New detectors and concepts for sub-100ps timing

Diego Gonzalez Diaz (Uludag University and CERN),
on behalf of the CERN-GDD group and a lot of people

22/2/2016, Ghent

Who needs timing?

- 10-20ps timing for minimum ionizing particles at sustained fluxes of 1-10MHz/cm^2 (and granularity $\leq$1cm^2) required for pile-up mitigation in sLHC (figures from CMS).
- 100ps timing can help to reconstruct directionality in both neutrino and 'neutrino-less' detectors by making use of Cherenkov light. It can also help at reducing backgrounds (Snowmass13).
- 100ps timing helps in muon tomography, by providing statistical information on the muon momentum (e.g.: P. Baeso at RPC2014). It also helps at muography, by suppressing random coincidences.
- sub-100ps timing helps PET scanners in the determination of the e$^+$ vertex position and suppressing backgrounds (e.g.: P.Fonte/A.Blanco, S. Majewski at CERN detector seminar)
- ~ps time resolution allows to determine jet composition as well as to match gamma vertexes (Snowmass13).
- sub-100ps: allows to correct for chromatic dispersion in DIRC detectors (Snowmass13).
- 100ps: next generation heavy ion experiments need it both for the start and time-of-flight detectors (e.g.: CBM).

……

Layout of the talk

A concept

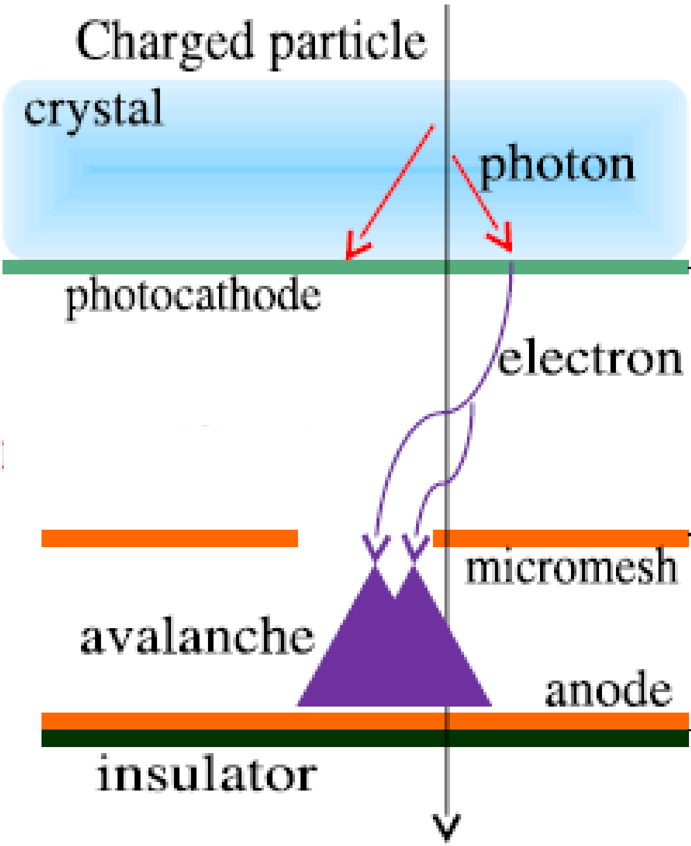
A crazy idea

A wild shot

PART I

A concept

Basic idea



Main sources of jitter per photo-electron

geometrical

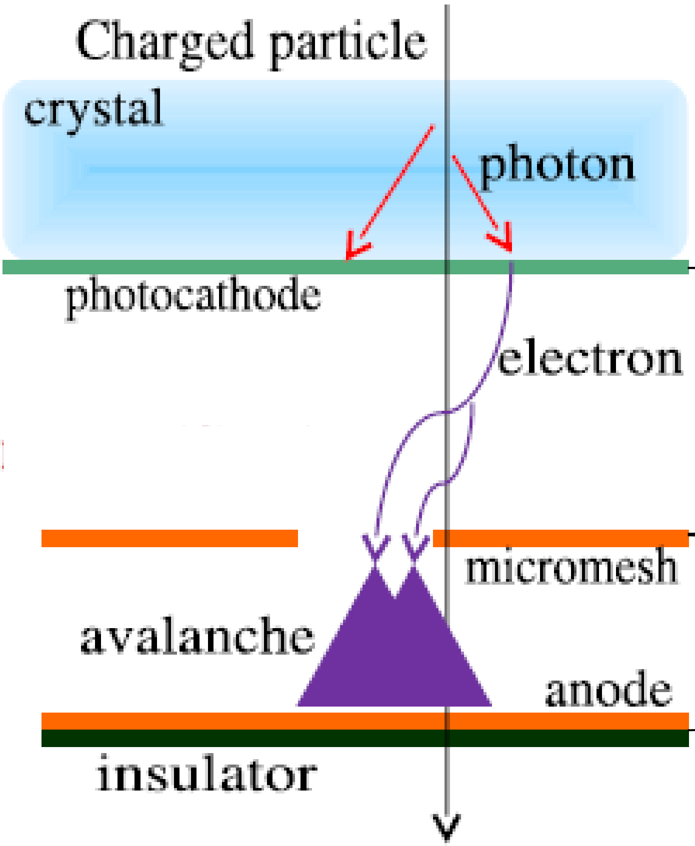
$$\sigma_{t,transit} = \frac{1}{\sqrt{12}}\frac{1}{(\cos\theta_{Ch})^2}\frac{h}{c}$$

diffusion	multiplication (~Furry law)
$\sigma_{t,d} \cong D_L^*(E_d)\sqrt{d}\,\frac{1}{v_d(E_d)}$	$\sigma_{t,m(d)} \sim \frac{1.28}{(\alpha(E_d)-\eta(E_d))v_d(E_d)}$
$\sigma_{t,a} \cong D_L^*(E_a)\sqrt{d}\,\frac{1}{v_d(E_a)}$	$\sigma_{t,m(a)} \cong \frac{1.28}{(\alpha(E_a)-\eta(E_a))v_d(E_a)}$

Successfully tried in
G. Charpak et al., NIM A478(2002)26
(σ_t = 680 ps/phe)

Basic idea

Main sources of jitter per photo-electron



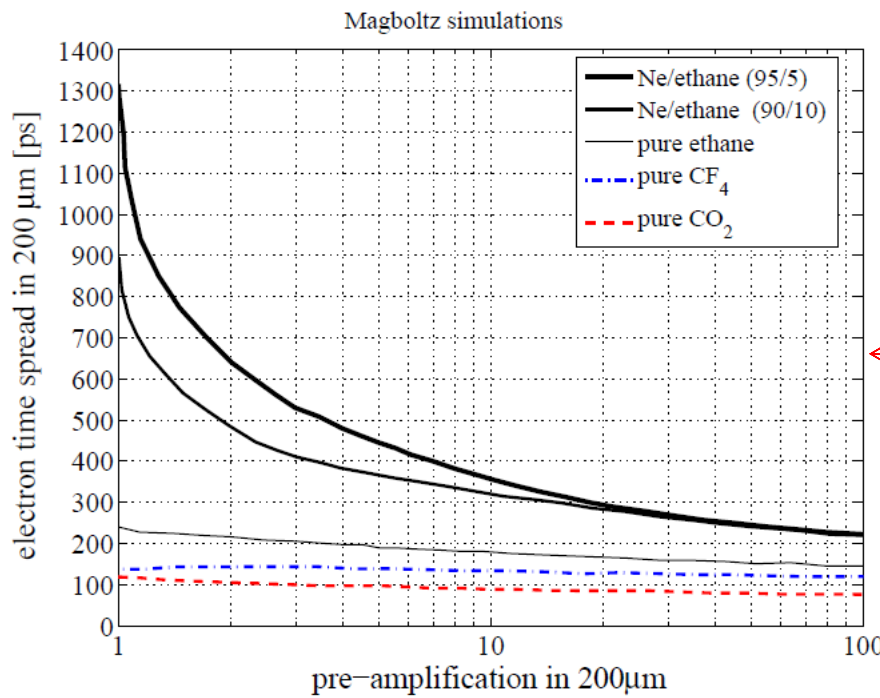
geometrical

$$\sigma_{t,transit} = \frac{1}{\sqrt{12}} \frac{1}{(\cos\theta_{Ch})^2} \frac{h}{c} \cong 25ps/cm$$

diffusion	multiplication (~Furry law)
$\sigma_{t,d} \cong D_L^*(E_d)\sqrt{d}\,\frac{1}{v_d(E_d)}$	$\sigma_{t,m(d)} \sim \frac{1.28}{(\alpha(E_d) - \eta(E_d))v_d(E_d)}$
$\sigma_{t,a} \cong D_L^*(E_a)\sqrt{d}\,\frac{1}{v_d(E_a)} \ll \sigma_{t,d}$	$\sigma_{t,m(a)} \cong \frac{1.28}{(\alpha(E_a) - \eta(E_a))v_d(E_a)} \ll \sigma_{t,m(a)}$

Successfully tried in
G. Charpak et al., NIM A478(2002)26
(σ_t = 680 ps/phe)

correctable through amplitude information
(e.g.: Constant Fraction Discriminator)



previous results

expected time resolution

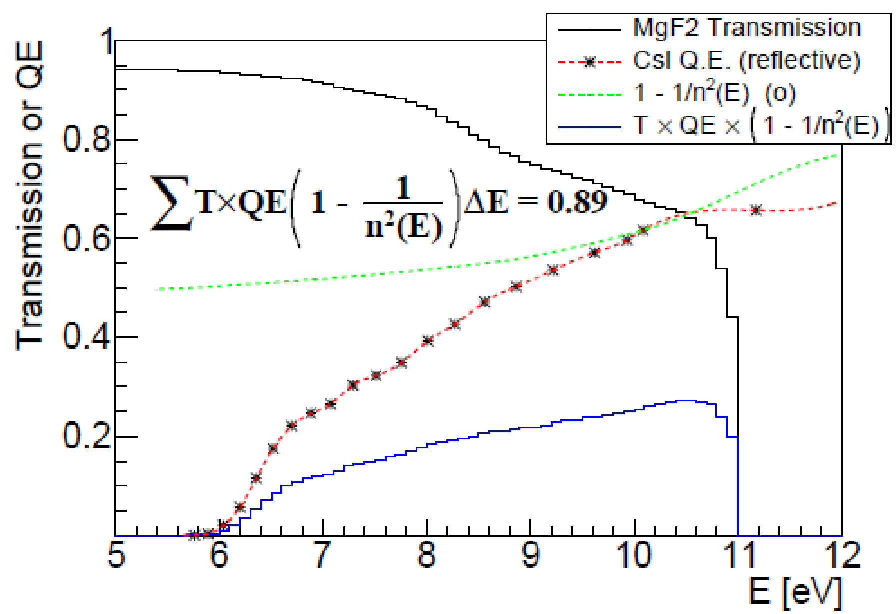
$$\sigma_{t,d} \cong D_L^*(E_d)\sqrt{d}\,\frac{1}{v_d(E_d)}$$

expected number of Cherenkov photons for mips

$$\frac{d^2N}{dEdx} = \frac{\alpha^2 z^2}{r_e m_e c^2}\sin^2\theta_c \approx \frac{370}{eVcm}\left(1-\frac{1}{n^2(E)}\right)$$

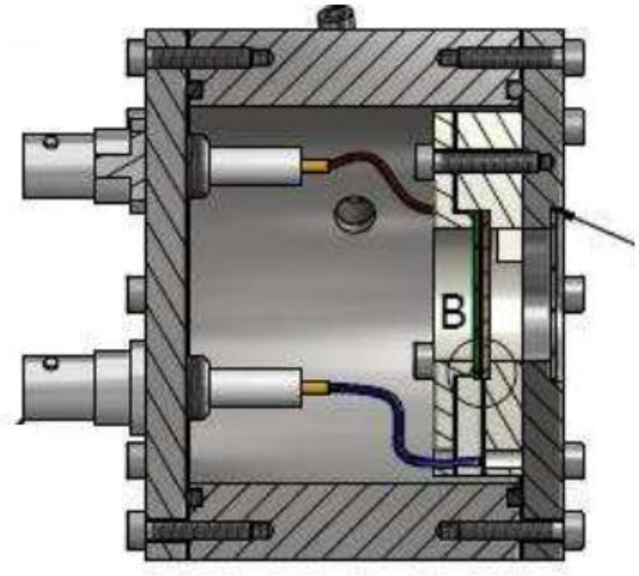
$$N_{p.e.} \approx 370L\int T(E)QE(E)\left(1-\frac{1}{n^2(E)}\right)dE$$

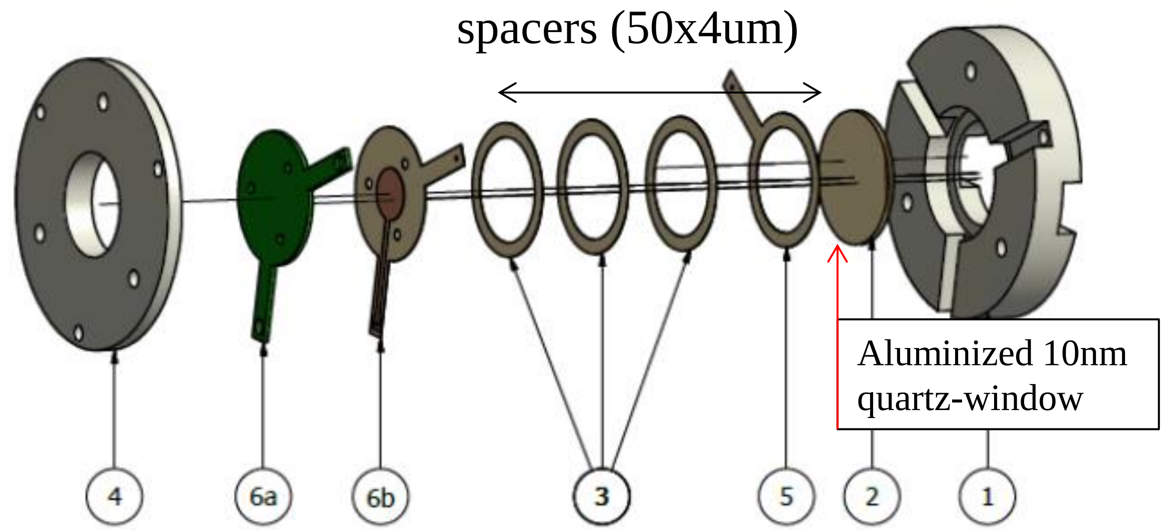
$N_{p.e.} \approx 100\text{-}150/cm$ ➡ ~50 per 3mm crystal



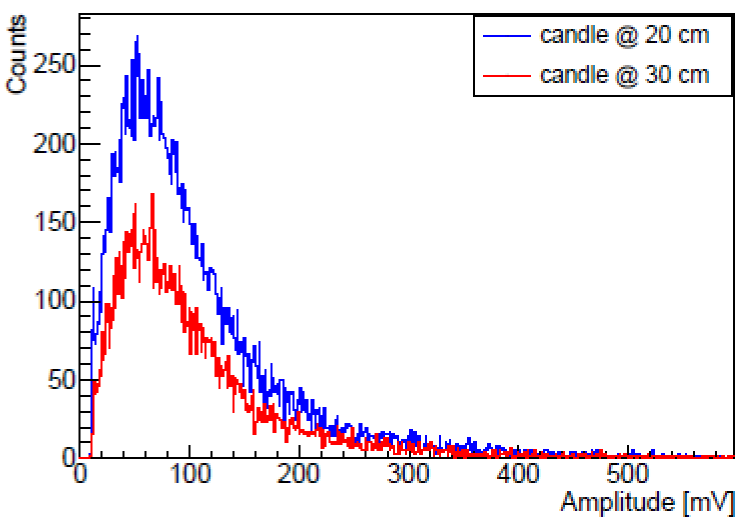
Thomas Papaevangelou et al, arXiv:1601.00123

The ‘proof-of-concept’ detector (in a nutshell)

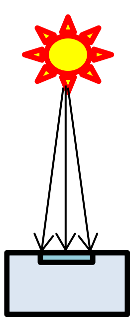


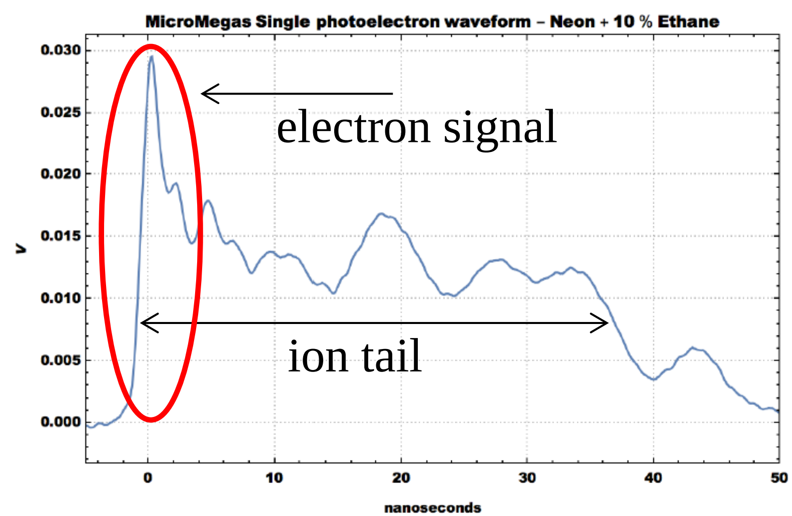


results from a candle (Ne/Ethane: 90/10)



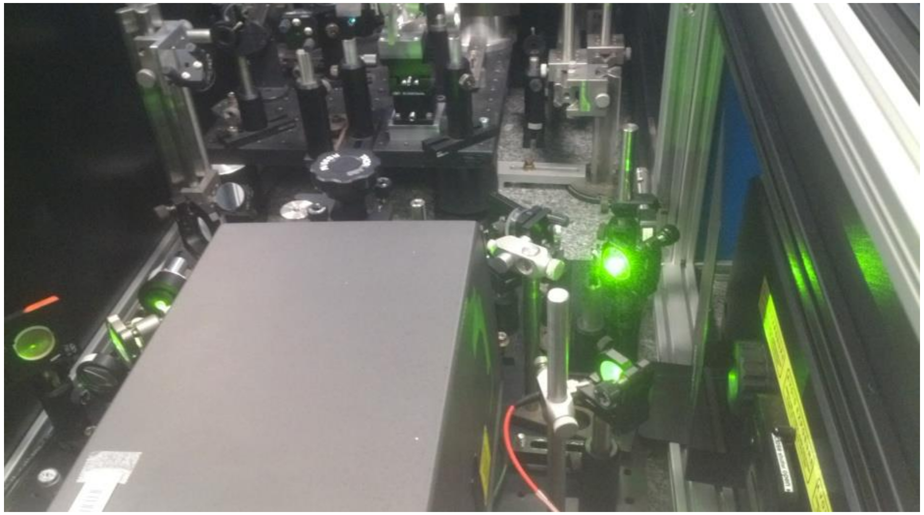
Single-photon charge distribution
(charge amplifier)

