Particle Identification with the High Granularity TPC Readout ROPPERI

Readout **O**f a **P**ad **P**lane with **E**lect**R**onics designed for p**I**xels

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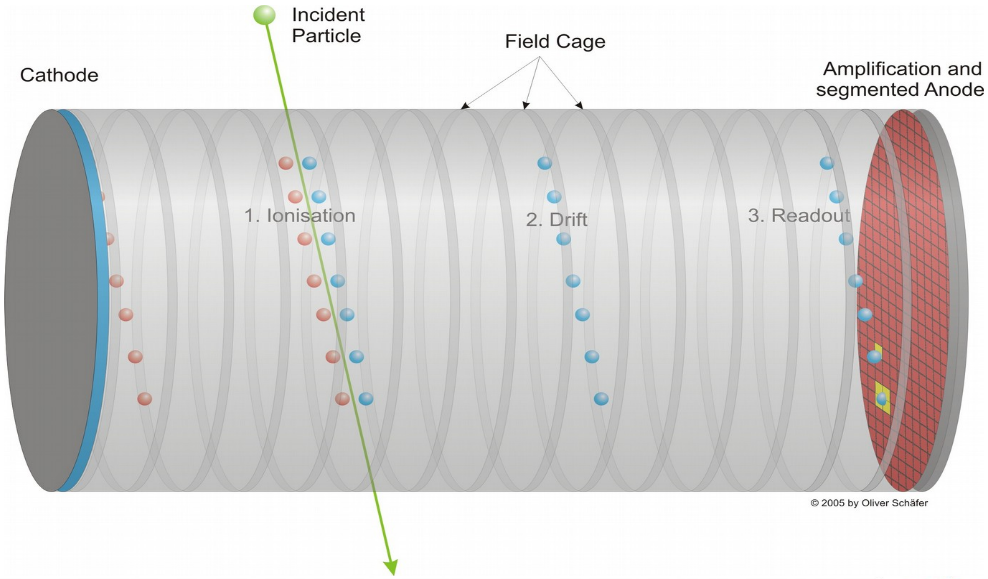
Content

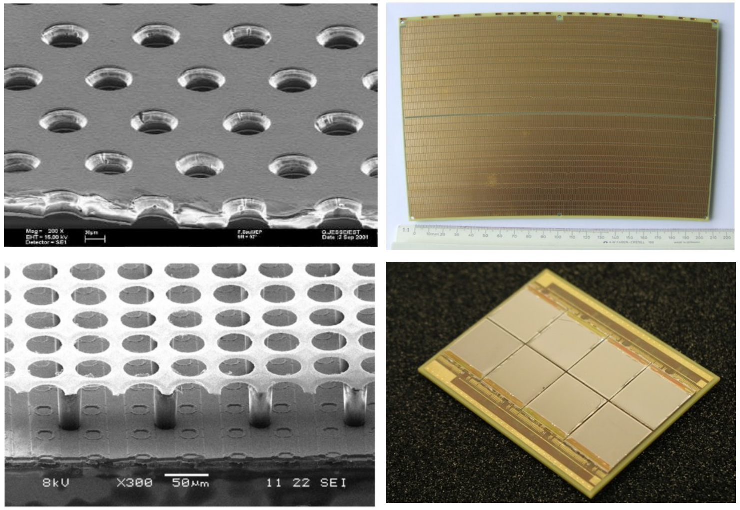
- Introduction & Idea

- Hardware
  - Board structure
  - Development status

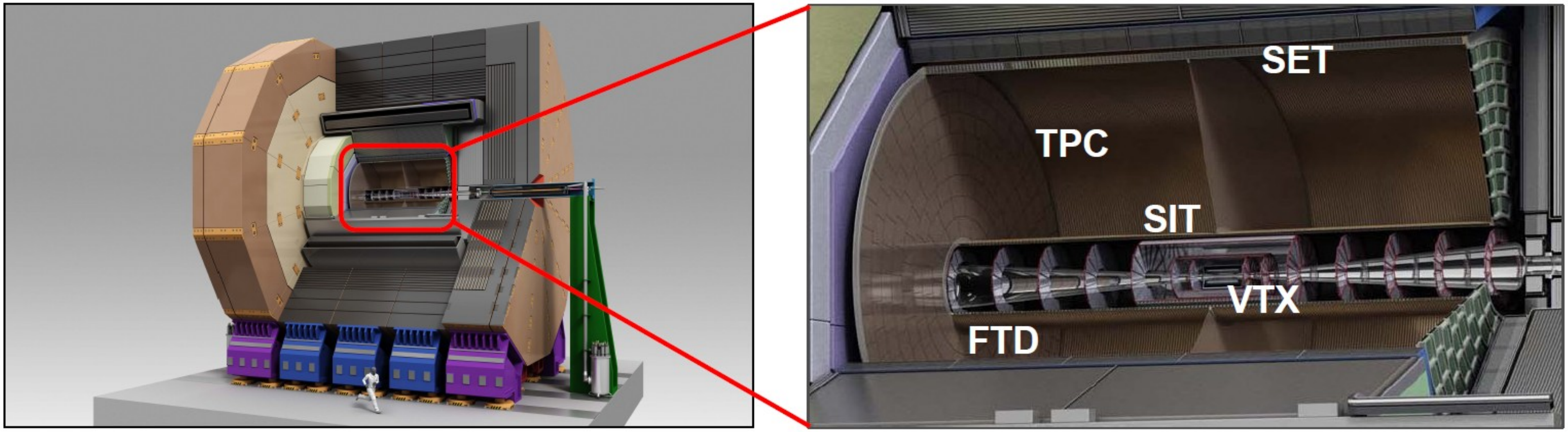
- Simulation
  - Cluster counting
  - MC chain structure
  - Identification performance

TPC Readout Technologies





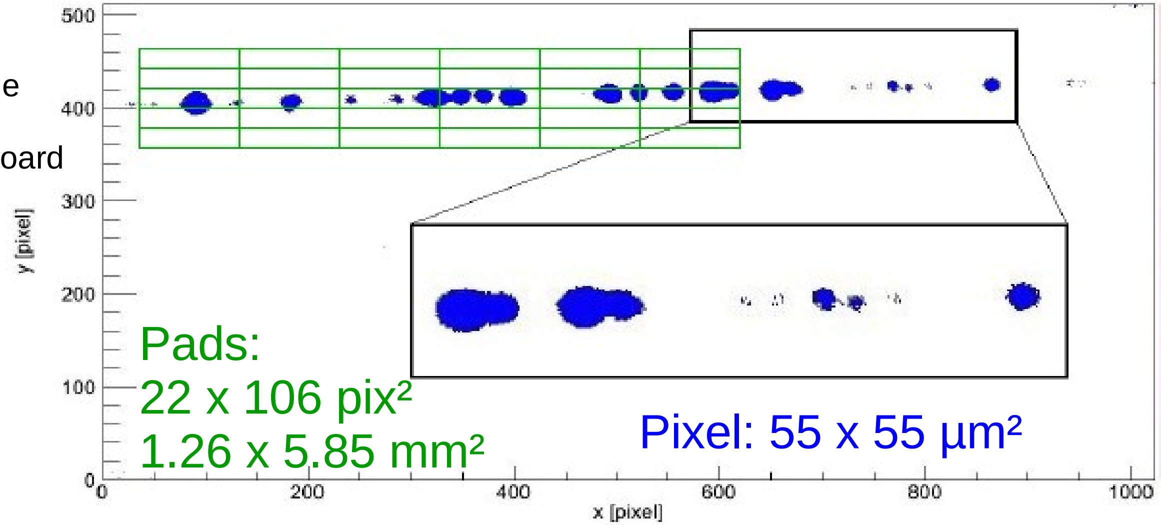
(a)



Idea: intermediate solution between pads and pixels

M. Lupberger: The Pixel-TPC:
first results from an 8-InGrid module

Here: GEMs + bare Timepix-Octoboard
with T2K gas



Pads:
22 x 106 pix²
1.26 x 5.85 mm²

Pixel: 55 x 55 µm²

- Clusters contain the primary information of the ionisation
- For a GEM-based system: Can we find a solution to resolve clusters?
- What is the optimal pad size to
  - improve double hit and double track resolution,
  - do cluster counting for improved dE/dx?

  → O(200µm)

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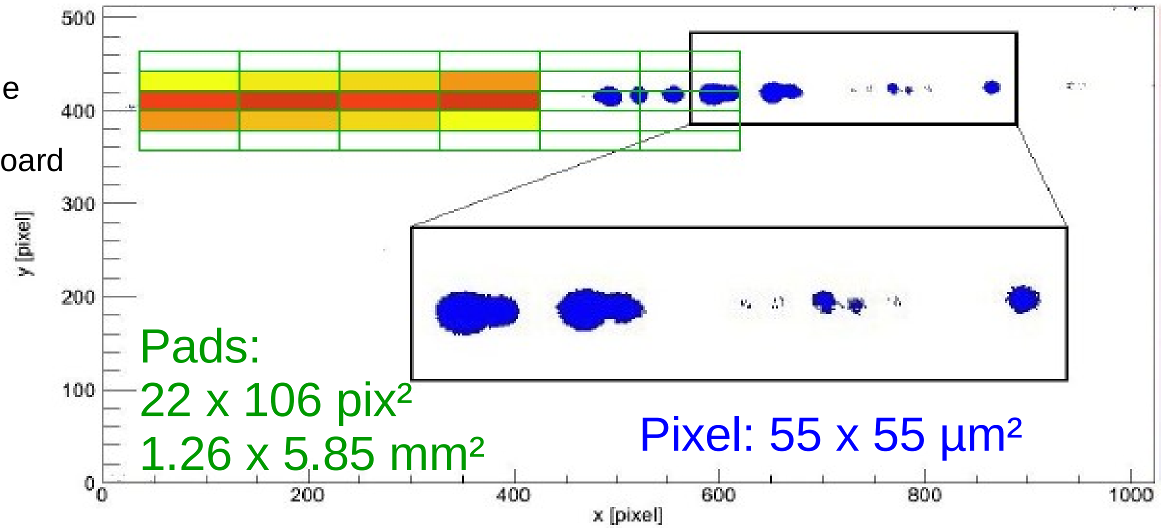

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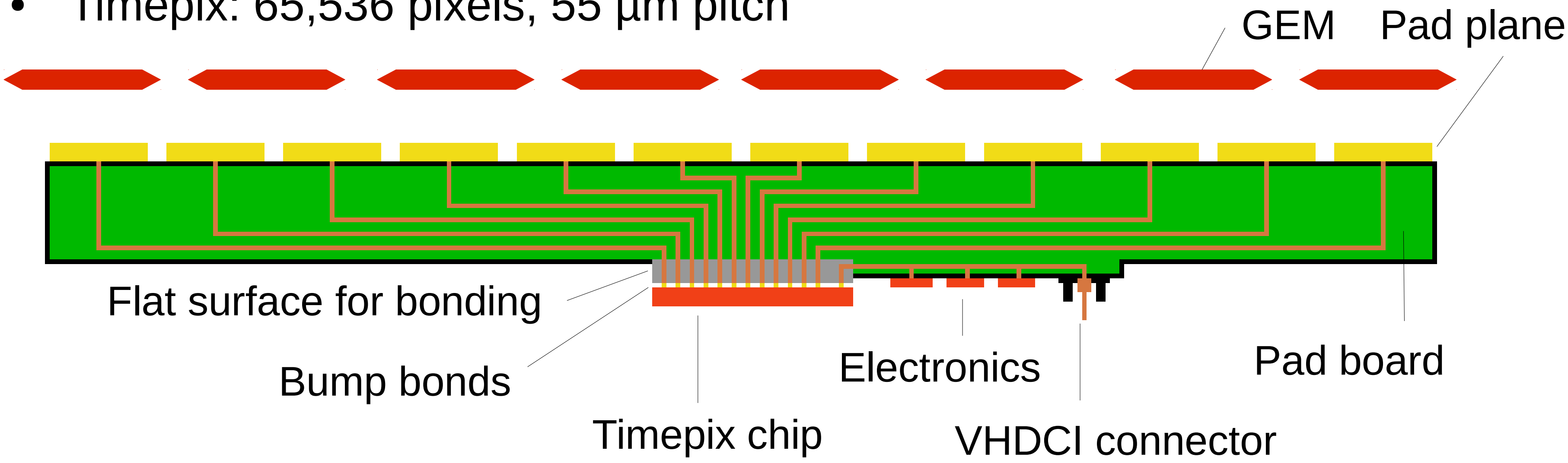
Idea

- For a GEM-based TPC readout: Match readout pitch with dimension of primary ionisation clusters
- Allow for:
  - Improved particle identification by dE/dx (cluster counting)
  - Improved double hit/track resolution
- Implementation:
  - Use separate pad plane for high flexibility and large area coverage
  - Use pixel chip for high integration → Timepix

