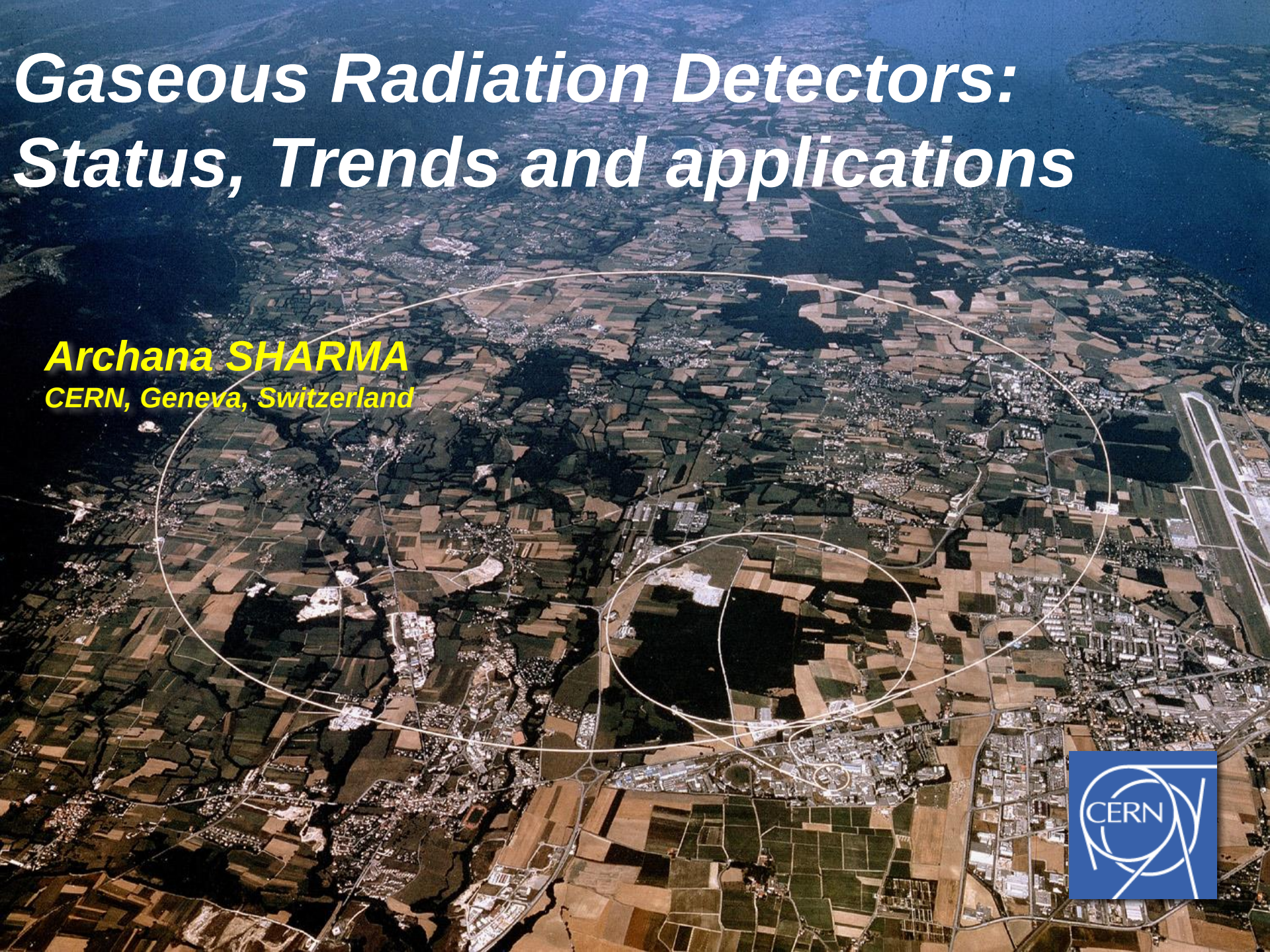
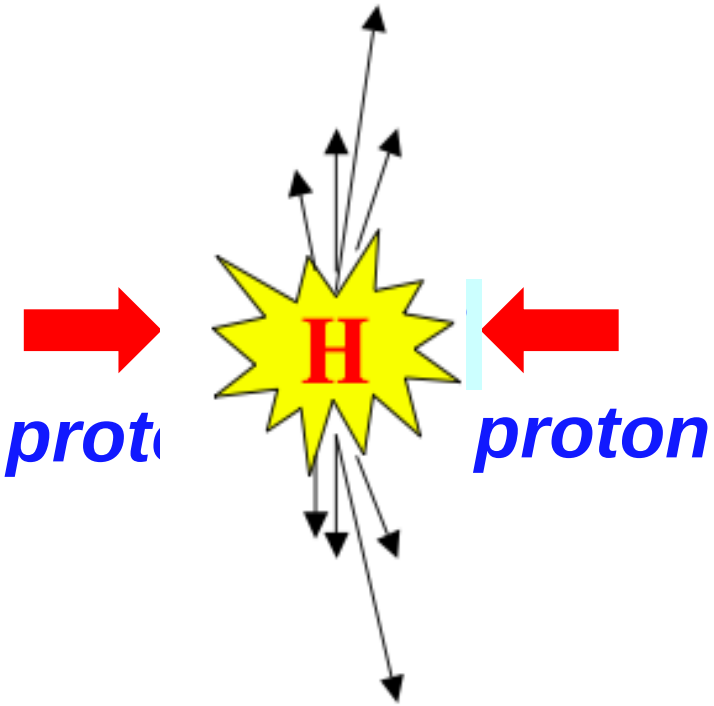
Gaseous Radiation Detectors: Status, Trends and applications

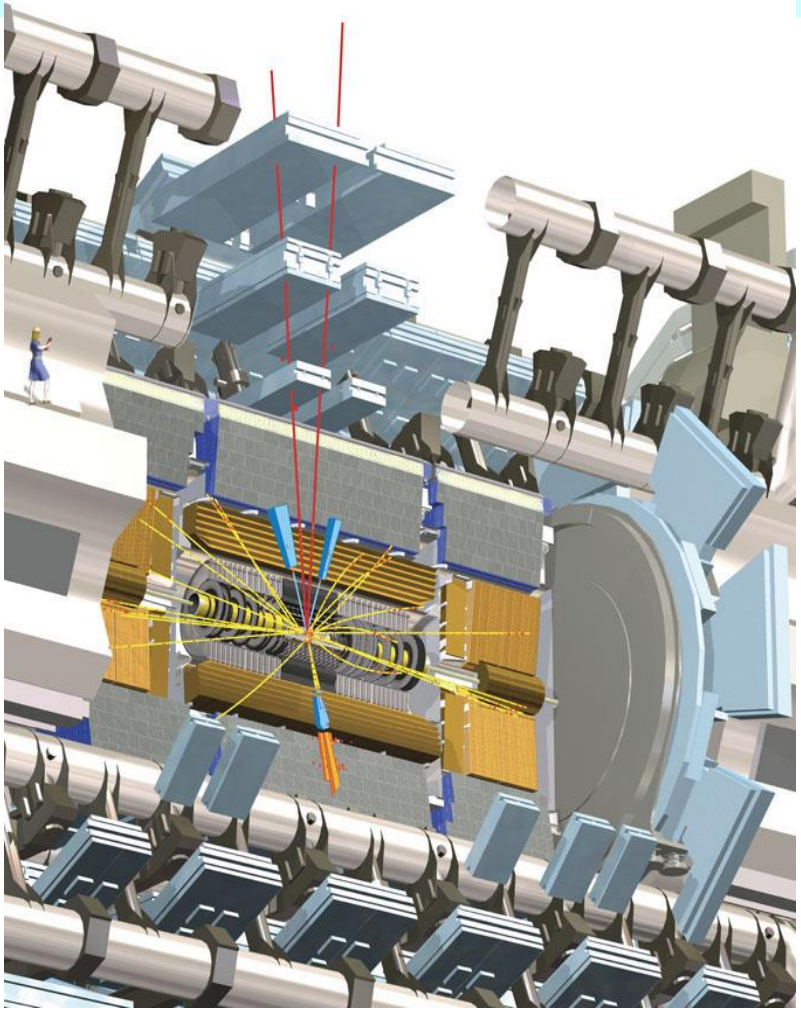


Archana SHARMA
CERN, Geneva, Switzerland

A Major Quest : The Higgs

Produced and detected Higgs Particles at a Particle Collider





Archana Sharma March 16, 2017

The Higgs particle - the last missing particle in the Standard Model

This Search Requires……

1. Accelerators : ***powerful machines that accelerate particles to extremely high energies and bring them into collision with other particles***

2. Detectors : ***gigantic instruments that record the resulting particles as they "stream" out from the point of collision.***

3. Computing : ***to collect, store, distribute and analyse the vast amount of data produced by these detectors***

4. Collaborative Science on Worldwide scale : ***thousands of scientists, engineers, technicians and support staff to design, build and operate these complex "machines".***

The Large Hadron Collider

7 TeV p + 7 TeV p
(3.5/4 TeV + 3.5/4 TeV)

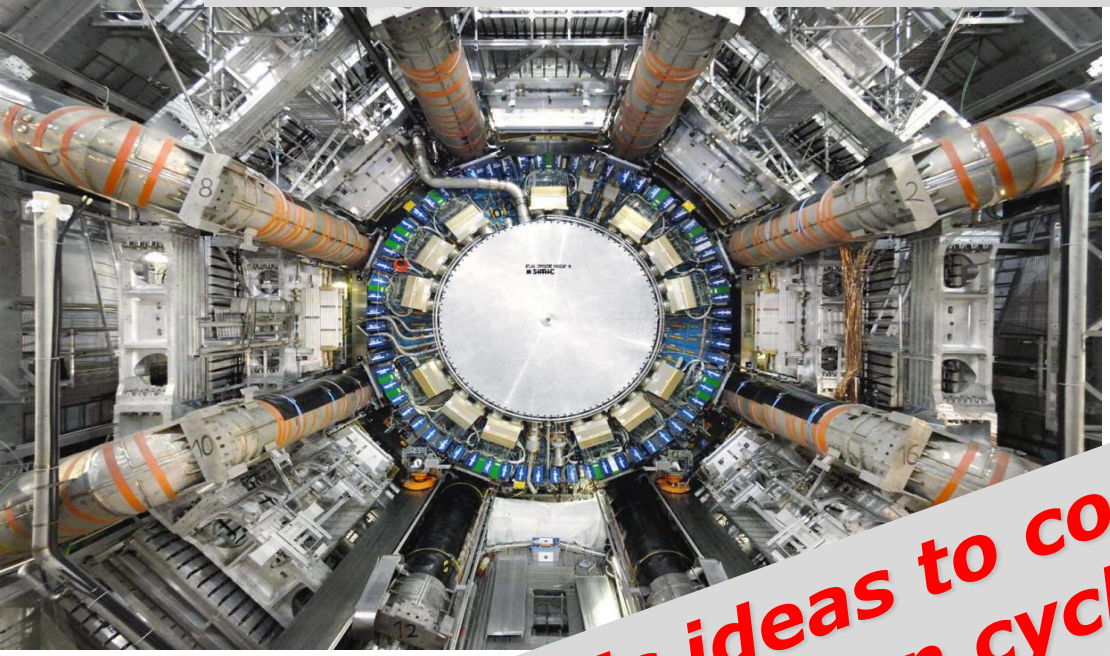
1 TeV = 1 Tera electron volt
= 10^{12} electron volt

Primary physics targets

- *Origin of mass*
- *Nature of Dark Matter*
- *Understanding space time*
- *Matter versus antimatter*
- *Primordial plasma*

The LHC is a Discovery Machine
The LHC now runs at 13 TeV as of 2015

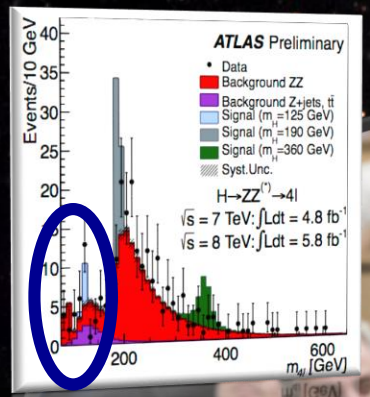
Triumphs of Instrumentation

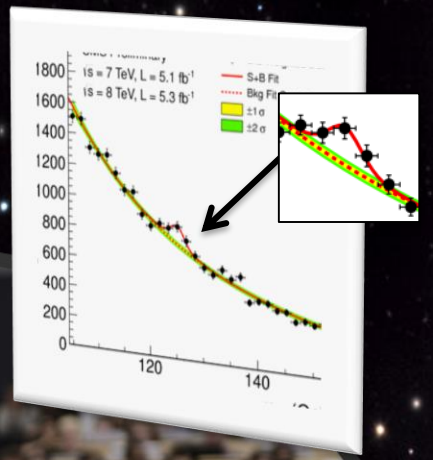


From basic ideas to complex detector systems →Design cycle of LHC > 20y!

Digital Cameras the Size of Cathedrals

Two of 10,000 people Presented some results in 2012





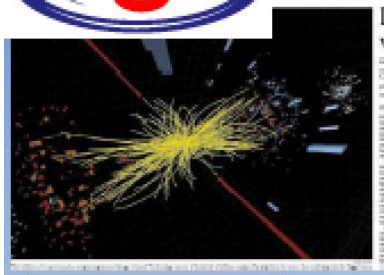
Fabiola Gianotti
ATLAS Spokesperson 2010-2012

Joe Incandela
CMS Spokesperson 2012-2013

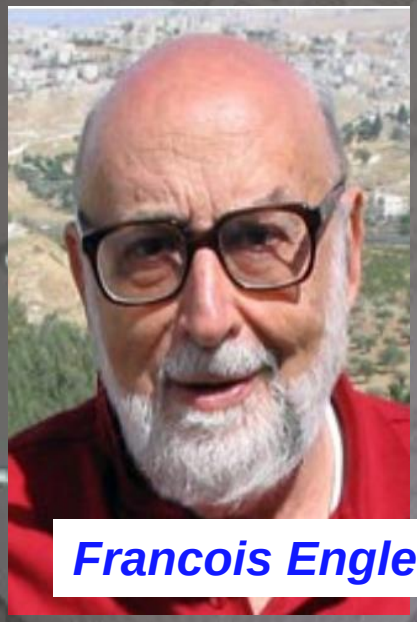
...that made a lot of physicists VERY happy...

July 4th 2012

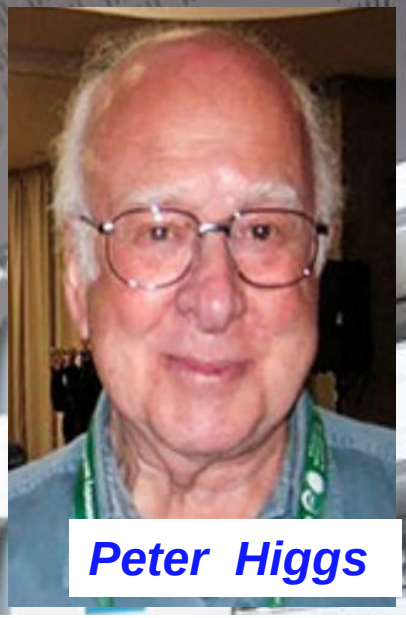
The discovery of a new particle



Tuesday 8 October 2013

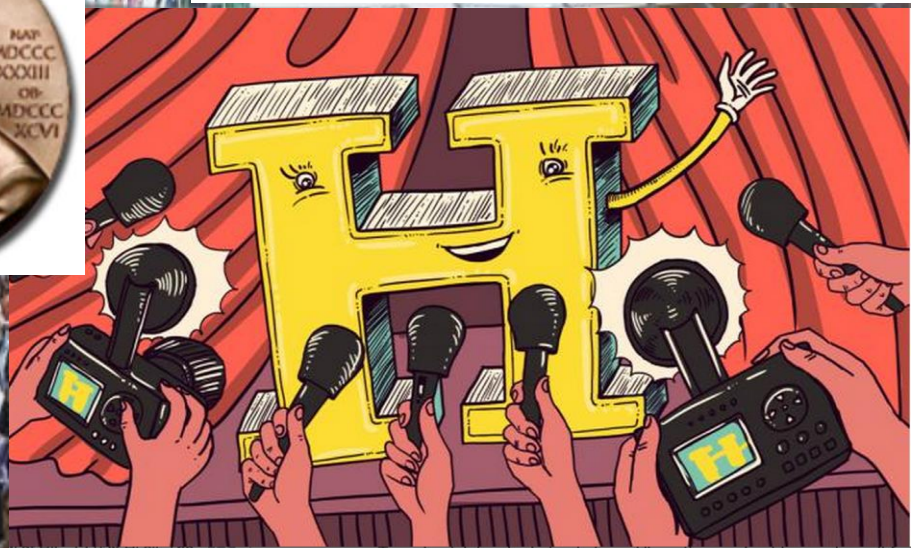


Francois Englert



Peter Higgs

Congratulations!!!!

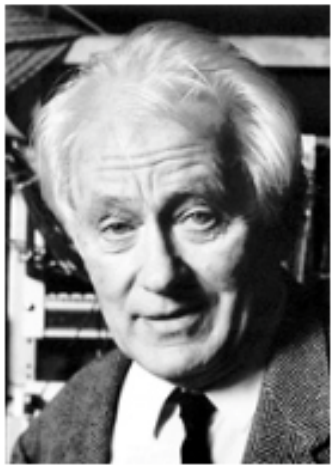


Wednesday 11th November 1992

The Nob
Georges

Share this: 20

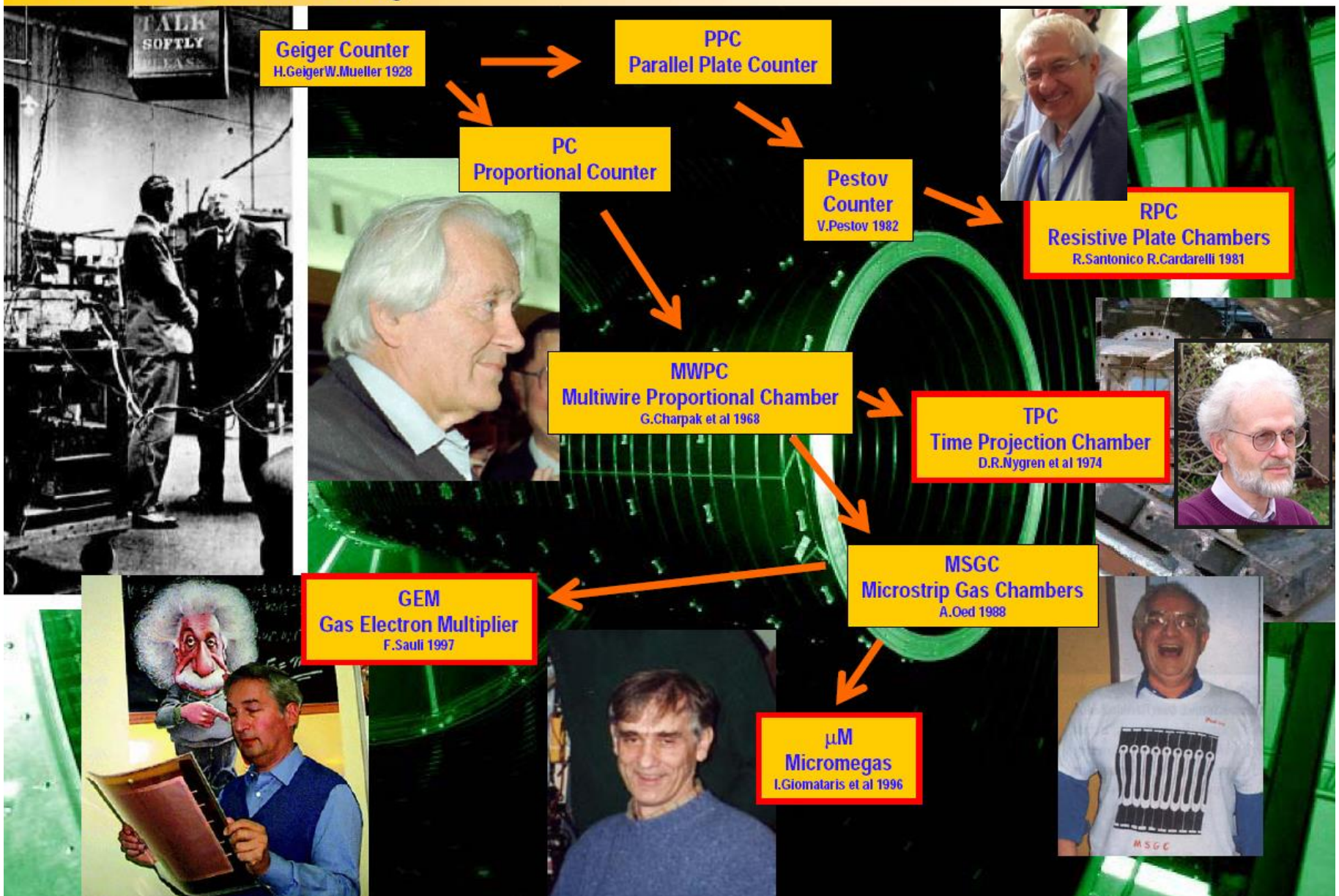
The Nobel Prize in Physics 1992



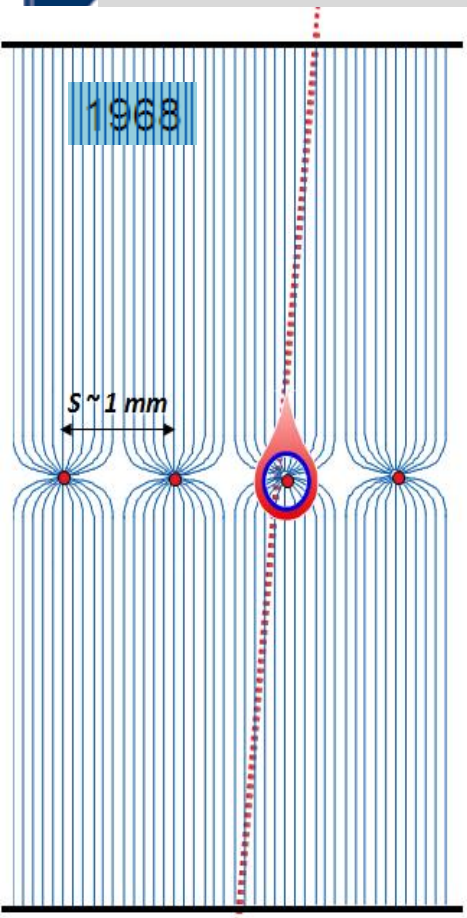
Georges Charpak
Prize share: 1/1

The Nobel Prize in Physics 1992 was awarded to Georges Charpak *"for his invention and development of particle detectors, in particular the multiwire proportional chamber"*.

Gaseous Radiation Detectors

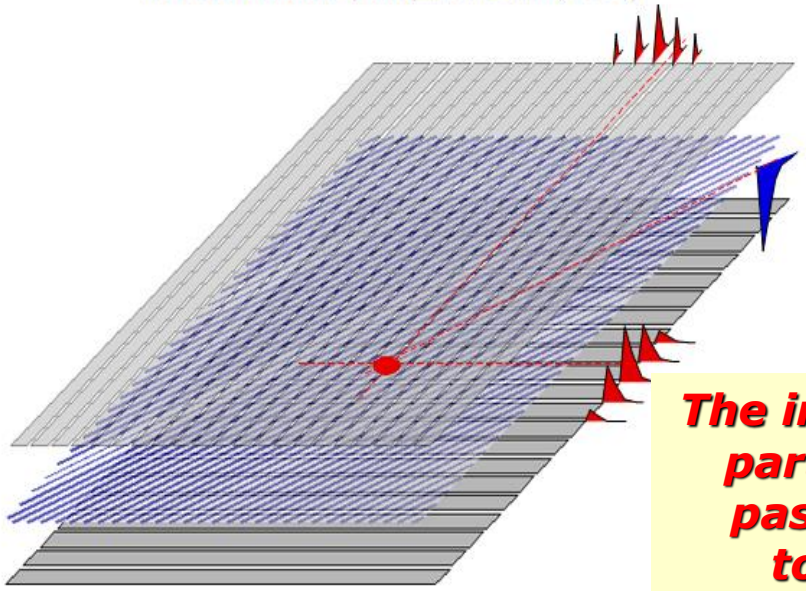


MWPCs : What a revolution !



