Precision Timing Measurement with MicroPattern Detectors*

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MPGD 2017
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- MicroPattern Detectors enable both spatial precision and <u>speed</u>
- the latter was motivation for Si development at CERN in 70's
- Recently a fast moving field
- Why and How is the subject of this talk

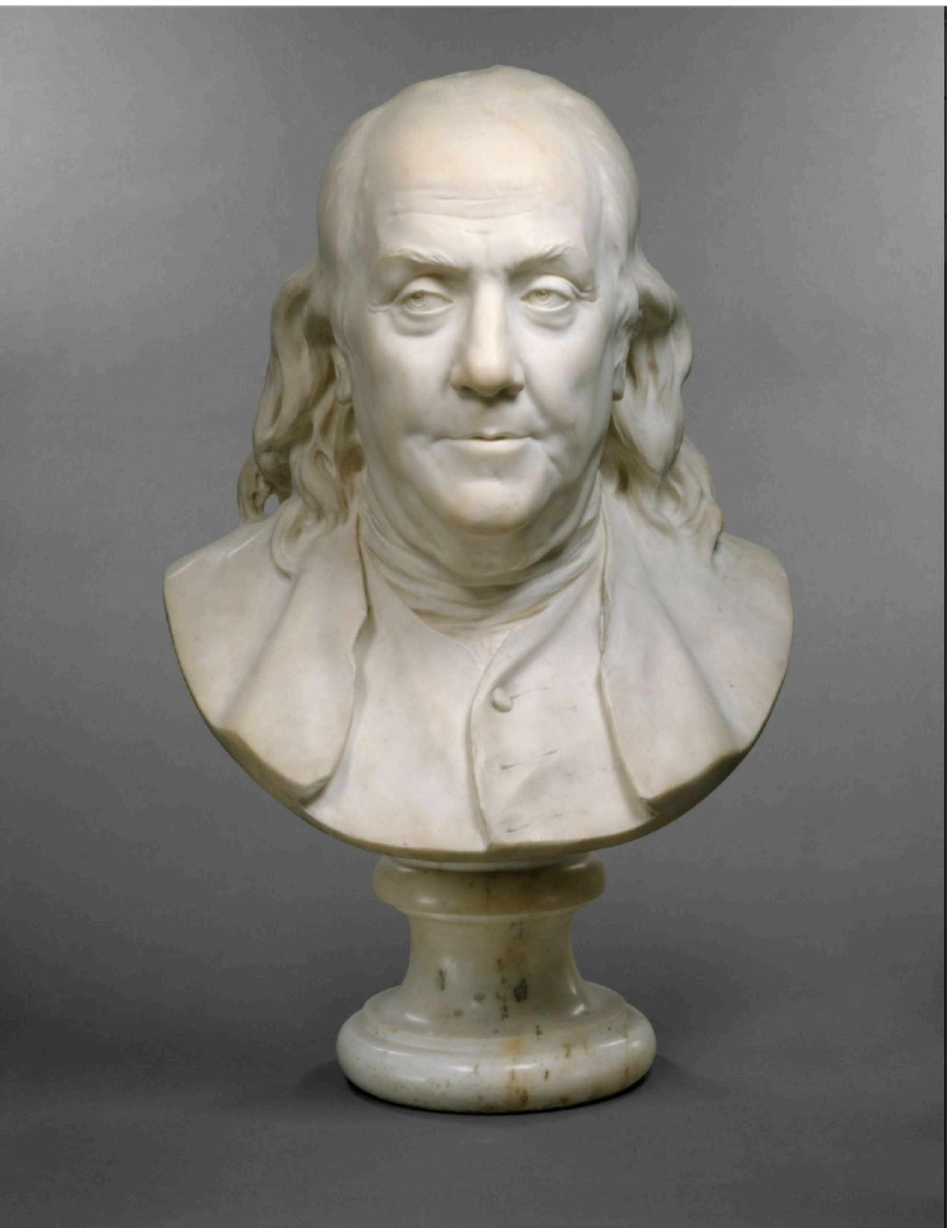
HELLENIC REPUBLIC
ARISTOTLE UNIVERSITY OF THESSALONIKI

National Centre for Scientific Research "Demokritos"

RMD A Dynasil Company

*=MPGD,MPSiD,MPVacD….

The Philadelphian



"the most accomplished American of his age and the most influential in inventing the type of society America would become."
Walter Isaacson, Ben Franklin (2003)

Jefferson had written, "We hold these truths to be sacred and un-deniable..."
Franklin changed it to, "We hold these truths to be self-evident."

Franklin was a physicist and elected to Royal Society of London at age 50.

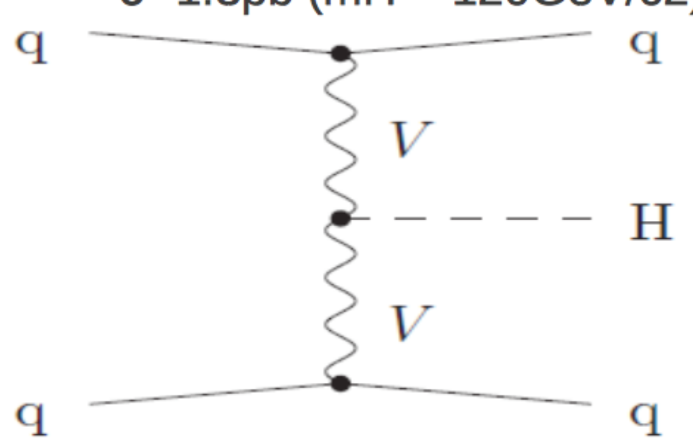
"Either write something worth read-ing or do something worth writing."
-Ben Franklin

(on PICOSEC we now have critical mass to do both)

what has changed:

- (trying not to repeat earlier excellent background)
    - Review by Jerry Va'vra https://arxiv.org/abs/1611.01713
    - CERN Precise Timing wkshop: https://indico.cern.ch/event/607147/ referred to as "CERN Wkshop"
- Until recently Particle ID (topic of Va'vra) has dominated Fast Timing
    - low rates and density: see e.g. C. Williams ALICE TOF
    - possible large area mapping to photosensor (eg DIRC)
- LHC topic of pileup Mitigation forced focus on MPDs
    - FP420 helped raise awareness of the need

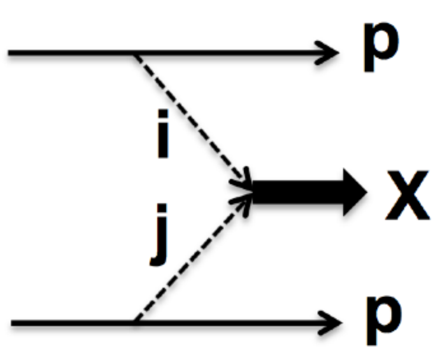
σ=1.3pb (mH = 120GeV/c2)



- However main emphasis has moved well beyond ForwardProtons->Endcap
- Worth keeping an eye on Physics need for large area <100 psec photodetectors
    - eg. J. Klein (@CERN Wkshop) and CHESS: https://arxiv.org/pdf/1610.02029.pdf

a brief personal timeline

- 10 years ago a proto-collaboration, mostly theorists and British LHC accelerator types- "fp420"
- technical problem of correlating leading protons w. central ->"On the Correlation of Sub-events in ATLAS and CMS/ TOTEM Experiments"- SNW, 2007 https://arxiv.org/pdf/0707.1500.pdf



- p detected 100's of m down beam pipe
- X in central detector=> correlate w. "subevent"
- ->hi-Lumi, pileup vertices, ~1 p /crossing

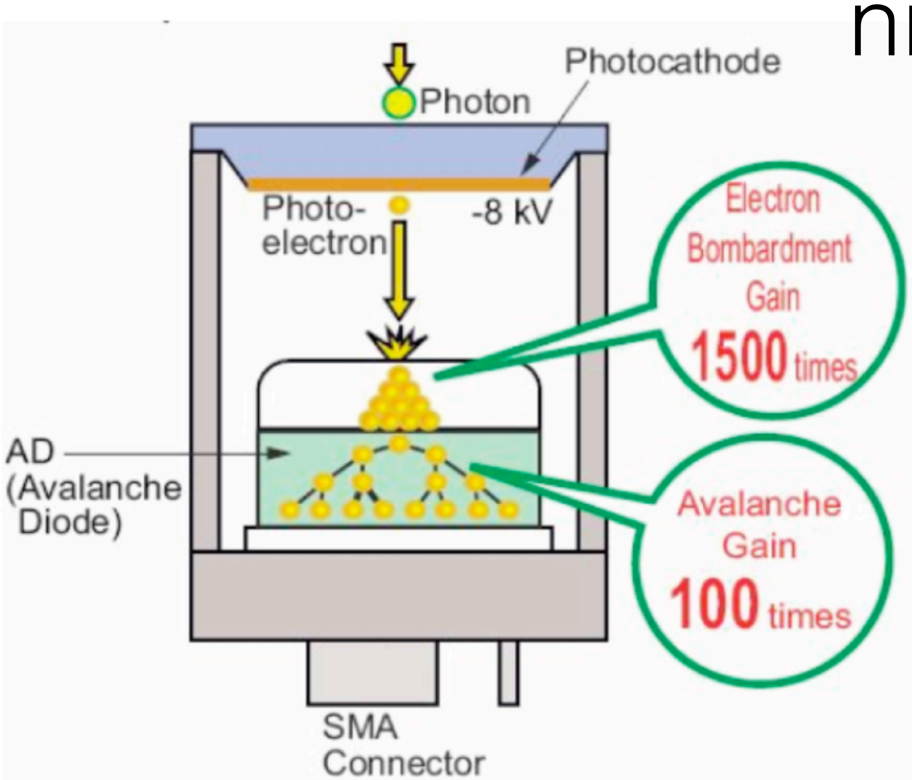
- in 2007 I gave a BNL seminar
- could any technology give p time to 10-20 psec?
- asked V. Issakov to come
- M.Zeller worked on Sandweiss
- many shook their heads
- Issakov got excited

Hybrid Avalanche Diode (HAPD) demonstrated MIP detection speed of AD (ie Silicon w. Gain)

- Issakov had found the work of Motohiro Suyama(Hamamatsu) &co. HAPD->pre-R10467u

- we (w. T. Tsang) collaborated w. HPK and measured 11 picosecond SPTR

nice device!~big lifetime gain on MicroChannelPlate PMT



A photodetector using a charged particle detector originally developed for photodetection (AD)

- irony of using such a device coupled w. a radiator for MIP detection got to us

similarly in PICOSEC we made a MIP detector out of photodetector originally based on tracking….

- ->https://arxiv.org/abs/0901.2530

Design of a 10 picosecond Time of Flight Detector using Avalanche Photodiodes

Sebastian White, Mickey Chiu, Milind Diwan, Grigor Atoian, Vladimir Issakov

(Submitted on 16 Jan 2009)

Photon vs. Charged Particle Timing

- HAPD developed as an alternate to MicroChannel Plate(MCP) PMT by Hamamatsu, with improved lifetime

- both (MCP&HAPD) promise excellent charged particle timing with Cerenkov photons from front window(see below)

- but detection in HAPD based on fast Si detector with Gain

- this suggests 2 possible approaches:

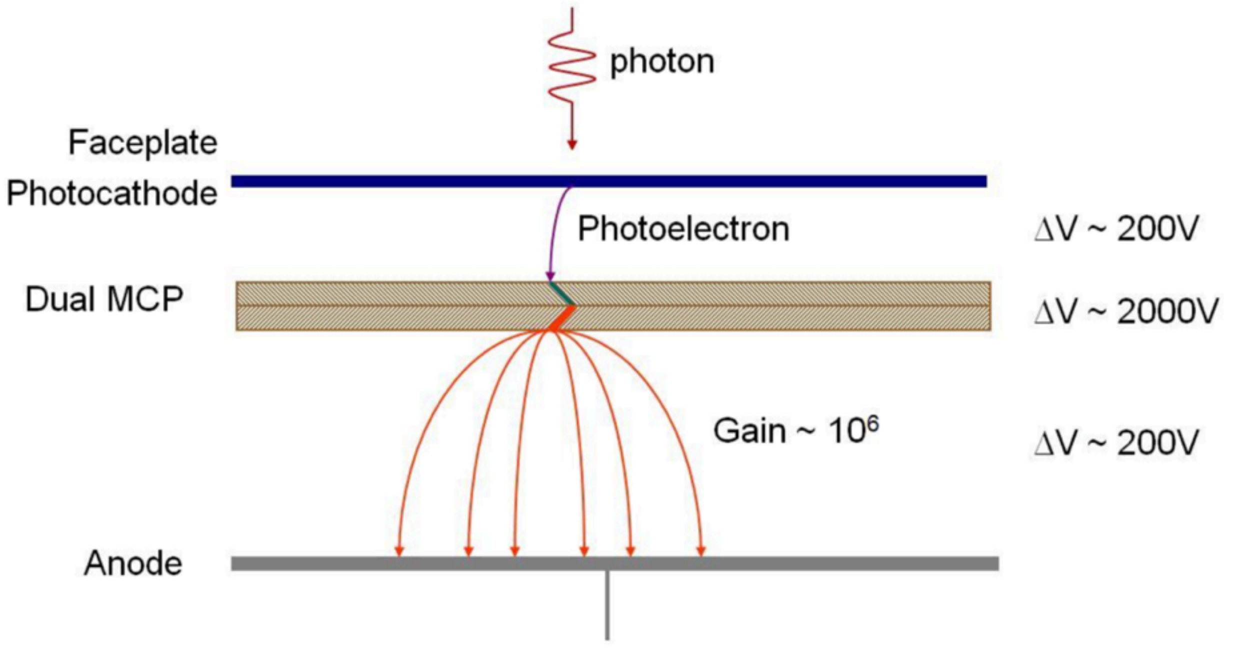
1)develop large area, cheaper, robust photodetector (ie LAPPD in H. Frisch talk(next) or PICOSEC, based on MicroMegas)

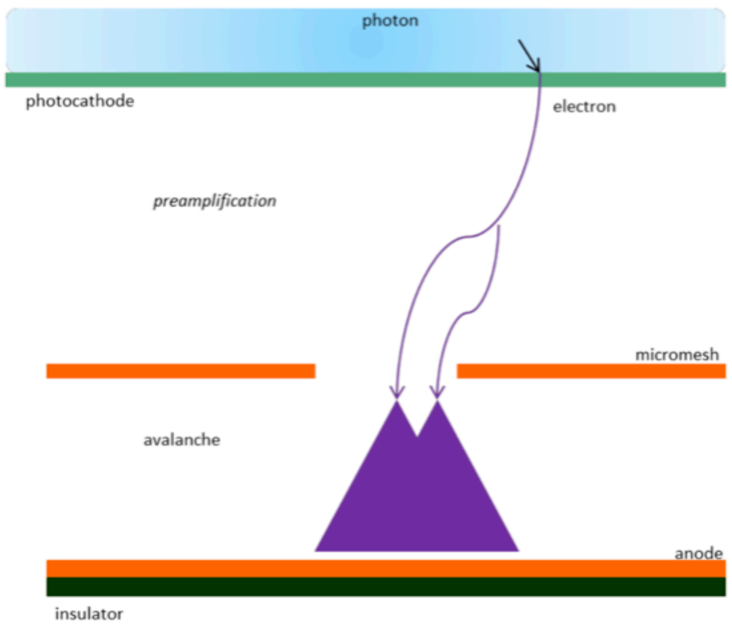
2)develop Silicon detector w. Gain suitable for large area coverage and better suited for Min Ionizing particles(in HAPD it is tiny and detects ~10keV e^-)

2016: 150 GeV muon Beam in H4. 2 Hamamatsu MCP(R3809u) used as basic timing Ref. Detailed mapping of MCP, PICOSEC and HyperFast SIlicon

ref.

