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Development of AC-LGADs for large-scale high-precision timing and position measurements

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La Biodola, Isola d'Elba

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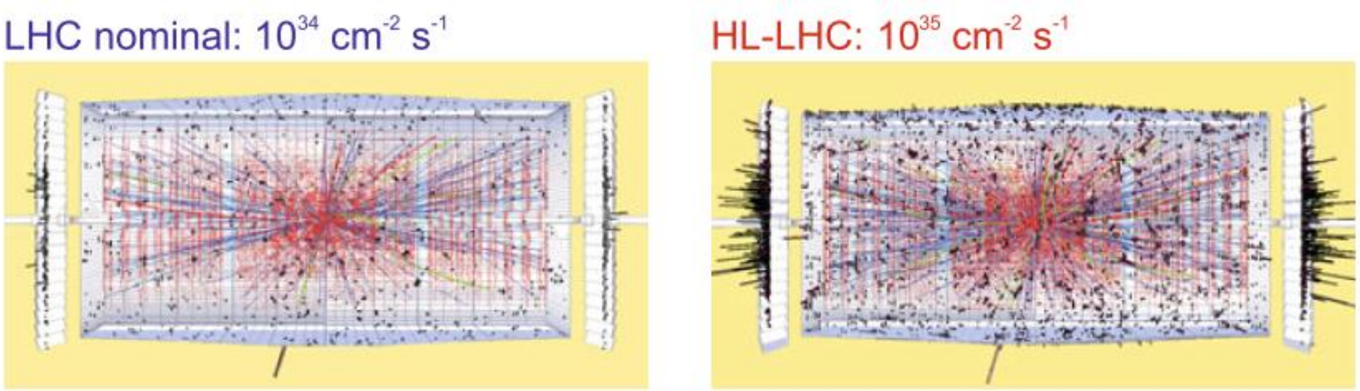
Precision tracking and timing

- LHC and HL-LHC: high energies, luminosities in p-p collisions – pileup and radiation damage
- Phase-2 upgrades for ATLAS and CMS: improvement of tracking detectors (silicon pixels and strips) + installation of dedicated timing detectors to reduce effect of pileup at extreme luminosities

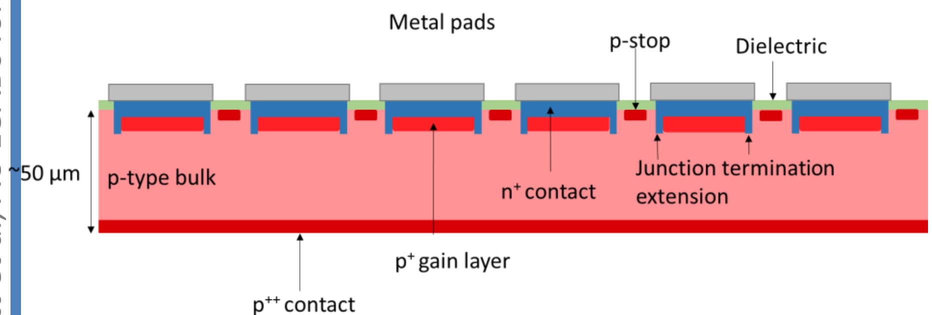


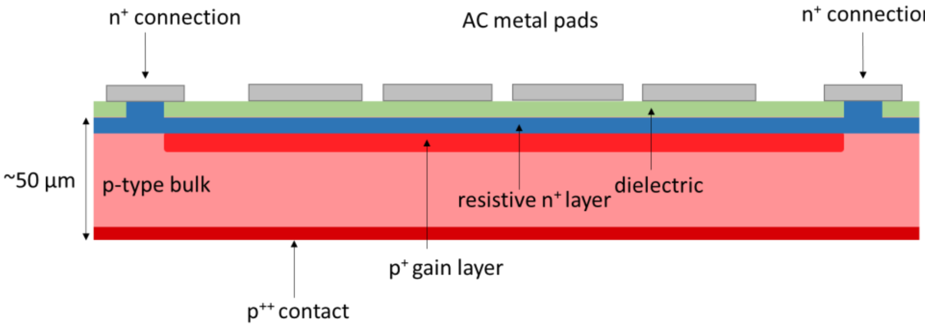
- 4D tracking is going to be essential in future high-energy physics experiments to mitigate effects of higher luminosity and pile-up and to improve tracking, vertexing and timing precision

CMS Collaboration, *A MIP Timing Detector for the CMS Phase-2 Upgrade*, CERN-LHCC-2019-003, 2019
ATLAS Collaboration, *A High-Granularity Timing Detector for the ATLAS Phase-II Upgrade*, CERN-LHCC-2018-023, 2018
H. F.-W. Sadrozinski et al, *4D tracking with ultra-fast silicon detectors*, Reports on Progress in Physics 2018, 81, 026101
D. Berry et al, *Snowmass White Paper: 4-Dimensional Trackers*, https://arxiv.org/abs/2203.13900, 2022

Low gain avalanche diodes

- Silicon low-gain avalanche diodes (LGADs) are studied by the CMS and ATLAS experiments for their endcap timing detector upgrades
  - Thin sensors, typical thickness 50 µm
  - Low to moderate gain (5-50) provided by p^+ multiplication layer
  - ➢ Timing resolution down to ca. 20 ps
  - ➢ Good radiation hardness up to 10^{15} n_{eq}/cm^2
- **A more recent development: AC-coupled LGAD**

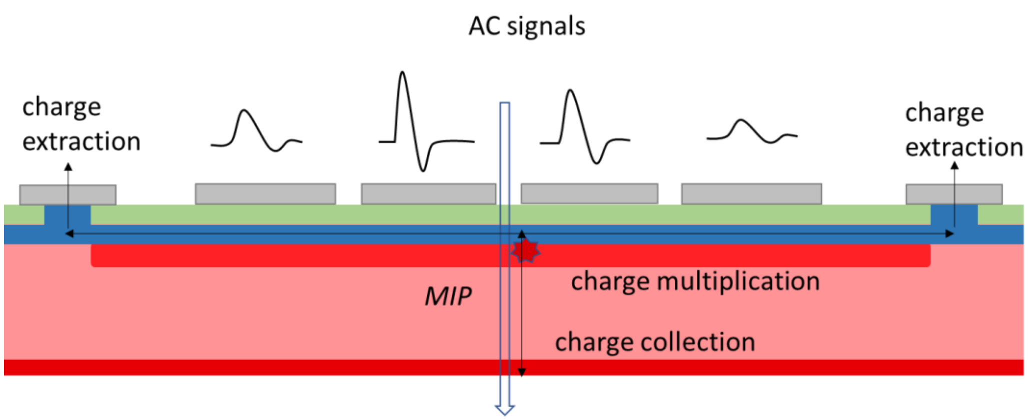




H. F.-W. Sadrozinski et al, *4D tracking with ultra-fast silicon detectors*, Reports on Progress in Physics 2018, 81, 026101
CMS Collaboration, *A MIP Timing Detector for the CMS Phase-2 Upgrade*, CERN-LHCC-2019-003, 2019
ATLAS Collaboration, *A High-Granularity Timing Detector for the ATLAS Phase-II Upgrade*, CERN-LHCC-2018-023, 2018

AC-coupled low gain avalanche diodes

- In AC-coupled LGADs, also referred to as Resistive Silicon Detectors (RSD), the multiplication layer and n^+ contact are continuous, only the metal is patterned:
  - The signal is read out from metal pads on top of a continuous layer of dielectric
  - The underlying resistive n^+ implant is contacted only by a separate grounding contact
  - No junction termination extension: fill factor ~100
- The continuous n^+ layer is resistive, i.e. extraction of charges is not direct
  - Mirroring of charge at the n^+ layer on the metal pads: AC-coupling
  - Strong sharing of charge between metal pads
  - **Extrapolation of position based on signal sharing – finer position resolution for larger pitch, also allowing for more sparse readout channels**



G. Giacomini *et al.,* Fabrication and performance of AC-coupled LGADs, *JINST* **2019**, 14, P09004
A. Apresyan *et al.,* Measurements of an AC-LGAD strip sensor with a 120 GeV proton beam**,** *JINST* **2020**, 15, P09038
S. M. Mazza, An LGAD-Based Full Active Target for the PIONEER Experiment, *Instruments* **2021**, *5*(4), 40

Key developments in (AC-)LGADs

- Gain layer doping
  - Suitable gain, breakdown voltage, radiation hardness…
- Thinner sensors: from 50 to below 30 µm
  - Faster signal rise time and charge collection time
  - Reducing Landau component of the timing resolution
    - ➢ **Towards 10 ps timing resolution**

- n^+ layer resistivity
- Dielectric
- Segmentation
  - Type: pad/pixel, strip
  - Geometry: rectangular, cross-shaped, ...
  - **Metal size**
  - **Pitch**

AC-LGAD strip sensors

Brookhaven National Laboratory

120 GeV proton beam at the Fermilab test beam facility

BNL 2021 Strip sensor
Metal width 80 µm, three different pitches:

