It’s a gas, gas, gas!

Gaseous Detectors -

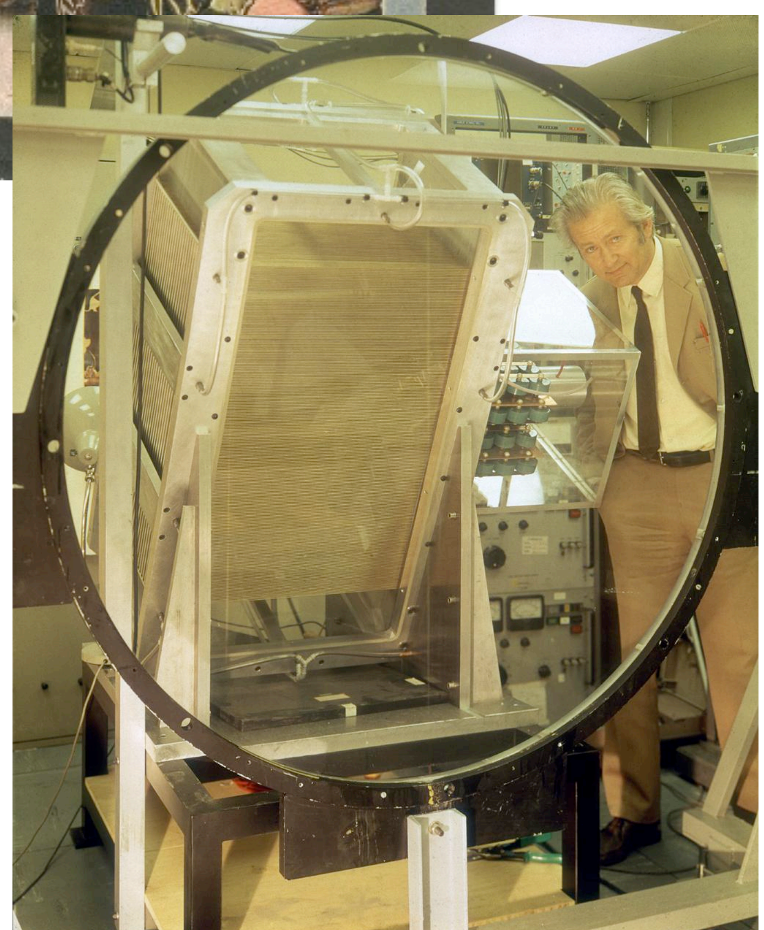
history, current applications and trends for the future

EDIT-2020 School for Detector and Instrumentation Technologies

24 February 2020

Christoph Rembser (CERN)

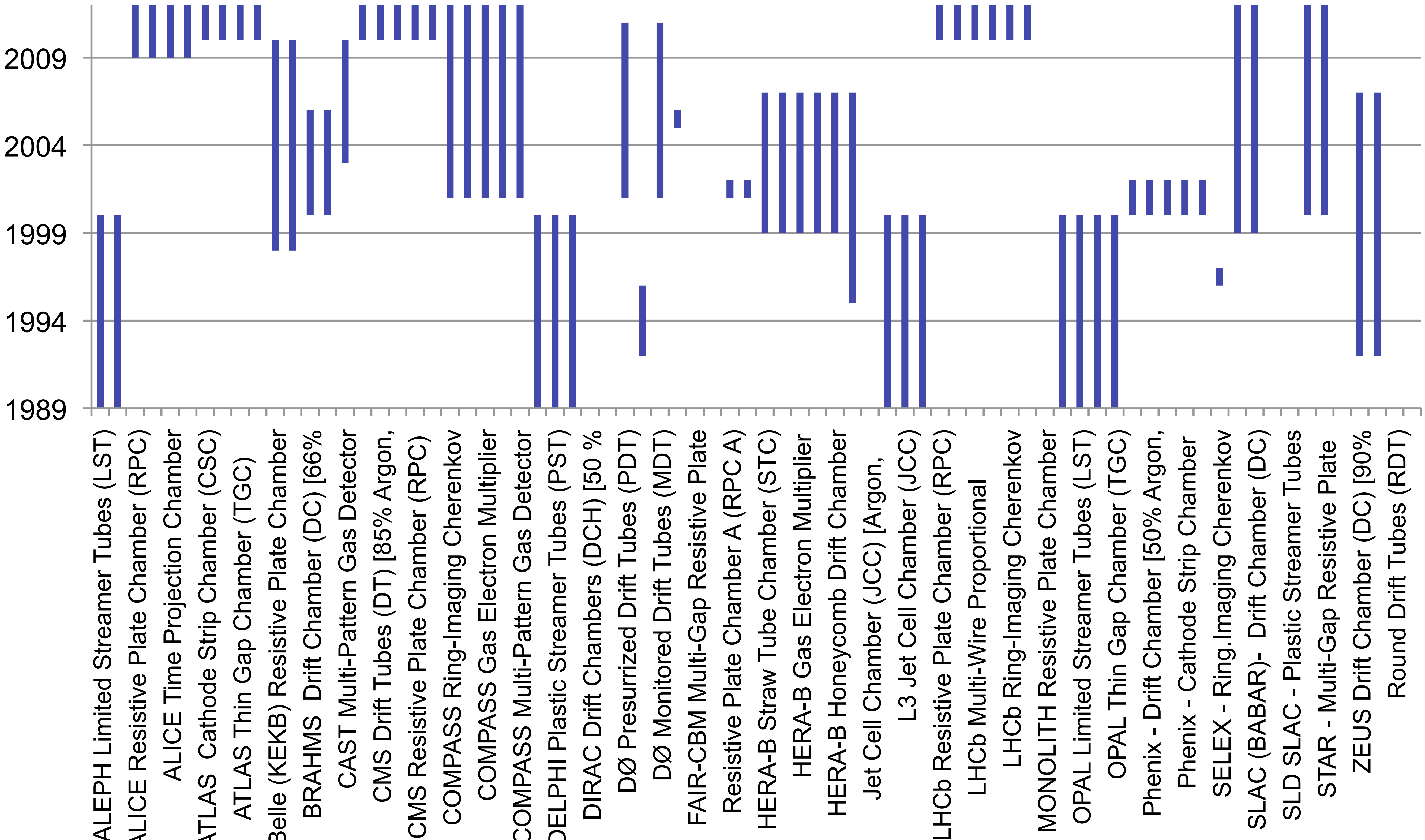
It’s a gas, gas gas!



- In 1968 the Rolling Stones released the album Jumpin’ Jack Flash;
- Even today it is still not clear where “gas, gas, gas” is coming from.
  Nowadays it is commonly used as an expression meaning “it’s hilarious” or “funny”.

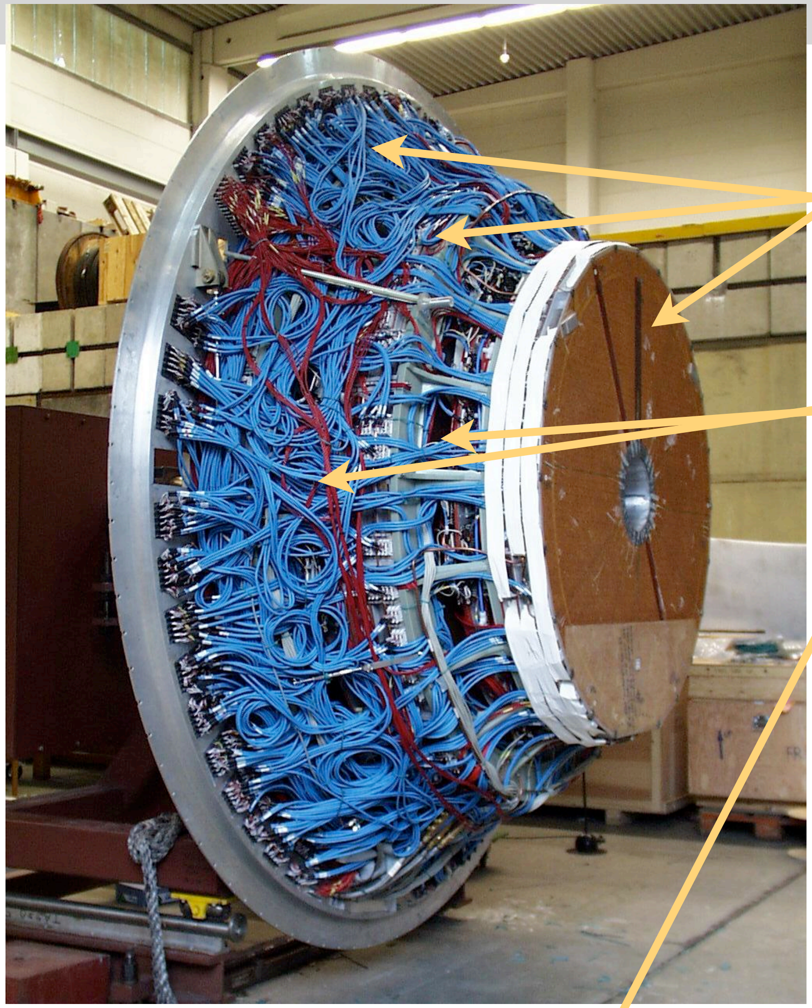
- Theories about a possible origin are
  - ➡ the effect of Nitrous Oxide (aka “laughing gas”) on one’s behavior that entered the everyday vocabulary or
  - ➡ it refers to “It’s a gas”, one of several records that were included in MAD magazine, 1963.
  - ➡ My opinion: Stones refer to the fact that 1968 essential features of gas filled particle detectors (Multi-wire proportional chambers and drift chambers) were clarified and their most useful potentialities brought to light, see
    “Some read-out systems for proportional multiwire chambers” by G. Charpak, R. Bouclier, T. Bressani, J. Favier, Č. Zupančič
    NIM Volume 65, Issue 2, (1968), p. 217–220
    and
    “The use of multiwire proportional counters to select and localise charged particles” by G. Charpak, R. Bouclier, T. Bressani, J. Favier, Č. Zupančič
    Nucl. Instr. and Meth., 62 (1968), p. 262.

(Some) Gaseous detectors in particle particle physics experiments in the last two decades



Slide from Archana Sharma, CMS Upgrade School 2014

...and some of the gaseous detectors missing in the list



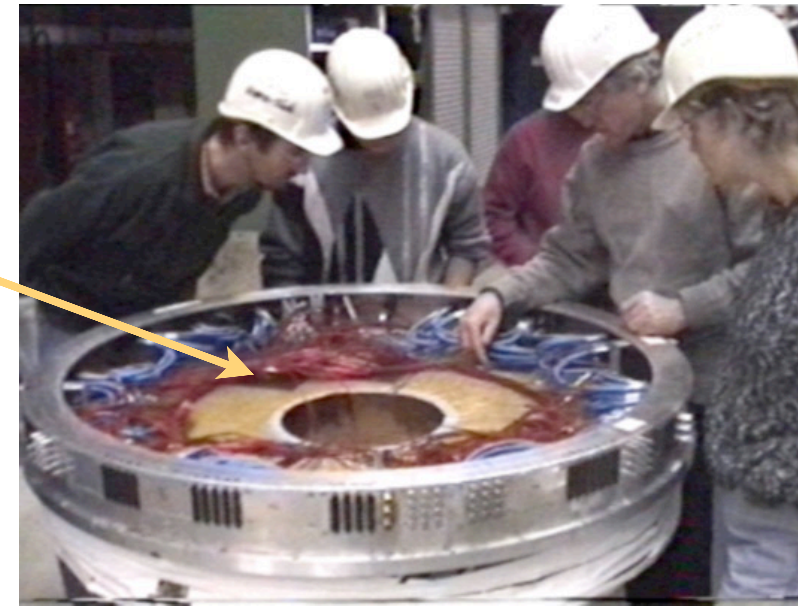
ZEUS Forward and Rear Tracking Detectors

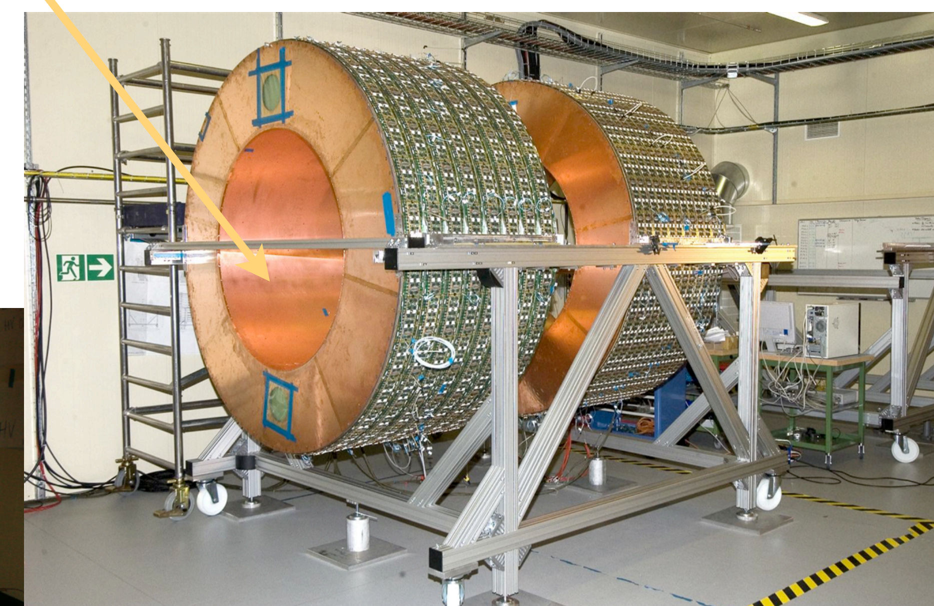
ZEUS Transition Radiation Detector

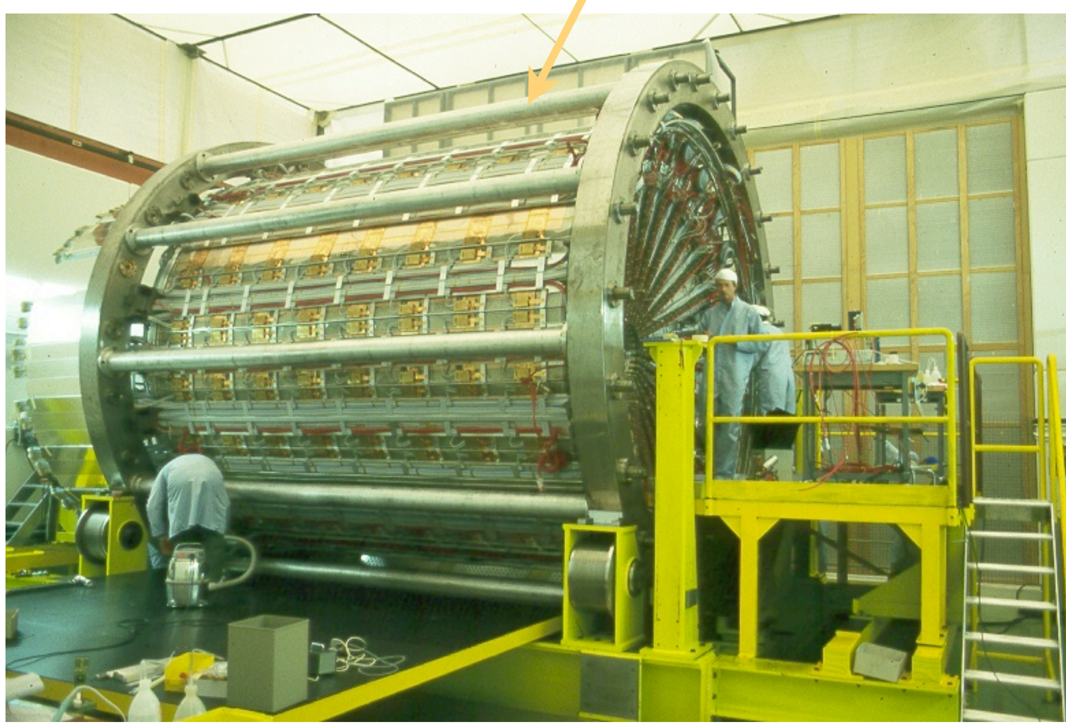
OPAL Jet Chamber

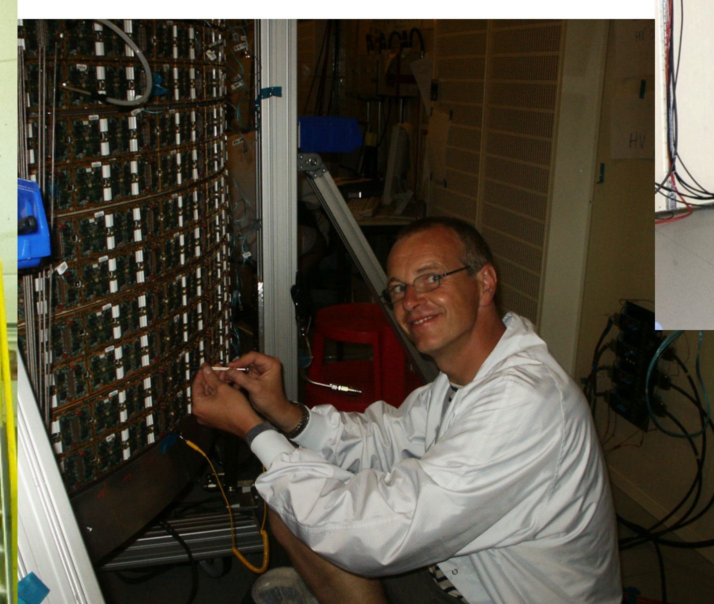
ATLAS Transition Radiation Tracker

(gaseous detectors CR worked with)









Gaseous detectors

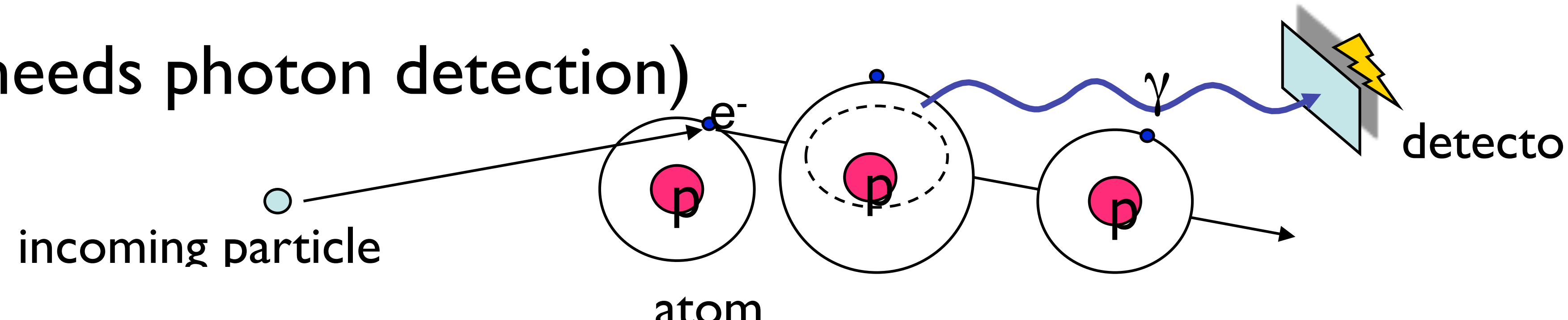
- Gas detectors are key technology for radiation detection in particle physics experiments;
  - ➡ provide efficient, low-mass, relatively cheap, relatively easy-to-build and radiation hard detector solutions;
  - ➡ intrinsically provide amplification of signal by gas amplification (less on-detector electronics) thus excellent single-particle sensitivity

…keep this features in mind!!!

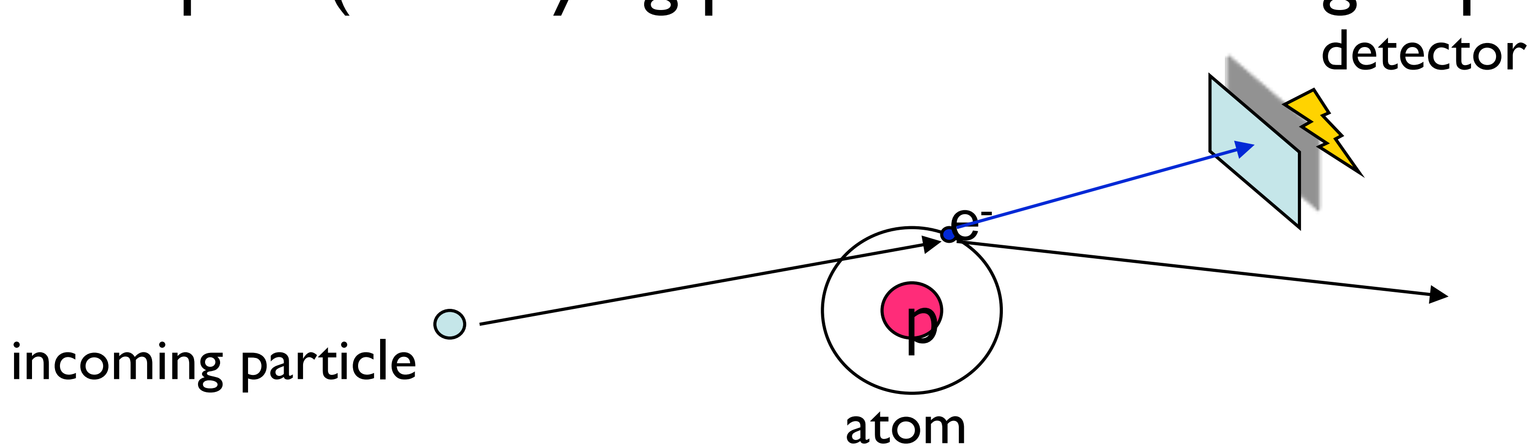
Particle interactions with matter

Main processes of charged particle interactions are:

- energy loss by Coulomb interaction with the atoms/electrons:
  - ➡ Exitation: the atom or molecule is excited to a higher level and a low energy photon is emitted with the de-excitation:
    atom* ➙ atom + γ
    (identifying process needs photon detection)



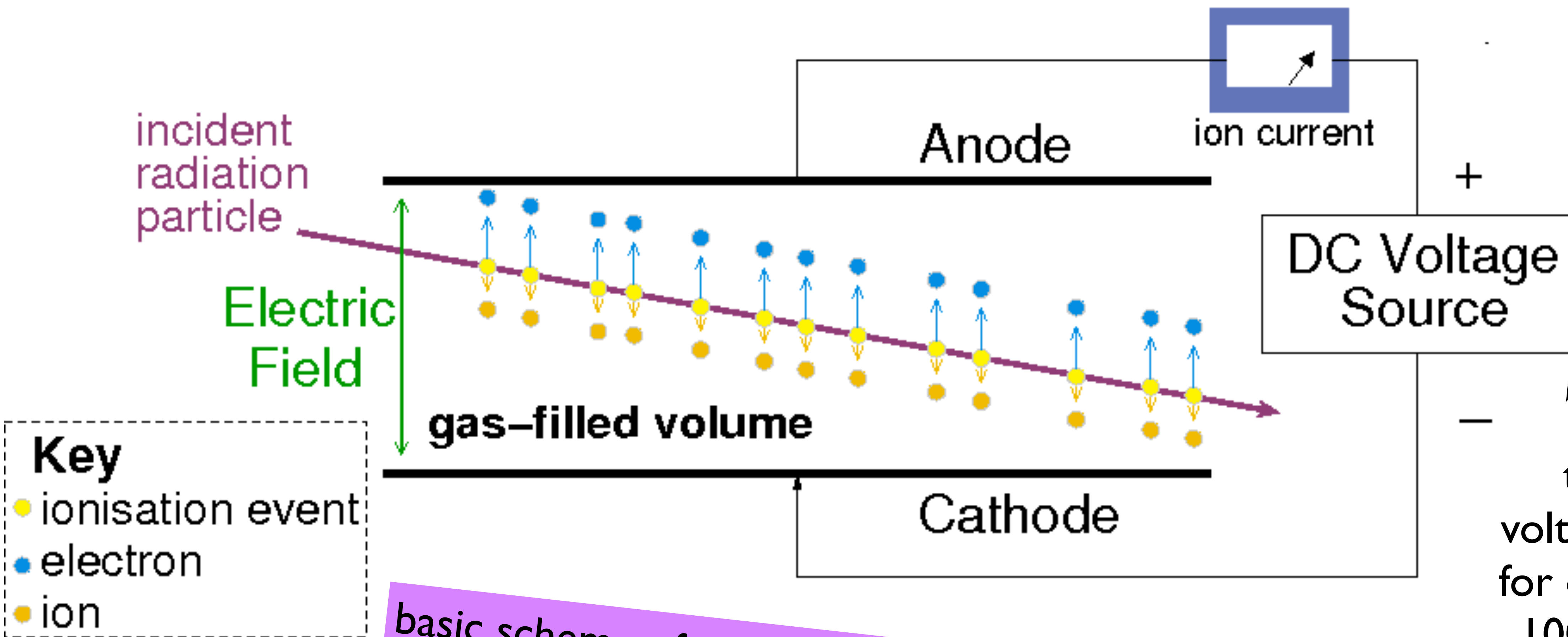
- Ionisation: an electron is kicked out from the atom
  - ➡ electron-ion pair (identifying process needs charged particle detection)



Gas-filled particle detectors - very basic working scheme

- **Gas-filled particle detectors** or **gaseous ionisation detectors** or **gaseous detectors**
  are radiation detection instruments used in particle physics.

- Make use the ionising effect of radiation upon a gas-filled sensor:
  if a particle has enough energy to ionise a gas atom or molecule, the resulting electrons and ions cause measurable current flow.



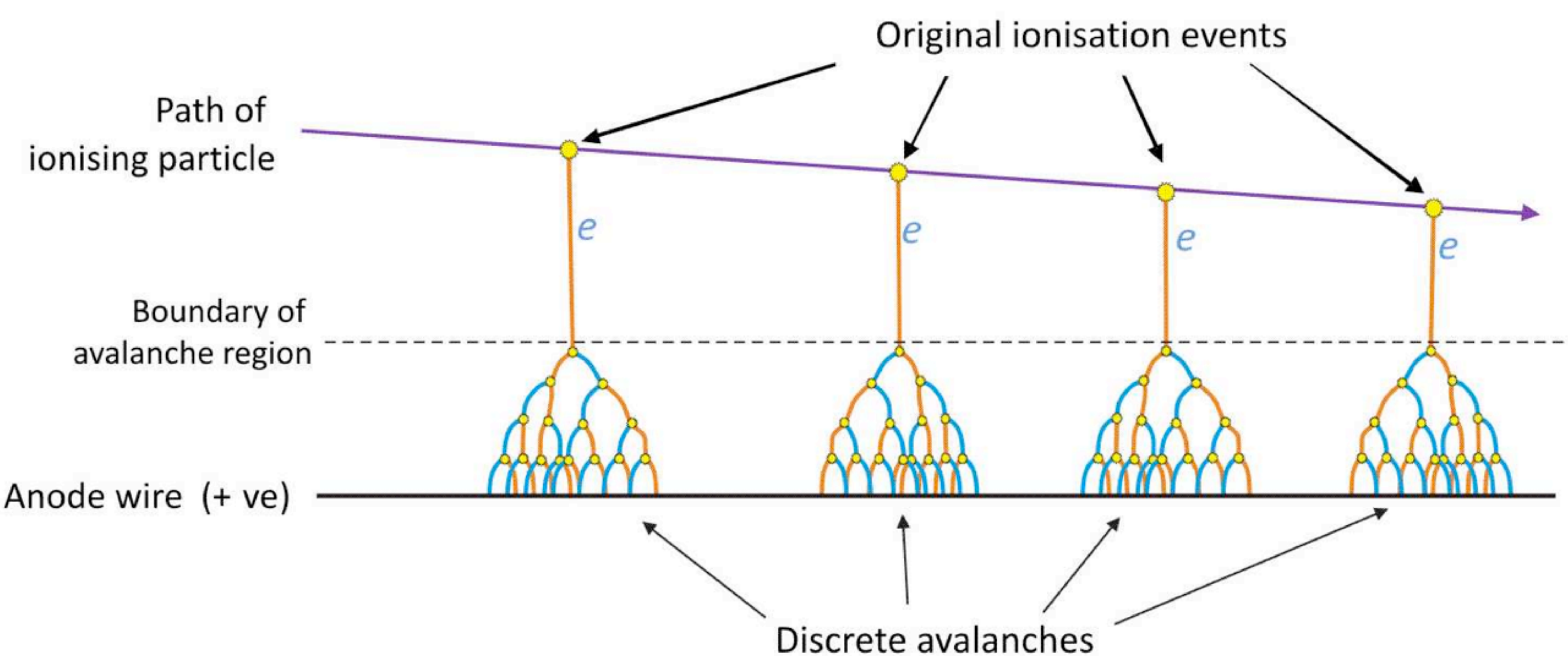
basic scheme of an ionisation chamber

typical voltage range for operation 100 - 500V (this is low).

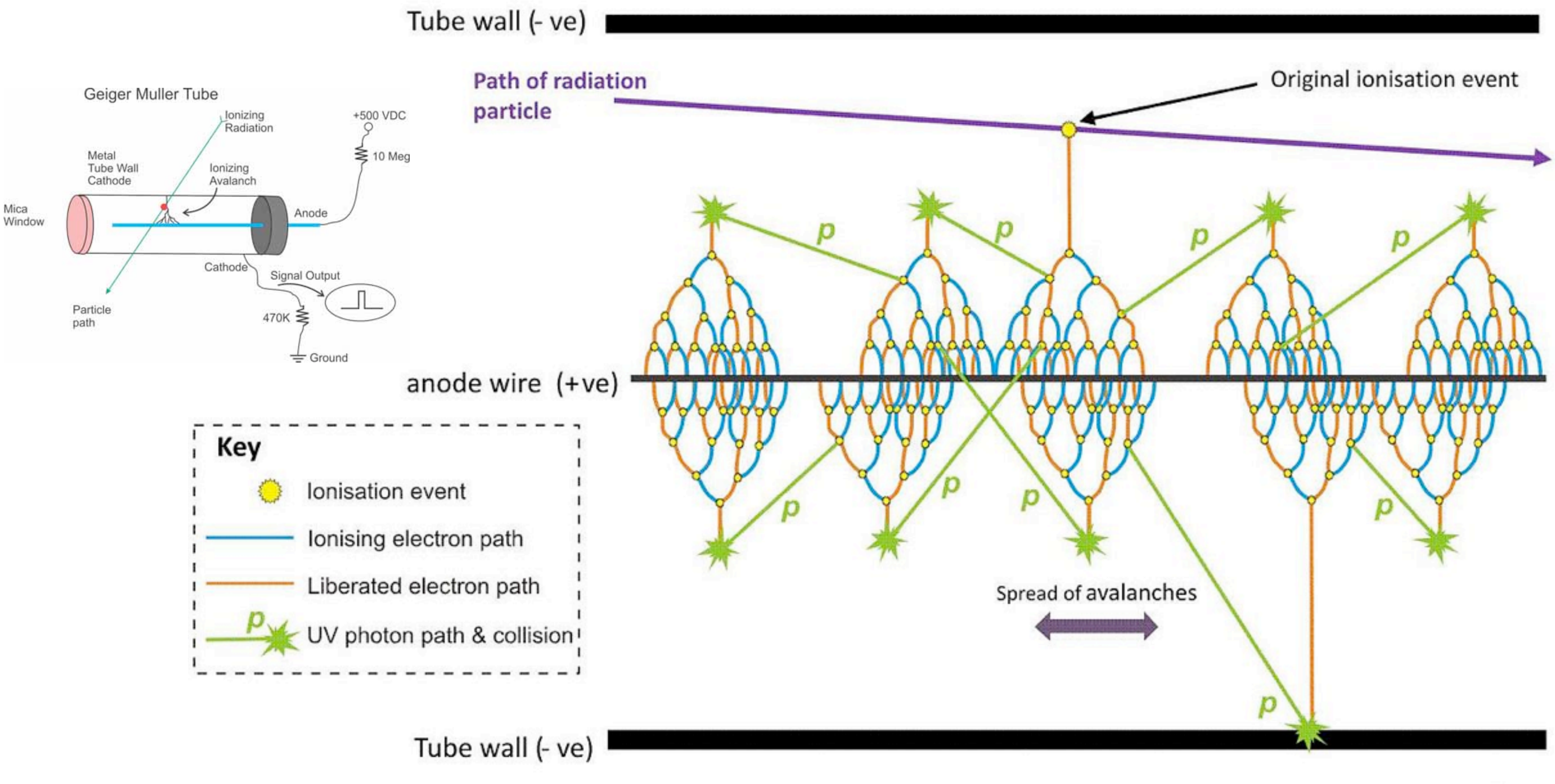
Electron avalanches enlarge the electronic signal

- in ionisation chambers: 100 e-ion pairs (typical number for 1 cm of gas) are hard to detect
  (typical noise of very modern pixel ASICs is ~ 100e-)
- Need to increase number of e-ion pairs

➡ trick: apply higher electrical field



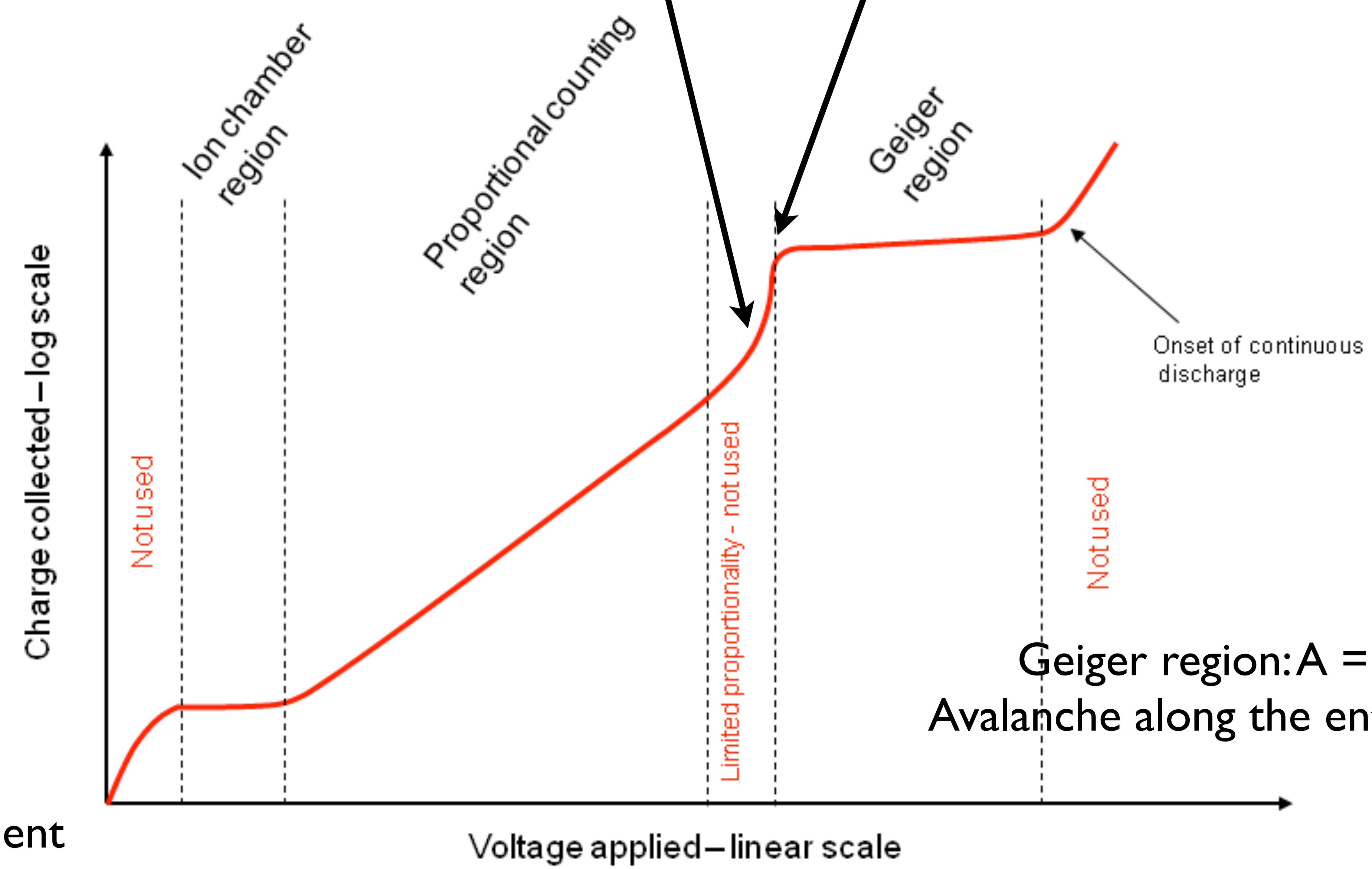
Spread of avalanches in a Geiger-Müller tube



Practical gaseous ionisation detector regions

Semi-proportional region: $A=10^4$-10^6

Saturation region: $A > 10^8$ (independent of the number of primary electrons)



Geiger region: $A = 10^8$
Avalanche along the entire wire

Attachment

Proportional region:
amplification $A = 10^3$-10^4

A word on gas mixtures

chamber gas: very hard choice!

