Results from Pilot Run for MEG II Positron Timing Counter

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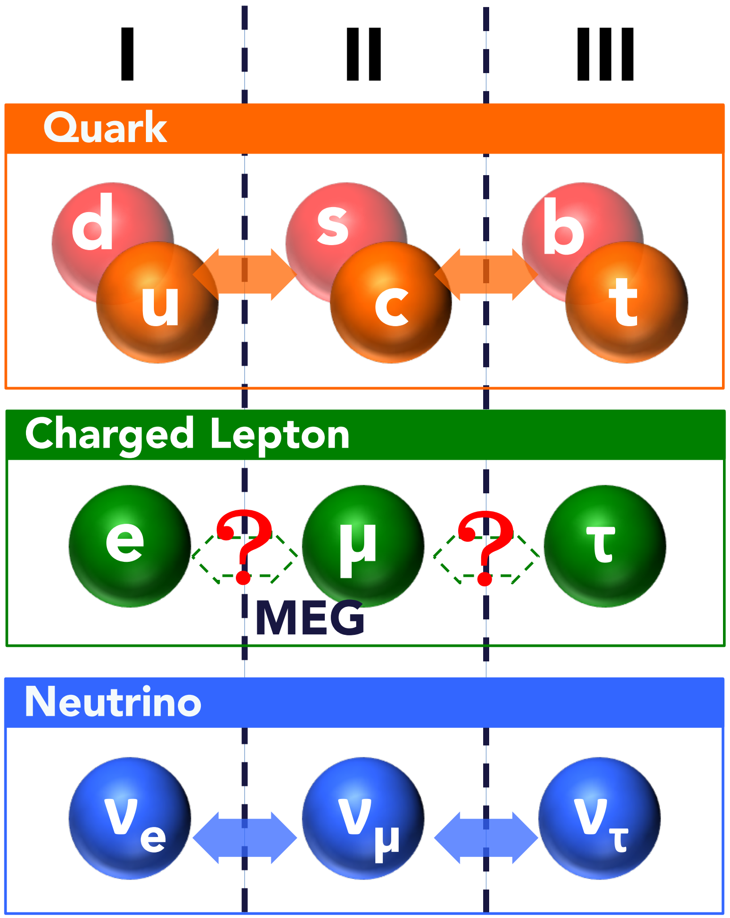
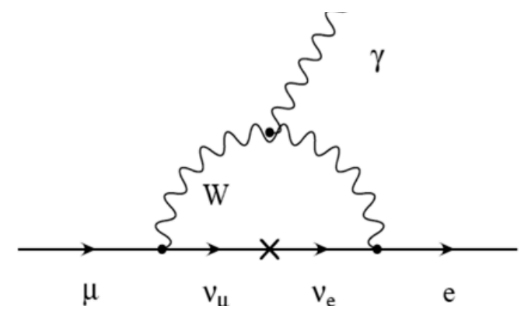
Charged Lepton Flavour Violation



- Inter-generational mixing have not been observed only for charged lepton sector.
- Too small branching ratio is predicted in the framework of the standard model + neutrino mass.



$$\mathcal{B}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{i1}}{M_W^2}\right|^2 \simeq 10^{-54}$$

- Beyond the standard model (SUSY GUT etc) predicts that charged lepton should also mix at experimentally observable rate: $O(10^{-11})\sim O(10^{-15})$

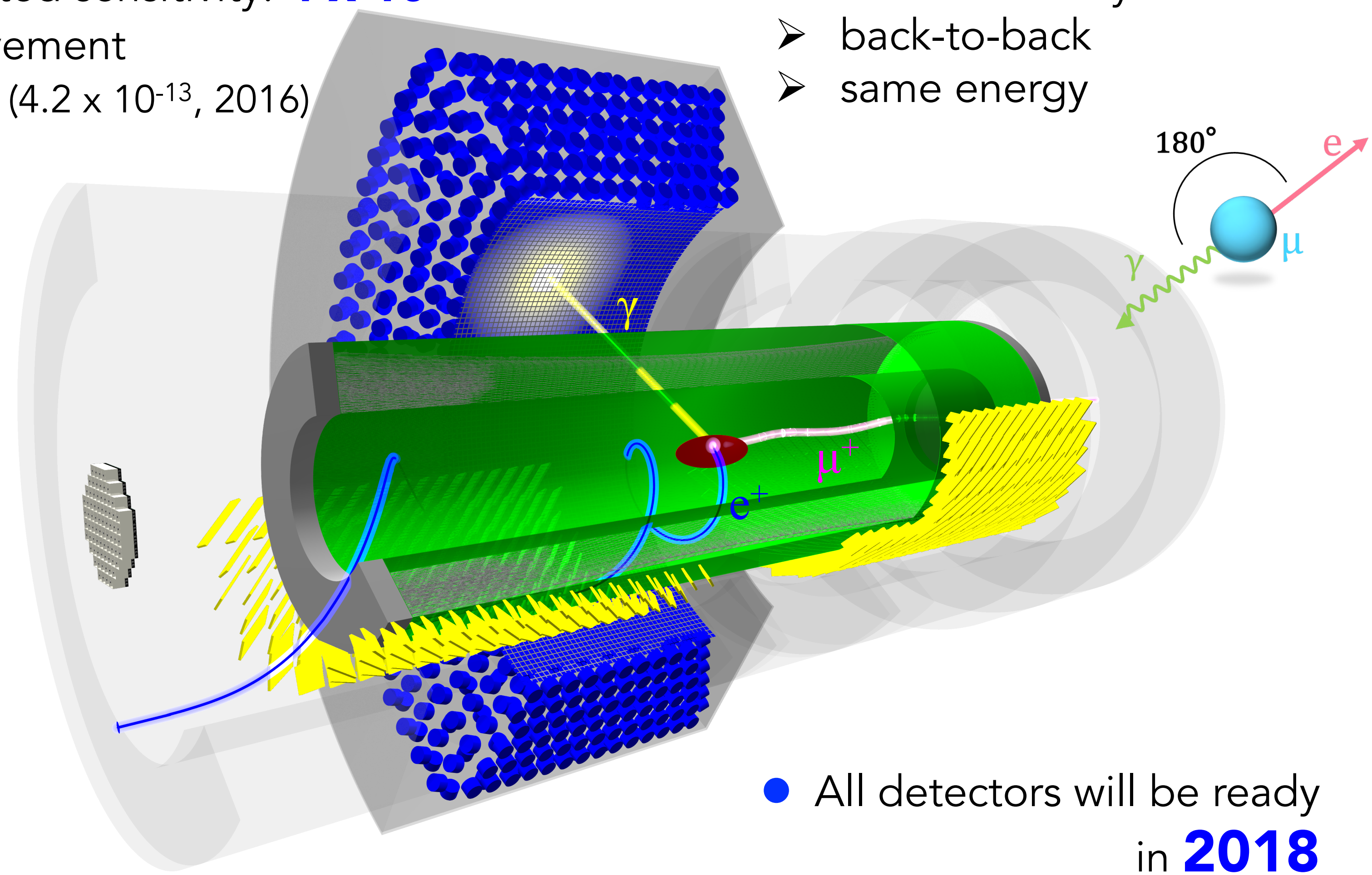
The discovery of cLFV is clear evidence for new physics

MEG II Experiment

At **P**aul **S**cherrer **I**nstitut in Switzerland

- Search for cLFV ($\mu^+ \to e^+\gamma$) with unprecedented sensitivity: **4×10^{-14}**
  - x**10** improvement from MEG (4.2×10^{-13}, 2016)

- **Signal (e^+, γ)**
  - Simultaneously emitted
  - back-to-back
  - same energy