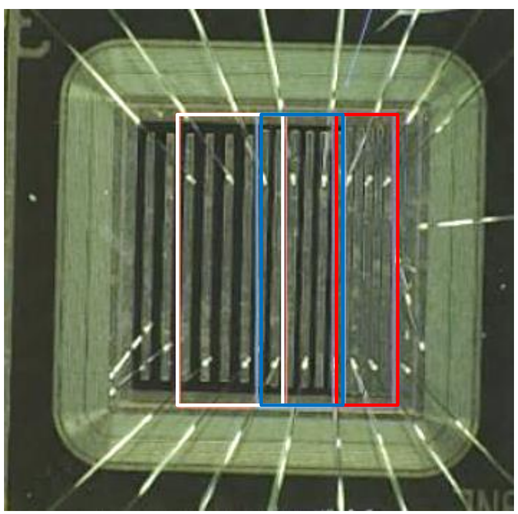
Narrow, 100 µm
Medium, 150 µm
Wide, 200 µm

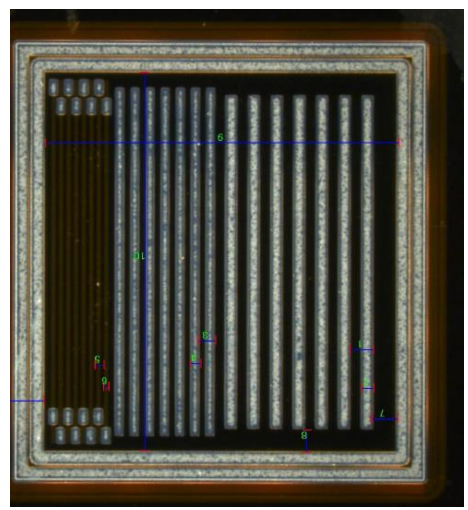
IR Laser TCT

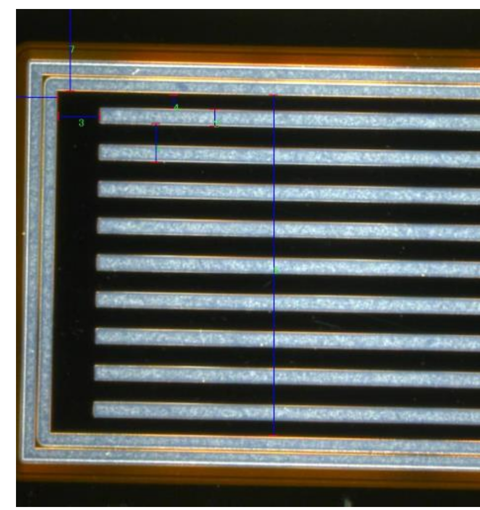
BNL 2021, new production
Variations in both pitch and metal width

- 100/200/300 µm pitch with 50 % metal
- Uniform strips: 500 µm pitch - 200 µm metal

Including long(er) strips of 1 cm and 2.5 cm







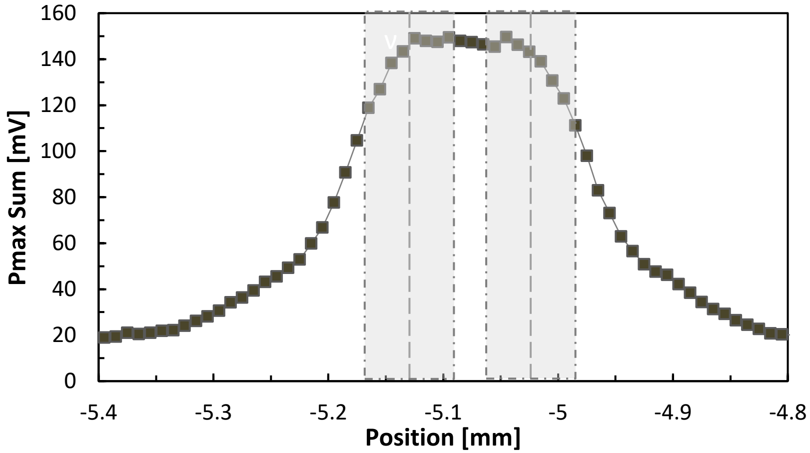
Strip length ca. 2.5 cm

C. Madrid, 39th RD50 Workshop, November 2021 (https://indico.cern.ch/event/1074989/contributions/4602013/)

Position resolution by signal sharing

Case of two adjacent strips

- Averaged maximum pulse height (*pmax*): The pmax sum ist not constant under the strip metal, but fairly constant between strip centers

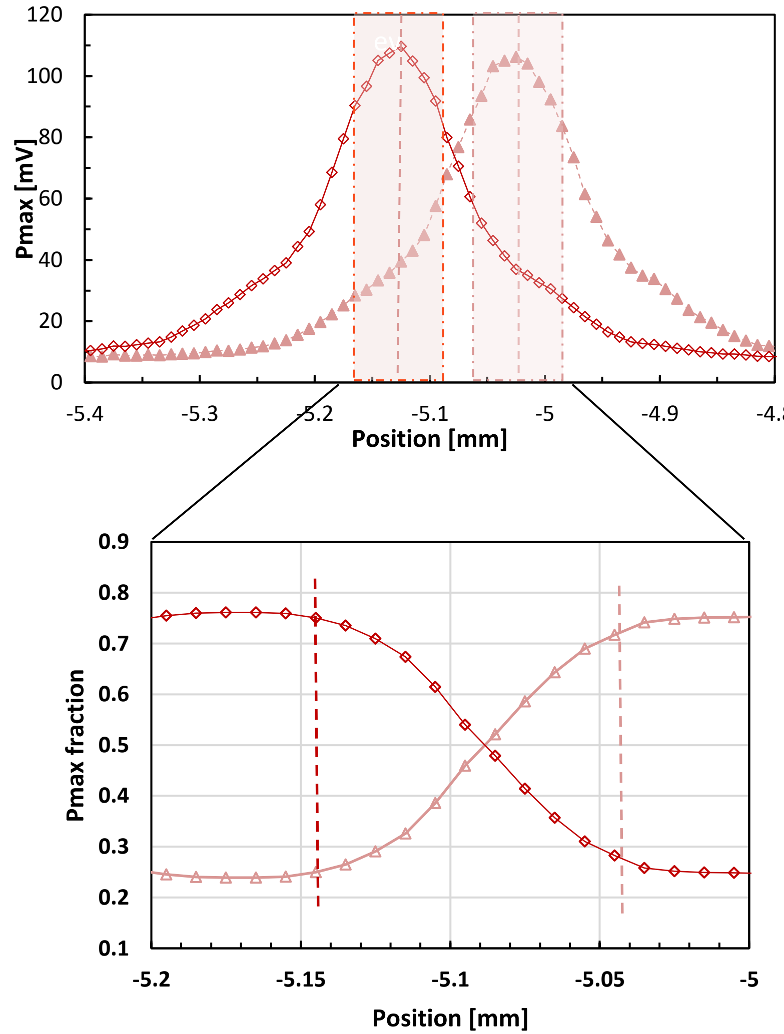


- The pmax fraction of an individual strip is defined as:

$$pmax\ fraction\ (channel) = \frac{pmax\ (channel)}{\sum pmax}$$

- The position resolution can be calculated from the fraction of pmax at a given position (fitted with an error function):

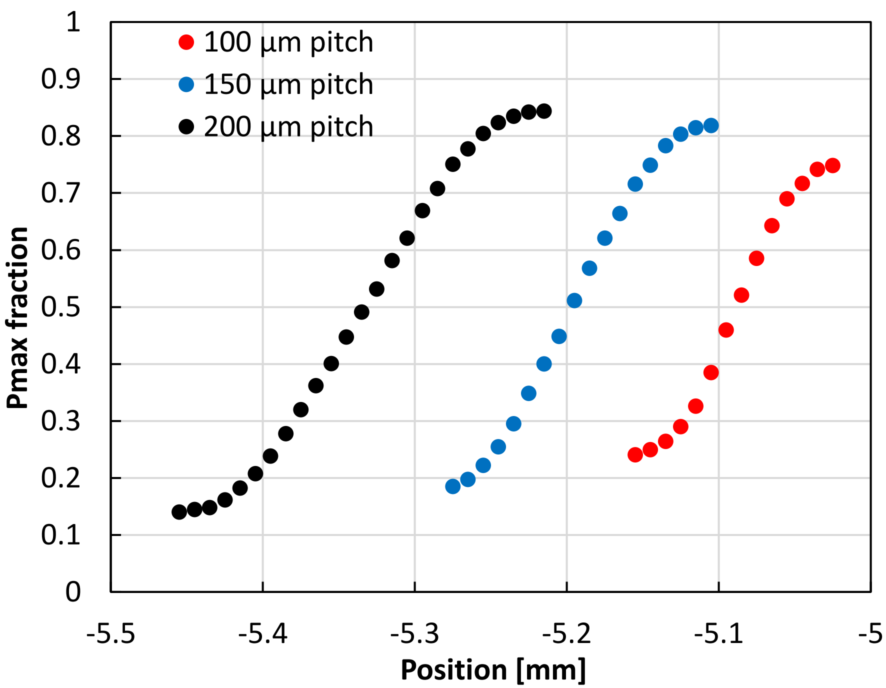
$$position\ resolution\ \sigma_{pos} = \sqrt{2}\frac{d(position)}{d(fraction)} / \frac{S}{N}$$