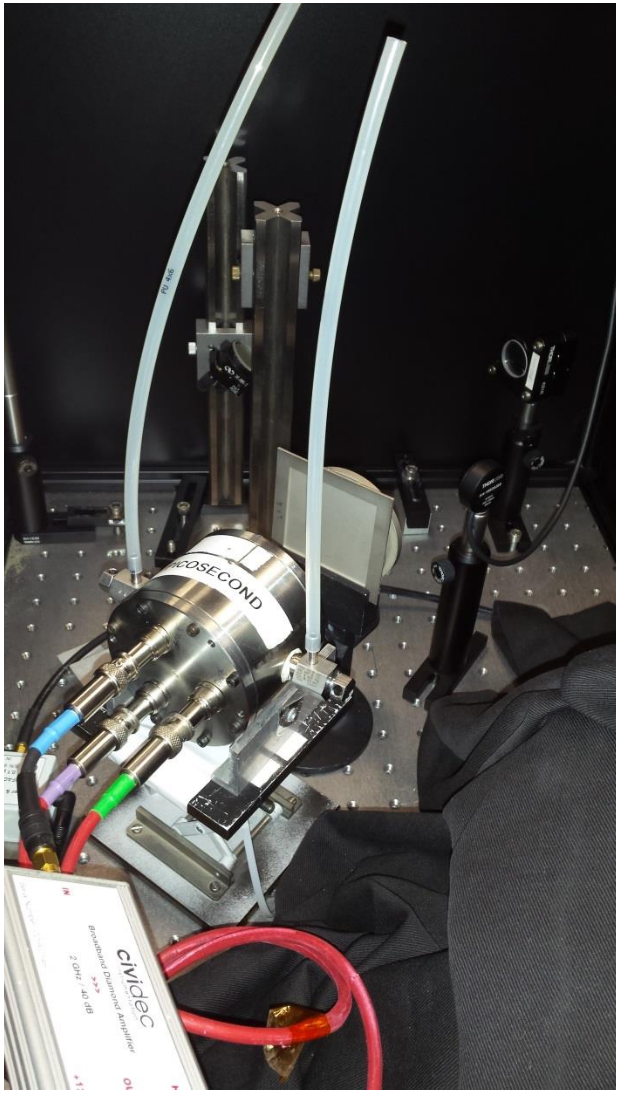




Typical single-photon pulse
(current amplifier)

Measurements @ IRAMIS laser facility

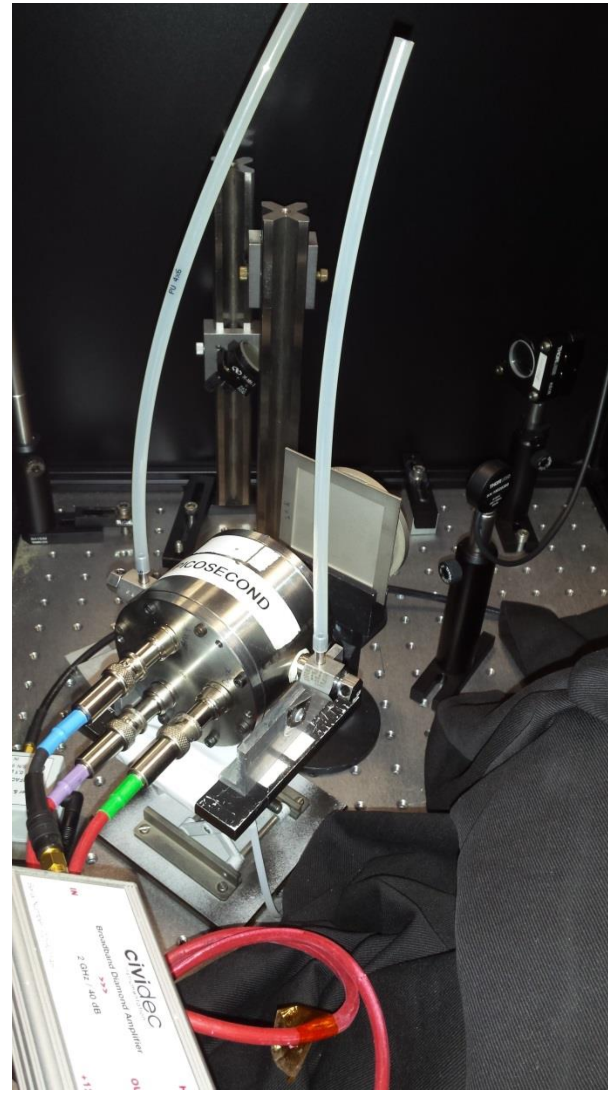




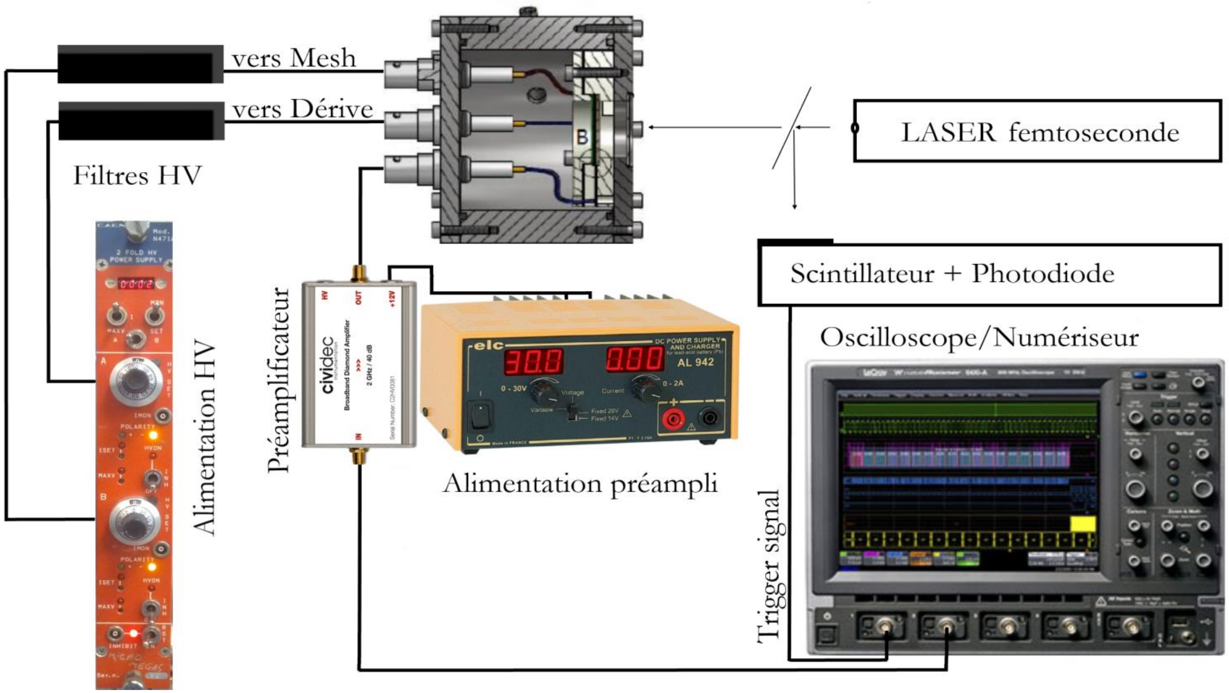
Measurements @ IRAMIS laser facility

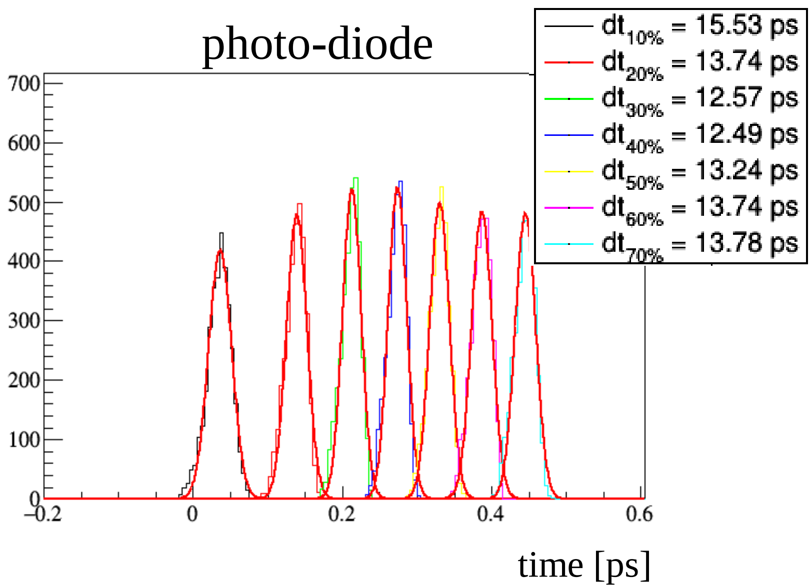
IRAMIS facility @ CEA Saclay
(***thanks to Thomas Gustavsson!***)

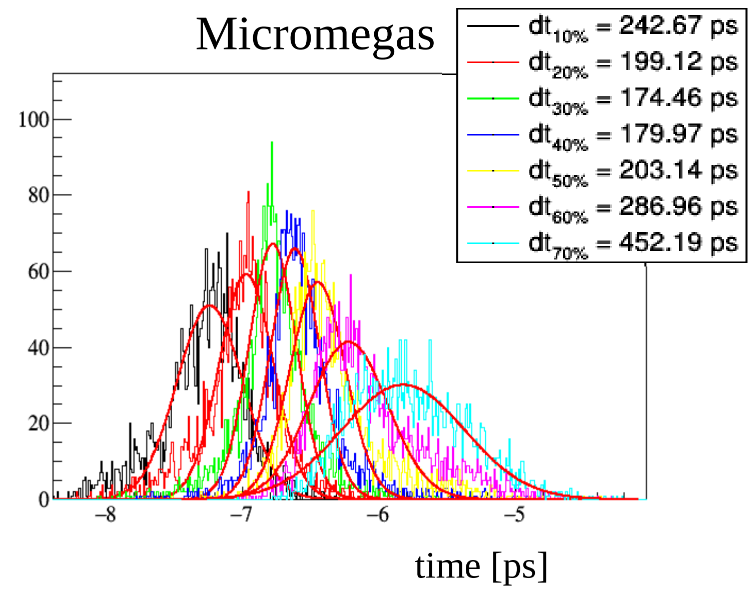
- UV laser with σ_t ~ 100 fs
- λ = 275-285 nm after doubling
- intensity ~ 3 mJoule / pulse
- Repetition rate 8 kHz
- **Light attenuators** (fine micro-meshes 10-20% transparent)
- Trigger from fast Photo-Diode
- Cividec 1 GHz, 40 db preamplifier + 2GHz scope
- Two detector configurations tested!:
  - ✓ Bulk Micromegas (mesh supported by pillars).
  - ✓ Microbulk Micromegas (holes done ‘a la’ GEM, no mesh as such).



Data taking and results

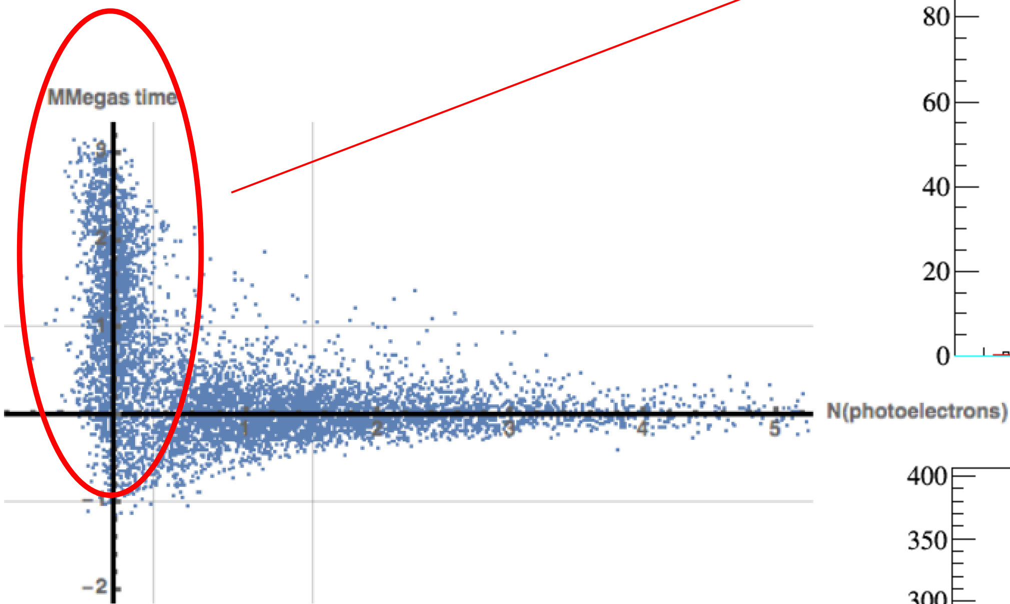


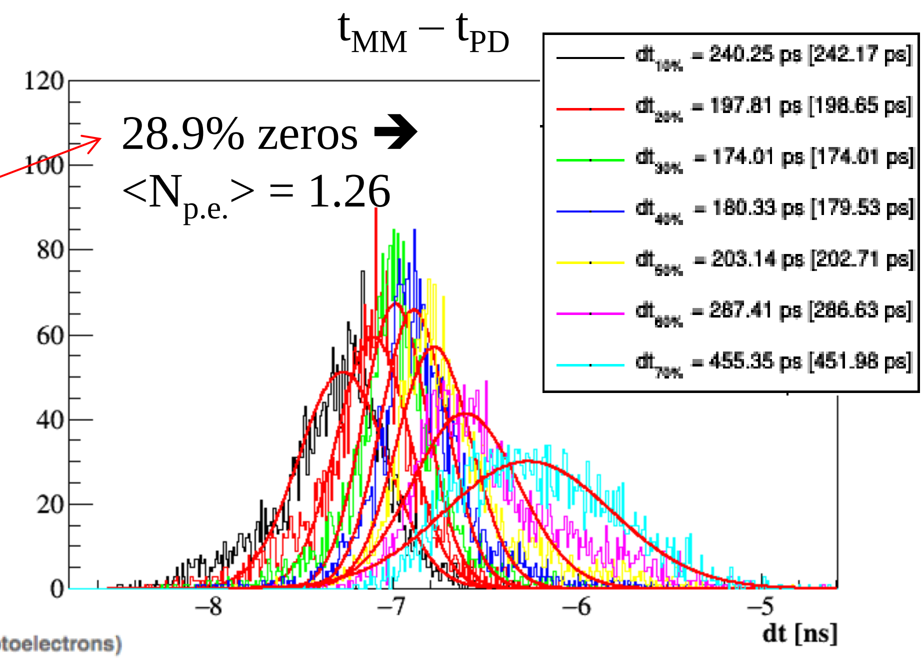


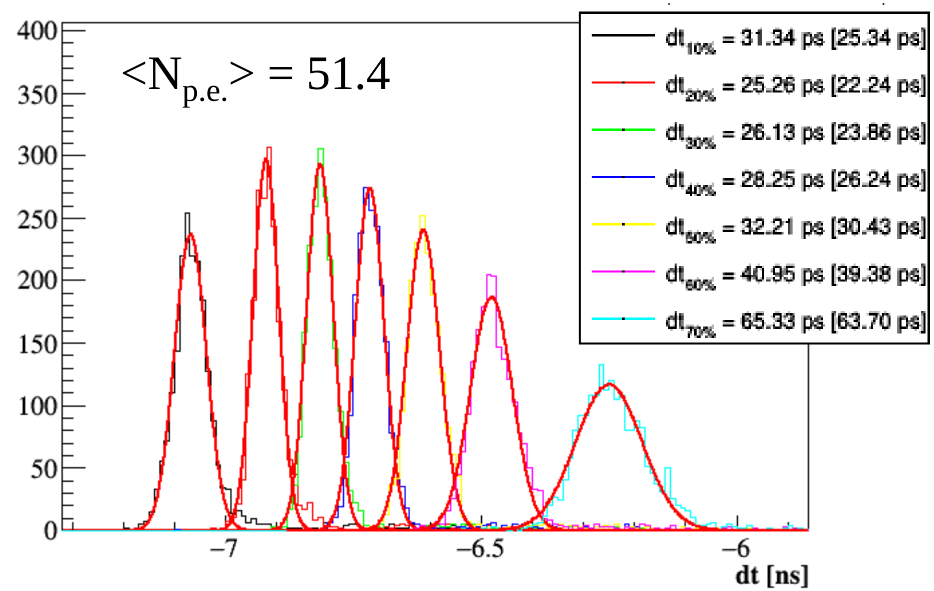


Single-photon determination

$E_{drift} = 10$ kV/cm





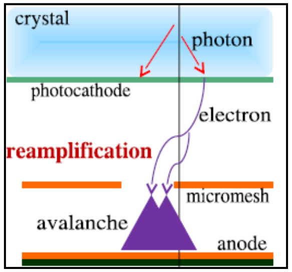


Developing a simple image…

n: 3D electron density

z: direction of the electric field

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



general hydrodynamic equations (field along z)

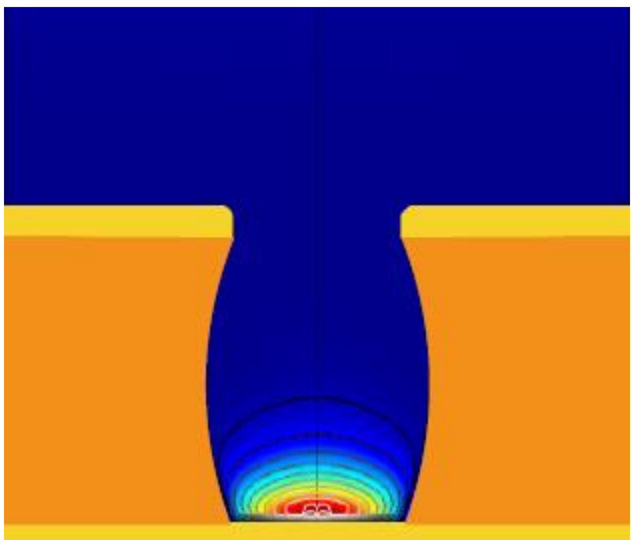
$$\frac{\partial}{\partial t}n = (\alpha - \eta)nv_d + D_T\left(\frac{\partial^2}{\partial x^2}n + \frac{\partial^2}{\partial y^2}n\right) + D_L\frac{\partial^2}{\partial z^2}n + v_d\frac{\partial}{\partial z}n$$