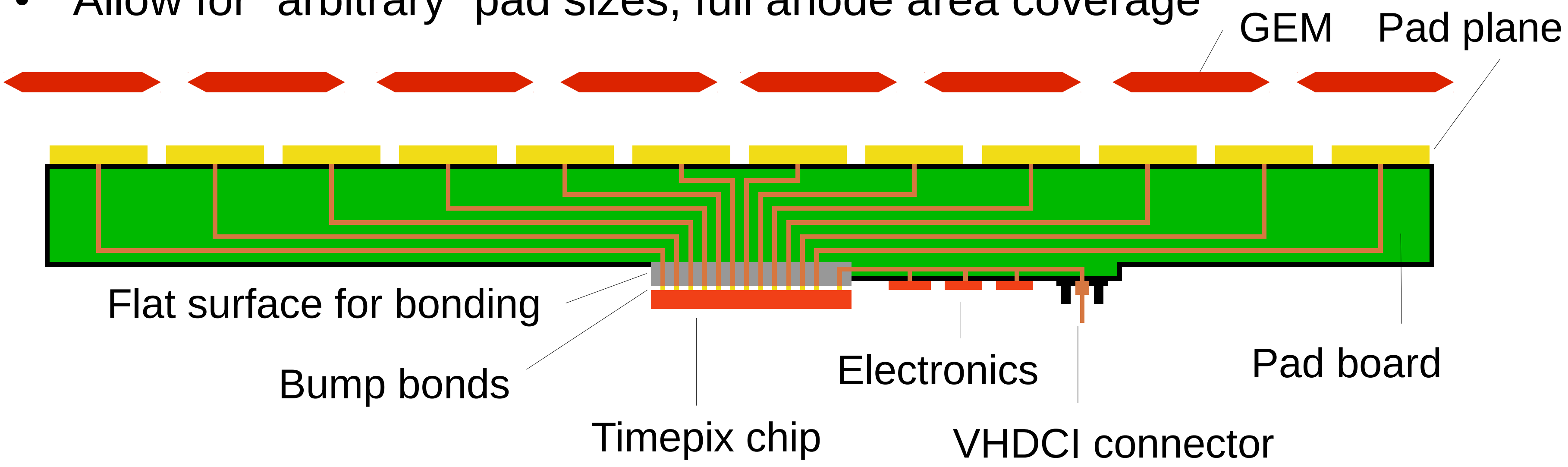
Ansatz

- GEMs, small pads, Timepix chip as readout electronics
- Connections from pads to chip are routed through the board, then bump bonded to the chip
- Timepix wirebond pads for the communication channels are on the same side as the pixels → also bump bonded, back to the board
- Timepix: 65,536 pixels, 55 µm pitch



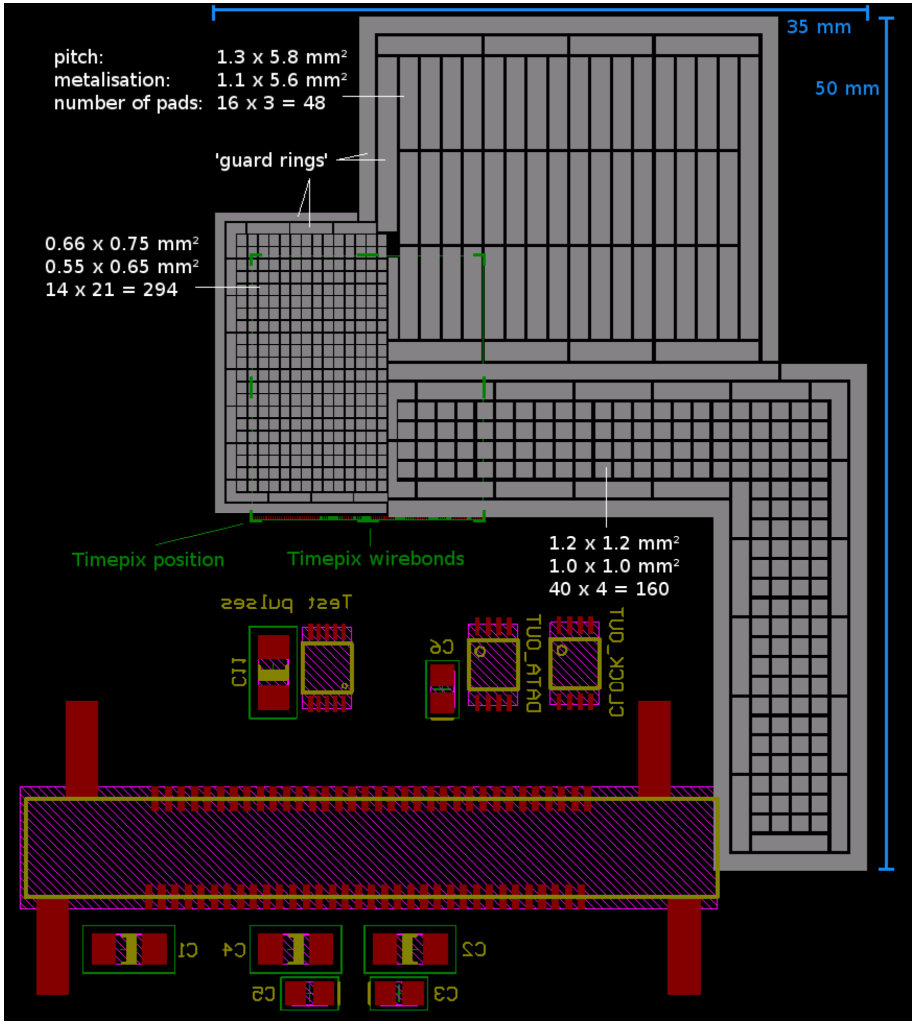
Benefits

- Compared to the existing GEMs+pads system:
  - Higher granularity → better occupancy, double track resolution, possible cluster counting
  - Square pads, several pads per charge cloud → no $\tan^2\theta$ -effect
  - High integration: O(30) smaller footstep
- Allow for “arbitrary” pad sizes, full anode area coverage



Hardware: Concept

- PCB of 9 x 9 cm²
- 3 pad sizes and different connection lengths to be tested, smallest pads with shortest connections directly on the chip → influence of capacitance
- 500 channels connected in total
- To be used with 10 x 10 cm² GEMs in a small TPC
- First prototype boards were delivered Jan-May, only 3rd production attempt successful



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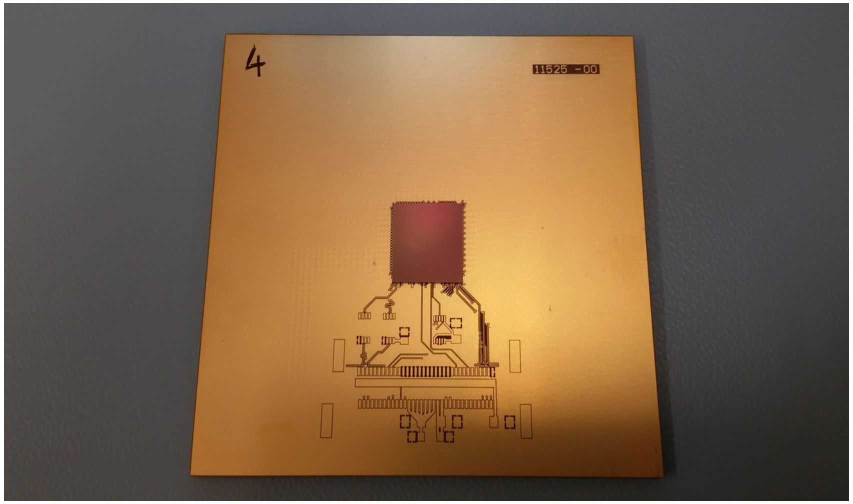

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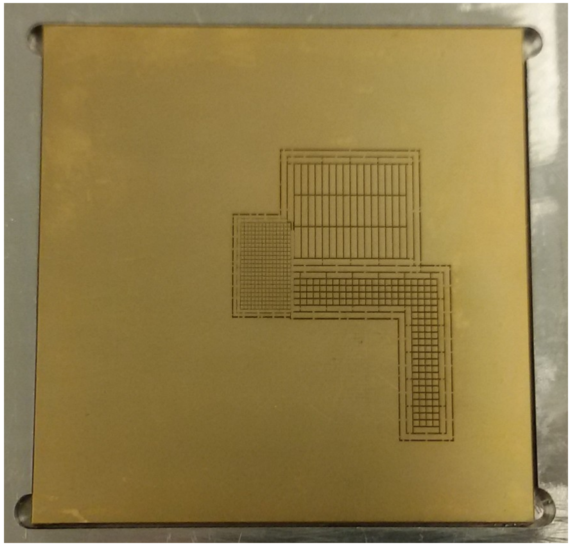
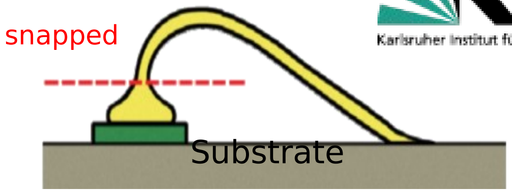
- First prototype boards were delivered Jan-May, only 3rd production attempt successful
- Electroless Nickel Electroless Palladium Immersion Gold (ENEPIG) coating

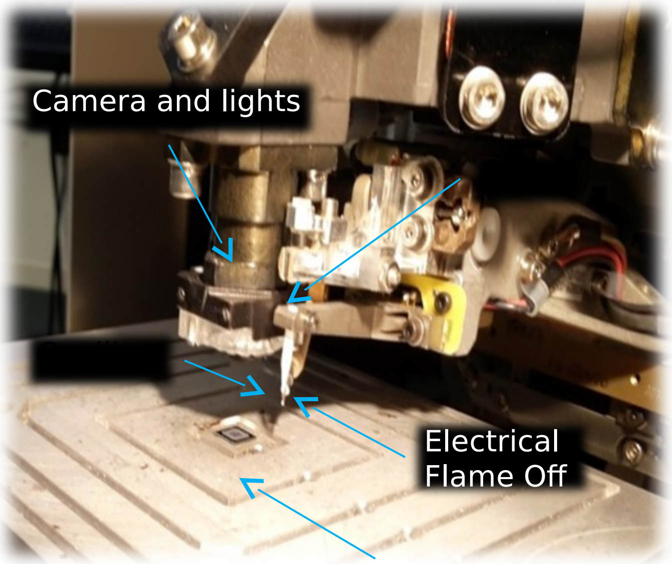


Stud Ball Bumping (SBB) process

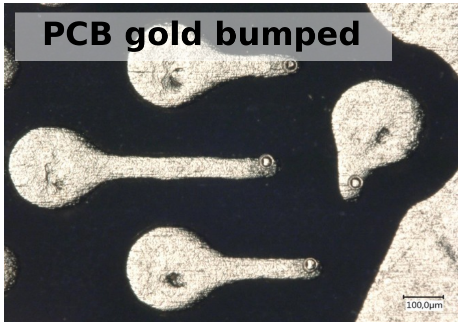
Gold stud bumping is an evolution of the ~ 60 years-old wire bonding process. **Gold stud ball**: the wire is snapped off after the ball is initially connected to the substrate

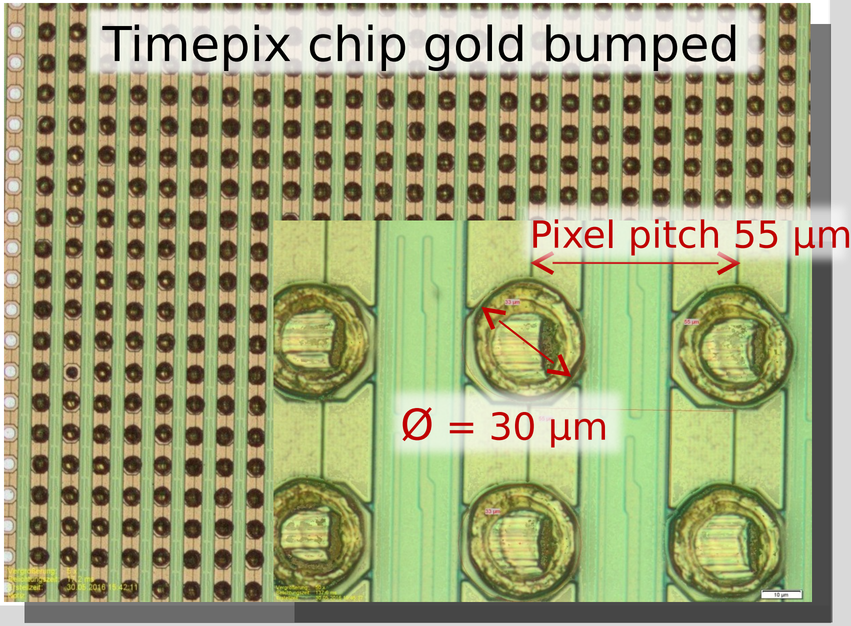


Gold Ball-wedge wire-bonding



- ✓ **Low-cost process**: direct deposition on Al pad (No UBM, lithography process)
- ✓ **Fast deposition**: 20 bumps/s
- ✓ **Short setup time**: ideal for single die bump-bonding (i.e. prototype and R&D)