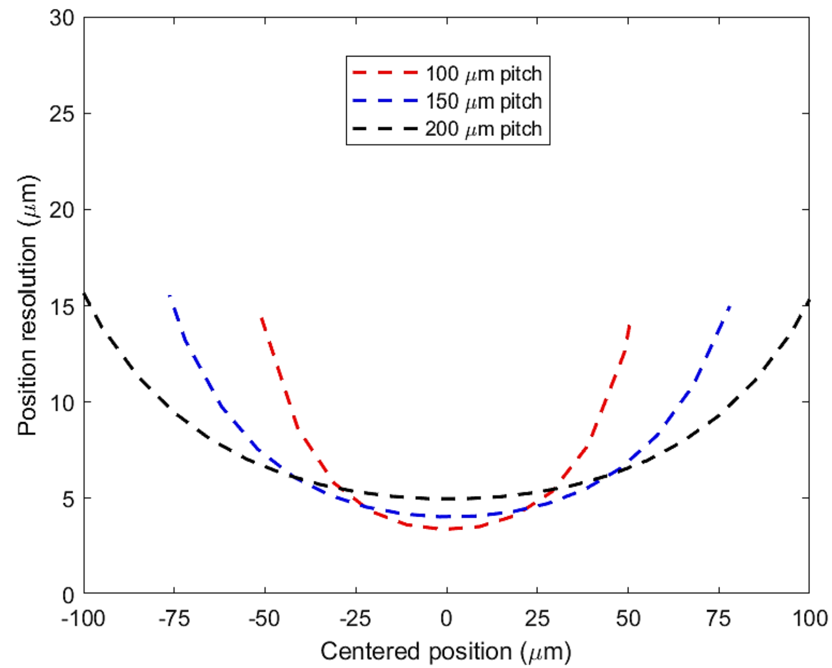


Signal-to-noise ratio is favourable in (AC-)LGADs due to their internal gain

Position resolution in BNL 2021 strips

- Strip pitch is expected to - and appears to - have a large impact on charge sharing as seen in the pmax fraction profile …
- … position resolution of ca. **15 µm** at the respective strip metal centers (end of the data points in the plot): in fact very similar for all three pitches
- Between strips, a position resolution of ~**6 µm** or less is reached; slightly better for smaller pitch
  - **At best, < 1/20 of the pitch**

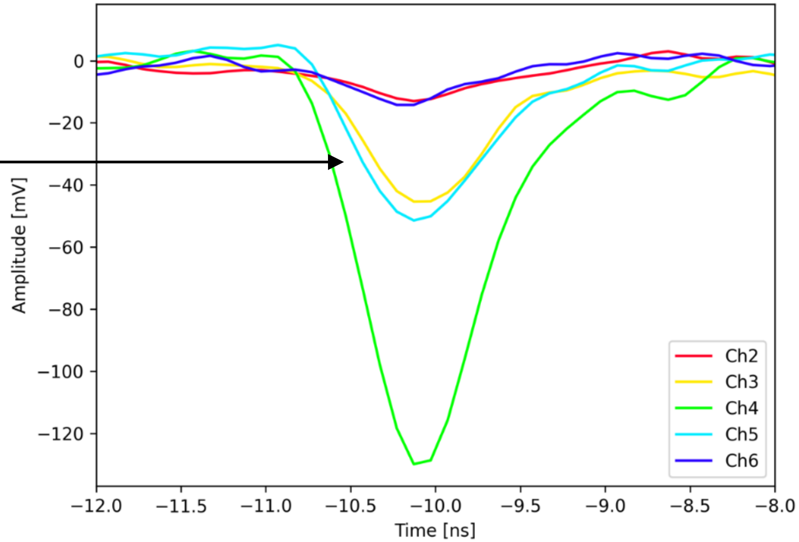




Timing resolution

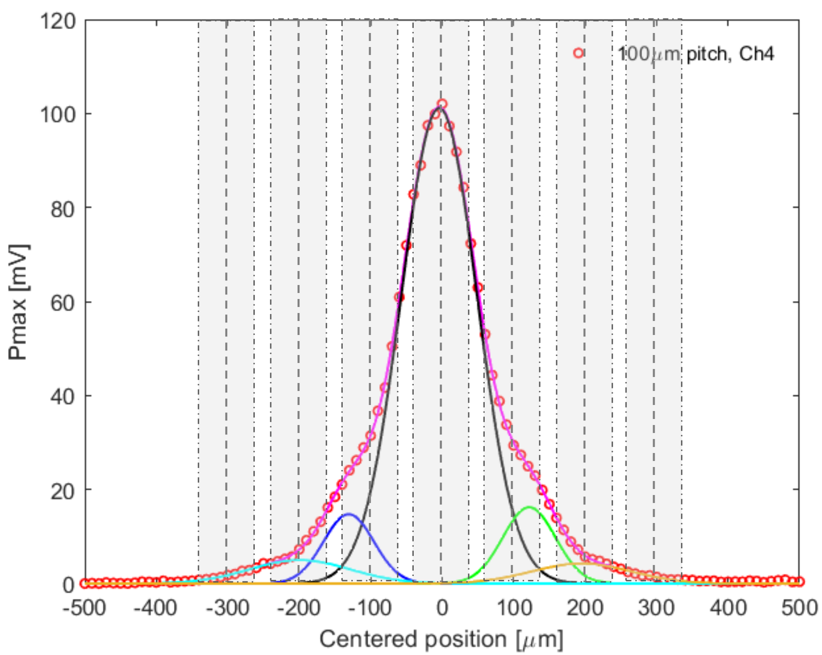
$$\boldsymbol{\sigma_t^2} = \boldsymbol{\sigma_{Landau}^2} + \boldsymbol{\sigma_{Jitter}^2} + \sigma_{TimeWalk}^2 + \sigma_{TDC}^2 + \sigma_{Distortion}^2$$

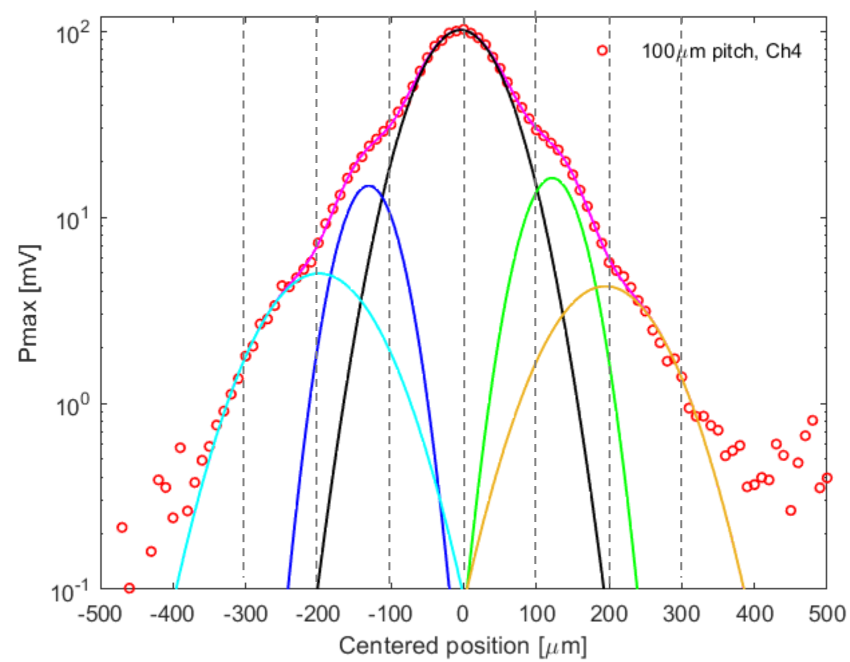
- AC-LGADs provide comparable performance to conventional LGADs, determined by largely by the gain layer: < 40 ps established, 20 ps reachable
- Impact of signal sharing on timing resolution:
  - Weighted reconstruction of several contributions can improve timing resolution
  - But: lower signal in individual segment increases rise time and reduces signal-to-noise ratio (and thus timing resolution through the jitter component)



Charge on neighboring strips

- Closer examination of the individual strips' pmax profiles reveals contribution from next and even second neighboring strip
- Actual sharing extends from the central strip almost to the far edge of the next neighbor
  - ➢ Localization indicates **induced** charge on the neighboring strips, not purely conduction through the resistive n^+ layer

