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DEI SVB NVMINE VIGET

National Centre for Scientific Research "Demokritos"

HELLENIC REPUBLIC
ARISTOTLE UNIVERSITY OF THESSALONIKI

University of Science and Technology of China 1958

8th symposium on large TPCs for low-energy rare event detection
5-7 December 2016
Paris

A picosecond Micromegas EUV photodetector

Thomas Papaevangelou, IRFU-CEA/Saclay
Representing:
CEA (Saclay), CERN (GDD), NSRC "Demokritos",
Princeton University, Thessaloniki University, USTC (Hefei)

The Collaboration

Started as an RD51 common fund project:

Fast Timing for High-Rate Environments: A Micromegas Solution

Awarded 3/2015

Collaborating Institutes:

- **CEA (Saclay)**
  T. Papaevangelou , I Giomataris, M. Kebbiri, M. Pomorski, T. Gustavsson, E. Ferrer-Ribas, D. Desforge, I. Katsioulas, G. Tsiledakis, O. Malliard, P. Legou, C. Guyot, P. Schwemling
- **CERN**
  *L. Ropelewski, E. Oliveri, F. Resnati, R. Veenhof, S. White, H. Muller, F. Brunbauer, J. Bortfeldt, M. van Stenis, M. Lupberger, T. Schneider, C. David, D. González Díaz**
- **NCSR Demokritos**
  G. Fanourakis
- **Princeton University**
  S.White, K.T. McDonald, Changguo Lu
- **University of Thessaloniki**
  S. Tzamarias
- **University of Science and Technology of China (USTC), Hefei**
  Zhiyong Zhang, Jianbei Liu, Zhou Yi

** Present Institute: University of Santiago de Compostela*

State-of-art precision timing

Solid state detectors

- Avalanche PhotoDiodes: (σ_t ~ 30 ps)
- Low Gain Avalanche Diodes (σ_t ~ 30 ps)
- HV/HR CMOS (σ_t ~ 80 ps)

➔ *Radiation hardness ?*

Gaseous detectors

- RPCs: (σ_t ~ 30 ps)
  ➔ *High rate limitation*
- MPGDs (σ_t ~ 1 ns)

Question:

Can a *MicroPattern Gaseous Detector* reach a timing resolution of the order of ***few tens of picoseconds?***

➔ *performance improvement by* ***~2 orders of magnitude***

Motivation: HL-LHC

➔ *Large-area, position-sensitive gaseous photomultipliers*

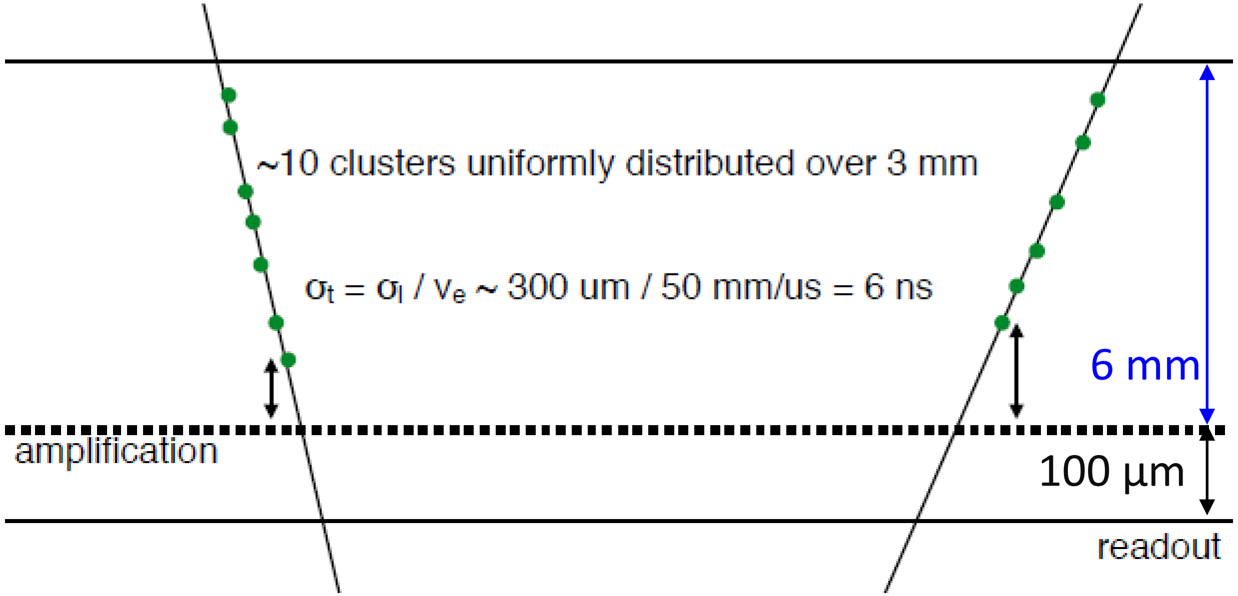
Main limitation on precision timing with MPGDs

Time response is limited by the continuous ionization on the drift region:

- ➔ spread of primary ionization clusters
- ➔ diffusion in the gas
- ➔ small drift velocity

Timing performance can be improved by

- ☞ simultaneous creation of primary electrons at the same distance from the mesh
- ☞ shorten the drift length



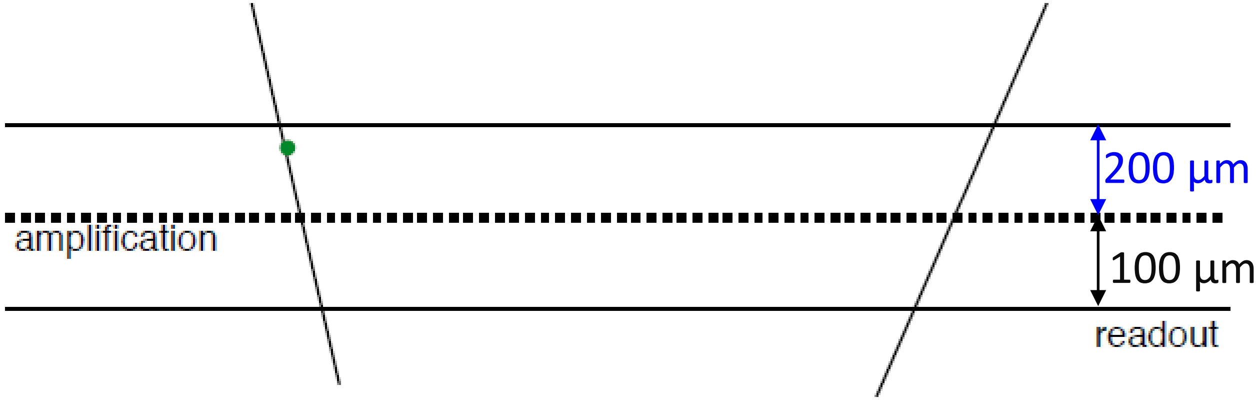
⇨ *Direct ionization of the gas cannot be used and should be suppressed*

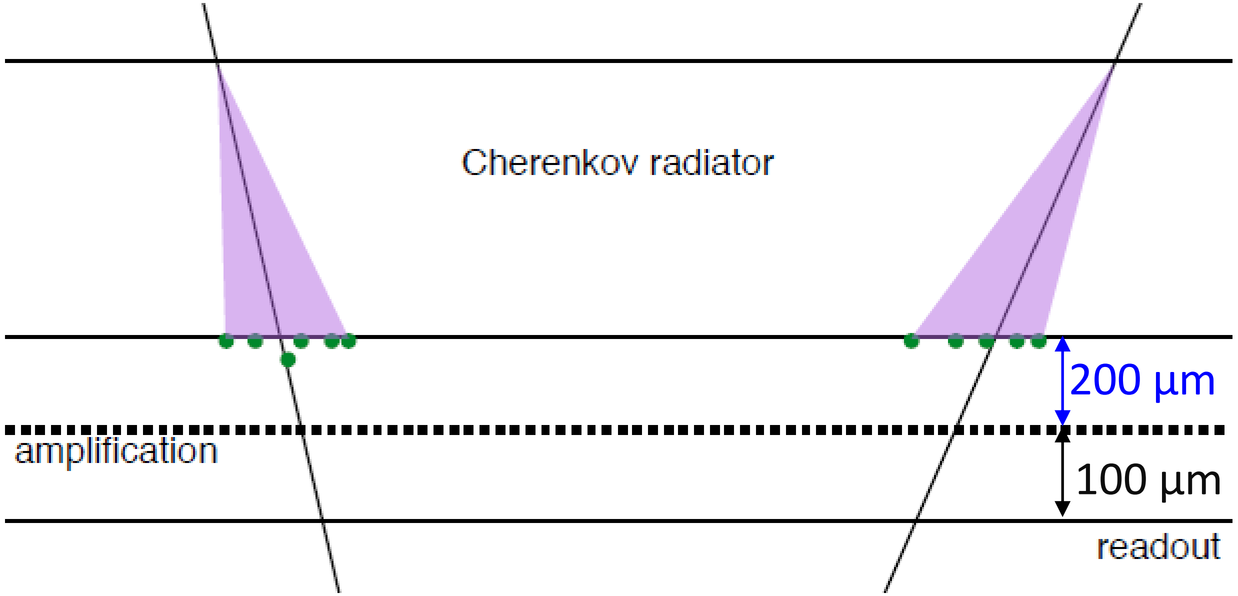
Improving MPGD timing

- ➢ Suppress primary ionization by reducing the drift gap (200 nm)
  - ✓ Limit diffusion
  - ✓ Pre-amplification possible

