Results from Large Area AC-LGAD Test Beam campaign in 2023

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ePIC Collaboration Meeting
Argonne National Laboratory

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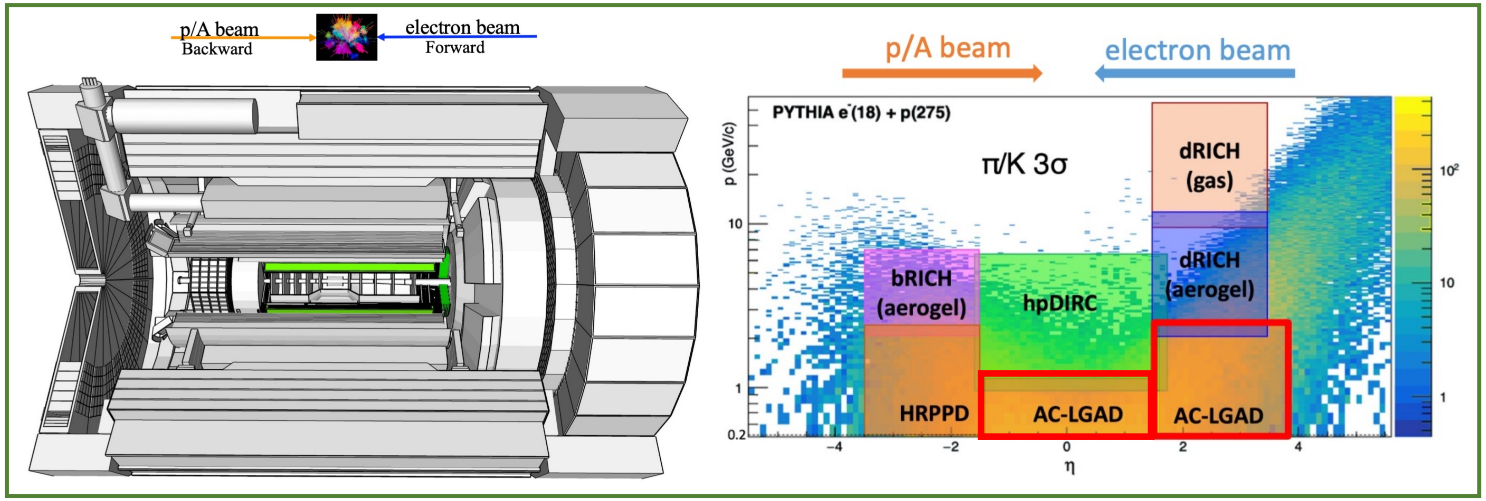
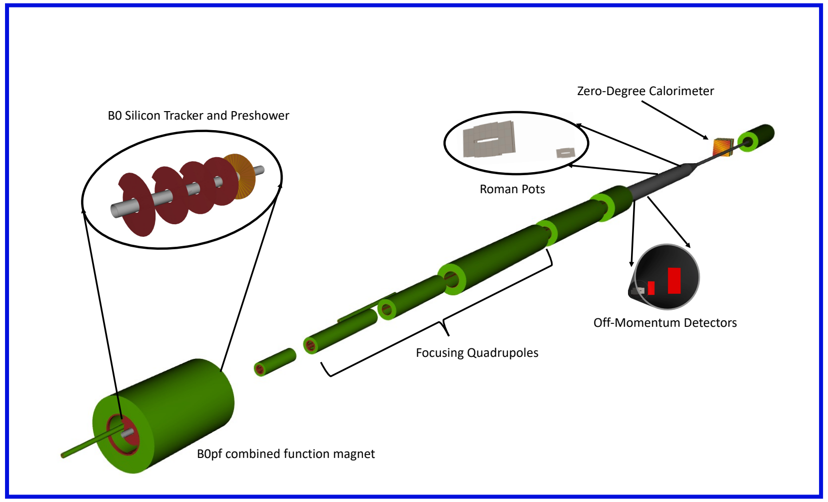
Specifications of ePIC AC-LGAD detectors in EIC:

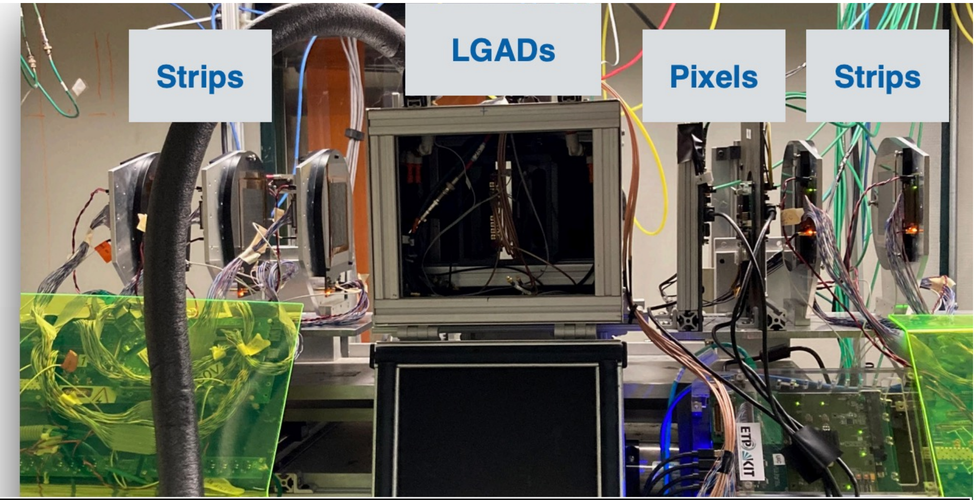


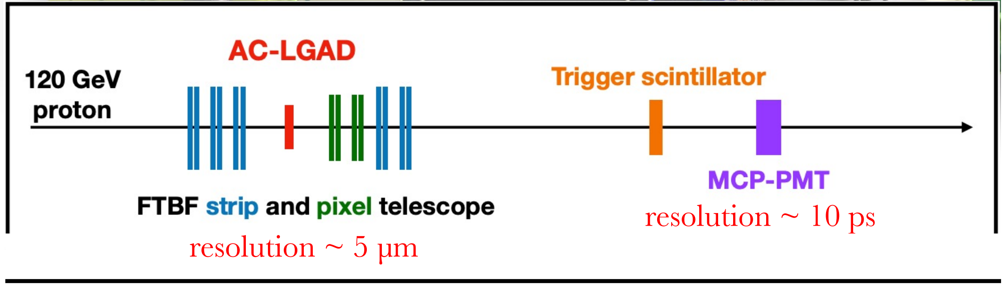


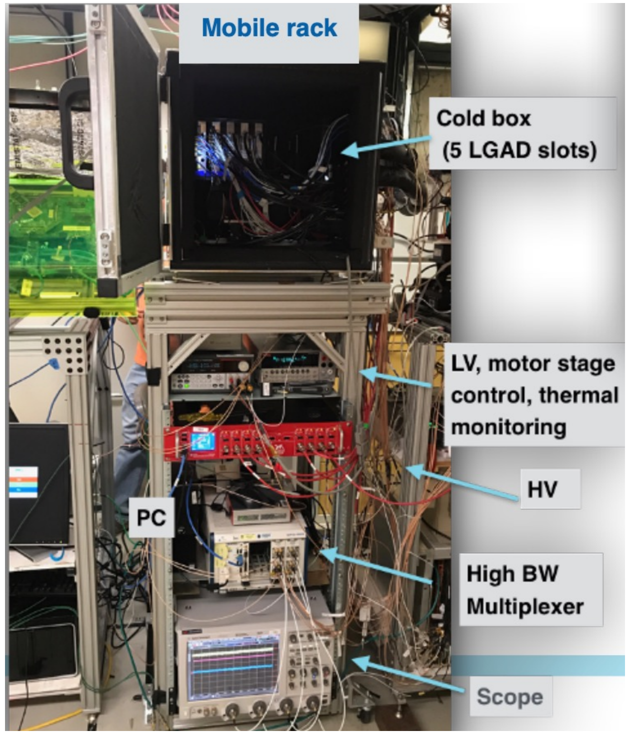
- Central: PID capabilities below the threshold of Cherenkov PID detectors
- Far forward:
  - B0: tracking capability for charged particles.
  - Roman Pots (RPs): scattered charged particles close to beam.
  - The off-momentum detector (OMD): charged particles from nuclear breakup.

	Angular accept.	Channel size (mm^2)	Timing Resolution	Spatial resolution	Material budget
Barrel ToF	$-1.4 < \eta < 1.4$	0.5*10	35 ps	30 μm in φ	0.01 X0
Forward ToF	$1.5 < \eta < 3.5$	0.5*0.5	25 ps	30 μm in x and y	0.025 X0
B0 tracker	$4.6 < \eta < 5.9$	0.5*0.5	30 ps	20 μm in x and y	0.05 X0
RPs/OMD	$\eta > 6$	0.5*0.5	30 ps	140 μm in x and y	no strict req.

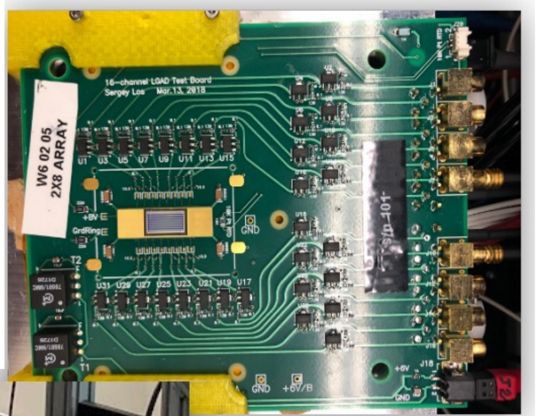
Fermilab test beam setup for AC-LGADs:





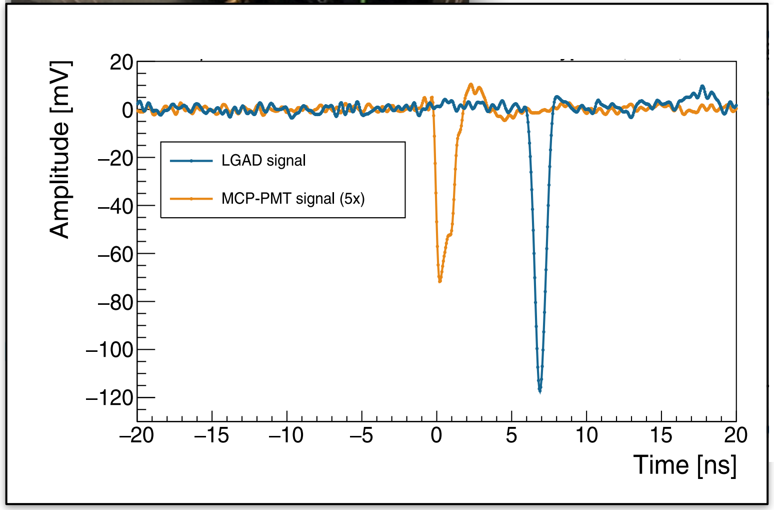


FNAL 16 Ch Board



Record 20k events during 4s spill

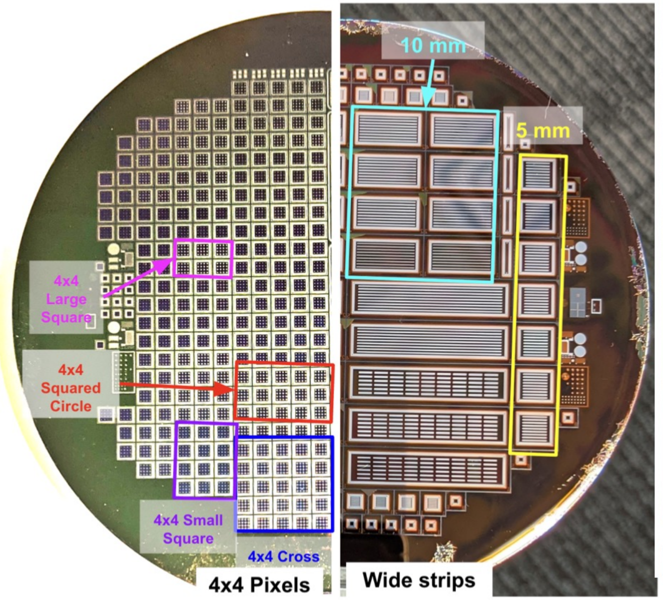
8-channel oscilloscope, 2 GHz, 10 GSa/s



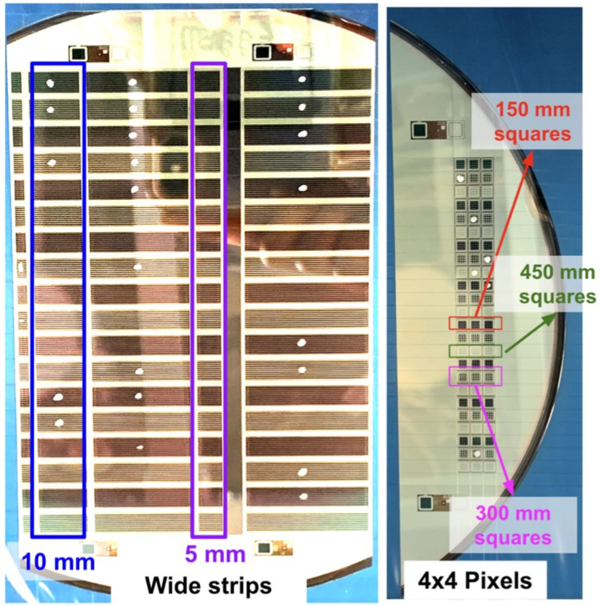
- 120 GeV primary proton beam from main injector
- AC-LGAD and MCP-PMT waveforms were recorded in the oscilloscope
- Stable temperature of 20^{0} C maintained inside the cooling block
- Optimal bias is a few volts below the breakdown (stable noise from the channels)
- Sensor alignment based on position of sensor along beamline and rotation around beam