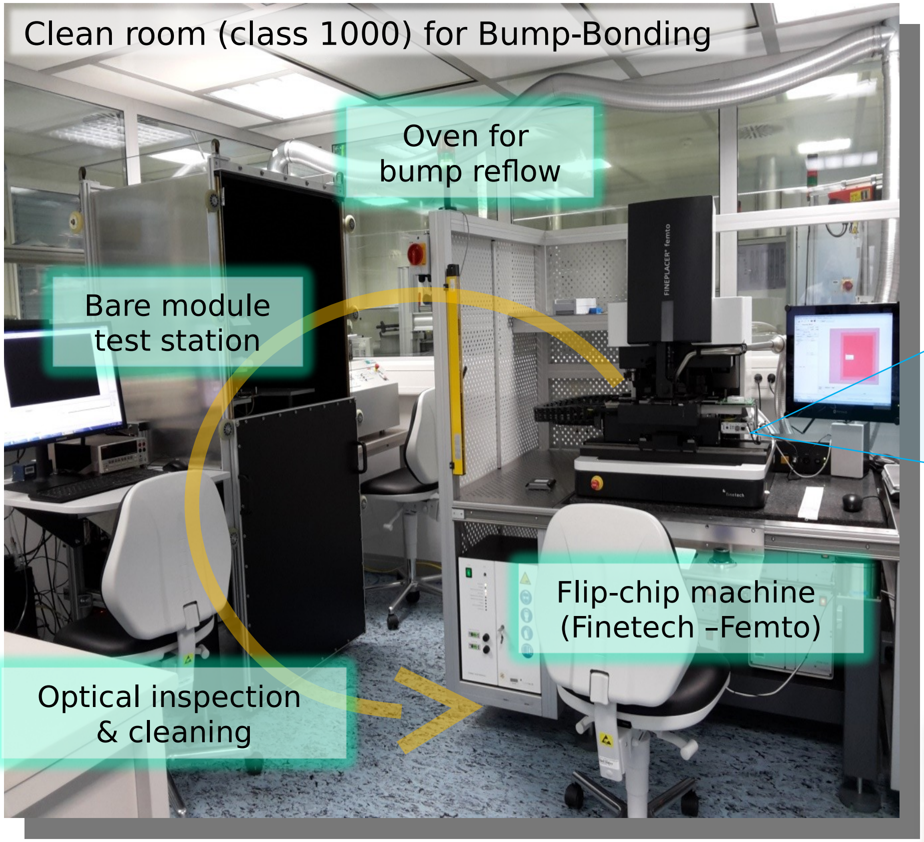


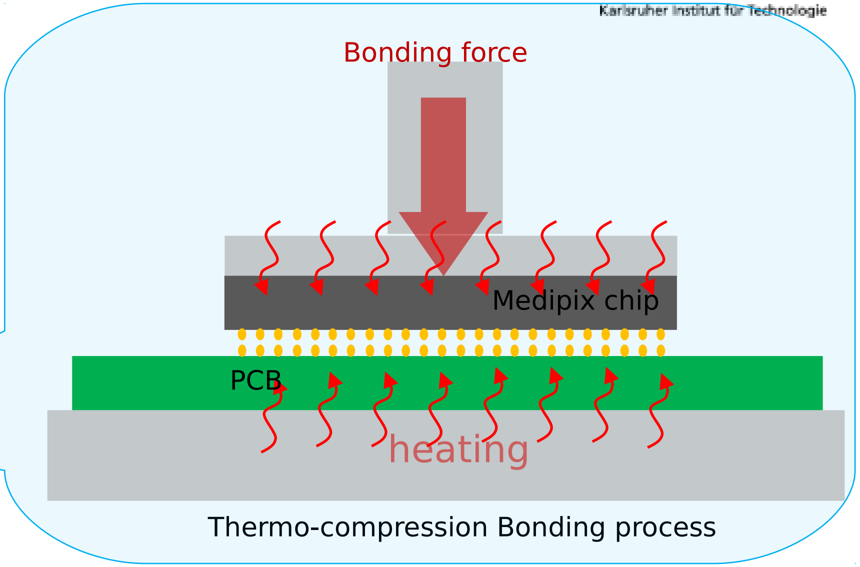


Achieved Bump & pitch size

Au wire diameter (µm)	Bump diameter (µm)	Minimum pitch (µm)
25	60	100
15	30	50
12.5	23	35

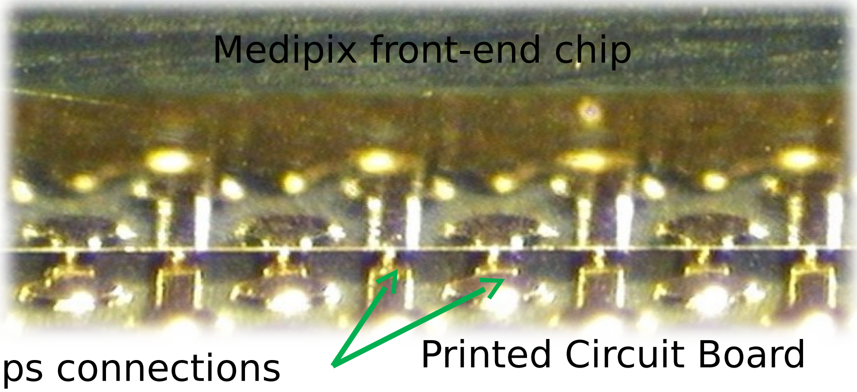
Bonding process





Thermo-compression Bonding process

Chip to PCB during the Bonding process



Cross-section of Gold Stud Bump-Bonding on CMS pixel detector

Bonding parameters:

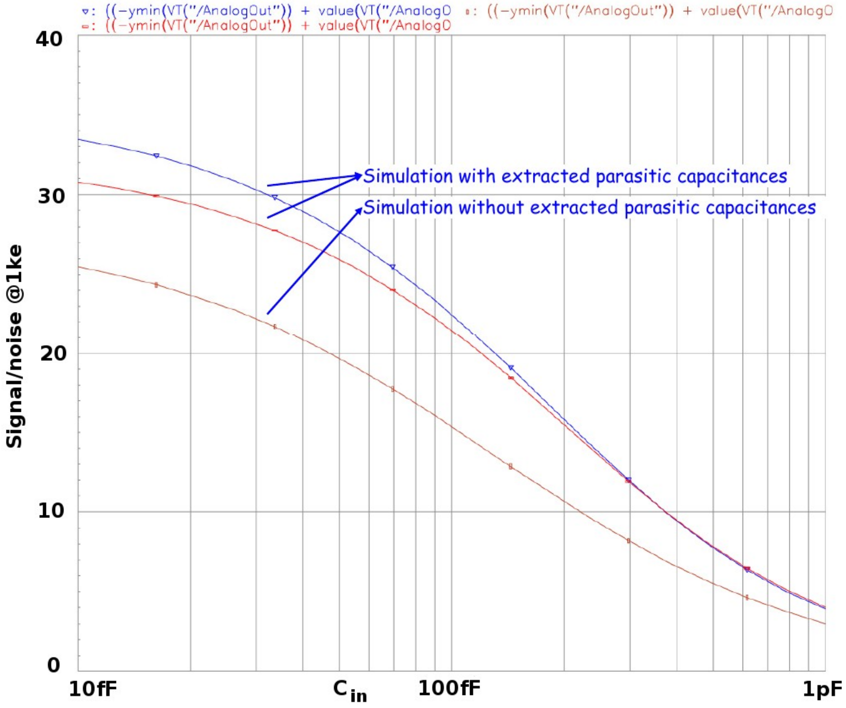
Bond Force :~ 5 gr/bumps,
Bond Temp.: ~very low,
Bond Time : few minutes ~

Hardware: Bonds vs. CTE

- Broken connections: no communication with chip, no data readout
- First time (?) bonding at 55 µm pitch directly from silicon to a PCB
- Problem: different coefficients of thermal expansion (CTE):
  - Si ~ 2.5 ppm/K, FR-4 ~ 15 ppm/K
  - → over 14 mm and at 250°C: ~ 40 µm offset
- Bond at 100°C
  - Worse metal diffusion
  - Still mechanical stress
- Got 1 reasonably good data set (of noise) before system broke again – What can we learn from that?

Hardware: Capacitance Challenge

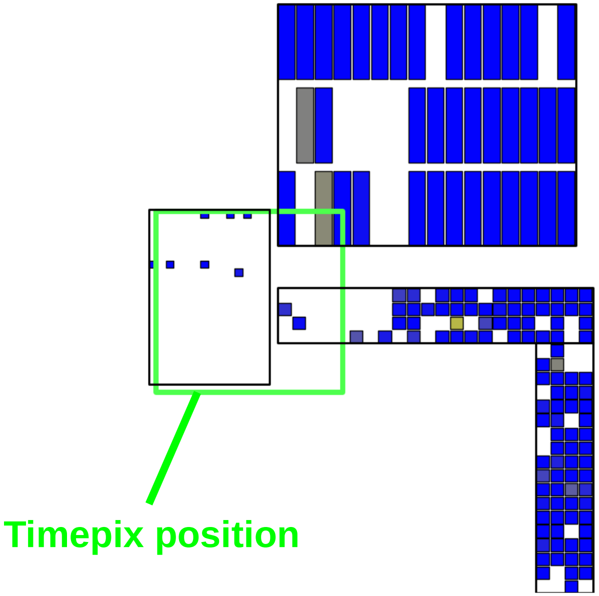
- With growing input capacitance the signal to noise ratio goes down
- Timepix was developed
  C < O(100fF)
- Capacitances:
  Pads: O(0.1pF)
  Lines: O(1pF/2.5cm)
  Bump bond connections: O(0.1pF)
- Gain for triple GEM stack: 2k-5k, potential for significant increase

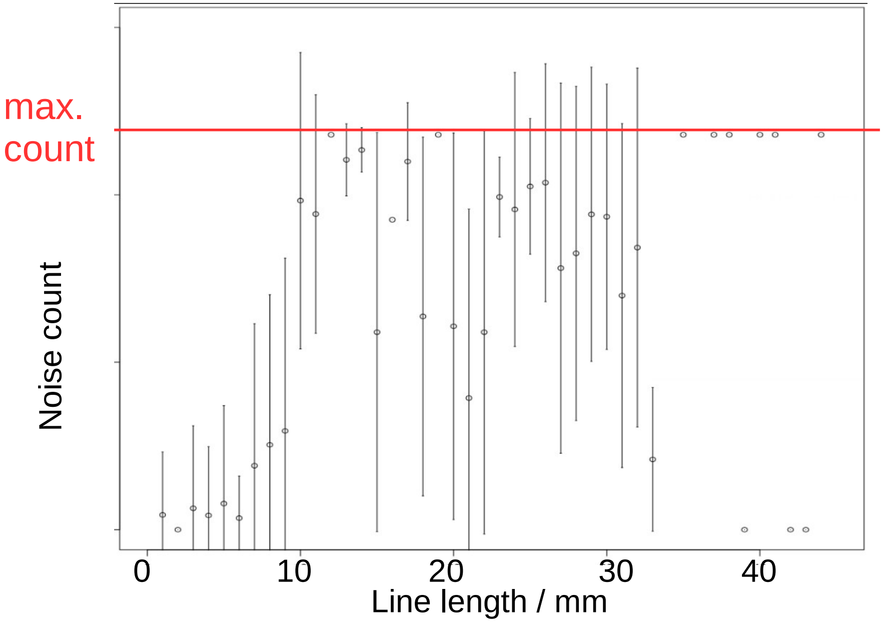


X. Llopart: Timepix Manual v1.0

Hardware: Noise data

- Correlation between pad distance from Timepix and noise consistent with expectation
- Used threshold: 380 counts, typical: 300-400 counts, 1 count = 25 e-

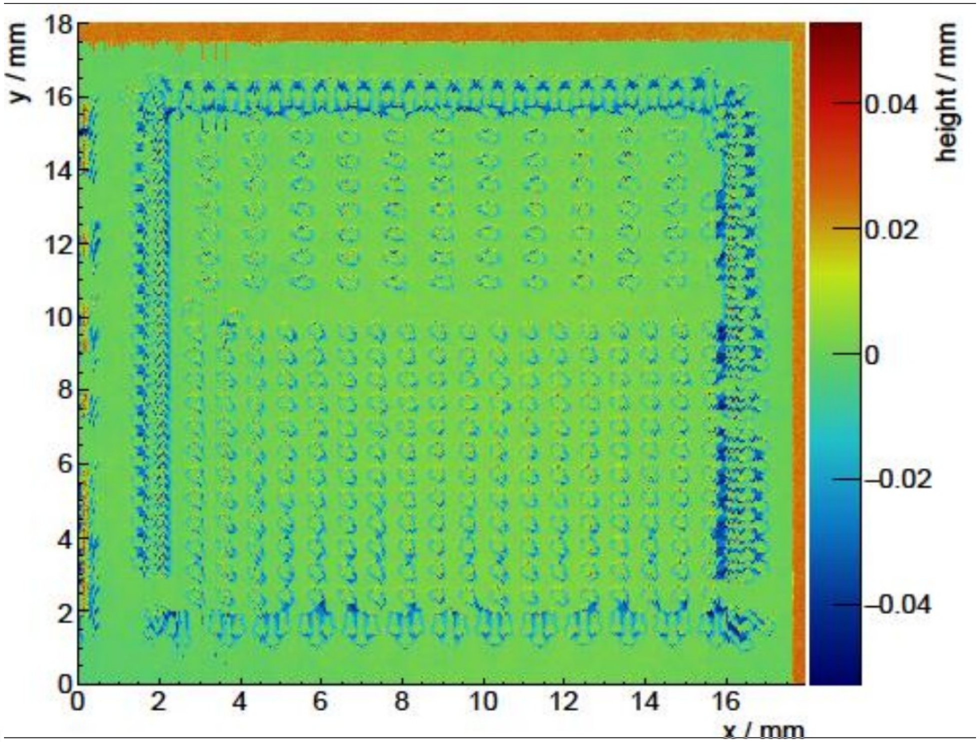




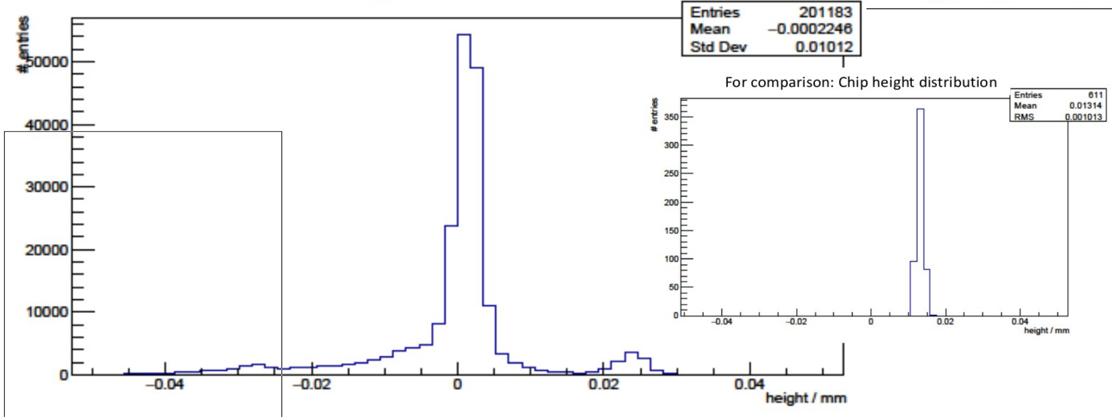
- Large errors, but some confidence reg. noise assumptions

