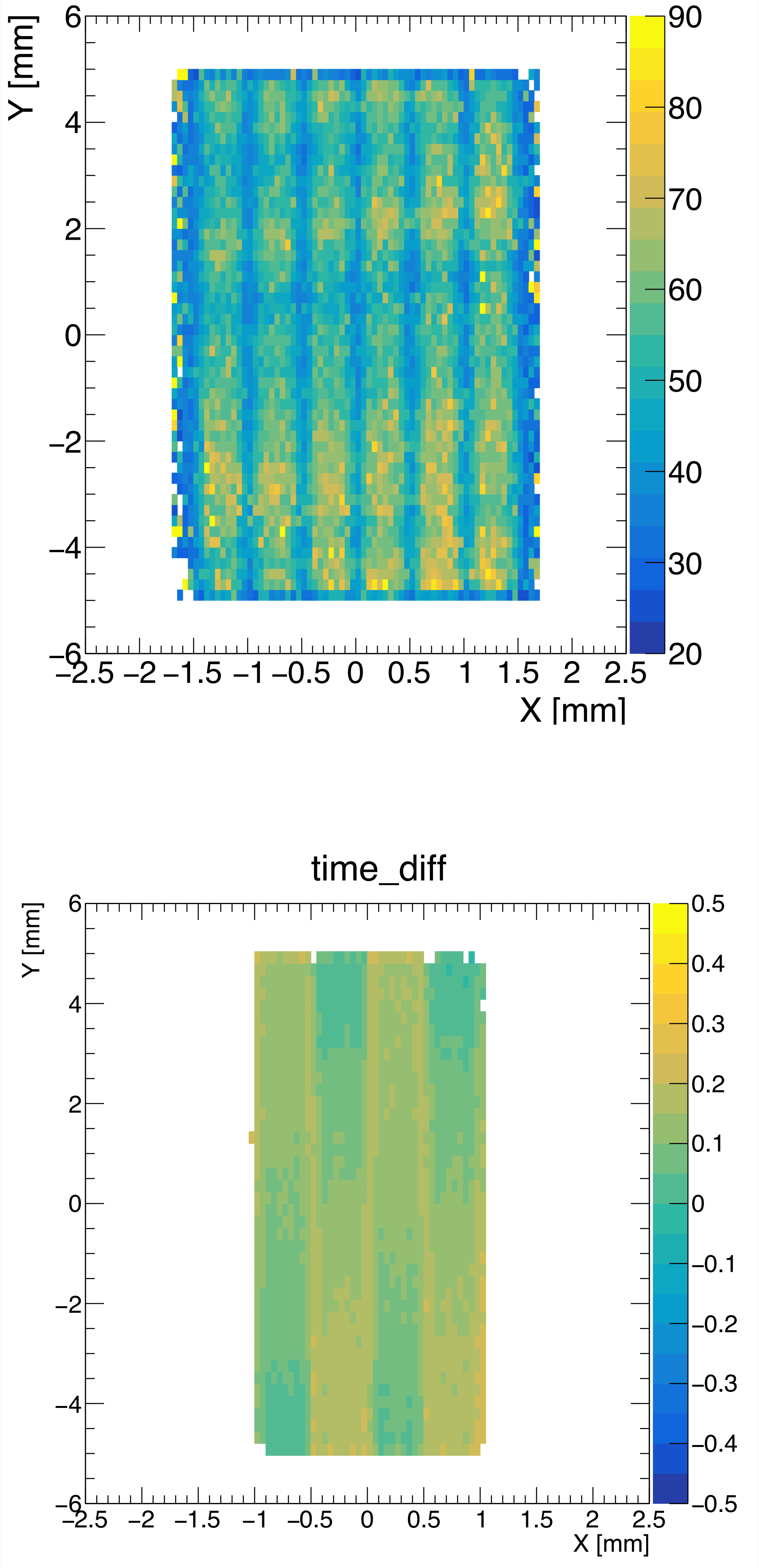
5 mm - 200 um metal



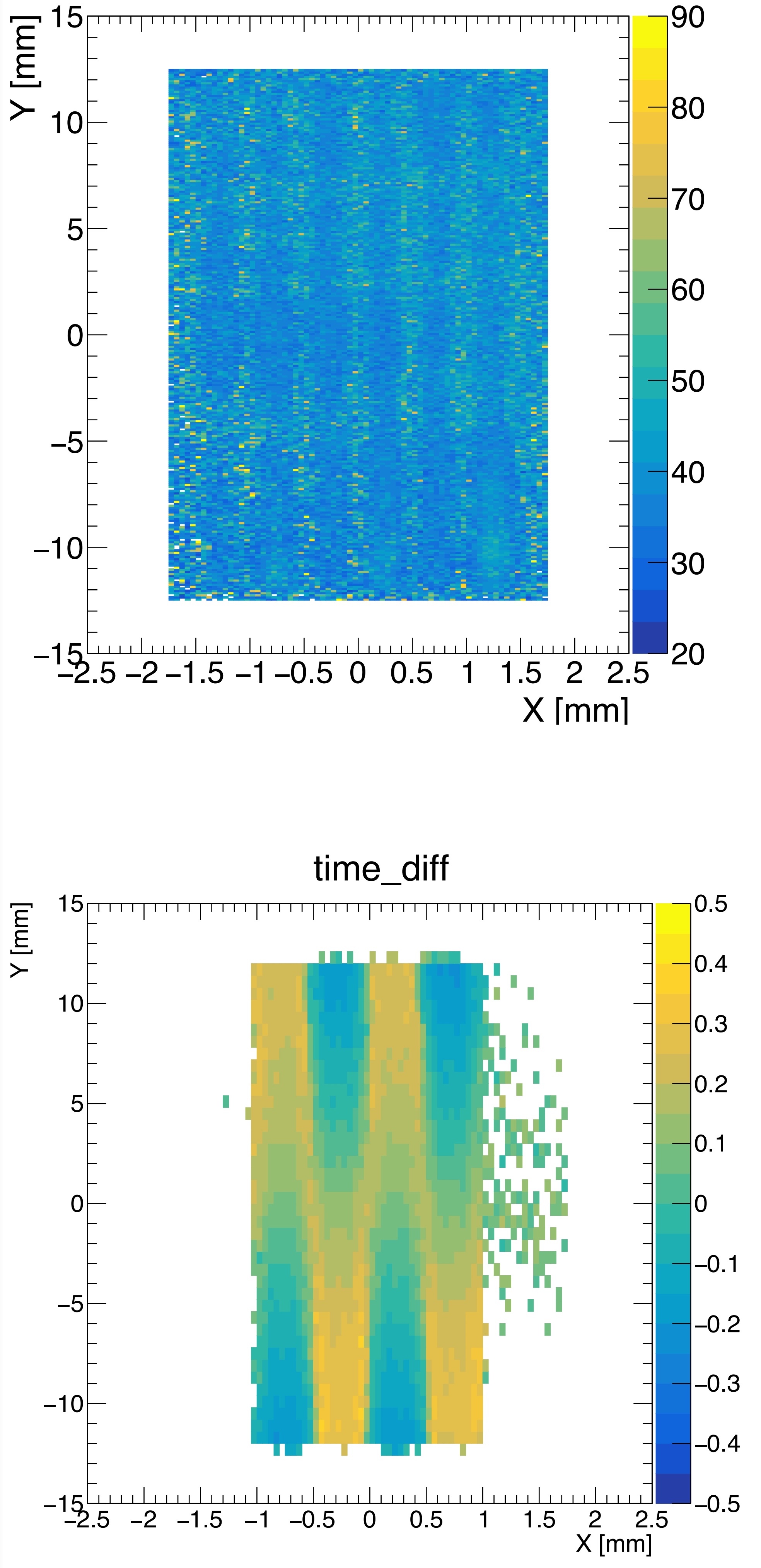
10 mm - 100 um metal



10 mm - 200 um metal

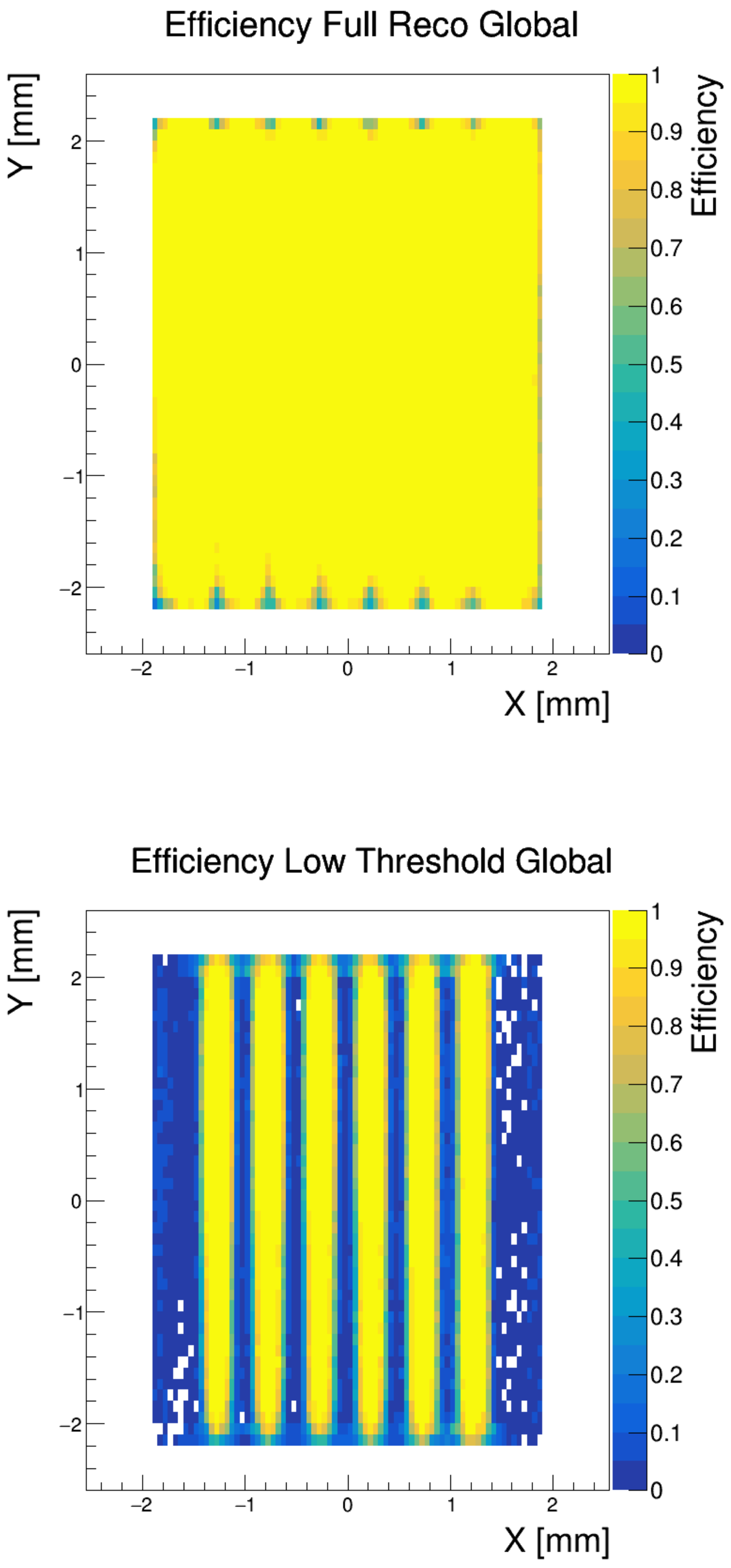


10 mm - 300 um metal

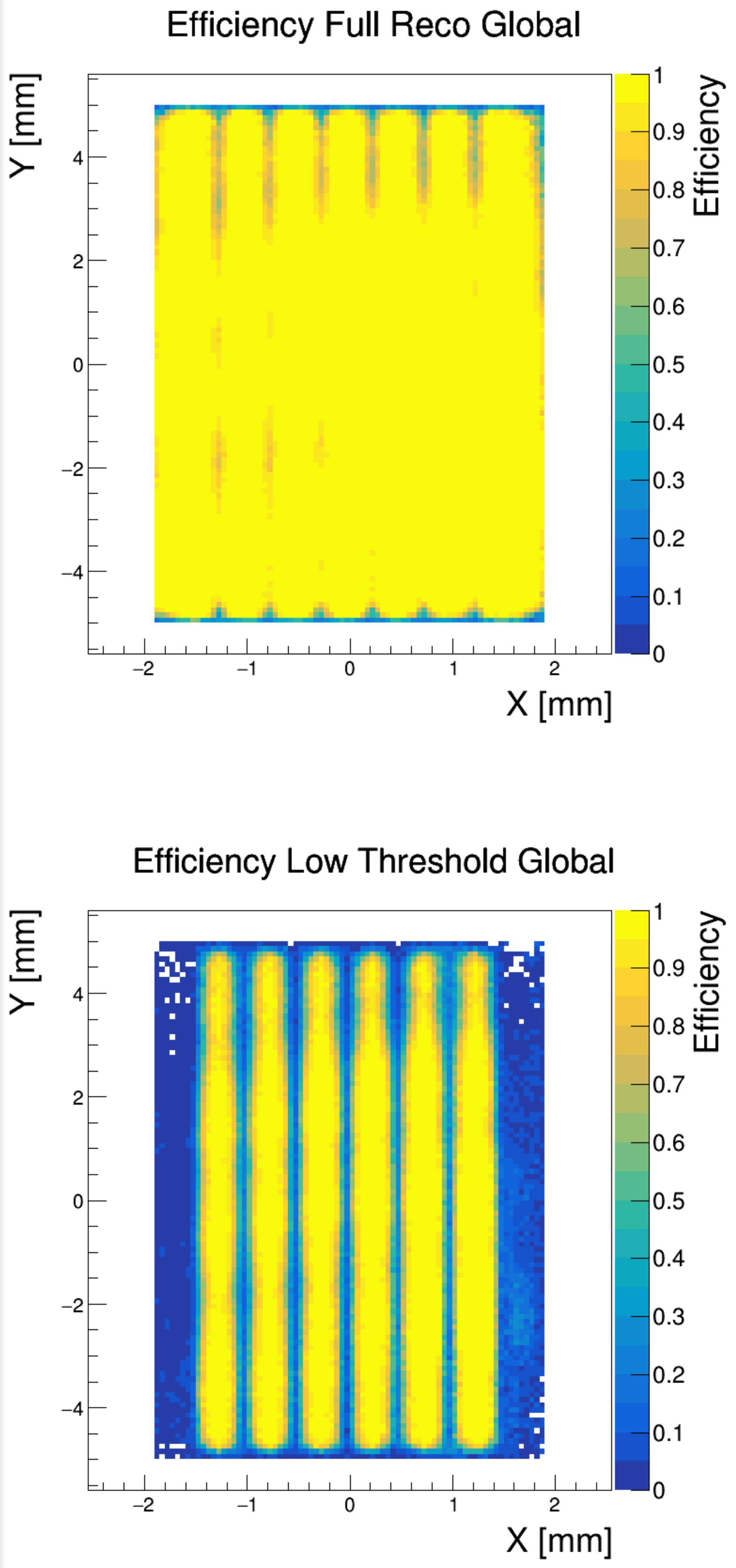


25 mm - 200 um metal

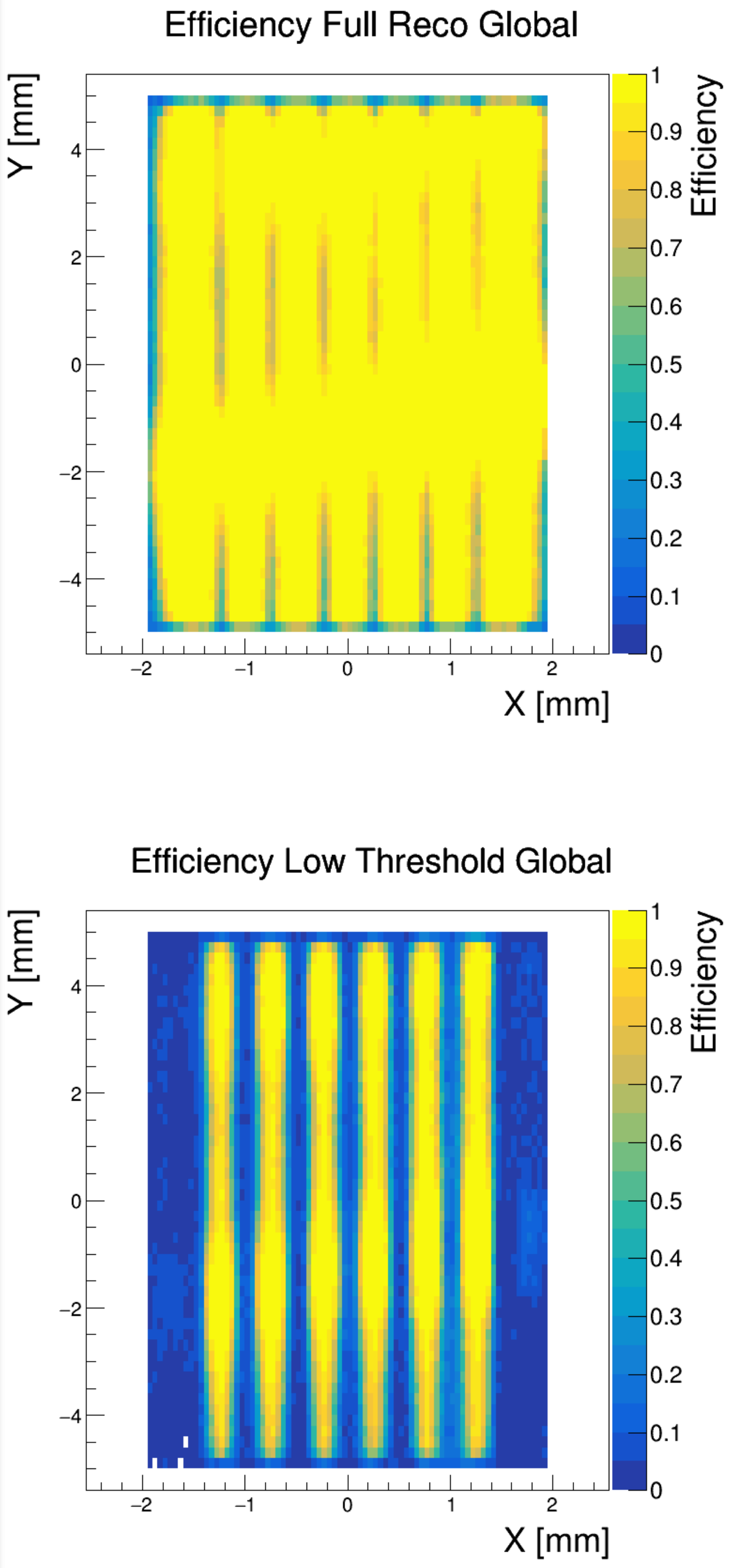
Efficiency



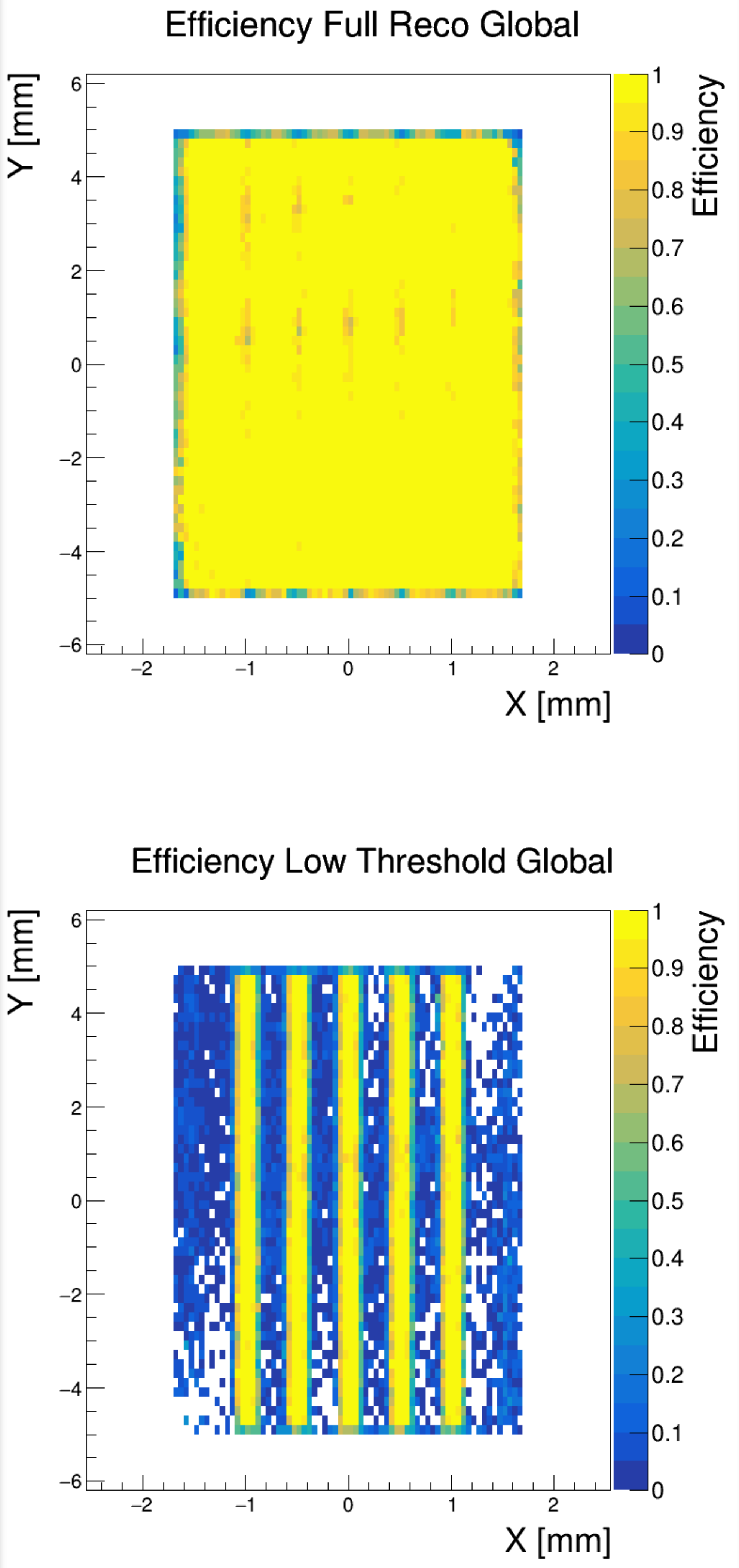
5 mm - 200 um metal



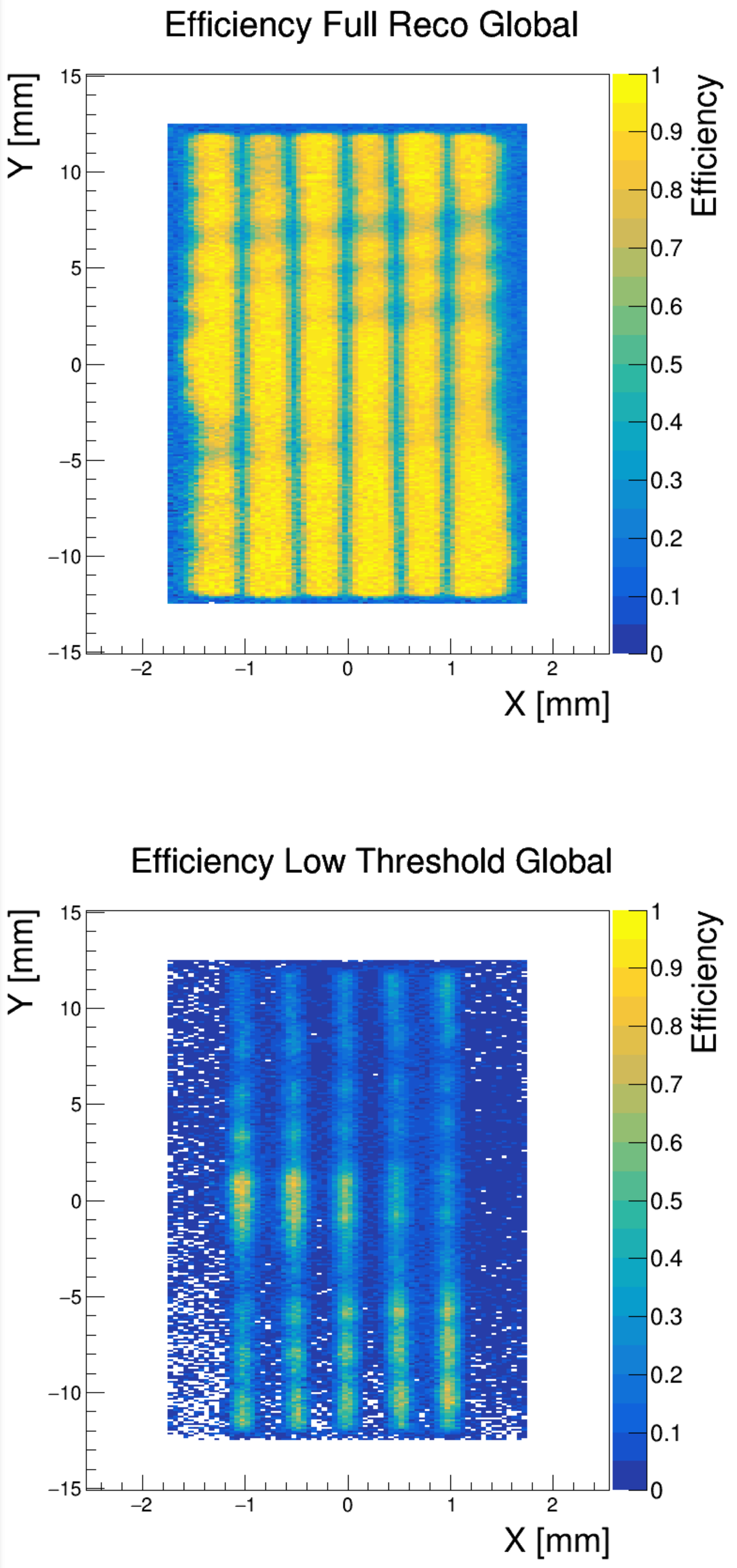
10 mm - 100 um metal



10 mm - 200 um metal

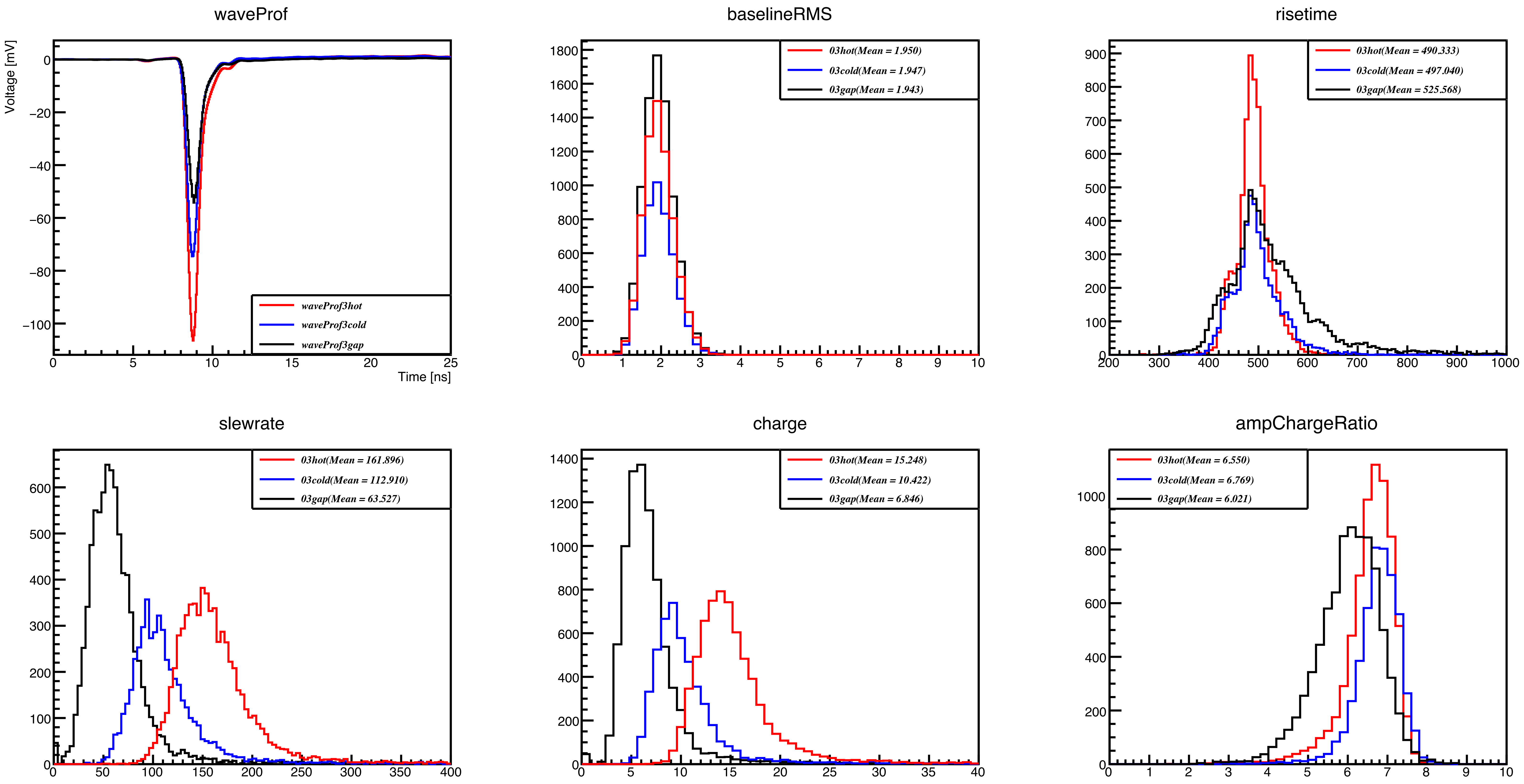


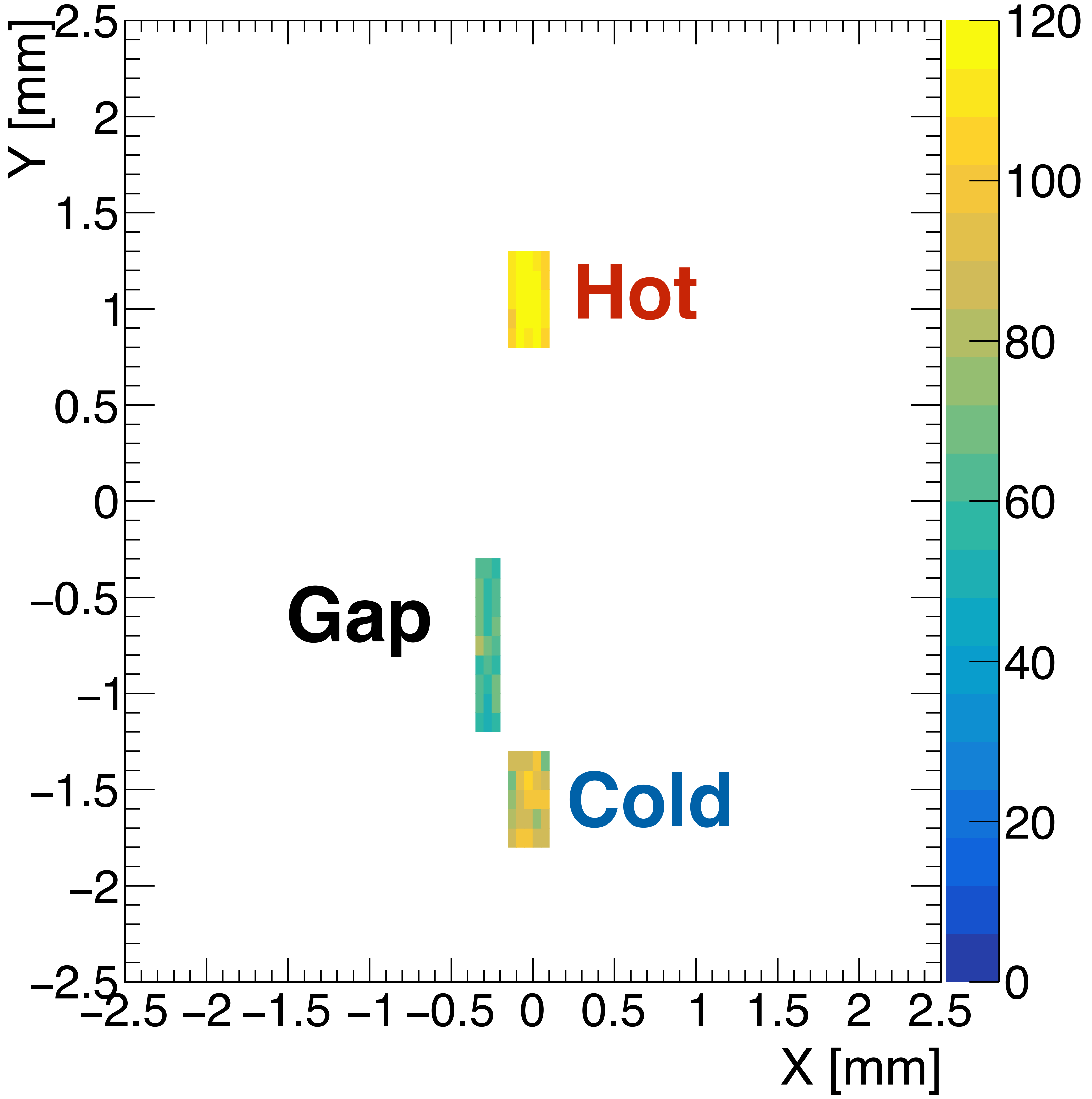
10 mm - 300 um metal



25 mm - 200 um metal

Regions of Interest Results: BNL 5mm





