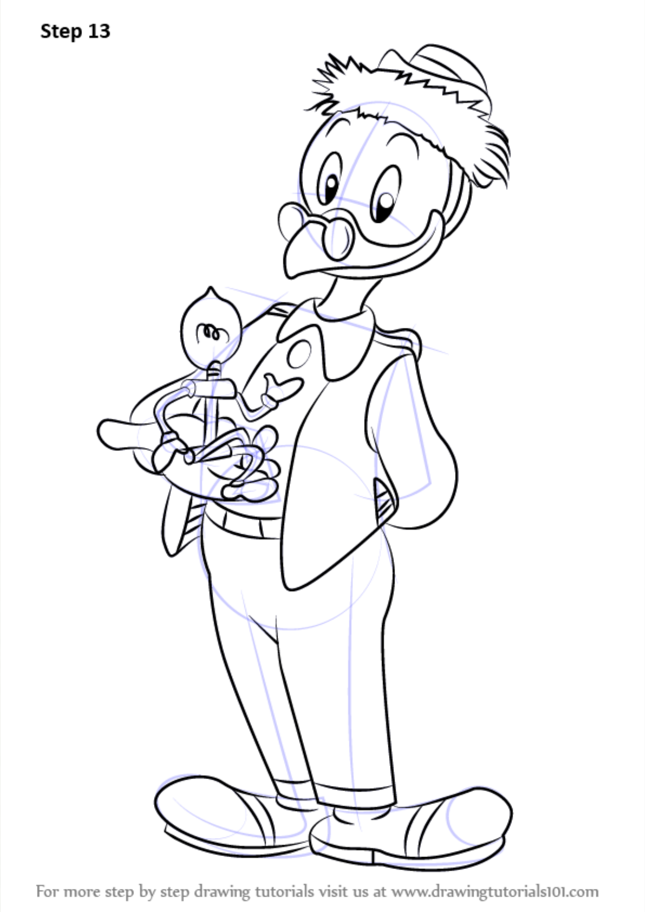
We have got an

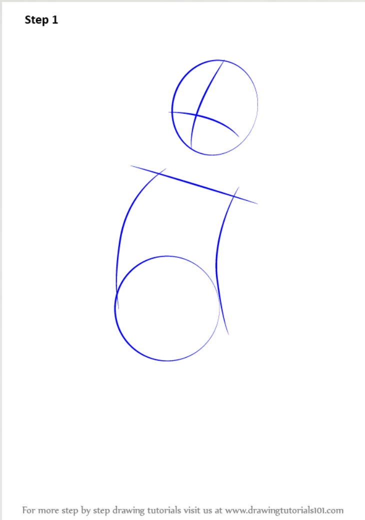
IDEA

an **I**nternational **D**etector for **E**lectron-Positron **A**ccelerator(s)

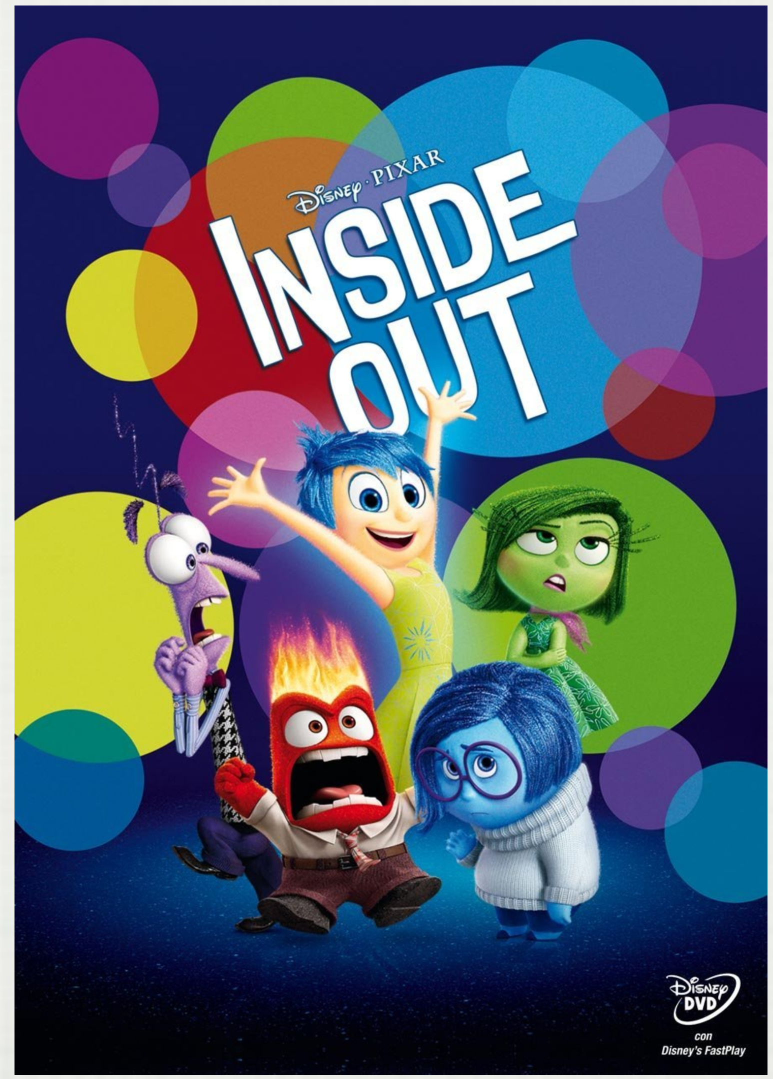


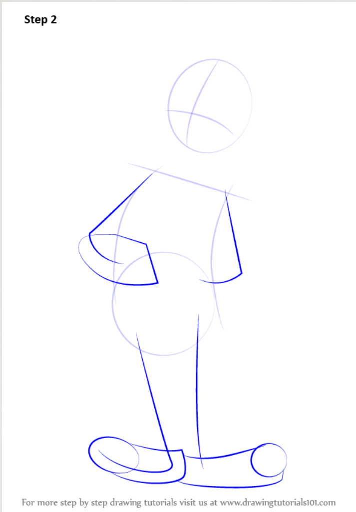
Workshop on Circular Electron-Positron colliders
Roma, May 24-26th, 2018

Massimo Caccia
Università dell'Insubria @Como & INFN-Milano



STEP 1: a look at the different technologies, with a different point of view and starting

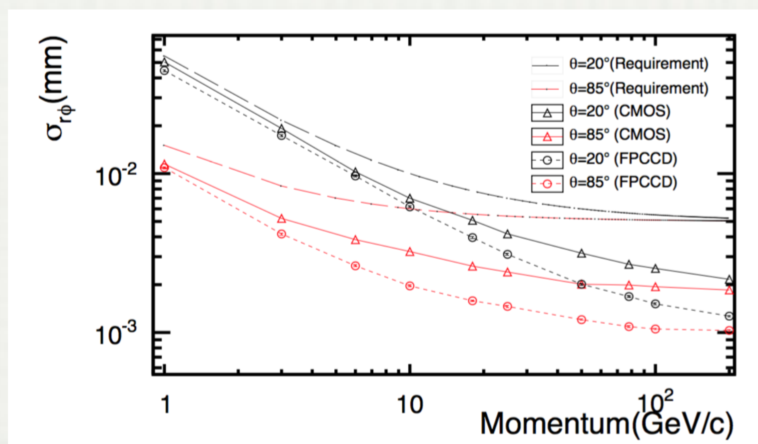




The essence of the designing and constructing a VERTEX DETECTOR:

fit 1 GigaPixel in a Diet Coke can & keep it cool!

☑ Physics First!



ILD DBD 2012

impact parameter resolution

Accelerator	a [μm]	b [μm·GeV/c]
LEP	25	70
SLC	8	33
LHC	12	70
RHIC-II	13	19
ILC	< 5	< 10

ILD LOI 2009

The ILC figures apply also when you go beyond the linear approximations

- a depends on the single point resolution and the ratio between the innermost radius and the lever arm:
  => σ_{sp} = 3 μm when R_{in} =16 mm and R_{out} = 60 mm

[The ILD and CePC baseline figures]

- b depends on the multiple scattering at the innermost radius:
  => thickness/layer = 0.15% X_0 [X_0 = 9.37 cm for Silicon]   [140 μm]

☑ The machine comes next; and we have to account for

the time structure of the beams:

at the CepC, collisions are equally spaced (in time) with a frequency depending on the number of bunches. In one of the configurations reported in Beijing-201609, we have:

- 50 bunches at the Higgs factory energy
- 5000 bunches at the Z factory energy [where I estimated 4 kHz event rate]

for a beam Xing every 5 μs (@Higgs) to 50 ns (@Zpole) [3.6 μs is the "official" number]

the expected Beam-induced background:

there is actually NO solid rock number and estimates have a significant dependence on the machine & final focus parameters (HongBo, 2018, Roma).

A rough figure says ≈ 2.5 hits/cm^2/Xing (I believe @Higgs energies)

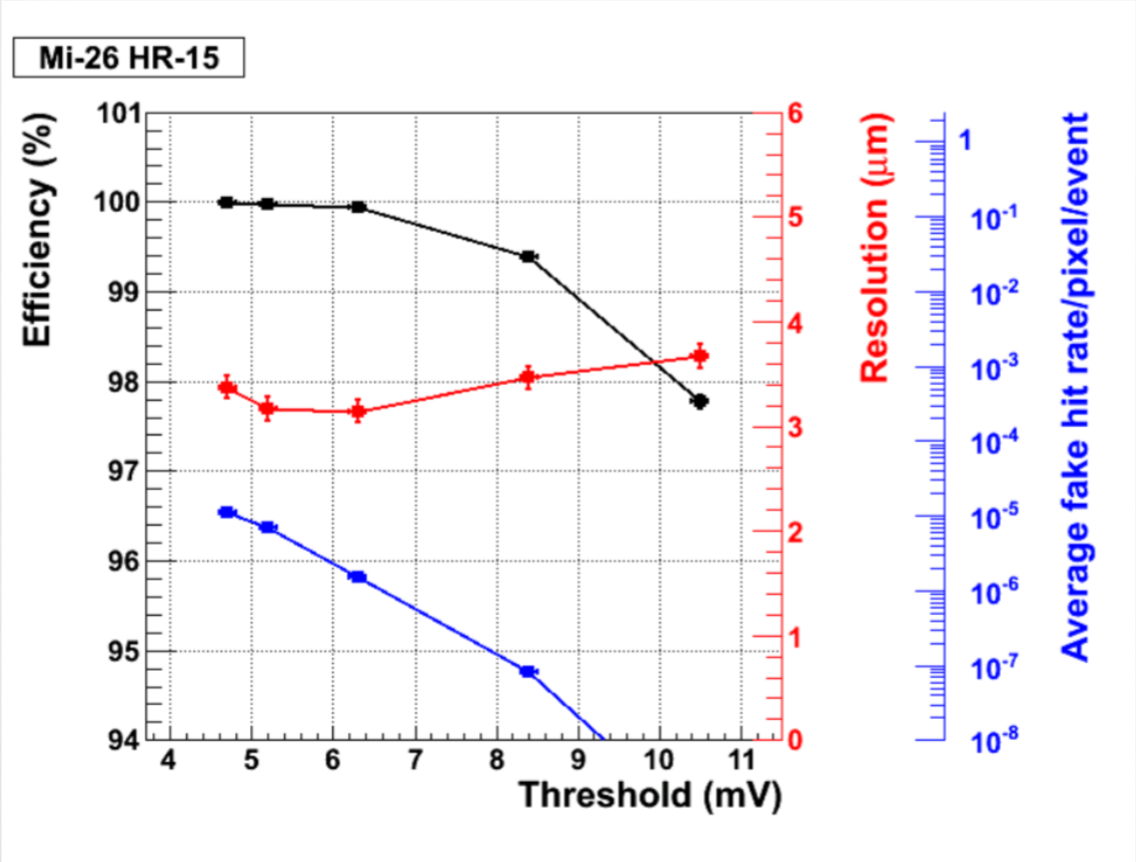
BUT:

- having the spectrum of the bckg particles is important to see if we have "loopers"
- we have to see how it scales with the energy

the expected radiation level: RELAX!

If we look a bit around we know that Monolithic Active Pixel Sensors (MAPS) are a good starting point:

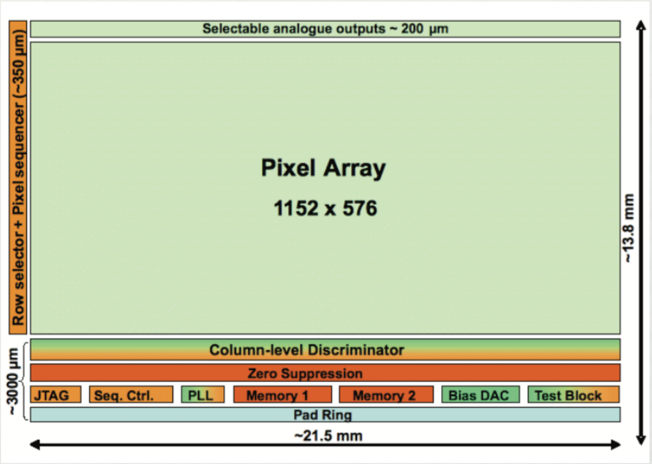
- MAPS have been shown to be able to provide the required resolution with a binary read-out:



M. Winter et al., arXiv: 1203.3750v1 (2012)

Test beam results for the MIMOSA-26 sensor:

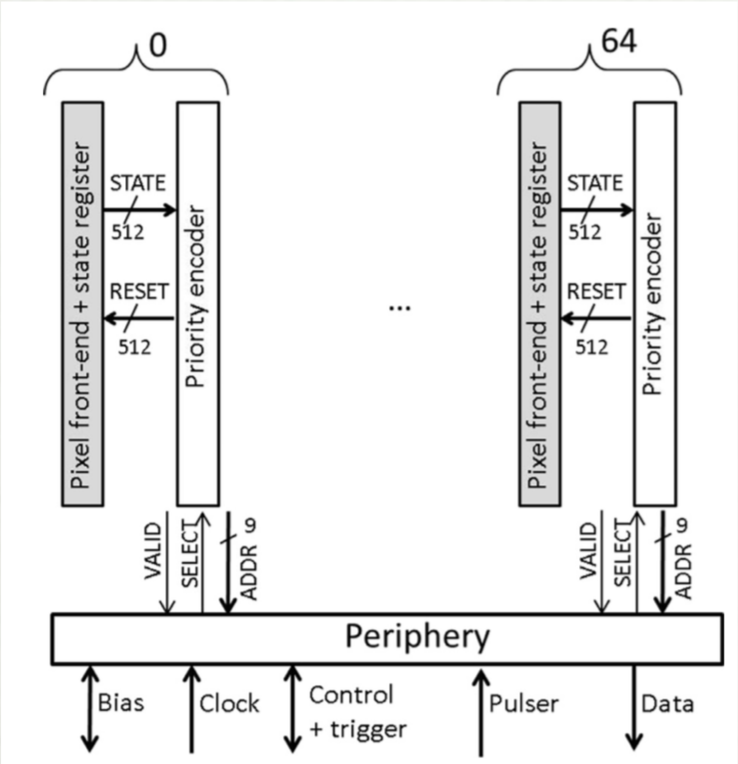
- 18.4 μm pitch (5.3 μm binary resolution)
- rolling shutter & end-of-column zero suppression (200 ns/pixel r.o. time)
- **250 mW/cm² power consumption**



