Topmetal Pixel Readout R&D for Gaseous Track Detectors

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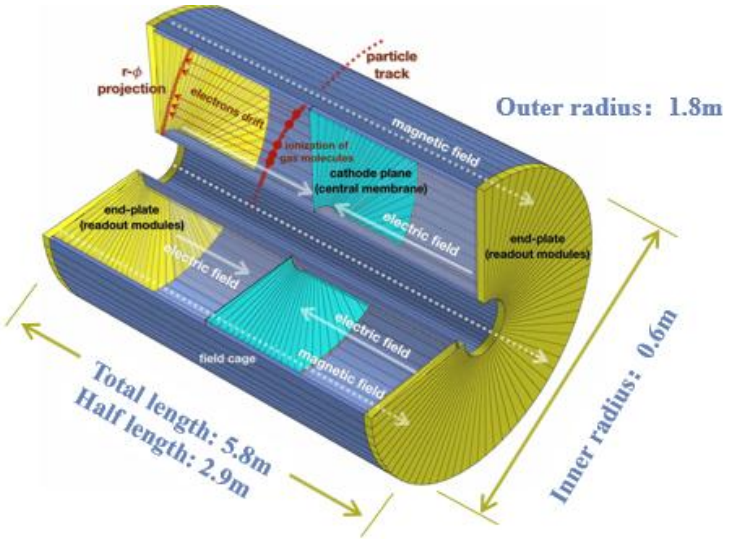
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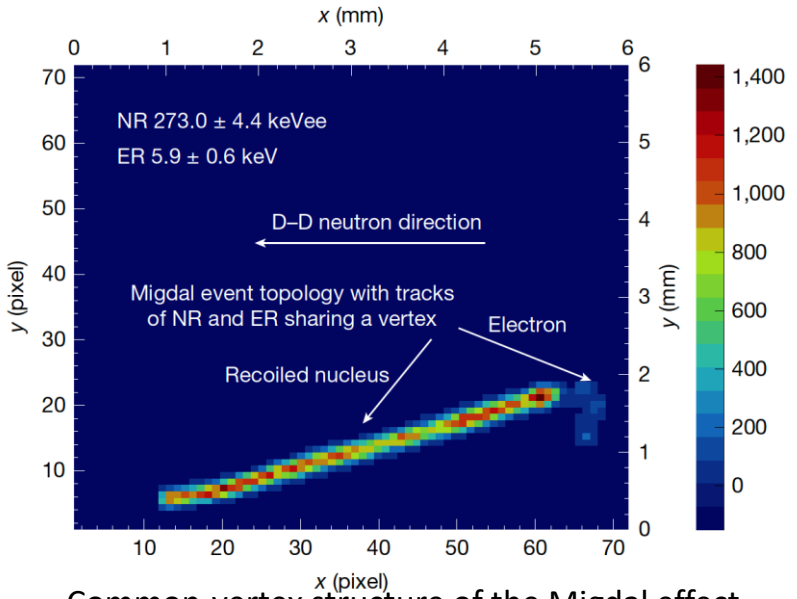
Physics Requirements for Precise Tracking

Nuclear, neutrino and dark-matter experiments need detailed, precise track information.

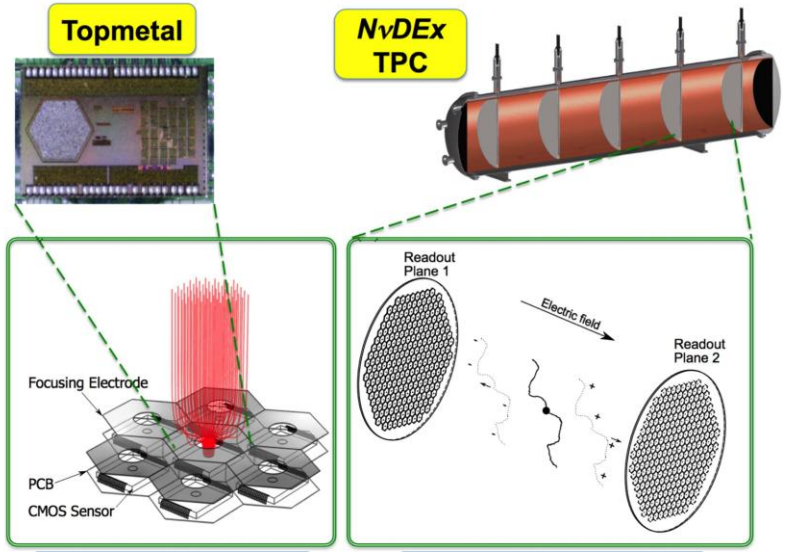
- **Cluster counting (dN/dx) improves PID (CEPC-TPC: 3σ at 20 GeV/c).**
- **Track images → identify event structures and reject backgrounds.**
- **Track length, direction and energy help identify particles and reconstruct events.**
- **These physics needs motivate the development of detectors with fine pixels ……**



CEPC-TPC



Common-vertex structure of the Migdal effect observed with Topmetal-GMCP



NvDEx-100 high-pressure TPC
The track shape helps distinguish signal from background.

Key Technologies for Gaseous Track Detectors

Observable	Physics use	Detector requirements
Small energy deposit	Low-energy e^- / nuclear recoils	**Low noise, low threshold, high collection efficiency**
Short track structure	Short-range charged particles	**Fine pixels, low diffusion, high signal-to-noise ratio**
Local charge density	PID / track-end features	**Pixel Key Technologies for Gaseous Track Detectorsharge measurement and sufficient dynamic range**
Common vertex / tracks	Correlated events	**Precise 2D imaging**
Track direction	Directional measurements	**Sufficient sampling points and timing information**
Large-scale operation	Stable, low background	**Uniform response, low power, scalable design**

High granularity readout help resolve tracks and primary ionization clusters.