- To study pulse shape based variables closer we defined R.O.I. selections
  - Also, used to quantify impact of non-uniformity (Cold vs. Hot)
- Each area defined such that number of events match

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Pulse shape variable summary

- Length (top row)
- Width (bottom row)

- Hot
- Cold
- Gap

Baseline RMS | Risetime | Amp/Charge Ratio | Slewrate | Jitter

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Pulse shape summary

- Hard to rule out difference between sensors is not simply caused by difference in gain
  - We do all comparisons with optimal bias voltage for each sensor
  - We know rise time hits a plateau past some bias voltage (~180V)
    - All sensors shown for bias above 215V
- See 2-strip efficiency gaps at the metal for all sensors
- Hot, cold, and gap pulses behave as expected
  - Only notable differences for amplitude dependent variables
- Assumed sensor area would be driving factor but seems like **length has largest differences**
- Pulse shape variables are mostly constant for different metal width

Timing Measurement

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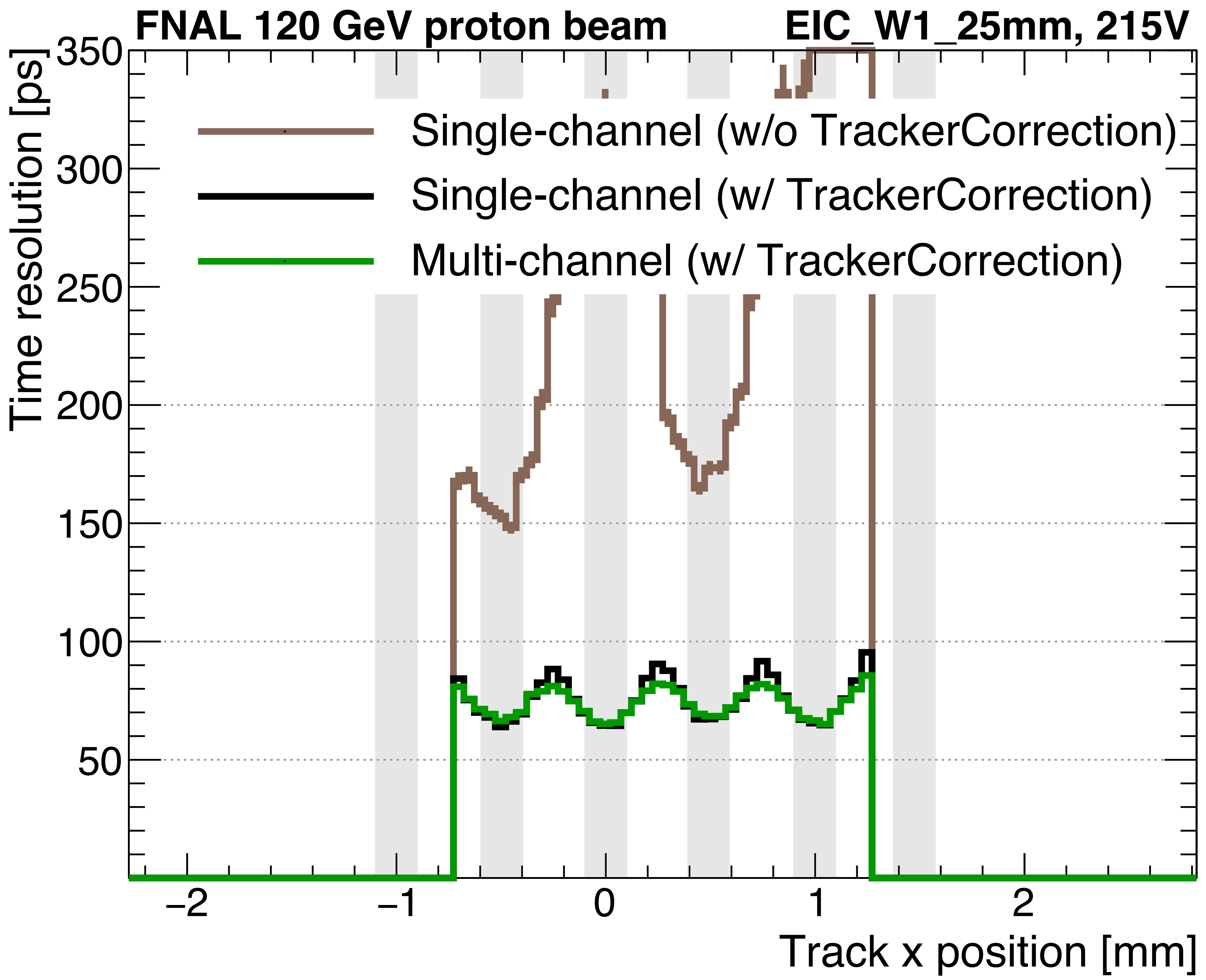
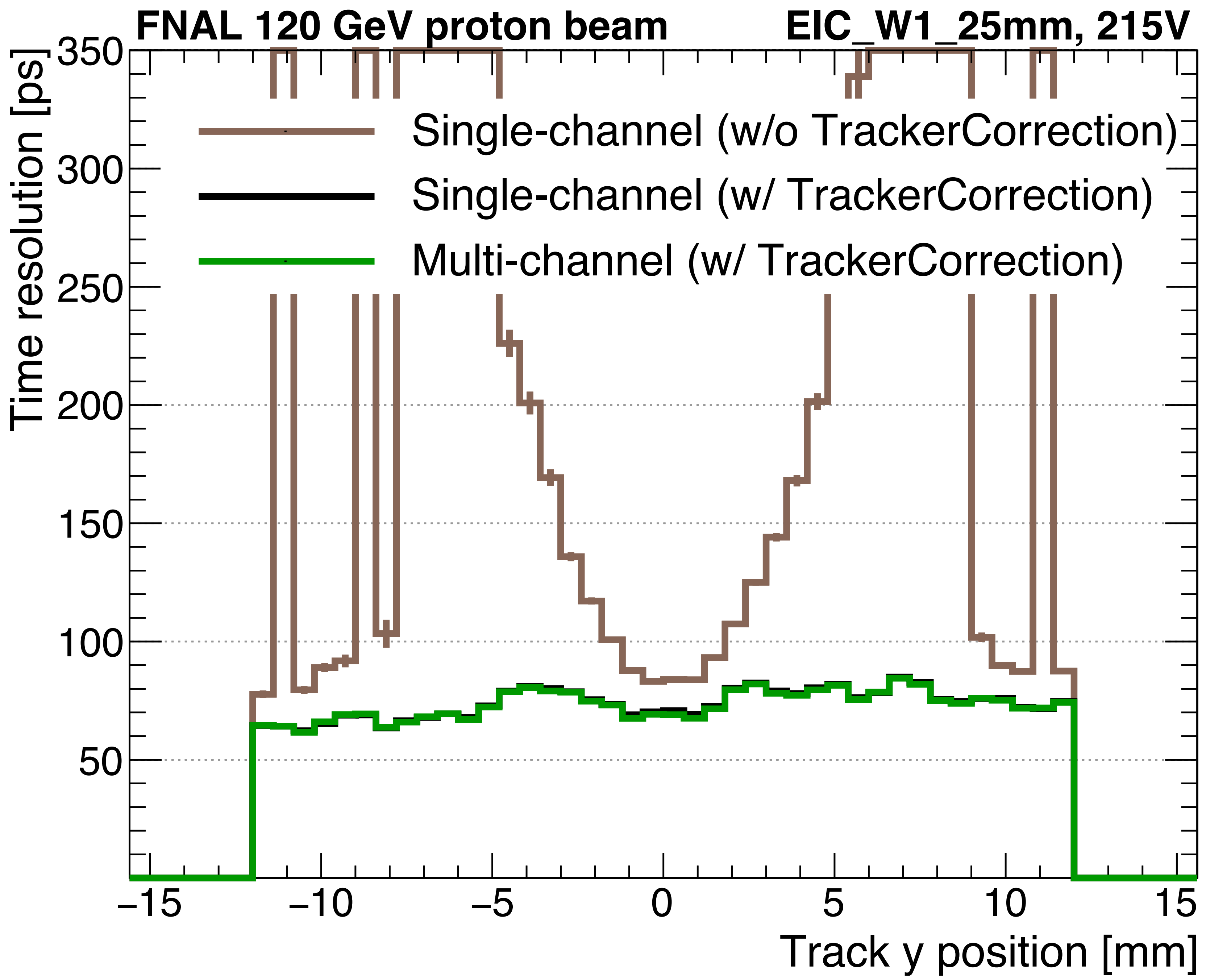
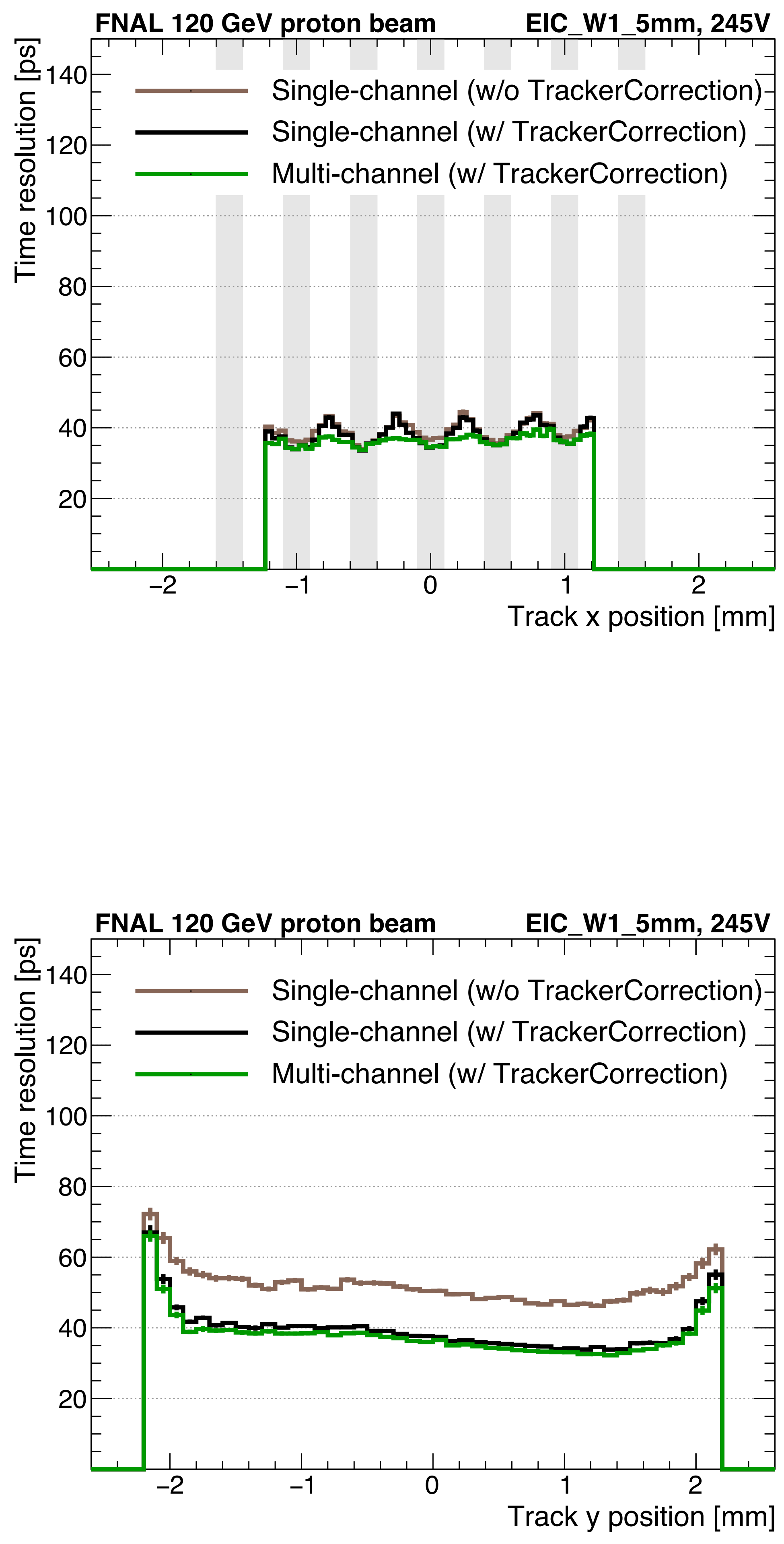
Time resolution