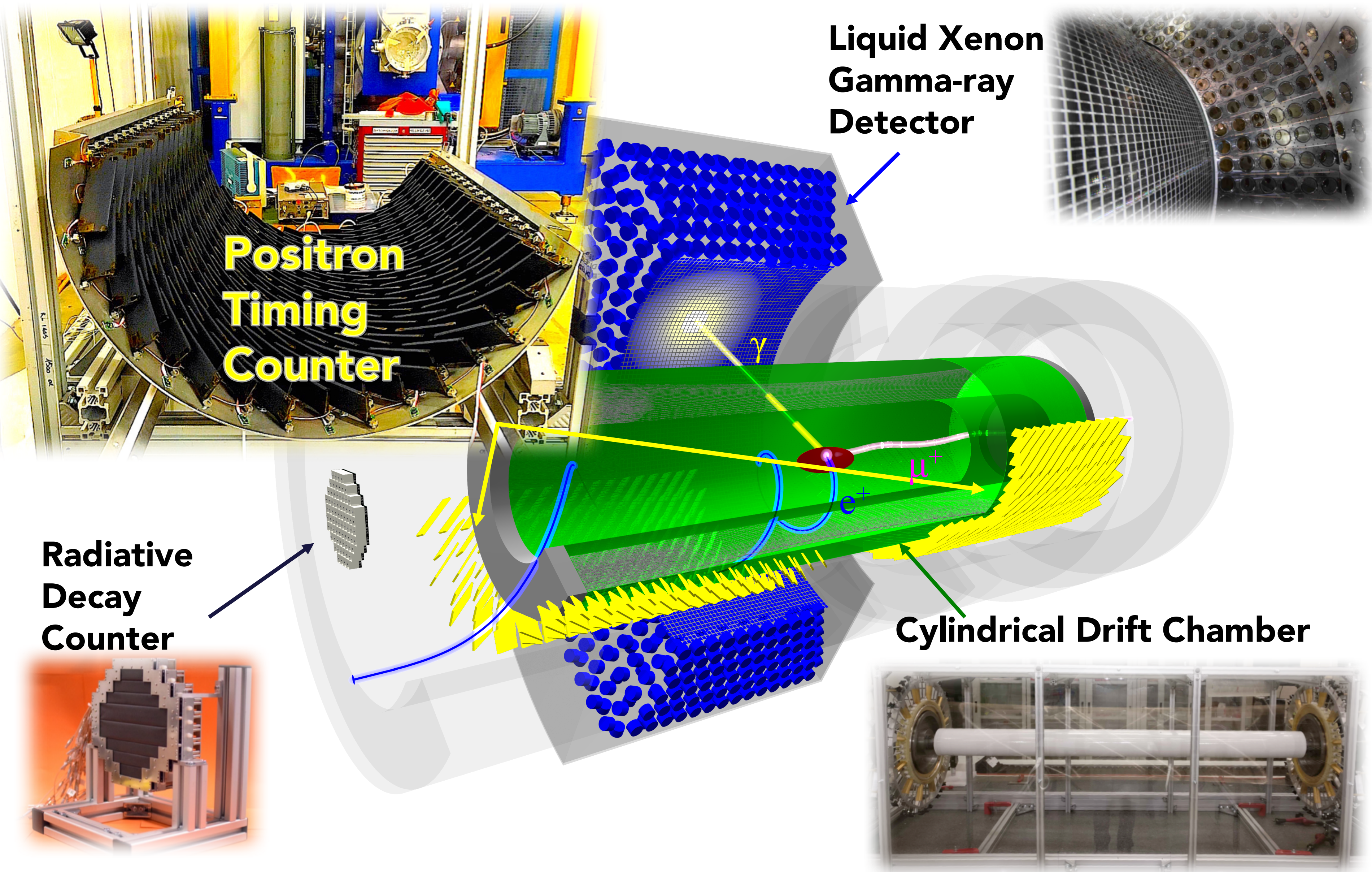


- All detectors will be ready in **2018**

- Improve every resolution by factor **2**

MEG II Detector

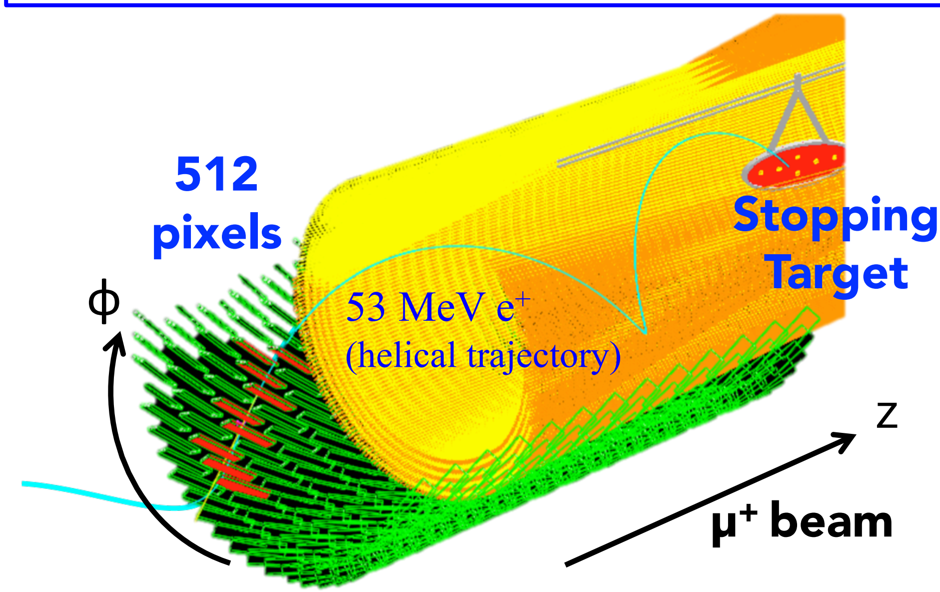
At **P**aul **S**cherrer **I**nstitut in Switzerland



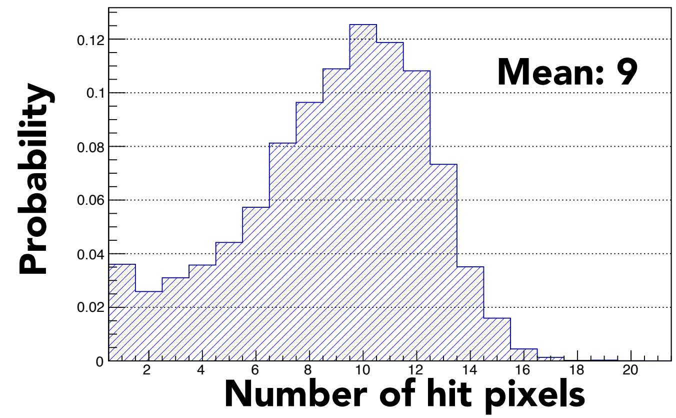
Positron Timing Counter (1): Concept

Key Concept

- Improve time resolution by averaging the signal time of multiple hits.



- Averaged hit multiplicity for signal e^+s: 9 (MC)



- The total time resolution is expected to improve with $\frac{1}{\sqrt{N_{\mathrm{hit}}}}$ and ~ 35 ps can be achieved at 9 hits.

Stochastic term

Constant term

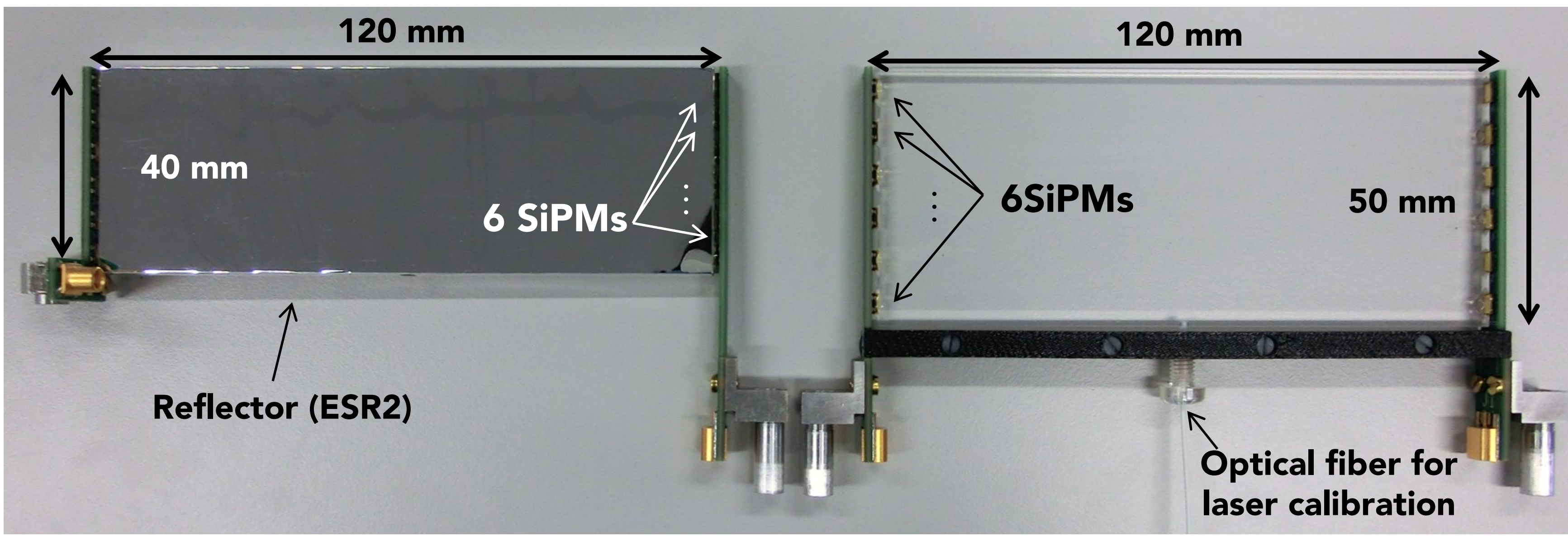
$$\sigma_{\mathrm{all}}(N_{\mathrm{hit}}) = \sqrt{\frac{\sigma^2_{\mathrm{intrinsic}}}{\mathbf{N_{hit}}} + \frac{\sigma^2_{\mathrm{inter-pixel}}}{\mathbf{N_{hit}}} + \sigma^2_{\mathrm{MS}}(N_{\mathrm{hit}}) + \sigma^2_{\mathrm{const}}}$$

Intrinsic resolution: 70〜80 ps

Multiple scattering: ~4 ps at 9 hits

Positron Timing Counter (2): Pixel

- Upstream (256 pixels) + Downstream (256 pixels)= 512 pixels
- Fast plastic scintillator (BC422, 40 (50) x 120 x 5 mm^3)
- Readout by 6 SiPMs* with series connection (in total 6144 SiPMs) at each of both sides.
- Time calibration accuracy among pixels: < 30 ps

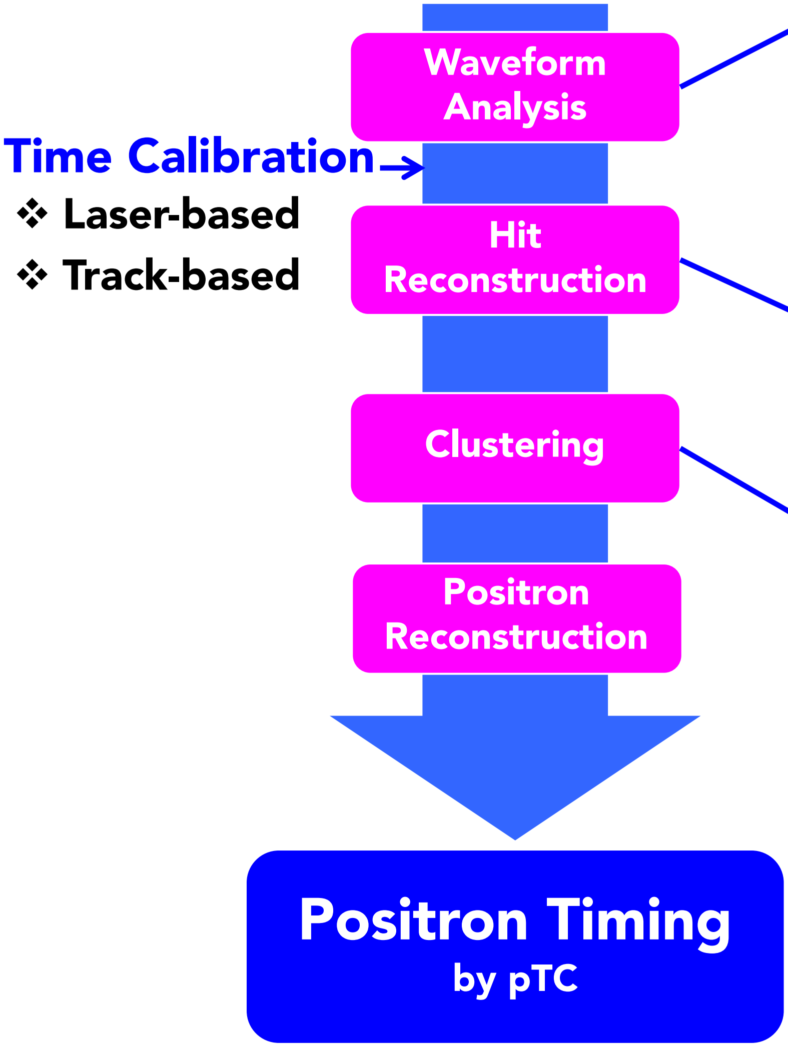


*AdvanSiD, ASD-NUV3S-P High-Gain, 3x3 mm^2, 50x50 μm^2, $V_{breackdown}$ ~ 24 V

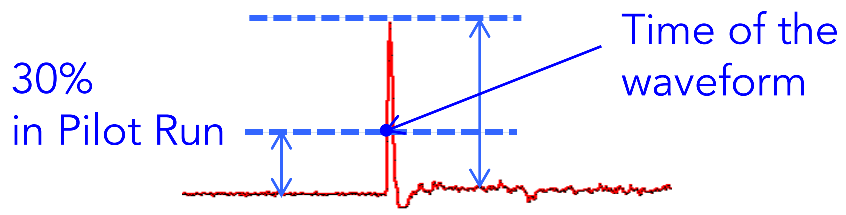
Purpose of This Study

To construct MEG II timing counter (pTC)
and evaluate its performance under the MEG II environment
towards coming physics run.