1) full 3D stochastic solution: computationally expensive (use Garfield++ or, even better: Garfield++/microscopic)

2) OR

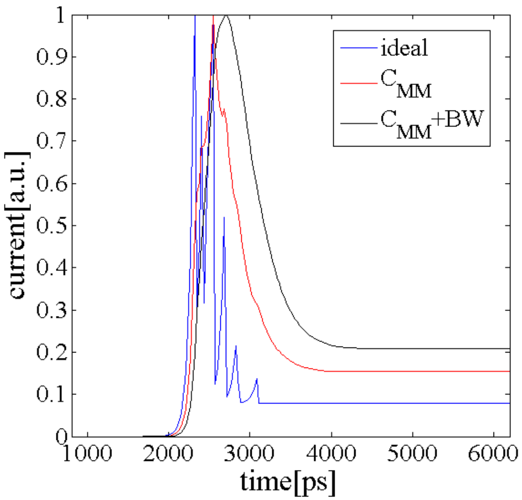
average solution for arbitrary geometries (e.g. COMSOL)

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

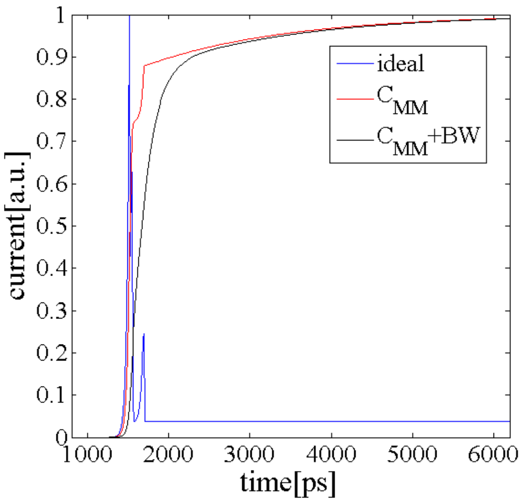


axi-symmetric model of microbulk Micromegas (color code: **electron density** at a given time)

bulk-MM

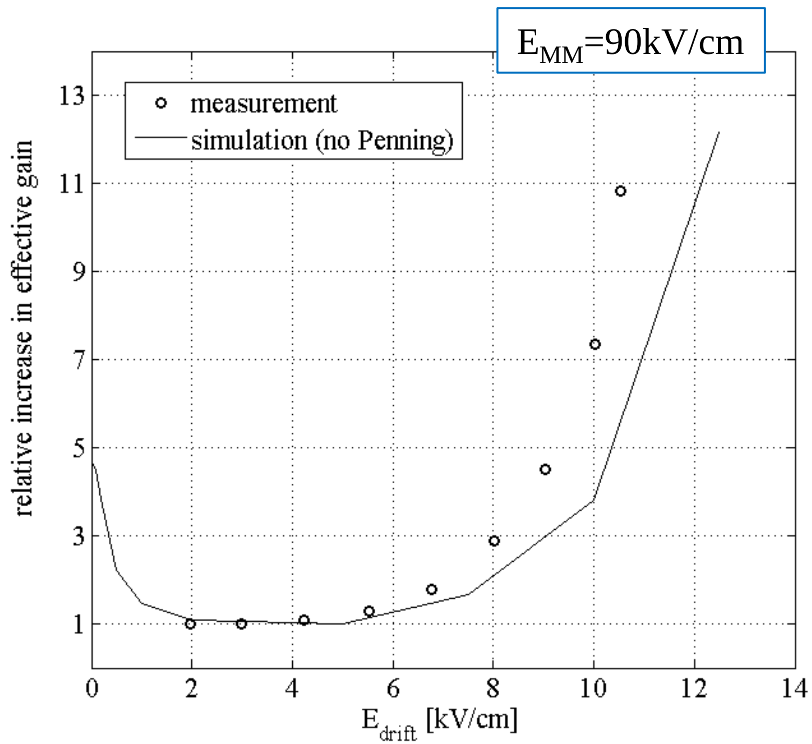


microbulk-MM



(**single-electron** induced signal)

Average solutions from hydro (transmission and gain)

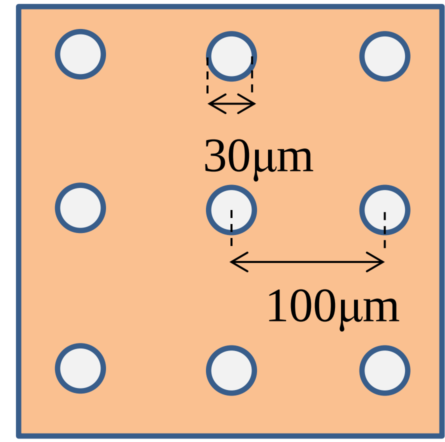


$$m^*(E_{drift}) \approx T \times m_{drift} \times m_{MM}$$

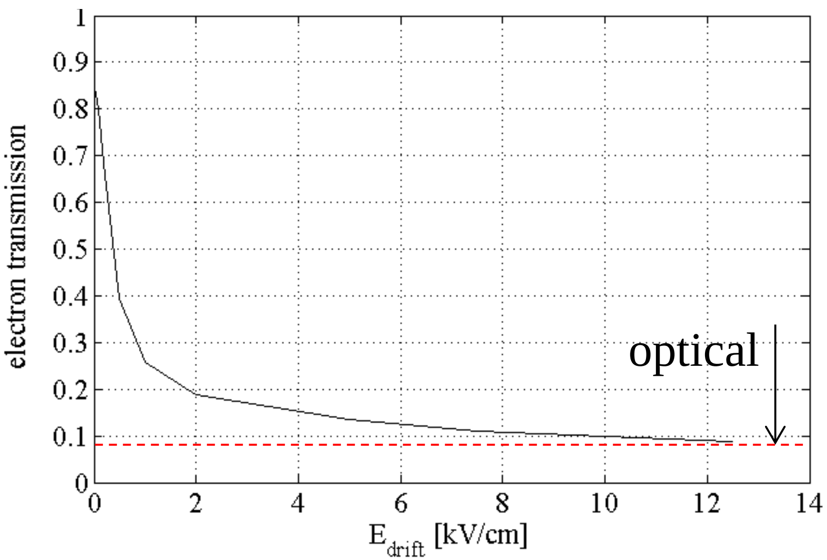
0.07

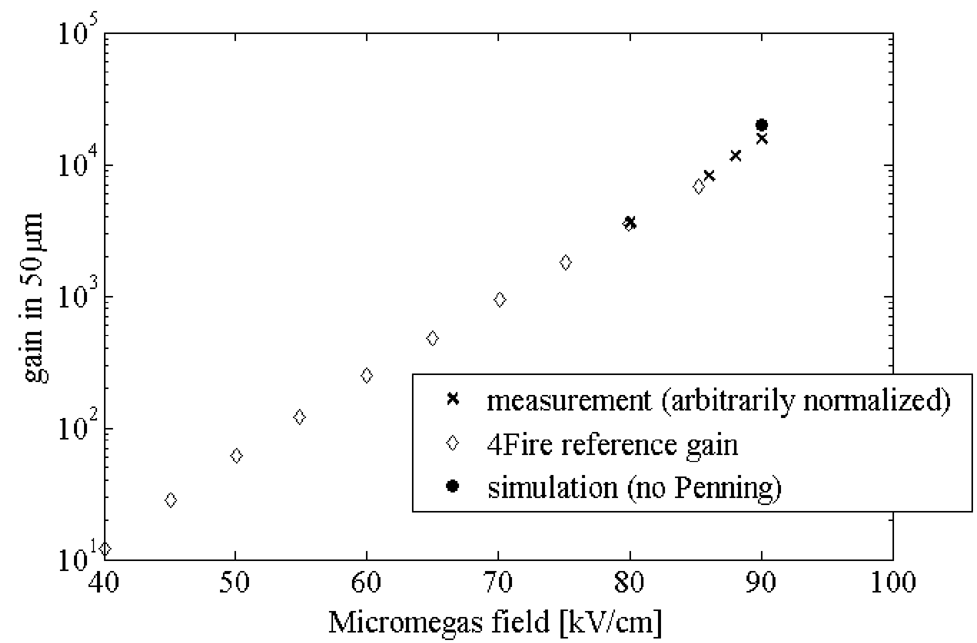
160

20000

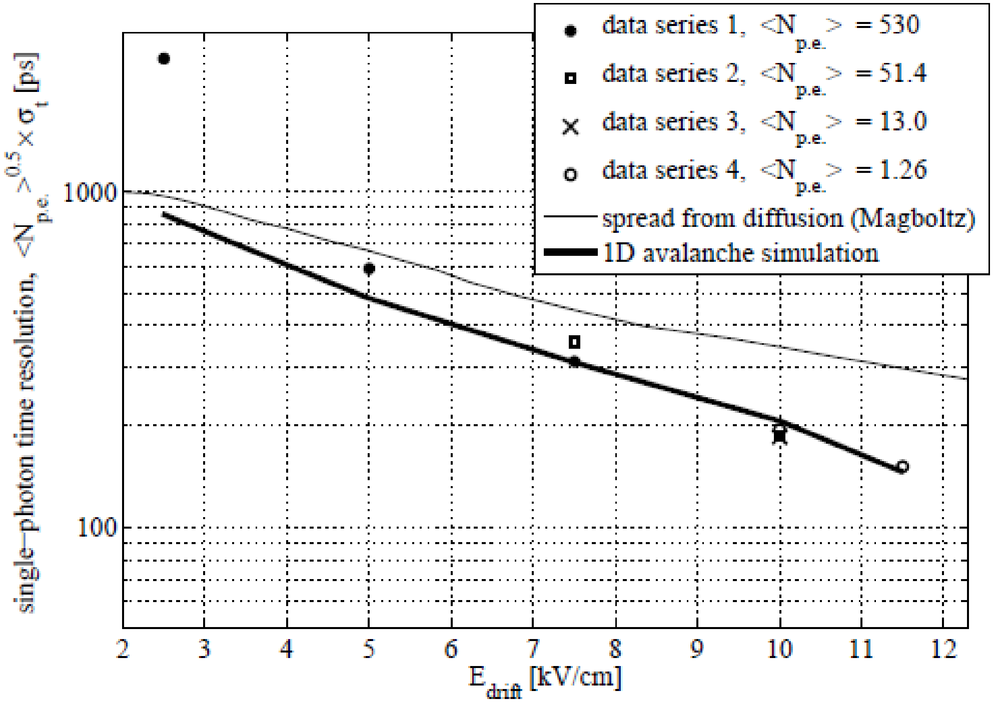


gap: 50 µm



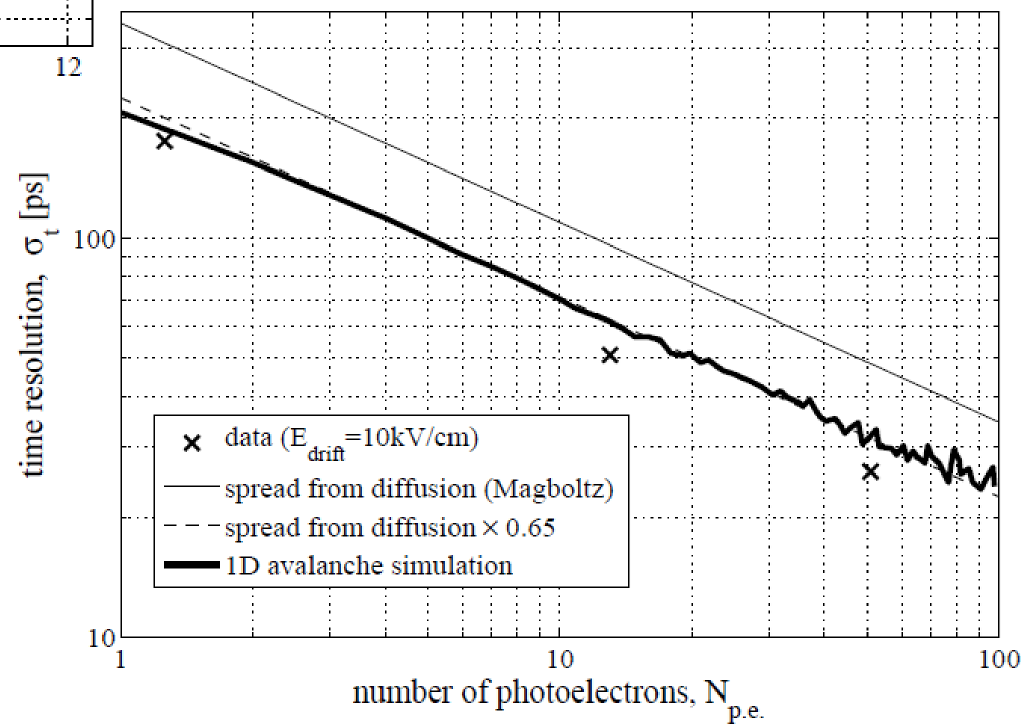


Stochastic solutions from 1D + hydro (time resolution)



Dependence with drift field

Dependence with number of photo-electrons



Truly diffusion-limited timing device!!

(with some minor role of pre-amplification)

PART III

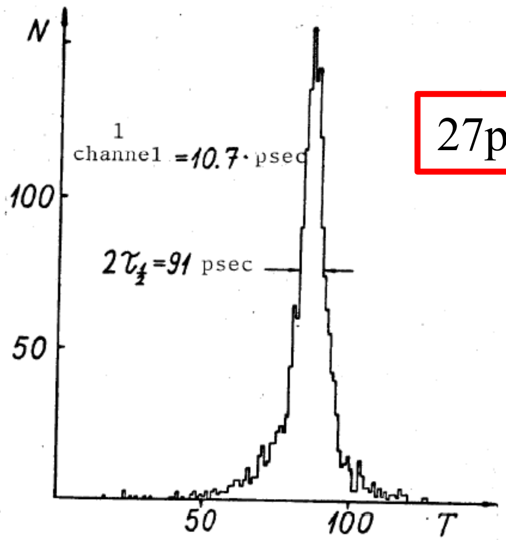
A wild shot

Visiting an old friend…

A PICOSECOND TIME OF FLIGHT SPECTROMETER FOR THE VEPP-2M BASED ON LOCAL-DISCHARGE SPARK COUNTER

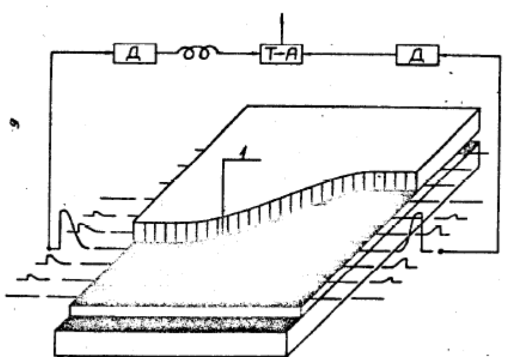
YU.N. PESTOV AND G.V. FEDOTOVICH

1978



27ps

FIGURE 4: Diagram of fluctuations in time delay between operation of two spark counters upon passage of individual cosmic ray particles



0.1 mm gap
12 bar
30cm length!
Streamer mode

+ ?

A 20 ps timing device—A Multigap Resistive Plate Chamber with 24 gas gaps

S. An[a], Y.K. Jo[a], J.S. Kim[a], M.M. Kim[a], D. Hatzifotiadou[b], M.C.S. Williams[b,*], A. Zichichi[c,d], R. Zuyeuski[a]

[a] World Laboratory, Geneva, Switzerland
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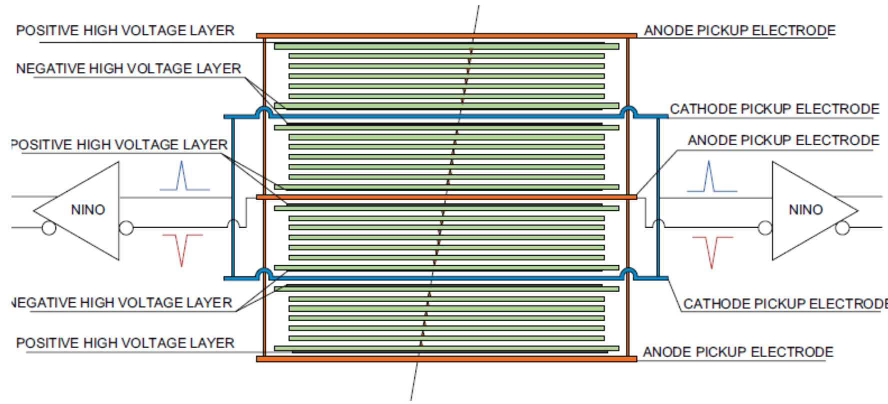
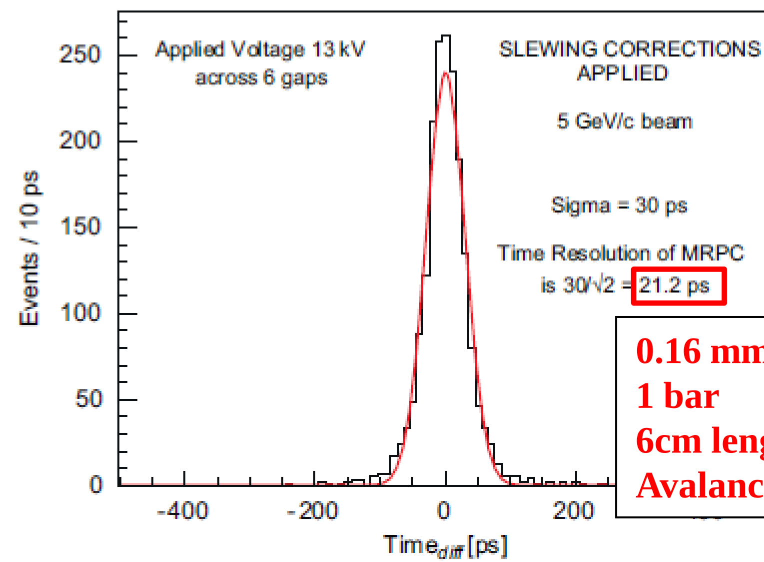
[d] PH Department, CERN, Geneva, Switzerland

2008

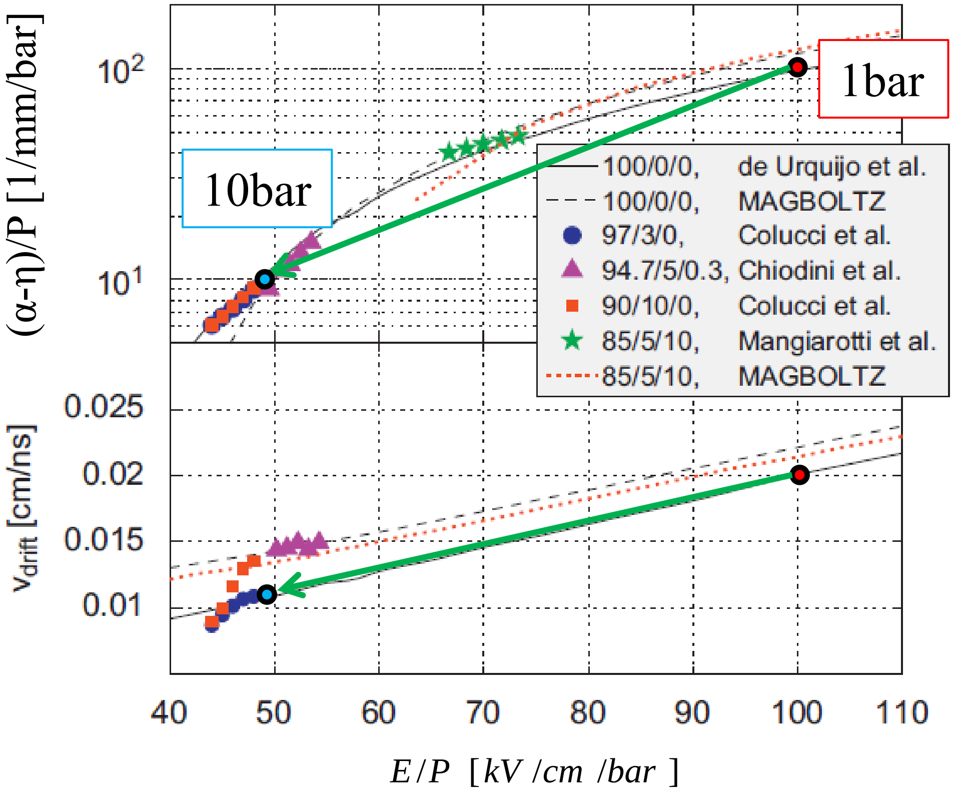




0.16 mm gap
1 bar
6cm length
Avalanche mode

Fig. 7. Time difference between the two MRPCs after correcting for time slewing.

Let's consider some facts



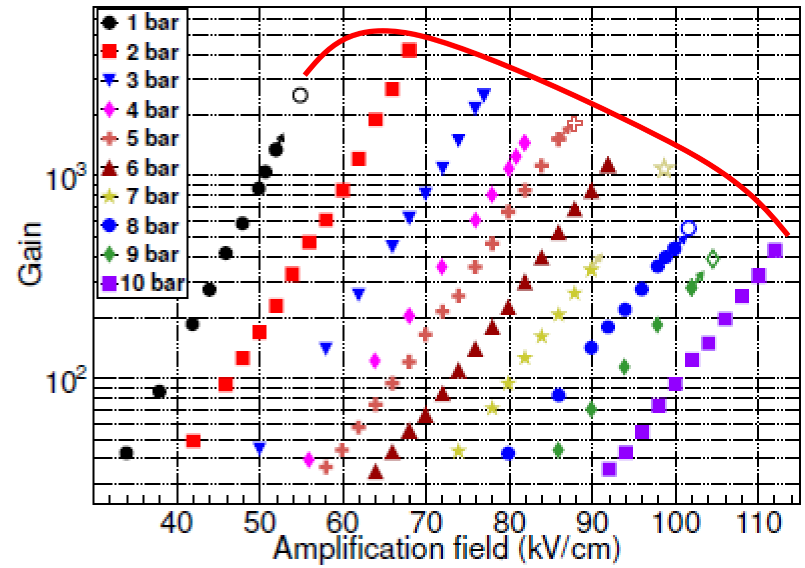
$$\alpha(E,P) \equiv \frac{P}{P_0}\alpha(E/P)$$

$$v_d(E,P) \equiv v_d(E/P)$$

$$\sigma_T(1bar) \sim \frac{K(N_o)}{\sqrt{N_o}(\alpha-\eta)v_{drift}} \sim 1.7\,x\,\sigma_T(10\,bar)$$

HV needed will go up to ±20kV!

Streamer onset also likely to appear earlier!



(Survey from Xe-TMA in 50um gap for illustration)

Combining small gaps and high pressure in multi-gap may yield the desired improvement factor necessary to reach the 10 ps level!

Conclusions

- A diffusion-limited Micromegas-based detector of 200um gap has been studied.
- When coupled to a photo-cathode, its intrinsic resolution was determined to be 200ps/$\sqrt{n_{ph}}$.
- When coupled to a VUV-transparent crystal, this value extrapolates to 20-30ps/mip.
- With the optimization of the gas and reduction of the drift gap, the value per photon could be brought down to 50ps/$\sqrt{n_{ph}}$ that is likely to be the limit of this technology for the foreseeable future.
- Consolidation of this detection technique requires of several steps (and a long roadmap…):
  - Validation with minimum ionizing particles.
  - Evaluation of photo-cathode ageing for large exposures.
  - Evaluation of the stability of the Micromegas detector at the flux of interest.

- A realistic concept for the 'Serpentine RPC' was introduced for the first time. Simulations show that signals in a compensated RPC ($C_m/C_0 = L_m/L_0$) can be efficiently routed through detectors whose electrodes are arranged in a delay-line configuration, and might be used for covering large areas under low multiplicities in an efficient way.

- We revisited the high pressure/narrow gap for bringing the RPC resolution below the 10ps scale. There is no clear-cut direction… but there is also no clear show-stopper!!.

With the essential collaboration of

Sub-100 picosecond charged particle
timing with MicroMegas
a proof of concept

representing:

L. Ropelewski, E. Oliveri, F. Resnati, Sebastian White, R. Veenhof (CERN)
I.Giomataris, T. Papaevangelu, T. Gustavsson, E. Delagnes, E. Ferrer, A. Peyaud (CEA/Saclay)
D. Gonzalez-Diaz(Zaragoza)
G. Fanourakis (Demokritos)
K. McDonald, C. Lu & Sebastian White (Princeton)

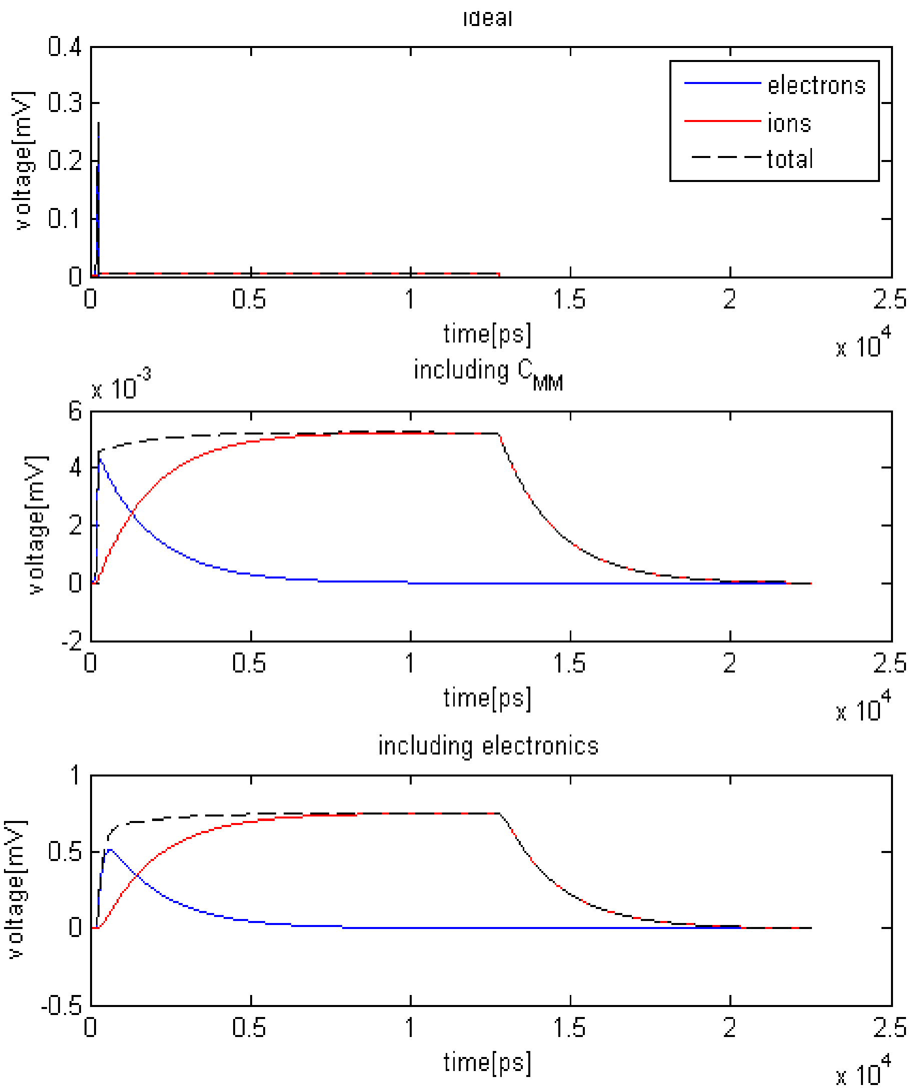
for RD51 common fund project: "Fast Timing for High Rate Environments: a MicroMegas Solution"- awarded 3/2015

Rogelio Palomo (Univ. Sevilla, ETSI)
Joaquín B. González (ETSI-CERN)

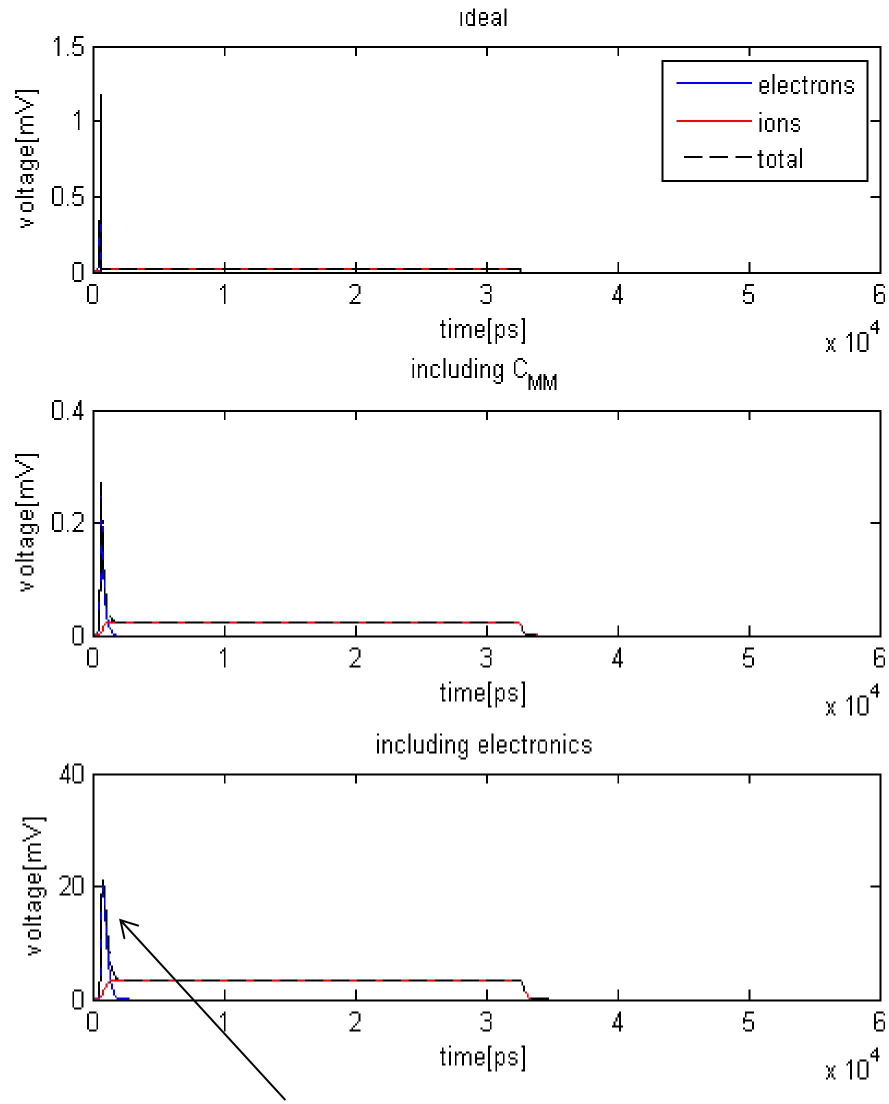
Appendix

average voltage signals created by single electrons entering the MM

Microbulk (~standard conditions)

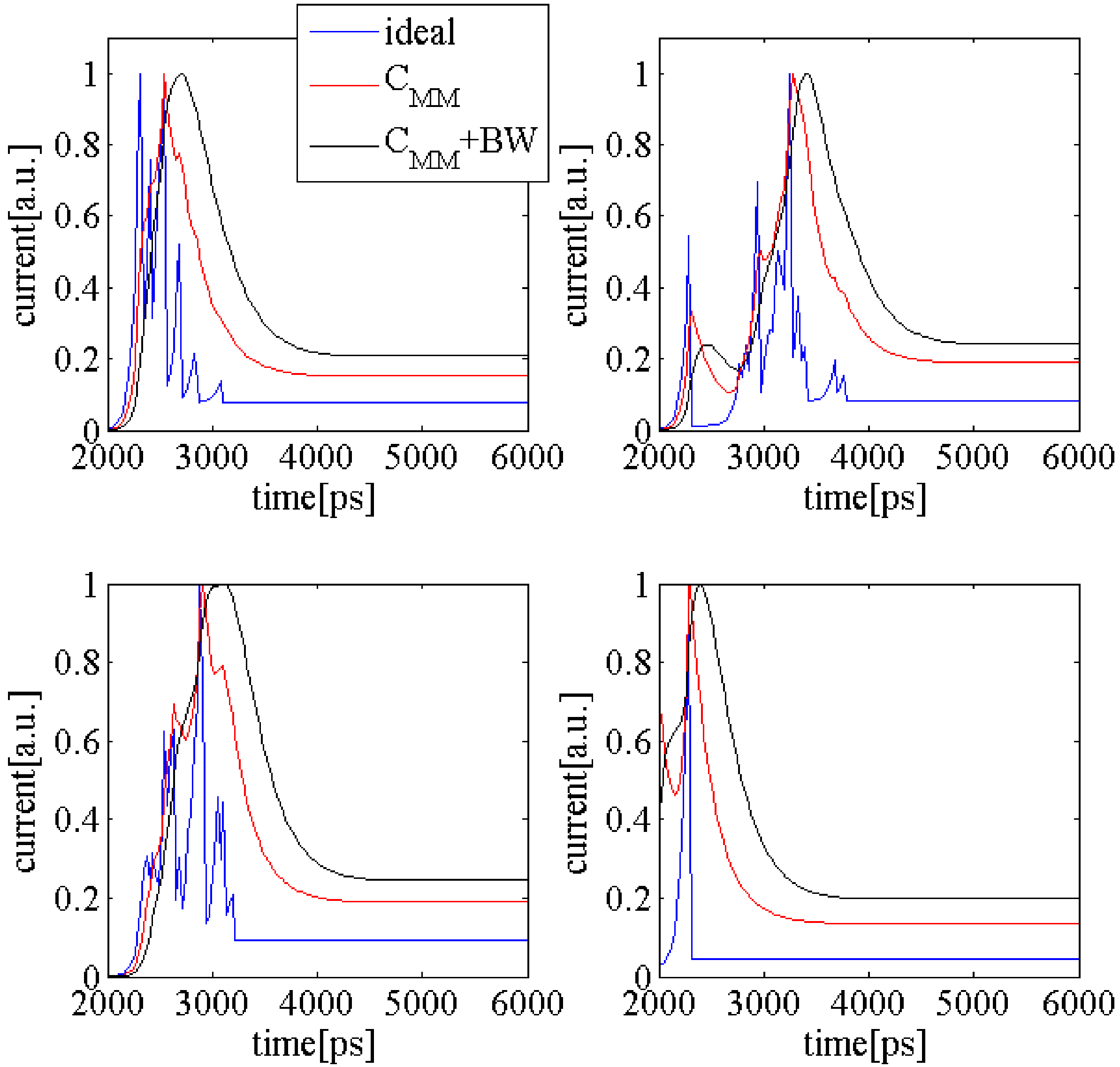


Bulk (~standard conditions)



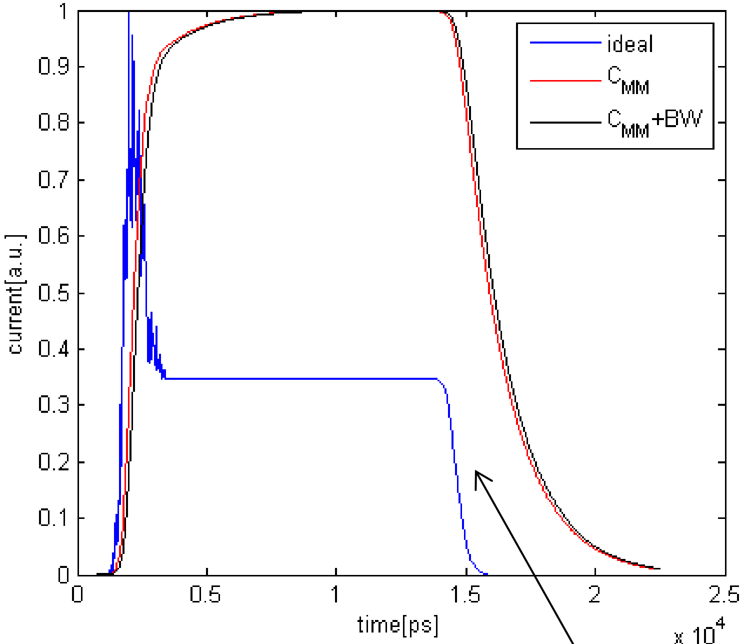
not very far from experimental data!

typical signals in the bulk detector (random selection)

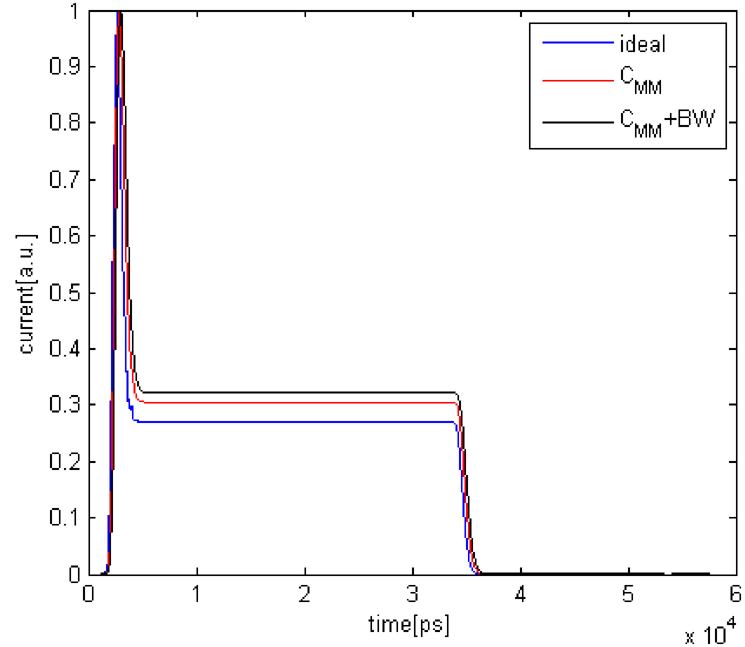


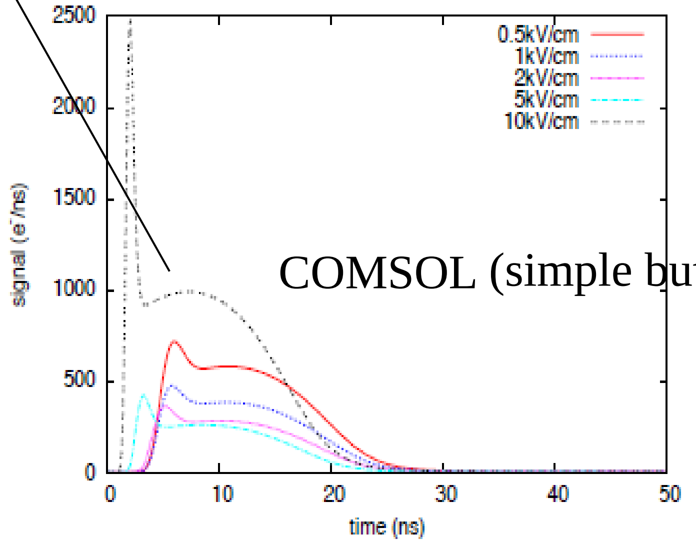
average over 1000 primary photo-electrons (E_{drift}=10kV/cm)

Microbulk



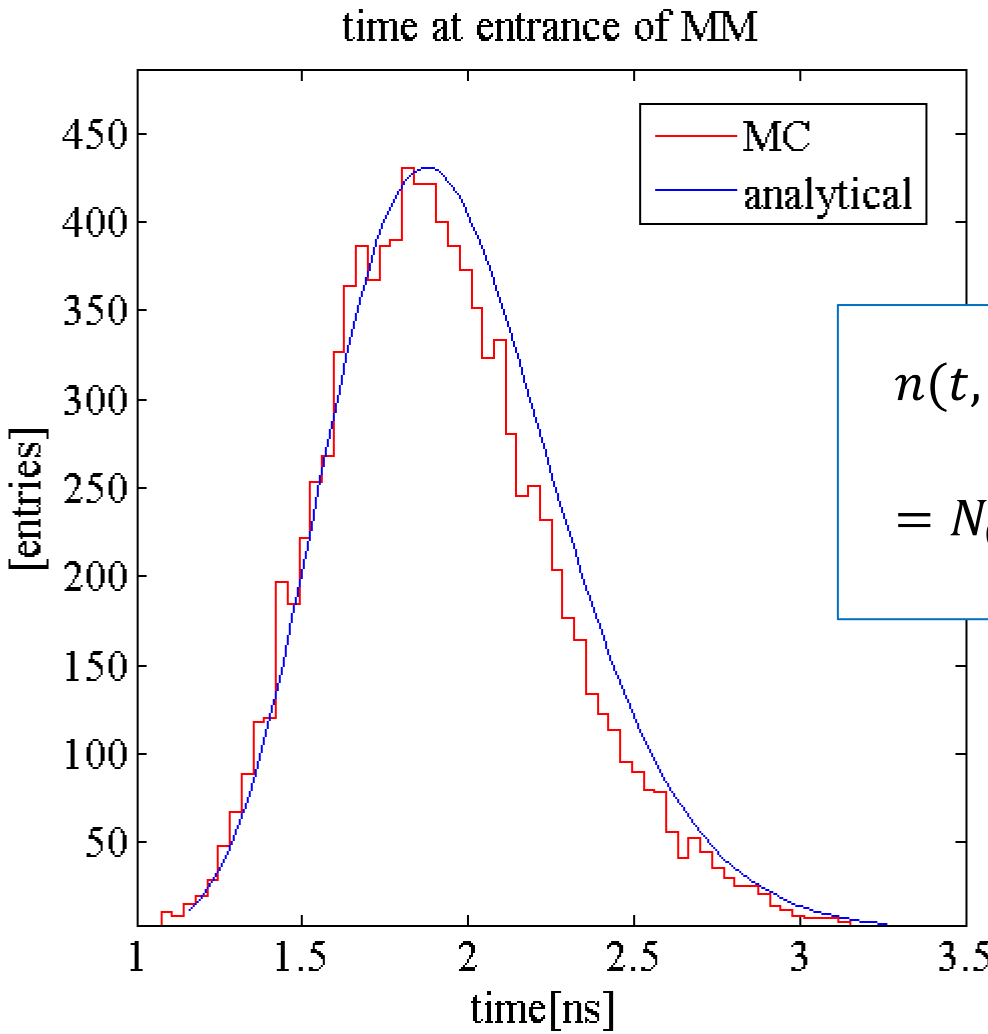
Bulk





COMSOL (simple but nice consistency check!)

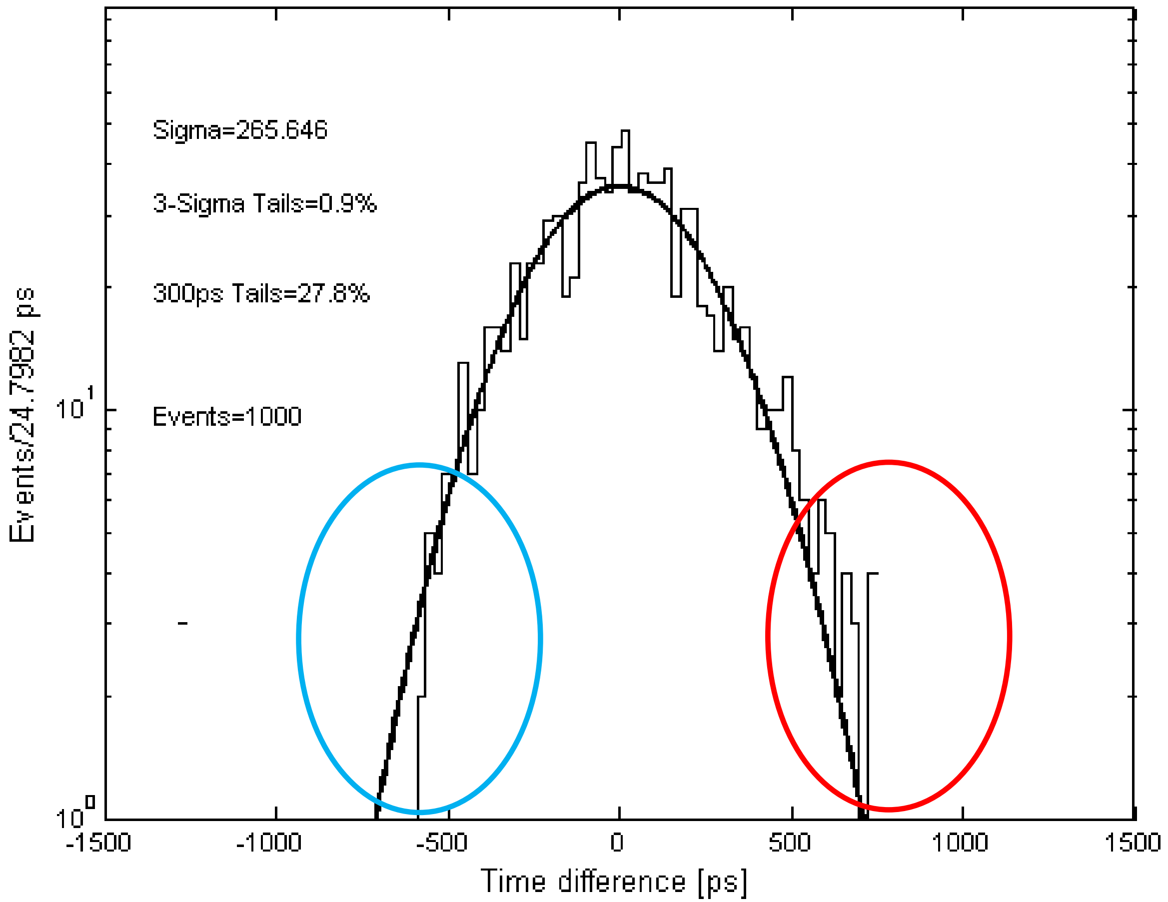
important MC technical information



$$n(t, z = z_{mesh}) \equiv \frac{dN}{dz}(t, z = z_{mesh})$$
$$= N_0 \frac{1}{\sqrt{4\pi D_L t}} e^{(\alpha-\eta)v_d t} e^{-\left(\frac{z_{mesh}-v_d t}{4 D_L t}\right)^2}$$

The arrival times of the electrons at the MM (after a random walk in the drift) MC can be computed analytically. This determines the ‘physical jitter’.
Note: even in absence of multiplication it is not a Gaussian although its rms approaches $D_L^*/v_d \sqrt{gap}$!.

analysis example: typical fitting routine

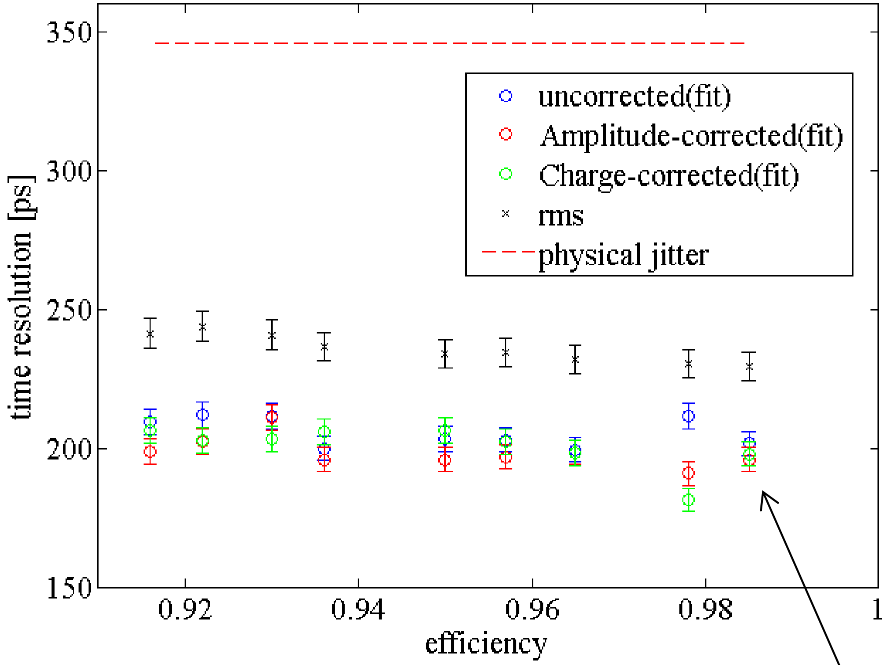


some small 1-2% 3-sigma tails always present

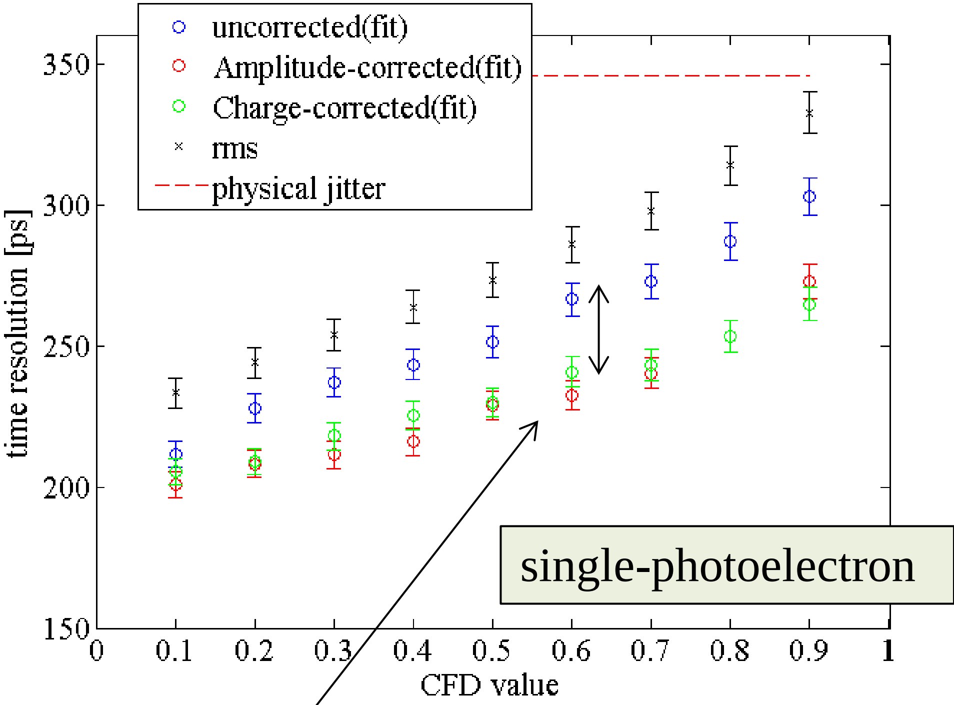
response for typical conditions (**bulk**)

(some technicalities related to analysis)

fixed threshold



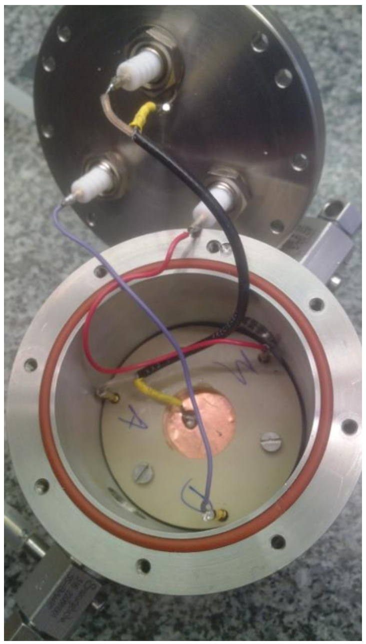
constant fraction



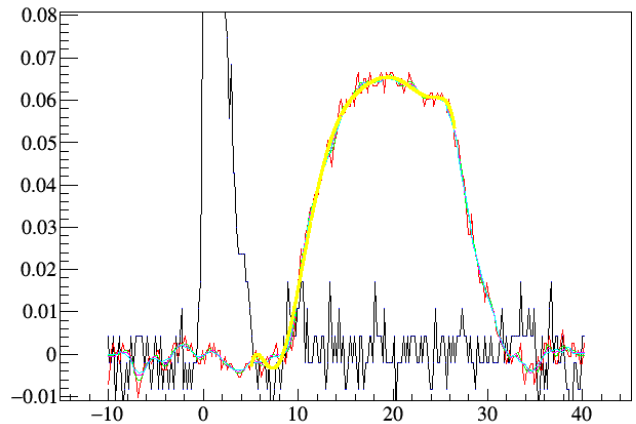
CFD introduces some correlation with amplitude

Response to single p.e.

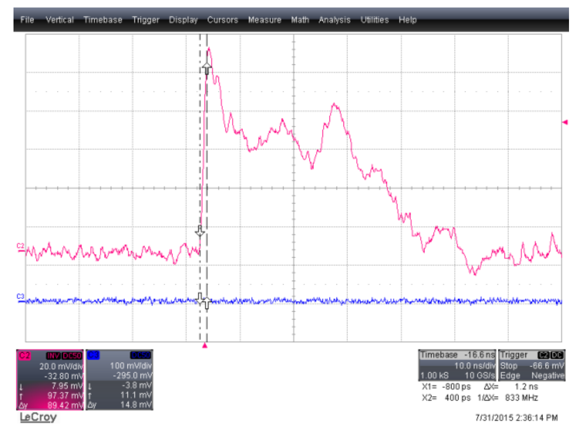
- Strong attenuation, so that events with no pulse appear
- UV light from continuous source (candle)

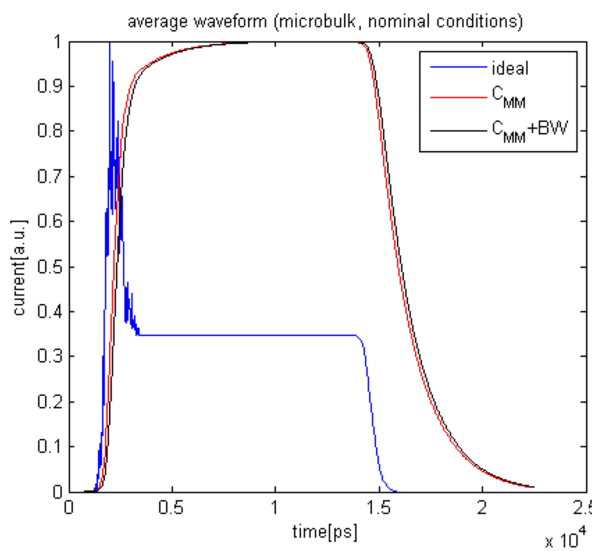


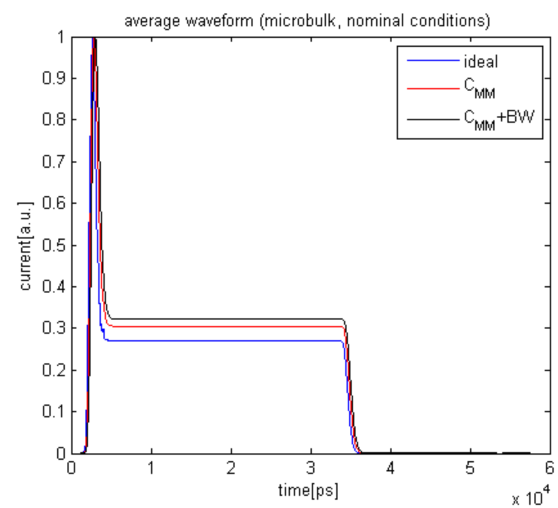
Microbulk



Bulk 128

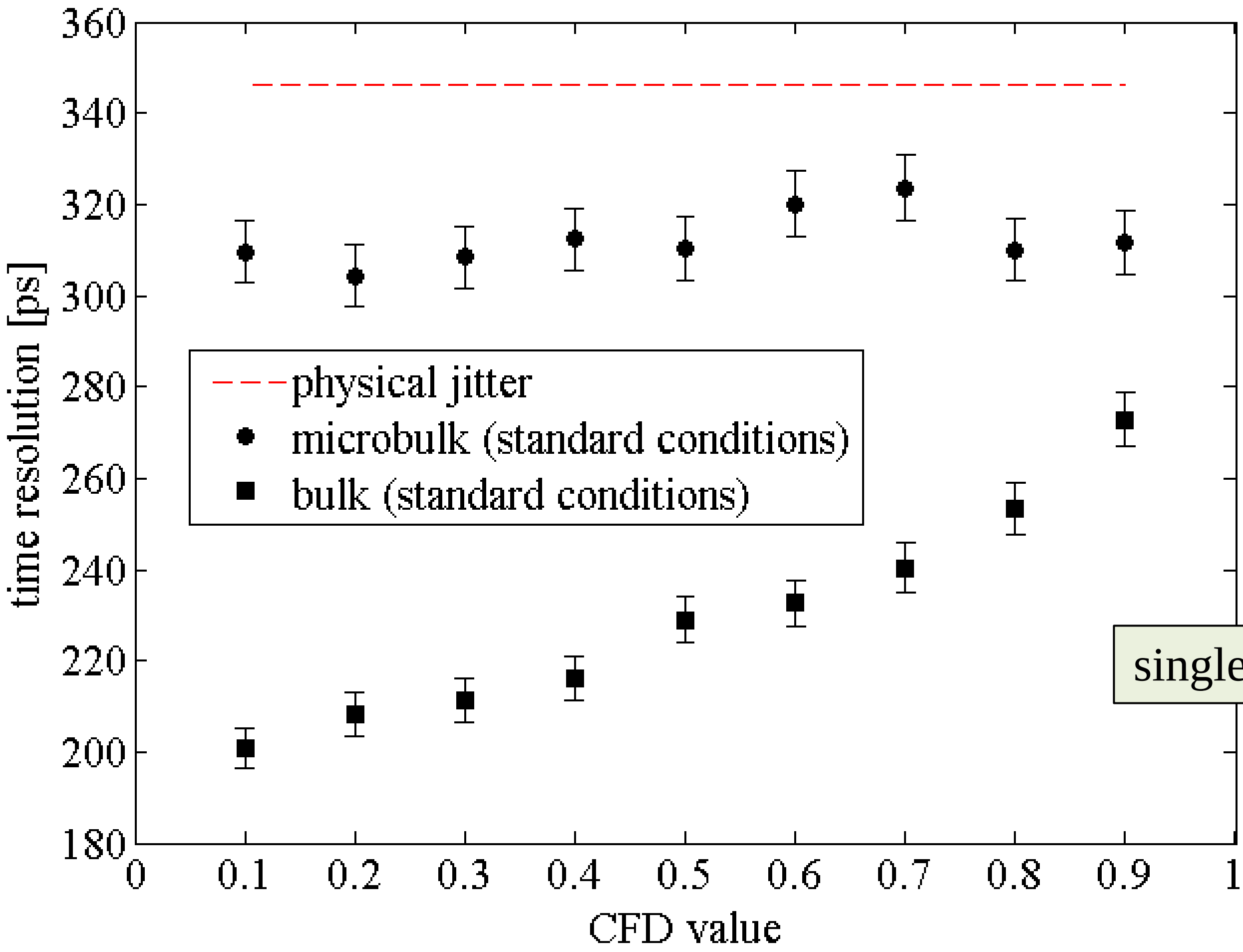






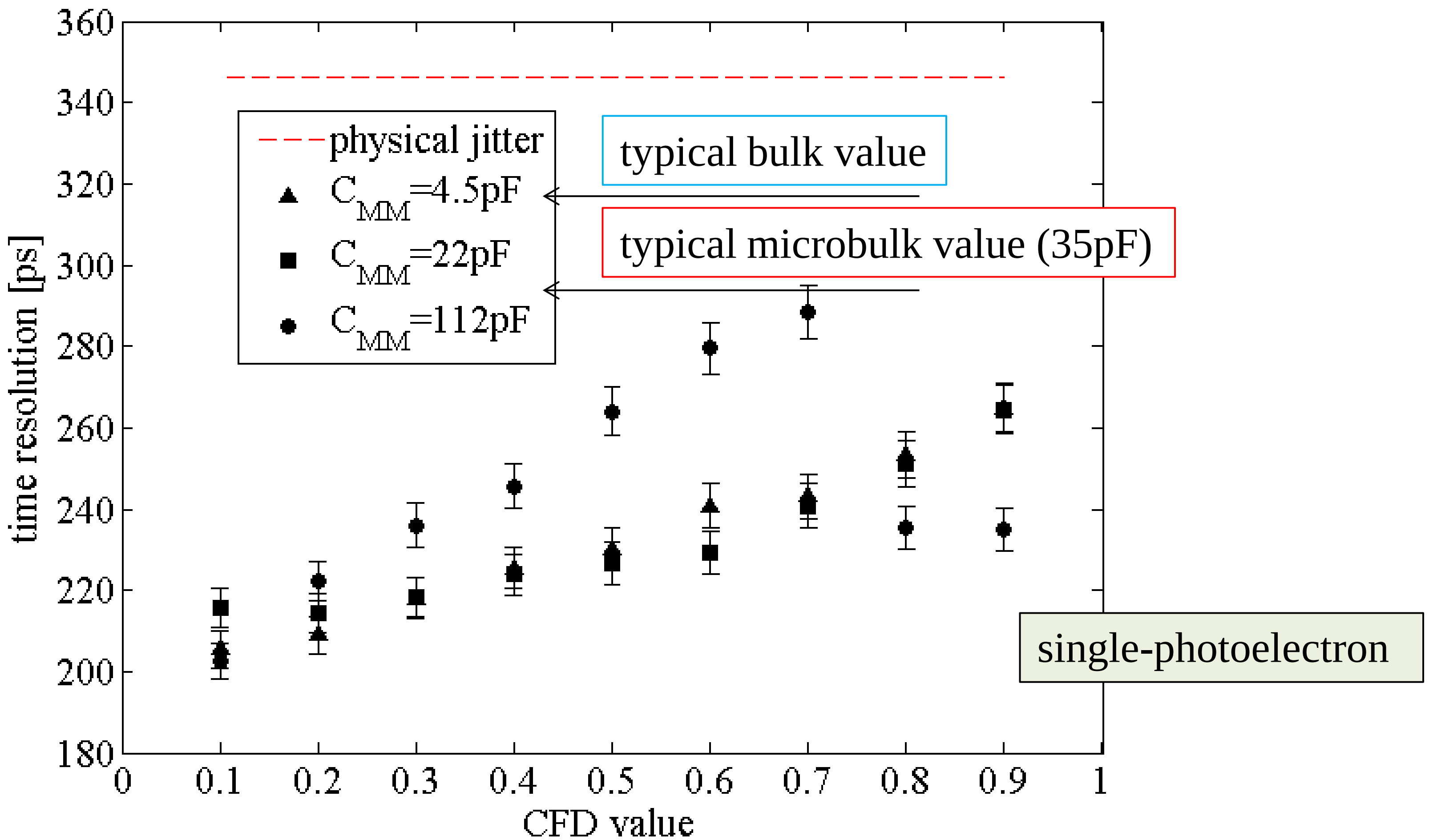
Signal modeling by D. Gonzalez Diaz & F. Resnati

influence of the detector technology



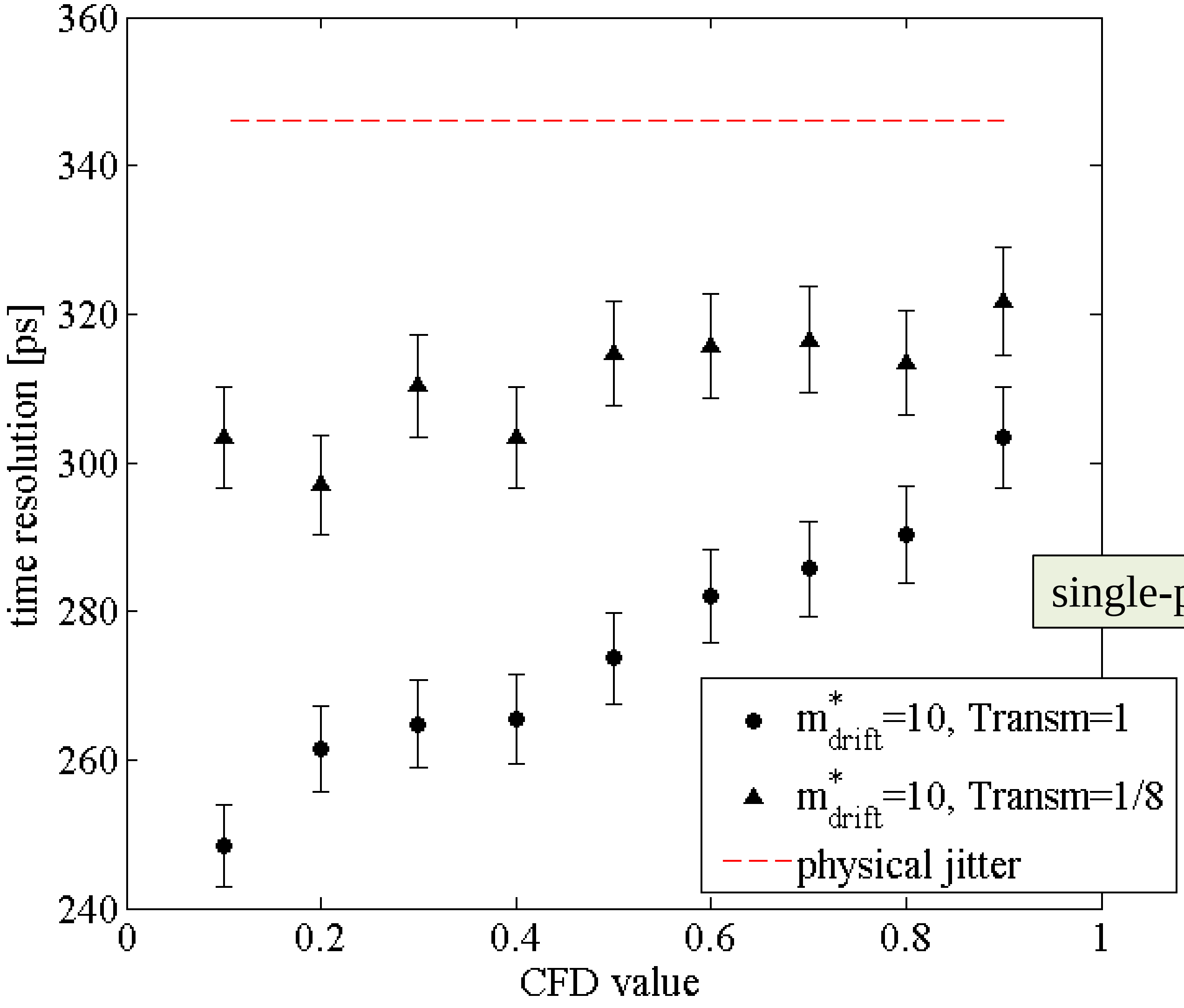
single-photoelectron

influence of the detector capacitance (**bulk**)



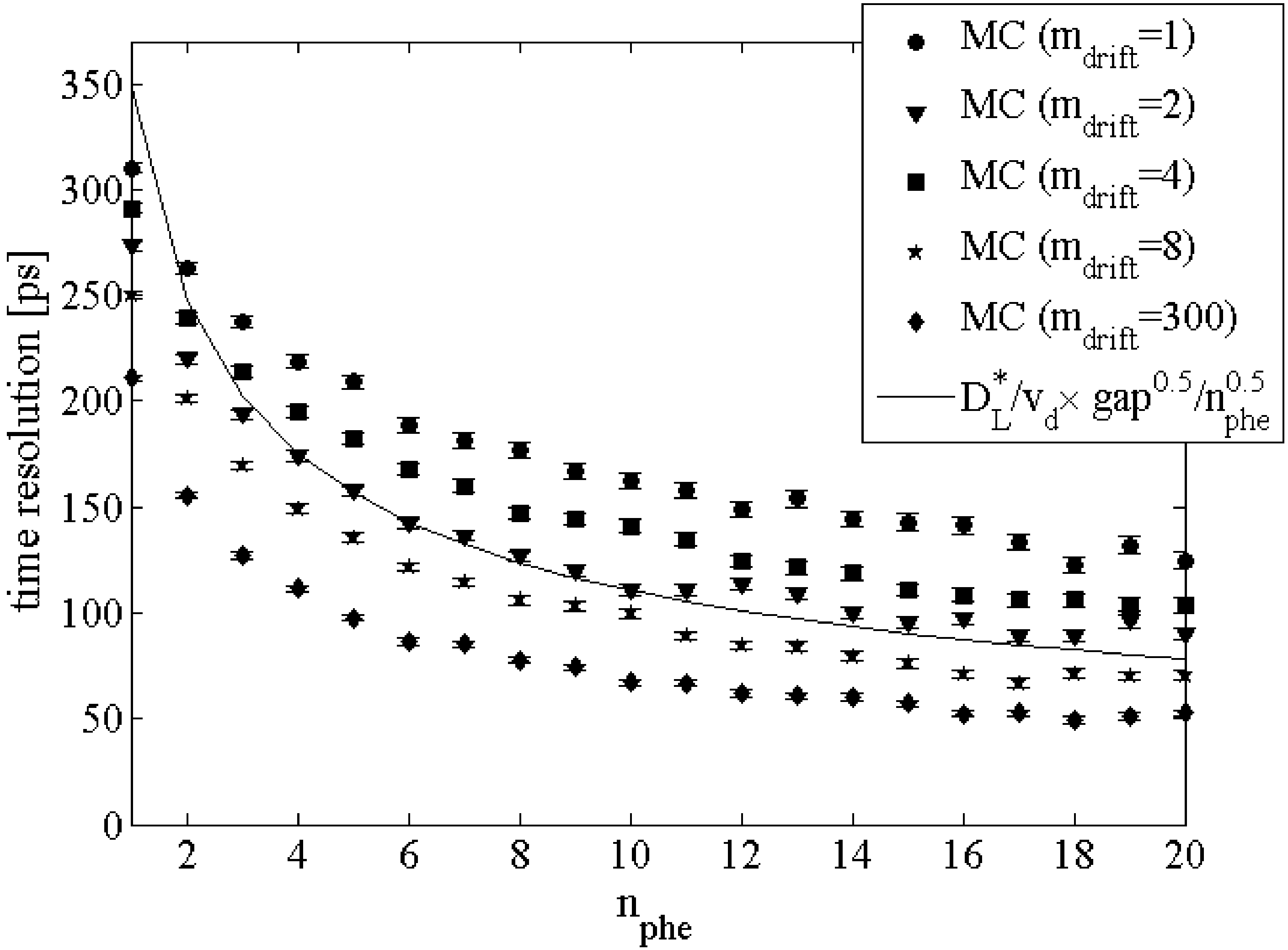
Note: signal integrity does affect timing directly, but S/N goes down by about 1/10!!

influence of the mesh transmission



single-photoelectron

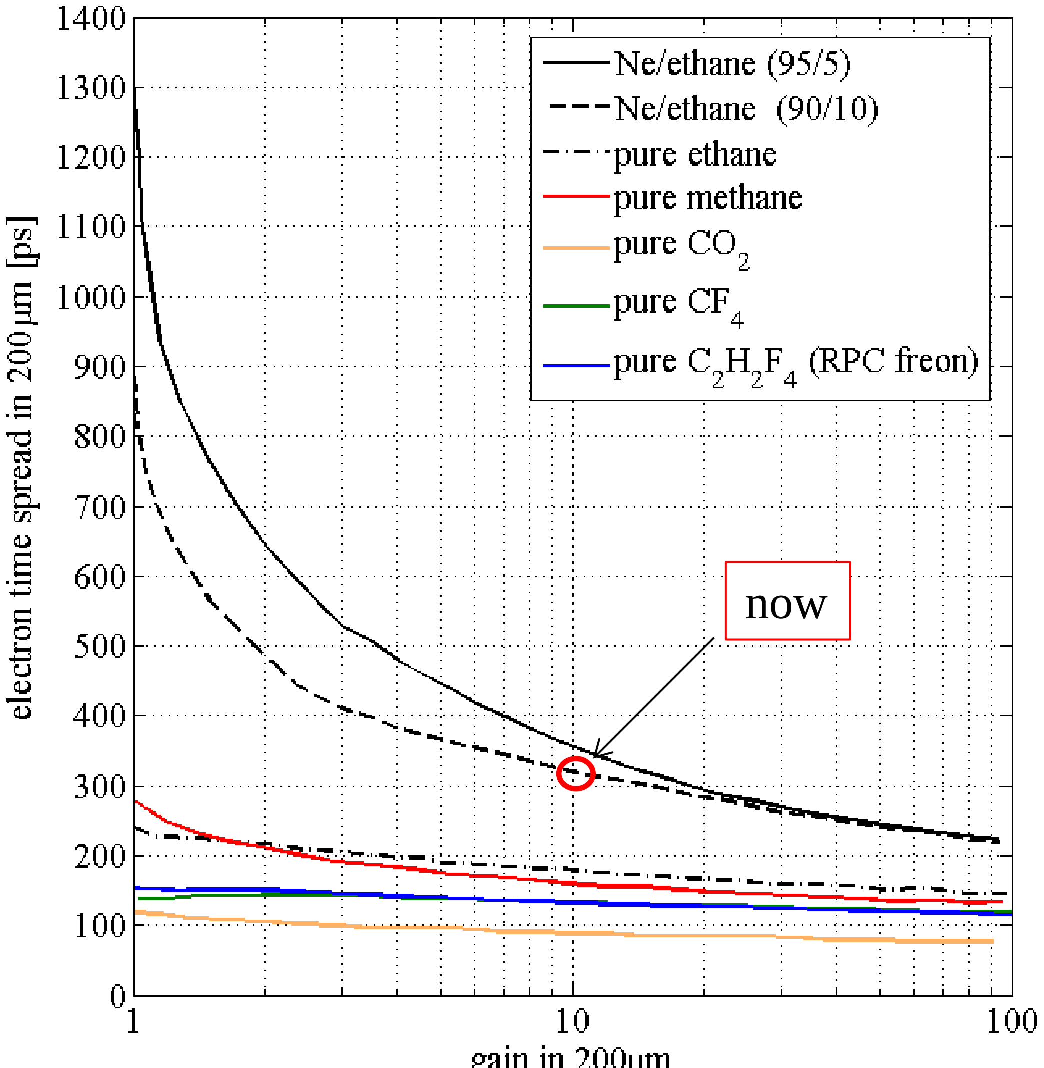
time resolution vs pre-amplification (at fixed drift field)



T=0.8

Optimum gas mixtures in timing Micromegas?