- ➢ Use a Cerenkov radiator
  - ✓ Photoelectrons emitted at the cathode (fixed distance from the mesh)

Pre-amplification will
➔ reduce the effect of longitudinal diffusion
➔ limit contribution of gas ionization





Project goal:
☞ **single photoelectron time jitter ~100 ps**
☞ **sufficient photoelectrons to reach timing response ~20 ps.**

Limiting the e⁻ diffusion in the gap

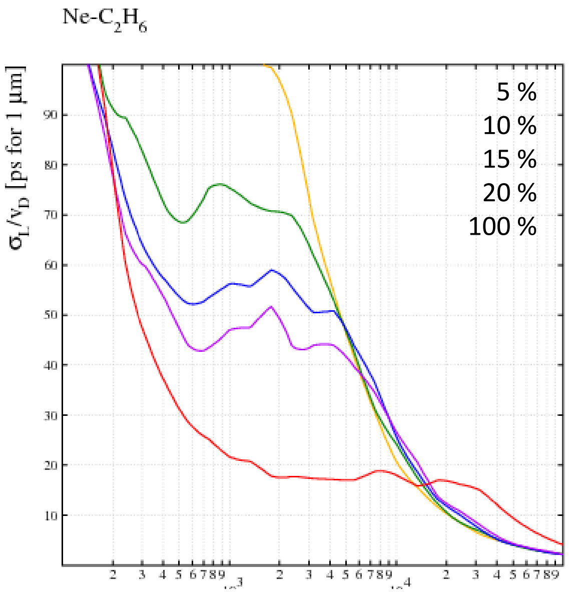
- Small drift gap + strong electric field
- Gas choice – simulation studies
  - ➔ Electron diffusion
  - ➔ Gain
  - ➔ Stability

Ne mixtures

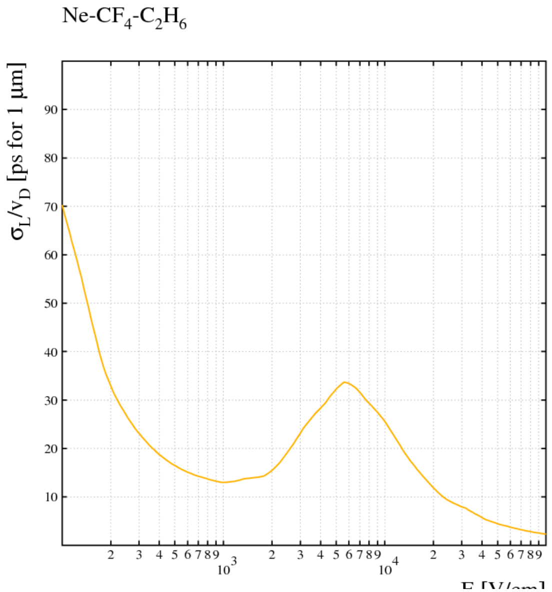
- ✓ Higher gain than Ar
- ✓ Less diffusion than He

➔ pre-amplification improves time resolution!

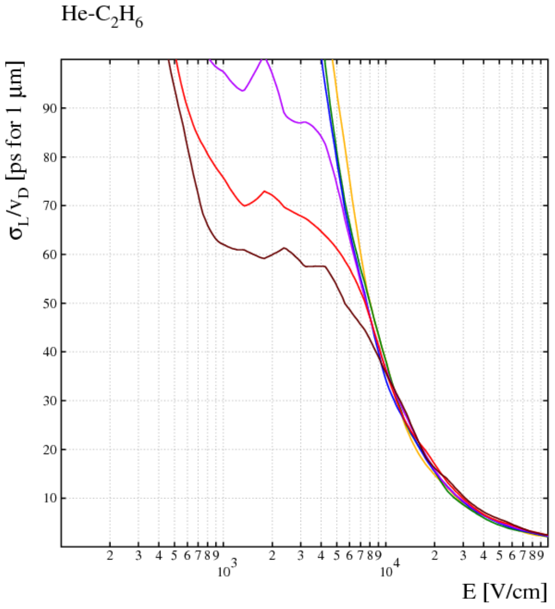
$Ne\text{-}C_2H_6$



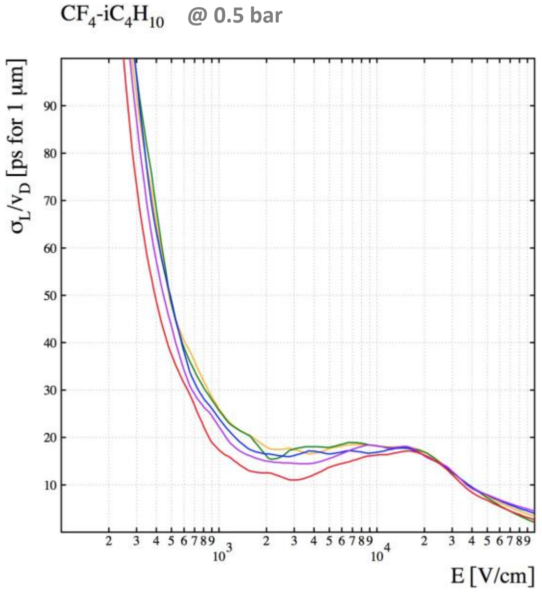
$Ne\text{-}CF_4\text{-}C_2H_6$



$He\text{-}C_2H_6$



$CF_4\text{-}iC_4H_{10}$ @ 0.5 bar



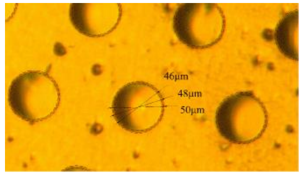
UV photon detection

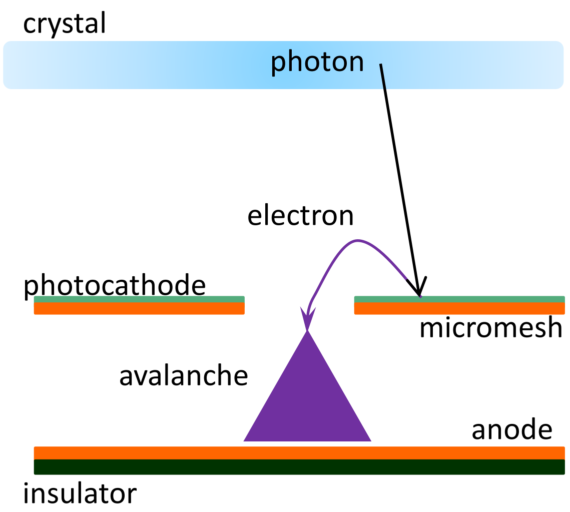
- **Reflective photocathode**:

  Photosensitive material is deposited on the top surface of the micromesh.