Positron Timing Reconstruction



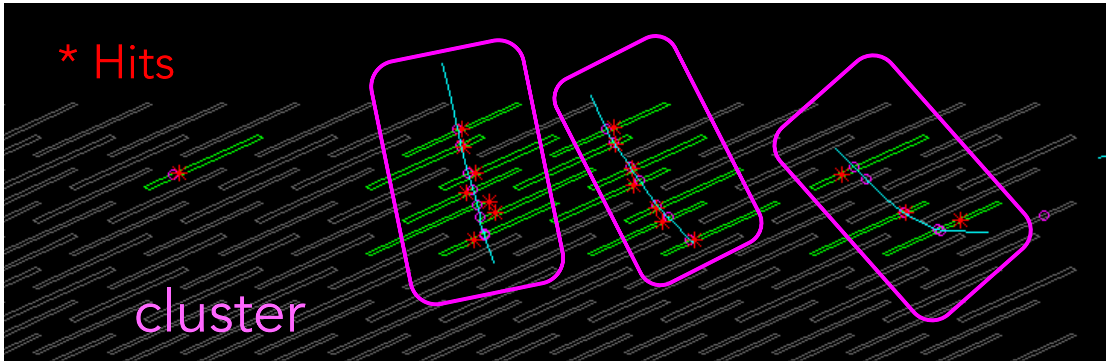
- Waveform time (t_1, t_2) is calculated by using constant fraction method.



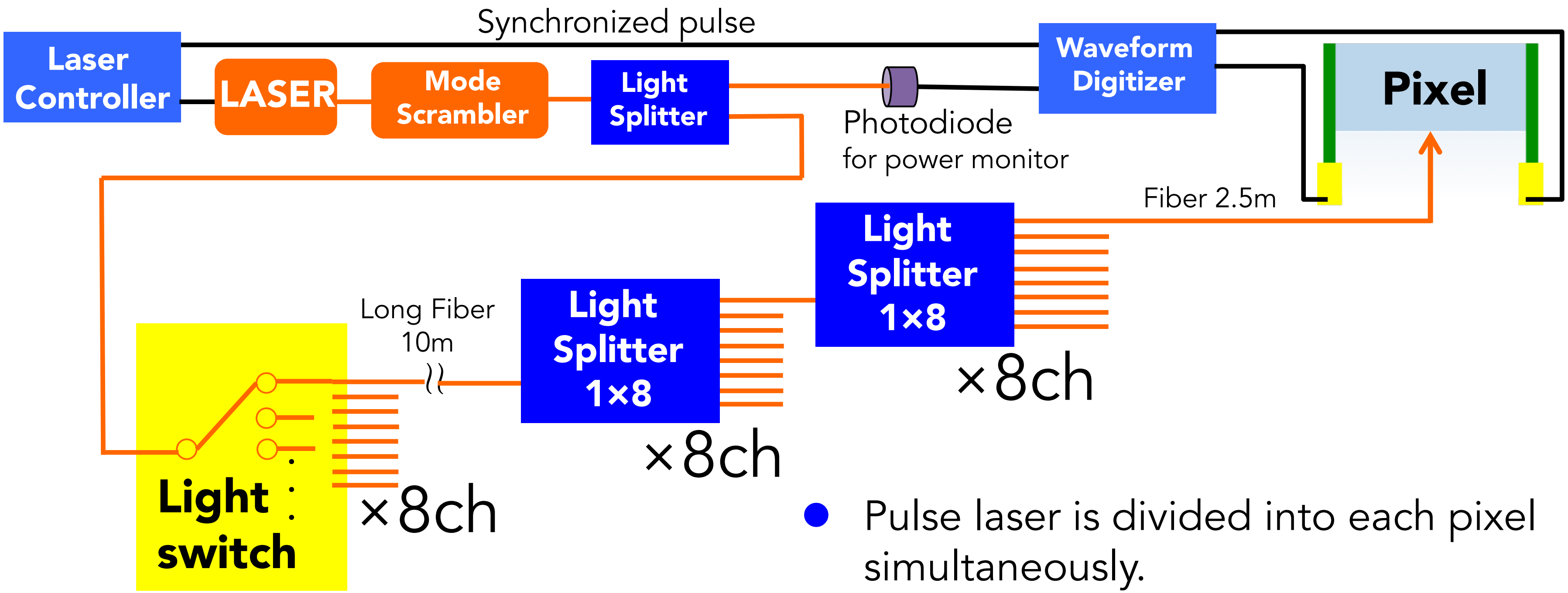
- Hit time (t_{hit}) is calculated by averaging both ends.

$$t_{hit} = \frac{t_1 + t_2}{2}$$

- Pixels are clustered by using hit time and pixel position.



Time Calibration: Laser-based



- Pulse laser is divided into each pixel simultaneously.
- PLP-10 (Hamamatsu) is used as a light source.

(cited from Hamamatsu HP)

-Wavelength 405 nm
-Wavelength FWHM < 10 nm
-Pulse duration typ. (max) 60 (100) ps

- Time offset of each pixel is measured relative to laser-synchronized pulse.
- Calibration uncertainty is estimated as 24 ps by testing all parts of laser calibration system.

Time Calibration: Track-based

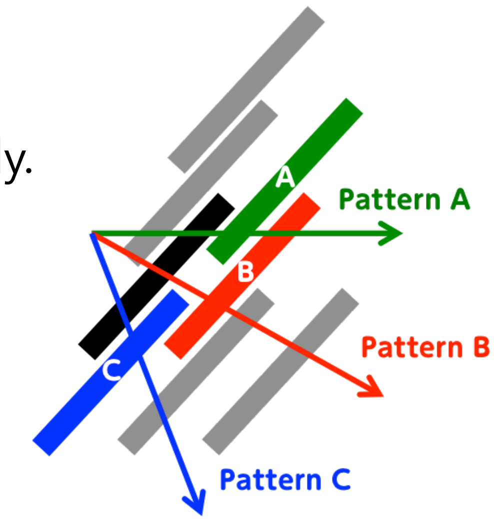
- Positron tracks from Michel decay ($\mu^+ \to e^+ \nu\nu$) are used for calibration.
  1. Assume every pixel has 3 different TOF b/w pixels (pattern A, B and C).
  2. Calculate these TOF values for every pixel by Monte Carlo*.
  3. Define χ^2 as the difference b/w measured time and expected time.
  4. Minimize χ^2 using Millepede II.
  5. Find ΔT_j.
- Calibration uncertainty is estimated as 11 ps by MC study.

Measured time

Expected time

$$\chi^2 = \sum_i^{N_{ev}} \sum_j^{N_{hit}} \left(\left(\boxed{T_{ij}} - \boxed{(T_{0i} + TOF_{ij} + \Delta T_j)} \right) / \sigma \right)^2$$