Large area AC-LGAD sensors in test beam campaign 2023:

BNL Wafer



HPK Wafer



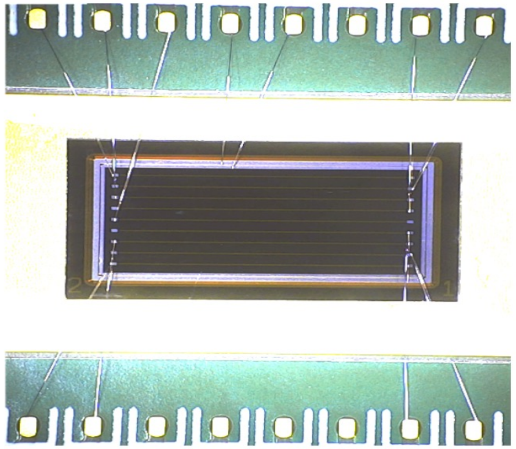
BNL

- Strip metal width variation
- Pixel sensors with different metal pad shapes

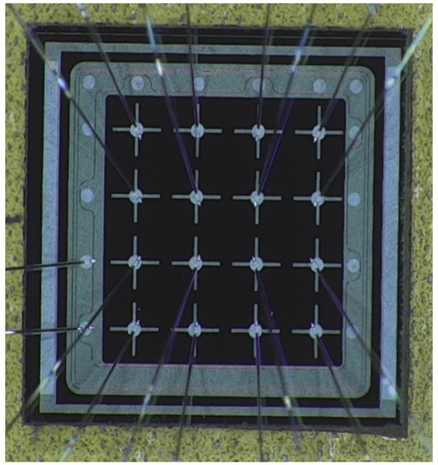
HPK

- Active thickness
- Strip or pad metal width
- Resistivity of n^+ layer
- Coupling capacitance of dielectric layer

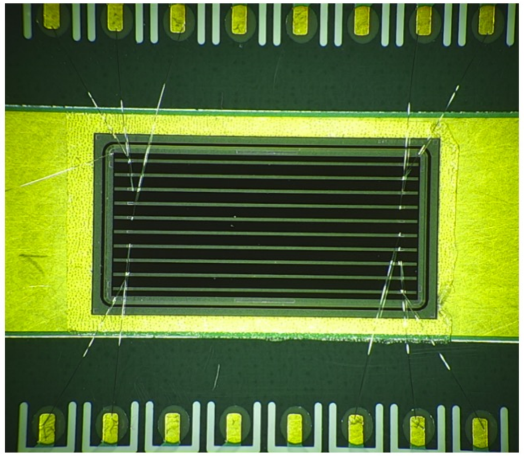
BNL strip sensor



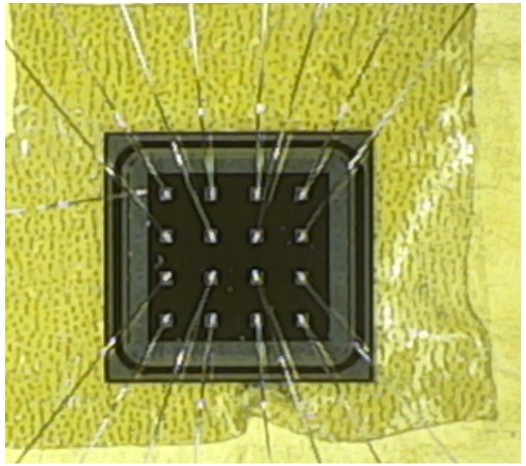
BNL pixel sensor (cross)



HPK strip sensor



HPK pixel sensor



Large area AC-LGAD sensors in test beam campaign 2023:

Strips

Name	Wafer	Pitch (µm)	Strip length (mm)	Metal width (µm)	Active thickness (µm)	Resistivity (Ω/□)	Capacitance (pF/mm^2)	Optimal bias voltage (V)
SH1	W9	500	10	50	20	1600	600	114
SH2	W4				50	400	240	204
SH3	W8						600	200
SH4	W2					1600	240	180
SH5	W5						600	190
SH6	W9			100	20	1600	600	112
SH7	W8				50	400	600	208

Large area strip sensors

- 1 cm length, 500 µm of pitch
- Metal width variation
- Active thickness variation
- Resistivity variation
- Capacitance variation

Pixels

Name	Wafer	Pitch (µm)	Metal width (µm)	Active thickness (µm)	Resistivity (Ω/□)	Capacitance (pF/mm^2)	Optimal bias voltage (V)
HPK 2 x 2 Square pixel							
PH1	WP1	500	450	20	1600	600	105
PH2	WP2			30	1600	600	140
PH3	WP3			50	1600	600	190
HPK 4 x 4 Square pixel							
PH4	W11	500	150	20	400	600	116
PH5	W9				1600	600	112
PH6	W8			50	400	600	200
PH7	W5				1600	600	185
PH8	W9		300	20	1600	600	112

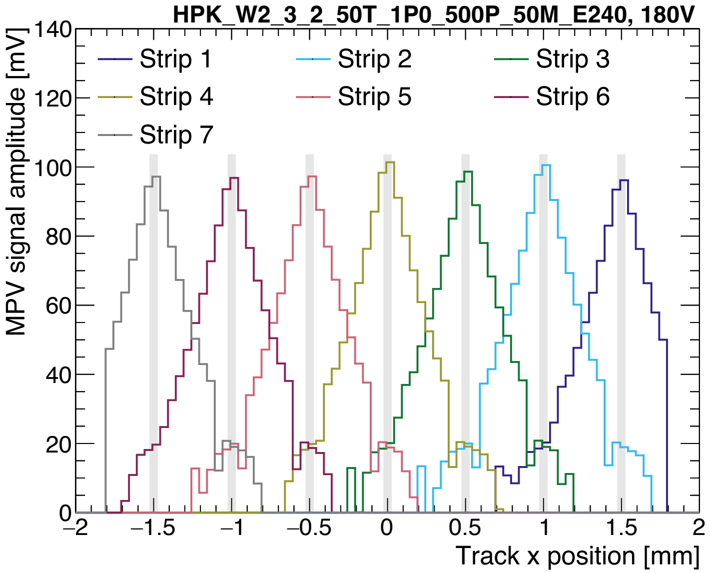
Large area pixel sensors

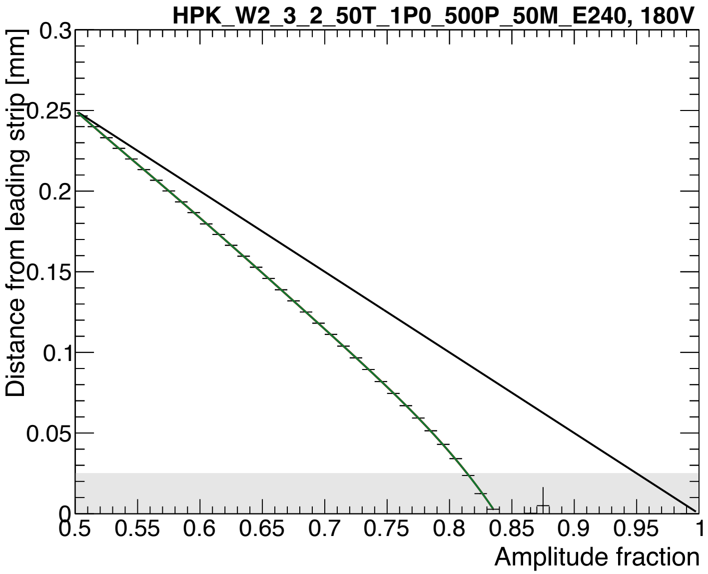
- 500 x 500 µm pitch
- Metal width variation
- Active thickness variation
- Resistivity variation

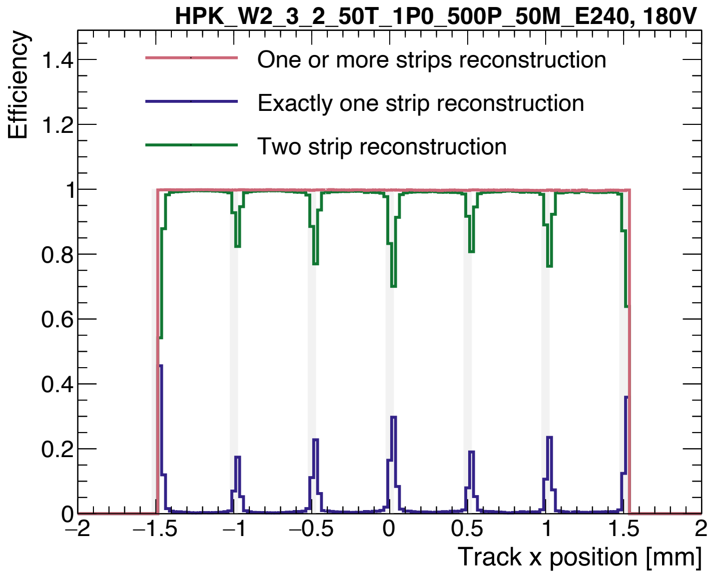
Spatial resolution in AC-LGADs:

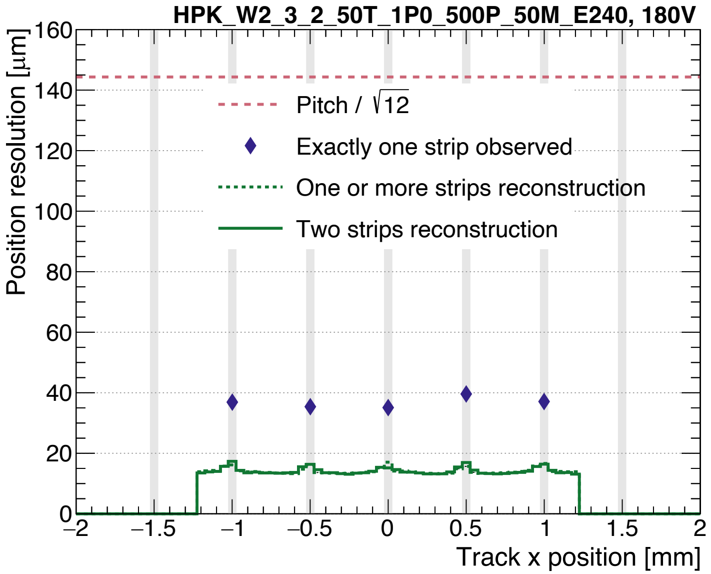
HPK Strip : 10 mm length, 500 μm pitch, 50 μm metal width, 1600 Ω/□ resistivity, and 240 pF/mm^2 capacitance