  Photoelectrons extracted by photons will follow the field lines to the amplification region

  - ✓ *Smaller ion backflow* ➔ radiation hardness
  - ✓ The photocathode does not "see" the avalanche ➔ *no photon feedback* ➔ *higher gain in single stage (~ 10^5)*
  - ✓ Higher electron extraction efficiency
  - × Reflection on the crystal
  - × e^- path variation
  - × Limitation to Microbulk / opaque meshes

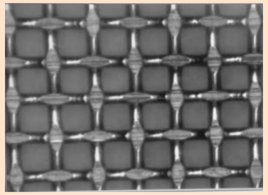


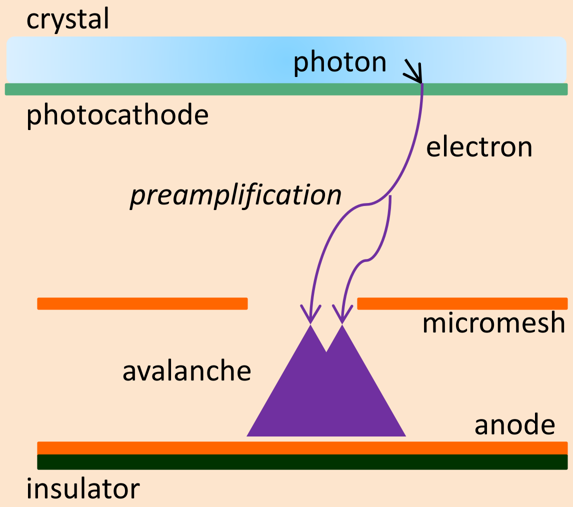


- **Semi-transparent photocathode**:

  Photosensitive material is deposited on an aluminized MgF_2 window (drift electrode)

  - ✓ Extra preamplification stage ➔ better long-term stability
  - ✓ higher total gain
  - ✓ Various MM technologies & gas mixtures possible
  - ✓ Decoupling of sensor - photocathode
  - × Lower photon extraction efficiency
  - × Photocathode exposure to sparks
  - × Ion backflow ➔ radiation hardness (?)





Thomas.Papaevangelou@cea.fr

Single-anode prototype

Tests with UV lamp / laser ➔ quartz windows

Sensor:

Microbulk Micromegas ø 1cm

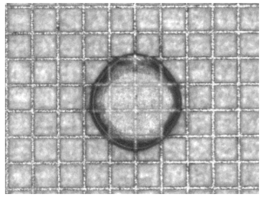
- ➢ Possibility to deposit CsI on the mesh surface
- ➢ Capacity ~ 35 pF

Bulk Micromegas ø 1cm

- ➢ Capacity ~ 8 pF
- ➢ Amplification gap 64 / 128 / 192 μm

Thin-mesh Bulk Micromegas (~5 μm)

- ➢ High optical transparency
- ➢ Amplification gap 128 μm



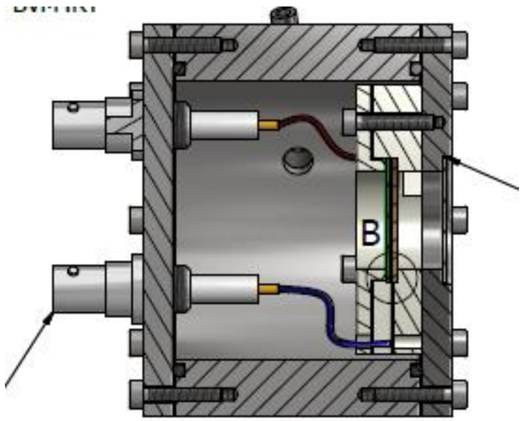
☞ Ensure homogeneous small drift gap & photocathode polarization

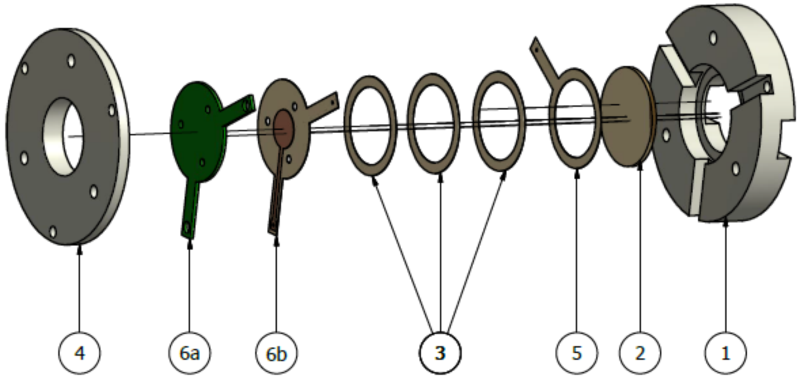
Photocathodes: MgF2 crystal +

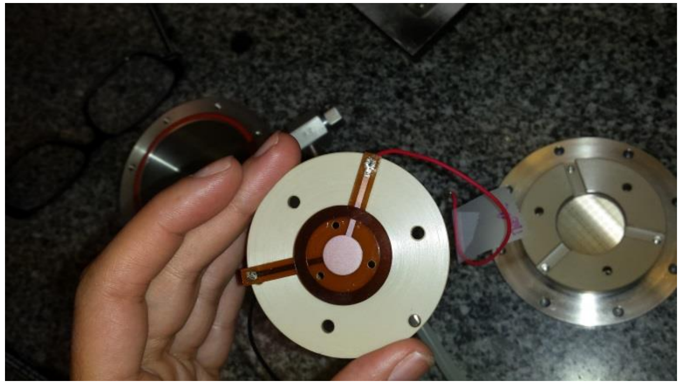
- Metallic substrate + CsI
- Metal (Cr, Al)
- Metallic substrate + polycrystalline diamond
- *Boron-doped diamond*

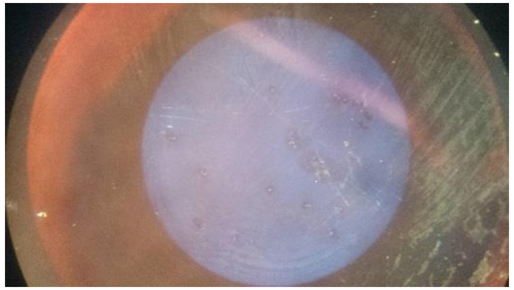
☞ New stainless steel chamber for sealed mode operation

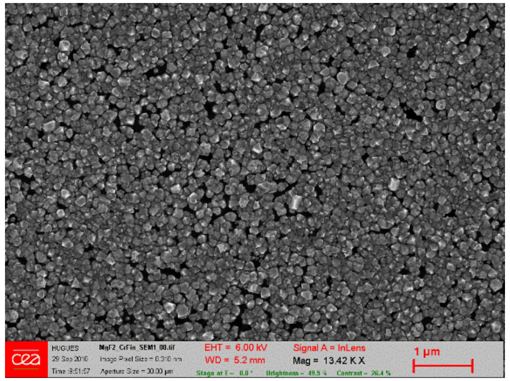
Very thin detector active part (<5 mm)