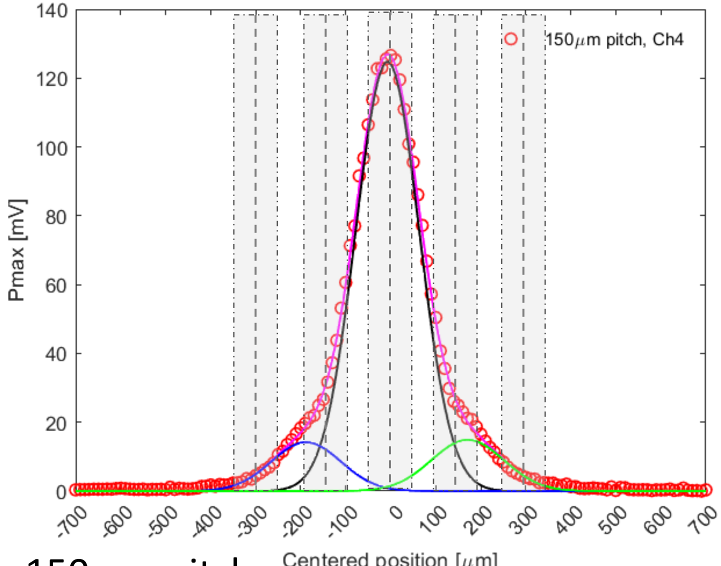


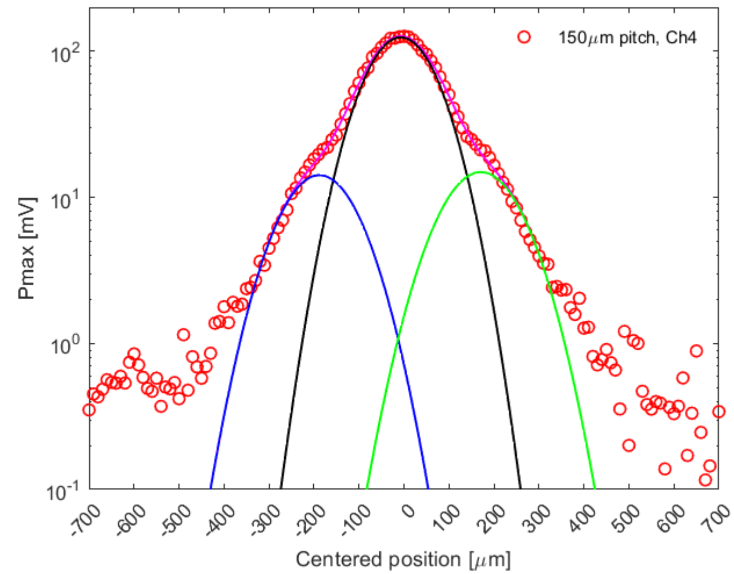


Narrow, 100 μm pitch

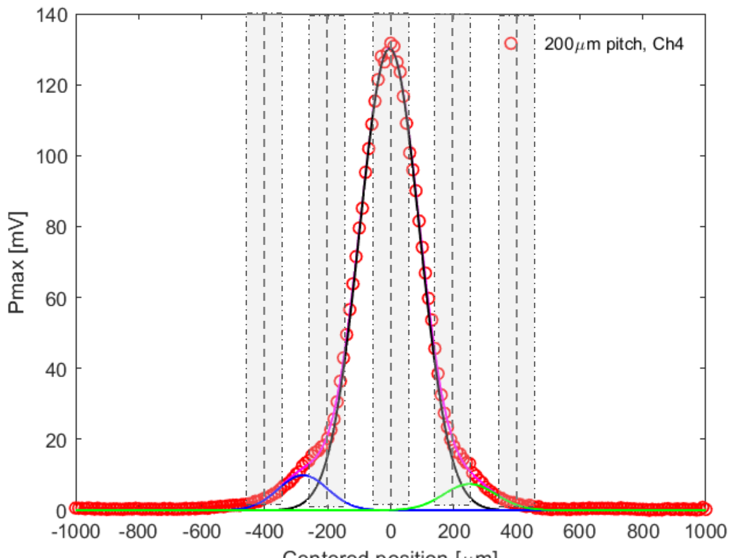
Charge on neighboring strips

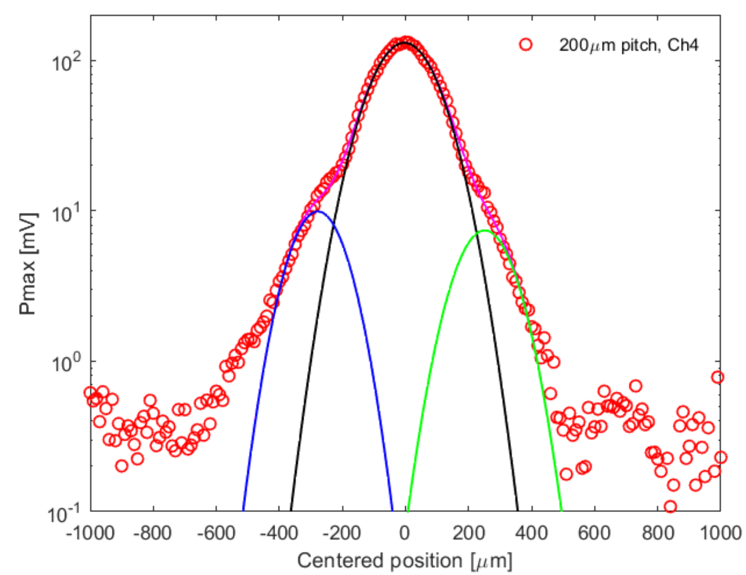
J. Ott et al, AC-LGADs for high-precision timing and tracking, PM2021





Medium, 150 µm pitch



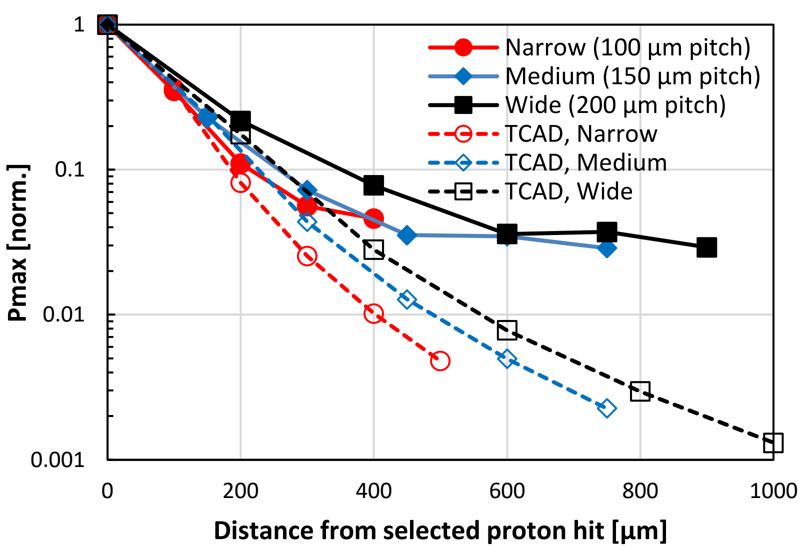


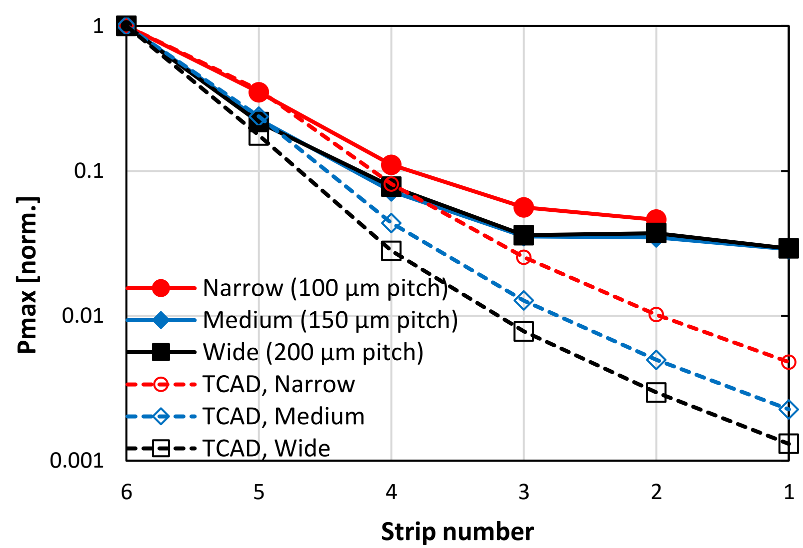
Wide, 200 µm pitch

Charge sharing at long distances

- Selection: proton track on strip #6
- "in-time" data within 1 ns time window of the main signal

- Constant, position-independent pmax (above noise) at longer distance from hit – not predicted by simulations
  - **Sharing or pick-up from the n^+ layer?**

