Simulation of the timing properties of scintillation detectors for SciTil

Lukas Gruber

Stefan Meyer Institute for Subatomic Physics, Vienna, Austria

PANDA TOF meeting
FZ Jülich
December 9, 2014

Johann Marton, Dominik Steinschaden, Ken Suzuki

Austrian Academy of Sciences

Outline

- Introduction: experimental results

- Monte Carlo simulation
  - Detector construction
  - Evaluation of time resolution
  - Comparison with experiment
  - Study of different geometries

- Summary & outlook

Experimental tests

Various independent experimental tests in the laboratory as well as at a beam test experiment have shown that a time resolution well below 100 ps (sigma) is feasible with the proposed scintillator tiles (rods) read-out with SiPMs.

Latest results from beam test at Jülich (Jan/Feb 2014):

- SciTil (28.5 x 28.5 x 5 mm^3): EJ-232 + Ketek PM3360TS → **σ ~ 83 ps**
- SciTil (28.5 x 28.5 x 5 mm^3): EJ-228 + MPPC S12572-025C → **σ ~ 95 ps**
- SciTil (30 x 30 x 5 mm^3): EJ-228 + Philips DPC → **σ ~ 35 ps**
- SciRod (120 x 5 x 5 mm^3): BC-420 + MPPC S12572-100P → **σ ~ 65 ps**

A. Lehmann, SciTil Meeting, July 24, 2014

Feasibility has been proven!
But: Geometry has to be finalized!

Monte Carlo simulation

- Geant4 version 9.4.04
- Simulation of single scintillation counters
- Push the time resolution to the limits
- Study different geometries (SciRod, MEG)
- Finalize geometry
- Study wrapping
- Better understanding of experimental results

The simulation includes: (up to now)

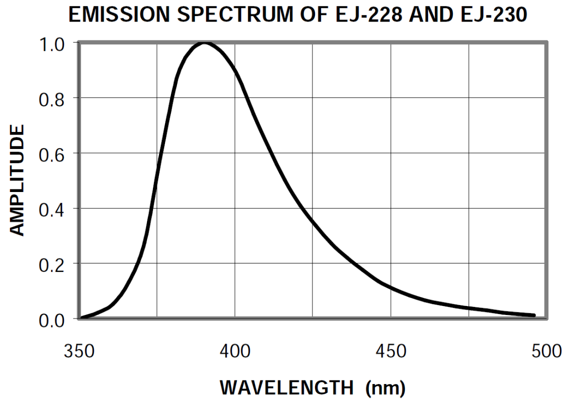
- Simulation of the energy loss of primary particle
- Simulation of the scintillation process:
  - light yield, rise-, decay time
  - characteristic emission spectra of scintillator
- Surface properties: polished ↔ rough, refractive index
- Optical coupling to photodetector (grease 100 µm)
- Tracking of optical photons: absorption, detection, ...
- Photodetector with 3x3 mm² active area:
  - PDE (wavelength and over-voltage dependent)
  - SPTR (Gaussian jitter)

Detector construction

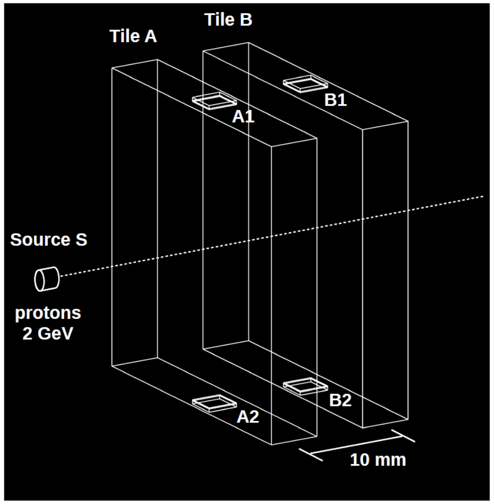
Input:

- Two scintillators with 2 SiPMs (3x3 mm^2) each
- SciTil and SciRod geometry
- EJ-228 (eq. BC-420): material parameters from data sheet
- Number of primary events: 10,000 events
- Primary particles: 2 GeV protons (test beam)
- Primary position: random position on scintillator surface
- Creation of primary particle defines time t = 0

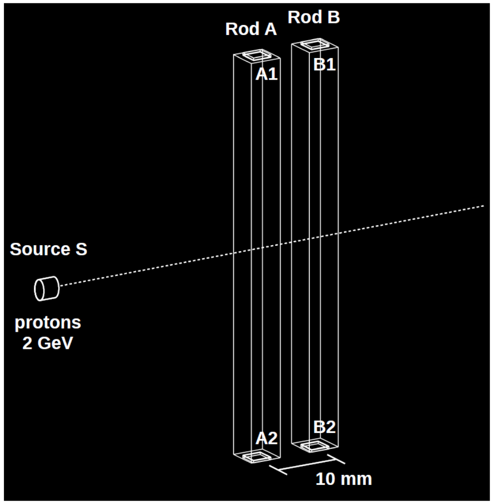
	EJ-228
Light yield [photons/MeV]	10,200
Rise time [ns]	0.5
Decay time [ns]	1.4
Refractive index	1.58
Light attenuation length [cm]	100



SciTil:
28.5 x 28.5 x 5 mm^3



SciRod:
120 x 5 x 5 mm^3



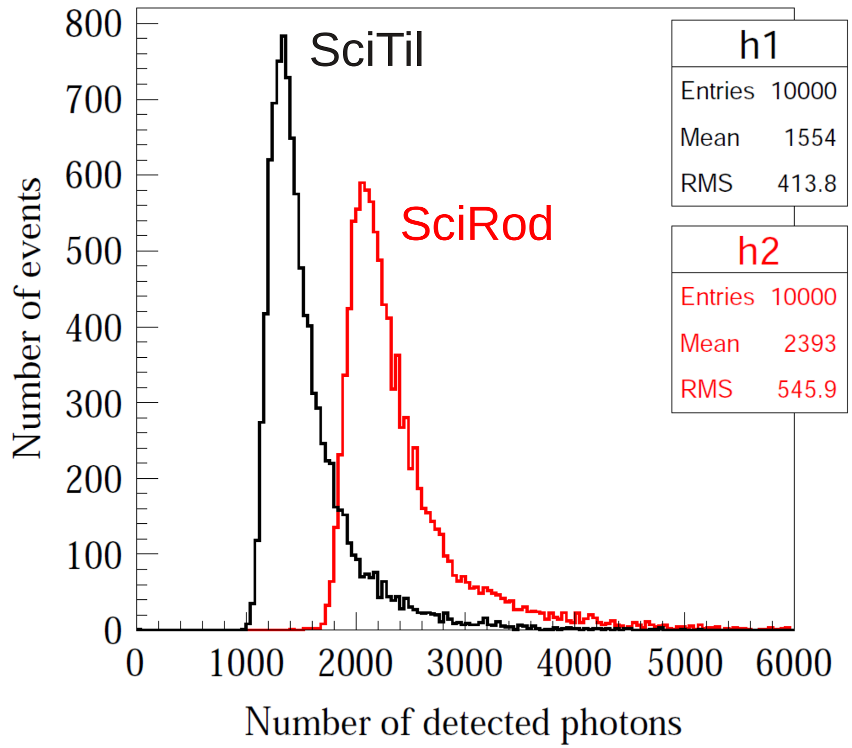
Output:

- Number of photons reaching the detector
- Photon arrival times

Number of photons

For the beginning we make two assumptions:

- Ideal photodetector: infinite time resolution, PDE = 1
- Perfectly polished scintillator surface (surrounded by air)



Absolute number of detected photons of course too large.