Time offset of each pixel
:What we want to know

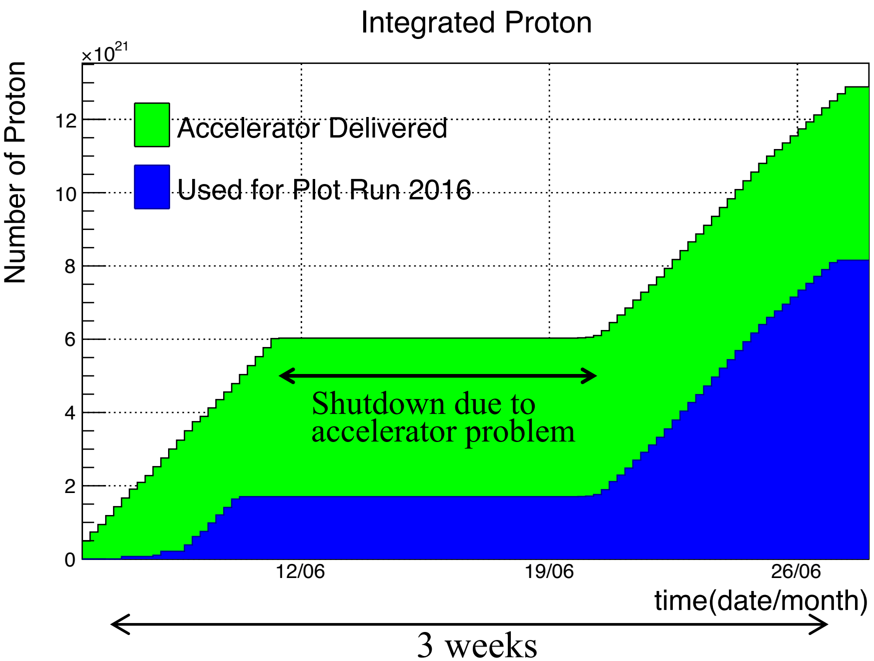


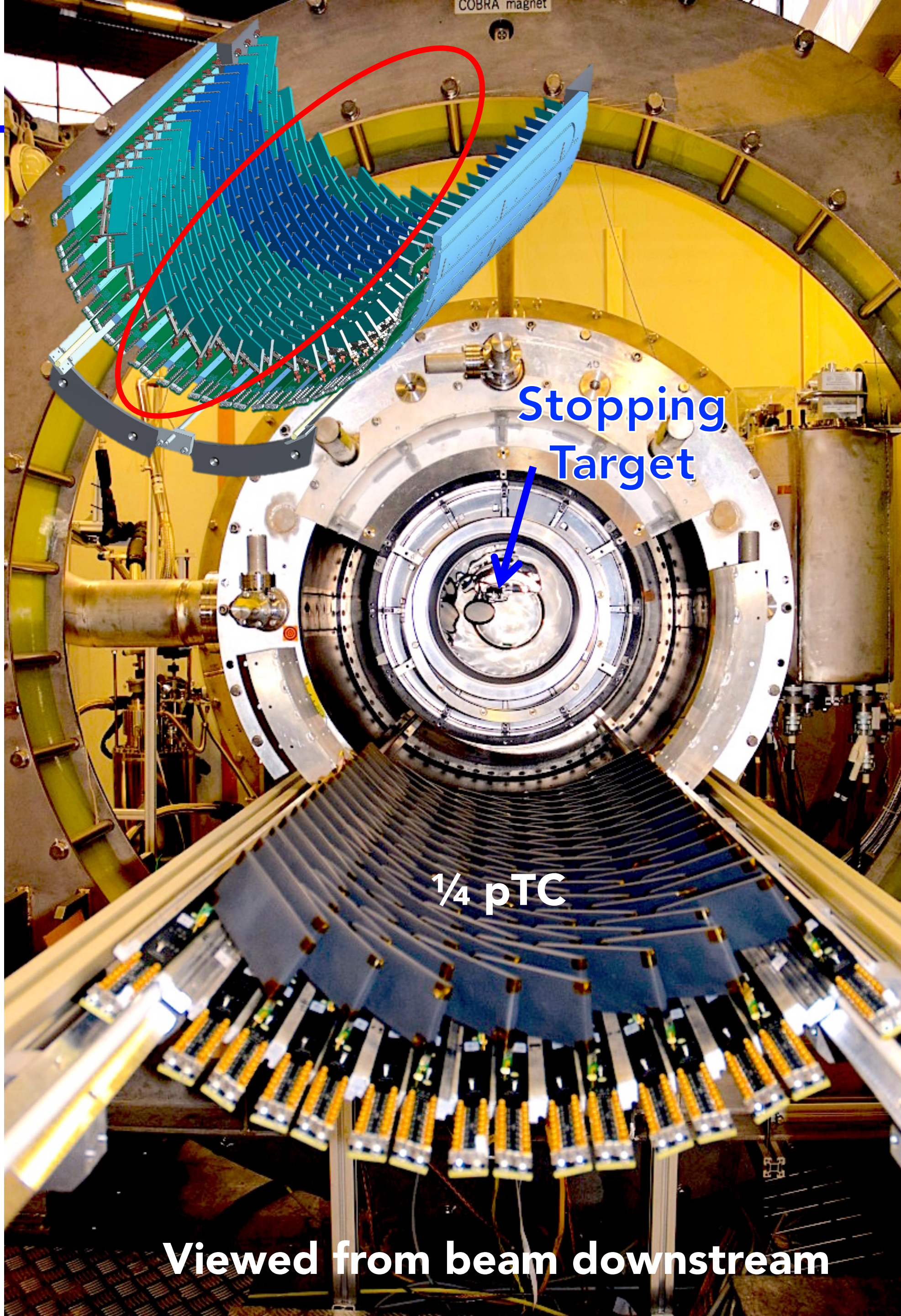
* This setup is for Pilot Run w/o DCH. TOF will be calculated by DCH in physics run.

Millepede II www.desy.de/~kleinwrt/MP2
A software provided by DESY to solve the linear squares problems, such as detector alignment and calibration based on track fits.

Pilot Run 2016

- 128 pixel (=1/4 of pTC) was installed.
- Laser calibration was partially installed (40 pixels).
- Beam time for 3 weeks.
- μ^+ beam with the same intensity as MEG II.
  (Stopping Rate: 7.0×10^7 Hz)





DAQ & Trigger

Integrated trigger and DAQ system is designed for MEG II.

Trigger

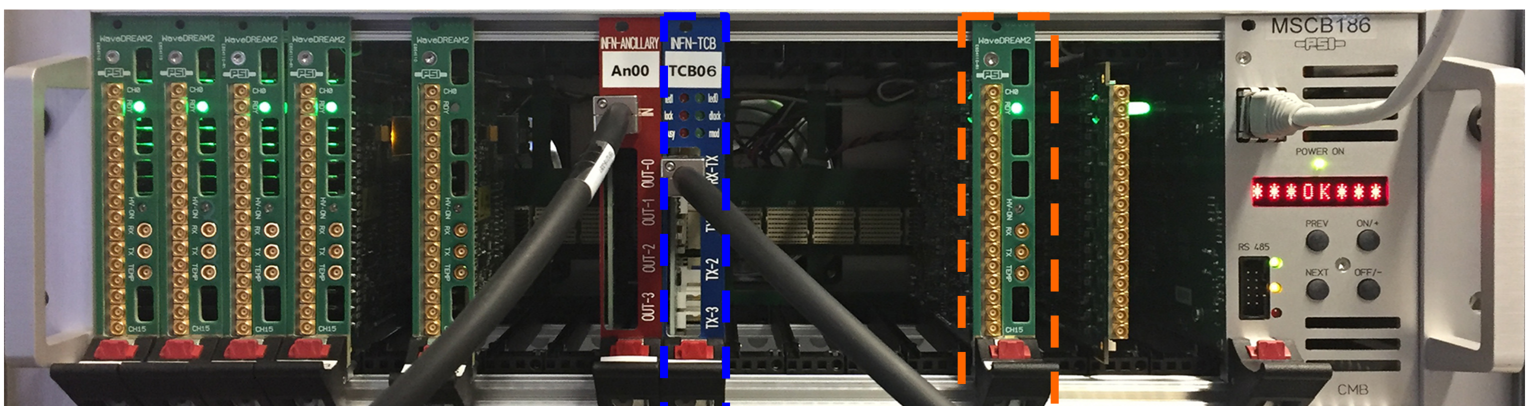
- Several trigger schemes were implemented in Pilot Run 2016.
  - Track-like
  - Multiplicity
  - OR
  - Laser
  - Pedestal

DAQ: WaveDREAM2

- Multi-functional board developed at PSI.
  - SiPM biasing (~ 240 V)
  - Amplifier (no pre amplifier)
  - Pole-zero cancellation
  - Waveform digitization at giga-sampling (DRS*4 chip)
  - First level trigger

*DRS = Domino Ring Sampler

WaveDAQ crate (= 16 WaveDREAM2 boards = 256 channels)

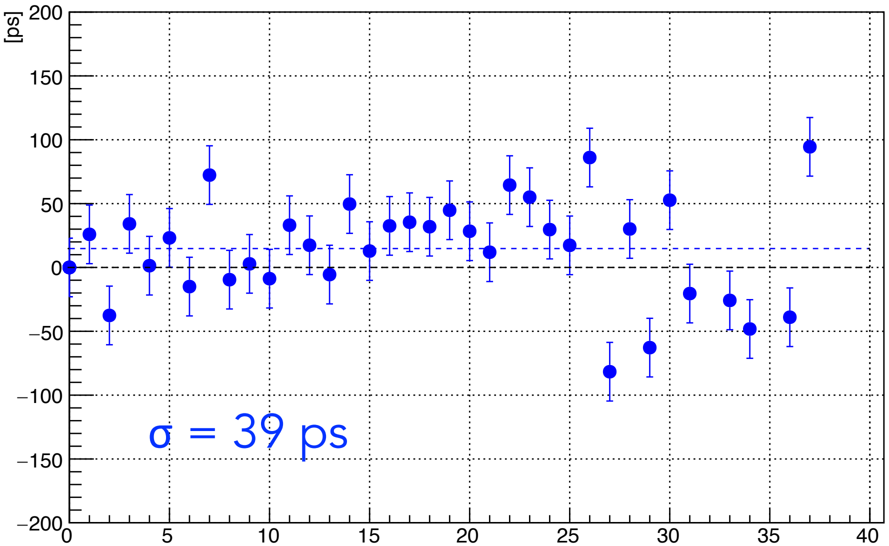


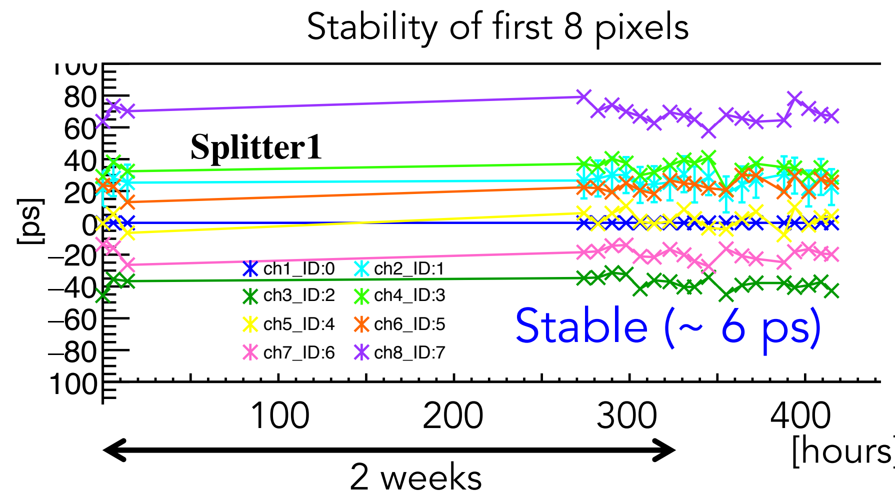
Trigger Concentrator Board

WaveDREAM2 board = 16 channels

Results Consistency b/w Time Calibration Methods

- Time-offset difference b/w laser-based method and track-based method (left) and its stability (right).





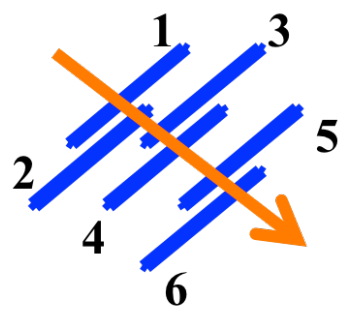
- The variation of time-offset difference is σ = 39 ps.
  - Including systematic uncertainty of laser-based and track-based methods.

- Time-offset difference is stable in time (~ 6 ps).