Hardware: Flatness

- Sufficient flatness of few µm required for bonding
- Measured after chip came off

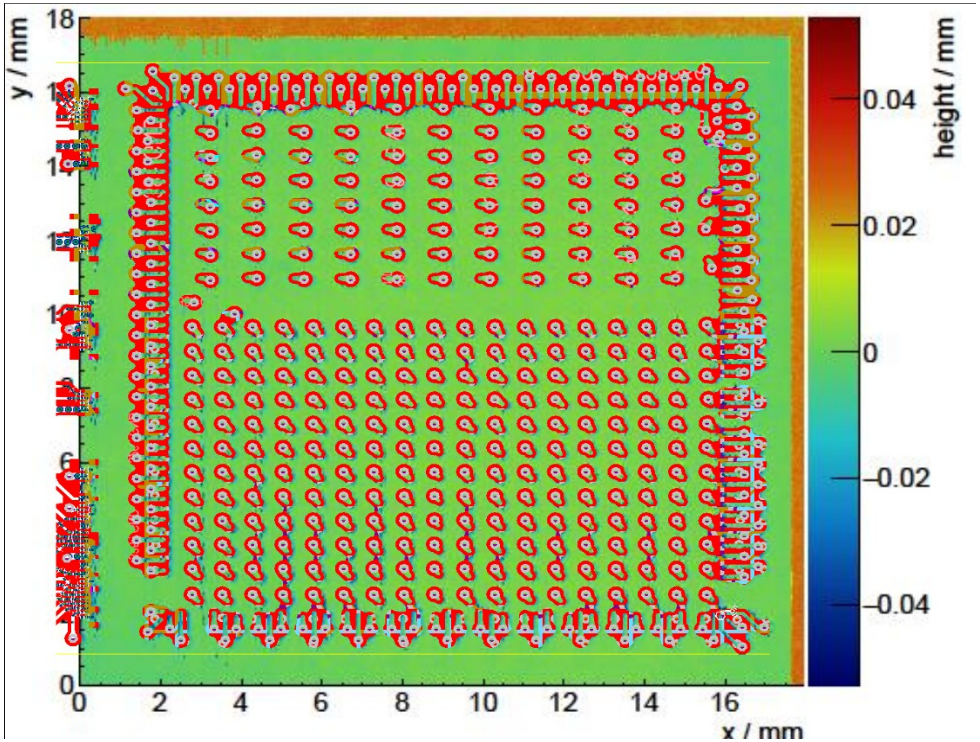


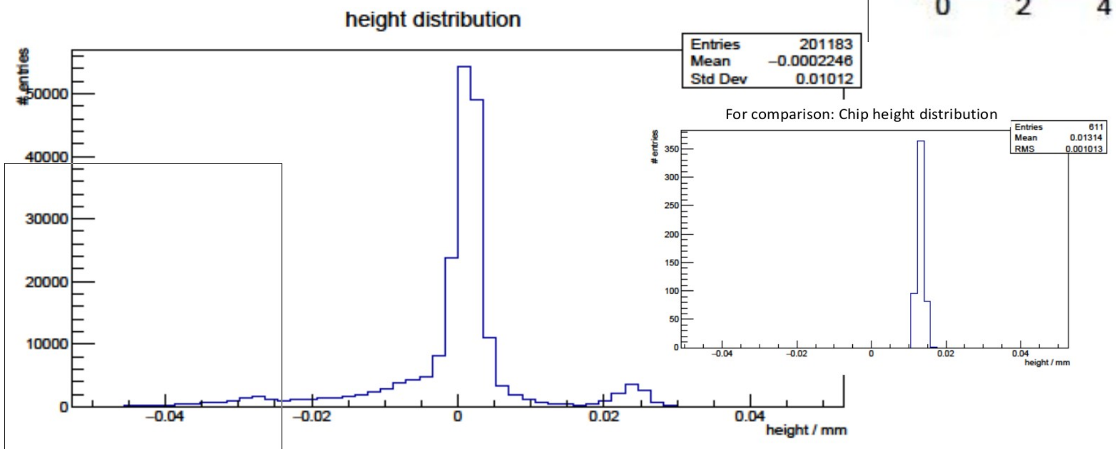
height distribution



Hardware: Flatness

- Sufficient flatness of few µm required for bonding
- Measured after chip came off
- Maps design file very well
- Central peak FWHM: 5 µm, areas without metalisation and surrounding area visible





Hardware: Consequences & Outlook

- Ordered new boards of 2 types with lower CTE
  - Type A: regular material layered with copper-invar-copper (8 ppm/K) delivered, currently in equipping, bonded afterwards
  - Type B: different base material (12 ppm/K) expected in Dec.
  - Small TPC and readout is set up and ready for performance tests of ROPPERI prototype
- Flatness measured, sufficient for bonding, under continuous observation

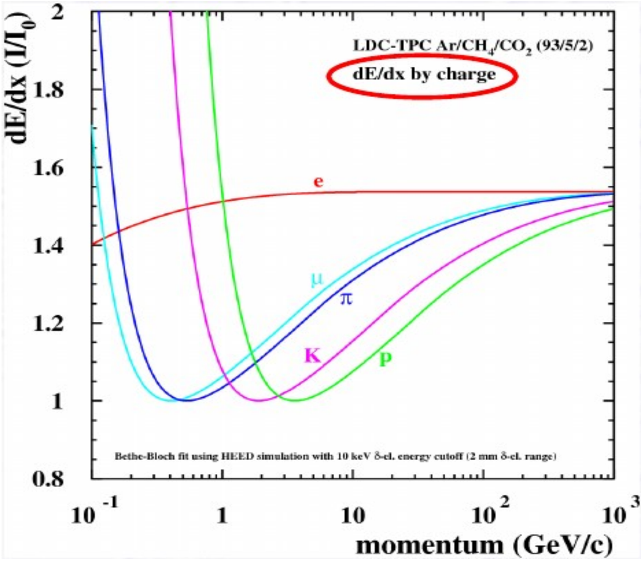
Software

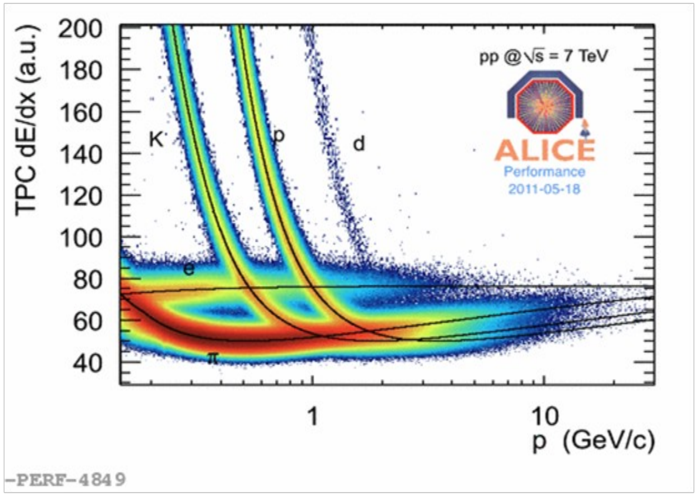
Part 2:
Simulation & Cluster Counting

dE/dx in a TPC

- Energy loss measurement is an advantageous intrinsic capability of TPCs
- Via Bethe-Bloch curve in combination with momentum this leads to the identification of the particle species
- The measurement is usually done via charge summation
- Due to large fluctuations in each ionisation step like δ-electrons the charge / distance distribution is Landau shaped → large RMS → mediocre correlation with energy loss

M. Hauschild: dE/dx and Particle ID Performance with Cluster Counting; at ILC Ws. Valencia 2006





ALICE Collaboration: A Very High Momentum Particle Identification Detector DOI: 10.1140/epjp/i2014-14091-5

Cluster counting

- The number of ionisation steps / distance is Poisson shaped
→ smaller RMS → better correlation → better particle identification
- Counting clusters allows for improved particle separation compared to conventional charge summation
- Depends on fraction of identified clusters (counting efficiency)
→ Need sufficient granularity to identify clusters!

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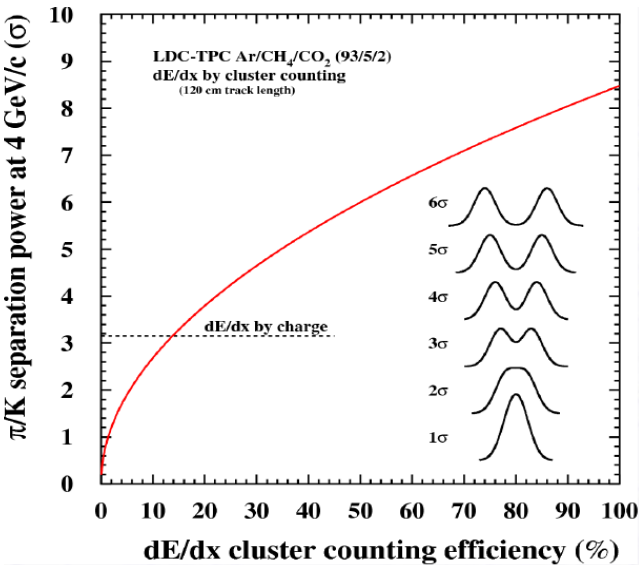
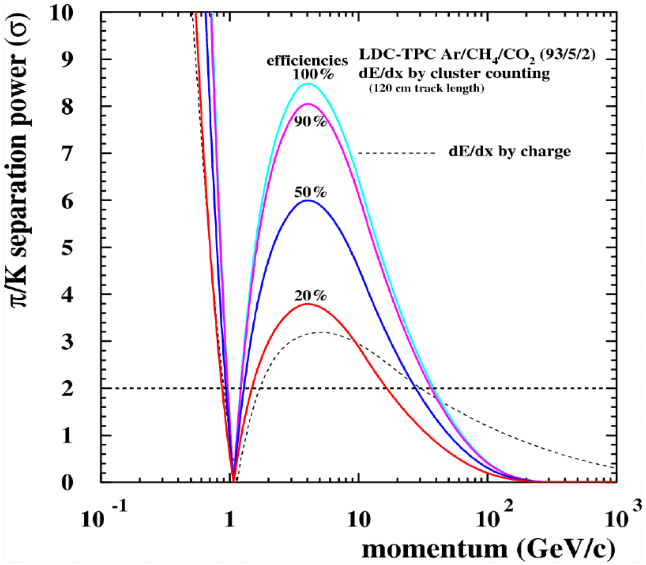
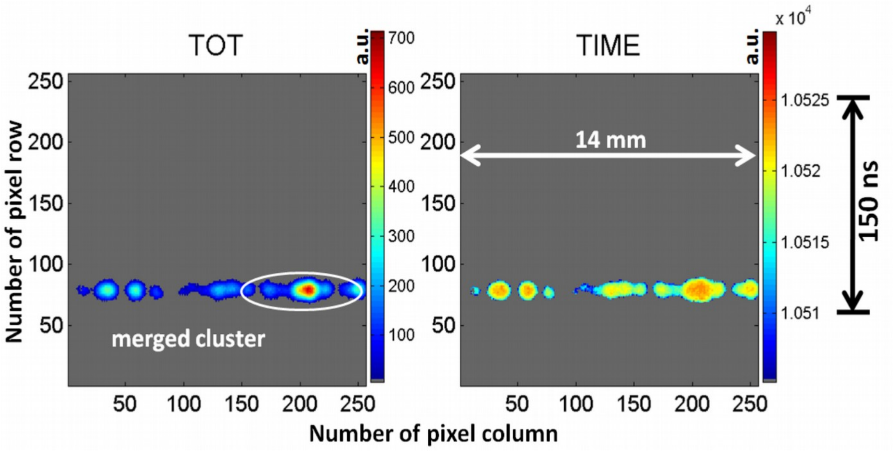




Cluster counting efficiency: ~25-30%



U. Renz: A TPC with Triple-GEM Gas Amplification and TimePix Readout

Example: Ar:CO_2 70:30

11 clusters /cm observed

40 clusters /cm expected

Efficiency may be increased with improved clustering algorithms

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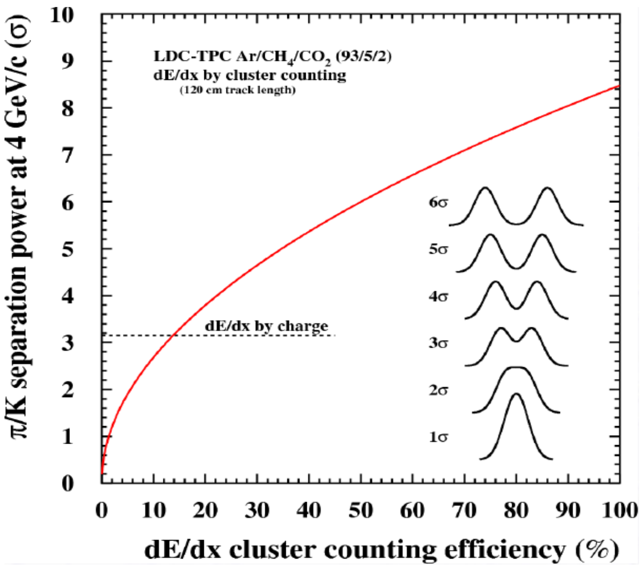
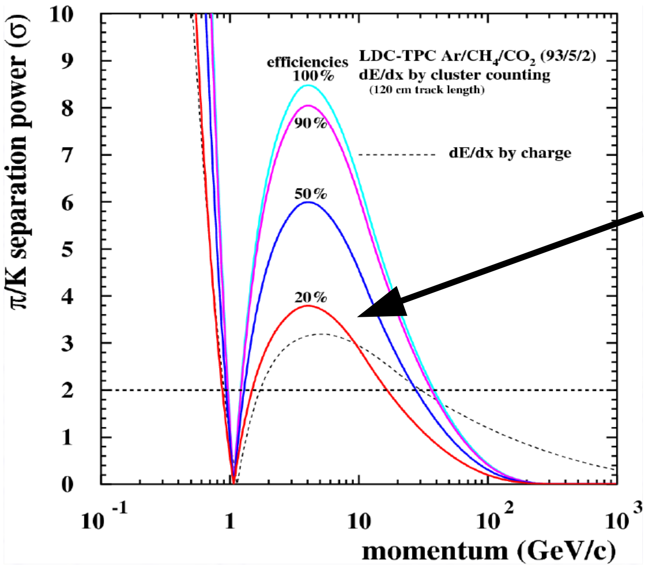