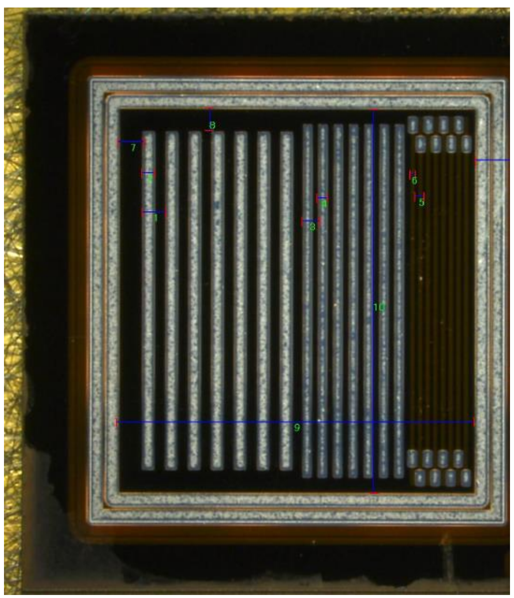


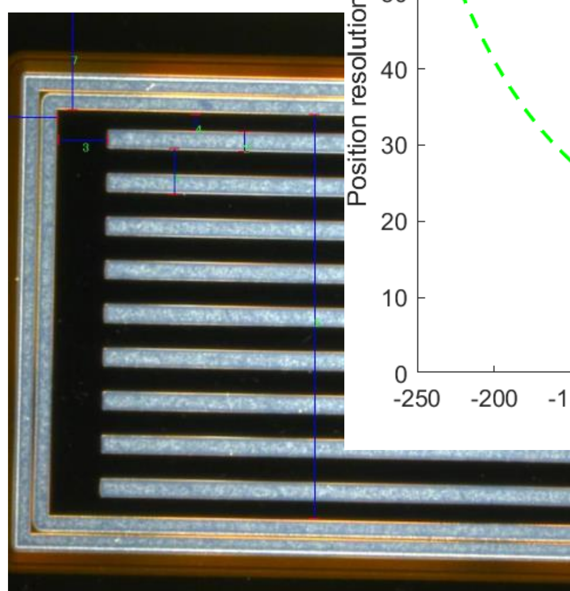


Laser study of charge sharing

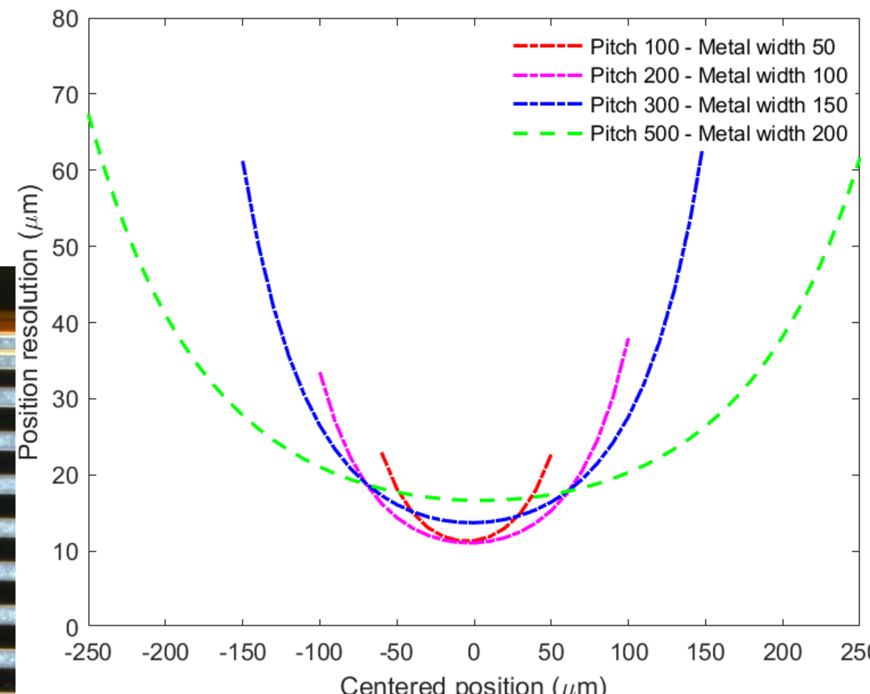
J. Ott et al, AC-LGADs for high-precision timing and tracking, PM2021

- 500µm-pitch/200µm-metal sensor differs from others in terms of charge sharing, but still provides < 20µm position resolution between metal strips
- **Strip *length* also increases charge sharing**





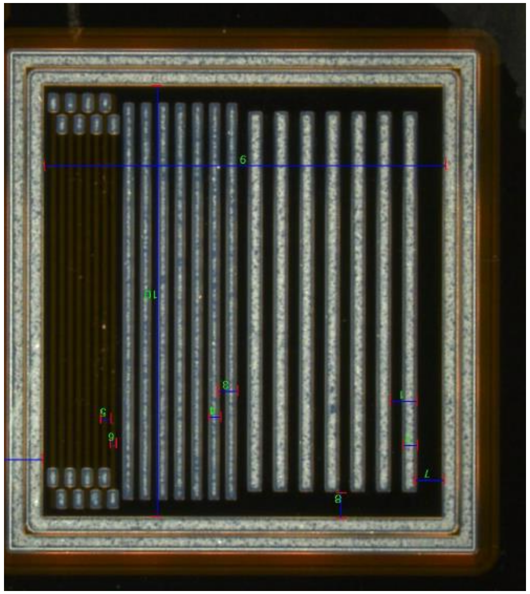
Strip length ca. 2.5 cm →

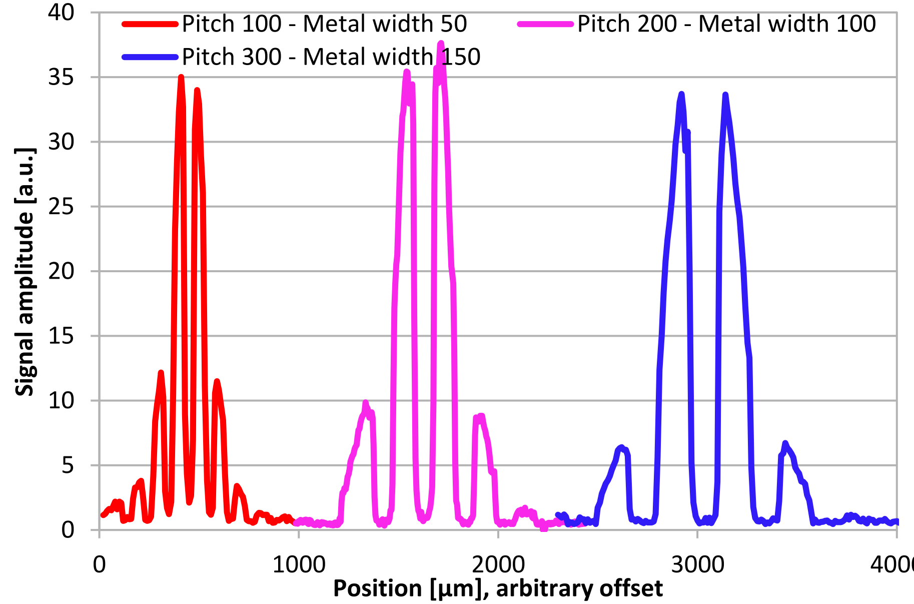


Laser study of charge sharing

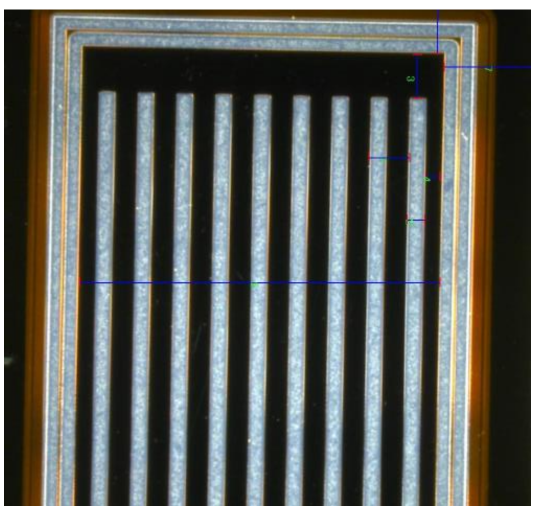
J. Ott et al, AC-LGADs for high-precision timing and tracking, PM2021