Time Resolution (1): Odd-Even Analysis

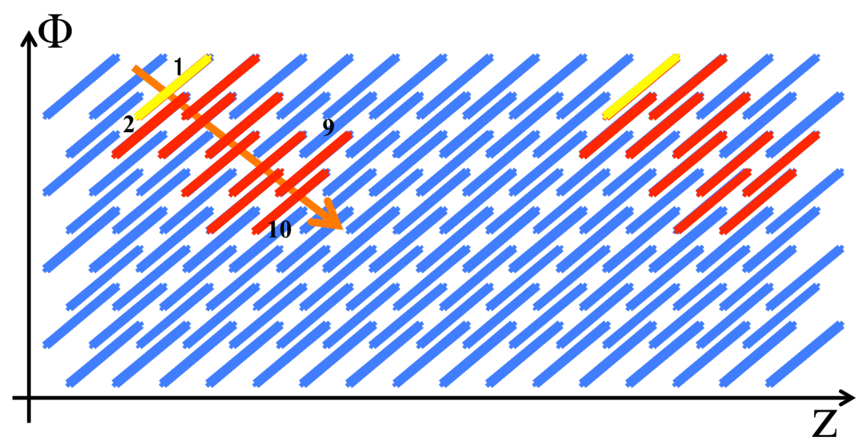
- Multi-counter resolutions are evaluated by the odd-even analysis.
- For a given consecutive pixels (right fig.), pixels are divided into 2 groups according to the order of positron tracks: "odd" and "even".
- Time difference (T_{nhits}) is defined as
  (average of "odd" pixels – average of "even" pixels)/2
- Calculated for N_{hit} = 2, 4, 6, 8, 10.

e.g. N_{hit} = 6



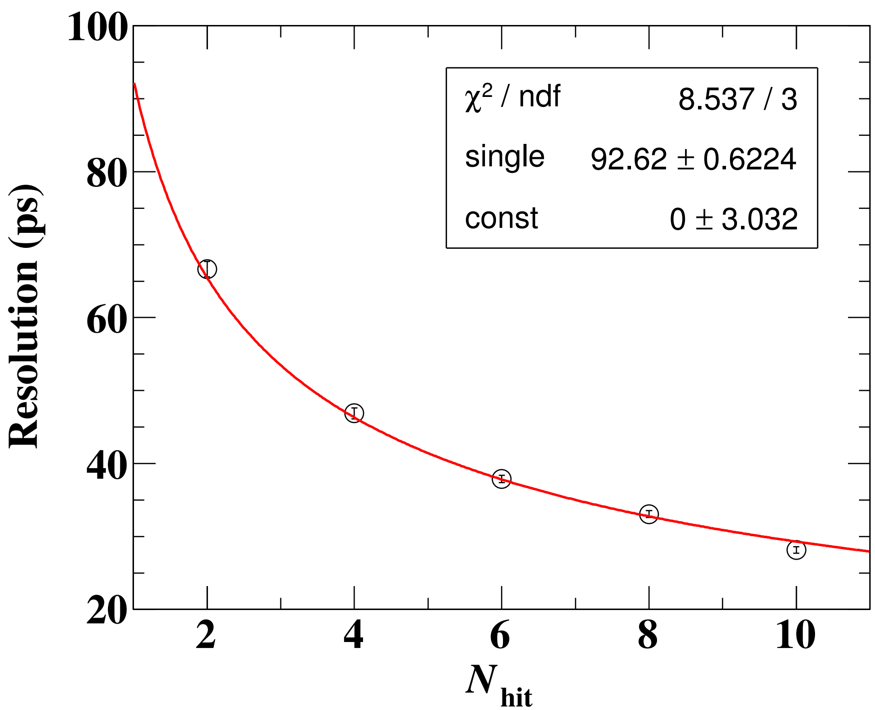
$$T_{6\text{hits}} = \left(\frac{T_1+T_3+T_5}{3} - \frac{T_2+T_4+T_6}{3}\right)/2$$

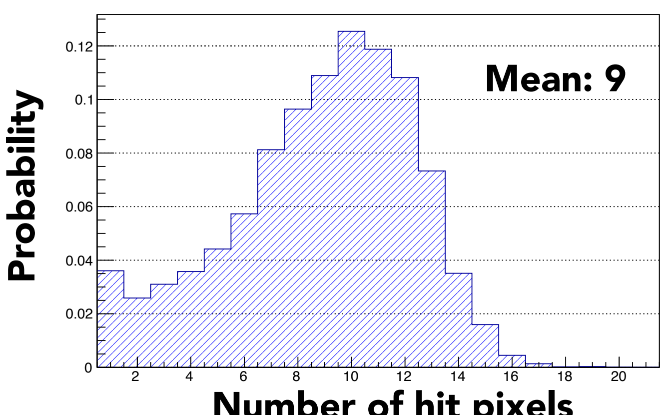
Selected 22 combinations in pilot run 2016



Time Resolution (2): Results

Total time resolution vs. number of hits





- The points are the weighted average of 22 pixel combinations.
- The red curve is the best fit function:

$$\sigma_{\mathrm{total}}(N_{\mathrm{hit}}) = \sqrt{\frac{\sigma^2_{\mathrm{single}}}{N_{\mathrm{hit}}} + \sigma^2_{\mathrm{const}}}$$

- $\sigma_{total}(9)$ = 31 ps was achieved.
- Overall resolution weighted with the probability of the number of hit pixels was 38 ps.

$$\sigma_{\mathrm{all}} = \sqrt{\sum_{\mathrm{N_{hit}}} p_{\mathrm{N_{hit}}} \sigma^2_{\mathrm{total}}(\mathrm{N_{hit}})}$$

➢ **A factor of 2 improvement** compared to TC at MEG.

pTC for MEG II was successfully constructed.

MEG II Status & Prospects

Now	2017	**Preparation for Pilot Run 2017**
Oct.		**Pilot Run 2017** ➢ Positron Timing Counter, Liquid Xenon Gamma-ray Detector, Radiative Decay Counter will be installed. ➢ ~7 weeks of combined detector DAQ is planned under the MEG II environment.
	2018	**Installation of all detectors** ➢ Including Drift Chamber.
Jul.		**Engineering Run** ➢ 6 months of performance data-taking. ➢ This run may evolve into physics run if things get ready.
		Physics Run ➢ Start searching for $\mu^+ \to e^+\gamma$ with unprecedented sensitivity.

Summary

Background

- The **MEG II** experiment will search for cLFV ($\mu^+ \to e^+\gamma$) with a sensitivity of **4×10^{-14}**
- pTC can achieve improved time resolution (~ **35 ps**) by averaging the signal time of multiple hits (~ 9).

Purpose

- To construct pTC and evaluate its performance under the MEG II environment.

Method

- 2 complementary time calibration methods have been developed.
- Full pTC was constructed and ¼ were installed.
  → **Pilot Run 2016** was performed.

Results

- 2 time calibration methods were **consistent** and **stable**.
- For Michel positrons, time resolution was **improved** by **a factor of 2** (38 ps) compared to MEG.

- **pTC for MEG II was successfully constructed.**
- **Engineering run is planned in 2018, and physics run follows.**

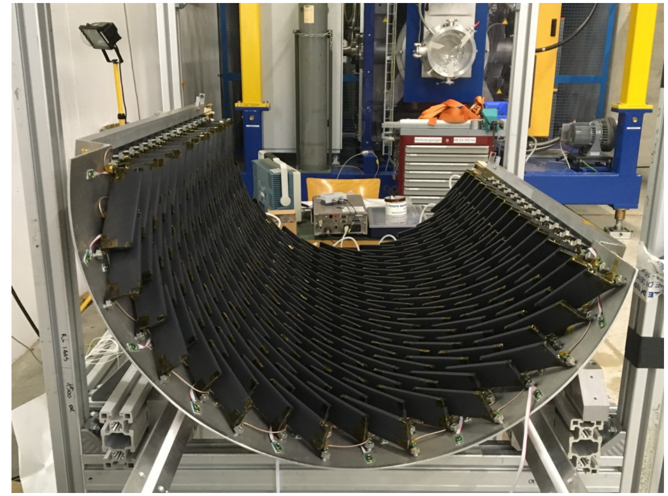
Backup Slides

Comparison

MEG I TC (31Oct2006)

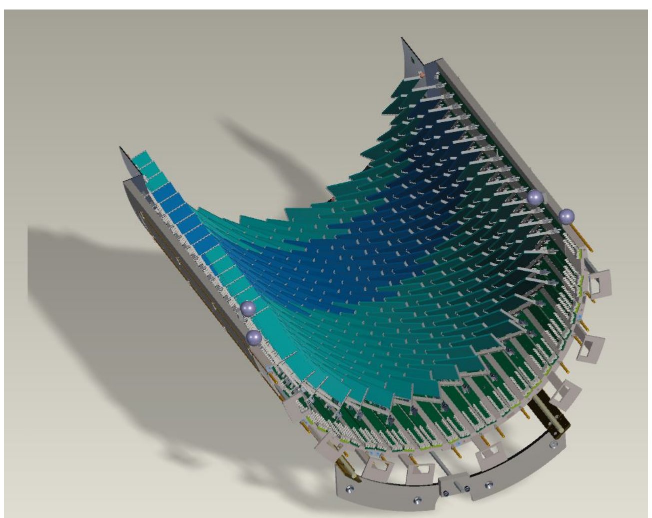
10 years!