DUT





MCP:

PICOSEC:

Similar/Different:

3mm C radiator:Quartz -> MgF2

Bi-Alkali pc -> CsI (also Metallic+..)

photoelectron yield: ~16 pe -> ~12 pe

limit to time jitter: TTS -> longitudinal diffusion

obscenely expensive -> cheap

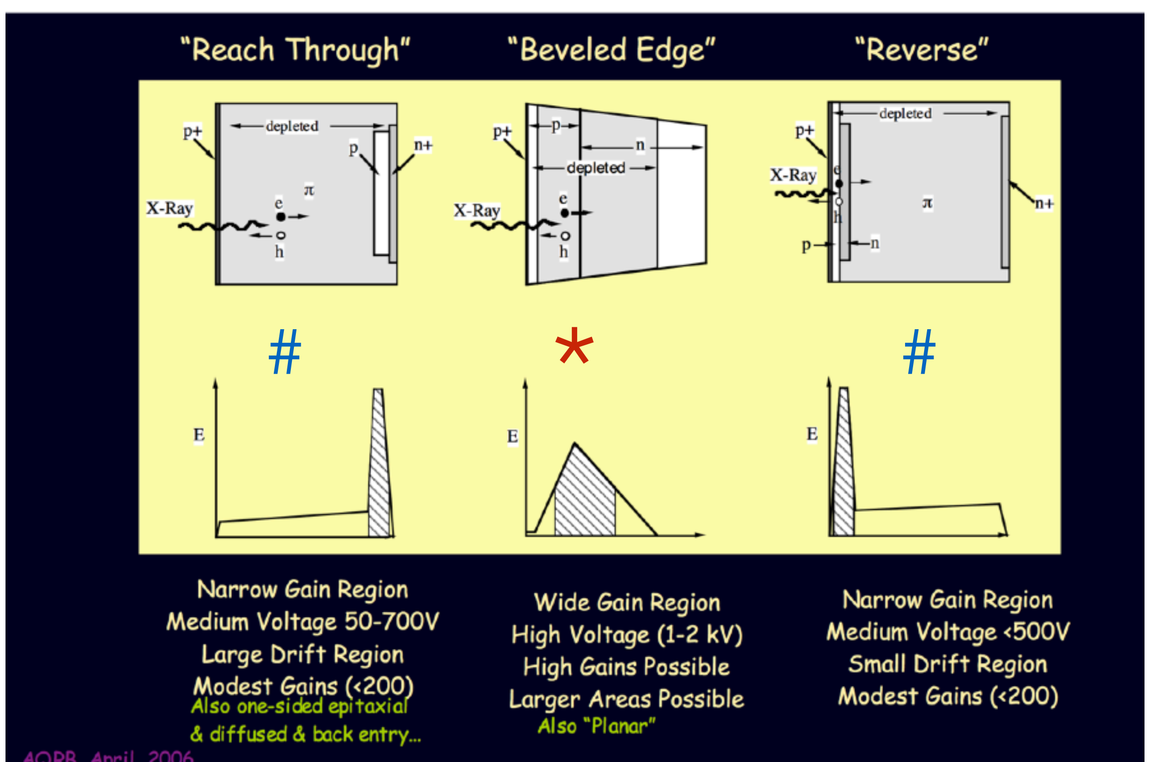
MIP time jitter: 5.5/Sqrt[2] psec -> 32 picoseconds

Basics of Silicon w.Gain for MPGD Experts

- for Silicon (and Diamond sensors) w/o Gain see e.g. Berretti&Minafra @ CERN Wkshop. Hard to get much below 100 picosecond MIP timing without Gain

- Silicon with internal gain (subject of our CERN SiSensorDevelopment working group) developed 60's and 70's in US & Canada. Nice MIP timing (~50 picosec) in papers from 70's & 90's (eg NIM A 337 (1994) p.362)

- Original structure based on superficial thin gain layer ("reach-through" technology) now used by many APD companies -and Centro Nacional de Microlelectronica(CNM).



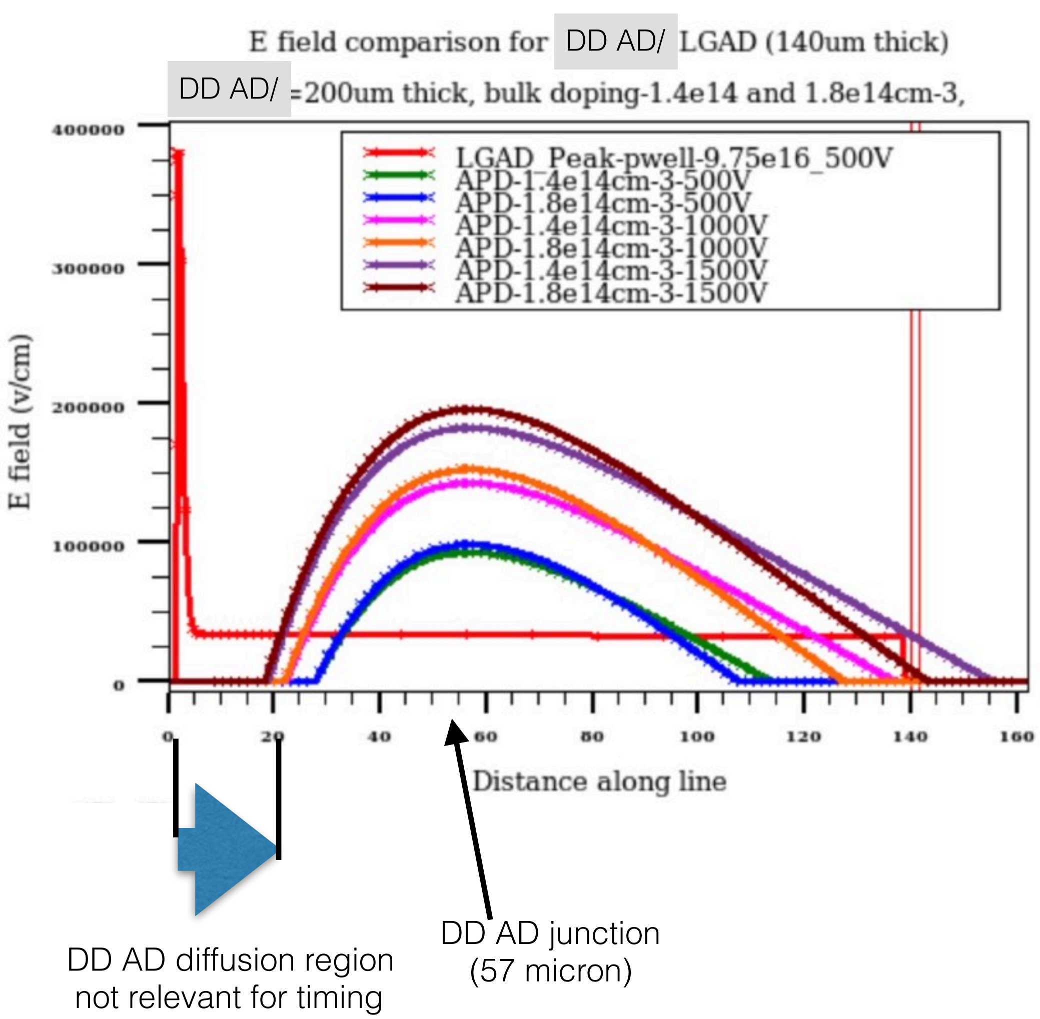
from 2006 SLAC talk about AD Options

2 basic types of AvalancheDiode

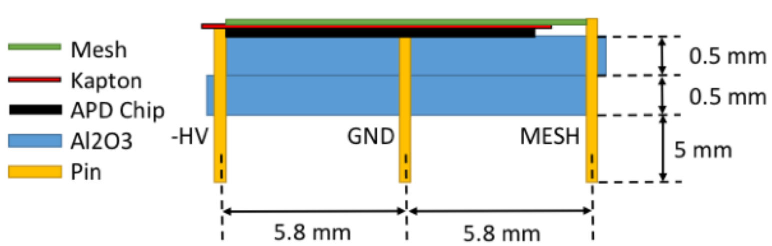
- low Gain w. drift (more common) #
aka. LowGain AvalancheDiode
-see Fabian Forster "LGAD" @CERN Wkshop

- DeepDepleted AvalancheDiode *
w. junction buried ~60 micron

Deep Depleted vs. "reach-through"



this is HyperFast Silicon(HFS)



packaged as 3 terminal device
-> ~3 picosec time uniformity/64mm^2

- recently thinner LGADs (~ 47 micron) tested at CERN(see Fabian @CERN wkshop)
- this leads to improved LGAD risetime
- but depletion depth for signal injection roughly the same for both devices (the latter determines limiting Landau contribution)

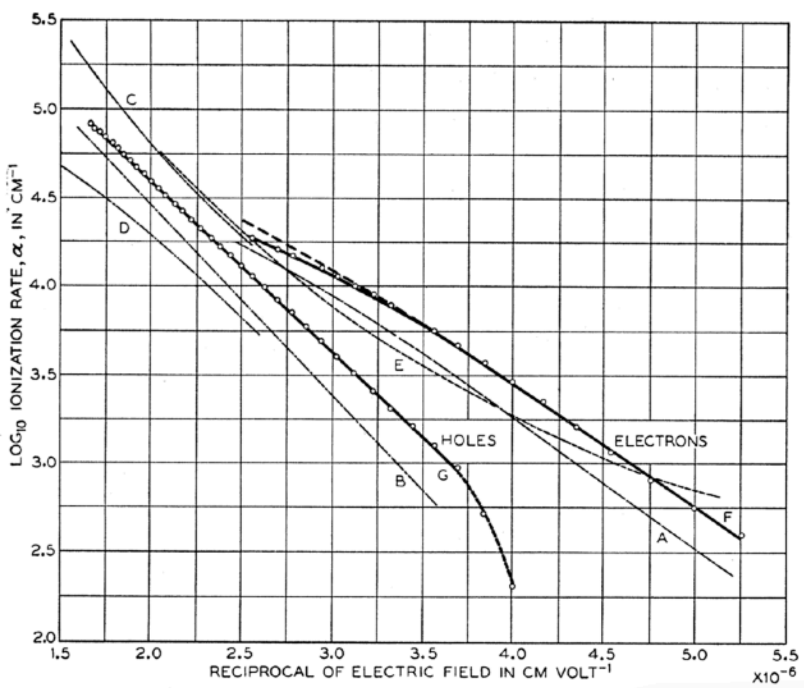
recent status (see wkshop)
HyperFastSi timing performance better and over larger Area (60-80 mm^2 vs. ~1.4 mm^2) than LGAD
LGAD more advanced in rad characterization
LGAD more activity in production cycles
both are studied in the CERN Silicon Sensor Development Group

HyperFastSi was tested together with the PICOSEC MicroPattern Gas Detectors and results reported below.

HyperFast Silicon(HFS) differs from LGAD in field structure and capacitive Readout

Field Strengths in Silicon

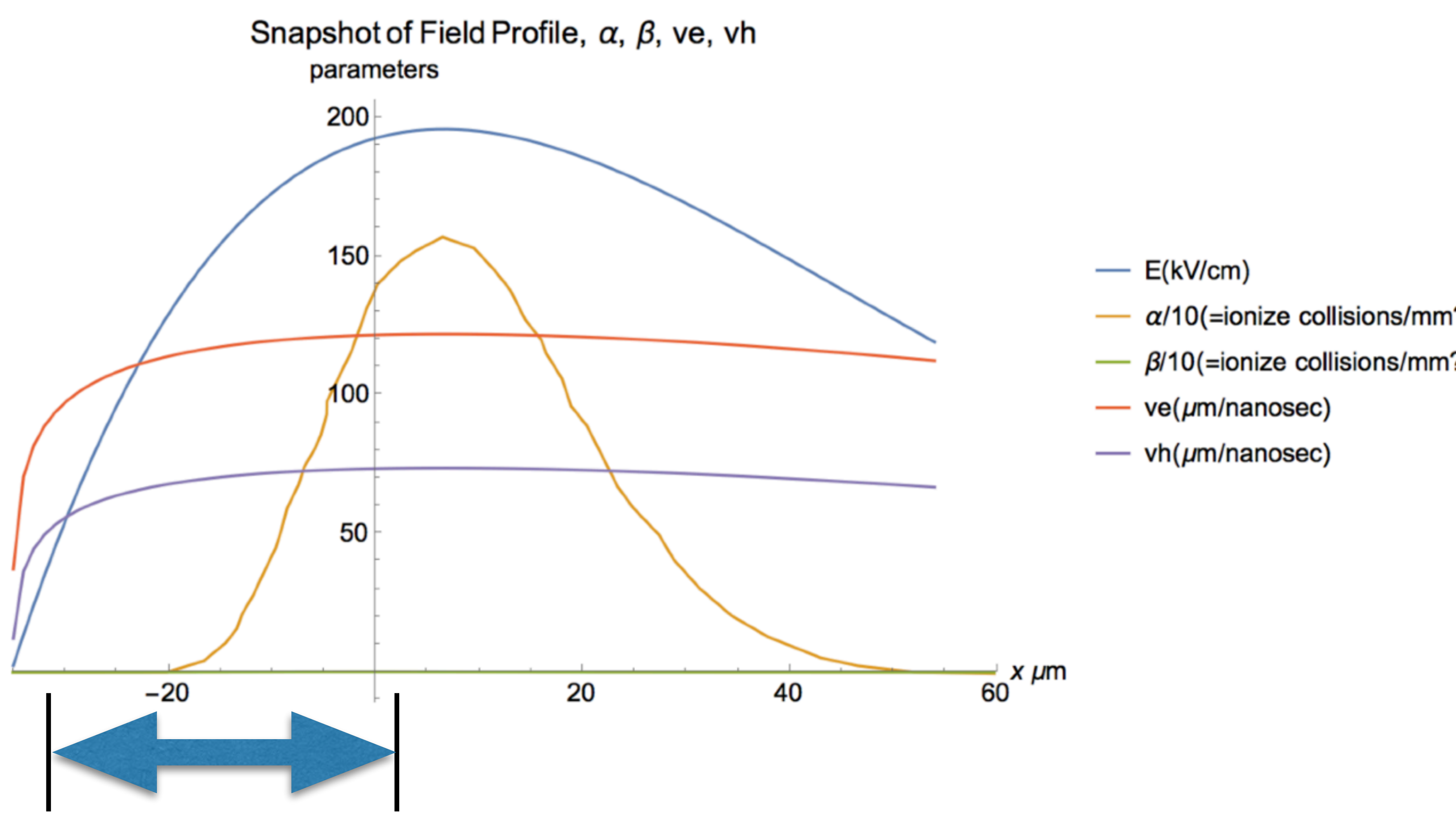
Fig. 1. The field dependence of the ionization rates for electrons and holes in silicon. Curves *A* and *B* are those obtained for electrons and holes, respectively, using the uniform field approximation and assuming that the ionization rates for electrons and holes are equal. Curves *C* and *D* represent the results obtained by Miller for electrons and holes respectively, while curve *E* represents McKay's averaged data. Curves *F* and *G* are those obtained for electrons and holes, respectively, for the case of a parabolic field distribution and assuming equal ionization rates for holes and electrons. No appreciable correction results to curve *G* when the ionization rates for holes and electrons are not assumed to be equal but the curve *F* (for electrons) deviates (as shown) to higher values of the ionization rate at the higher fields.