Goal: better than 20%

Software

- Simulation and reconstruction chain: MarlinTPC within the ILCsoft framework
- Primary ionisation and drift of individual electrons → transfer IDs of respective clusters to match with hits later
- Digitisation incl. pixelated noise

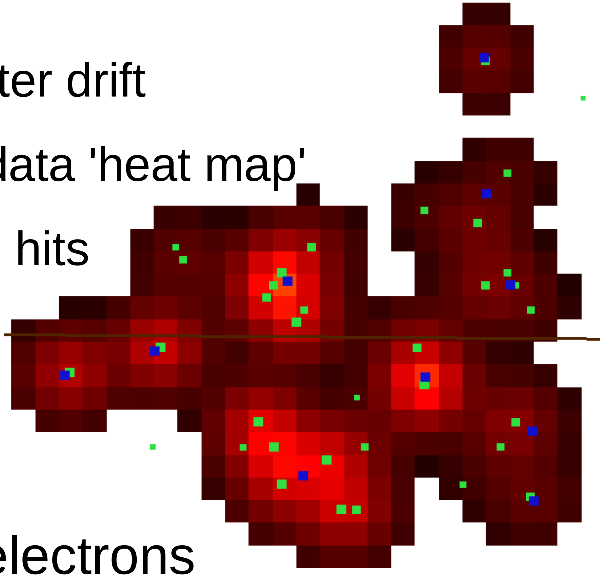
Simulation
- Generate MCParticles
- Primary Ionisation
- Drift
- GEM Amplification
- Projection onto Timepix
- Timepix Digitisation

Reconstruction
- Export to .fits
- Source Extractor
- Import to .slcio
- Tracking: Hough Trafo

Analysis
- Analysis
  e.g. cluster-hit
  identification

Software

- Cluster identification via external software 'Source Extractor' → returns 'hits' for tracking [http://www.astromatic.net/software/sextractor]
- Event display:
  - Green: electrons after drift
  - Red: digitised raw data 'heat map'
  - Blue: reconstructed hits



- Assign drifted electrons to hits
- match IDs, look for 'double uniques': all electrons from exac. 1 cluster go into exac. 1 hit → get 'exact cluster-hit-identification' efficiency

Simulation
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Analysis
- Analysis e.g. cluster-hit identification

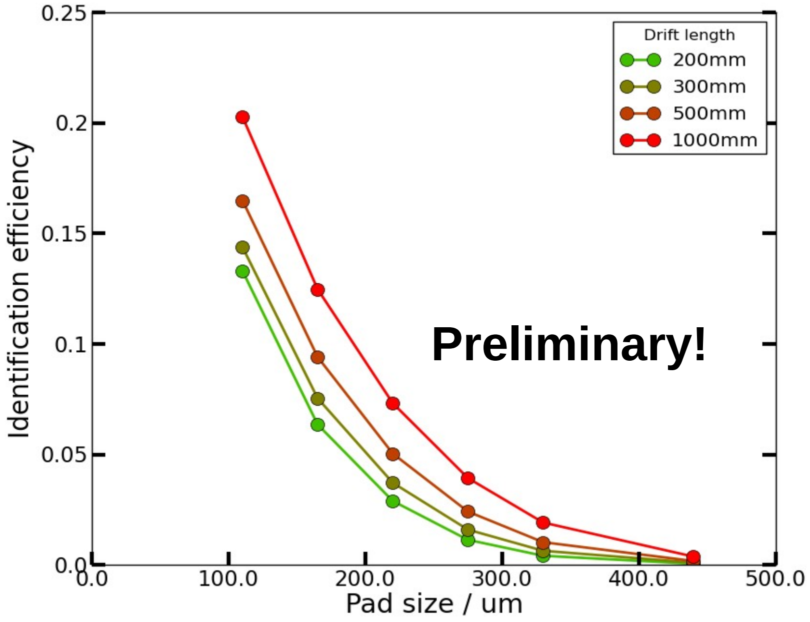
Cluster-Hit Identification Efficiency

- Track length = 300 mm
- B = 1 T

- Lower limit on 'cluster counting efficiency'

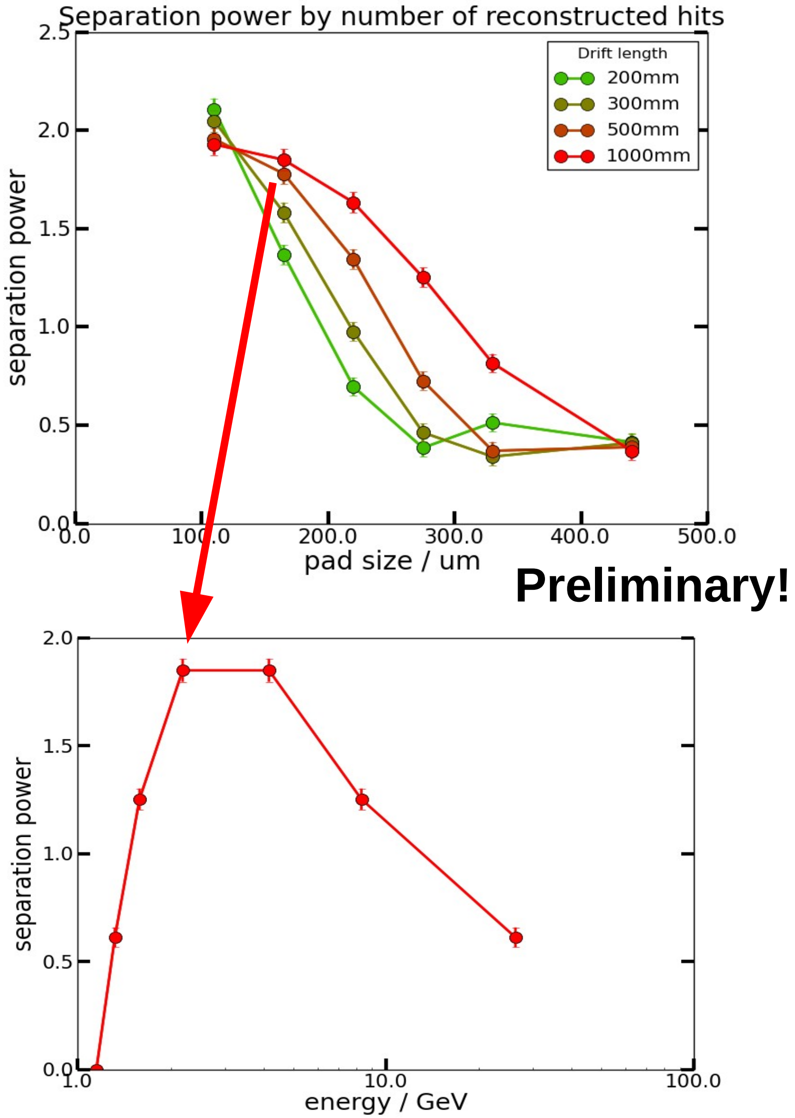
- But what about separation power?

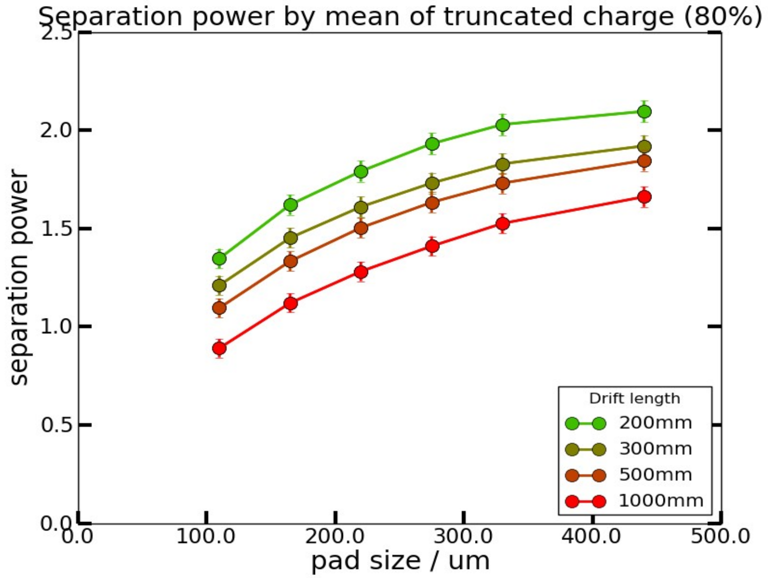
→ $$S = \frac{|\mu_\pi - \mu_K|}{\sqrt{\frac{1}{2}\left(\sigma_\pi^2 + \sigma_K^2\right)}}$$



Preliminary!

Pion-Kaon Separation Power



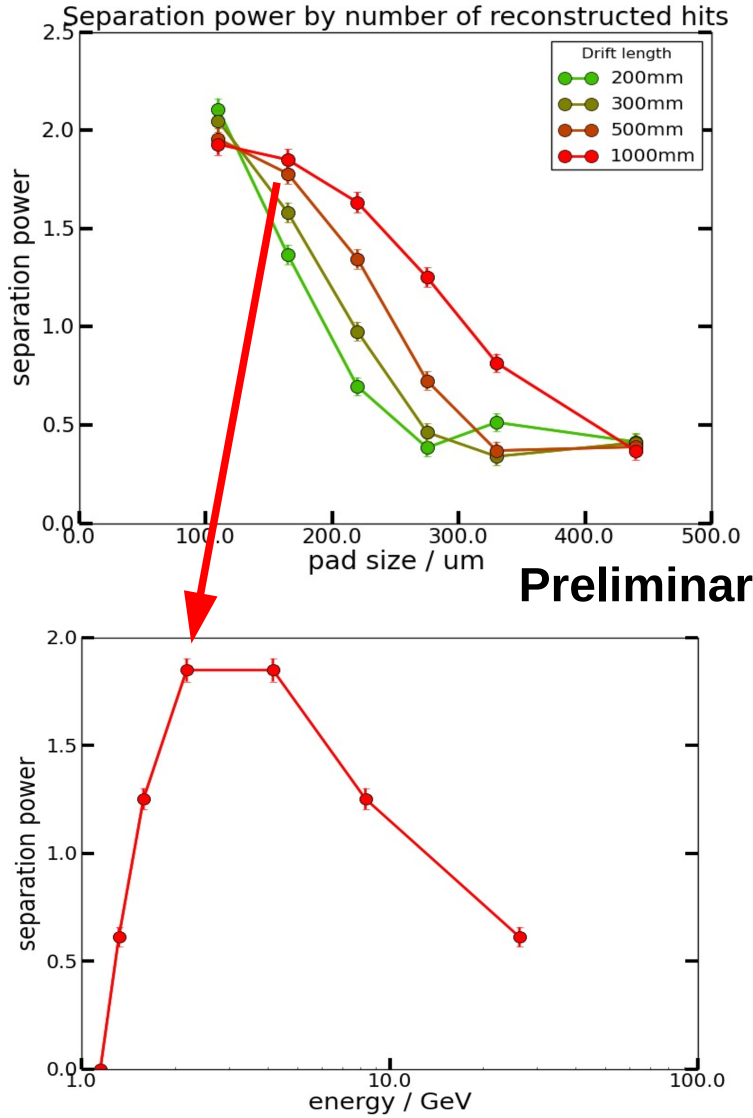


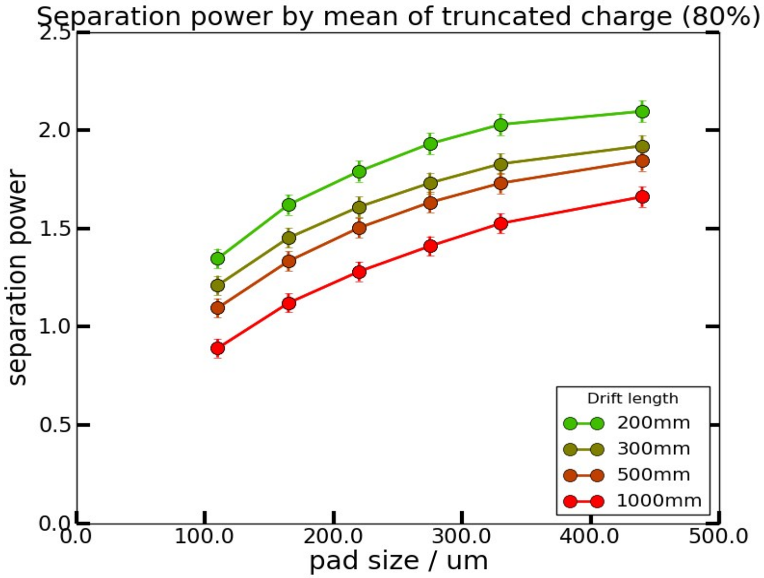
Preliminary!