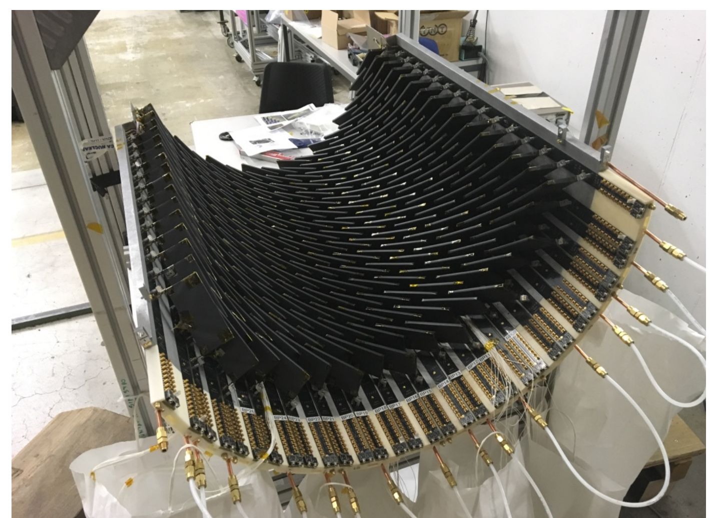
MEG II TC (21Nov2016)



CAD

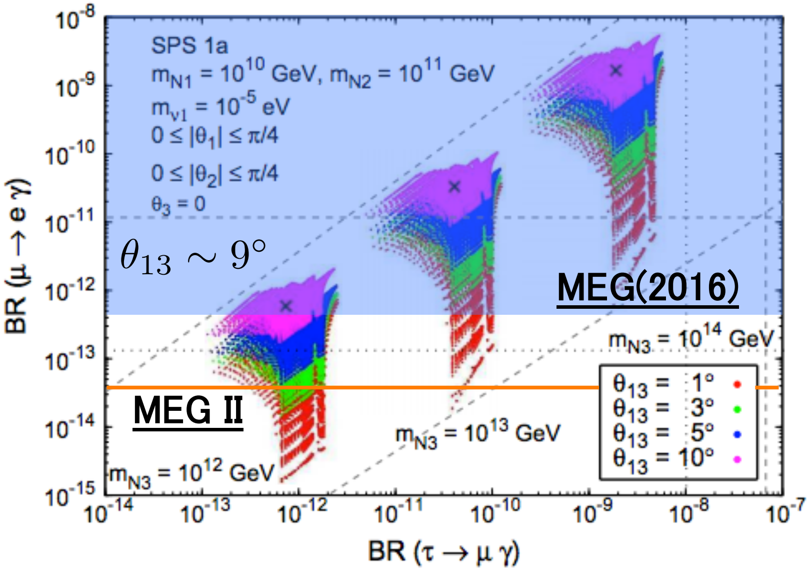
Reality!!



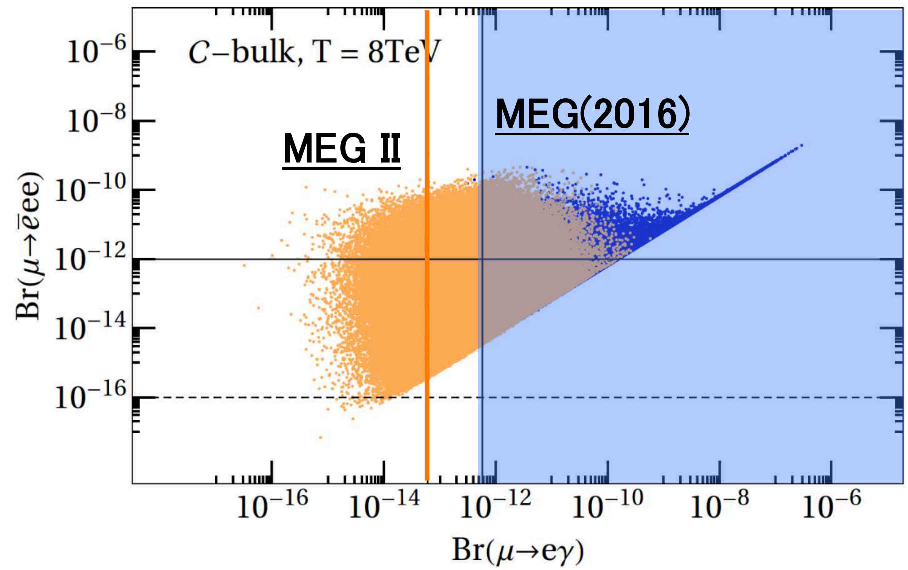


MEG and Beyond the Standard Model

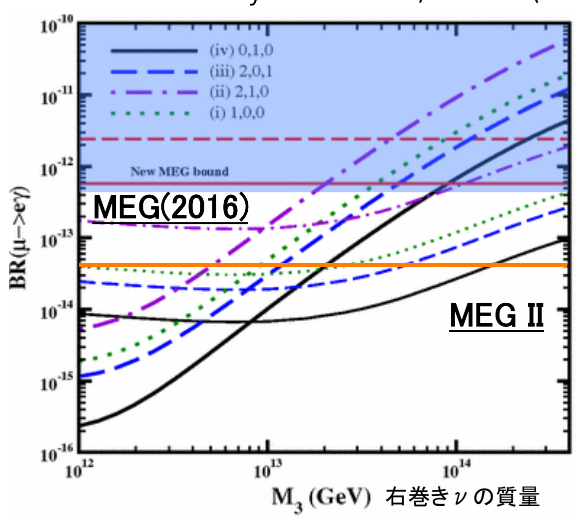
SUSY-Seesaw JHEP11(2006)090

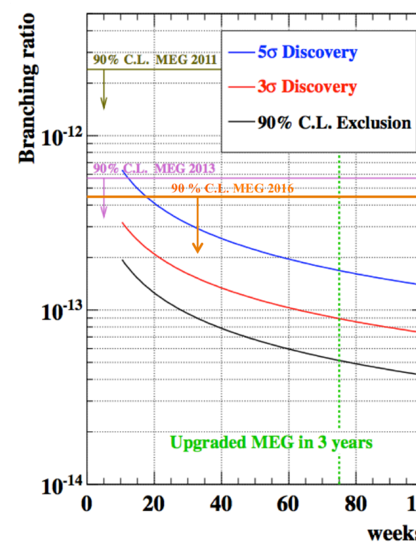


Extra Dimension Nucl. Phys. B 906 (2016) 561



SUSY-GUT Phys. Rev. D 88, 075005(2013)





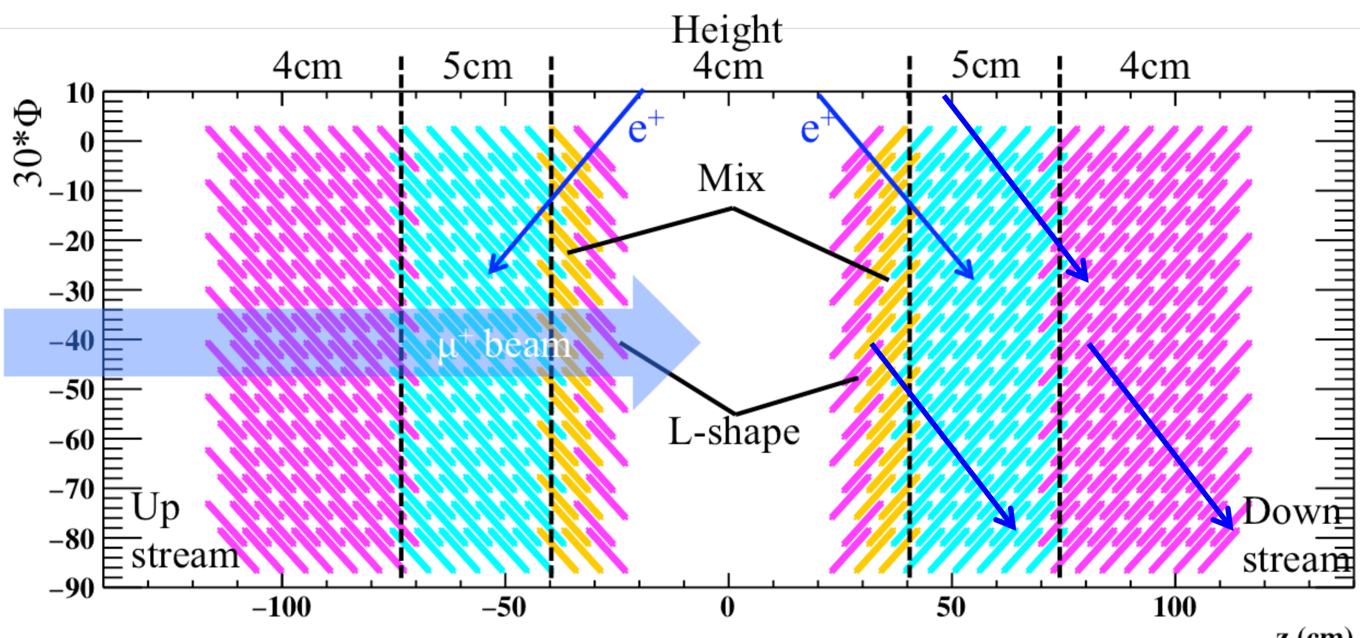
MEG II Expected Performance

Table 8 Resolutions (Gaussian σ) and efficiencies of MEG II compared with those of MEG

PDF parameters	MEG	MEG II
E_{e^+} (keV)	380	130
θ_{e^+} (mrad)	9.4	5.3
ϕ_{e^+} (mrad)	8.7	3.7
z_{e^+}/y_{e^+} (mm) core	2.4/1.2	1.6/0.7
E_γ(%) (w >2 cm)/(w <2 cm))	2.4/1.7	1.1/1.0
$u_\gamma, v_\gamma, w_\gamma$ (mm)	5/5/6	2.6/2.2/5
$t_{e^+\gamma}$ (ps)	122	84
Efficiency (%)		
Trigger	≈ 99	≈ 99
Photon	63	69
e^+	30	70

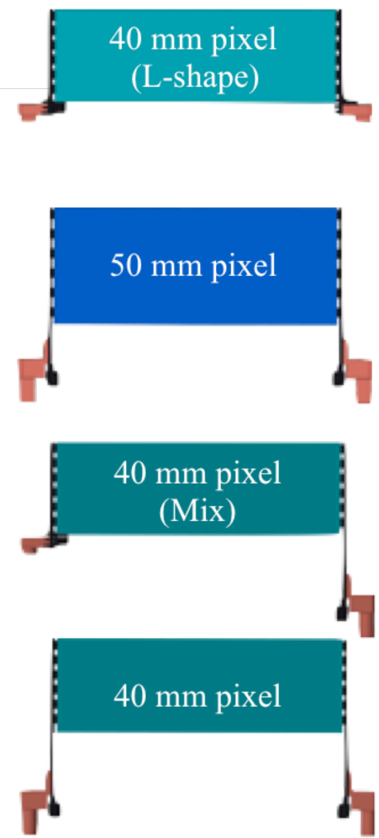
Positron Timing Counter (2): Pixel

- Upstream (256 pixels) + Downstream (256 pixels)= 512 pixels
- Fast plastic scintillator (BC422, 40 (50) x 120 x 5 mm^3)
- Readout by 6 SiPMs (AdvanSiD, ASD-NUV3S-P High-Gain) with series connection (in total 6144 SiPMs) at each of both sides.
- Time calibration accuracy among pixels: < 30 ps