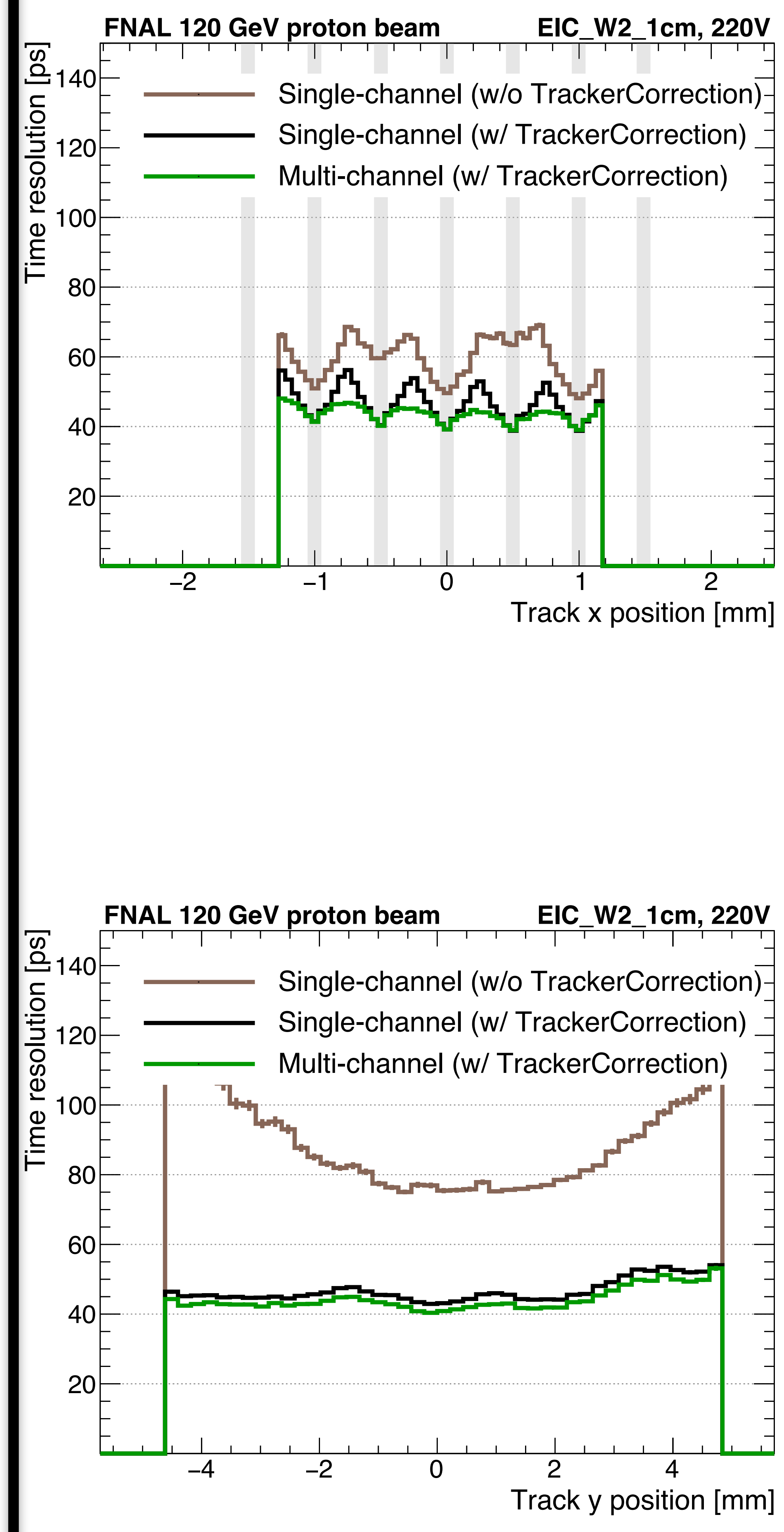


- The time resolution can be **calculated 3 different ways this year**
  - Take the time for max amplitude channel vs. the photek time (usual method)
  - Take the amplitude weighted time vs. the photek time (shown in last paper)
  - Finally, take the tracker corrected time vs. the photek time (new this year)
- **The improvement made by the time delay corrections was massive**