With SciRod about a factor 1.6 more photons are detected.

Comparison with experiment:

A. Lehmann, SciTil Meeting, July 24, 2014

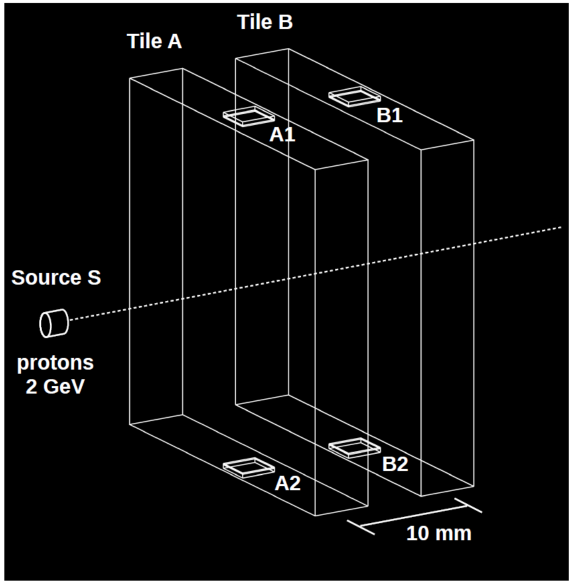
SciTil: N_{avg} = 120

SciRod: N_{avg} = 220

Factor 1.8

Evaluation of time resolution

From the simulation we get the arrival times of all detected photons $N = N_A + N_B$



Tile A: SiPM A1 → $\{t_{A1,1}, t_{A1,2}, t_{A1,3}, \dots , t_{A1,N_{A1}}\}$

SiPM A2 → $\{t_{A2,1}, t_{A2,2}, t_{A2,3}, \dots , t_{A2,N_{A2}}\}$

Tile B: same as Tile A

By ordering the values in ascending order we get samples of ordered time stamps with sample sizes N_{A1}, N_{A2}, N_{B1} and N_{B2}.

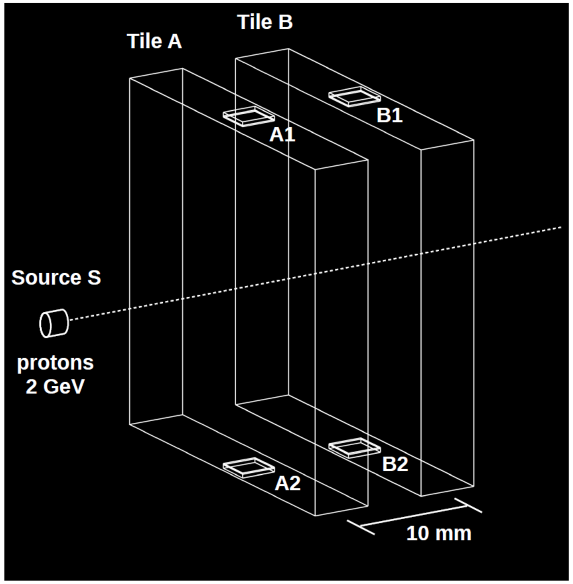
Tile A: SiPM A1 → $\{t_{A1,(1)}, t_{A1,(2)}, t_{A1,(3)}, \dots , t_{A1,(N_{A1})}\}$

1^{st} 2^{nd} 3^{rd} ... order statistic

Same for other samples (detectors)

Evaluation of time resolution

Just like in the experiment, the time resolution of a single tile can be estimated by using the time-of-flight (TOF) and the corresponding TOF resolution. Tile A and Tile B are identical in the simulation.



TOF: $T_{AB} = T_A - T_B$

TOF resolution: $\sigma_{AB}^2 = \sigma_A^2 + \sigma_B^2$

Time resolution of a tile: $\sigma_A = \sigma_B = 1/\sqrt{2}\ \sigma_{AB}$

The tile trigger time T_A can be defined in different ways using the ordered sets of time stamps from the detectors. (Same for Tile B and T_B)

1.) First: $T_A = t_{A1,(i)}$ if $t_{A1,(i)} < t_{A2,(i)}$

$T_A = t_{A2,(i)}$ if $t_{A1,(i)} > t_{A2,(i)}$

2.) Fixed: $T_A = t_{A1,(i)}$ or $T_A = t_{A2,(i)}$

i^{th} order statistic

3.) Mean: $T_A = (1/2)*(t_{A1,(i)} + t_{A2,(i)})$

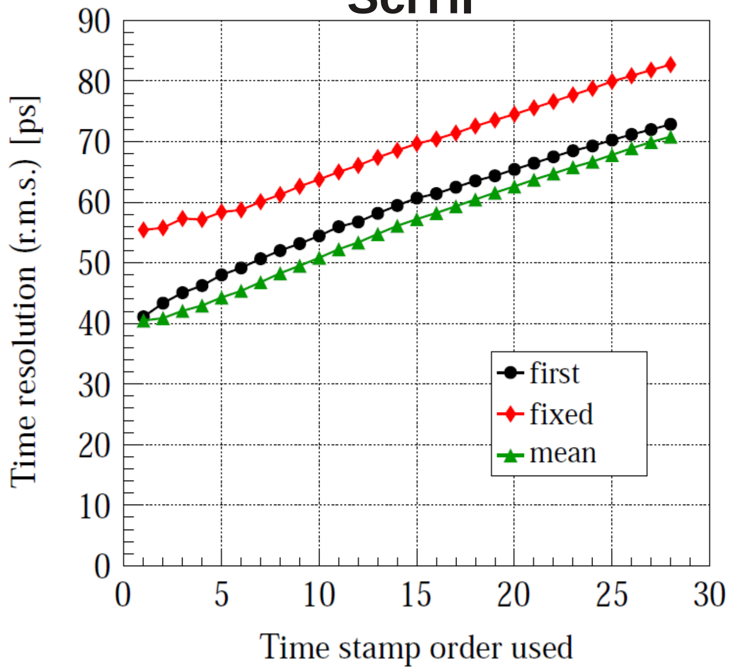
The i^{th} order statistic (time stamp order) is equivalent to the threshold level in the experiment.