High-rate MWPC with digital readout:
Spatial resolution is limited to s_x ~ s/sqrt(12) ~ 300 μm

TWO-DIMENSIONAL MWPC READOUT CATHODE
INDUCED CHARGE (Charpak and Sauli, 1973)



Spatial resolution determined by: Signal / Noise Ratio
Typical (i.e. 'very good') values: S ~ 20000 e: noise ~ 1000e
Space resolution < 100 μm

The invention revolutionized particle detection, which passed from the manual to the electronic era.

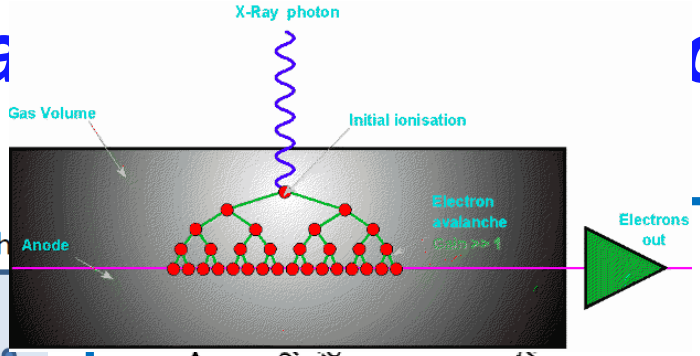
1992

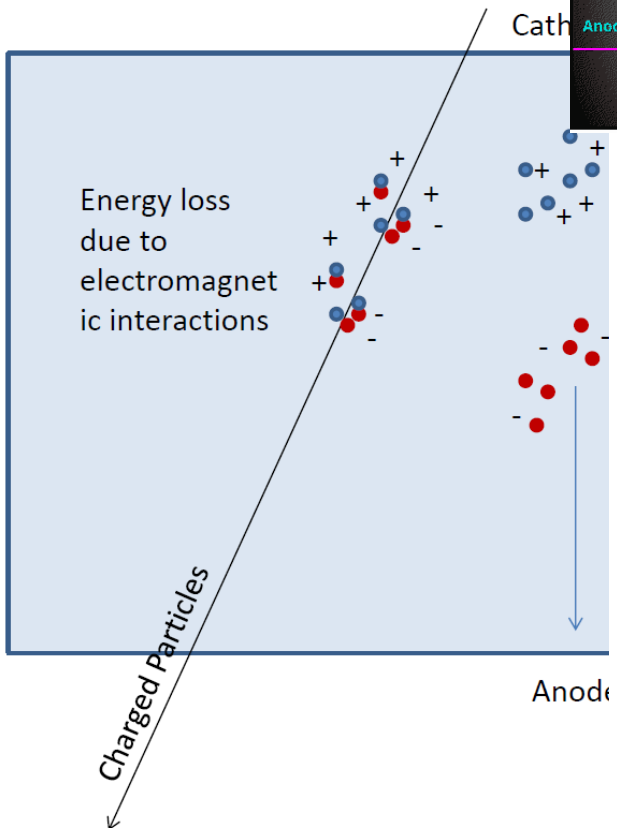
Georges Charpak
1924 – 2010

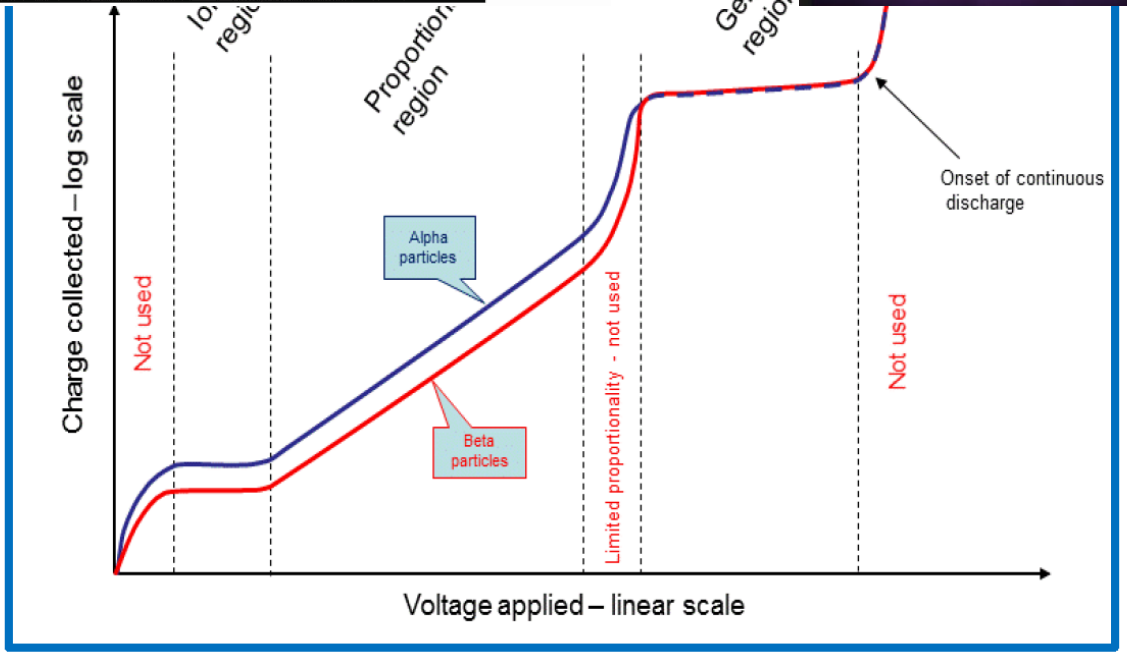
Archana Sharma, March 29, 2017

Gas & Electric Field

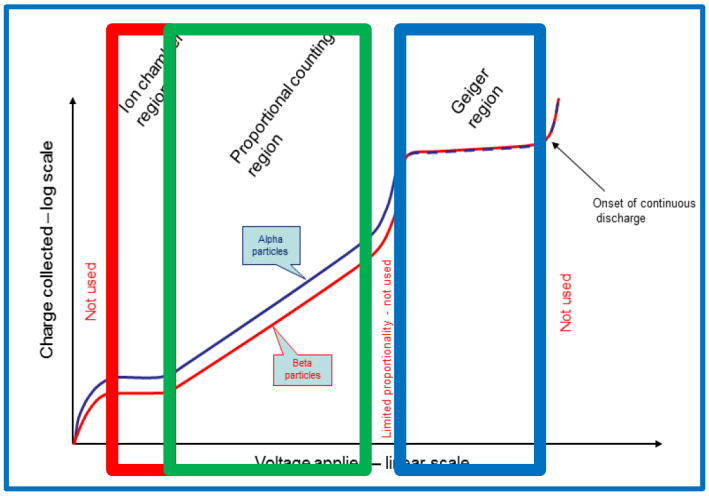
How do "typica ctors work?







Gas & Electric Field



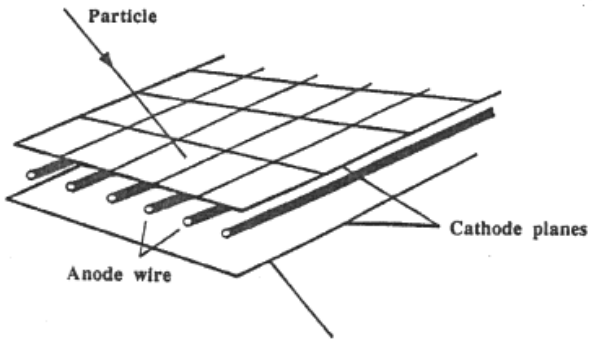
Geiger-Müller tubes operate at higher voltage: each electron-ion pair creates an avalanche. UV photons are produced and create multiple avalanches which spread along the anode wire.

Pros:

- ✓ *Cheap, robust detector with a large variety of sizes and applications*
- ✓ *Large output signal from tube*
- ✓ *Can measure overall gamma dose*

Cons:

- ➢ *Cannot measure energy of radiation*
- ➢ *High dead time → does not sustain high radiation rates*
- ➢ *Sustained high radiation levels will degrade fill gas*



In Proportional counters the output current pulse generated is proportional to the energy deposited by the radiation. The Wire chamber is an example of proportional counter used as a research tool.

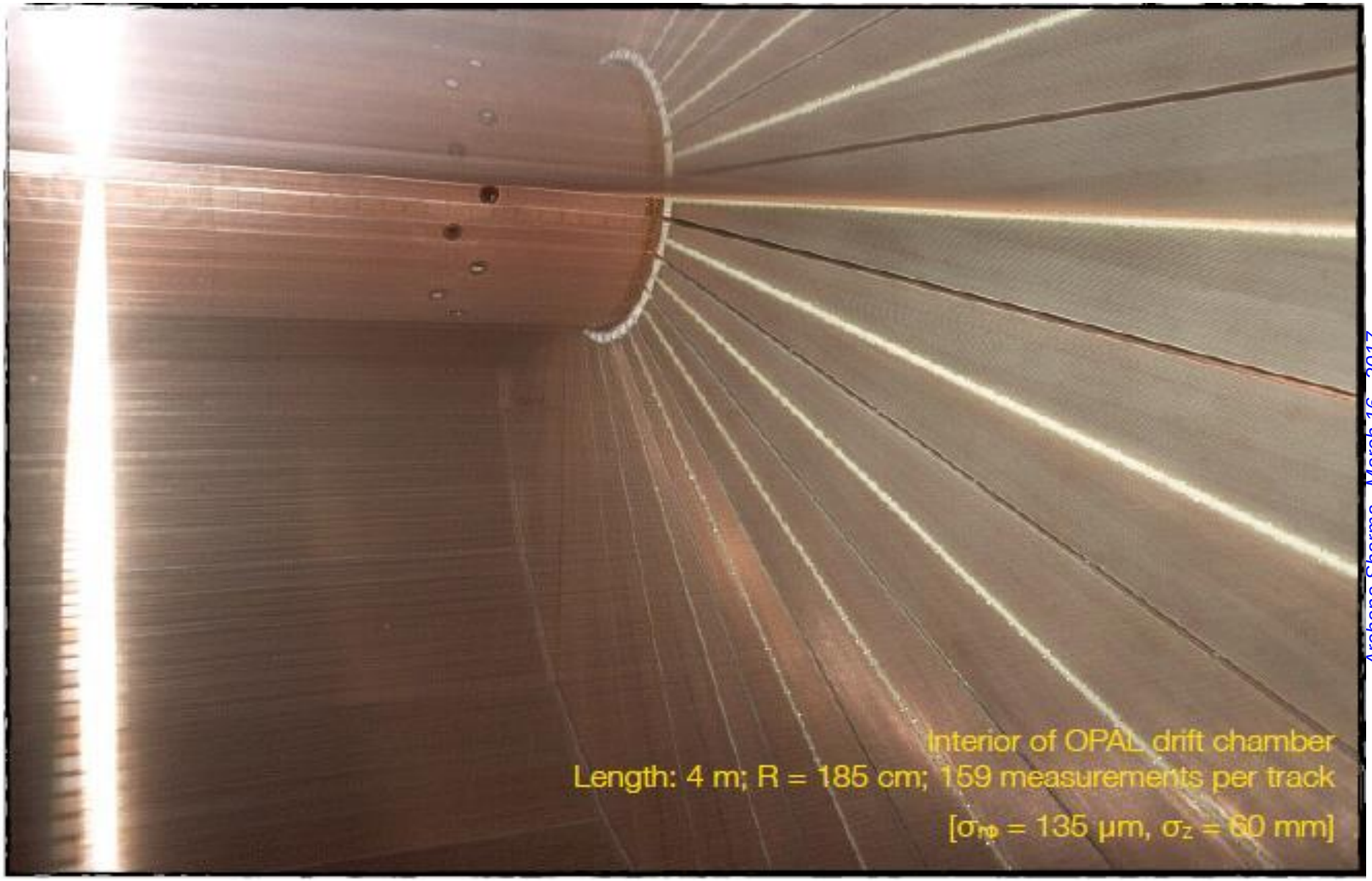
Pros:

- ✓ *Can measure energy of radiation and provide spectrographic information*
- ✓ *Can discriminate between alpha and beta particles*
- ✓ *Large area detectors can be constructed*

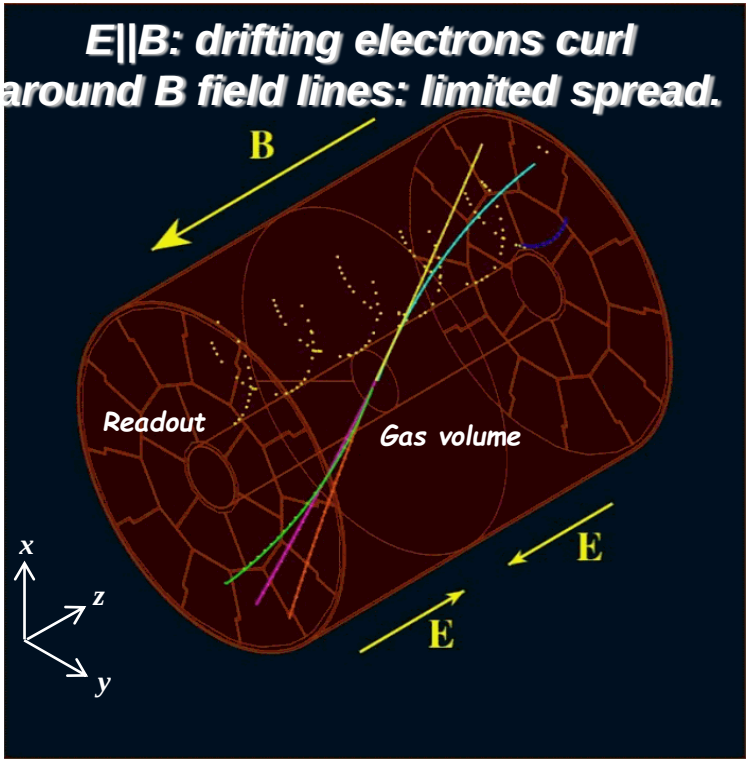
Cons:

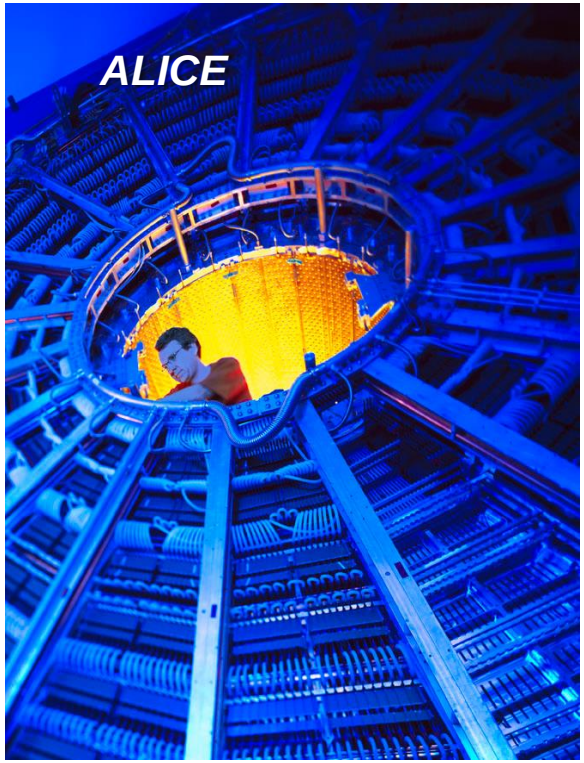
- ➢ *Anode wires delicate*
- ➢ *Time resolution limited by distance between the wires*

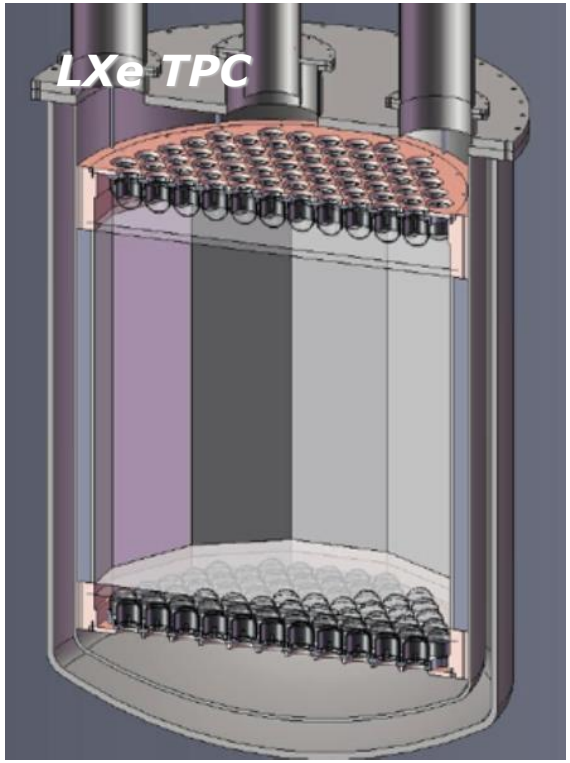
Enormous Wire Chambers



Time Projection Chambers







Separate two regions:

- Long drift along z ~ 1-3 m;
- Amplification at the end plate

Challenges:

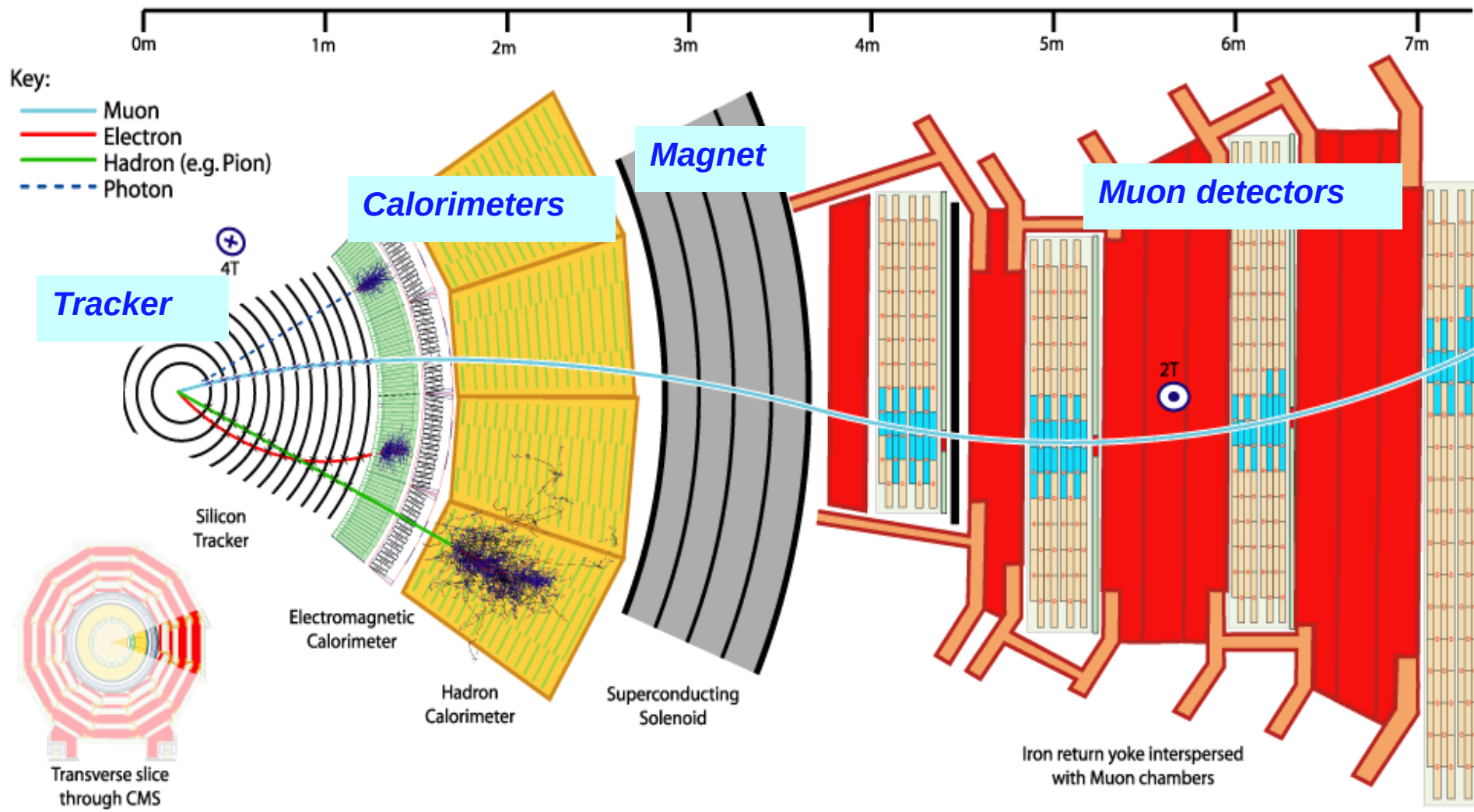
Long drift time; limited rate capability

Powerful tool for:

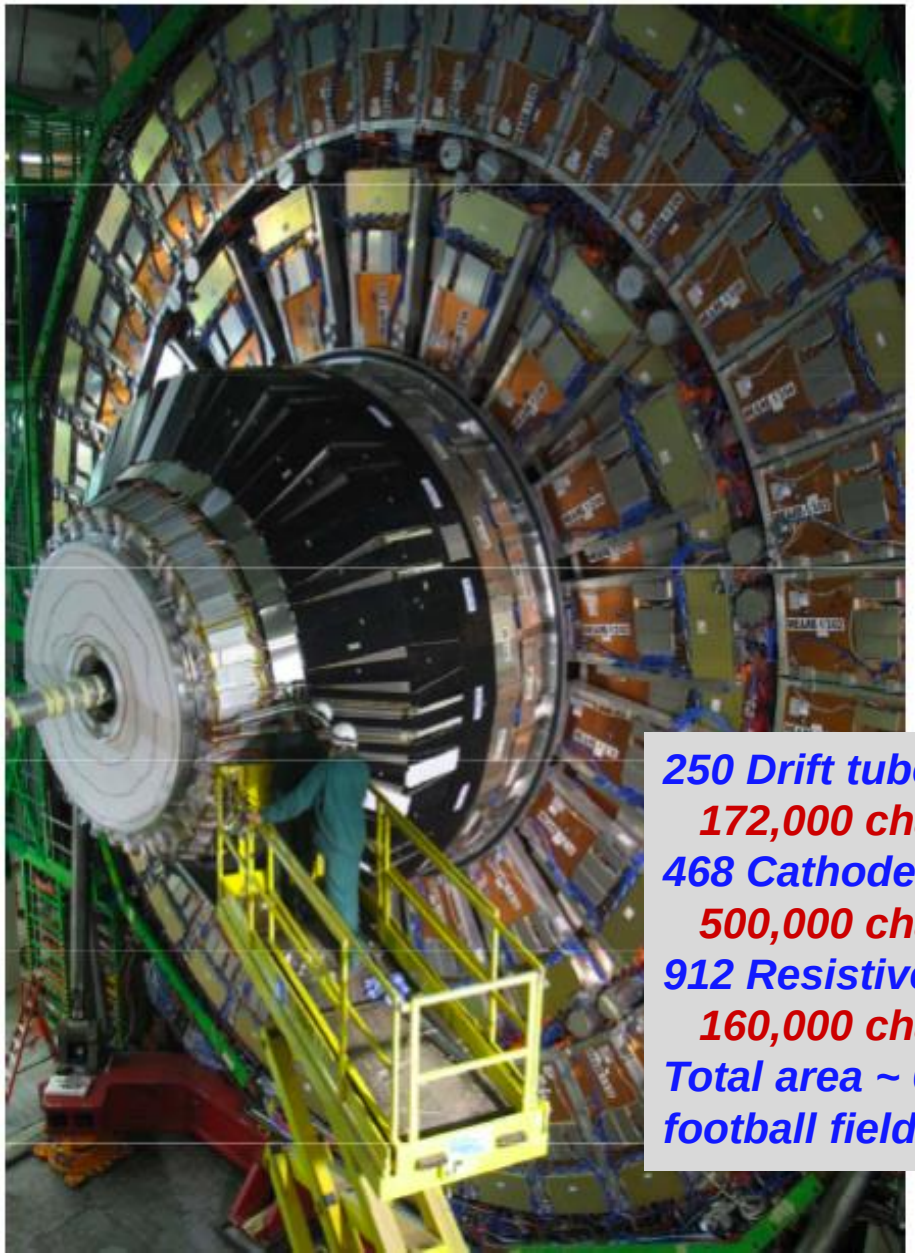
- Lepton Colliders
- Modern heavy ion collisions
- Liquid and high pressure noble gases for neutrino and dark matter physics program