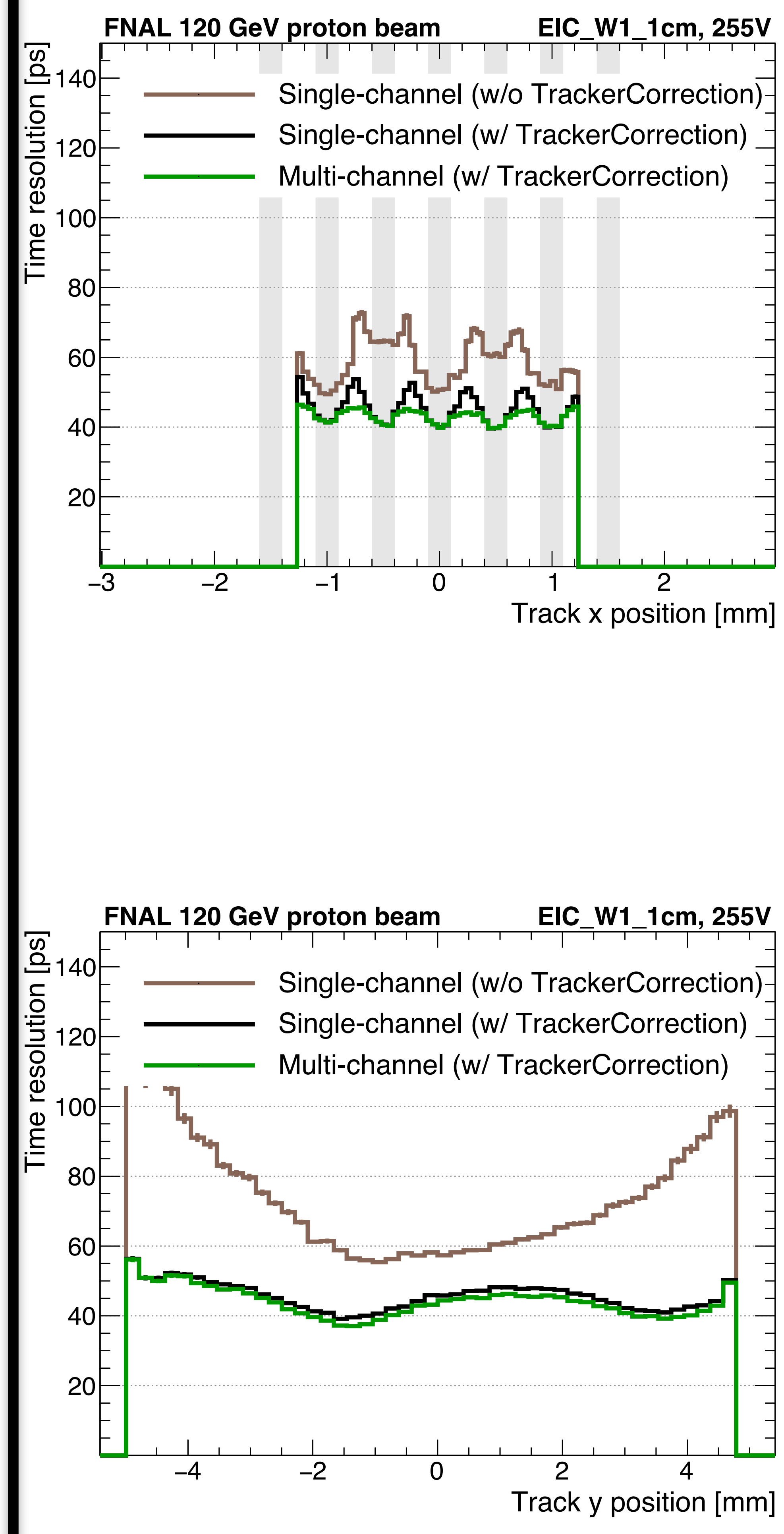
Time resolution



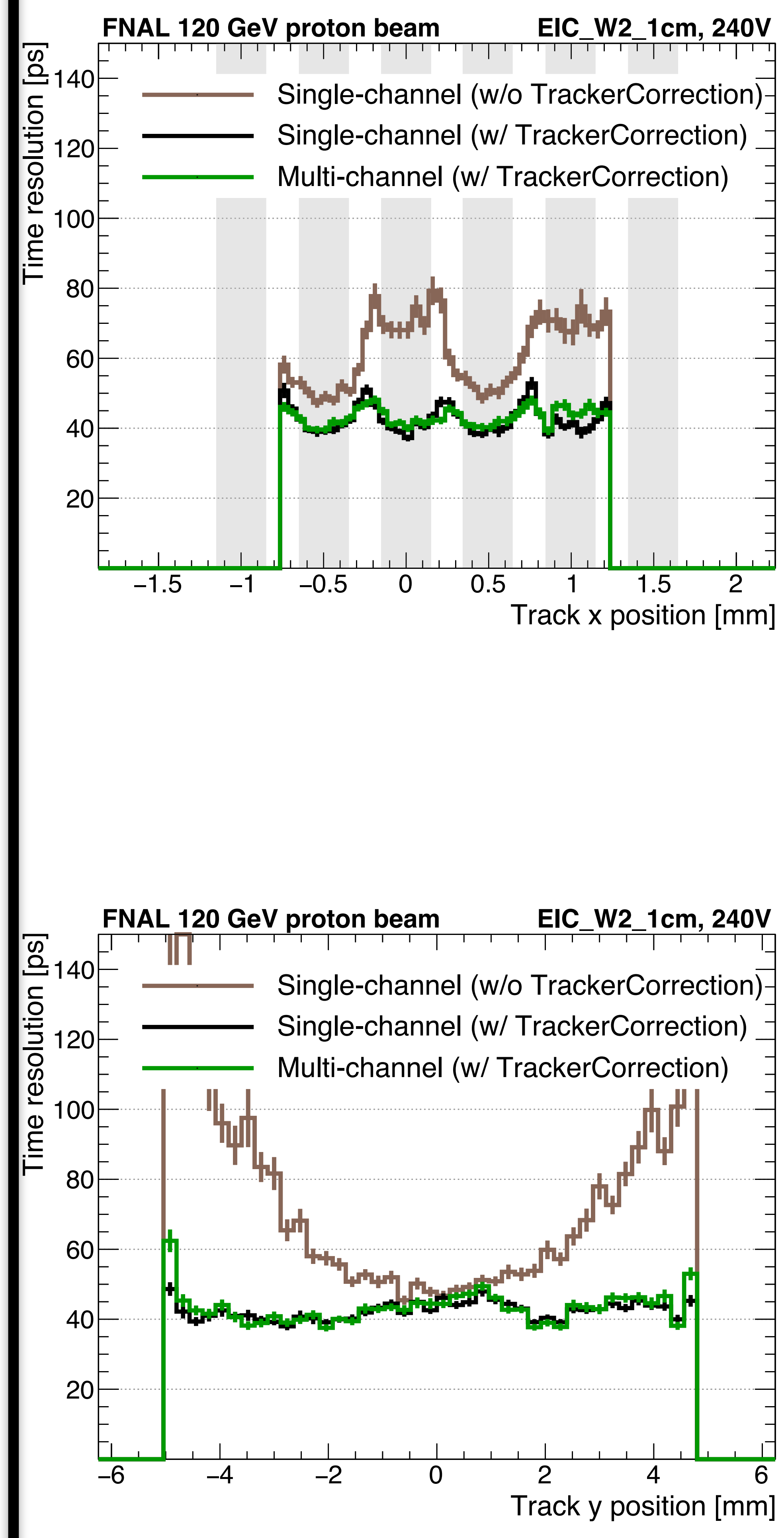
5 mm - 200 um metal



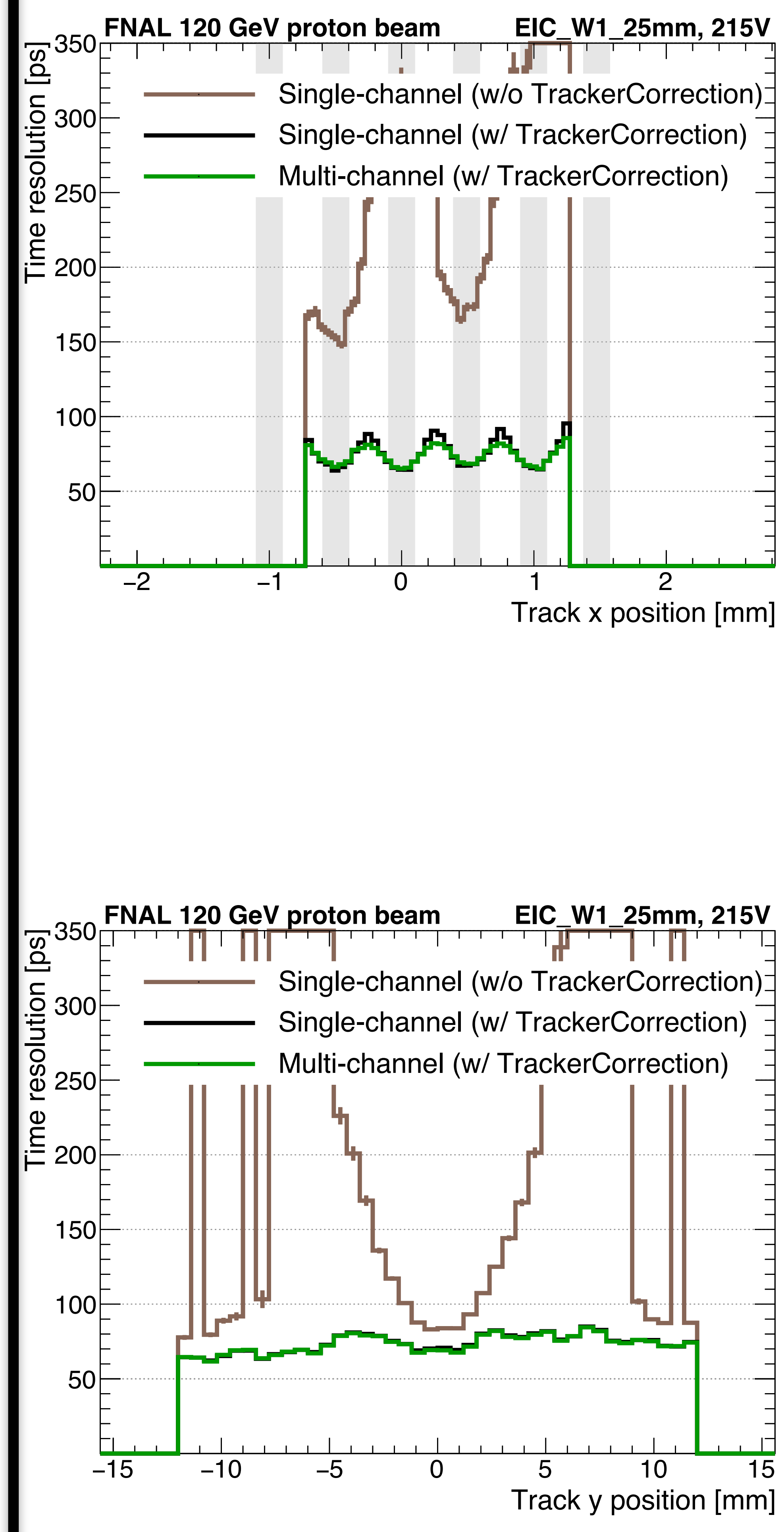
10 mm - 100 um metal



10 mm - 200 um metal



10 mm - 300 um metal



25 mm - 200 um metal

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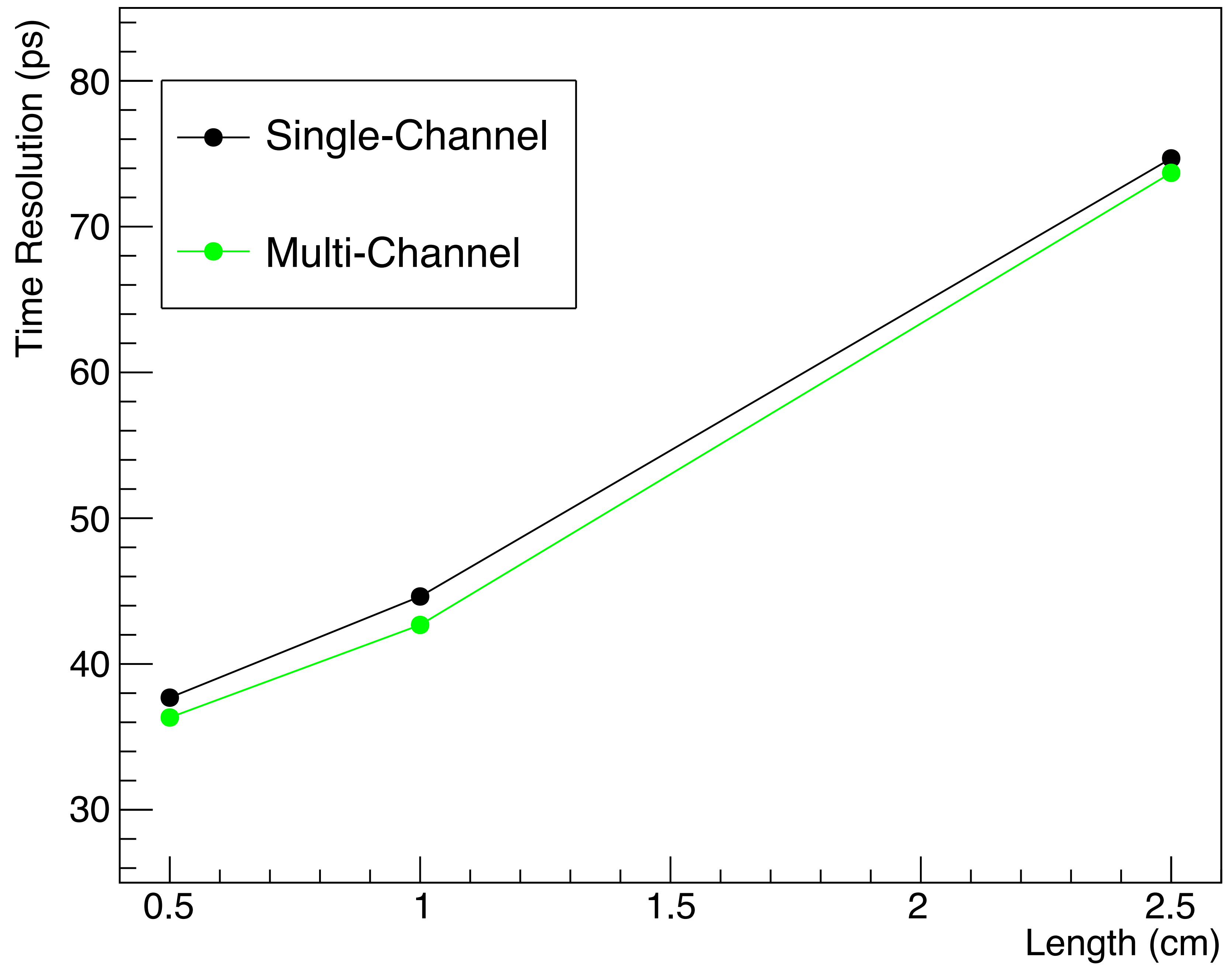
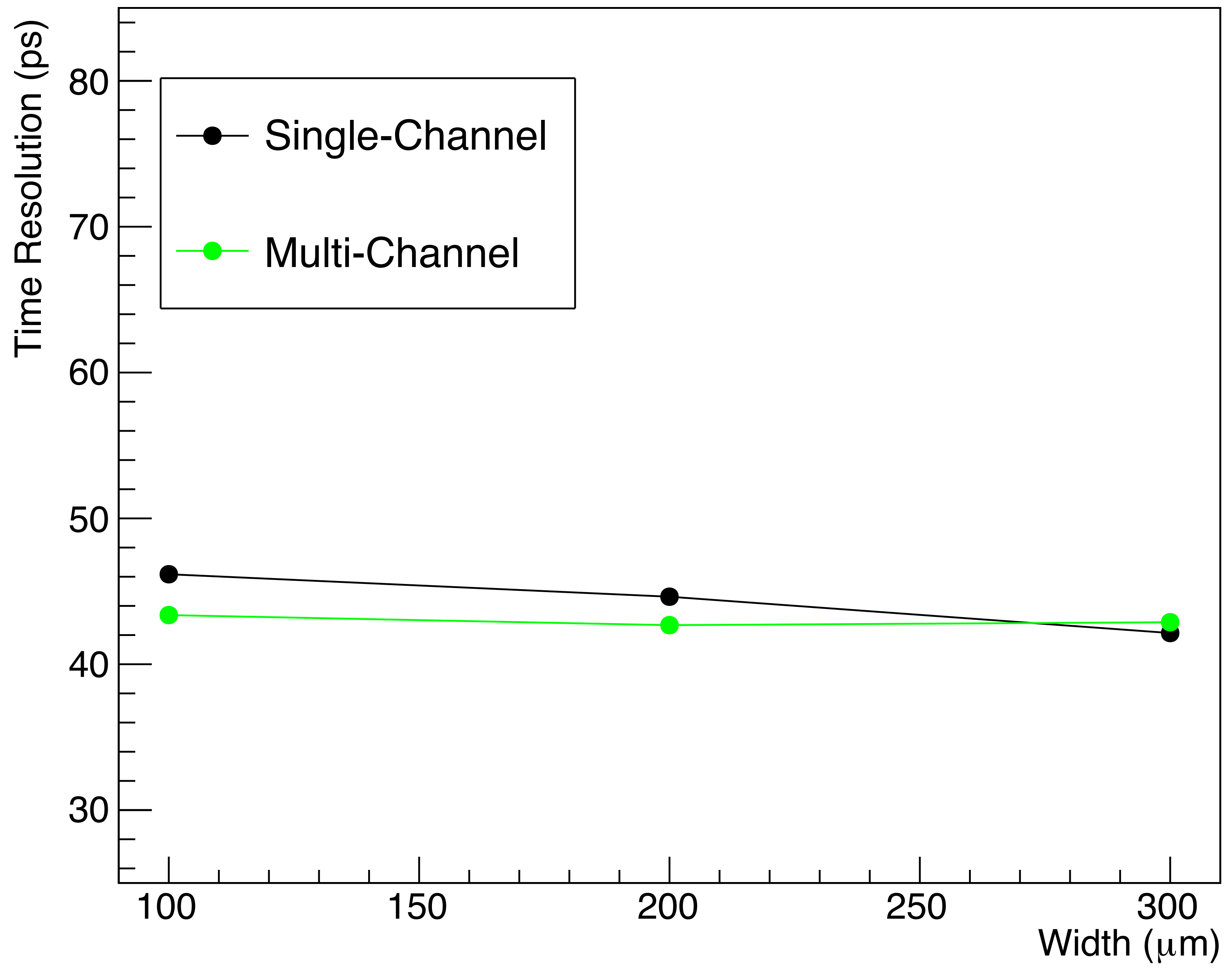
Time resolution

5 mm - 200 um metal | 10 mm - 100 um metal | 10 mm - 200 um metal | 10 mm - 300 um metal | 25 mm - 200 um metal

Time Resolution





- The overall time resolution as a function of tested metal size does not change much
  - Showing error from fit
- **Time resolution as a function of length increases with length**
  - Hard to determine if it is strictly related to non-uniformity
- **Larger metal size decreases fraction of events with multiple good hits**
  - Implies multi-channel time not as effective for larger metal sensors

Time resolution

Sensor	Time Resolution (Single Channel)	Time Resolution (Multi Channel)	Time Resolution (Multi Channel) Hot Region	Time Resolution (Multi Channel) Cold Region	Time Resolution (Multi Channel) Gap Region
5 mm 200 um Metal	37.7 ps	36.3 ps	31.6 ps	37.5 ps	39.5 ps
10 mm 100 um Metal	46.2 ps	43.4 ps	35.6 ps	48.8 ps	44.5 ps
10 mm 200 um Metal	44.6 ps	42.7 ps	33.9 ps	41.7 ps	46.2 ps
10 mm 300 um Metal	42.1 ps	42.9 ps	41.7 ps	50.6 ps	46.4 ps
25 mm 200 um Metal	74.7 ps	73.7 ps	54.4 ps	76.5 ps	81.5 ps

Position Measurement

Position reconstruction

- Similar to last year the position reconstruction can be done calculating the distance from the max strip's center, Δx, which can be modeled as a function of the amplitude fraction $f = a_1/(a_1 + a_2)$:

$$\Delta x = P\ h(f) = P\left(\frac{1}{2} + \sum_{i=1}^{n} c_i (f - 0.5)^i\right)$$

- The expected resolution can then be calculated using propagation of uncertainty:

$$\sigma_x^{\text{expected}} = P\frac{\sigma_N}{a_1 + a_2}\left|\frac{dh}{df}\right|\sqrt{1 - 2f(1-f)}$$

- Which is dependent on the pitch, signal-to-noise, derivative of $h(f)$, and a signal sharing component

- Then the only piece of information needed is to measure the $h(f)$ function for each sensor

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Position reconstruction fit: h(f)

- Dotted lines shows projection of fit after max fraction cut off
  - Large amplitude fraction makes determining correct side of max strip to add the deltaX difficult

- The size of the metal has an impact on functional form
  - Want smaller derivative -> smaller resolution
  - More uniform uncertainty with linear function

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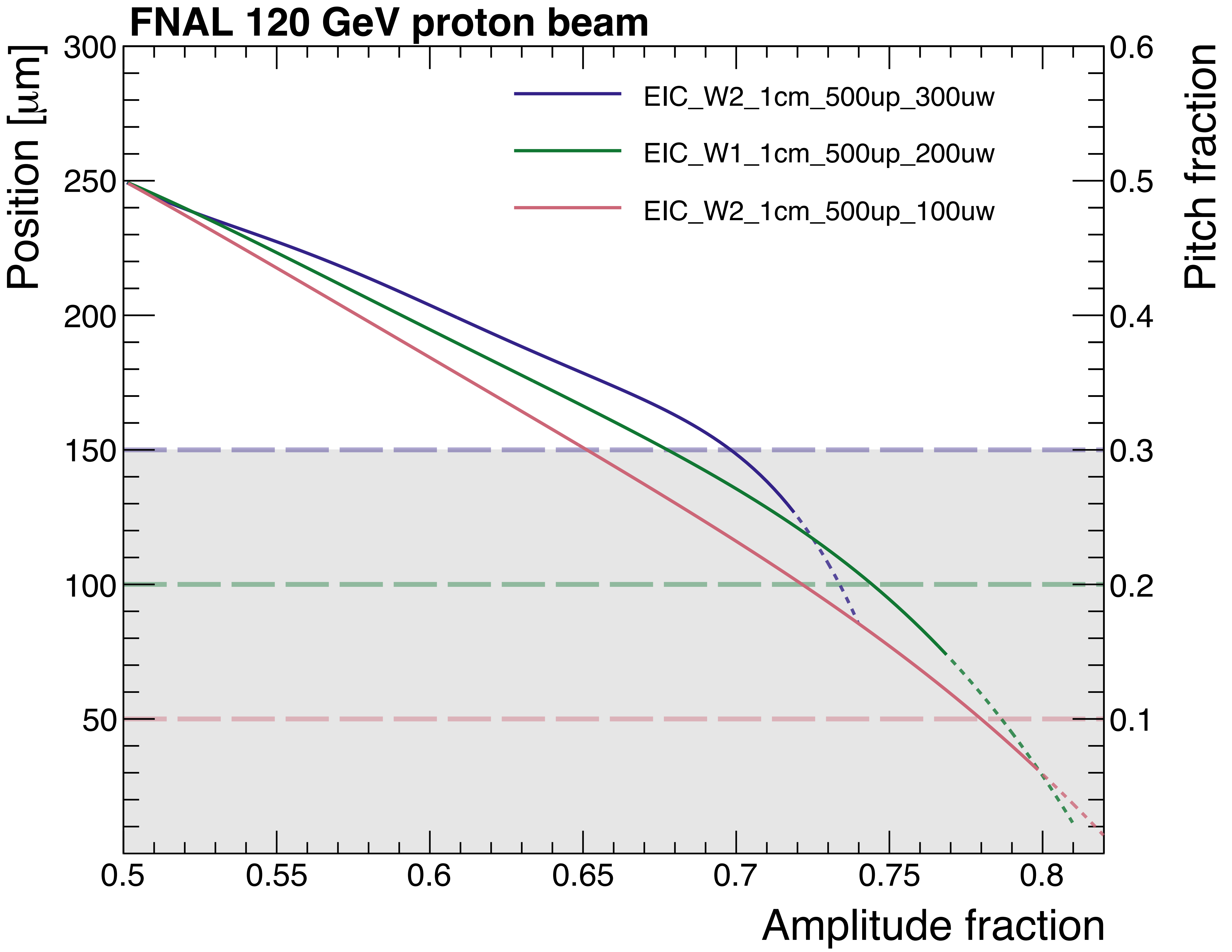