- Signal sharing between strips enables the x position reconstruction
- Amplitude fraction $f = a1 \,/\, (a1 + a2)$ where $a1$ and $a2$ are the leading and sub-leading strip amplitudes
- Two-strip reconstruction at gap and one-strip reconstruction on metal







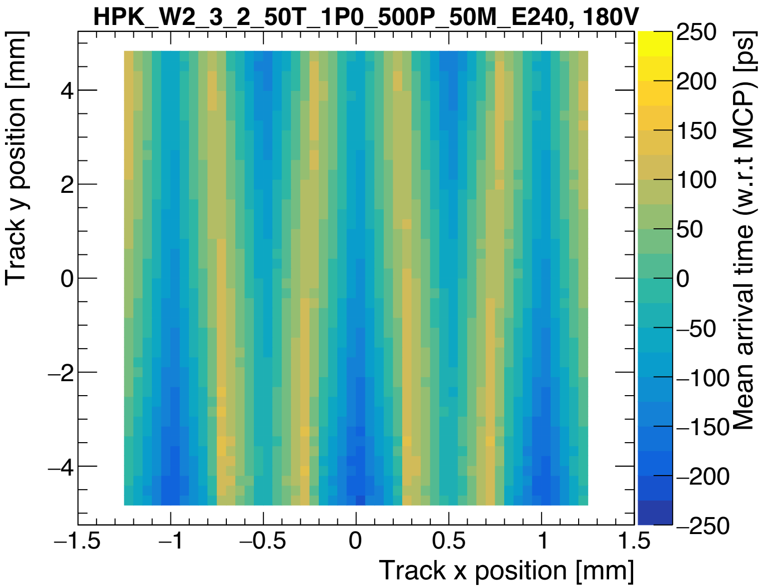


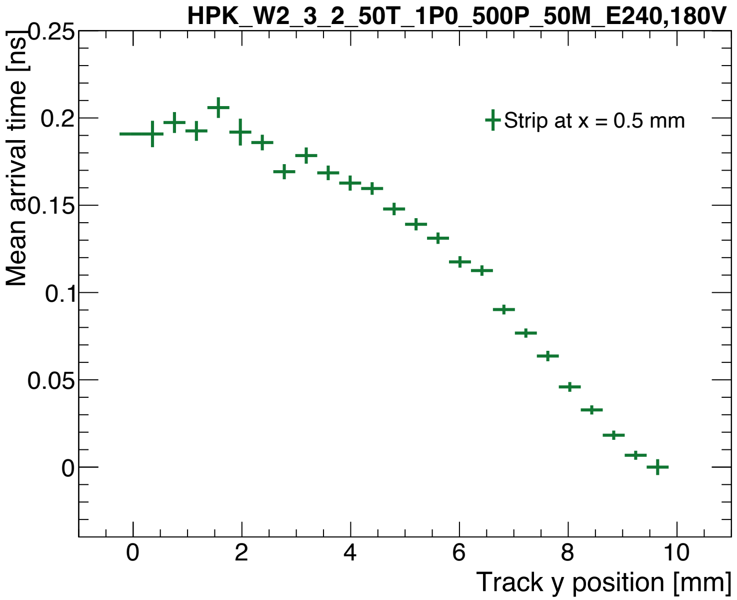
- Efficiency reaches ~100%
- Two-strip resolution ~ 12 – 15 μm
- One-strip resolution ~ 40 μm on metal

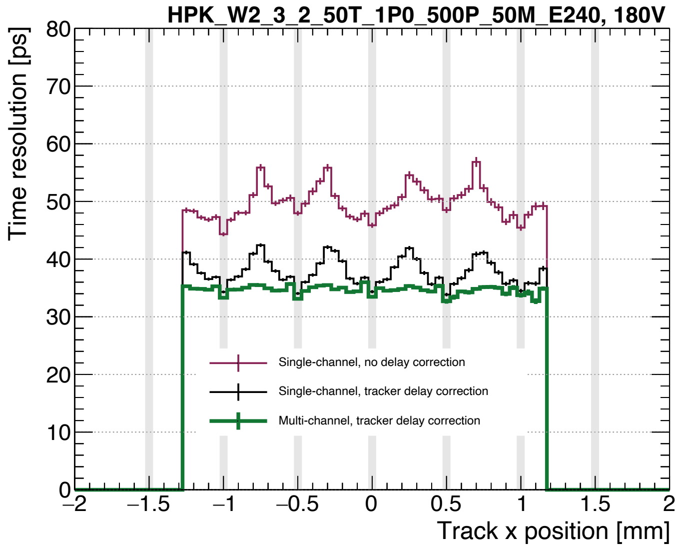
Time resolution in AC-LGADs:

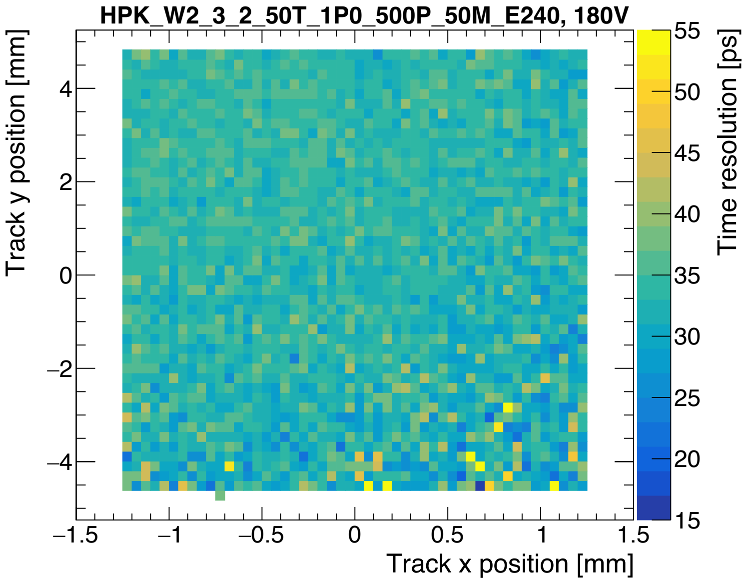
HPK Strip : 10 mm length, 500 μm pitch, 50 μm metal width, 1600 Ω/□ resistivity, and 240 pF/mm^2 capacitance

- Due to larger electrodes, distant signals arrival with delays O(100 ps)
- Position-dependent time delay correction is essential, using the external tracker
- Delay map use the resolution of 50 μm for x position and 200 μm for y position
- Multi-channel time stamp, $t_{reco} = \frac{a_1^2 t_1 + a_2^2 t_2}{a_1^2 + a_2^2}$





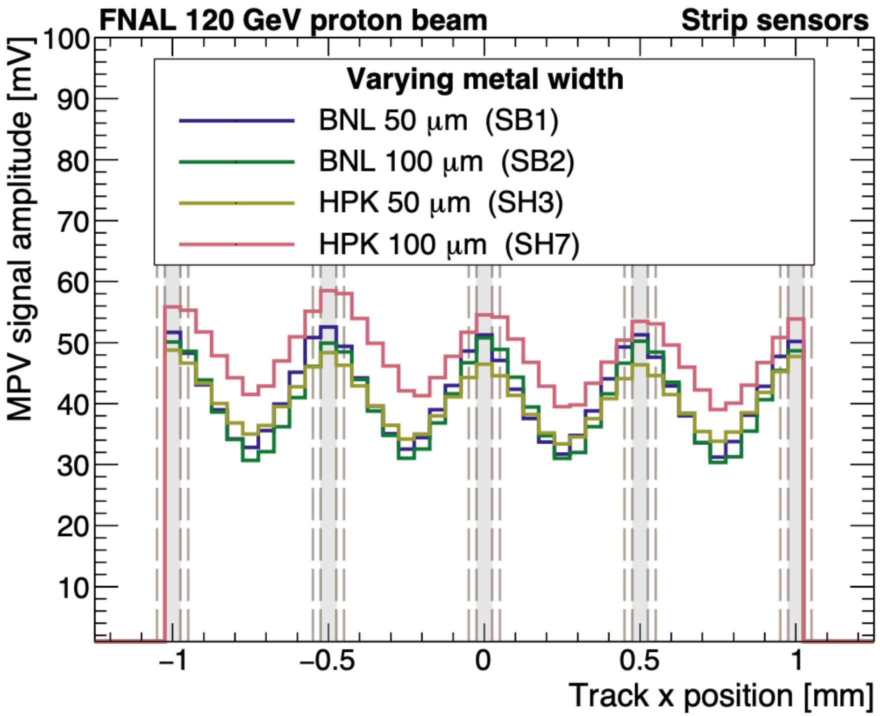


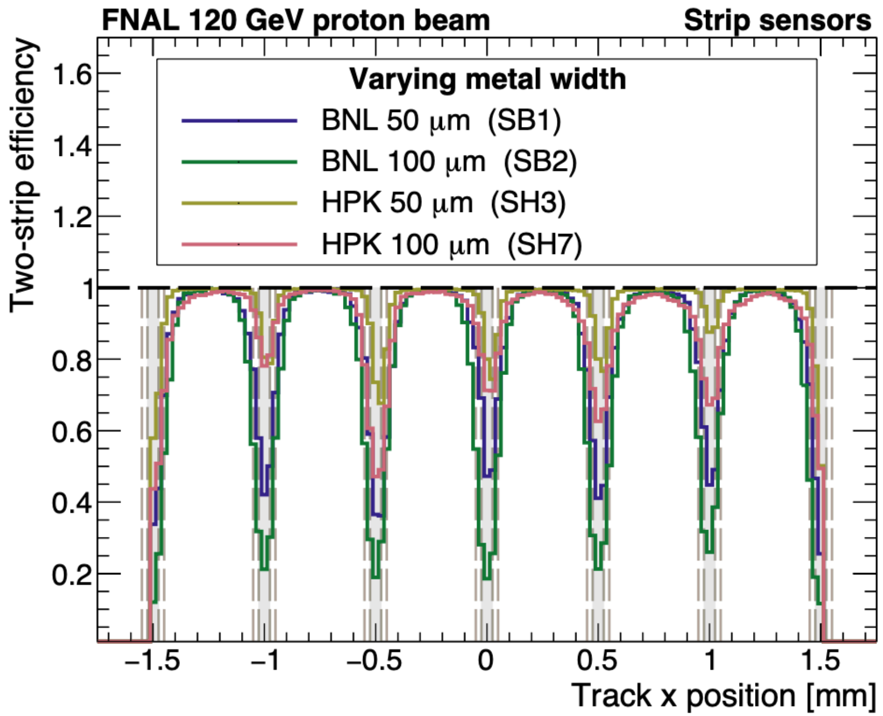


- Without delay correction, the time resolution ~ 45 – 55 ps
- Adding the tracker-based delay corrections improves the resolution to ~ 35 – 42 ps
- Using multi-channel timestamp with delay correction, time resolution ~ 34 ps

Metal width variation in AC-LGAD strip sensors:

HPK & BNL Strip : 10 mm length, 500 μm pitch, and 50 μm thickness

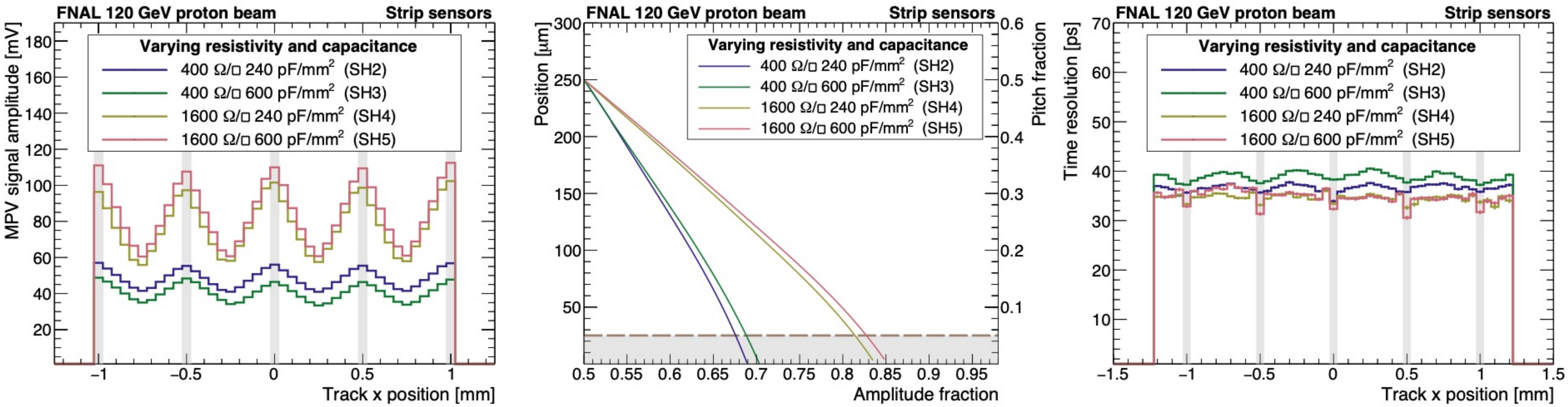




- Resistivity, capacitance were kept same for BNL and HPK strips sensors separately
- No significant difference in signal sizes has been observed
- Smaller metal width corresponds to slightly larger two-strip efficiency