Relevant Parameters
for gas detectors

Differences due to δ-electrons

Ionization energy	:	E_i
Average energy/ion pair	:	W_i
Average number of primary ion pairs [per cm]	:	n_p
Average number of ion pairs [per cm]	:	n_T

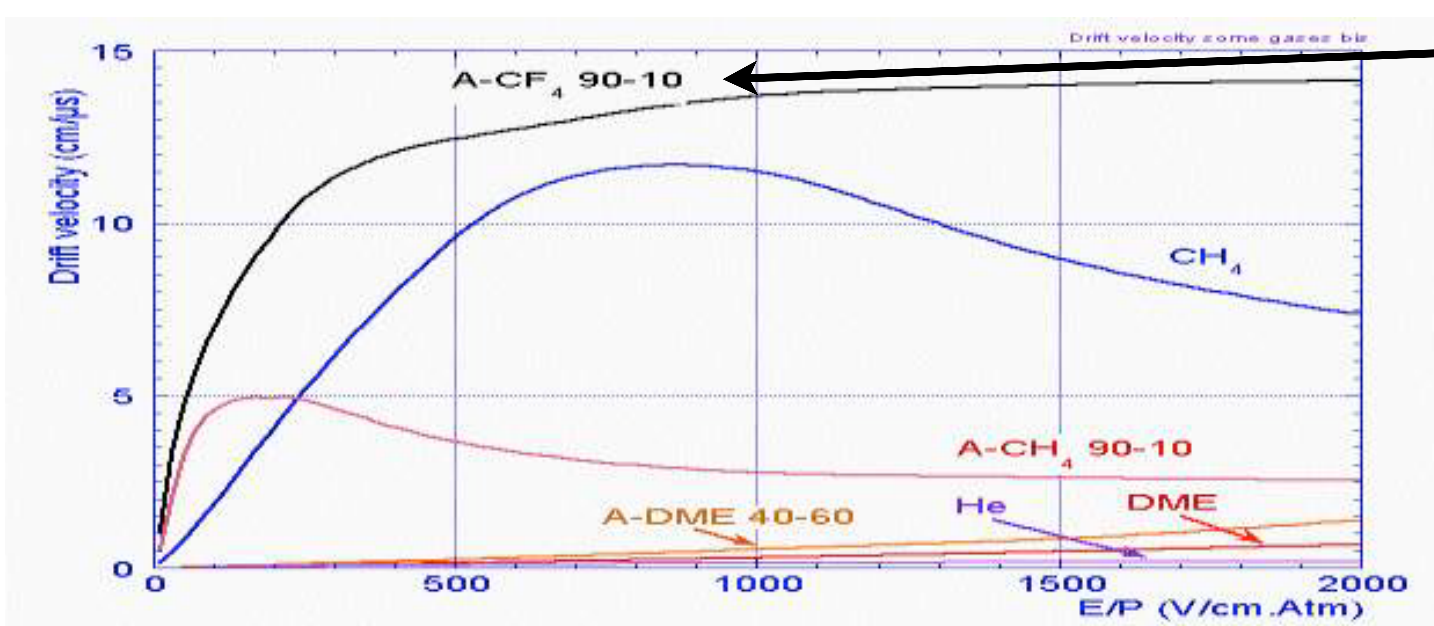
$$\langle n_T \rangle = \frac{L \cdot \left\langle \frac{dE}{dx} \right\rangle_i}{W_i}$$

[about 2-6 times n_p]
[L: layer thickness]

δ-electrons lead to secondary ionization and limit spatial resolution; typical length scale of secondary ionization: 10 μm. Example: kinetic energy: T_{kin} = 1 keV; gas: Isobutane ➛ range: R = 20 μm ...
[using R [g/cm²] = 0.71 $(T_{kin})^{1.72}$ [MeV]; valid for T_{kin} < 100 keV]

Gas	<Z>	ρ [g/cm³]	E_i [eV]	W_i [eV]	dE/dx [keV/cm]	n_p [cm⁻¹]	n_T [cm⁻¹]
He	2	$1.66\cdot10^{-4}$	24.6	41	0.32	5.9	7.8
Ar	18	$1.66\cdot10^{-3}$	15.8	27	2.44	29.4	94
CH_4	19	$6.7\cdot10^{-4}$	13.1	28	1.48	18	53
C_4H_{10}	34	$2.42\cdot10^{-3}$	10.6	23	4.50	46	195

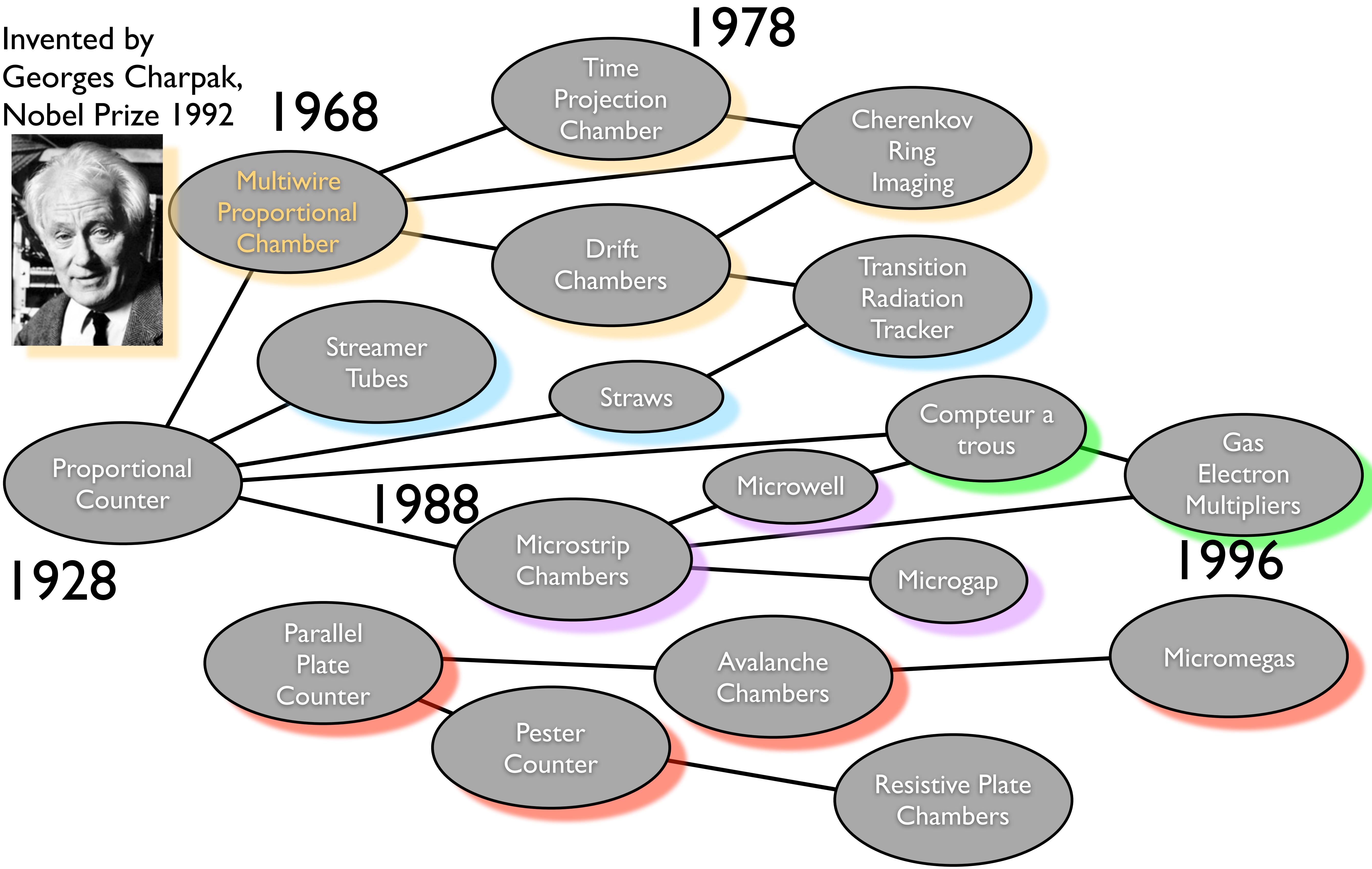
Drift velocity (and diffusion) of electrons
are gas mixture dependent
Electron drift velocity (w)
(τ : mean collision time)
w = e/2m Eτ



additional gases (as here CF4) are pollutants/ quenchers added on purpose eg. to speed up drift or to restric UV avalanches

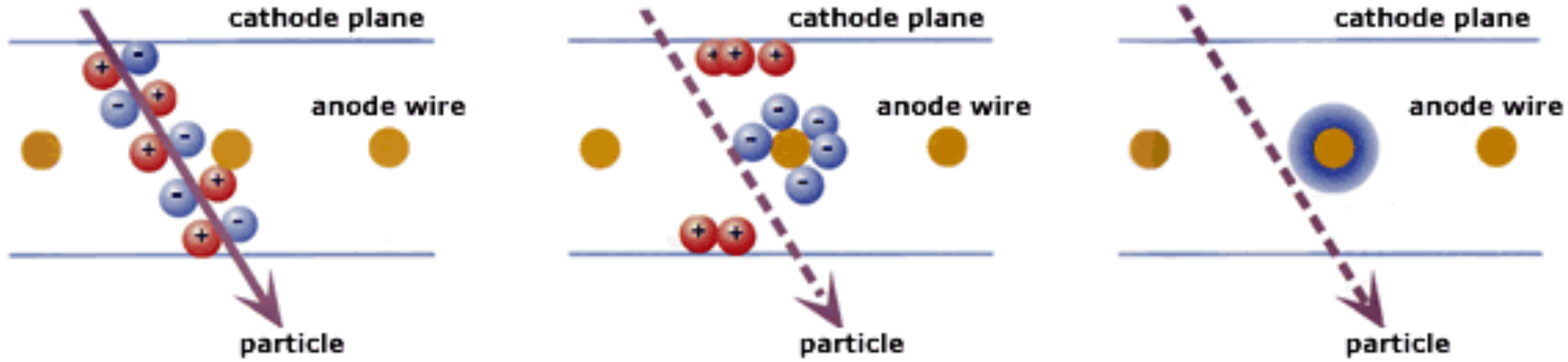
Gaseous particle detectors: a zoo

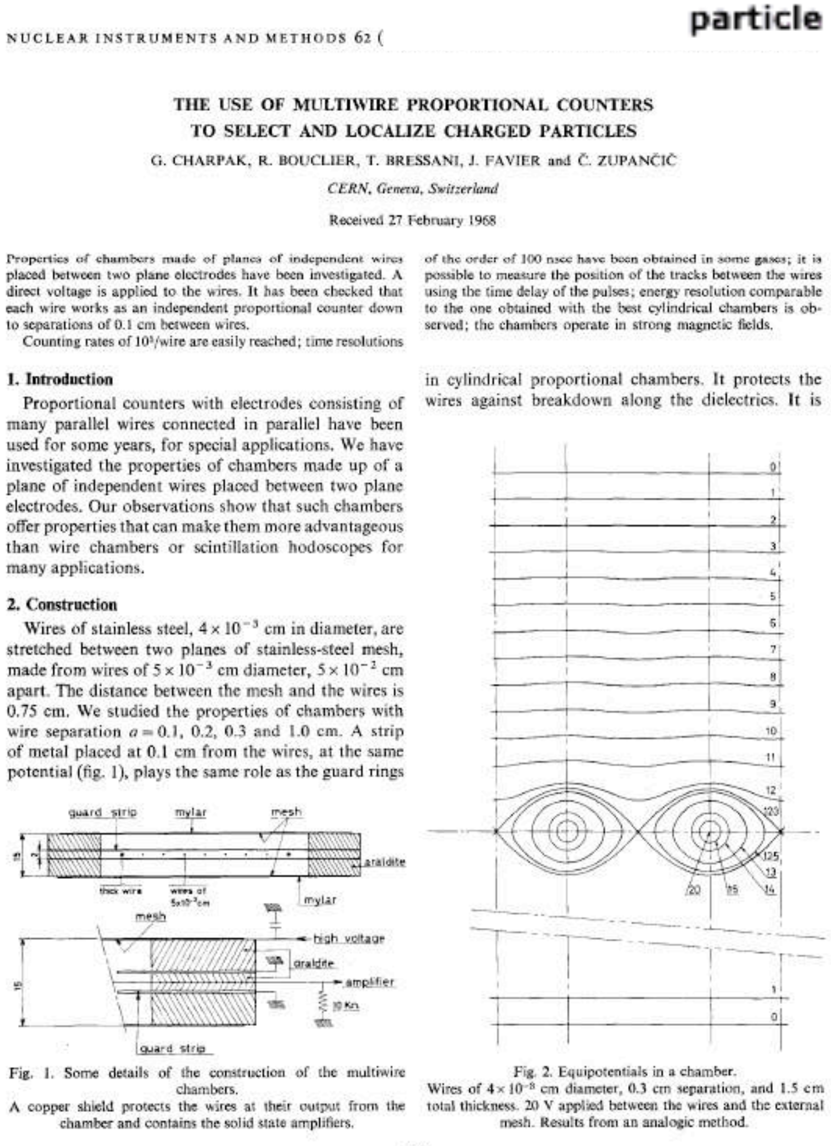
Invented by
Georges Charpak,
Nobel Prize 1992



Gaseous detectors for tracking particles - the first steps

- Multi-wire proportional chamber (MWPC)





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THE USE OF MULTIWIRE PROPORTIONAL COUNTERS TO SELECT AND LOCALIZE CHARGED PARTICLES

G. CHARPAK, R. BOUCLIER, T. BRESSANI, J. FAVIER and Č. ZUPANČIĆ

CERN, Geneva, Switzerland

Received 27 February 1968

Properties of chambers made of planes of independent wires placed between two plane electrodes have been investigated. A direct voltage is applied to the wires. It has been checked that each wire works as an independent proportional counter down to separations of 0.1 cm between wires.

Counting rates of 10^5/wire are easily reached; time resolutions of the order of 100 nsec have been obtained in some gases; it is possible to measure the position of the tracks between the wires using the time delay of the pulses; energy resolution comparable to the one obtained with the best cylindrical chambers is observed; the chambers operate in strong magnetic fields.

1. Introduction

Proportional counters with electrodes consisting of many parallel wires connected in parallel have been used for some years, for special applications. We have investigated the properties of chambers made up of a plane of independent wires placed between two plane electrodes. Our observations show that such chambers offer properties that can make them more advantageous than wire chambers or scintillation hodoscopes for many applications.

2. Construction

Wires of stainless steel, 4×10^{-3} cm in diameter, are stretched between two planes of stainless-steel mesh, made from wires of 5×10^{-3} cm diameter, 5×10^{-2} cm apart. The distance between the mesh and the wires is 0.75 cm. We studied the properties of chambers with wire separation $a = 0.1$, 0.2, 0.3 and 1.0 cm. A strip of metal placed at 0.1 cm from the wires, at the same potential (fig. 1), plays the same role as the guard rings in cylindrical proportional chambers. It protects the wires against breakdown along the dielectrics. It is

Fig. 1. Some details of the construction of the multiwire chambers.
A copper shield protects the wires at their output from the chamber and contains the solid state amplifiers.

Fig. 2. Equipotentials in a chamber.
Wires of 4×10^{-8} cm diameter, 0.3 cm separation, and 1.5 cm total thickness. 20 V applied between the wires and the external mesh. Results from an analogic method.

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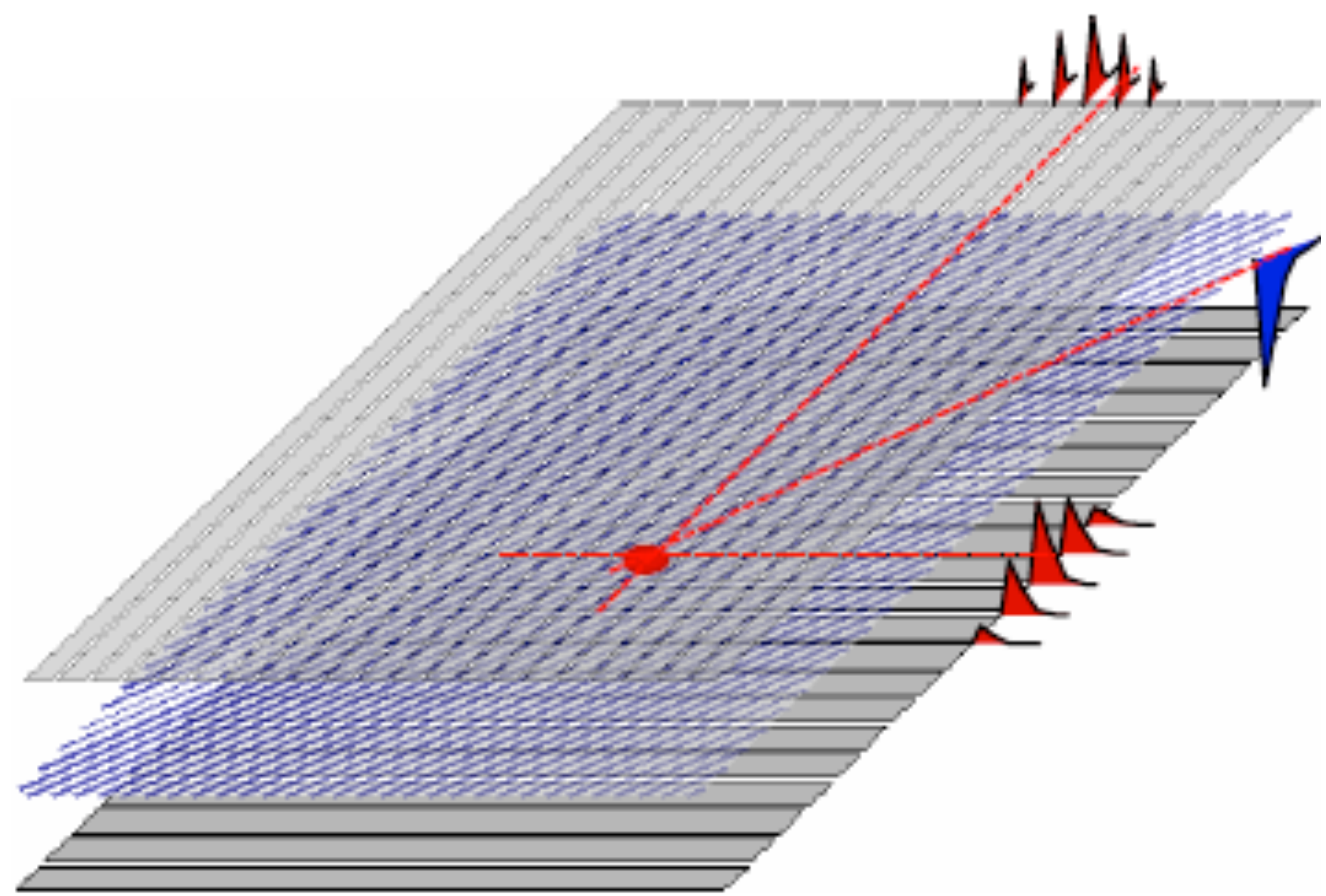
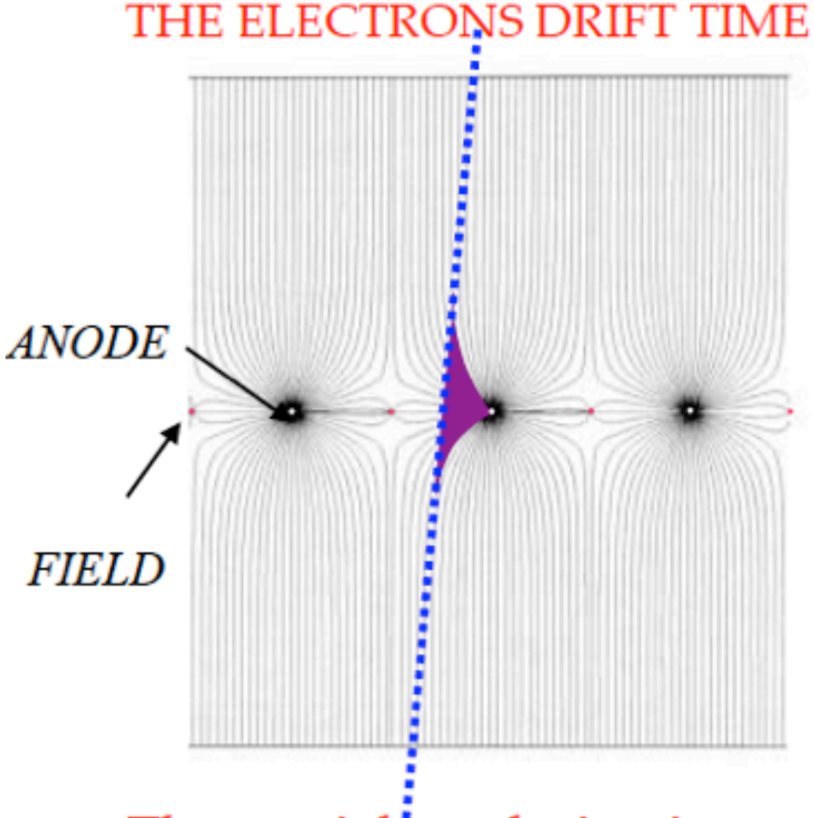


Drift chambers

FIRST DRIFT CHAMBER OPERATION (H. WALENTA ~ 1971)
HIGH ACCURACY DRIFT CHAMBERS (Charpak-Breskin-Sauli ~ 1973-75)

THE ELECTRONS DRIFT TIME PROVIDES THE DISTANCE OF THE TRACK FROM THE ANODE:



Measure drift time t_D
[need to know t_0; fast scintillator, beam timing]

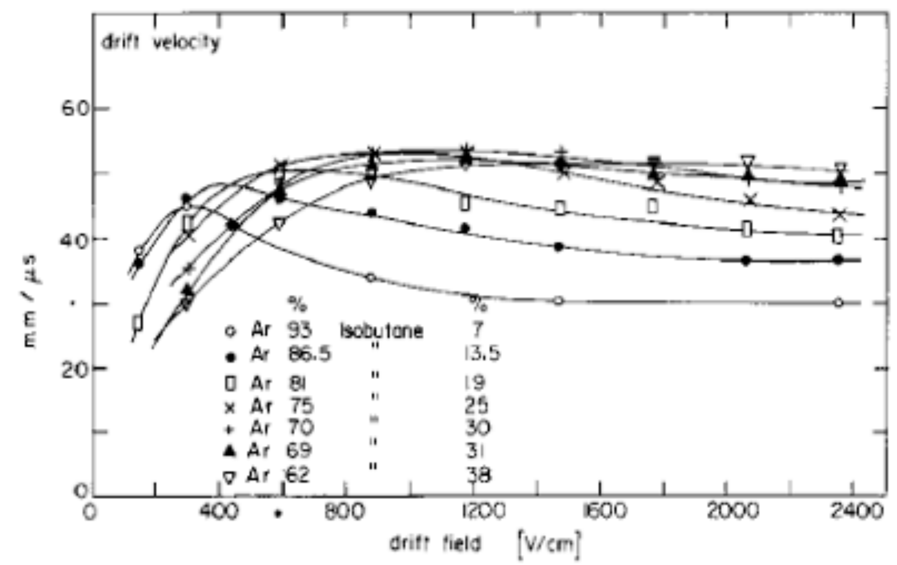
Determine location of original ionization:

$$x = x_0 \pm v_D \cdot t_D$$
$$y = y_0 \pm v_D \cdot t_D$$

If drift velocity changes along path:

$$x = \int_0^{t_D} v_D \, dt$$

In any case:
Need well-defined drift field ...

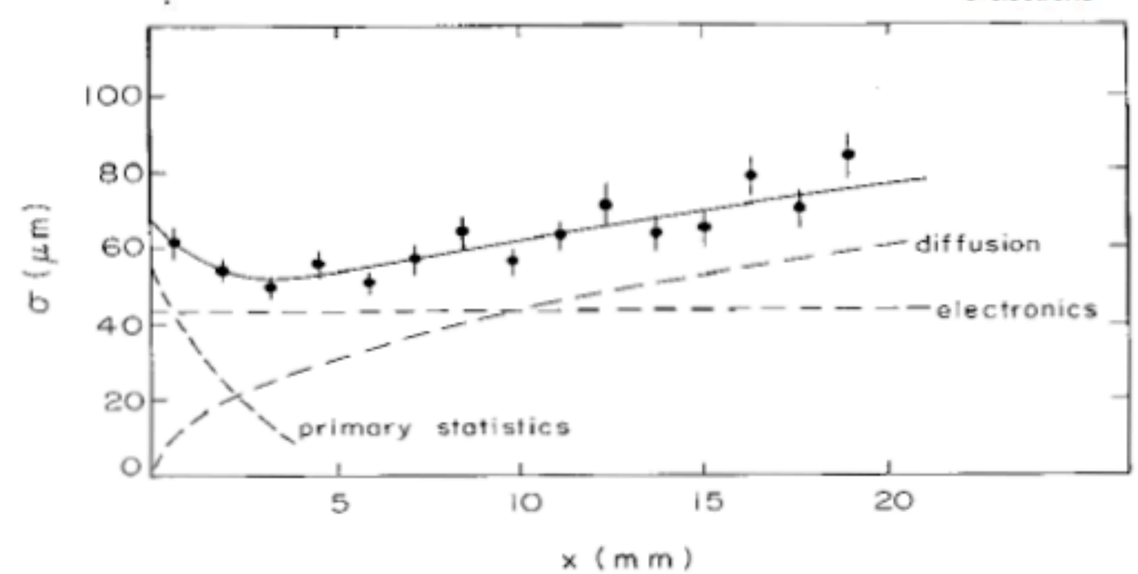


The spatial resolution is not limited to the cell size

$$\sigma_x^2 = \underbrace{\left(\frac{1}{64N^2}\right)\cdot\frac{1}{x^2}}_{\text{1st ionization statistics}} + \underbrace{\frac{2D}{v_d}\cdot x}_{\text{diffusion}} + \underbrace{\sigma_{\text{const}}^2}_{\text{electronics, δ-electrons}}$$

Factors affecting spatial resolution:

- Distribution of primary ionization
- Diffusion
- Readout electronics
- Electric field (gas amplification)
- Range of 'delta electrons'



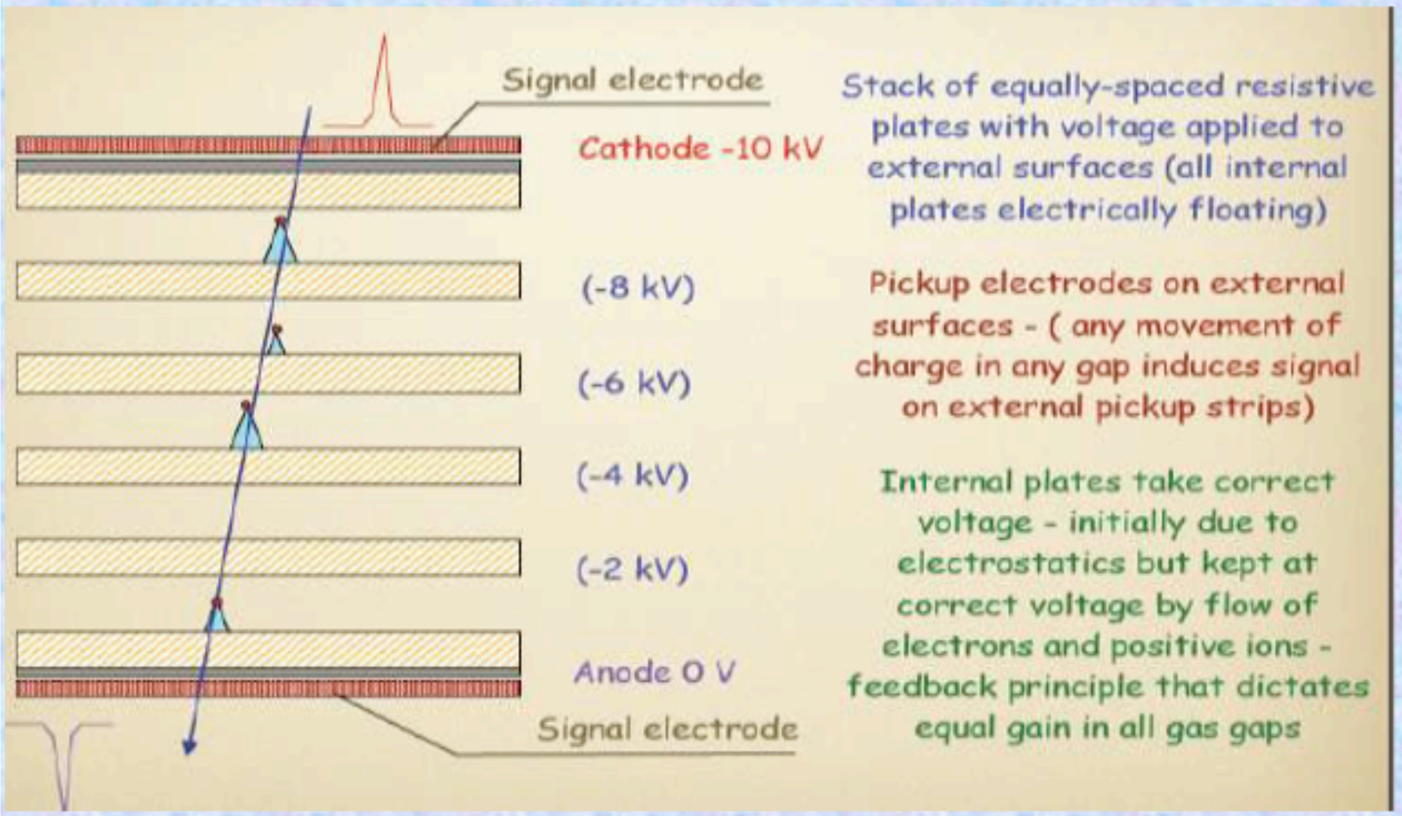
Timing is crucial (ALICE multi-gap RPC)

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

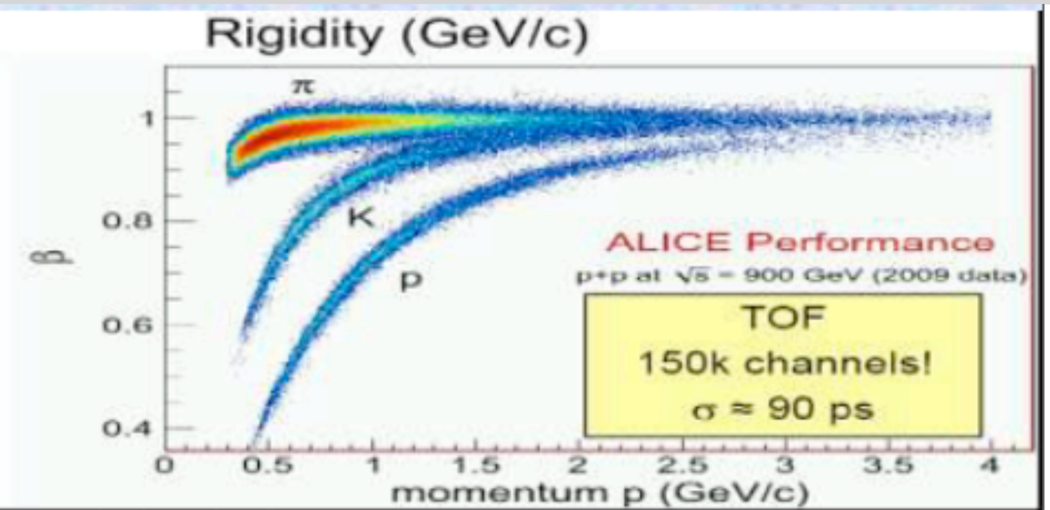
$$T_1 - T_2 = \frac{L}{c}\left(\frac{1}{\beta_1} - \frac{1}{\beta_2}\right) = \frac{L}{c}\left(\sqrt{1+m_1^2/p^2} - \sqrt{1+m_2^2/p^2}\right) \cong (m_1^2 - m_2^2)L/2cp^2$$

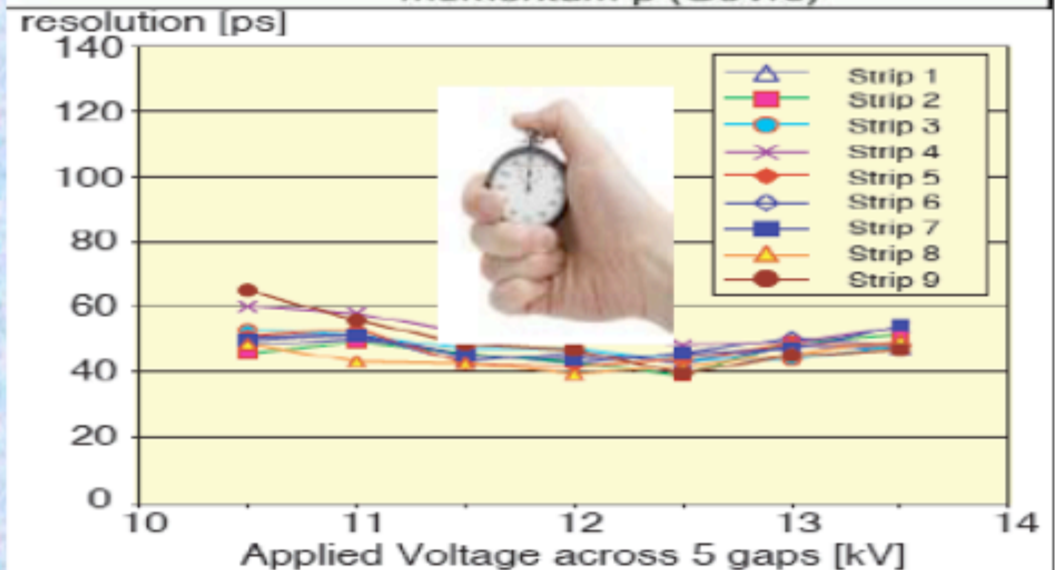
- Traditional technique:
  - Scintillator + PMT ~ *o* (100 *psec*)
- Breakthrough with a spark discharge in gas
  - Pestov counter → ALICE MRPC ~ 50*psec*

Multi-Gap Resistive Plate Chamber: Basic Principle



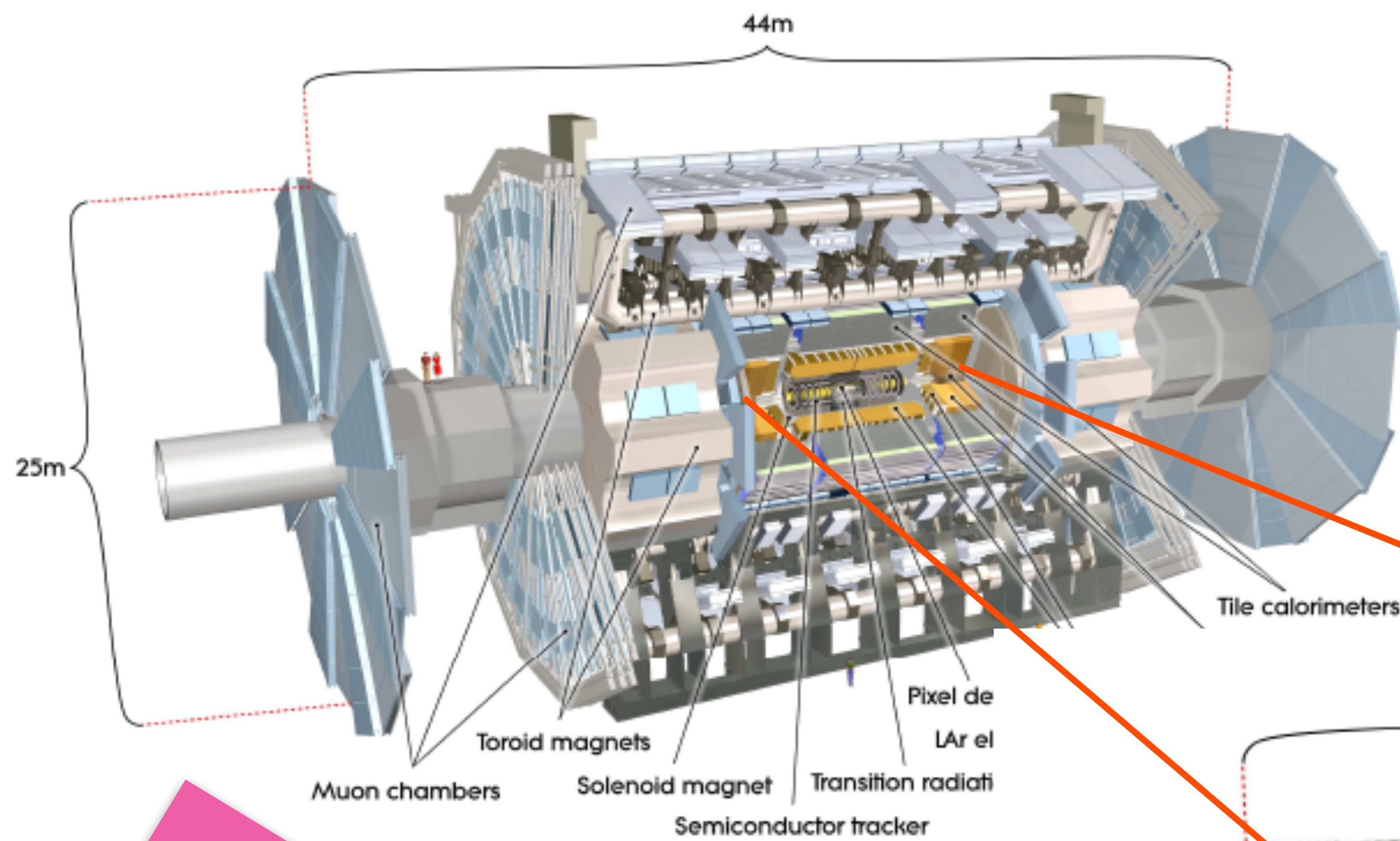
C. Williams, CERN Detector Seminar
"ALICE Time of Flight Detectors":
[http://indico.cern.ch/conference Display.py?confId=149006](http://indico.cern.ch/conferenceDisplay.py?confId=149006)





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)

The ATLAS Transition Radiation Tracker (TRT)

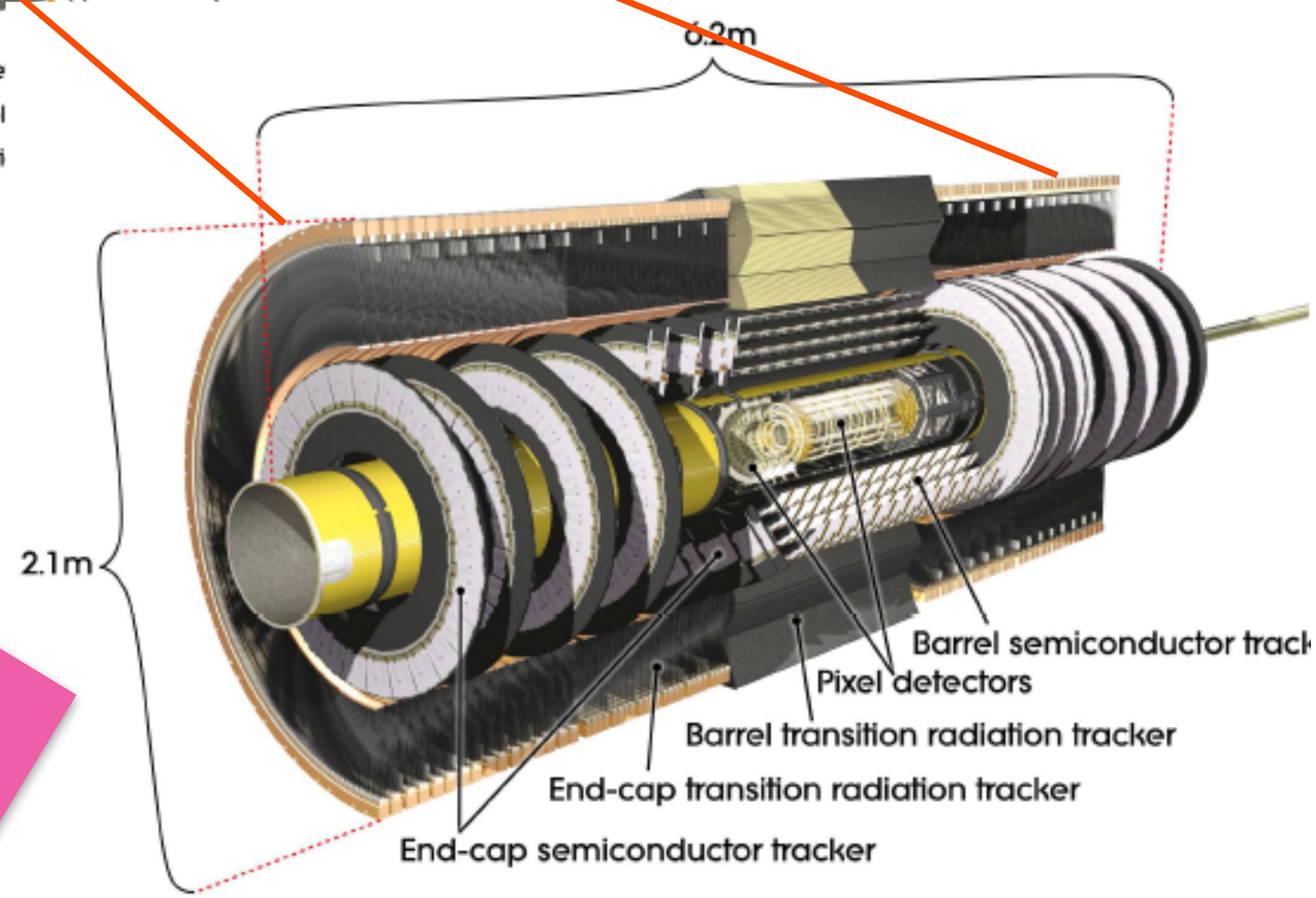


TRT is the outer part of the ATLAS Inner Tracking Detector

➙ measures charged particle tracks with momenta >0.5 GeV;