Time resolution

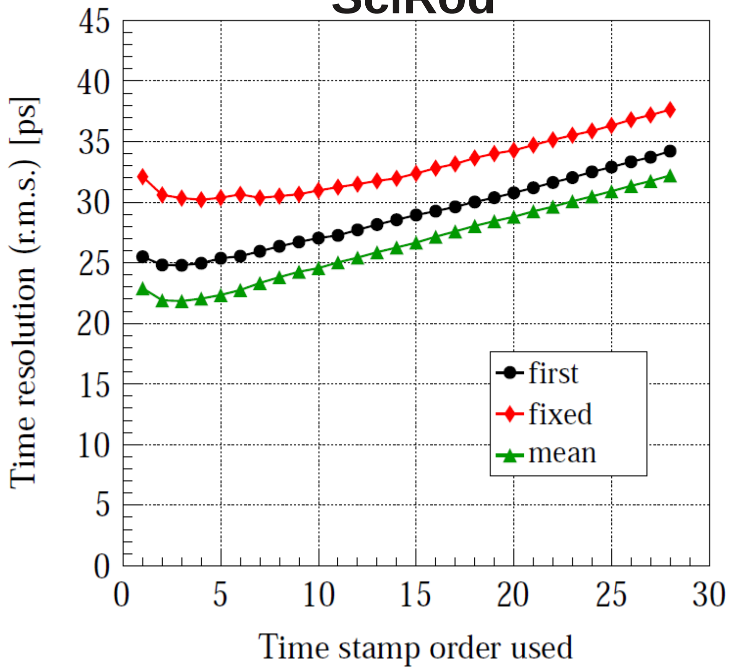
For the beginning we make two assumptions:

- Ideal photodetector: infinite time resolution, PDE = 1
- Perfectly polished scintillator surface (surrounded by air)

SciTil



SciRod

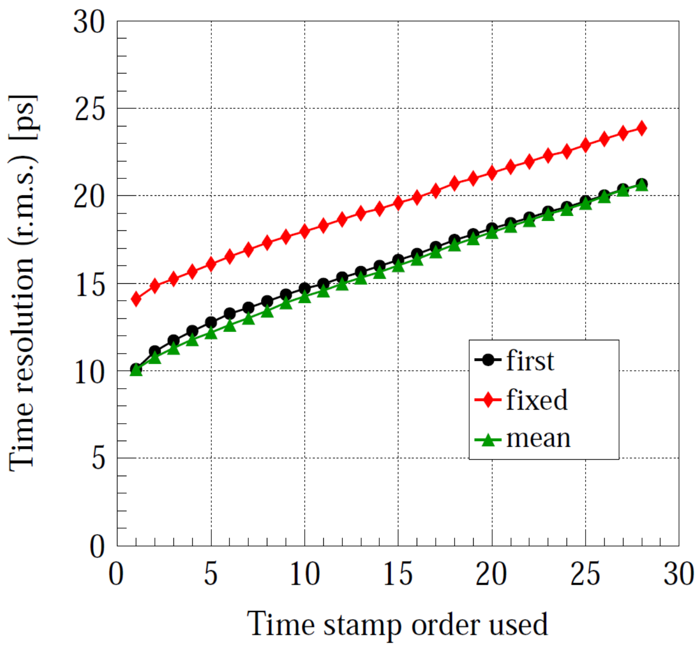


- **SciRod geometry provides nearly a factor 2 better time resolution.**
- **Taking the mean of the two detector time stamps results in the best time precision (will be used for further simulations).**
- **Triggering on the first detected photons does not necessarily provide the best time resolution, due to the influence of photon propagation.**
- **From photon counting statistics we expect that the first photon provides best timing.**

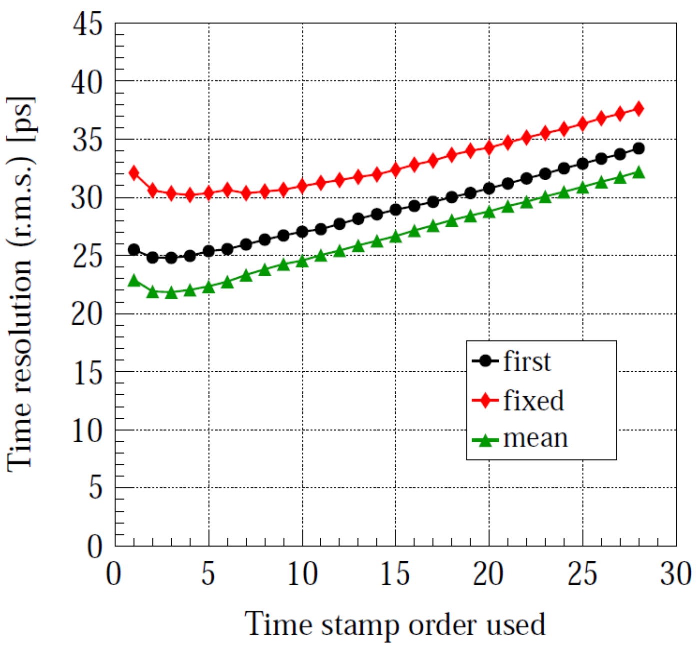
Influence of photon propagation

To show the impact of photon propagation we can shrink the scintillator to 3 x 3 x 3 mm³ (minimizes the influence of photon propagation) and compare the obtained time resolution with the one obtained with the SciRod geometry.

3 x 3 x 3 mm³



SciRod

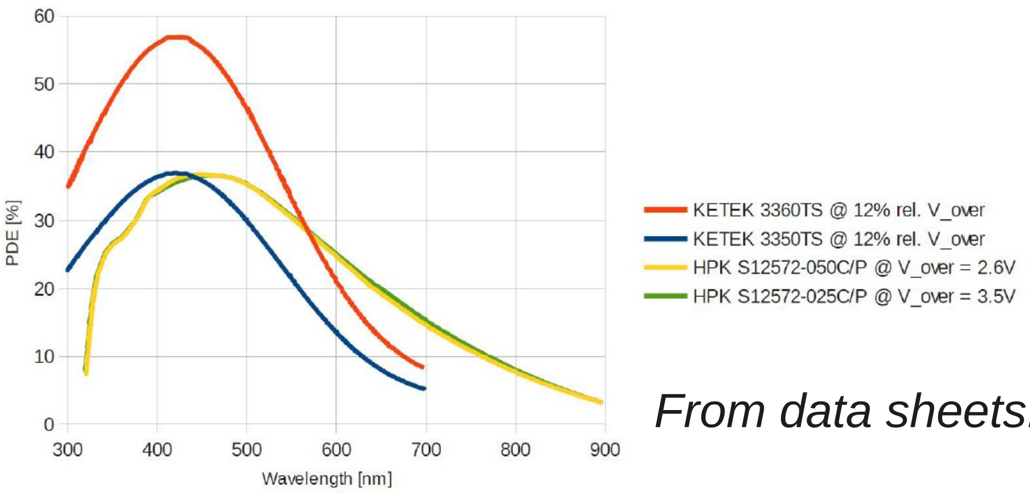


- **Taking the mean of the two detector time stamps results in the best time precision.**
- **From pure photostatistics it can be expected that the first photon provides best timing.**
- **However (depending on the geometry), the optimum threshold can change due to the influence of photon propagation**

Parameter tuning

In order to achieve more realistic results we have to include the PDE and SPTR of the photodetector. Furthermore we have to model the surface roughness of the scintillator.

- Including wavelength and over-voltage dependent PDE of the SiPM within the DetectorConstruction.cc

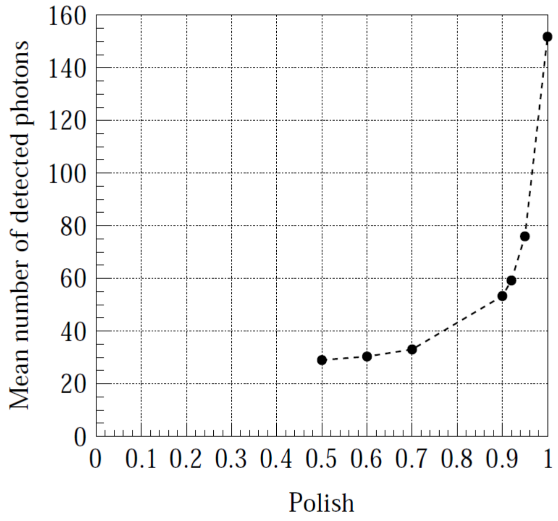


From data sheets.