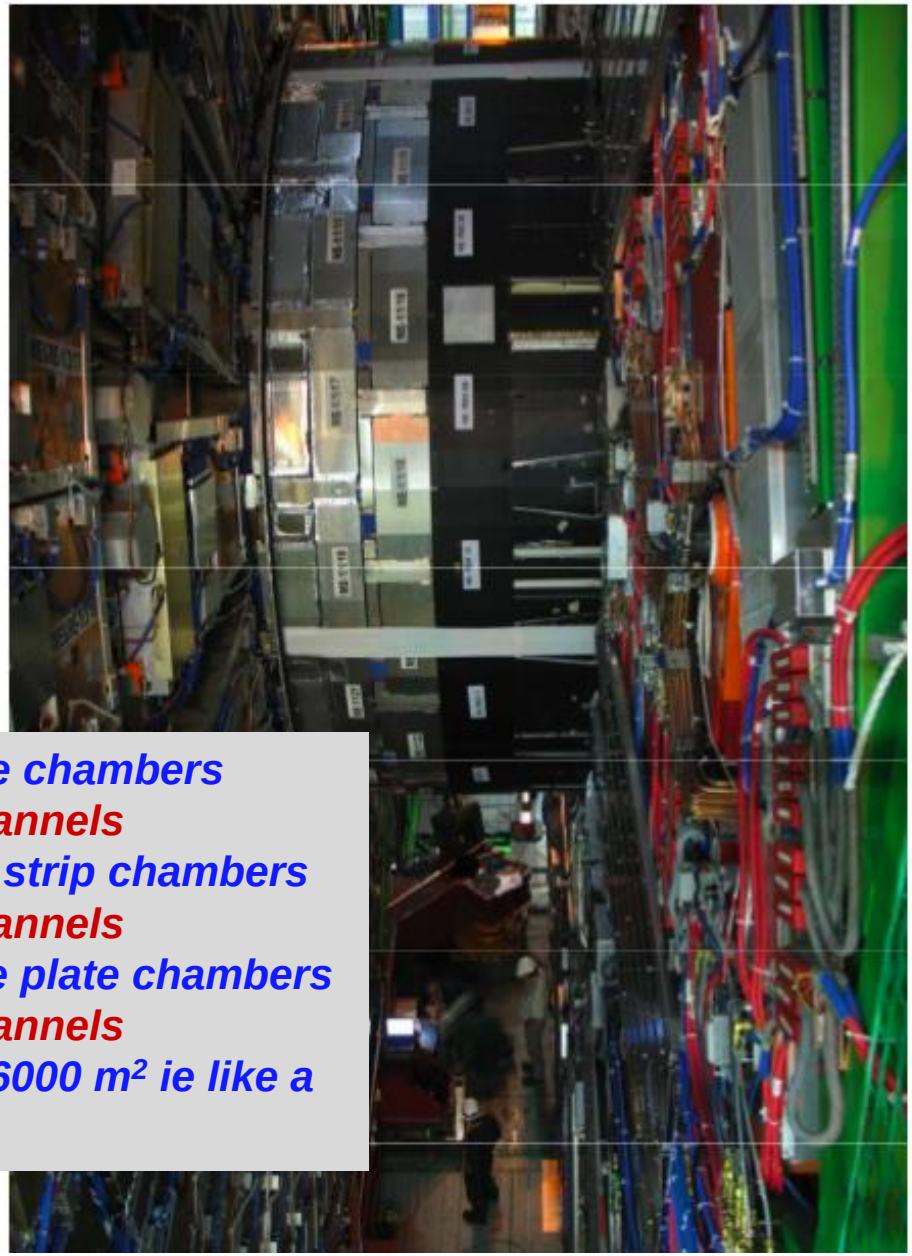
Archana

Particles in the detector



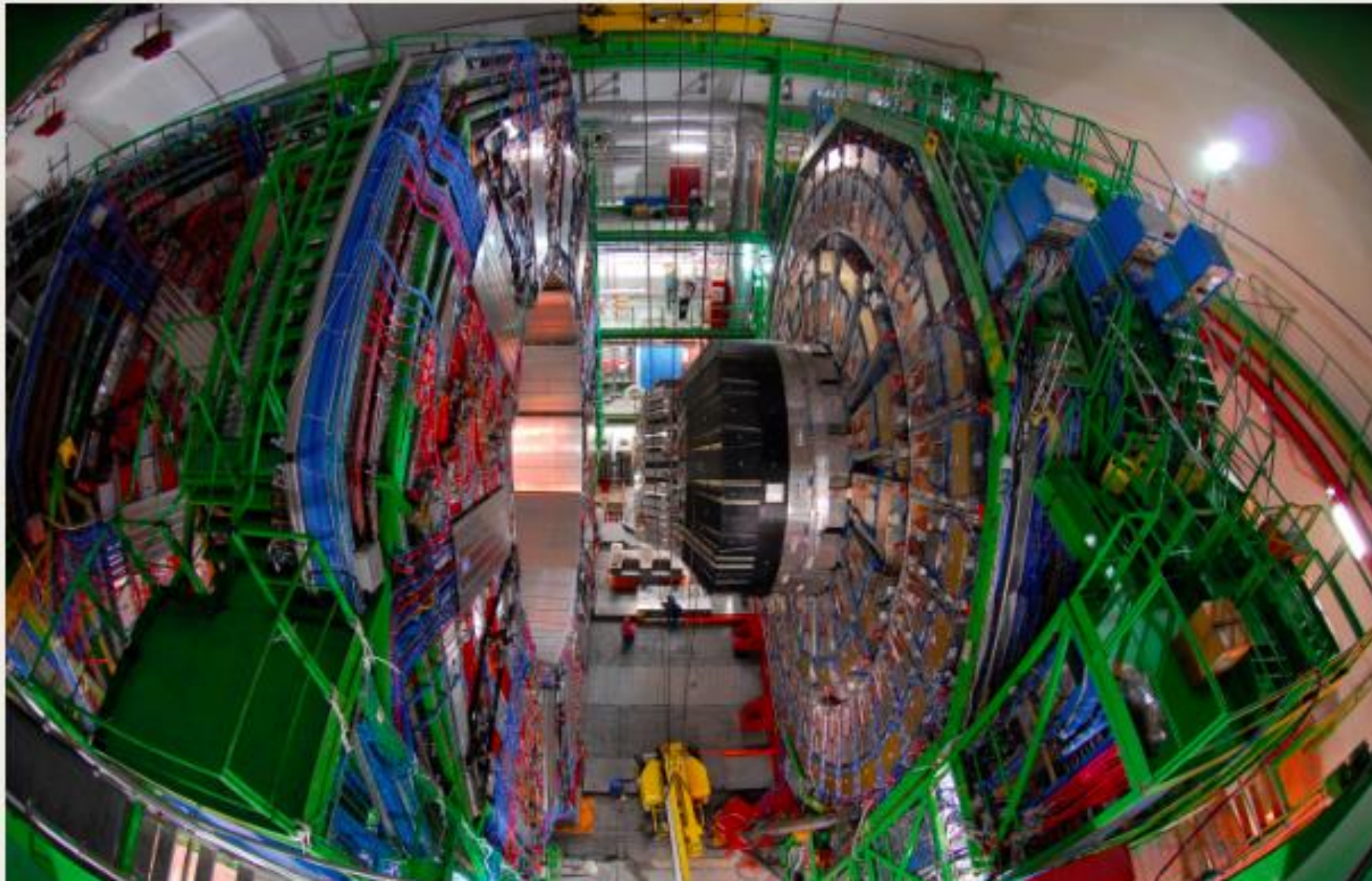
CMS Muon Detectors





250 Drift tube chambers
172,000 channels
468 Cathode strip chambers
500,000 channels
912 Resistive plate chambers
160,000 channels
Total area ~ 6000 m² ie like a football field

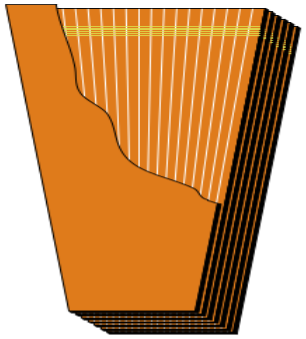
CMS Muon Endcap



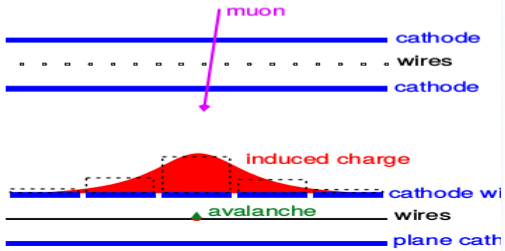
CMS Muon Detectors

Cathode Strip Chambers: CSC

- Up to 3.4 m long, 1.5 m wide
- 6 planes per chamber
- 9.5 mm gas gap (per plane)

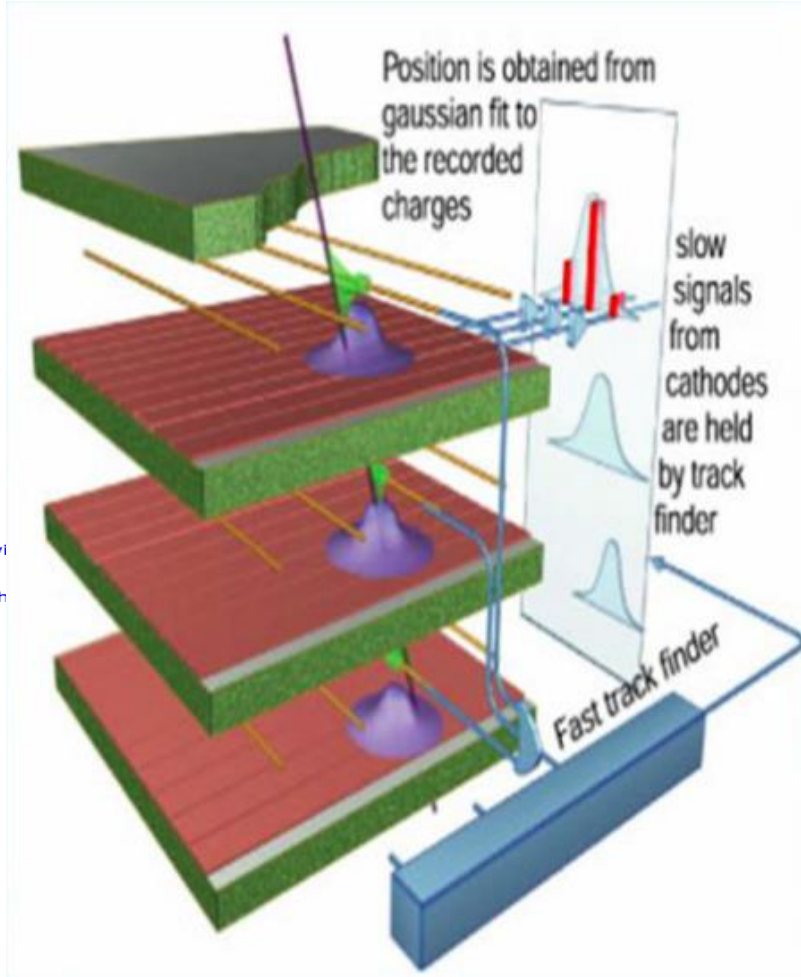


- 50 μm wires spaced by 3.2 mm
- 60 ns maximum drift-time per plane
- 5 to 16 wires ganged in groups
- Wires measure r



- 6.7 to 16.0 mm strip width
- Strips run radially to measure φ
- 150 μm resolution for chambers (75 μ m in station 1)

- Gas: Ar(40%)+CO2 (50%)+CF4 (10%)
- HV ~3.6 kV
- B-field up to 3 T in station 1



CMS Muon Detectors

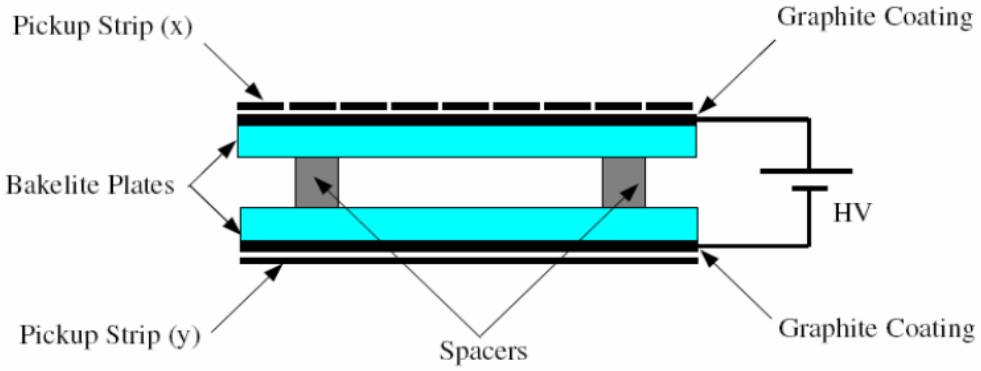
Resistive Plate Chambers RPC

Endcap RPCs contain trapezoidal shaped HPL gas gaps, that are organized in a double-layer configuration with a copper strip readout panel placed in between

Each CMS RPC endcap station consists of three concentric rings, called REx/1-3 (station x=1,2,3)

CMS RPC requirements.

Parameters	Allowable ranges
Efficiency	>95%
Time resolution	⩽ 1 ns
Average cluster size	⩽ 2 strips
Rate capability	2 kHz/cm^2
Mean avalanche charge	2.5–5 pC



Limitations

RPC rate capability which is limited by space charge

Problem of Aging

CMS Muon Detectors

RPC

612 total chambers
Six barrel stations in radius

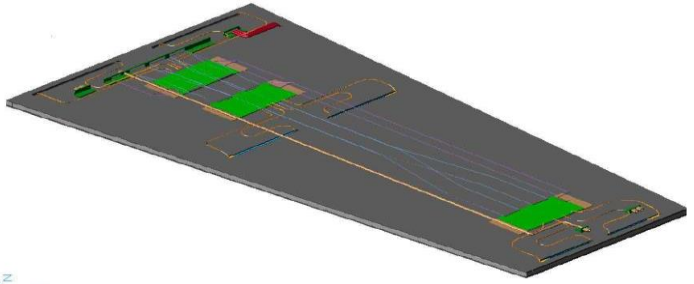
Long strips in barrel ⇒ high intrinsic noise rate (~50 Hz/cm^2)

Linseed oil applied to surfaces to reduce noise

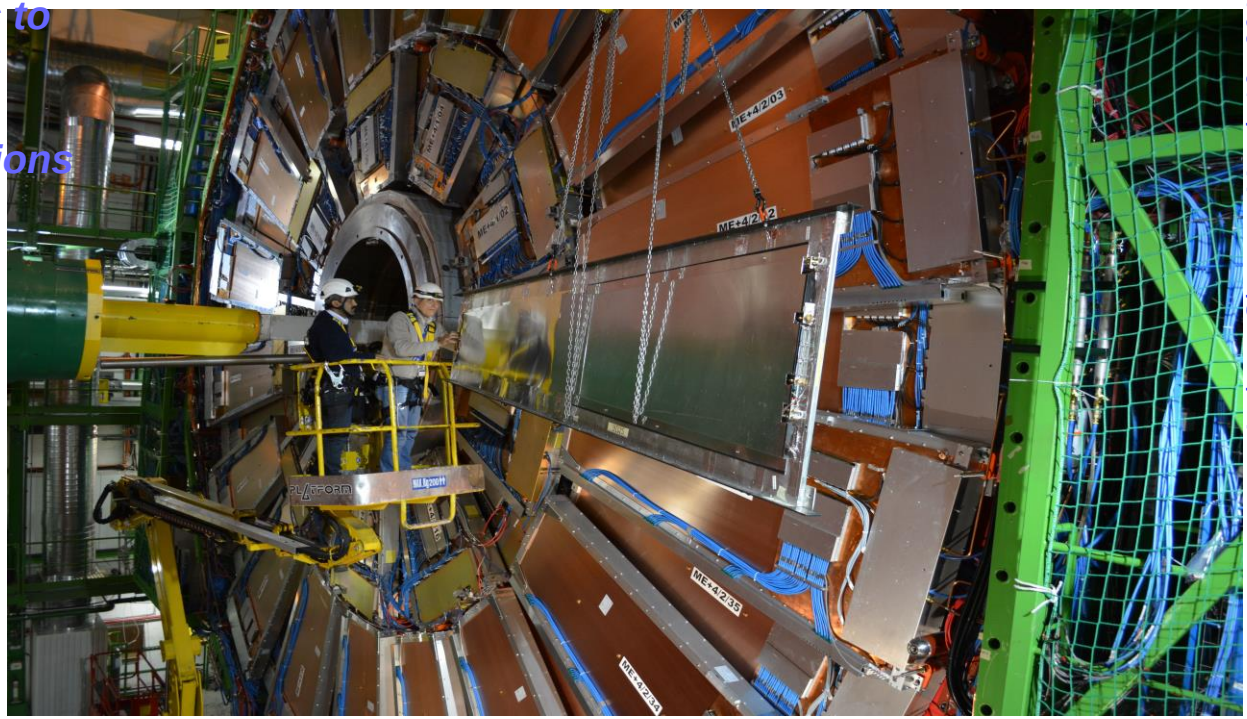
Trigger makes use of all 6 stations

Four endcap stations in z

Rate capability to 1 kHz/cm^2 using avalanche mode



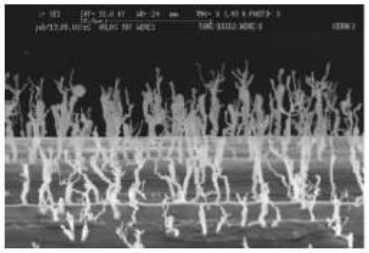
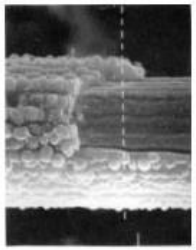
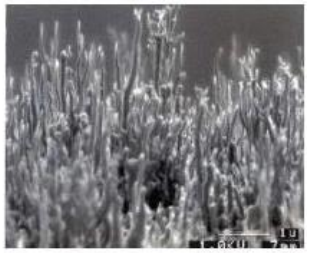
Schematic layout of an endcap chamber



"Classic" Gaseous detectors

Pros

- Large area at low price
- Flexible geometries
- Good spatial, energy resolution

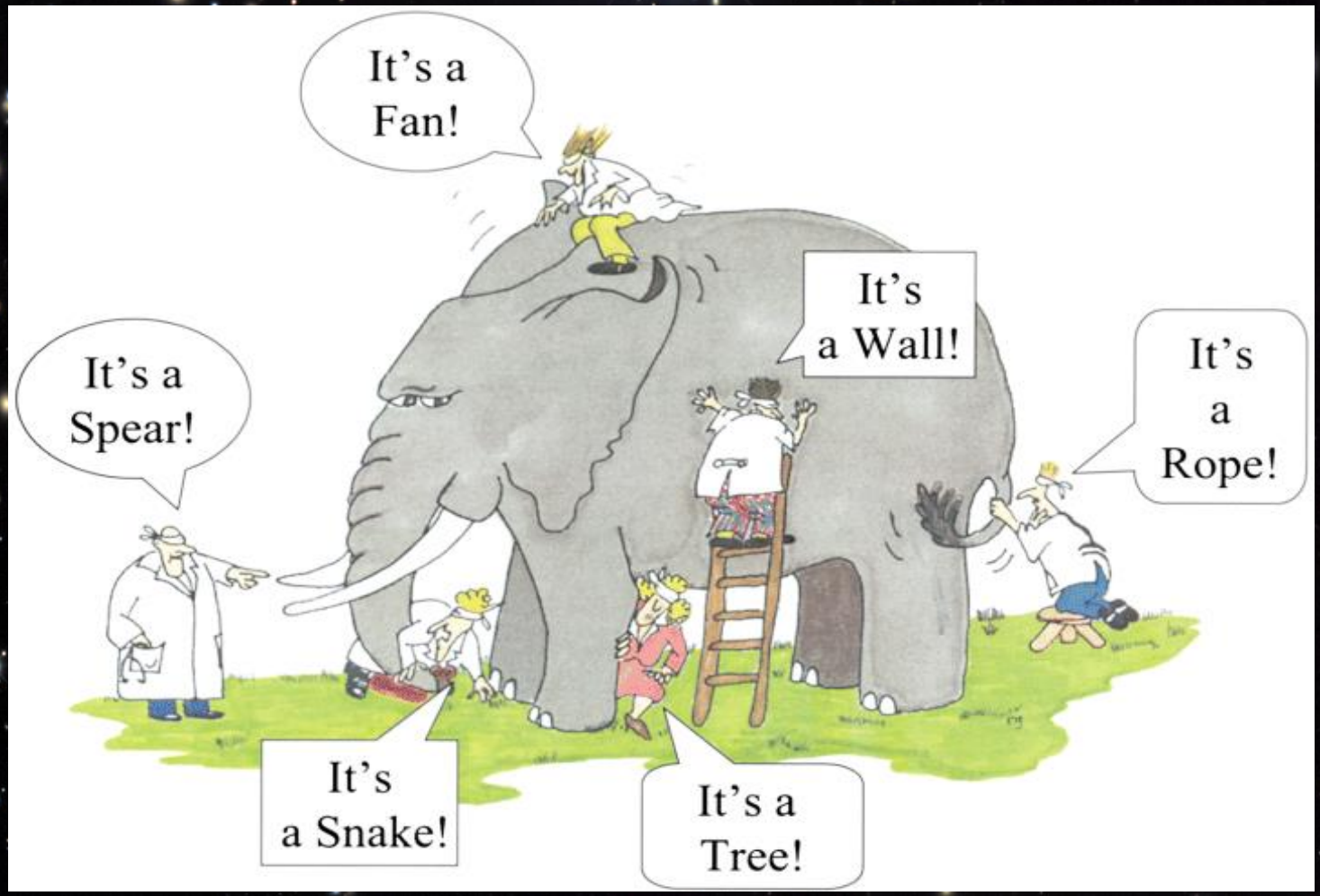
Cons

- Slow ion motion → fast gain drop at high fluxes:
  - Space charge accumulation, distortion of electric field…
- Limited multi-track separation: minimum wire distance ~1mm
- Aging

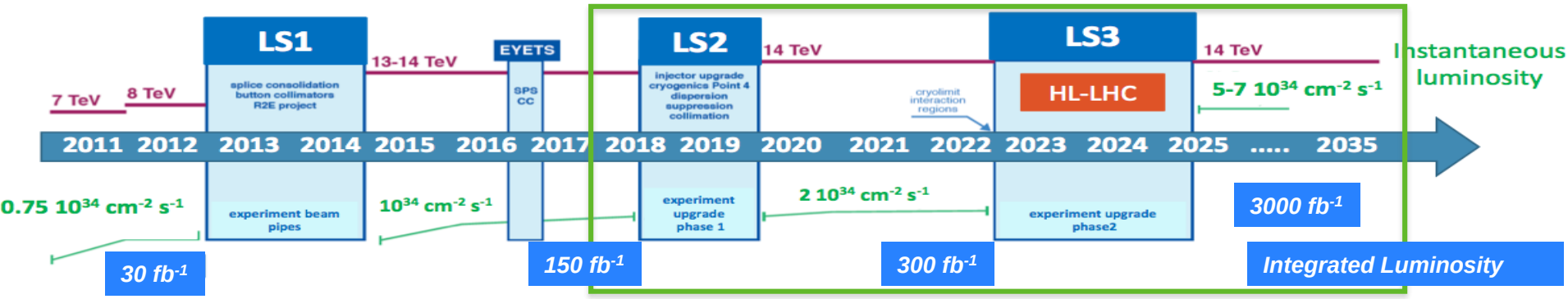
But…

WE CANNOT FAIL AT HIGH LUMINOSITY !!