The pitch/√12 rule has been violated

If we look a bit around we know that Monolithic Active Pixel Sensors (MAPS) are a good starting point:

* sophisticated architectures with ON PIXEL sparsification have been designed and qualified:

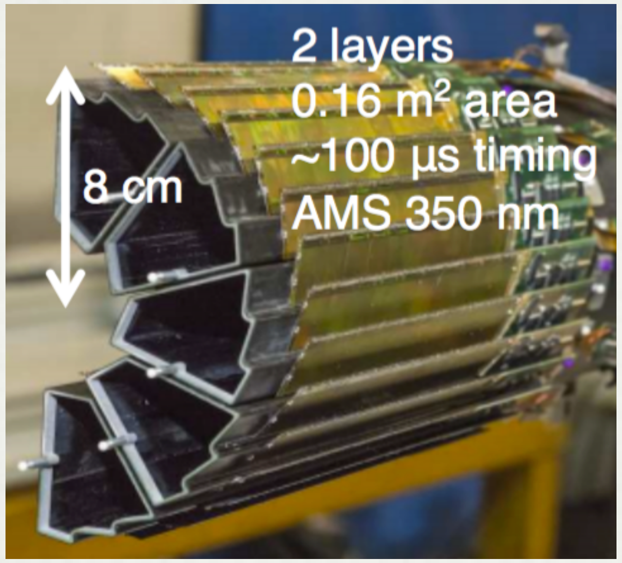


- 1 discriminator/pixel + 1bit memory cell
  ⇢ analog info locally processed
- the integration time is independent from read-out (r.o.) time
- the r.o. time is dependent from the pixel occupancy
- current power consumption at the level of 50 mW/cm^2 (ALPIDE)

-NIM A 765 (2014) 177 + A 785 (2015) 61
-pixel 2014 proceedings published on JINST (doi:10.1088/1748-0221/10/03/C03030)

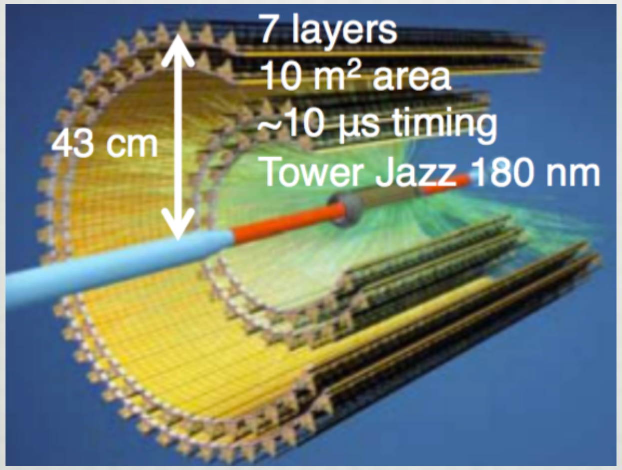
If we look a bit around we know that Monolithic Active Pixel Sensors (MAPS) are a good starting point:

- large systems have been designed and commissioned (or will be, in a short while):



- 400 sensors
- 0.9 Pixel each
- power dissipation 170 mW/cm²

nothing but a toy compared to what is envisaged for the ITS of the ALICE experiment:



	σ_{sp}	$t_{r.o.}$	Dose	Fluency	T_{op}	Power	Active area
STAR-PXL	$< 4\ \mu m$	$< 200\ \mu s$	150 kRad	$3{\cdot}10^{12}$ n_{eq}/cm^2	30-35°C	160 mW/cm^2	0.15 m^2
ITS-in	$\lesssim 5\ \mu m$	$\lesssim$ **30** μs	**2.7 MRad**	**$1.7{\cdot}10^{13}$ n_{eq}/cm^2**	30°C	$<$ 300 mW/cm^2	0.17 m^2
ITS-out	$\lesssim 10\ \mu m$	$\lesssim$ **30** μs	100 kRad	$1{\cdot}10^{12}$ n_{eq}/cm^2	30°C	$<$ **100 mW/cm^2**	$\sim$ **10 m^2**

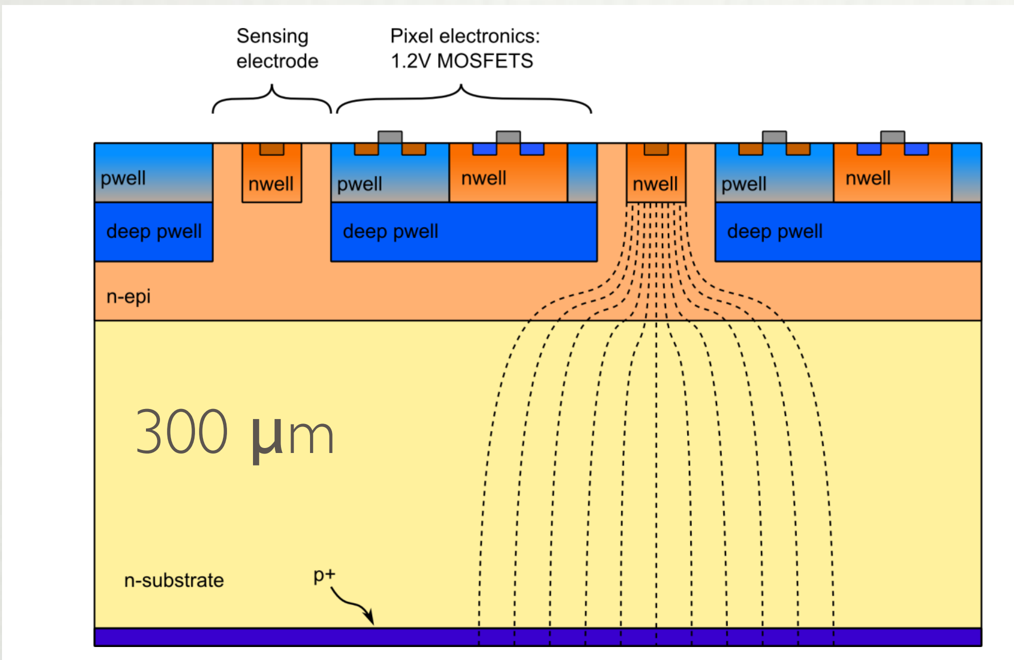
a development based on:

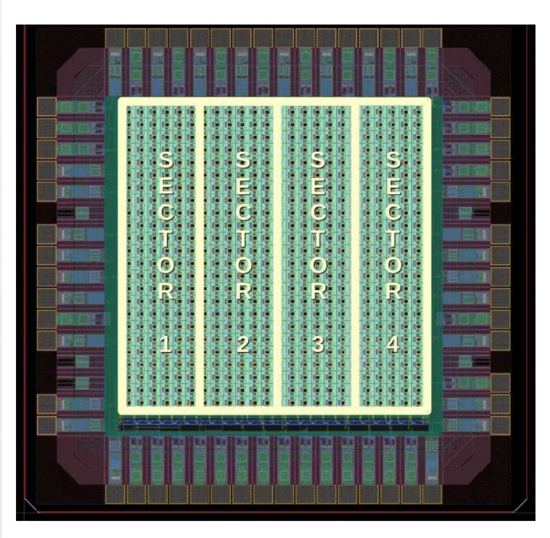
- new technologies (Tower-Jazz 180 nm)
- and new design (on pixel sparsification)

If we look a bit around we know that Monolithic Active Pixel Sensors (MAPS) are a good starting point:

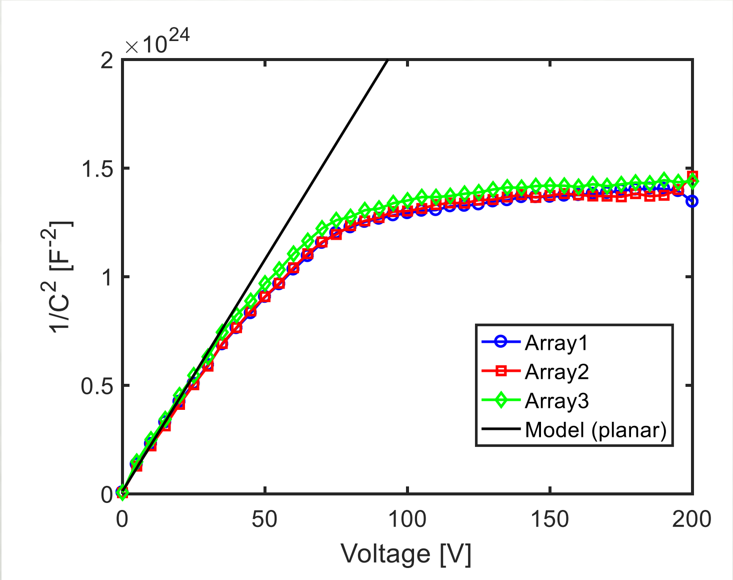
* and new technologies based on high resistivity substrates are very appealing:

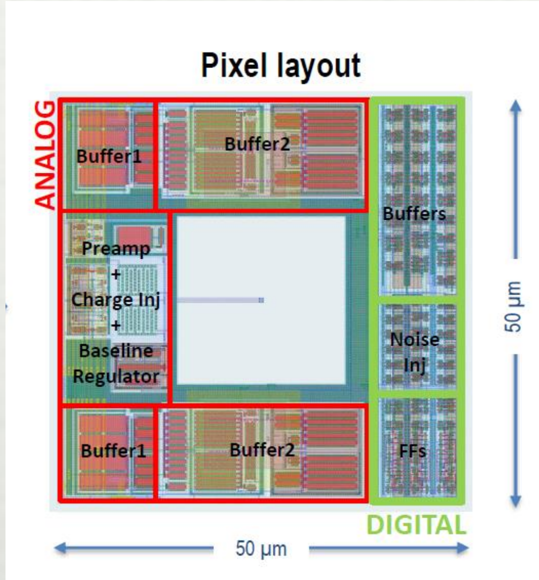
The INFN SEED (Silicon with Embedded Electronics Development, partnership with LFoundry):

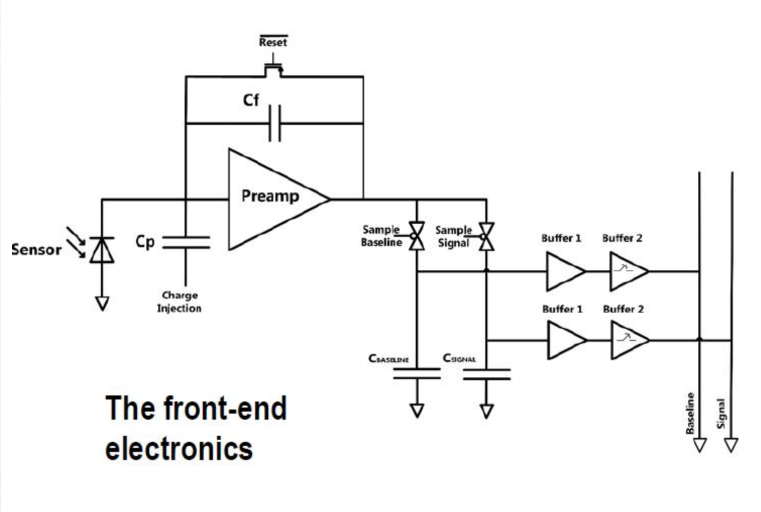




- die area 2x2 mm2
- 24x24 pixel array
- Equivalent Noise Charge: 50 e- rms at room T







S. Panati et al. , IEEE-NSS 2017 Conf. record

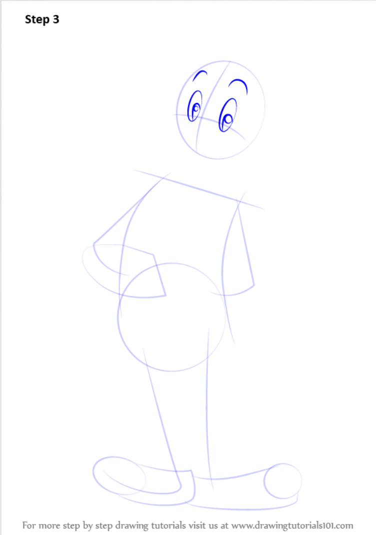
Vertex Detector Conclusions:

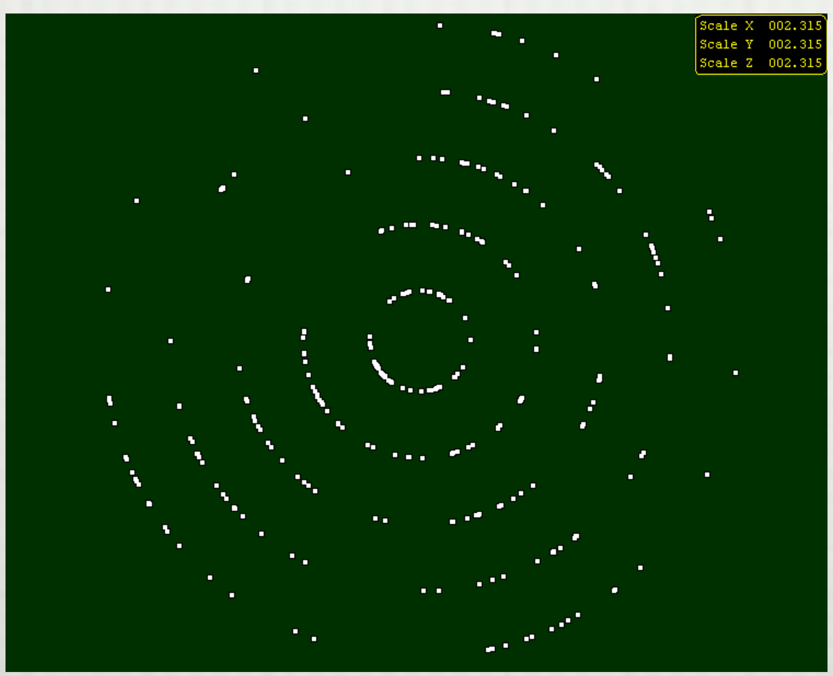
- The new technologies certainly offer unprecedented opportunities
- Running conditions at the Z shall be carefully considered in designing the detector
- the real CHALLENGE, to me, will be designing an architecture providing the required data evacuation rate with the MINIMUM power dissipation (<20 mW/ cm^2), resulting by an optimisation of the ANALOG CELL, the digital architecture, the clock distribution

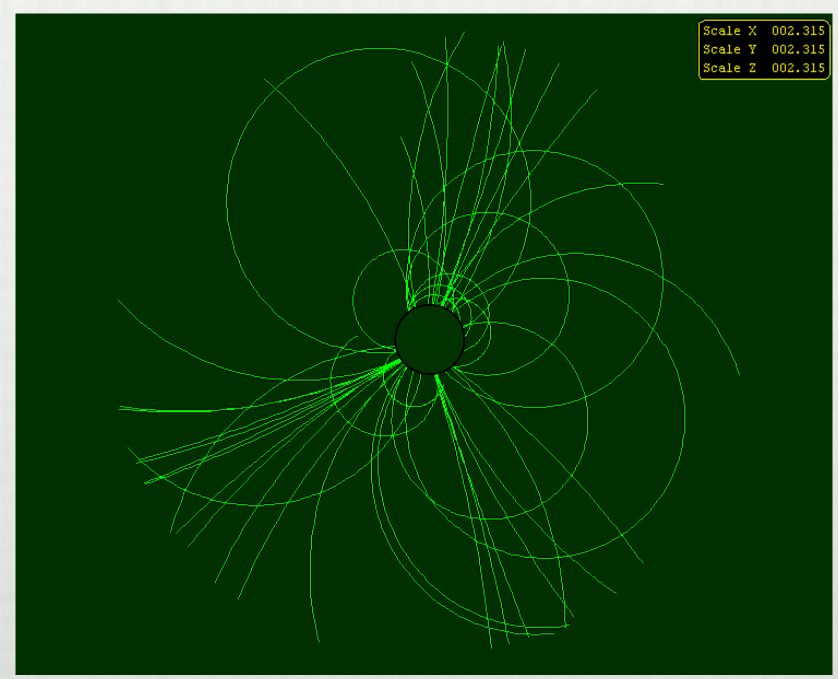
But I'm confident that fun and excitement will exceed pain & fear!