➙ identifies electrons with momenta between 1 and 150 GeV

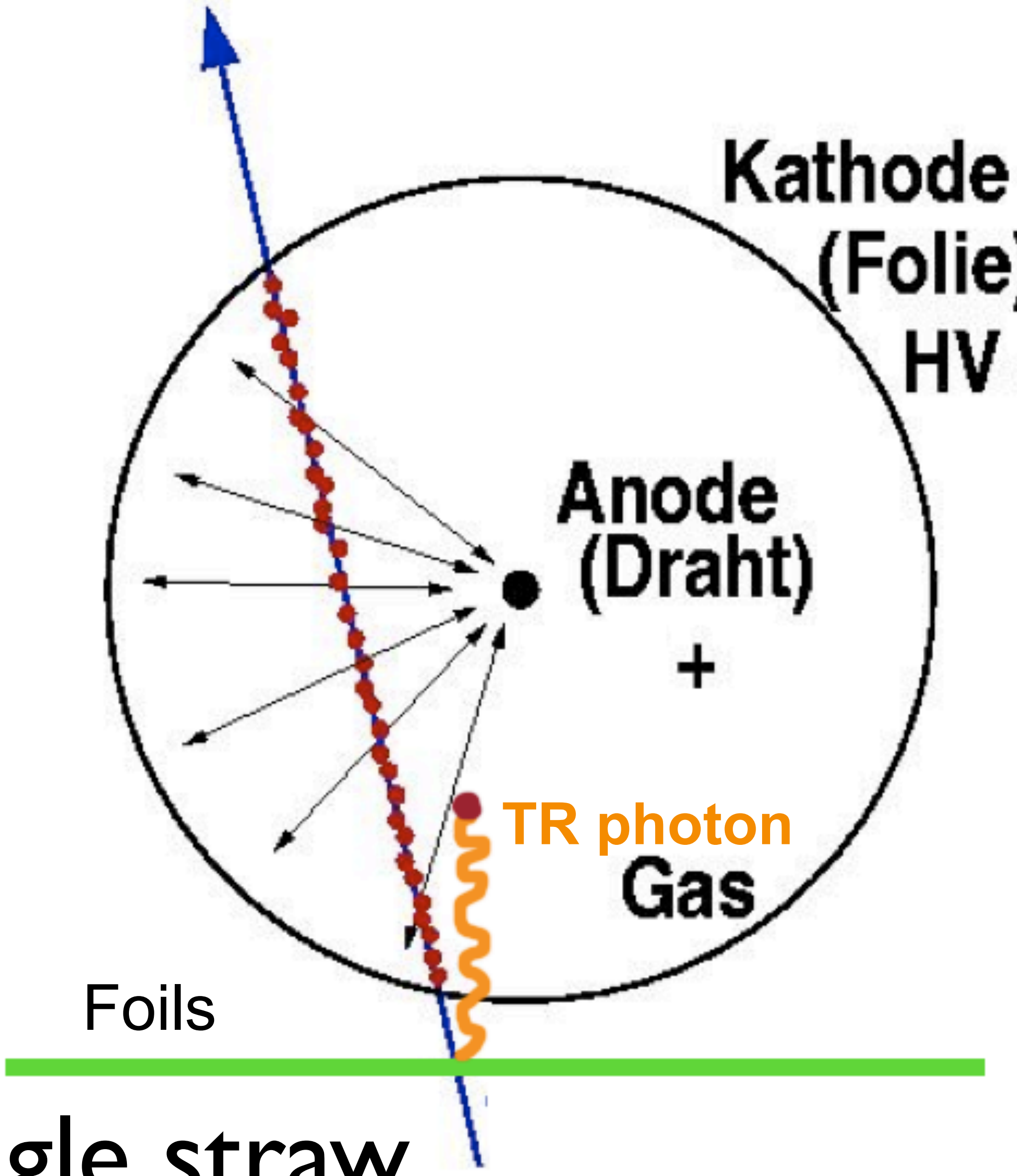
➙ works within a 2T magnetic field



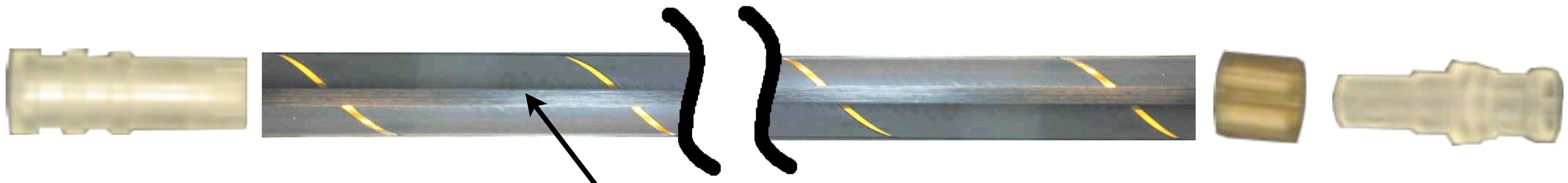
Another challenge:
tracking and particle identification
at the LHC

The ATLAS TRT

- Transition radiation -> X-ray photon is emitted when charged particle traverses boundary of materials with different di-electrical properties
- Depends strongly on the relativistic factor of the particle which makes it usable for particle identification
- used at LHCb, ATLAS
- advantages: additional info to tracking: ⇒ particle identification
  - not (too) expensive
  - robust (assembly & transport)
- ATLAS Transition Radiation Tracker
  - 35 track points



A single straw



stiff straw, supported by **carbon fibre strips**, allows self supporting structures, thus reduced material inside the detector

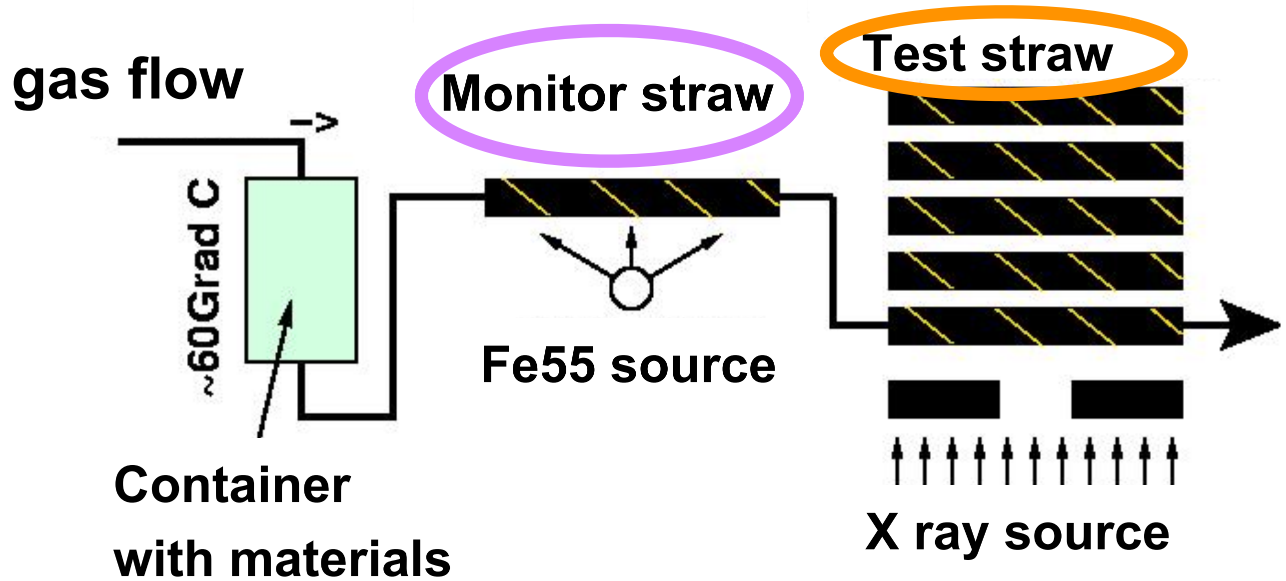
The history of an LHC detector

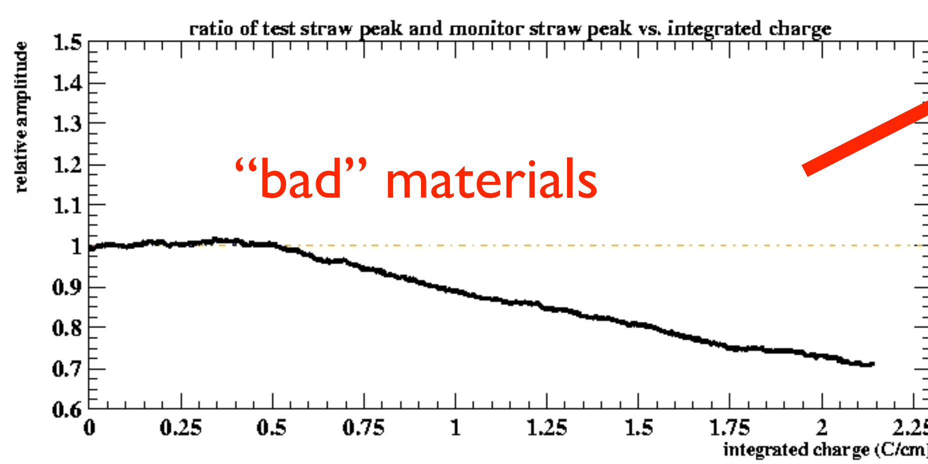
Example: the ATLAS TRT

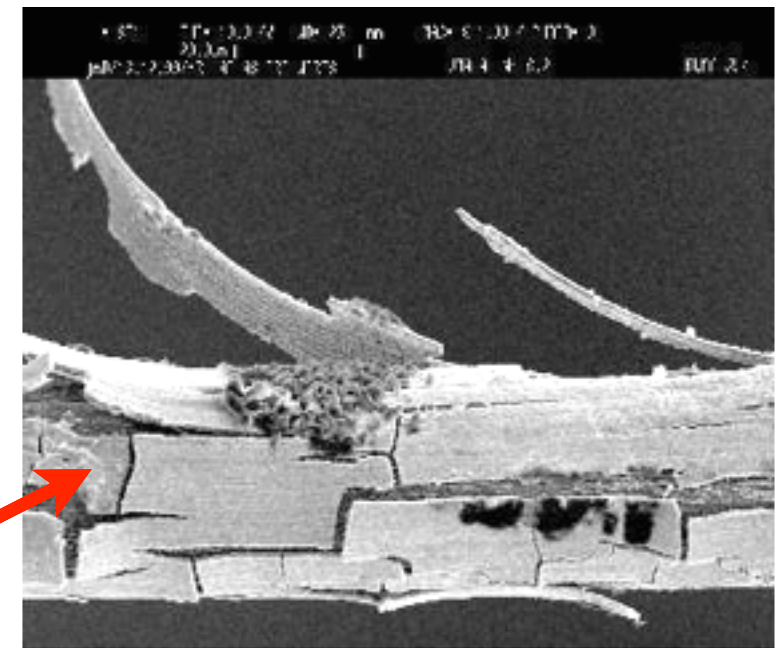
- 1989: R&D for the TRT begins (1990: RD6)
- 1994: LHC machine approved. First full-size TRT prototype completed (10'000 channels for end-cap wheel)
- 1996-1998: major Technical Design Reports for ATLAS construction approved, test beams
- 2000: assembly of barrel modules and end-cap wheels start.
  Front-end electronics specified and vendor chosen.
- 2002: wire-joint trouble
- 2003-2004: web trouble
- 2000-2007: many other troubles
- 2006: first cosmic tracks recorded
- 2006: installation of barrel ID in ATLAS
- 2007: installation of ID end-caps in ATLAS
- 2008: TRT routinely operated, first LHC beam seen (beam splashes)
- 2009: first proton collisions recorded
- 2010: first high energy proton collisions

Mandatory for detectors in high radiation environment (as the LHC): test of materials

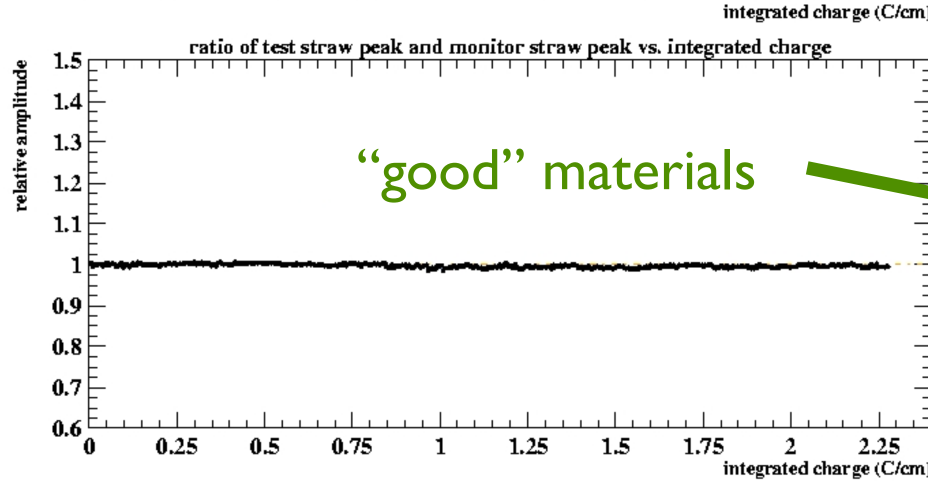
Example: tests for radiation hardness of all TRT materials

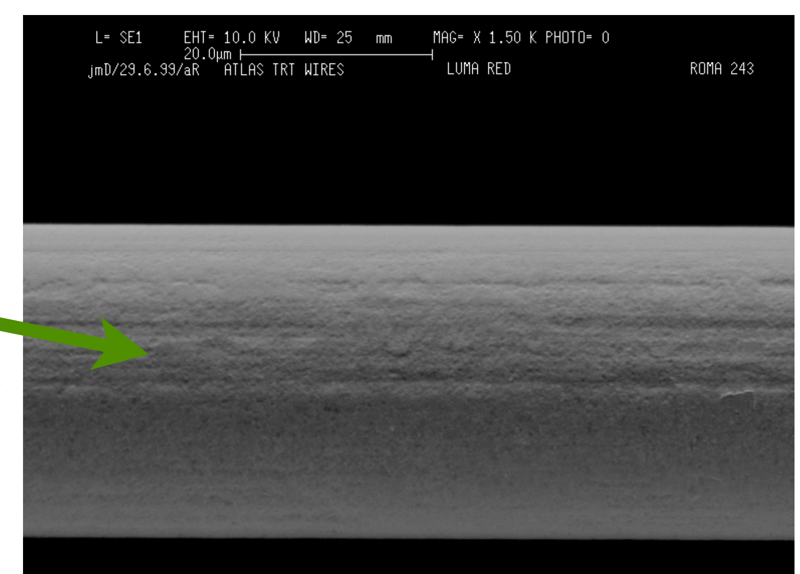






Check ratio of height of signal amplitude for test straw (radiated) and monitor straw (not radiated)

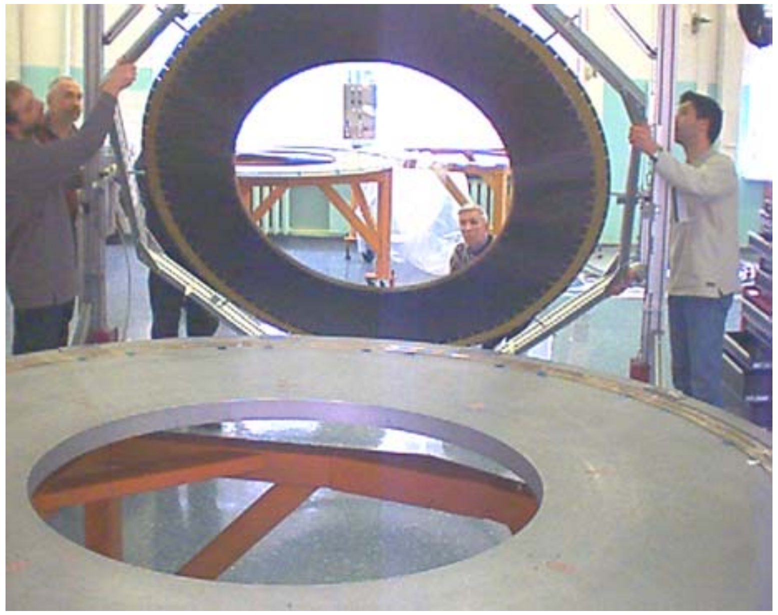




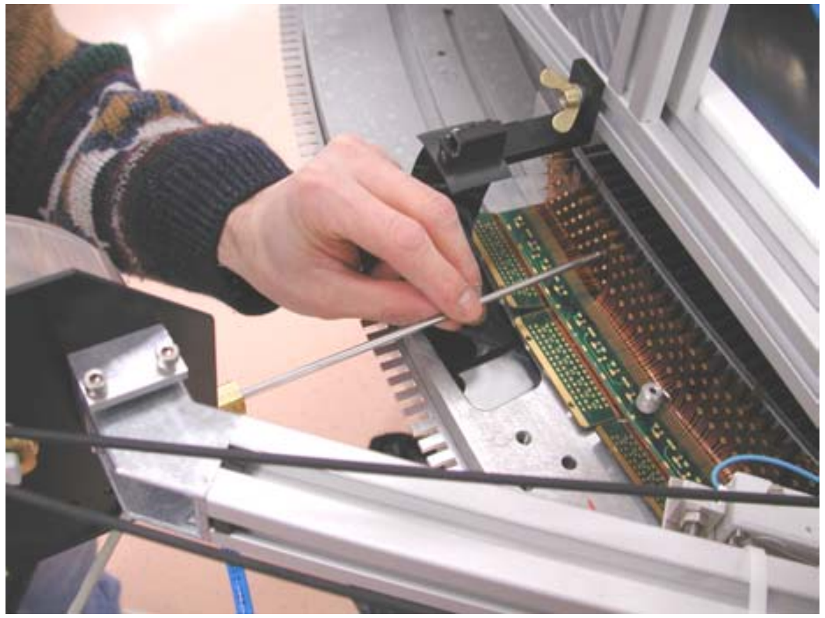
TRT end cap wheel production

- basic element: wheel with 4 straw planes

Installation of straws (tests leak tightness)

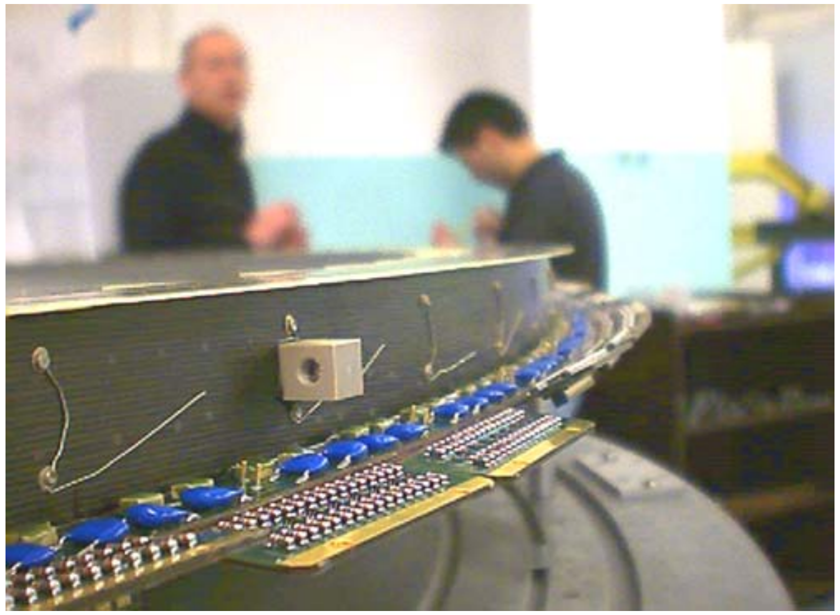


Transfer of wheel…

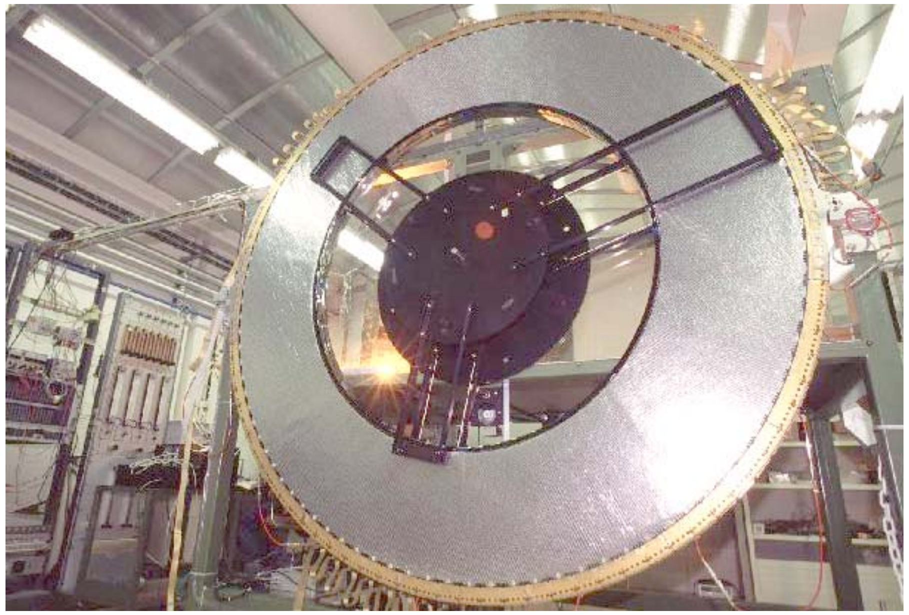


…to string wires

Fixating and connecting wires (tests wire tension & HV)



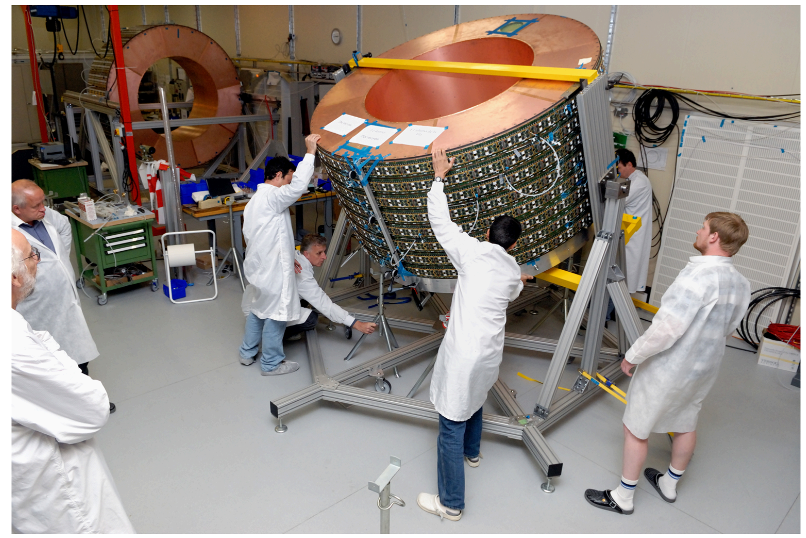
Sealing of wheel (tests leak tightness & HV)



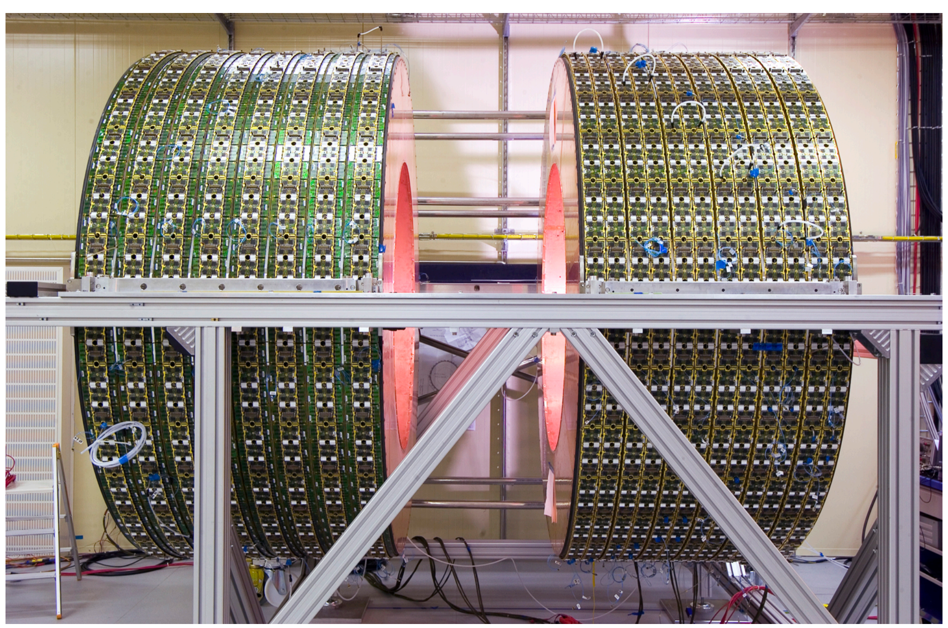
Final acceptance tests (test wire centricity etc.)

Mounting TRT end cap

After the wheels have been stacked...

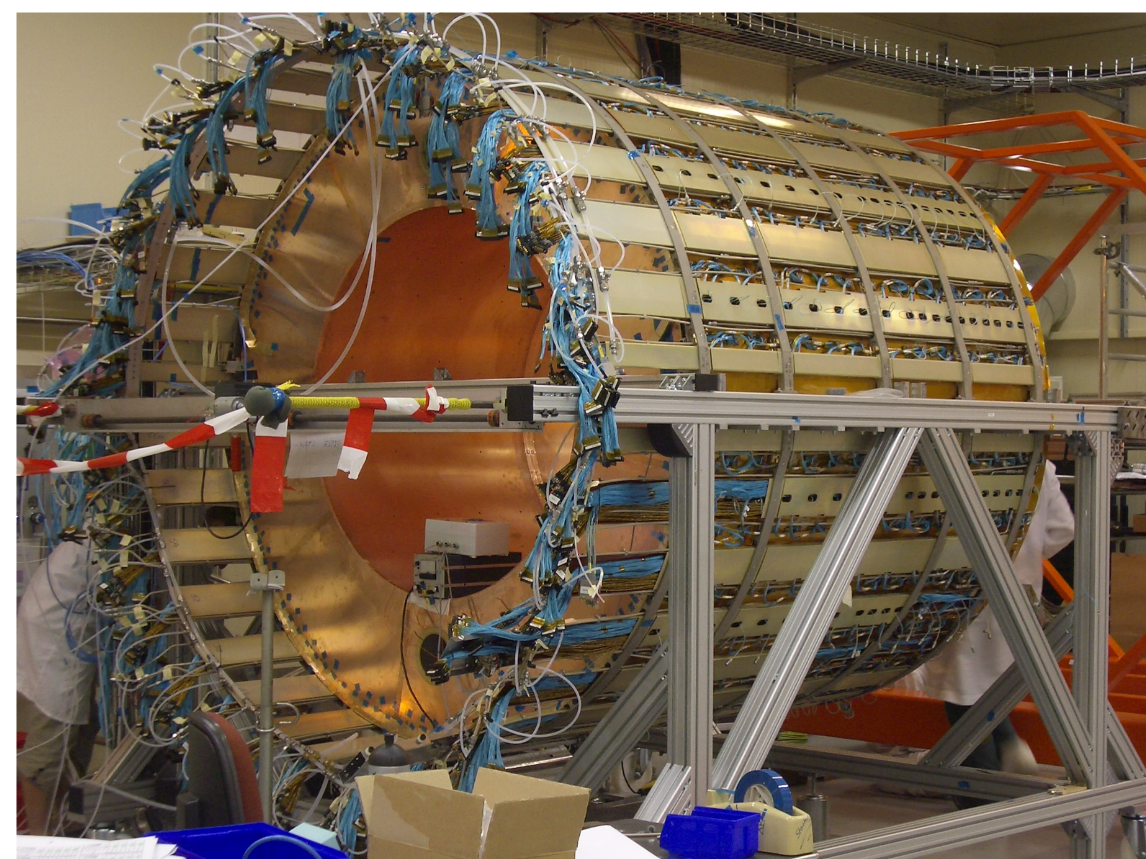


...the stack is rotated.



The two stacks of an end cap

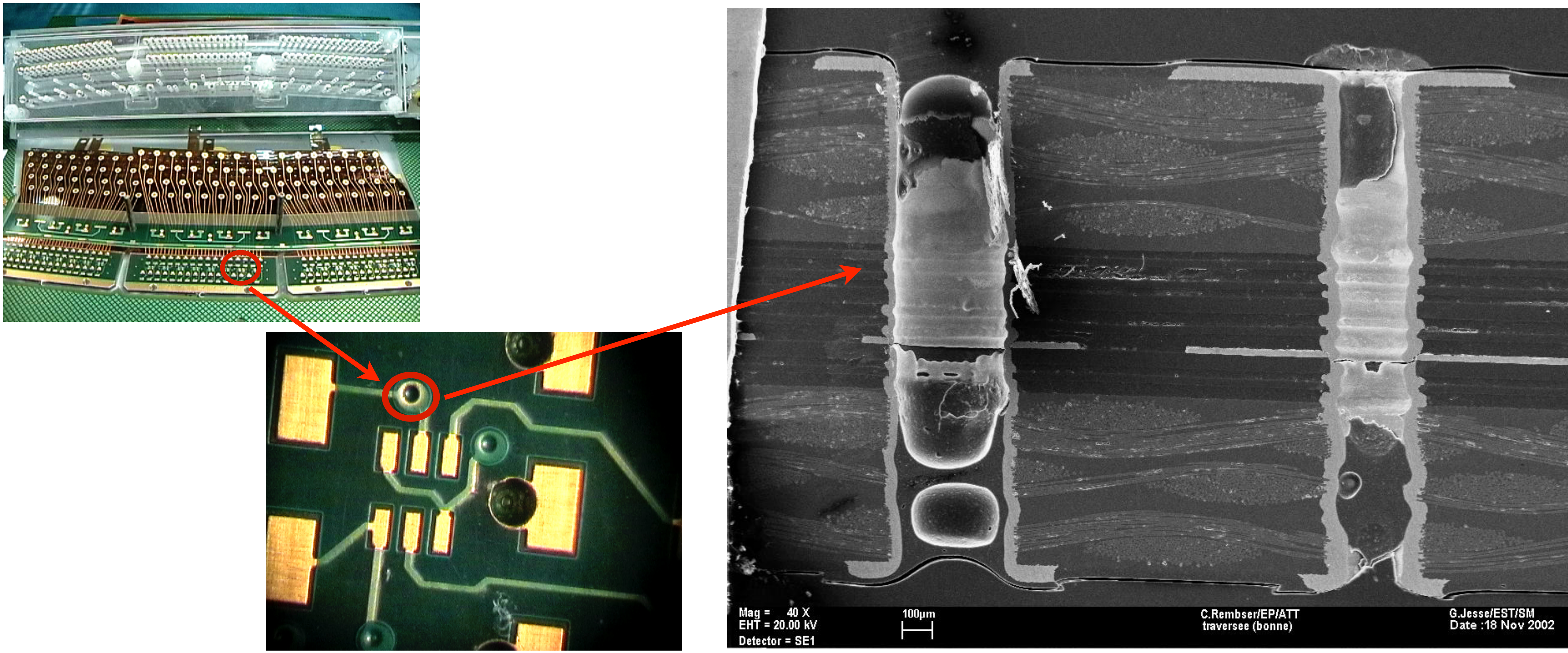
The ready end cap, with all cables, pipes and supports (0.8% dead channels; ~50 man years of work)



Bad surprises (1)

- Wheel end cap electronics boards
  (connecting straws to HV, read-out and main mechanical structure of end-caps)

  ➡ many problems during production and manufacturing

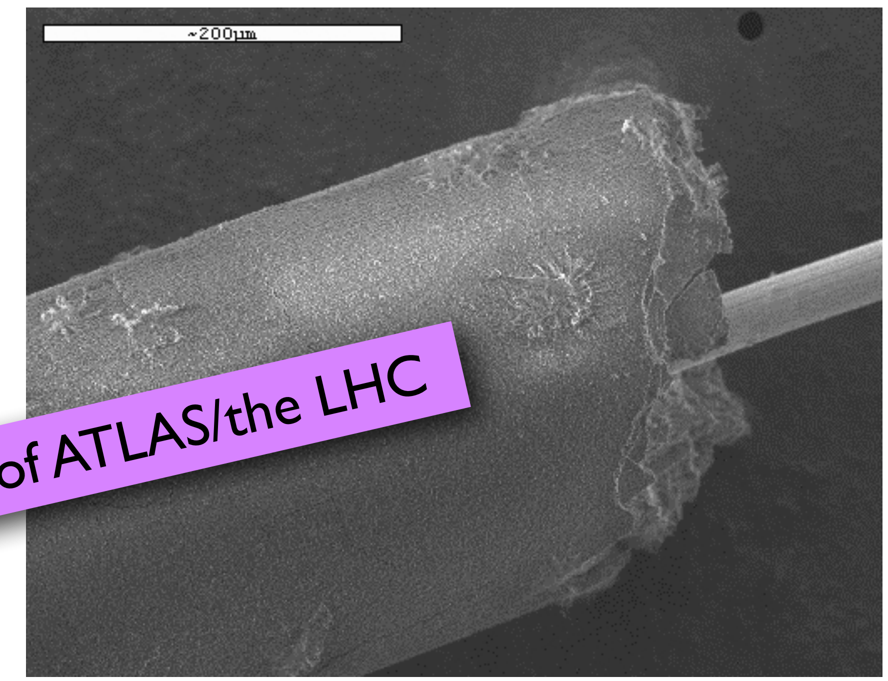


When building detectors

- ensure excellent quality control!!!
- ensure good contact to production companies!!!

ATLAS TRT: bad surprise during assembly

- Original TRT gas mixture (70% Xe, 20% **CF_4**, 10% CO_2) was destroying the detector (2002)
  - ➡ glass wire joints of barrel TRT "melting" with radiation 0.3-04 C/cm, less than 1 year nominal LHC operation
  - ➡ Reason: hydrofluoric acid HF

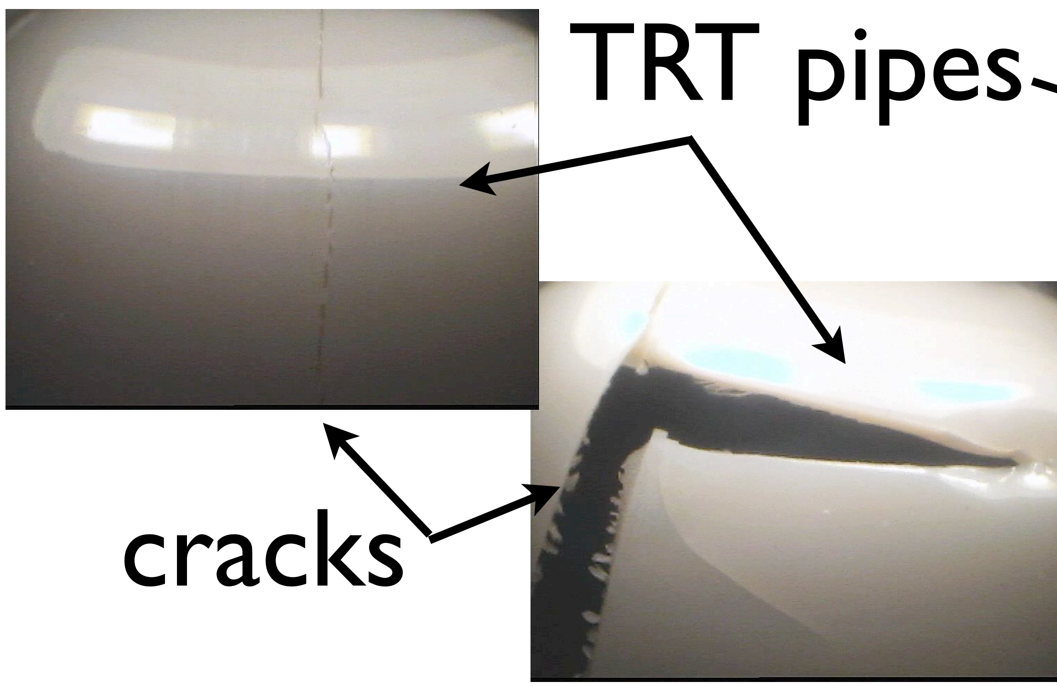


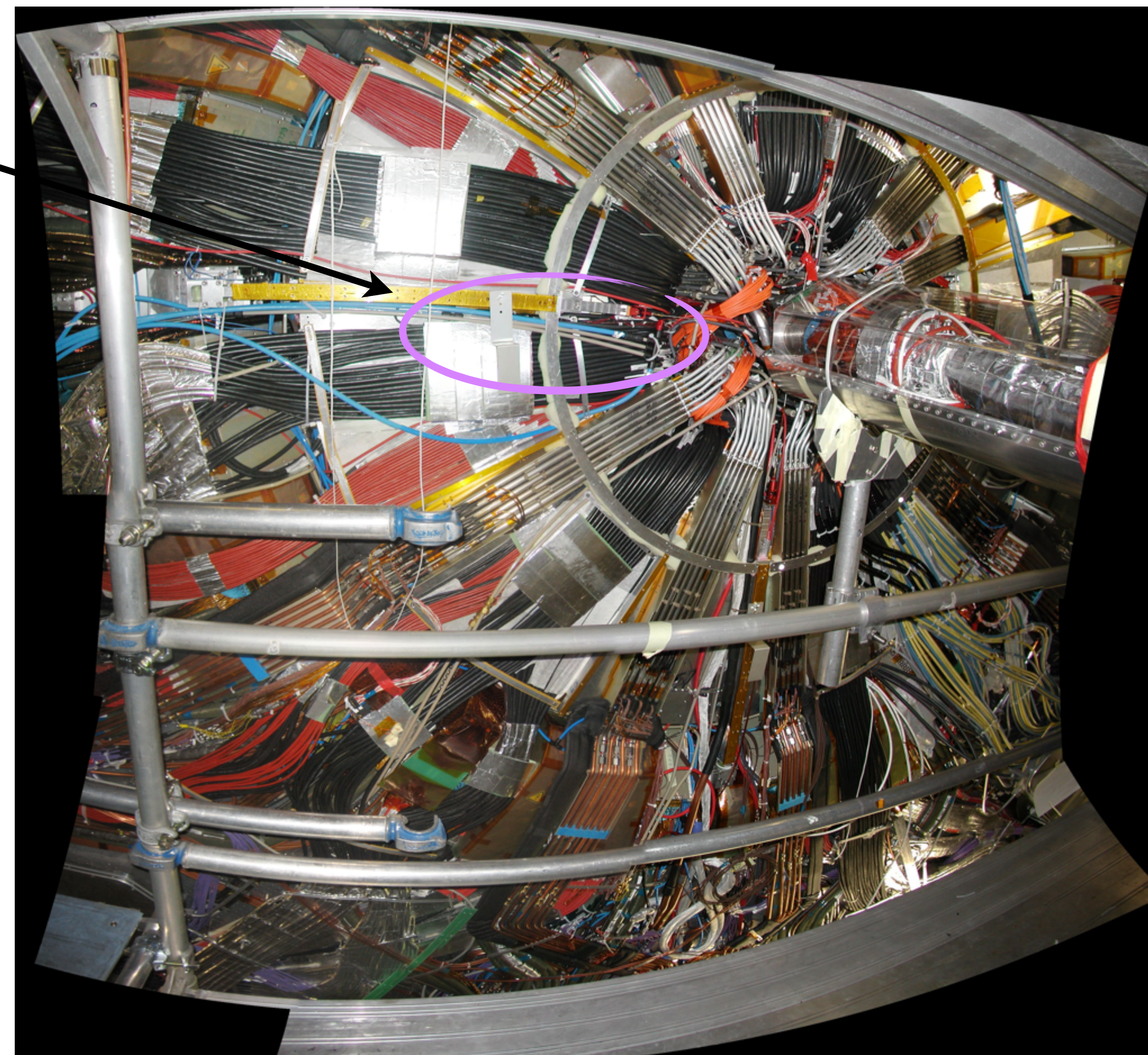
One of CRs personal nightmares of ATLAS/the LHC

- Within one year, a new mixture was developed 70% Xe, 27% CO_2, 3% **O_2**
  - ➡ O_2 very unusual, strong quencher ("eats" electrons)
  - ➡ only works for TRT as straws have small diameter (we are very lucky!)