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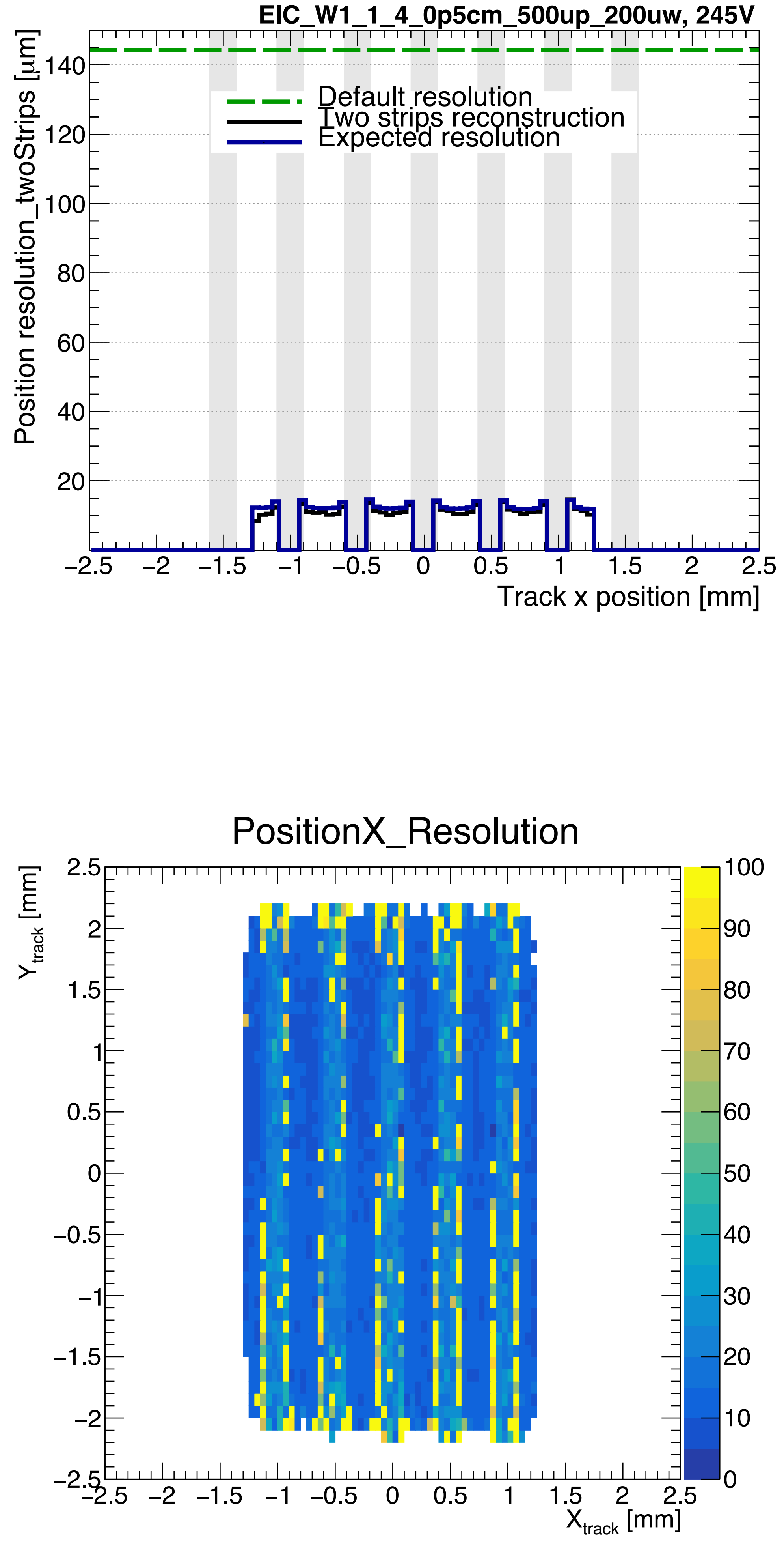
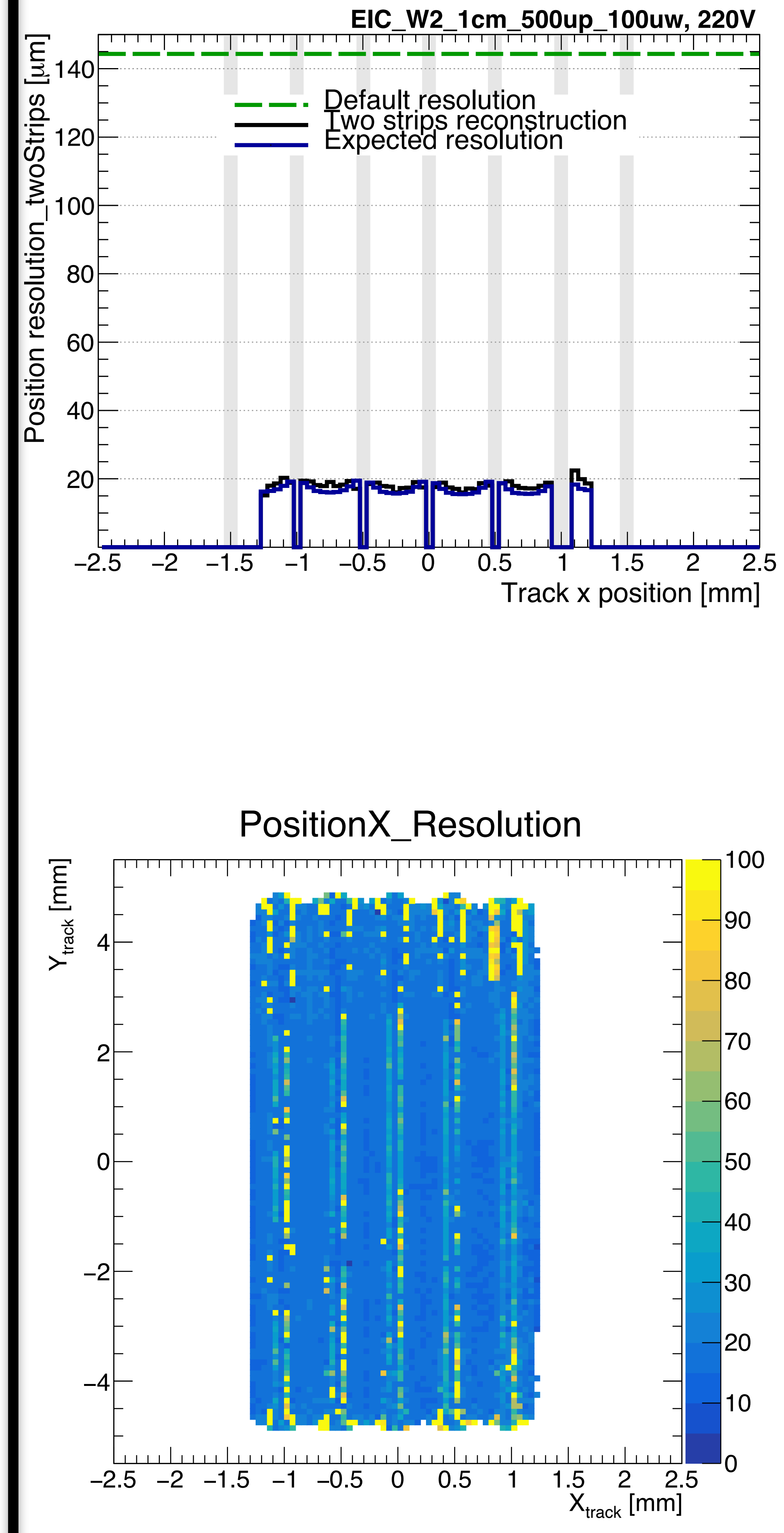
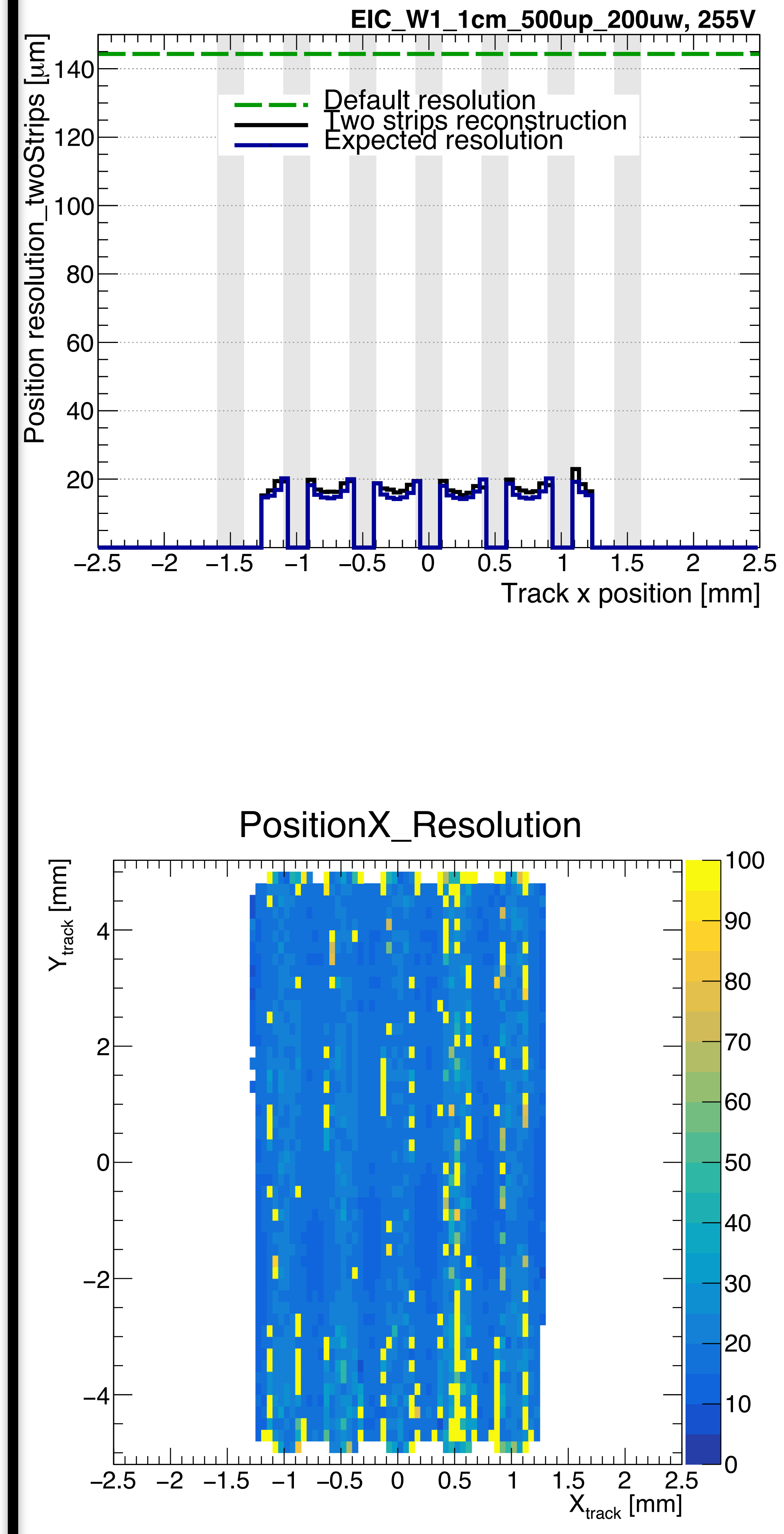
Position resolution