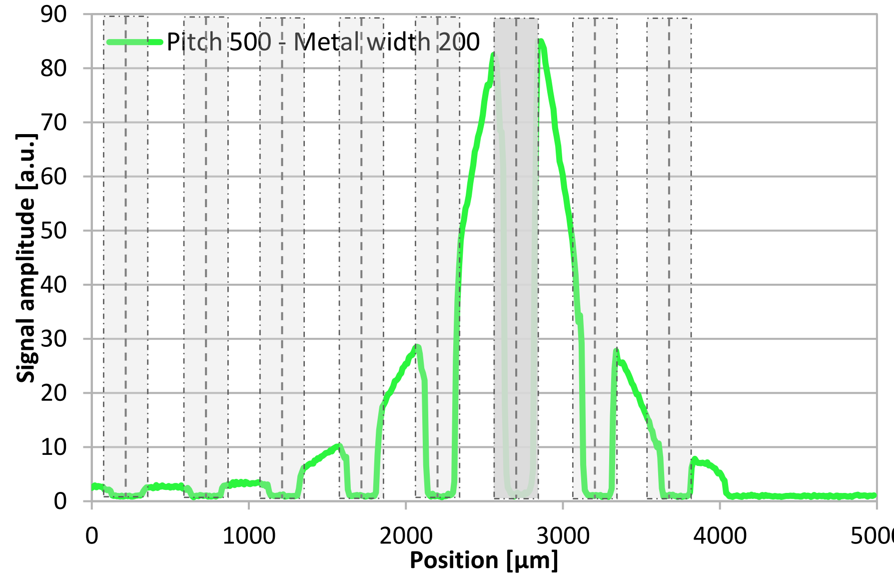
~0.5 cm





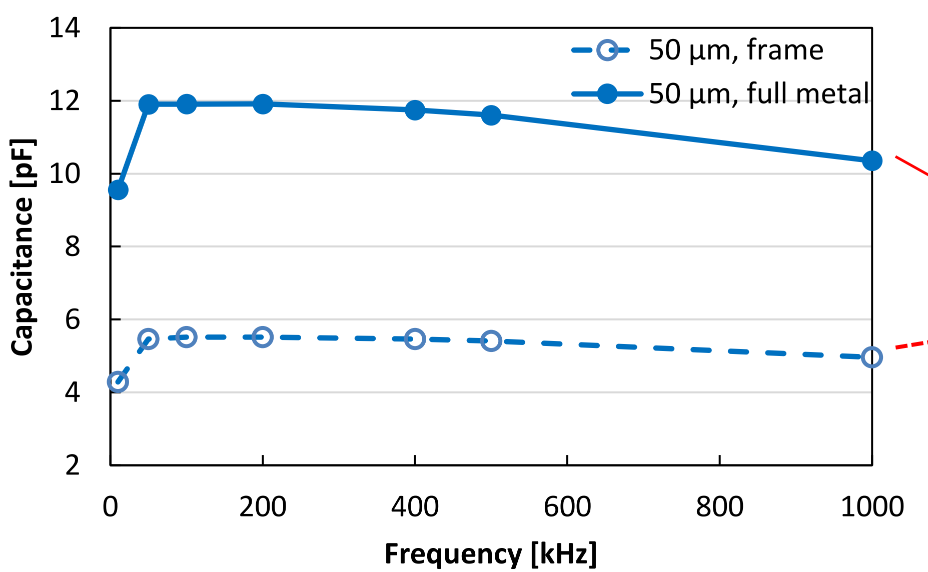
~2.5 cm

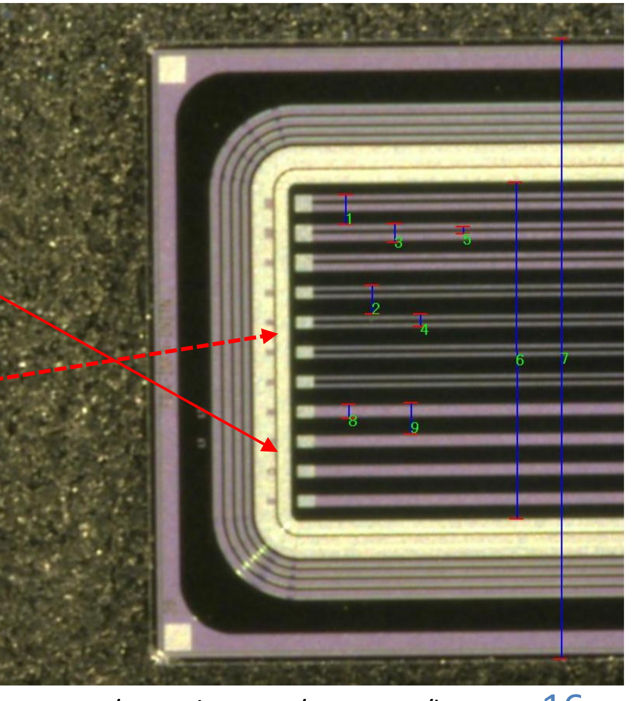




Electrode shape and capacitance

- Emphasis on electrode shape and geometry in FBK RSD2*
  - Various shapes: strips, regular rectangles, circles, crosses, stars…
  - Geometry: electrodes arranged on a square grid or on triangles
  - Metallization: e.g. cutting out the metal on strips, leaving a "frame" instead of a fully metallized strip
    - ➢ ***Direct impact on electrode capacitance***

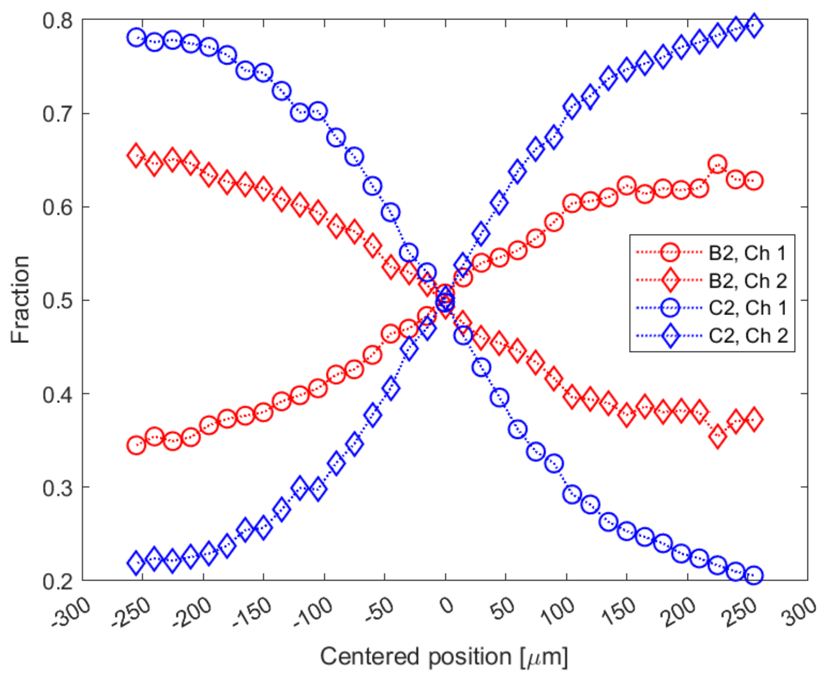


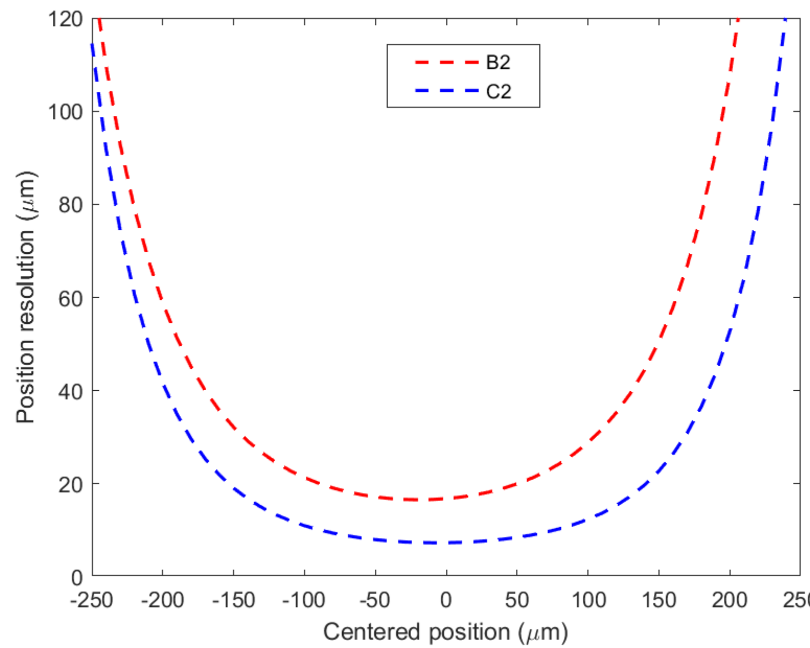


*M. Mandurrino et al, 39th RD50 Workshop, November 2021 (https://indico.cern.ch/event/1074989/contributions/4602006/)

Impact of n^+ implant dose on position resolution

- Charge sharing in terms of pmax fraction, and subsequently position resolution can be determined in the same way for pad sensors
- B2 and C2 refer here to different n^+ implant doses*
  - Effect of n^+ resistivity on is significant
  - **n^+ resistivity is another parameter to tune charge sharing (to the requirements of specific applications)**

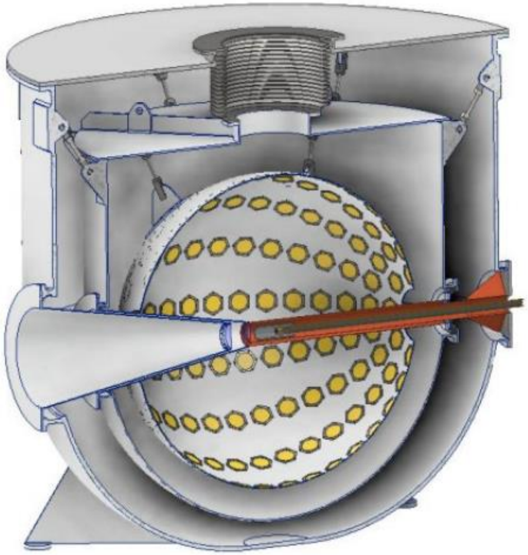


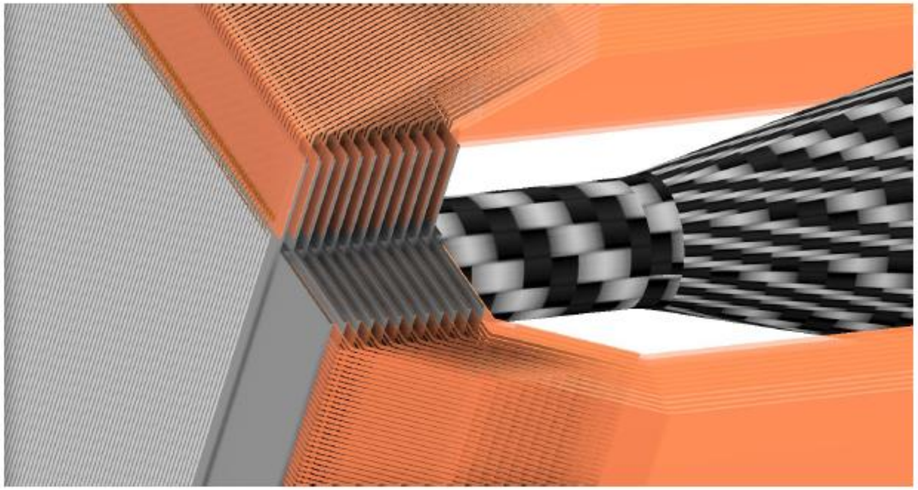


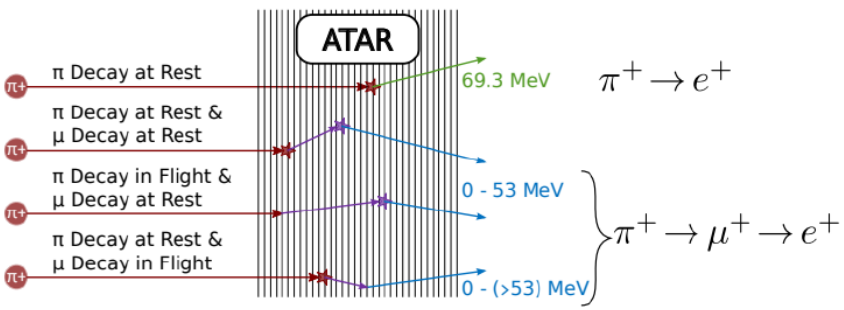
* K. Nakamura *et al*, First Prototype of Finely Segmented HPK AC-LGAD Detectors, JPS Conf. Proc. 34, 010016 (2021)