Upstream 256 pixels

Downstream 256 pixels



Amplifier

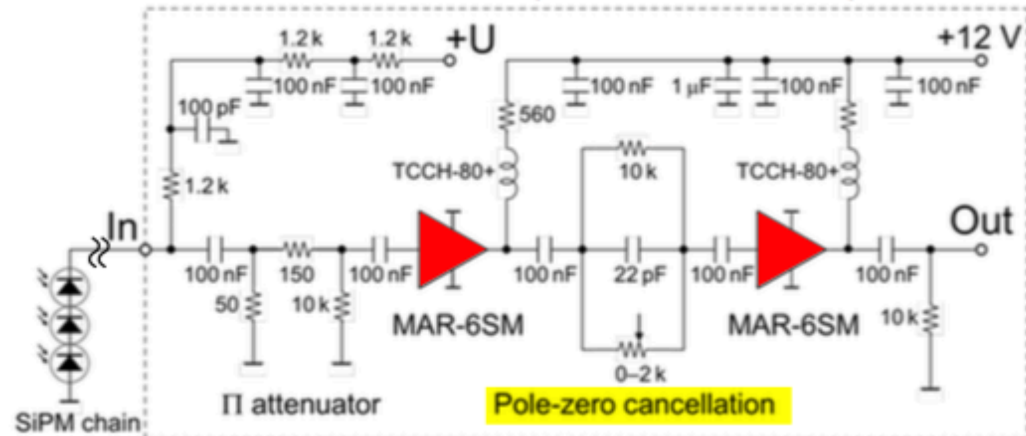
- For higher flexibility and applicability, **simple readout system** is important
- High-bandwidth low-noise **voltage** amplifier (2-cascade) with **50Ω** input impedance
  - ☐ Allows long signal-transmission.
  - ☐ However, forms slow RC time constant with SiPM high capacitance, especially with larger area.

Two counter-measures

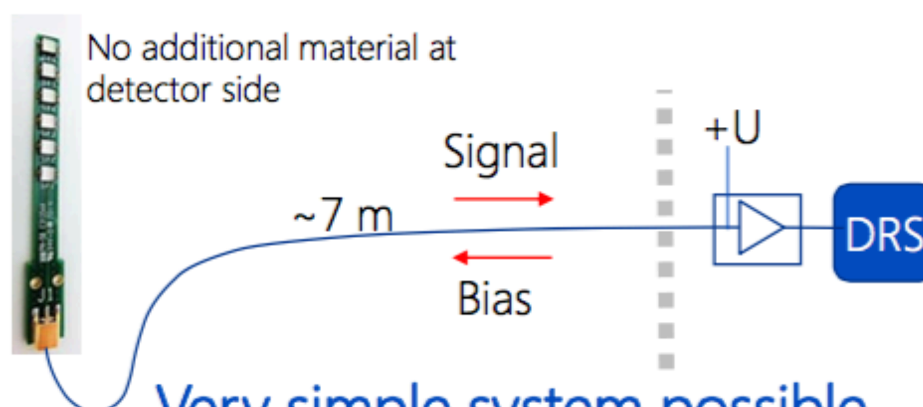
1. **Pole-zero cancellation** circuit to pickup leading-edge part signal and to quickly restore stable baseline

✓ Against high dark count

By U. Greuter & A. Stoykov (PSI)



Input impedance: ~50Ω
Gain: 970 V/A
Bandwidth: 800 MHz



Very simple system possible

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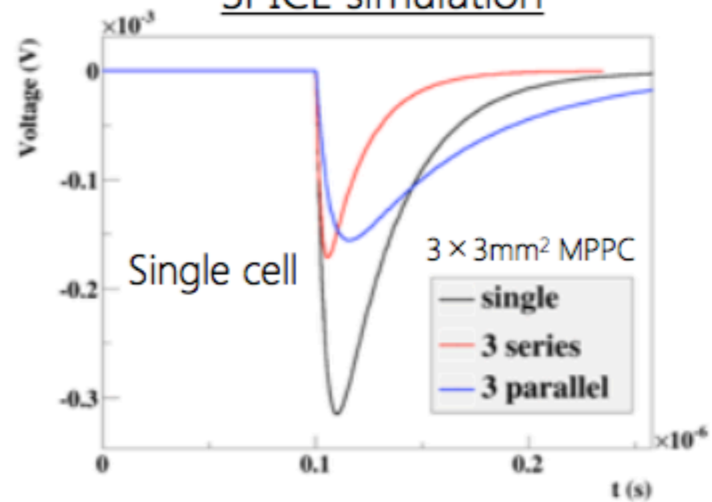
Series connection of SiPMs

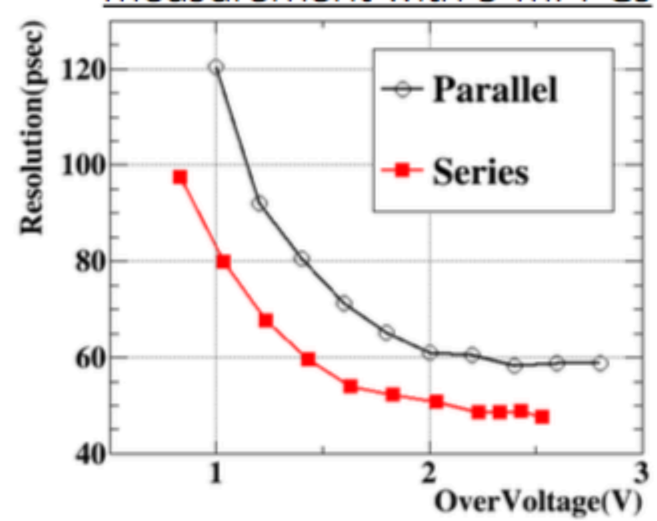
- SiPMs have high capacitance
  - Terminal capacitance ~300 pF for 3 × 3 mm² SiPM
- This forms a slow RC time-constant with amplifier input impedance
  - 3 × 3 mm² : 300pF × 50Ω = 15 ns
  - 3 × 9 mm² : 900pF × 50Ω = 45 ns !!

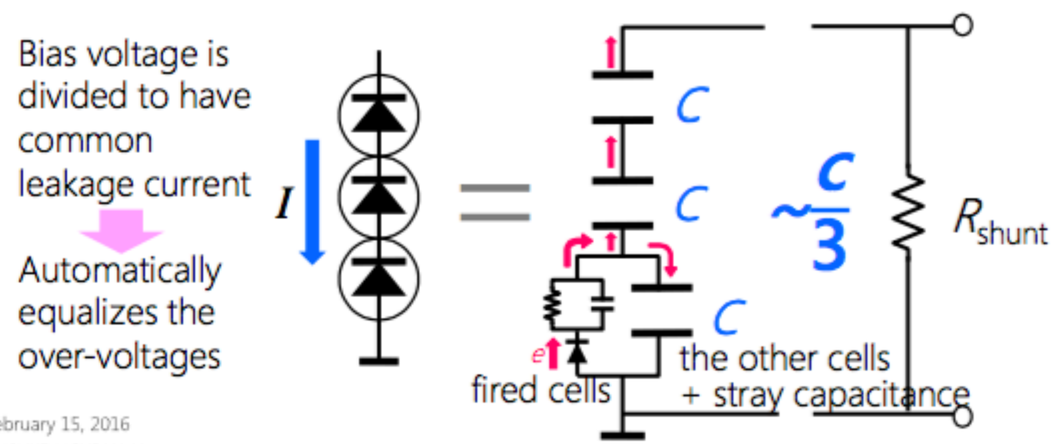
  → *One of limitations for large area SiPMs or array of SiPMs with parallel connection*
- This large capacitance works as capacitive coupling when connected **in series**

SPICE simulation



Measurement with 3 MPPCs





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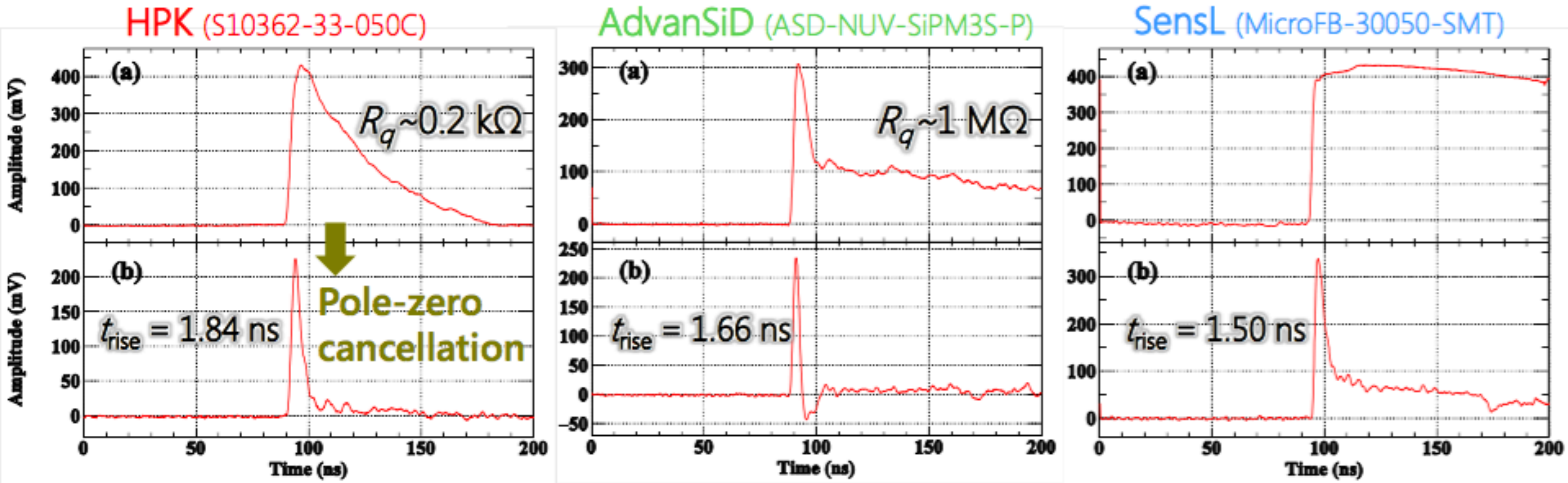
Specifications of AdvanSiD SiPM ASD-NUM3S-P-50-High-Gain