We have only just started to understand the Higgs boson… and we need to look from every angle



UPGRADES for future



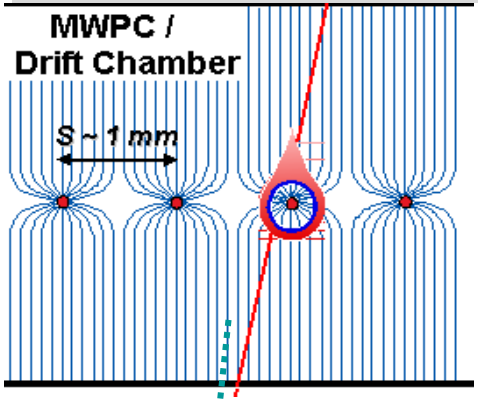
A new machine, for high luminosity, to measure the H couplings, H rare decays, HH, Vector boson scattering, other searches and difficult SUSY benchmarks, measure properties of other particles eventually discovered in Phase1.

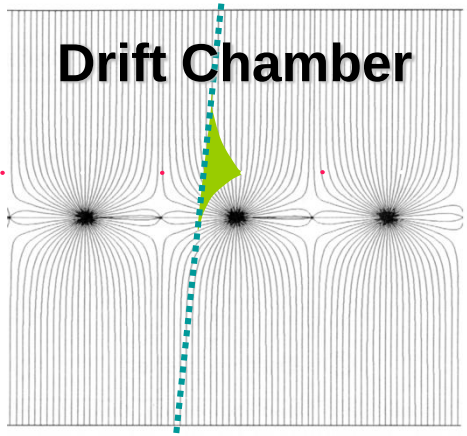
Goal: keep at least the same performance as in Run 1

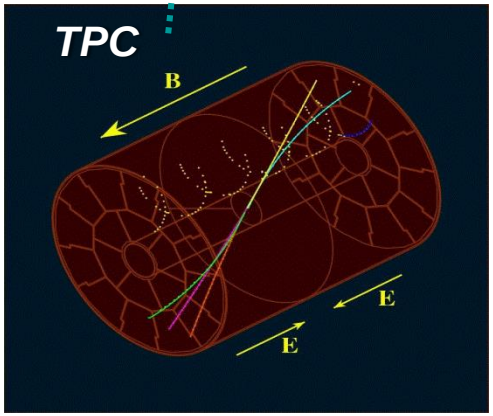
CMS Upgrades

- ***New tracker (4 pixel layer +3 disks), Track information at L1***
- ***Calorimeters with higher granularity***
- ***Muon endcap***

Gas Detectors : Advanced Concepts



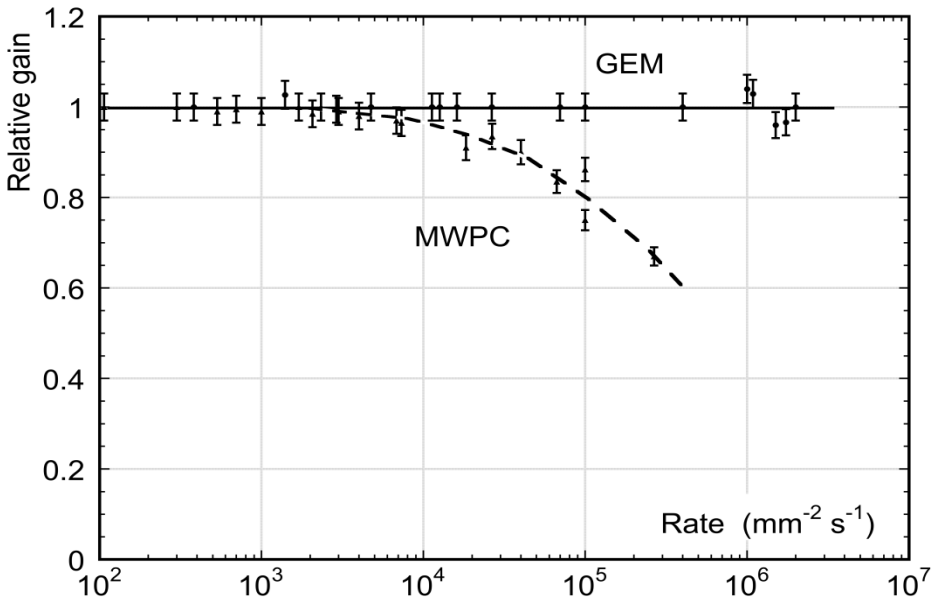




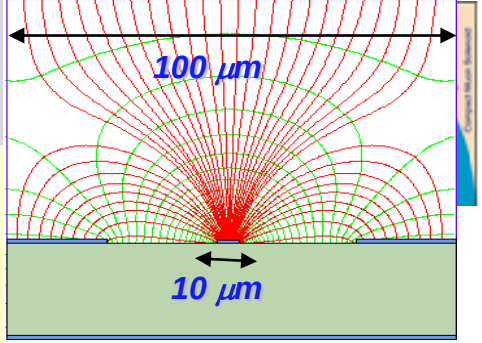
Higher Rate, enormous occupancy:
1D easily saturated → 2D → 3D

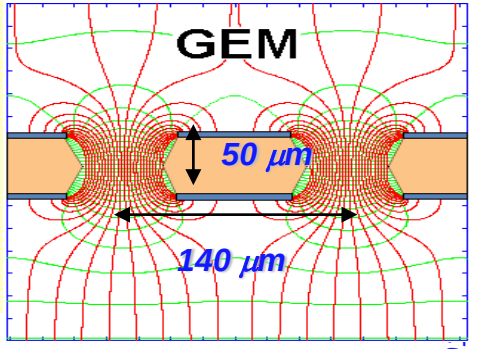
➢ ***Silicon detectors:***
Strips →Pixels (2D)→ 3D-Si det.
& 3D electronics integration

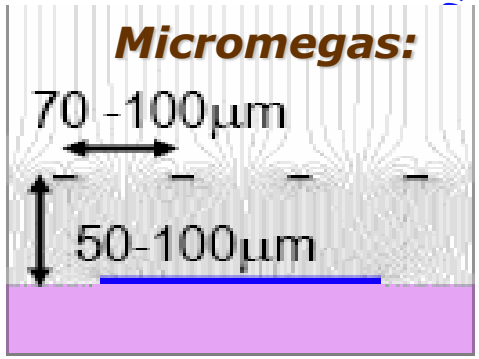
➢ ***Gaseous detectors***
Wire Chamber → Wireless MPGD (2D)
→ InGrid/Timepix (3D)

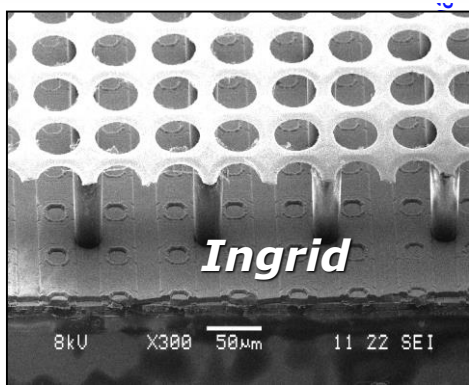


Advances in Micro-electronics & Etching Technology → Micro pattern Gaseous Detectors



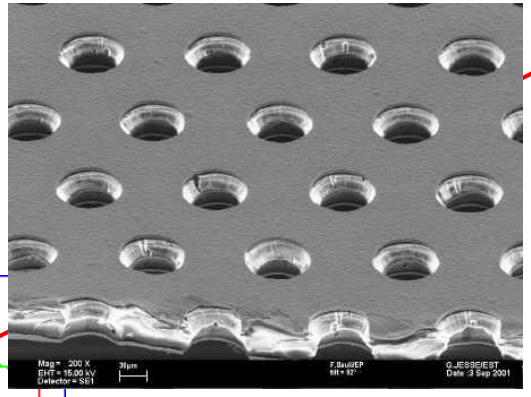


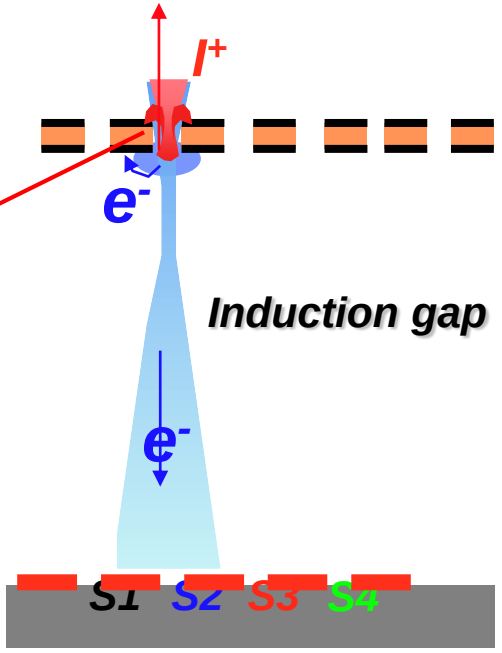


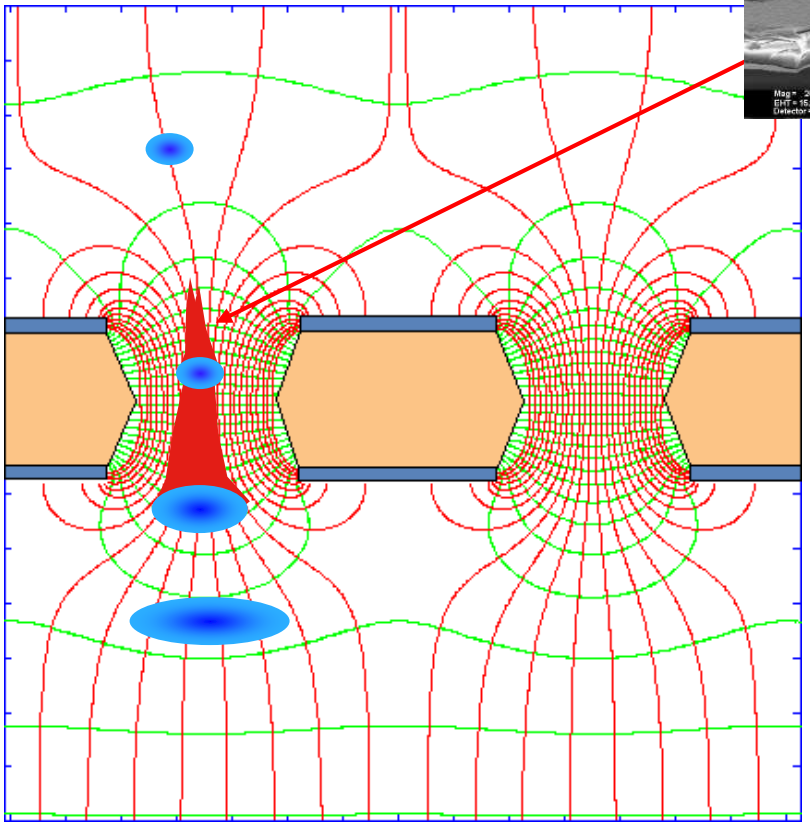


GEM : Gas Electron Multiplier

Thin metal-coated polymer foil chemically pierced by a high density of holes







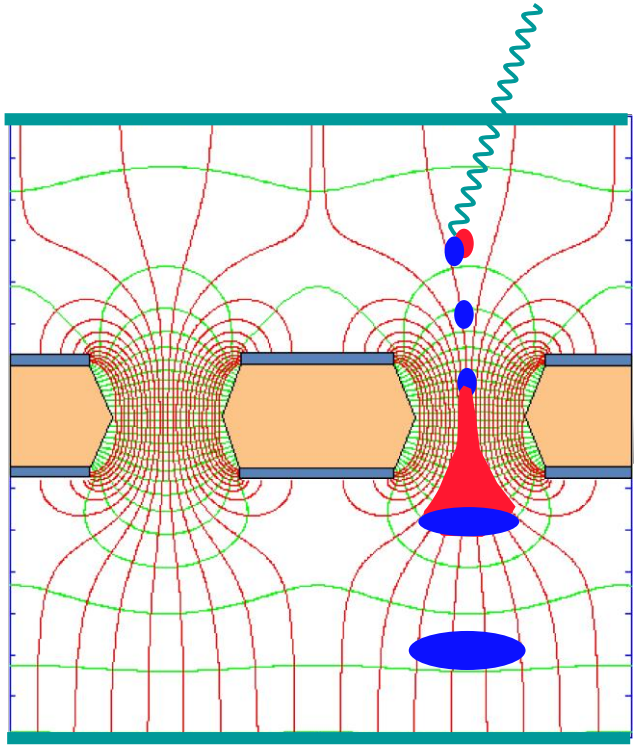
Electrons are collected on patterned readout board.

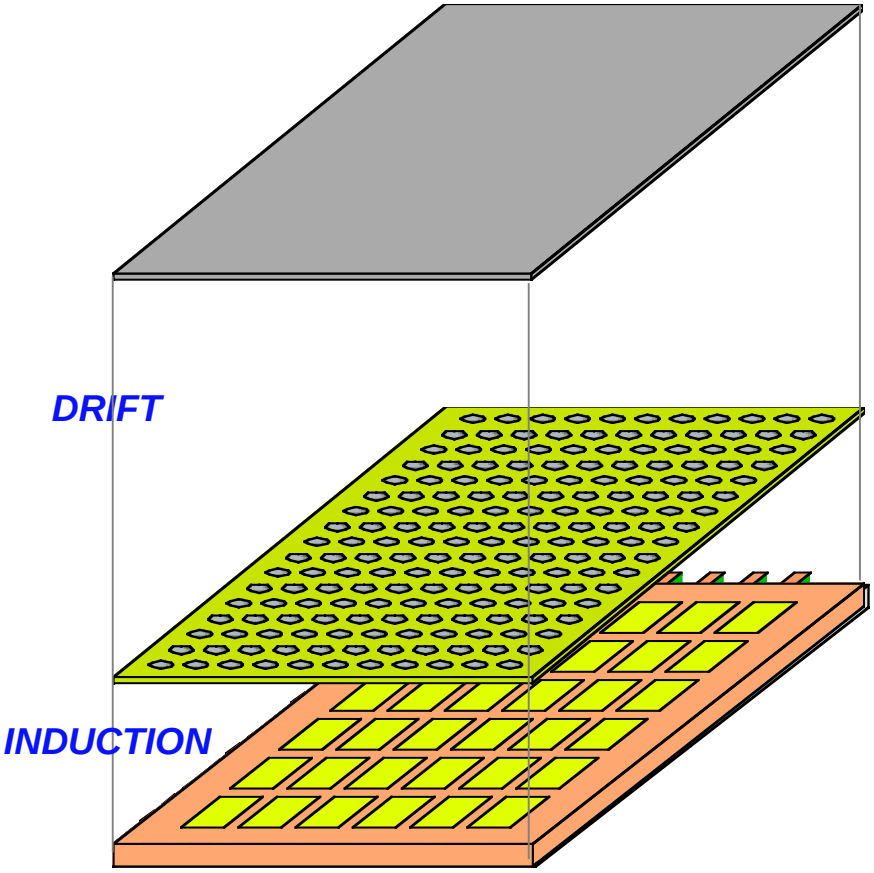
A fast signal can be detected on the lower GEM electrode for triggering or energy discrimination.

All readout electrodes are at ground potential.

Gas Detectors : Advanced Concepts : GEM

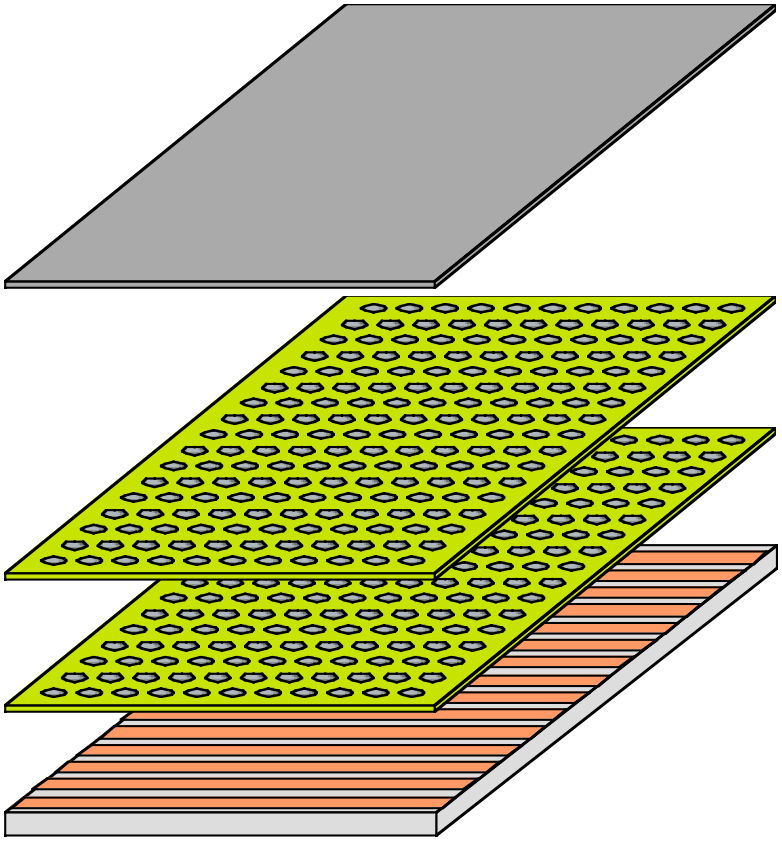
AMPLIFICATION AND TRANSFER
SINGLE GEM DETECTOR:



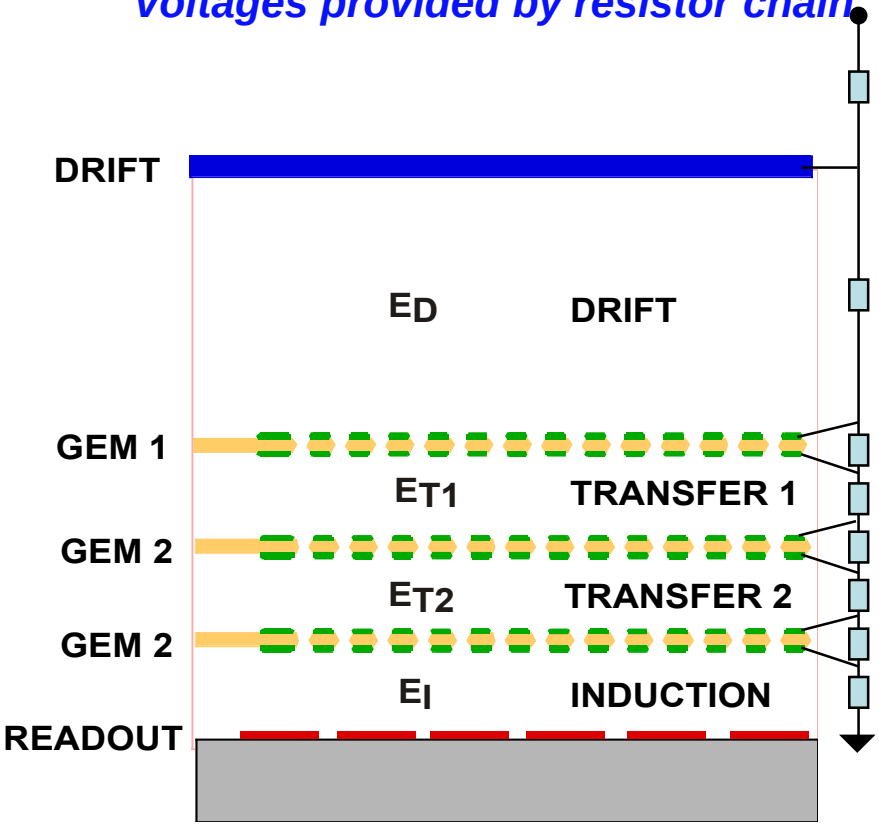


MULTIPLE GEM DETECTORS: : Advanced Concepts

HIGHER GAIN
LOWER OPERATING VOLTAGE AND/OR SAFER OPERATION

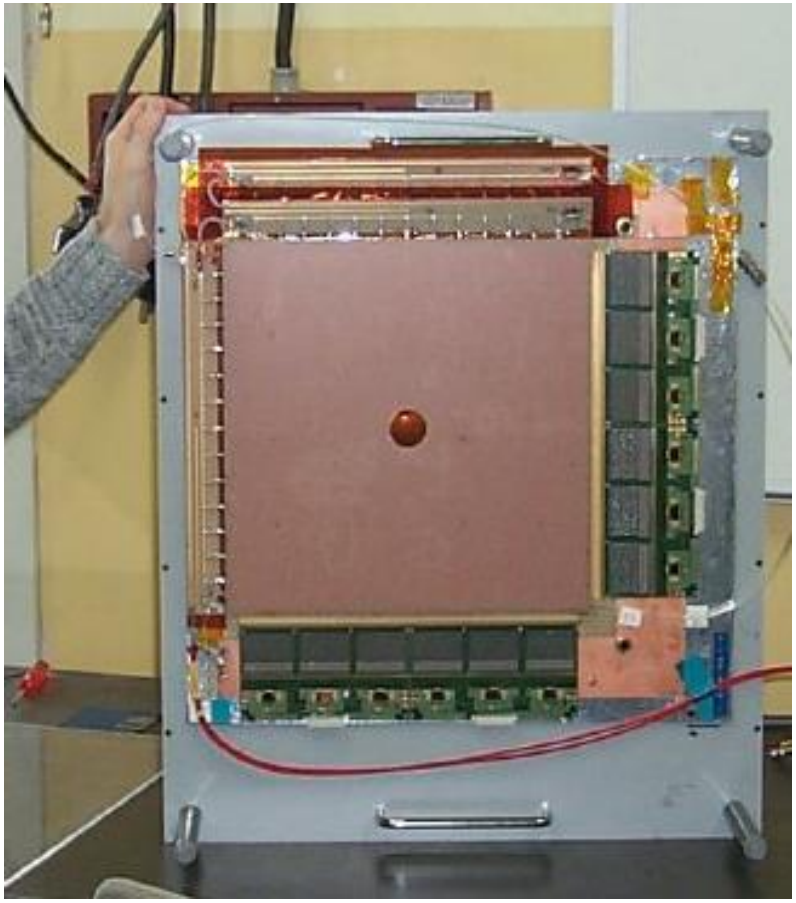


UP TO 5 CASCADED GEMS TESTED
(for single photoelectron detection)
Voltages provided by resistor chain



GEM DETECTORS: SIMPLE, LIGHT CONSTRUCTION

COMPASS Triple-GEM detector
31x31 cm^2 active, 2-D readout:

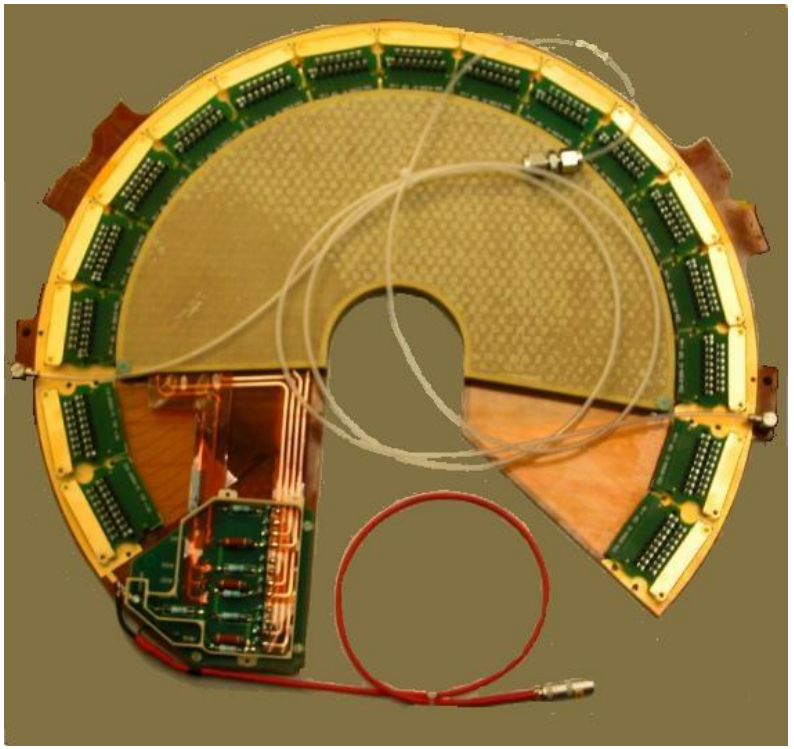


22 detectors operational

Thickness ~ 0.7% X_0 in active area
Can be reduced to ~ 0.15% X_0

A. Bondar et al,
Nucl. Instr. and Meth. 556(2006)495

TOTEM Triple-GEM (Forward CMS)
30 cm Ø, strips&pads readout

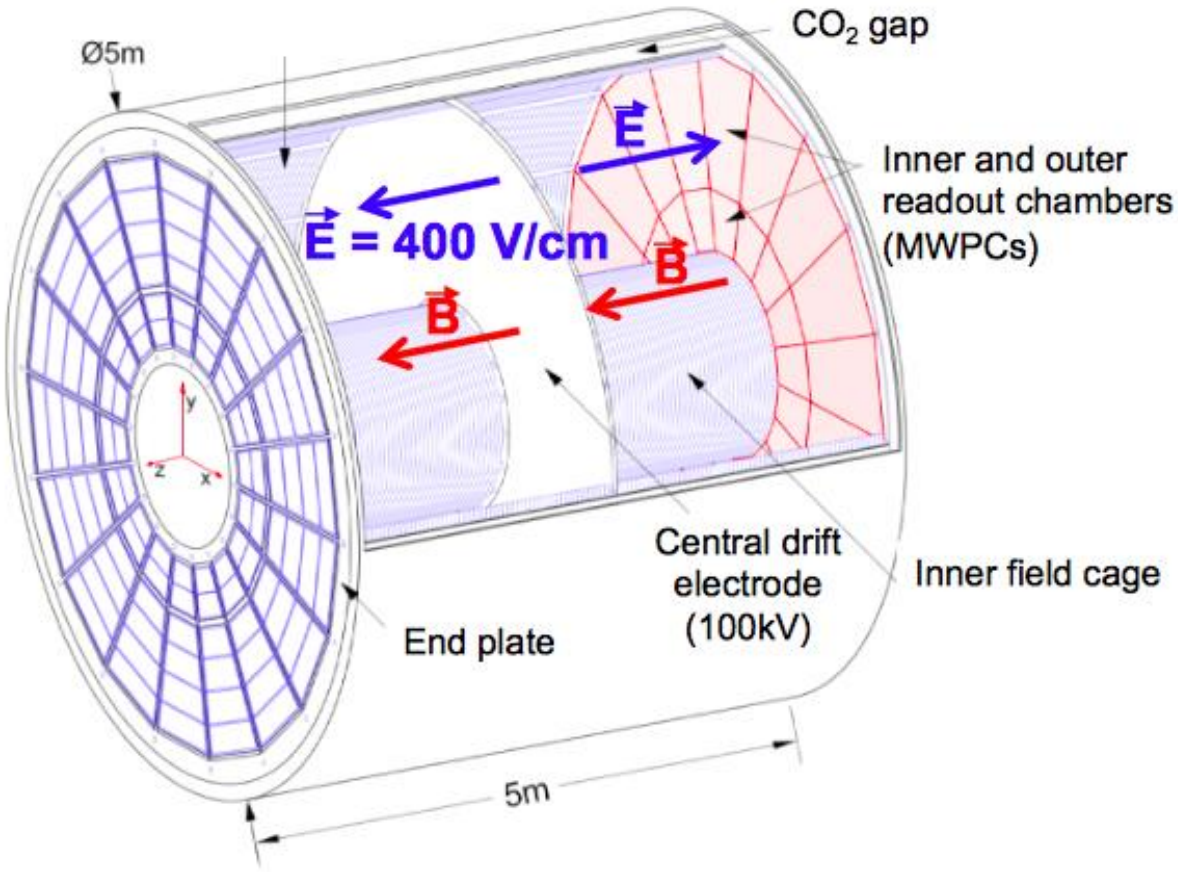


50 detectors in construction

A Large Ion Collider Experiment

ALICE

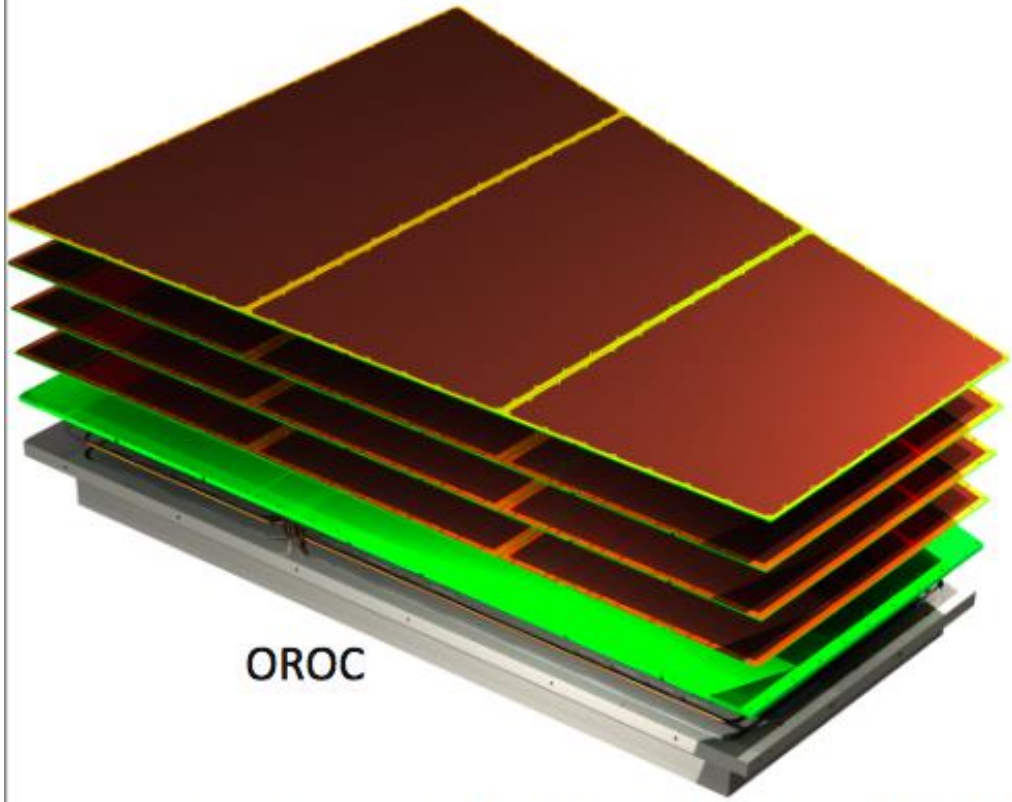
ALICE TPC IN NUMBERS

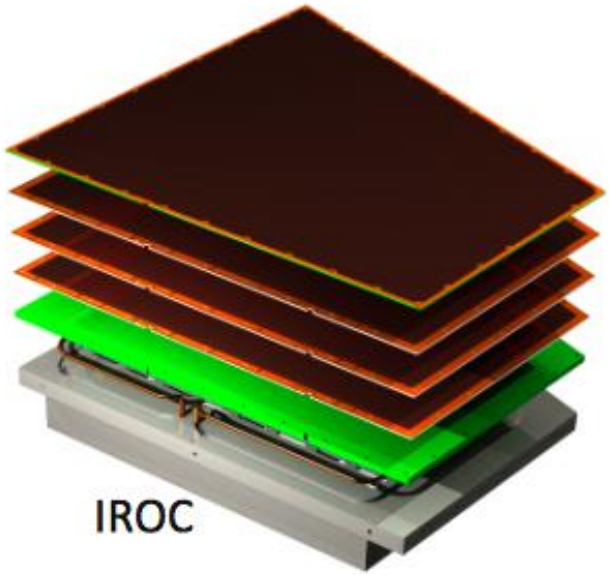


- Length 5 m
- Diameter 5 m
- Active volume 88 m^3
- B = 0.5 T
- Readout area 32 m^2
- Channels ~570 000

ALICE TPC : GEM UPGRADE

TECHNICAL SOLUTION: 4-GEM STACK



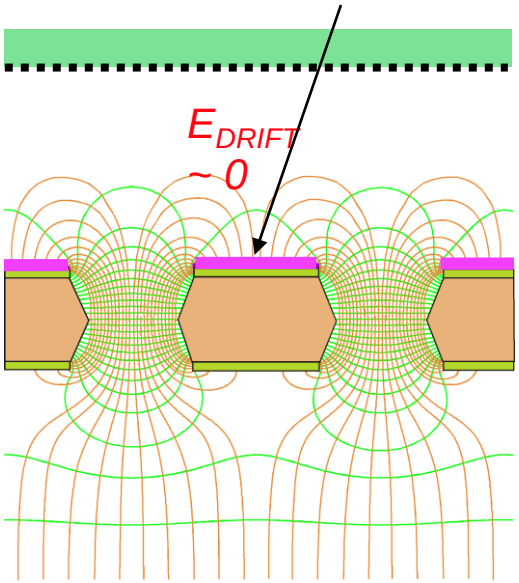


- large-size single-mask foils from CERN PCB workshop
- 1/layer in IROC, 3/layer in OROC

→ Technical solution approved by LHCC

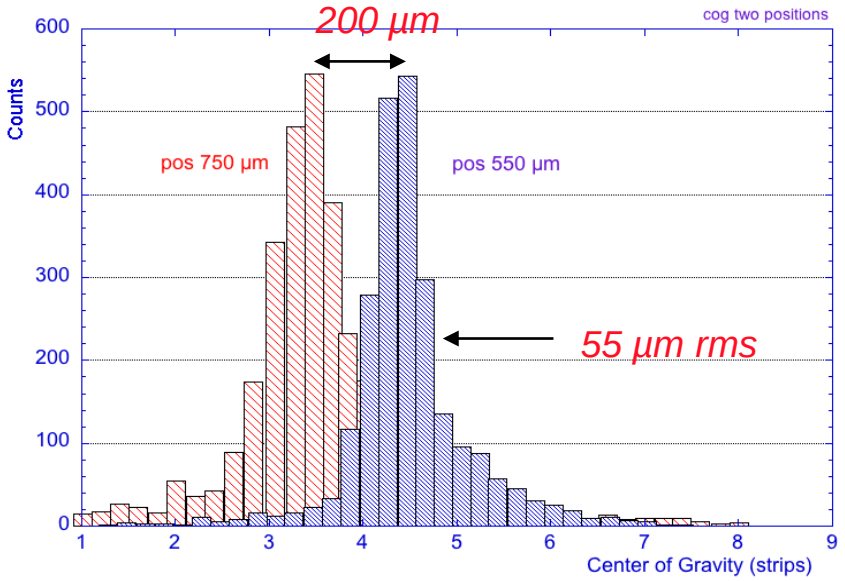
PHOTON DETECTION WITH GEM

Reflective CsI Photocathode deposited on upper GEM face



R. Bouclier et al, IEEE Trans. Nucl. Science NS-44(1997)646

SINGLE PHOTOELECTRON SPACE ACCURACY CENTER-OF-GRAVITY MEASUREMENT FOR TWO COLLIMATED UV PHOTON BEAMS 200 µm APART:

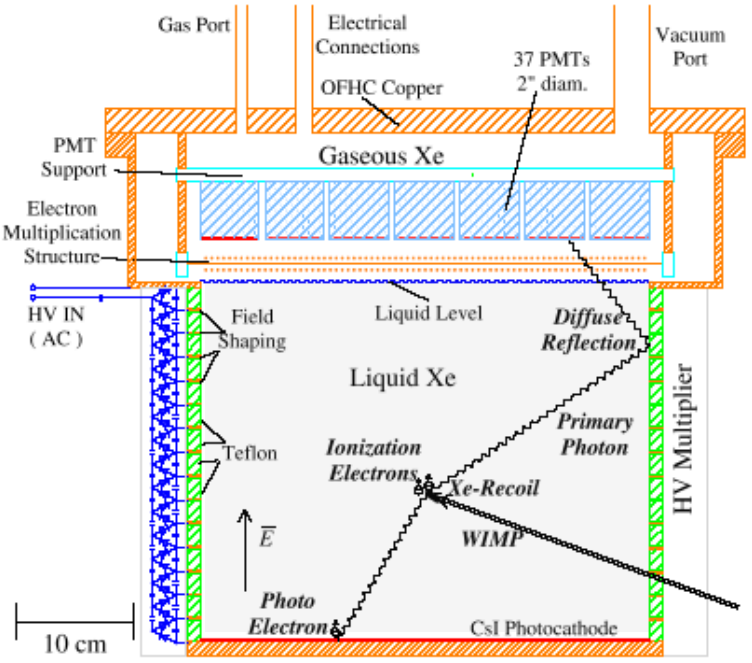


T. Meinschad et al
Nucl. Instr. and Meth A535(2004)324

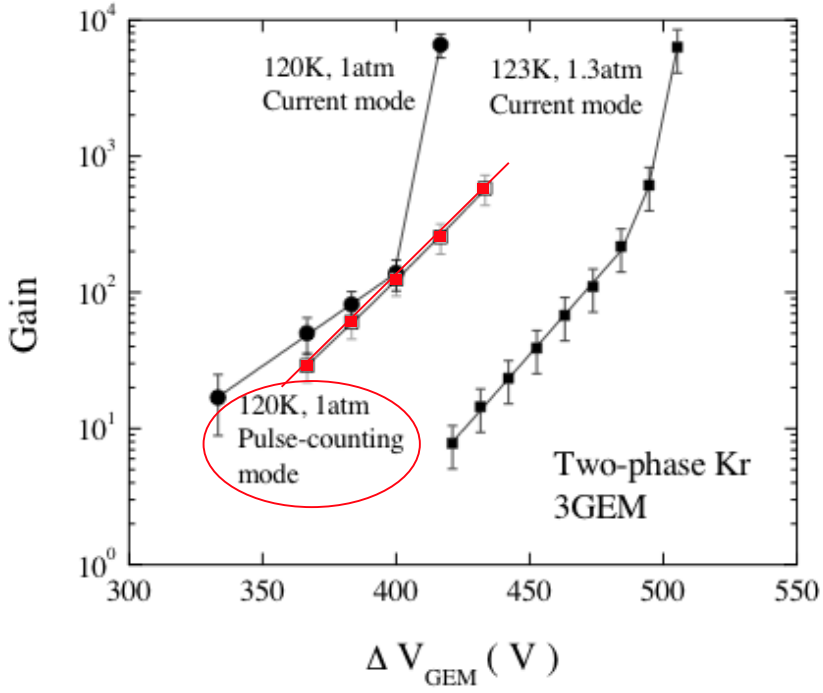
TWO-PHASE CRYOGENIC DETECTORS

EXTRACTION FROM LIQUID AND MULTIPLICATION IN GAS PHASE

XENON: Dark Matter and WIMPs search

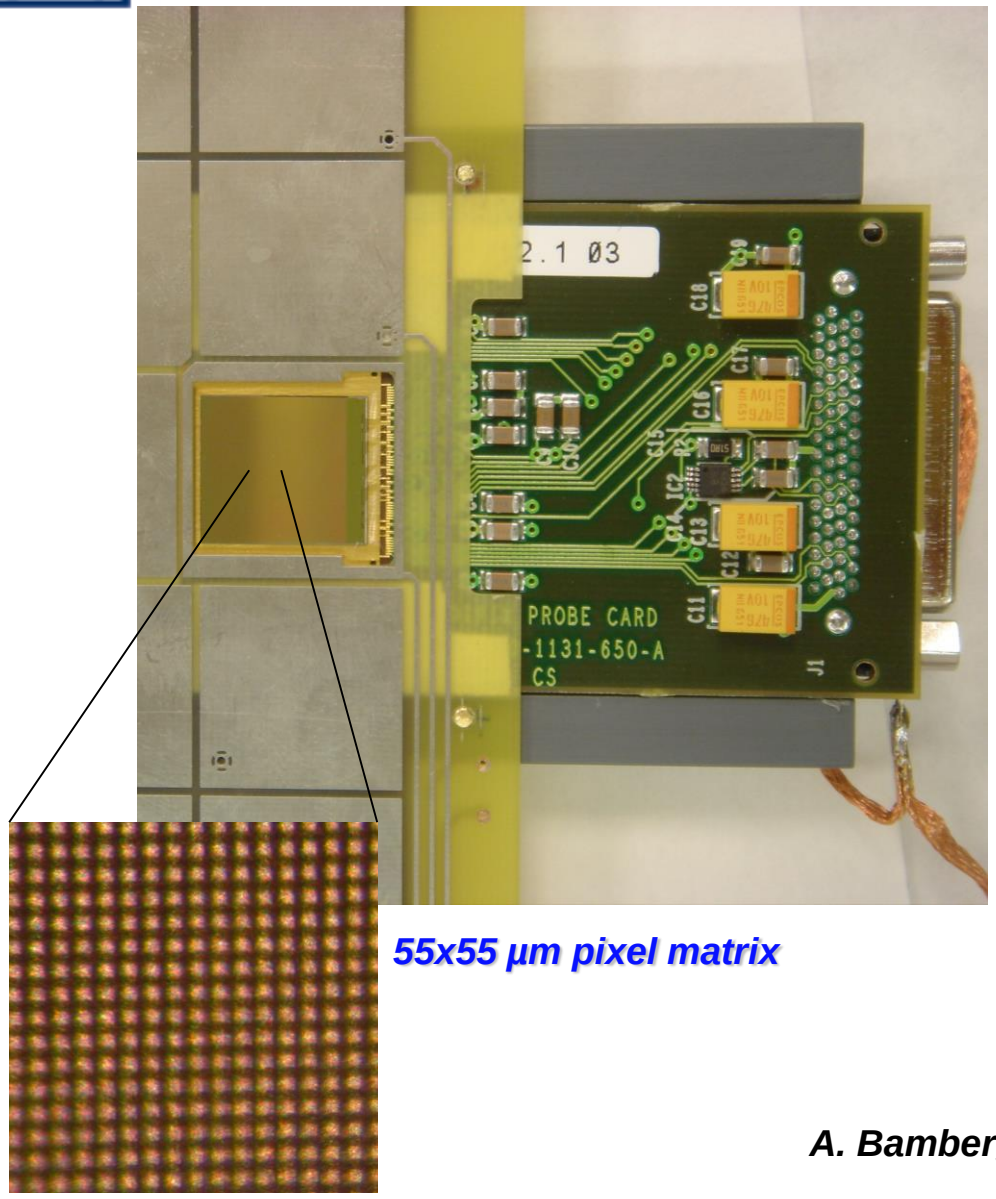


EXTRACTION AND MULTIPLICATION IN KRYPTON:



A. Bondar et al, Nucl. Instr. and Meth. A548(2005)439

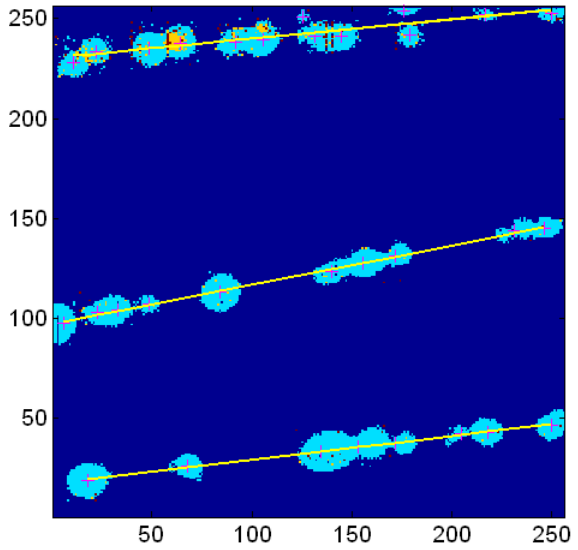
PIXEL READOUT OF GEM DETECTORS: MEDIPIX



55x55 μm pixel matrix

- Digital readout: preamp / discriminator
- Two DAC thresholds (low, high)
- Noise RMS ~ 150 e^-/channel

Triple GEM+MEDIPIX2
A-CO_2 70-30



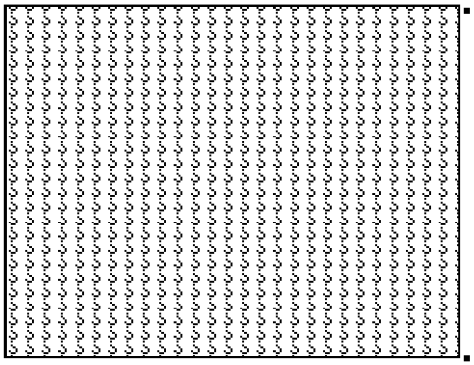
ROBUST:
No damages to MEDIPIX in 10 months of running

A. Bamberger et al, IEEE NSS (Puerto Rico 2005)

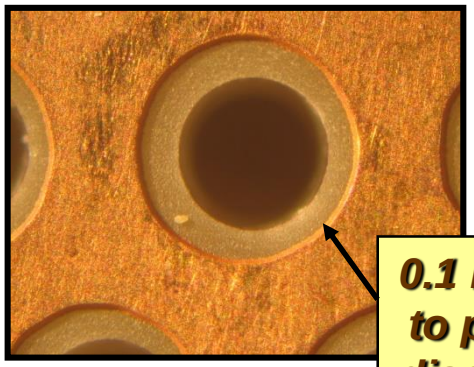
THICK GEM MULTIPLIERS (THGEM)

Simple & Robust → Manufactured by standard PCB techniques of precise drilling in G-10 (and other materials) and Cu etching

STANDARD GEM
10^3 GAIN IN SINGLE GEM



THGEM
10^5 gain in single-THGEM



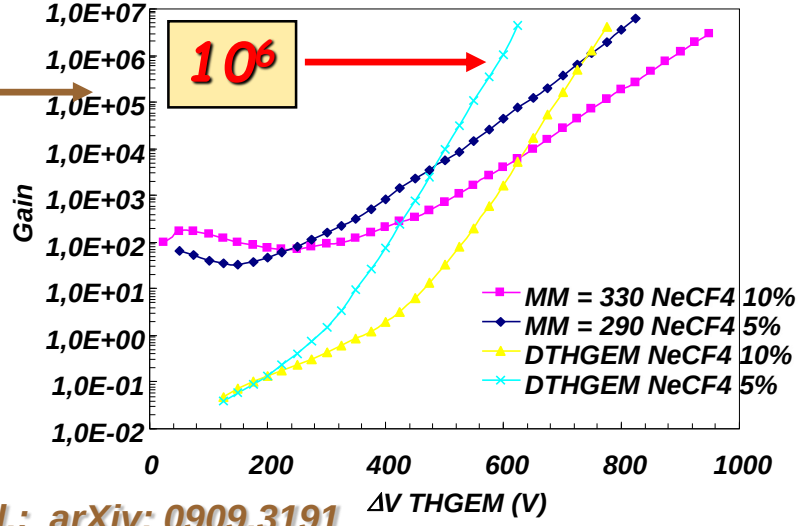
Other groups developed similar hole-multipliers:

- Optimized GEM: L. Periale et al., NIM A478 (2002) 377.
- LEM: P. Jeanneret,
- PhD thesis, 2001.