Upper:
track length = 300 mm
separation for maximum
ionisation difference

Lower left:
pad size = 165 µm
drift length = 1000 mm

Pion-Kaon Separation Power



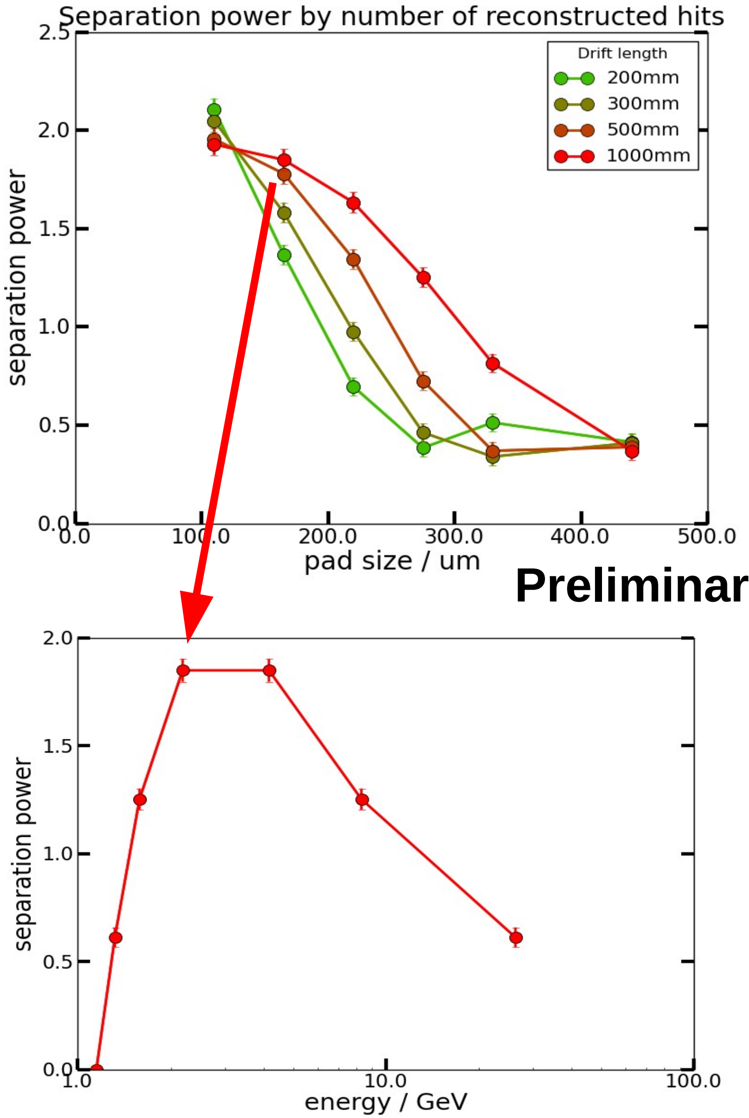


Preliminary!

Upper left: 'inverted' order of drift length because of less bunching, thus more single electrons reconstructed

Upper right: drops with lower pad size because of pixel charge threshold

Pion-Kaon Separation Power



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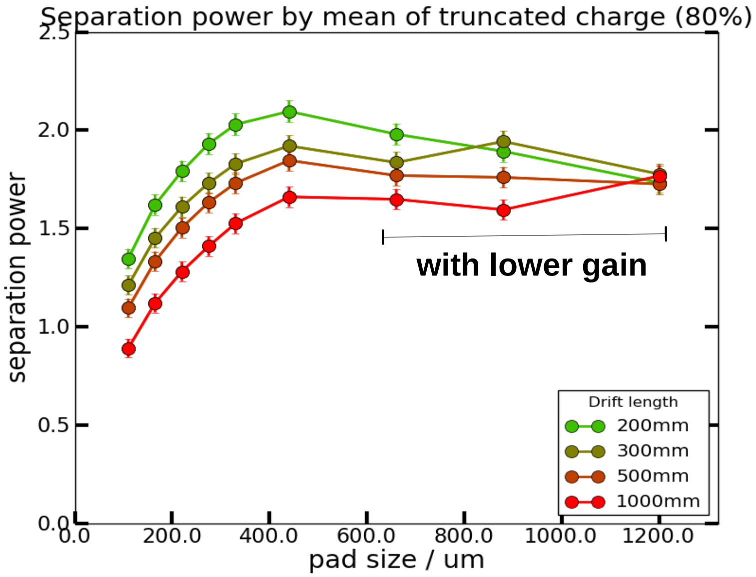
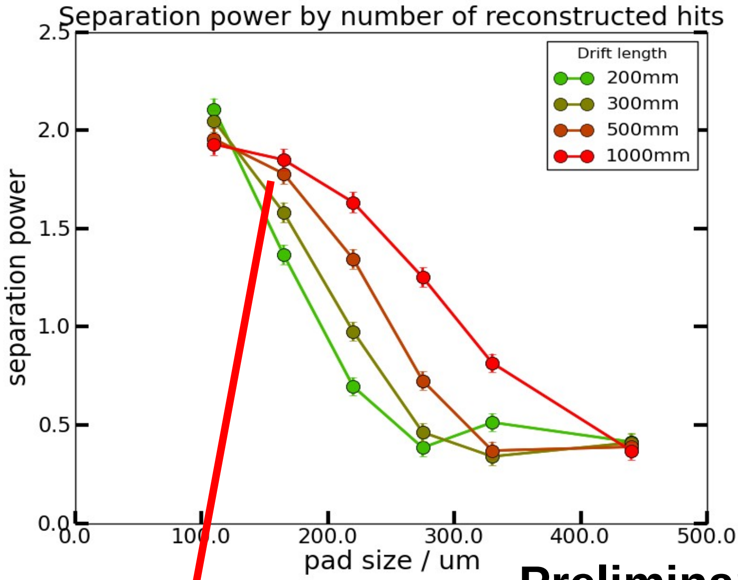


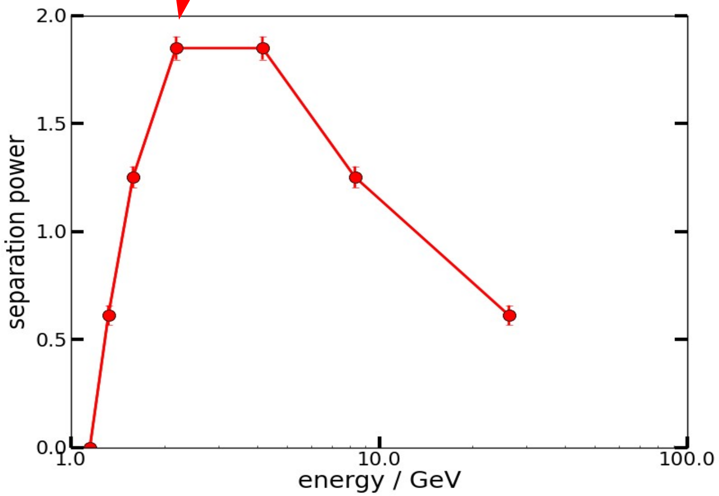
with lower gain

Upper left: 'inverted' order of drift length because of less bunching, thus more single electrons reconstructed

Upper right: drops with lower pad size because of pixel charge threshold, drop to larger pad size expected

Pion-Kaon Separation Power





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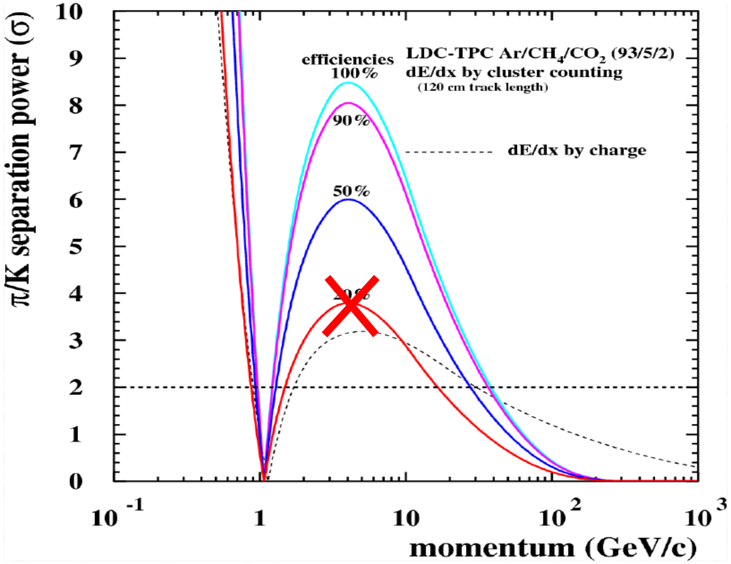
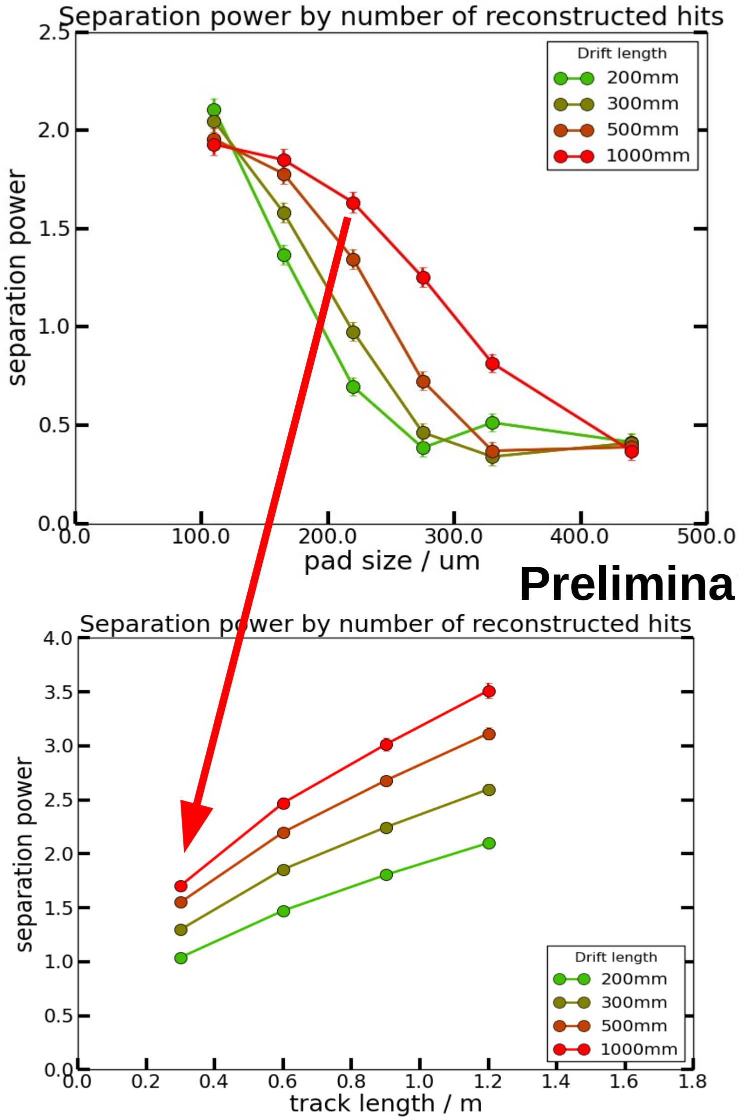


Extrapolation by sqrt(n) to ILD with track length = 1.35 m gives a separation power of 3.8 with 165 µm pads and 3.4 with 220 µm pads

→ improvement to conventional charge based measure

Pion-Kaon Separation Power



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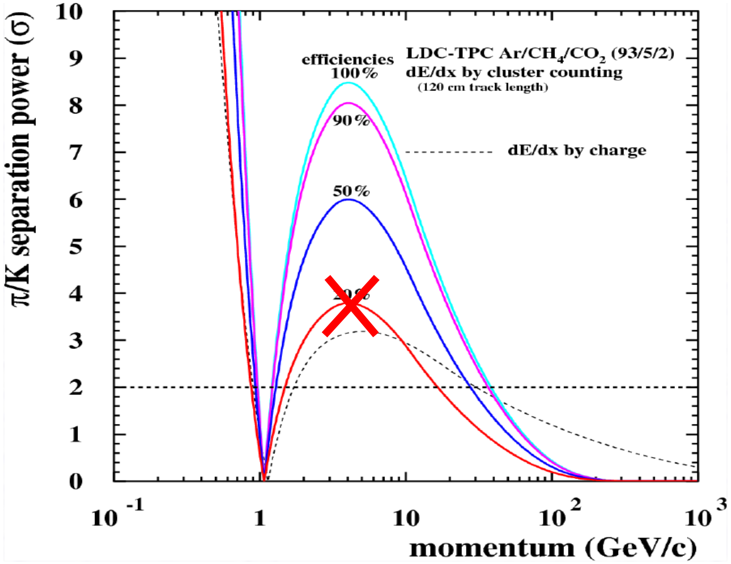


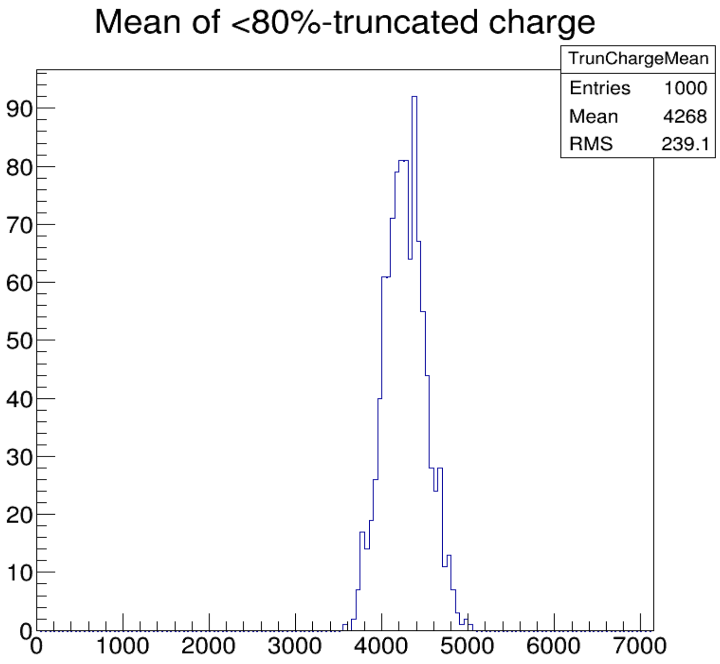
Validity of scaling with sqrt(n) not certain

Extrapolation by combining events:

scaling exponent = 0.52 +/- 0.02
S = 3.5 +/- 0.1

What about resolution?