One step up: the main TRACKING system

In principle, we have two options:

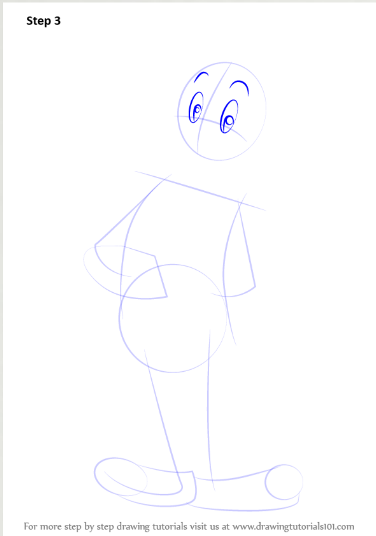






ILC events by Graham Wilson, Como workshop 2013

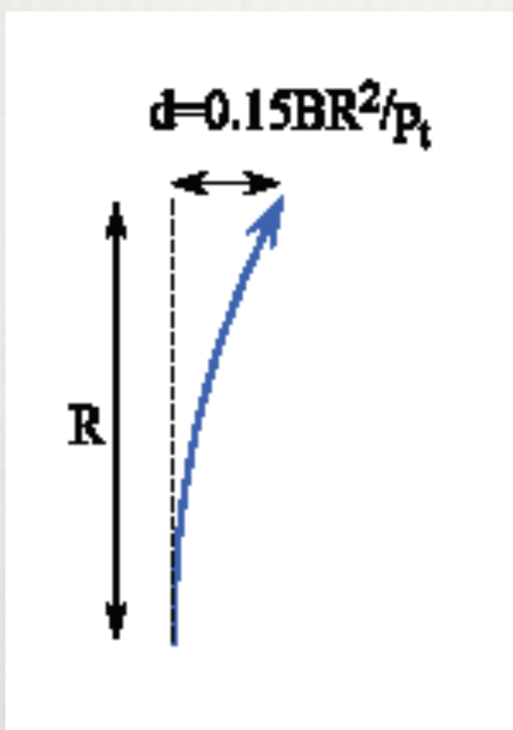
One step up: the main TRACKING system



In practice, we do not since the EMITTANCE PRESERVATION at the IR constraints the B field to be at the 2T level.

So, in order to:

- guarantee a good neutral/charged separation at the calorimeters:



- the required curvature resolution at the 10^{-5} level [about a factor 10 better than LEP]

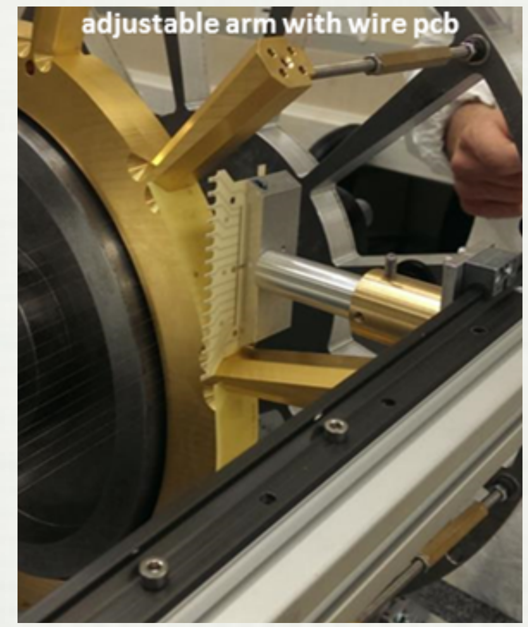
$$\frac{\Delta p_t}{p_t} = \frac{8\sqrt{5}\sigma_{xy}}{0.3BR_{out}^2\sqrt{N}}p_t \oplus \frac{0.0523}{\beta BL} sin\theta\sqrt{\frac{L}{X_0}}$$

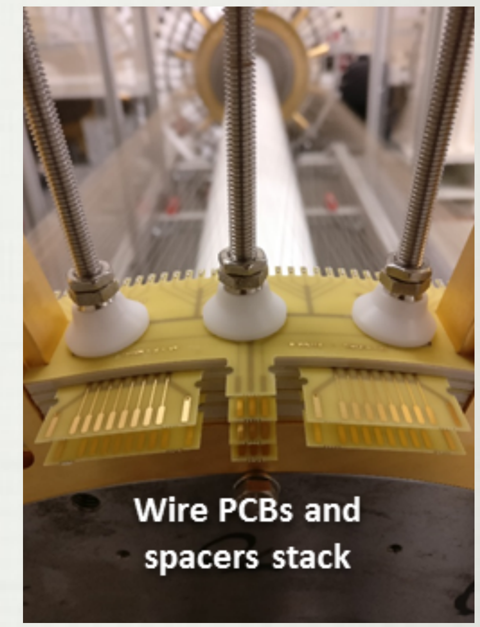
$$\Delta\phi_0 = \frac{4\sqrt{3}\sigma_{xy}}{R_{out}\sqrt{N}} \oplus \frac{0.0136}{\beta p}\sqrt{\frac{L}{X_0}}$$

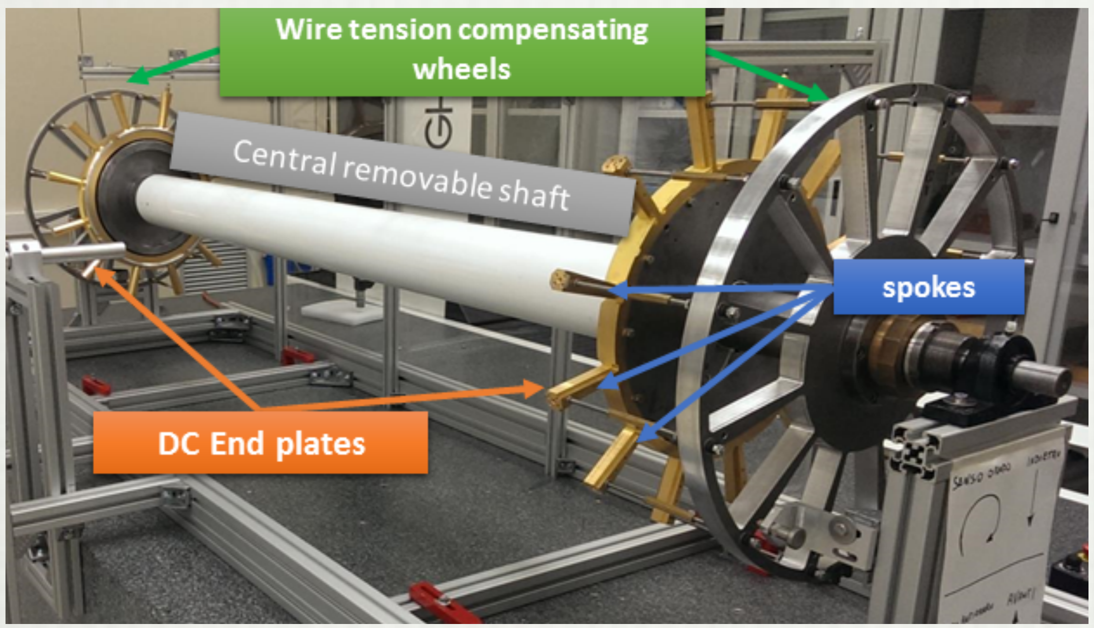
$$\Delta\theta = \frac{\sqrt{12}\sigma_z}{R_{out}\sqrt{N}}\frac{1+tan^2\theta}{tan^2\theta} \oplus \frac{0.0136}{\beta p}\sqrt{\frac{L}{X_0}}$$

We have to be LARGE, precise & LIGHT => there is no other detector than a 3D gas detector imager

Time Projection is not the only way and DRIFT chambers have been shown* to be an interesting alternative:

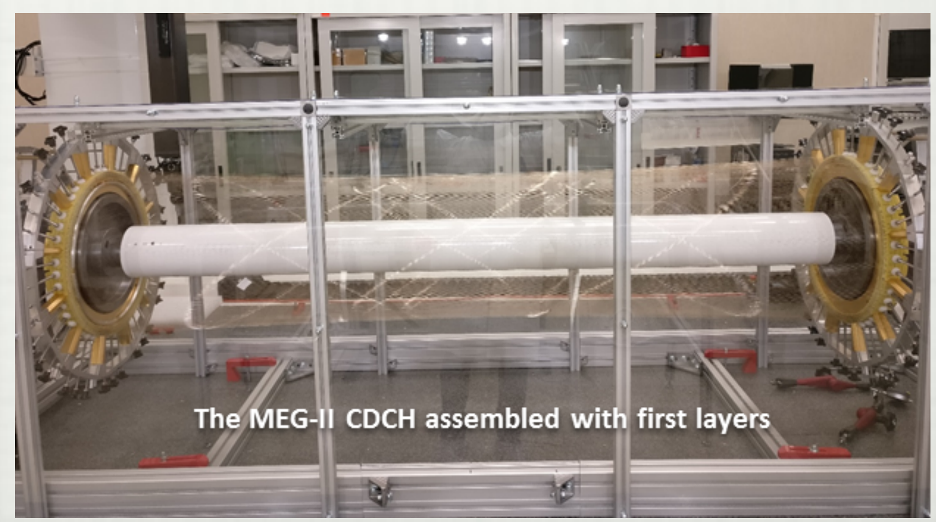






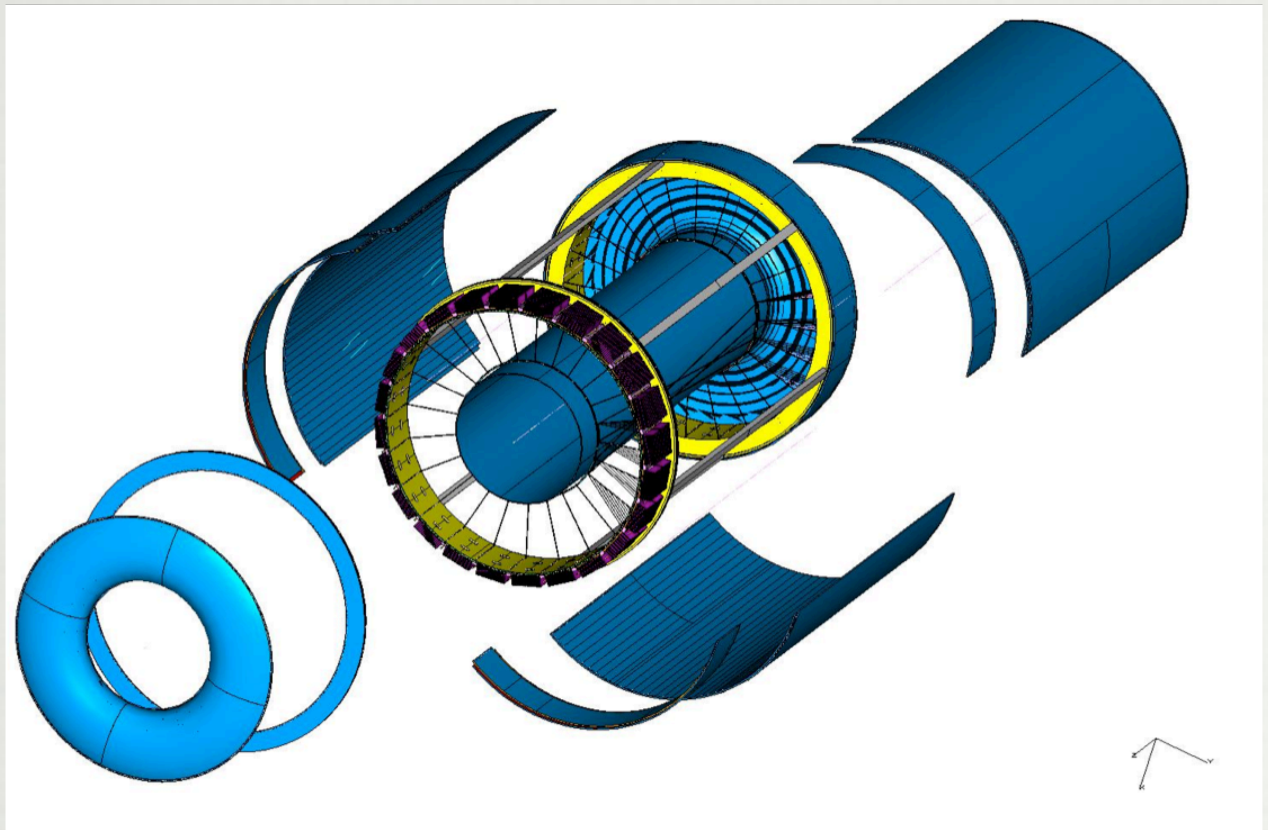
Dimensions of the MEG II chamber:

- L = 193 cm
- R_{in} = 17 cm
- R_{out} = 30 cm
- 10 layers for each 30° azimuthal sector



* - M. Adinolfi et al., The tracking detector of the KLOE Eexperiment. NIM. A 488 (2002) 51
- A. M. Baldini et al., Single-hit resolution measurement with MEG II drift chamber prototypes. 2016 JINST 11 P07011
- G. Chiarello, The full stereo drift chamber for the MEG II experiment, 2017 JINST 12 C03062

its BIG BROTHER is being proposed as the main tracker of IDEA:

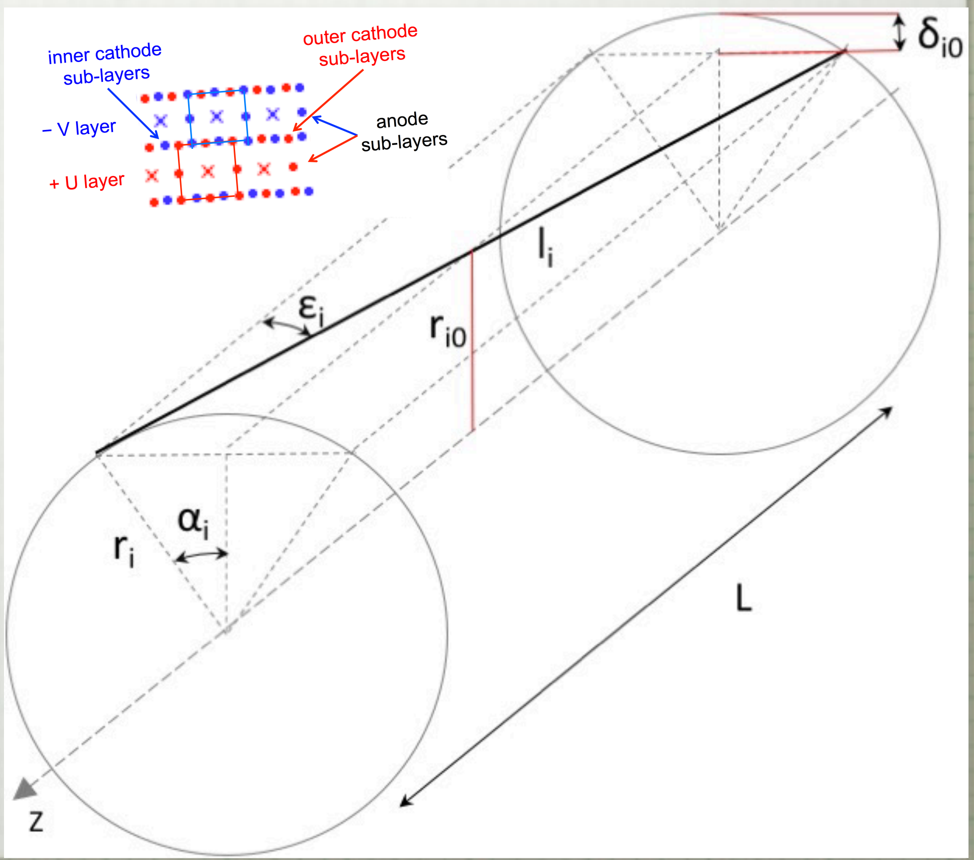


The IDEA drift chamber by numbers:

- L = 400 cm
- R_{in} = 35 cm
- R_{out} = 200 cm
- 112 layers for each 15° azimuthal sector
- 56 448 squared drift cells of about 12-13.5 mm edge
- max drift time: 350 ns in 90%He-10%iC_4H_{10}

The "wire cage" and the "gas envelope" are decoupled

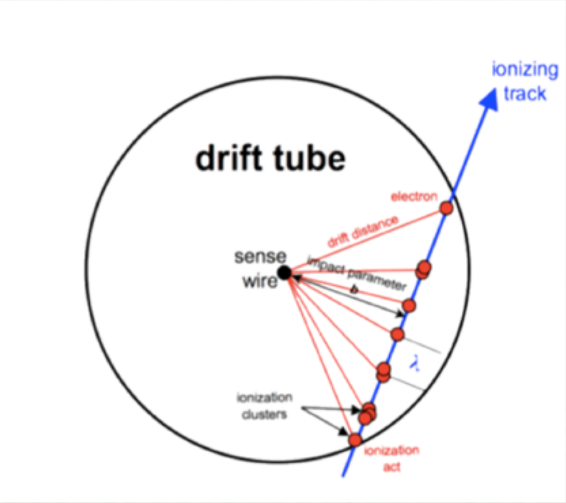
- The stereo angle α is generated stringing the wire between spokes @ 2 sectors (30°) distance
- α ∈ [20 mrad (1.1°); 180 mrad (10.3°)], increasing with R
- the electrostatic stability is achieved when the wire tension is about 25g, for a total load of about 7,7 tons!

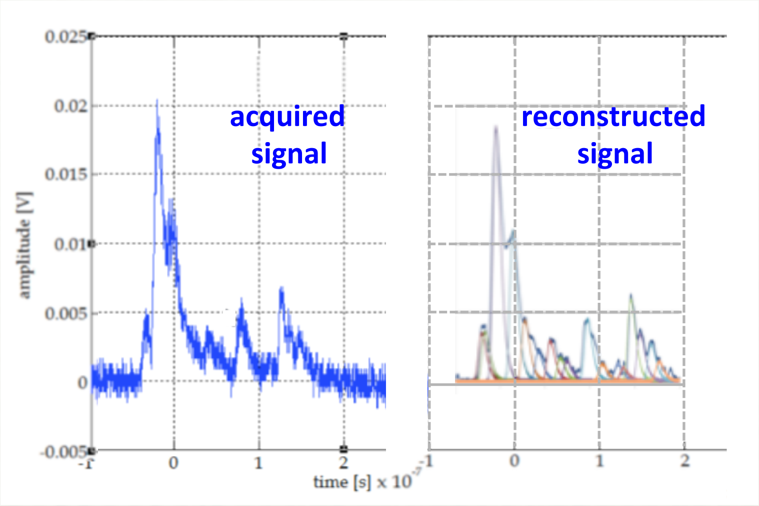


strong points of the DRIFT chamber:

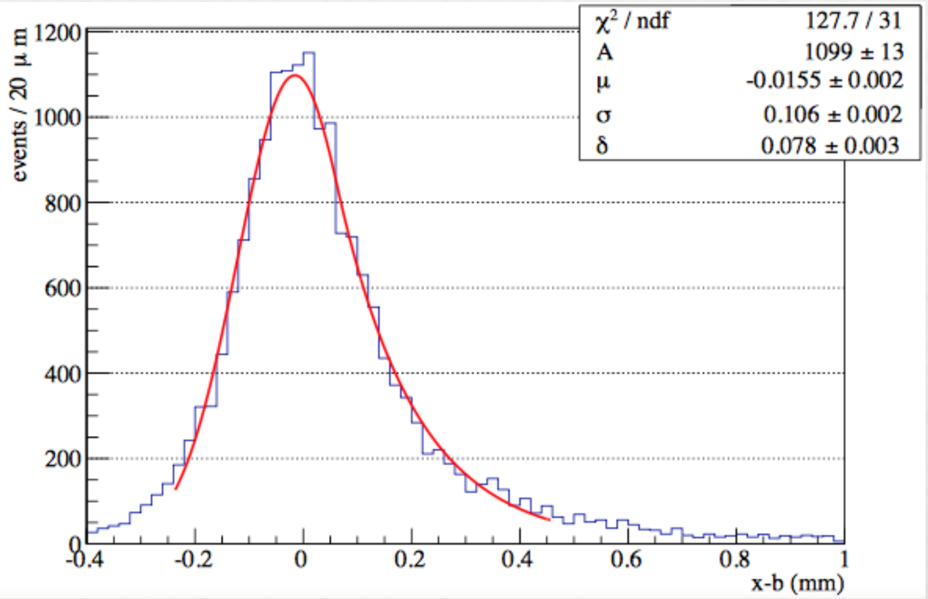
- strong but light:
  - 1.6% X_o in the barrel [8% for the TPC - Joao, Yesterday]
  - 5% X_o in the fwd/bkwd directions (end plates included)

- cluster timing for improved spatial resolution:





- record the time of arrival of electrons generated in every ionisation cluster (≈12cm^{-1})
- reconstruct the trajectory at the position most likely generating the sequence

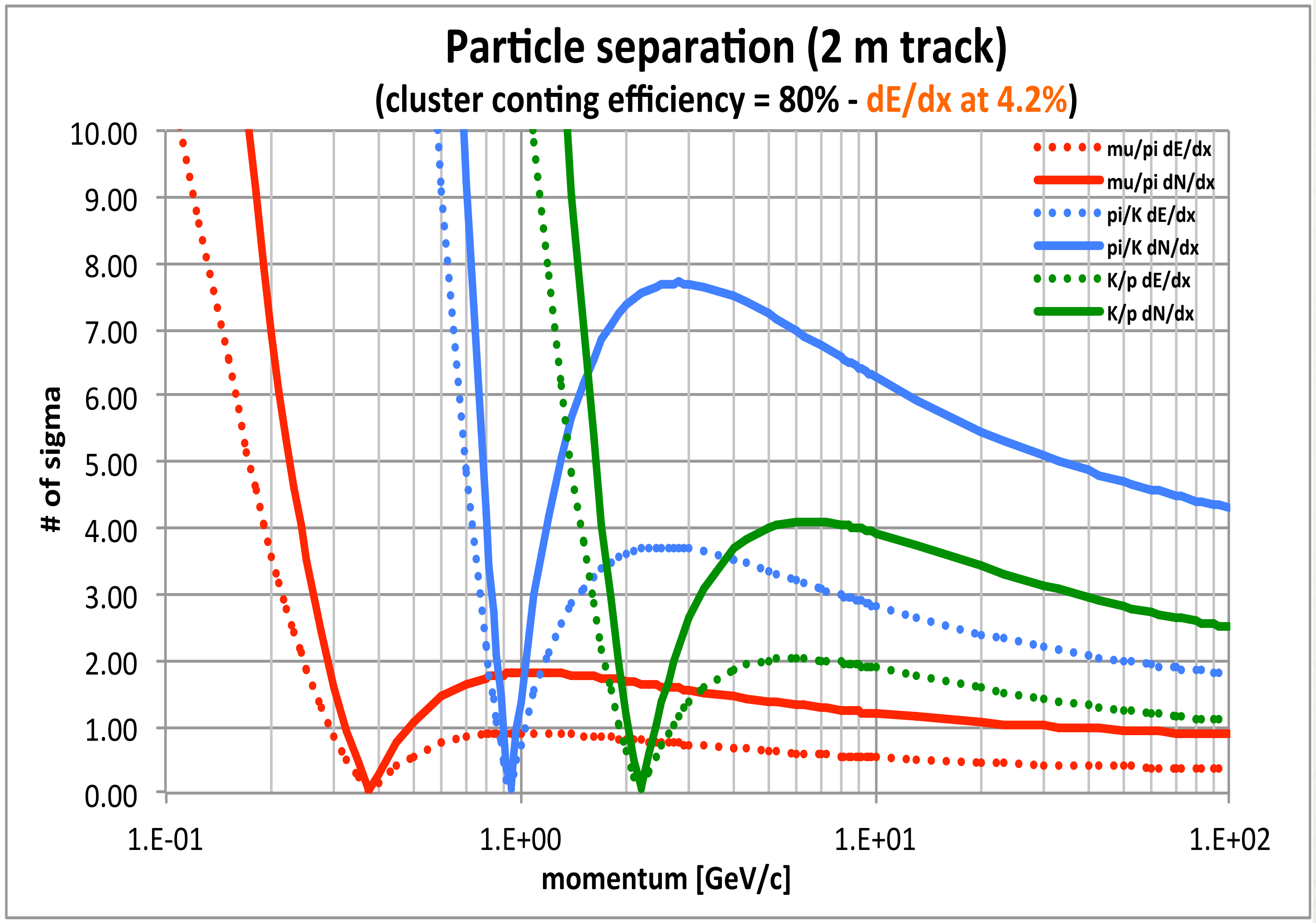


measured resolution for the MEGII prototype, corresponding to

$\sigma_{xy} \approx 100\ \mu m$

$\sigma_z \approx 1000\ \mu m$

- **cluster counting for improved particle identification:** it is essentially based on the well known method of measuring the [truncated] mean dE/dX but it replaces the measurement of an ANALOG information with a DIGITAL one, namely the number of ionisation clusters per unit length:



$$\frac{\sigma_{dE/dx}}{(dE/dx)} = 0.41 \cdot n^{-0.43} \cdot \left(L_{track}[m] \cdot P[atm]\right)^{-0.32}$$ ≈ 4%

from *Walenta parameterization (1980)*

$$\frac{\sigma_{dN_{cl}/dx}}{(dN_{cl}/dx)} = \left(\delta_{cl} \cdot L_{track}\right)^{-1/2}$$ ≈ 2%

from *Poisson distribution*

Tassielli, FCC week 2018 + references

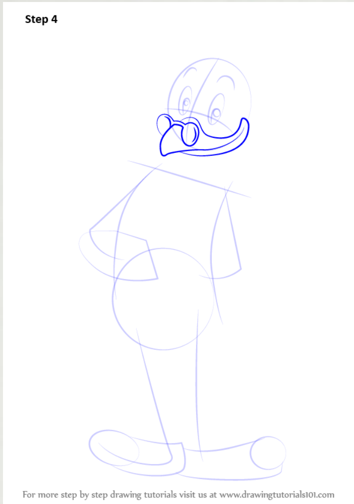
- compliance with the rates at the Z pole [**a potential problem with the TPC]**:
  - a MEG2 prototype has been successfully tested till a rate O(100 kHz/cm^2)
  - simulation studies at the Z pole and up to 380 GeV indicate that ion drift related problems shall not be an issue

Drift Chamber Conclusions:

it sounds good, as long as you can crunch in real time all of the numbers…

[you do need to digitise the waveform from every sense wire at 2Gs/s on 8 bits => unless you process in real time, the required bandwidth skyrockets to 1 Tb/s…]

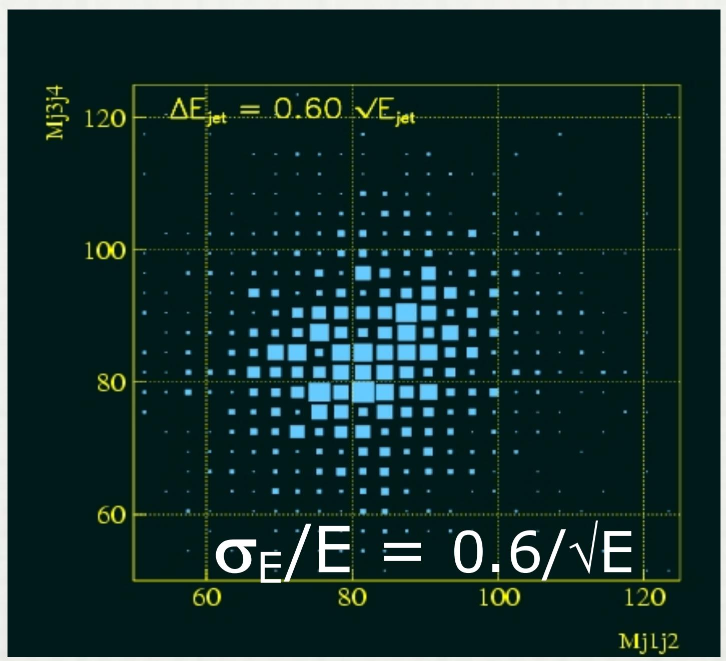
* for further details, see the talk by G. Tassielli