C. Shalem et al, NIMA558 (2006) 475;

- Effective single-electron detection (high gas gain ~10^5 (>10^6) @ single (double) THGEM)
- Few-ns RMS time resolution
- Sub-mm position resolution
- MHz/mm² rate capability
- Cryogenic operation: OK
- Gas: molecular and noble gases
- Pressure: 1mbar - few bar

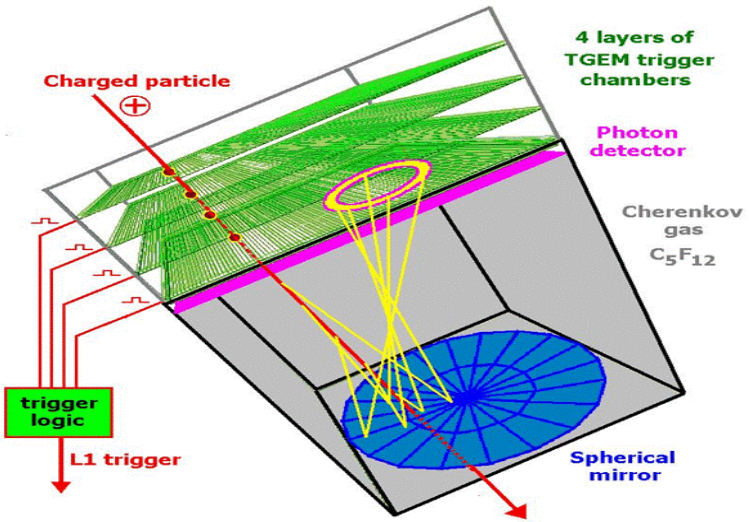
Double THGEM or THGEM/Micromegas



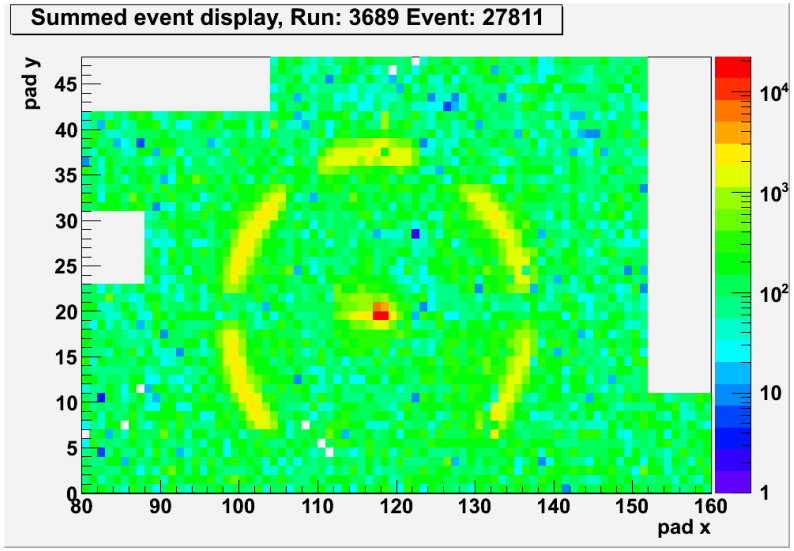
C. Azevedo et al.; arXiv: 0909.3191

Thick GEMS for ALICE

Very High Momentum Particle Identification Detector (VHMPID) based on THGEM



***May 2011* beam test (15 mm of radiator):**



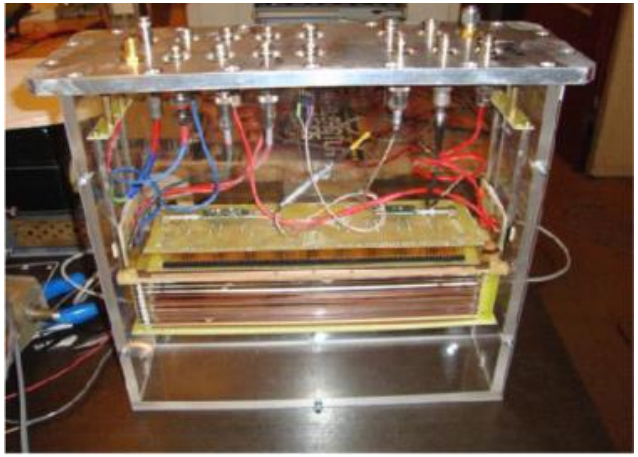
Archana Sharma March 16, 2017

https://twiki.cern.ch/twiki/pub/Sandbox/VHMPIDLoI/vhmpidLOI_v18.pdf

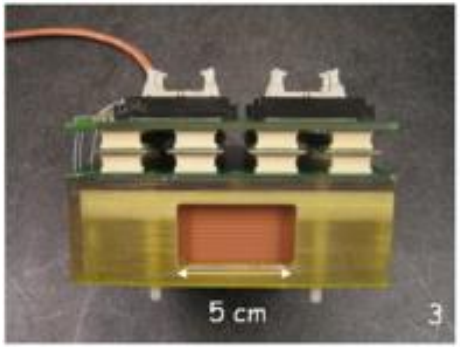
Beam Line Instrumentation

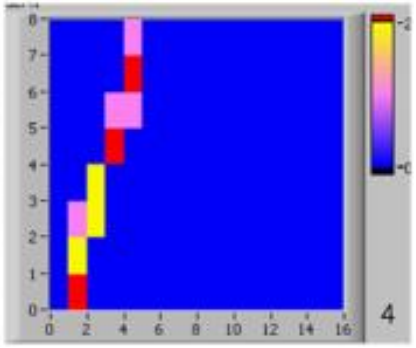
GEM-based TPC for beam monitoring:

Event-by-event particle tracking and characterization of rare ion species

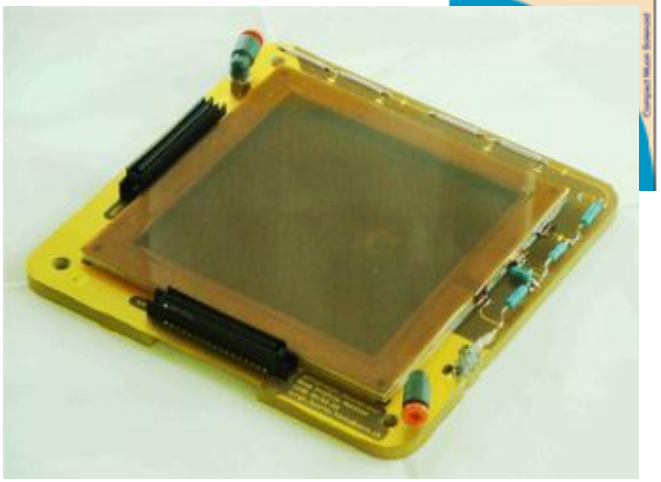


F. García et al., "Prototype development of a GEM-TPC for the Super-FRS of the FAIR facility," NSS/MIC, 2011 IEEE, pp. 1788 - 1792.



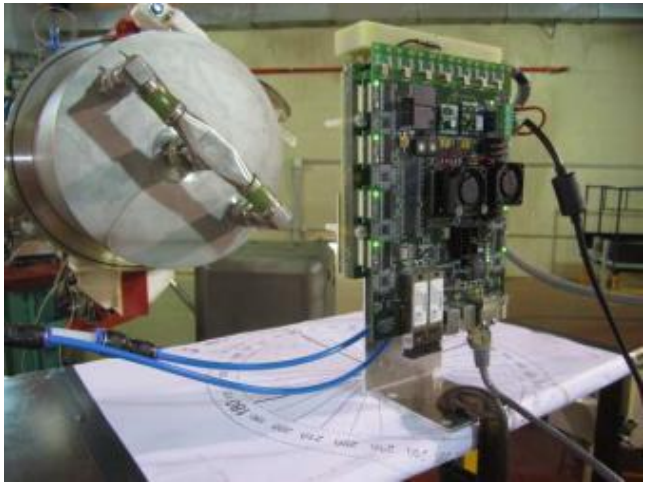


F. Murtas et al., "Applications in beam diagnostics with triple GEM detectors," Nucl. Instr. & Meth., vol. 617, no. 1–3, p. 237–241, 2010.



Ultra-light single GEM for low energy antiproton beam profiling

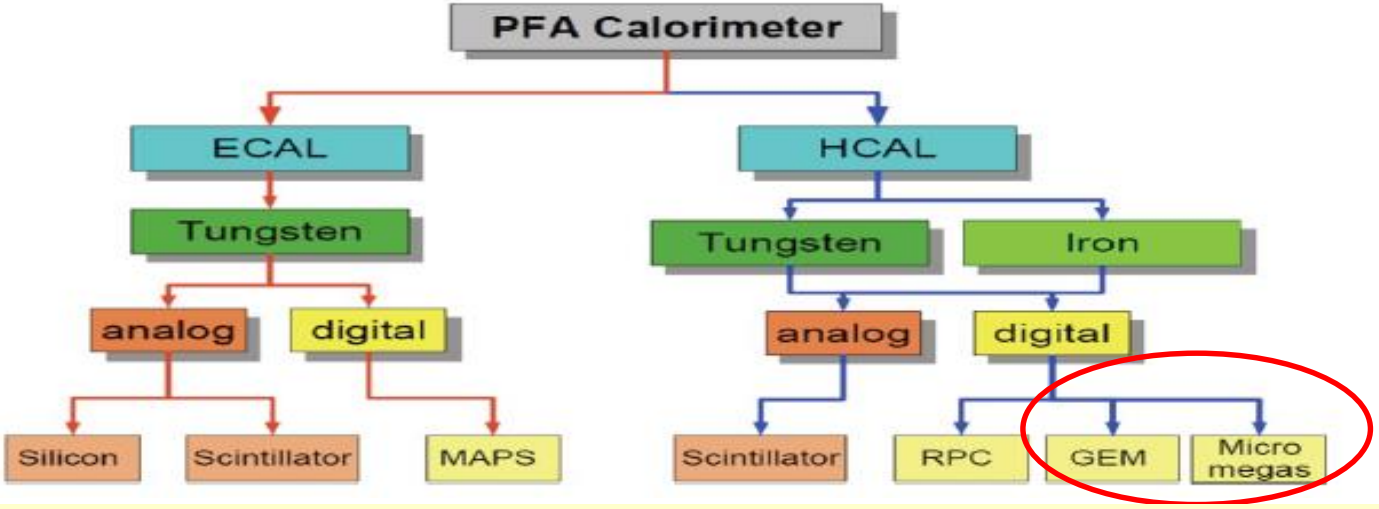
S. Duarte Pinto et al., "GEM-based beam profile monitors for the antiproton decelerator," 2012 JINST 7 C03001.



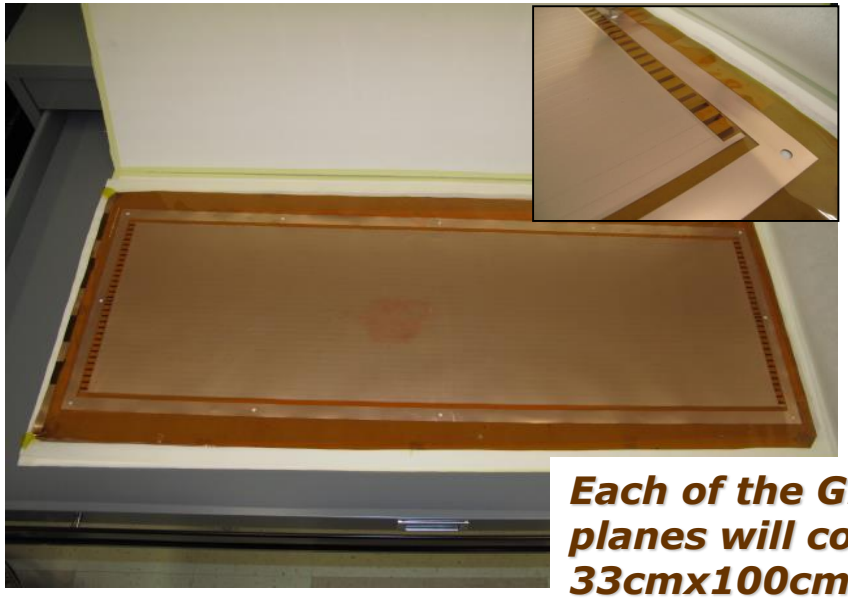
Triple GEM neutron beam monitor using polyethylene converter

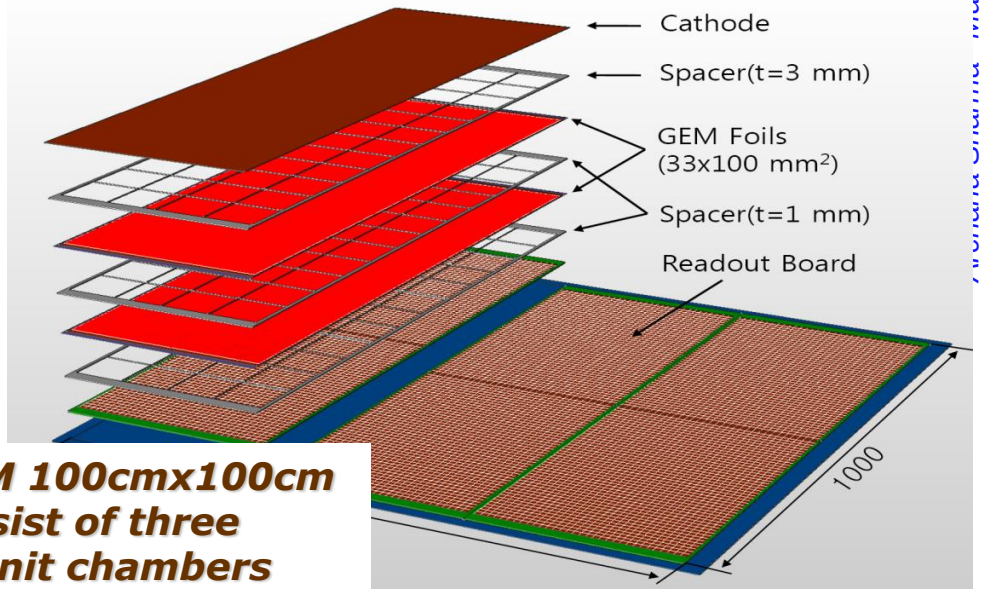
G. Croci et al., "nGEM neutron diagnostic concept for high power deuterium beams," 2012 JINST 7 C03010

GEMs for Calorimetry: Advanced Concepts



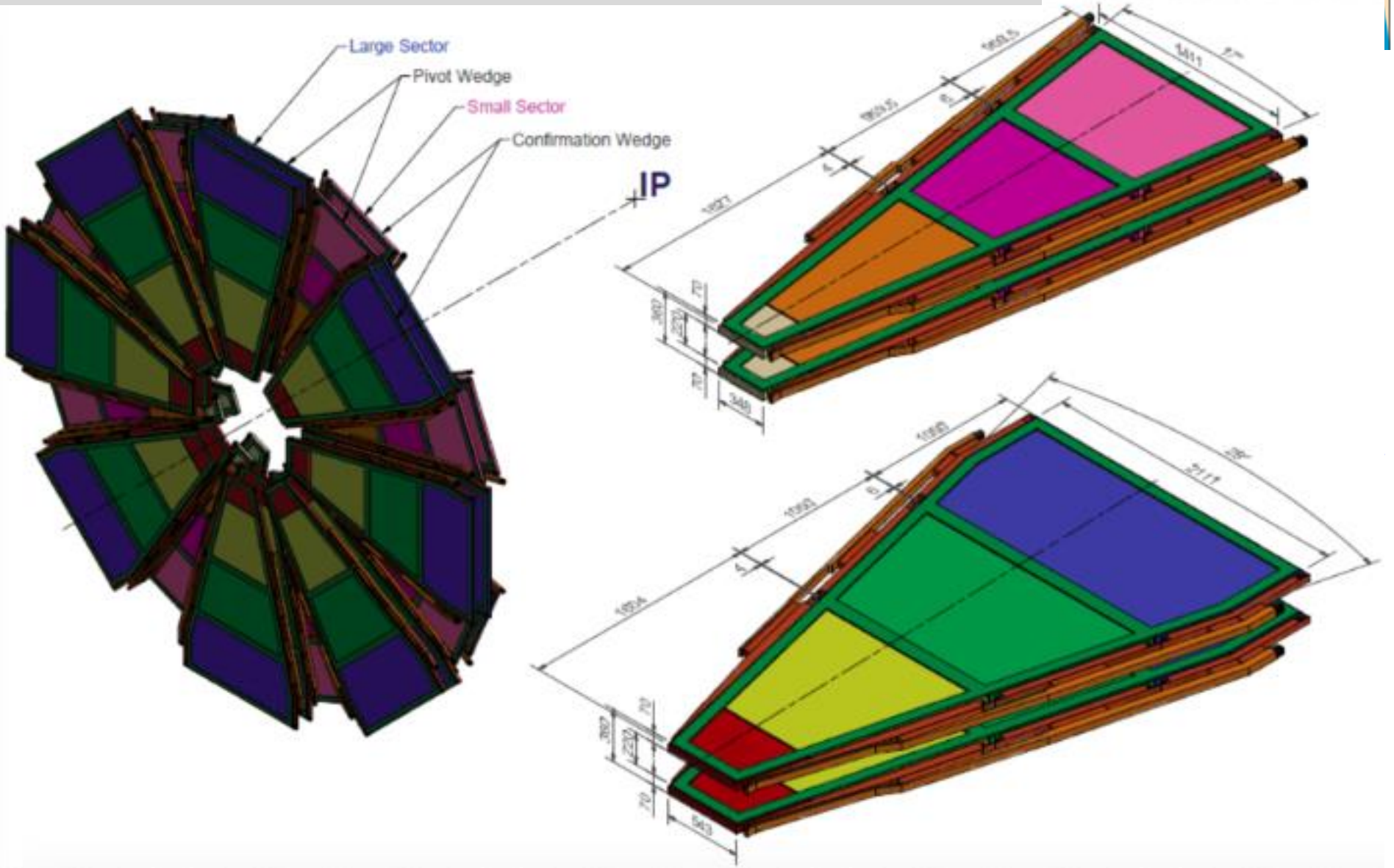
Towards Large Area 100 cm x 100 cm GEM Detector for DHCAL !!!





Each of the GEM 100cmx100cm planes will consist of three 33cmx100cm unit chambers

ATLAS new small wheel upgrade



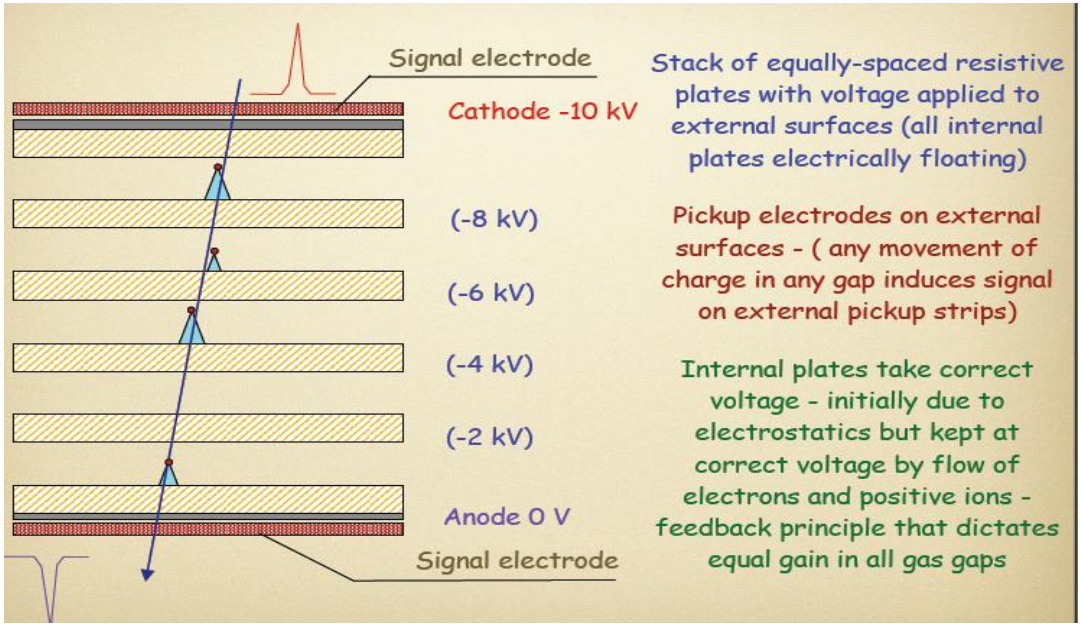
ALICE Multi-Gap RPC : Timing Resolution

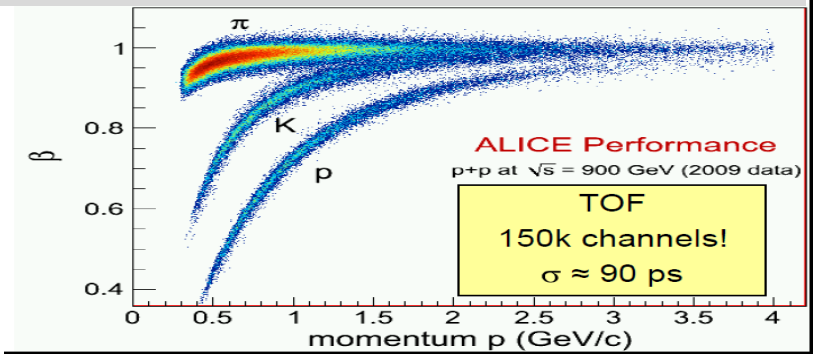
- **Relevant scale in HEP: t ~ L(m)/c ~ o(ns)**

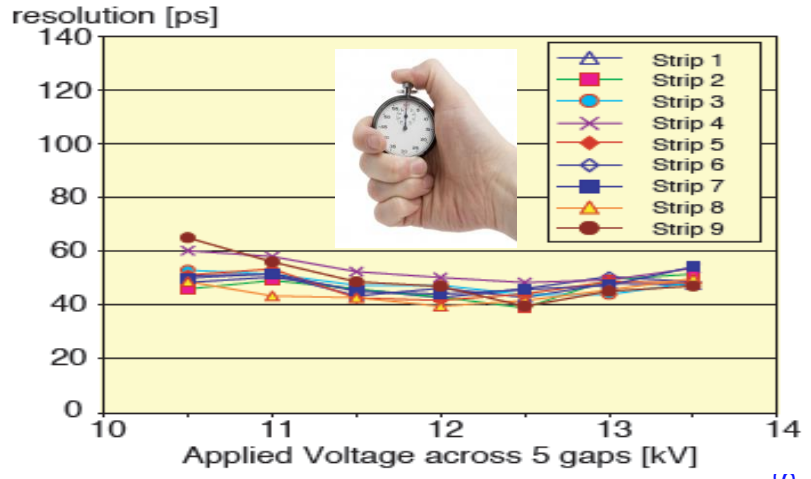
$$T_1 - T_2 = \frac{L}{c}\left(\frac{1}{\beta_1} - \frac{1}{\beta_2}\right) = \frac{L}{c}\left(\sqrt{1 + m_1^2/p^2} - \sqrt{1 + m_2^2/p^2}\right) \cong (m_1^2 - m_2^2)L/2cp^2$$