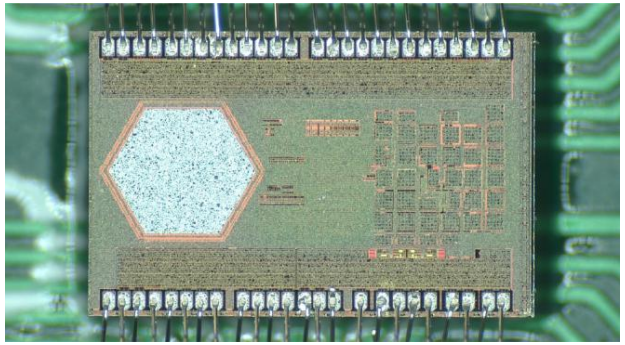
Low noise and a wide dynamic range detect weak signals.

Large-area readout measures long tracks and ionization density.

Key challenges:

- **Reliable integration of MPGD structures and fine pixels**
- **Power consumption and cooling**
- **Chip tiling and large-area readout**

From Pad readout to pixel readout ....



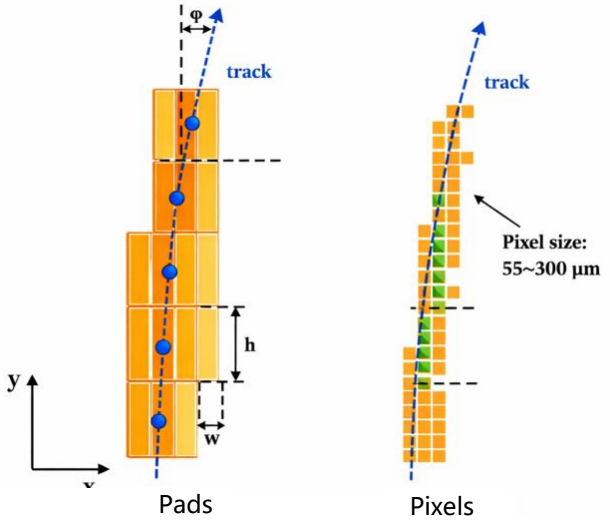
Key Technologies for Gaseous Track Detectors

Millimeter pads measure energy loss but cannot resolve individual primary ionization clusters.

Fine pixels make dN/dx studies possible.

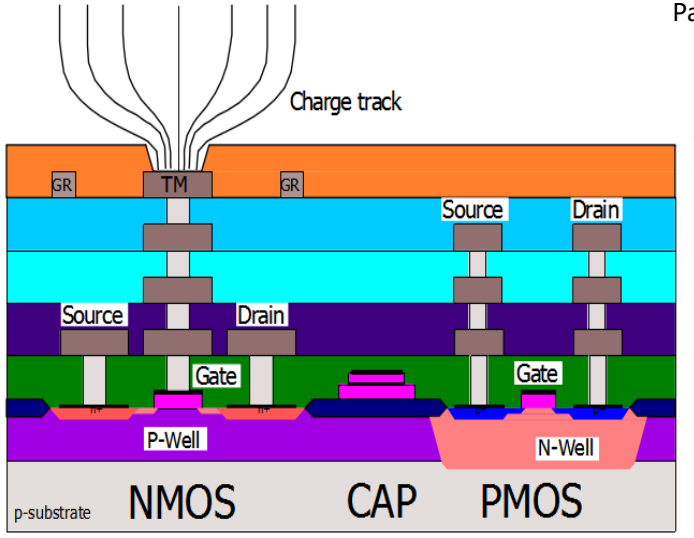
GridPix with 55 µm Timepix readout.

- **dN/dx resolution: ~2.9% at 1 T, shows the potential of pixel readout for PID.**
- **Power consumption: ~2 W/cm²**
- **Limited flexibility in customizing chip dimensions……**

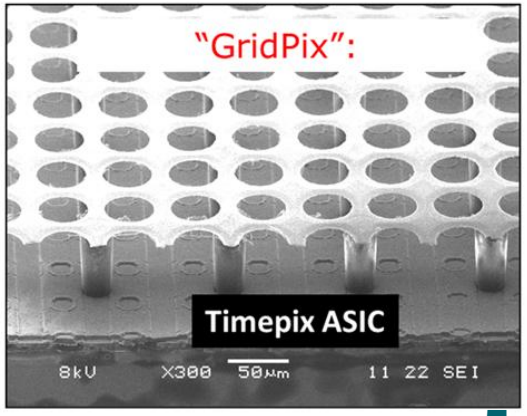


Topmetal readout for precise tracking

Exposed top metal collects charge.
Direct primary-charge or amplified-charge readout
Very low noise: ENC of a few tens of electrons



Topmetal operating principle



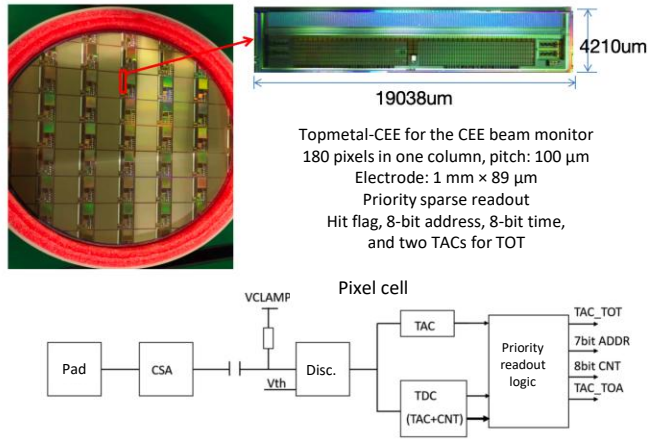
GridPix readout scheme

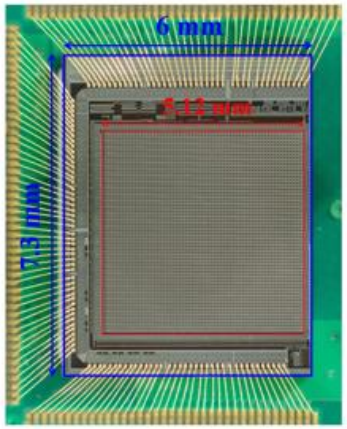
Applications of Topmetal Chips

Topmetal applications include Migdal observations, CXPD, CEE detector R&D and NvDEx……

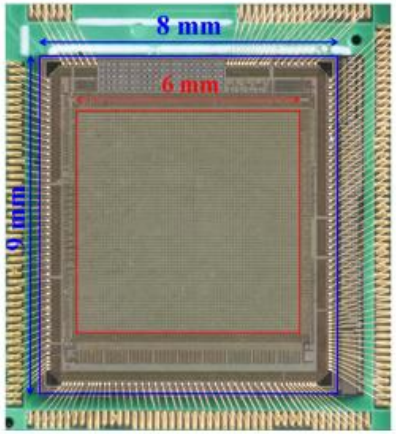
They cover space-based X-ray polarimetry, nuclear physics and rare events.