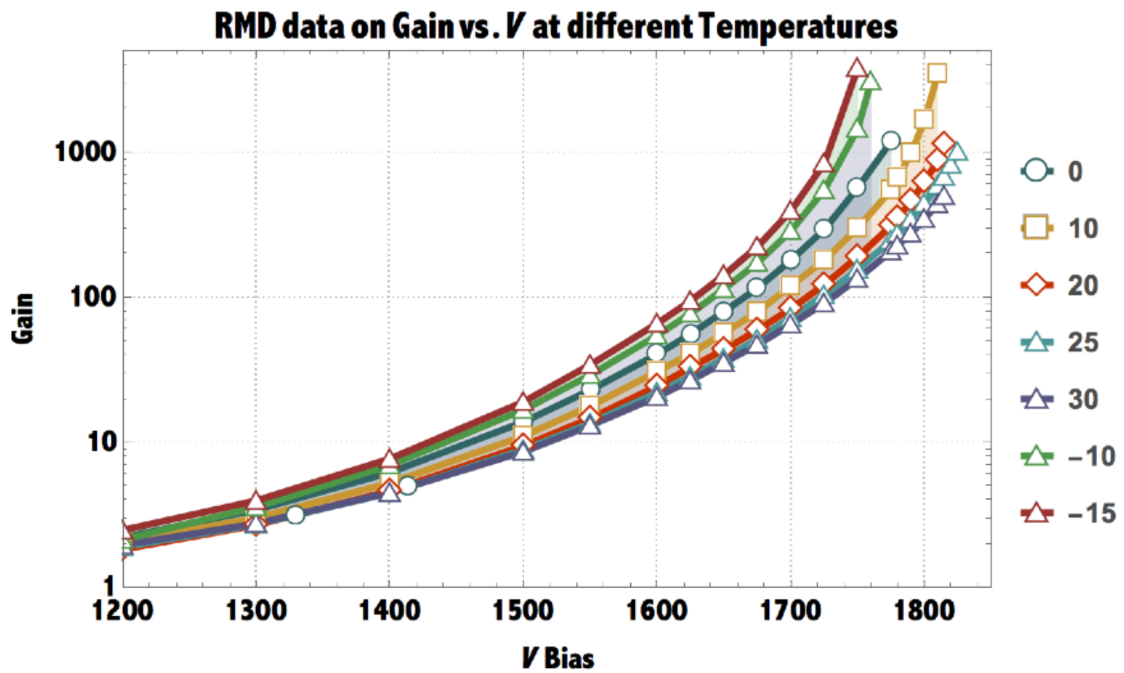
data/models of
impact ionization vs. E.
We are evaluating them for
use in Silvaco simulation package

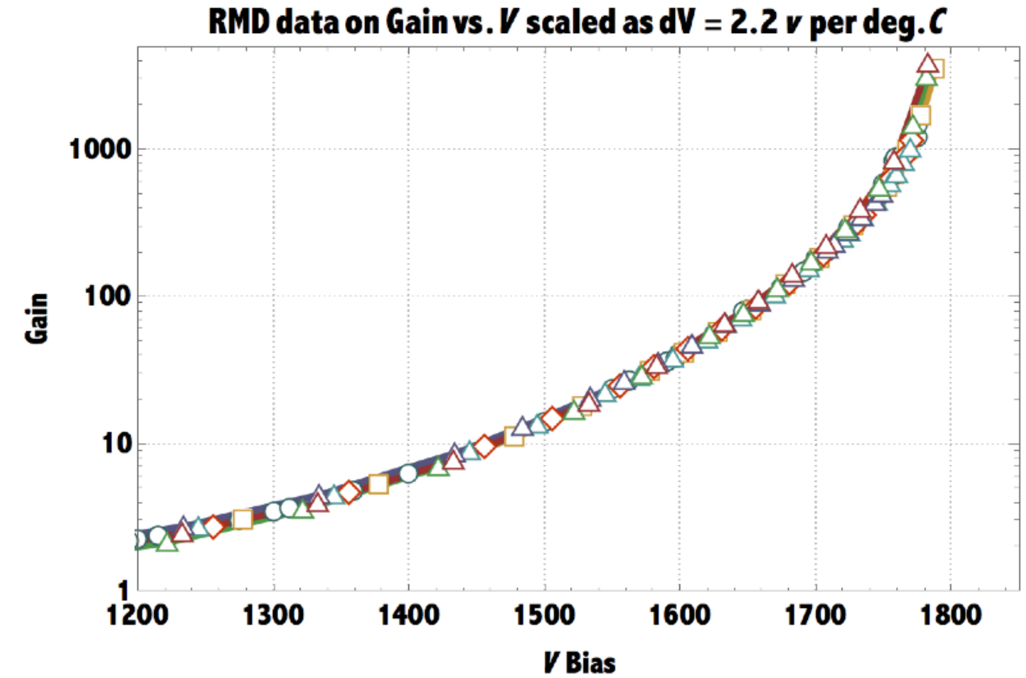
cartoon generated
from another dataset
-> rough features of gain
and charge motion

Gain(>100) defines region:
e in this range are multiplied
followed by charge motion to right
h multiplication low so ignore

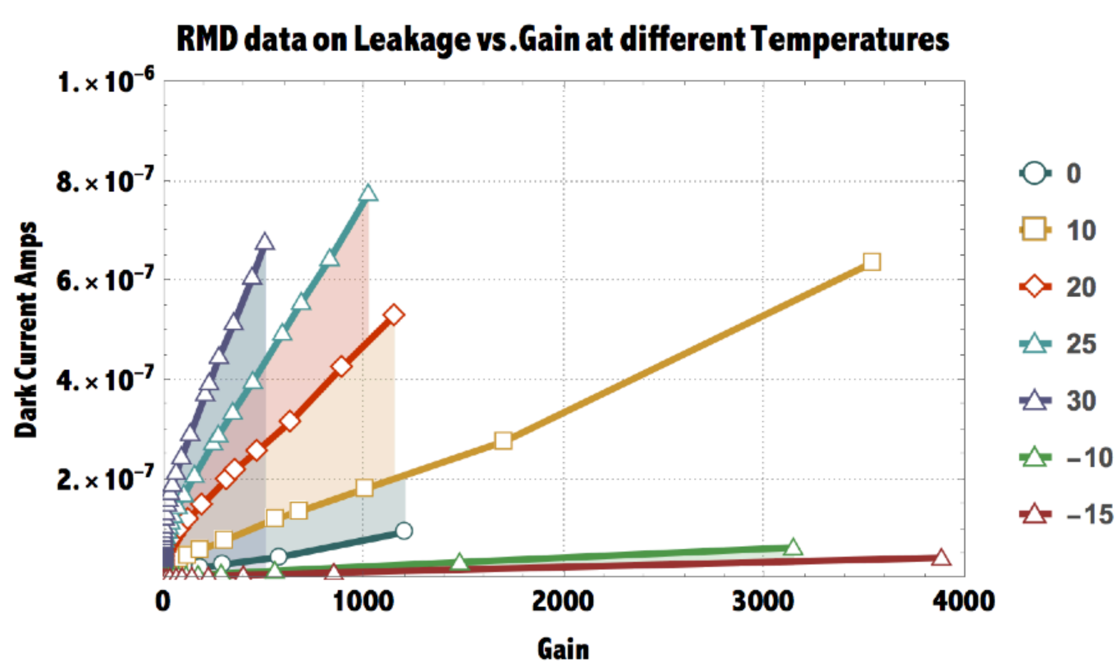


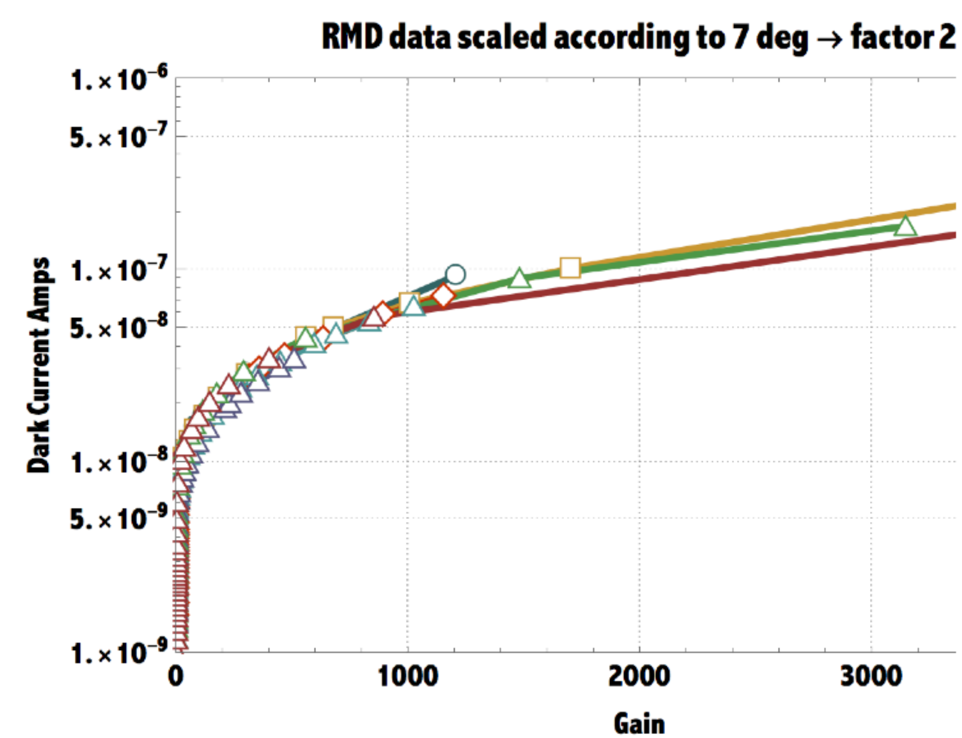
Gain ->structure of signal. Use our data to constrain models.





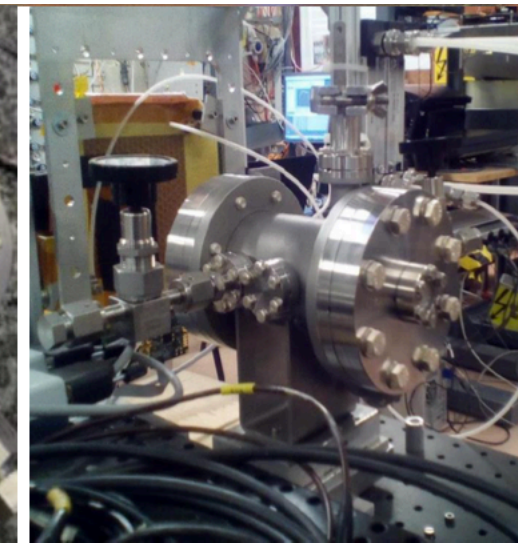
some surprises! Here I apply RMD rule of thumb for stabilizing gain and find a scaling too good to be accidental. Then apply known bulk leakage vs. T.