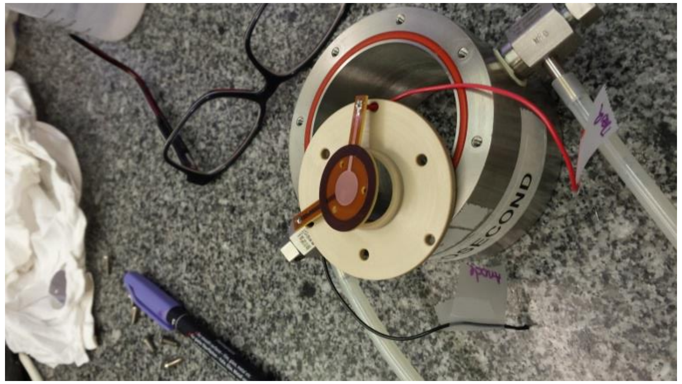








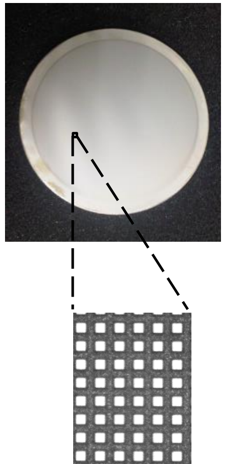


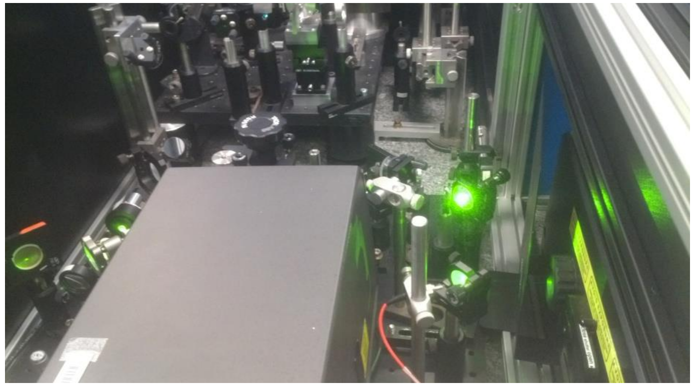


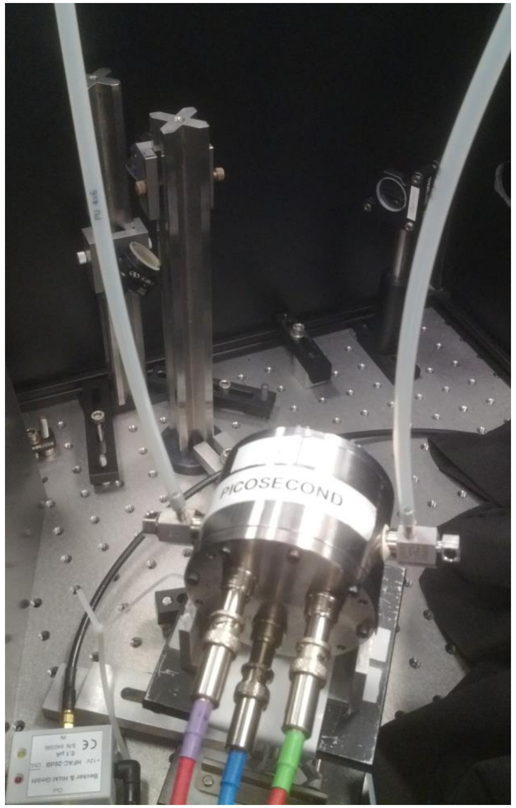
Proof of principle with UV fs laser

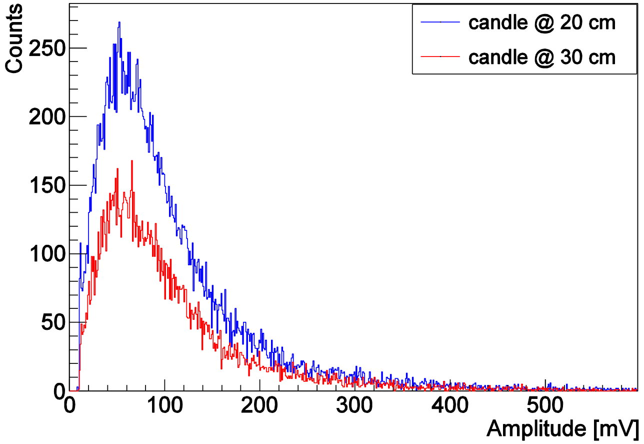
IRAMIS facility @ CEA Saclay

- UV laser with σ_t << 100 fs
- λ = 275-285 nm after doubling
- intensity ~ 3 mJoule / sec
- Repetition 9 kHz - 8 MHz
- **Light attenuators** (fine micro-meshes 10-20% transparent)
- Trigger from fast PD
- Cividec 2 GHz, 40 db preamplifier

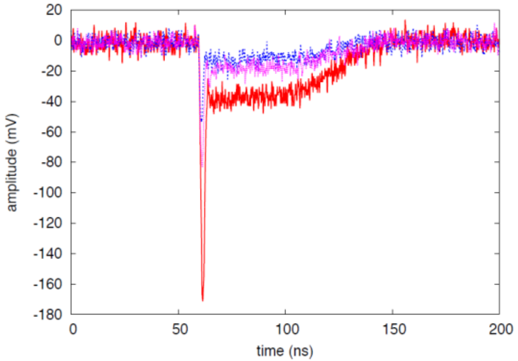








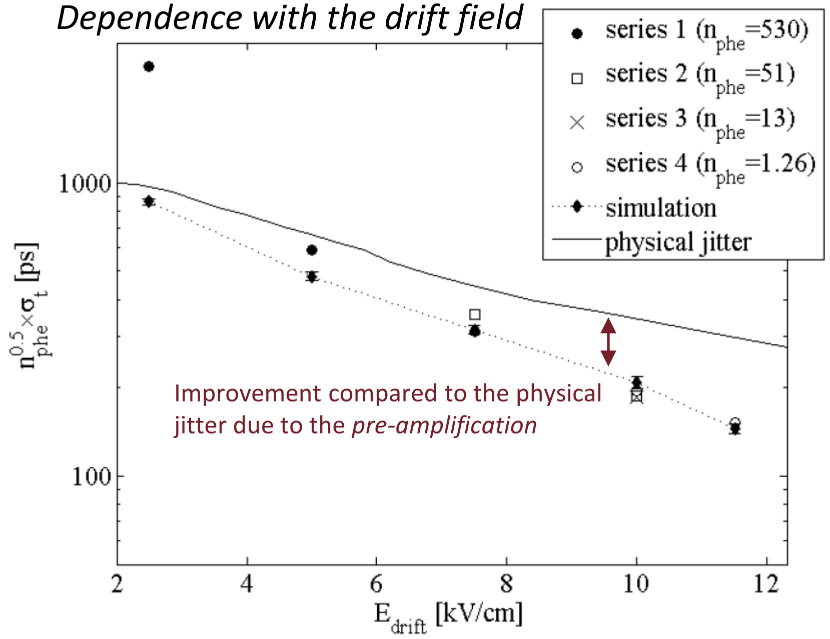
Single photoelectrons from a candle's flame using a charge preamplifier.



Laser test results

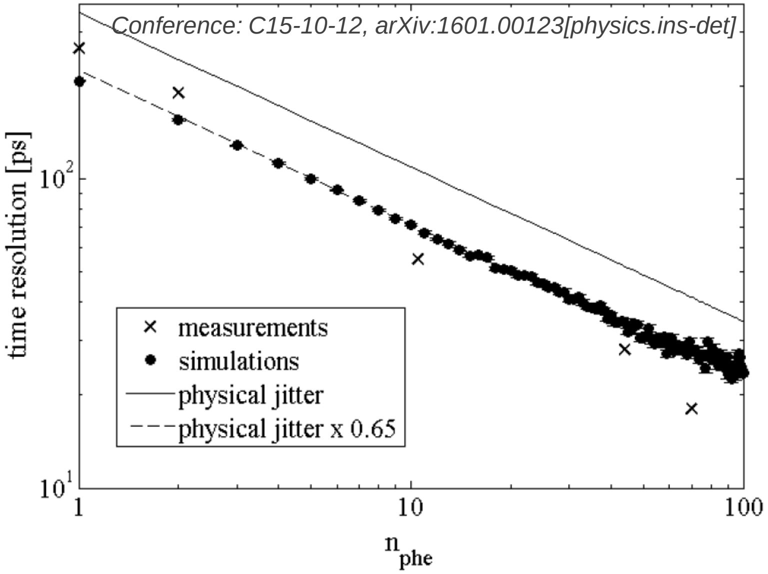
- Metallic photocathodes (10 nm Al on quartz)
- 2015 run: Ne (90%) + C_2H_6 (10%)
  - No gas circulation - gas renewed every 24 h
  - Single p.e. **σ_t~180 ps** @ ~12 kV/cm^2
- May 2016 run: Ne (80%) + C_2H_6 (10%) + CF_4 (10%)
  - No gas circulation. Gas renewed every 24 h
  - Similar performance, analysis to be completed
  - Single p.e. **σ_t ~ 150 ps** @ ~15kV/cm
  - Gain degradation was observed => detector not leak tight
- New run planned January 2017
  - ➔ Leak tight detector / gas circulation
  - ➔ More gasses (low pressure CF_4 + iC_4H_{10})
  - ➔ Smaller drift gaps
  - ➔ Thin bulk