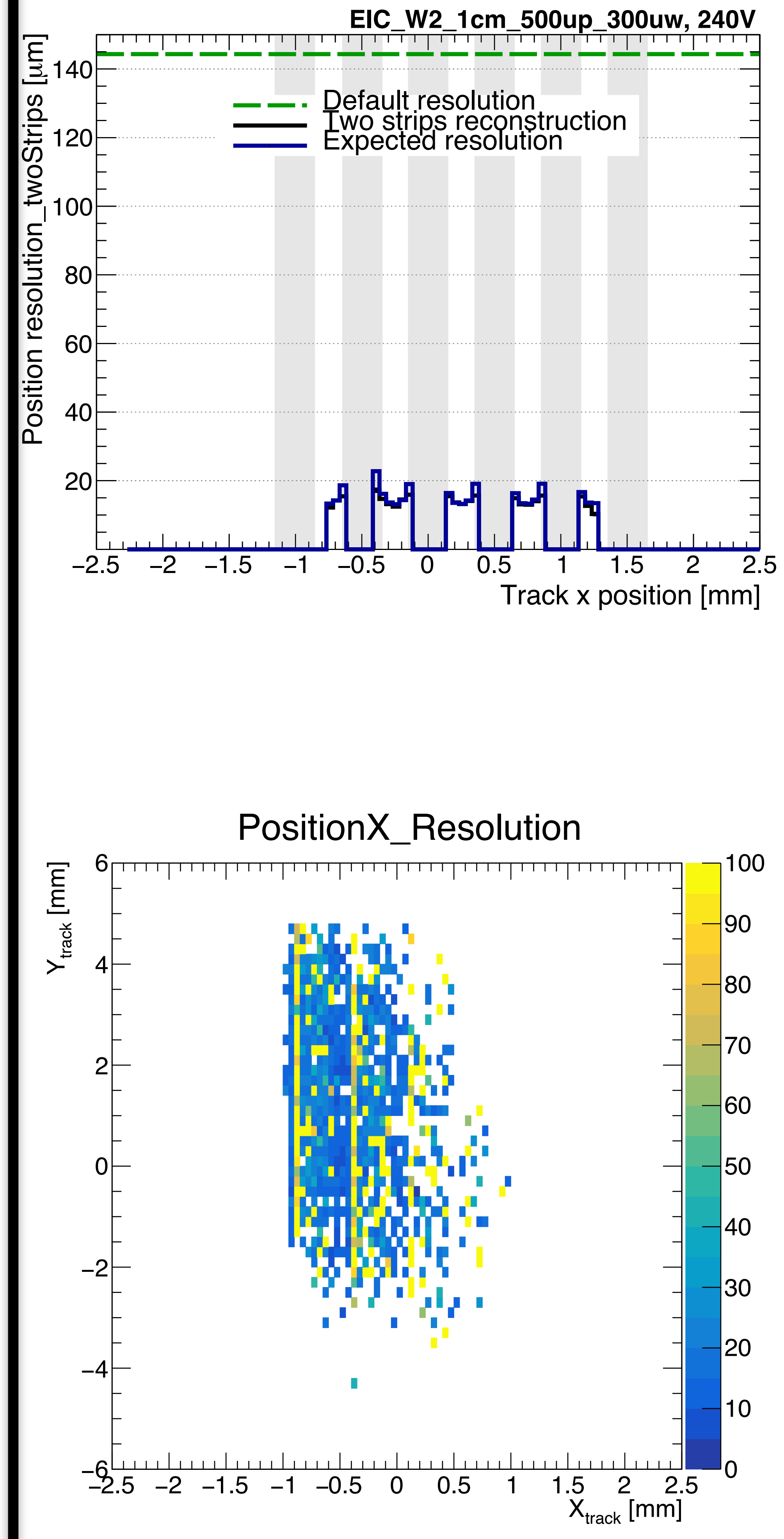
5 mm - 200 um metal



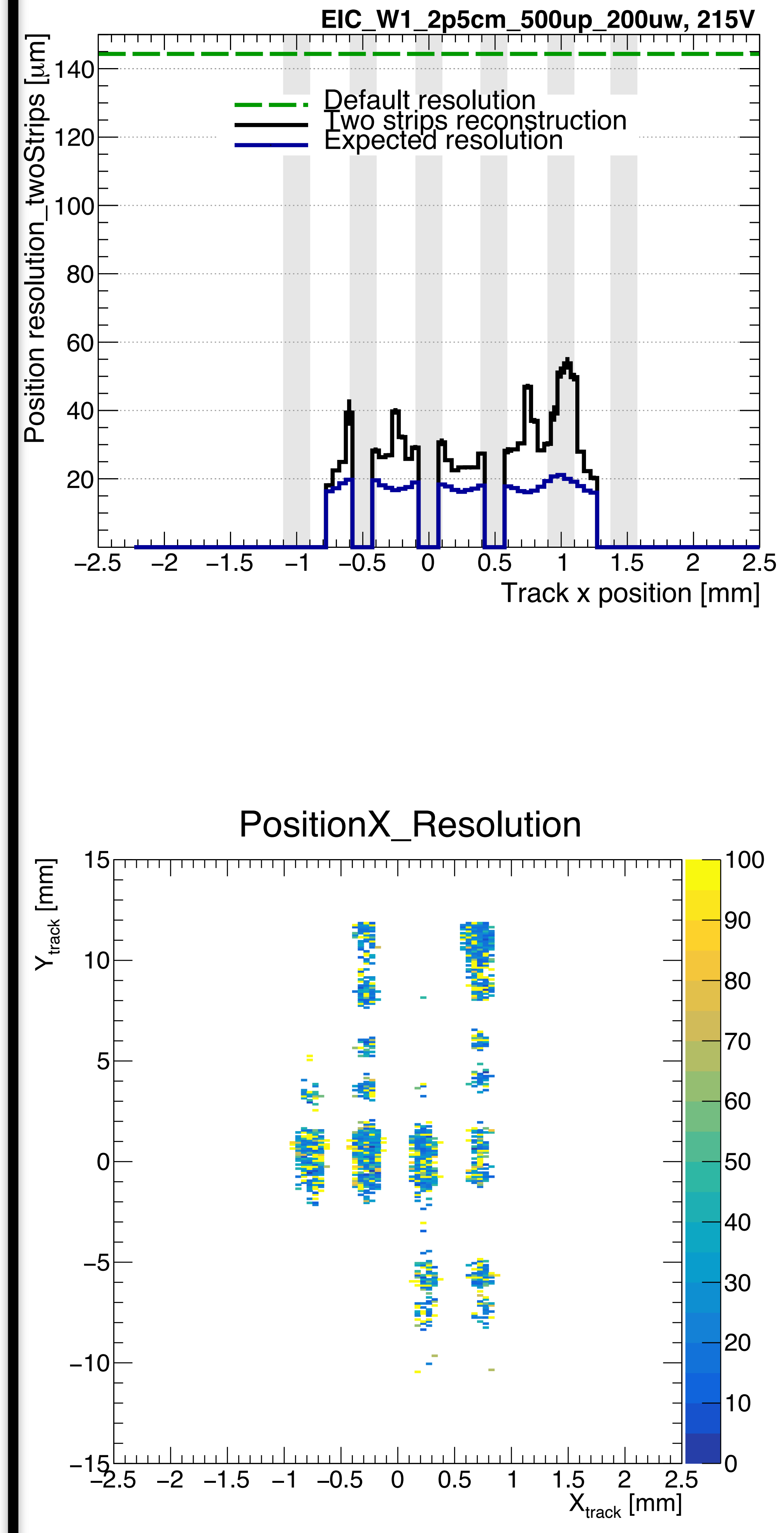
10 mm - 100 um metal



10 mm - 200 um metal



10 mm - 300 um metal



25 mm - 200 um metal

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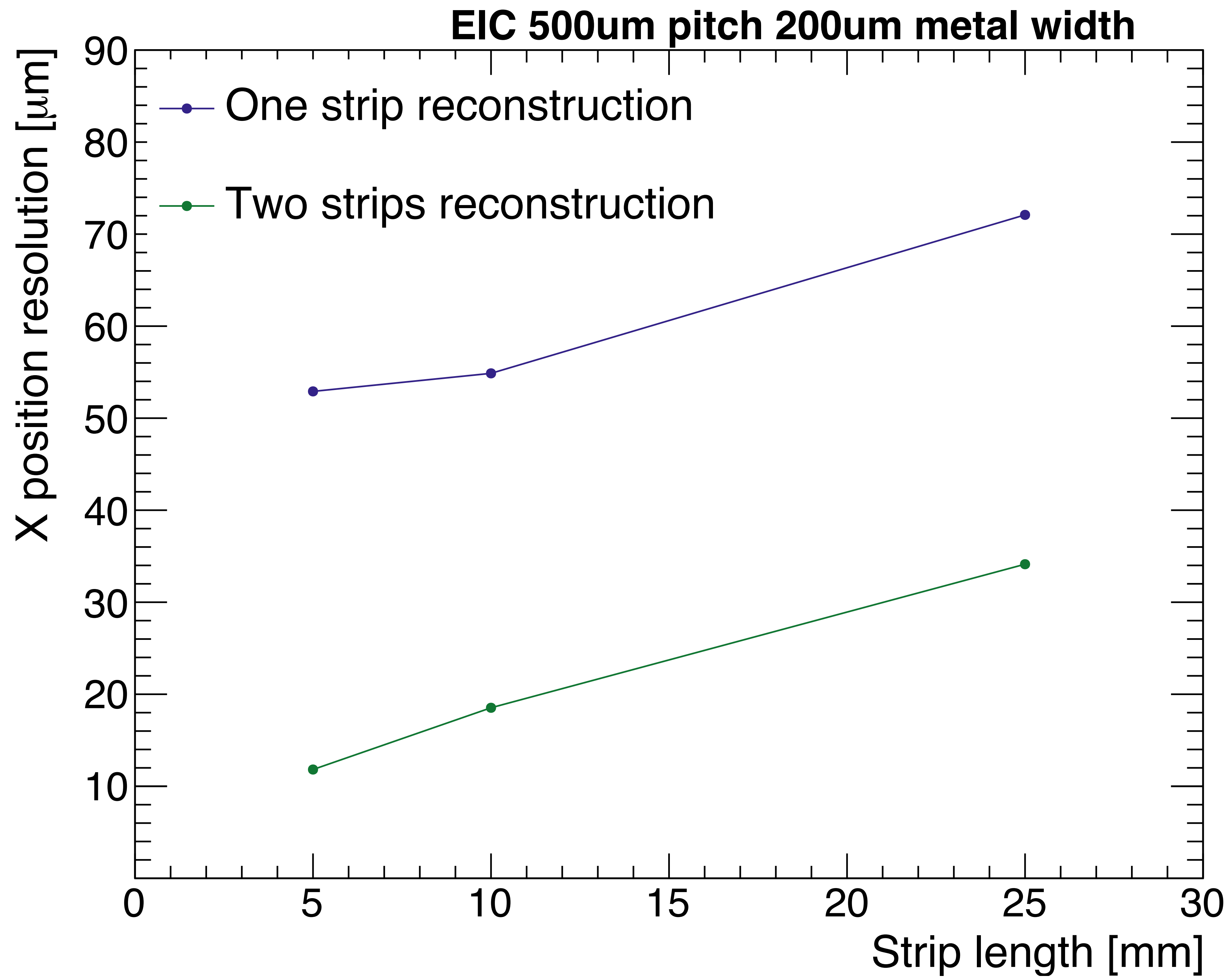
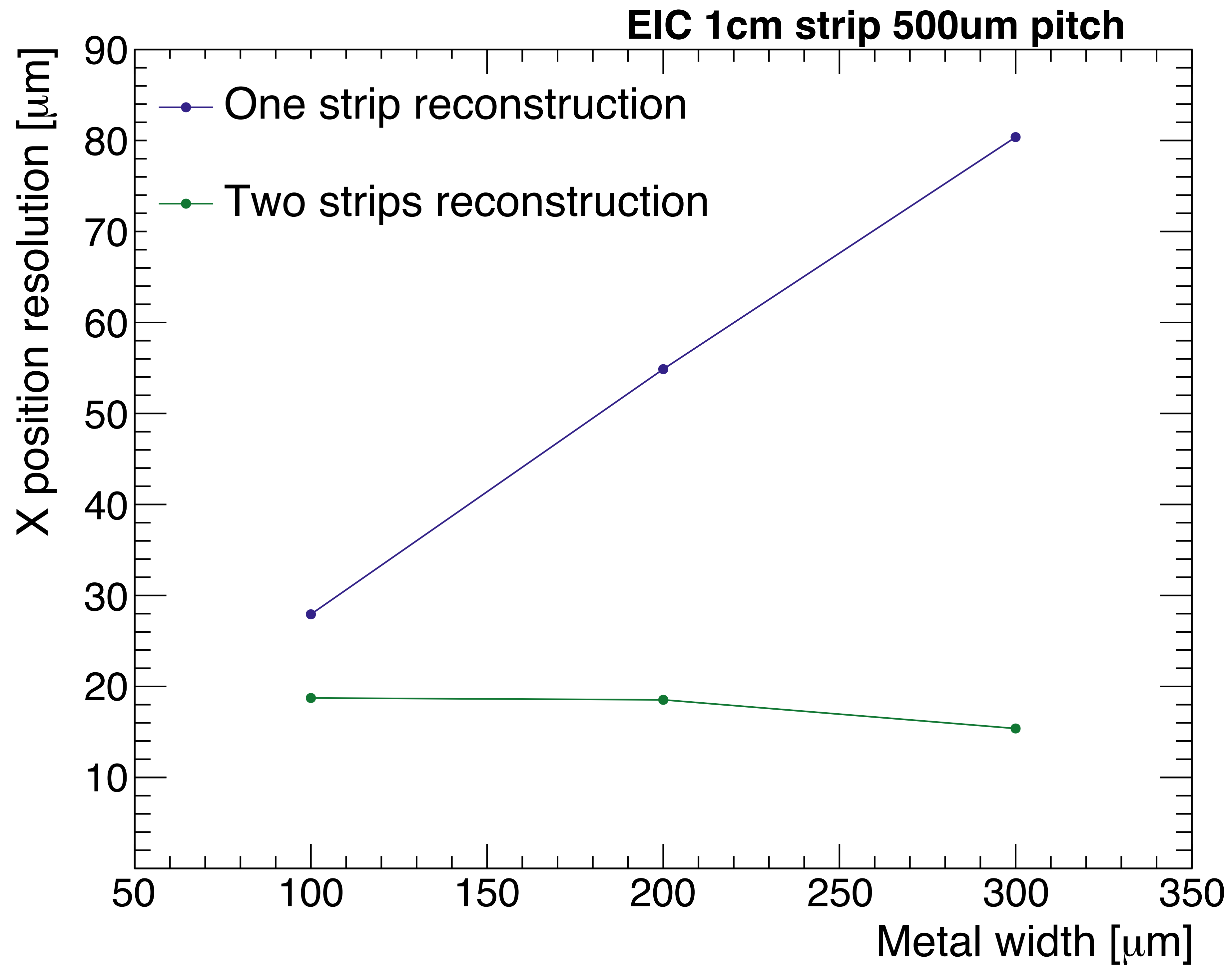
Position resolution summary





- **Two strip reco only available for gap hits; However works very well even with non-uniformity**
  - One strip reconstruction ~ metal size/sqrt(12)
- **Two strip reco not too dependent on metal size**
- **Resolution is worse for longer strip**
  - Could be related to non-uniformity

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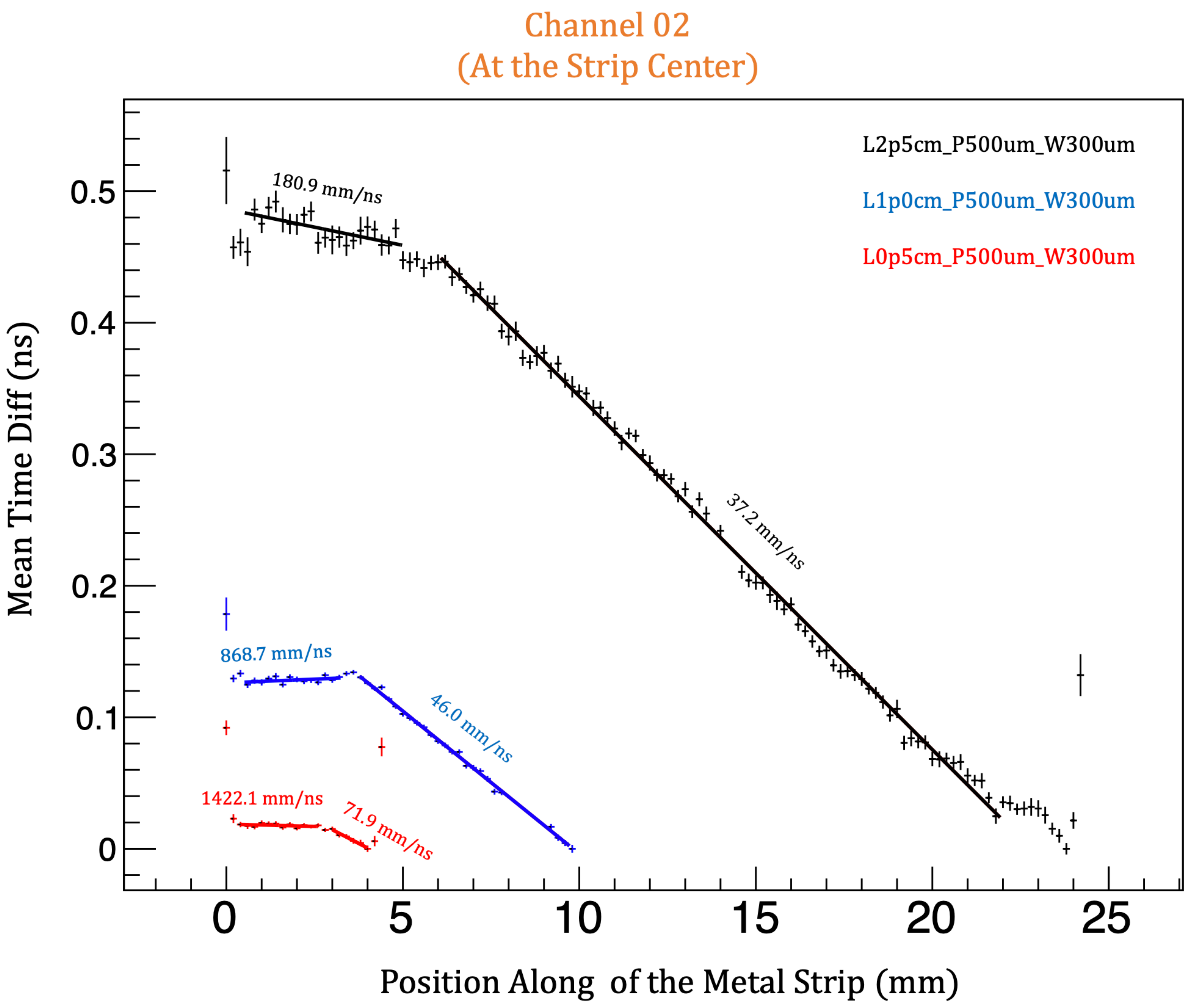
“Velocity” Measurements

