Ultrafast Timing for HL-LHC era

preamble: Tools/Enabling Technologies

Sebastian White, CERN/Princeton/(Pisa)

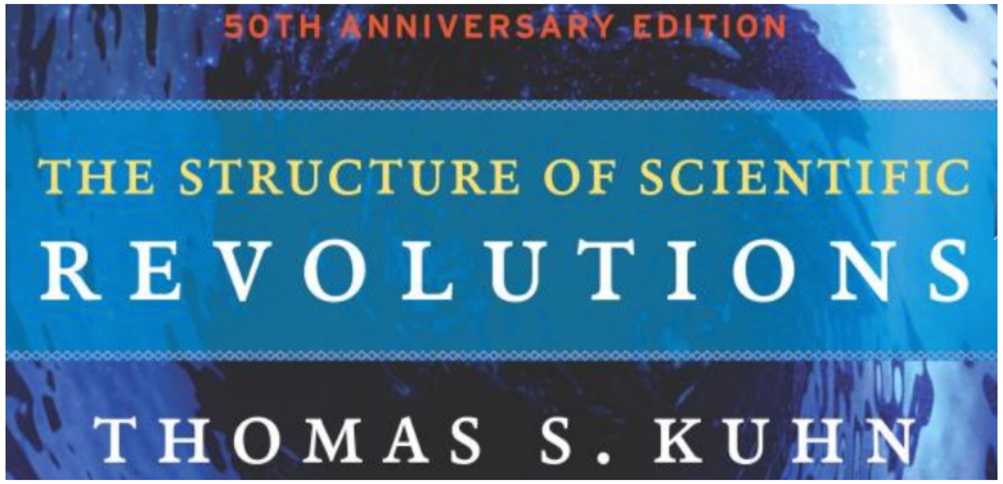
Pisa Seminar — Mar. 24, 2015

Cloud Chamber 1950 NEVIS Cyclotron Lab

Leon

Aldo

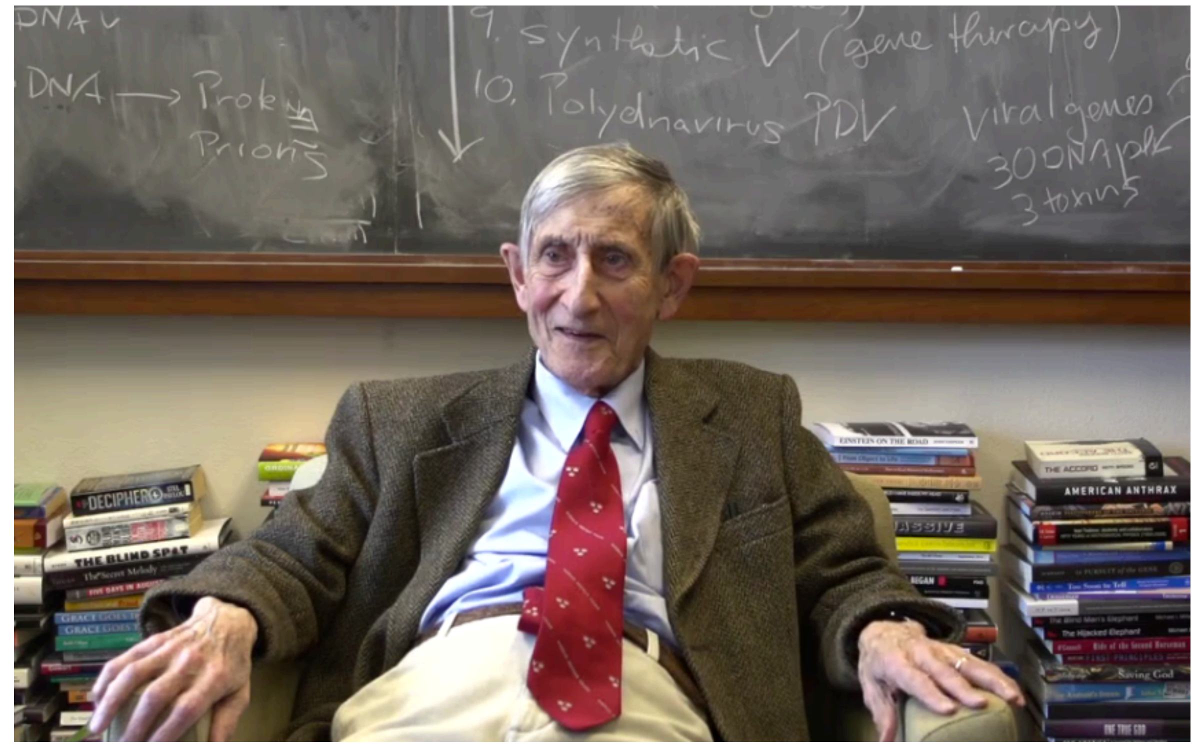
Ideas and Tools



HISTORY OF SCIENCE

Is Science Mostly Driven by Ideas or by Tools?

1. Freeman J. Dyson



"In almost every branch of science, and especially in biology and astronomy, there has been a preponderance of tool-driven revolutions…" Freeman Dyson, "Imagined Worlds", 1997

Quoted by W. Riegler in 2008 CERN Academic Lectures. It became popular with managers arguing for Instrumentation funding (ie Snowmass). I recently corresponded with Dyson to get an update:

...2012 article in Science:``Is Science Mostly Driven by Ideas or by Tools?" As you will see, the answer to the question is that both are important. Sometimes ideas are dominant and sometimes tools.

You can quote me on both sides of many questions. I am glad to hear that Tolstoy is alive in Lausanne. Yours, Freeman.

Dyson, private communication, May 2013

Donald Glaser:

"After winning the Nobel Prize, Glaser began to think about switching from physics into a new field. He wanted to concentrate on science, and found that as the experiments and equipment grew larger in scale and cost, he was doing more administrative work."

moved to Molecular Biology ~1960

founded Cetus Corp.-the first Biotech company ~1971

Donald A. Glaser

Luis Alvarez:

Alvarez industrialized bubble chamber physics, which led to a golden age of physics at Berkeley.
Later in life he developed techniques to map the pyramids and worked on dinosaur extinction.

Luis Alvarez

Georges Charpak:

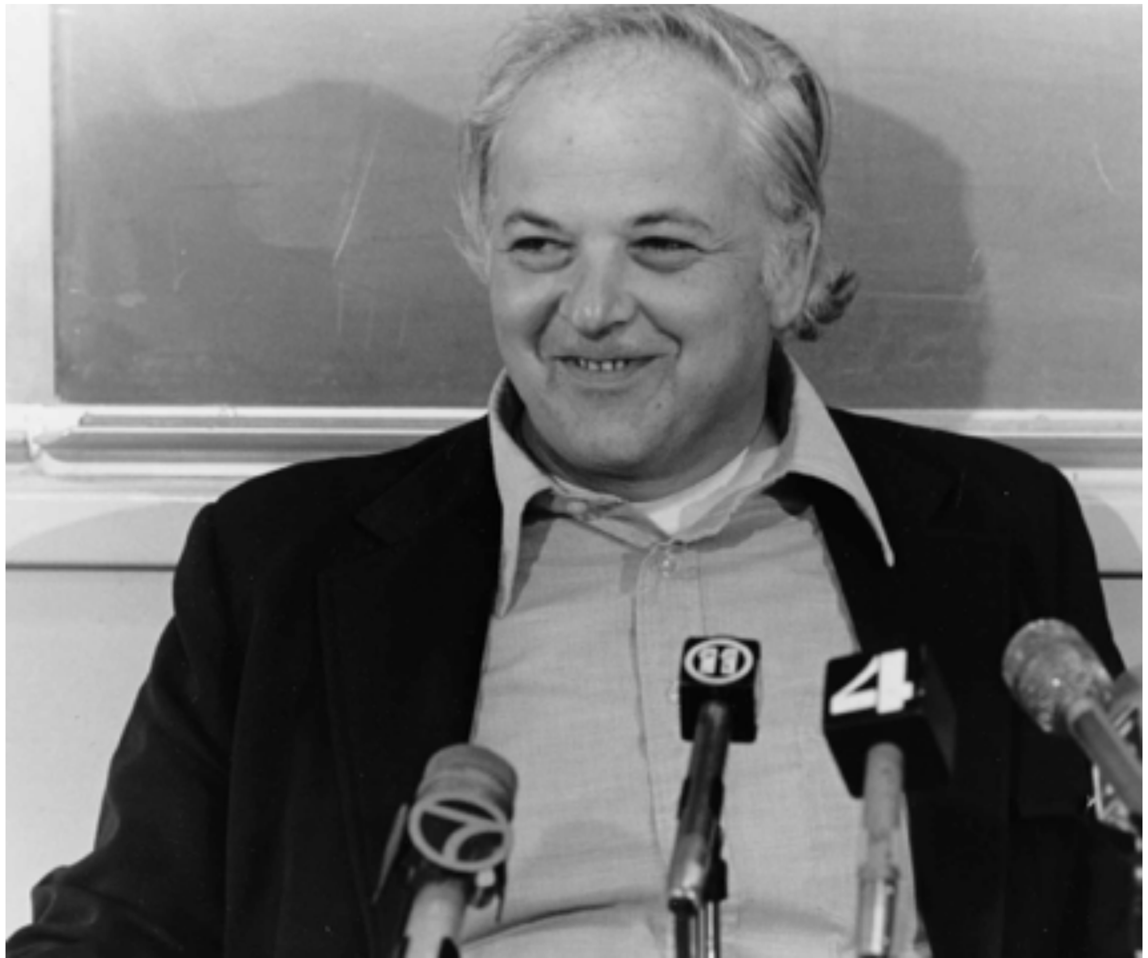
"When I came to CERN I found myself in a milieu which was like a reserve in Africa. Big game hunters -and the prey was some big physics discovery. I thought I would be poaching on their territory. I found that it was easier to make a fortune by selling them weapons. In other fields people have found this to be the best way to become rich."

Burton Richter:

"High Energy Colliding Beams: What is their Future?"

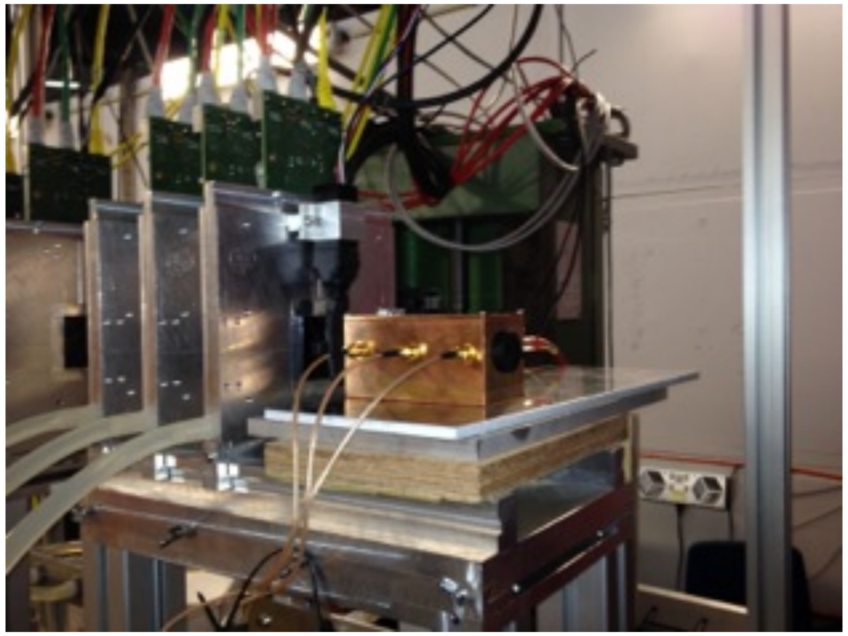
" I see too little effort going into long range accelerator R&D, and too little interaction of the three communities needed to choose the next step, the theorists, the experimenters, and the accelerator people. Without some transformational developments to reduce the cost of the machines of the future, there is a danger that we will price ourselves out of the market"

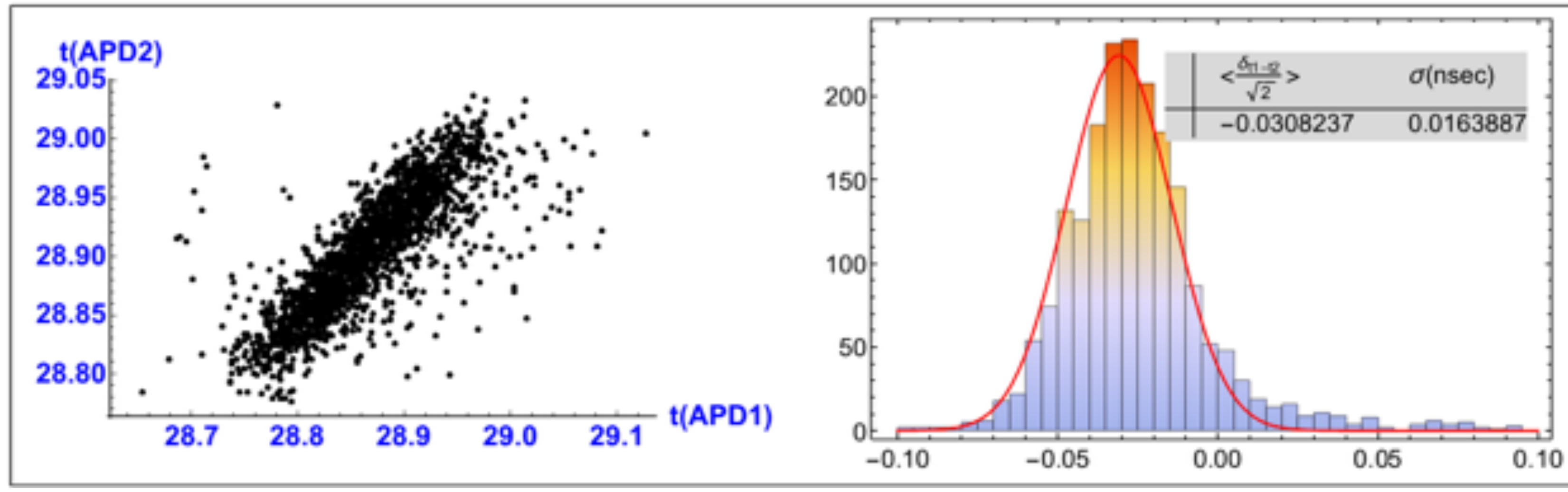
"The events per beam crossing and per unit length along the collision region are going to make serious problems for the detectors. Having 50 times the events per beam crossing [mu=7,000] will require something new in detectors. Having the mean spacing between vertices go from 1.3 mm to 2.5 microns will probably also require something new in detector technology. Getting the experimenters involved in setting parameters is necessary in building something that can really do the physics.
I understand that CERN is setting up such a group. It is about time"



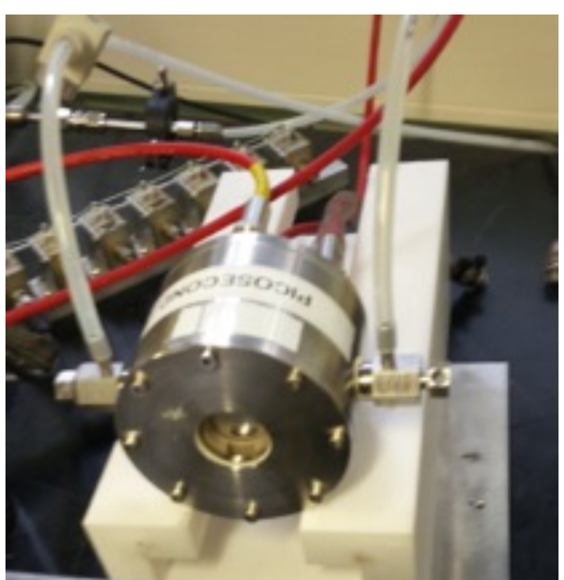
Timing as a pileup Mitigation tool for HL-LHC

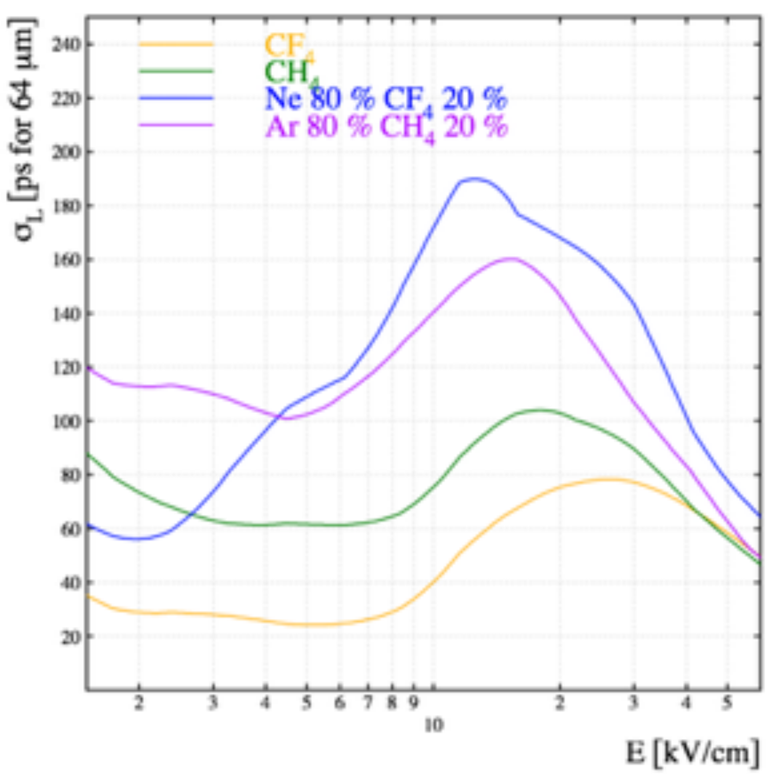
Si technology



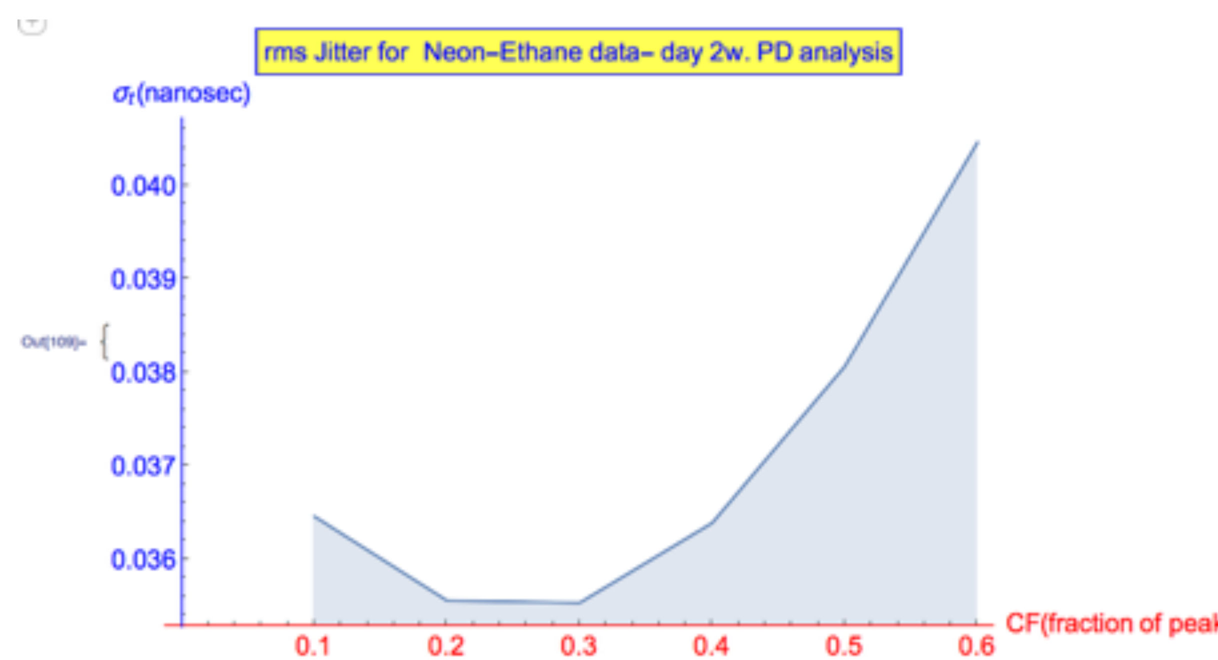


MPGD technology





Initial test on March 10 !



Collaborators:

- new tools for pileup mitigation based on timing: Started 2007 in FP420, 2010 DOE ADR&D and ATF AE55(McDonald and White,co-PIs), in 2014 USCMS&RD51

US-CMS PhaseII R&D

Development of Precision Timing Pileup Mitigation Tools within the Context of a Dual Readout Calorimeter for CMS: *Proposal Submitted to US-CMS*

Crispin Williams[a], Andrea Vacchi[b], Paul Lecoq[c], Rob Veenhof[c], Eric Delagnes[d], Ioannis Giomataris[d], Changuo Lu[e], Kirk McDonald[e], Chris Tully[e], Jim Olsen[e], Richard Wigmans[f], Yuri Gershtein[g], Vladimir Rekovic[g], Umesh Joshi[h], Marcos Fernandez Garcia[i], Thomas Tsang[j], Sebastian White[k,]*

RMD/DYNASIL:

Richard Farrell, Mickel McClish

FEE development:

Mitch Newcomer, Susan Fowler, Brig Williams (U. Penn.)

Hamamatsu Photonics:

Motohiro Suyama

Photocathode Development:

Anatoly Ronzhin (FNAL)

DAQ techniques:

Eric Delagnes, Dominique Breton, Herve Grabas, Stefan Ritt, LRS/Teledyne, Roman Zuyeuski

RD51

Request for Project Funding from the RD51 Common Fund
- Date: 20-05-2014

Title of project: Fast Timing for High-Rate Environments: A Micromegas Solution

Contact persons: *Sebastian White (co-PI),CERN/ Rockefeller sebastian.white@cern.ch*
Ioannis Giomataris (co-PI), Saclay ioa@hep.saclay.cea.fr

RD51 Institutes:

1. *IRFU-Saclay, contact person Ioannis Giomataris*
ioa@hep.saclay.cea.fr
+ Alan Peyaud, Eric Delagnes +Thomas Papaevangelou, Esther Ferrer

2. *NCSR Demokritos, contact person George Fanourakis*
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+SEBASTIAN WHITE swhite@rockefeller.edu
+ Eraldo Oliveri and Filippo Resnati
+RD51&Uludag University, Rob Veenhof veenhof@mail.cern.ch

4. *Universidad deZaragoza, Diego González Díaz*
diegogon@unizar.es

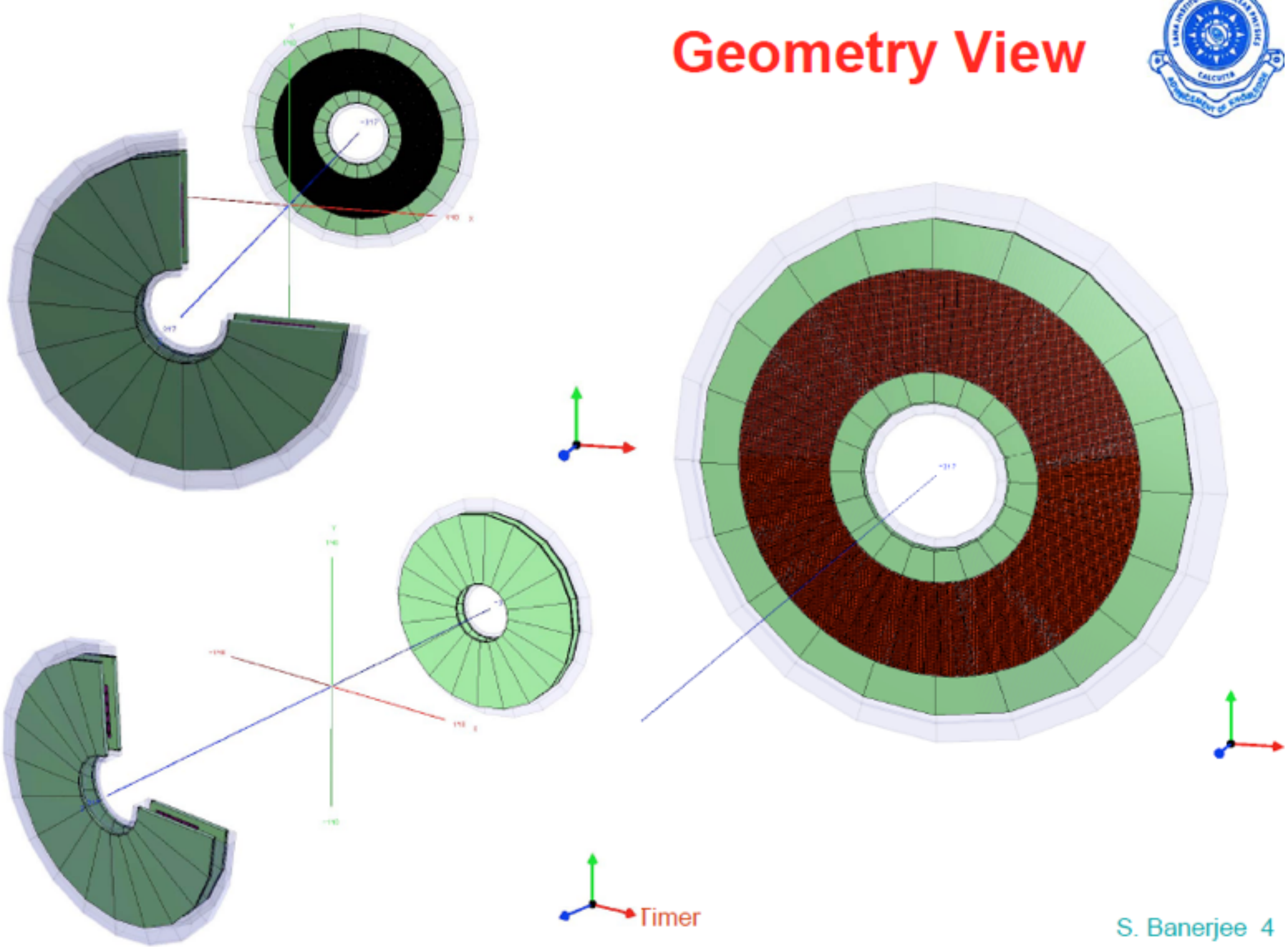
Ext. Collaborators:

1. *Rockefeller/FNAL, contact person Sebastian White*
swhite@rockefeller.edu

2. *Princeton University, contact person K.T. McDonald,*

RD51 Common Project approved last week!

Our group has been developing a dedicated fast timing solution with Si or MPGD options for end cap



pileup mitigation challenge

see. S. White, “R&D for a Dedicated Fast Timing Layer in the CMS Endcap Upgrade”, Proceedings of 2014 Workshop on Picosecond timing
http://arxiv.org/abs/1409.1165

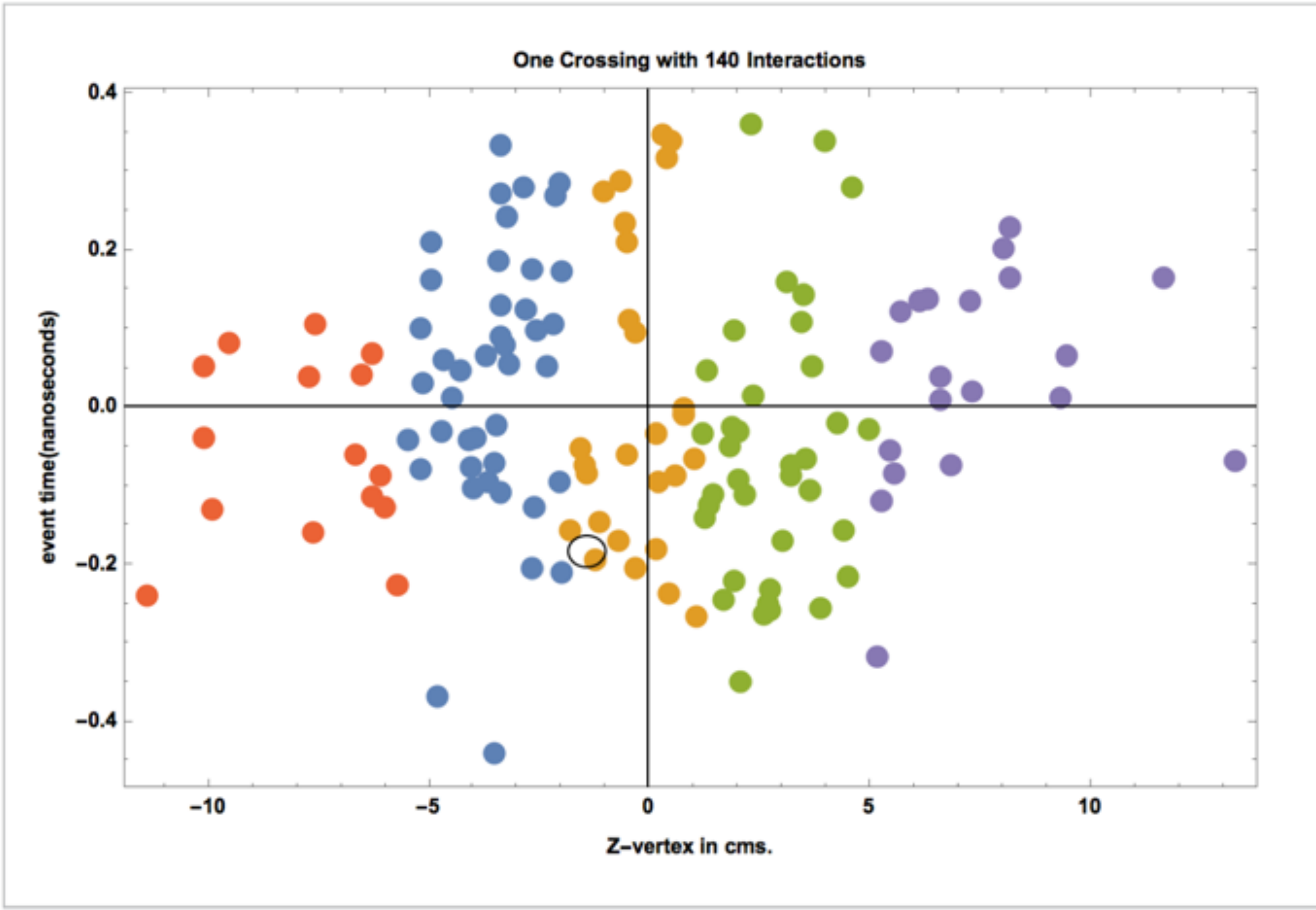


Fig. 1. Simulation of the space(z-vertex) and time distribution of interactions within a single bunch crossing in CMS at a pileup of 140 events- using LHC design book for crossing angle, emittance, etc. Typically events are distributed with an rms-in time- of 170 picoseconds, independent of vertex position.

How could one make such a plot?

ie turn
this
1-d plot into a 2-d plot

above plot starts from the work-horse for vertex finding-the CMS inner tracker

many CMS talks about precision timing start from assumption that vertex time is known (??)

though I am an enthusiast for precision timing, I don't believe CMS can afford to build 2 systems!

should calorimeter drive timing?

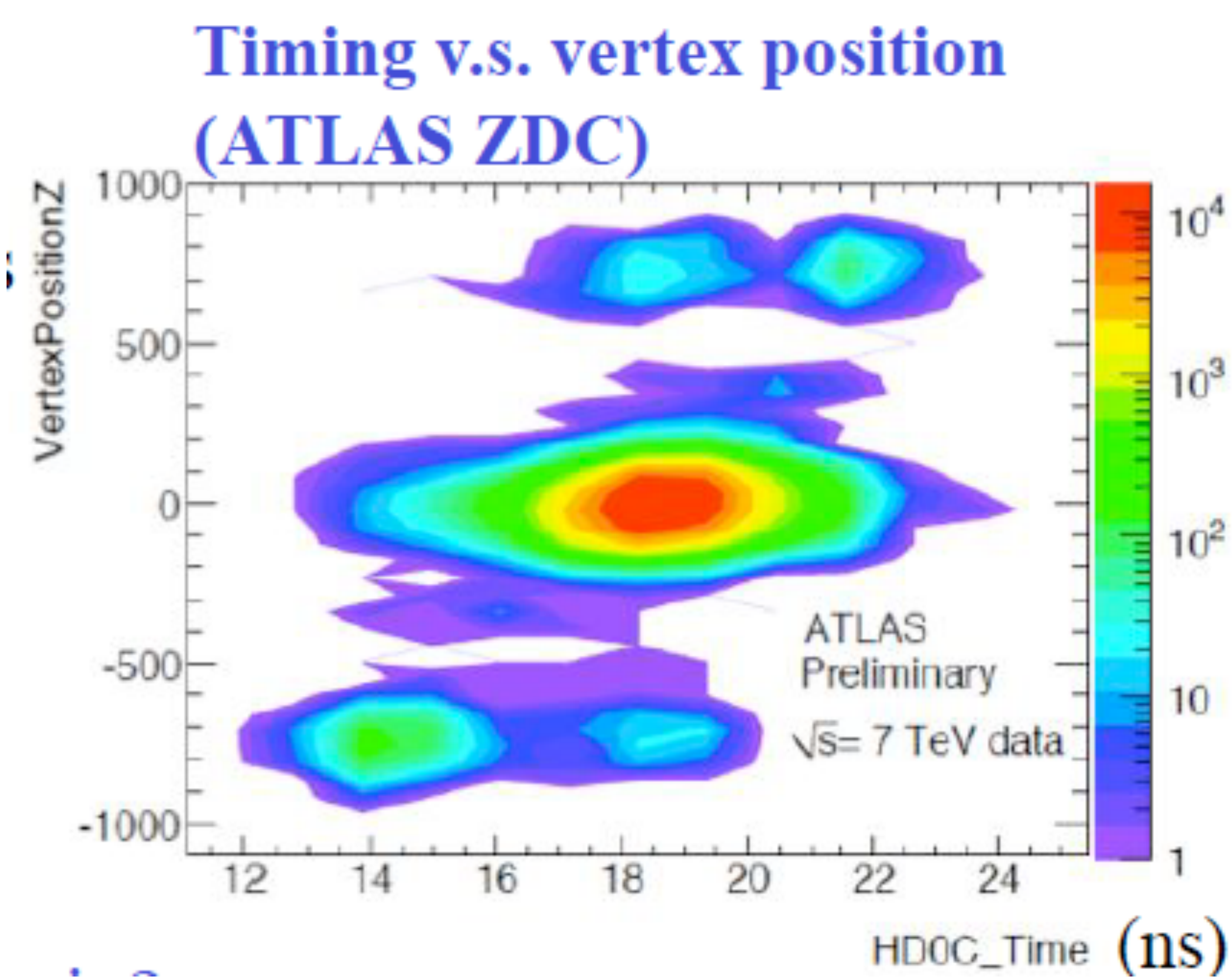
simple considerations make it attractive:

- projective emcal or dual readout intrinsically fast
- combined with high photostatistics->good performance (eg SPACCAL, DRC)

however DRC was down-selected. Initial talk of a fast wave-shifter on the shashlik calibration fiber inconclusive?

->We focus instead on a dedicated timing layer.<-

- realistic 10-20picosecond timing at high rates @radiation environment hard enough without combined function (see eg NA62 lessons).



in 2010 we showed ZDC calorimeter timing could resolve micro-bunches from SPS Rf
http://xxx.tau.ac.il/abs/1101.2889
still ~an order of magnitude needed to resolve in-time pileup

We focus on timing layer for EndCap region of Phase-2

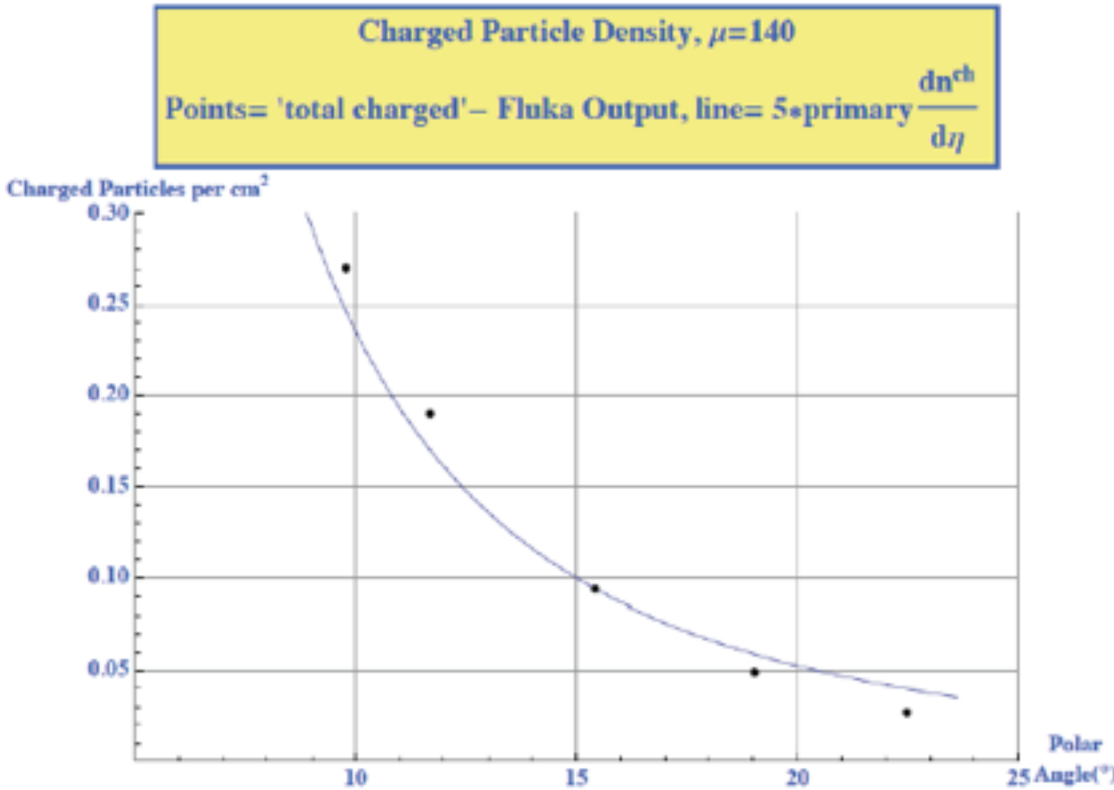
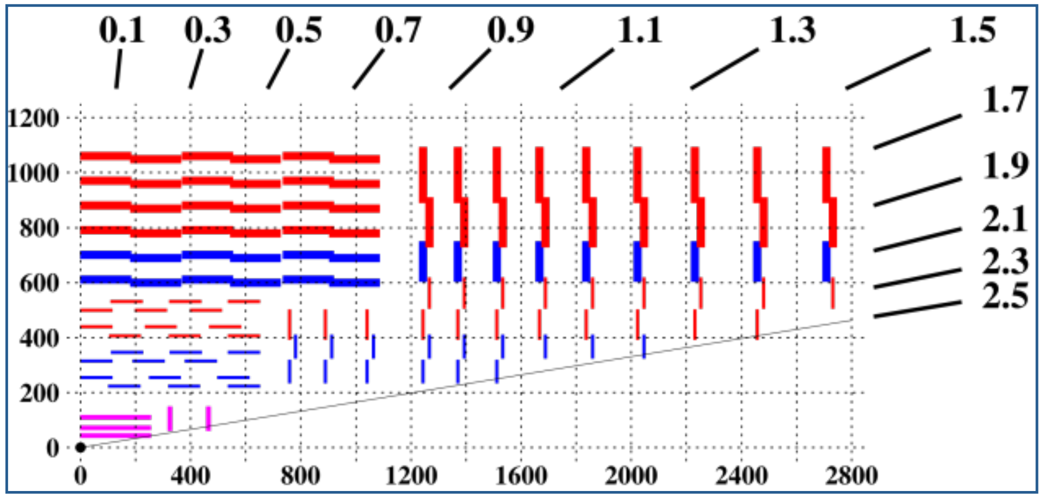
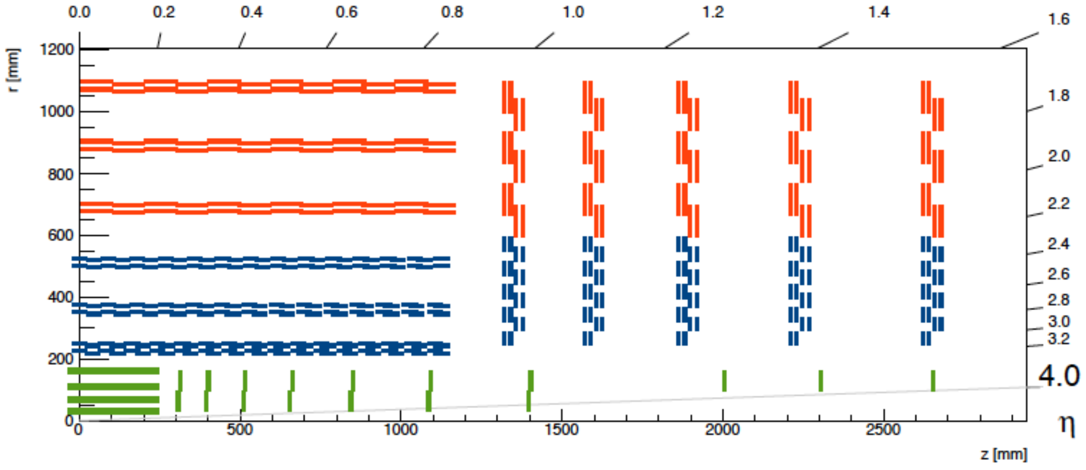


Figure 2: The charged particle density in the region of the dedicated timing detector. The points are FLUKA output for "total charged". The line is calculated from estimates of primary charged particle density-dn/deta- scaled up by a factor of 5. FLUKA output is roughly consistent with a constant factor over this angular range.

current model in CMSSW matched to:



if tracker extended in Phase2, complementary role?



physics justification for timing layer likely stronger if we can extend timing well beyond eta=2.6

=>our RD51 MicroMegas development could enable this

Sensor Technology

- better to understand whether anything available/affordable/ survivable if physics demands timing
- good first start is to talk to commercial manufacturers. We have been working directly with Hamamatsu responsible for MCP/ PMTs for past 7 years, so had easy access to info

Some MCP/PMT facts-Hamamatsu perspective

- nice SPTR (~15 picosec)
- pricey(>$10k/cm^2)
- nice work by Belle people 8 yrs ago. No one has come close.
- notoriously unsuited for high rates (Q_{anode}^{max}~0.1C)
- a small area PC alternative now available for high rates (HAPD)
- in many ways, in LHC culture, MCP is a *"MacGuffin"*

What else is out there?

good place to start is “Picosecond Workshop” series started by Henry Frisch (ie Clermont meeting last March)

- traditionally PET and low rate HEP-ie Henry’s LAPPD project primarily for neutrino expts.(see his TIPP 14 talk)
- Crispin W’s ALICE-TOF is large LHC precedent(but low rate)
- we have been only project to report on CMS PhaseII
- some related generic-ie Sta Cruz “LGAD” and diamond det.
- we reported on long running development of Si option +GasPMT starting up+electronics development
- good progress on WFDs reported by Delagnes, Ritt, Breton (over last 3 years have collaborated w. them @Saclay&PSI)

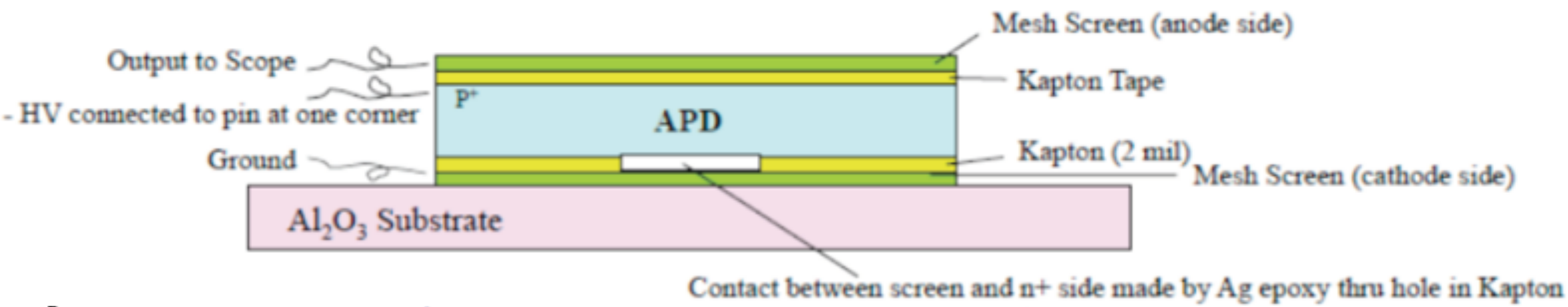
we reported on 2 technologies

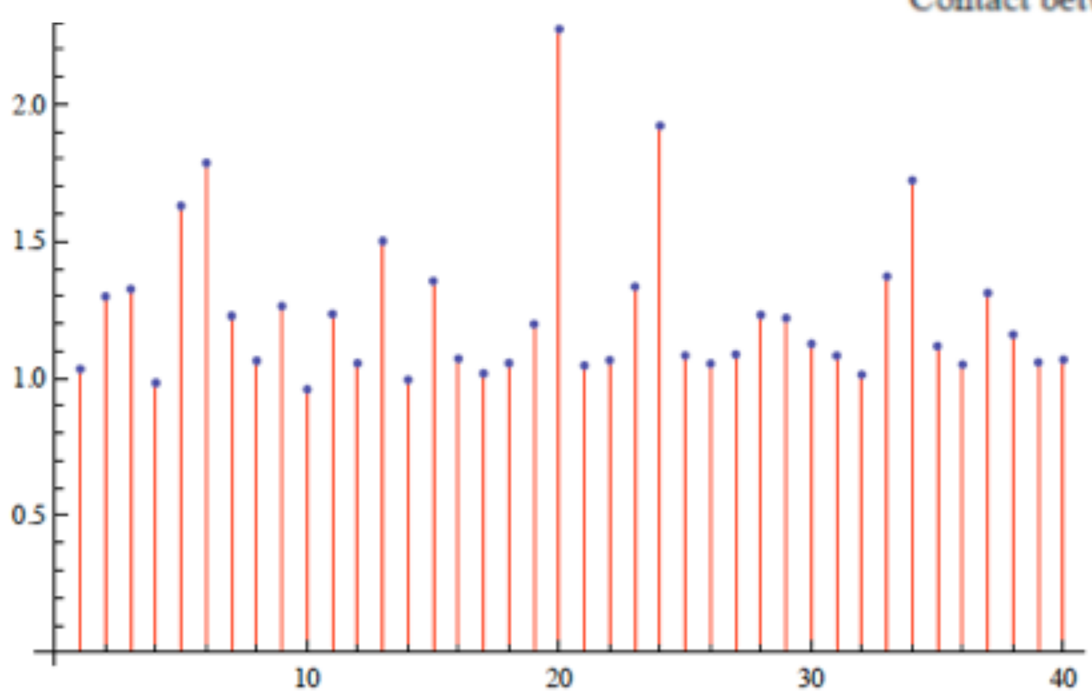
(we started work on 2nd option a year ago as a hedge against concerns about cost and rad hardness -particularly if eta>3)

Si option:(many presentations to FCWG over past 2 years)

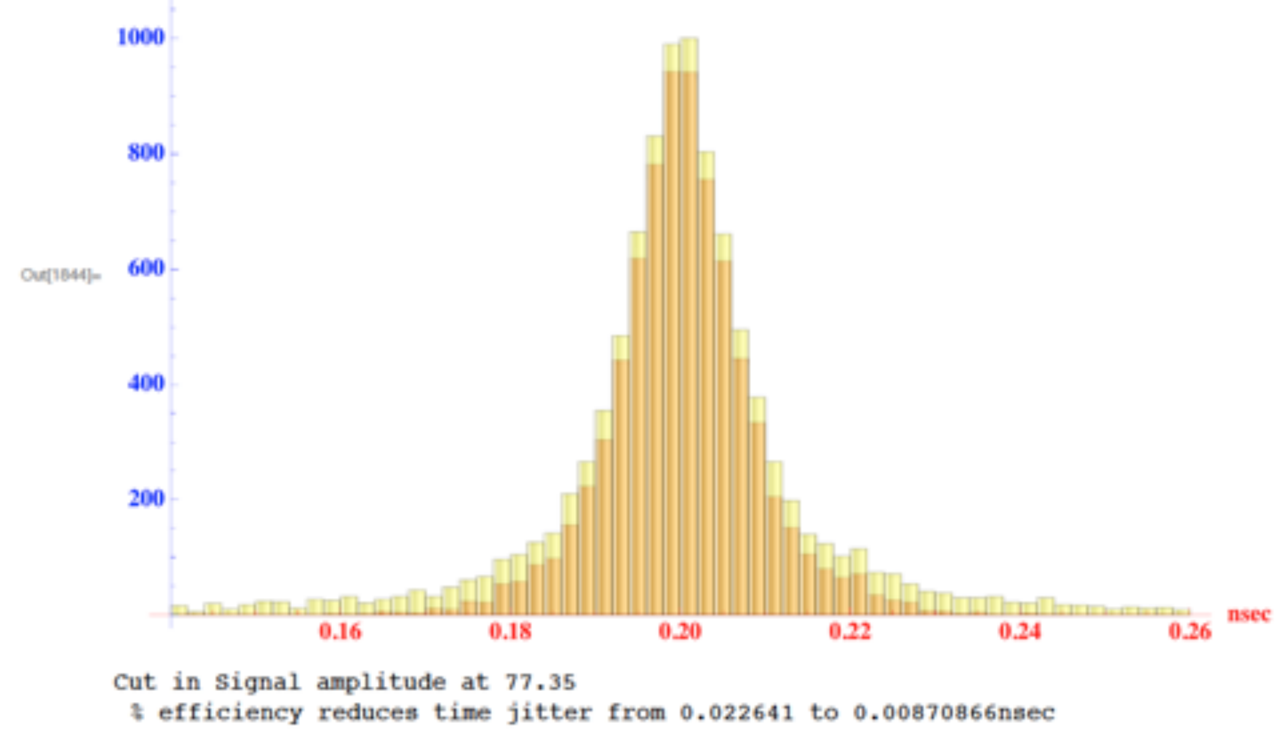
- useful object lessons from NA62 GTK project
- 1) Landau/Vavilov contribution to time jitter

Top Screen Output Connection (capacitively coupled)

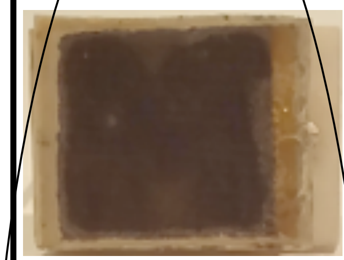
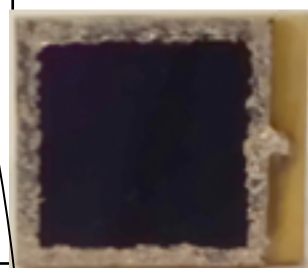
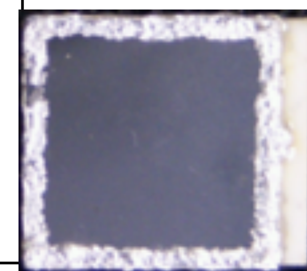
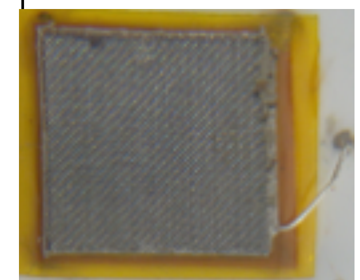
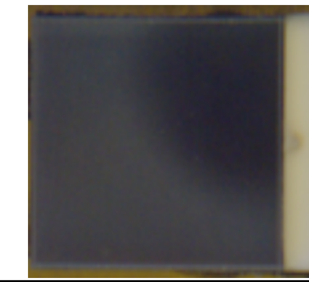
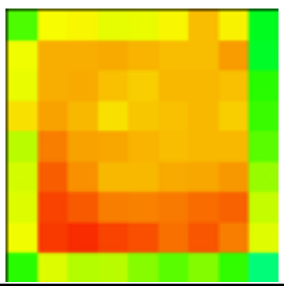
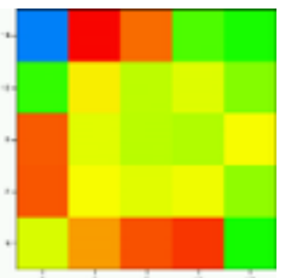
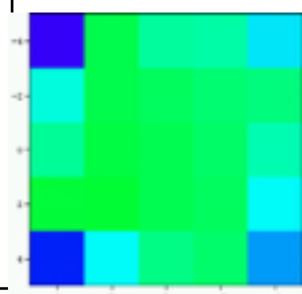
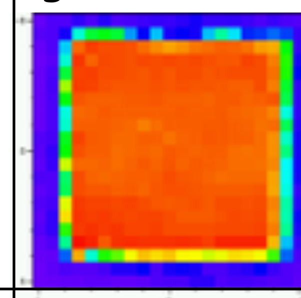
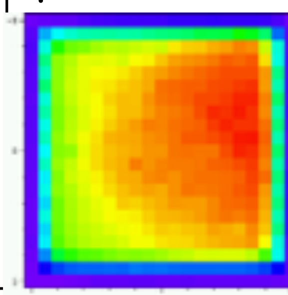
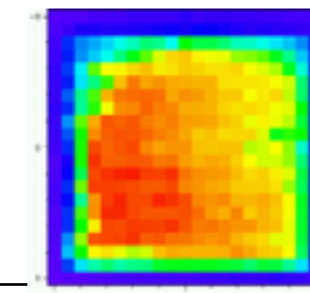
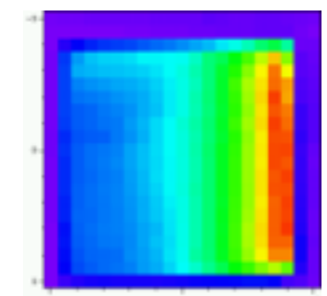
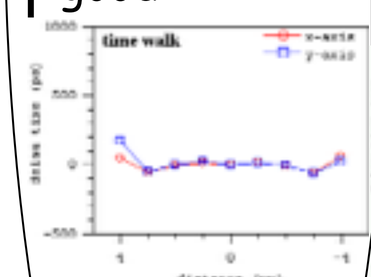
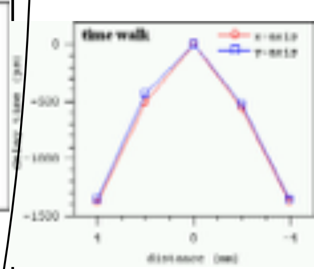
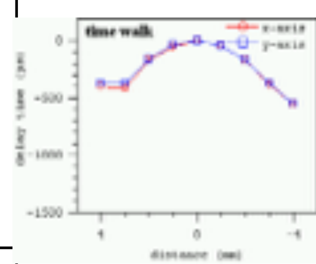
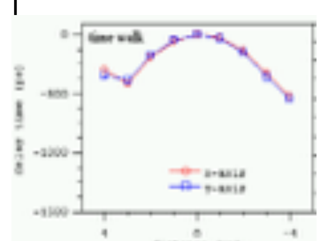
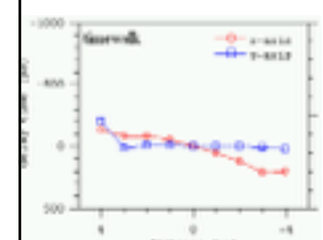
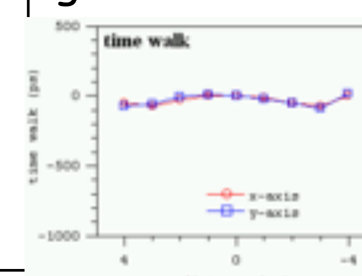
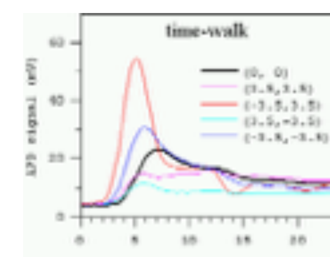
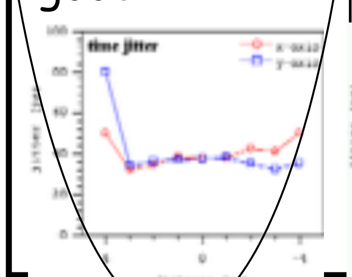
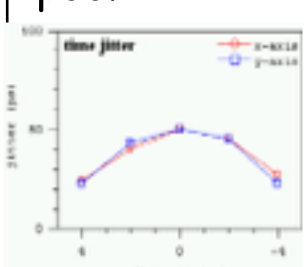
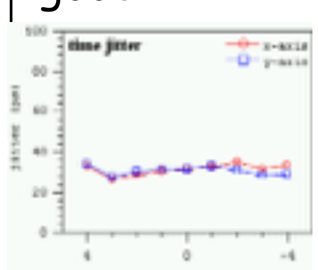
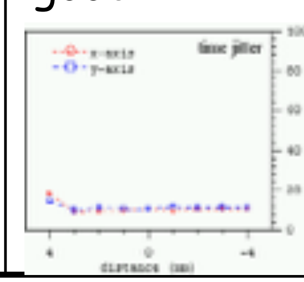
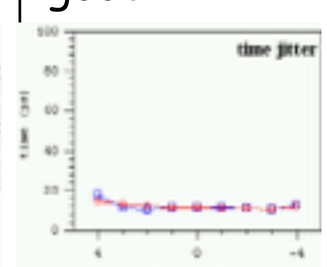
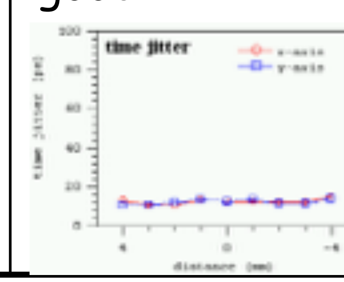




Simulated energy deposit/per each of 40 1 micron layers-typical event



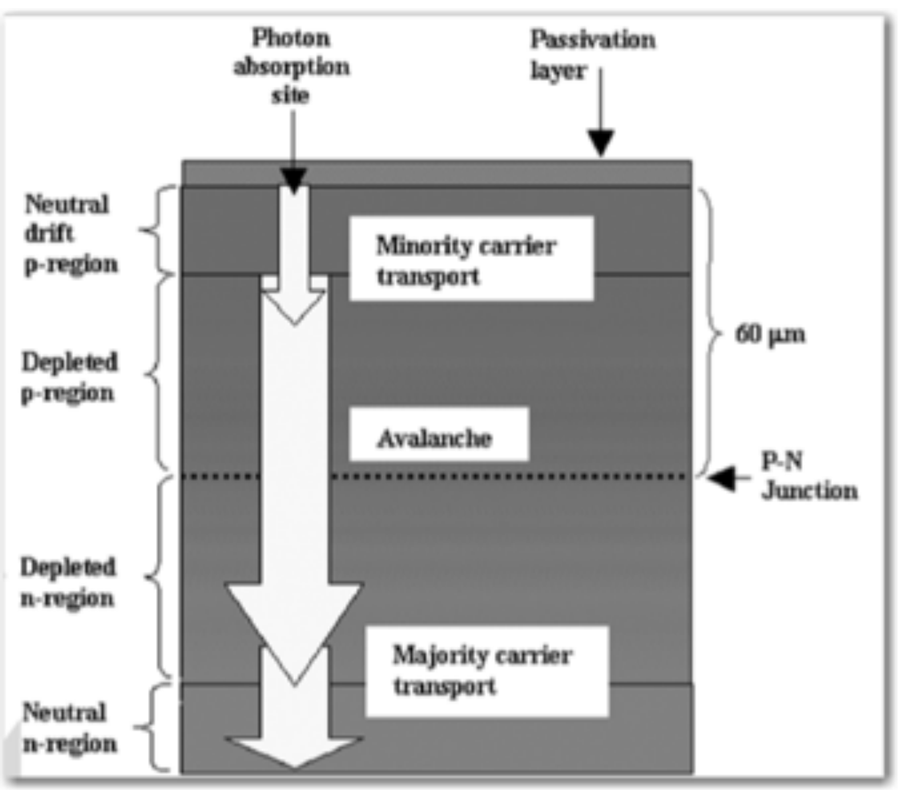
Summary of RMD 8x8 mm^2 APDs Dec. 13, 2013

	Dec.13, 2013 432-6 Mesh	Nov.14, 2013 4 (previously graphene)	Nov.14, 2013 432-6-In	Oct.22, 2012 193A-6-In	Oct.22, 2012 420-3-4	Nov. 20, 2012 432-5	Sept. 26, 2012 unknown
	Al-mesh Au sintered 	In-edged No Au 	In-edged Au sintered 	In-edged Au sintered 	Al-coated No Au 	Al-mesh No Au 	standard n+ diffusion No Au 
spatial uniformity	good 	fair 	fair 	good 	poor 	poor-fair 	poor 
time walk	good 	poor 	fair 	fair 	good 	good 	poor 
time jitter	good 	poor 	good 	good 	good 	good 	poor data not available

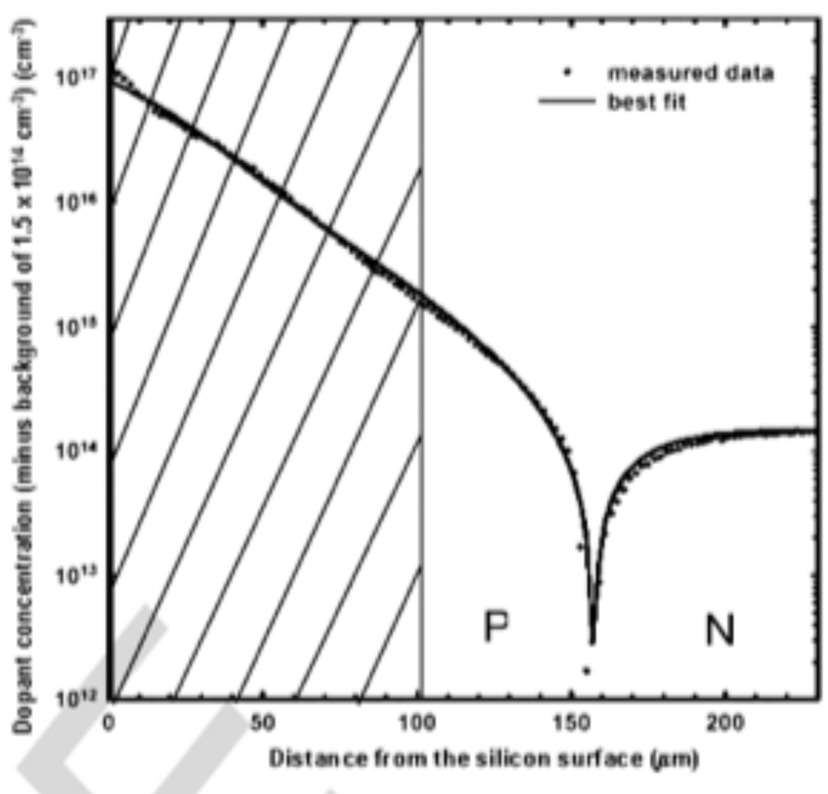
2) weighting field uniformity (and internal series resistance elimination)

RMD/Dynasil Deep Depleted APD

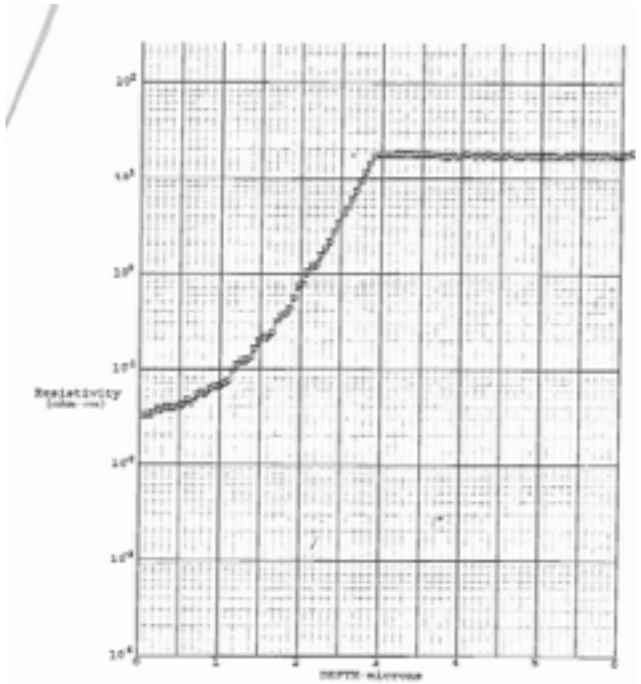
- very different from planar Si detector w/o gain
- signal modeling more similar to drift chamber
- effective thickness ~40 micron-> ~2.6 k e-h/MIP
- science of rad damage in APDs developed in CMS
    - Since January I am receiving CERN support to initiate fast timing in RD50 (&RD51)
    - starting in RD50 to further characterize and device model
    - At Princeton we are taking over packaging and metallization (relation with RMD now as a chip supplier)



structure



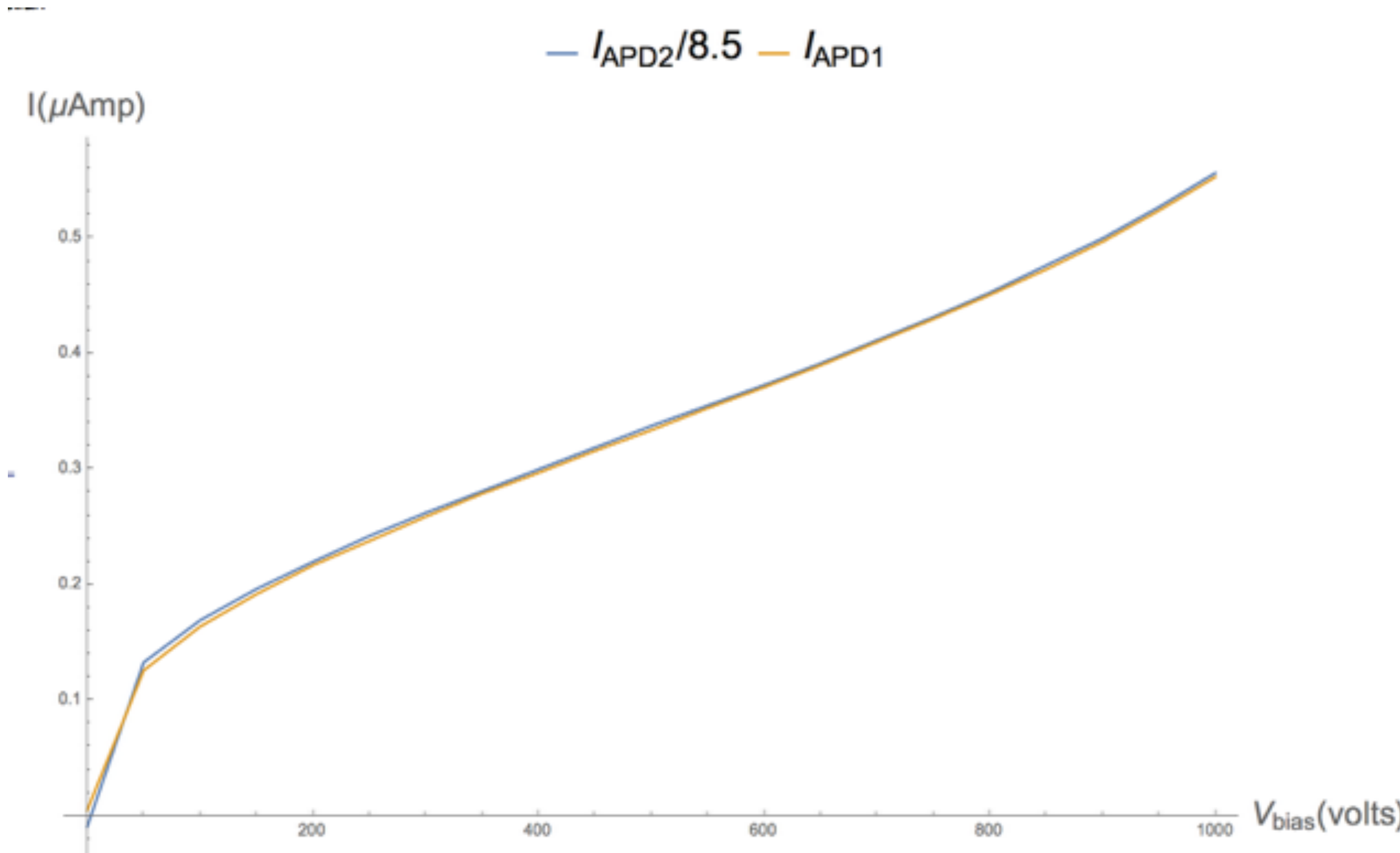
thinning



post-processing

recent progress on Si rad dam issues

- big jump in exposure to ~10^14 protons
- perfect scaling of I w. exposure
- no evidence for gain degradation
- updating CERN RD50 capability for higher bias



Measurements performed with SAMPIC on Nov 21st at CERN using S. White's APD setup

Draft V0.0

E. Delagnes CEA/IRFU/Sedi

S. White

1 Description of the setup.

The measurement setup used is shown on Fig.1 and Fig. 2. A custom-made fast pulser based on bipolar transistor breakdown generates short pulses. Its output is splitter in two parts by a passive splitter. A first output of the splitter drives a VCSEL, providing then short laser pulses which are sent, through an optical fiber to a White's "mesh- APD". The intensity of the light pulse received by the APD can be changed by modifying the optical coupling between the optical fiber and the APD. The output voltage of the APD is taken on the mesh, amplified by 50dB before to be sens to be digitized by SAMPIC. The second output of the splitter, attenuated by 10 dB is sent to another channel of the same SAMPIC chip.

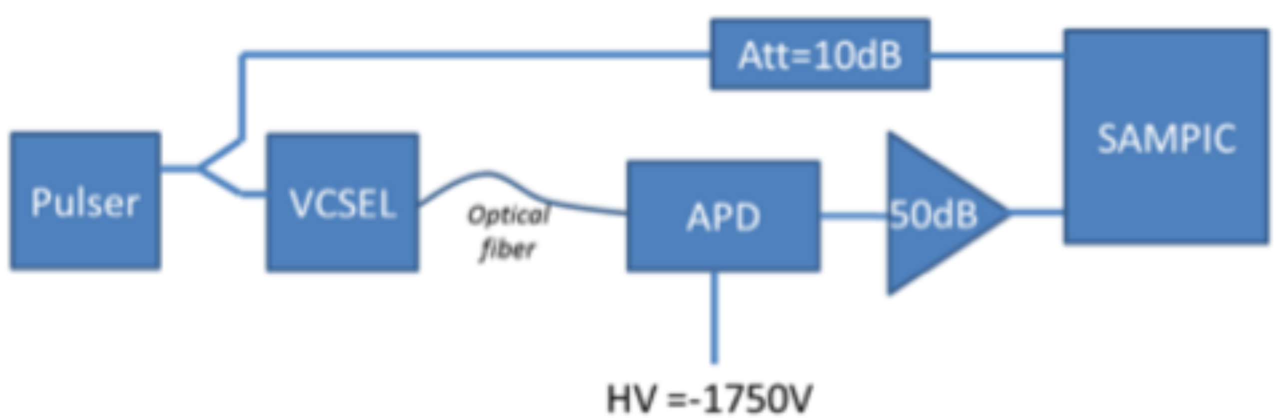


Figure 1: Principle of the test setup

tests w. SAMPIC/DRS4.. digitizers

Sampic result @1 MIP w.
"Simple Constant fraction"

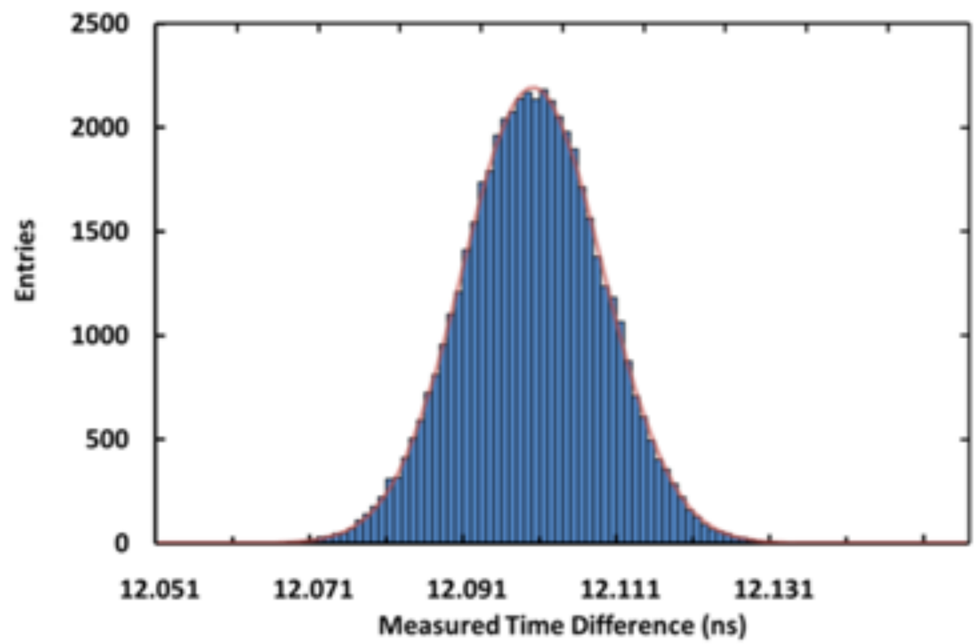
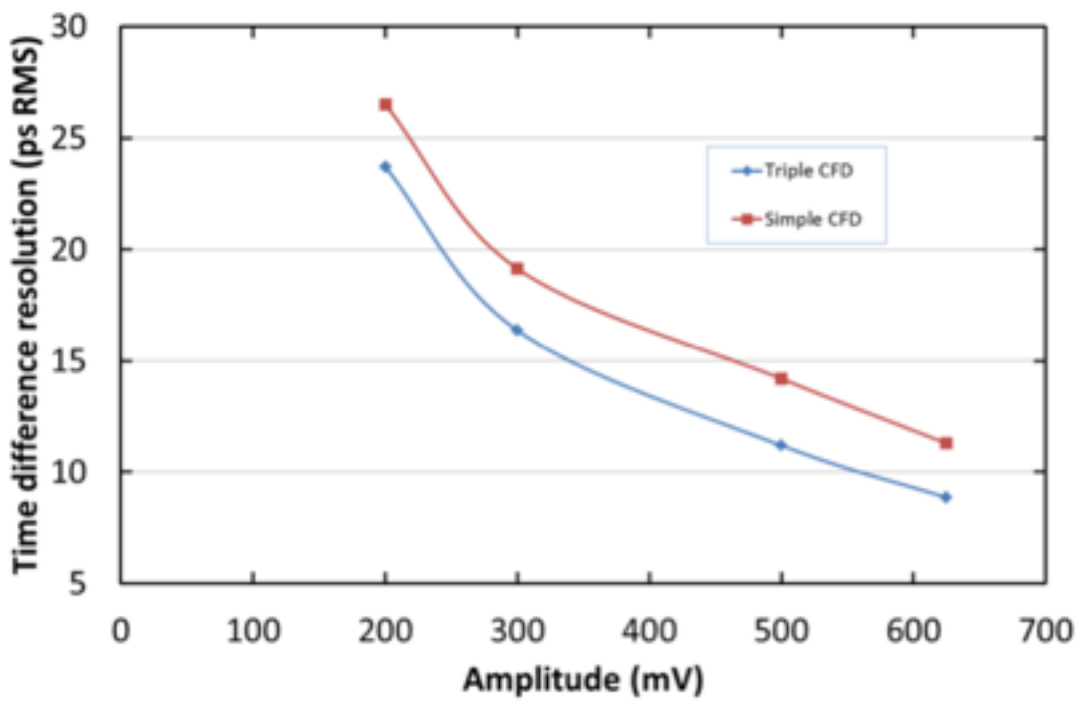


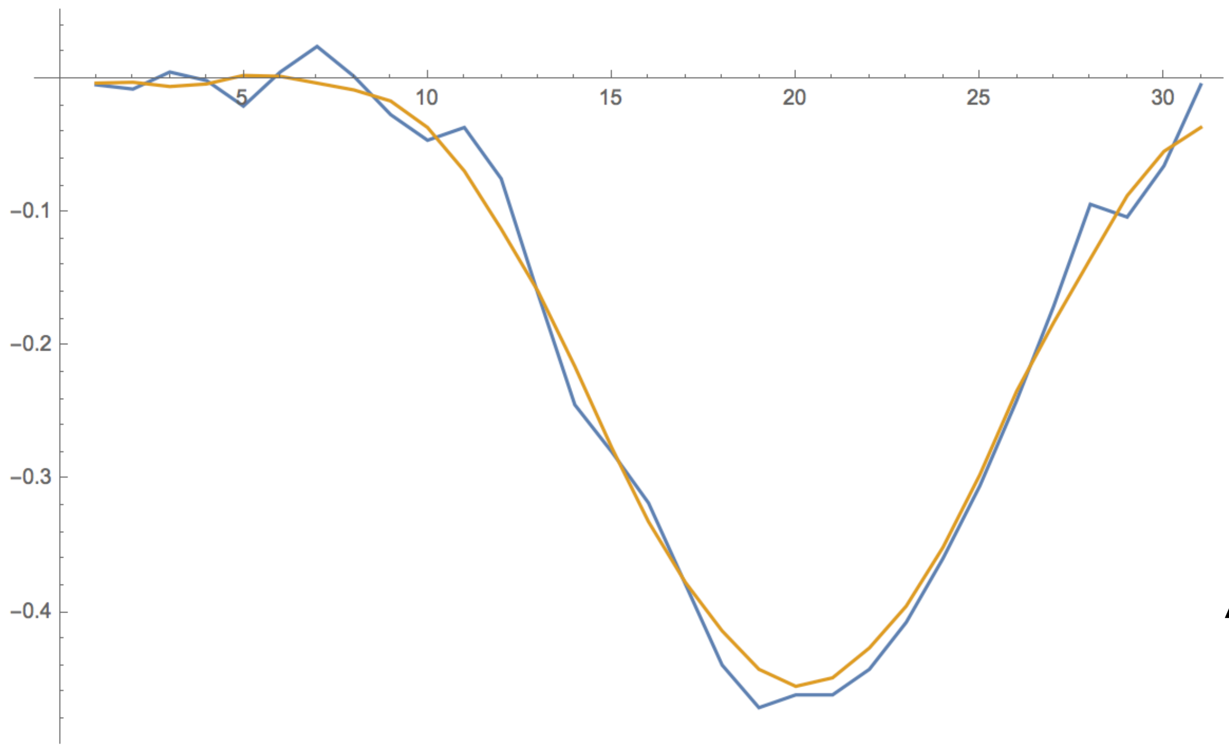
Figure 4: Distribution of Time difference between pulser and detector signals (+ Gaussian fit in red) for amplified detector signal amplitude of 600mV. The standard deviation is 12 ps RMS.

Amplitude Dependence
1 MIP= ~580 mV



Common issues on FEE and signal processing

```
ListPlot[{wave, WienerFilter[wave, 1.5, .1]}, Joined → True, ImageSize → Large]
```



<-waveform w. 30 pts@0.2ns/point
tR~2 nsec w. commercial amp

unoptimized Wiener filter seems effective.
A signal with 2 nsec t_R contains no frequencies higher than 200 MHz.

"Greg's desk"

most relevant literature comes from outside our field (radar, GPS)

[1] N. Wiener 1949, Extrapolation, Interpolation, and Smoothing of Stationary Time Series, John Wiley & Sons, New York.

[2] R. E. Kalman 1960, *"A new approach to linear filtering and prediction problems,"* Transactions ASME, Ser. D, Journal of Basic Engineering, 82, pp. 35-45.

[3] S. K. Mitra, and J. F. Kaiser (eds.) 1993, Handbook for Digital Signal Processing, John Wiley & Sons, New York, 1268 p.

[4] Y. C. Chan, J. C. Camparo, and R. P. Frueholz 2000, *"Space-segment timekeeping for next generation satcom,"* Proceedings of the 31st Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 7-9 December 1999, Dana Point, California, USA, pp. 121-132.

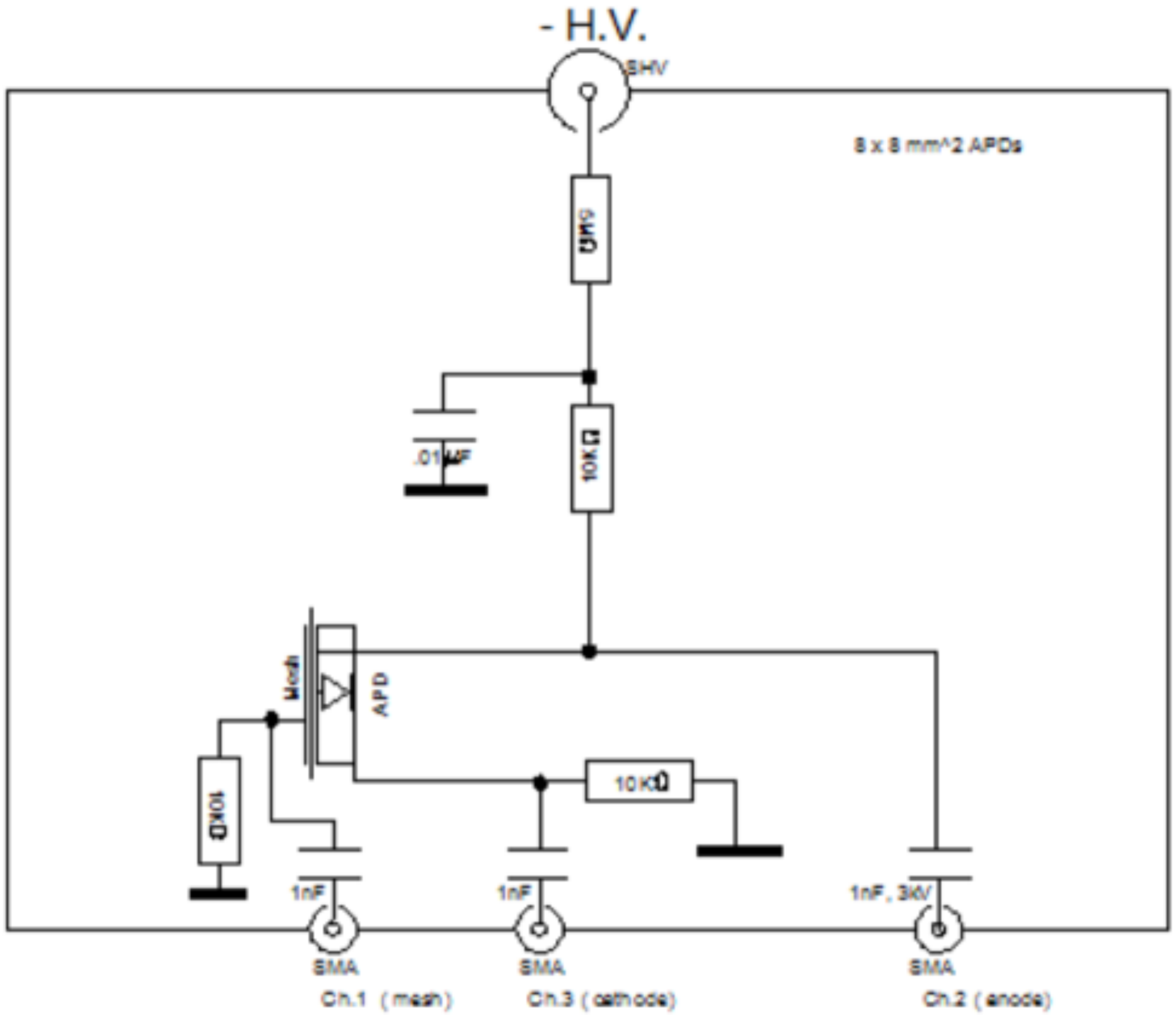
Fabrication costs

- currently sold at ~$1k/cm^2 in small quantities (ie 10% of MCP-PMT cost)
- production cost in quantity ~$1/mm^2 (ie 1% of MCP-PMT cost)
- SBIR proposal to study cost at large scale for specific charged particle app.

Lifetime/rad dose

•beam tests by RMD(and by us) show that cooled detector would have identical (noise) performance to ones we test warm up to now @10^{13}n/cm^2. Recently we got new exposures to 10^14 and will go another order of magnitude at least.
•Also calculation using CMS scaling rules (see our 2009 paper).
•We are comfortable to ~10^{14} but concern about higher.
•starting next round of rad exposures (BU, Fermilab help?)

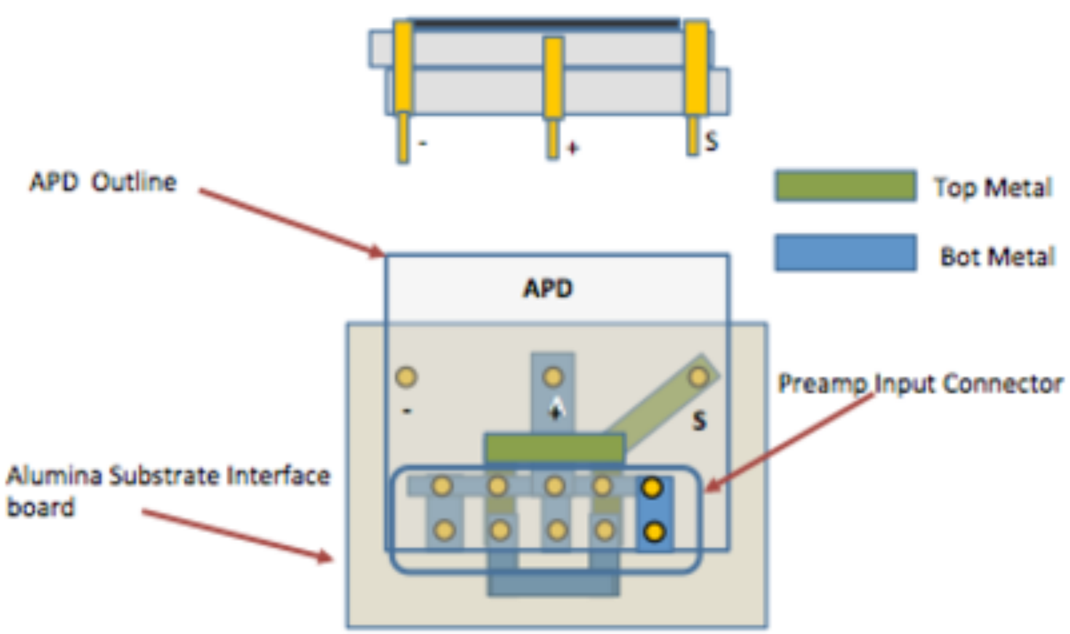
also systematic measurement of all terminals, vs. position, etc. to develop improved modeling



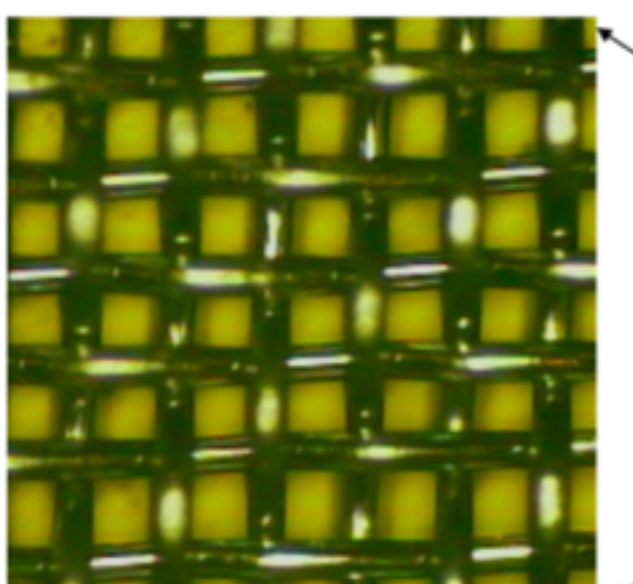
most previous results from mesh readout only

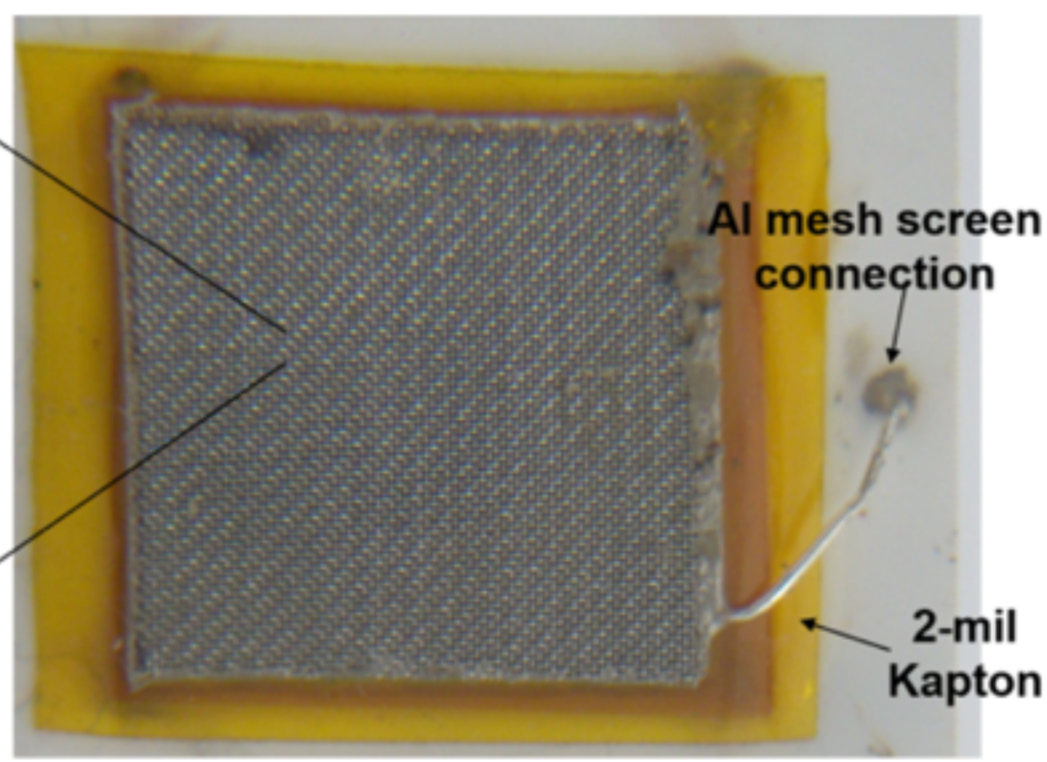
Examples:

Double Sided Alumina Soln. (Better)



work with RMD to develop new packaging (1st stage)

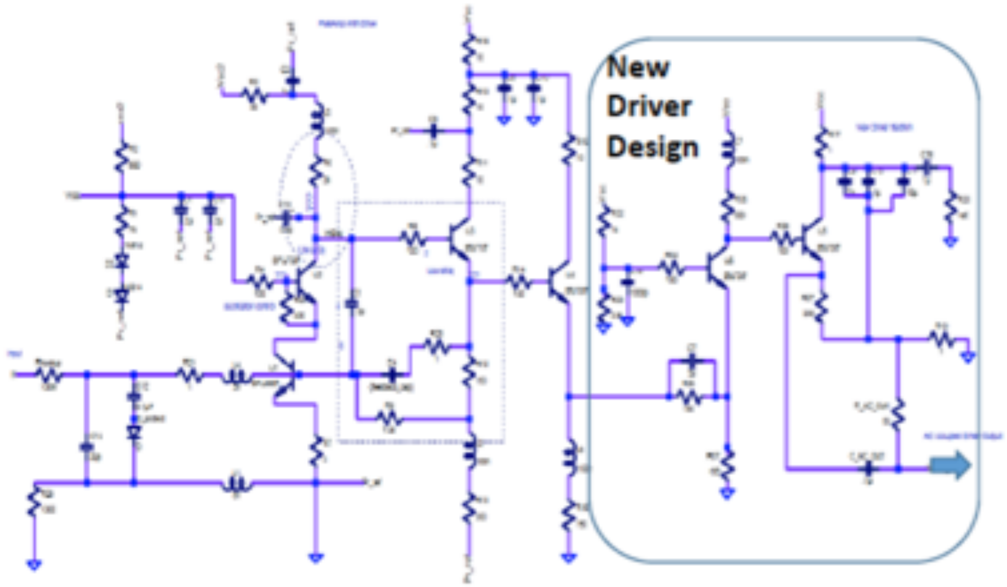


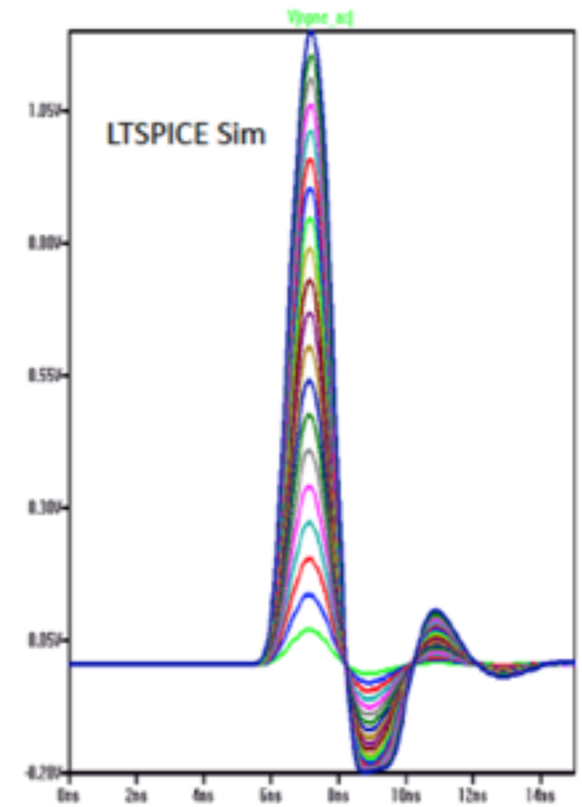


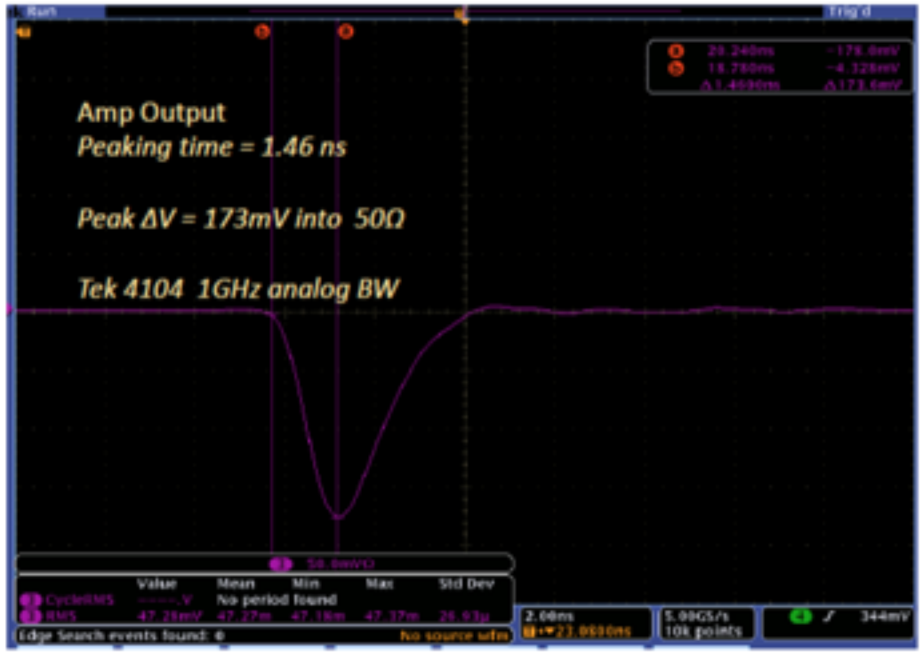
also improved mesh fab (working with Rui)

Progress on new Transimpedance Amp

Fast-amp with new driver





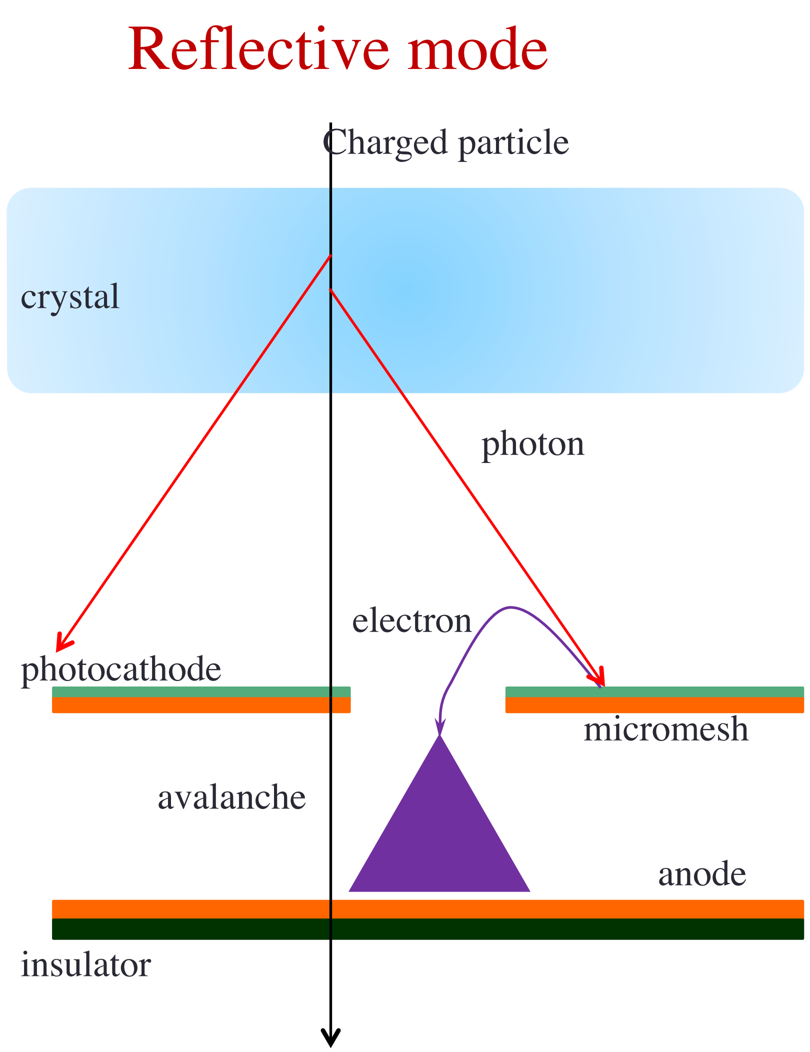


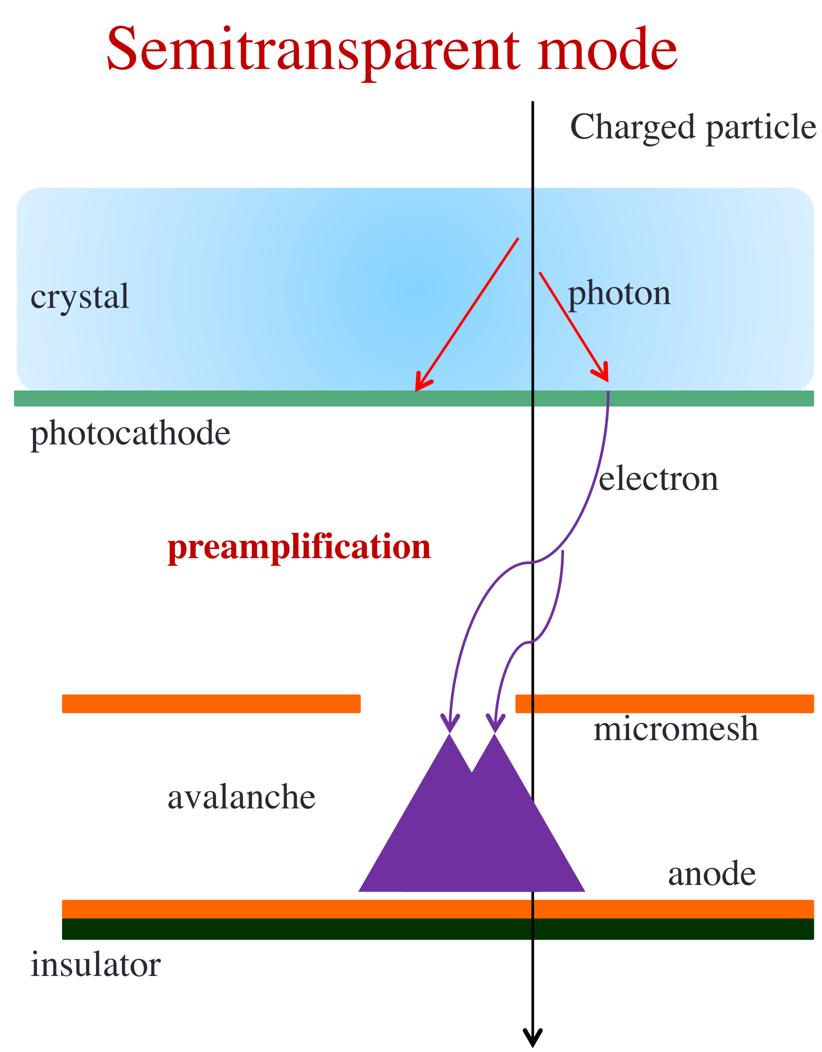
real response
to test pulse

MPGD alternative development:

Primary ionization: photoelectrons

- ➢ Cherenkov light produced by charged particles crossing a MgF_2 crystal
- ➢ Photoelectrons extracted from a photocathode (CsI)
  - ➔ Simultaneous & well localized ionization of the gas





Thomas responsible for construction and commissioning of Saclay test chamber

Limited diffusion

- Small drift gap + strong electric field
  ➔ Limited diffusion

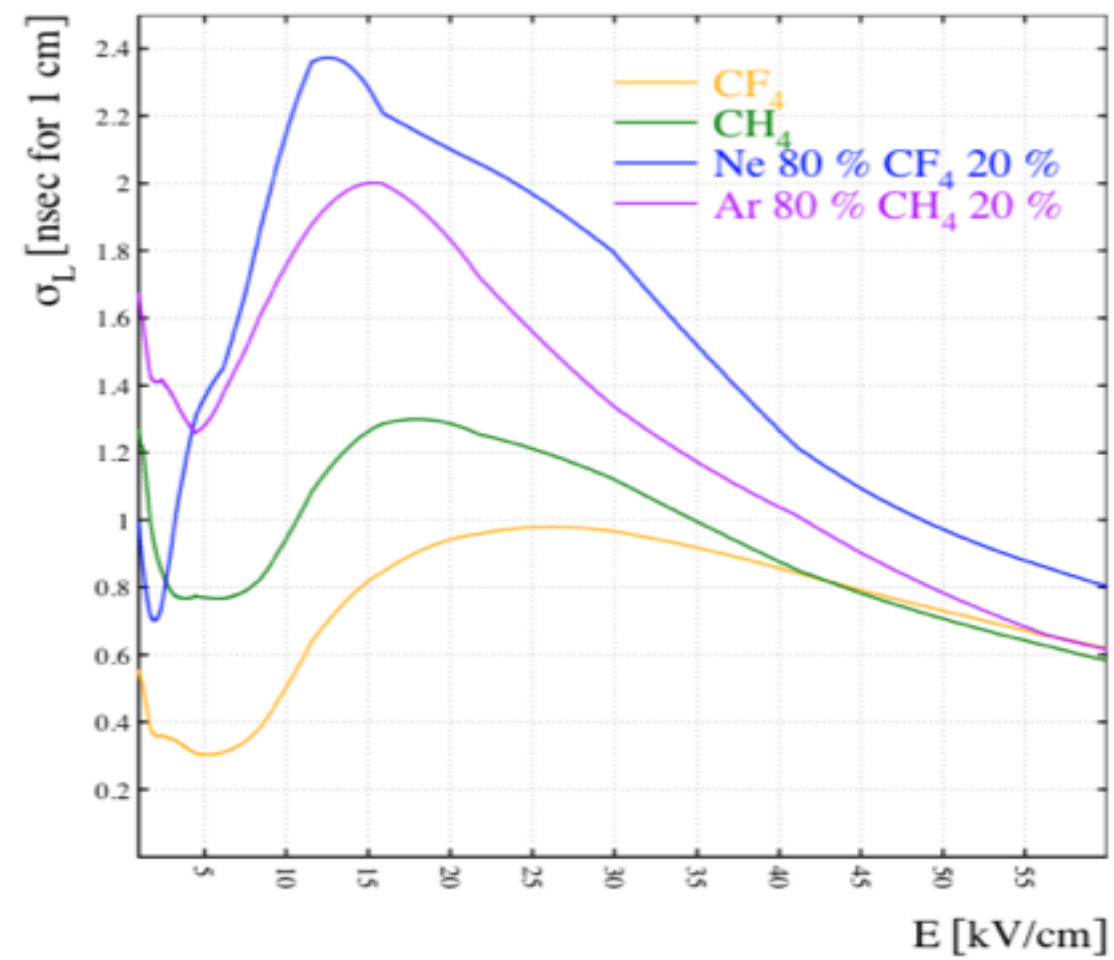
Simulations:

✓ Few hundred μm drift field can provide time jitter per electron < 100 ps (Ed ~ 5kV/cm)

✓ Several gas mixtures possible

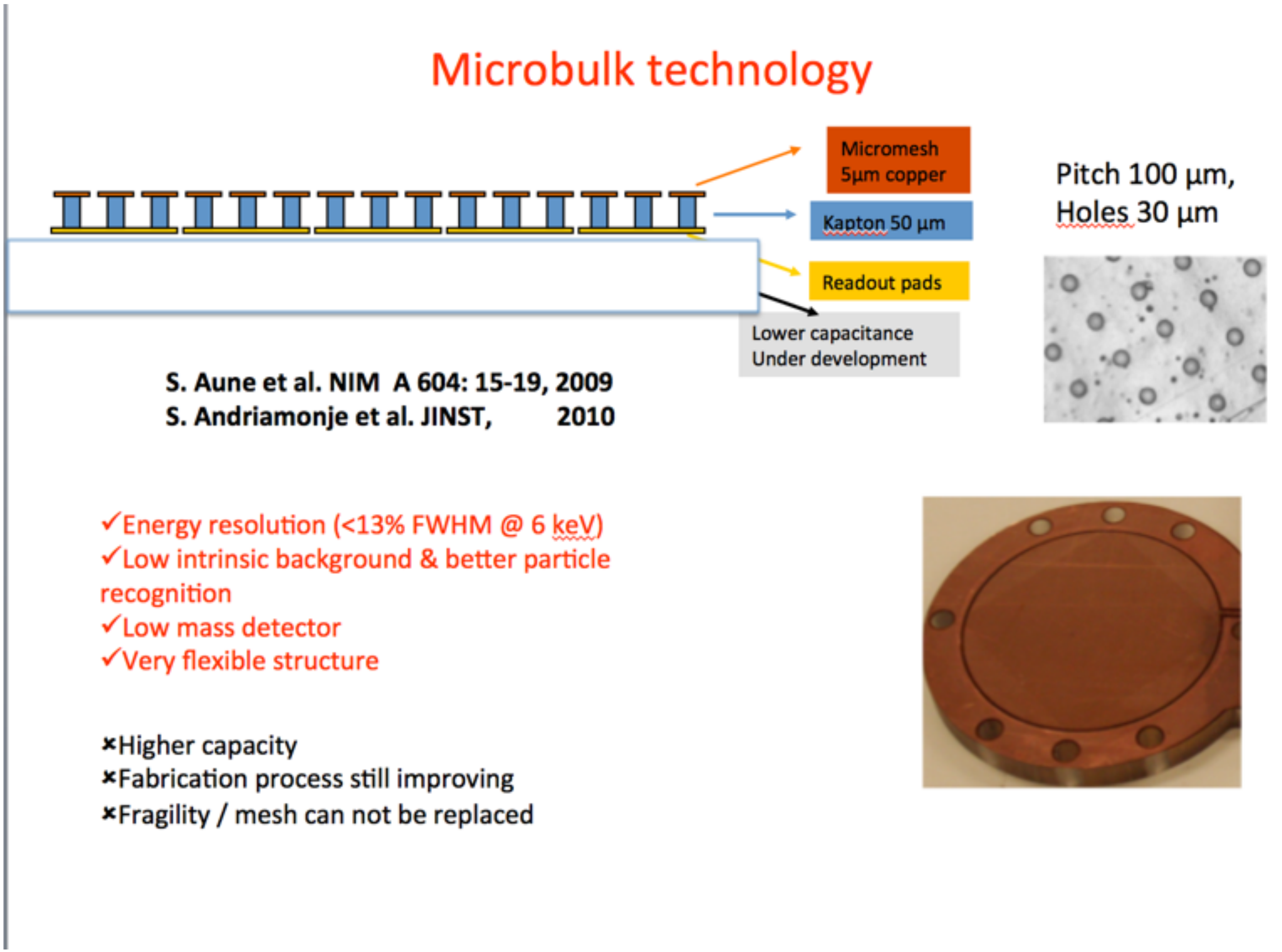
✓ Good performance for high amplification fields (>50 kV/cm)

➔ preamplification!



Longitudinal time jitter in 1-cm drift gap as function of the drift field for several gas mixtures. *(R. Veenhof)*

This initial test used Microbulk technology for amplification structure.
Potential time jitter reduction with higher pitch.
Used Ne-Ethane (10%). CF4 nominally will yield lower jitter.
210 V in 200 micron “drift region” led to limited pre amplification gain.
440V across micro bulk in run shown below.
initial test with 10nm Al used as “pc” with very low (~10^-6) qe
n-photon ~ Cerenkov photon yield in final design



Detector design

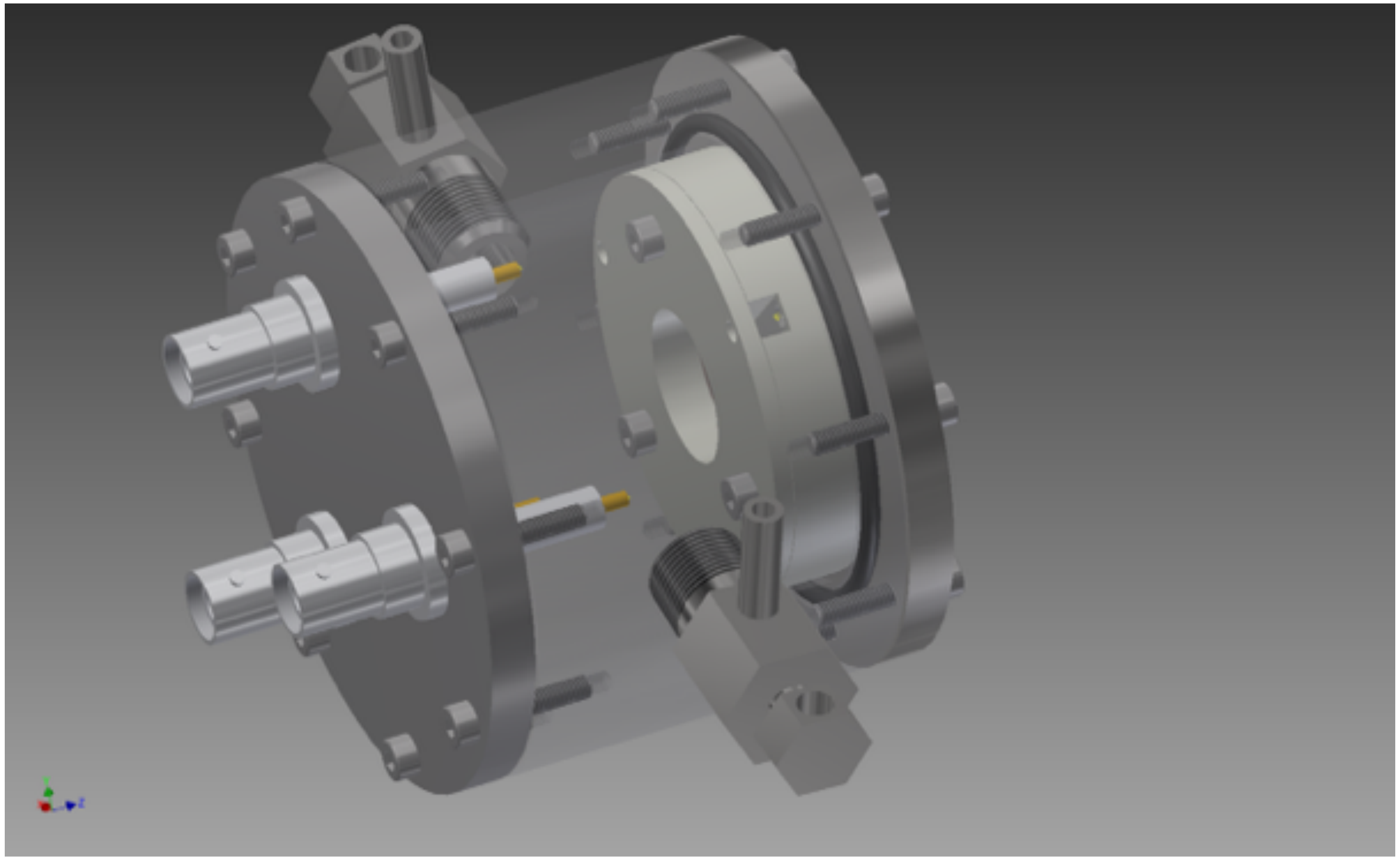
First tests with UV lamp / laser ➔ quartz windows

Microbulk Micromegas ø 1cm

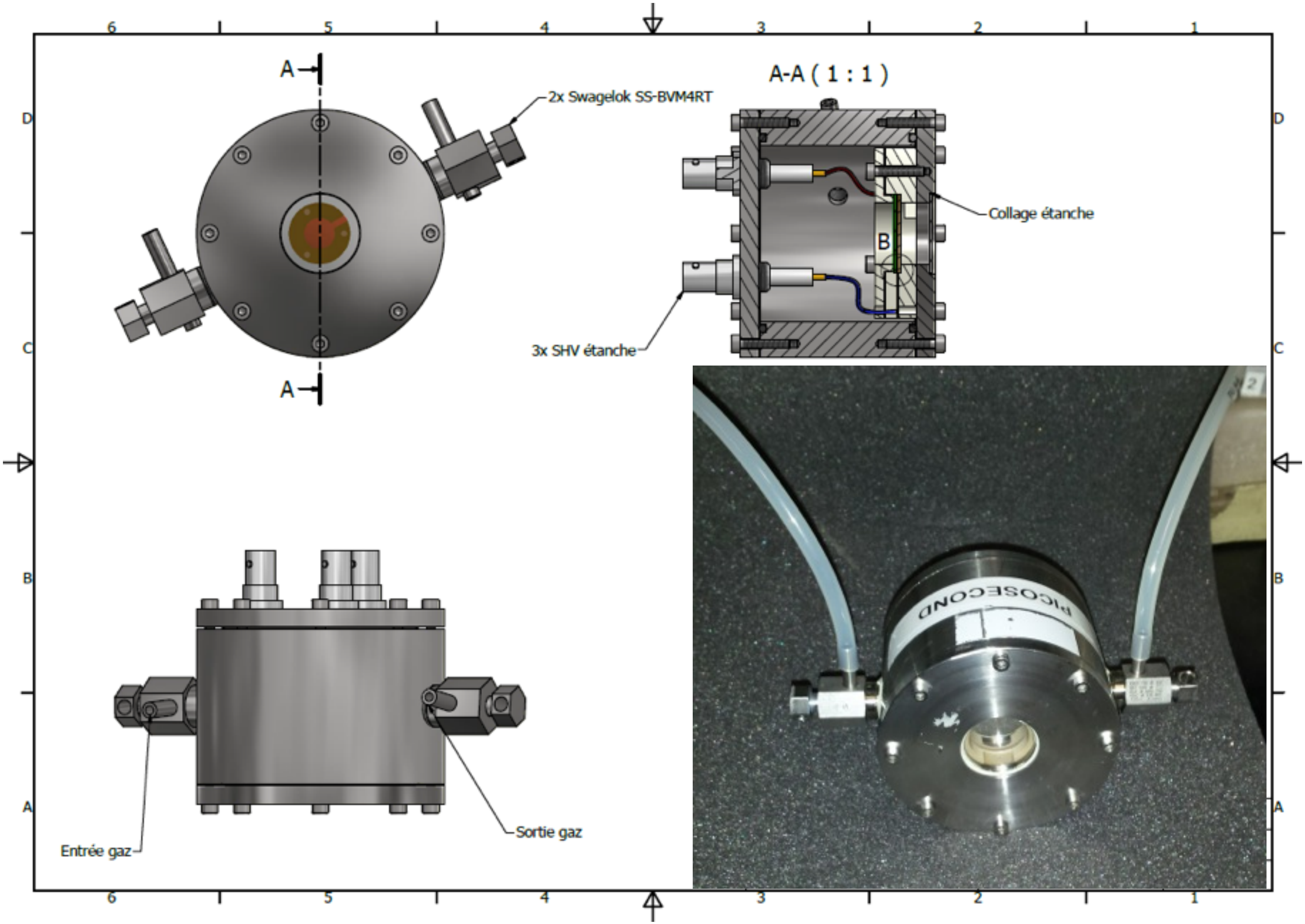
- ➢ Possibility to deposit CsI on the mesh surface
- ➢ Capacity ~ 35 pF

Ensure homogeneous small drift gap + contacts

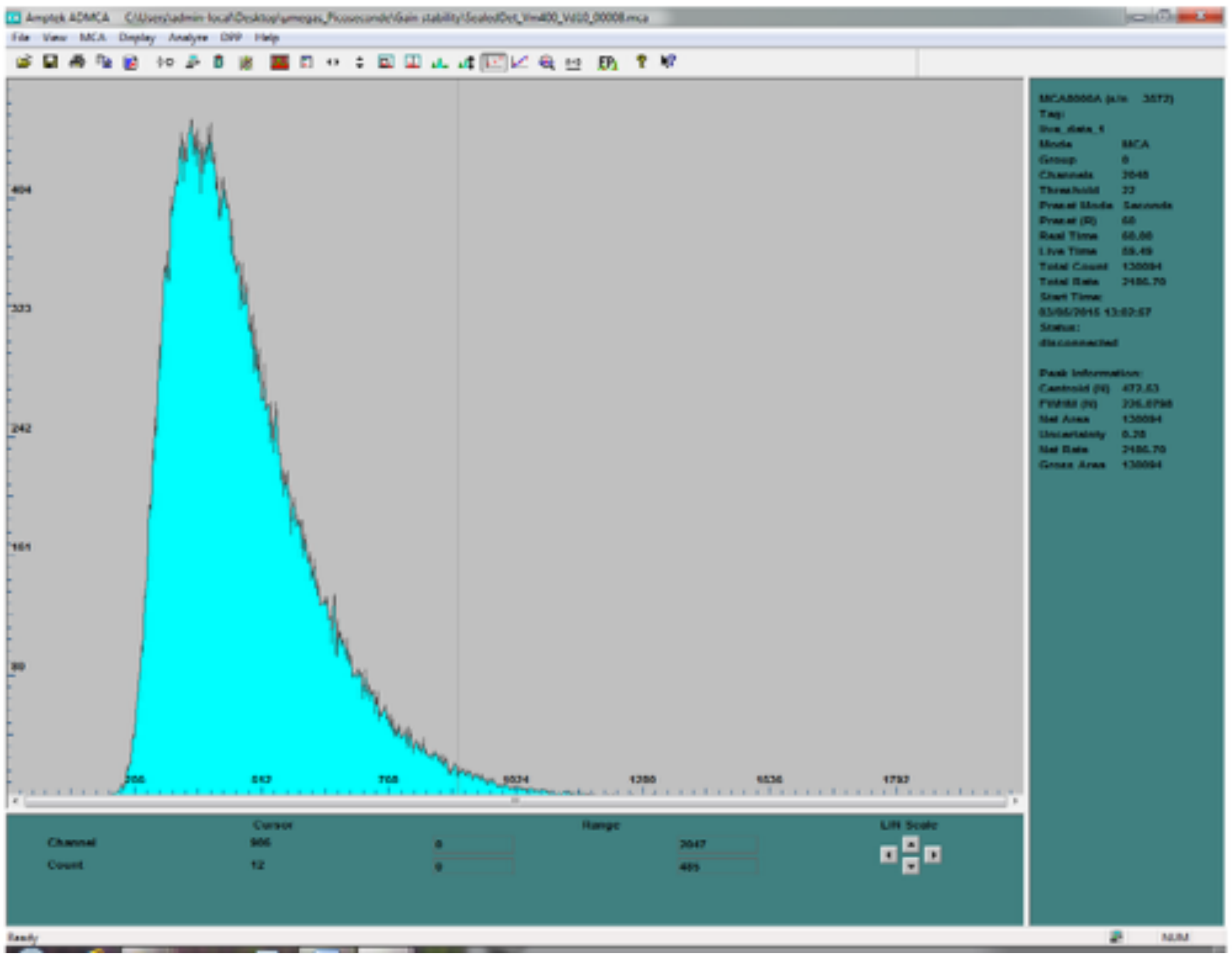
Stainless steel chamber for sealed mode operation

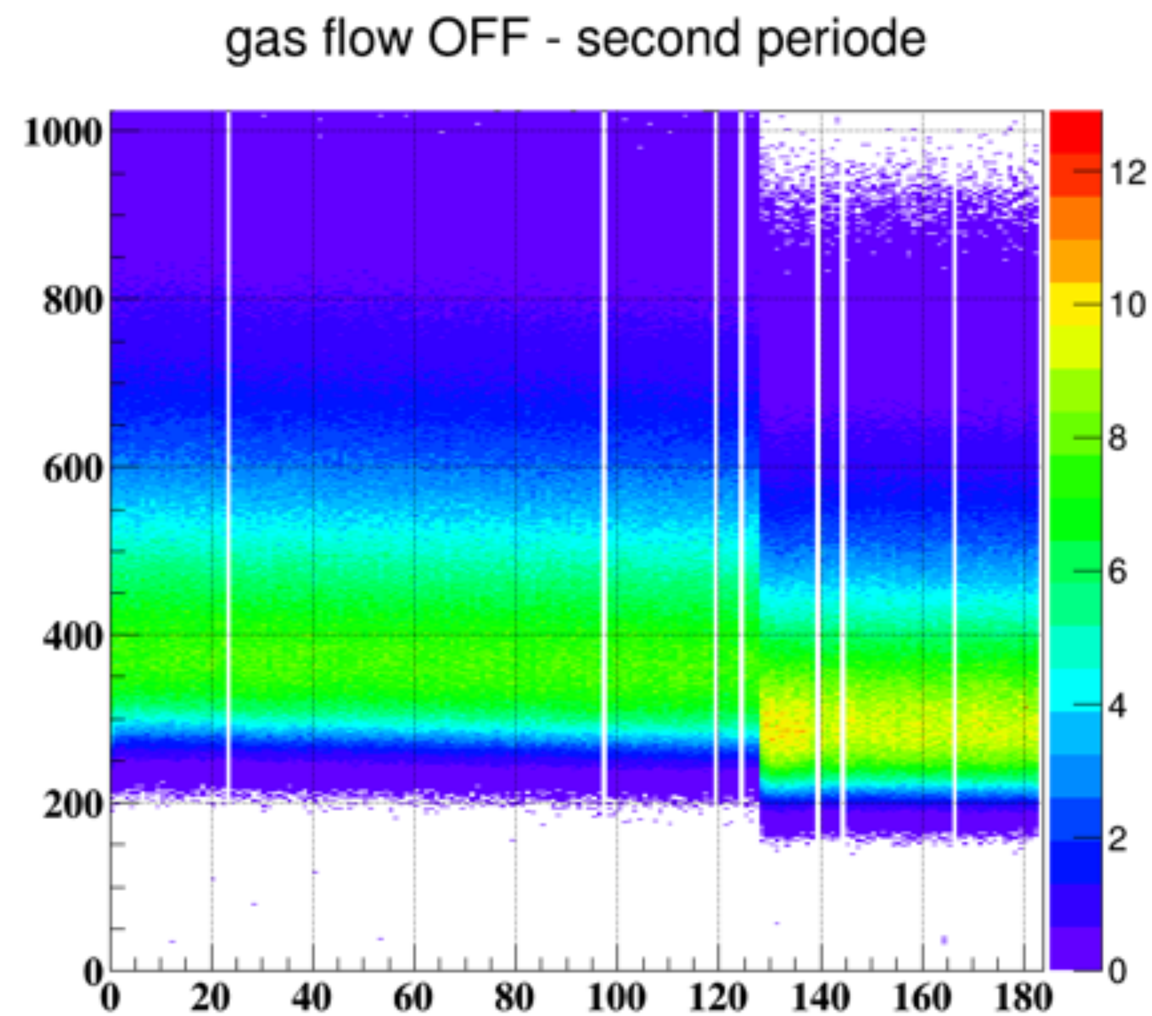


Detector design



Tests with deuterium flash lamp





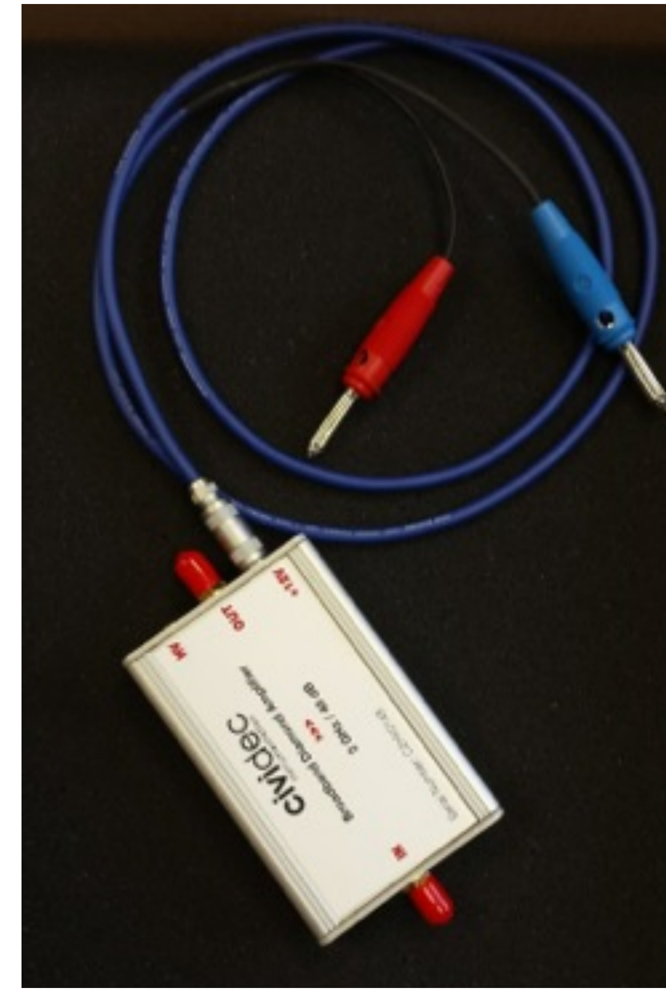
Estimated ~20 photoelectrons per pulse by comparing with the amplitude of the signal from a candle

24 hour run in sealed mode. Lamp not very stable

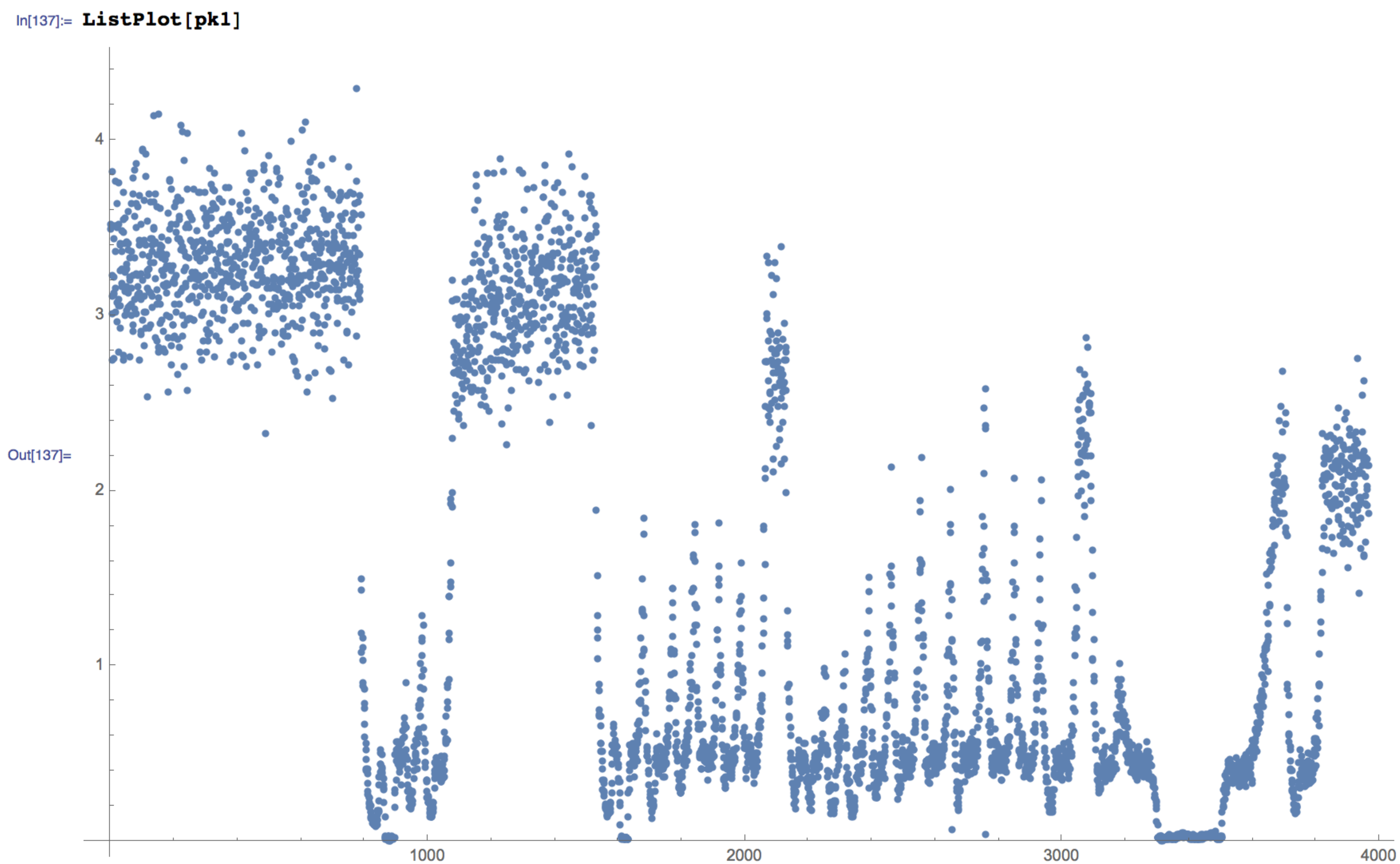
Tests with femtosecond laser

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

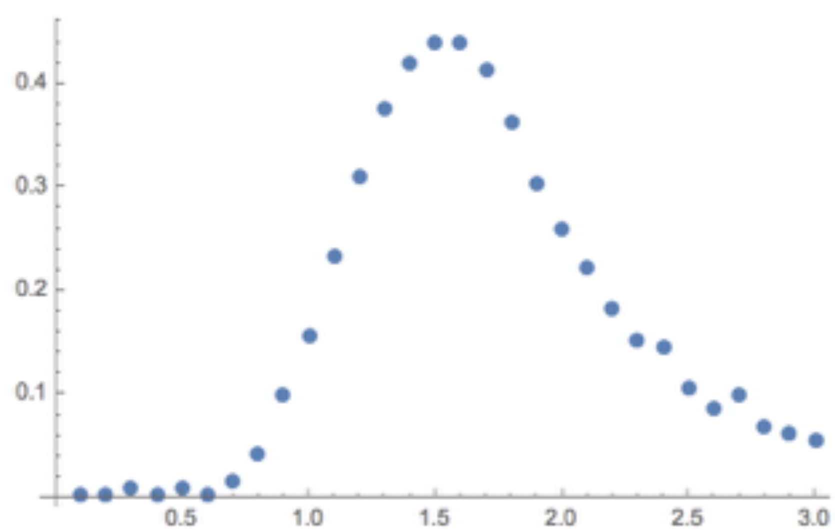
- UV laser with σ_t ~ 100 fs
- λ = 285 nm after doubling
- intensity ~ 3 mW
- Repetition 5 MHz (!!) - limitation on gain
  - ➔ Reduced to 8 kHz on the second day
- Sealed mode
- Trigger from fast PD
- Cividec 2 GHz current preamplifier

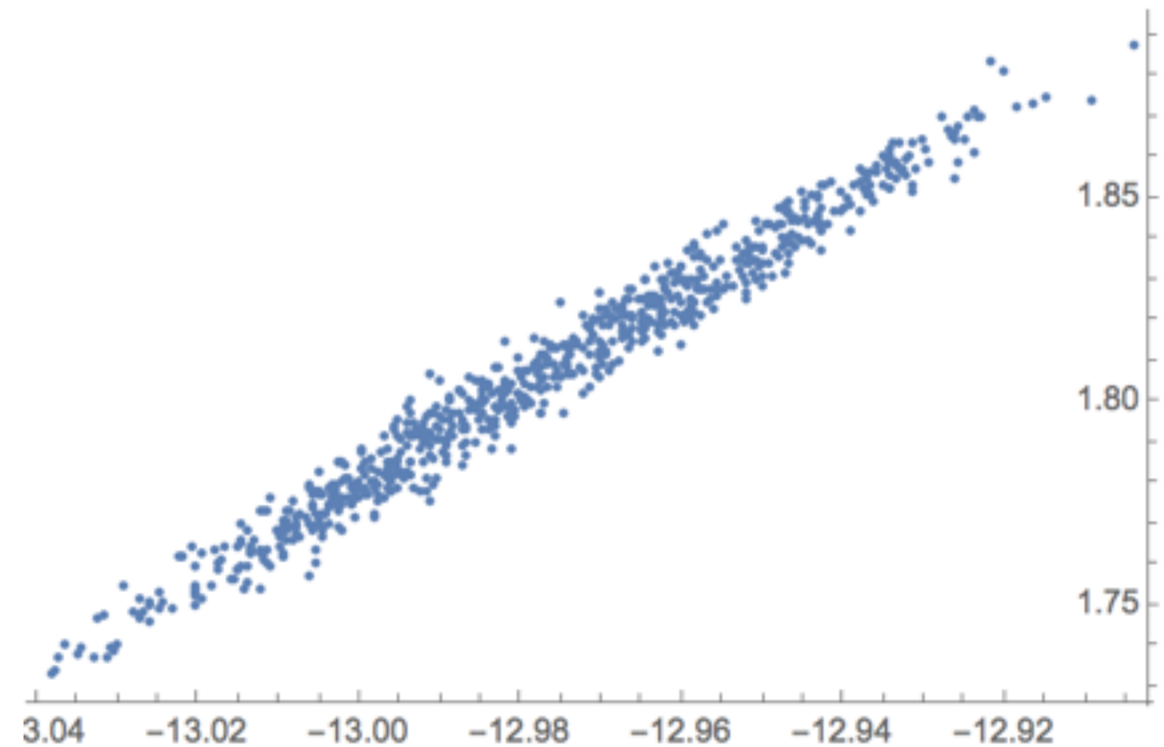


amplitude vs. event no.



Removing Jitter due to laser trigger (from PD)

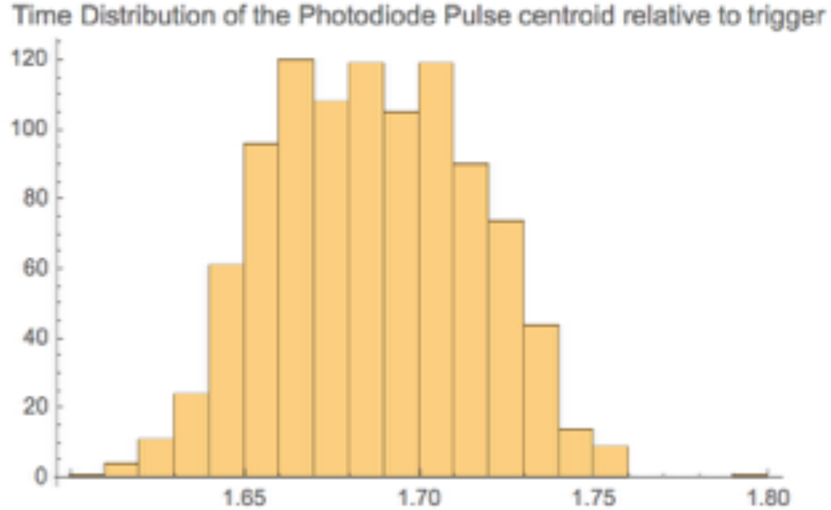


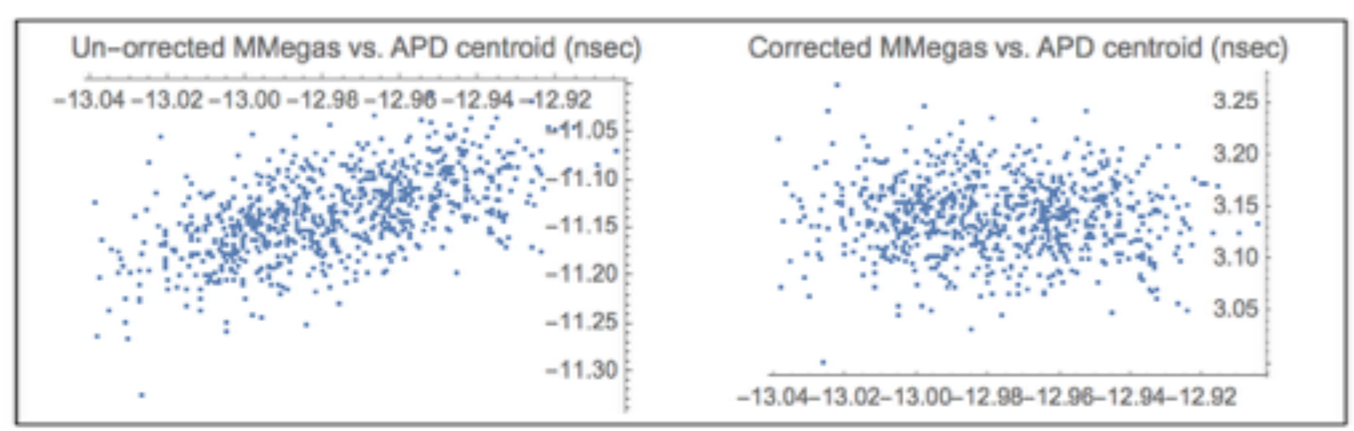


CF method and centroid perfect correlation

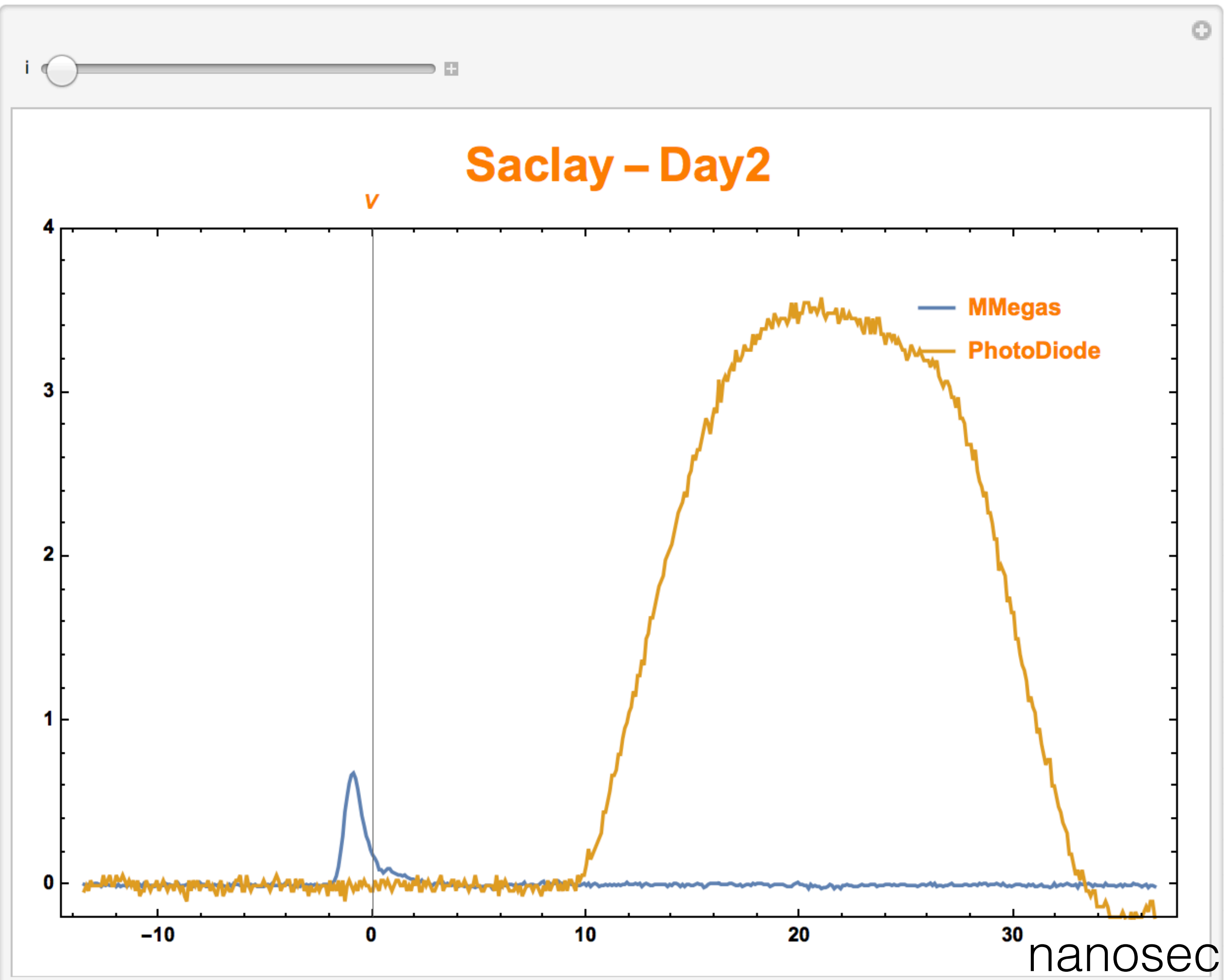
```
rmsa = RootMeanSquare[meana - mma]
0.0288653
```

Time Distribution of the Photodiode Pulse centroid relative to trigger



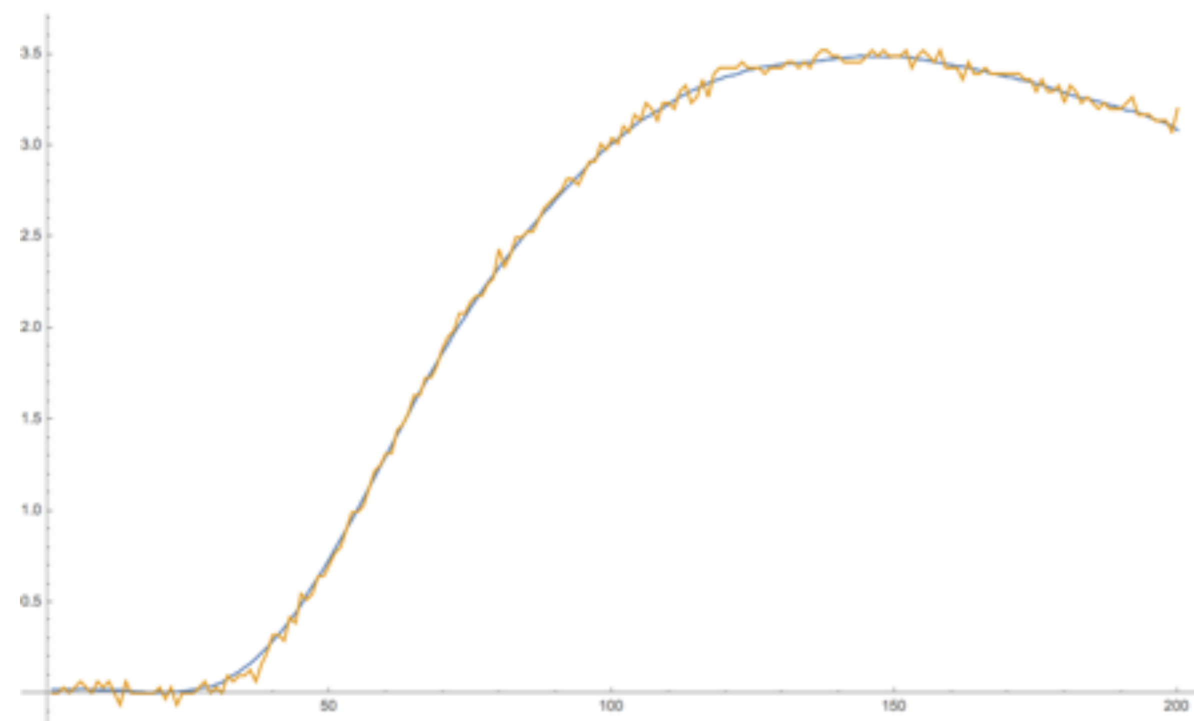


Laser PD and MMegas



nanosec

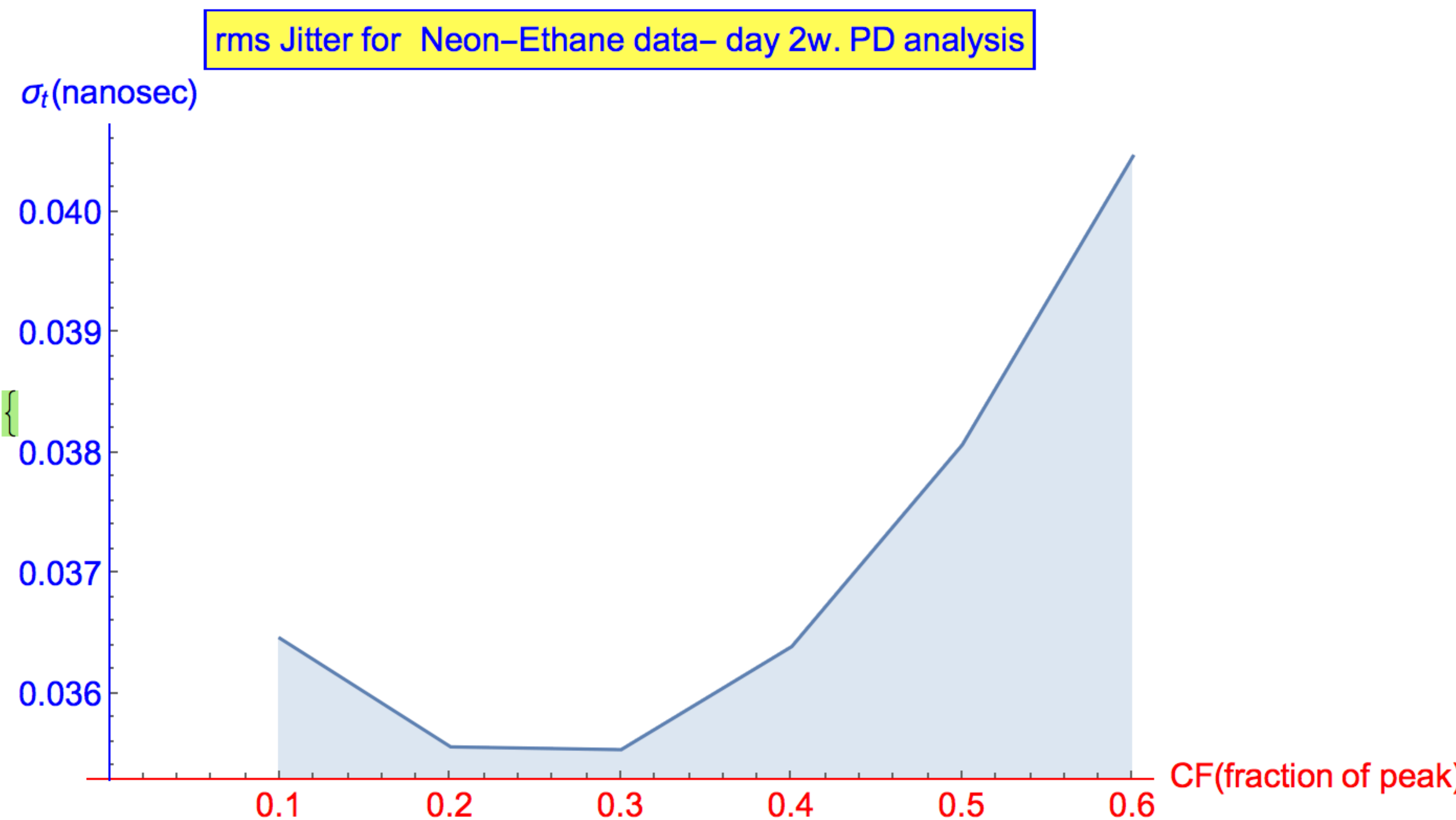
filtering mostly for digital noise



0.1 nanosec bins

jitter in 1st 750 events

Out[109]=



0.1	0.0364597
0.2	0.0355588
0.3	0.0355354
0.4	0.0363913
0.5	0.0380673
0.6	0.0404614

some summary remarks

- In both Si and MPGD we are now in a new position more directly in control of technology- less dependent on industrial partners
- 2nd chamber from CERN soon ready
- we are very interested in working with people who are experts in photocathode development and SEMs
- beam tests in summer will focus on charged particle performance (complementing Si data we have from FNAL, PSI, DESY and CERN SPS

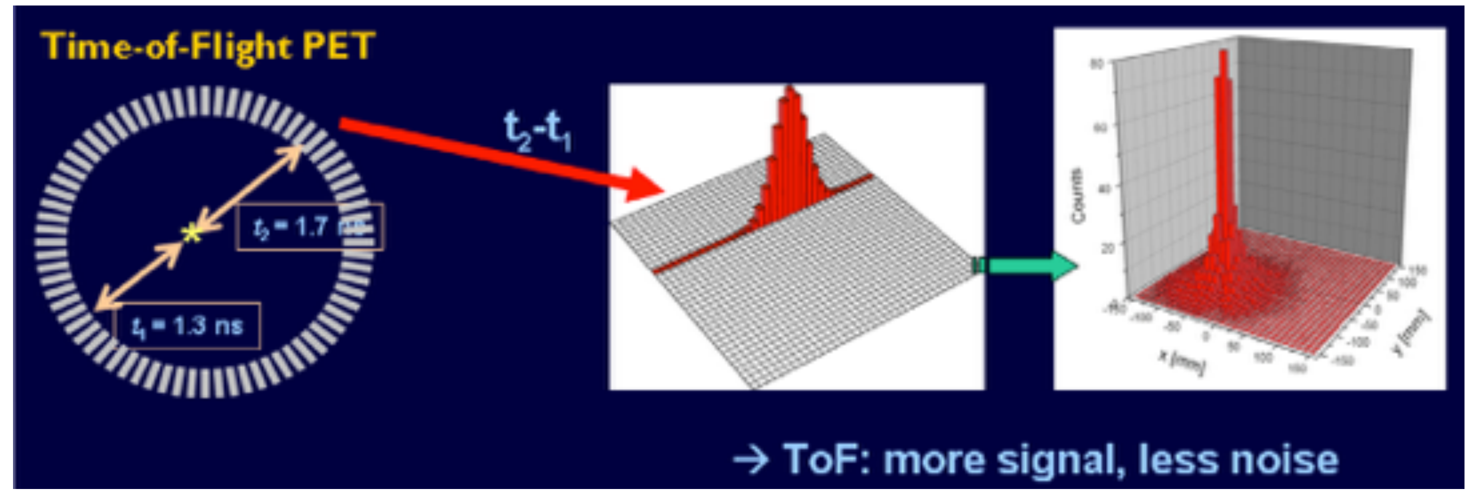
Postscript: Fast Timing in Brain Imaging

"detector-centric" objective

->EU "Picosec" initiative but

- PET images the level of Sugar-uptake in the brain.
- Sugar is not the main energy source.
- The level of activity not necessary indicator of Cognitive Function

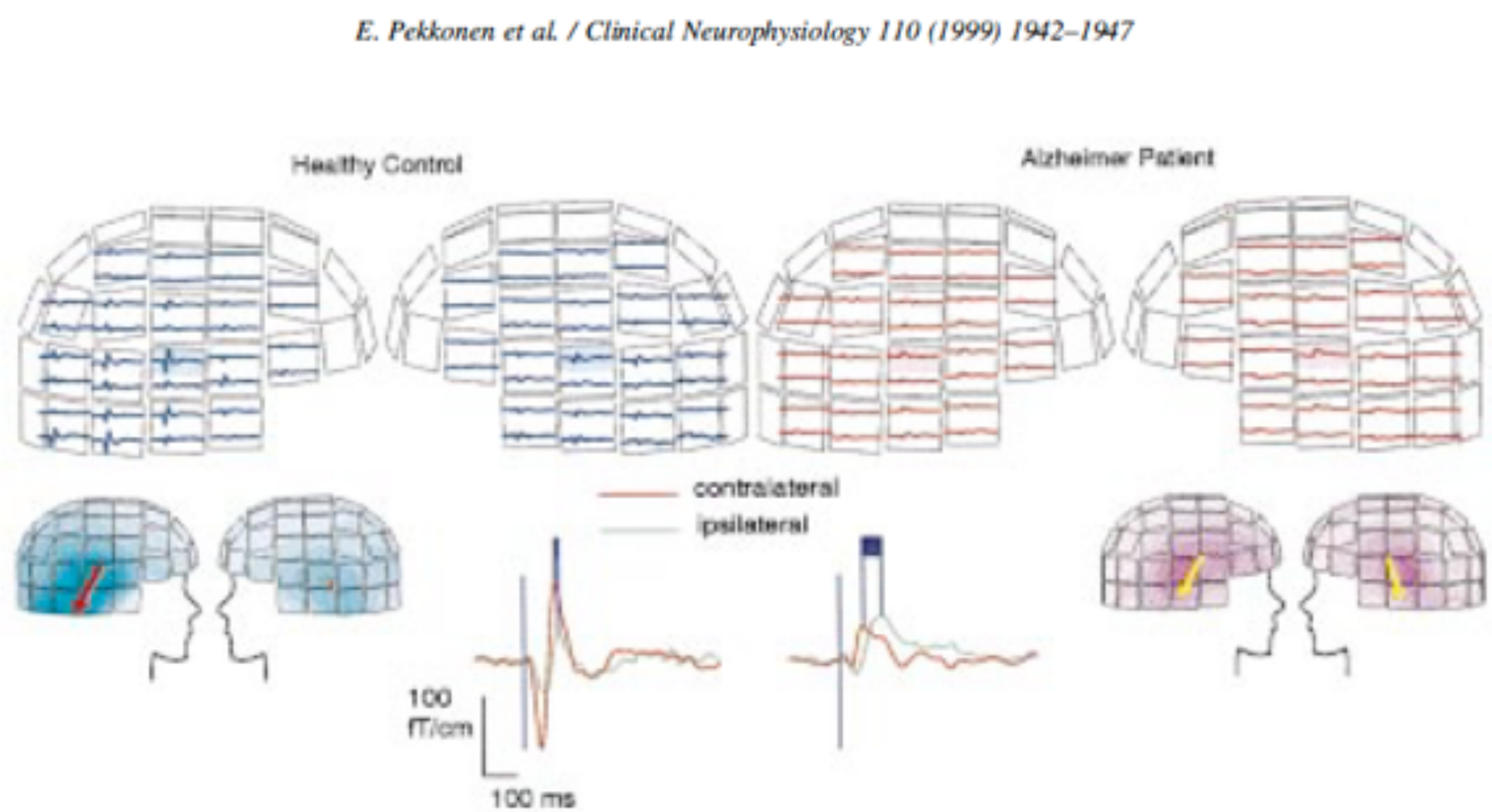
=>



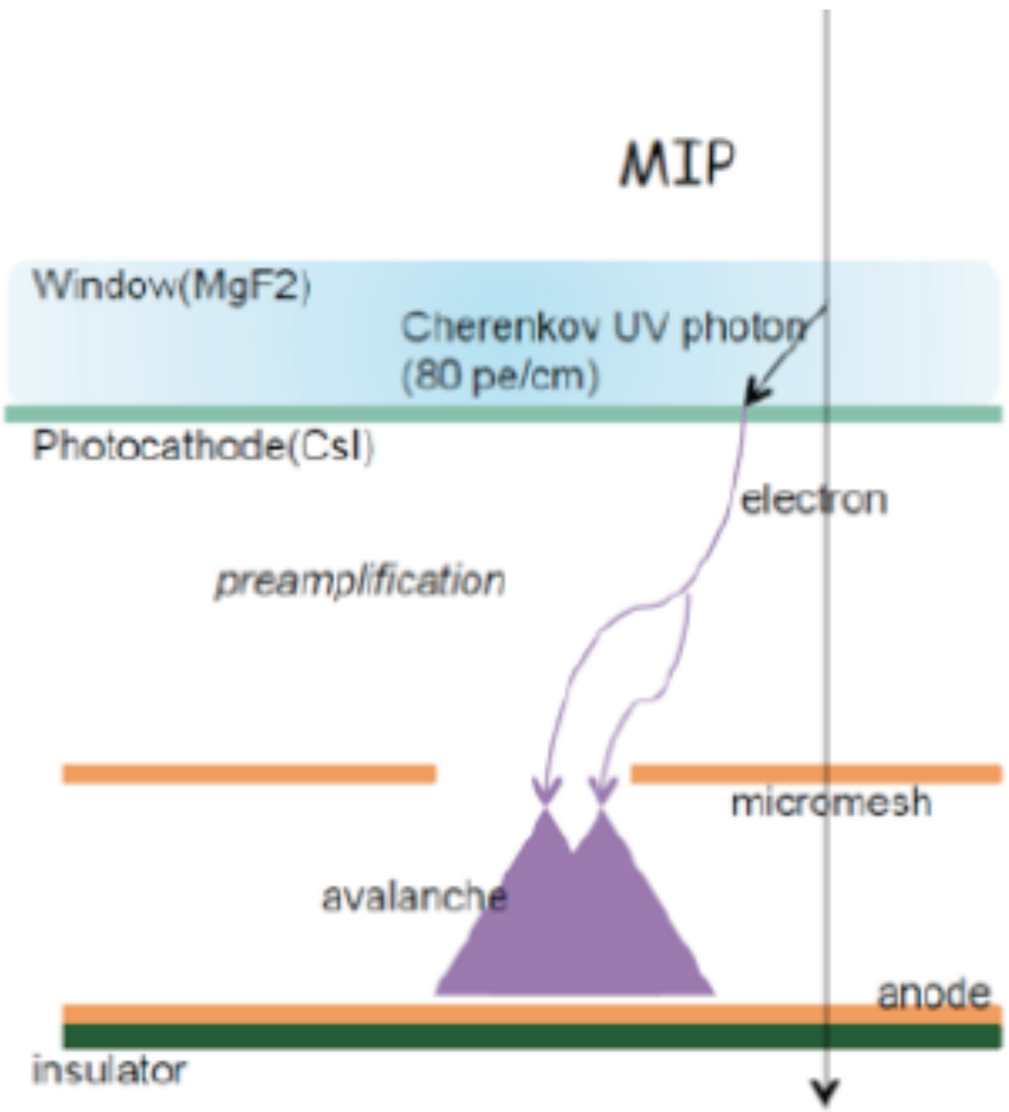
Neuroscientist Objective

- MagnetoEncephalography is the only non-invasive technique to image the brain on the time scale of neuronal activity.
- Delayed response to external stimulus and its dependence on complexity of the pathway is potentially a powerful bio-marker for Alzheimer's and other diseases.
- It could be used to provide early detection and guide therapies, etc.

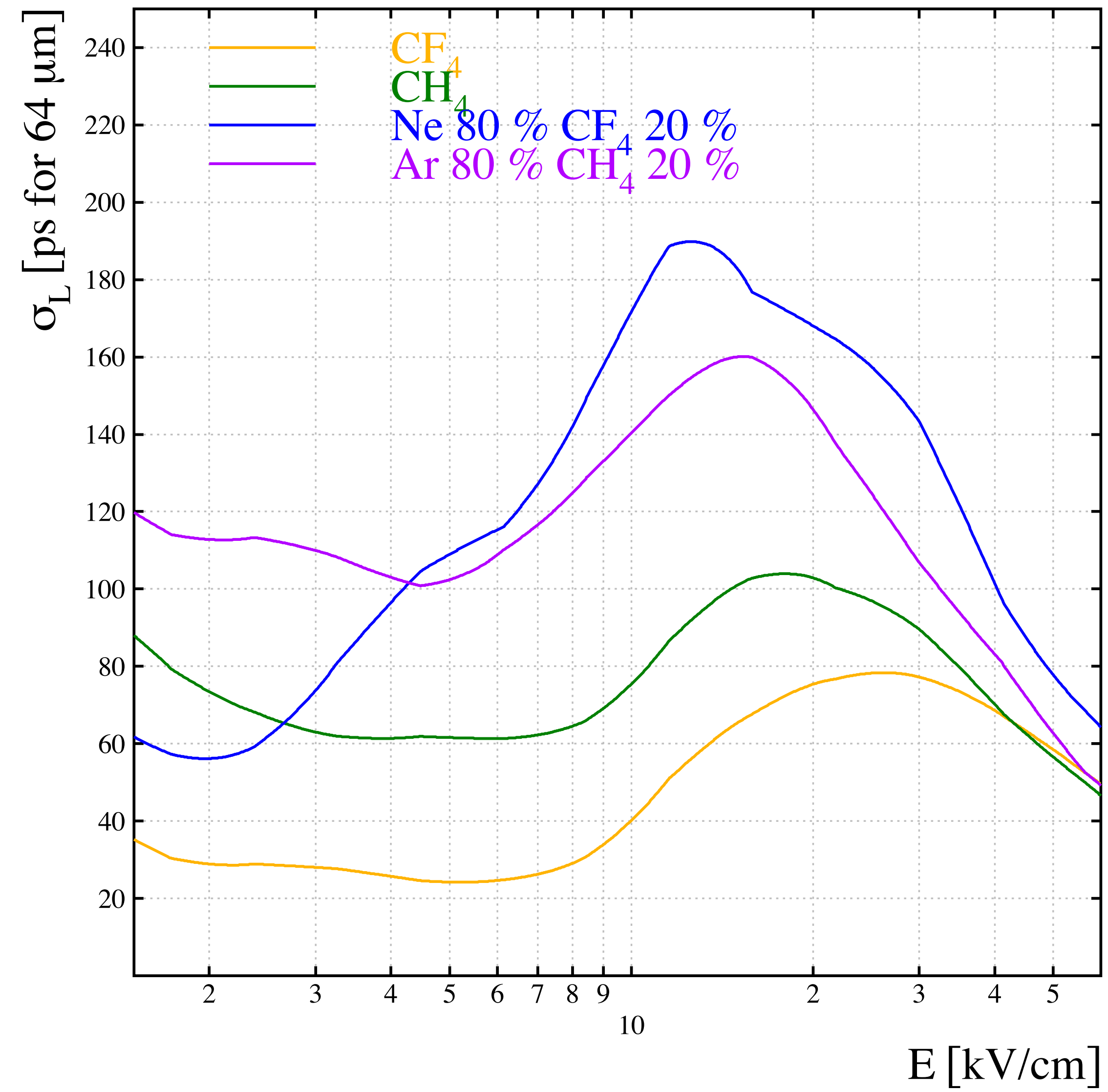
=>



for both issues have started GasPMT parallel effort



transparent pc version



(Rob Veenhof calculation)

now building test chambers @Saclay and CERN
look forward to working with FNAL detector group
on rad hard Photocathode development, etc.
(A. Ronzhin is an expert)