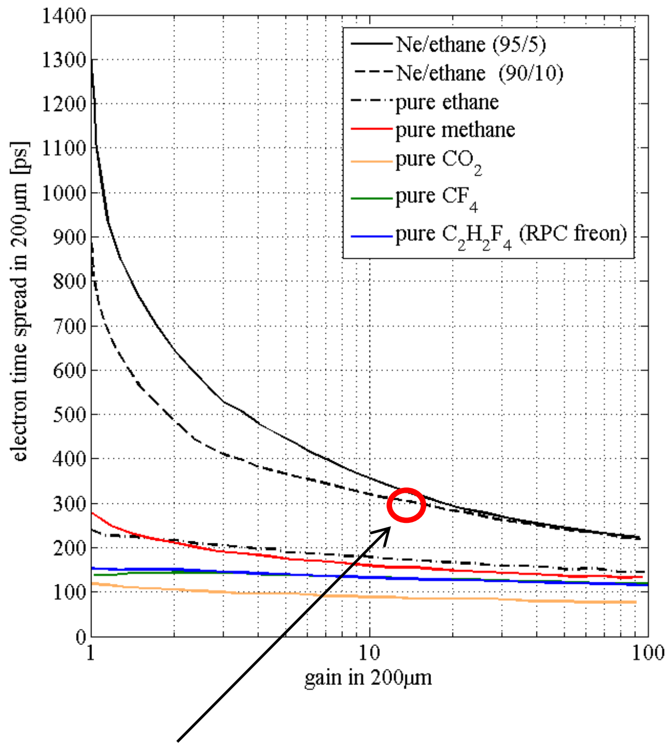
Dependence with the drift field



Improvement compared to the physical jitter due to the *pre-amplification*

Dependence with the number of photoelectrons





2015 operation point

Improvement of single electron time spread ➔ operation at few p.e. regime

Beam tests with 150 GeV muons @ SPS H4

June 2016

- Sensors:
  - *Standard bulk Micromegas*
- *Photocathodes:*
  - *CsI photocathodes (Saclay):*
    - 3mm MgF_2 + 6 nm Al + 10.5 nm CsI
    - 3mm MgF_2 + 8 nm Al + 10.5 nm CsI
  - Al photocathode (8 nm)
- Gas mixtures:
  - $Ne/C_2H_6/CF_4$ (80/10/10)
  - Ne/CH_4 (95/5)
  - *No gas circulation. Gain deterioration observed*
  - CO_2 (sealed/flushed)

August 2016

- Sensors:
  - *Bulk Micromegas with reduced pillars*
  - *Thin mesh bulk Micromegas*
- *Photocathodes:*
  - *CsI photocathodes:*
    - 2 mm / 3 mm MgF_2
    - 6 nm Al / 5.5 nm Cr substrate
    - 11 nm / 18 nm / 25 nm CsI (Saclay / CERN)
  - *Metallic photocathodes:*
    - 3 mm / 5 mm MgF_2
    - 8 nm Al / 10 nm Cr
  - *Diamond photocathodes:*
    - 3 mm MgF_2 + 6 nm Cr + B-doped diamond (100 nm)
    - 5 mm MgF_2 + B-doped diamond (100 nm) - failed
- Gas mixtures:
  - $Ne/C_2H_6/CF_4$ (80/10/10) (flashed / sealed mode)
  - Ne / C_2H_6 (sealed mode / mixed by volume)
  - CF4 / C_2H_6 (sealed mode / mixed by volume)

Sep. - Oct 2016

- Sensors:
  - *Bulk Micromegas with reduced pillars*
  - *Thin mesh bulk Micromegas*
- *Photocathodes*
  - *CsI photocathodes:*
    - 2mm, 3mm, 5mm MgF_2
    - 6nm Al / 5.5 nm, 3nm, 4.5 Cr substrate
    - 11nm, 18nm, 25nm, 36 nm… CsI (CERN)
    - Hamamatsu photocathode (?)
  - *Metallic photocathodes:*
    - 3 mm / 5 mm MgF_2 (+new provider)
    - 6 nm, 9nm, 12 nm, 15nm… Cr
  - *Diamond photocathodes:*
    - 3 mm / 5 mm MgF_2
    - 3 nm, 6 nm Cr + B-doped diamond (100 nm)
- Gas mixtures:
  - $Ne/C_2H_6/CF_4$ (80/10/10) (flashed / sealed mode)
  - CF4 / C_2H_6 (sealed mode / low pressure)

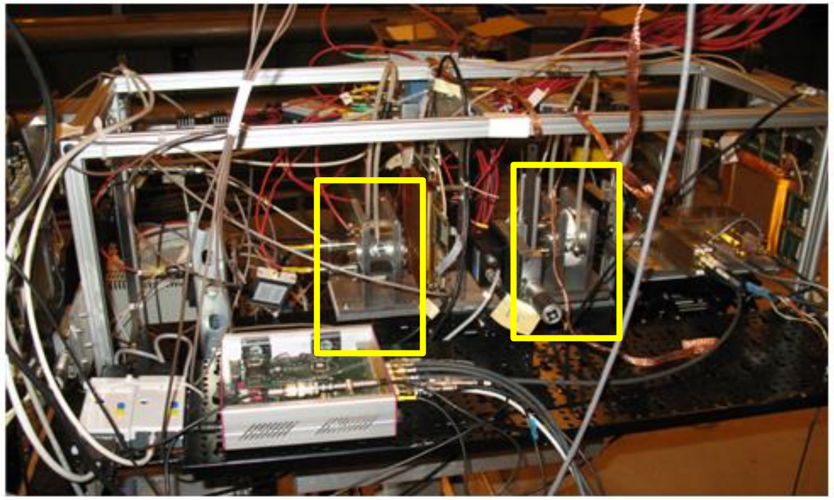
Further studies:

- ✓ Trigger area (also) larger (border region)
- ✓ Improve signal quality (mesh at ground, better connectors, …)
- ✓ Different drift gaps
- ✓ Different and improved preamps
- ✓ Sampic acquisition

SPS measurement Setup

- ➢ Trigger: coincidence of two 5x5 mm2 scintillators and a veto downstream (avoid showers)
- ➢ Tracker: three GEMs to measure where the triggered particle passed (reject showers too)
- ➢ Time reference: two Hamamatsu MCP-PMTs (160 ps rise time)
- ➢ Tracking acquisition: APV25 + SRS
- ➢ Timing acquisition: CIVIDEC C2 preamp + 2x 2.5 GHz LeCroy scopes (synchronised with the tracker) and SAMPIC

Triggering, Tracking and Timing



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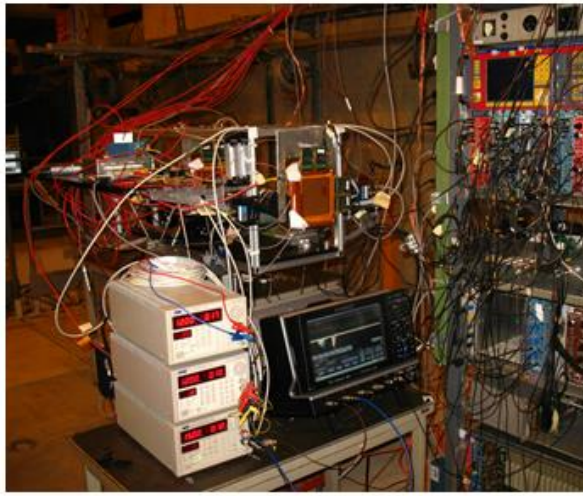
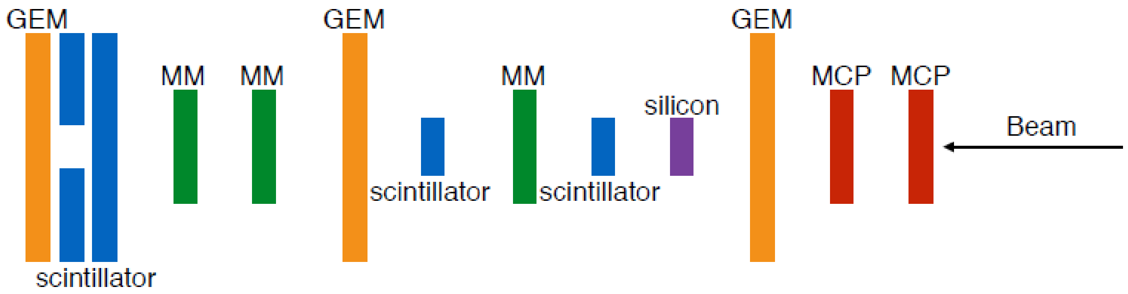
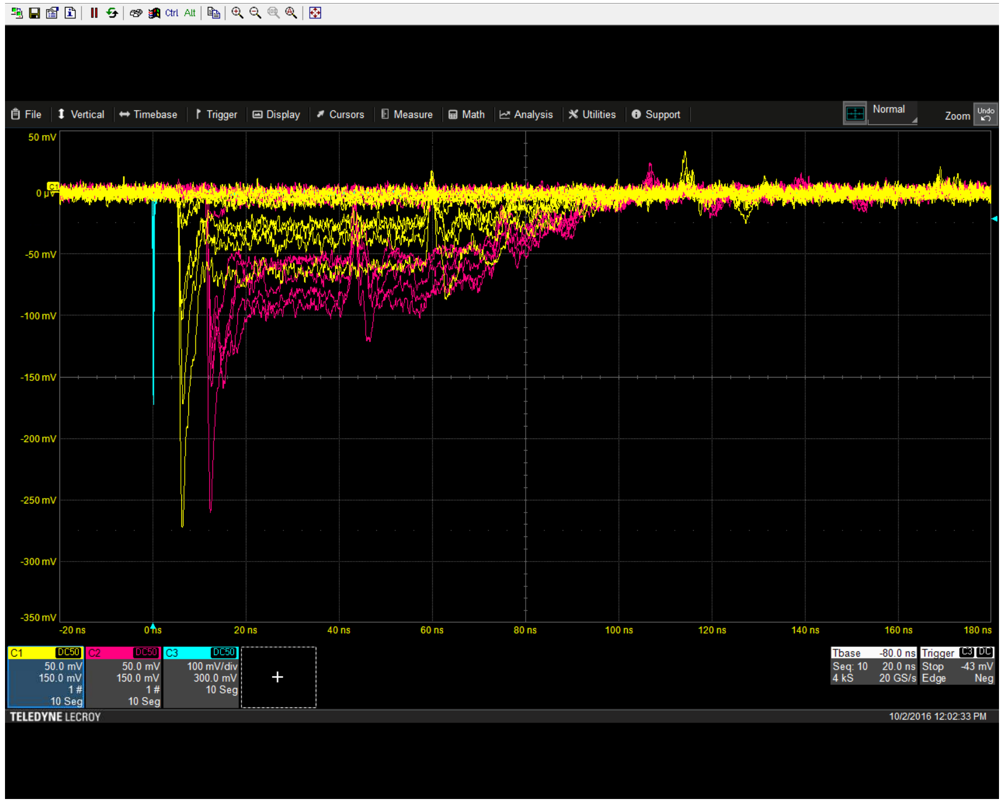