- Working on measuring “velocity” of signals vs y and x direction
  - Can be used for possible y-direction reco
- Overall values not too surprising
- However, see a **plateau region for signals coming from the opposite side of the wirebond**
  - What could cause this?
  - Do these signals take a different path?
- Also, noticed velocity values depend on wirebond location
  - Up vs. down wirebonds have different velocities



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Y position reconstruction

- A new interesting use of long AC-LGAD strip sensors is to use time information to reconstruct the y position along the strips
- The position from the center of the sensor, Δy, can be modeled by assuming the signal first moves along the x direction then along the y direction yielding:

$$\Delta y = \frac{v_y}{v_x}\left(\frac{P}{2} - \Delta x\right) + \frac{1}{2}v_y \Delta t = g(\Delta x(f), \Delta t)$$

- Which is in general modeled by some function $g(\Delta x(f), \Delta t)$ and assuming the velocity along the x and y directions are a constant
- Using the first function directly gives an expected y uncertainty of:

$$\sigma_y^{\text{expected}} = \frac{v_y}{v_x}\sqrt{\sigma_x^2 + \frac{1}{2}v_x^2\sigma_t^2}$$

- Plugging in the numbers we have on hand gives a rough estimate of the resolution:

$$\sigma_y^{\text{expected}} \approx \frac{50}{2}\sqrt{0.02^2 + \frac{1}{2}2^2 0.04^2} \approx 1.5\text{mm}$$

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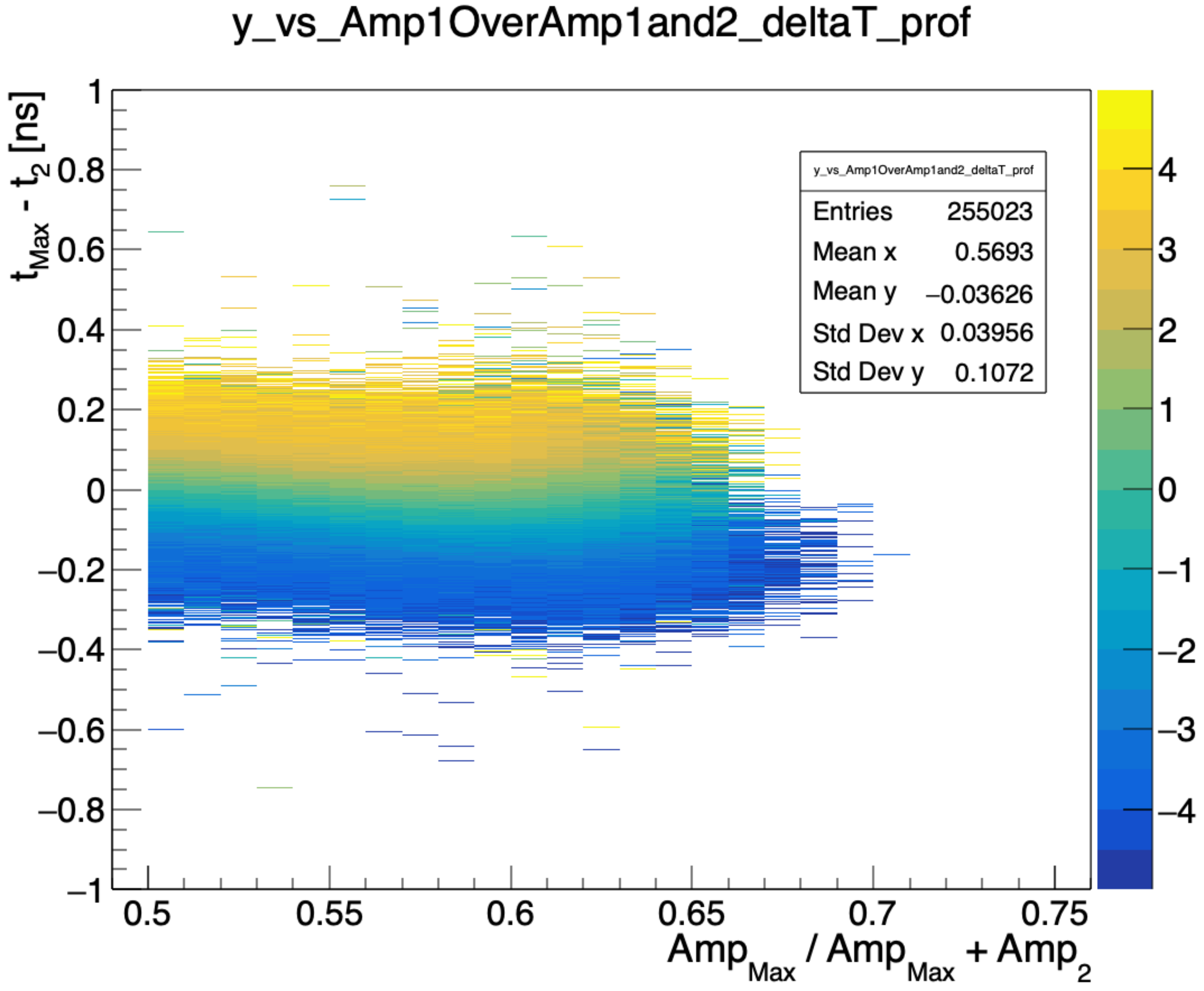
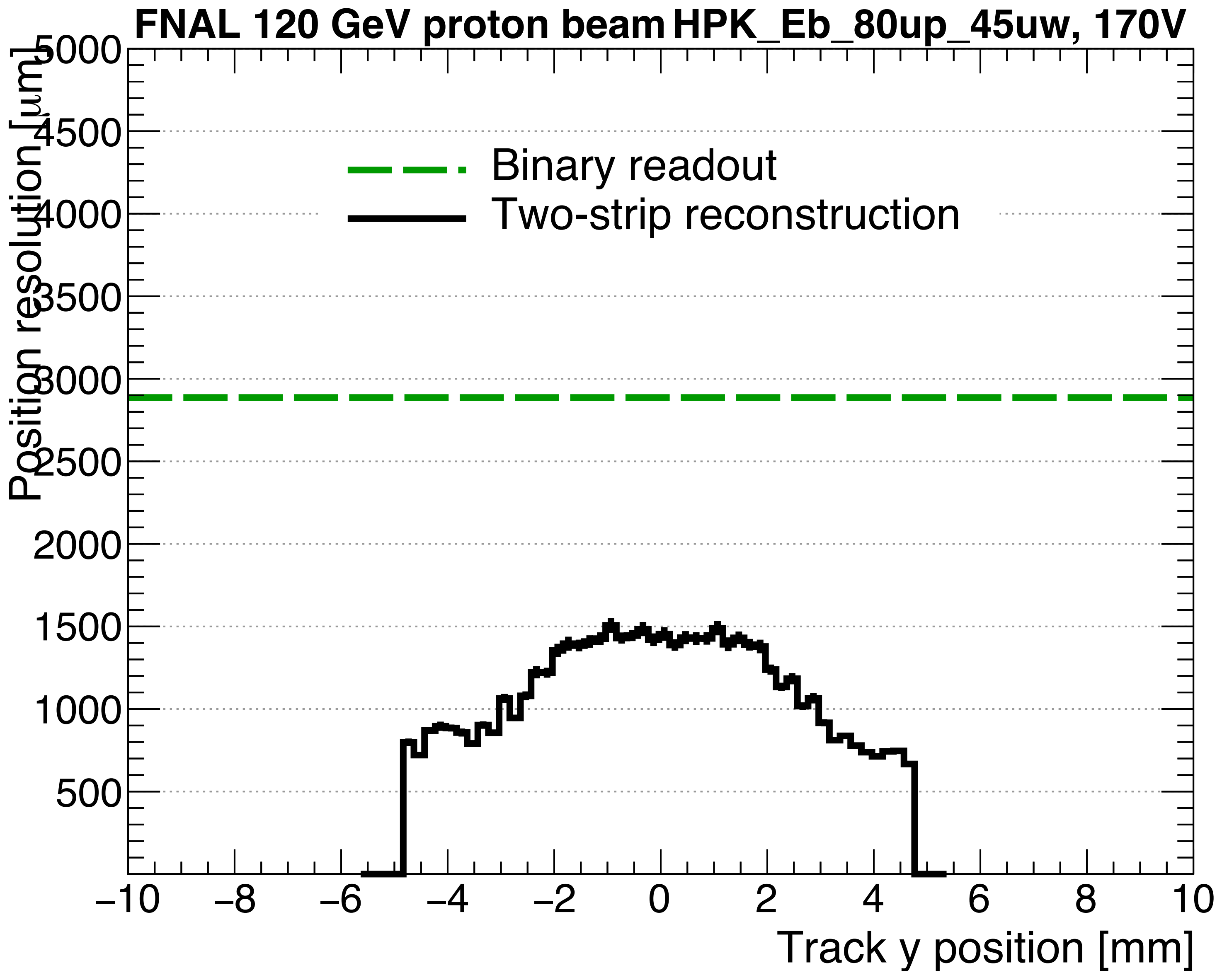
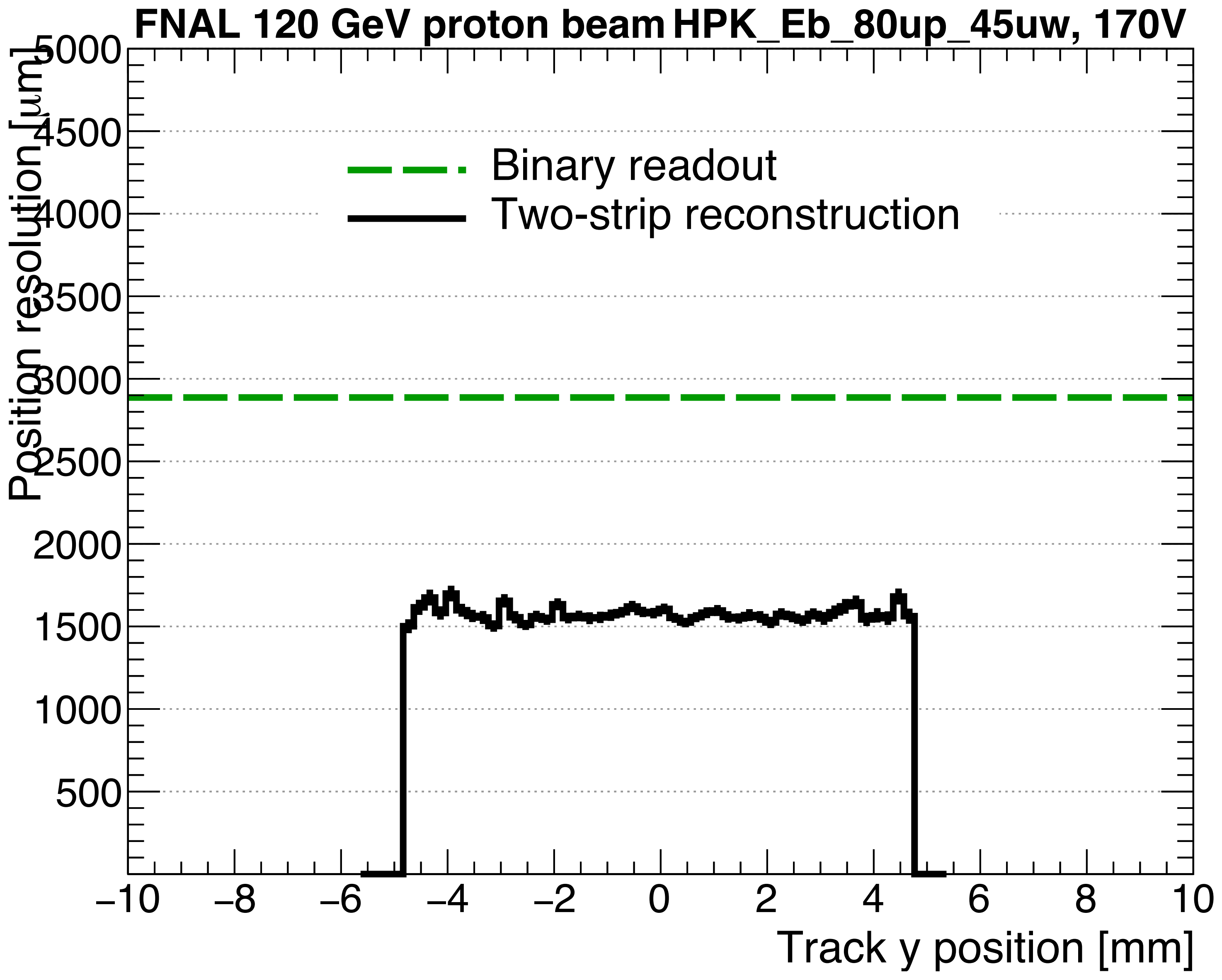
Y position reconstruction







- There are two methods that we have now to do the y reconstruction
  - Using the formula on previous slide directly or using a lookup table of deltaT and amplitude fraction, f
- Both methods are shown here for HPK sensor (Work in progress)
  - Plan to produce results for all sensors soon
  - The measured resolution agrees well with the expected value of about ~1.5 mm
- **Not the most useful outcome but perhaps has a purpose for some AC-LGAD use case**

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Summary

- **Large sensors will need to have a position dependent delay correction**
  - Need reasonable track measurement to correct time
- There is an issue with efficiency but should be corrected with gain uniformity
  - **Even with non-uniformity we manage to get great results; was not clear it was possible a-priori**
- **Sensor length rather than sensor area matters for pulse shape variables**
  - Initially assumed results would depend strongly on area -> sensor capacitance;
  - Risetime and slewrate noticeably different for longer sensors
  - Contributes to worse time resolution
- **For this large pitch and current resistivity two strip x-position reconstruction only available in gaps**
  - Direct metal hits should have ~metal size/sqrt(12) resolutions assuming it couldn't be a gap hit
- **Time resolution is uniform after time corrections for all sensors**
  - Fixing non-uniformity should correct this further
- **All sensors satisfy time resolution < 50ps and position resolution < 30 microns**

Next step

- What should be studied for next round of sensors?
  - **Study large pitch sensors with narrow metal**
- Continue studying sensor length
  - Sensor area does not seem to drive performance
  - Change in rise time has biggest impact on time resolution
    - Not driven by capacitance but rather superposition of reflections?
- Minimize metal area size
- Recover 2-strip reconstruction for the full sensor
  - Change pitch
  - Increase signal size
- Explore readout
  - Wirebond locations
  - Tune readout board for larger sensors