BUT...

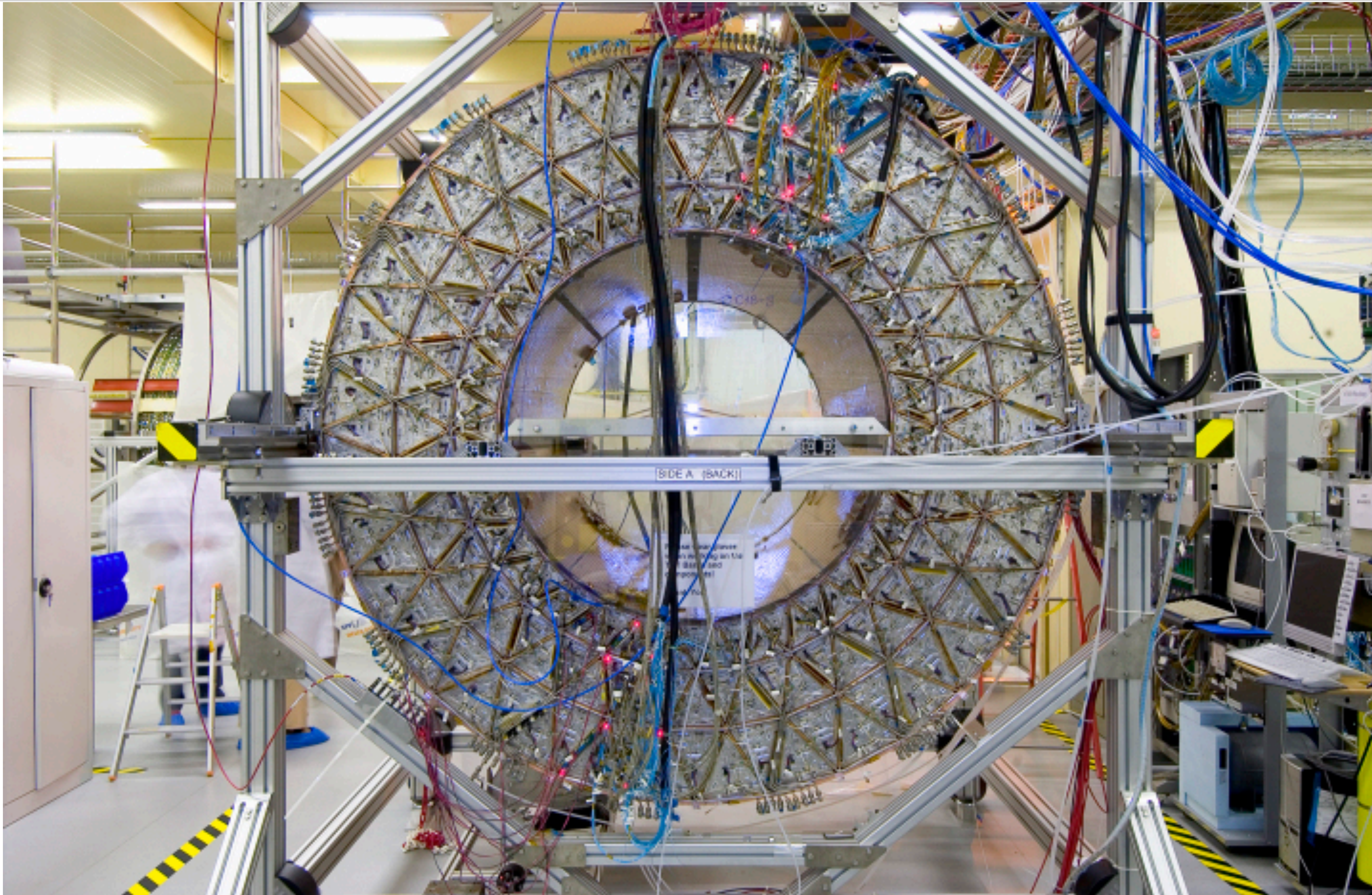
- Cracks in outlet pipes of active gas developed in 2012
  - ➡ gas losses: 150l/day instead of <0.5l/day up to 2011;
  - ➡ reason: aggressive ozone produced when active gas mixture is radiated, ozone attacks plastic gas pipes (although plastic material has been validated - but material seem to have changed properties when being heated and bent....)
  - ➡ hope to fix leaks during LS1...



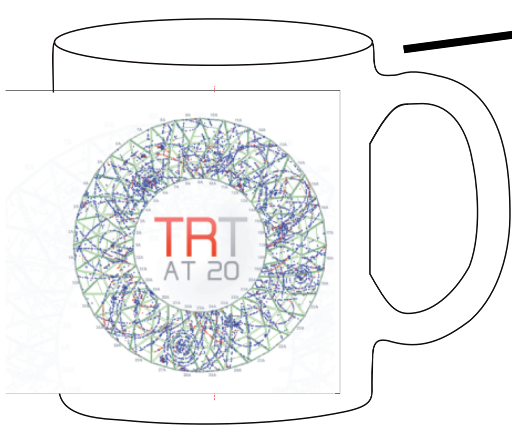


Difficult to access!!!
Might be necessary to switch to cheaper Ar based gas mixture in the future.

The ATLAS TRT: inspired by a historical design?



A supporter of the ATLAS TRT

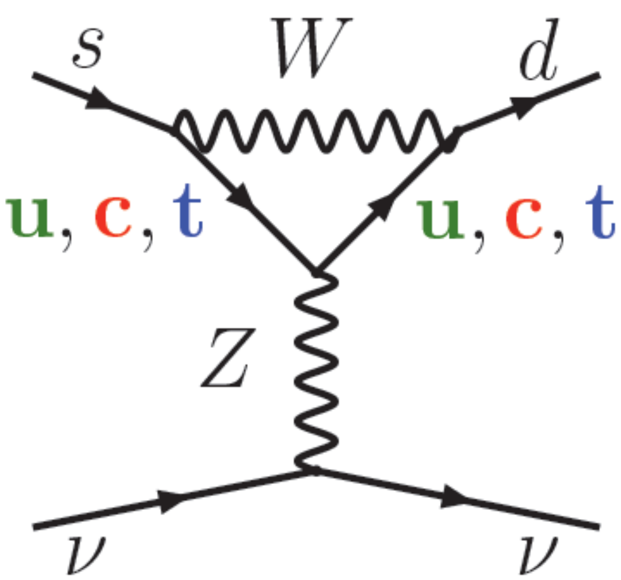


TRT coffee mug

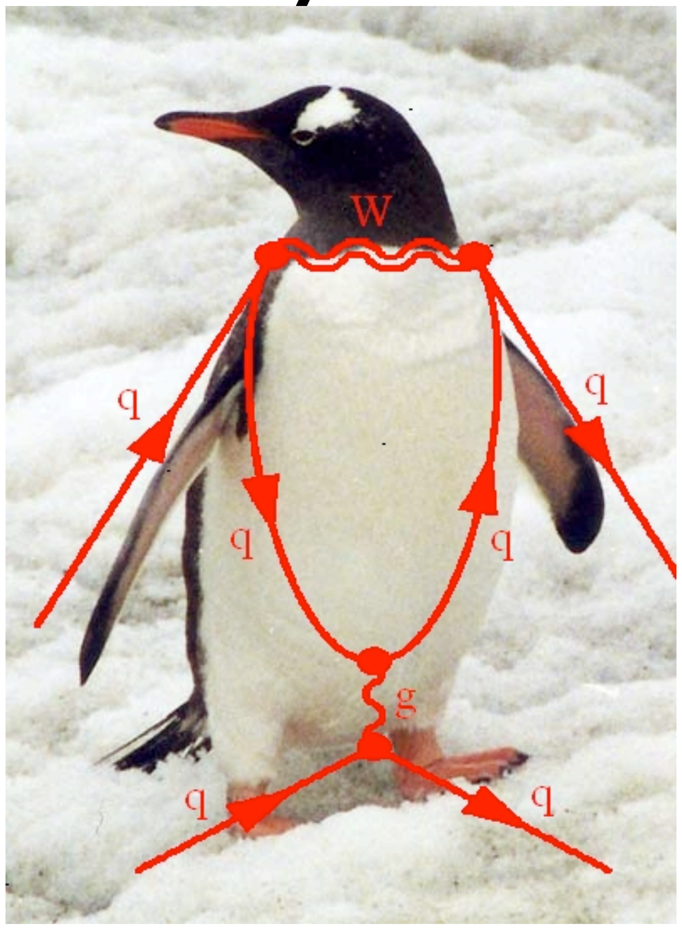
Probing the Standard Model

- NA62 is searching for ultra-rare kaon decays

$K \to \pi \nu \bar{\nu}$

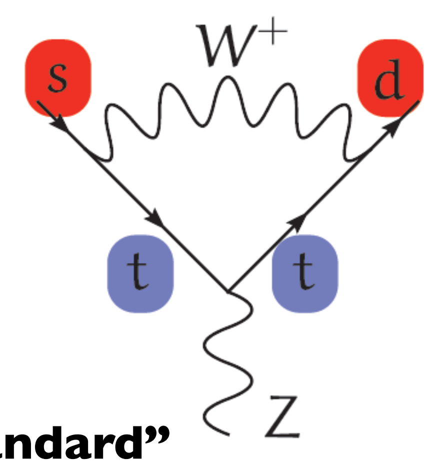


...so-called "penguin graph"

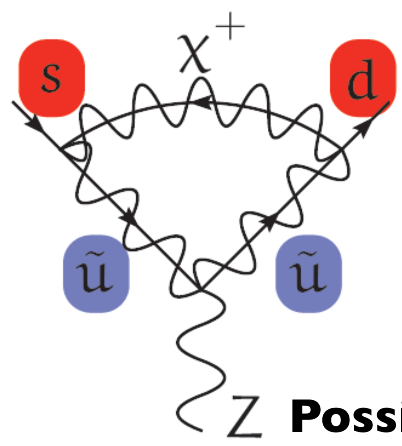


The contribution to these processes due to the Standard Model is **strongly suppressed (<10^{-10})** and **calculable with excellent precision (~%)**

They are very sensitive to possible contributions from **New Physics**



"Standard" Penguin

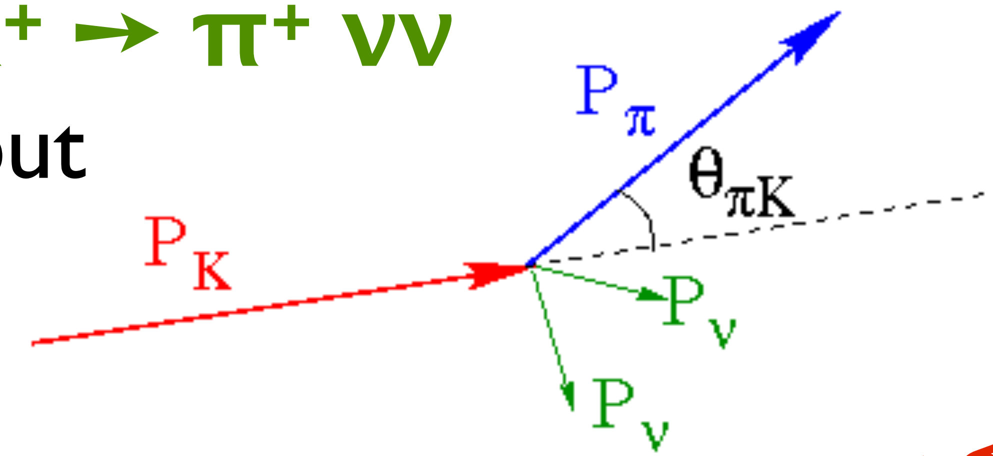


Possible "Super-Symmetric" Penguin

N62: experiment to measure rare kaon decays

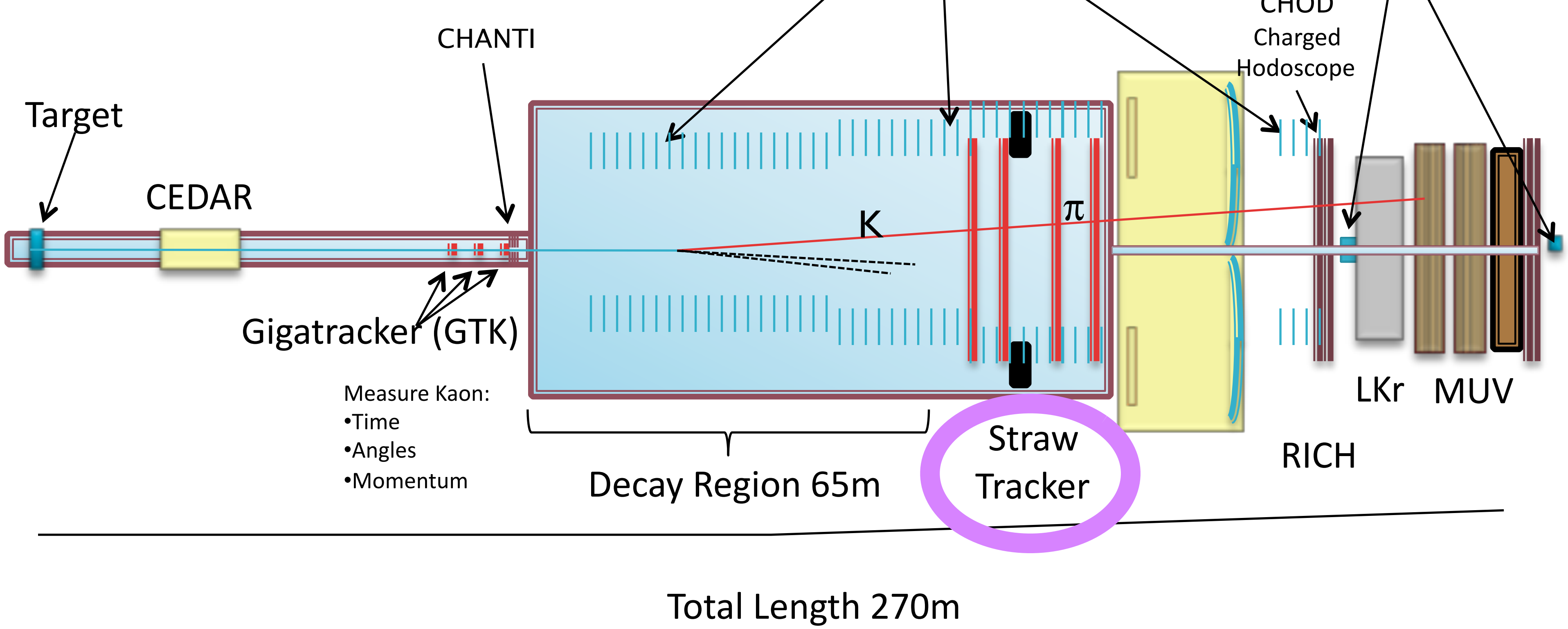
Need gaseous detector!

Goal of the experiment:
Measure rate of rare kaon decay $K^+ \rightarrow \pi^+ \nu\nu$
Rate in Standard Model: ~O(10^{-6}) but much enhanced when there is physics beyond the SM



Main background
$K^+ \rightarrow \pi^+ \pi^0$

SPS primary p: 400 GeV/c
Unseparated beam:
- **75 GeV/c**
- **750 MHz**
- **π/K/p (~6% K⁺)**



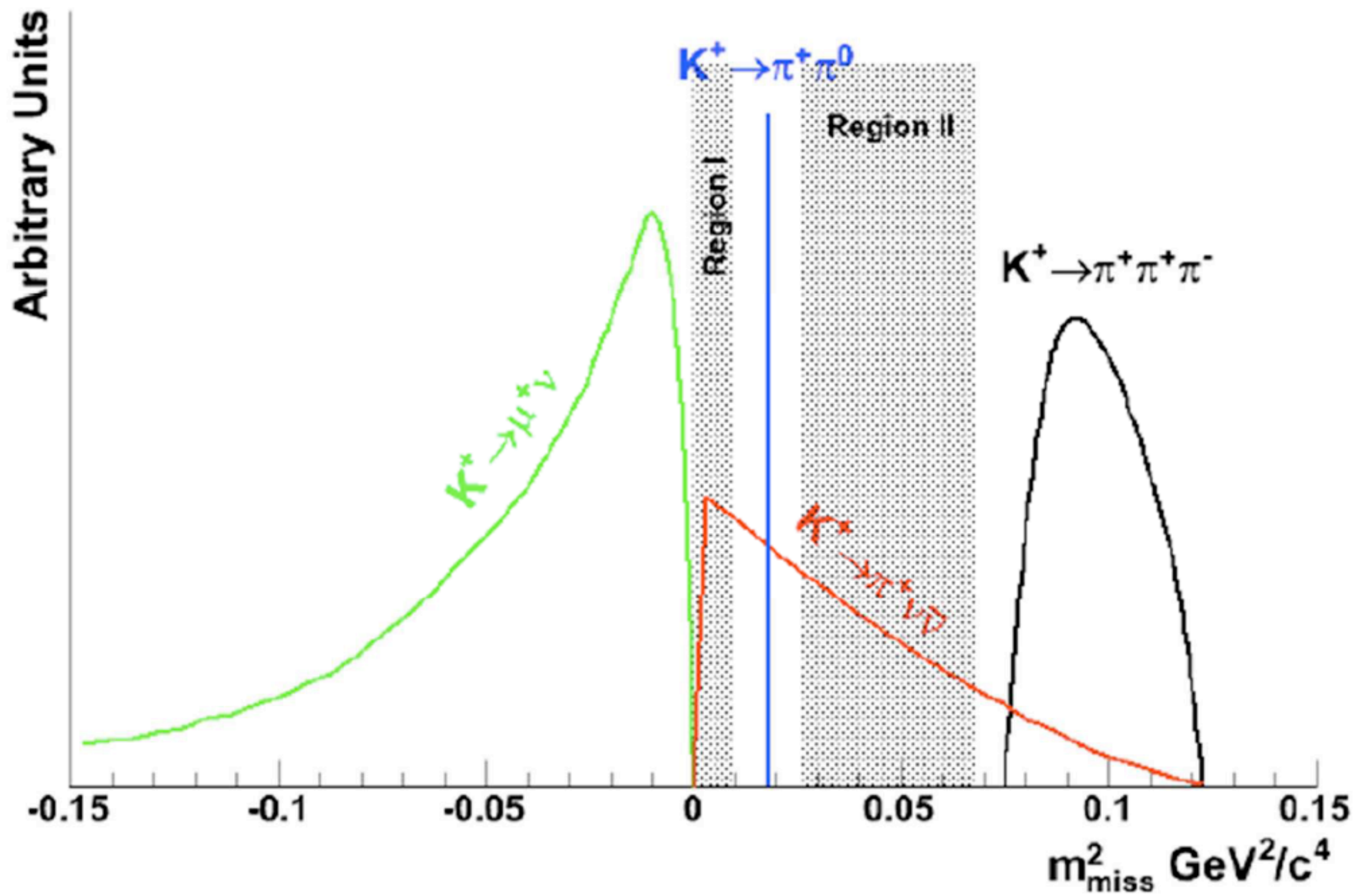
Beam line:
- CEDAR: K ID
- Gigatracker: beam particle ID
- CHANTI: Charged particle veto

Detector region:
- pion tracks: straws
- particle ID: LKr, RICH
- muon rejection: MUV
- photon rejection: LKr, LAV, SAV

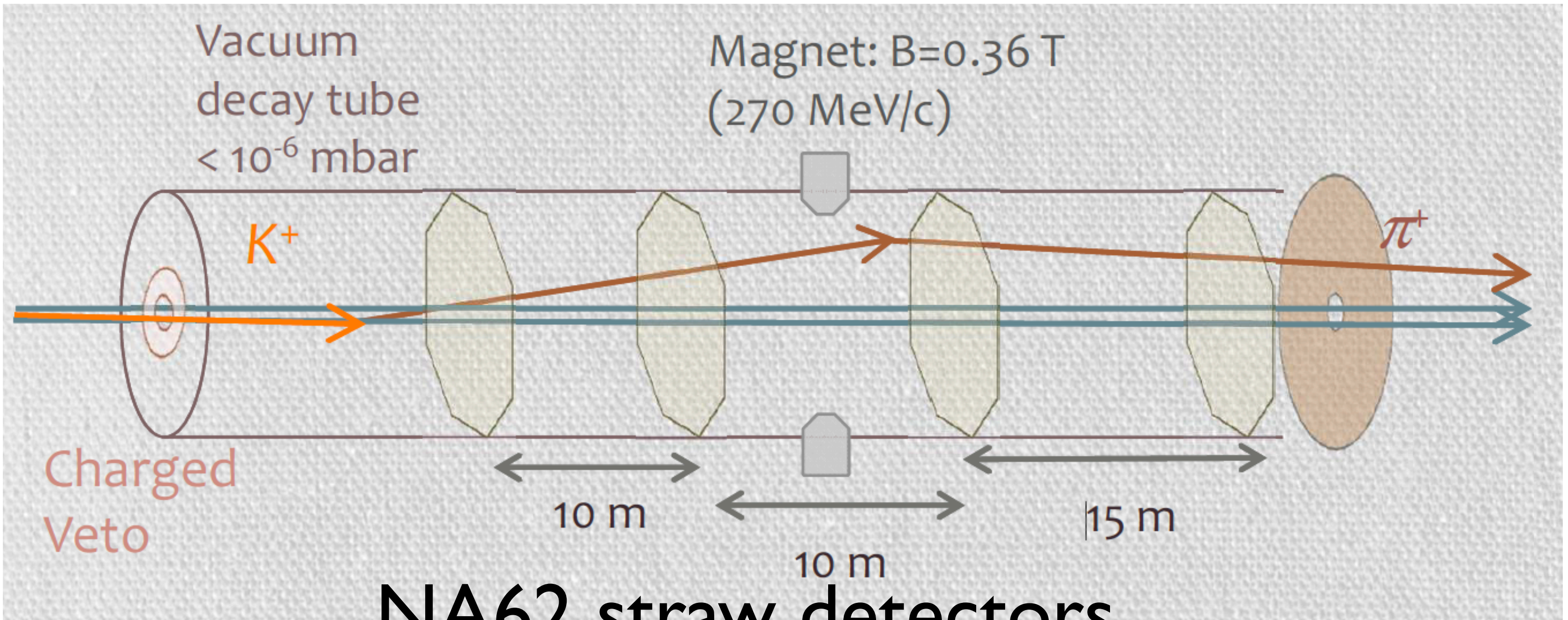
- K+ rate: 11 kHz

Kinematical rejection $M^2_{miss}=(P_K-P_{Track})^2$

Compute the missing mass using hypothesis that the particle is a pion →



- kaon momentum P_K measured by Gigatracker
- pion momentum P_{Track} measured by straws

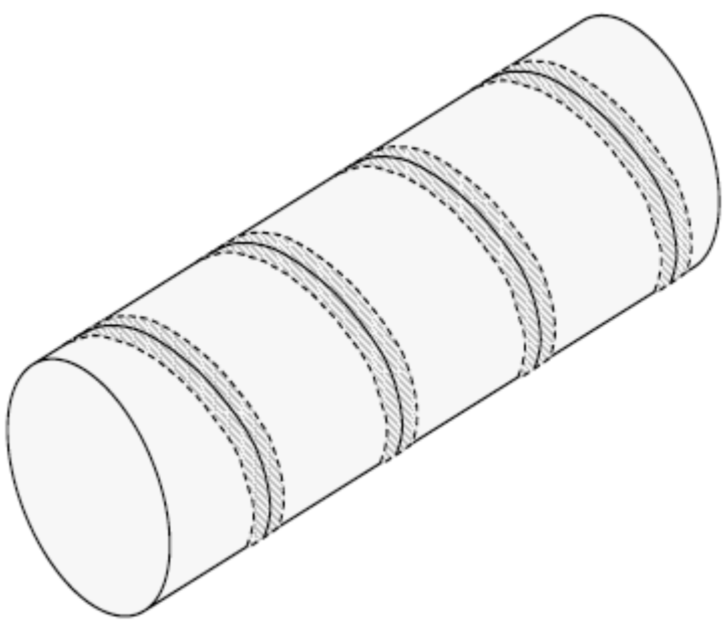


NA62 straw detectors

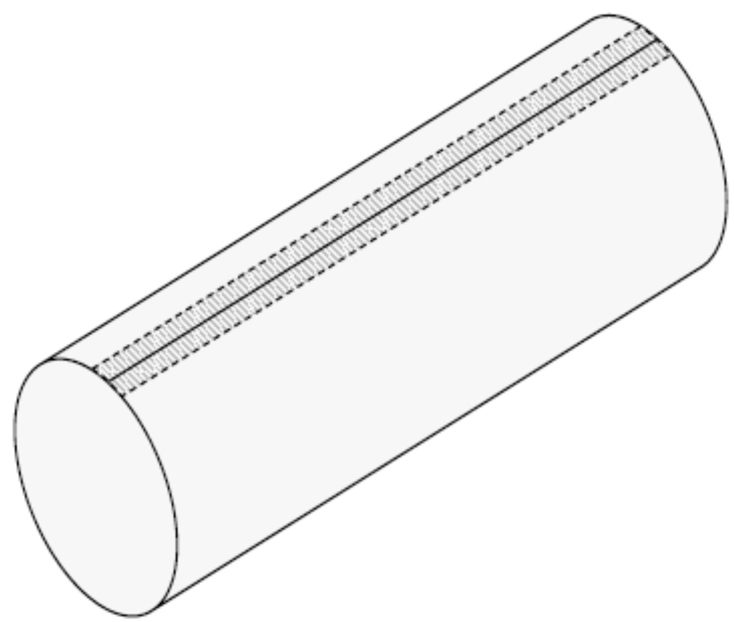
The NA62 straw tube detector

- 4 stations with 4 "views" in each station
- Each view has 448 (4x112) straws → 448x4x4 = 7168 straws
- Operate in vacuum at 1x10^{-6} mbar
- straw: 2.1m long with ∅=9.8mm, mechanically independent straw
- Pretension of wire in straws of 1.5 kg and two intermediate spacers for positioning. Mandatory for the horizontal straws (x) and the straws at 45 degrees (u,v)
- Precise tracking (<120 μm)
- Particle rate in the straw: up to 0.5 MHz
- Non-flammable gas mixture CO_2 (90%)+ CF_4 (5%) + Isobutane (5%)

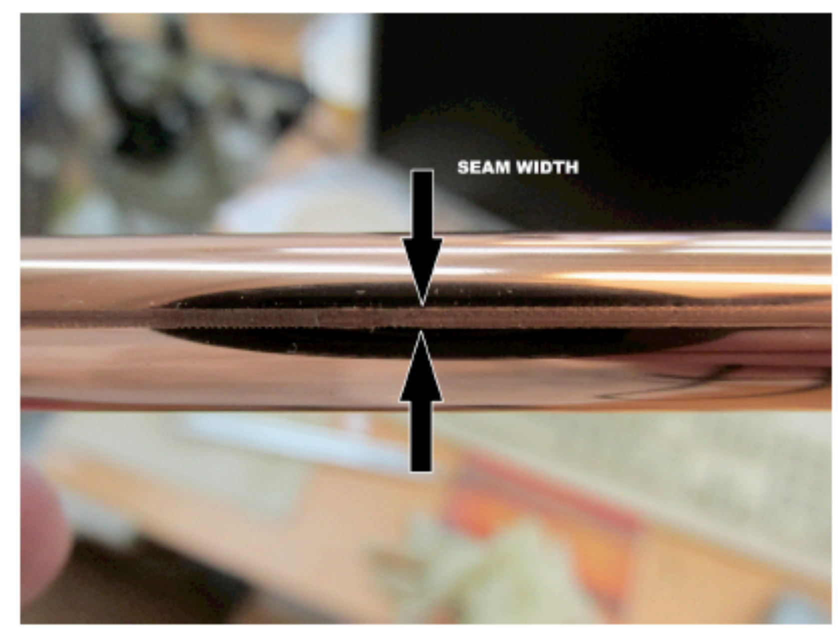
Advantage gaseous detector: 1.5% X0!



“traditional” doubly-wound style



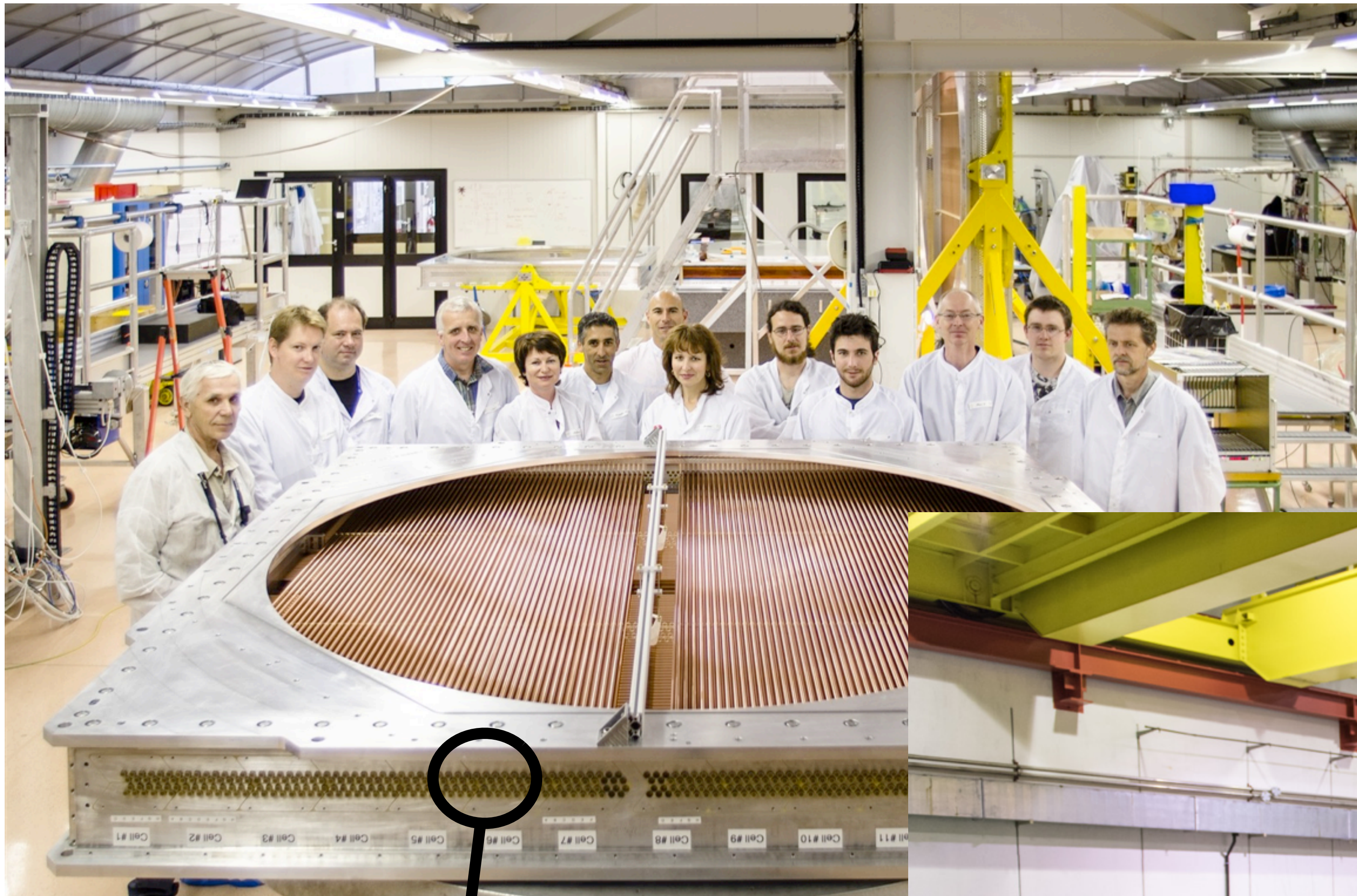
NA62/COMET straight adhesion style

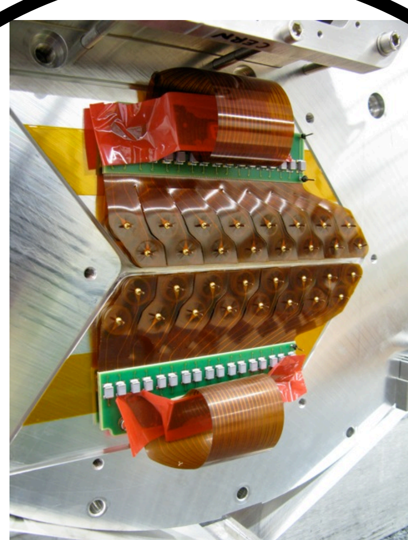


completed straw with its ultrasonic welding seam

NA62 Straws

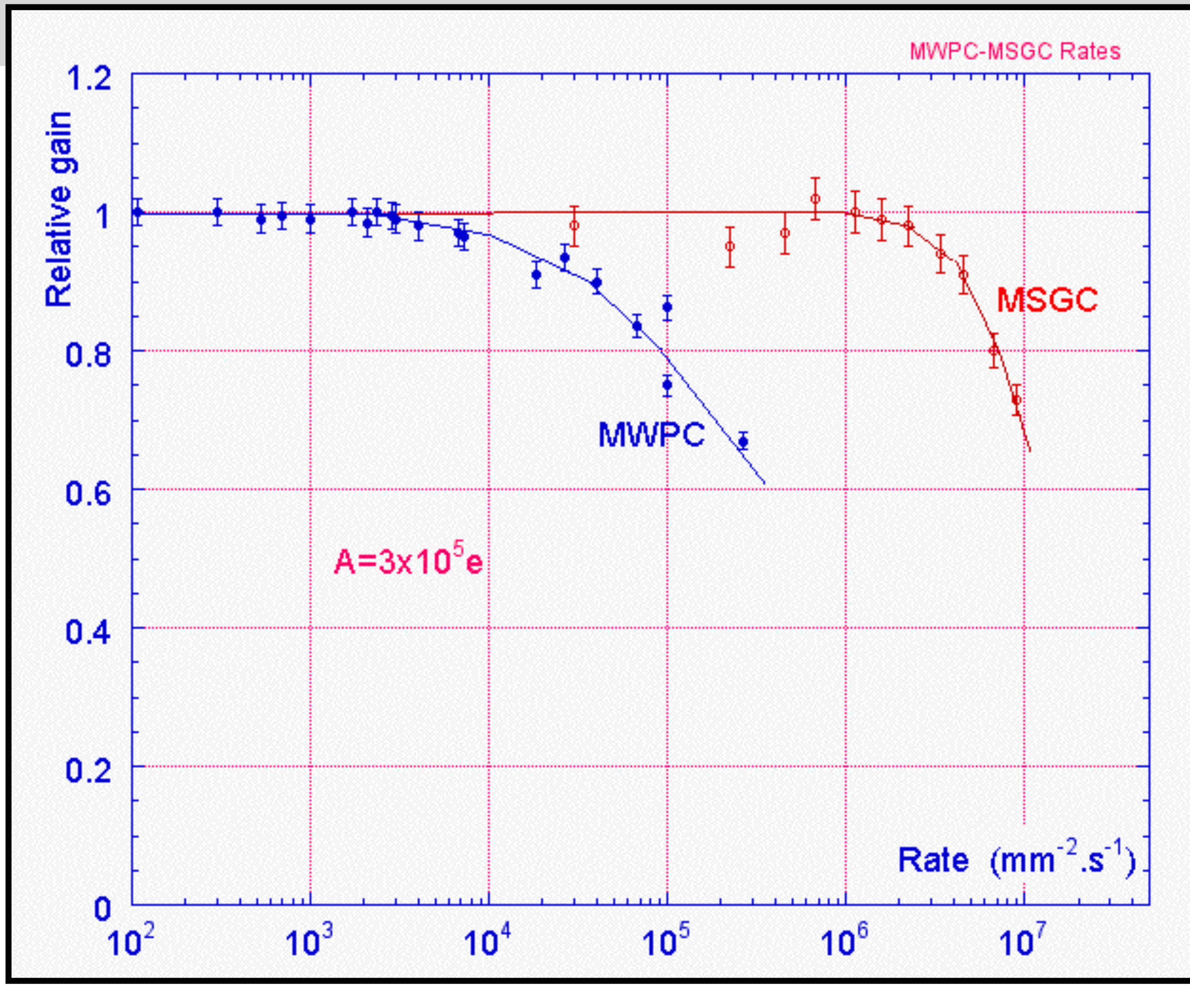
- Straws installed
- NA62 started data taking in November 2014