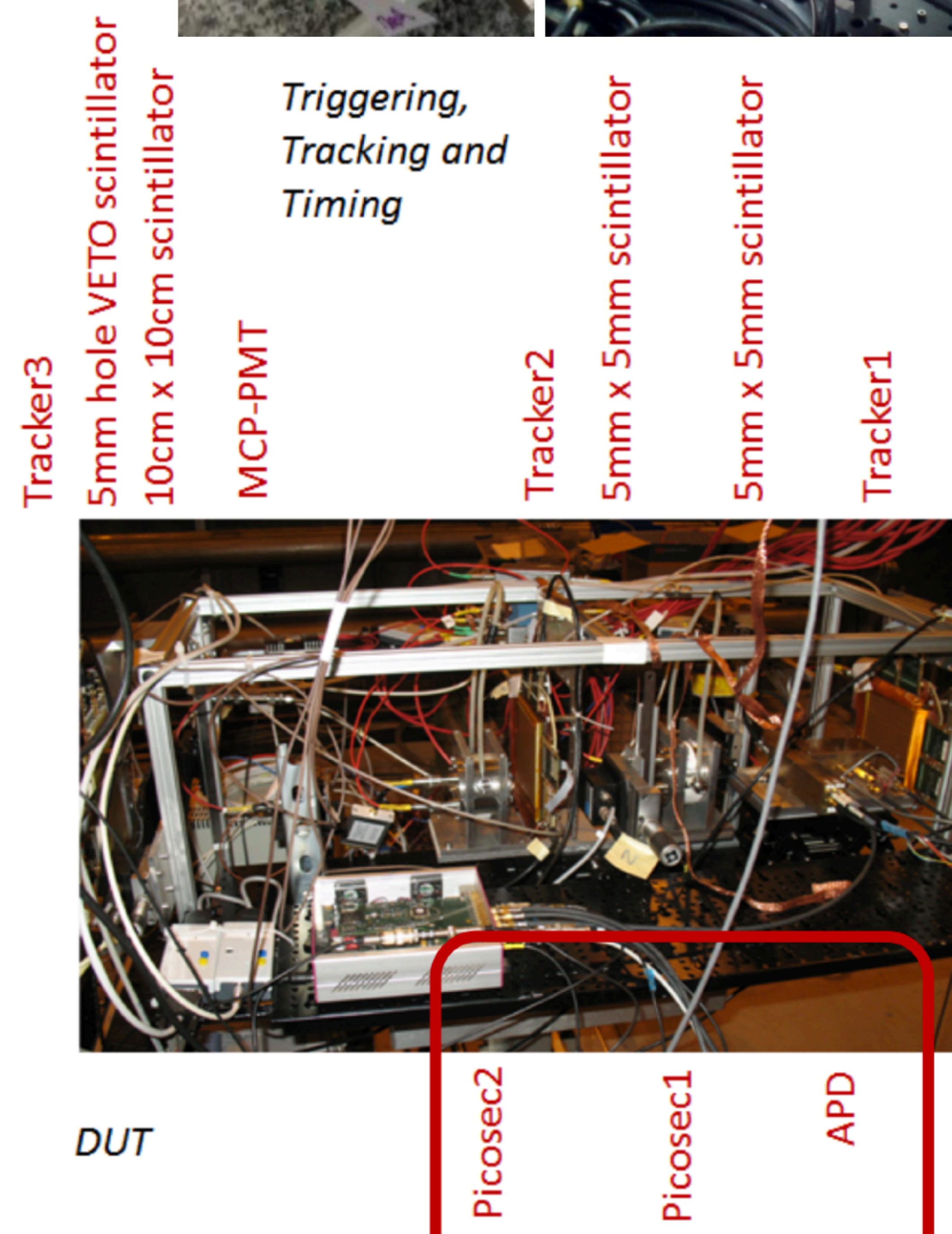


Beam/Laser performance tests 2016/17

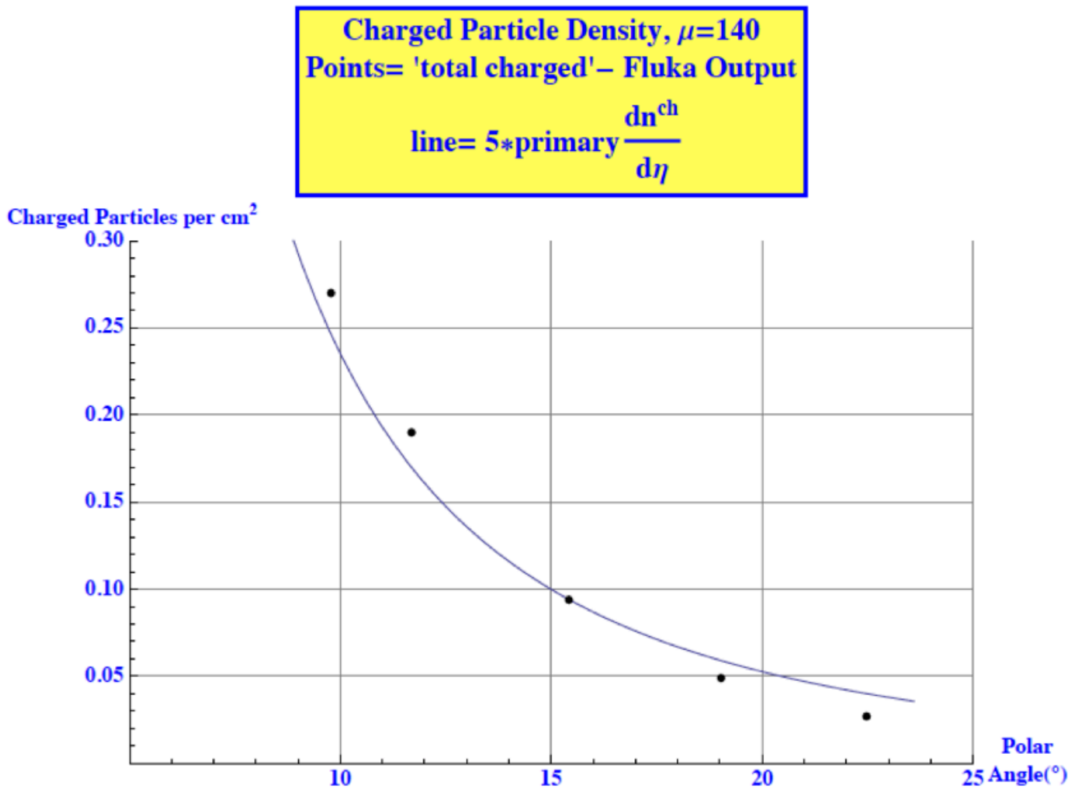
PICOSEC laser (~100femtosecond UV)
@Saclay->Jan.'17 again June'17



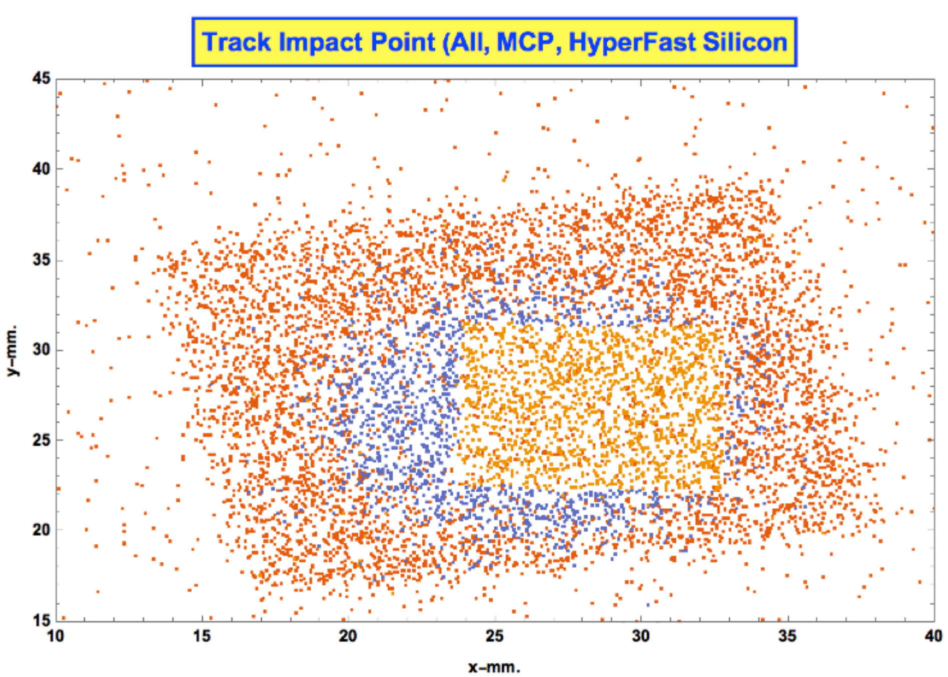
CERN North Area campaign



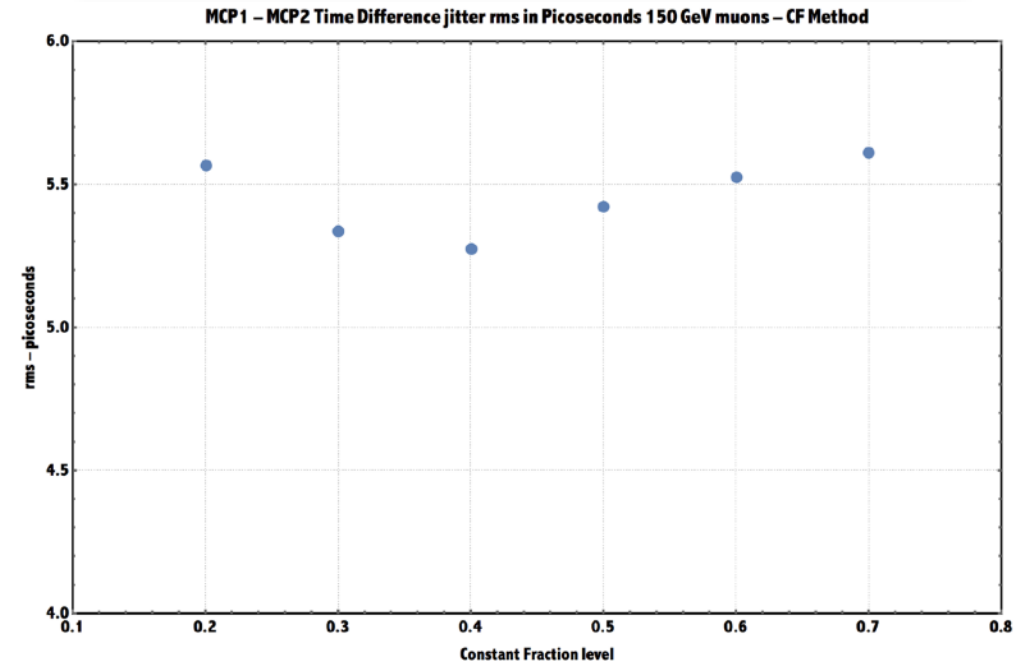
Right Pixel Size/Response maps



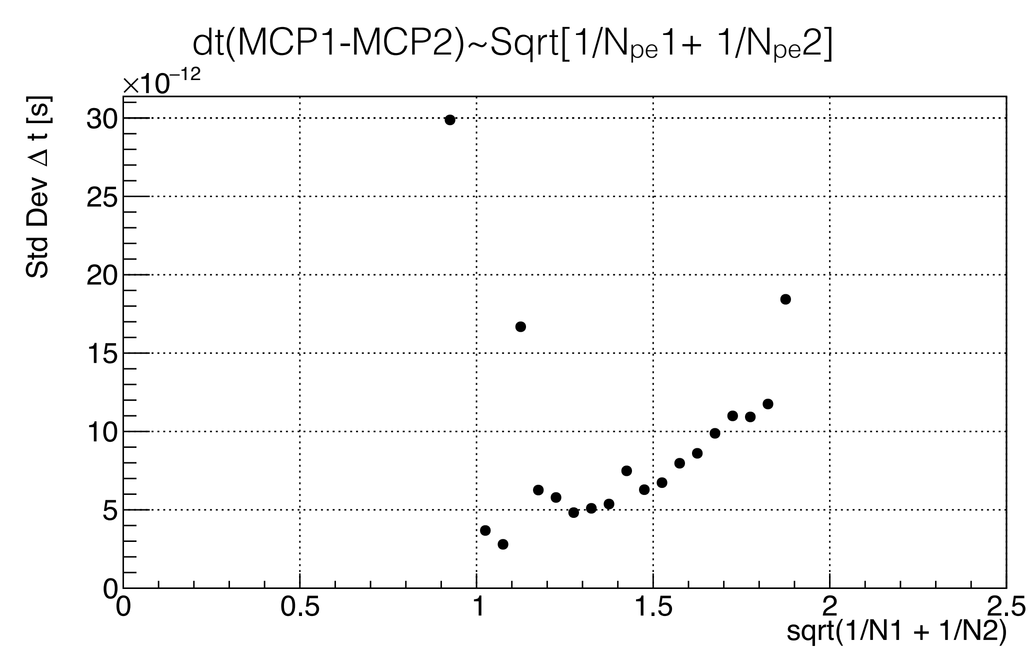
Our ~1cm pixel size correct!
Very nice tracking tool in H4
remove edges-> realistic array



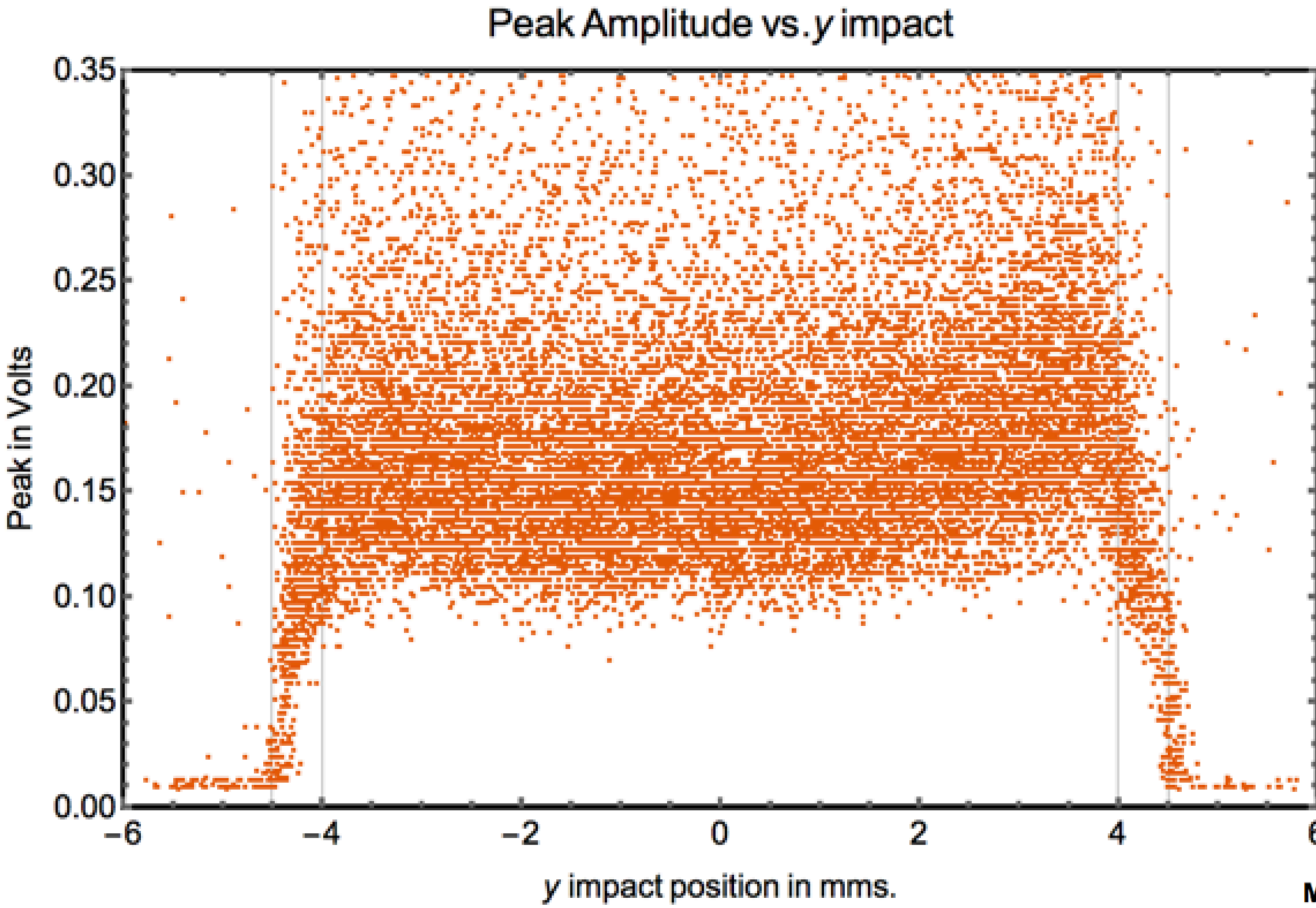
remove edges-> nice Poisson
MCP: <Npe>~16
world record time resolution!