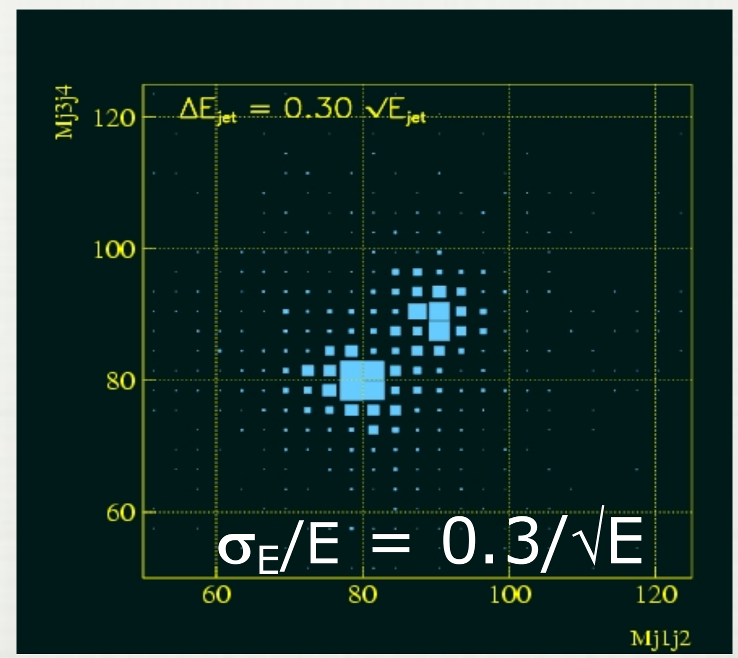


One more step: measuring the ENERGY

We know what we want:

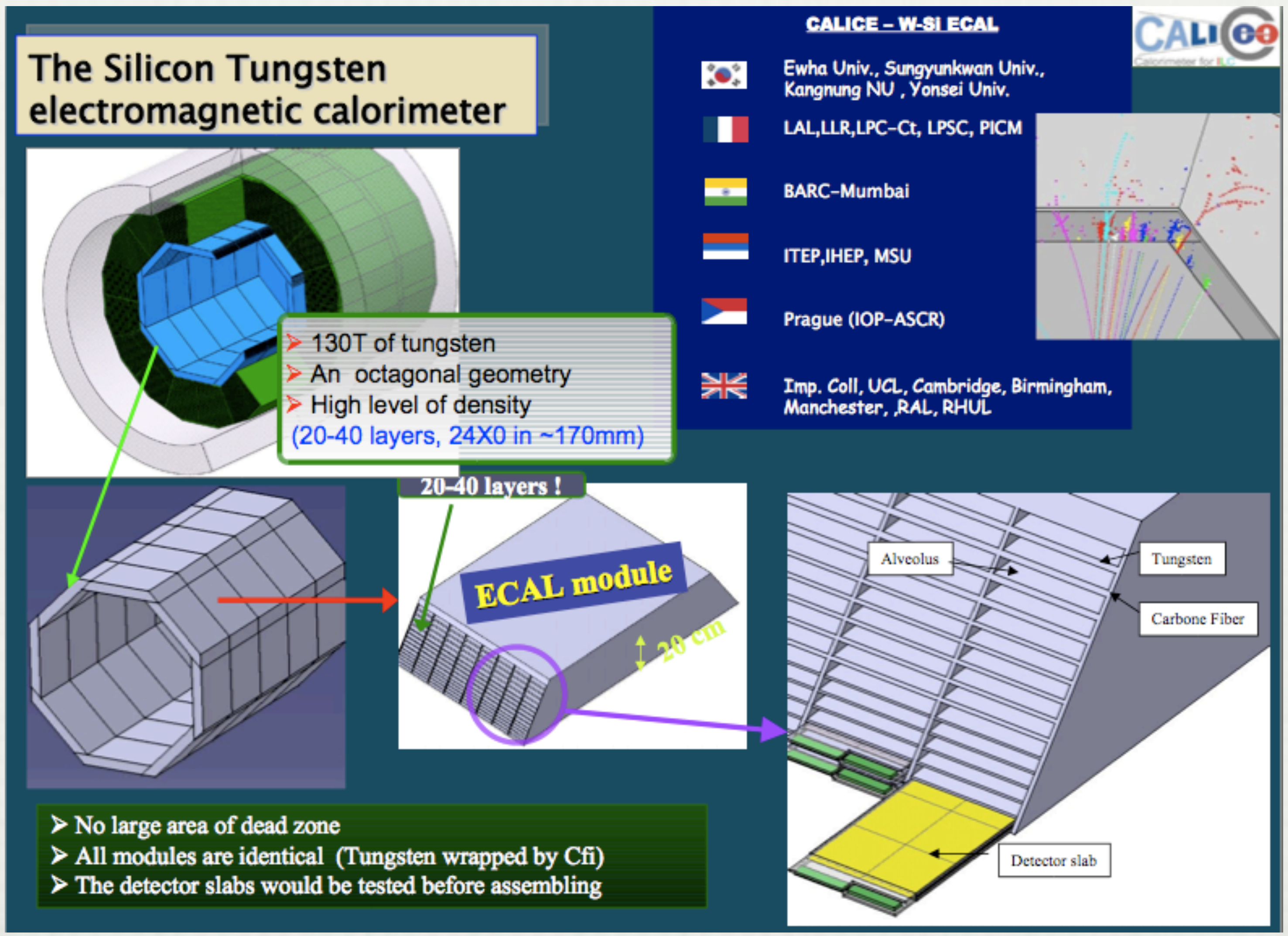
The Blue Plot!





- separating hadronically decaying W's from Z's helps for channels where kinematic fits will not work and, obviously, to reduce combinatorics
- in order to compensate from a degraded resolution, 20-40% higher integrated luminosity is required

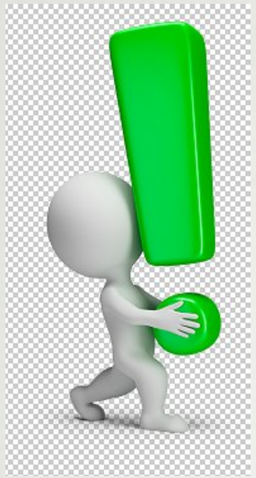
We know there is one solution: CALICE Calorimeter for ILC



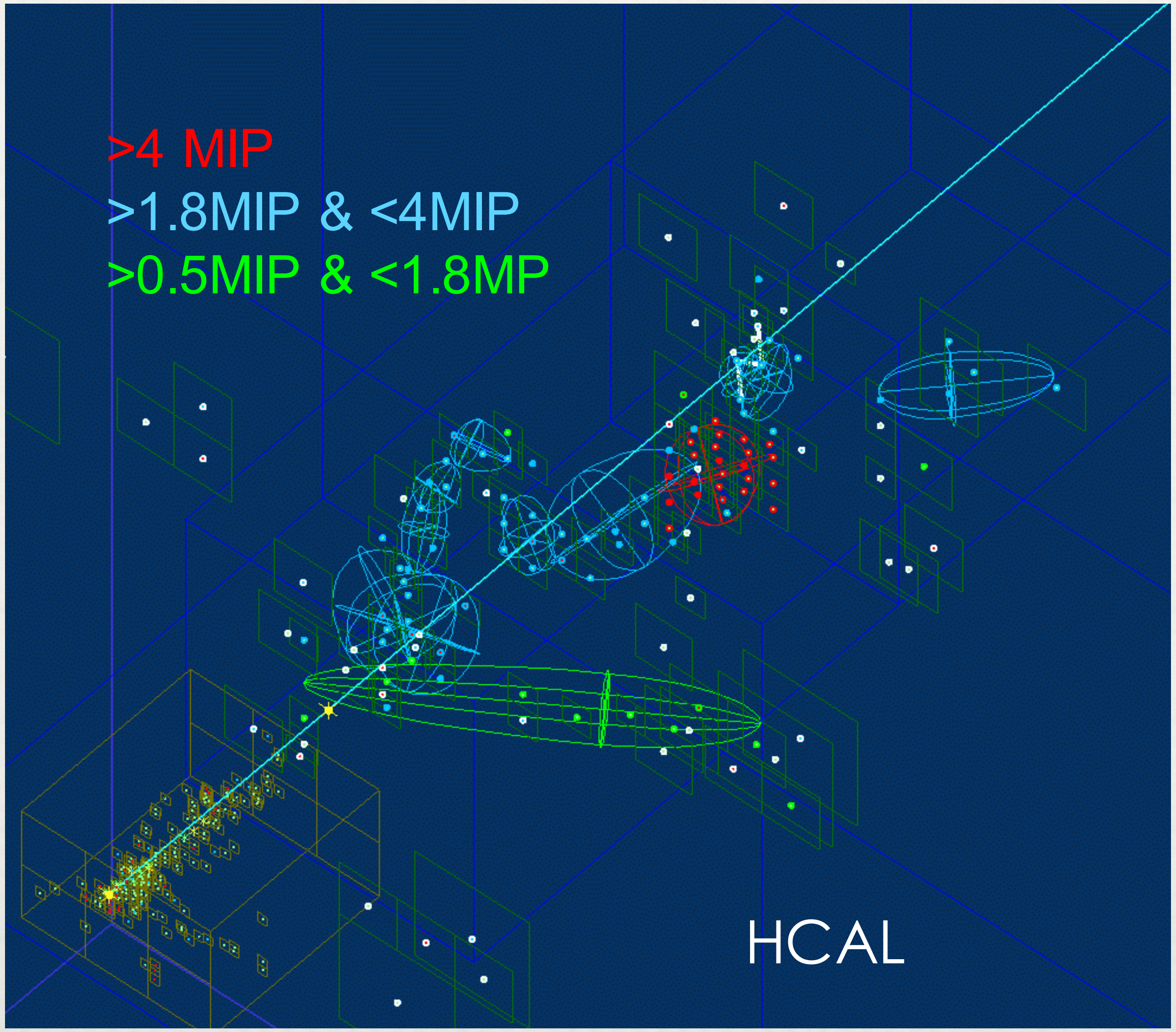
WARNING! pre-optimisation studies! Actual numbers are likely to be different

- 130T of Tungsten (watch the commodity market..)
- 3000 m^2 of pixelated Silicon
- 250 Mpixel (well calibrated and stable…)

Today: reduced to 100 Millions….



We know there is one solution:



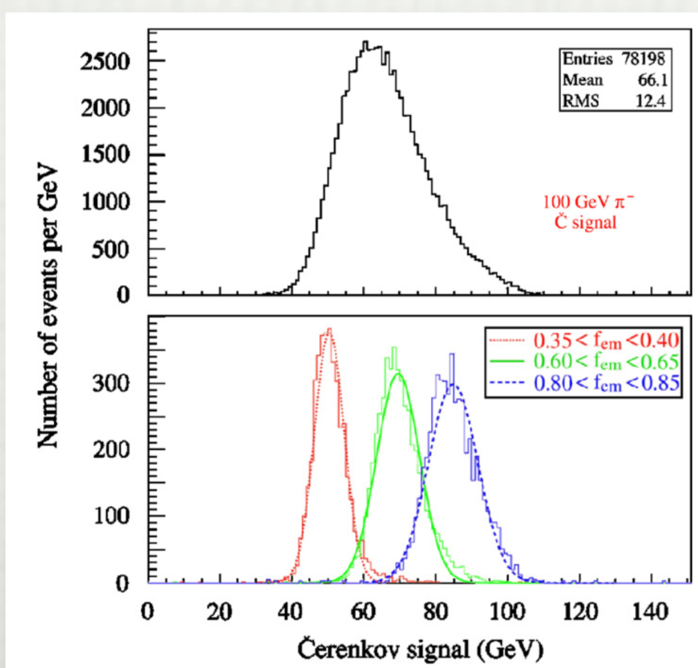
WARNING! pre-optimisation studies! Actual numbers are likely to be different

Can I get there in a different way?

We know that:

- Calorimetry is a "fluctuation game" [leakage, sampling, e.m. fraction, invisible energy, noise];
- In hadron initiated showers, the main fluctuations in the event-to-event response are due to:
  - the share between the e.m. and and hadronic component
  - the fluctuations in the "invisible energy"

and the e.m. component is giving a significant contribution, growing with energy:



an example of the improvement that can be expected in the measurement of a sample of 100 GeV **π**'s if $f_{e.m.}$ is NOT measured (top plot) or if $f_{e.m.}$ bins are singled out

R. Wigmans, NIM A572 (2007) 215-217

We also know that:

- if you embed in the same calorimeter a detector responding primarily to the e.m. fraction and detector responding to the total dE/dX, you can single out $f_{e.m.}$.