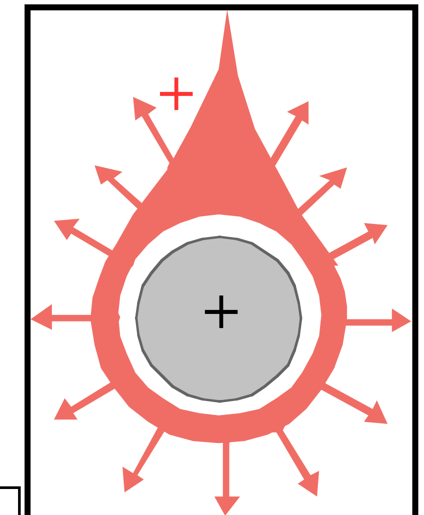


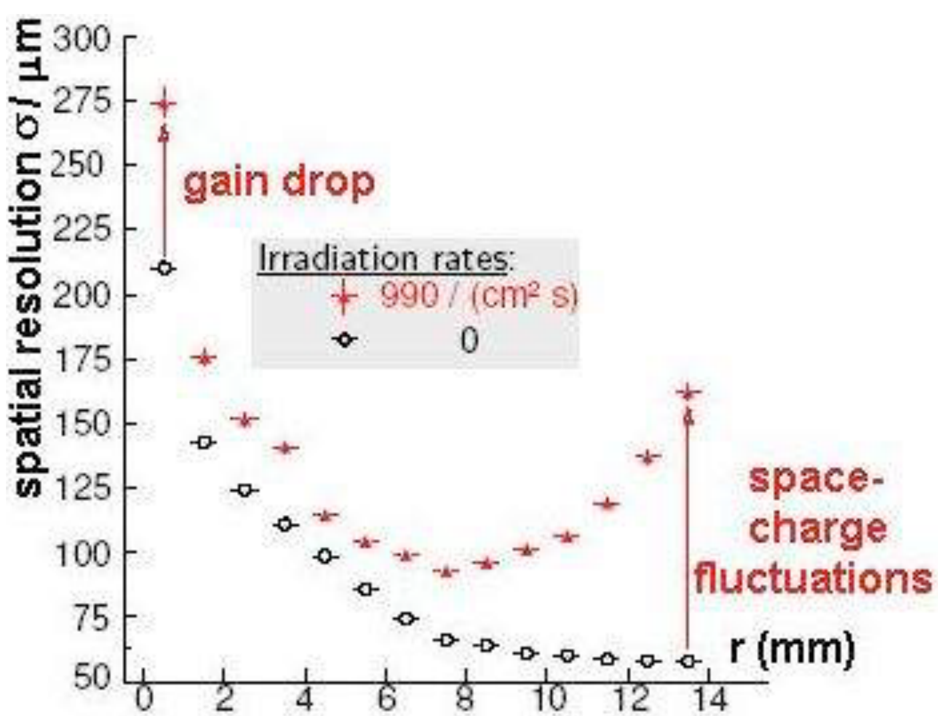
NA62 - work in 2012

Limitations of multi-wire chambers



ILITY > 10^6/mm^2 s
URACY ~ 40 µm rms
SOLUTION ~ 400 µm

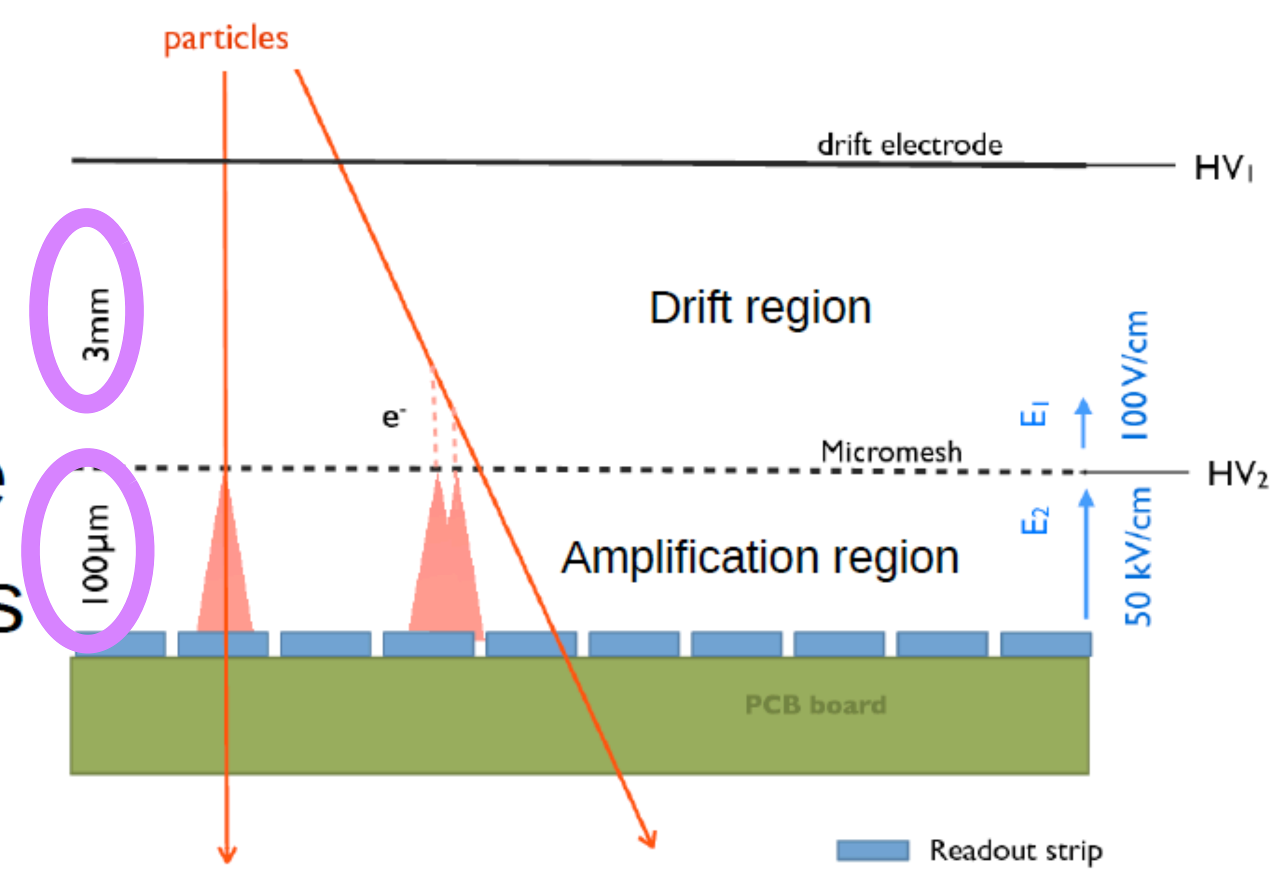




Micro-pattern gaseous detectors-detector concept

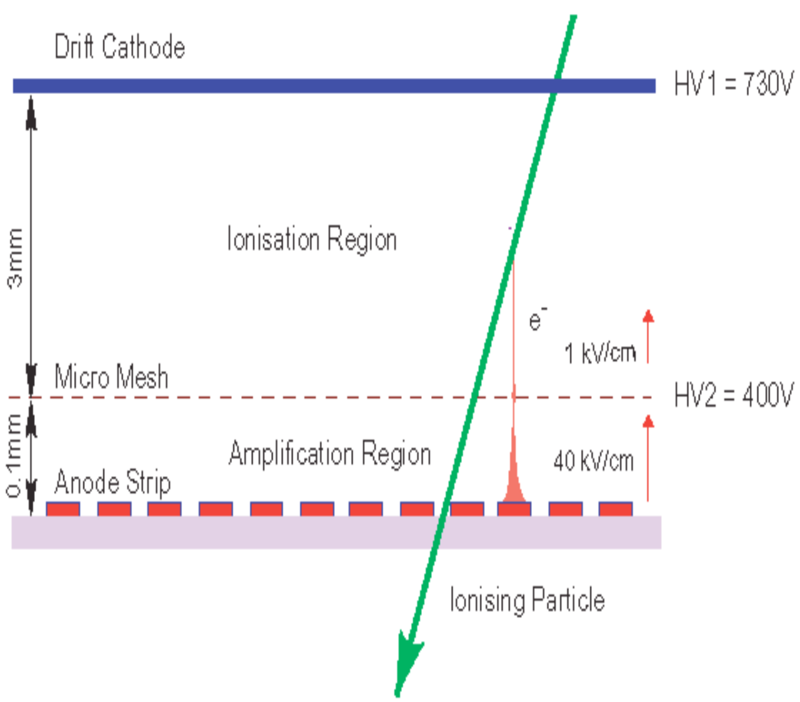
Impressive advancement in microelectronics & etching technologies allow small structures - excellent resolution and high rate capability

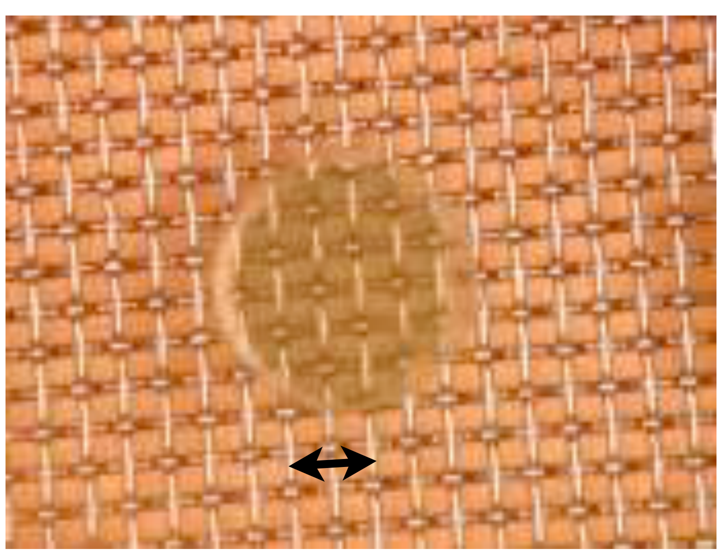
- Primary ionisation of gas molecules by particle (drift region)
- Charge multiplication (amplification region)
- MPGDs: amplification structure O(10 µm): GEM or Micromegas
- Charge readout: O(1 mm) pads/strips or O(10 µm) pixel



Commonly used MPGDs

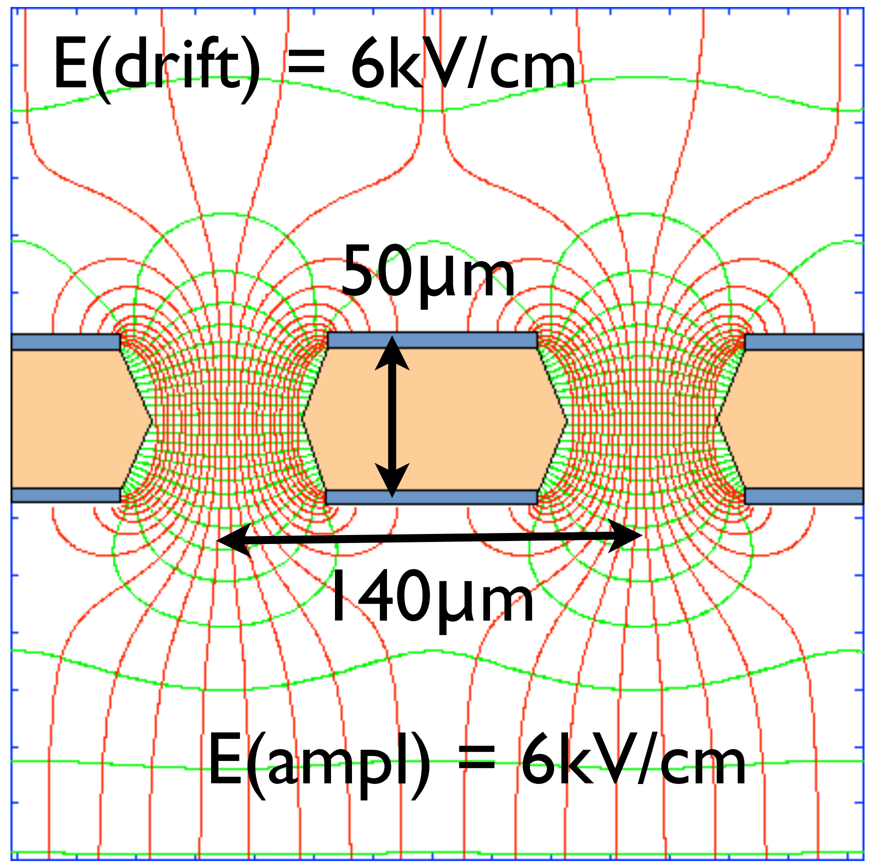
Micromegas

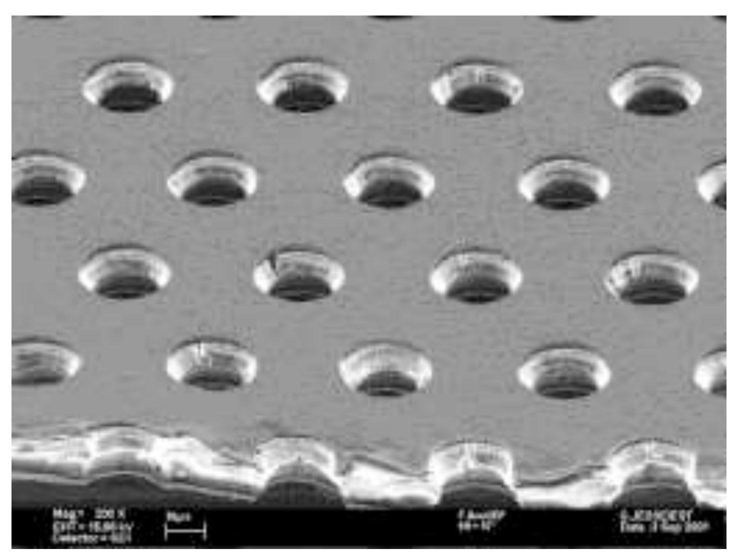




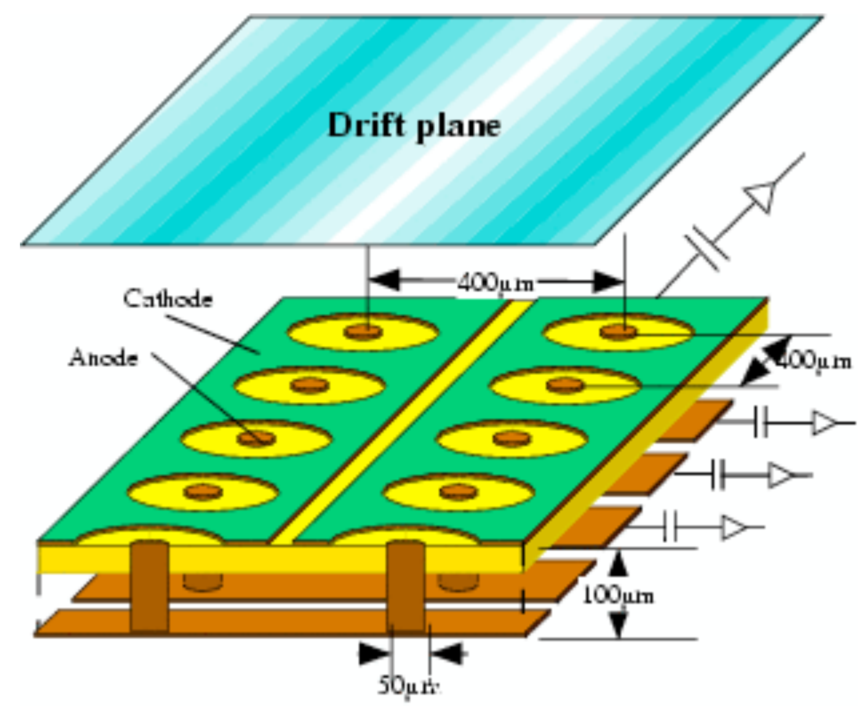
2x(70-100)μm

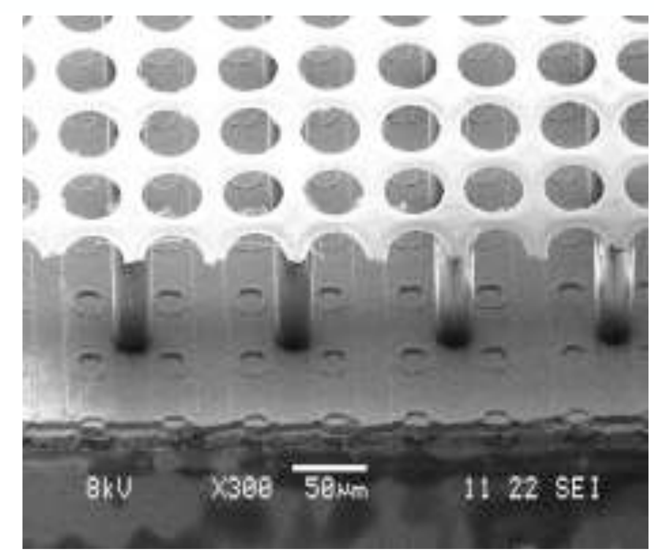
Gas Electron Multiplier GEM



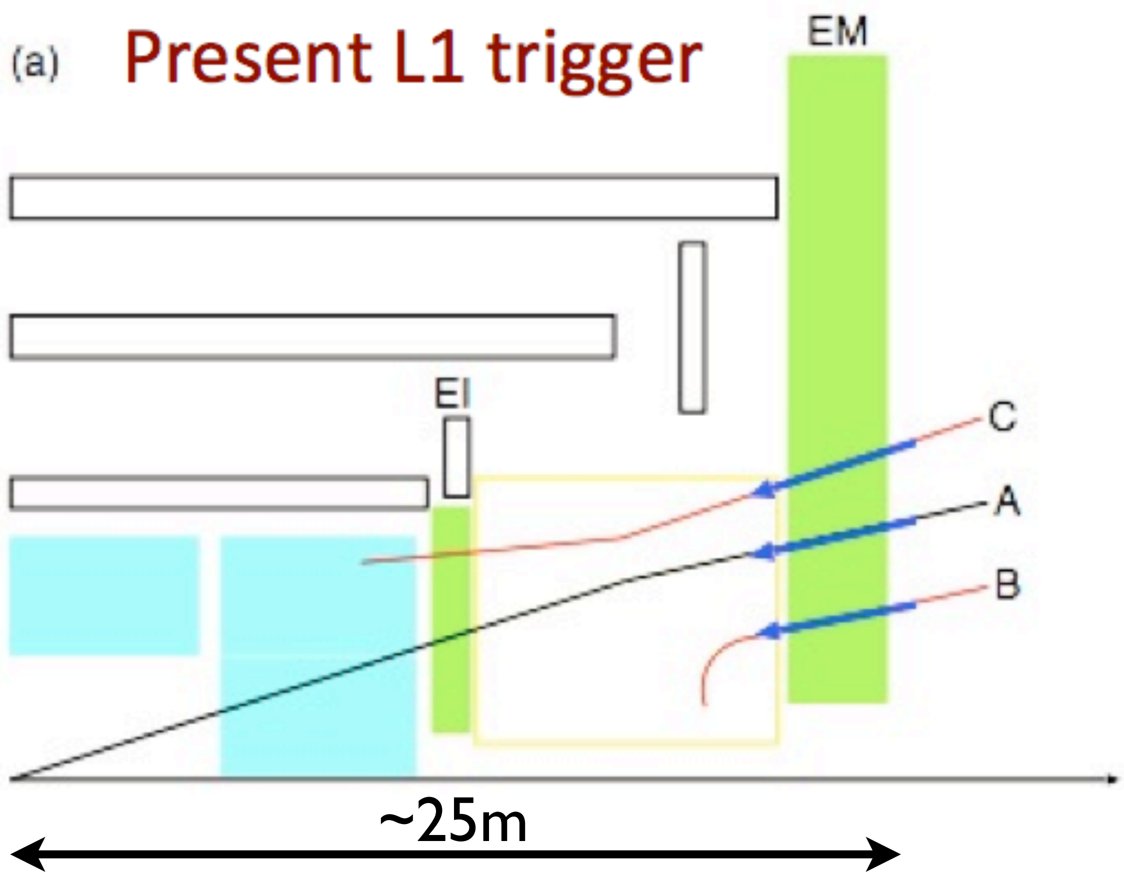


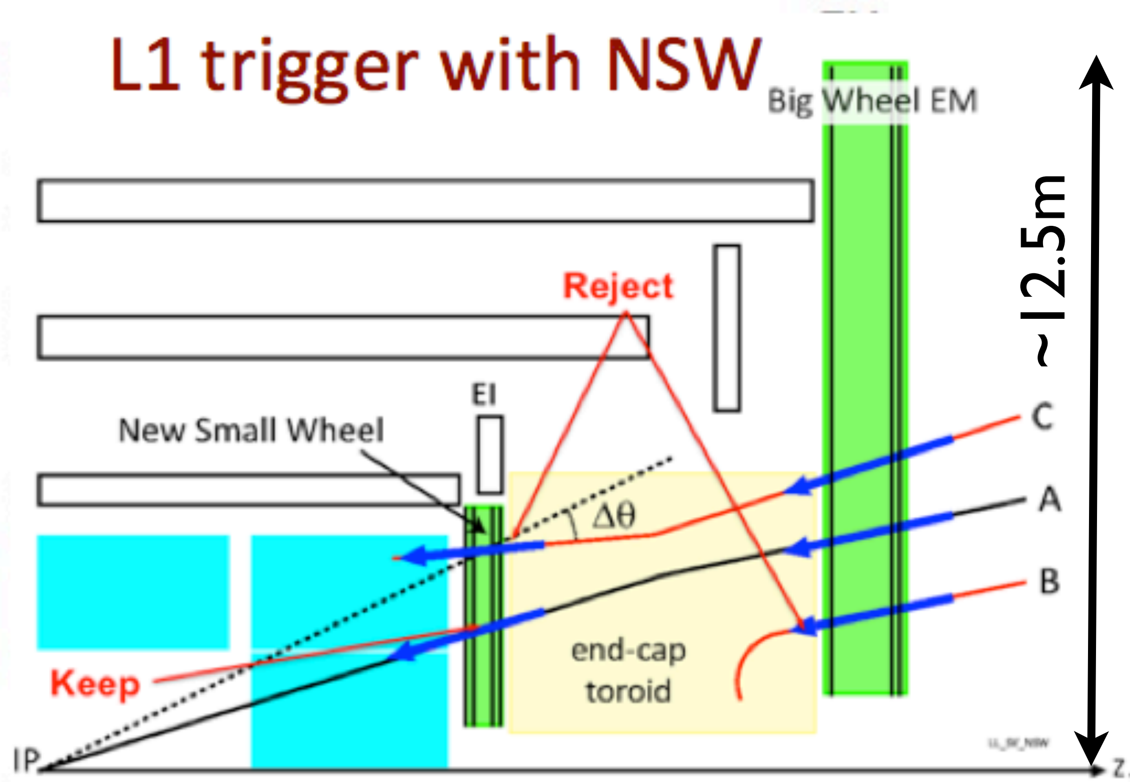
Micropixel chamber





ATLAS muon chamber upgrade (I)



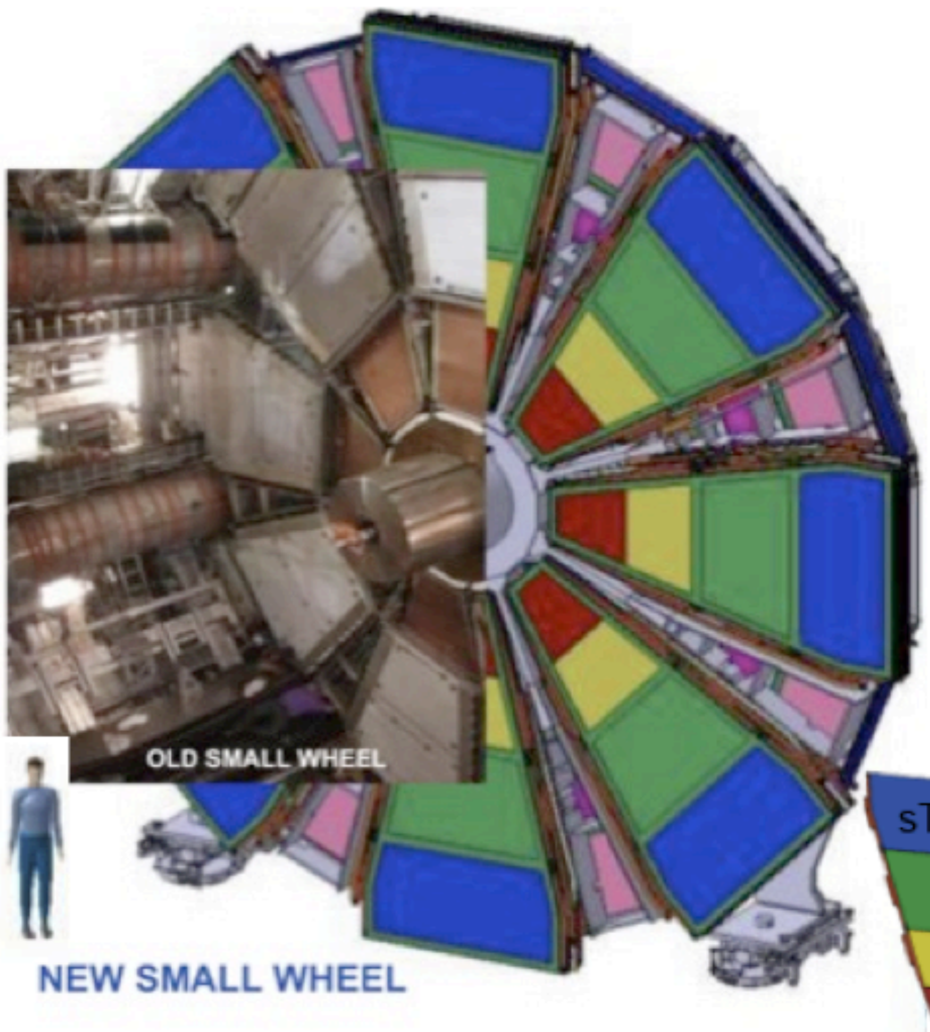


New small muon wheel (NSW), $1.2 < |\eta| < 2.7$:

- providing improved trigger for forward direction and precision tracking
  - ➡ new fast precision tracker working at luminosities up to $7 \cdot 10^{34}$ cm^{-2}s^{-1}
  - ➡ kill the fake triggers by requiring high quality (<1mrad) pointing segments;

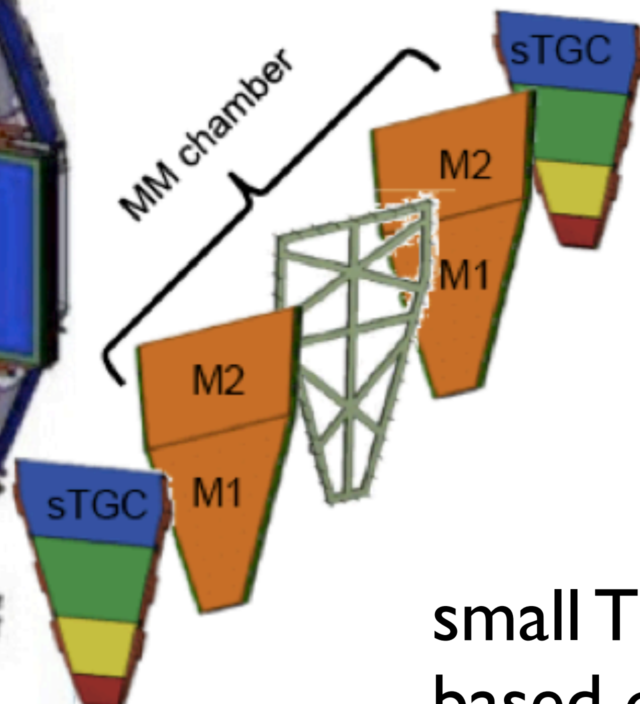
Installation during next long LHC shutdown 2017/2018.

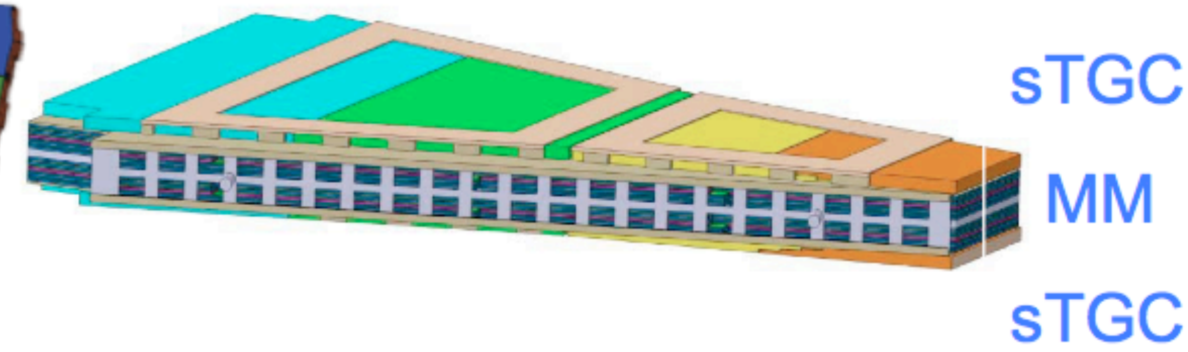
ATLAS muon chamber upgrade (2)

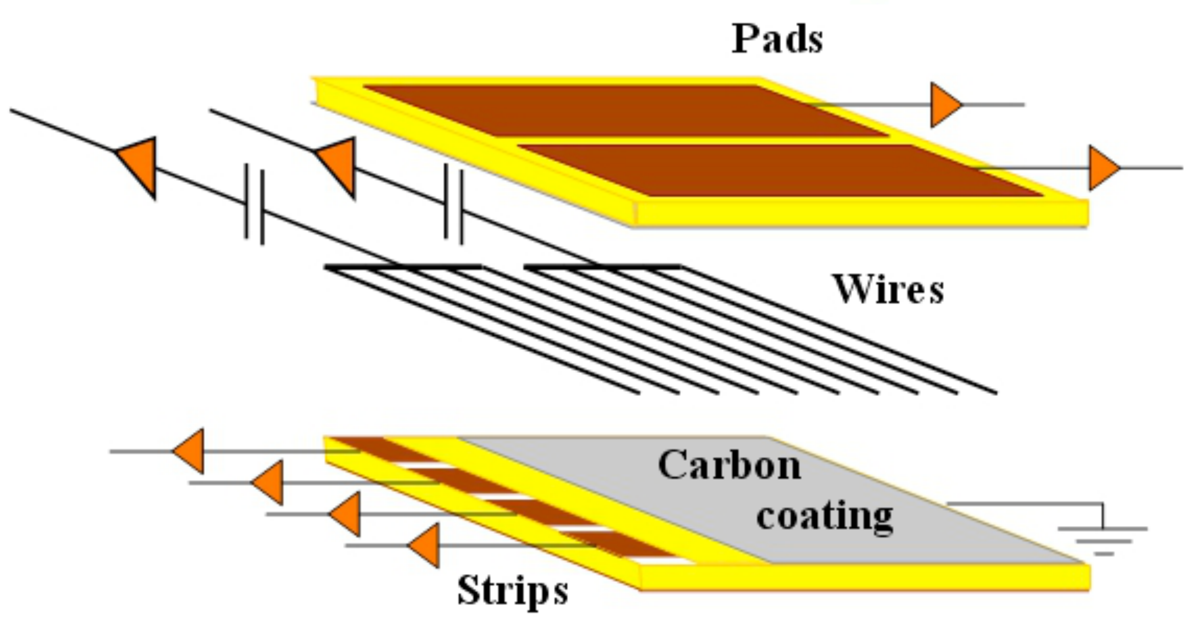


NSW will utilize two detector solutions:

- Small strip Thin Gas Chambers (sTGC) as primary trigger
- Micromegas (MM) for primary precision tracker



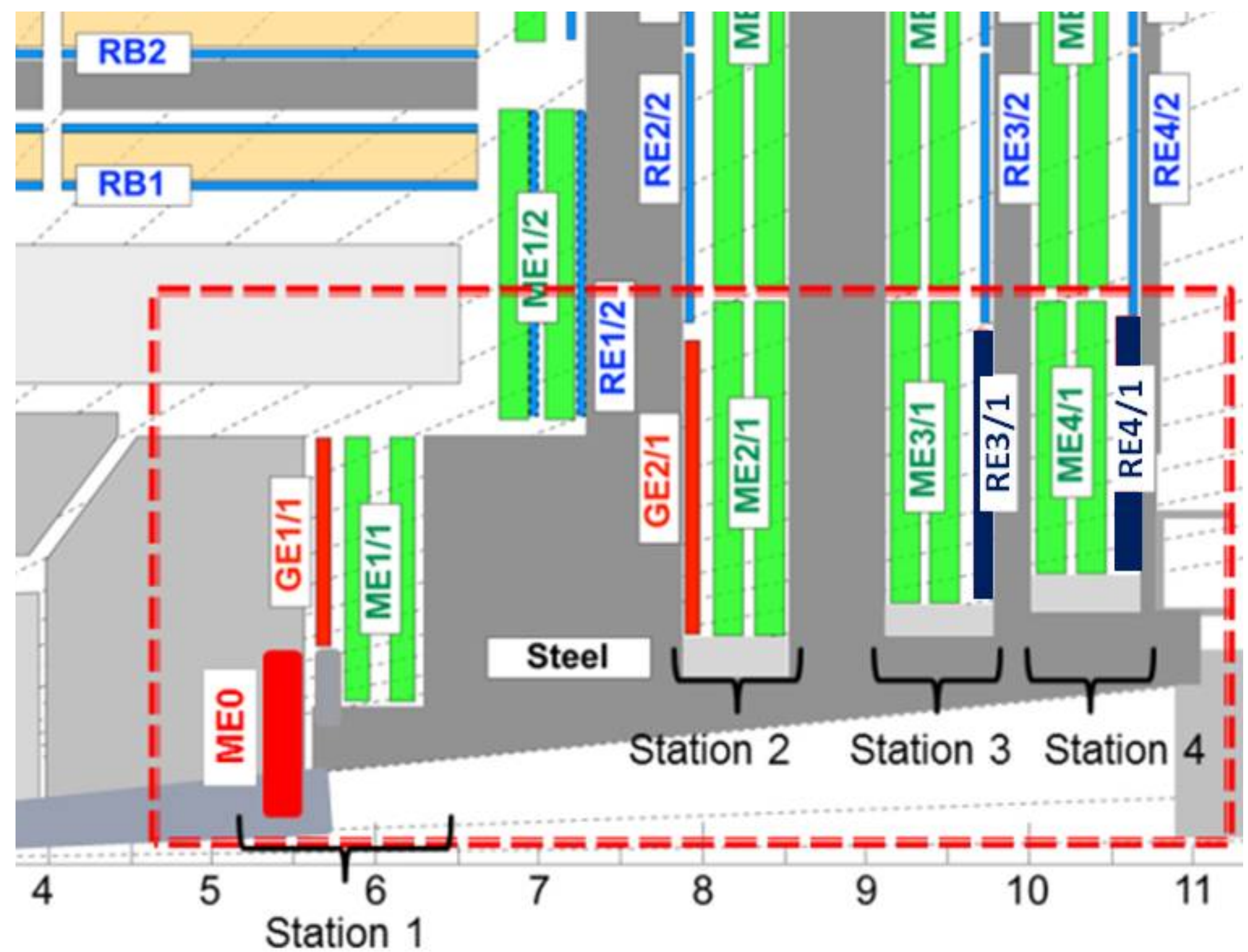




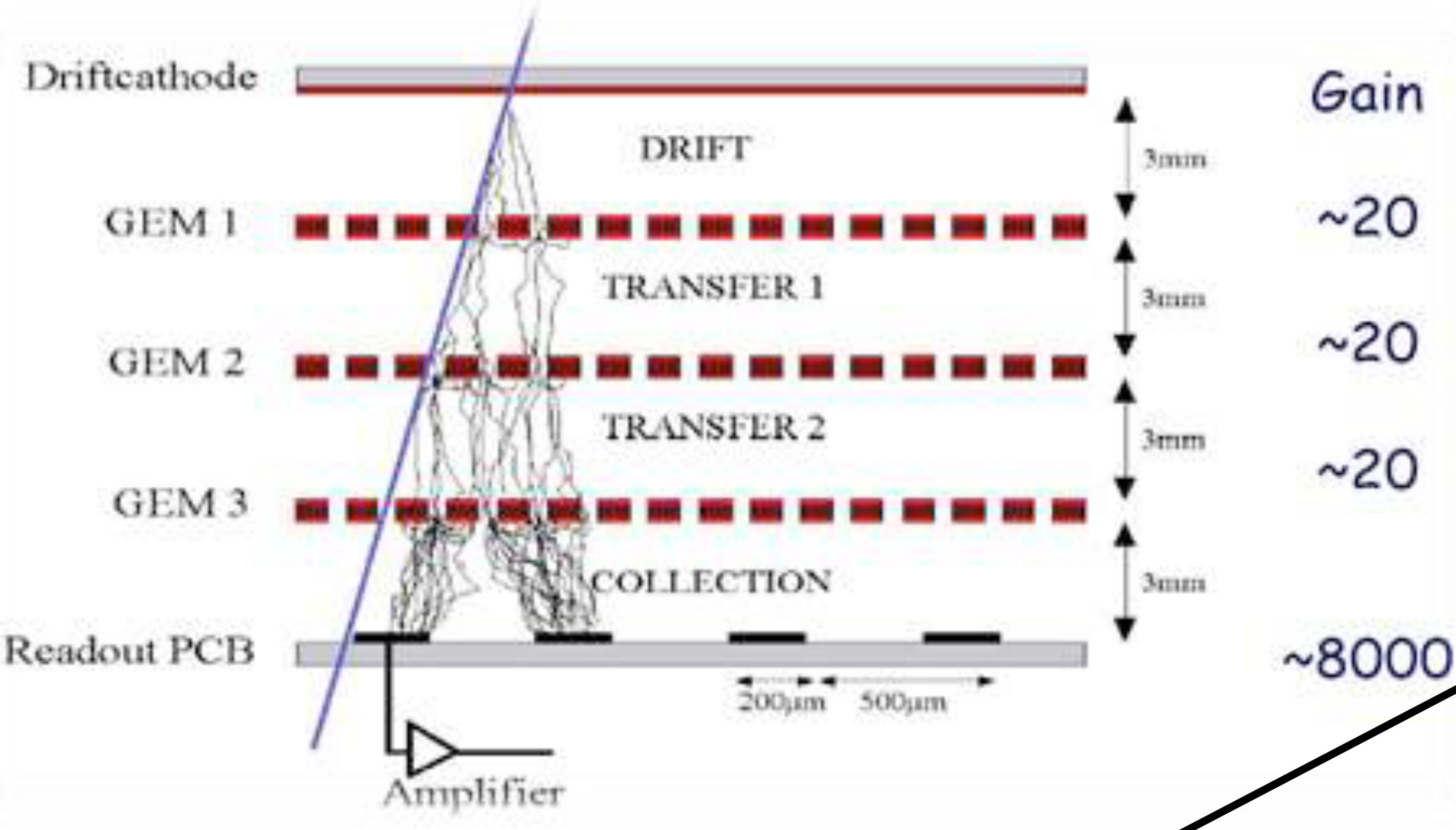
small Thin Gap Chambers:
based on proven ATLAS TGC technology;
Improvements:
➙ pads
➙ wire readout
➙ strip charge readout
Operating voltage: 2.9 kV.
Use of a self−quenching gas
(55% CO_2, 45% n−pentane)