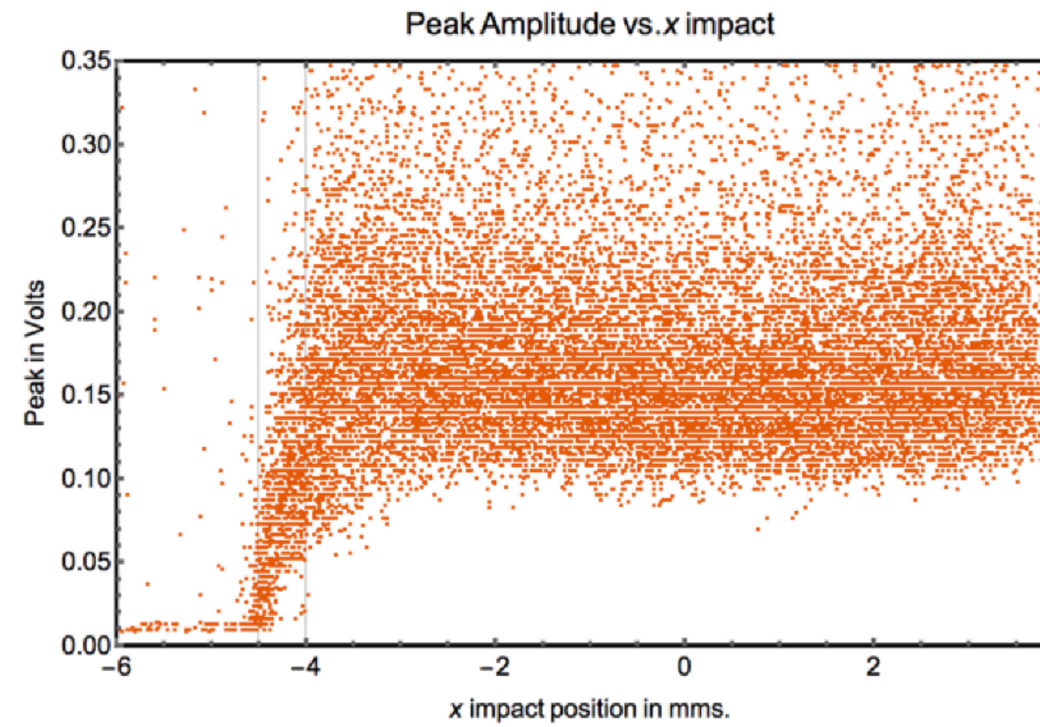


non-Gaussian tails understood

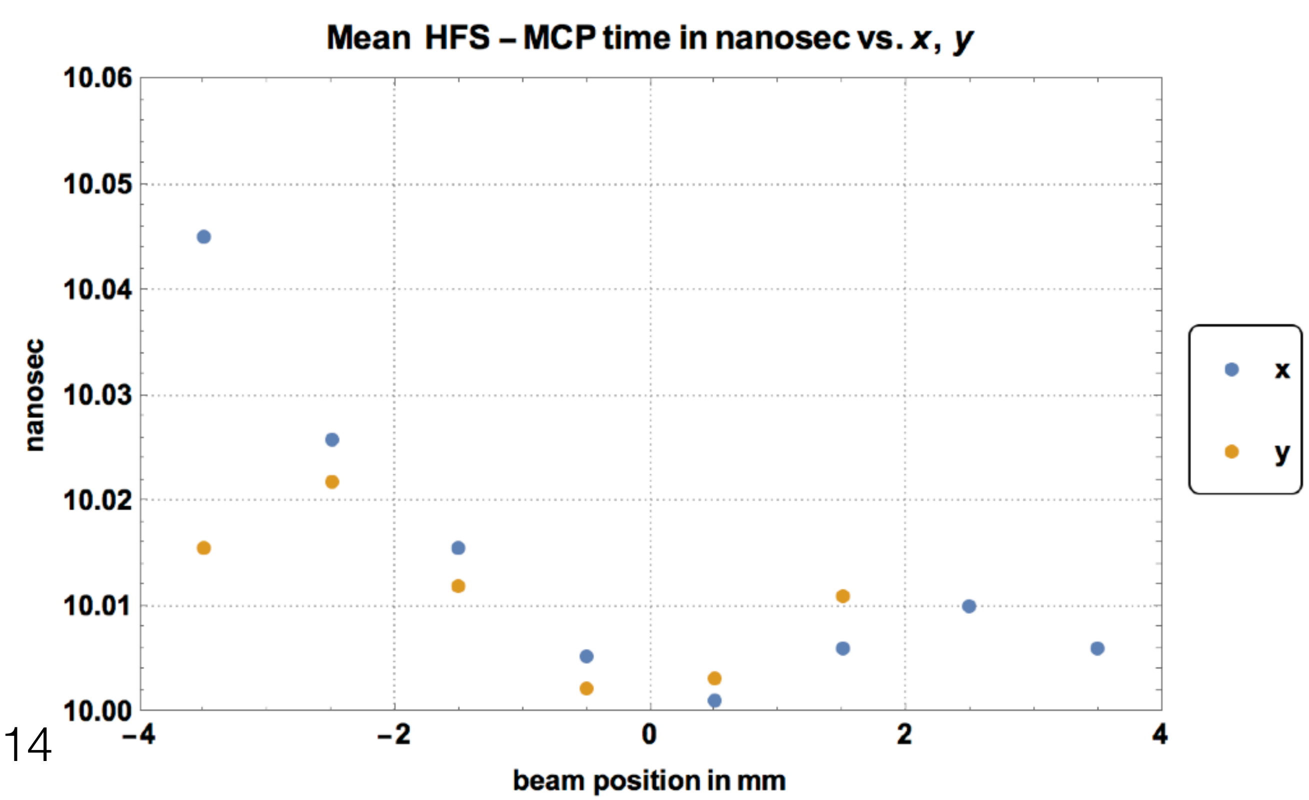


HFS- mapping Landau Distribution vs. muon data impact position

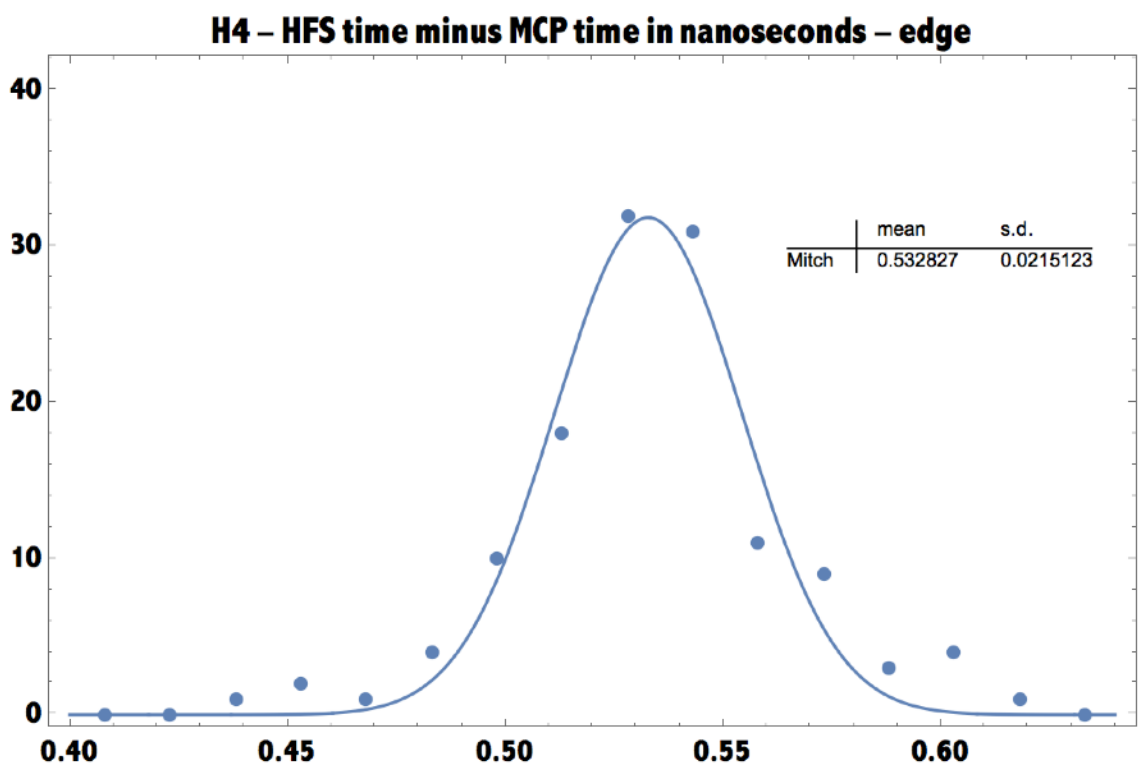


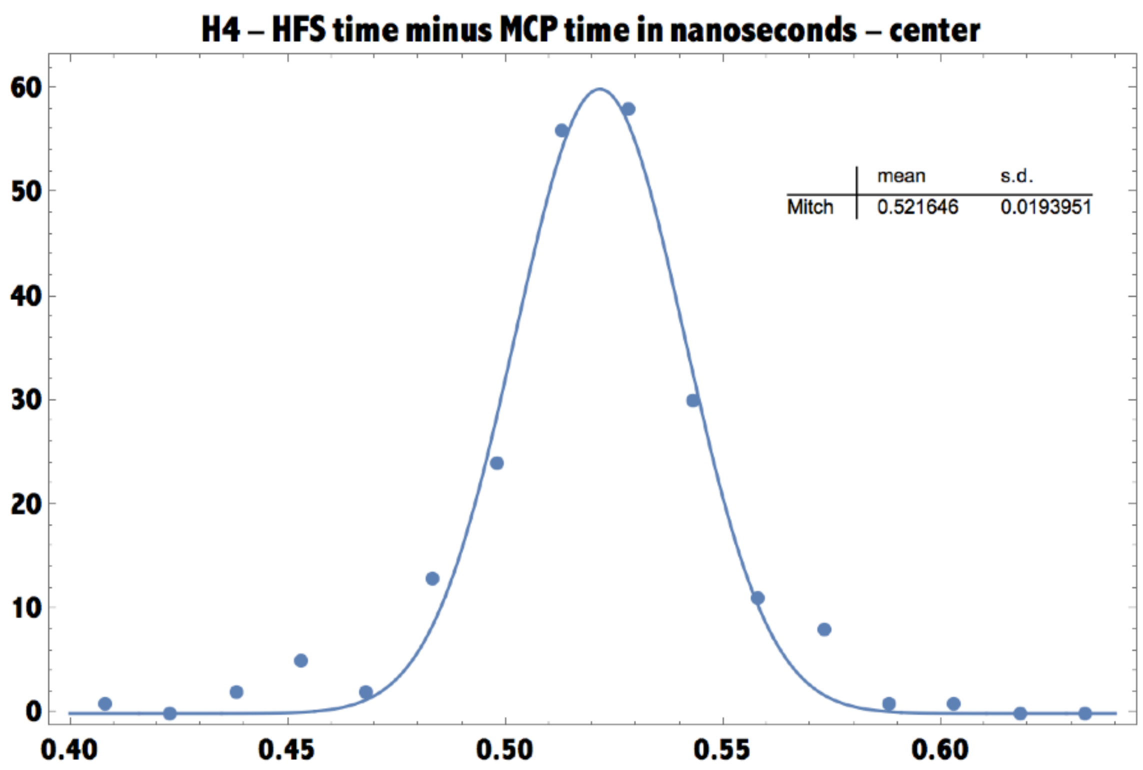


time of arrival scan
w. 150 GeV muons
(excursions >10 picos
attributed to current packaging)



very preliminary look at timing on detector edge





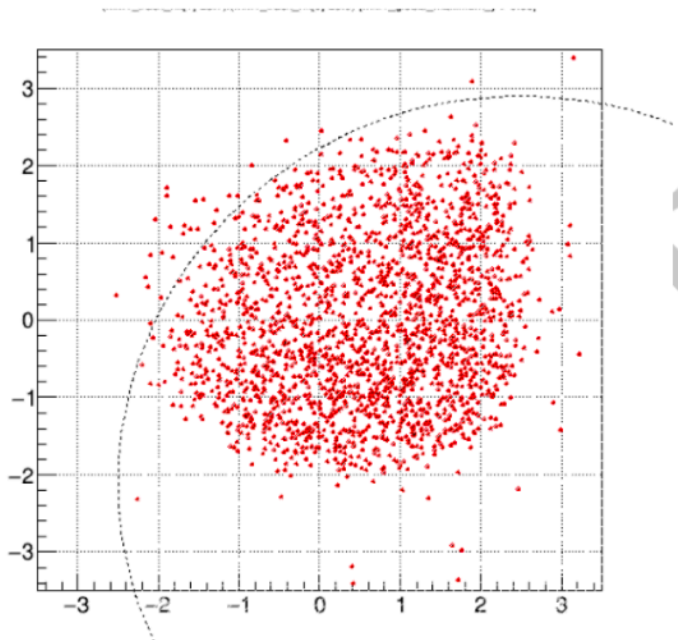
edge structure of these High field Si complicated. It has been difficult to evaluate w. laser model

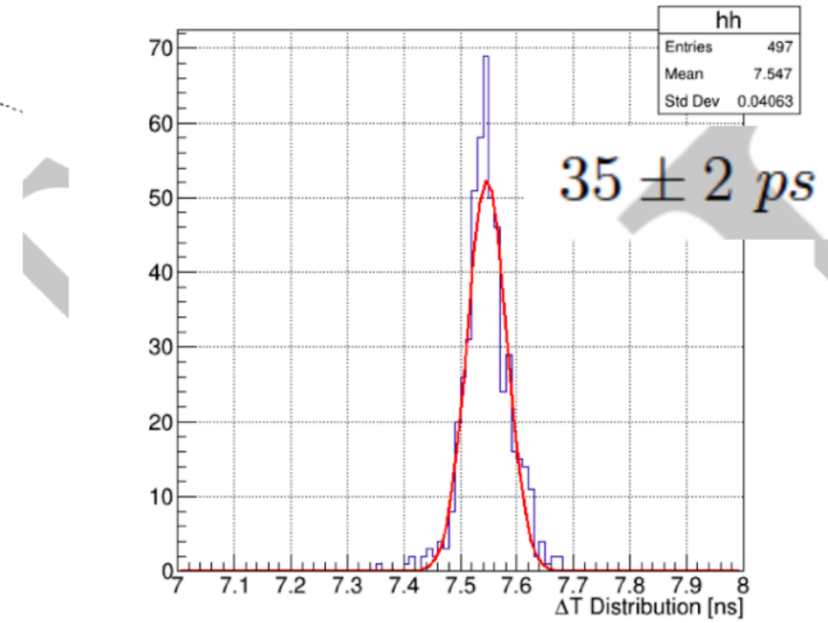
first look at edge behavior very encouraging!

take small difference of edge behavior from bulk with grain of salt

timing algorithm preliminary small pulse height distortion

Use similar selection in PICOSEC:





negligible factors:

1) C photon spread
2) transit spread through mesh
3) electronics/noise
4) digitization

run	V_{anode} [V]	$-V_{cathode}$ [V]	E_{MM} [kV/cm]	E_{drift} [kV/cm]	D_L [$\sqrt{\mu m}$]	D_T [$\sqrt{\mu m}$]	$v_{d,drift}$ [μm/ps]	$v_{d,MM}$ [μm/ps]	physical jitter $D_L/v_d \sqrt{g_{drift}}$ [ps]	transverse spread $D_T \sqrt{g_{drift}}$ [μm]	pre-amp ~ $\exp(\alpha^* g_{drift})$ simulated	estimated
Ne/CF4/C2H6 (80/10/10)@1bar												
277	450	325	35.2	16.25	1.62	2.31	0.132	0.20	174	33	20.5	
278	450	300	35.2	15	1.55	2.33	0.124	0.20	177	33	11.4	
279	425	325	33.2	16.25	1.62	2.31	0.132	0.20	174	33	20.5	
280	425	300	33.2	15	1.55	2.33	0.124	0.20	177	33	11.4	
281	425	350	33.2	17.5	1.70	2.29	0.140	0.20	172	32	38.0	
282	450	275	35.2	13.75	1.48	2.35	0.115	0.21	182	33	6.7	
* 284	450	350	35.2	17.5	1.70	2.29	0.140	0.21	172	32	38.0	
285	475	250	37.1	12.5	1.43	2.42	0.106	0.22	191	34	3.8	
286	475	275	37.1	13.75	1.48	2.35	0.115	0.22	182	33	6.7	
287	475	300	37.1	15	1.55	2.33	0.124	0.22	177	33	11.4	
288	475	325	37.1	16.25	1.62	2.31	0.132	0.22	174	33	20.5	
289	450	325	35.2	16.25	1.62	2.31	0.132	0.20	174	33	20.5	