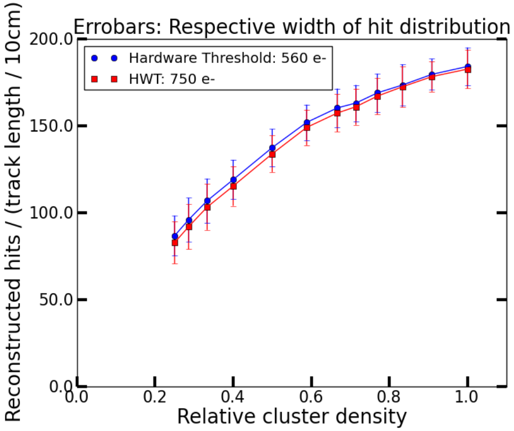
- Higher granularity → many more scanning point, higher statistics
- dE/dx resolution by charge:
  - 220 µm pitch, 1 m drift, 30 cm track
  - RMS / Mean = 5.5 %
  - Select lower 80 % of active pads, create mean of those
  - > Normalisation by number of pads
  - > deltas don't create a large signal in one pad, but active more pads, get 'normalised away'

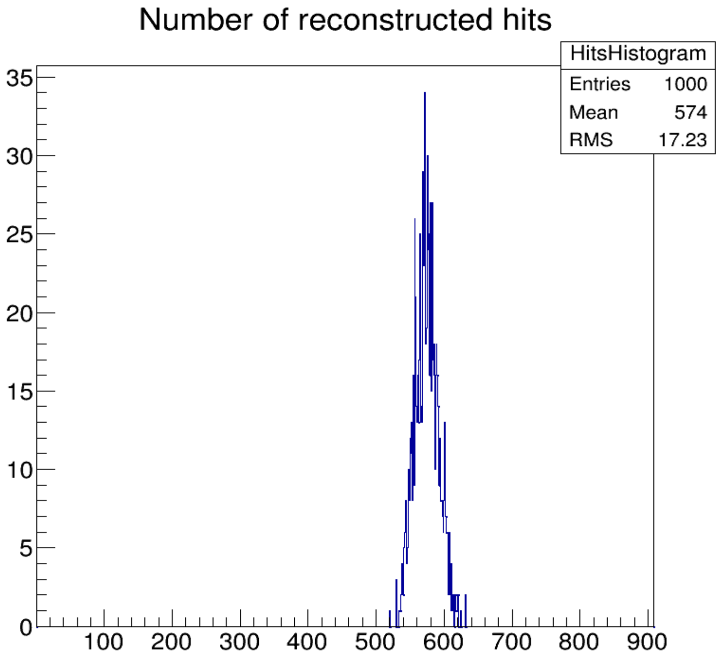


- Comparing the same quantities?

What about resolution?

- Even more extreme for number of recontructed hits
- 'Resolution': 3 %
- Additional effect: saturation of number of recontructable hits vs. cluster density





- → Use separation power

Summary

- Proposal for a GEM-based high granularity TPC readout
- Significant improvement of integration together with possible enhancement of performance

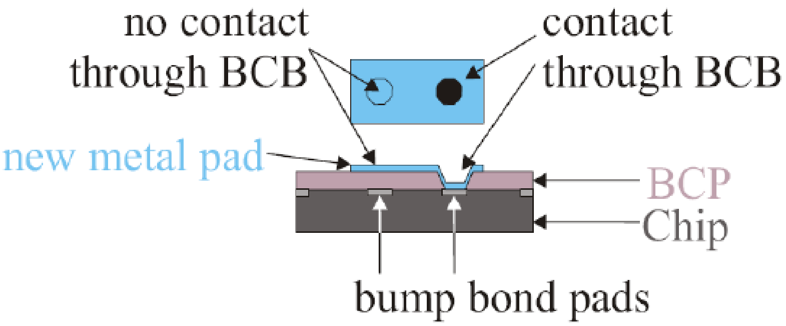
- First boards showed challenge of bonding process, nonetheless delivered a first minimal data set
- New boards are in queue, setup is ready for detailed performance tests
- MC simulation show improvement in particle separation power compared to conventional dE/dx by charge
- There is room for further identification performance improvement

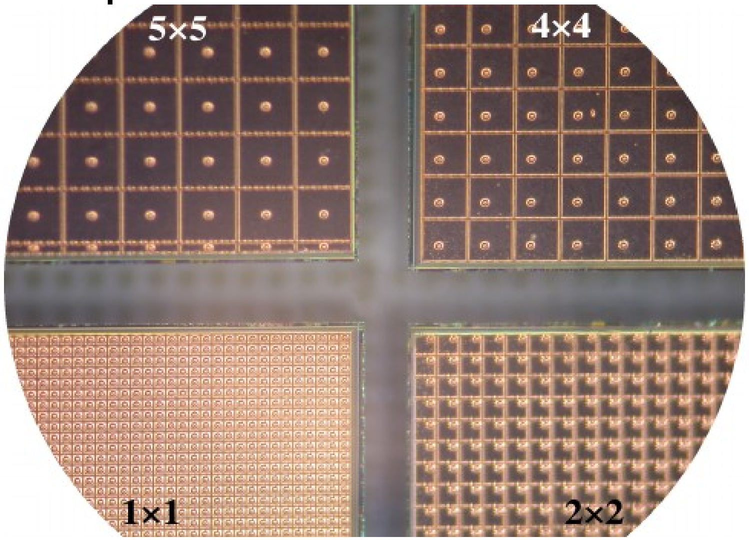
Backup

- Electrons per cluster cumulative probabilities:
  - 1.0 0.821794331000000
  - 2.0 0.879242412700000
  - 3.0 0.897898070500000
  - 4.0 0.910314166900000
  - 5.0 0.918034836170000
  - 6.0 0.922509673040000
  - 7.0 0.925692479580000
  - 8.0 0.929221928340000
  - 9.0 0.934327023790000
  - 10.0 0.941701050600000

Former Tests with GEMs + pixels

- GEMs + Timepix, by Uni Bonn and Uni Freiburg
  - Charge depositions spread continuously over O(100) pixels (compared to Micromegas)
  - High gains (60k to 100k) necessary for signal/noise
- Large pixels by adding metal pads to chip

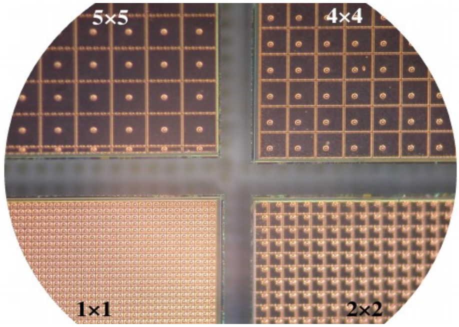


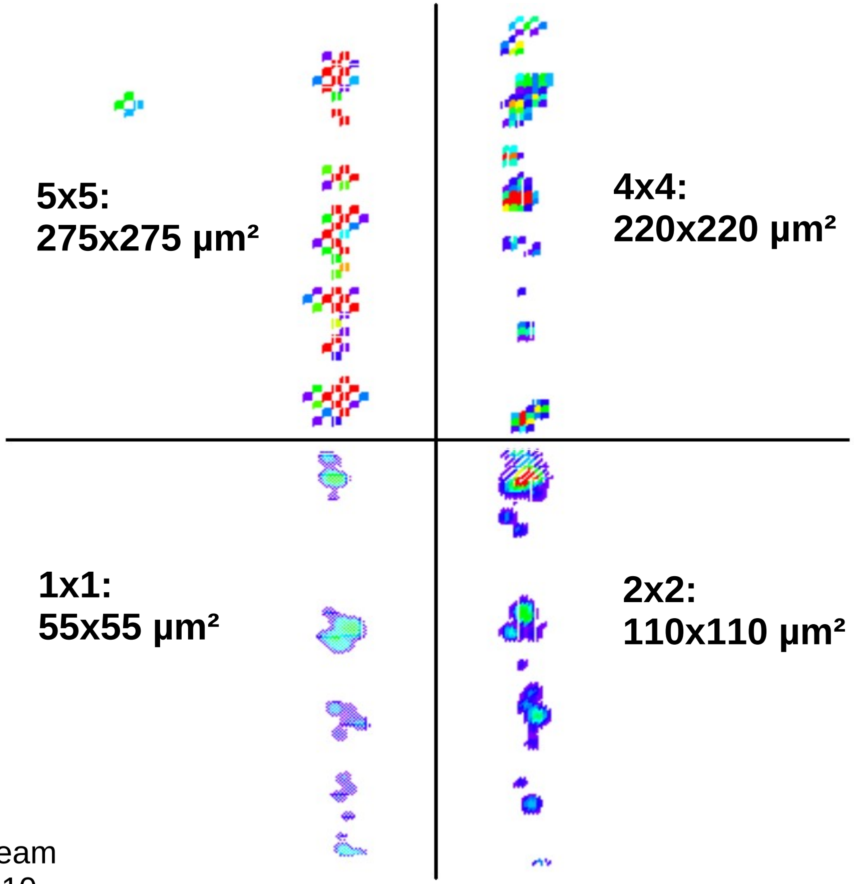


J. Kaminski: Measurements during the October test beam with the GEM-TPC and Timepix; at RD-51 meeting 2010

Former Tests with GEMs + pixels

- Clusters visible with large pixels → How large can one go?
- Similar to our approach
- But: still need up to 120+ chips per module
- Utilize full chip!
- Utilize full anode area!





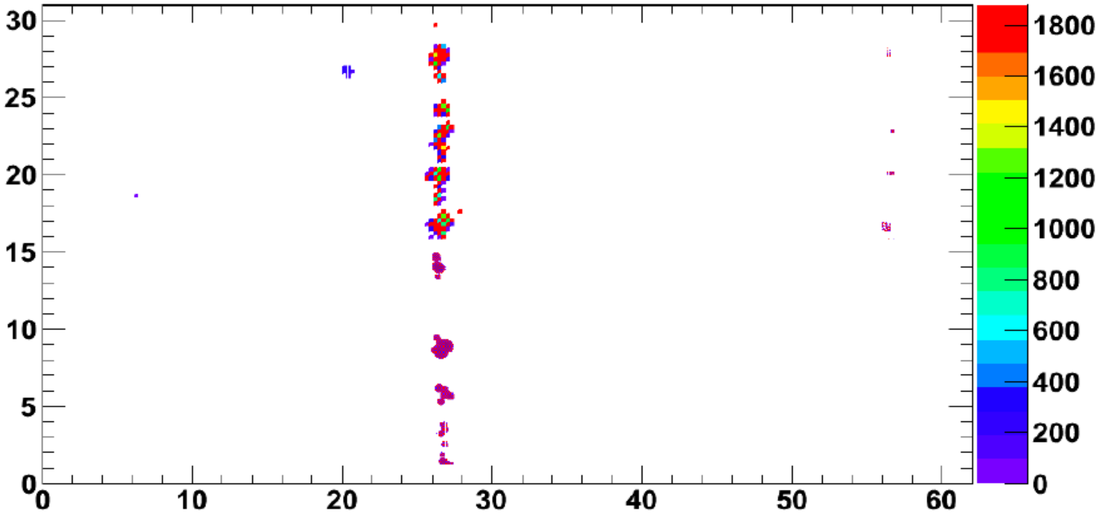
J. Kaminski: Measurements during the October test beam with the GEM-TPC and Timepix; at RD-51 meeting 2010

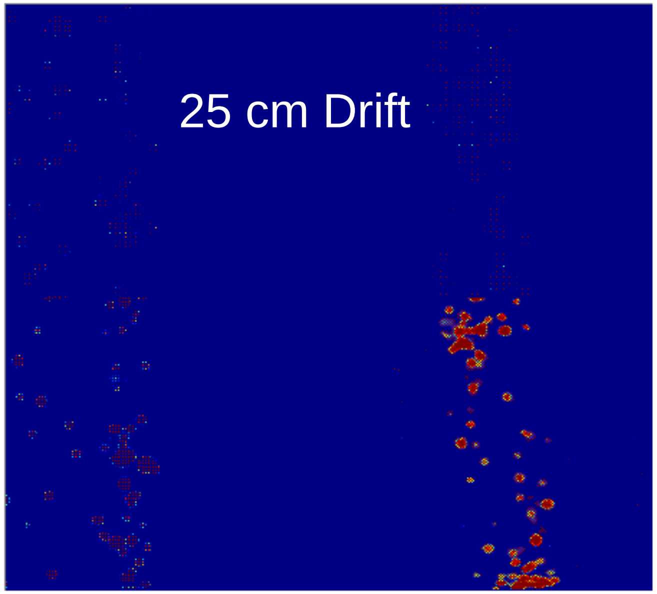
GEMs + pixels: event displays

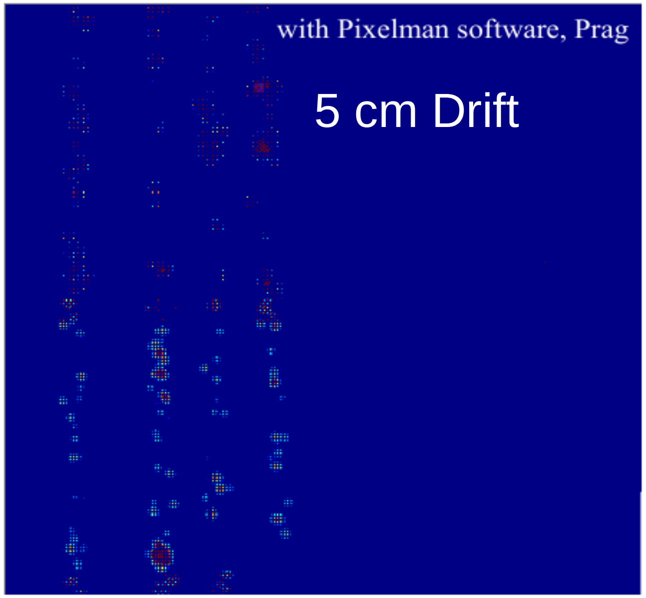
- Large pixels Timepix

  [5x5 | 4x4]