These applications show the potential of Topmetal for weak-charge detection and precise track imaging.

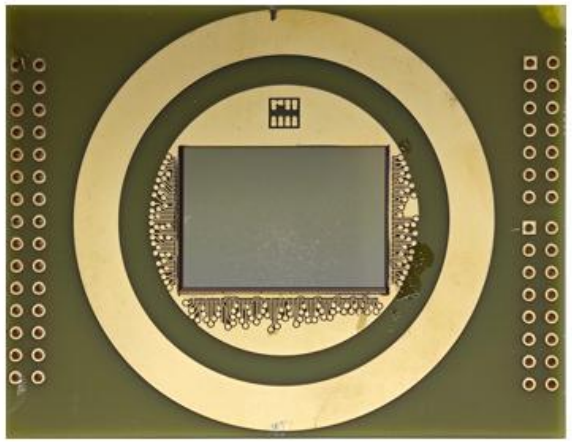




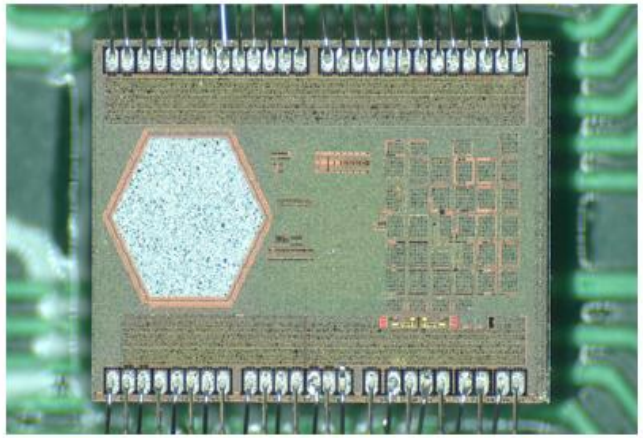
Topmetal-I



Topmetal-II

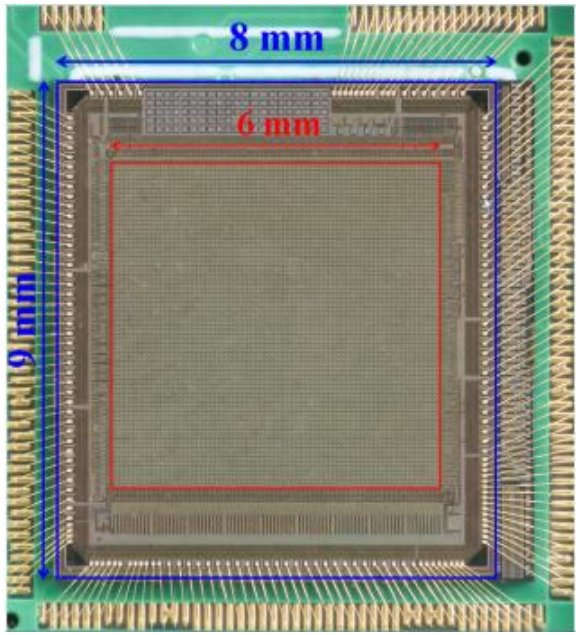


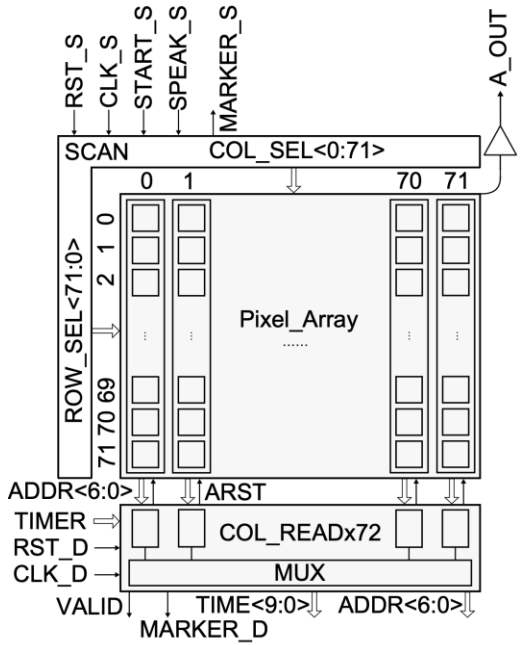
Topmetal-L



Topmetal-S

Topmetal: Direct Charge Collection and Imaging

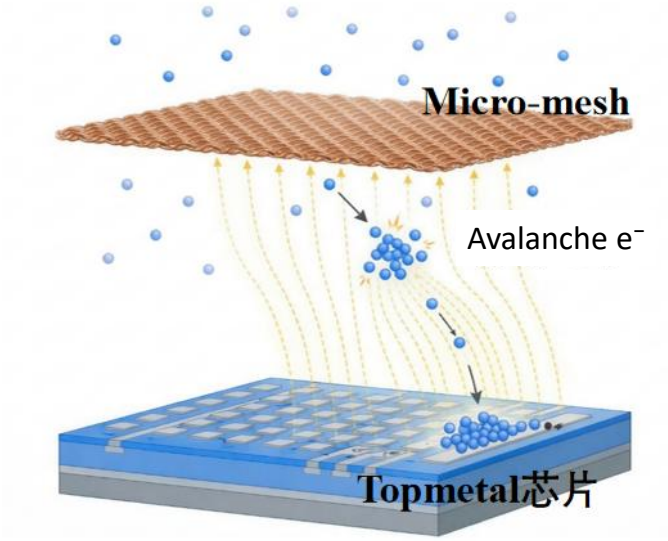




Topmetal-II
ENC: ~13.9 e⁻
Pixel size: 83 × 83 μm²
Pixel array: 72 × 72
Sensitive area: 6 × 6 mm²
Electrode size: 25 × 25 μm²

Advantages for gaseous detectors

- **Low noise and low power (~0.2 W/cm²)**
- **Coupling to GEM, Micromegas or GMCP**
- **Pixel size can be optimized**



Topmetal–Micromegas operating principle

Topmetal Readout: Two Research Approaches

Validate Topmetal readout performance.