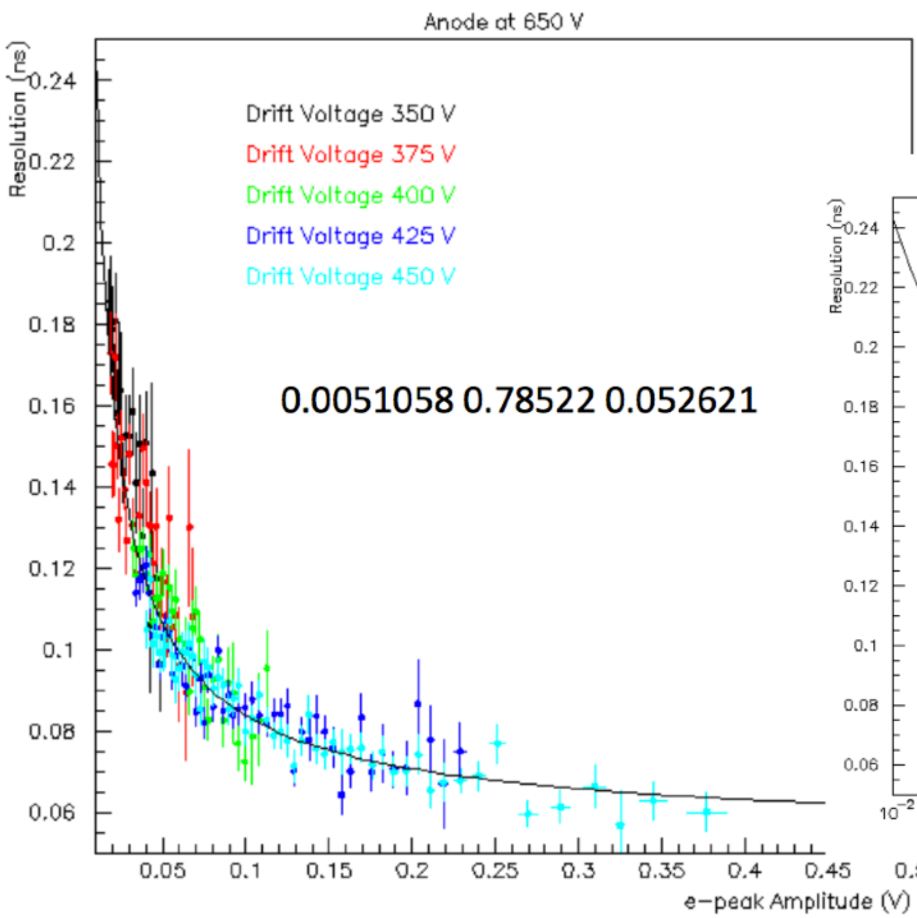
typical parameters (compiled by D. Gonzalez). cp Si

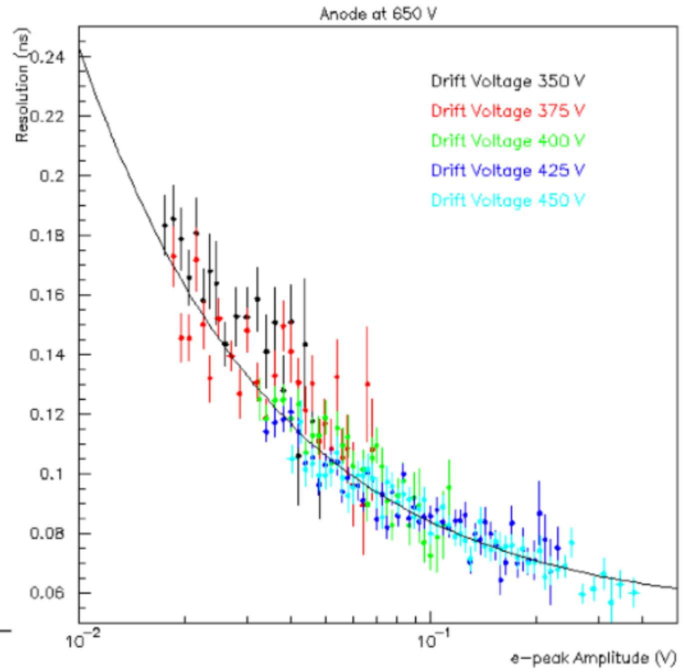
Laser data(particularly SPTR) useful for understanding current limit

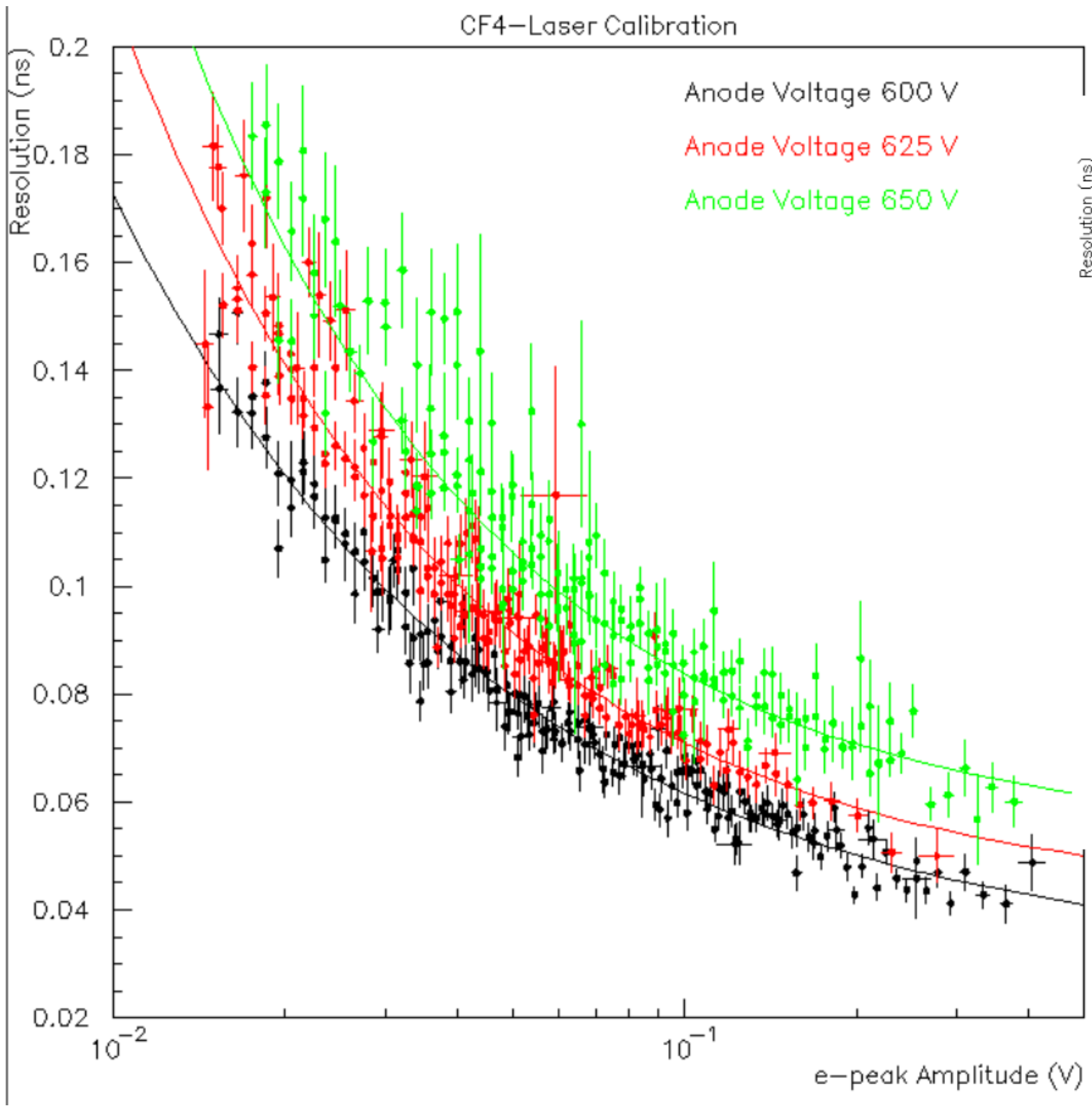
various measurements w. Ne+C2H6+CF4 and 0.5bar CF4 +quencher(shown below)

these show that physics of drift/preamp dominates

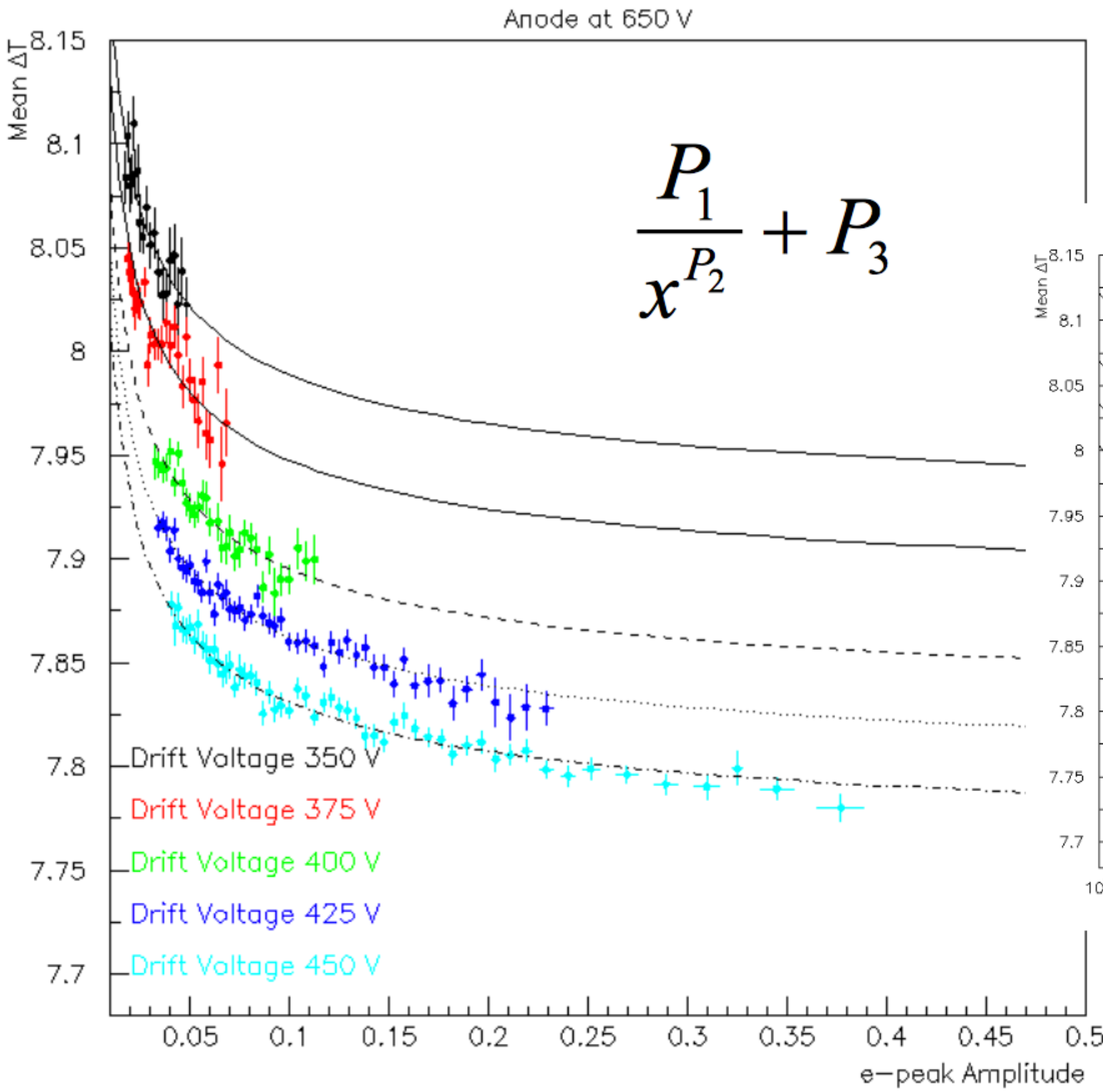
rather than gain in MM stage

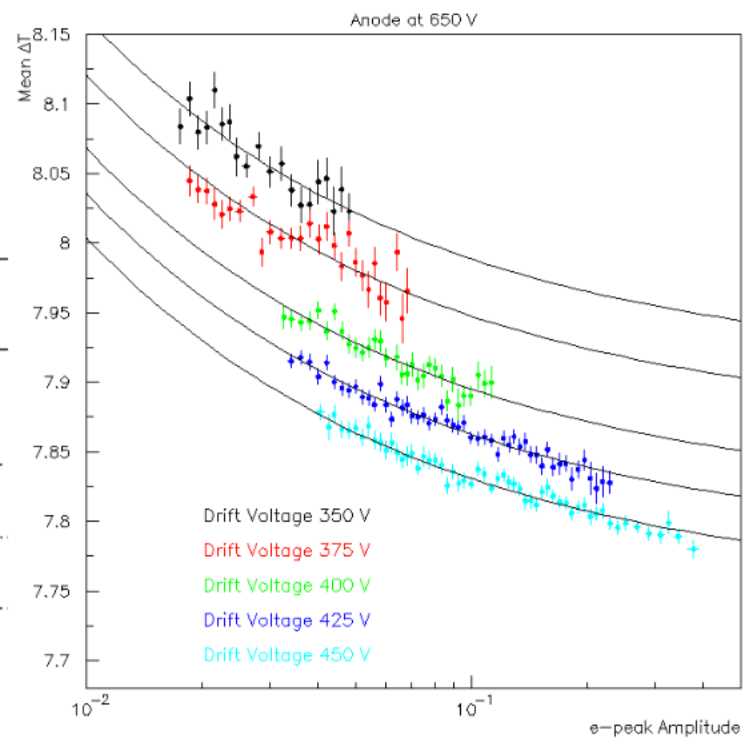






Slewing after CF timing





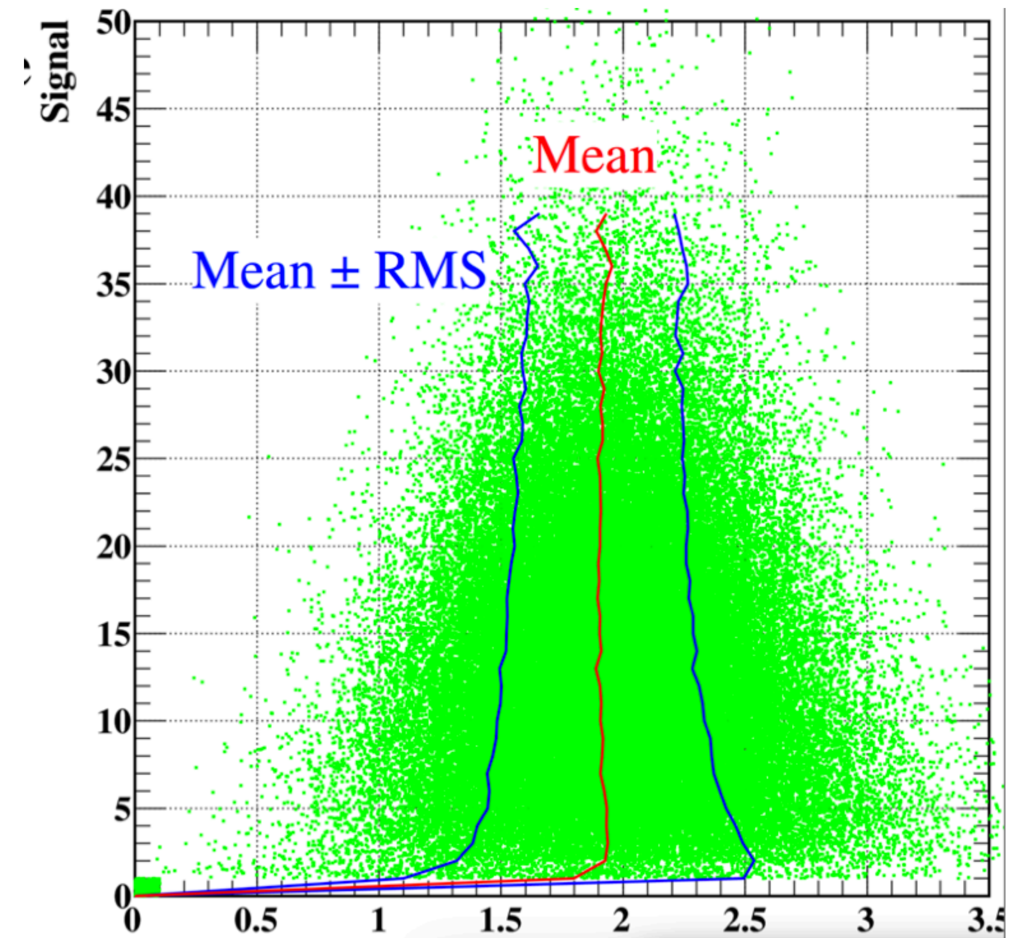
there is also a systematic (slewing) shift in both Single e and MIP data in spite of CF technique

more like a shift arising from fluctuations in Townsend multiplication (reproduced by our MC)