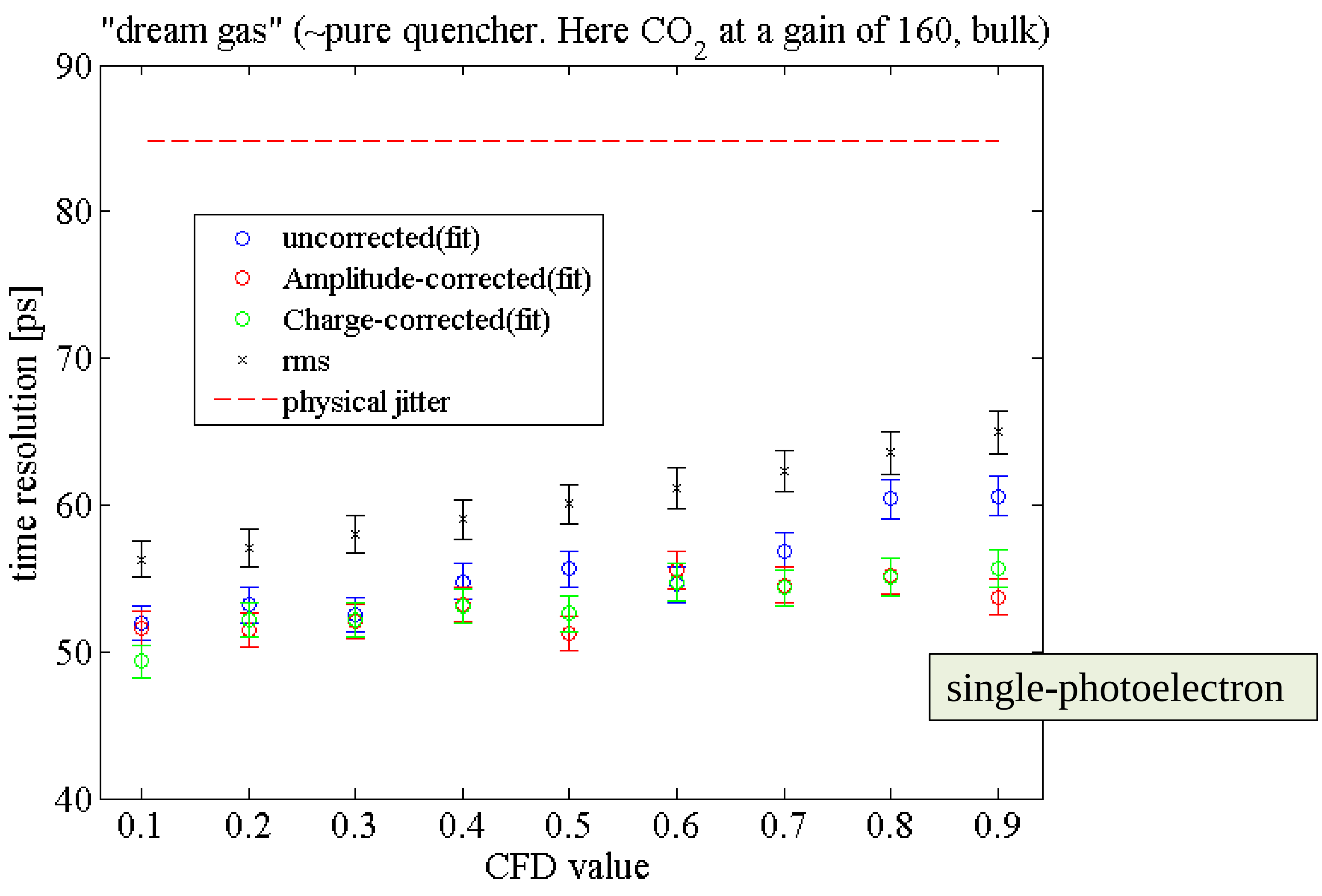
Look for the minimum time spread ('fastest mixture') at any given gain



Simulations from Rob Veenhof ($C_2H_2F_4$ from data)

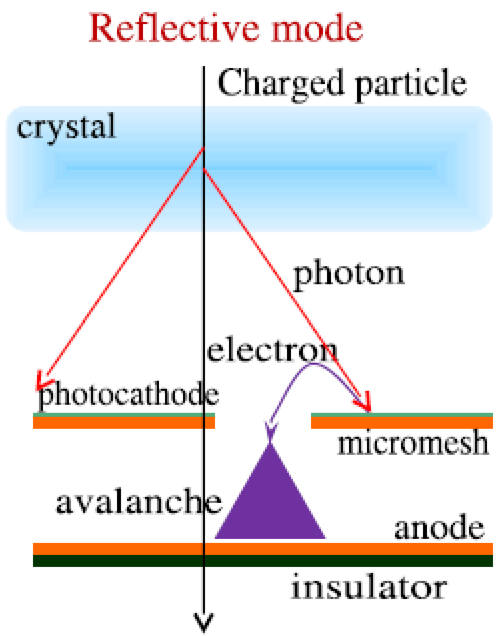
Notes:

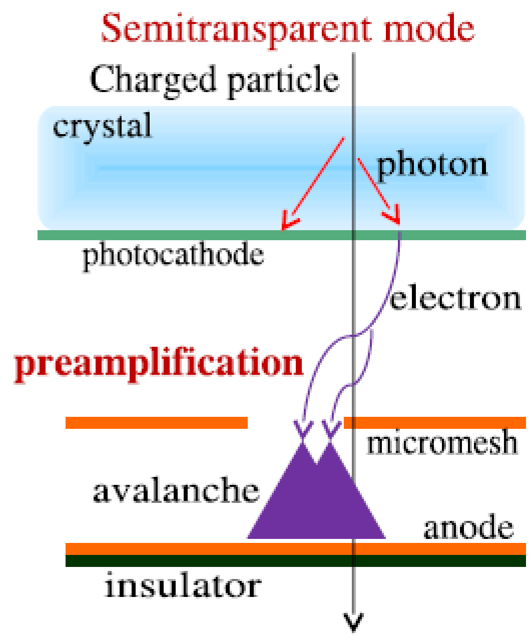
- Working fields in the MM for pure quenchers need to be about x2 higher. May limit the gain in case of defects.
- Drift fields for pure quenchers need to be about x3 higher.
- Dissociative attachment for CO_2 and freons expected to be compensated by gain. Needs to be verified.

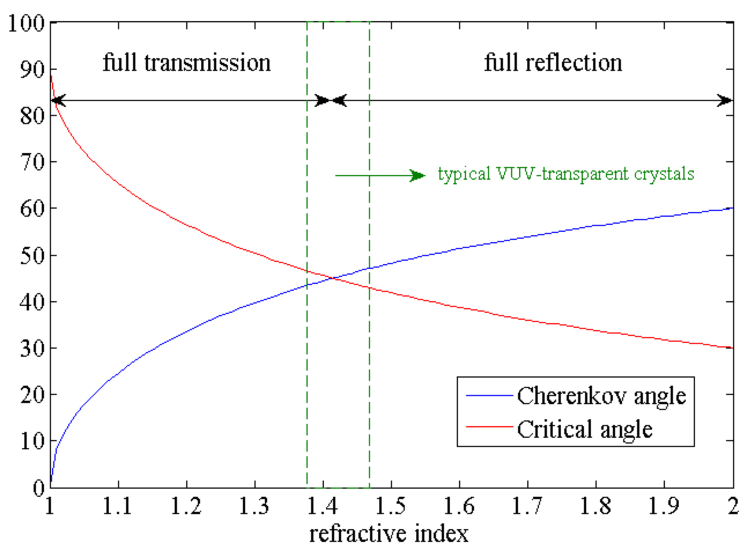


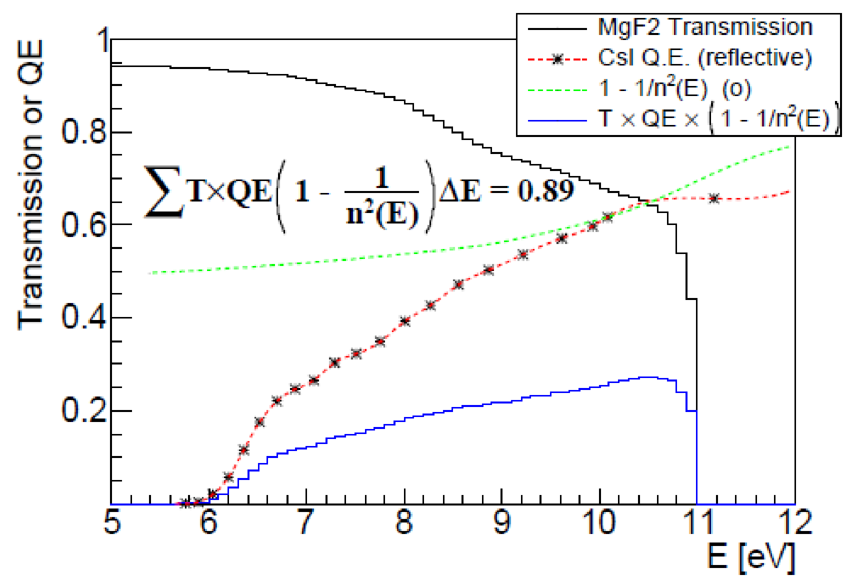
"dream gas" (~pure quencher. Here CO2 at a gain of 160, bulk)
time resolution [ps]
90
80
70
60
50
40
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
CFD value
uncorrected(fit)
Amplitude-corrected(fit)
Charge-corrected(fit)
rms
physical jitter
single-photoelectron

Micromegas in other modes





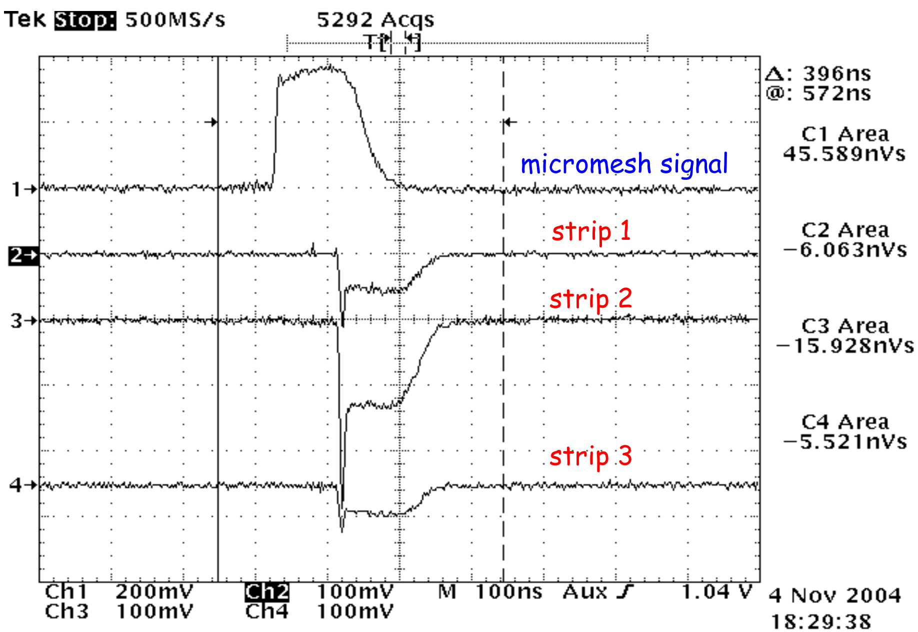


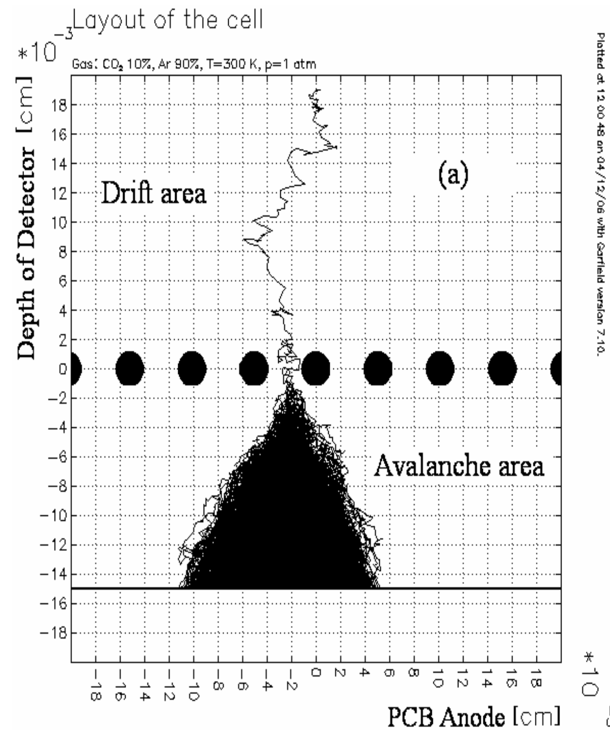


Micromegas time scales

The electron multiplication takes place in high E field (> 20 kV/cm) between the anode (strips, pads) and the mesh in one stage

small amplification gap (50-150 μm)
- fast signals (~ 1 ns)
- short recovery time (~50 ns)
- high rate capabilities (> MHz/cm^2)
- high gain (up to 10^5 or more)



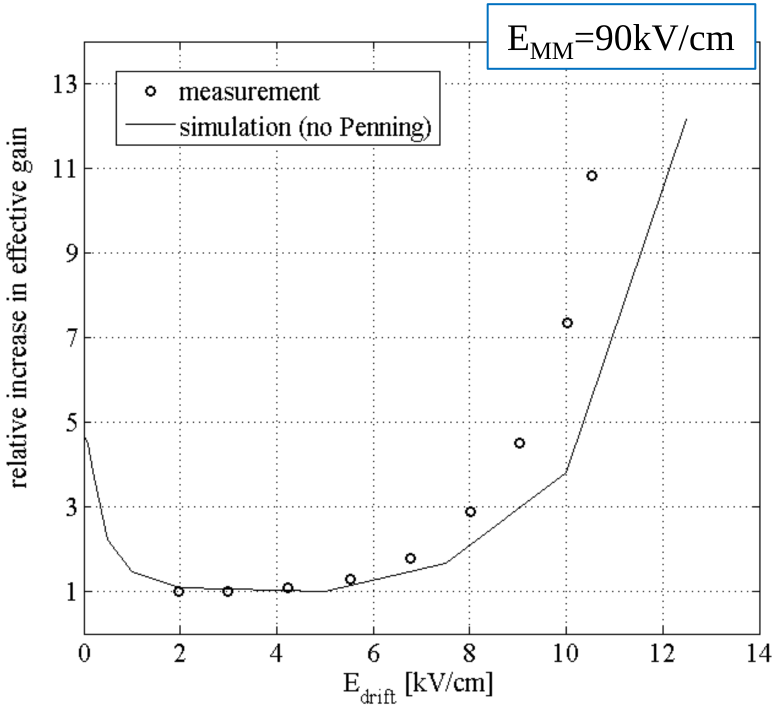


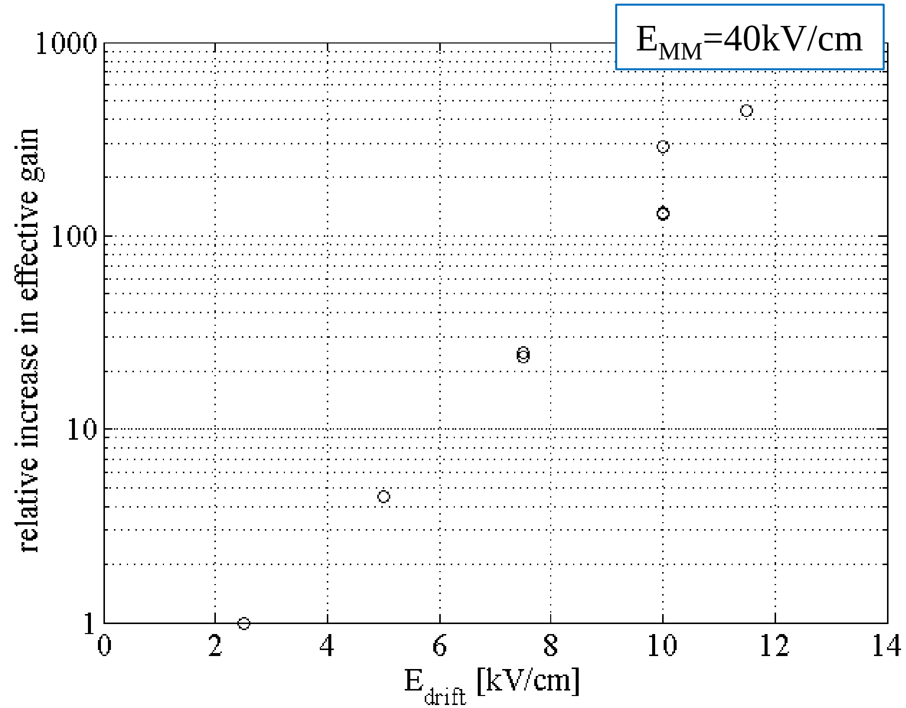
A GARFIELD simulation of a Micromegas avalanche (Lanzhou university)

Time response is limited from the continuous ionization on the drift gap

note 2 (what about bulk?)