Optimize the chip, gas gain structure and readout system together.

Develop large-area arrays: chip tiling, uniform response, power and long-term stability.

Study 1: Direct readout without gas gain

Goal: direct primary-charge measurement

Advantages

- Simple detector structure
- No gain fluctuations or gas discharge
- Charge patterns close to primary ionization

Limitations

Electronic noise limits sensitivity.

Best suited to large signals, such as α tracks.

Study 2: MPGD gain with Topmetal readout

Goal: validate MPGD–Topmetal integration

Advantages

Lower effective threshold

Low-energy electrons and nuclear recoils

Response tunable through MPGD voltage

Key challenges

Dynamic range and data collection / buffering / output

CMOS protection against discharges

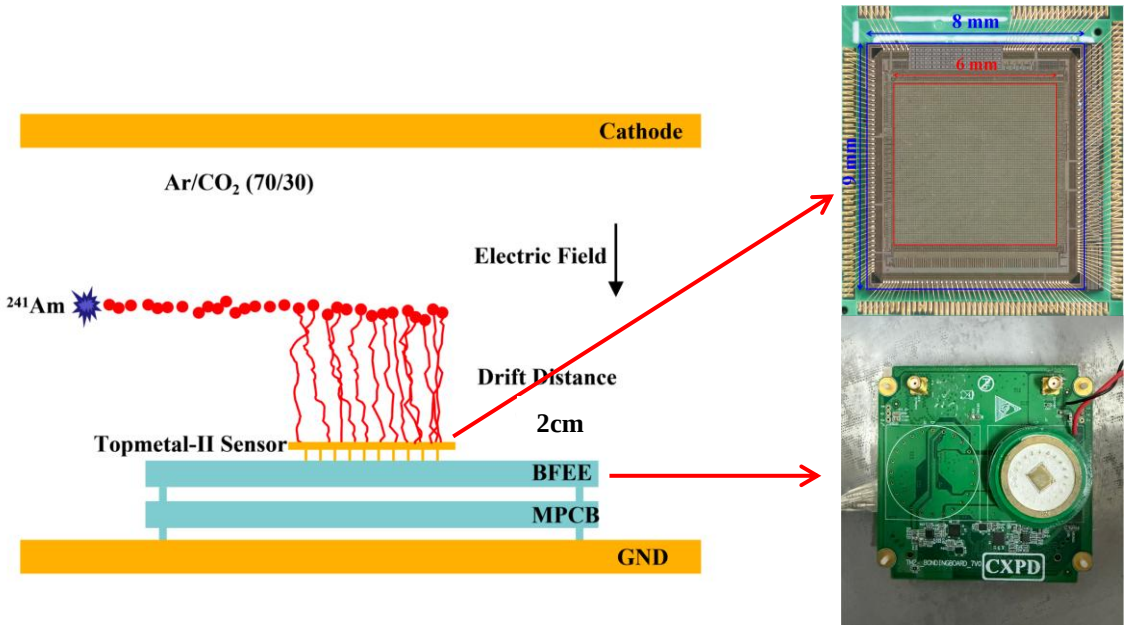
Large-area readout

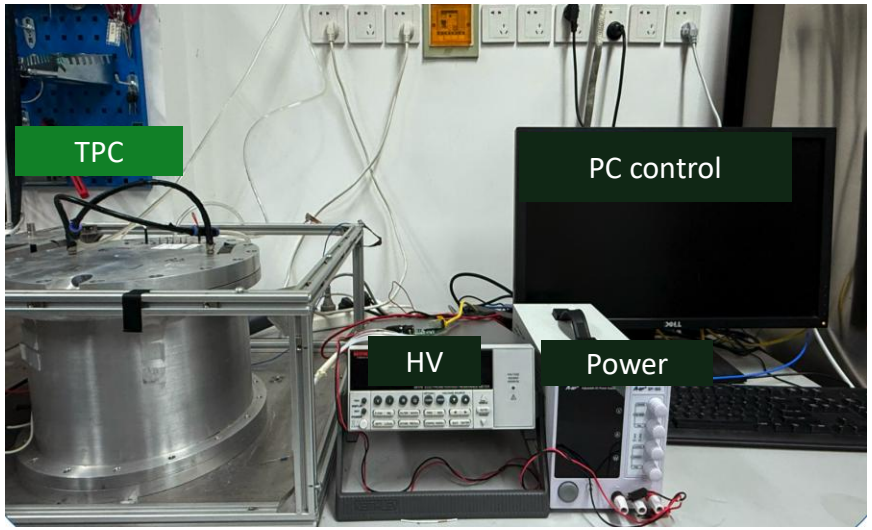
Study 1: Direct Readout without Gas Gain

Goal: directly collect primary ionization charge and image tracks in 2D.

Gas: Ar/CO_2 = 70/30
Drift distance: 2 cm
α source: ^{241}Am, 5.49 MeV
Readout: Topmetal-II CMOS sensor

Pixel array: 72 × 72
Pixel pitch: 83 μm
Direct positive-ion collection
No gas amplification