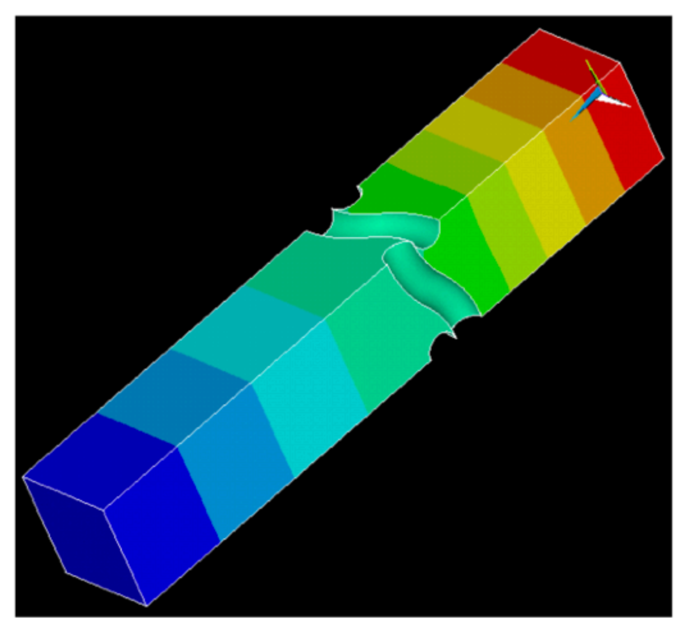
no slewing correction in 35 psec result. how best to employ it for MIPs?

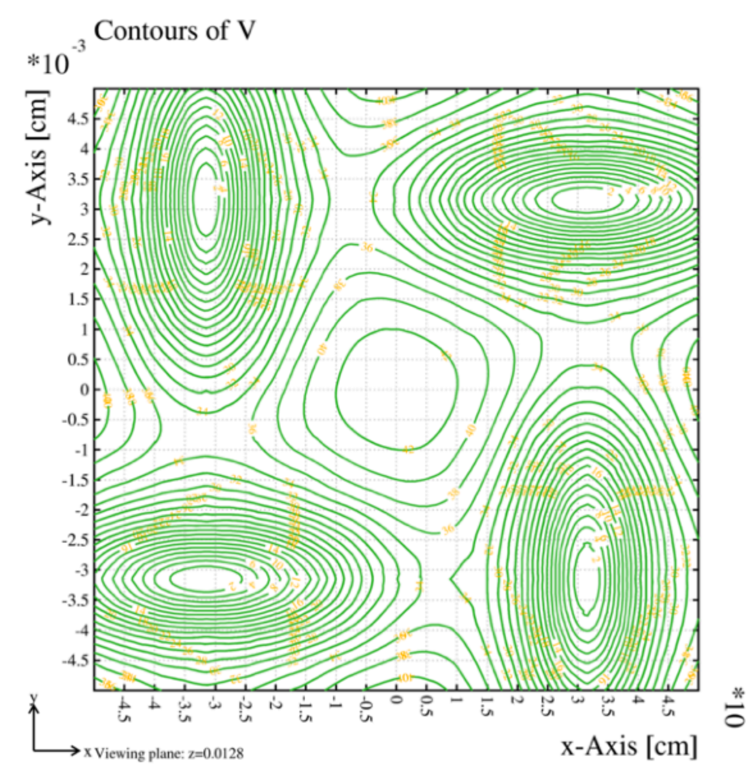
modeling of Performance

We are timing an electron cloud
starting from 12 pe
grows through preampfification
effect of diffusion growth largely
suppressed after initial multiplication



simulation shows
TTS spread through mesh
negligible vs. diffusion



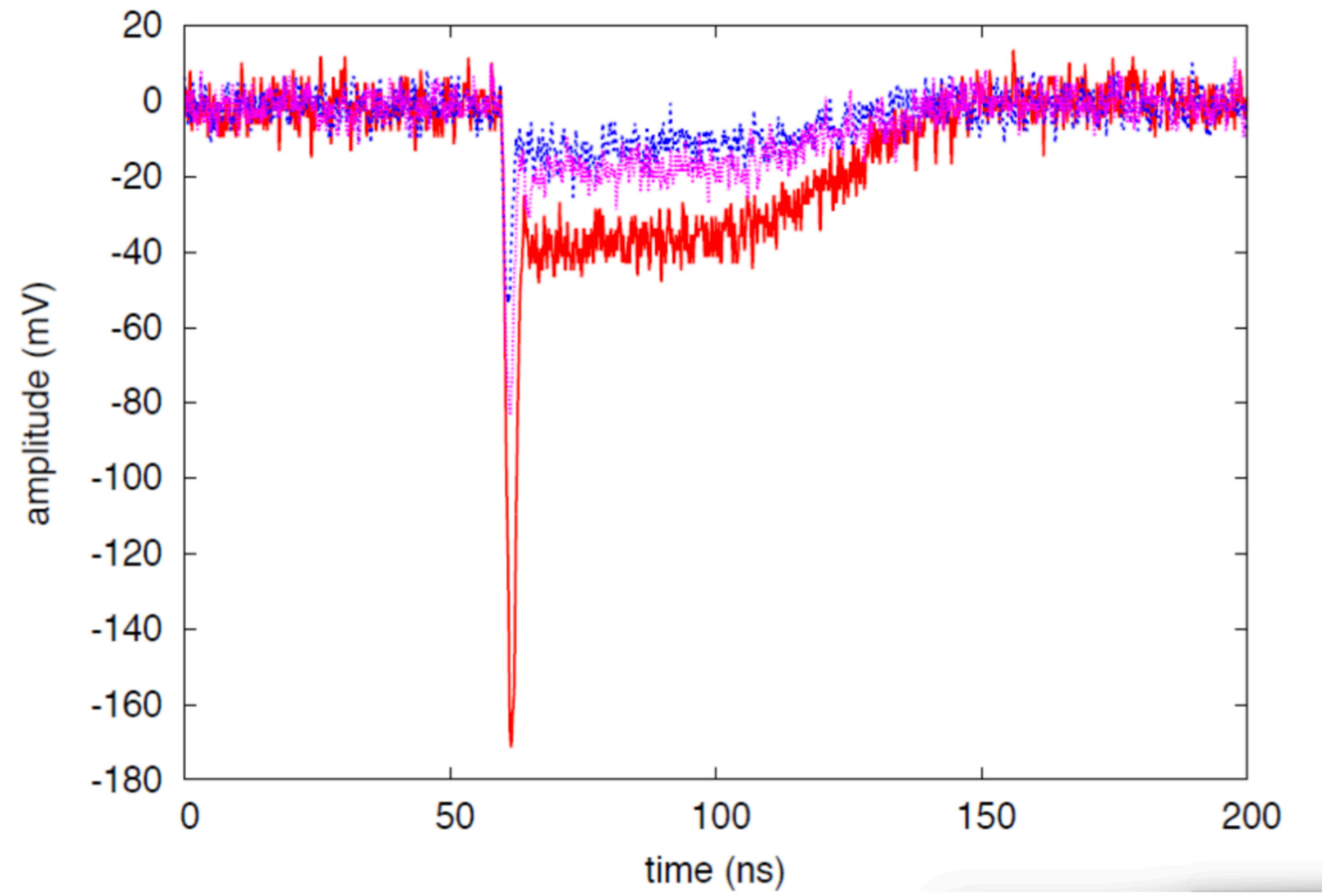


Electronics/algorithms

We've had lot's of enthusiastic support for HFS and PICOSEC

up to now SNR not dominant issue

many filtering exercises more or less redundant with fitting

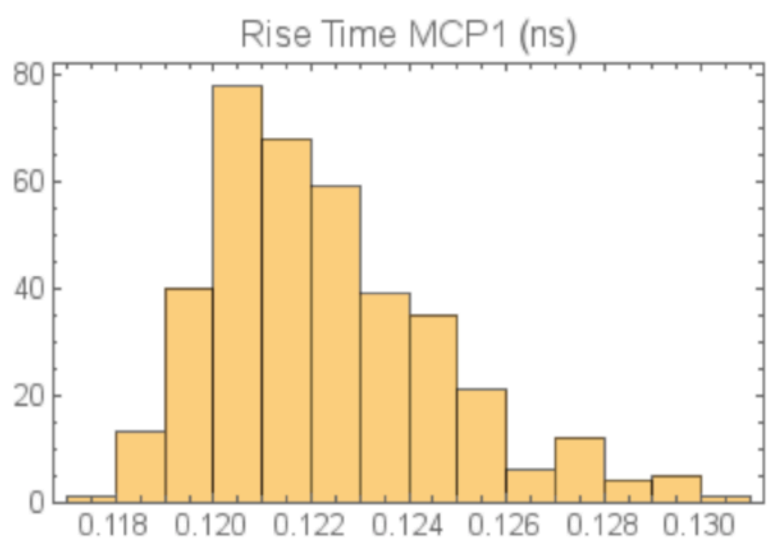


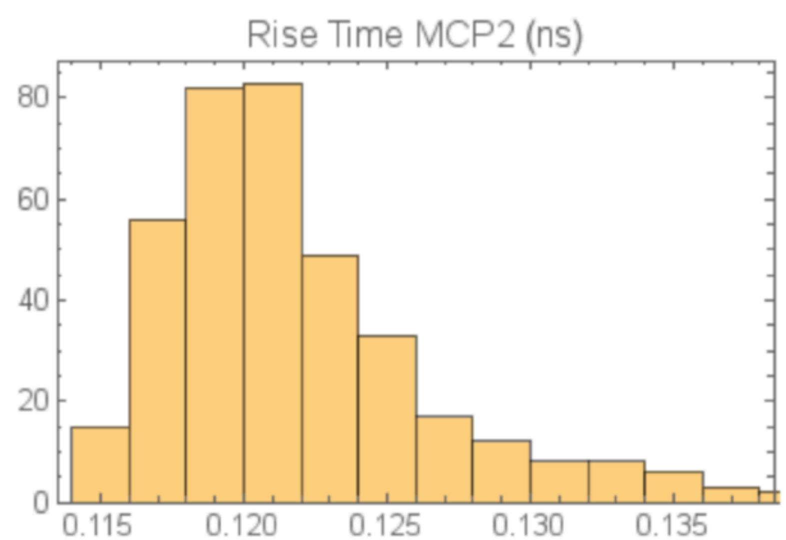
we are timing the narrow e-peak in PICOSEC usually using CF timing on a local fit to leading edge

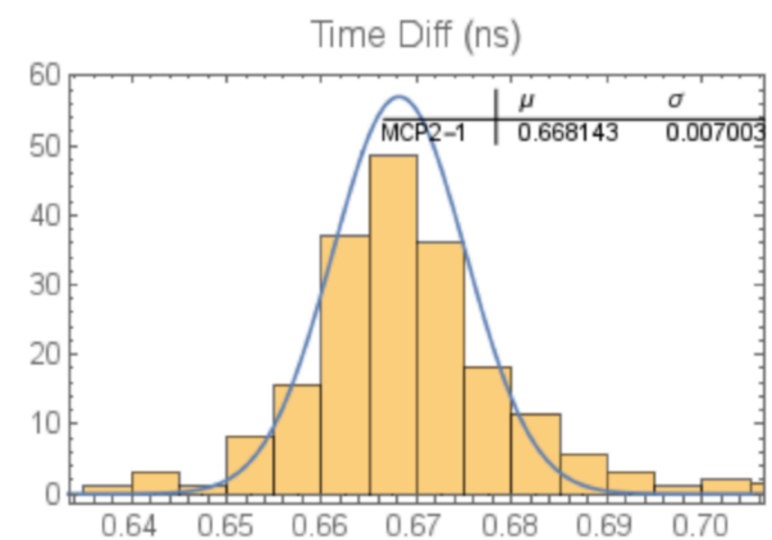
maybe signal modeling is more robust (next)

also parallel activities of interest to any timing community

https://www.wolframcloud.com/objects/jhernandez/testFileImportAndPlot







Summary of where we are

- I skipped a lot but refer you to the CERN wkshop (in particular Harry van der G., M. Lucchini as well as PICOSEC talks)
- at LHC, CMS proceeding w. “hermetic timing” w. barrel using SiPM(see Luchini). End cap layer has some built in contingency for technology and budget
- returning to Ben Franklin quote: We are back in a new beam campaign in July and pushing for paper draft before then.
- we try to model and, where possible, grasp the basic detector physics which will improve timing performance and <u>robustness</u>
- the latter is, of course, the hard work ahead

Thanks to the organizers for an enjoyable conference!