Resistivity and capacitance variation in AC-LGAD strip sensors :

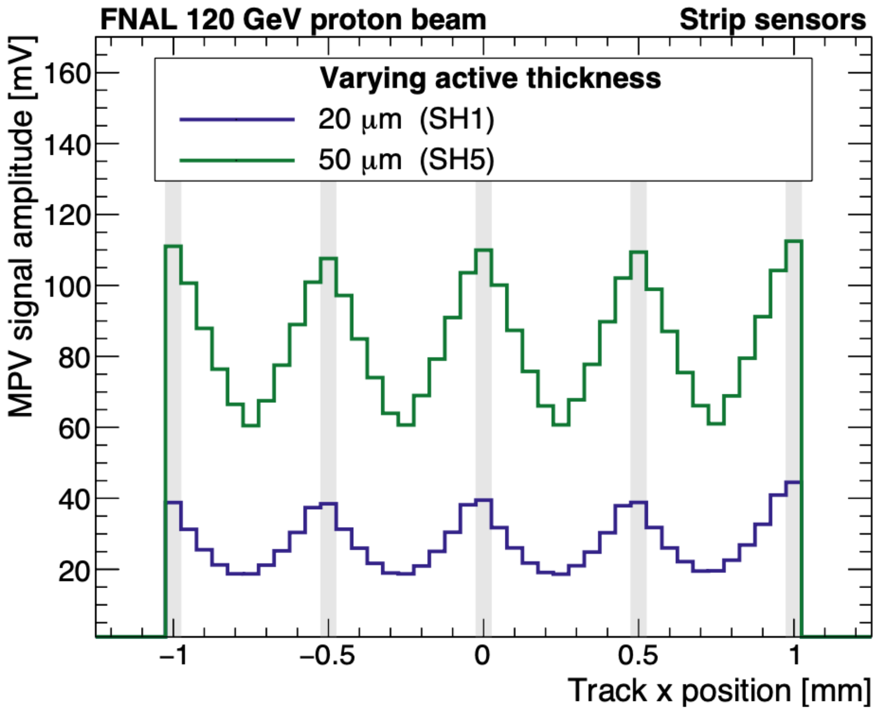
HPK Strip : 10 mm length, 500 μm pitch, and 50 μm thickness

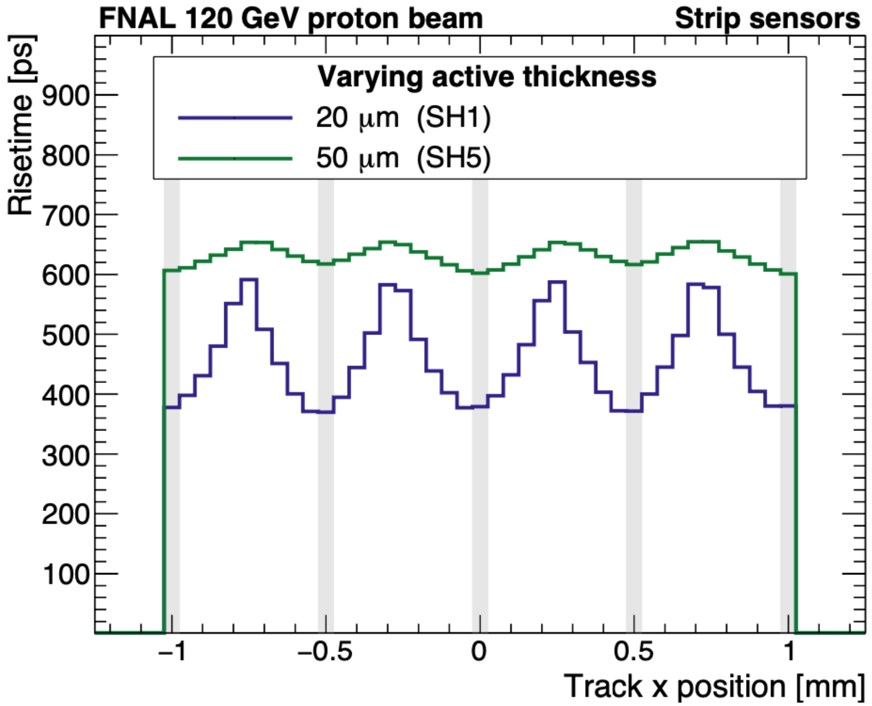


- Larger resistivity shows larger signal size
- A slight variation in amplitude between different coupling capacitance
- Larger charge sharing observed for smaller resistivity, a slight variation for different coupling capacitance
- Time resolution ~ 34 ps for 1600 Ω/□ resistivity, around 3 - 6 ps improvement from 400 Ω/□

Active thickness variation in AC-LGAD strip sensors :

HPK Strip : 10 mm length, 500 μm pitch, 50 μm metal width, 1600 Ω/□ resistivity, and 600 pF/mm² capacitance

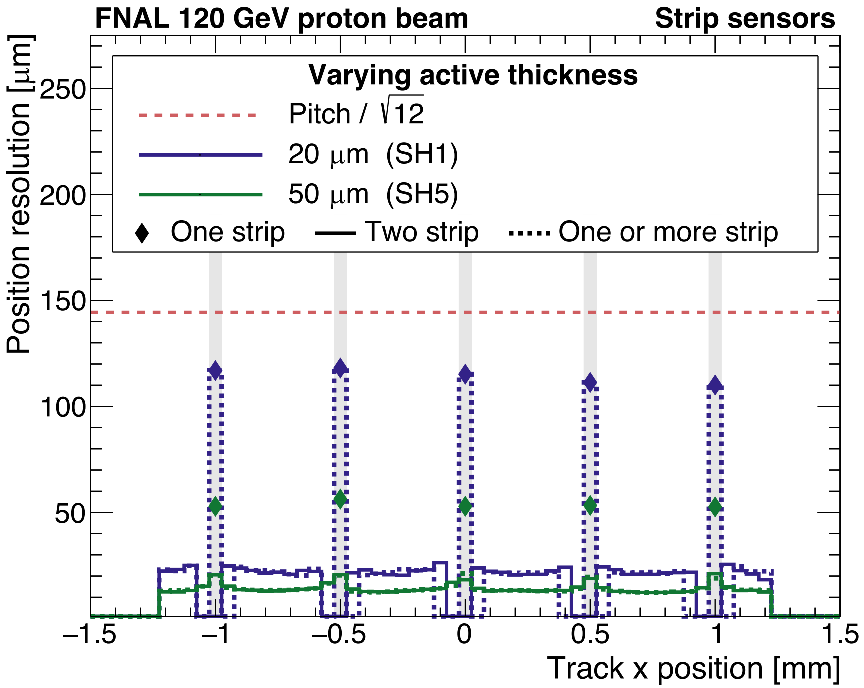


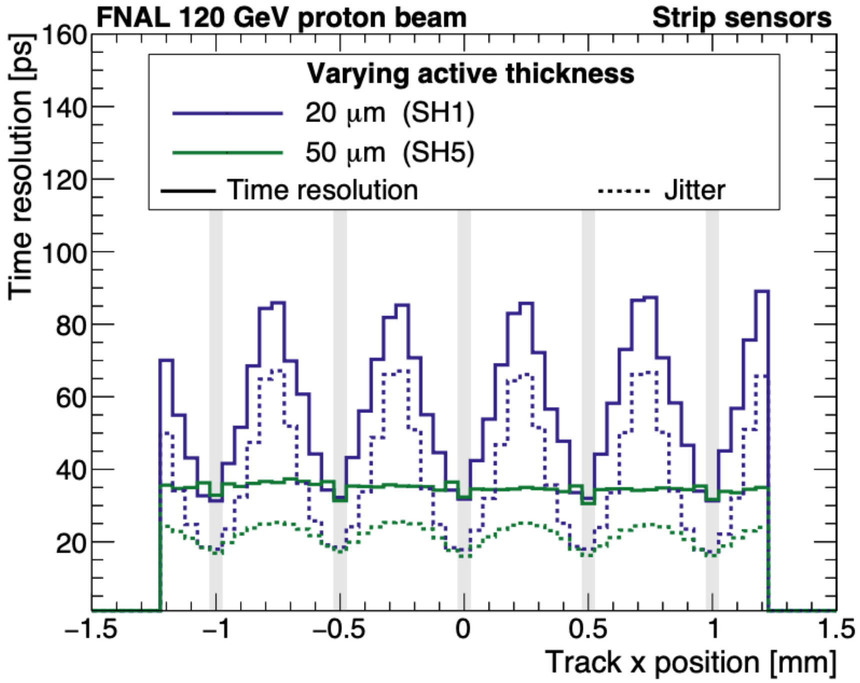


- 2.5 – 3 times larger signal for 50 μm thick sensor compared to 20 μm
- Almost uniform risetime across the surface for 50 um thick sensor
- A large variation in risetime between gap and metal for 20 μm thick sensor
- Slower signal and smaller amplitude in gap contribute to larger jitter = risetime/(S/N) component in 20 μm thick sensor

Active thickness variation in AC-LGAD strip sensors :

HPK Strip : 10 mm length, 500 µm pitch, 50 µm metal width, 1600 Ω/□ resistivity, and 600 pF/mm² capacitance

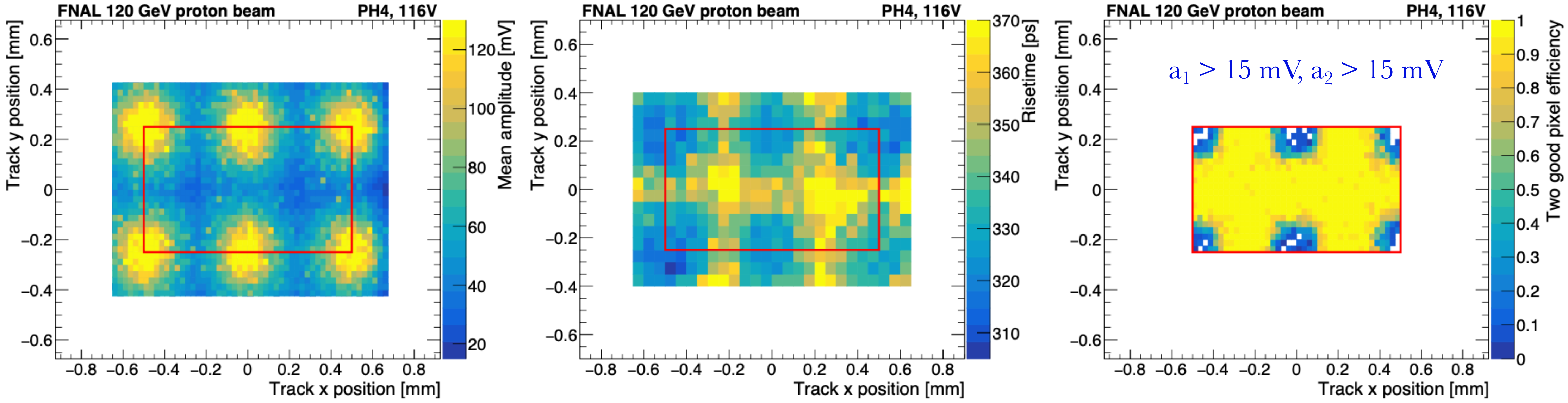




- Two strip position resolution ~ 12 – 15 µm for 50 um thick sensor and ~ 20 um for 20 um thick sensor
- Exactly one strip position resolution ~ 50 µm for 50 um thick sensor and ~ 110 – 120 µm for 20 um thick sensor
- Larger jitter component in gap contribute to poor time resolution for 20 um thick strip sensor
- Time resolution is uniform (~ 34 ps) across surface for 50 um thick strip sensor