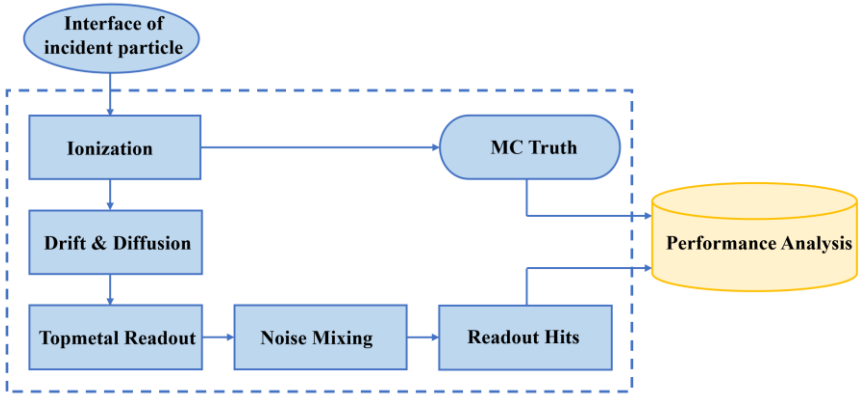




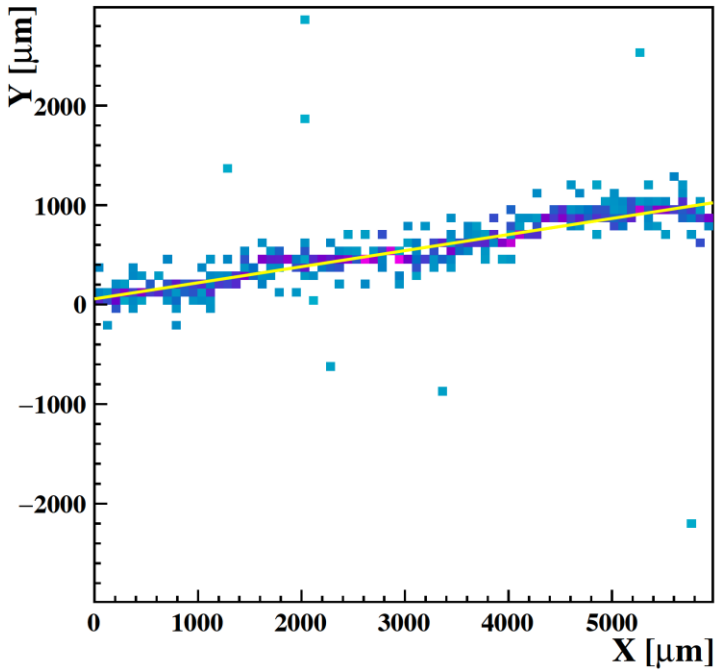
Study 1: Simulation of Direct Readout

Positive-ion diffusion is nearly thermal at low fields.

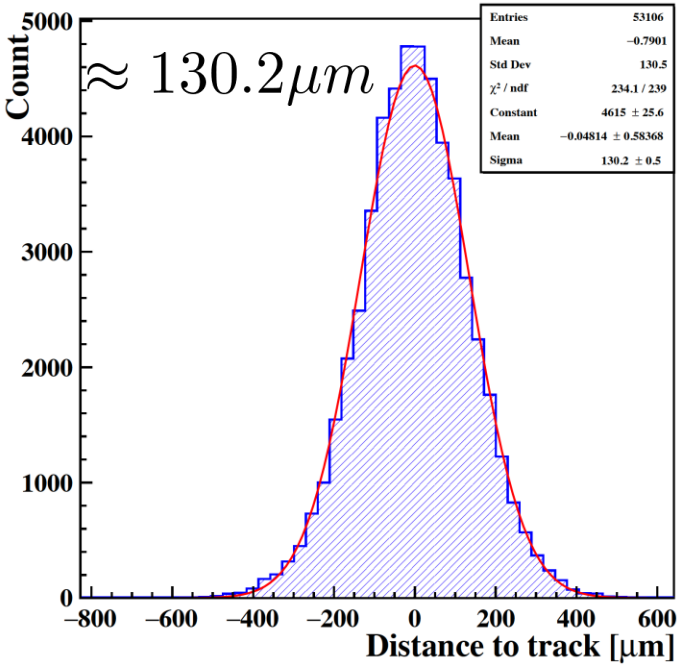
Same conditions as the experiment:
T = 293 K, L = 2 cm, E = 500 V/cm
SRIM ionization, Garfield++ drift and diffusion,
pixel response, noise / threshold and SVD fitting



Simulation Framework



Pixel response to drifting ions

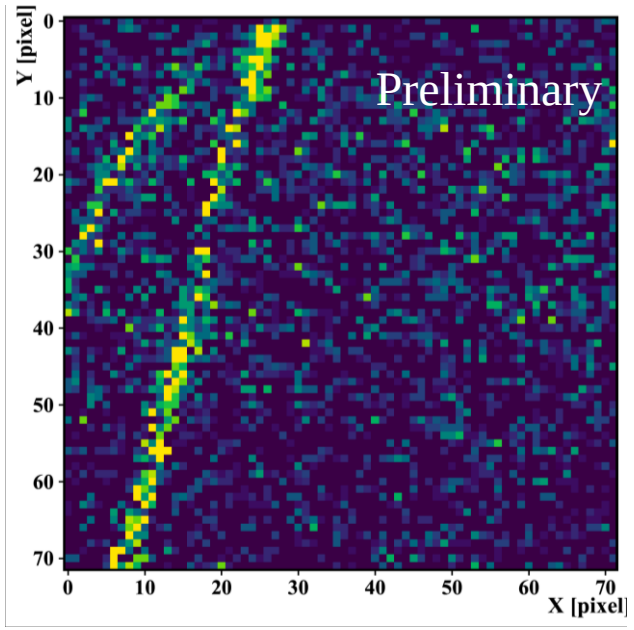


Transverse distribution after SVD

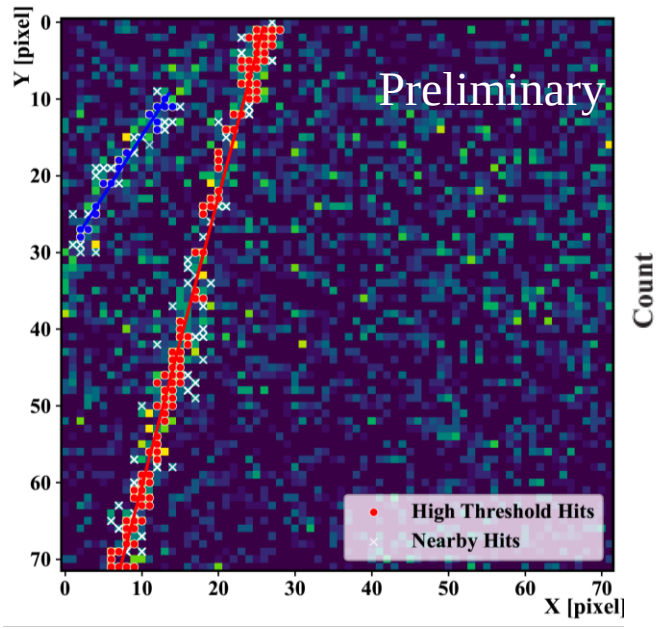
Study 1: Track Reconstruction and Width

To analyze the measured charge images → developed a complete reconstruction procedure.
Extract tracks from 2D pixel charge images and measure the transverse track width.

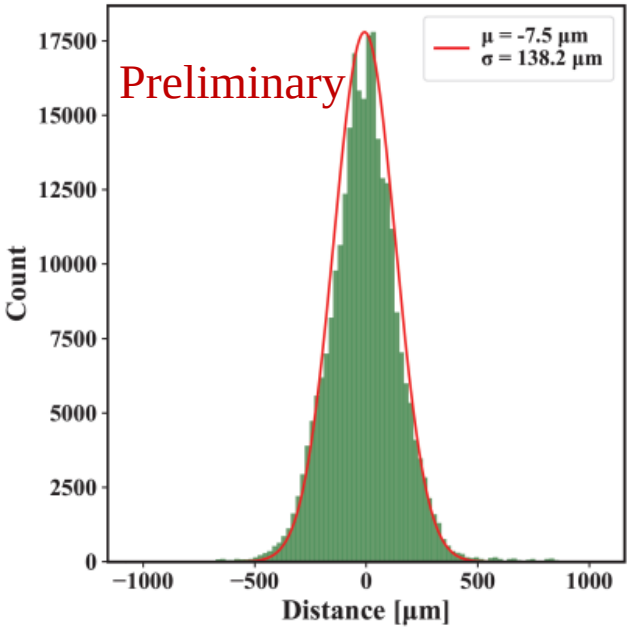
- Raw data correction
- Signal selection
- Track reconstruction
- SVD fitting
- Track width analysis



Directly measured ionization track



Reconstructed track



Simulation after reconstruction $\approx 130.2\mu m$ → **Measured** $\approx 138.2\mu m$

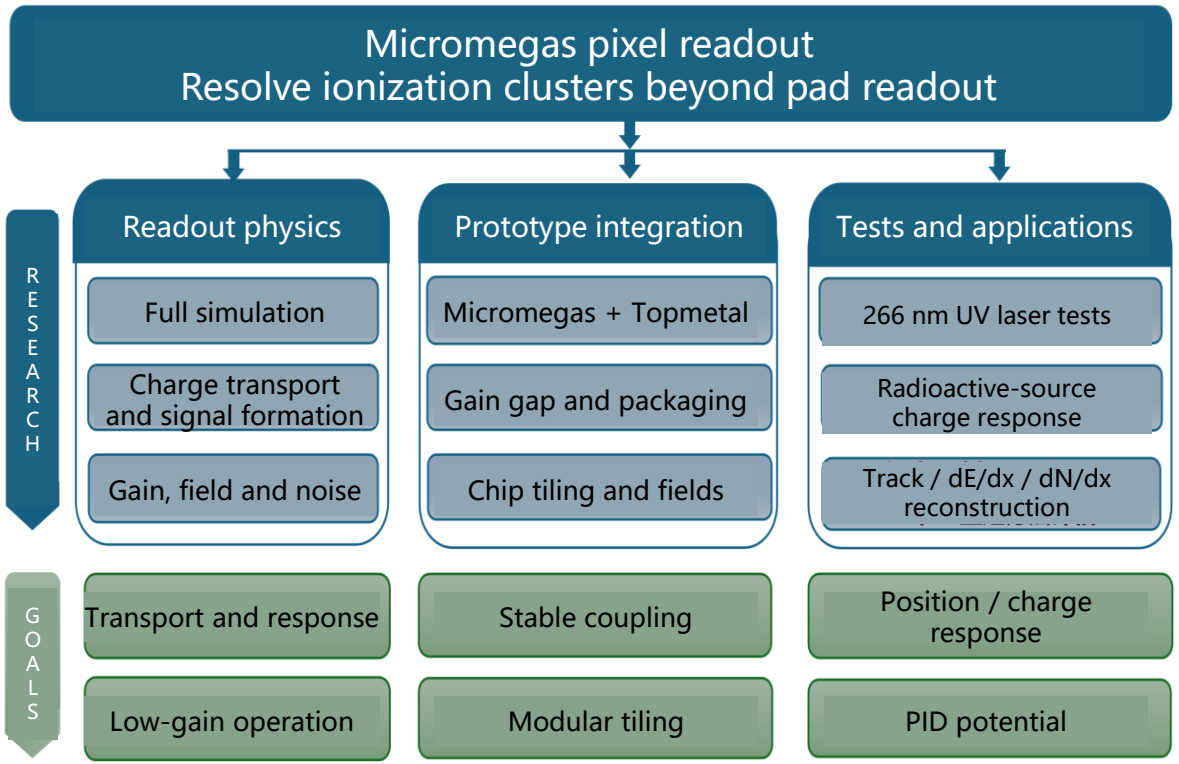
Topmetal can directly image ionization tracks without gas amplification.
This avoids avalanche gain fluctuations and additional transverse broadening.

Study 2: MPGD Gain with Topmetal Readout

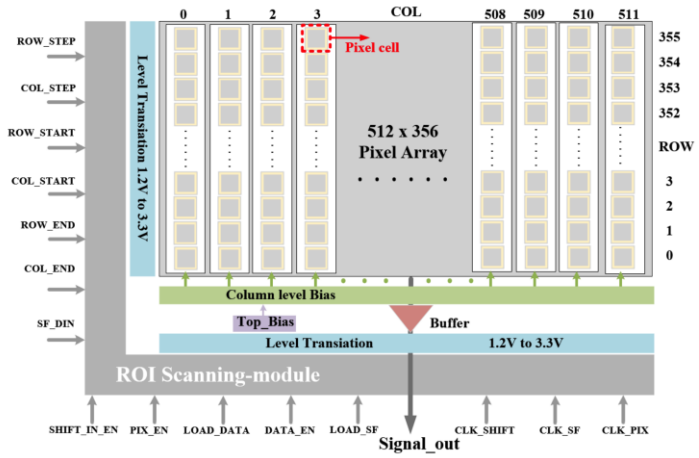
MPGD gain brings weak ionization signals into the Topmetal detection range.

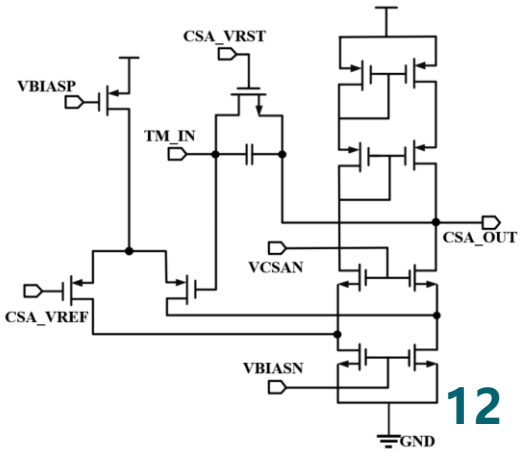
CXPD has provided initial tests of Topmetal readout and system stability.

We test GEM–Topmetal-L coupling and explore large-area Micromegas integration.



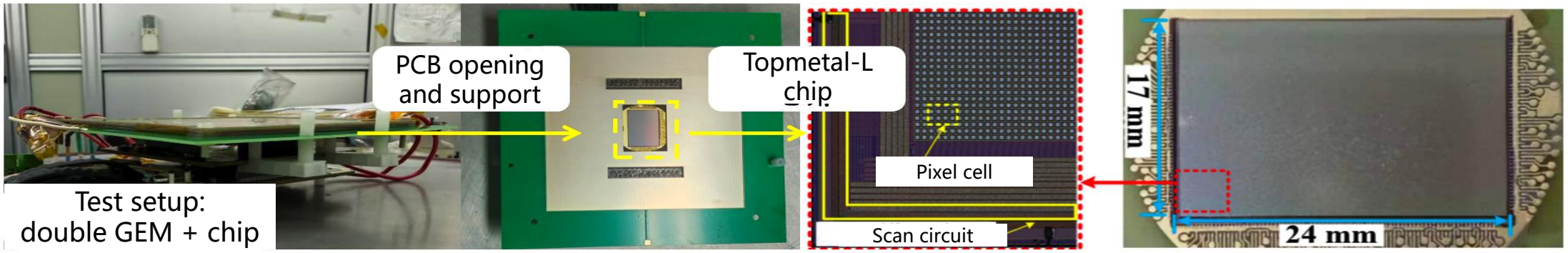
Topmetal-L
Array: 356 × 512
Pixel size: 45 µm
Power: 0.195 W/cm²
ENC: ~22.8 e⁻

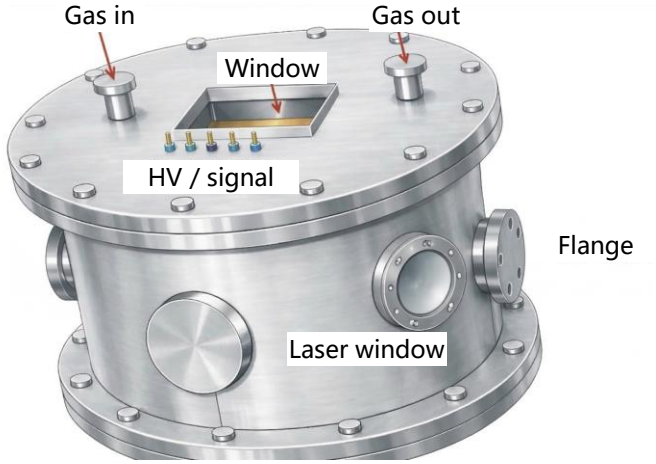


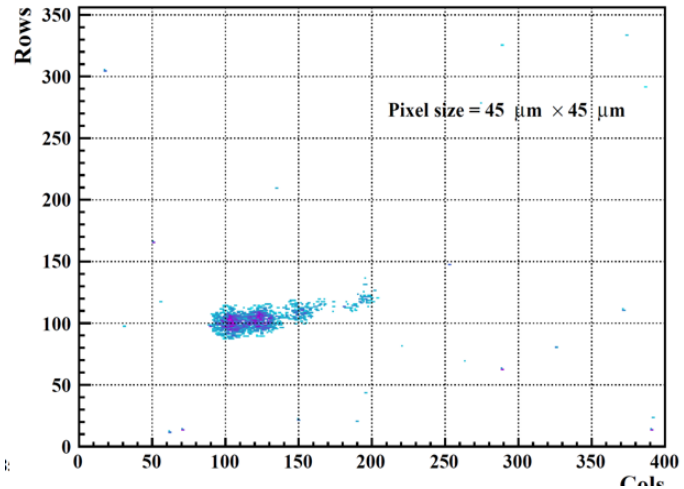


Study 2: GEM–Topmetal-L Test

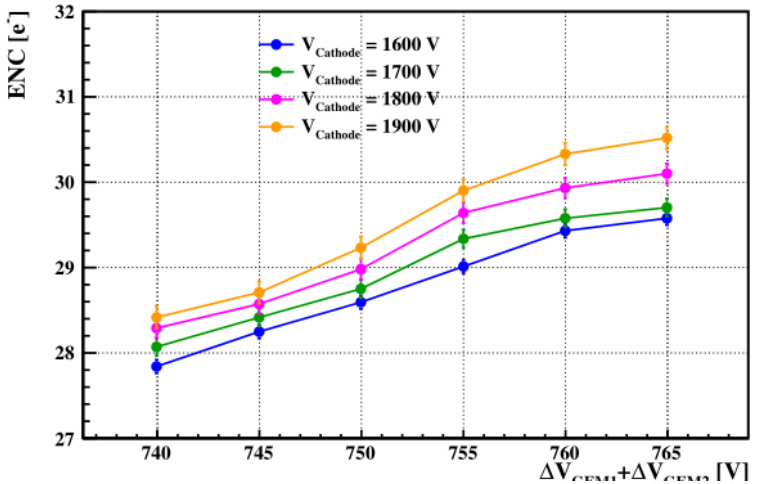
We test Topmetal-L with a double-GEM structure.
With a ^{55}Fe source, GEM-amplified electrons form clear charge patterns on the chip.
The results demonstrate effective pixel readout of amplified electron signals.







^{55}Fe test results

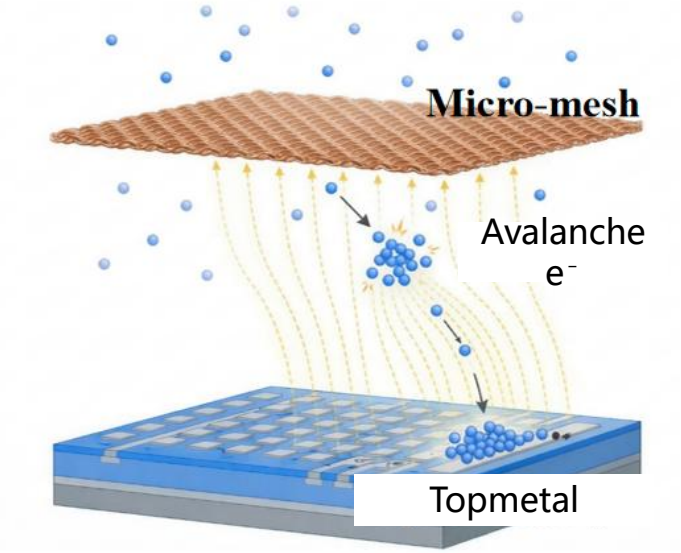


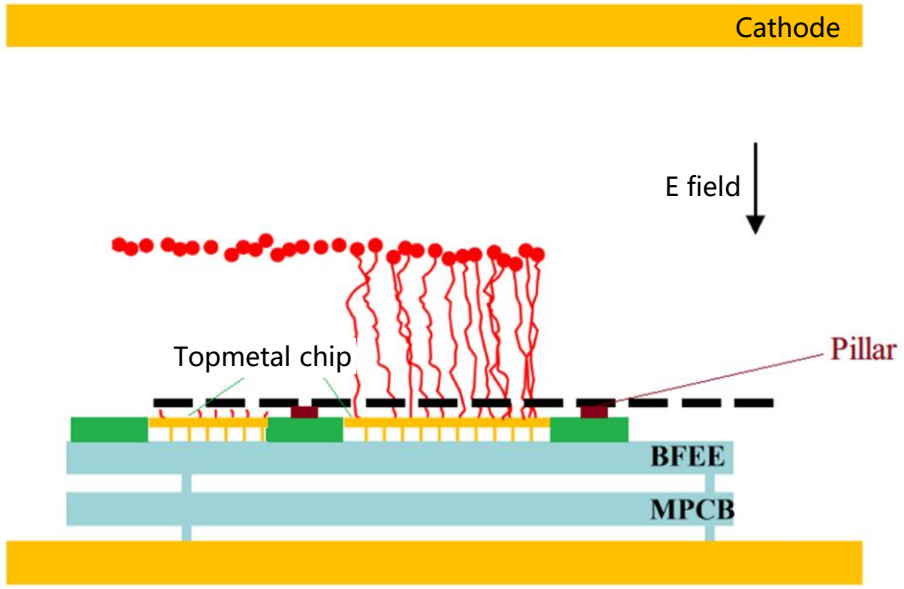
Noise versus GEM voltage

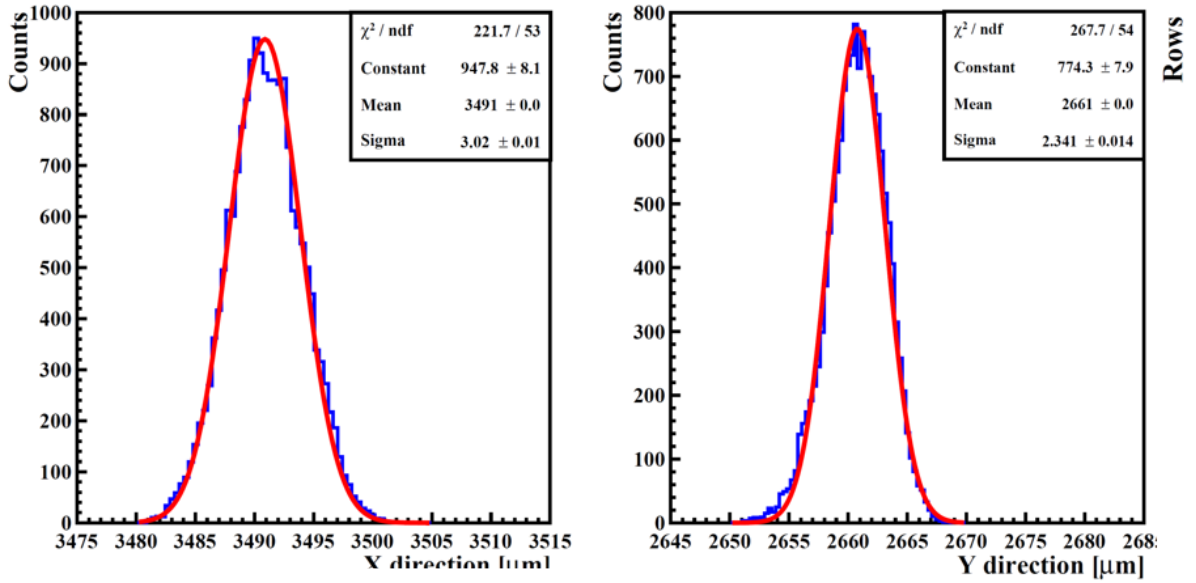
Next Steps

Test Topmetal with Micromegas.
Fabricate the mesh and chip separately.
Integrate them with precision tooling.
Extend the area with modular chip tiling.

Fine-pixel dN/dx studies
Long laser-track reconstruction







UV laser pointing stability

Summary and Outlook

We study direct Topmetal readout and MPGD-amplified readout.

Direct 2D imaging of 5.49 MeV α tracks gives a transverse width $\sigma \approx 138.2$ μm.

Double-GEM tests confirm effective Topmetal-L readout of amplified electrons.

Next steps

Optimize gain, threshold, spatial resolution and stability of GEM/Micromegas–Topmetal-L.

Develop low-power, large-area modules with multiple chips.

Study laser tracks and dN/dx cluster counting.



THANK YOU