This was proposed (and successfully demonstrated in a series of different implementations) using Cherenkov light [produced by relativistic particles and dominated by the e.m. shower component] and scintillation => DUAL READOUT CALORIMETRY

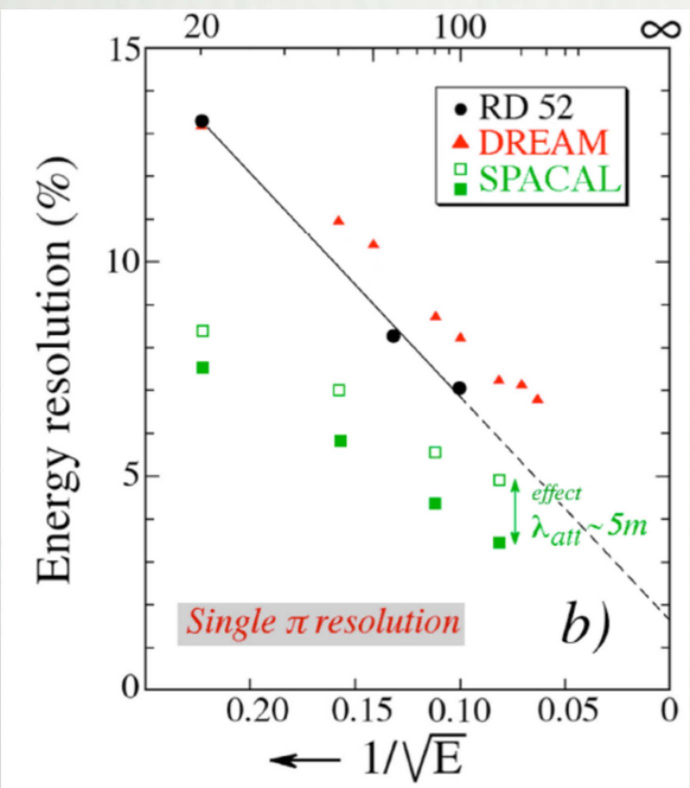
see the talks by:

- J. Hauptman
- R. Ferrari
- R. Santoro

Two exemplary results from the **DREAM/RD52 calorimeters:**

[NIM A537 (2005) 537-561 - NIM A735 (2014) 130-144 - NIM A732 (2013) 475]

Single π resolution vs energy



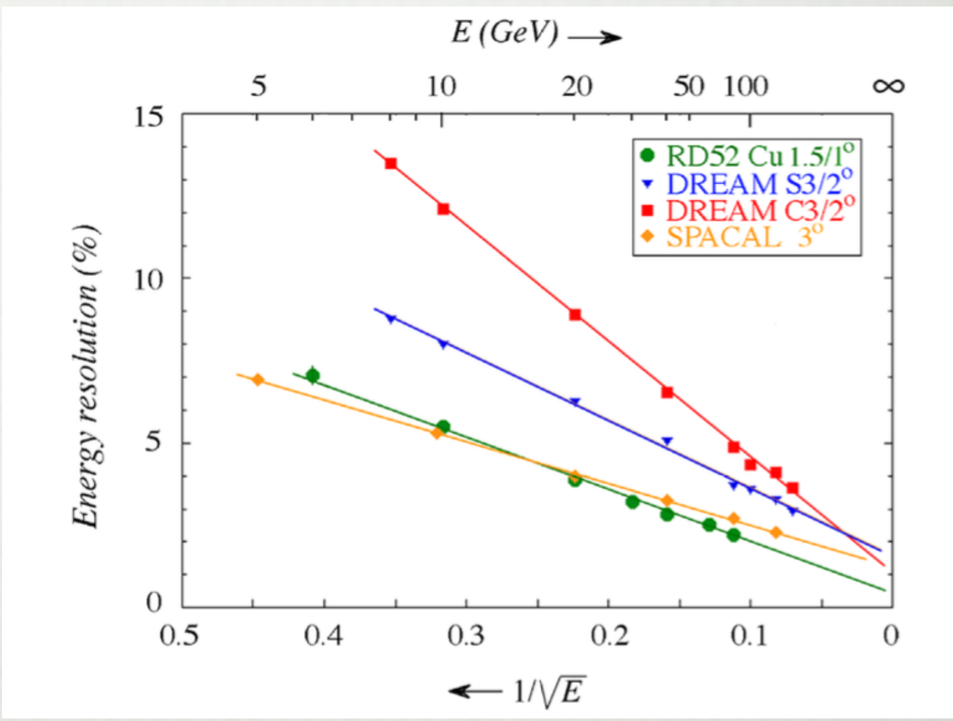
$$\frac{\sigma}{E} = \frac{53\%}{\sqrt{E}} + 1.7\%$$

- referred to the RD52 calo with Pb converter
- affected by lateral leakage and light attenuation

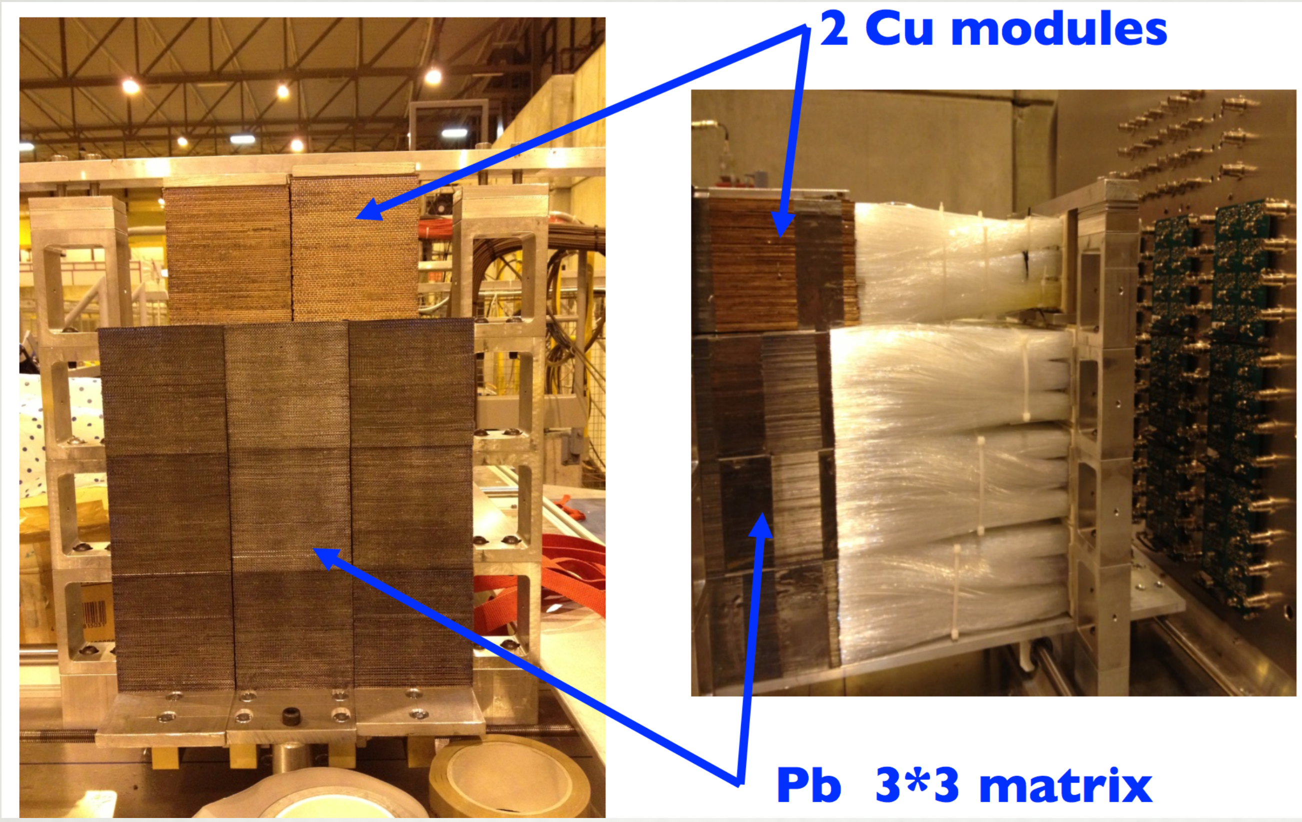
VERY CONSERVATIVE

(the SPACAL values are close to 30%/sqrt(E))

Electromagnetic Resolution

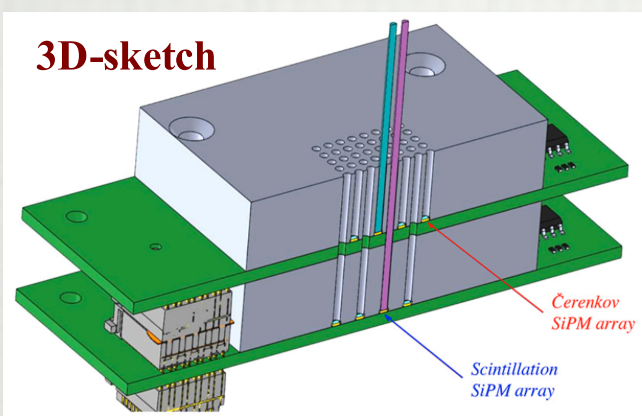


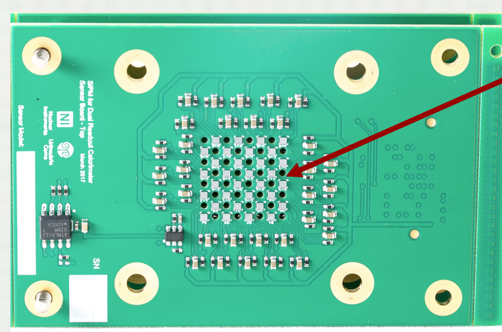
$$\frac{\sigma}{E} = \frac{11\%}{\sqrt{E}} + 1\%$$

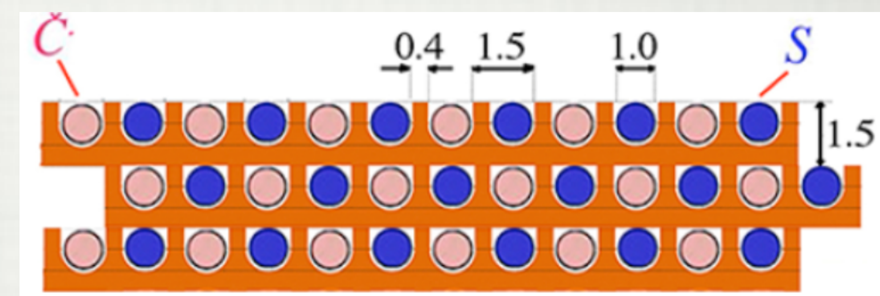


So far, the idea of integrating such a detector concept in a 4π detector turned the DREAM into a nightmare

And it was so until when the Silicon age entered the photonics world and **PMT were replaced by SiPM:**

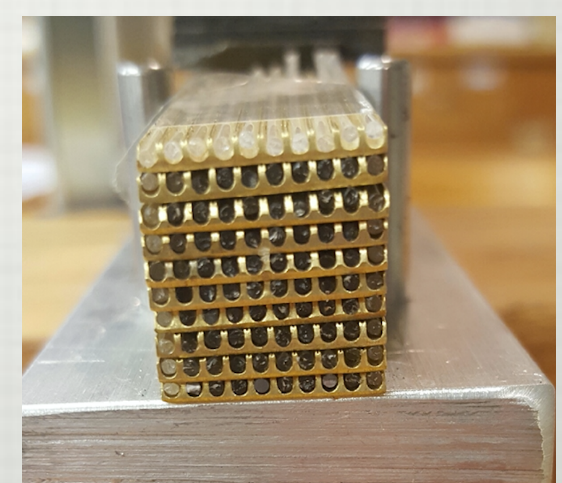




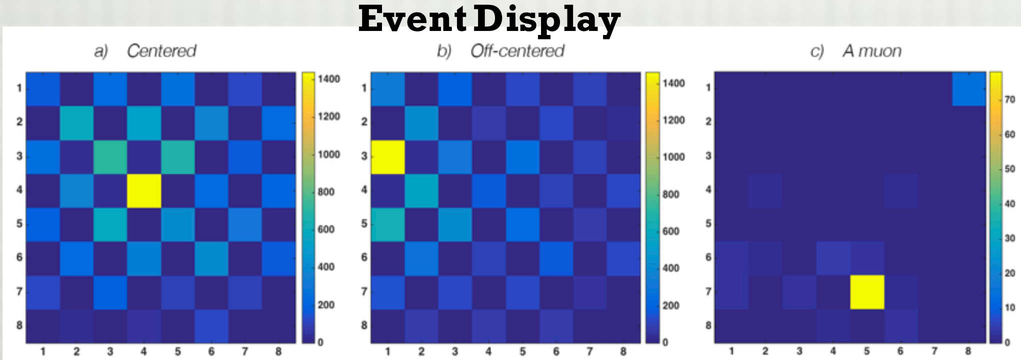


[sampling fraction 4.5%]

10x10 fibers



Event Display

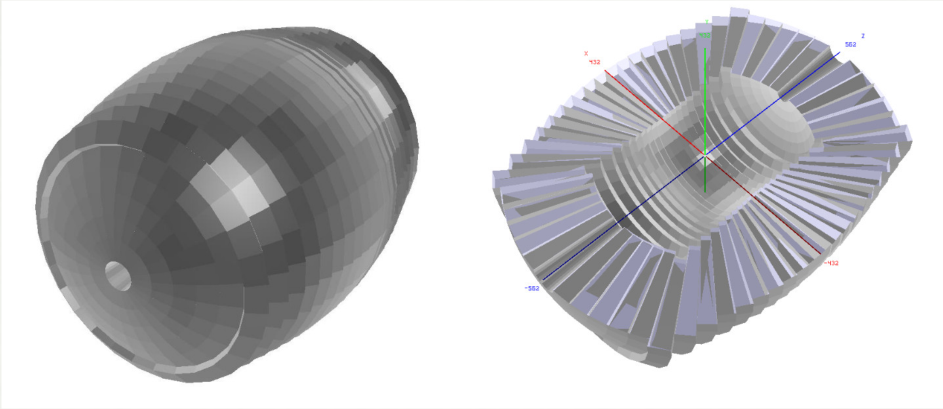


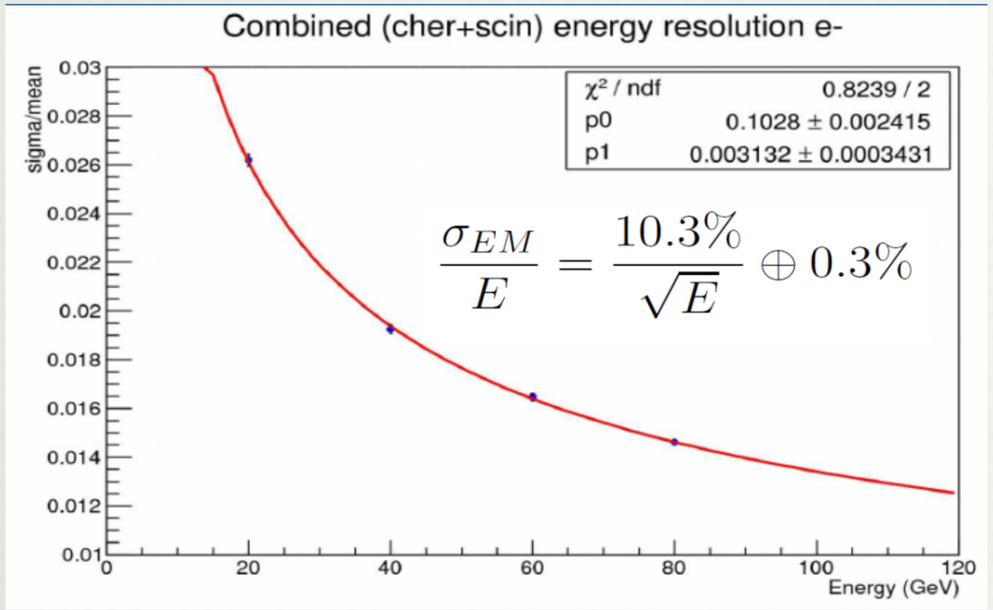
more info:

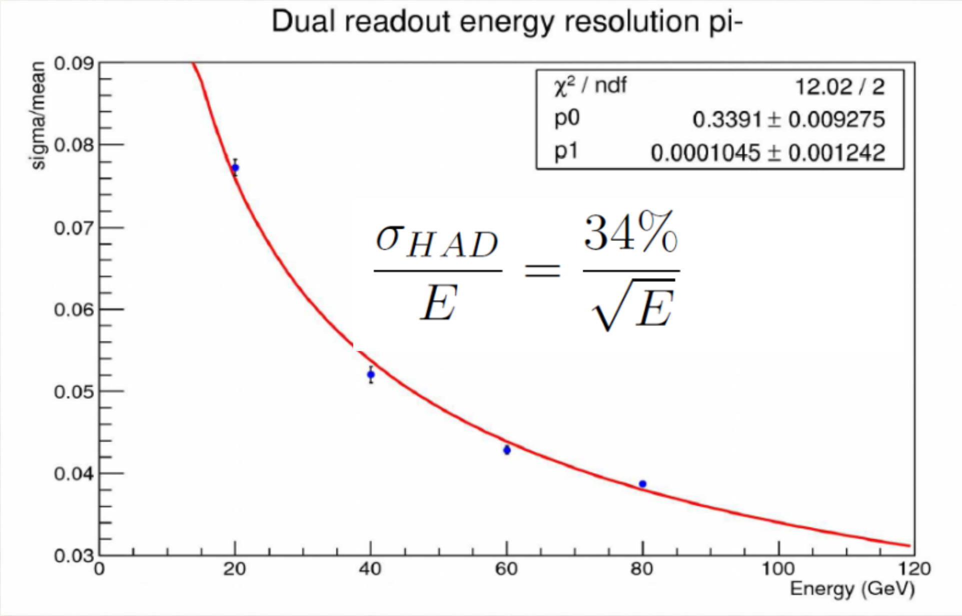
- talk by R. Santoro NOW!
- our NIM paper, available on the ArXiv: 1805.03251

Results by:

* the 2016-2017 beam tests
* a preliminary simulation of a 4π geometry







Made us confident this can be a solution worth being considered

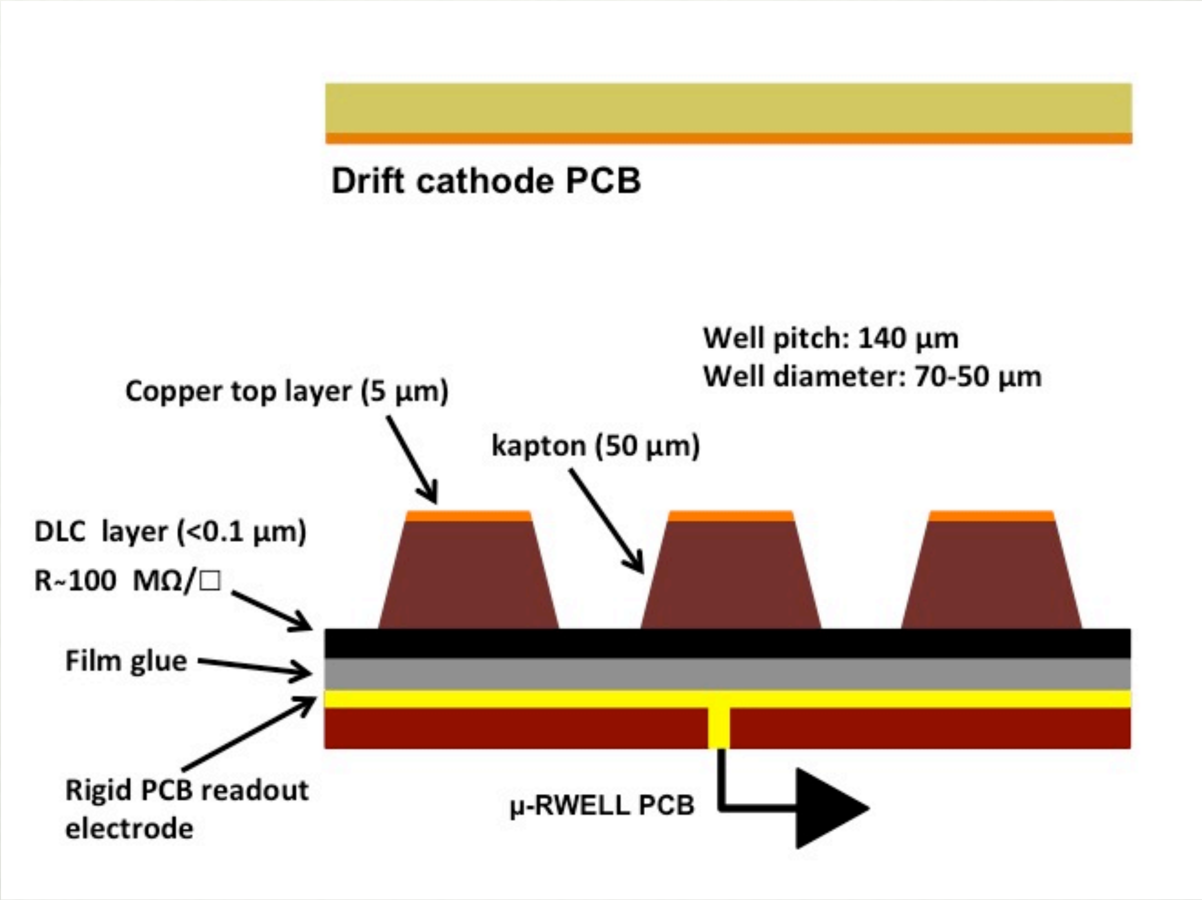
When SIZE matters most than RESOLUTION
(e.g. pre-showers, muon detectors and wherever a large area with moderate single point precision is what you need)

=> Micro Pattern Gas Detectors enter the game

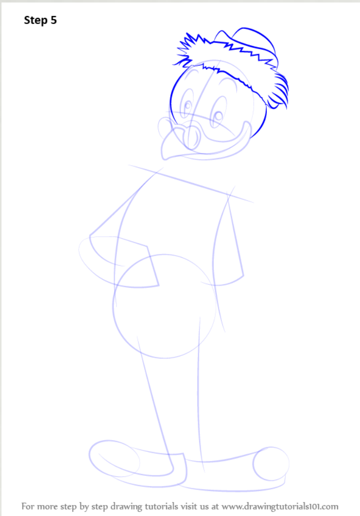
In the MPGD world, there is one technology that looks particularly promising for its characteristics and the possibility to be industrialised: the **μ-RWell**

It essentially consists of:

* a patterned Kapton foil (amplification stage)
* a resistive layer sputtered on the back of the Kapton foil to quench the multiplication and avoid sparks (DLC = Diamond Like Carbon)
* a patterned PCB for readout



- Bencivenni et al., 2017 JINST 12 C06027
- Bencivenni et al., 2015 JINST 10 P02008



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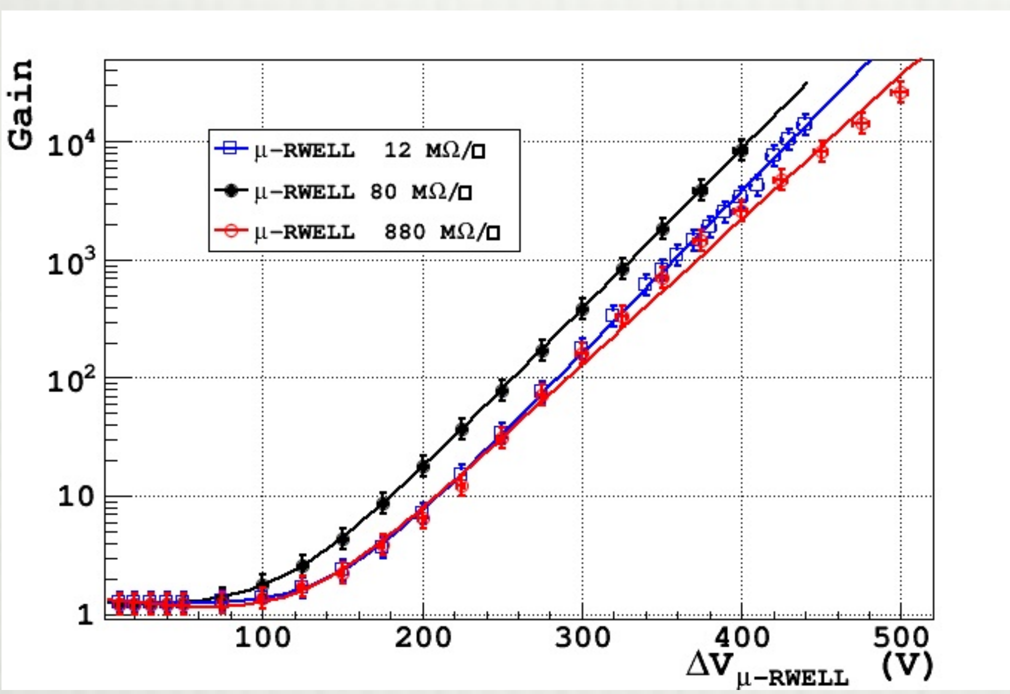
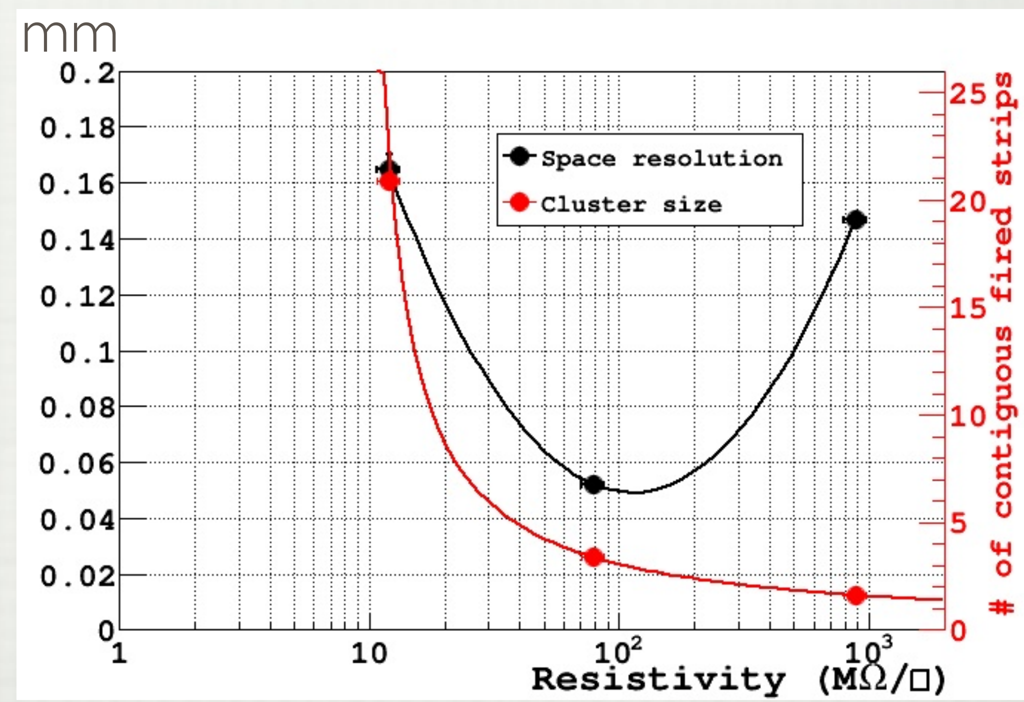


Gain vs Voltage



Cluster size and resolution vs Resistivity

Also worth saying that:

- the camera stands rates up to 35 kHz/cm^2 (simplest process)
- time resolutions at the few ns level have been measured

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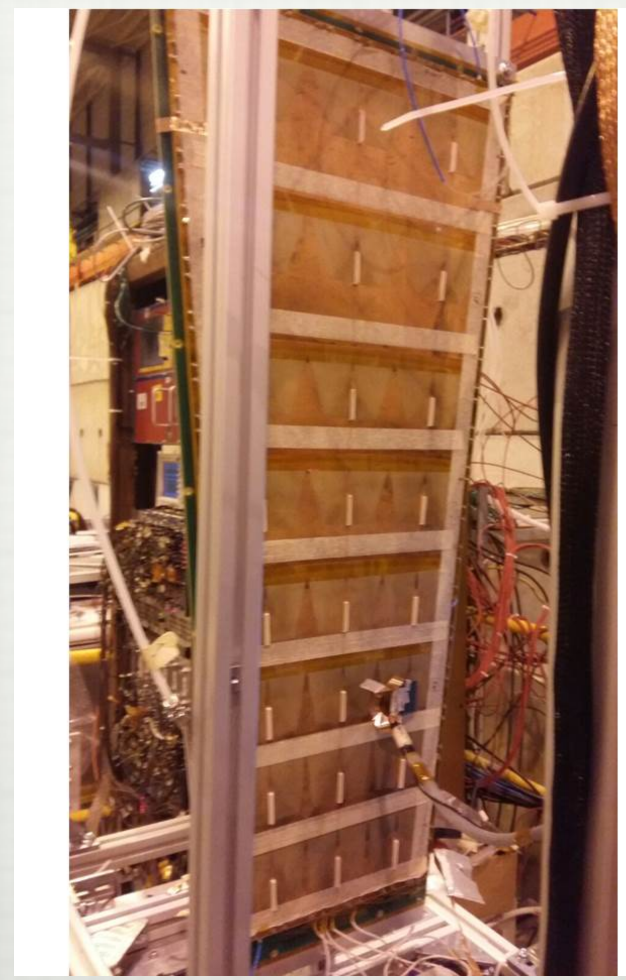
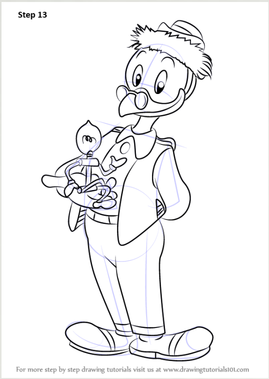
a 1.2 x 0.5 m^2 prototype has been produced in collaboration with an industrial partner (ELTOS s.pa)

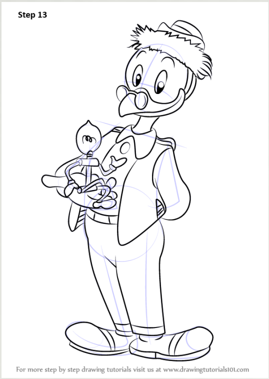


Now that we got the pieces, we can try to assemble the detector & complete the exercise:



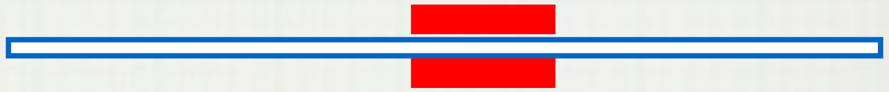
Detector Layout:

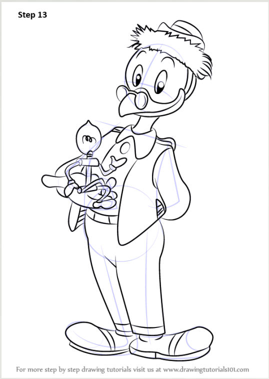
- Beam Pipe (≈1.5 cm radius)



Detector Layout:

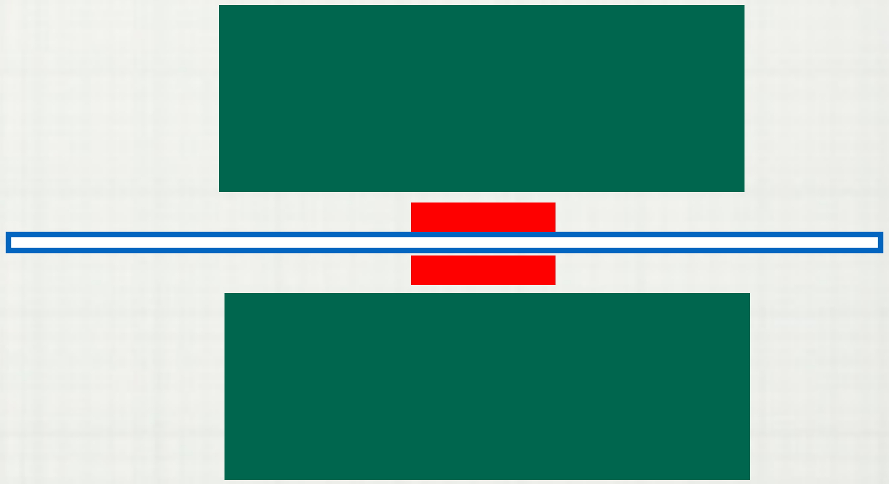
- Beam Pipe (≈1.5 cm radius)
- Vertex Detector ()

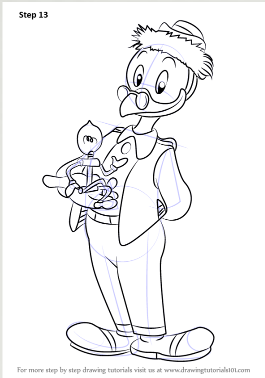




Detector Layout:

- Beam Pipe (≈1.5 cm radius)
- Vertex Detector (R ∈ [1.7; 34] cm) A BIG Coke can…
- Drift Chamber (L = 400 cm, R ∈ [35; 200] cm)





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- Beam Pipe (≈1.5 cm radius)
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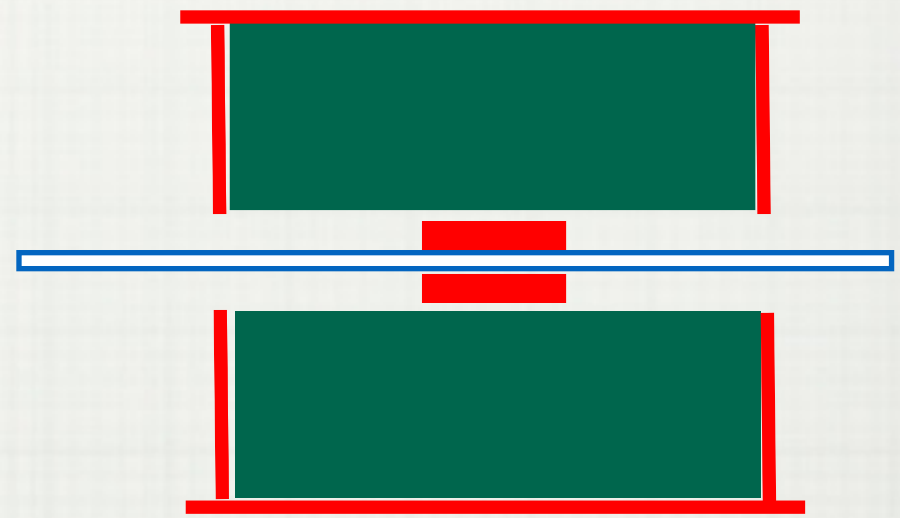
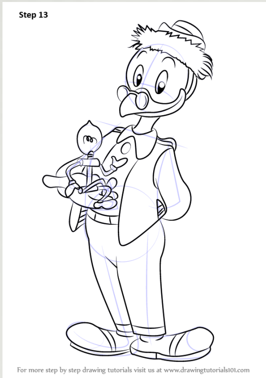
- Outer Silicon Layer (strips)





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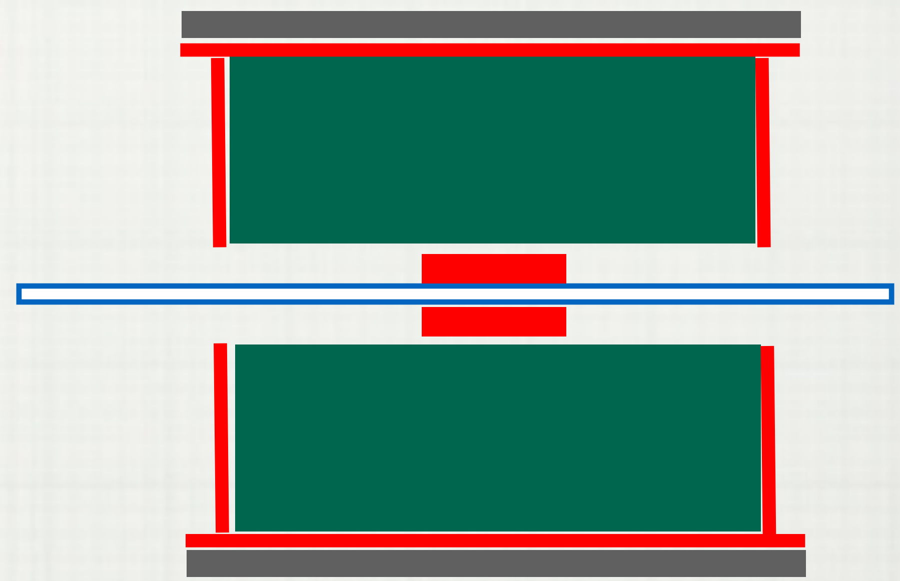
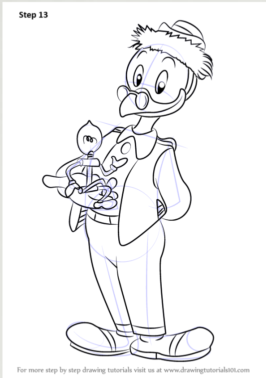
- SC Coil (2T, ≈2.1m); THIN! 30 cm ($0.74X_0$; 0.16 λ @90°)





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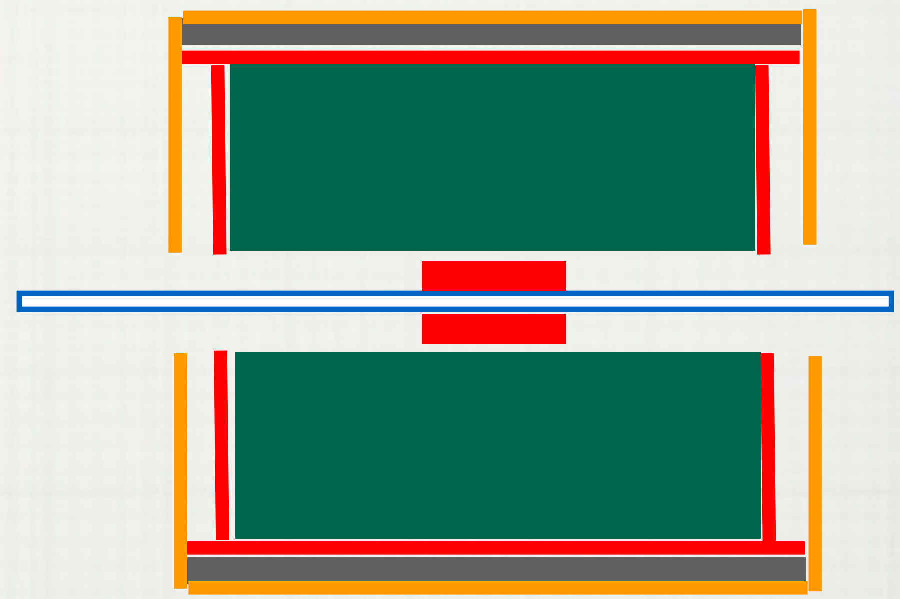

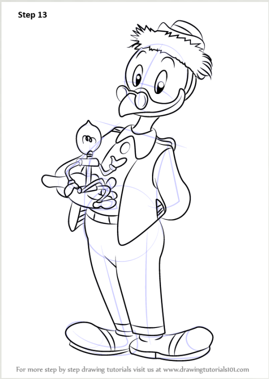

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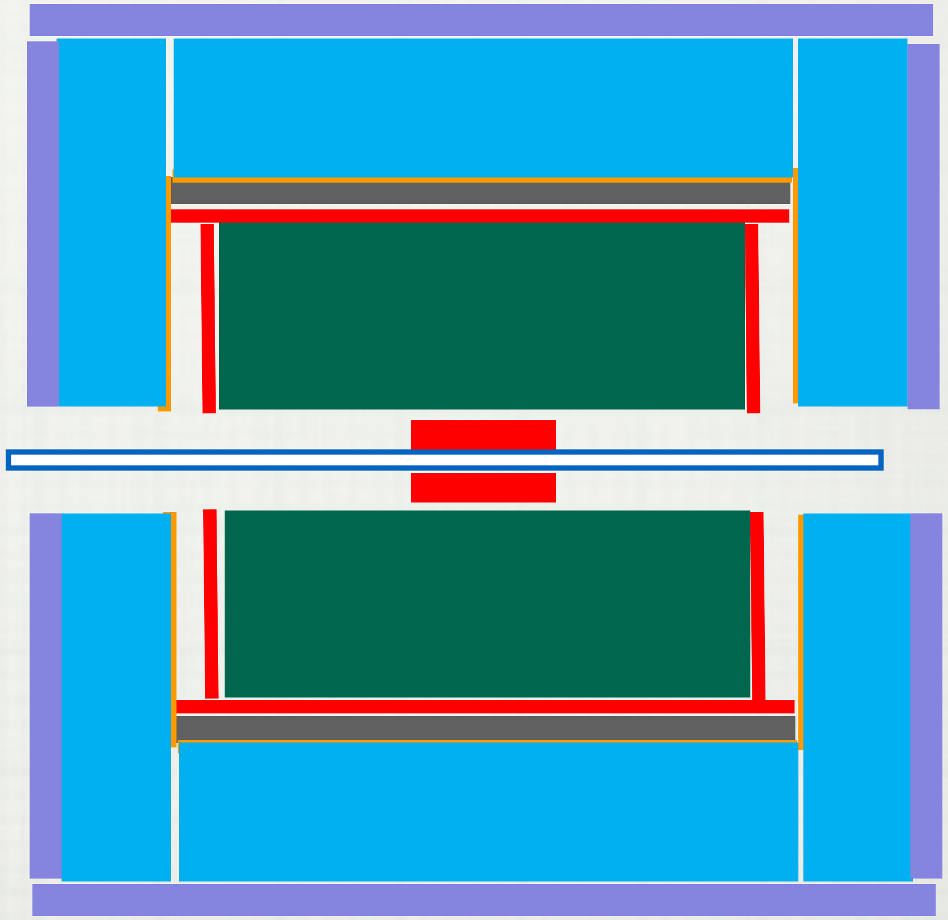
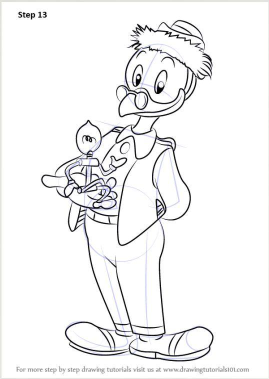
- pre-shower (1-2 X_0)
- Dual Readout Calorimeter (2m, 7 λ)
- Yoke & Muon Chambers





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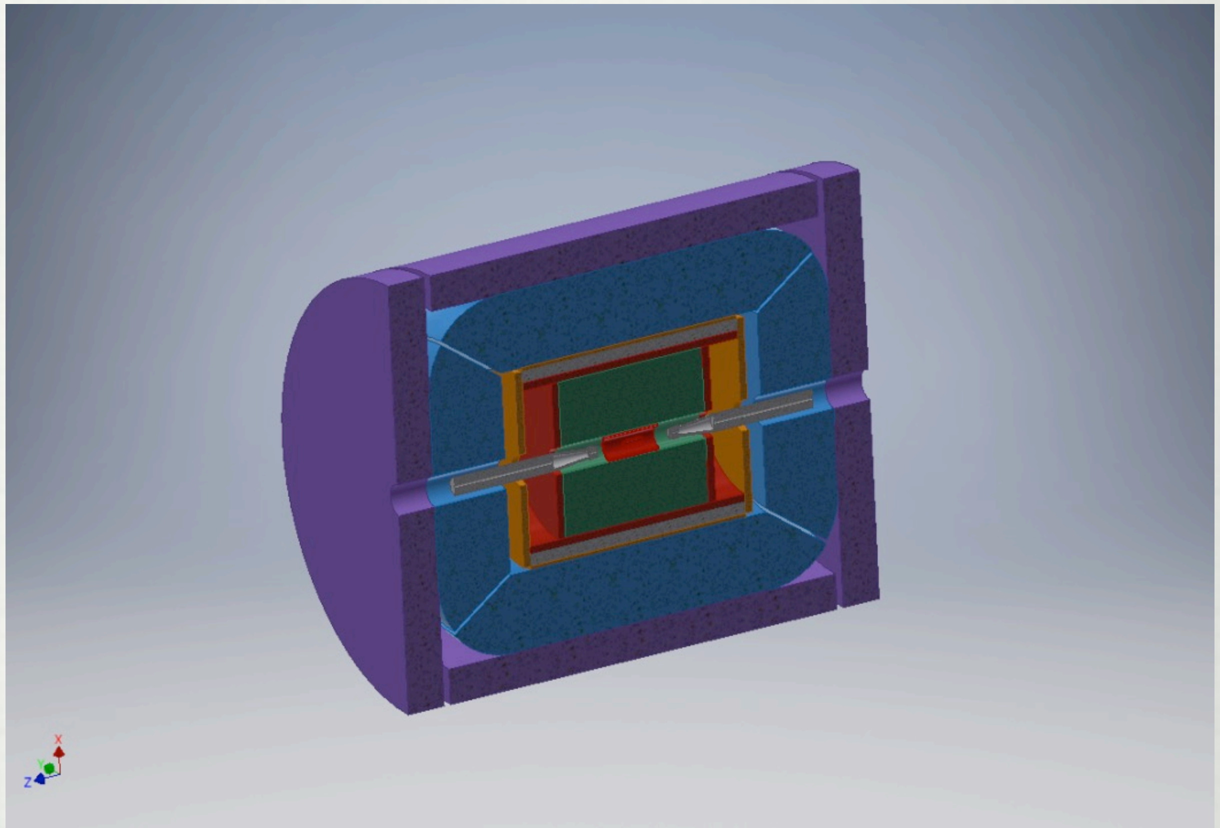

Conclusions:

We know it is still a long way to go but:

* time is on our side

* and we hope to have a good team walking with us!