AC-LGAD pixel sensors:

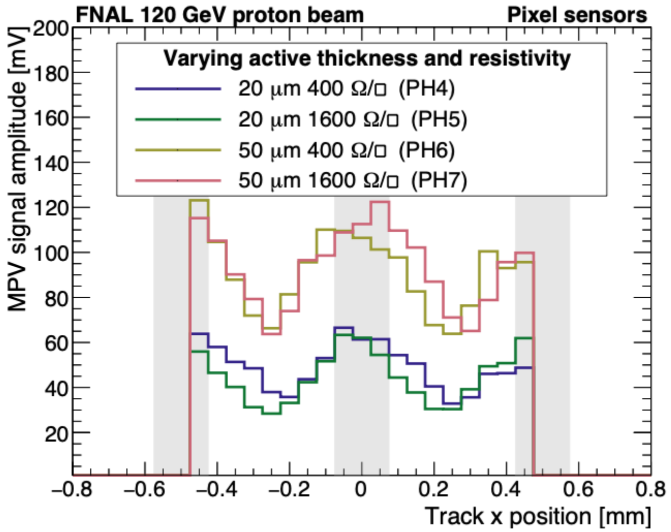
HPK Pixel : 500 x 500 μm pitch, 20 μm thickness, 150 μm metal width, 400 Ω/□ resistivity, and 600 pF/mm^2 capacitance

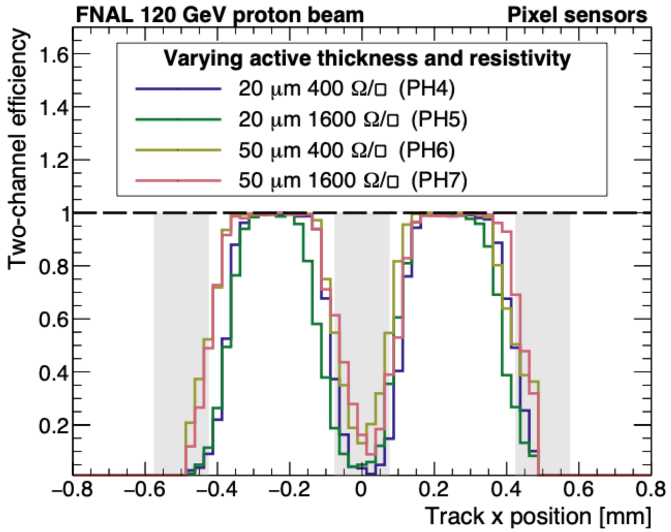


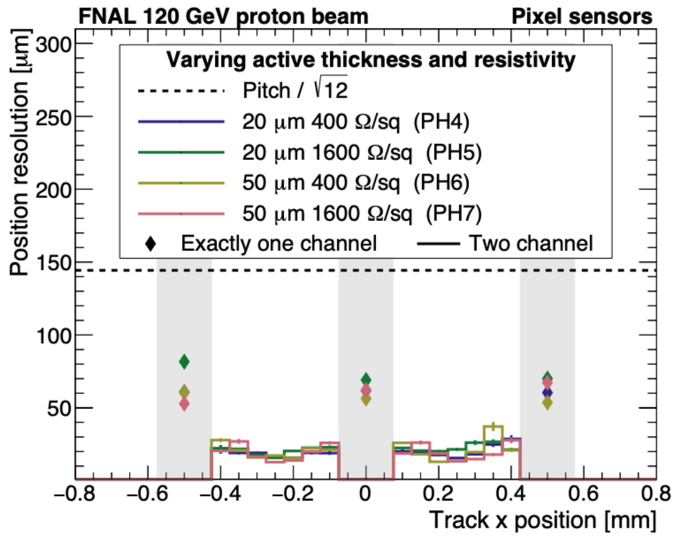
- Larger signal size in metal pads compared to gap region
- Faster signals in metal pads and relatively slower in gap region
- For each event, the amplitude from two channels in column has been added to enhance the charge sharing in gap regions
- Two-channel efficiency ~ 1 in gap region and suffers in metal region

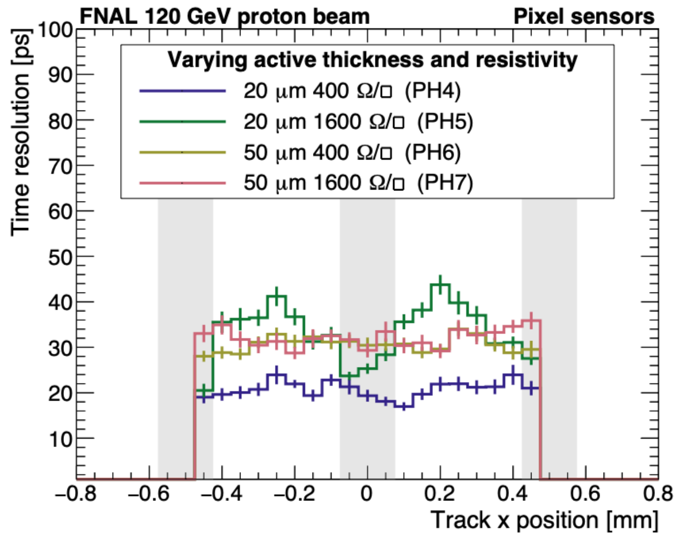
Active thickness and resistivity variation in AC-LGAD pixel sensors :

HPK Pixel : 500 x 500 μm pitch, 150 μm metal width, and 600 pF/mm^2 capacitance







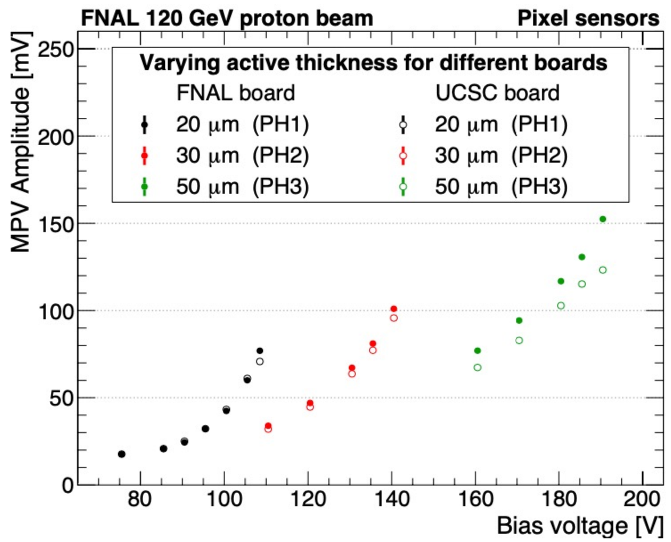


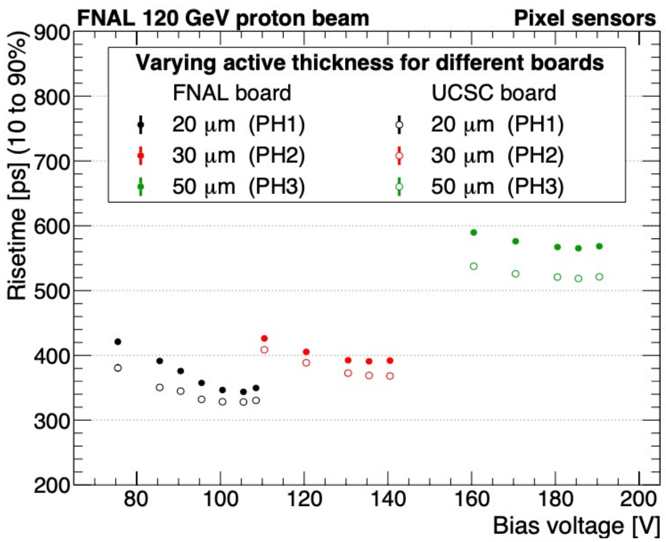
- Overall signal sizes are similar for different resistivity with same thickness
- Two-channel efficiency reaches unity in the mid-gap region
- Two-channel position resolution ~ 15 - 30 μm
- Position resolution in metal pads can be improved by further reducing the metal pad width
- Time resolution ~ 20 ps for 400 Ω/□ resistivity and 20 μm active thickness

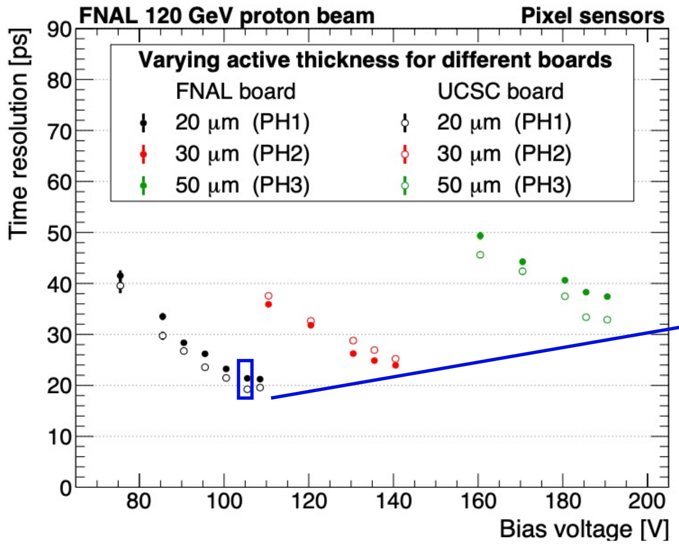
(*) the gray box only represents the location of metal pad; it also contain the gap region between metal pads in same column

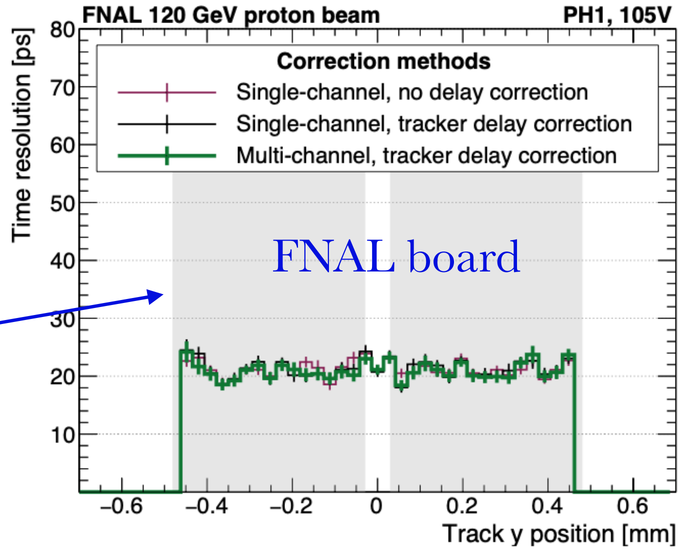
Bias scan of AC-LGAD pixel sensors with 450 um metal width :

HPK Pixel : 500 x 500 μm pitch, 450 μm metal width, 1600 Ω/□ resistivity, and 600 pF/mm^2 capacitance









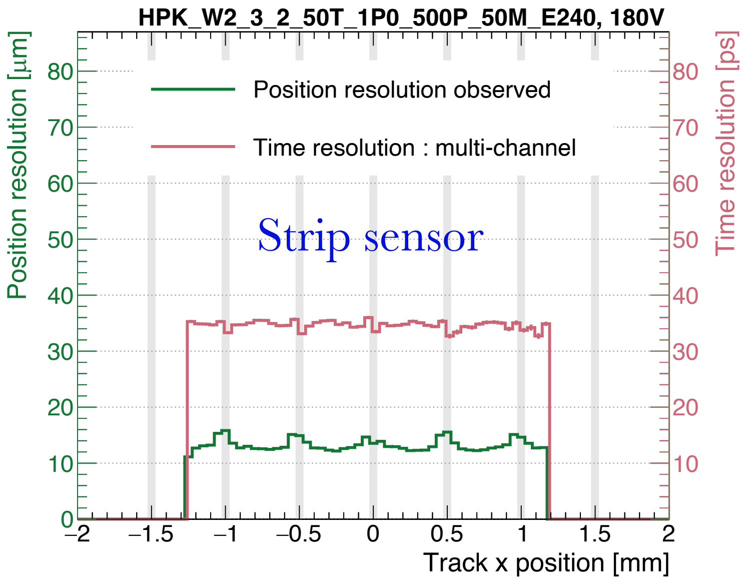
- Operational bias ranges differs with thickness variation
- Faster signal (smaller rise time) for 20 μm thick sensors at the optimal bias
- ~ 20 - 21 ps of timing resolution for 20 um thick sensor at optimal bias 105 V
- Time resolution is almost uniform across the surface
- Similar performance between FNAL and UCSC boards