(no simulations yet)





$m^{*}(E_{drift}=10kV/cm) \approx T \times m_{drift} \times m_{MM}$

0.07 160 20000

$m^{*}(E_{drift}=10kV/cm) \approx T \times m_{drift} \times m_{MM}$

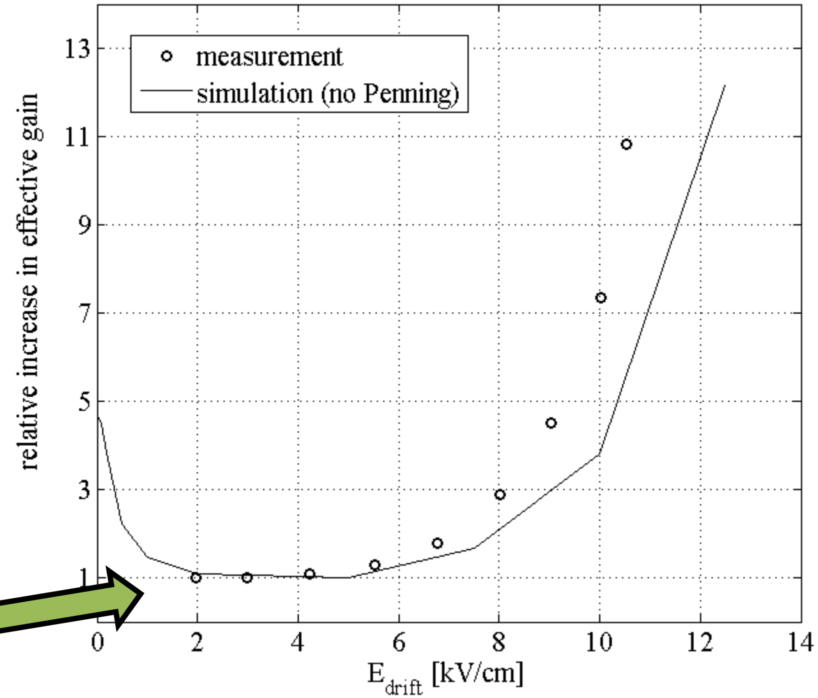
0.8? 160 **10^3 ?**

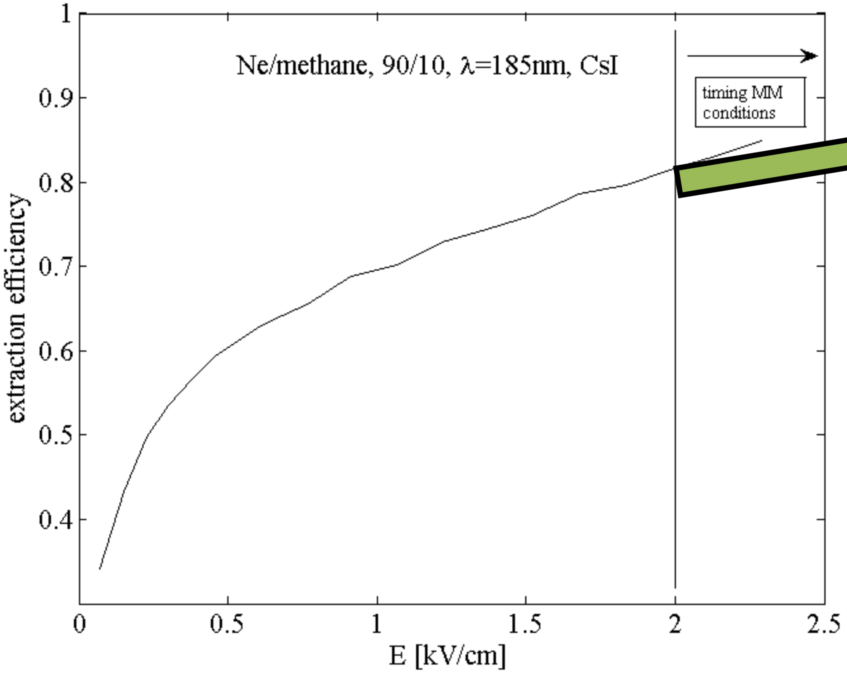
assume these values in the following (if nothing else is said: E_{drift} = 10kV/cm)

note 1

$$m^* = T(E_{drift}, E_{amp}) \times m_{drift}(E_{drift}) \times m_{MM}(E_{MM}) \times \varepsilon_{ext}(E_{drift}) \quad ?$$

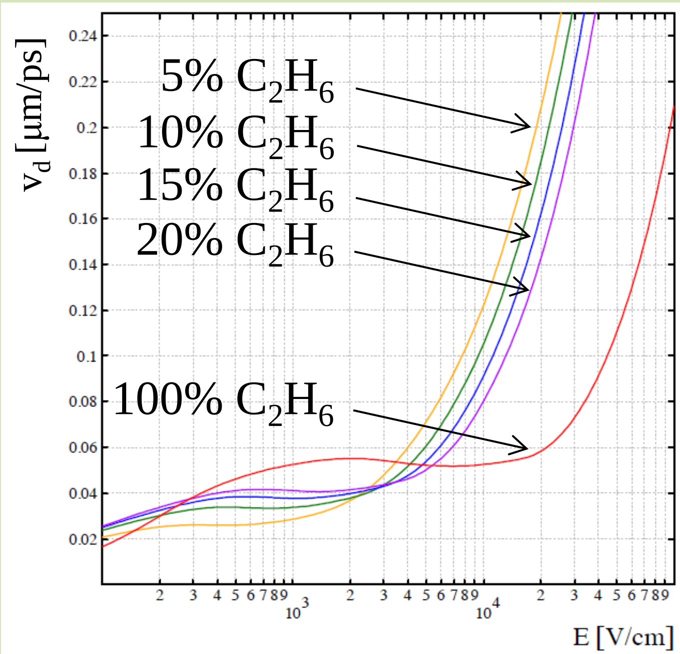
Measurements of photoelectron extraction efficiency from CsI mixtures of Ne with CH_4, CF_4, CO_2, N_2
J. Escada et al., JINST, 4(2009)P11025

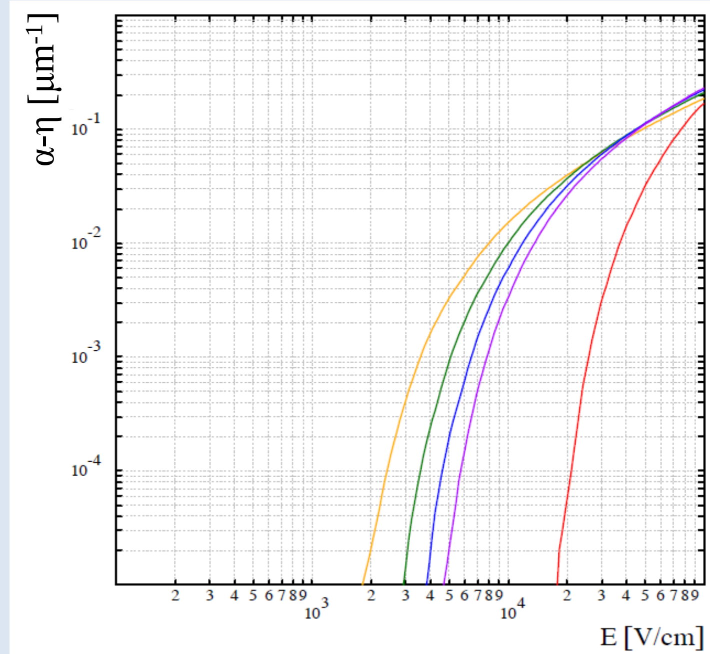


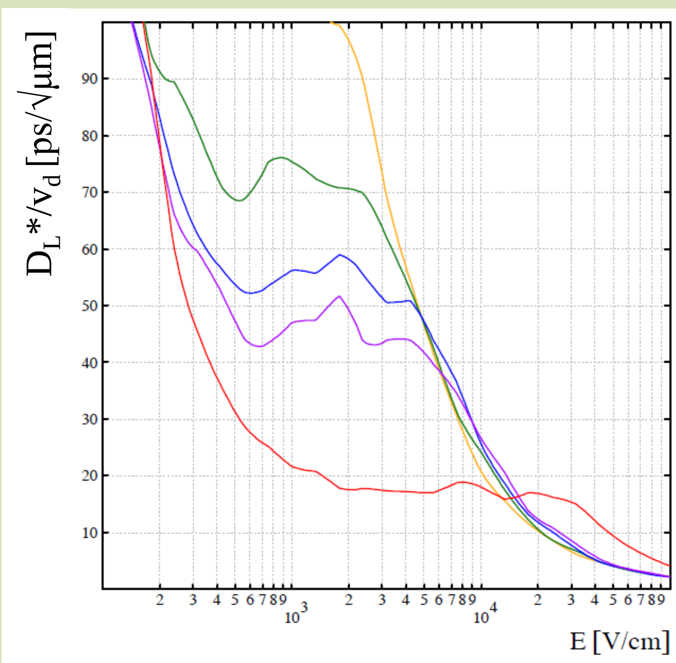


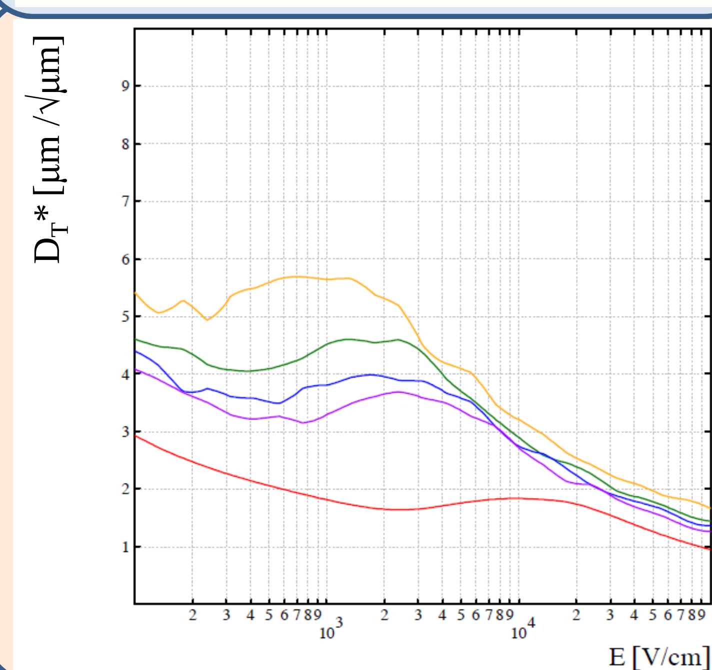
Extraction efficiency probably just some 20% shy of saturation at most.

input parameters for simulations: Ne–C_2H_6 (Magboltz, S. F. Biagi)





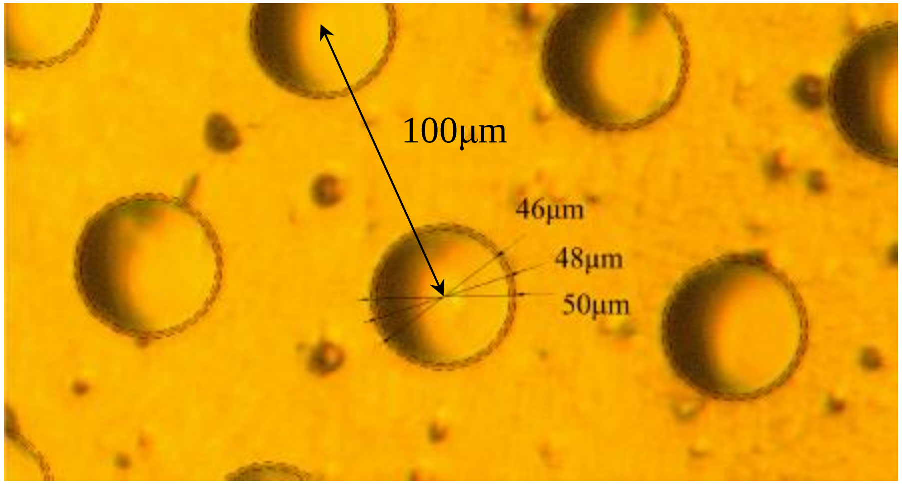




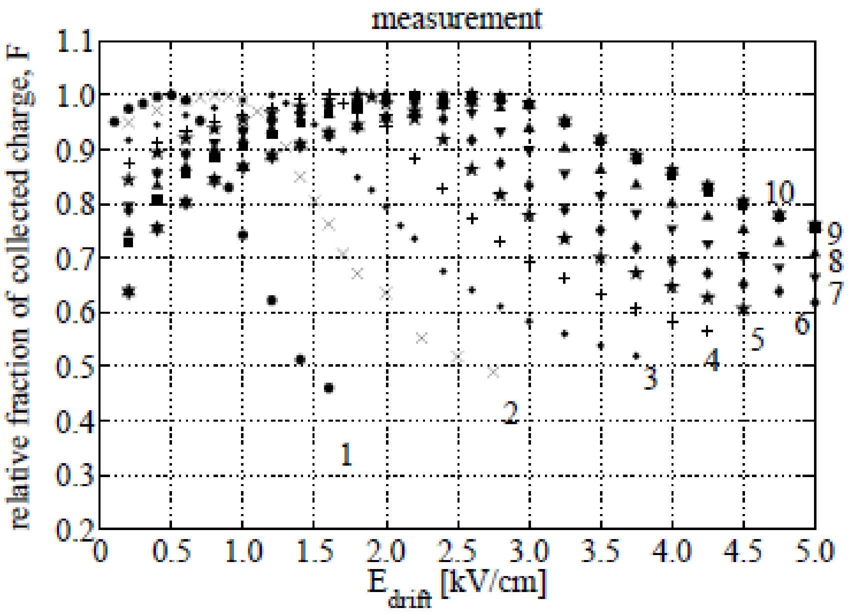
average solutions from hydro (benchmark)

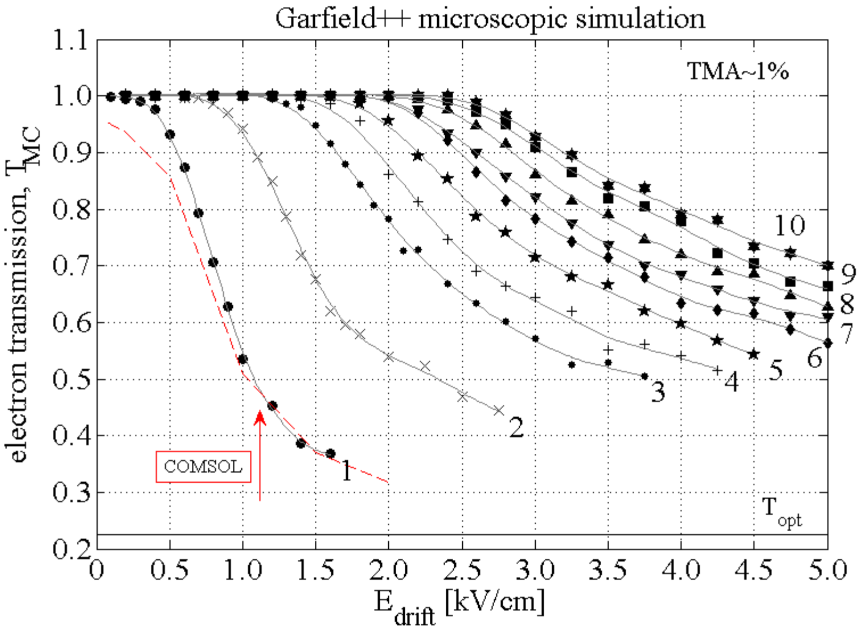
F. Resnati

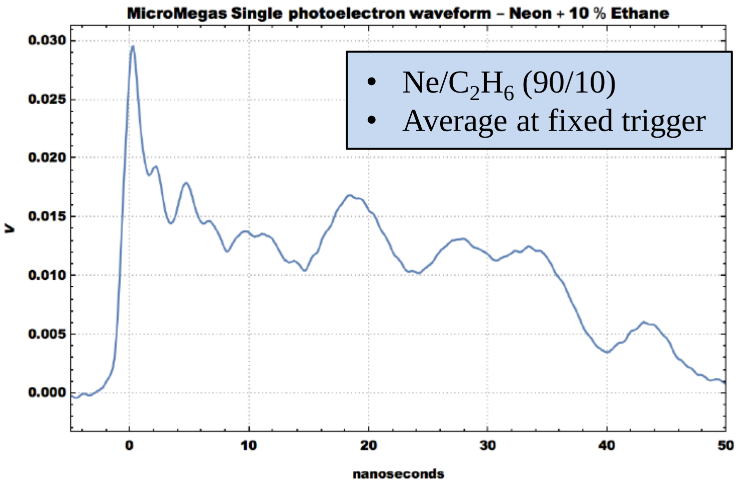
(Xe-TMA published data
with Garfield++/microscopic)



Modelling the behaviour of microbulk Micromegas in Xenon/trimethylamine gas
E. Ruiz-Choliz et al., NIM A, 799 (2015) 137-146.



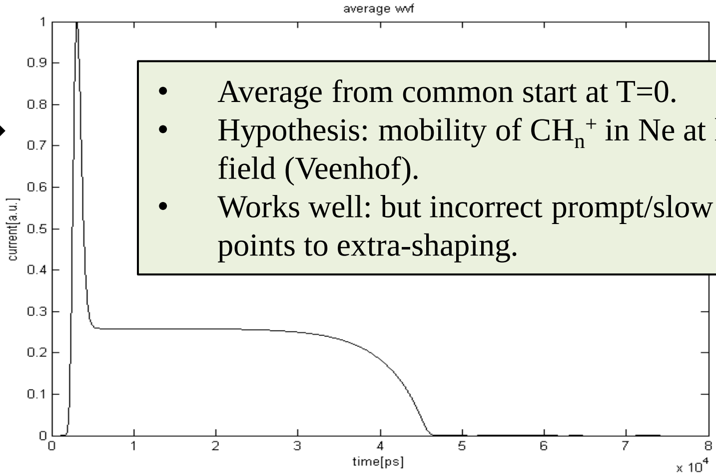




- Ne/C_2H_6 (90/10)
- Average at fixed trigger

data

sim



- Average from common start at T=0.
- Hypothesis: mobility of CH_n^+ in Ne at low field (Veenhof).
- Works well: but incorrect prompt/slow ratio points to extra-shaping.