- **Traditional technique:**
  - **Scintillator + PMT ~ *o* (100 *psec*)**
- **Breakthrough with a spark discharge in gas**
  - **Pestov counter → ALICE MRPC ~ 50*psec***

Multi-Gap Resistive Plate Chamber: Basic Principle





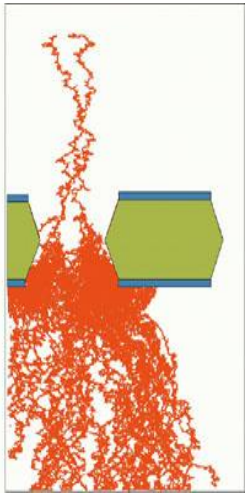


Technology	Time resolution
• Pestov Counter	30-50 ps
• RPC	~ 1-5 ns (MIP)
• MultiGap RPC	~ 50 ps (MIP)
• GEM	~ 1-2 ns (UV) ~ 5 ns (MIP)
• Micromegas	~ 700 ps (UV) ~ 2-5 ns (MIP)

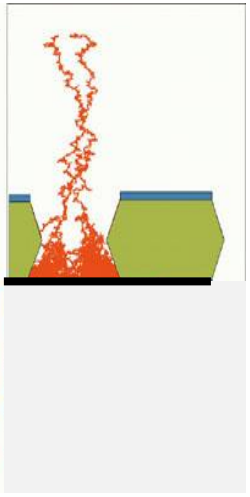
C. Williams, CERN Detector Seminar "ALICE Time of Flight Detectors": http://indico.cern.ch/conferenceDisplay.py?confId=149006

Gas Detectors : Advanced Concepts

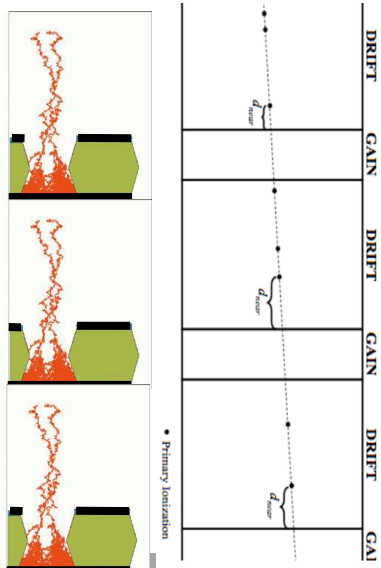
Standard MPGD



Resistive MPGD



Multi-layer Resistive MPGD

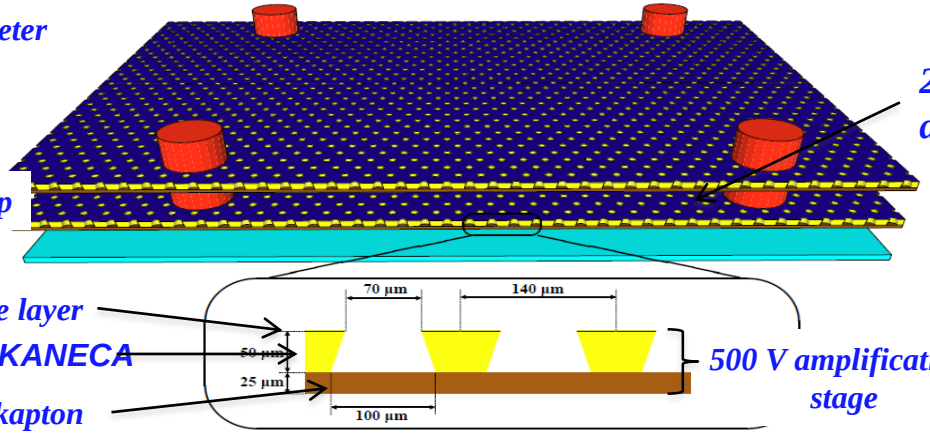


New generation of MPGD Fast Timing Micropattern :FTM

The overall structure is transparent to the signal
Signal can be extracted in each amplification stage

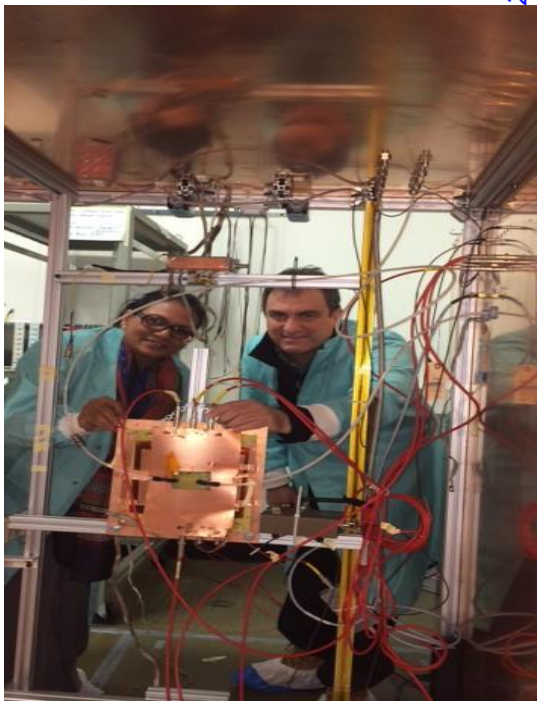
Structure of the FTM Detector

Detector Layout & Parameters



- DLC coating on the top
- Perforated foils
- Antistatic polymide foils
- Two layers separated by Pillars
- Pick-up electrode

2017

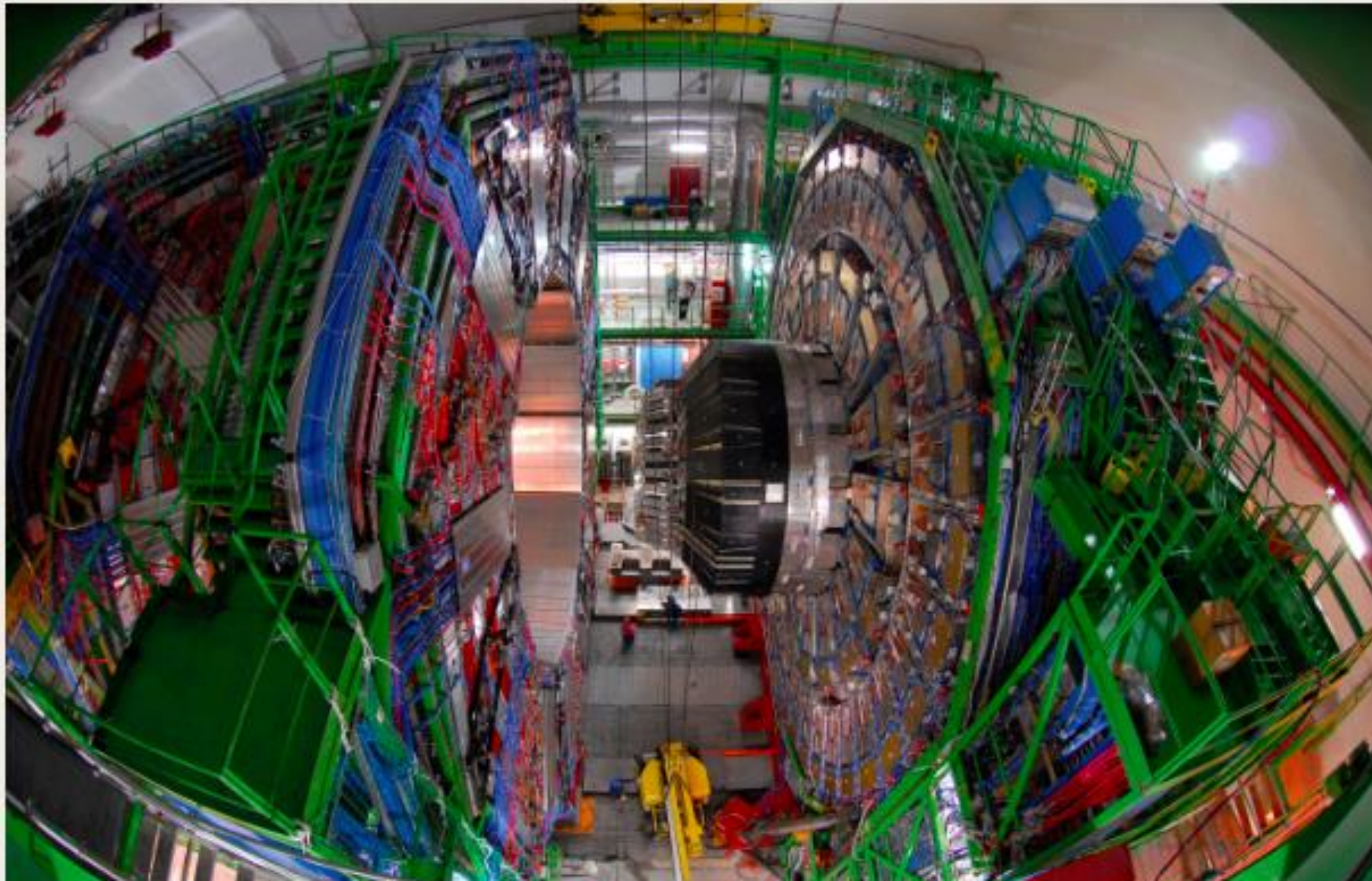


Fullly resistive amplification stage:

- Signals picked up by the external electrodes;
- High rate capability;
- Sub ns time resolution with several gaps in cascade;

Reference:arXiv:1503.05330v1
European Patent Application 14200153.6
M. Maggi, A. Sharma, R. De Oliveira

CMS Muon Endcap 2003----

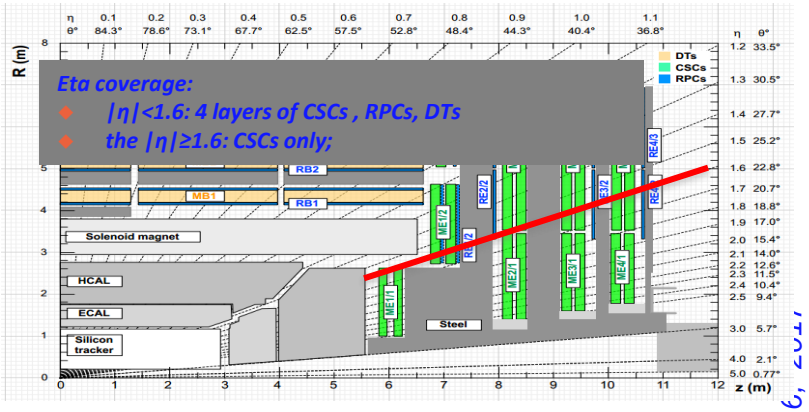


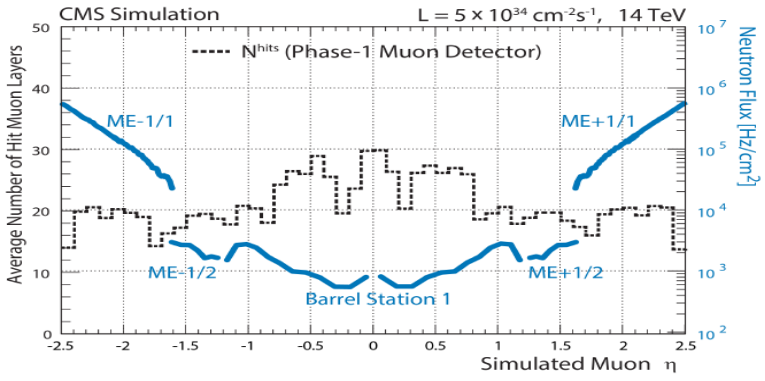
Forward muon system challenges

The forward region $|\eta| \geq 1.6$ is very challenging

- **Redundancy**: the highest rates in the system vs fewest muon layers
- **Rate** : in 100's of kHz/cm^2 and higher towards higher eta and worse momentum resolution

  → already a challenge post LS2.
- **Longevity:** Accumulated charge ~C/cm after many years of LHC operation
- **Electronics:** High occupancy/rate and latency increases exceed capabilities of the existing electronics





Archana Sharma March 16, 2017

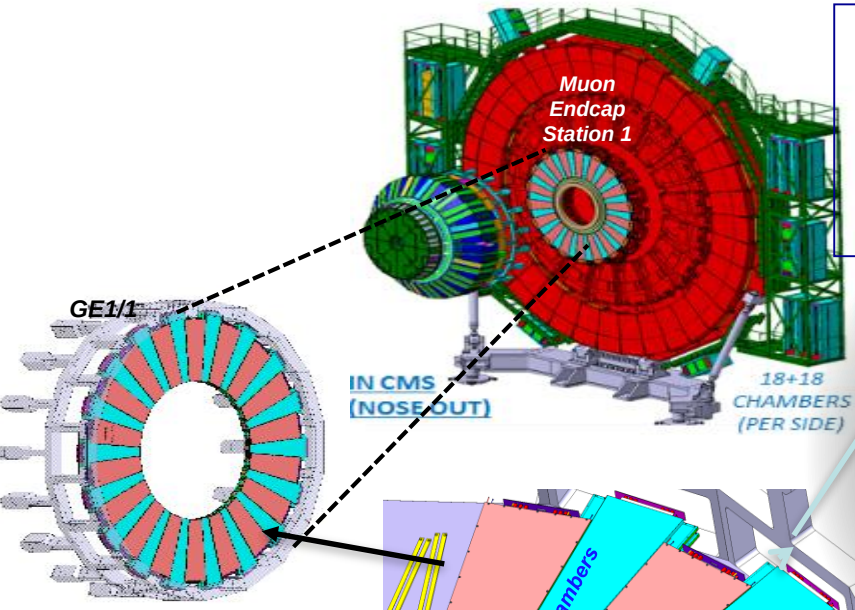
CMS Muon Upgrade: The GE1/1 design

GE1/1 in high-η region 1.5<|η|<2.2

10^0 trapezioidal triple-GEM Superchambers

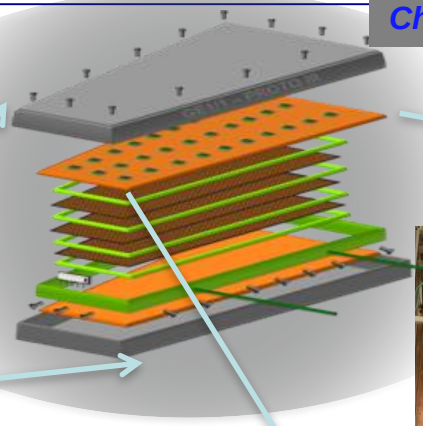
Long (1.5<|η|<2.2) and short (1.6<|η|<2.2) version

36 superchambers in each endcap



Installation in LS2

Chamber



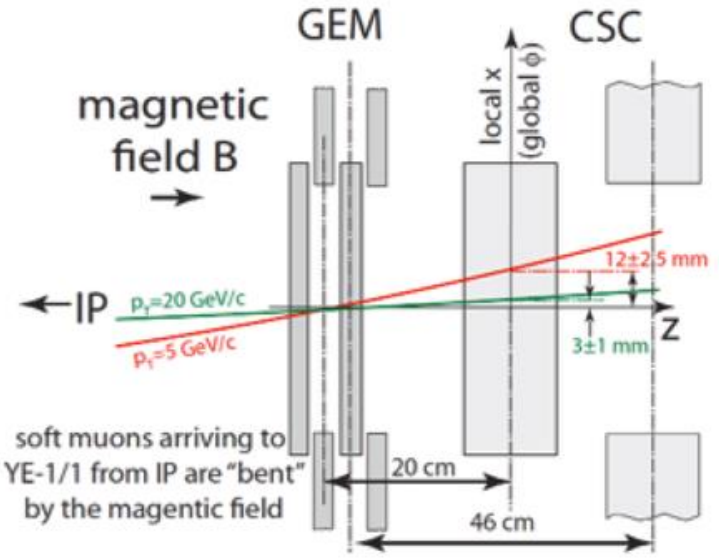
Front-end

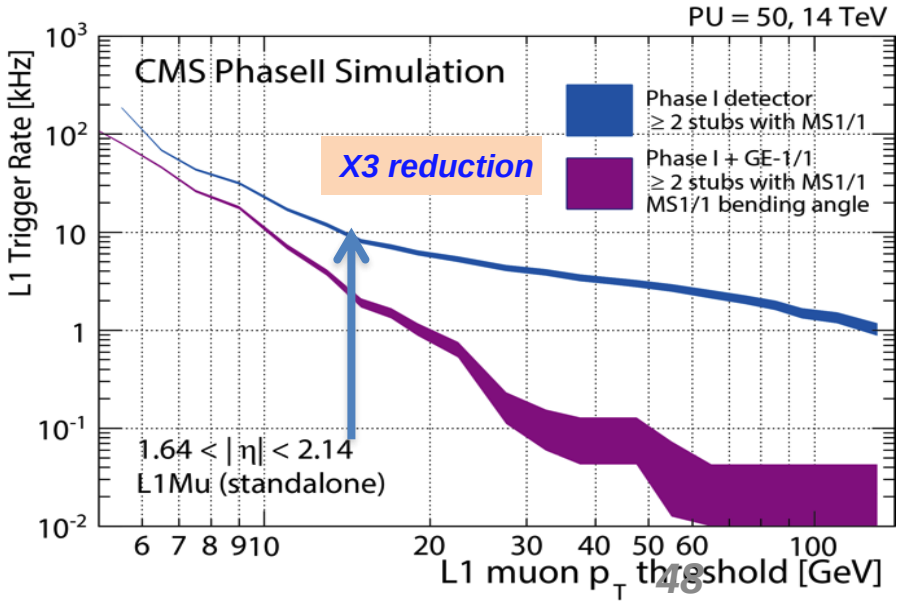
New handle: bending angle

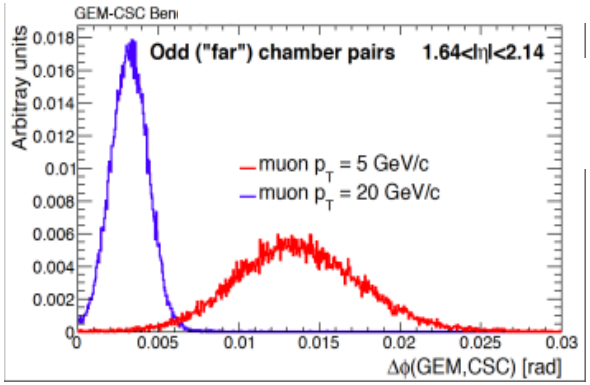
Forward trigger for $|\eta|>1.6$ relies entirely on the CSC system:

- ***Measurement driven by internal chambers: least scattering, strong B field.***

GEM detector in front of CSC can measure muon bending angle in magnetic field and add redundancy



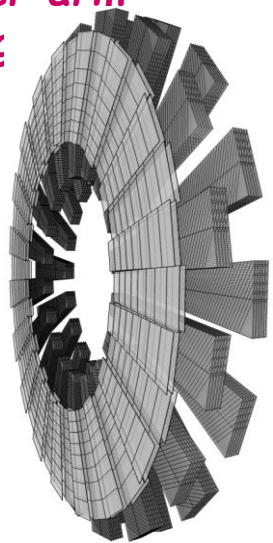




maintain 15 GeV online threshold, keep < 5 kHz rate, high efficiency

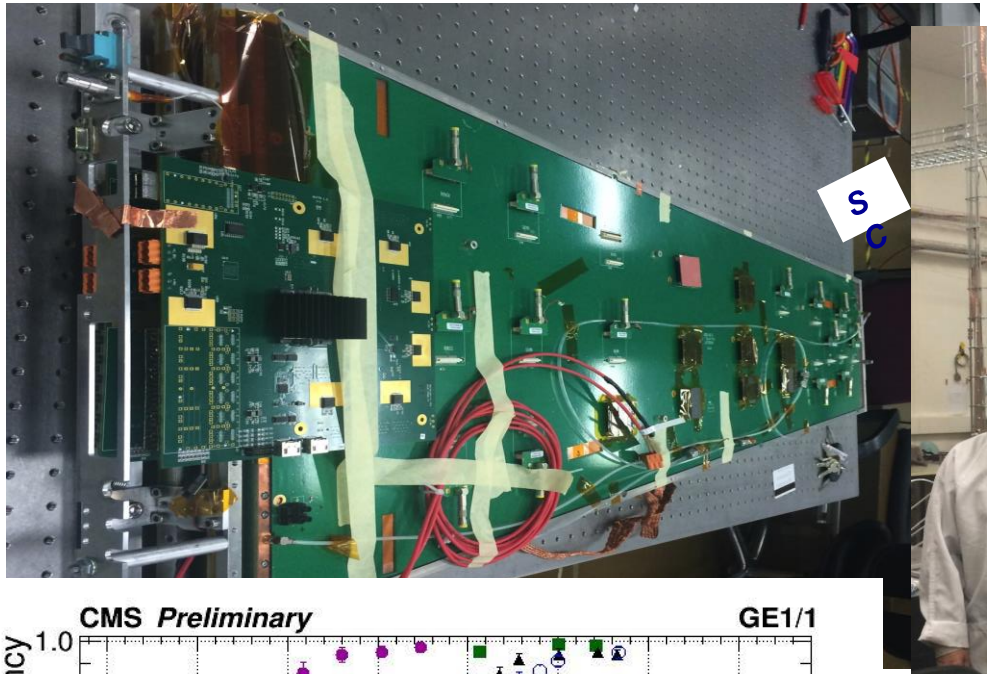
Lever arm - trigg

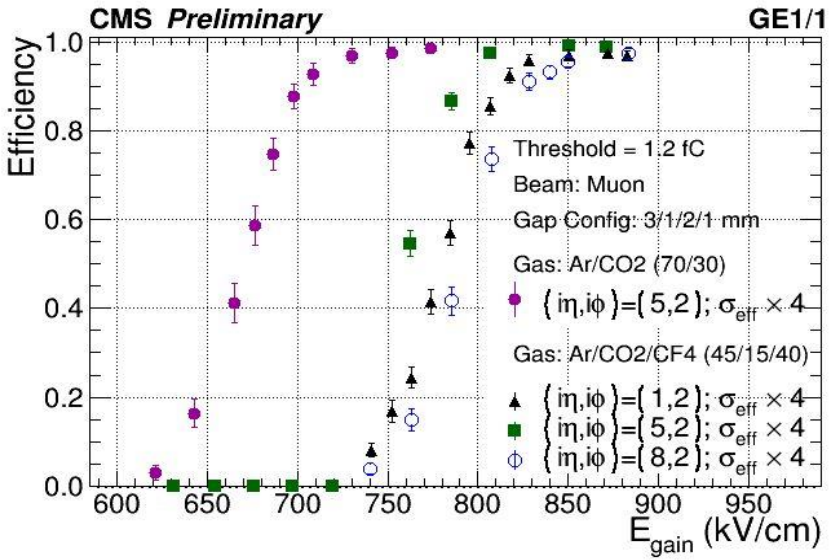
Marc



Production and tests of prototypes

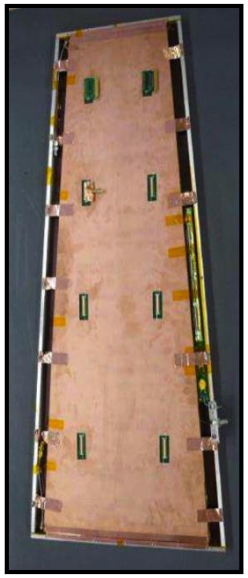
CERN 186

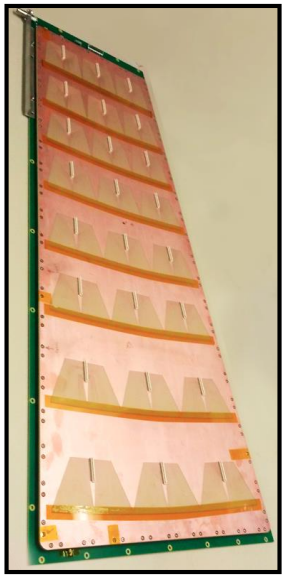
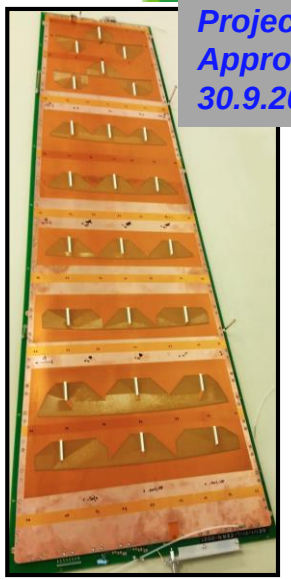