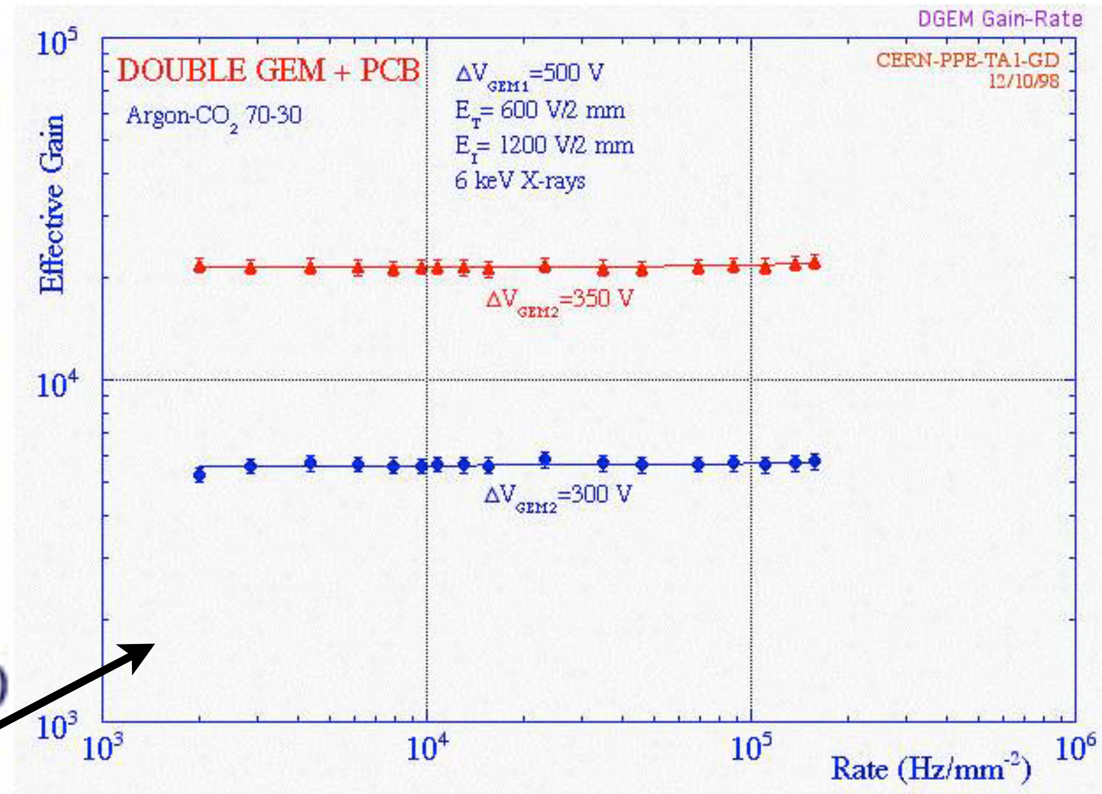
CMS muon chamber upgrade (1)

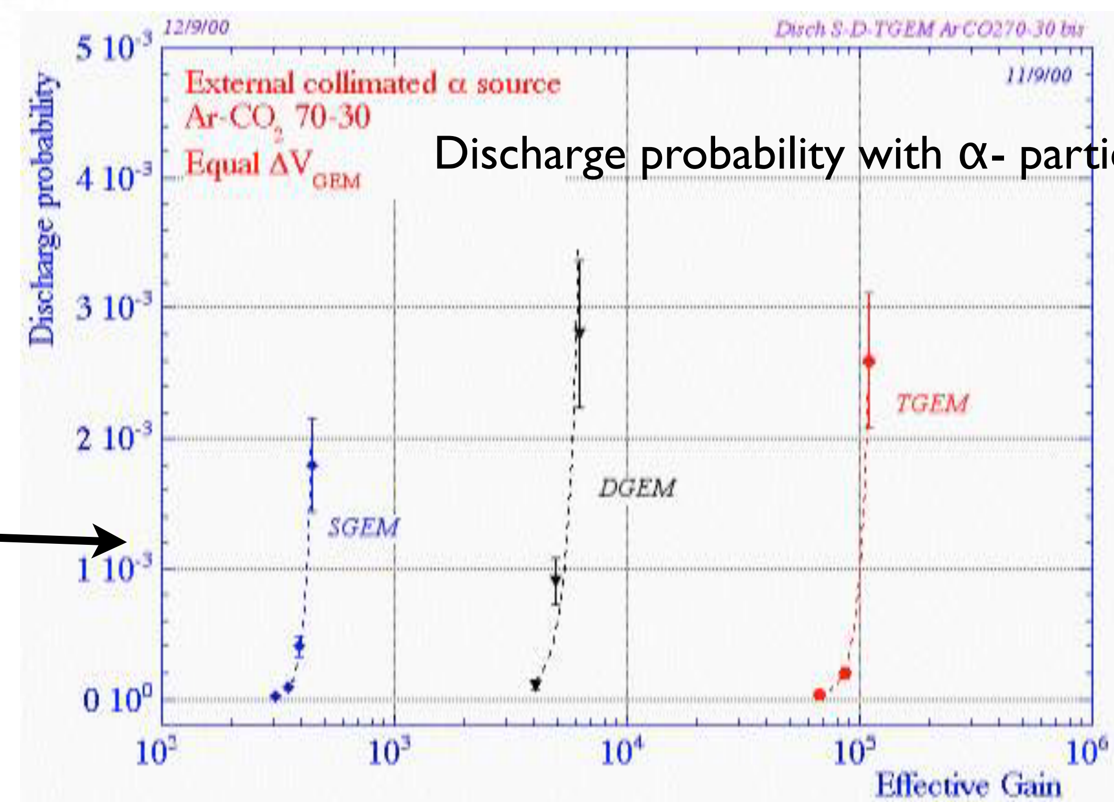
- Consolidation
  - ➡ Existing detectors have worked very well, want to protect the large investment;
  - ➡ R&D progressed: aging of chambers studied and partially understood, electronics, eco-friendly gases (no core cost assumed);
- Forward 1.6<|h|<2.4 enhancements
  - ➡ L1 trigger rate reduction, enhance efficiency via redundancy;
  - ➡ GEMs: GE1/1 and GE2/1;
  - ➡ iRPCs: RE3/1 and RE4/1;
- Very forward extension
  - ➡ Extend muon tagging coverage, ME0 with GEM technology;
  - ➡ 6 layer stub, baseline 2.0<|h|<3.0;



CMS uses triple GEMs







Discharge probability with α- particles

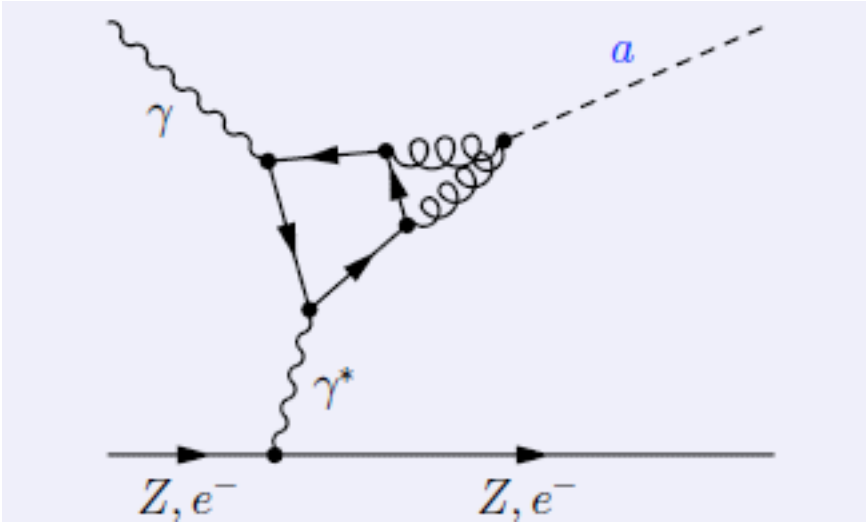
High-rate capability for triple GEMS > 10^5 Hz/mm^2;
No space-charge phenomena

Multiple GEM structure strongly reduces probability of discharges

Axions and Chameleons: candidates for dark matter and dark energy

Some riddles in particle physics:

- ★ What is our universe made of? What is dark matter and dark energy?
- ★ Non-observation of CP violation in strong interaction
- ★ Smallness of electric dipole moment of neutron
  ($d_n < 0.29 \times 10^{-25}$ e cm)
  - ➡ Peccei–Quinn (PQ) mechanism is elegant solution for the strong CP problem and can explain small d_n.
  - ➡ Pseudo-Goldstone-Boson (**Axion**) arising from PQ mechanism
  - ➡ Candidate for all or parts of Cold Dark Matter



Primakov effect

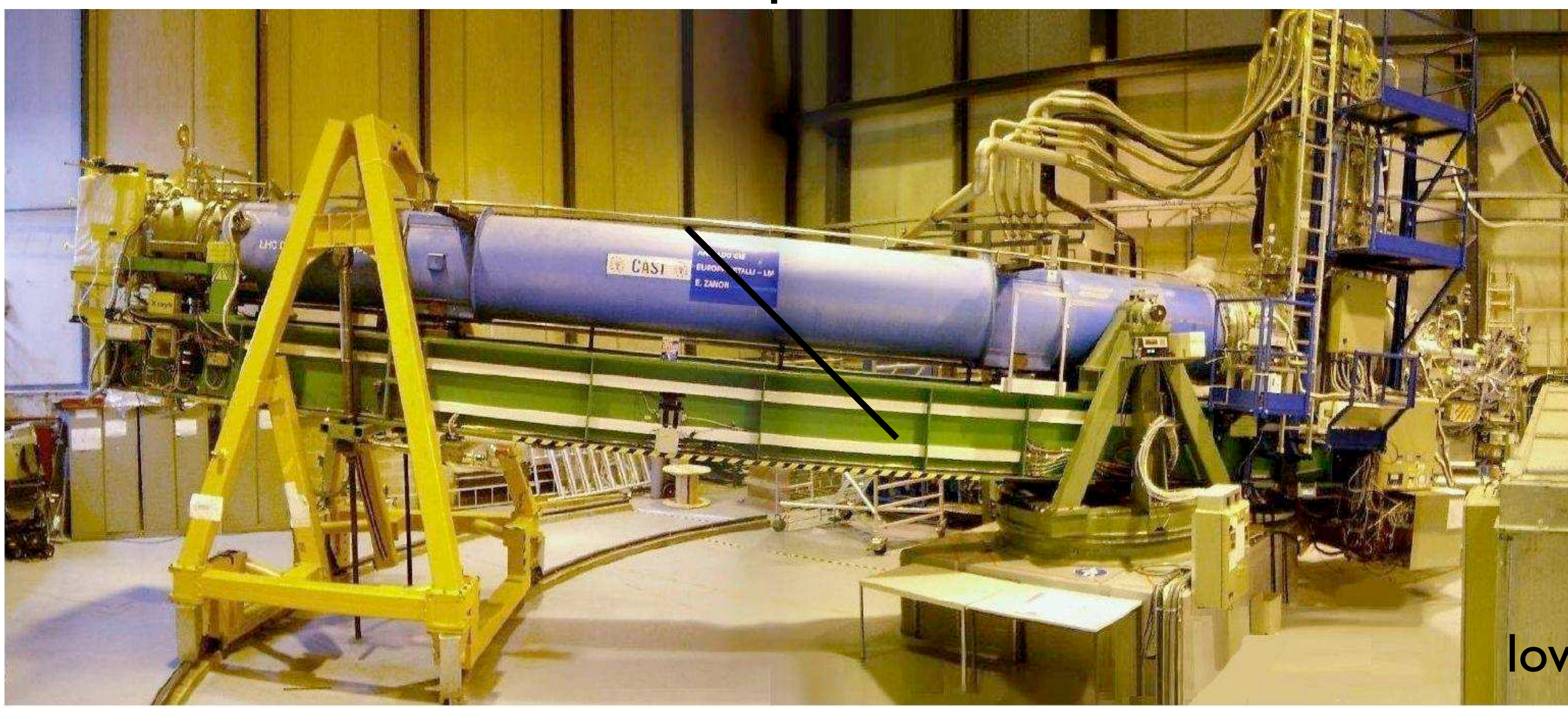
- Axion Coupling to ordinary matter
  - ➡ Very small coupling constants
  - ➡ Mixing with π0 leads to coupling to two photons
- Production in the Sun's core via Primakoff effect

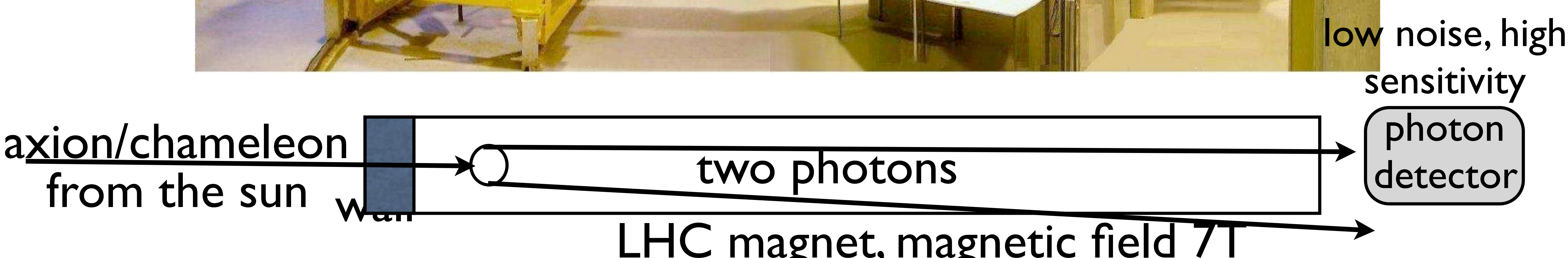
- Dark energy as a new form of matter
- Scalar fields interacting with matter and photons could be
- strong candidates
- Constraints would lead to large gravitational effects and a
- fifth force with long range
- Exploit screening mechanisms to avoid unnatural models
- **Chameleon** screening: Models with a density dependent
- effective mass
  (Brax, Lindner and Zioutas - Phys. Rev. D 85(2012), 043014)

Searching for axions/chameleons

- Primakoff effect generates huge axion/chameleon flux from the sun
- Axions/chameleons can reconvert to photons inside large ~B fields

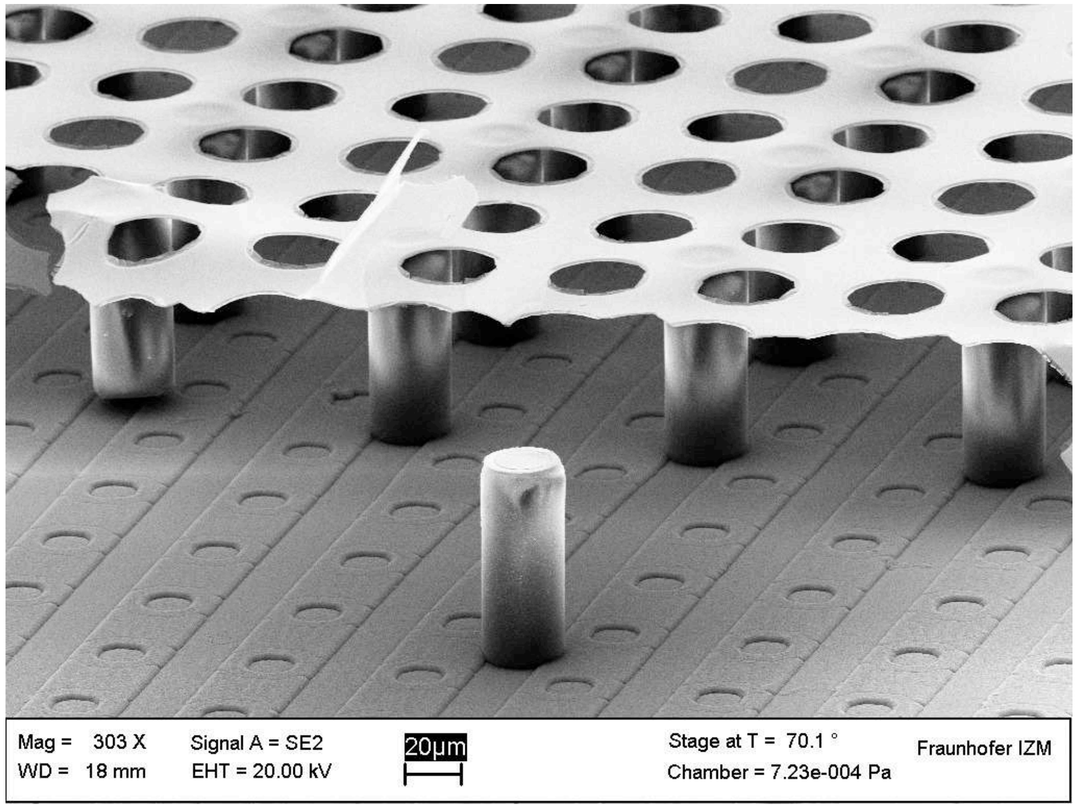
→ CAST, an axion experiment at CERN

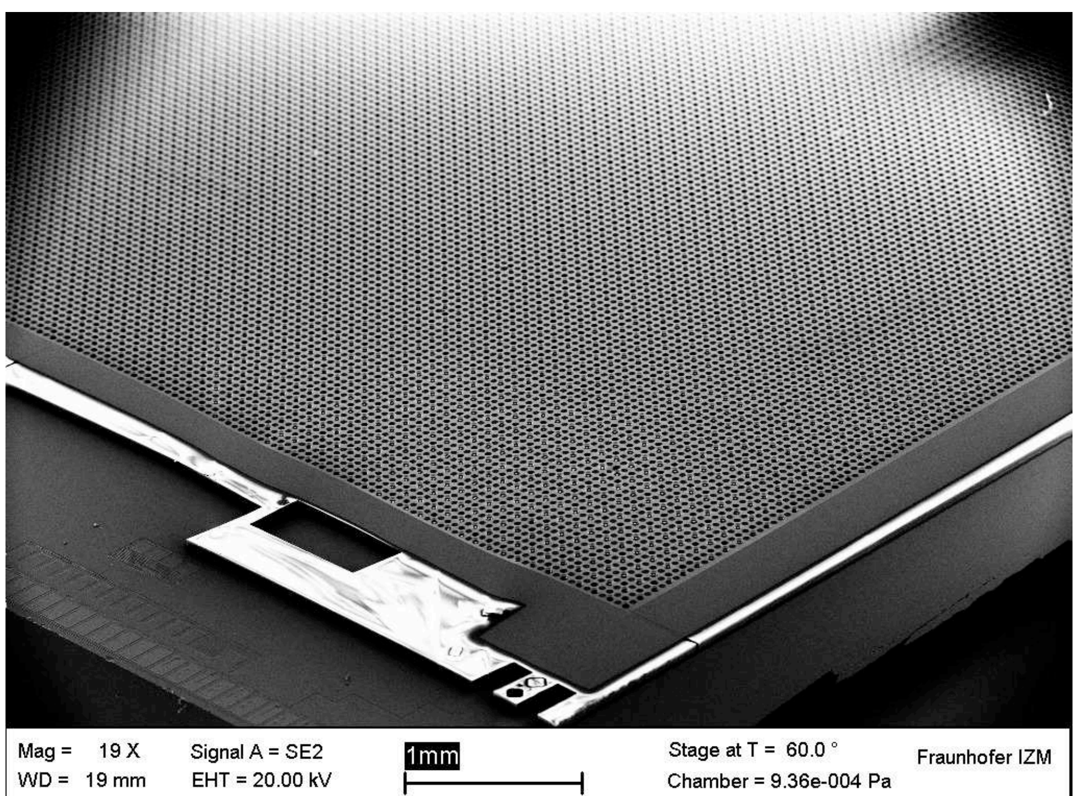


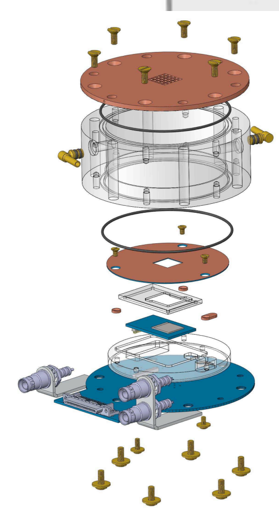


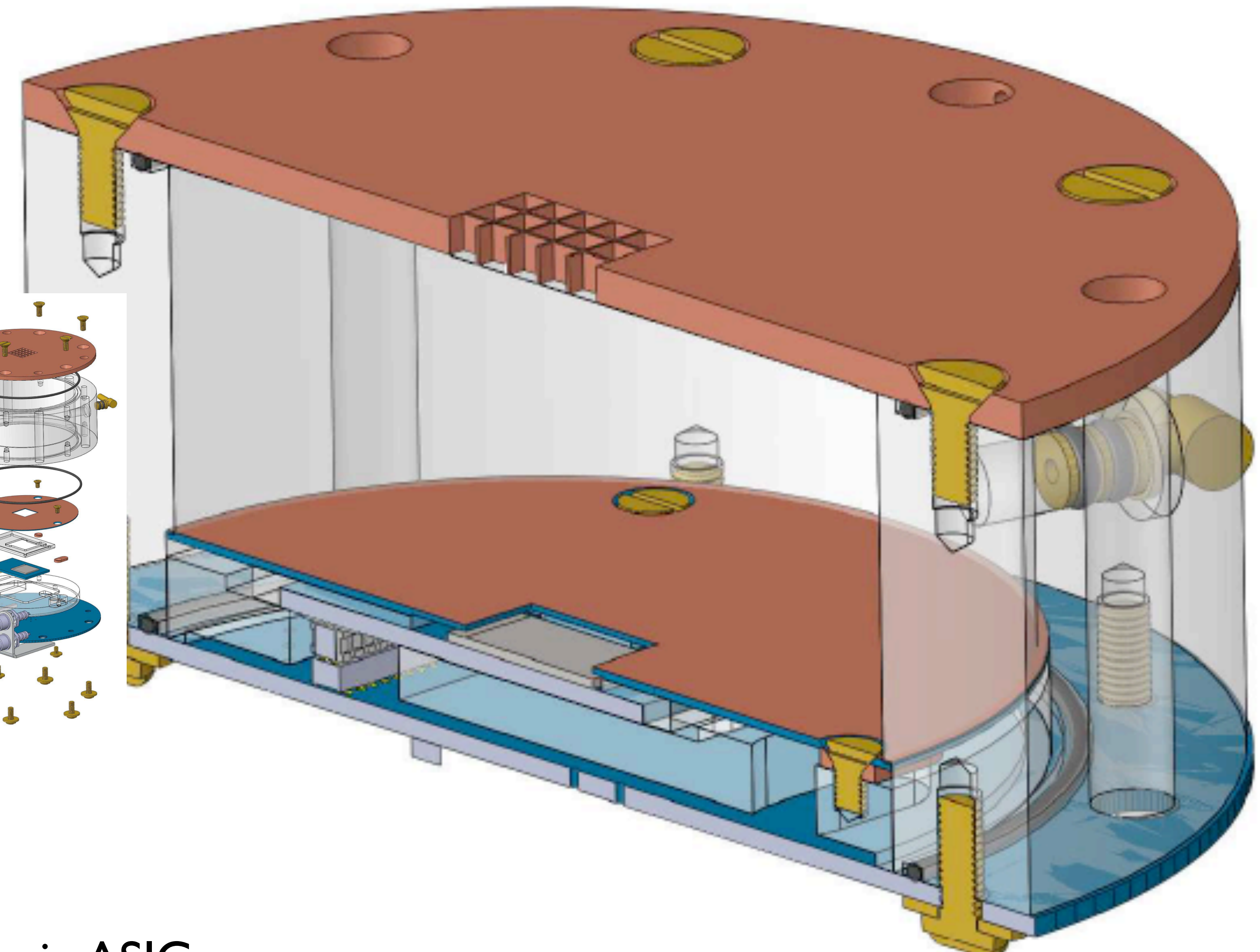
"Light shining through the wall" experiment

Photon detector for CAST: an InGrid







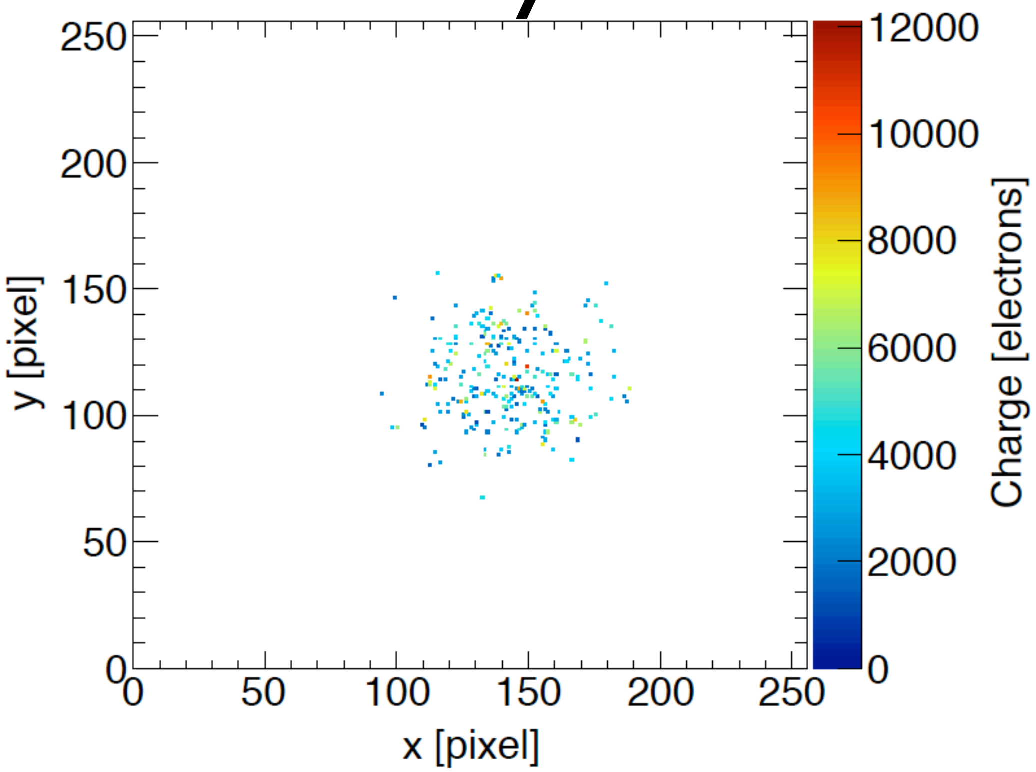


Timepix ASIC
256 × 256 pixels, 55 × 55 µm2 pitch, 1.4 × 1.4 cm^2 active area
Charge sensitive amplifier and discriminator in each pixel, 90 e ENC

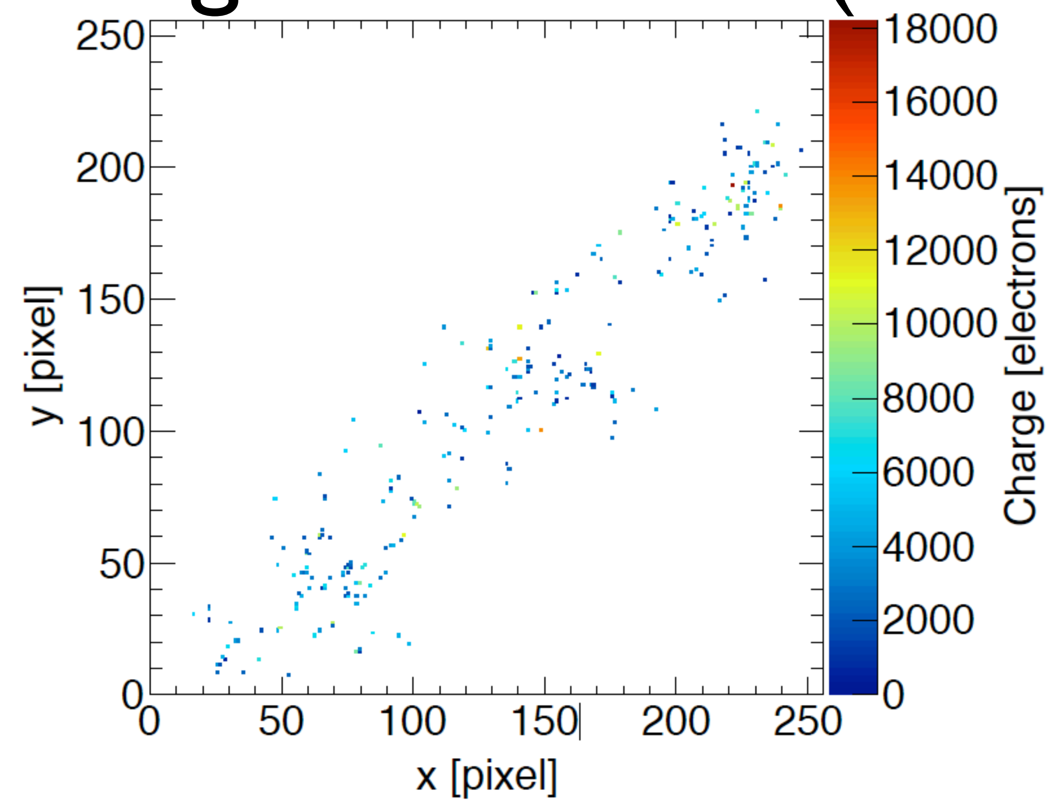
Micromegas on top of Timepix ASIC
Fabrication by means of photolithographic postprocessing
Each avalanche is collected on one pixel
Detection of single electrons possible

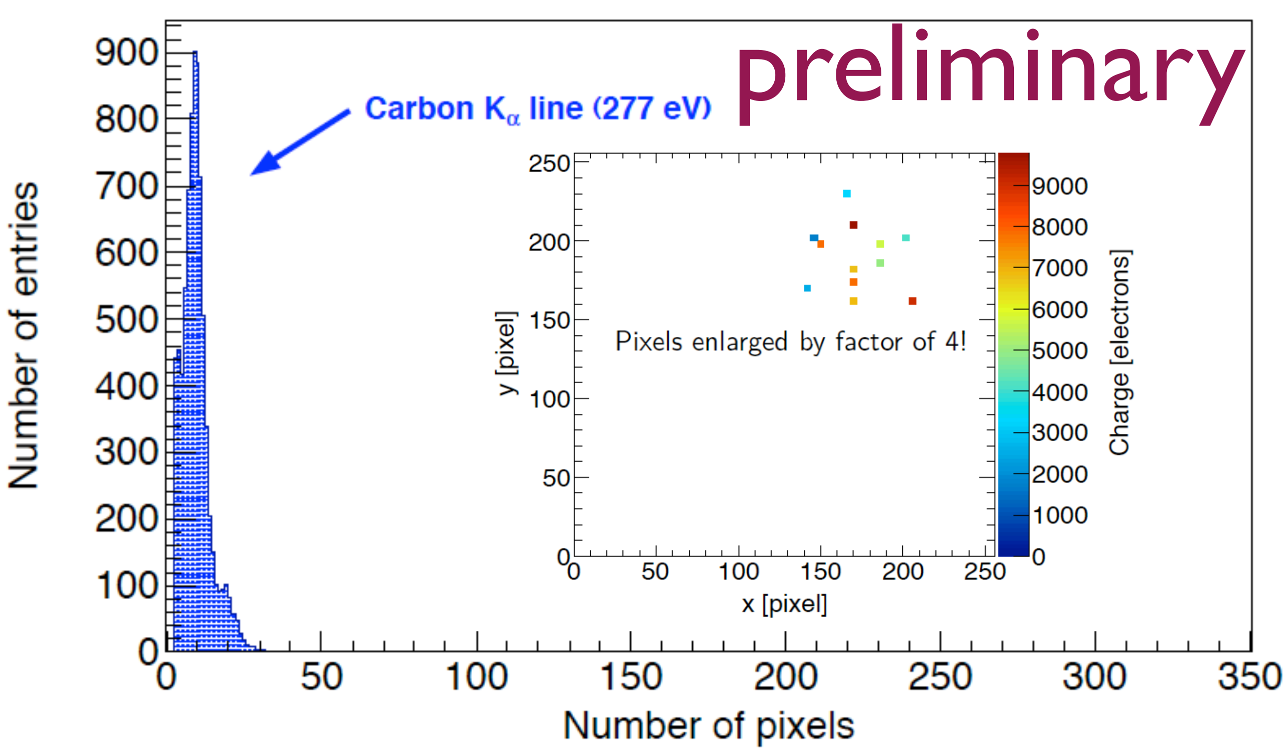
CAST-InGrid performance

X-ray event



background event (a track)





Achieved energy resolution:

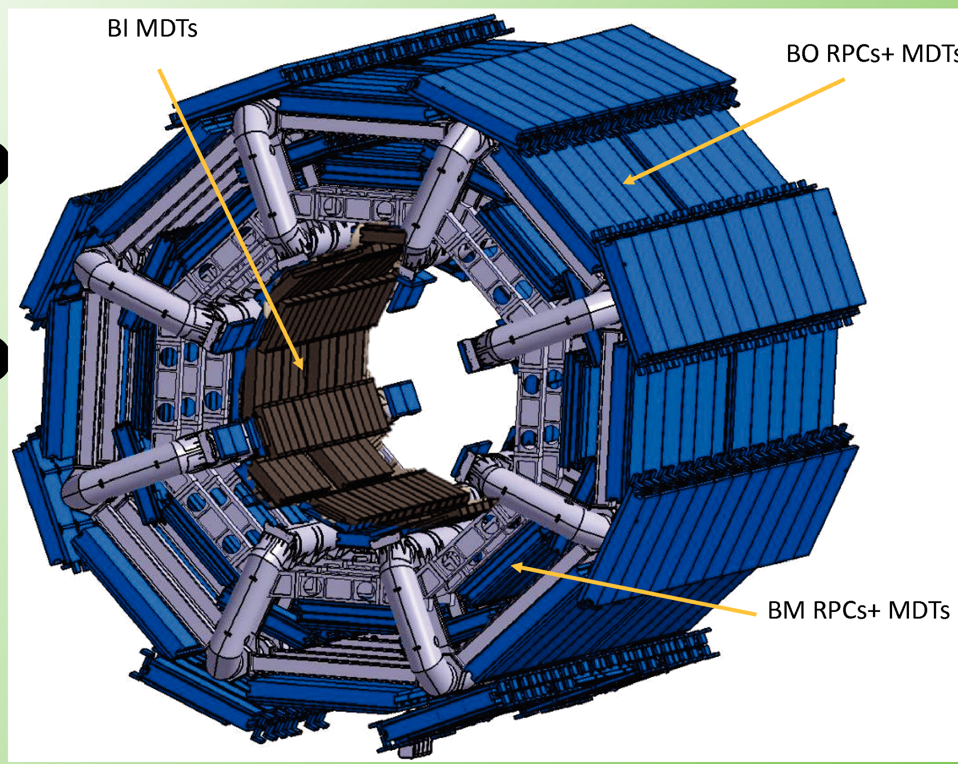
➞ Resolutions down to $\sigma E/E$ 3.85% at 5.9 keV were observed in Ar/iC_4H_{10} 90/10 at optimized settings

➞ Energy determined from pixel counting

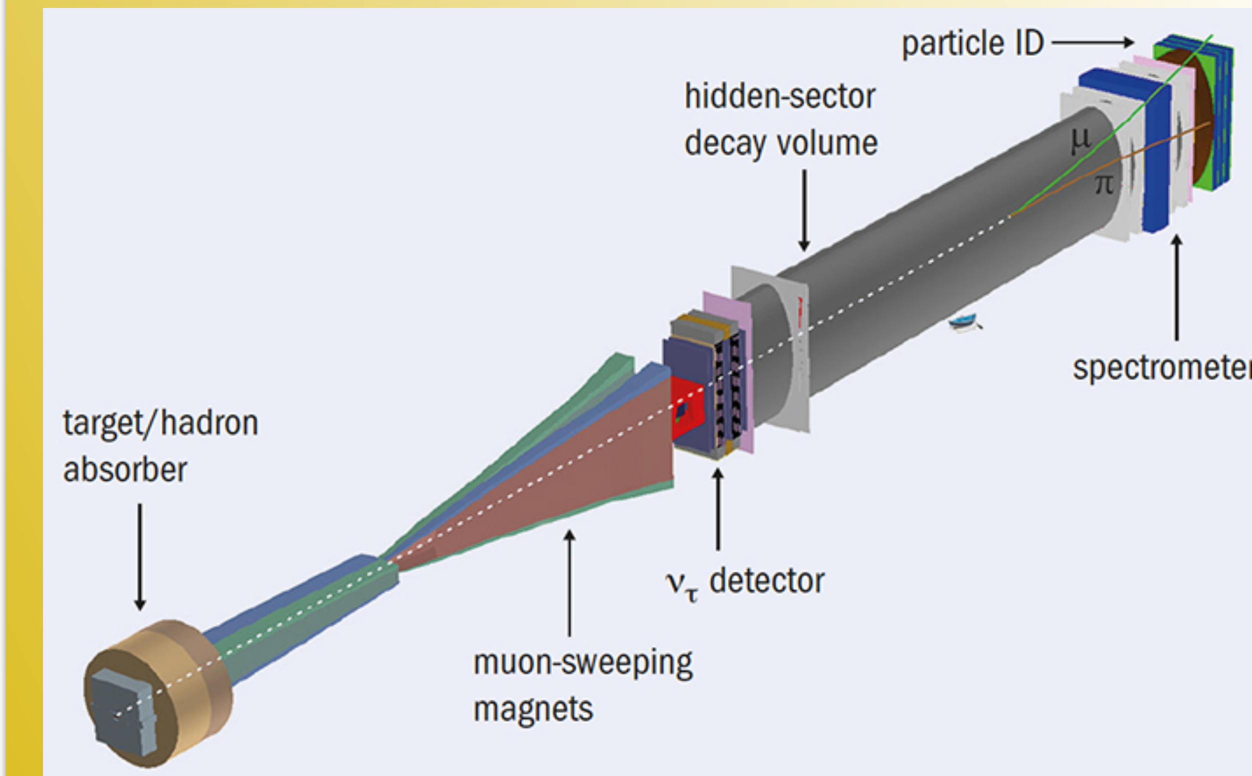
➞ In Ar/iC_4H_{10} 97.7/2.3 resolutions down to $\sigma E/E$ 5.33% at 5.9 keV are possible