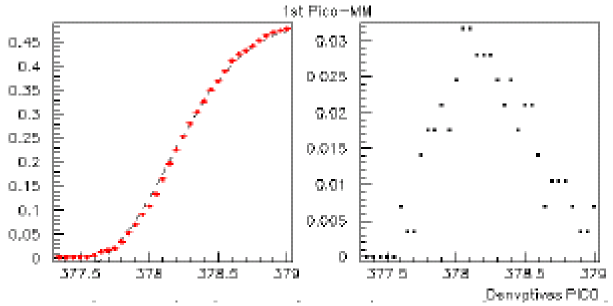
C1 DC50 50.0 mV 150.0 mV 1 # 10 Seg
C2 DC50 50.0 mV 150.0 mV 1 # 10 Seg
C3 DC50 100 mV/div 300.0 mV 10 Seg
Tbase -80.0 ns Seq: 10 20.0 ns 4 kS 20 GS/s
Trigger C3 DC Stop -43 mV Edge Neg
10/2/2016 12:02:33 PM

Thomas.Papaevangelou@cea.fr

Data analysis strategies

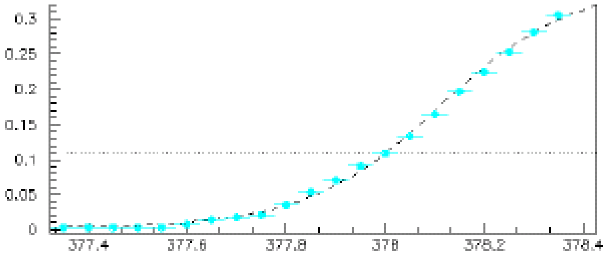
Four Fitting Strategies
Timing at C.F. (20% of the Peak)

- Global Sigmoid



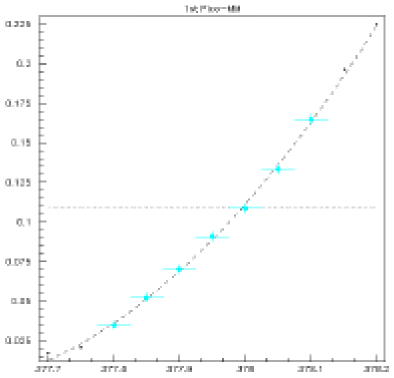
- Earlier Sigmoid
(the inflection point is also a middle point)

$$f(t)=\frac{R_1}{1+e^{-R_2(t-R_3)}}+R_4$$

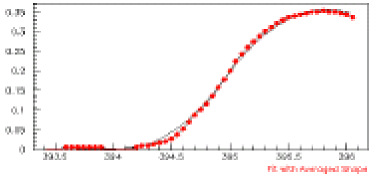


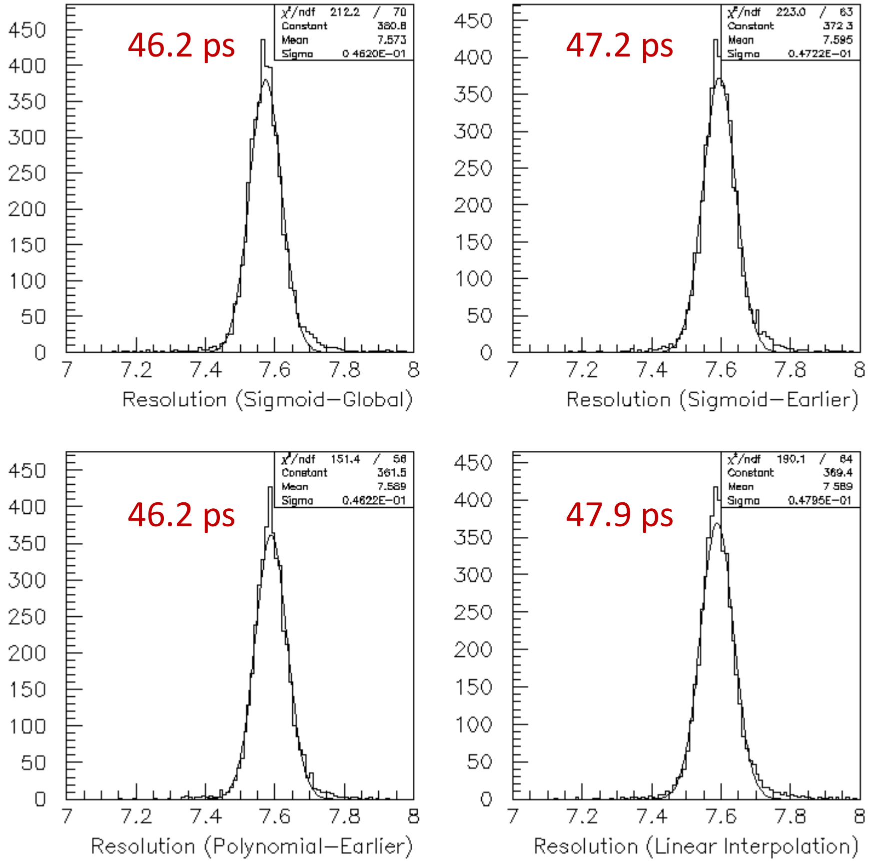
- Polynomial Fit up to the inflection Point

- Linear Interpolation



An extra strategy… Fit based on the average shape
See later….





Analysis by S. Tzamarias

- ➢ Robust results, ~independent on the analysis
- ➢ Asymmetry, deviation from Gaussian distribution

➔ Dependence on the amplitude

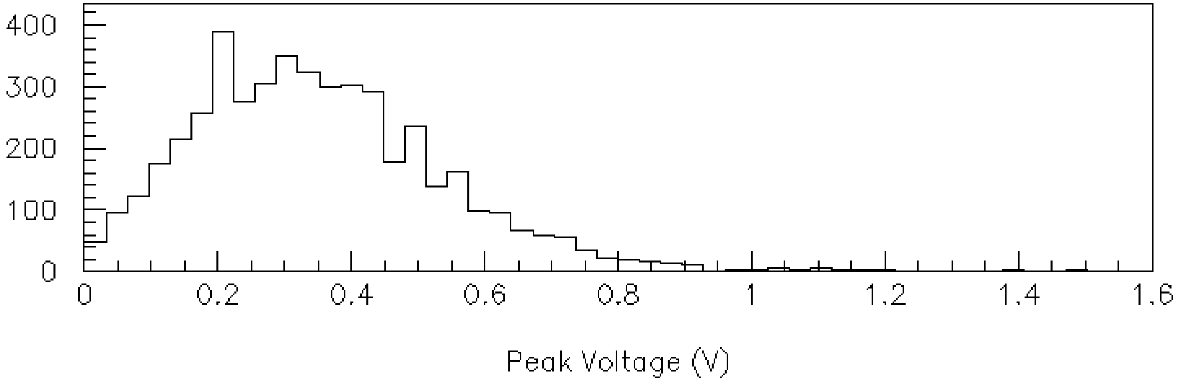
Preliminary results from beam tests.