- Model the surface roughness of the scintillator using the GLISUR model in Geant4. The roughness is indicated by the parameter “Polish”. If this value is < 1, then a random point is generated in a sphere with radius (1-polish) and the corresponding vector is added to the vector of specular reflection. SetPolish(0) means maximum roughness.

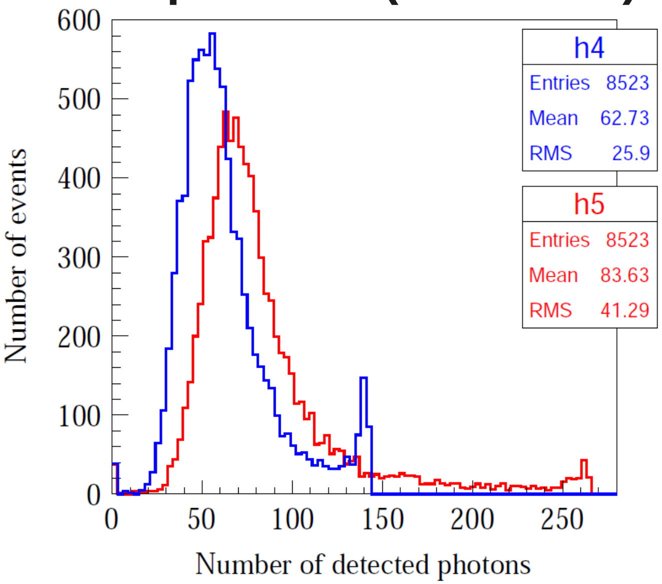
Comparison with experiment

- Varying the parameter “Polish” and compare the number of detected photons in the simulation with the experiment.

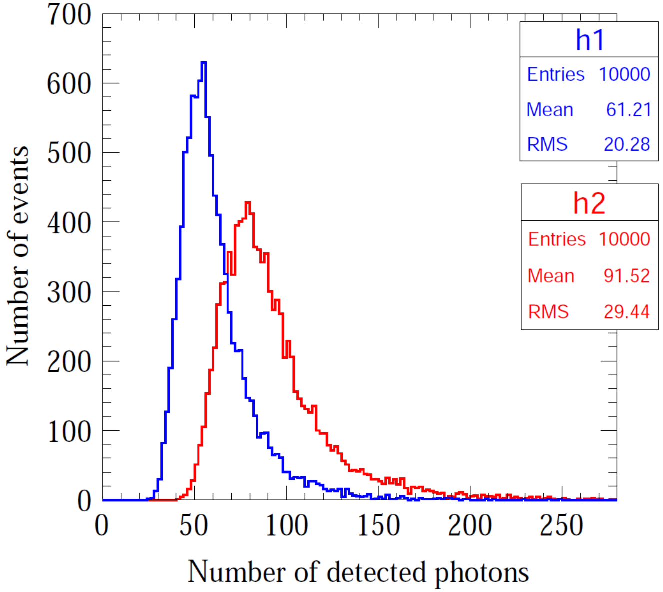


A good agreement has been found setting SetPolish(0.93).

Experiment (test beam)



Simulation



Blue: MPPC 12572-050P
1.3 V over-voltage

Red: Ketek PM3350TS
2 V over-voltage

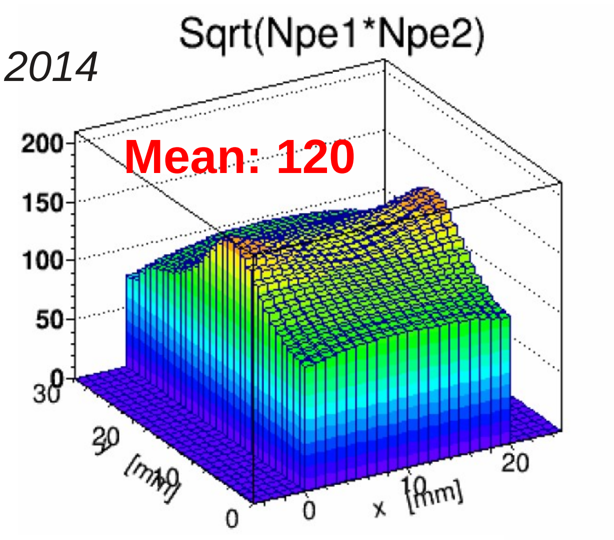
Comparison with experiment

Comparison with other experiment. Adapt PDE to higher over-voltage. SetPolish(0.93)

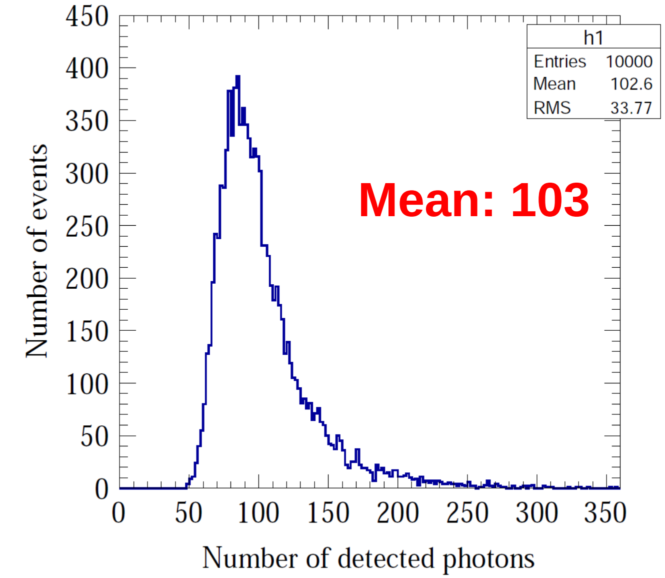
Experiment (^{90}Sr source)