Future HEP challenges

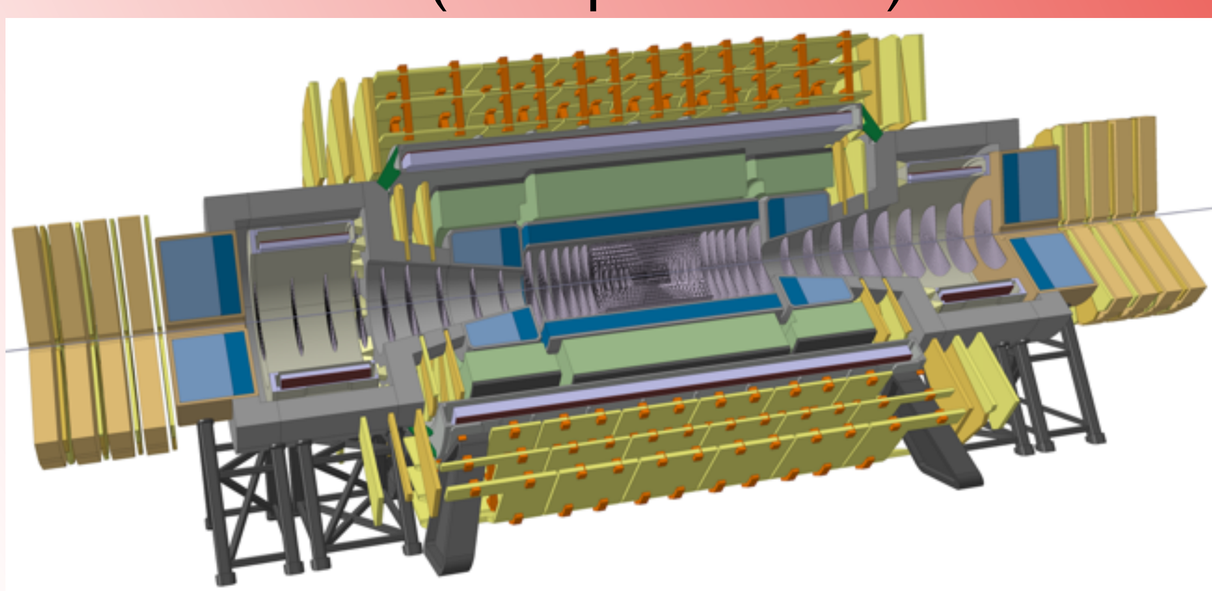
LHC upgrades (example ATLAS Phase-2)



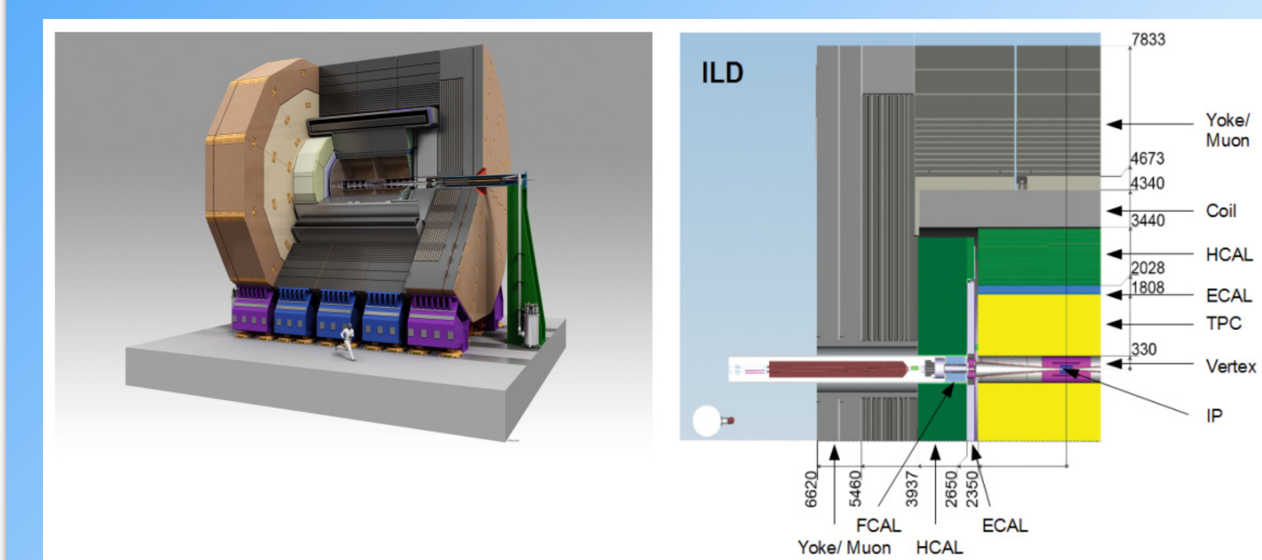
Fixed-target programmes (example SHiP)



FCC detectors (example FCC-hh)

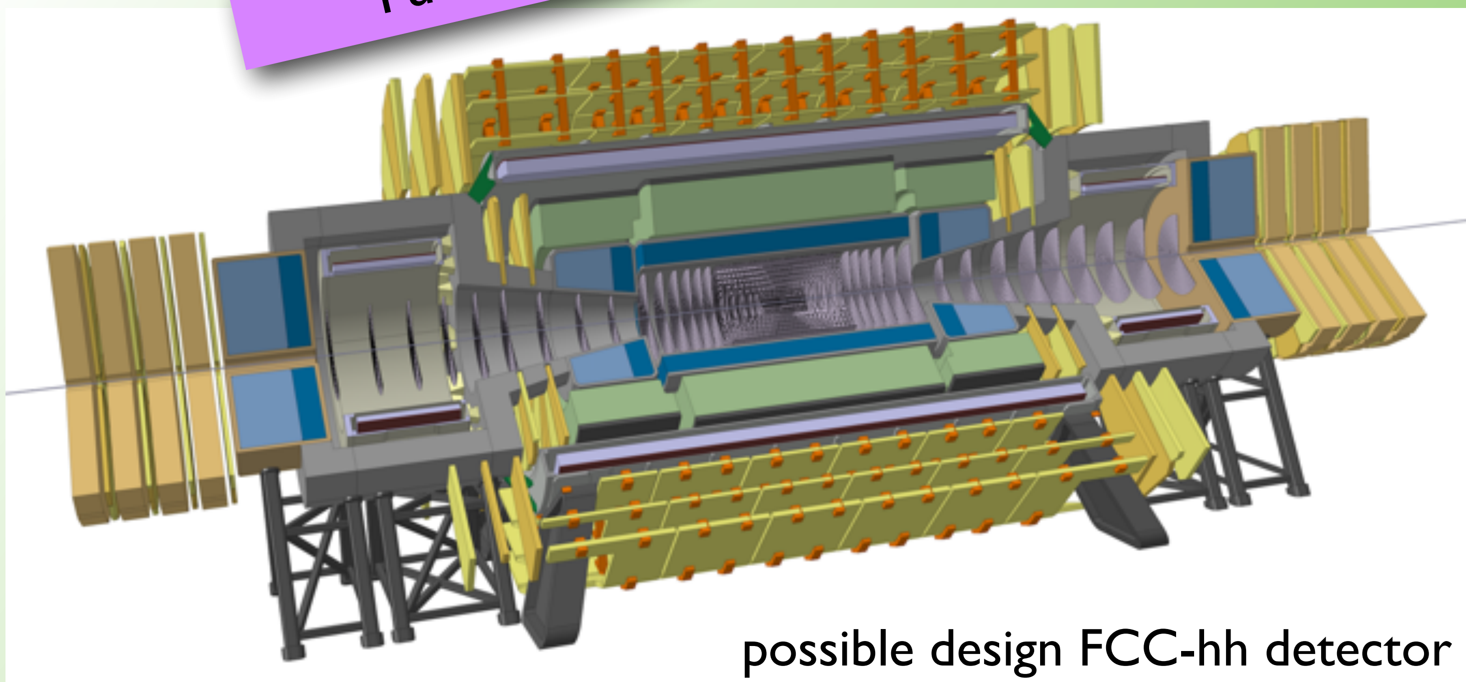


ILC/CLIC detectors (example ILD)

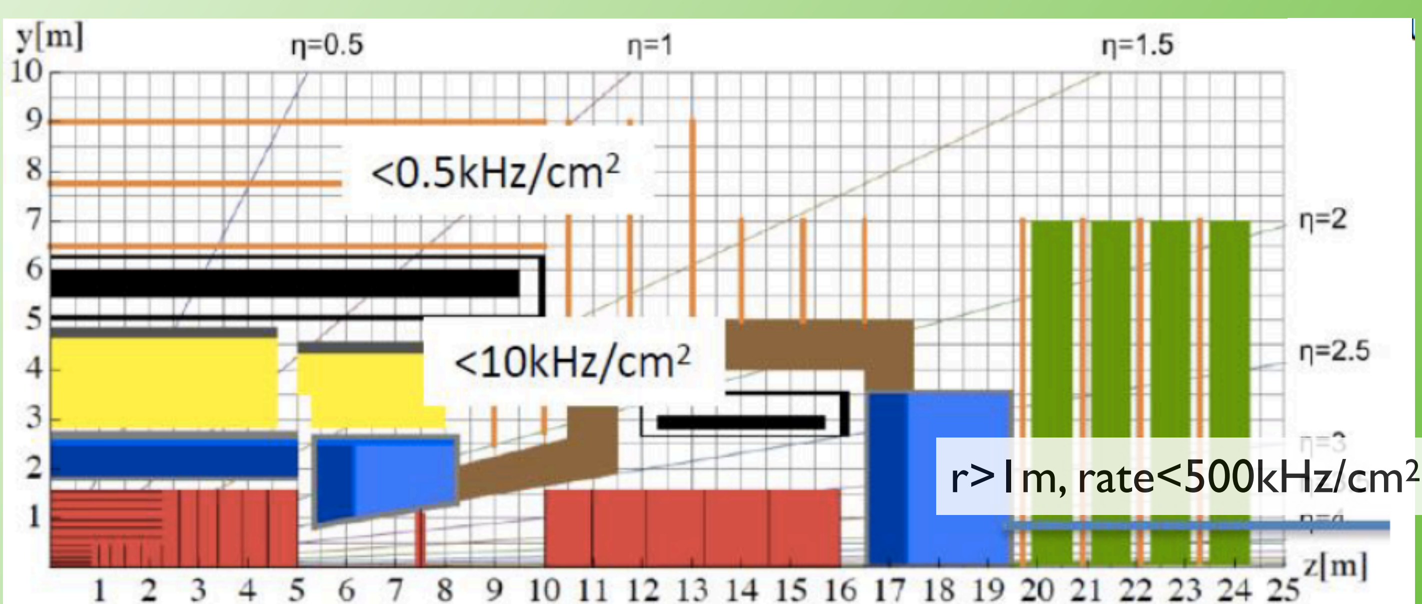


Example FCC-hh

Future challenges



possible design FCC-hh detector



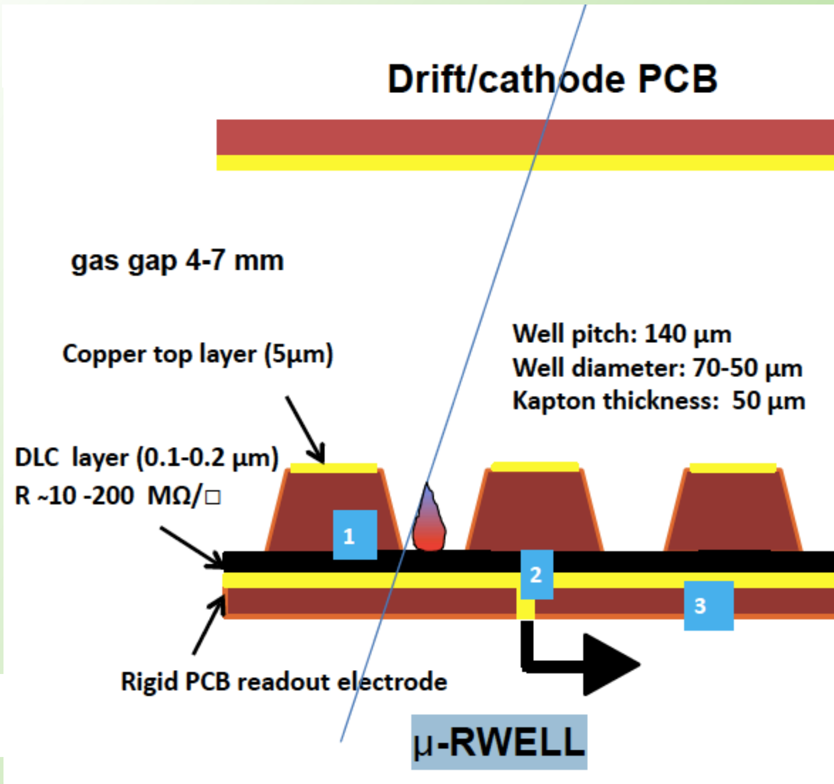
Current systems

ATLAS muon system HL-LHC rates (kHz/cm2)	
MDTs barrel	0.28
MDTs endcap	0.42
RPCs	0.35
TGCs	2
Micromegas and sTGCs	9-10

Active areas (m²)	
Micromegas and sTGCs	>2'000
GE1/1, GE2/1, ME0	>200
FCC-hh (Barrel, forward, very forward)	~10'000, 3'000,300

HL-LHC muon system technologies OK for most of FCC-hh detector area; Area to cover will be huge! Need gas detectors!

Examples for ongoing R&D



G. Bencivenni et al., 2015_JINST_10_P02008

Collaboration of INFN, CERN, Eltos

- µ-RWELL detector composed of two elements: cathode and the µ-RWELL_PCB
- The µ-RWELL-PCB combines

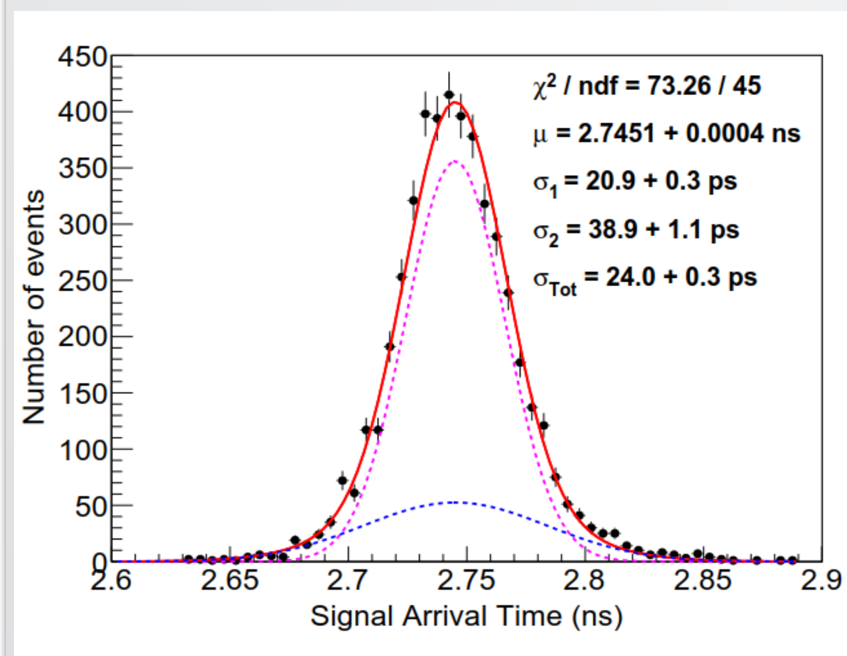
1. WELL patterned kapton foil as "amplification stage"
2. "resistive stage" for the discharge suppression & current evacuation
3. standard readout PCB

➡ Improved spark-resistance, less components, simpler construction

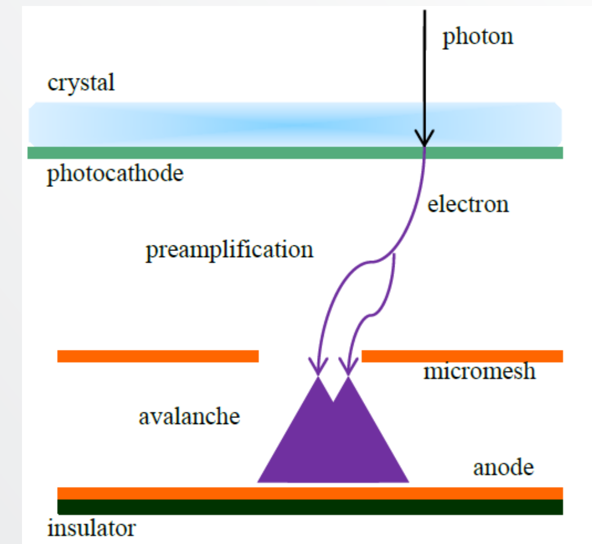
from presentation by G. Bencivenni et al

Development of high rate, spark-protected tracking detectors and fast photon detectors with solid convertors.

Solid convertors allow to increase both efficiency and the time resolution.



J. Bortfeldt et al., https://arxiv.org/abs/1712.05256



New Bulk MM readout
3 mm MgF2 + 5.5nmCr + 18nm CsI
Drift = -475V, Anode=+275V
24 ps with Single Stage GD!

Many more excellent examples!
See workshop https://indico.cern.ch/event/702148/
or summary by Eraldo https://indico.cern.ch/event/696066/

Ongoing activities worldwide &

	Activity/summary	Speaker/
1	GD Research for AD2020 and beyond	F. Sauly
2	Possible further developments of micropattern detectors	V Peskov
3	InGrid& GridPix	H.Van Der
4	R&D on double gas phase MMs using graphene	T. Geralis et al
5	Progress in MPGD -based photon detectors	S. Dalla Torre et
6	Robust gas-avalanche multiplier concepts with resistive elements	A. Breskin et al
7	The μ-RWELL	G. Bencivenni
8	Large-area MM detectors - Mesh-support studies industrial production	J. Wotschack et
9	Embedded Resistors	M. Chefdeville
10	Thin GEMs	Stefano
11	Fast Timing MPGD	P. Verwilligen et
12	R&D at USTC/China	Y. Zhou
13	High Resoultion TPC based on GEM optical readout	D. Pinci et al
14	New design of a thick gas electron amplifier	A. Reshetin et
15	A new generation of (M)RPC	I. Laktineh et al
16	Muon Detector Development at the MPI for Physics	H. Kroha et al
17	Neutron Gaseous Detector R&D Activities at ESS ERIC	D. Pfeiffer et al
18	Detector electronics - RD51 and beyond	H. Mueller et al
19	RD51	L. Ropelewski

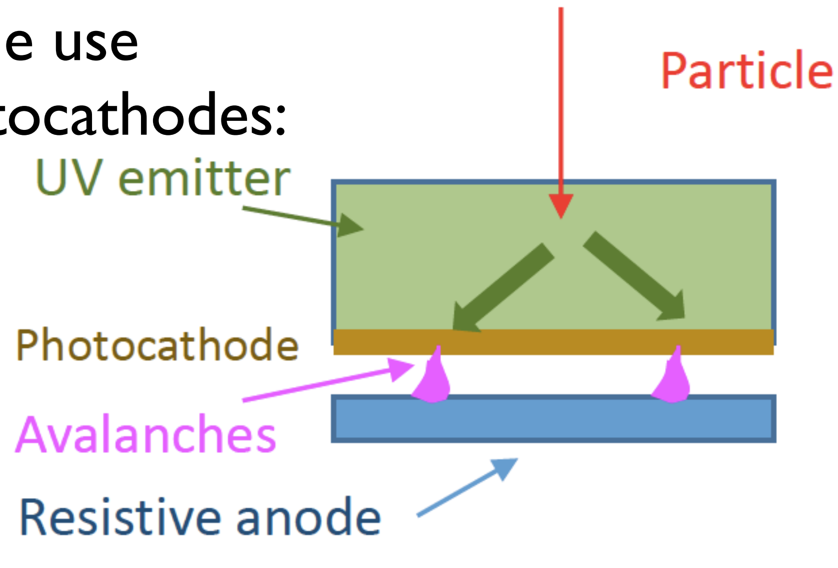
Worldwide active community, collaborating very well & efficient. Glimpse on activities: see e.g. contributions to CERN EP R&D Working Group meeting, https://indico.cern.ch/event/702148/

At CERN and EP, strong efforts in

- Experiments: participation of groups and support groups in CMS GEMs, ATLAS MicroMegas, ALICE TPC… ;
- RD51: development of advanced gas-avalanche Micro-Pattern Gas Detector (MPGD) Technologies.
  R&D support for the LHC experiments and upgrades, generic R&D; development, maintenance of software and simulation tools, development and maintenance of software of SRS electronics, industrialisation of the MPGD technology, maintenance and extension of the RD51 laboratory and test beam infrastructure, efforts in education & training for MPGDs, organisation of a series of specialised workshops.
- Reduction of Greenhouse gases (GHG, $C_2H_2F_4$, CF_4 and SF_6) for GD's: recirculation systems and use of less invasive gases (also CERN-wide: CEPS - CERN Environmental Protection Steering Board).

Development of novel technologies

Example use of photocathodes:



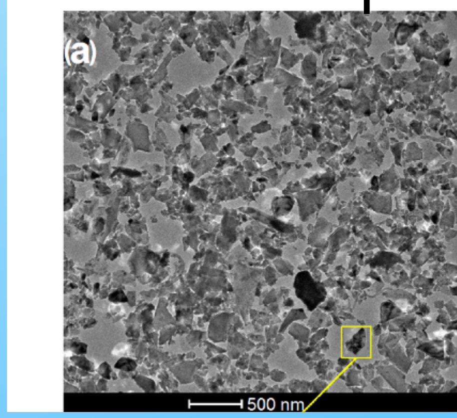
P. Fonte et al., NIM A443,2000,201 ("timing" RPCs)

Example **photon detectors**: CsI photocathodes, but sensitive to sparks and ion bombardment.
Alternative: use of new materials for photocathodes?

Diamond-like carbon films

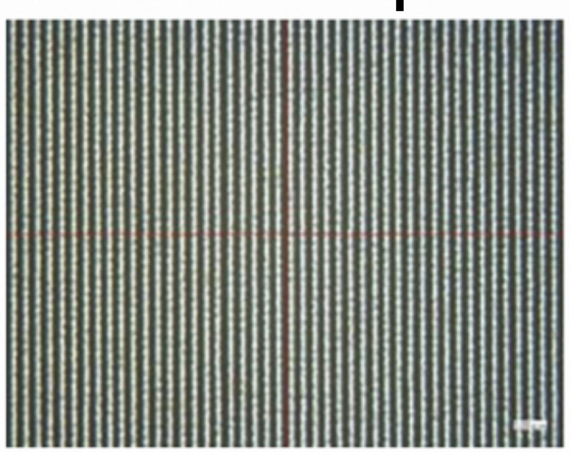
Image from: https://www.jenoptik.com/products/optical-systems/solutions-and-integrated-technologies/optical-coatings/diamond-like-carbon-coatings-dlc

Nano diamond powder

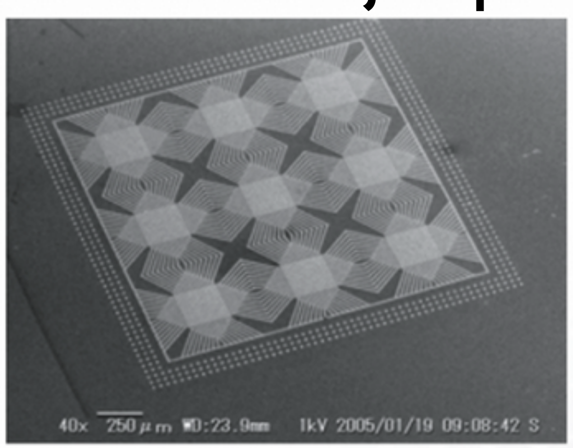


Highly efficient and stable ultraviolet photocathode based on nanodiamond particles L.Velardi, A.Valentini, and G. Cicala, Appl. Phys. Lett. 108, 083503 (2016)

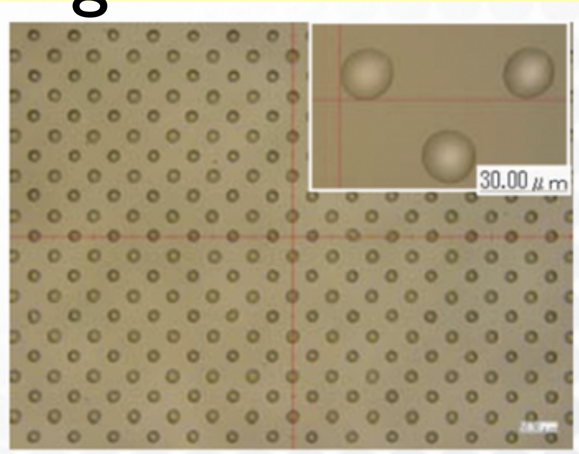
New manufacturing processes: possibilities of inkjet printing



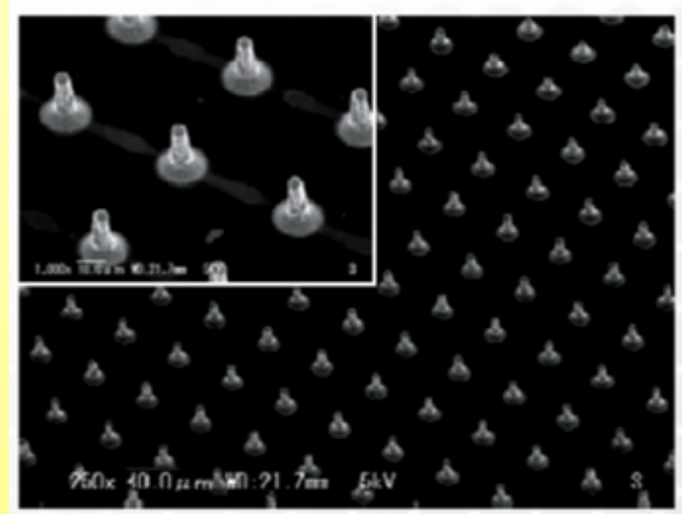
Silver ink, L/S=1 μm



Circuit pattern



Microlens (resin ink)



Microbump
Diameter=5 μm, Height=20 μm

"Future prototyping… you print your detector and you validate electrical field configuration, signal induction, charge evacuation …"

see R. De Oliveira, https://indico.cern.ch/event/702068/sessions/265605/attachments/1597953/2532624/Rui.pdf

Activities in EP R&D on gas

- ➡ **Activity 1:** Solutions for large area gas based detector systems;
- ➡ **Activity 2:** Tools for gas based detector R&D;
  - Gas analysis and gas studies;
  - Simulation and modelling;
  - Electronics and instrumentation;
- ➡ **Activity 3:** Development of novel technologies;
- ➡ **Activity 4:** Fast optical read readout.

Summary

- Gas-filled particle detectors are widely used in HEP and Nuclear Physics, neutrino experiments, Dark Matter searches, ground-based astroparticle and space experiments as well as spin-off outside HEP field (e.g. medicine, homeland security);
- They can provide light (low-mass), (relatively) cheap, easy-to-build, radiation hard detector solutions for specific measurements;
- Trend is towards micro-pattern gaseous detector technologies, with integrated detector electronics. But also "standard" detectors are still widely used.
- Interesting times to come!

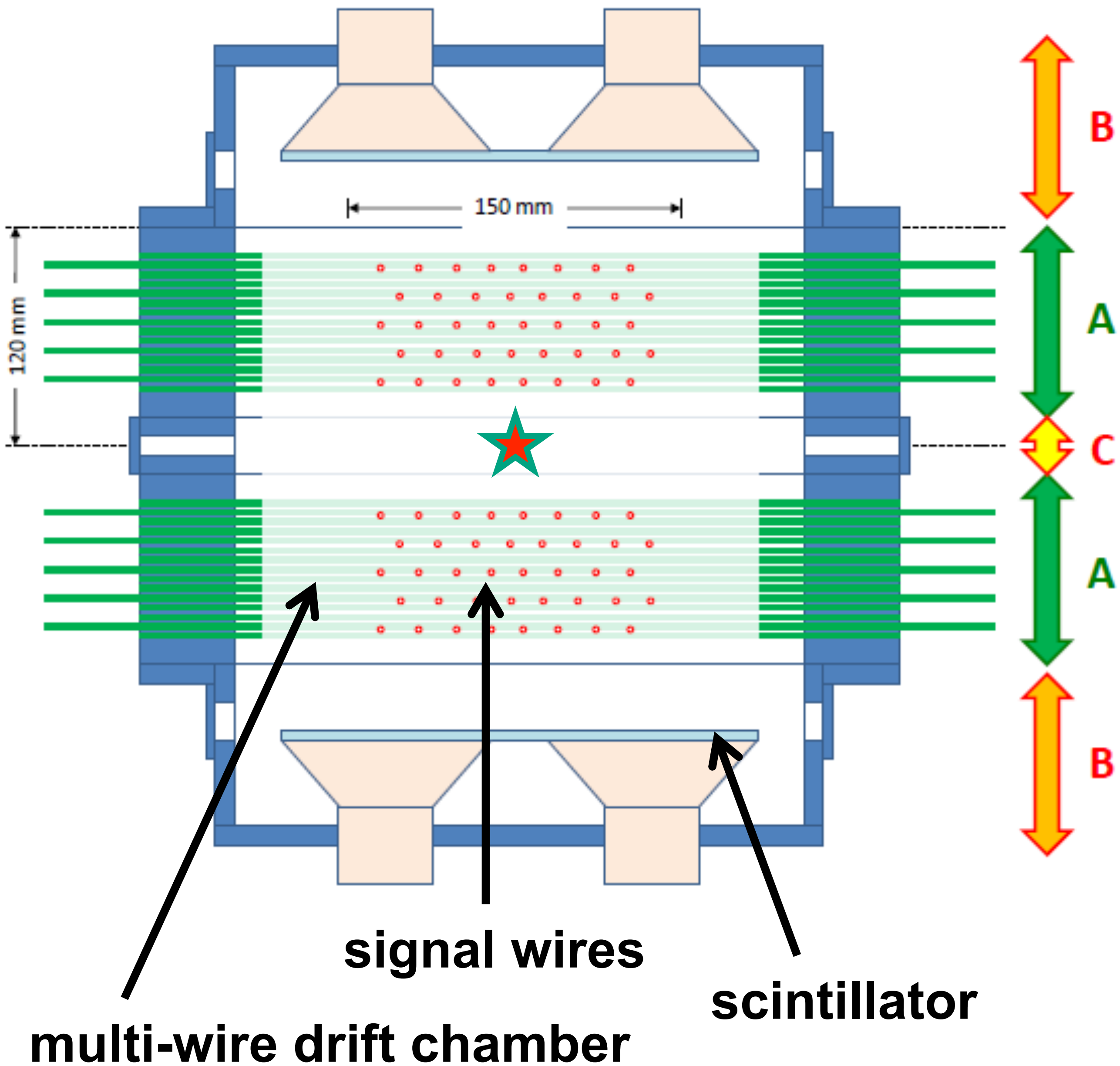
…and join the CERN R&D programme on gas detectors (if interested, contact Eraldo Olivieri or CR)!

Backup slides

β spectrum shape measurements with the miniBETA spectrometer at the KU Leuven

Univ. Krakow – Univ. Leuven

$$d\Gamma \propto G_F \; F(Z,E) \left[1 + k' \, E_\beta \; b_{WM} + k'' \, \frac{b_{Fierz}}{E_\beta} \right]$$



1. **high β-endpoint energies**
   (^{14}O, ^{19}Ne, ^{32}P, ^{114}In, fission products, …):

   →weak magnetism

2. **low β-endpoint energies**
   (^{45}Ca, ^{60}Co, ^{67}Cu …) :

   → scalar / tensor type weak interactions

3. **improve current knowledge on electron scattering**

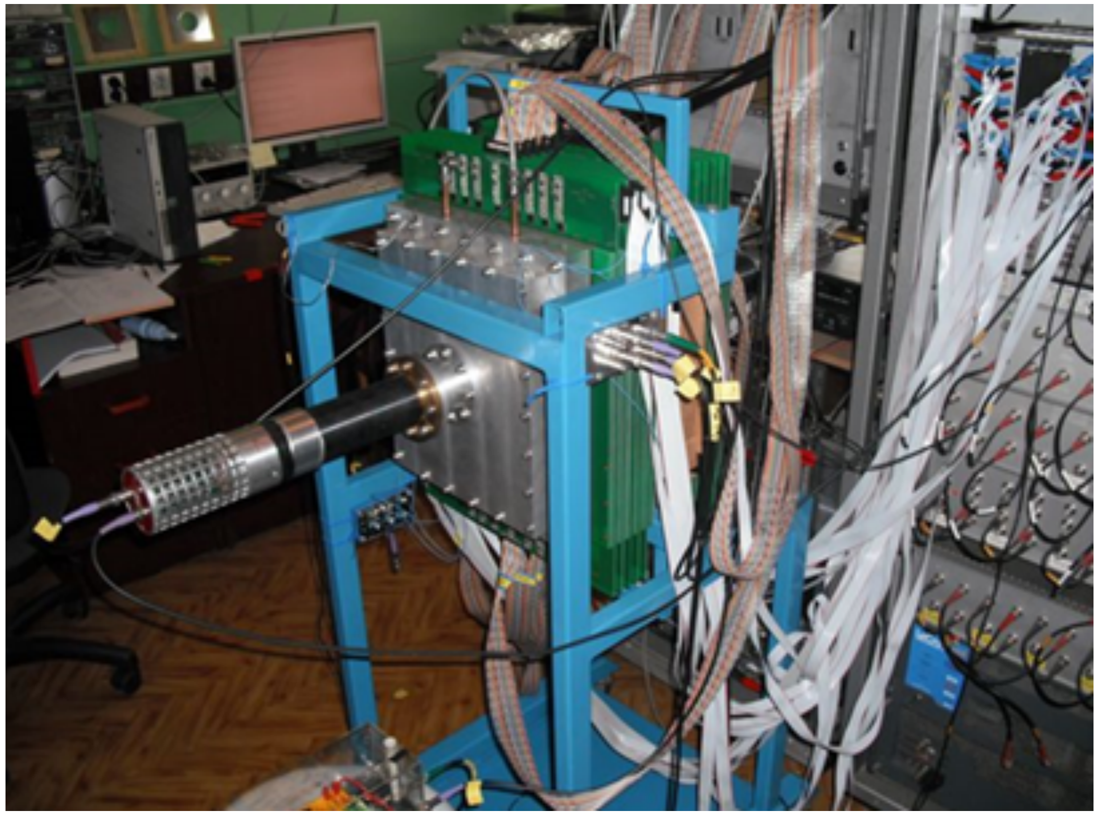
   →improve precision of Geant4 for β particles

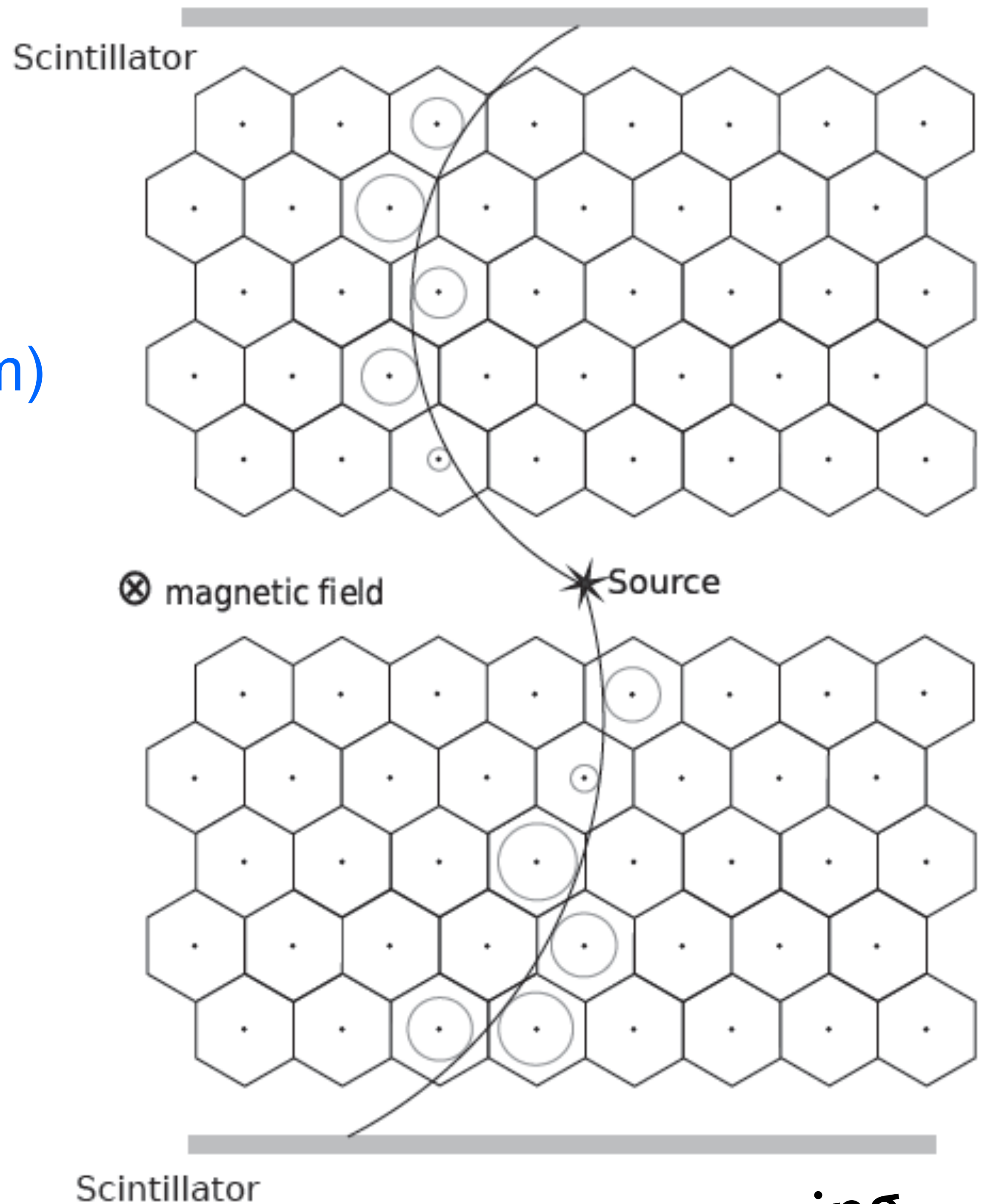
A table-top experiment!