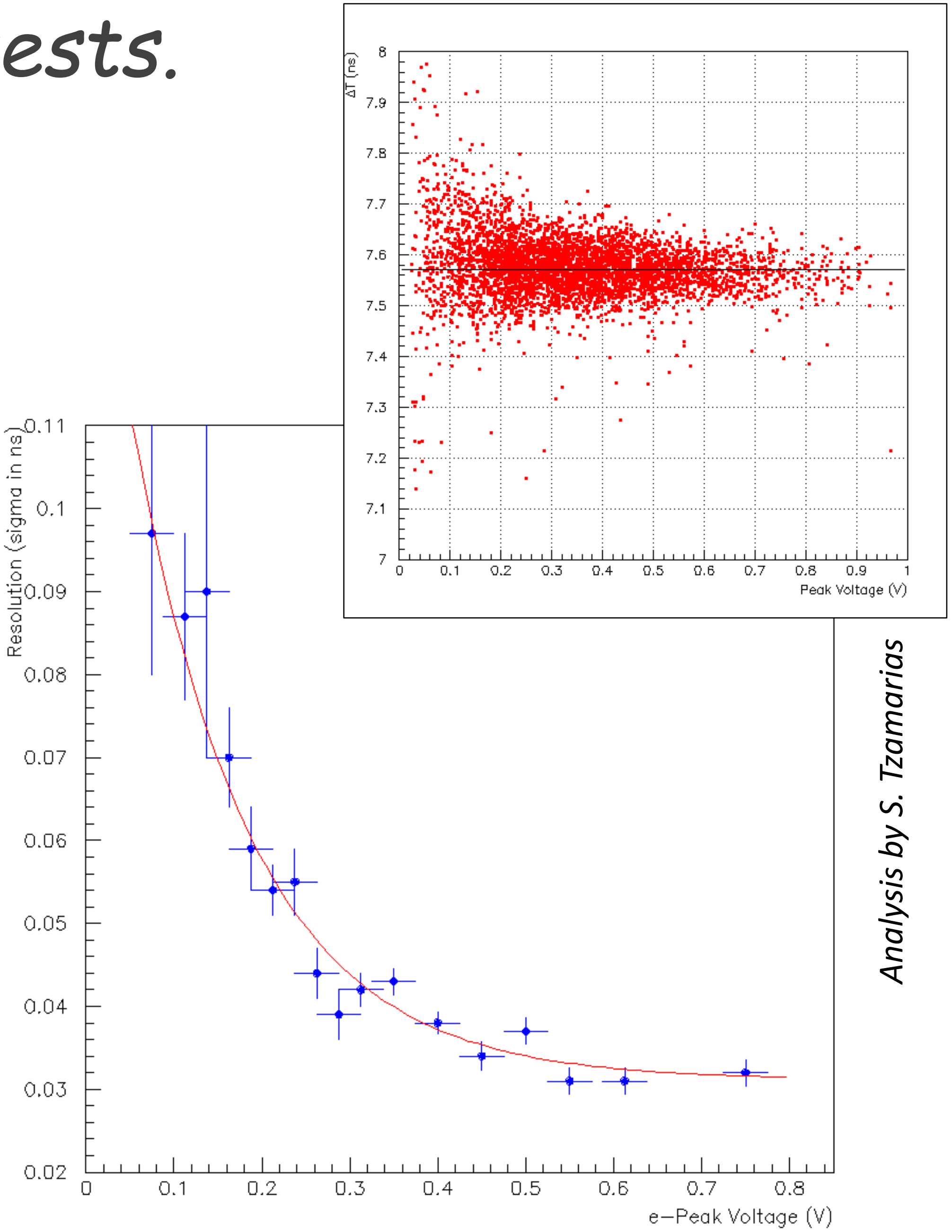
Data analysis in progress. Data from different detector configurations to be analyzed. First results for:

- 3mm MgF_2
- 5.5 nm Cr + 18 nm CsI (2 days old)
- V_a = +450 V (36 kV/cm)
- V_m = 0 V (grounded)
- V_d = -350 V (17.5 kV/cm)
- Sealed @ 1010 mbar, Ne + 10% iC_4H_{10} + 10% CF_4

$\sigma_t \approx 45$ ps, $\langle N_{p.e.} \rangle \approx 9$

100 % efficiency for MIPS
from the scintillator trigger



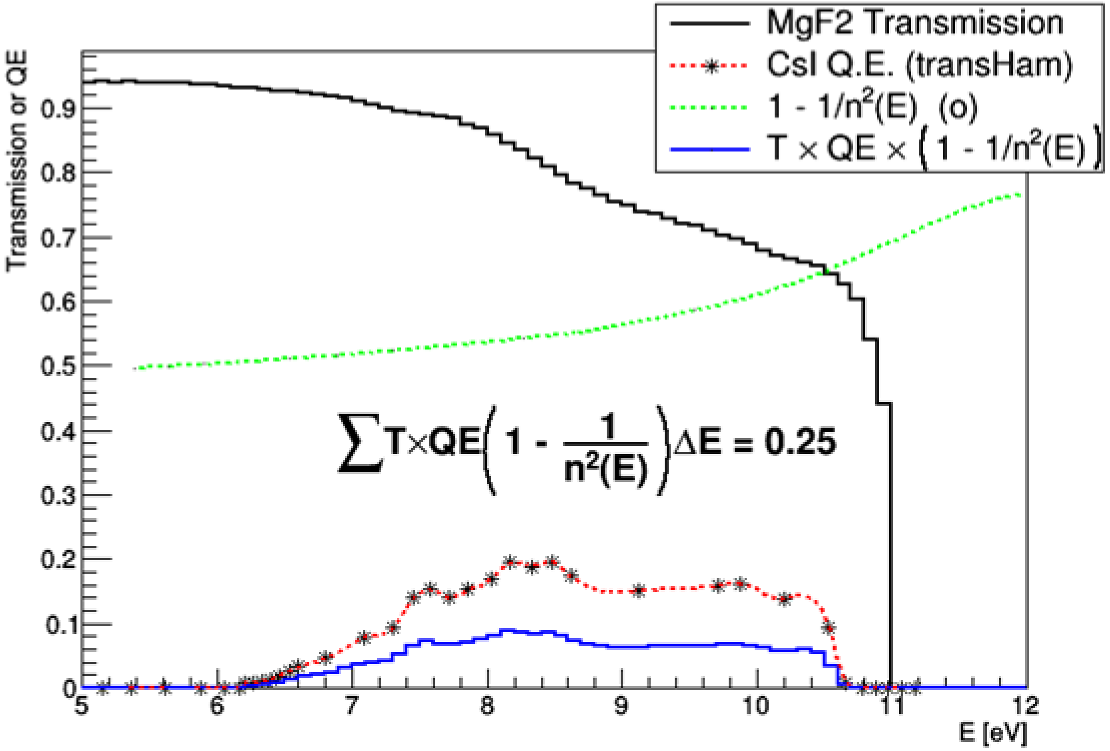


Analysis by S. Tzamarias

Expected number of p.e. per MIP

A MIP passing through a crystal will emit:

$$N_{p.e.} \approx 370L \int T(E)QE(E)\left(1-\frac{1}{n^2(E)}\right)dE$$



For a MgF_2 crystal and a CsI photocathode with typical bibliography values for *QE*(*E*), *T*(*E*) and *n*(*E*) as seen, we expect:

370 × 0.25 = 92 p.e./cm

for a **3 mm MgF_2** crystal we would expect **~28 p.e.**

Single photoelectron calibration runs have been taken using a cigarette ***lighter's flame*** for all detector settings. Analysis pending. For the time being matching the amplitude spectra with Poisson distributions we estimate **~10 p.e. per MIP**

Margin for improvement!!

Conclusions - Outlook

We have coupled a Micromegas detector with a radiator/photocathode in order to **surpass the physical constrains on precise timing with MPGDs**, aiming to an important improvement of their performance (~two orders or magnitude are needed in order to be considered for the HL-LHC upgrade)

- The detector has been tested with a **femtosecond UV laser** in order to investigate **the time spread of single photoelectrons**.
  σ_t ~ 150 ps for single p.e. has been measured with a standard bulk Micromegas in **semi-transparent** mode without gas circulation. More tests to follow.