Example of future experiments: PIONEER

- New pion decay experiment approved at PSI, data taking to be started in 2028 - first beam time assigned for May 2022
- Design baseline for the Active TARget: 2x2 cm^2 area with 48 planes of 120 µm thick AC-LGAD strips, pitch ca. 200 µm
    - Large energy deposition by stopping particles: need sufficient charge sharing to provide good spatial resolution, but not enough to occupy large areas of the sensor from one hit





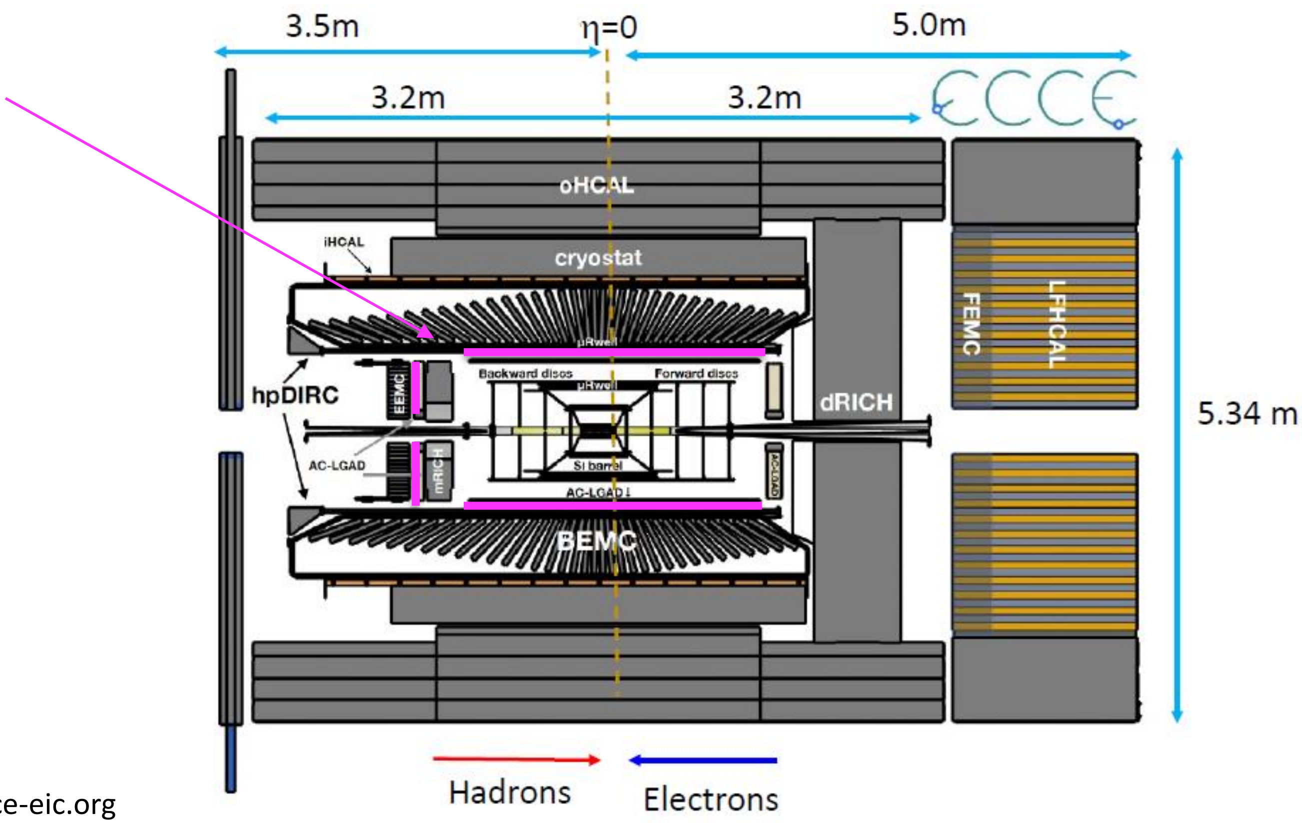


Poster

PIONEER: Studies of Rare Pion Decays, https://arxiv.org/abs/2203.01981 (2022)
S. M. Mazza, An LGAD-Based Full Active Target for the PIONEER Experiment, *Instruments* **2021**, *5*(4), 40

Electron-Ion Collider Detector 1

- Recently issued recommendation for Detector 1: largely based on the ECCE design, also influence from ATHENA
- Both designs include a time-of-flight particle ID detector layer with AC-LGADs as baseline technology



https://www.ecce-eic.org
T. Horn et al, https://indico.bnl.gov/event/14994/contributions/60656/attachments/40379/67415/ECCE-Bi-Weekly-Meeting-03282022.pdf
https://indico.bnl.gov/event/15371/contributions/62712/attachments/40742/68079/Detector%201%20Introduction%20and%20Overview%20Rev%205.pdf

Electron-Ion Collider Detector 1

- Recently issued recommendation for Detector 1: largely based on the ECCE design, also influence from ATHENA
- Both designs include a time-of-flight particle ID detector layer, with AC-LGADs as baseline technology
- *R&D efforts ongoing and ramping up!*

- Radiation hardness of timing detectors less challenging - more important:
  - **Combination of precise temporal and spatial resolution: 25 ps and 30 µm / hit**
  - Low material budget
- Decisions on sensor geometry and fabrication, and readout electronics to be made soon

https://www.ecce-eic.org
T. Horn et al, https://indico.bnl.gov/event/14994/contributions/60656/attachments/40379/67415/ECCE-Bi-Weekly-Meeting-03282022.pdf
https://indico.bnl.gov/event/15371/contributions/62712/attachments/40742/68079/Detector%201%20Introduction%20and%20Overview%20Rev%205.pdf

Summary

- Thanks to signal sharing, AC-LGADs can achieve remarkable position resolution even with large and widely spaced electrodes
  - Less than 1/20 of the pitch
- Charge sharing in AC-LGADs is a complex phenomenon, and is influenced by the pattern of the metal electrode (width, pitch, geometry), as well as n^+ layer resistivity
  - Induction of signal on neighboring electrodes is observed
  - Examination of the noise distributions in terms of pulse height *and* time improves the separation of real signals from noise

➢ **Extensive ongoing research on AC-LGADs towards precision timing and 4-dimensional tracking in future colliders and experiments**
  - Efforts will provide valuable information for adjusting the properties of future AC-LGAD sensors to their targeted applications
  - Including development of readout electronics!

➢ Precise timing and position resolution and fast charge collection time is also attractive to other fields, such as synchrotron beam monitoring, photon counting, etc

Thank you!

US-Japan Collaborative Consortium
(Development of AC-LGADs for 4D trackers)

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Finnish Cultural Foundation

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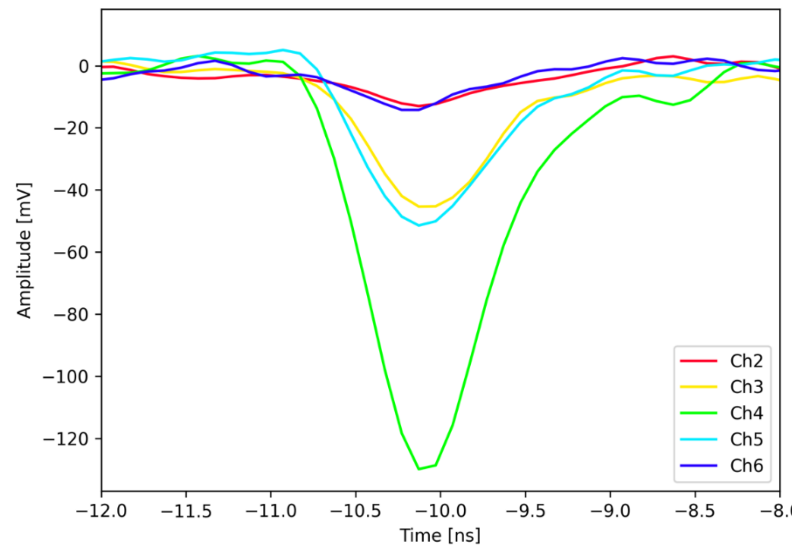
Thank you!