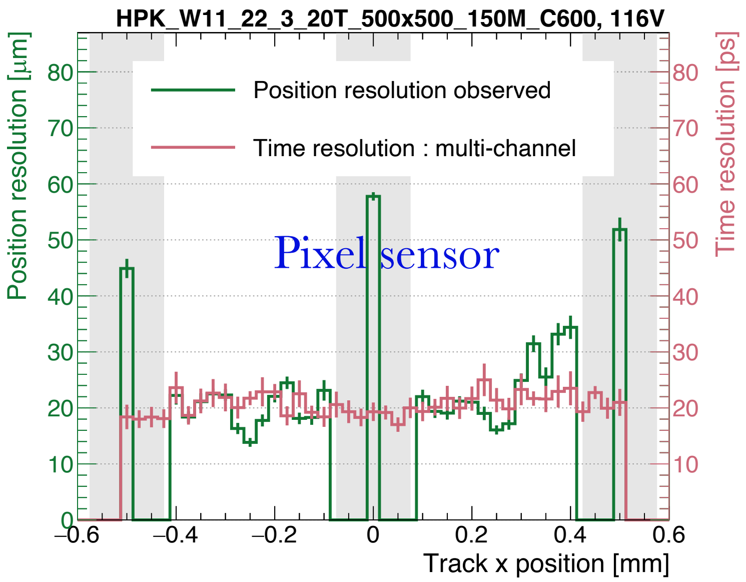
Summary:

- Large, coarse pitch AC-LGAD sensors show promising 4D performance with timing resolution comparable to LGADs,
    - spatial resolution ~ 20 - 30x smaller than pitch
    - 100% fill factor

- Optimal strip sensor with 50 μm thickness, 50 μm metal width, 1600 Ω/□ resistivity, and 240 pF/mm^2 capacitance
    - position resolution ~ 12 – 15 μm
    - time resolution ~ 34 ps
    - prototype strip sensor promising for BToF in EIC

- Optimal pixel sensor with 20 μm thickness, 150 μm metal width, 400 Ω/□ resistivity, and 600 pF/mm^2 capacitance
    - position resolution ~ 15 – 30 μm in gap and ~ 50 um in the metal
    - time resolution ~ 20 ps
    - prototype pixel sensor shows potential for FToF, B0, RPs/OMD





AC-LGAD team:

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LBNL: Ryan Heller, Zhenyu Ye

Caltech: Si Xie

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The University of Iowa: Ohannes Kamer Köseyan

Yerevan Physics Institute: Aram Hayrapetyan

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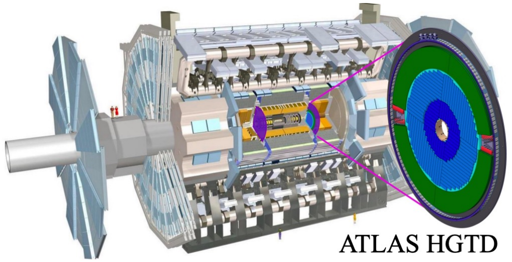
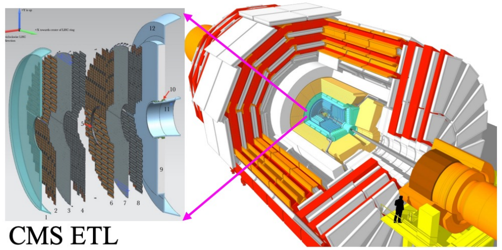
Extra slides:

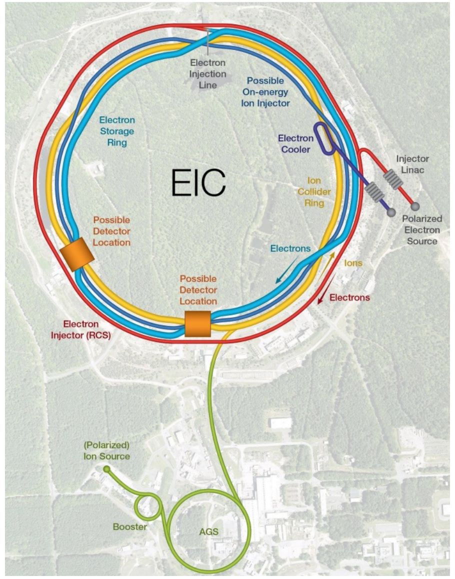
AC-coupled Low Gain Avalanche Diode (AC-LGAD) sensors:

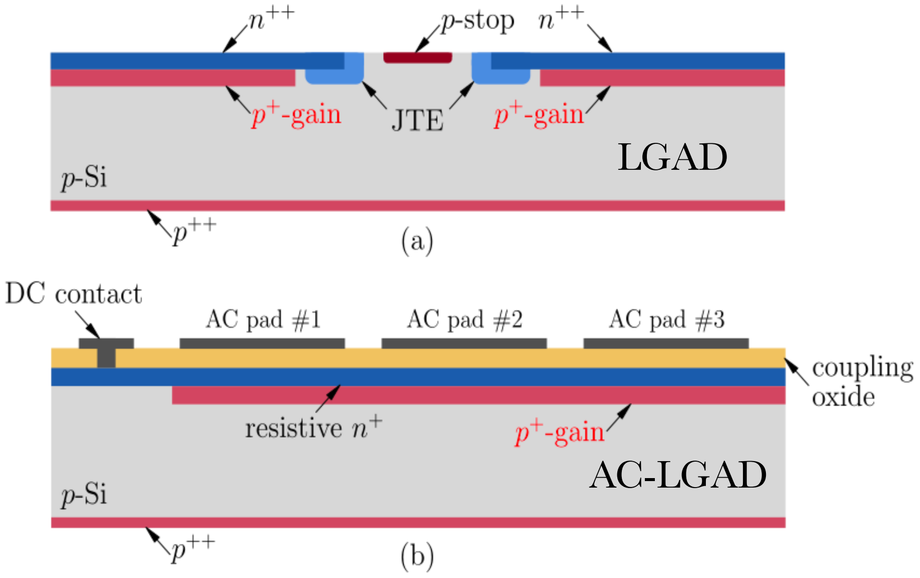
- Large area LGAD detectors for fast timing are being built by ATLAS (6.4 m^2) and CMS (14 m^2) for data taking in 2028+
  - Timing resolution of O(10 ps)
  - Not able to achieve a 100% fill factor
  - Position resolution limited to $\sqrt{1/12}$ of cell size





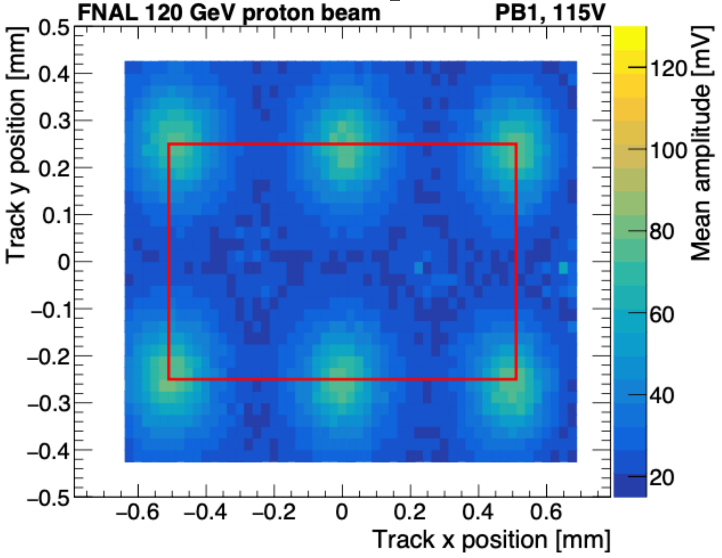
- **AC-LGAD:** Electrical signals in the resistive but continuous n^+ layer are AC-coupled to metal electrodes
  - 100% fill factor
  - Much better spatial resolution due to signal sharing
  - Precise timing resolution similar like LGAD
  - 4D trackers at future high energy experiments
  - Proposed for EIC experiments
    - ➢ Central: ToF PID and tracking
    - ➢ Far forward: Timing and tracking



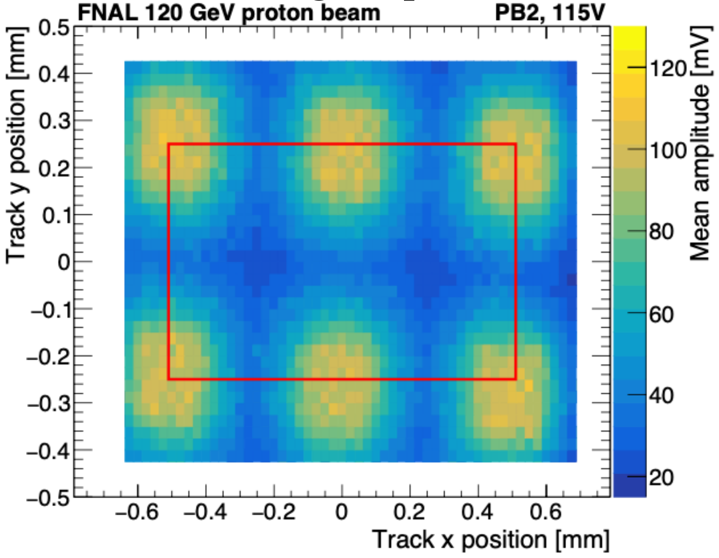


BNL pixel sensors:

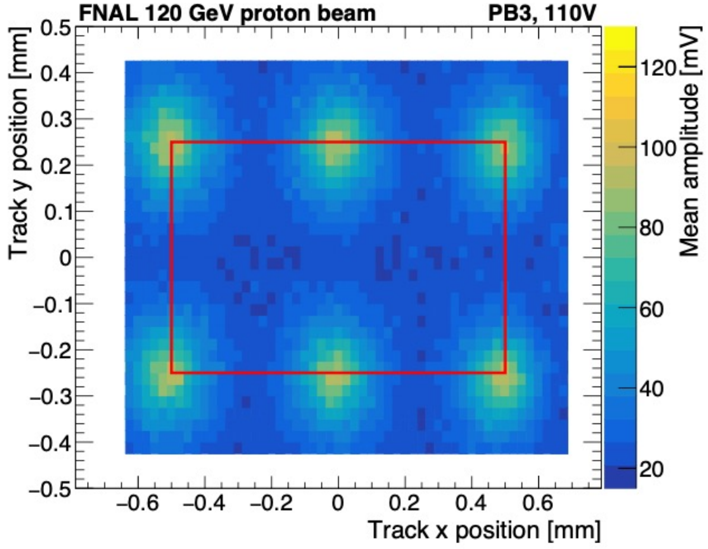
Small Square



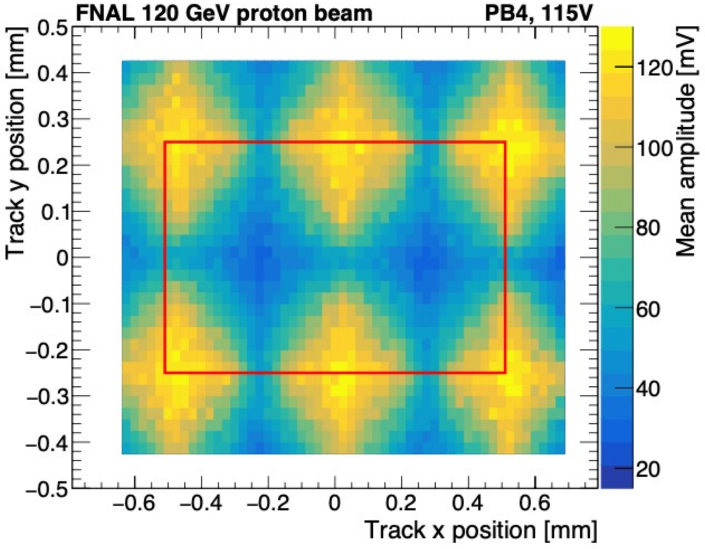
Large Square



Circular Square



Cross Square



BNL pixel sensors:

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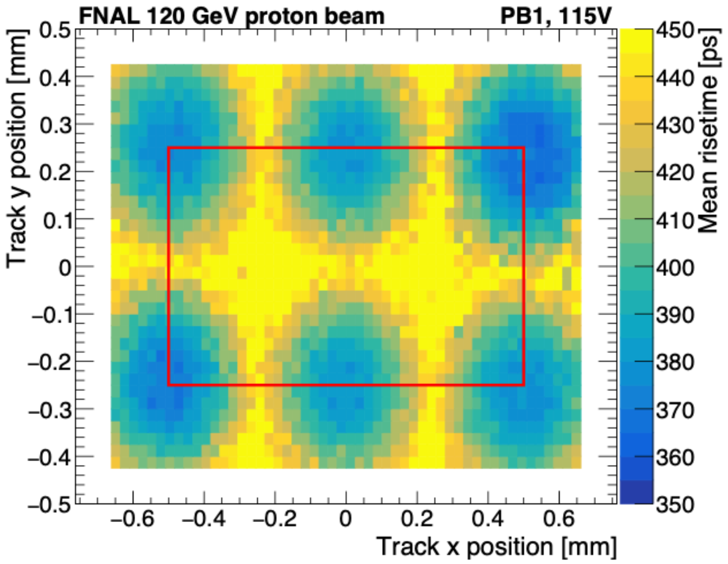
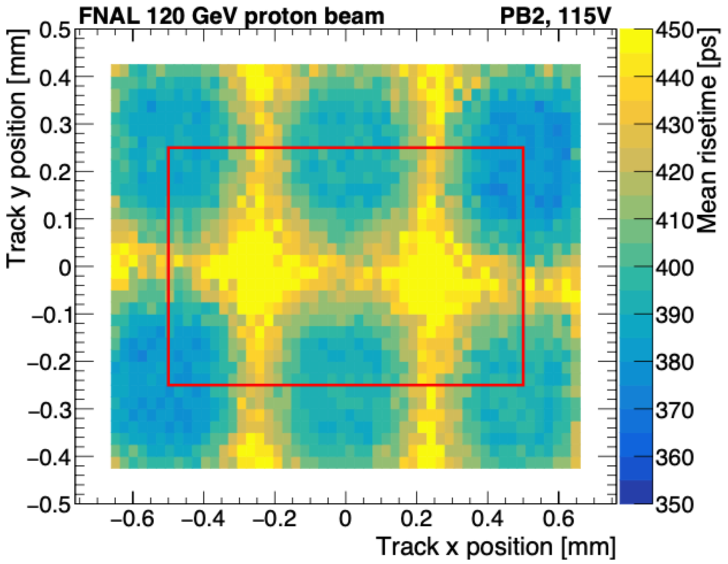


Large Square



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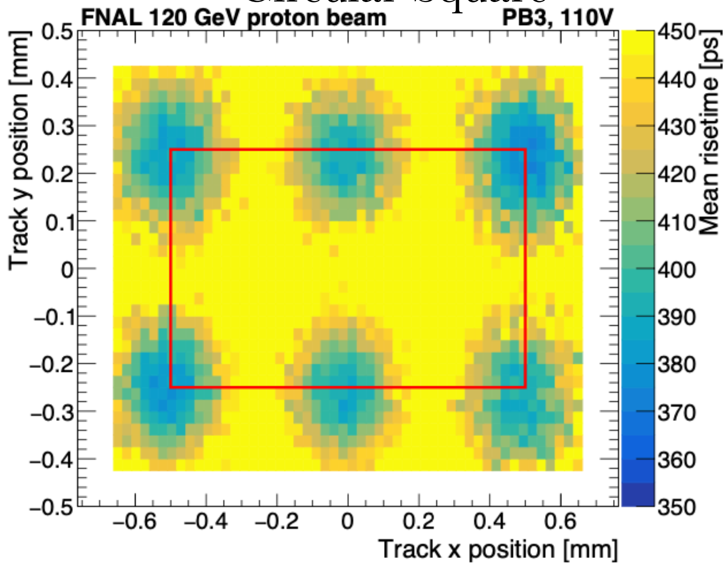
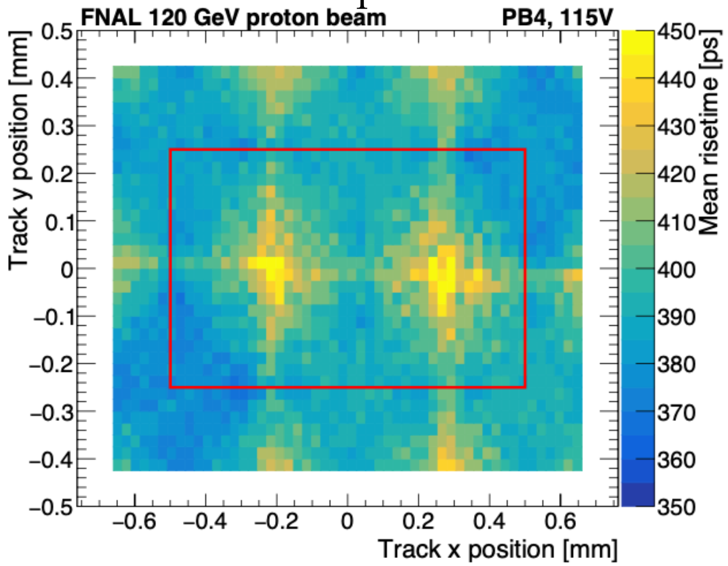
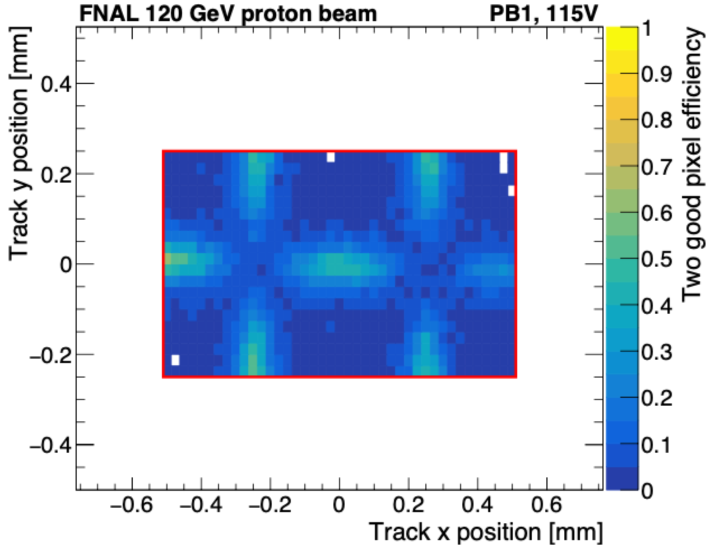


Cross Square

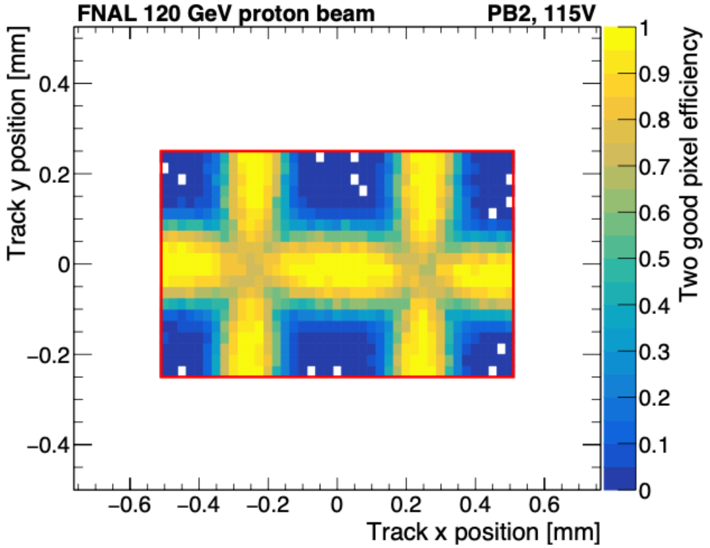


BNL pixel sensors:

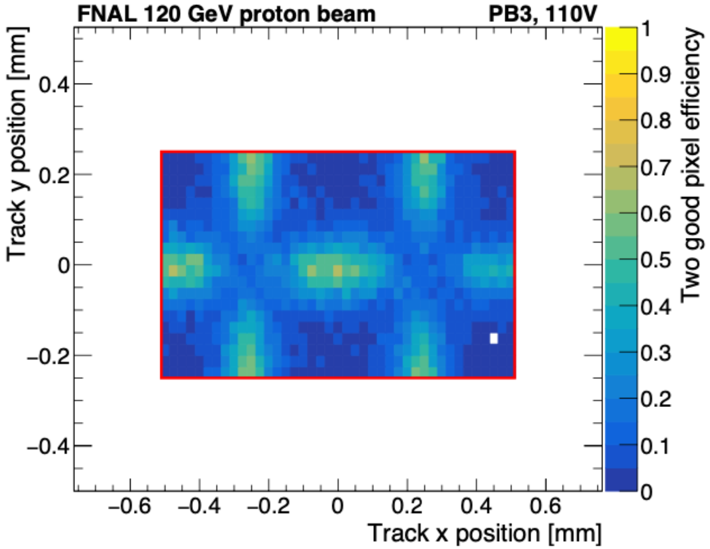
Small Square



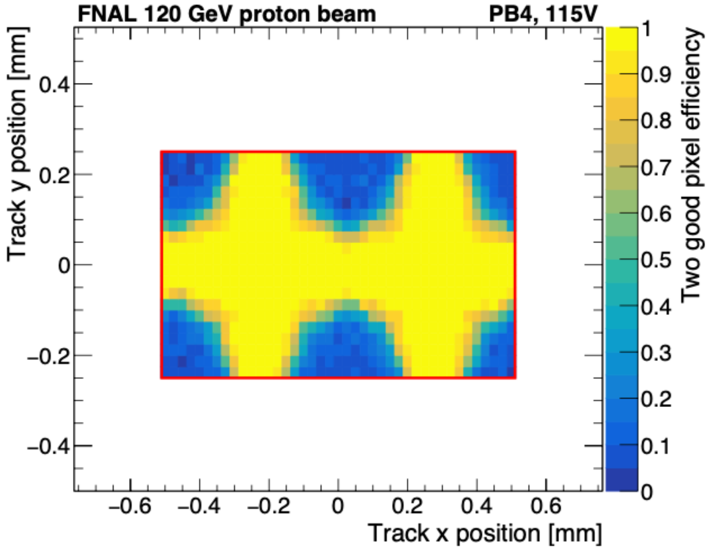
Large Square



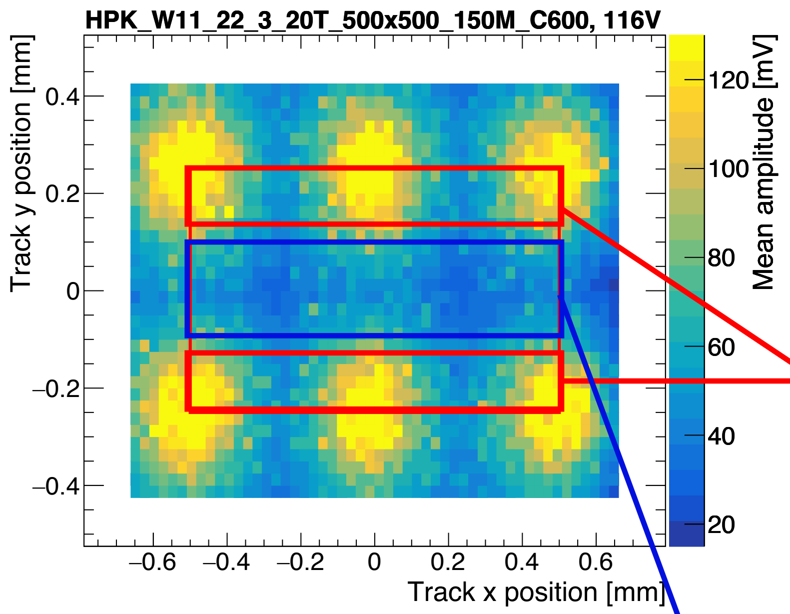
Circular Square

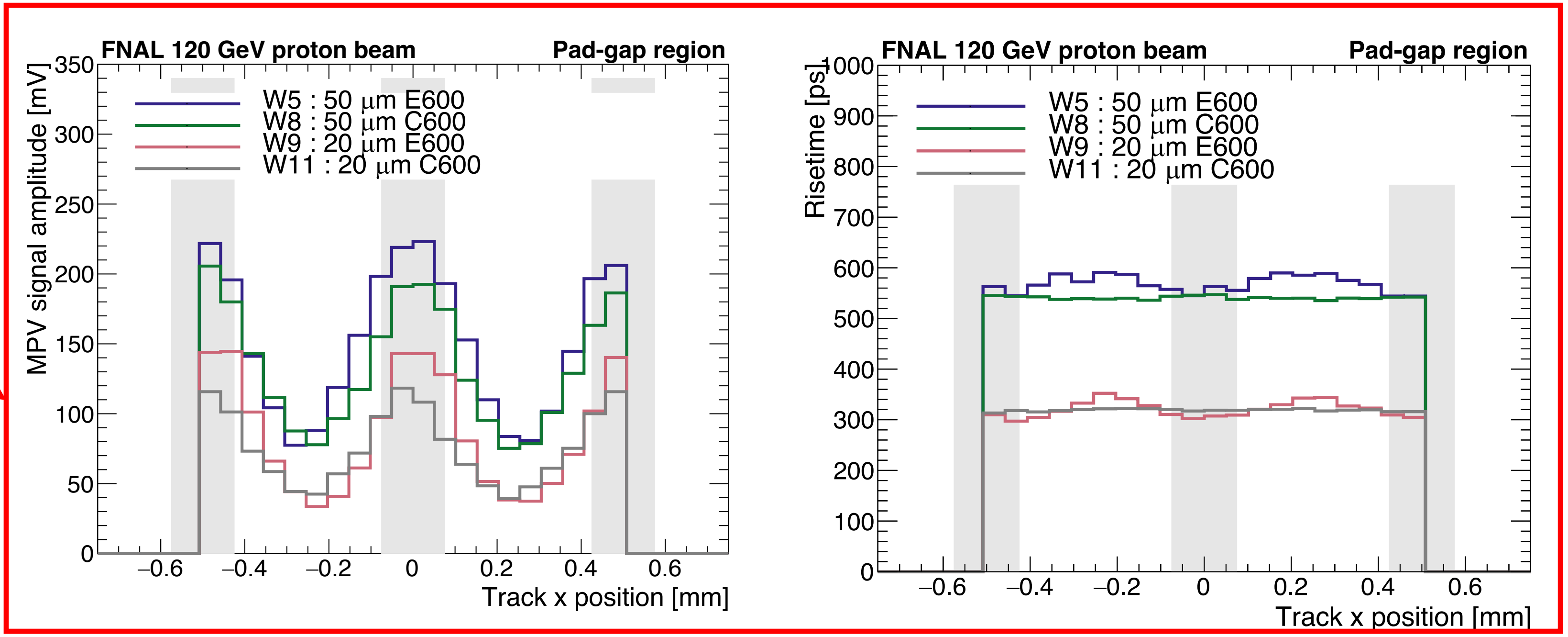


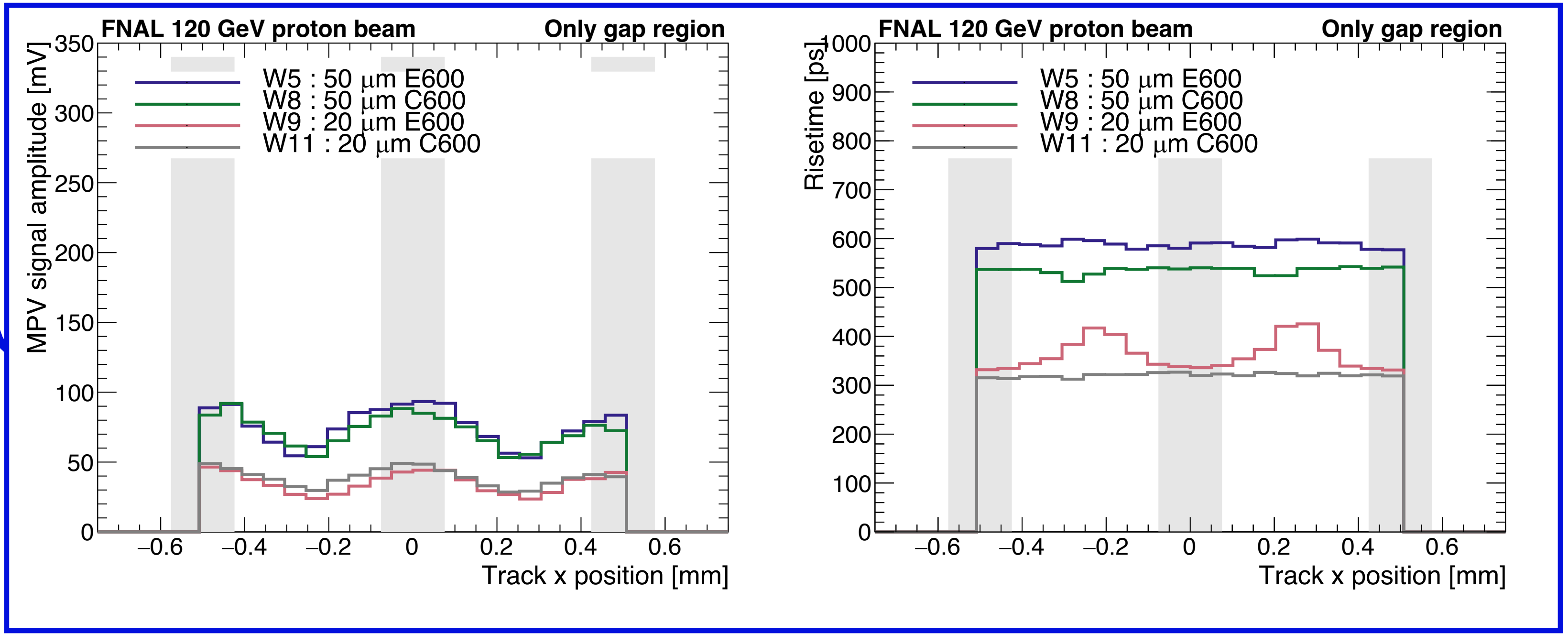
Cross Square



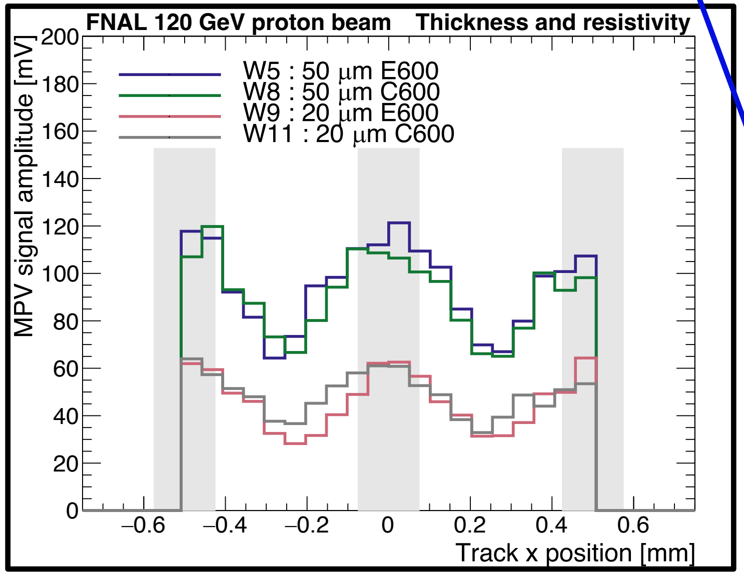
Active thickness and resistivity variation in AC-LGAD pixel sensors :



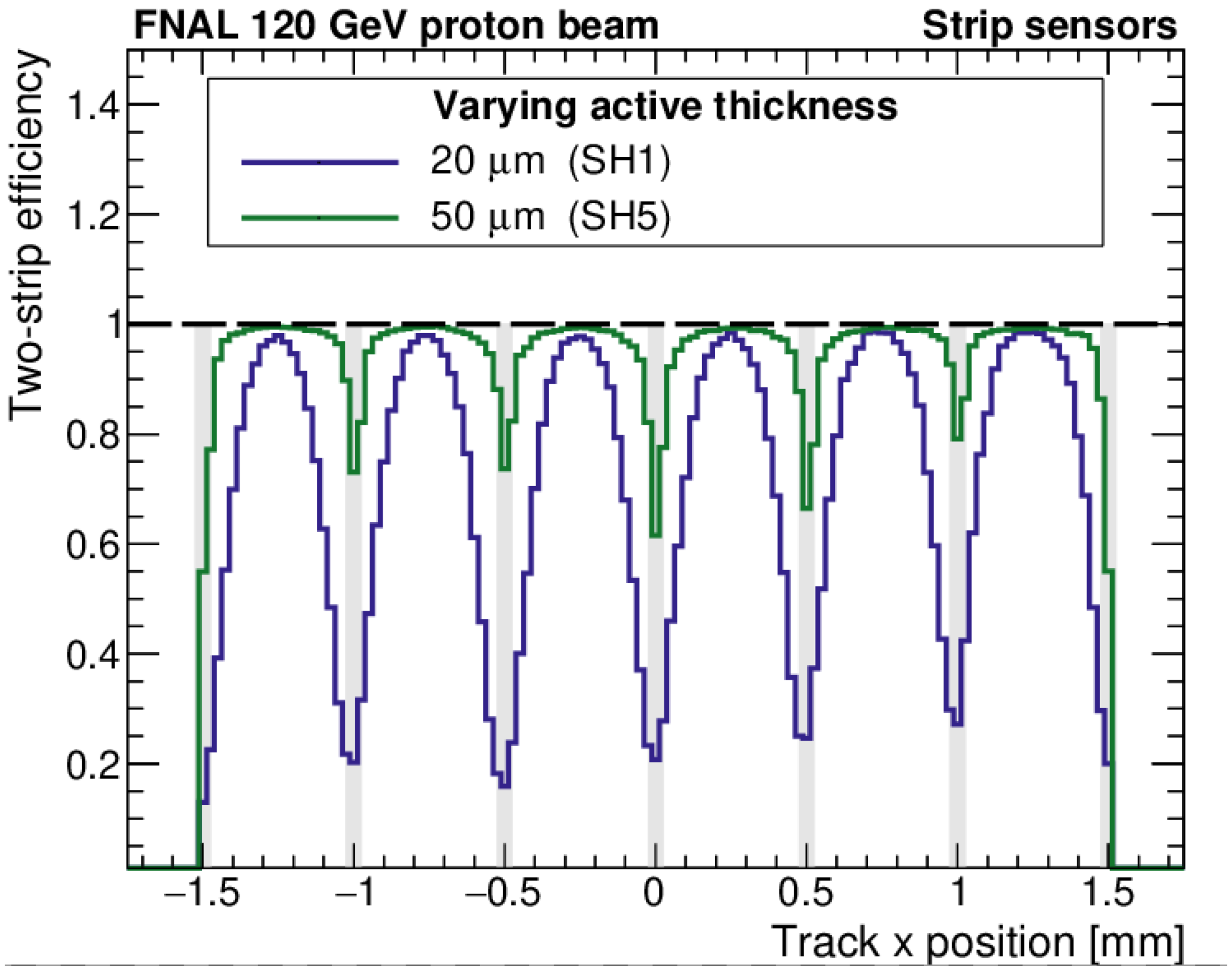




In the region of interest



Active thickness variation in AC-LGAD strip sensors :



x position reconstruction in pixel sensor: