CRETE 17

The 2017 Conference on the Applications of Nuclear Techniques

Crete, June 11 – 17, 2017

Libation scene on a painted sacrophagus found at Haghia Triada. The priestess and her handmaiden are pouring the contents of conical vessels on an altar adorned with double-axes *(on the left)*.

1

The new Inner Tracker based on GEM detectors for the BESIII Experiment

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on behalf of the CGEM-IT Group

INFN Istituto Nazionale di Fisica Nucleare

HORIZON 2020

Outline

- BESIII Experiment
- The new CGEM Inner Tracker
- Beam Test Measurements
  - Planar and Cylindrical prototypes
- Readout Electronics: TIGER ASIC
- Conclusions and Outlook

BESIII Experiment @ BEPCII

Running since 2009, forseen to run until 2022

- Double Ring 237 m circumference
- Large crossing angle ±11 mrad
- Achieved Luminosity $1 \times 10^{33}\ cm^{-2}\ s^{-1}$ @ $\psi(3770)$
- Optimum Energy 1.89 GeV
- Energy Spread 5.16×10^{-4}
- No. of Bunches 93
- Bunch length 1.5 cm
- Total current 0.91 A

BEPCII - Beijing e^+e^- Collider

EMC CsI(Tl) crystals
- Energy resolution 2,5% @1GeV
- Spatial resolution 6mm

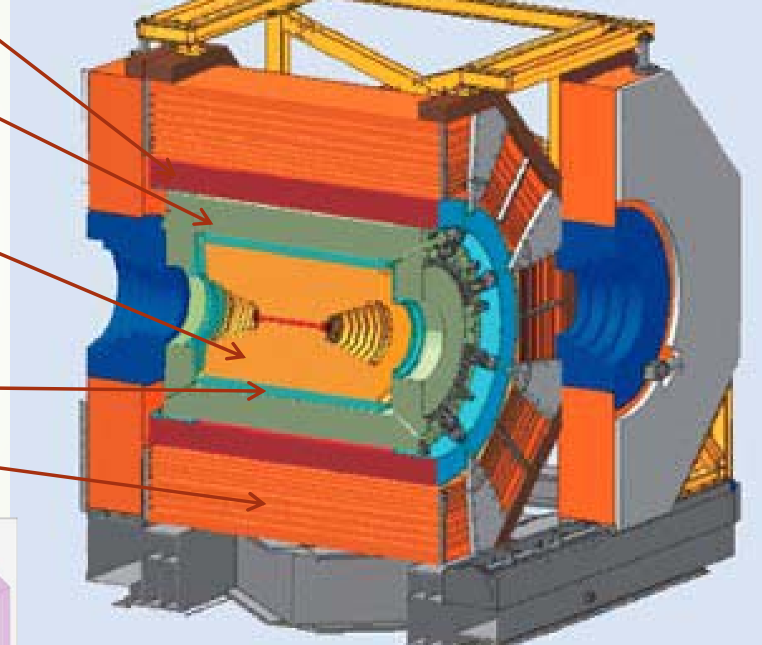
MDC
- Spatial resolution $\sigma_{r\phi}$ = 130μm
- Momentum resolution 0.5% @1GeV
- dE/dx resolution 6%

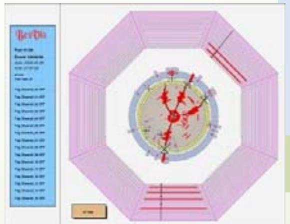
TOF
- Time resolution 80(110) ps barrell (endcaps)

Muon Counter RPC (9)Barrel, (8)Endcaps
- Spatial resolution 1.5 cm

SC Magnet 1T

Acceptance 93%





NIM A614, 345(2010)

Excellent performance detector

Physics goals cover a large and diverse range

Charmonium, Open Charm and Light Hadron Spectroscopy, τ-physics and more

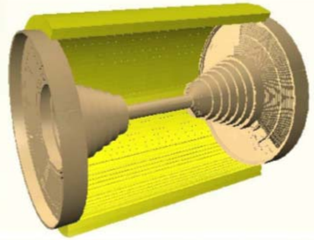
$\sqrt{s}$ = 2 - 4.6 GeV

Aging of the MDC Inner Tracker

MDC (Main Drift Chamber)

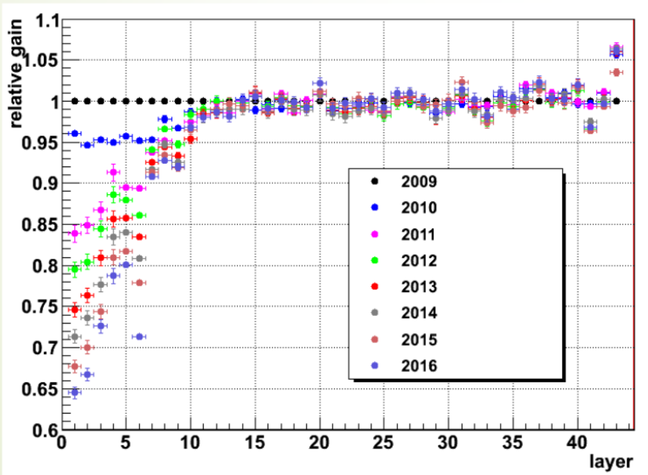
43 layers into Two Trackers sharing the same He-based gas mixture

- Inner Tracker
  - 8 stereo-layers
- Outer Tracker
  - 12 axial layers
  - 16 stereo layers
  - 7 axial layers



Performance

- Spatial resolution $\sigma_{r\phi}$ = 130μm
- Momentum resolution 0.5% @1GeV
- dE/dx resolution 6%



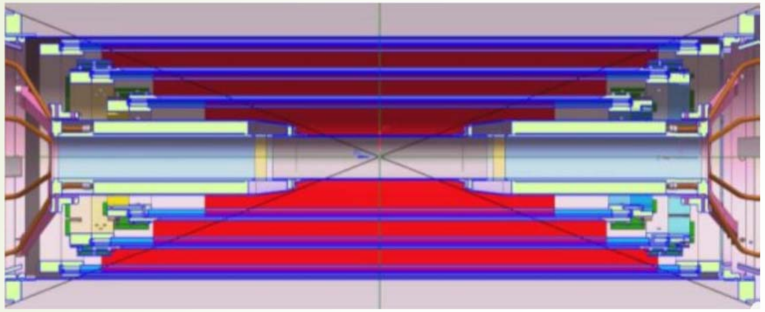
Issues

- Significant ageing in the Inner Tracker
- The increase of Luminosity is speeding up the ageing
- Working at lower HV to keep current under control
- Lower Efficiency
- Gain loss/year ~ 4%

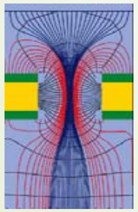
How to run until 2022 and beyond ?
A replacement is needed

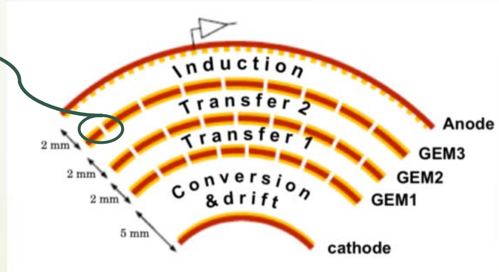
CGEM: a new Inner Tracker for future data taking

Replace the 8 layers of MDC with 3 layers of cylindrical triple GEM



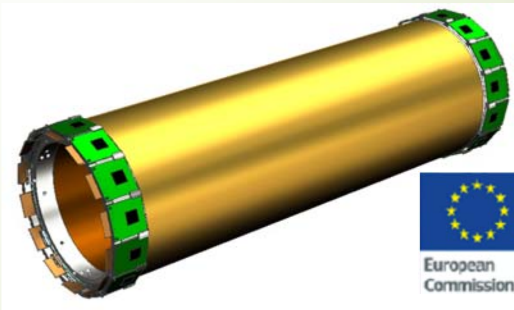
Each layer is made by a triple GEM 5/2/2/2 moulded upon a cylindrical shape





Requirements

- Spatial resolution $\sigma_{r\text{-}\phi}$ ~130 μm, σ_z ~ 1 mm
- Momentum resolution ~ 0.5 % @ 1 GeV/c
- Rate capability 10^4 Hz/cm^2
- Efficiency ~ 98%
- Material budget ≤ 1.5 % X_0 all layers
- Solid angle coverage ~ 93 %
- Magnetic field1T
- Inner radius 78 mm Outer radius 179 mm



Beneficiaries and Partner Organisation
INFN (FE, LNF, TO)
Mainz U - Uppsala U - IHEP

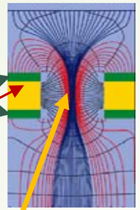
European Commission
HORIZON 2020
BESIIICGEM Project
RISE-MSCA-H2020-2014 call

arXiv:1706.02428

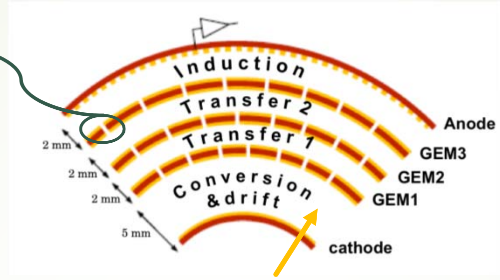
GEM Technology

3 µm Copper

50 µm Kapton

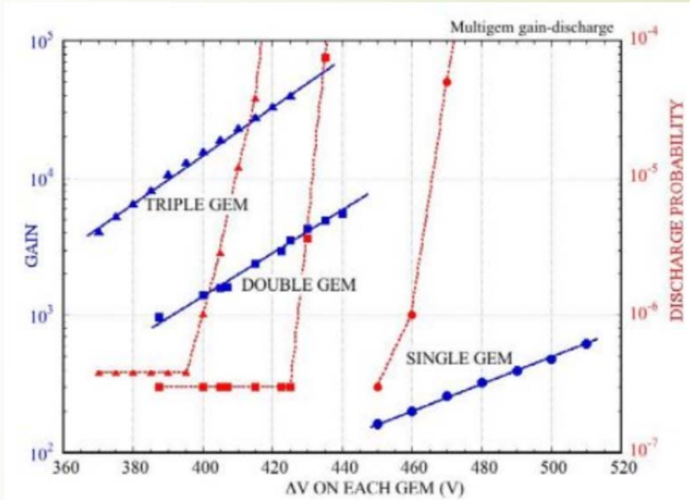


E field 10^5 V/cm



E field 1.5 kV/cm

- XV segmented anode
- Readout strips (pitch, X, V) 650/570/130 µm



- The signal depends on the gas mixture, the geometry and the applied fields
- High efficiency needs a gain of 10^3 -10^4 , while safety standard requires a discharge probability below 10^{-5}

The GEM foils placed between anode and cathode provide a gain of ~10^3-10^4 at lower voltages → lower discharge probability

Physics advantages using CGEM in BESIII

- Better analysis for final states with **short life particles**
- Better precision on **secondary vertex** reconstruction
- **XV** readout improves spatial resolution in **z coordinate (2mm → 1mm)**
- Triple-GEM technology shows higher resistance to **high particle flux**
- Triple-GEM technology shows **lower aging effects**

Vertex resolution of K^0_s and Λ particles improves between 2 and 3 times over the drift chamber

State of the Art and Innovation

Previous Experiment

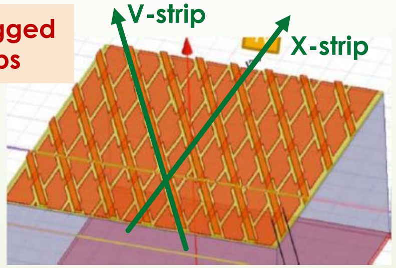
- First Cylindrical GEM detector (4 layers) designed and implemented by **KLOE-2** at DAϕNE
- Operated at **0.5 T** with a spatial resolution of **350 μm**
- **Digital** readout (XV strips with stereo angle 25°-30°)

Innovations @BESIII

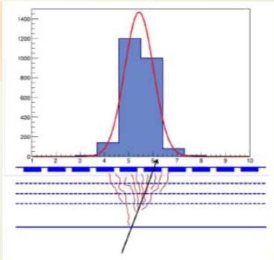
- Cathode and Anode frame made of **Rohacell** instead of Honeycomb
- New anode design with a **jagged layout** to reduce of **30%** the inter-strip capacitance
- **Analogue** readout to achieve the required spatial resolution with a limited number of channels
  - → **TIGER**, a dedicated custom ASIC to provide **Charge and Time** measurements by TDC, ADC and ToT
  - → Both **Charge** and **Time** information will be used to reconstruct the position **with B = 1T**

Rohacell $X_0 \sim 0.33$ % per Layer

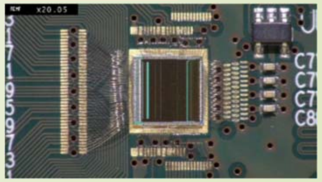
Jagged strips



Analogue readout



TIGER ASIC



Measurements of performance

Beam Test
• Planar GEM December 2014 @ CERN
• Planar GEM June 2015 @ CERN
• Planar GEM May/June 2016 @ CERN
• Cylindrical GEM October 2016 @ CERN
• Cylindrical GEM next July 2017 @ CERN

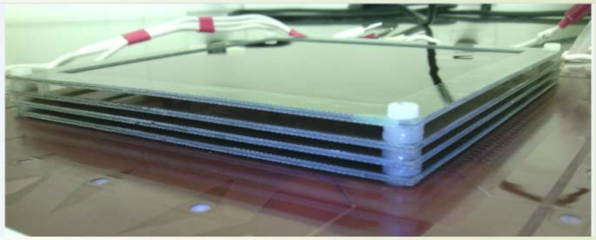
Cosmic rays
• Cylindrical GEM ongoing

@ CERN
• H4 beam line at SPS, North area

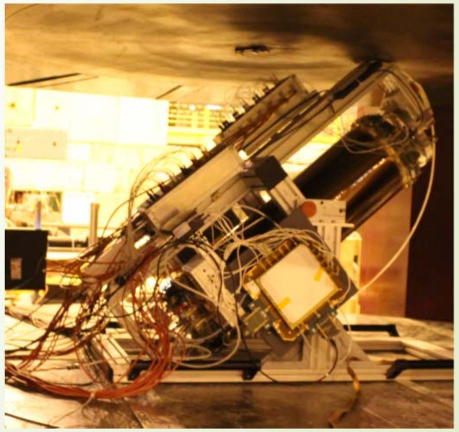
Magnetic field
• GOLIATH dipole
• B field 1.5 T both polarity

Beam
• Muons/pions
• Momentum 150 GeV/c
• Intensity 10^4-10^6 events/spill

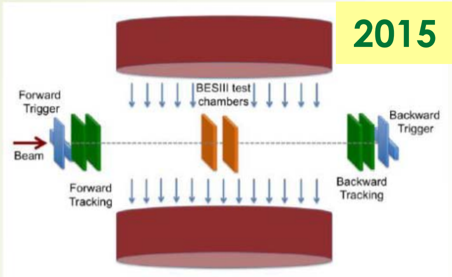
Planar triple GEM prototype

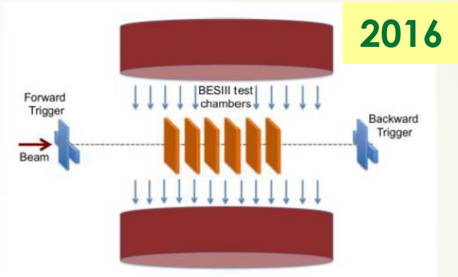


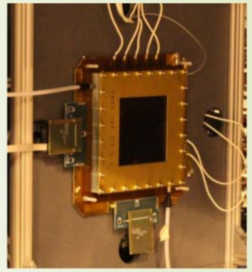
Cylindrical triple GEM



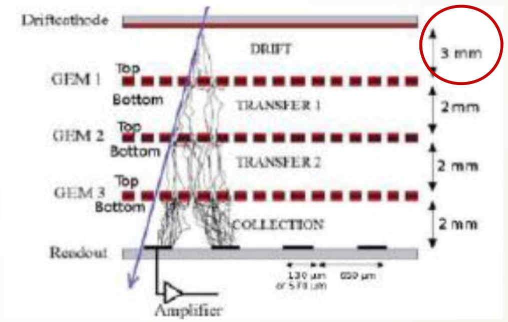
Beam test with Planar GEM

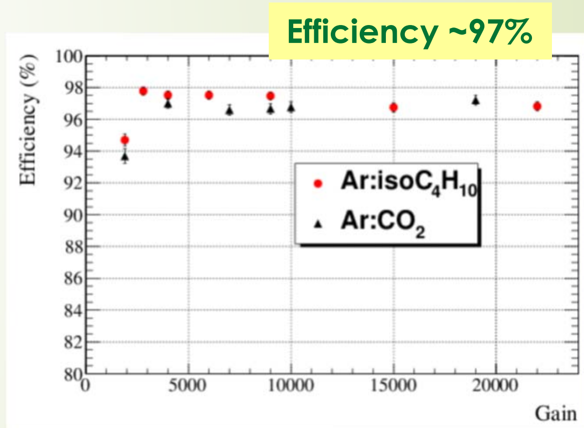






- Triple GEM 10x10 cm²
- X view + Y view
- Strip pitch 650 μm
- Gas mixture
  - Ar/CO_2 (70/30)
  - Ar/iC_4H_{10} (90/10)
- Readout by APV25 ASIC



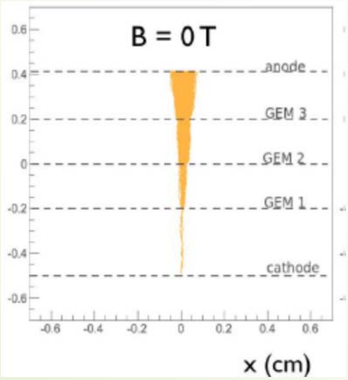


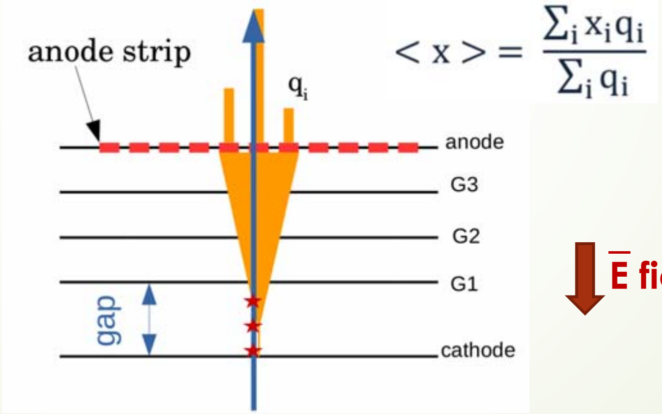
- Performance measured with different geometries, gas mixtures and E fields
- Efficiency plateau on the two views reaches ~97% at a gain of ~6000

The Charge Centroid method

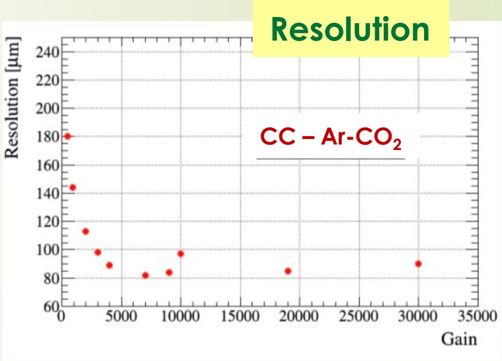
- The avalanche size depends on the gas diffusion, which is affected by E field and gas mixture
- A weighted average position is measured from the fired strips and its performance is better than the digital readout, which is limited by the strip pitch

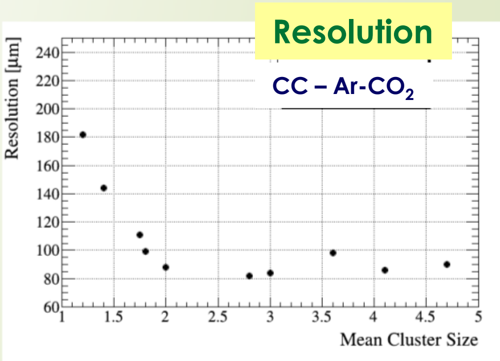
Results with Orthogonal tracks and B = 0
- The charge distribution on the anode is Gaussian → Charge Centroid method





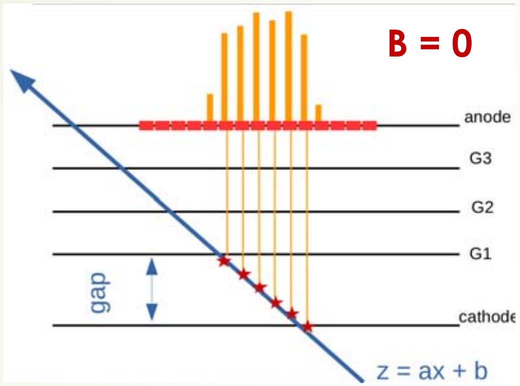
$\overline{E}$ field

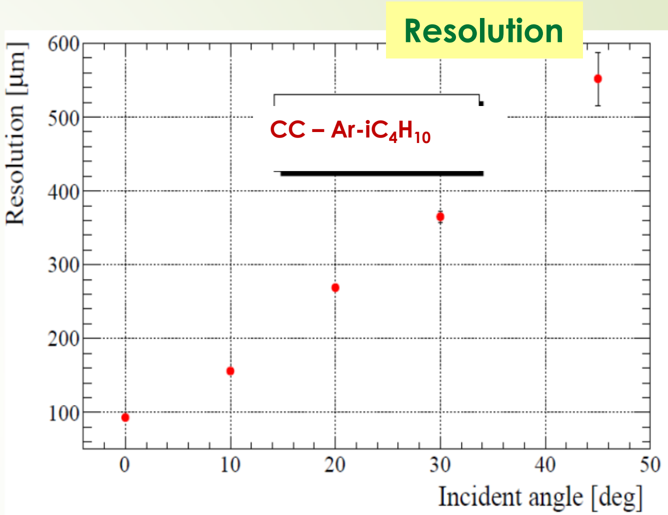




The best performance of CC method is achieved when the number of fired strip > 2

The Charge Centroid method



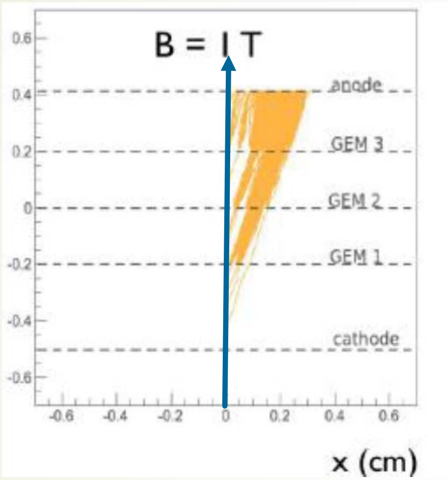


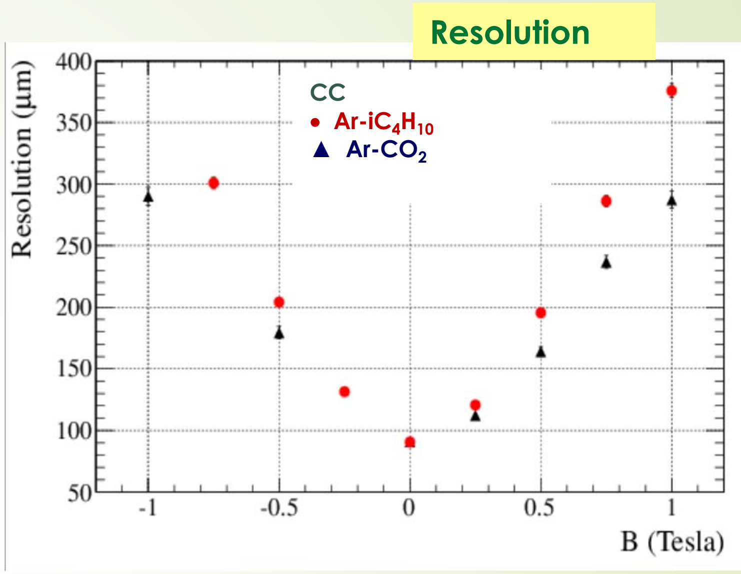
Inclined tracks and B = 0

- The cluster size increases and the charge distribution on the anode is **no more Gaussian**

→ Charge Centroid method fails

The Charge Centroid method





B ≠ 0

• The simultaneous presence of E and B fields bends the electron trajectories

→ the charge distribution on the anode is **no more Gaussian**

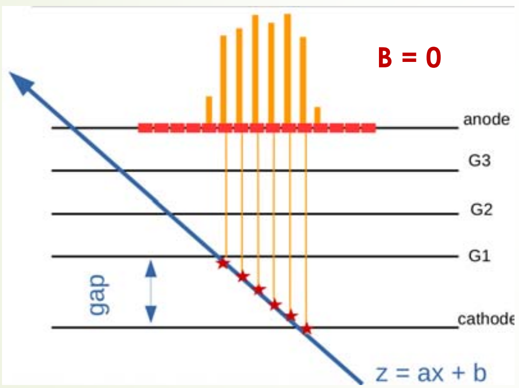
→ Charge Centroid method fails again

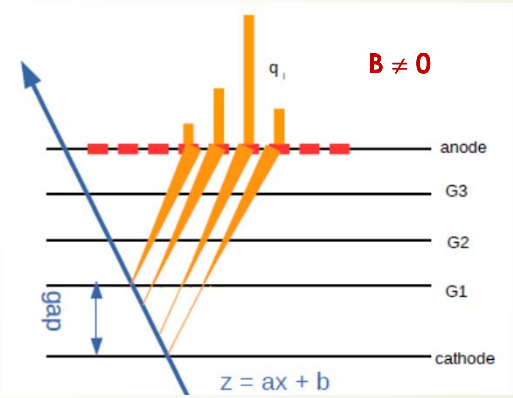
Inclined tracks and/or magnetic field increase the cluster size

A different method to reconstruct the position is needed

The µTPC method

- Inclined tracks and/or magnetic field → Increase cluster size → The µTPC can be used
- The drift gap is seen as **a micro Time Projection Camber** JINST, 9 C01017, 2014
- The spatial resolution can be improved for inclined tracks and with $B \neq 0$ using the Time information on each strip and the drift velocity



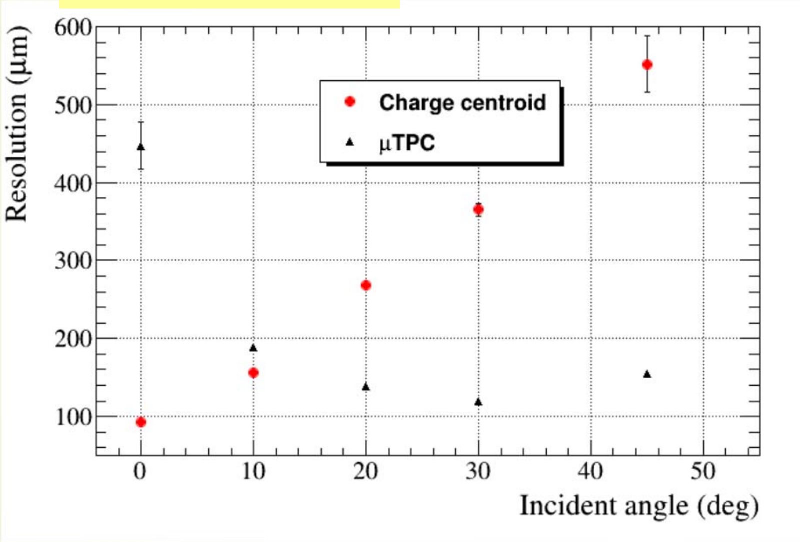


$$x = \frac{\frac{gap}{2} - b}{a}$$

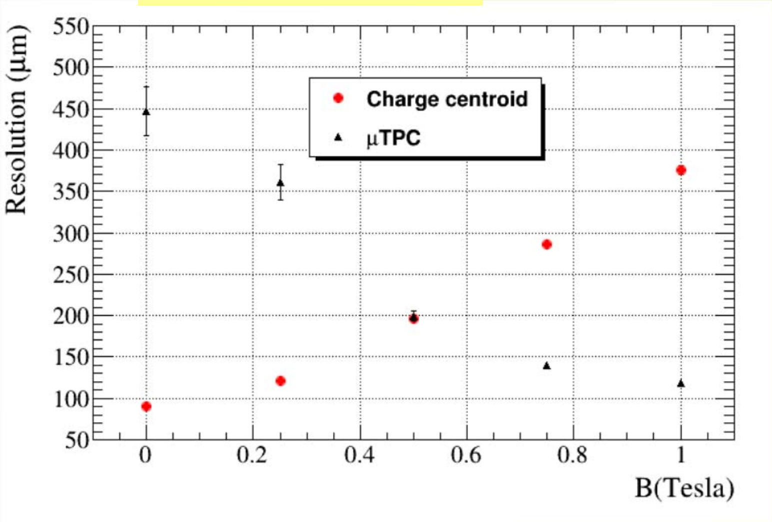
- Knowing the drift velocity from Garfield simulation, a bi-dimensional point is assigned to each fired strip. These points are used to reconstruct the track in the conversion region
- A linear fit is used to reconstruct the path and to measure the particle position

Charge Centroid & µTPC methods

Resolution vs angle

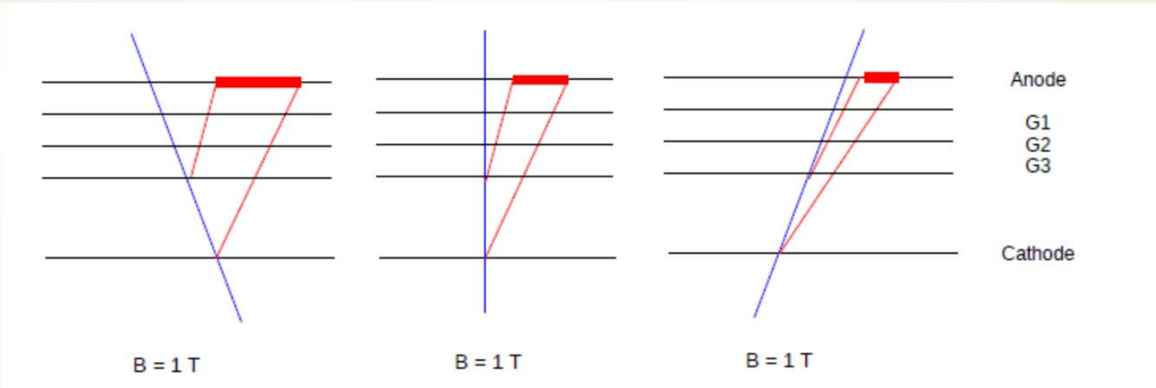


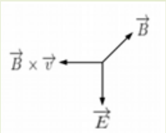
Resolution vs B field



A combination of the two methods is needed

Inclined tracks and B ≠ 0





de-focusing | neutral | focusing

Two different effects can be observed

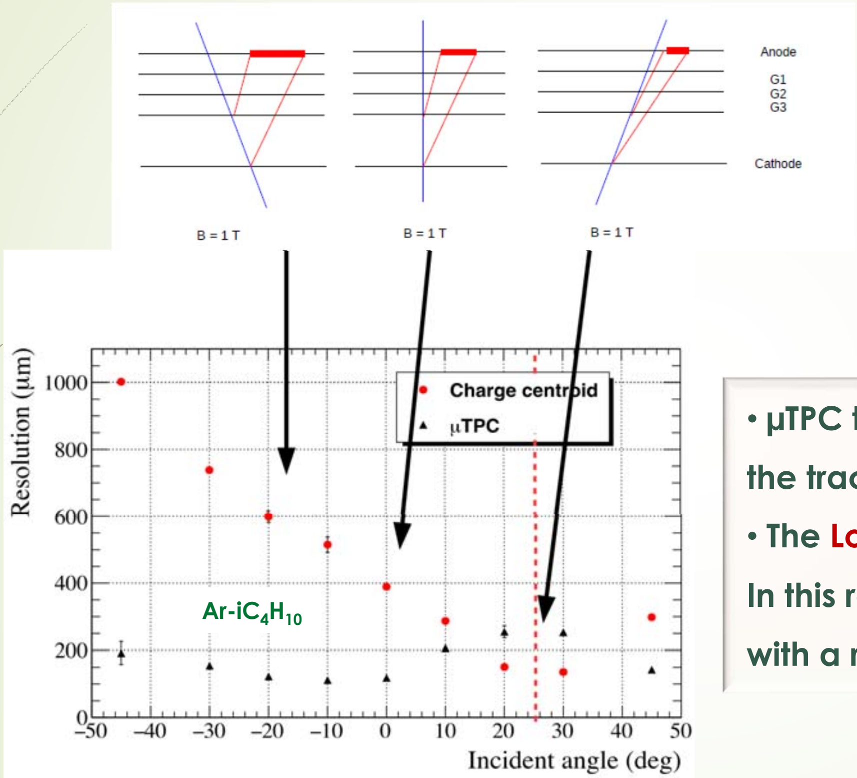
- focusing effect: Lorentz & inclination angles concordant

→ smaller cluster size

- de-focusing effect: Lorentz & inclination angles discordant

→ bigger cluster size

Combining Charge Centroid & μTPC methods



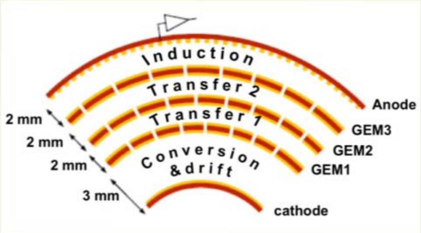
B = 1T

- μTPC takes into account the Lorentz angle to reconstruct the tracks with B ≠ 0
- The Lorentz angle using Ar-iC_4H_{10} @ 1.5 kV/cm drift field is ~ 26° In this region CC is more efficient. In the other regions μTPC is flat with a resolution ~ 130 μm

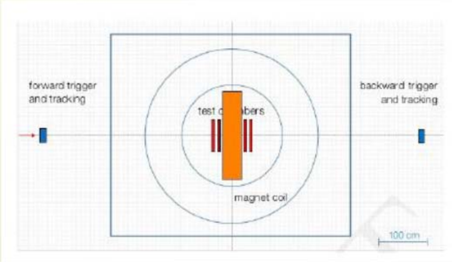
A combination of the two methods should keep the resolution stable in the full range of incident angle

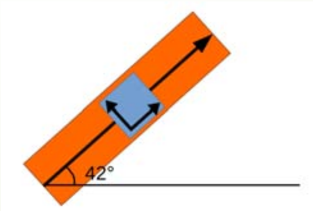
Beam test with the Cylindrical triple-GEM

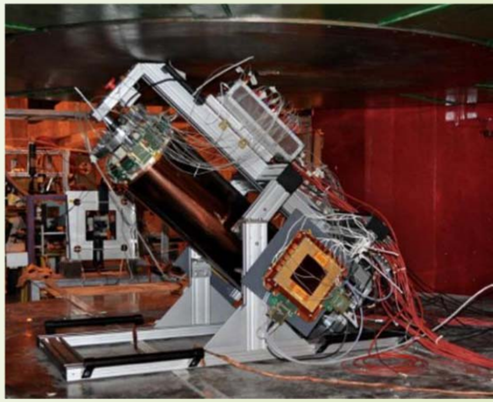
- First beam test @ CERN with prototype of Layer-2
- 3 mm drift gap (new Layer with 5 mm is under assembly)
- Gas mixture Ar/CO_2 (70/30)
- X and V views, only X instrumented
- CGEM and 4 planar GEM have been used



Goals
- CGEM at 42° to test the performance along the longitudinal strip @ B = 1 T
- Test the stability of the detector under beam conditions
- Test under high intensity pion beam
- Comparison between cylindrical and planar GEM measurements





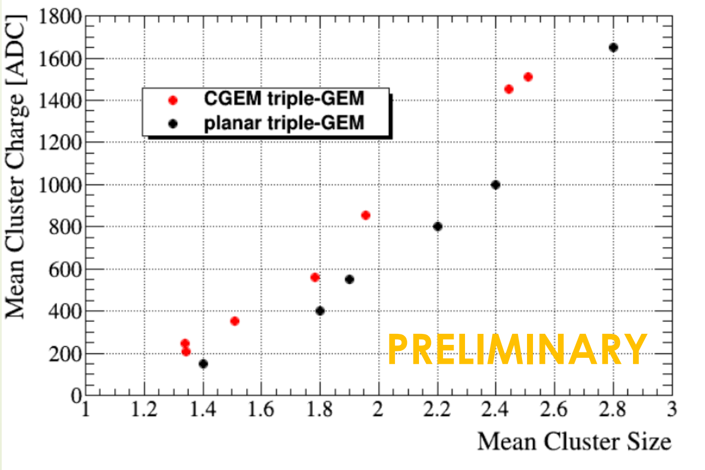


Test under extreme conditions
- HV = 400 V for each GEM foil → gain 10^5 → Stable
- High intensity beam → some tenth of kHz/cm^2 → No current peaking problem

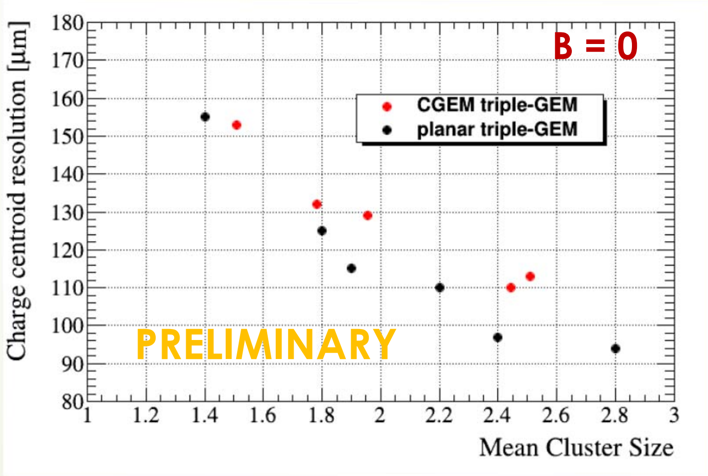
Comparison between Planar and Cylindrical triple-GEM

- Analysis as a function of cluster size
- Measurements with orthogonal pion tracks and B = 0
- Cluster size shows the number of the fired strips. This is related to the signal dimension rather than to the gain and the drift properties of the electron

Mean Cluster Charge vs Mean Cluster Size



CC Resolution vs Mean Cluster Size



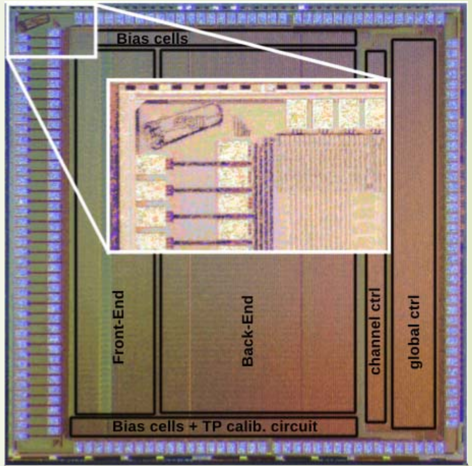
CC Resolution shows that the CGEM performance is in agreement with planar GEM

Readout Electronics: TIGER ASIC

Our Aim: Spatial Resolution ≤ 130 μm ⇒ Analogue Readout is nedeed

Requirements

- Should provide Charge and Time measurements for Charge Centroid and μTPC modes and feature a fully-digital output
- Input charge: 1 – 50 fC
- Sensor Capacitance: up to 100 pF
- Rate per Channel: 60 kHz (safety factor of 4 included)
- Time resolution: 4-5 ns
- Power consumption ~ 10 mW/channel
- Should be radiation tolerant for Single Event Upset

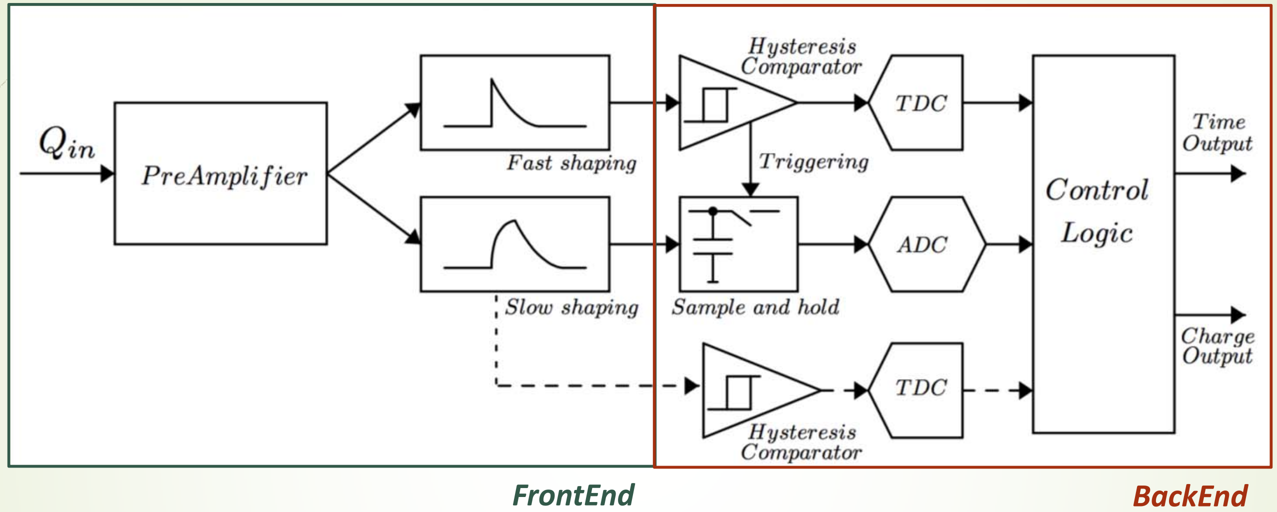


Tape out of 1st silicon May 2016

- 64-channels
- 5x5 mm^2 UMC110 CMOS
- Digital Backend inherited from TOFPET2 ASIC for PET medical applications (+ SEU)

A custom ASIC has been designed and developed
TIGER (Torino Integrated GEM Electronics Readout)

TIGER Design



arXiv:1706.02267

- First silicon Tape-out MPW in May 2016
- Test on silicon started in Nov 2016

Front End

- Charge Sensitive Amplifier + two shapers (Time and Charge)

Time-based readout

- Single or double threshold readout
- Time stamp on rising/falling edge (sub-50 ps binning quad-buffered TDC)
- Charge measurement with Time-Over-Threshold

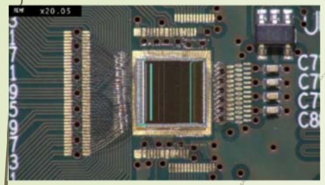
Time and amplitude sampling

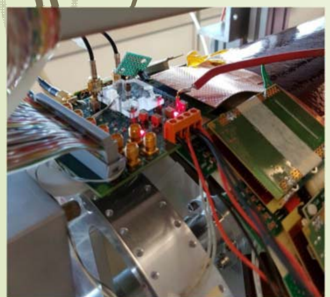
- Time stamp on rising edge (sub-50 ps binning quad-buffered TDC)
- Sample-and-Hold circuit for peak amplitude sampling

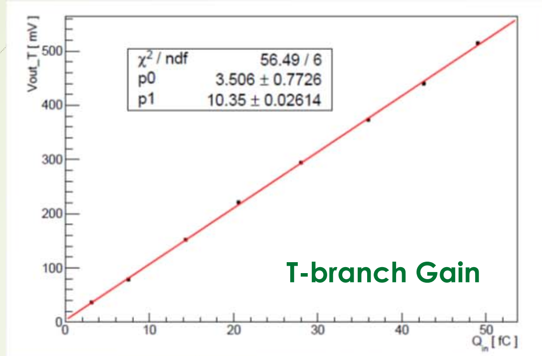
→ Slow shaper output voltage is sampled and digitised with a 10-bit Wilkinson ADC

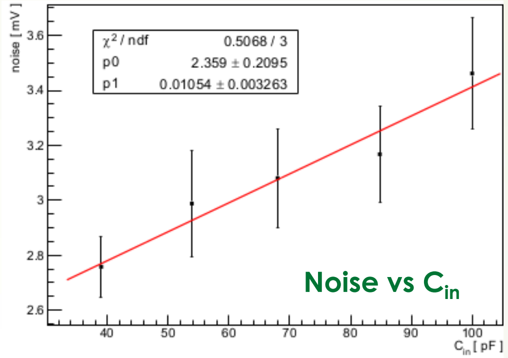
- TDC/ADC local controller
- on-chip bias and power management
- on-chip calibration circuitry

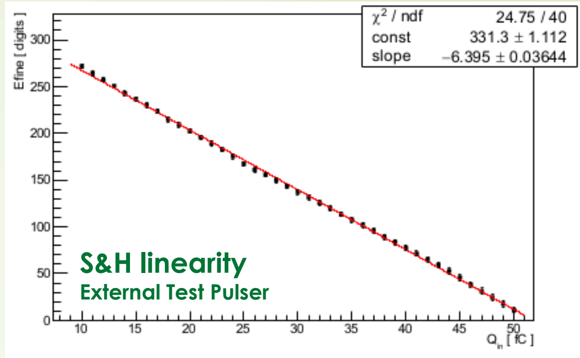
TIGER preliminary tests











- ✓ *T-branch Gain* ≈ 10.4 mV/fC in agreement with simulations
- ✓ RMS Noise ≈ 3.5 mV @ 100 pF 50% higher than simulations - RMS Jitter ≈ 3.7 ns for Q_{in} = 3 fC @ 100 pF
- ✓ Charge measurement with S&H: linearity assessed

Electrical characterization

- Time-based readout working properly
- Charge measurement S&H linearity assessed
- Baseline dependence on Temp, due to bias conditions of holder circuit → minor revision needed
- Second Prototype not needed → Engineering Run within July 2017

Test with CGEM prototype

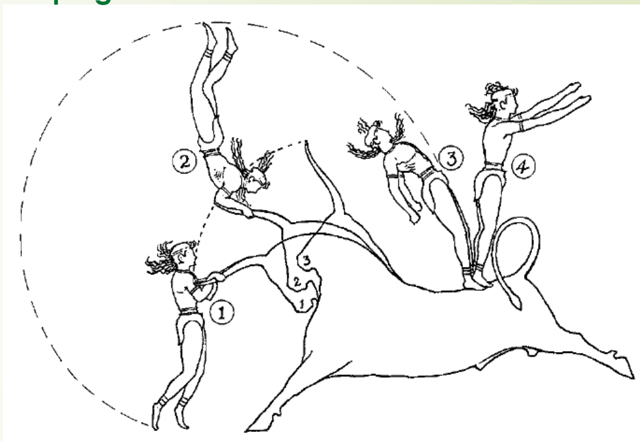
- First signals acquired with Cosmic rays and ^{90}Sr source – Data analysis ongoing
- Next step: test with conditions close to the final ones (HV system, cables, FEB, …)

Conclusions and Outlook

- An innovative Cylindrical GEM detector with Charge and Time readout is under construction and test to replace the BESIII Inner tracker which is affected by ageing
- Performance and optimization of a **planar GEM prototype** have been studied under several conditions (HV, gas mixtures, fields)
- Combining **Charge Centroid and μTPC modes**, the spatial resolution is stable and results are beyond the state of the art for GEM detectors operated in B field
- A **first Cylindrical GEM** layer has been tested w/o B field and **its performance is close to planar GEM**
- A second Cylindrical GEM layer is almost ready for **test beam @ CERN in July 2017**
- **TIGER:** a custom ASIC for analogue readout (featuring Charge and Time measurements) has been developed and it is under test with real CGEM signals with cosmic rays and ^{90}Sr source
- **TIGER engineering run** is foreseen with minor revisions and different design flavours **within July 2017**
- Three CGEM layers will be tested with TIGER and will be ready for **shipping in February 2018**
- CGEM detector installation @ IHEP is planned **in Summer 2018**

We have a tight and challenging schedule ahead

Bull-leaping in the Minoan Ancient World in Crete

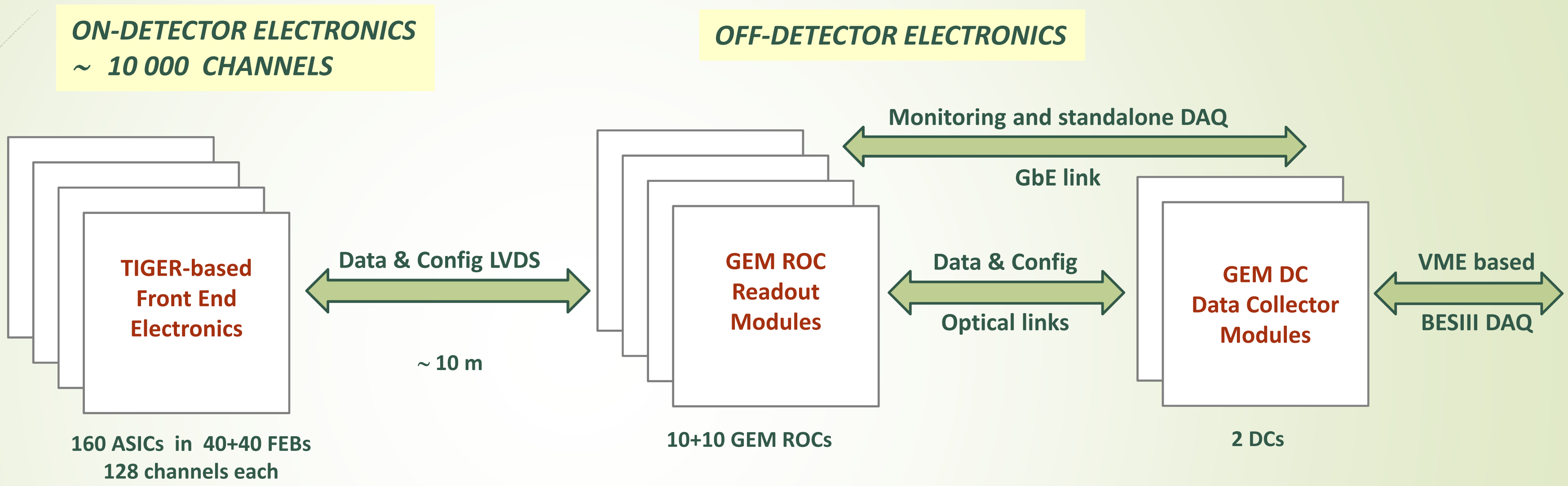


But we are ready for the bull-leaping

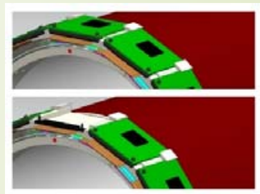
Spares

Libation scene on a painted sacrophagus found at Haghia Triada. The priestess and her handmaiden are pouring the contents of conical vessels on an altar adorned with double-axes *(on the left)*.

Readout Electronics



- **ON-DETECTOR electronics**
  Front End boards located on the detector to preserve the S/N ratio



- **OFF-DETECTOR electronics**
  Readout Cards and Data Collector boards as close as possible to the detector