A. Lehmann,
SciTil Meeting, July 24, 2014

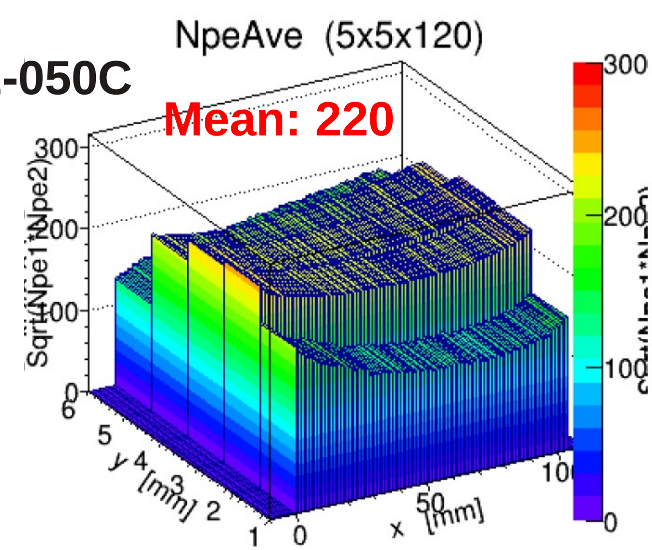
SciTil
MPPC 12652-050C

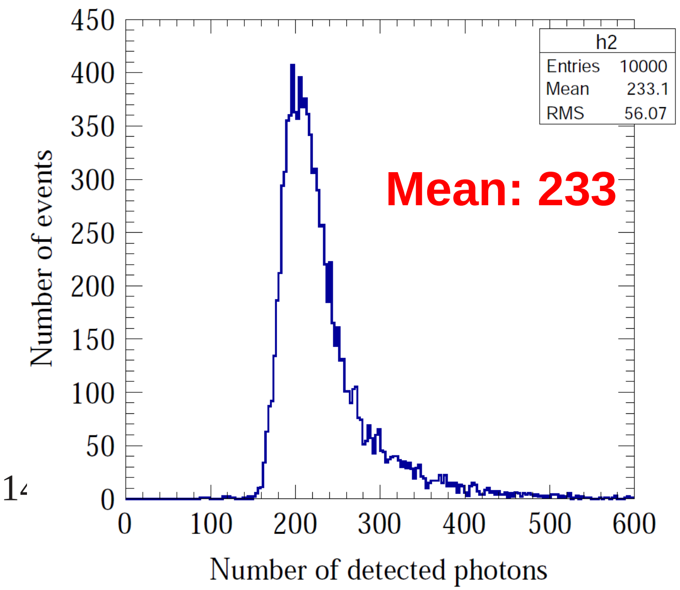


Simulation



SciRod
MPPC 12652-050C



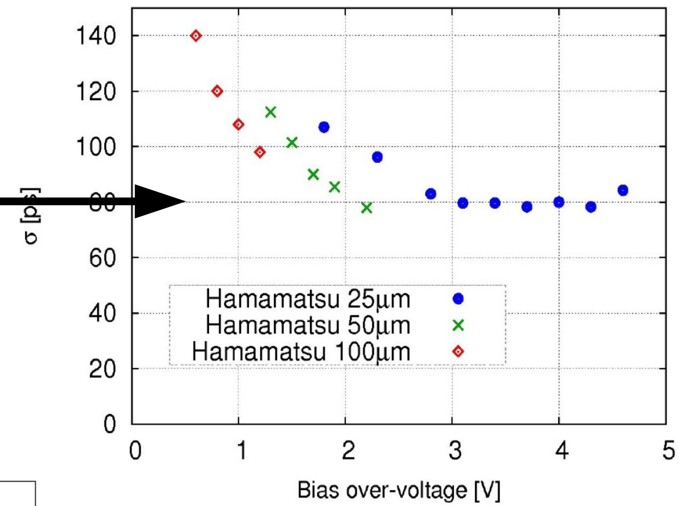


Single photon time resolution

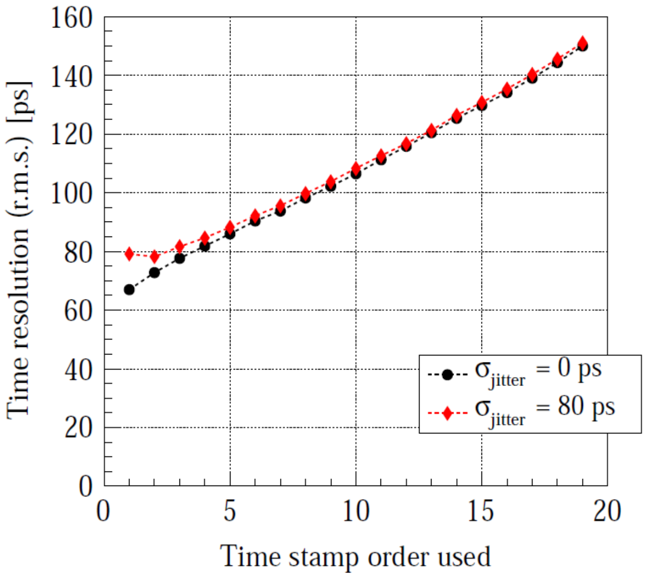
In order to model the SPTR of the SiPM we add a Gaussian jitter to the time stamps obtained from the simulation and then order the time stamps as before.

S. Gundacker, PhD Thesis, TU Wien, 2014

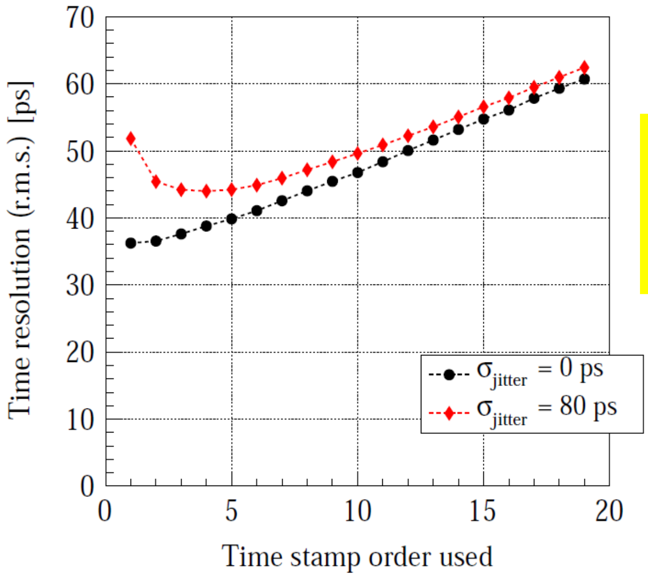
We assume a SPTR of 80 ps as the best value obtained for the MPPC with 50U and 25U pixels.



SciTil



SciRod



- **SPTR affects the influence of photon counting statistics and the optimum threshold.**

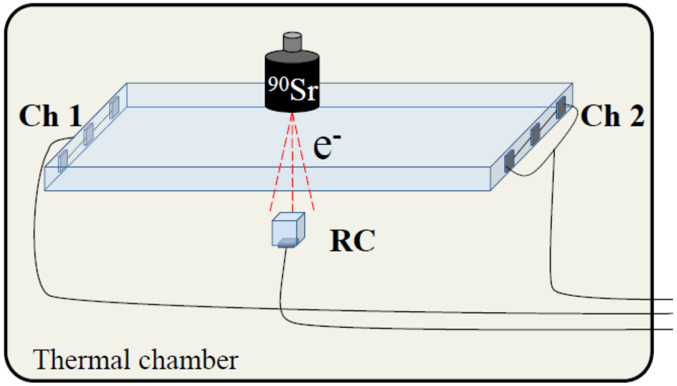
Comparison with experiment (best values with HPK):
SciTil: ~ 95 ps
SciRod: ~ 60 ps

MEG geometry

As an alternative to SciTils and SciRods one could think of wider bars, read-out by a larger number of SiPMs connected in series (or parallel).

High precision timing counter for the MEG experiment

Paolo W. Cattaneo et al.,
"Development of High Precision Timing Counter Based on Plastic Scintillator with SiPM Readout",
IEEE Trans. Nucl. Sci., Feb. 2014,
arXiv: 1402.1404v1



The current MEG II layout foresees scintillator bars with dimensions of 120 x 40 x 5 mm² read-out by 6 SiPMs on each side connected in series.

Time resolution of about 60 ps reached.