Many thanks to Nathal Severijns for his input to this slide!

miniBETA spectrometer

- 80 hexagonal cells
  (10 planes with 8 signal wires
  [$\phi = 25\mu m$, NiCr 8020])
- X-Y space resolution 0.5mm
- Z position from charge division (4 mm)
- energy resolution <10keV.
  (from curvature of track in B-field)
- 300 mbar (He 70%, isobutane 30%)

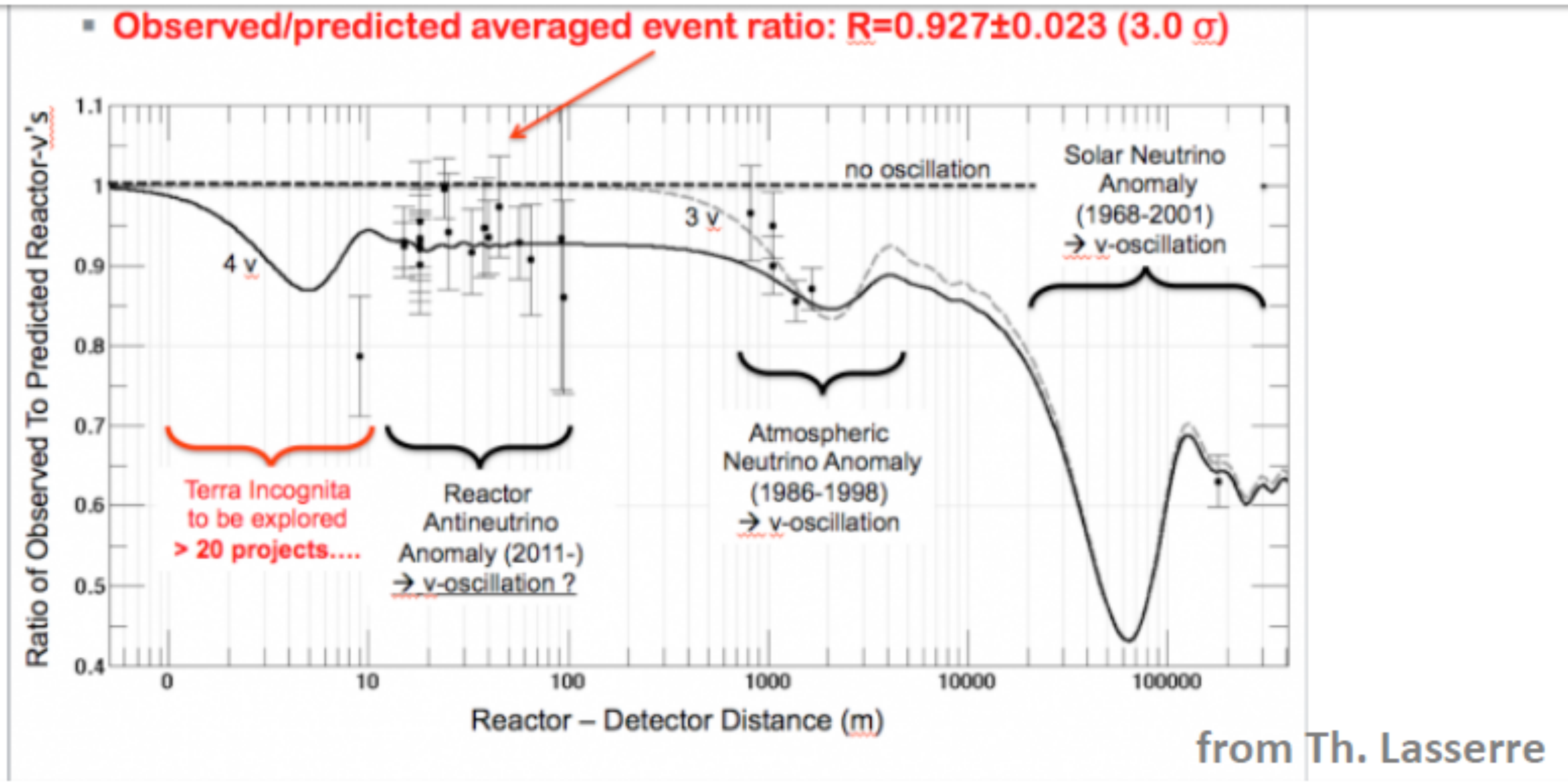




commissioning ongoing

Many thanks to Nathal Severijns for his input to this slide!

The reactor antineutrino anomaly



The effect mostly comes from the detailed physics involved in the nuclear beta-decay of fission fragments in the reactor

…understanding electromagnetic interactions

TABLE I. Gamow-Teller decays and the associated parameters needed for a computation of the weak-magnetism slope parameter using the CVC hypothesis.

P. Huber, Phys. Rev. C 84, 024617 (2011) and Phys. Rev. C 85, 029901(E) (2012)

Decay	$J_i \to J_f$	E_γ (keV)	Γ_{M1} (eV)	b_γ	ft (s)	c	b_γ/Ac	$\lvert dN/dE \rvert$ (% MeV^{-1})	Ref.
$^{6}He \to {}^{6}Li$	$0^+ \to 1^+$	3563	8.2	71.8	805.2	2.76	4.33	0.646	[28]
$^{12}B \to {}^{12}C$	$1^+ \to 0^+$				11640	0.726	4.35	0.62	[38]
$^{12}N \to {}^{12}C$	$1^+ \to 0^+$				13120	0.684	4.62	0.6	[29]
$^{18}Ne \to {}^{18}F$	$0^+ \to 1^+$				1233	2.23	6.02	0.8	[30]
$^{20}F \to {}^{20}Ne$	$2^+ \to 2^+$				93260	0.257	8.9	1.23	[31]
$^{22}Mg \to {}^{22}Na$	$0^+ \to 1^+$				4365	1.19	5.67	0.757	[55]
$^{24}Al \to {}^{24}Mg$	$4^+ \to 4^+$				8511	0.85	6.35	0.85	[56]
$^{26}Si \to {}^{26}Al$	$0^+ \to 1^+$				3548	1.32	3.79	0.503	[32]
$^{28}Al \to {}^{28}Si$	$3^+ \to 2^+$				73280	0.29	2.57	0.362	[57]
$^{28}P \to {}^{28}Si$	$3^+ \to 2^+$				70790	0.295	2.53	0.331	[57]
$^{14}C \to {}^{14}N$	$0^+ \to 1^+$				1.096×10^9	0.00237	276	37.6	[38]
$^{14}O \to {}^{14}N$	$0^+ \to 1^+$				1.901×10^7	0.018	36.4	4.92	[26]
$^{32}P \to {}^{32}S$	$1^+ \to 0^+$	7002	0.3	26.6	7.943×10^7	0.00879	94.4	12.9	[39]

$$\frac{dN}{dE} = \frac{4}{3M_n}\frac{b}{Ac}$$

$$\frac{dN}{dE} = 0.7(3)\%\ \mathrm{MeV}^{-1}$$

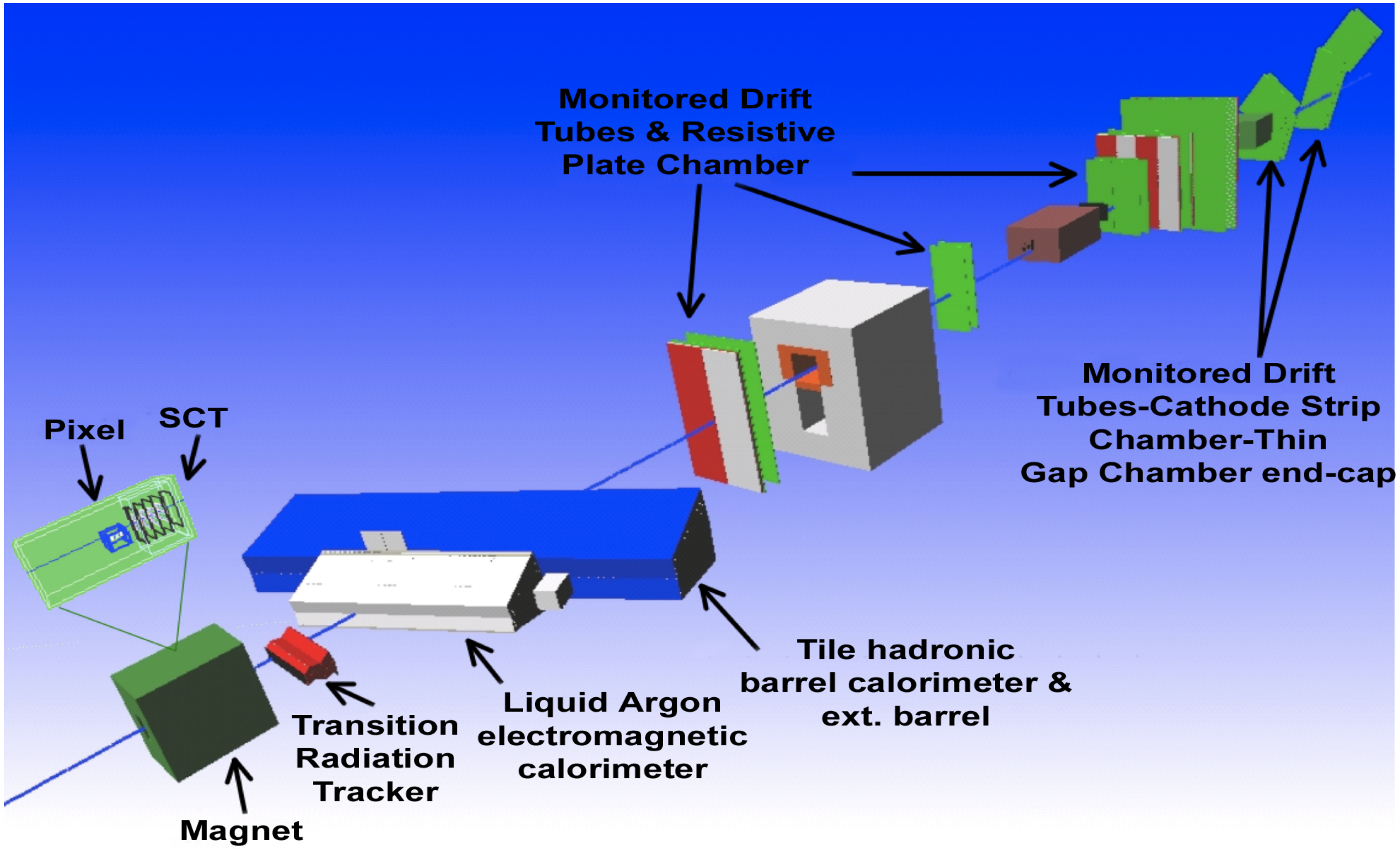
$$\frac{dN}{dE} = 5(11)\%\ \mathrm{MeV}^{-1}$$

Note: **shift of dN/dE by +0.5% MeV^{-1} causes a shift of the reactor anti-neutrino rate by -1%**

Could indicate breakdown of impulse approx. if log *ft* is large, or be due to electromagnetic interaction which is then very much amplified due to the large hindrance of the β decays.

Many thanks to Nathal Severijns for his input to this slide!

Test-beams are vital!

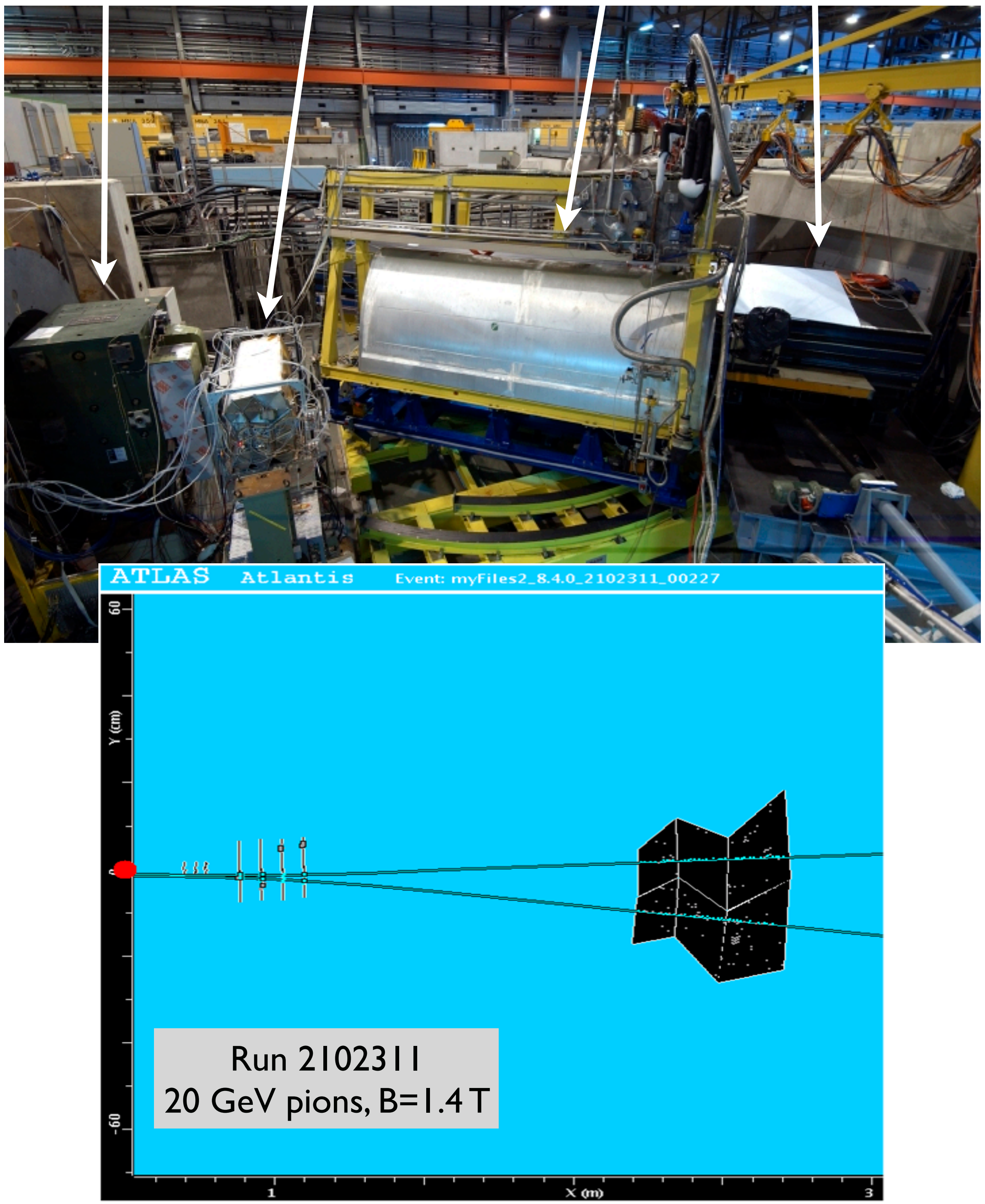


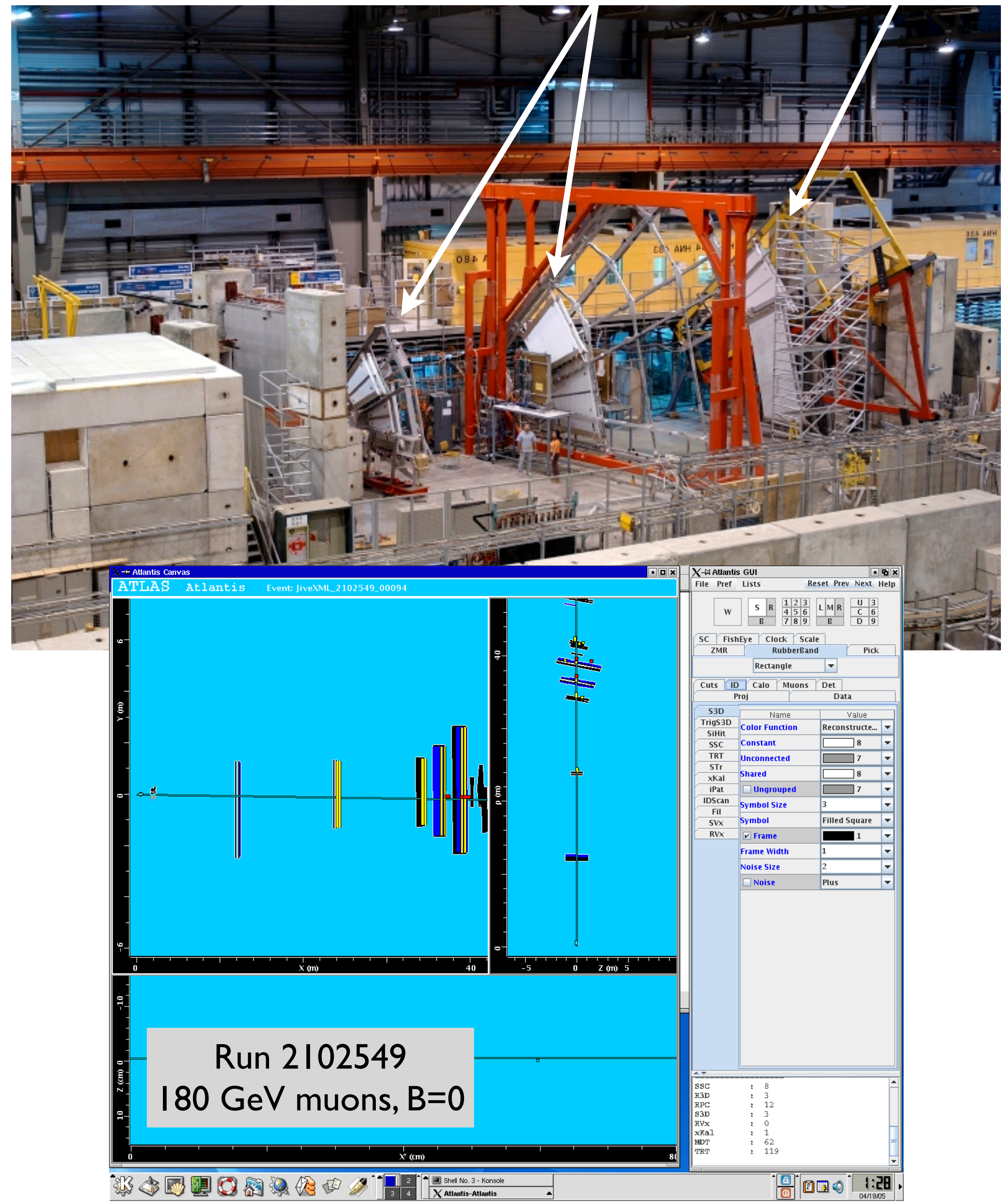
- Test beams at
  → technology and system tests, calibration & validation - not only for detectors but also for electronics and software!
  → teams were given goals & milestones (i.e. progress of projects could be monitored);
  → shifts/work in the test beam are great to meet colleagues from other subsystems!

- Big campaigns
  → ATLAS Combined test beam in 2004;
  → CMS Cosmic challenge (2007) with CMS detector in CMS cavern.

ATLAS in North Area (H8), 2004

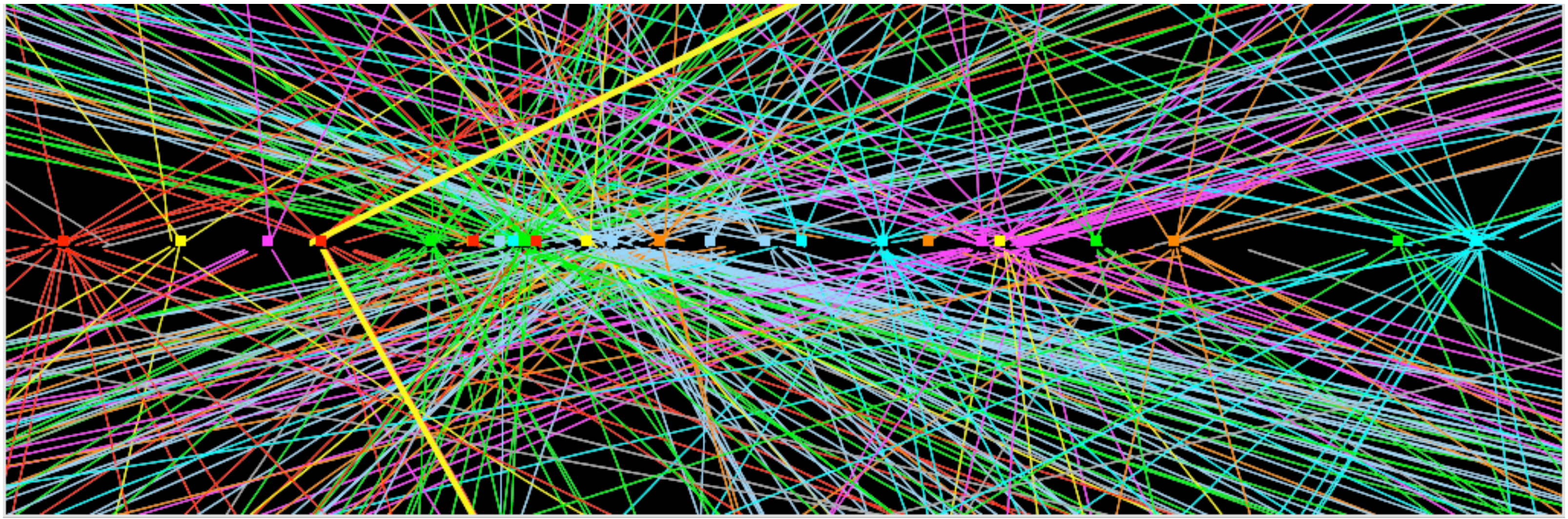
Pixels, SCT and TRT | Liquid Argon & Tile Calorimeters | Muon detectors, trigger cambers and drift tubes





Challenged by the LHC machine

- LHC up to now operated with bunch spacing of 50ns (25ns design) but high bunch currents to achieve luminosity;
- average number of interactions per bunch crossing about twice the design (24 interactions per b.c.)
  - ➡ challenge for tracking and vertexing, trigger, lepton isolation, jet energy scale/ resolution, missing transverse energy reconstruction, reconstruction CPU time…



ATLAS, Z→μμ, pile-up 25

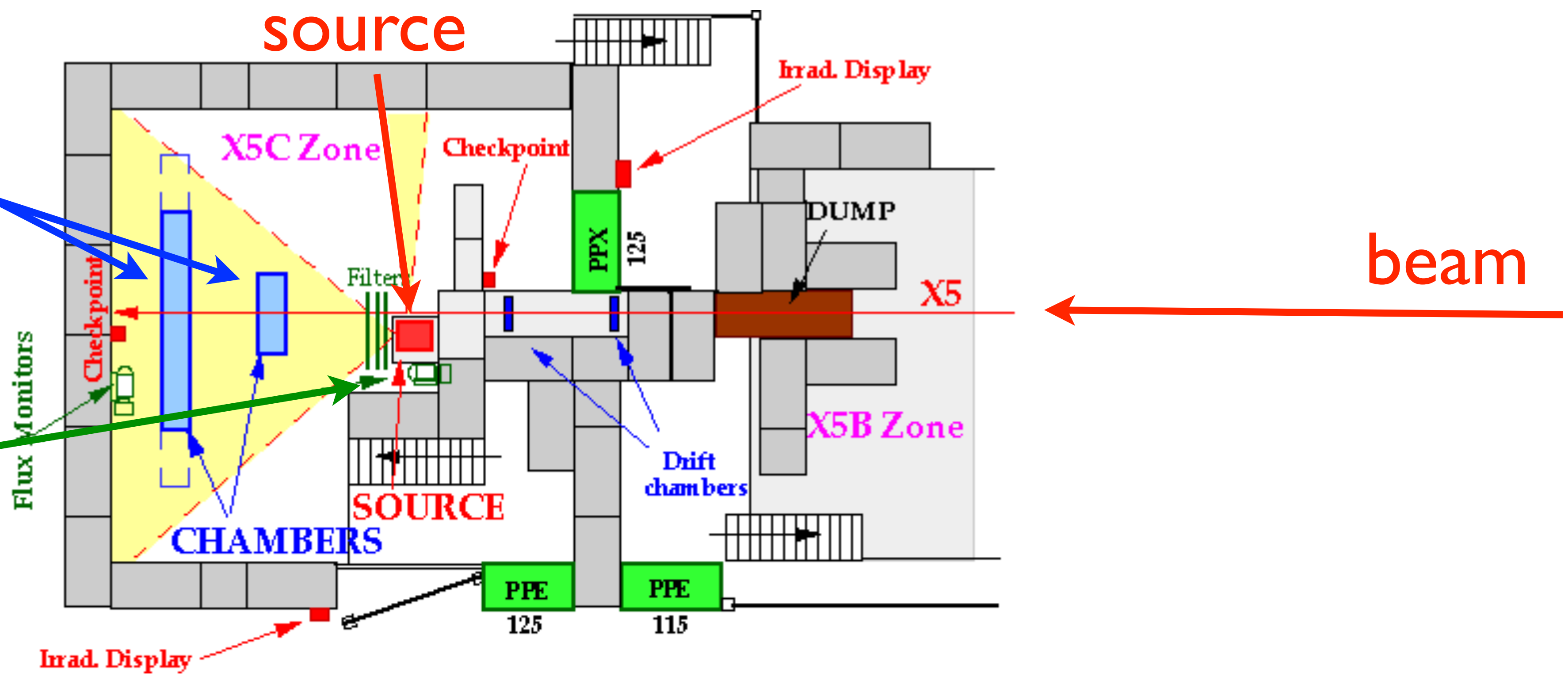
Impressive to see how detector teams solved this problem!

One of the miracles of the LHC…

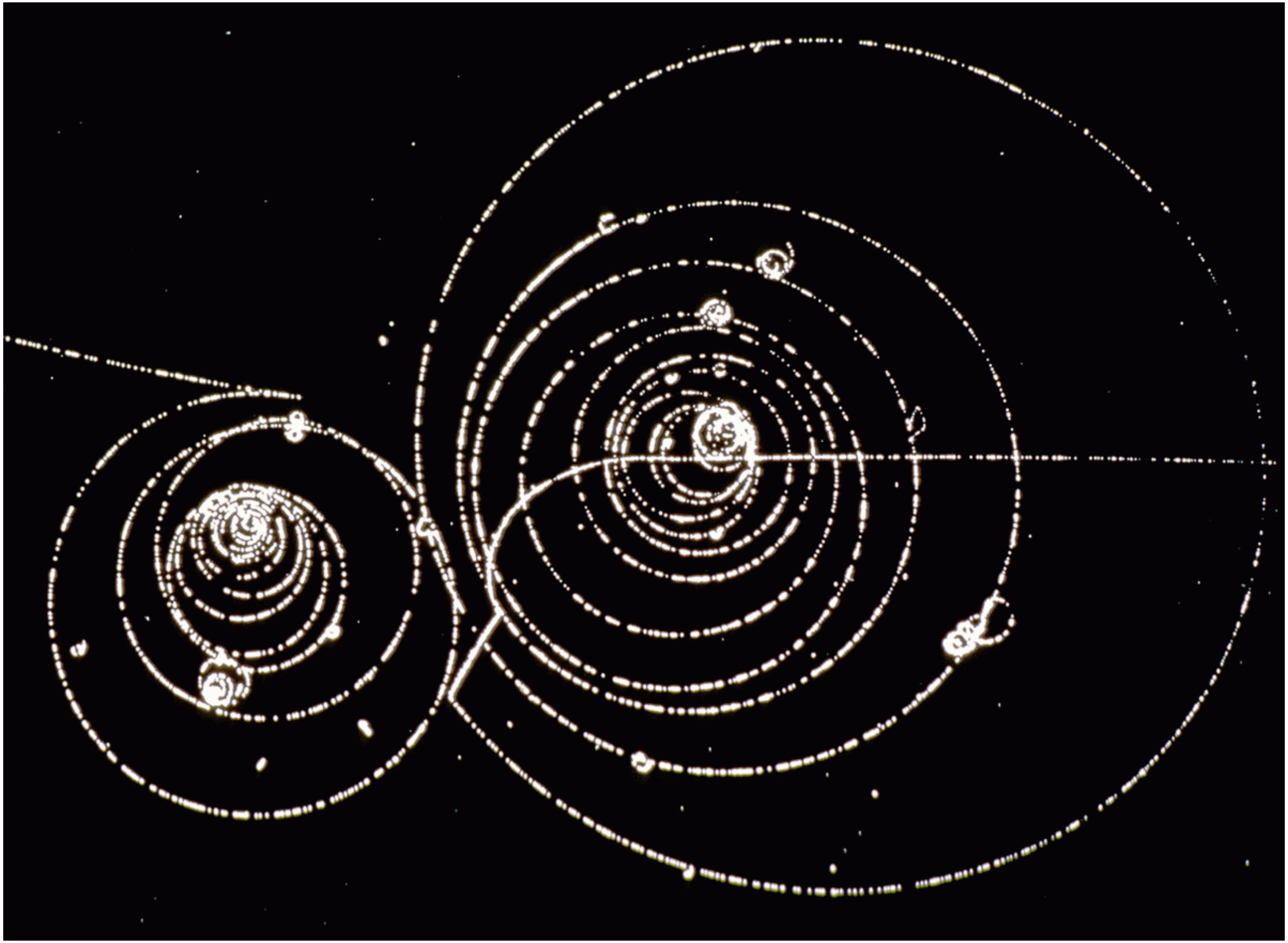
Massimiliano Ferro-Luzzi (LHCb, LHC Programme Coordinator up to 2011):
"I (and many others) had been more or less brainwashed for years that 50ns was not possible, because it would not be possible to satisfy the requests of all experiments… .
… LHCb had to suffer a bit, due to the higher pile-up, but they magnificiently coped with it,operating at 4 or 5 times the pile-up which the experiment was designed for another example of the great creativity and adaptability of physicists!"

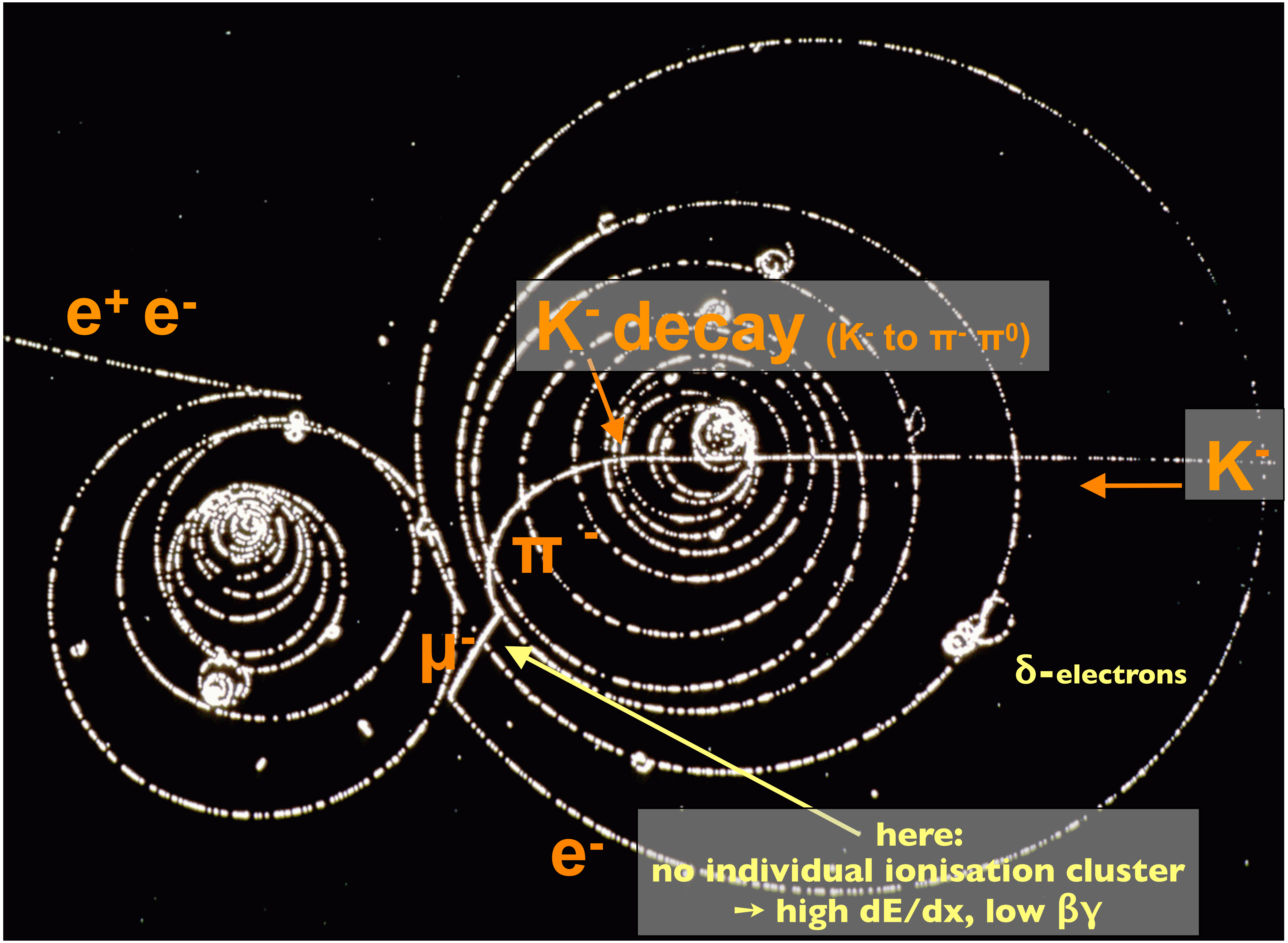
Special and mandatory for LHC: the Gamma Irradiation Facility GIF

- Gamma source CS^{137} 740 GBq (1997) with 662 keV photons plus parasitic muon beams O(100 GeV) from SPS in West Area
  - ➡ West Area closed and beams stopped in 2004
- Feature & idea: test **operation** and **aging** of large area detectors (RPCs, TGCs, drift tubes...) **at high rates (kHz/cm²)**
  - ➡ photons from source provide background - beam particles are the signal;



- Main users: LHC experiments
  - ➡ fully booked over last 16 years, many publications an notes (e.g. search in NIMA: >200 articles);
- Still in operation today to help with aging problems;
- New GIF (GIF++) under construction in SPS North Area, ready for beam in 2015.

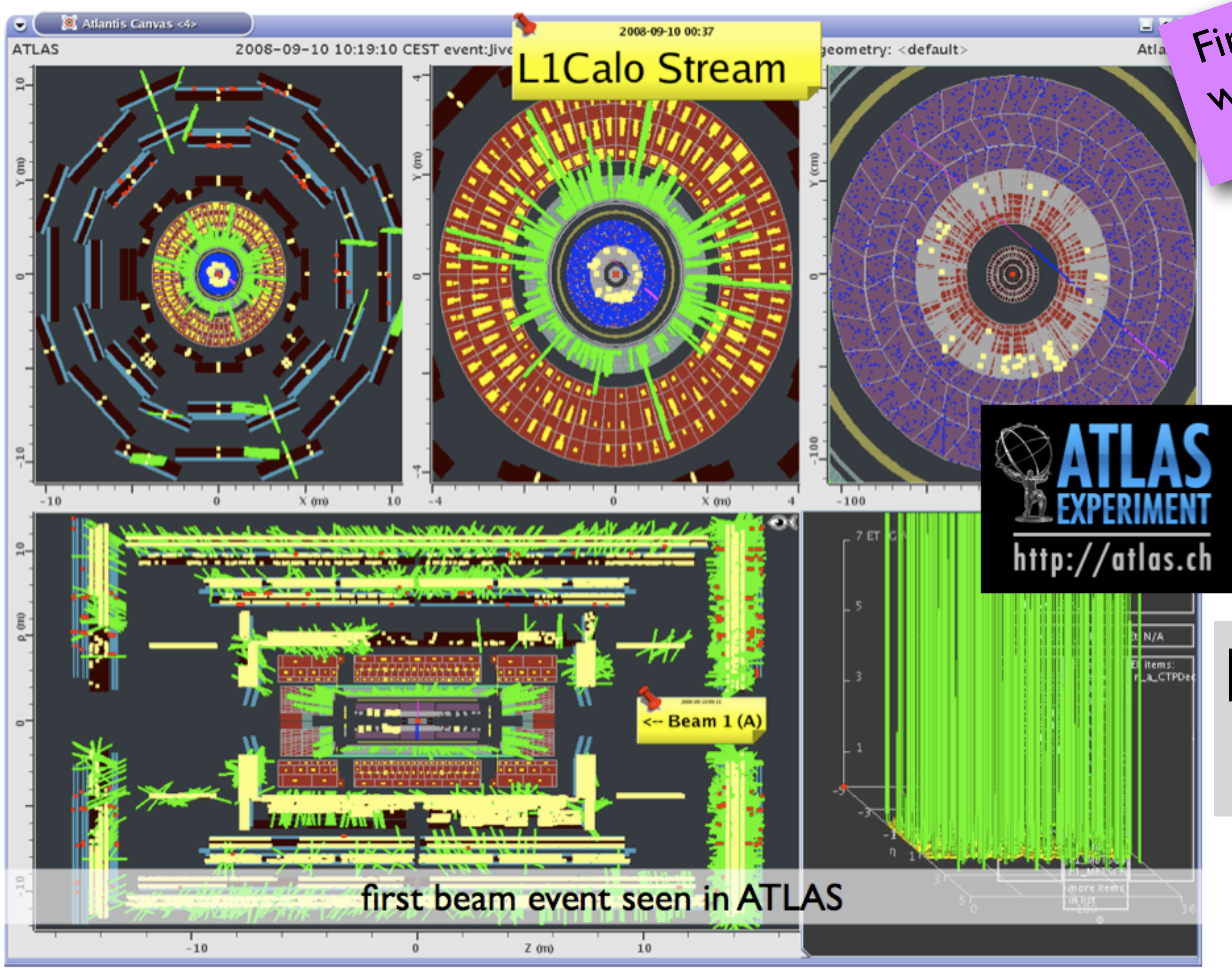



e+ e-
K- decay (K- to π- π0)
K-
π -
μ-
δ-electrons
e-
here:
no individual ionisation cluster
→ high dE/dx, low βγ

Beam “Splashes” were important!

- 2008: Single beam in LHC was steered onto collimator close to experiment ➝ spray of secondary/tertiary particles made that almost all electronic channels fired
  - ➡ important to understand/calibrate detectors

First beam day 10 September 2008 was for many colleagues their LHC highlight!



Thanks to experiences with single beam, low energy collisions, the break in 2009 to repair the LHC machine was not “lost” at all!

Be brave! Switch on your detector!