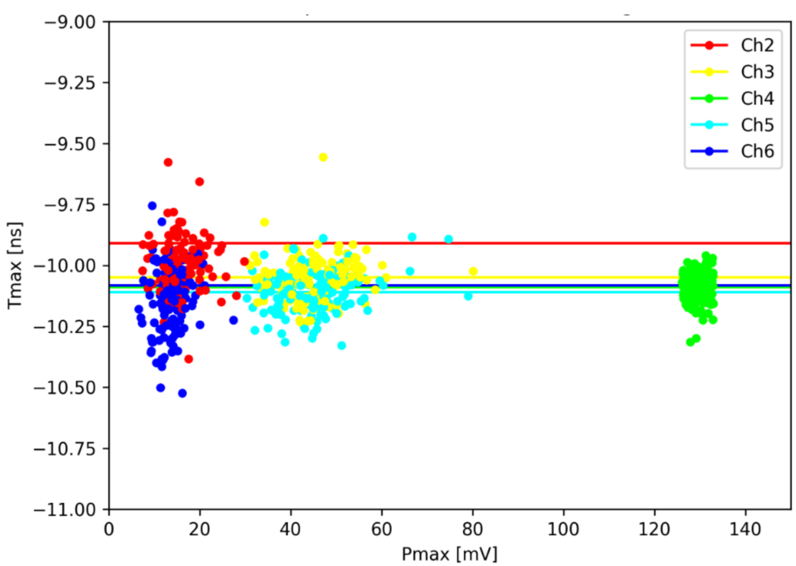
BACKUP

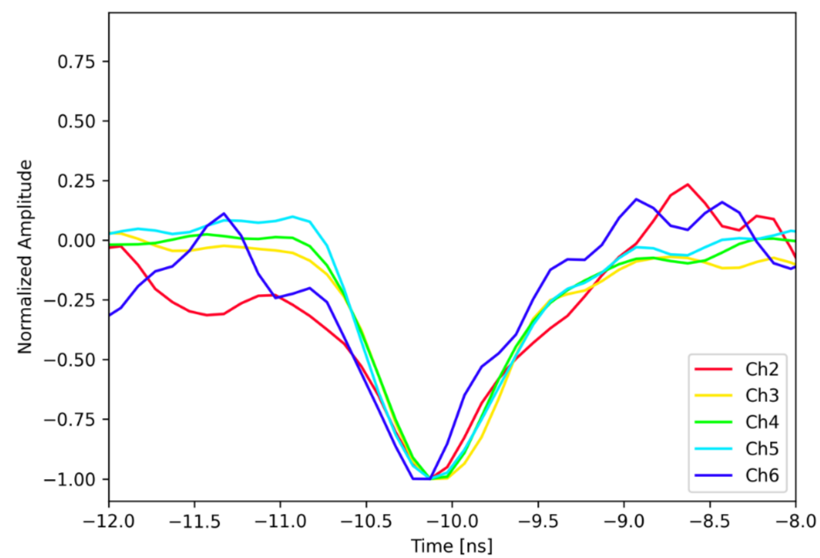
Signal pulse shapes

J. Ott et al, AC-LGADs for high-precision timing and tracking, PM2021

- Signal in second neighbors is observed, but with lower amplitude, wider spread in pmax and peak time *tmax*
- Pulse shape (when amplitude is normalized) is in fact not distinctly different



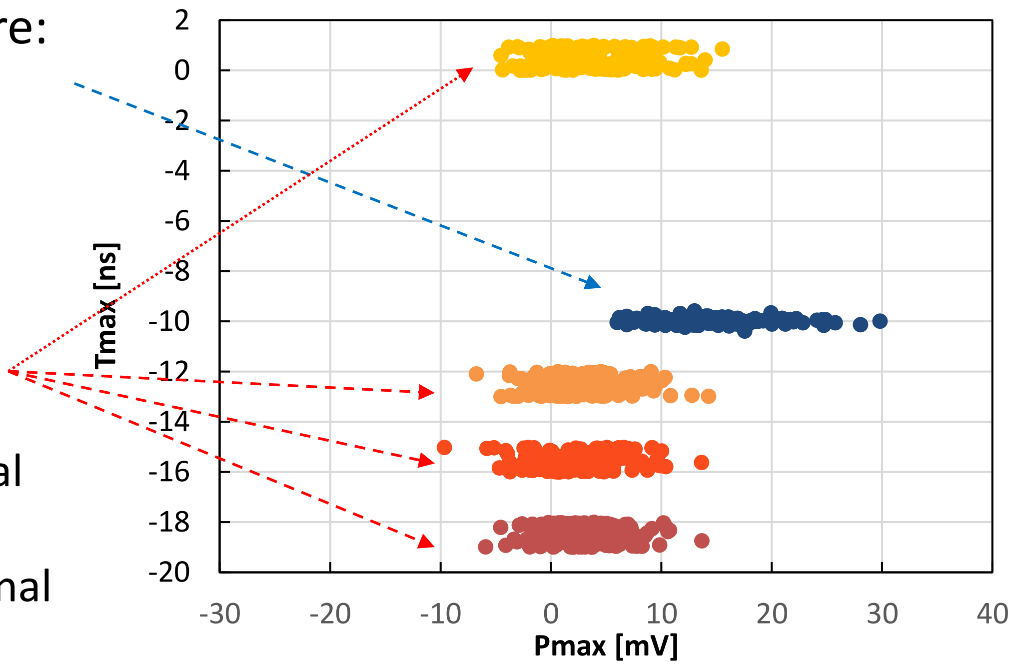




Pmax - tmax

- Test beam: time stamp relative to trigger
- Especially with fast sensors like (AC-)LGADs, precise timing of the signal is interesting for the understanding charge sharing and the role of noise

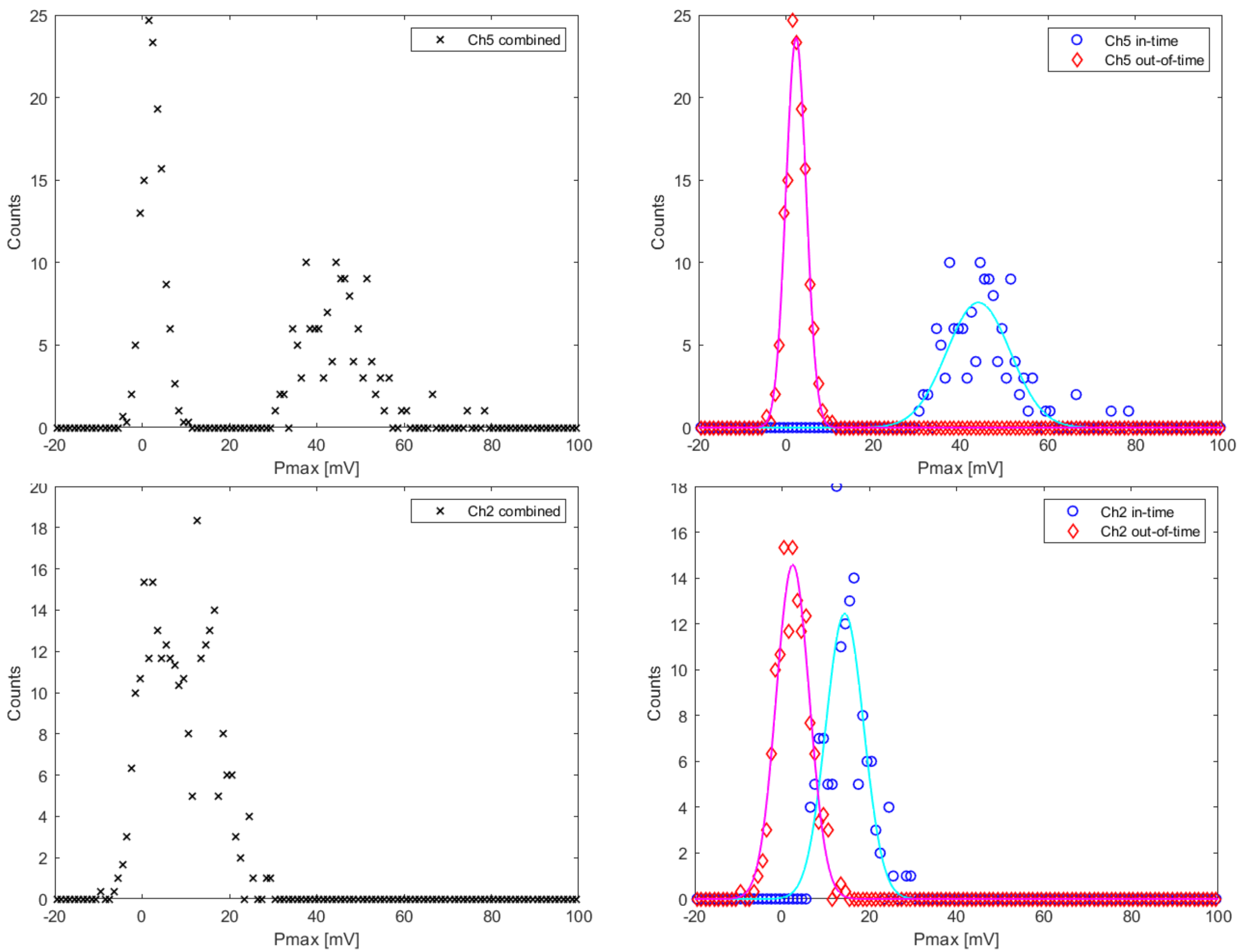
- *in-time* events: within certain tmax bin of the trigger - here: within 1 ns of the channel under investigation
- *out-of-time* events: events outside of the decided timeframe
  - Out-of-time bin after signal has higher noise: analysis focuses on bins before signal



J. Ott et al, AC-LGADs for high-precision timing and tracking, PM2021

Separation of real signals: In-time vs out-of-time

- Noise and signal pmax distributions can be distinct – or very close together, almost indistinguishable
  - **Visible by in-time/out-of-time separation**



Separation of real signals: In-time vs out-of-time

- Smaller time window reduces noise contribution to signal

- The choice of model used to describe the signal (mean, Landau, Gaussian) does not have a strong impact on signal/noise separation
- Even at large distances from the triggered channel, in-time signal pulse heights are above the noise floor