  [1x1 | 2x2]



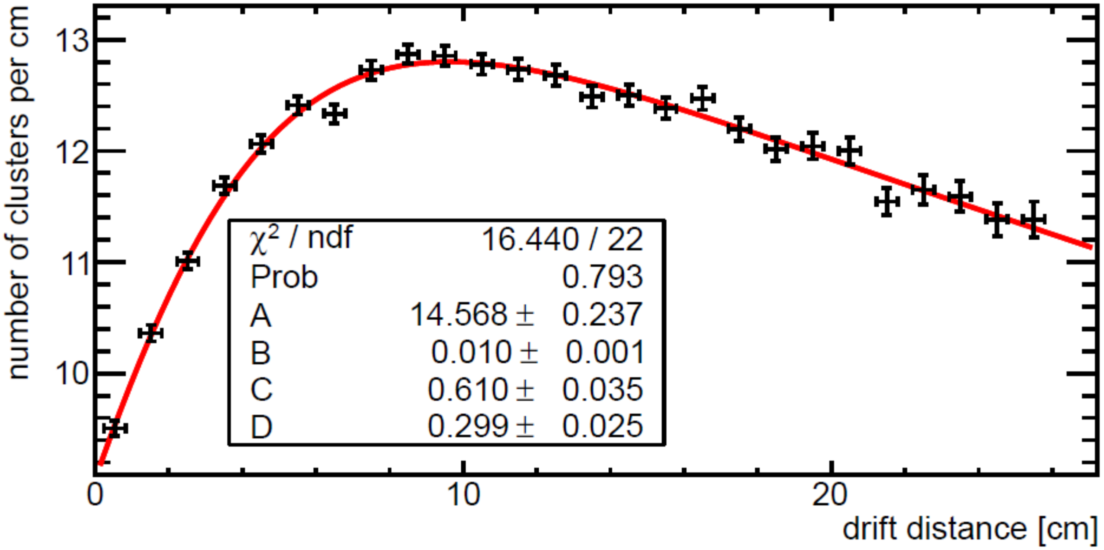




J. Kaminski: Measurements during the October test beam with the GEM-TPC and Timepix; at RD-51 meeting 2010

Cluster counting efficiency

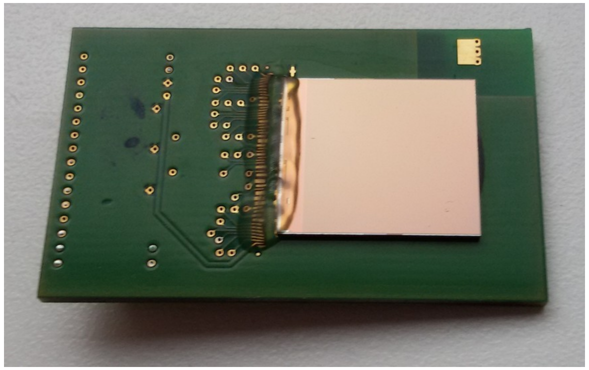
- Here:
  - He:CO_2 70:30
  - Expected: 15.15 clusters/cm
  - Approaches without absorption 14.6 clusters/cm



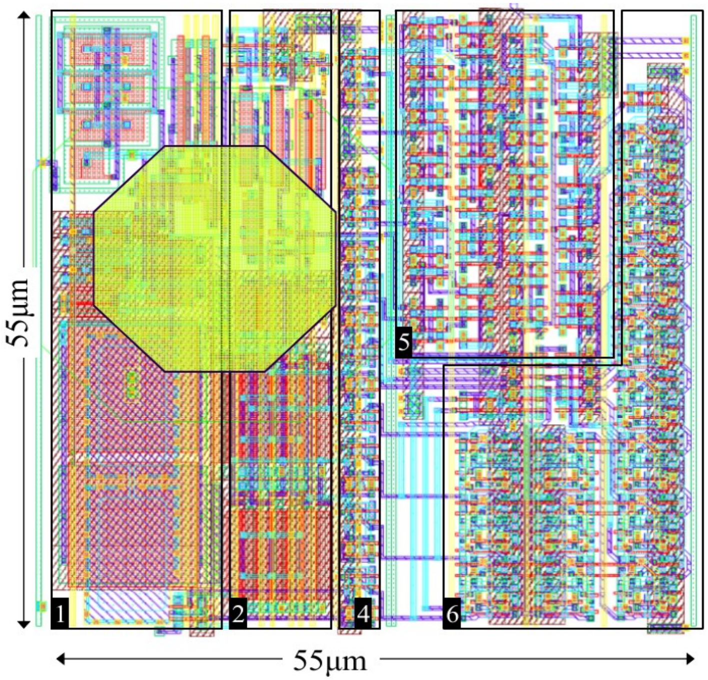
χ^2 / ndf	16.440 / 22
Prob	0.793
A	14.568 ± 0.237
B	0.010 ± 0.001
C	0.610 ± 0.035
D	0.299 ± 0.025

Dissertation: C. Brezina

Readout: Timepix



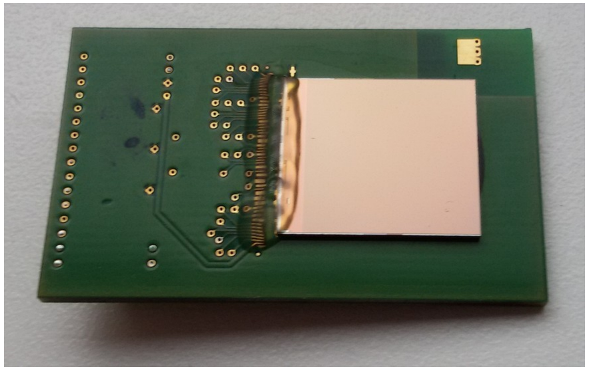
- Advancement to the Medipix chip (RD51, CERN) with the capability for time measurement
- Geometry:
  - 256 x 256 pixels, 55µm pitch
  - 1.4 x 1.4 cm² active area
- Pixel floor plan:
  octagon: Al opening for input signal
  1: preamplifier
  2: discriminator/digitisation
  4: configuration
  5: mode selection
  6: 14-Bit shift register (max. 11810)

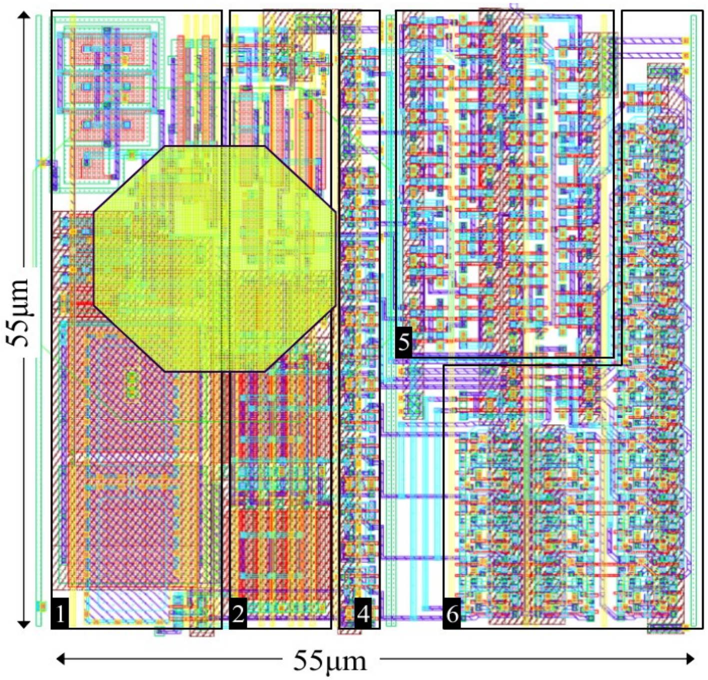


X. Llopart: Timepix Manual v1.0

Readout: Timepix

- Mode selection (per pixel) in 5:
  - “Time of arrival” (ToA) gives timing information
  - “Time over threshold” (ToT) gives charge information
  - For the Timepix3 (2^{nd} generation) both modes can run simultaneously
- External reference clock with up to 100MHz / 10ns
- During a given shutter window the register counts and is read out afterwards (serial 10ms, parallel 300µs)

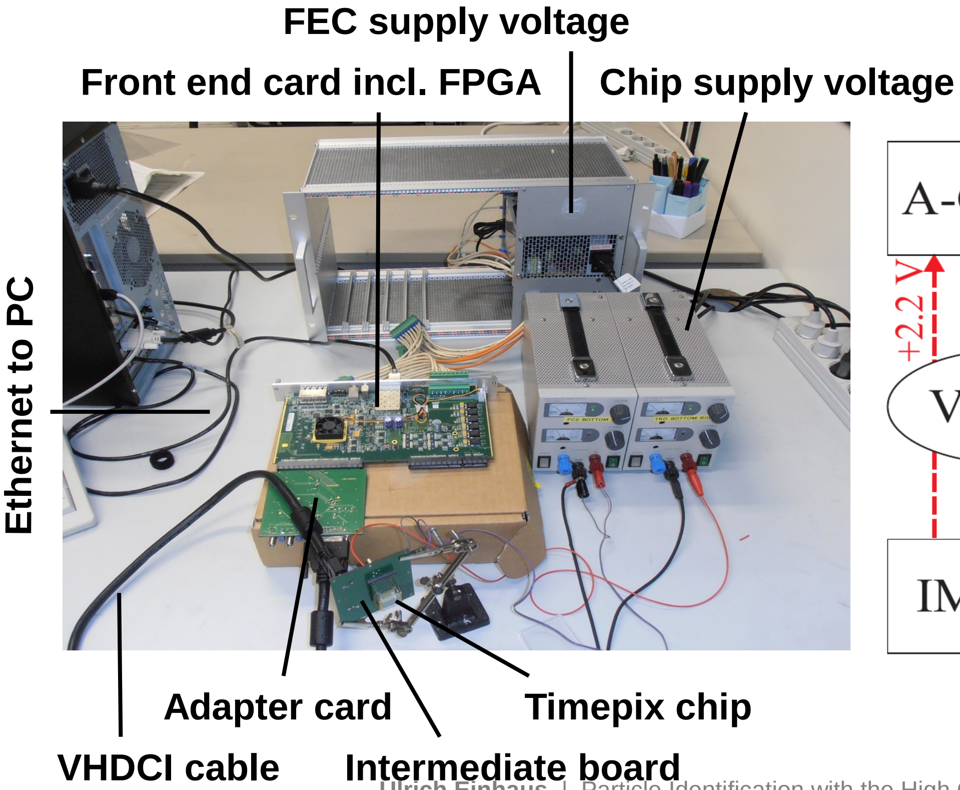


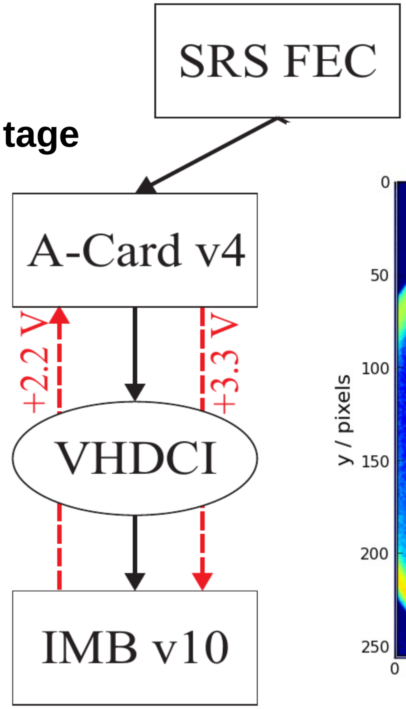


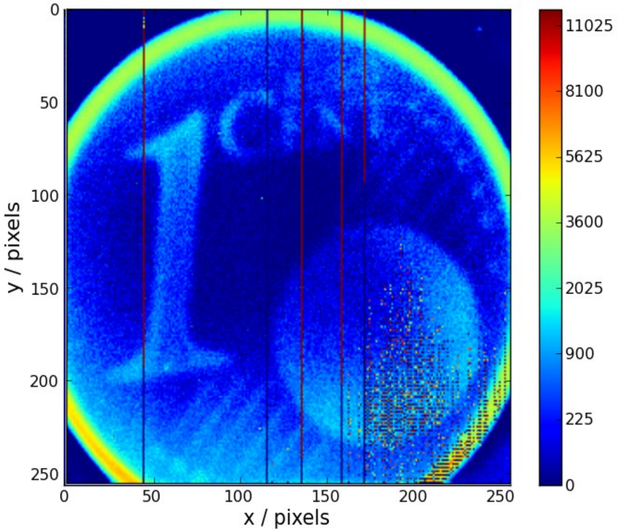
X. Llopart: Timepix Manual v1.0

Hardware Status

- Readout chain based on the Scalable Readout System (SRS) from CERN established







Timepix3

- Simultaneous modes “time of arrival” and “time over threshold”
- To be used after proof-of-principle
- Exchange of information and experience with photon science groups at DESY (member of Timepix3 collaboration)

UNIMOCS prototype TPC