- **Try to simulate MEG geometry and compare it with SciTil and SciRod.**

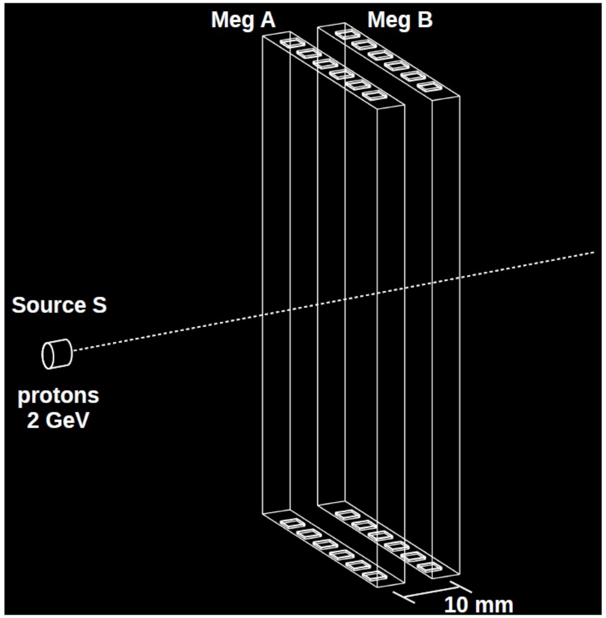
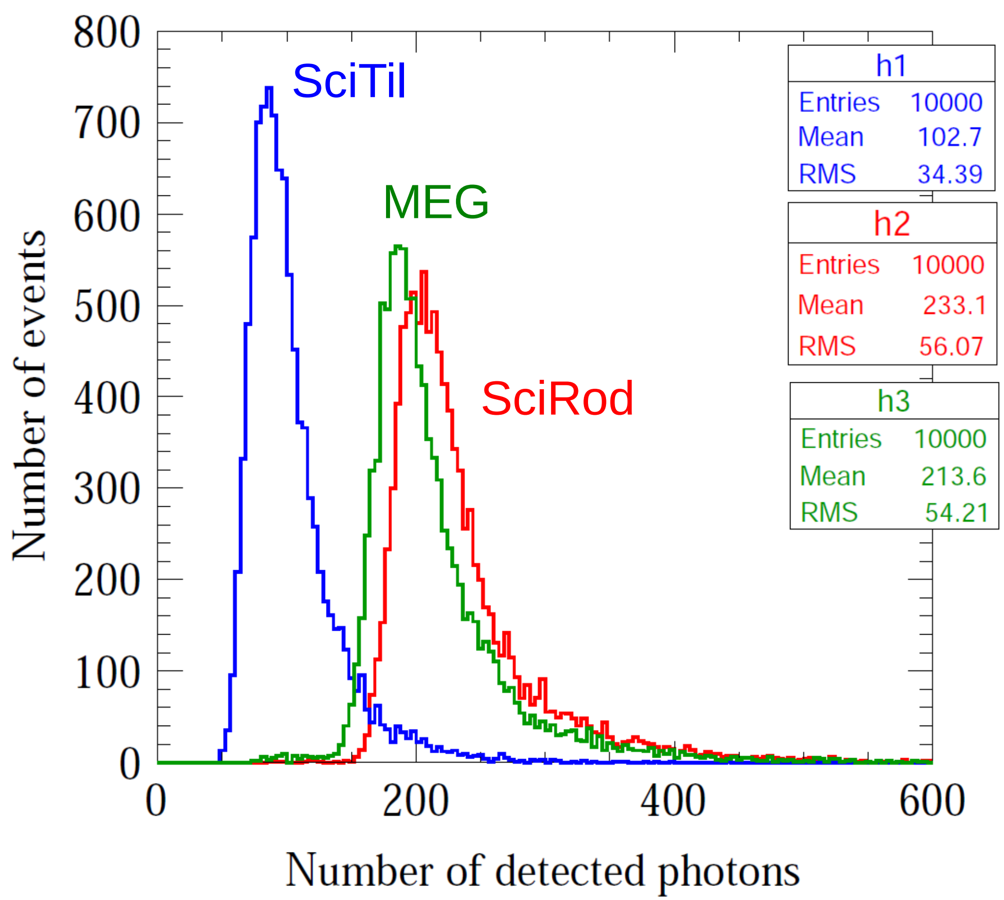


Figure 11: The simulated MEG geometry.

Number of photons



Most photons can still be detected with SciRod.

Comparison with experiment:

A. Lehmann, SciTil Meeting, July 24, 2014

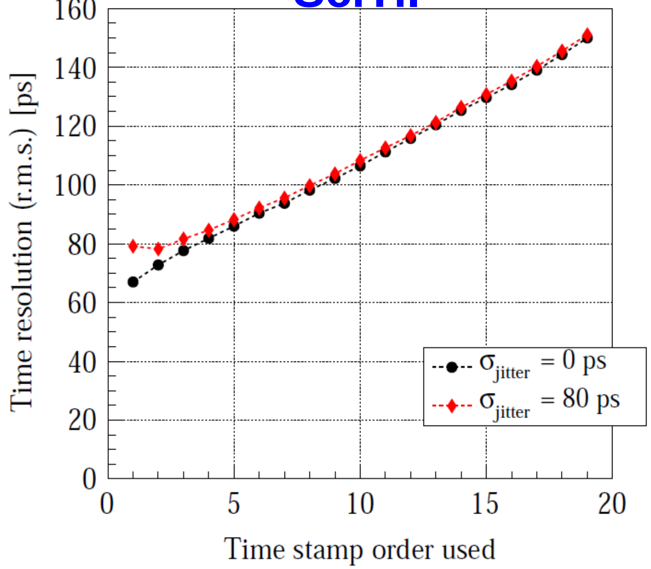
SciTil: $N_{avg} = 120$

SciRod: $N_{avg} = 220$

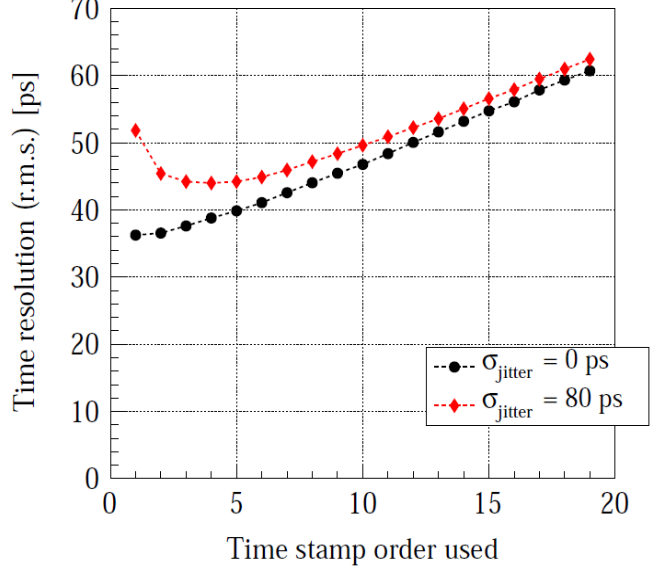
Factor 1.8

Time resolution

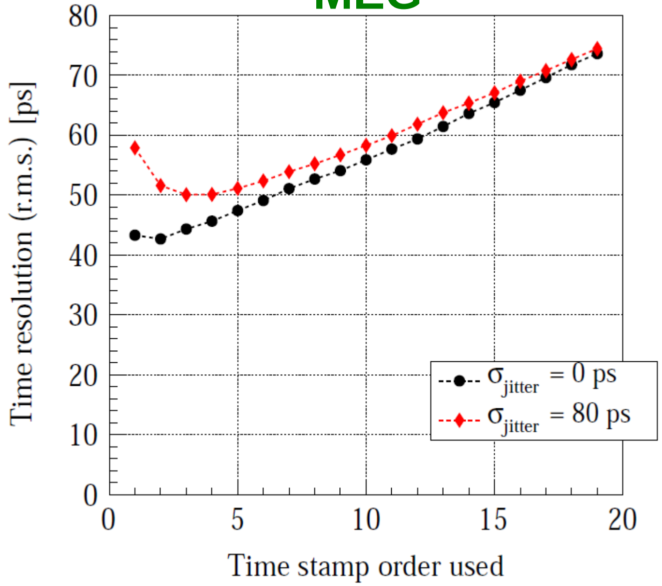
SciTil



SciRod



MEG



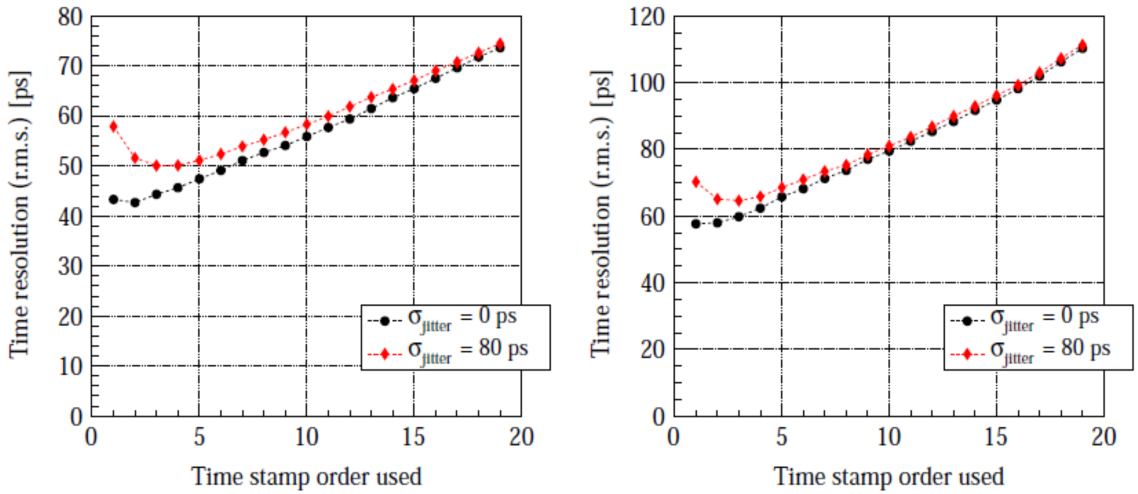
- **Best time resolution in the simulation achieved with SciRod.**
- **SciRod and MEG show however comparable results.**
- **Both geometries clearly better than SciTil.**
- **Influence of SPTR accordingly larger.**

Comparison with experiment:

Paolo W. Cattaneo et al., arXiv: 1402.1404v1

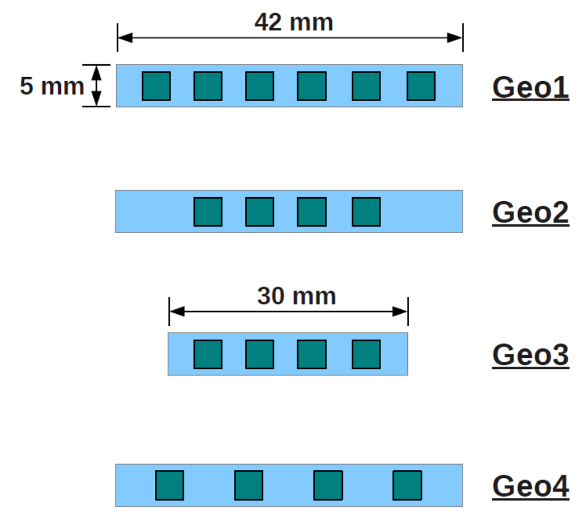
MEG resolution ~ 62 ps (with only 3 SiPMs per side)