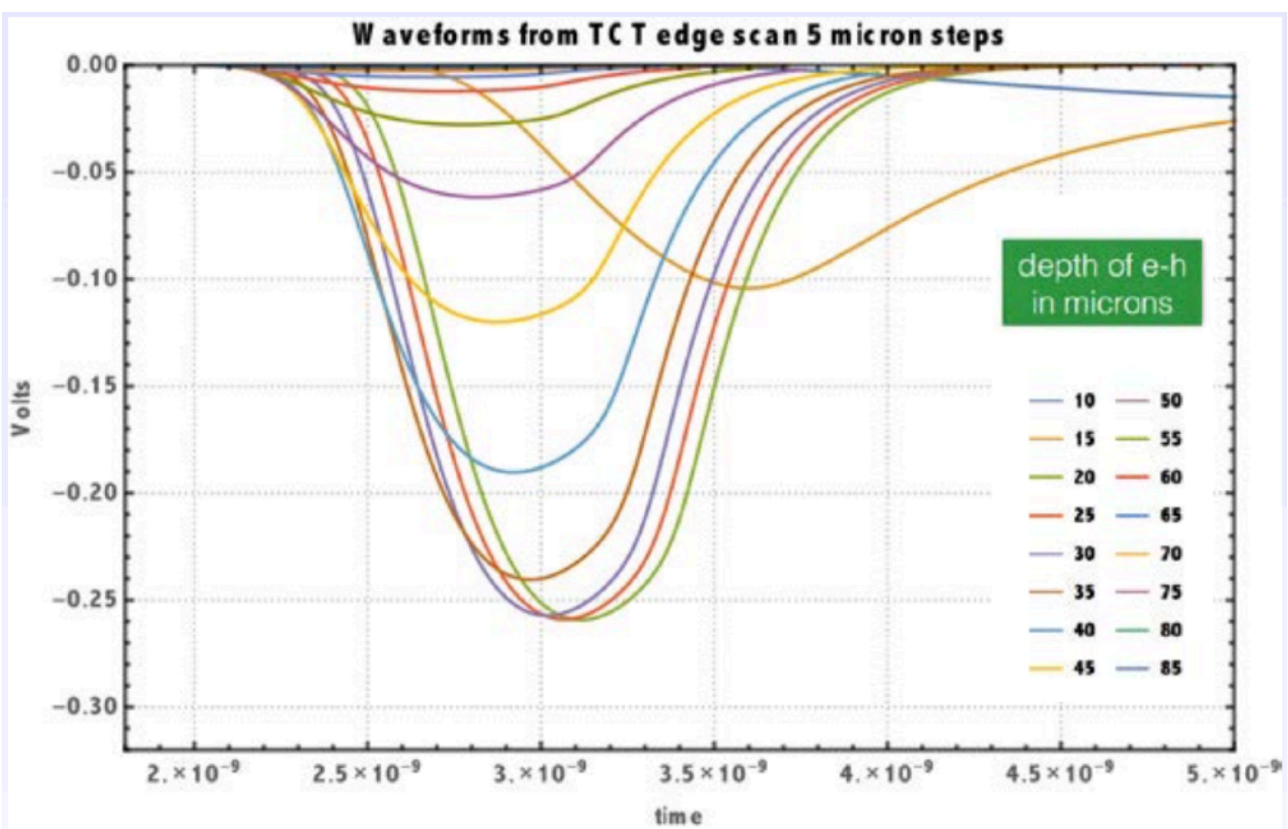
Backup

basic difference between Silicon(HFS) and PICOSEC

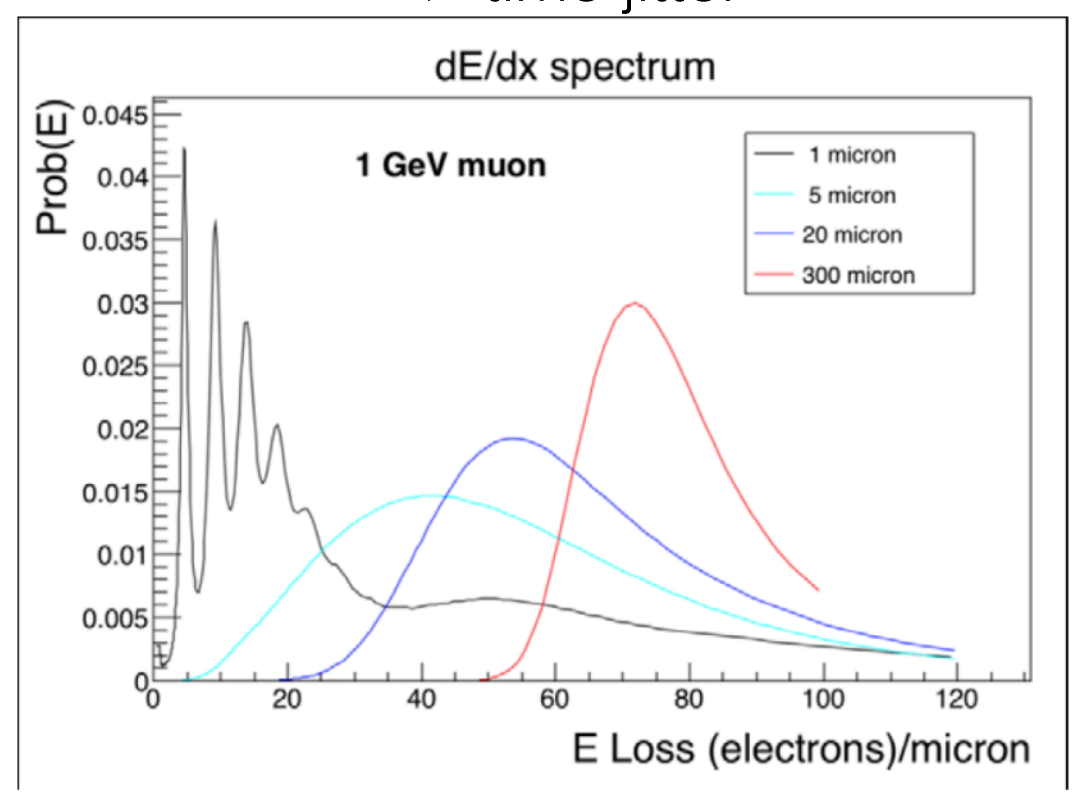
- Landau/Vavilov fluctuations in HFS e-h distribution along MIP-> limiting stochastic nature of Si timing

- in PICOSEC, Cerenkov photoelectrons are isochronous but fluctuations in first Townsend impact->physics limit

HFS is a “thin” detector



nevertheless fluctuating E_{dep} in slices -> time jitter

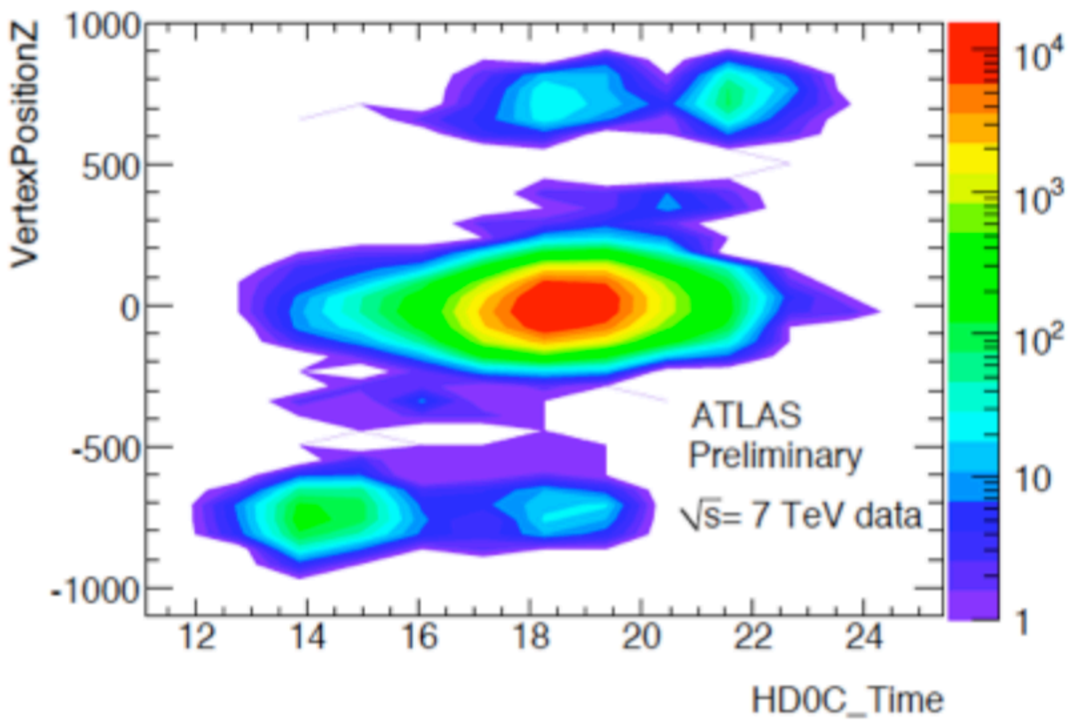


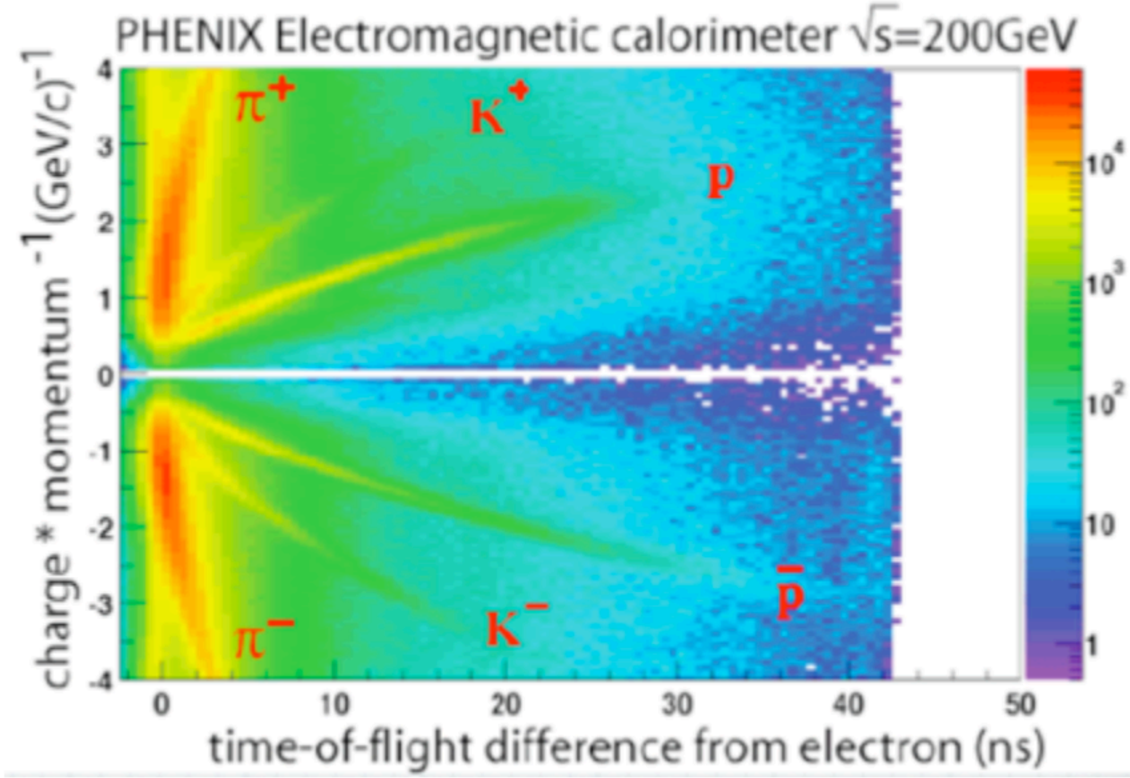
simulation in Mathematica, collaborated w. Su Dong (SLAC)
presented by M. Moll @ RD50 collab mtg 2016

Previous experience with calorimeter timing measurements

BNL-Yale built ATLAS ZDC timing(Quartz-Tungsten Shashlik) resolves 400 MHz micro-bunch structure in LHC (only LHC detector to achieve this?)
despite reduced bandwidth from low quality cable runs & 40 MSa/s sampling

15,552 tower PHENIX shashlik also used for hadron id via TOF
despite low energy deposit of ~0.5 GeV hadrons and TTS in un(longitudinally)-segmented calorimeter





The Z vertex distribution from inner tracker vs. the time of arrival of showers in ZDC-C relative to the ATLAS clock calculated from waveform reconstruction using Shannon interpolation of 40 MegaSample/sec ATLAS data (readout via the ATLAS L1calo Pre-processor modules). Typical time resolution is ~200 psec per photomultiplier (see ATL-COM-LUM-2010-022). The two areas outside the main high intensity area are due to satellite bunches. Note that this plot also provides a more precise calibration of the ZDC timing (here shown using the ZDC timing algorithm not corrected for the digitizer non-linearity discussed in ATL-COM-LUM-2010-027). With the non-linearity correction the upper and lower satellite separations are equalized.

State of the art in Si w. Gain in 2007 (and still today)

- 1994 paper on MIP timing with Avalanche Diodes by McIntyre et al. (wrote the book on AD- and patents):Andrew Hauger et al., “A Time of Flight detector based on Silicon avalanche diodes”, Nuclear Instruments and Methods A 337 (1994) 362-369.

- mostly the same detector parameters as MPGD- (electron/hole drift velocities, impact ionization-Townsend…)

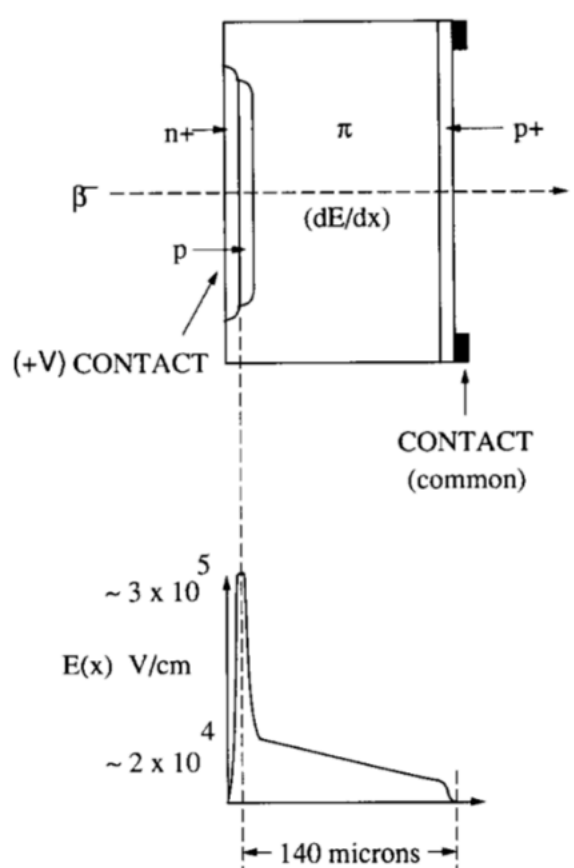


Fig. 2. Schematic AVD profile and resulting electric field distribution. The peak field corresponds to the multiplication region.

Table 1
Time resolution, gain and breakdown voltage of the diode modules

Diode module	σ_{time} (ps)	Gain ($V_{BD} - V_{bias} = 10$ V)	V_{BD} (V)
1	65	47	425
2	66	31	409
3	78	32	348
4	87	49	404

not bad for 23 years ago!
aka Low Gain Avalanche Diode
see Fabian’s talk