- The Micromegas photodetector has been tested with 150 GeV muon beam. Data taking is on-going.
  σ_t ~ 45 ps has been measured for 3 mm MgF2 + 5.5 nm Cr substrate + 18 nm CsI photocathode. The estimated number of photoelectrons for this photocathode was: **$\langle N_{p.e.} \rangle \approx 9$**

- Results from various radiator/photocathode setups are pending.

➔ *Big margin for improvement: gas / drift gap / photocathode studies & optimization*

Yet to be addressed:

- ***Resistive detector***
  - ✓ discharge resistance
  - ✓ dynamic range
  - ☞ maintaining the signal quality
- ***Multiple-pad readout performance***
  - ✓ Design a pixelated prototype (~5x5 cm^2)
  - ✓ Readout Electronics (Sampic)
- ***Radiator & photocathode aging / radiation hardness***
  - ☞ IBF, photon feedback, discharges
  - ☞ Particle flux (high rate tests @ IRAMIS / ORPHEE)
  - ☞ Deterioration with time
  - ✓ Metallic photocathodes
  - ✓ Polycrystalline diamond photocathodes
  - ✓ *Operation in reflective mode*
- ***Polycrystalline diamond as secondary emitter***
  - ✓ Replace the crystal + photocathode with secondary electron emitter
    - ☞ Robustness / radiation hardness
    - ☞ No radiator - flexible choice of substrate material
    - ☞ Possibility to increase thickness towards 1 μm!
  - ✓ Investigate materials with high secondary electron yield. (Doped-) diamond deposition, DLC, graphene…

  - ☞ *multi layer detector*
  - ☞ *graphene layer for photocathode protection ?*

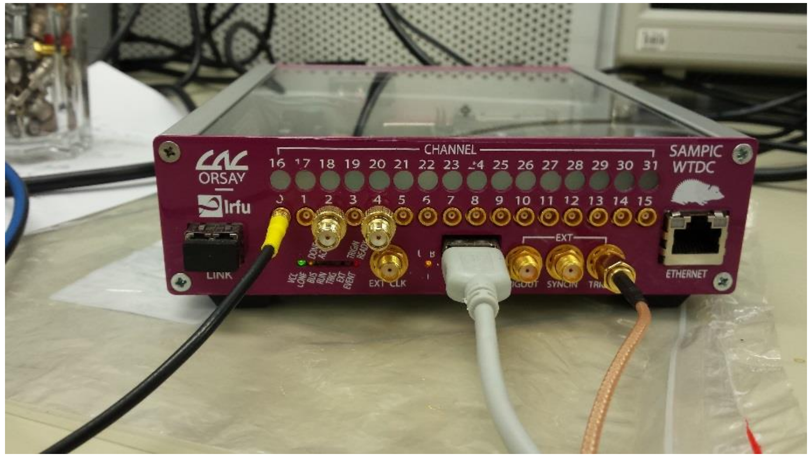
Irfu Thomas.Papaevangelou@cea.fr

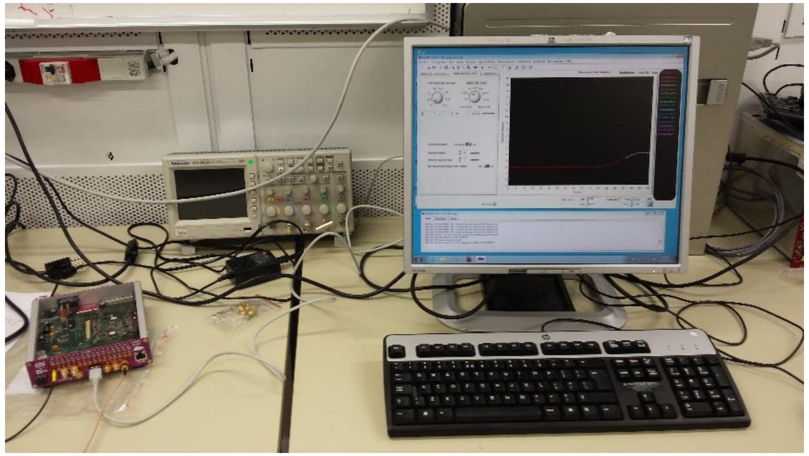
Thank you!

Next steps (Electronics)

- Electronics for pixelated detector
  - ✓ SAMPIC (D. Breton / LAL Orsay, E. Delagnes IRFU/CEA)
  - ✓ Radiation hard amplifiers → Mitch Newcomer / PENN
  - ✓ Onboard electronics ?
  - ✓ Improve signal transfer lines, bandwidth

SAMPIC
1.5 GHz bandwidth
10 Gs/s (used at 6.4 Gs/s
11 bit
64 samples
16 channels
Maximum rate ~500 kHz)





http://arxiv.org/abs/arXiv:1604.02385

Thomas.Papaevangelou@cea.fr

Signal Modeling (D. Gonzalez Diaz, F. Resnati, R. Veenhof)

general hydrodynamic equations (field along z)

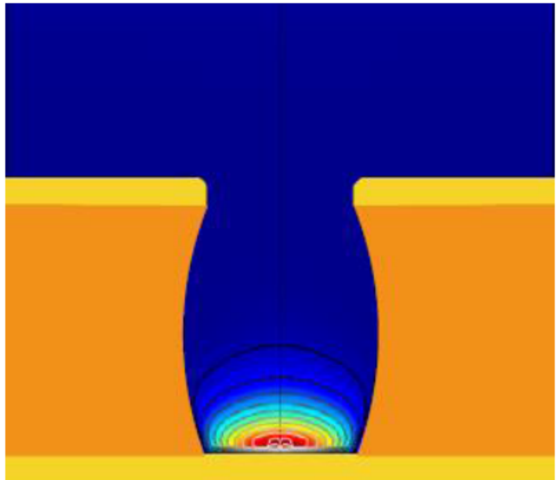
$$\boxed{\frac{\partial}{\partial t} n = (\alpha - \eta) n v_d + D_T \left(\frac{\partial^2}{\partial x^2} n + \frac{\partial^2}{\partial y^2} n\right) + D_L \frac{\partial^2}{\partial z^2} n + v_d \frac{\partial}{\partial z} n}$$

n: 3D electron density
z: direction of the electric field

$$D^*_{T,L} = \sqrt{\frac{2D_{T,L}}{v_d}}$$ units: [length$^{0.5}$]

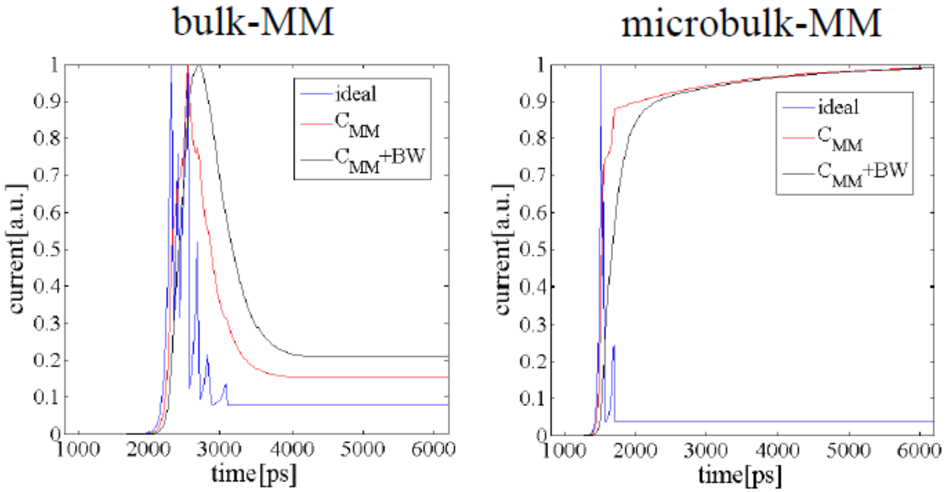
full 3D stochastic solution: computationally expensive
(use Garfield++ or, even better: Garfield++/microscopic)->R. Veenhof/S.Biagi

average solution for arbitrary geometries (e.g. COMSOL)



axi-symmetric model of microbulk (color code: **electron density** at a given time)

stochastic solution from 1D-treatment (‘a la’ Legler)



(**single-electron** induced signal)