CHAMBERs

Project Approved 30.9.2015



2010 2011 2012 2013 2014 2015

R&D phase **Toward production phase** **TDR**

GE1/1-I
-> first 1m-class GEM detector ever built
-> single-mask technology
-> 99x(22-45) cm^2
-> 1024 readout channels
-> gap config. 3/2/2/2
-> use of spacer grid and glue

GE1/1-II
-> Optimization of the electric field configuration
-> single-mask technology
-> 99x(22-45) cm^2
-> 3072 readout channels
-> gap config. 3/1/2/1
-> use of spacer grid and glue

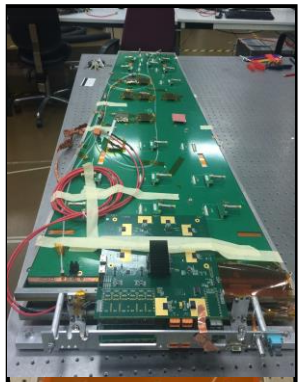
GE1/1-III
-> first use of the self-stretching technique
-> single-mask technology
-> 99x(22-45) cm^2
-> 3072 readout channels
-> gap config. 3/1/2/1
-> No spacers but glue on the external frame

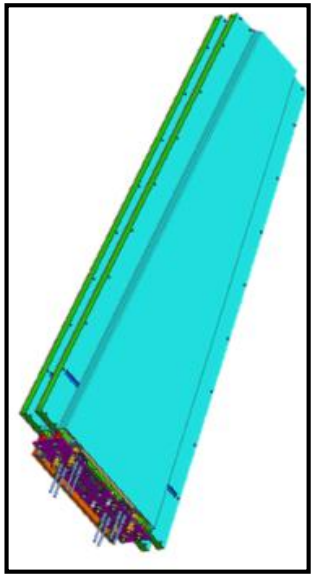
GE1/1-IV
-> Optimization of the mechanics and assembly
-> single-mask technology
-> 99x(22-45) cm^2
-> 3072 readout channels
-> gap config. 3/1/2/1
-> No glue/no spacers

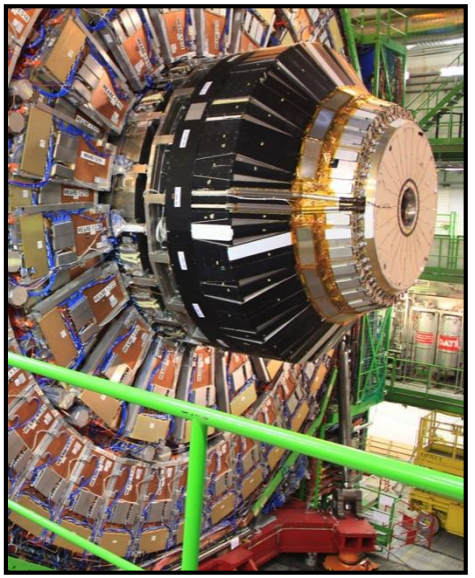
GE1/1-V
-> Optimization of the mechanics
-> stretching apparatus inside the gas volume
-> single-mask technology
-> 99x(22-45) cm^2
-> 3072 readout channels
-> gap config. 3/1/2/1
-> No glue/no

GE1/1-VI
-> Optimization of the mechanics
-> single-mask technology
-> design for long and short detectors
-> 99x(22-45) cm^2
-> 120x(20-50) cm^2
-> 3072 readout channels (new mapping)
-> gap config. 3/1/2/1

To Super CHAMBERs







2016 | **2017** | **2018** | **2019**

Slice test installation

Production phase & installation

GE1/1-VII (slice test)

- *-> Optimization of the mechanics*
- *-> Optimization of the grounding Optimization of the HV distribution*
- *-> single-mask technology*
- *-> 99x(22-45) cm²*
- *-> 120x(20-50) cm²*
- *-> 3072 readout channels*
- *-> gap config. 3/1/2/1*

GE1/1-VIII (LS2)

- *-> External (w.r.t . CERN) production sites certification and chamber components shipment*
- *-> GE1/1 chamber assembly and certification*
- *-> Super chamber mechanics optimization*
- *-> First test with final*

- *-> GE1/1 super chamber assembly and certification with final front-end electronics*
- *-> First batch of Superchamber shipped to P5*

- ***GE1/1 super chambers ready in P5 for installation***
- ***Installation and cabling of all super chambers***
- ***Commissioning in situ with cosmic muons***
- ***Super chamber characterization in situ with cosmic muon***
- ***First data with LHC beam***

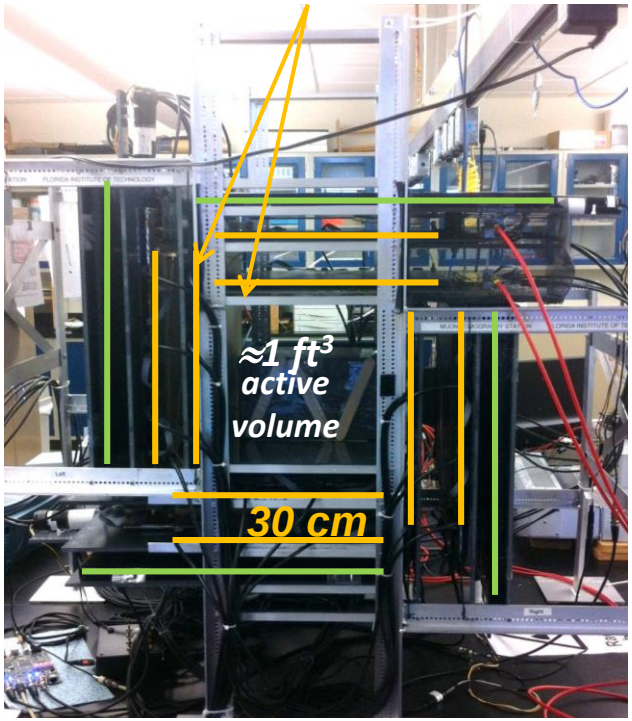
Visit of Pakistan Delegation to GEM Lab 14-3-2017

Archana Sharma March 16, 2017

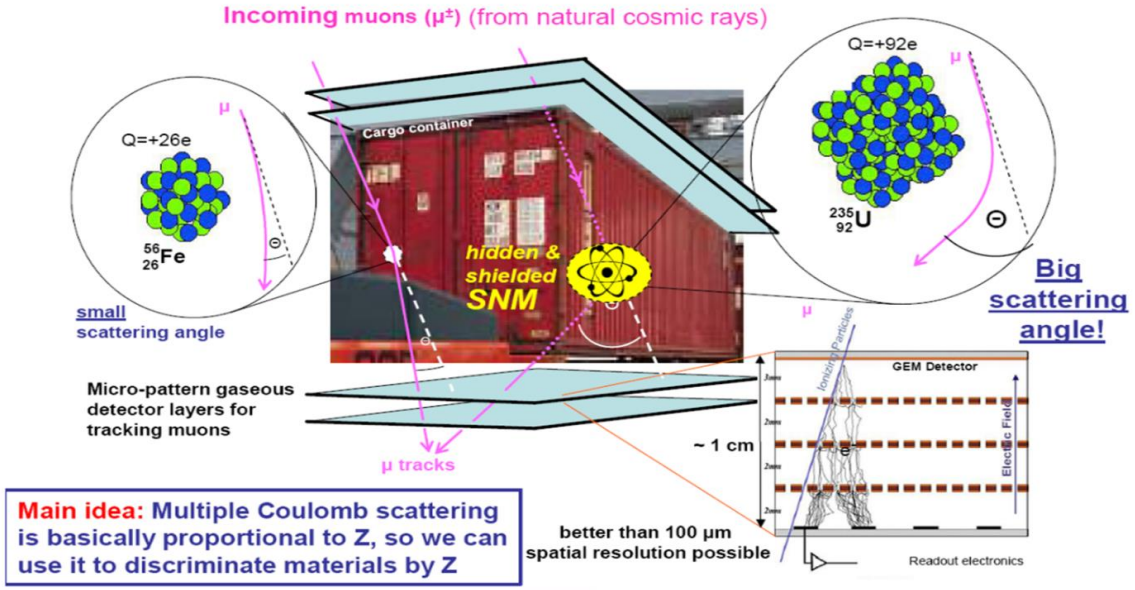
Muon Tomography for Homeland Security

http://www.economist.com/node/21552169

Triple GEM for Muon Tomography

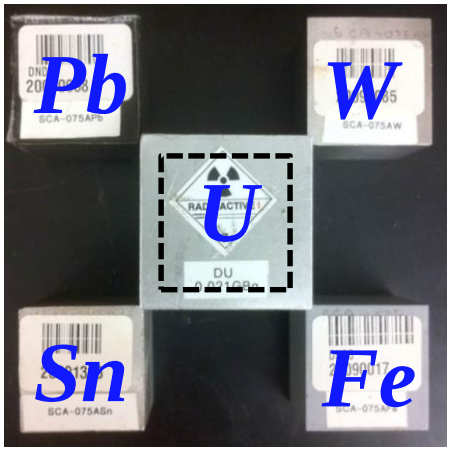


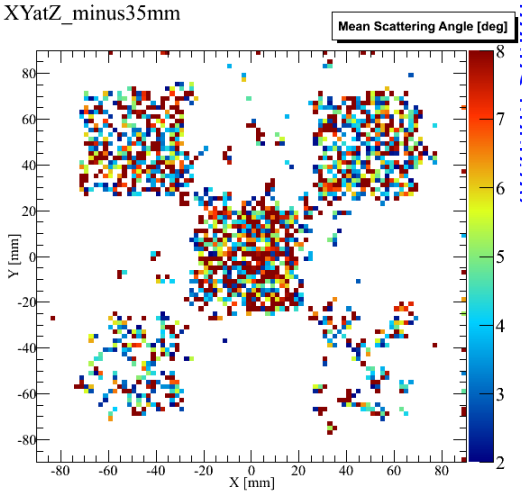
Florida Tech Cubic-Foot MT Prototype



Main idea: Multiple Coulomb scattering is basically proportional to Z, so we can use it to discriminate materials by Z

Principle of Muon Tomography (MT) based on Cosmic Ray Muons: Five targets with various Z





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Temporal Tomography: Advanced Concepts

- **Measurements on samples of small scales or large sizes**

The mechanical parameters are unknown to a mass scale:
Effective stress?
Friction effective?
Damage?

- **Empirical methods**

Measure:
Mechanical parameters in small scale

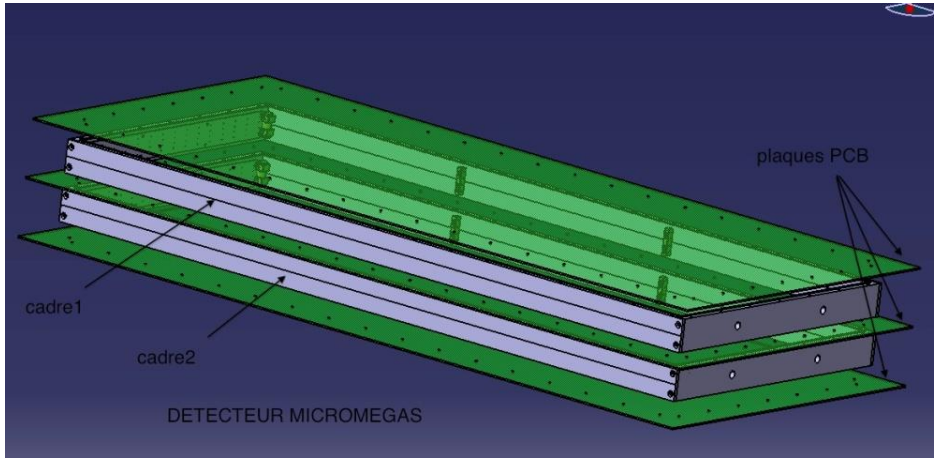
Qualitative description of the rock mass (scale fracturing, alteration, hydraulic ...)

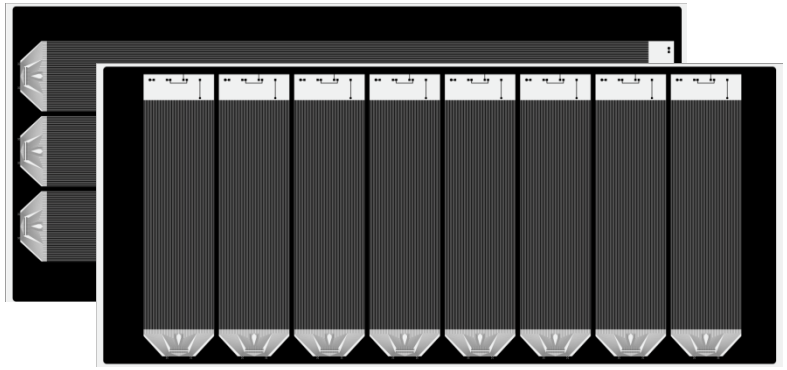
New measurement ability (km of lateral extent, multi-hm thickness) of the spatial and temporal evolution of rock density function of water saturation, total porosity, mechanical condition and damage at in situ scale

- Monitoring of aquifer resources and reserves
- Monitoring the stability of volcanoes
- Monitoring the stability of underground vacuum and rock mass instabilities
- Monitoring the tunnels

Qualification of the prototype telescope developed in 2009-2011 at GEOAZUR & LSBB in collaboration with the consortium RD51/CERN

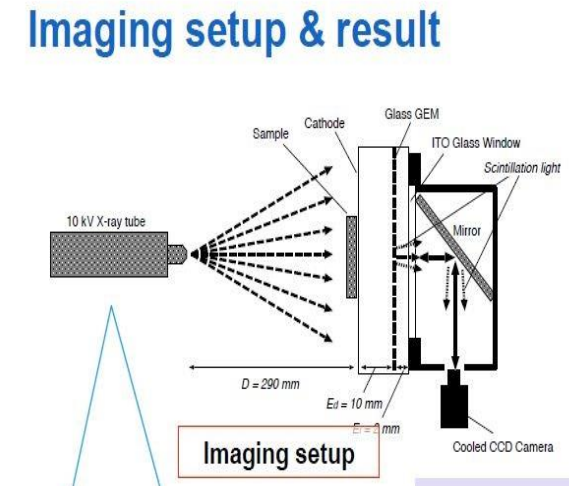
Develop a range of 80 large-area muon telescopes → new operational tool for the characterization and monitoring

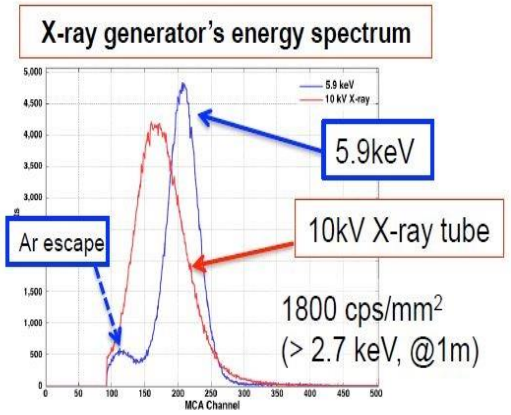




Luggage inspection, food inspection, defect scanners

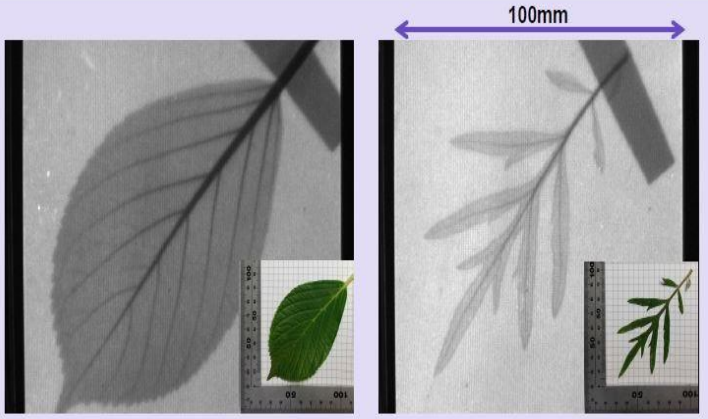
- GEM combined with a scintillation gas (CF_4) is used.
- Very good spatial resolution in the method, shown on the right





[9]

Amptek Co. Mini-X
(Max. 4W)

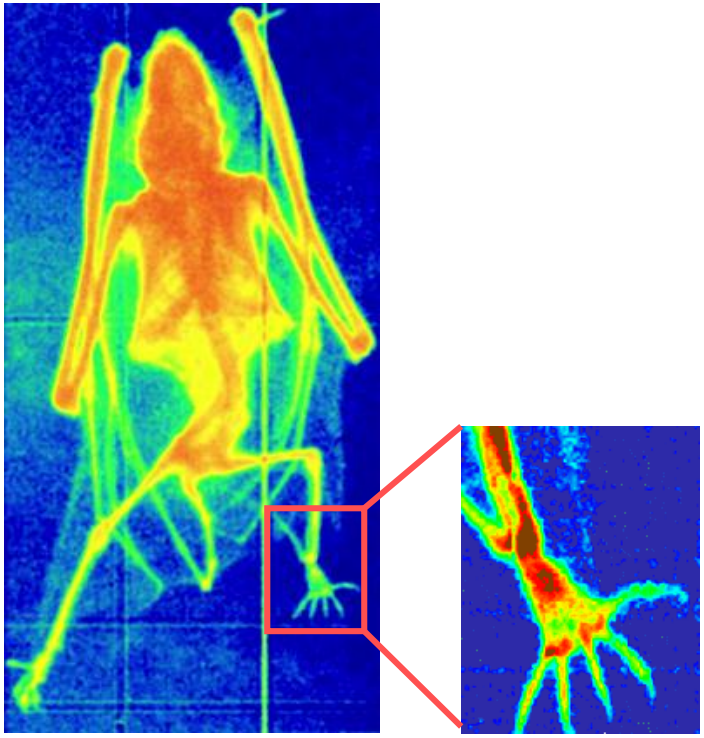


Obtained image of leaves (2 sec integration time)[10]

Excellent spatial resolution ≈500μm
Quick imaging of low Z material with low energy X-rays (≈7 keV)

[9] www.amptek.com
[10] T. Fujiwara, et al., Review on Scientific Instruments (Submit

Improving Digital Imaging

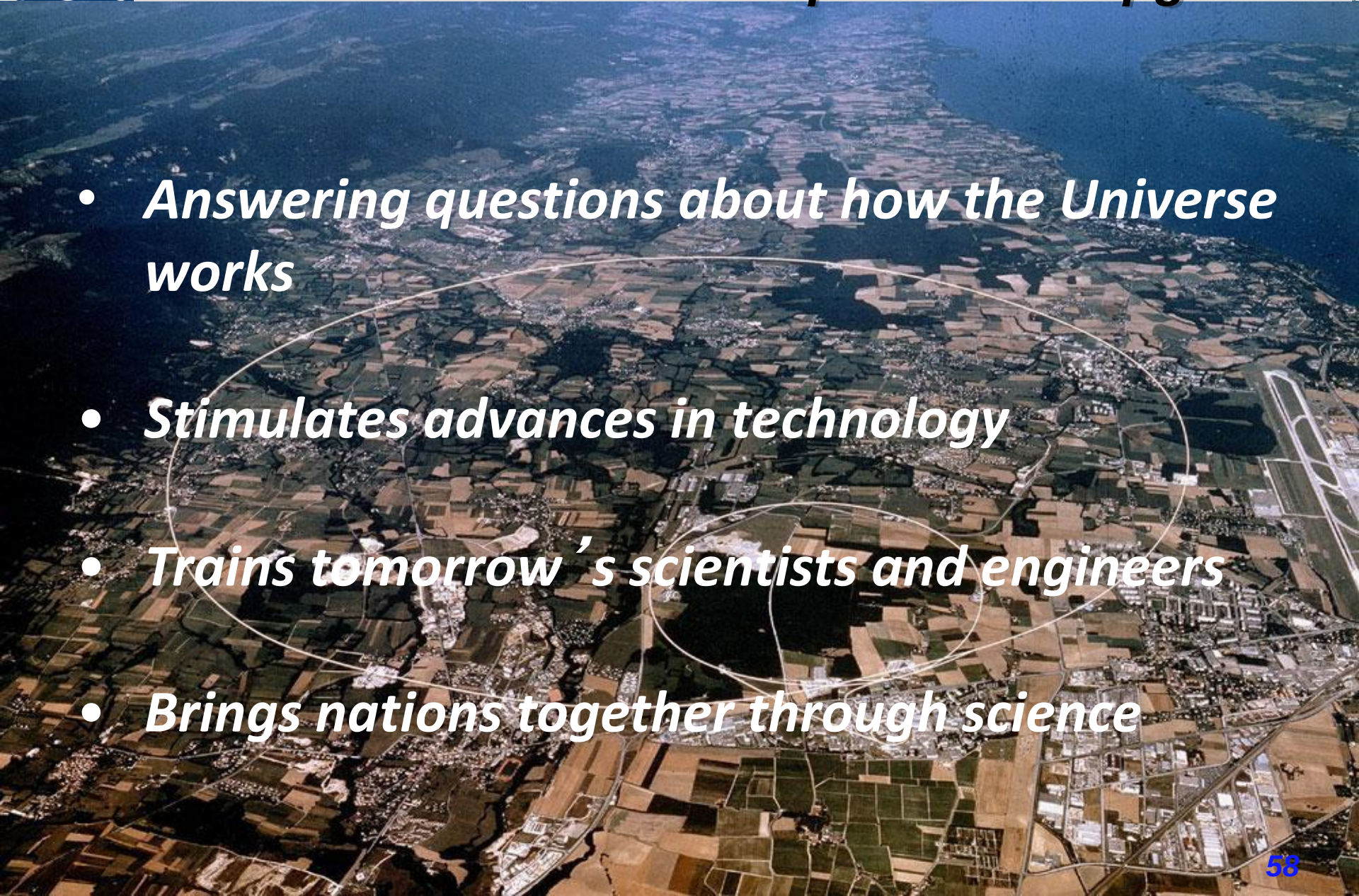


Radiography of a bat, recorded with a GEM detector

A little history : A full career !

- 1980: LEP not yet built, but physicists think ab
- 1984: Glimmerings of the LHC (2x5...9 TeV, s
- 1988: SSC approved (Waxahachie, Texas);
- 1989: First collisions in LEP and SLC, R&D f
- 1993: SSC construction cancelled;
- 1994: LHC approved (start in 2005)
- 1995: Discovery of the top quark at Fermilab;
- 1996: ATLAS and CMS approved. 1997: ALI
- 2000: end of LEP running, no Higgs yet;
- 2005: first cosmic seen in the ATLAS pit;
- 2006: new CERN accelerator control centre re
- 2007, June: the last dipole magnet lowered to
- 2008: LHC start;
- 2008, 10. September - 10:28: first full turn of a
- 2008, 19. September - failure during powering
- 2009, 23. November: protons collide again! (3
- 2010, 30. March: first high energy proton colli
- 2012, 4. July: Higgs-like particle seen!
- 2012, 8. November: First observation of B_s

Outlook : A promise for gaseous detectors At future machines and experimental upgrades



- *Answering questions about how the Universe works*
- *Stimulates advances in technology*
- *Trains tomorrow's scientists and engineers*
- *Brings nations together through science*