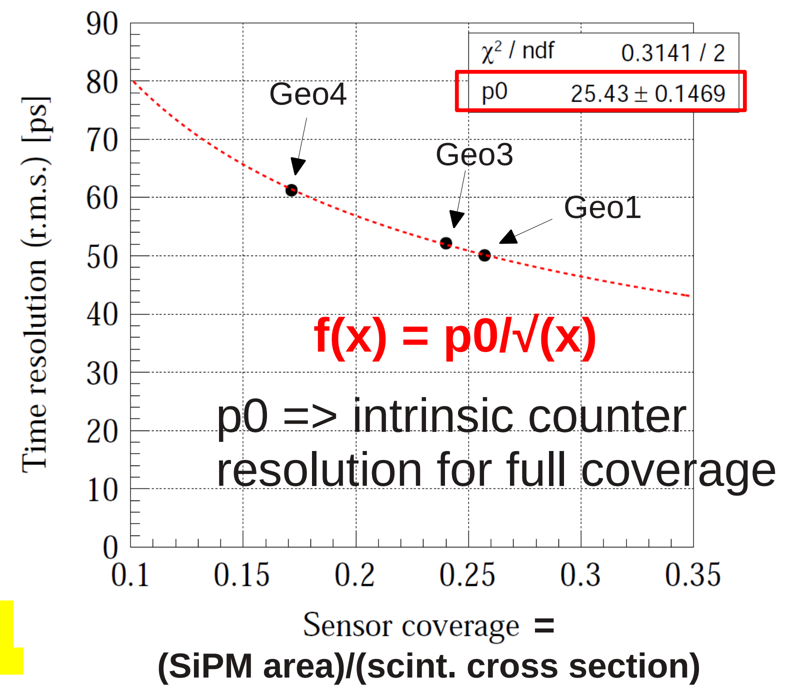
Geometry modifications



(a) Geo1 (b) Geo2

(c) Geo3 (d) Geo4





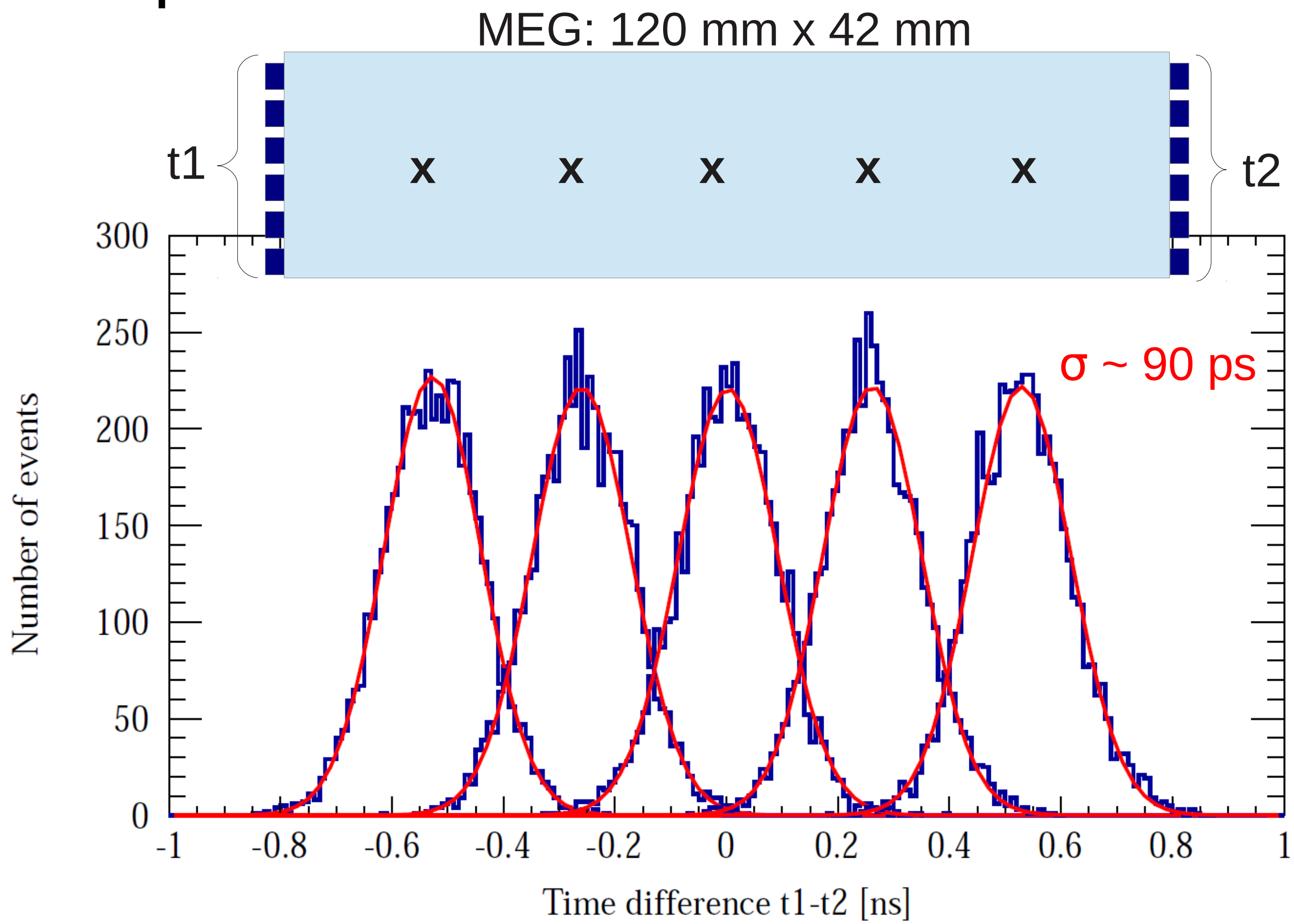
- **The larger the sensor coverage the better the timing.**

Position resolution

A MEG-like geometry could reduce the number of the SciTil channels and the total costs, while sustaining good time resolution.

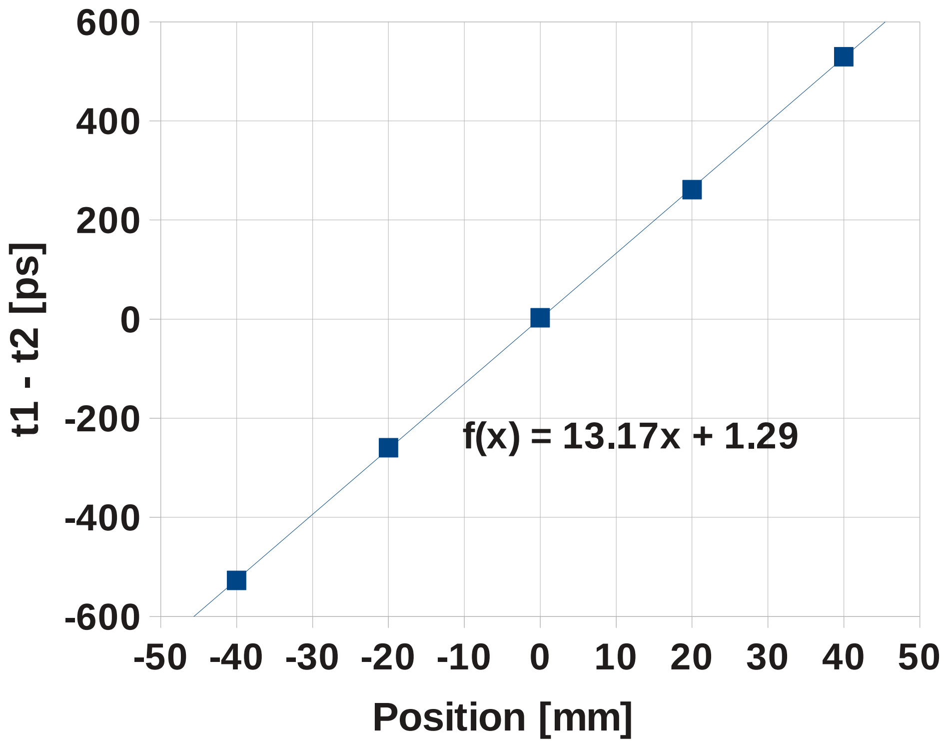
But what about the spatial resolution?

One could use the time difference between measured times at the two bar ends to estimate the hit position.



Position resolution

Relation between time difference and hit position from simulation:



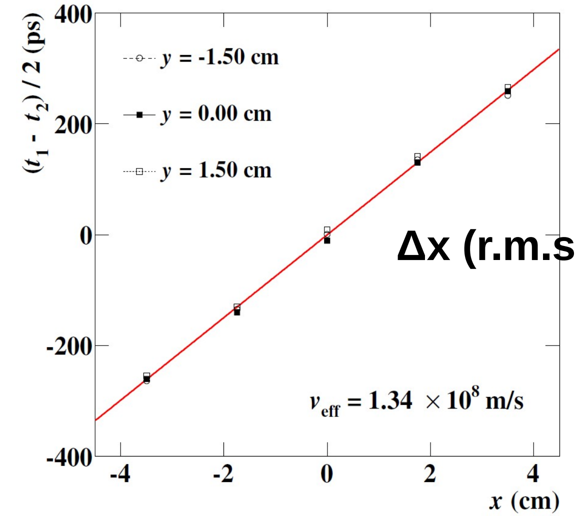
From the slope we can estimate the effective speed of light: $v_{eff} = 7.6 \times 10^7$

Position resolution with σ(t1-t2) = 90 ps:
Δx (sigma) = 6.8 mm
Δx (FWHM) = 16.1 mm

Comparison with experiment:

Paolo W. Cattaneo et al., arXiv: 1402.1404v1

MEG geometry (90 x 40 x 5 mm²)



Δx (r.m.s.) = 8 mm

A. Lehmann, SciTil Meeting, July 24, 2014

SciRod geometry (120 x 5 x 5 mm²)

σ(t1-t2) = 100 ps → Δx (FWHM) = 13 mm

Summary and outlook

- **The simulation shows good agreement with experimental results.**
- **To further improve this agreement, electronics noise and maybe even the measured single photon time response (“real” SiPM signals) could be considered in the simulation.**
- **The simulation shows that photostatistics and photon propagation as well as the SPTR of the SiPM influence the time resolution and affect the threshold settings. This has been also observed in experiment.**
- **The MEG or a modified MEG geometry could be an alternative to SciTils or SciRods. The simulation shows that a time resolution in the order of 50 – 60 ps can be reached, which is comparable to the values obtained with SciRods. This may need to be checked experimentally!**
- **The hit position in longitudinal direction (along the bar) could be estimated using the difference between the arrival times measured at the bar ends. A position resolution in the order of 16 mm (FWHM) was found in the simulation.**
- **Since the double hit probability for a single counter rises as the scintillator surface increases, it has to be checked if the efficiency of SciTil can be sustained with the larger scintillators at high event rates.**

Thank you !