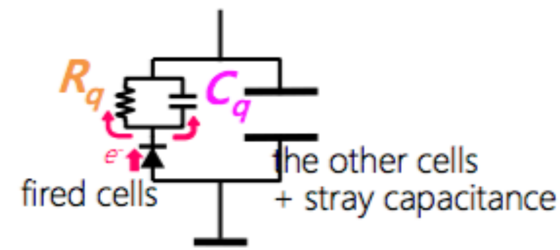
Parameter	Value	Unit
Effective active area	3×3	mm^2
Cell size	50×50	μm^2
Cells number	3600	
Spectral response range	350 to 900	nm
Peak sensitivity wavelength	420	nm
Breakdown voltage V_{BD}	24 ± 0.3	V
Work voltage range	$V_{BD} + 2$ to $V_{BD} + 3.5$	V
Dark count	< 100	kcps/mm^2
Gain	3.3×10^6	
V_{BD} temperature sensitivity	26	mV/°C

Slide from Y. Uchiyama in VCI2016

SiPM Comparison: Pulse shape (3-series)

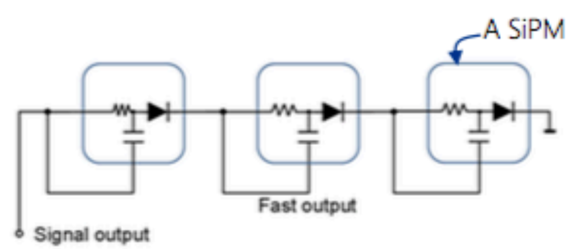


- Pulse shape depends on R_q & C_q
  - C_q is important for the fast signal
  - Slow tail by larger R_q can be omitted with pole-zero cancellation



- SensL's fast output terminal can be used to make very fast rise time

A method to combine the fast output into the normal signal line (by N. Pavlov)



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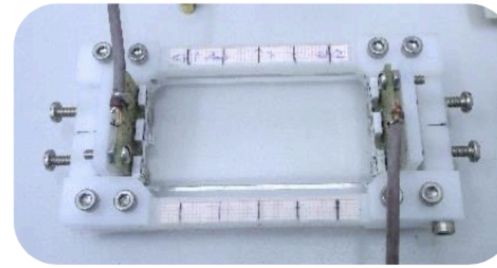
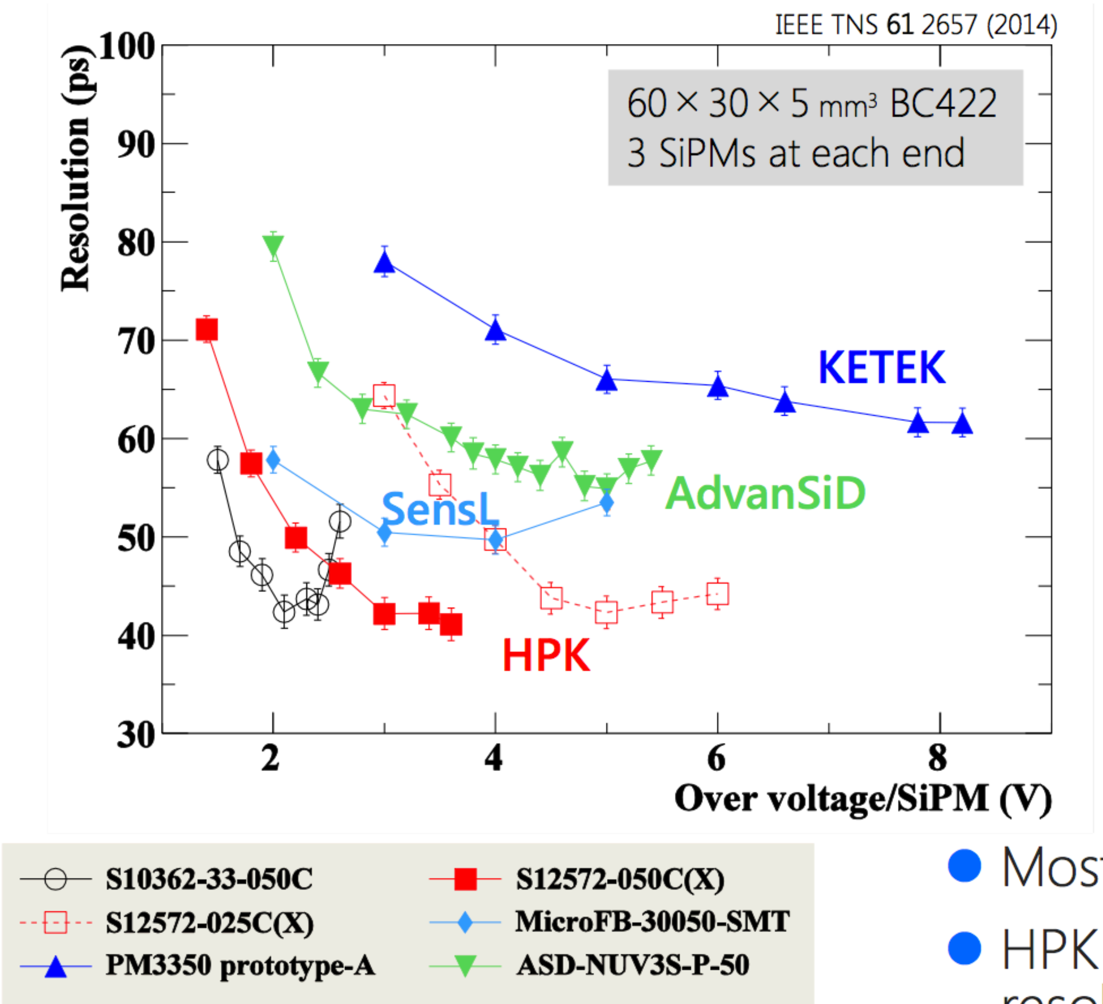
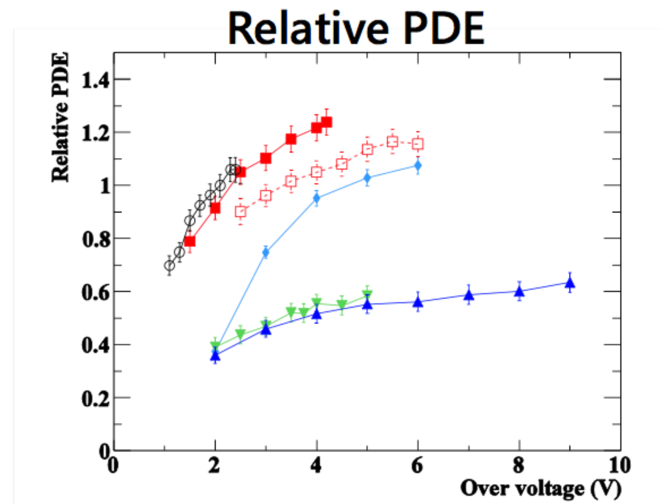
SiPM Comparison

As of 2013

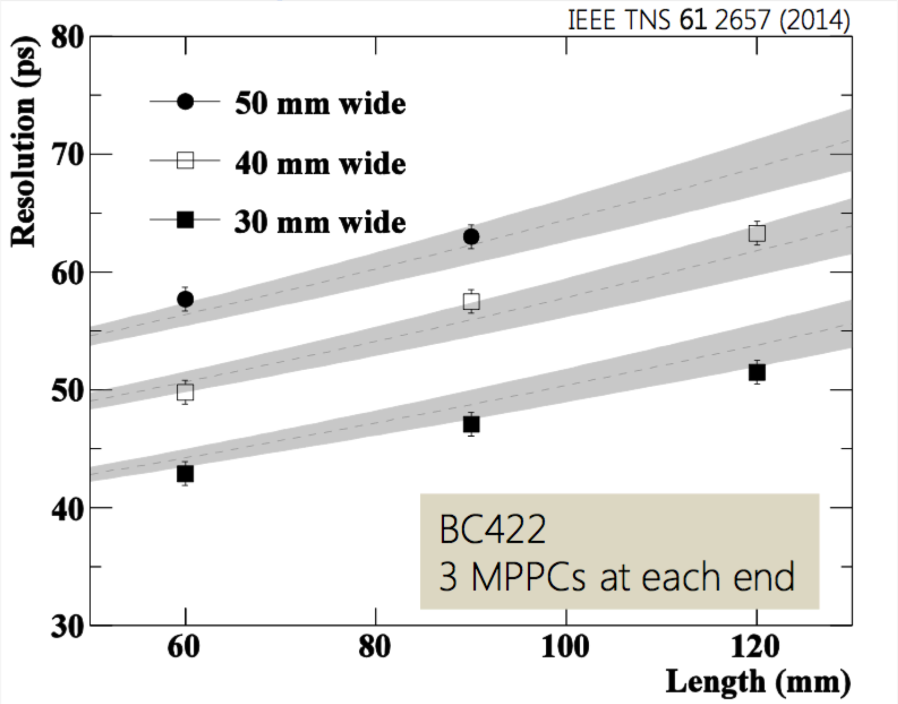






- Most relevant parameter is **PDE**
- HPK MPPCs give the best time resolution

Size dependence



- Size dependence is well on the photon statistics calculated with
  - Sensor coverage × Scint. light attenuation
- σ<70 ps achieved up to
  - Length = 120 mm
  - Width = 50 mm

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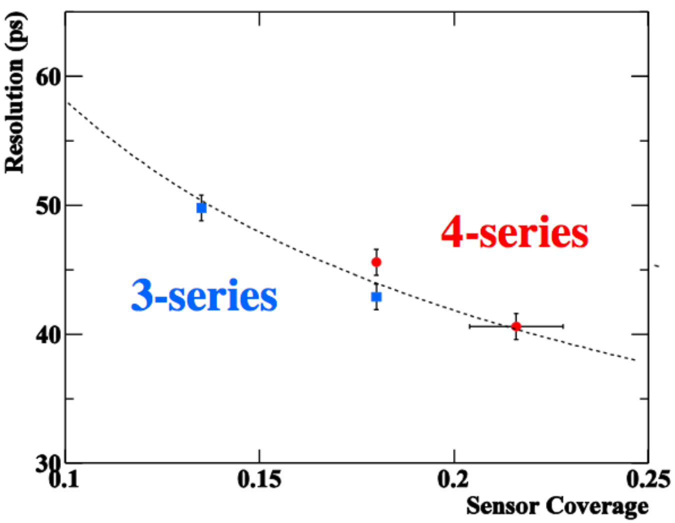
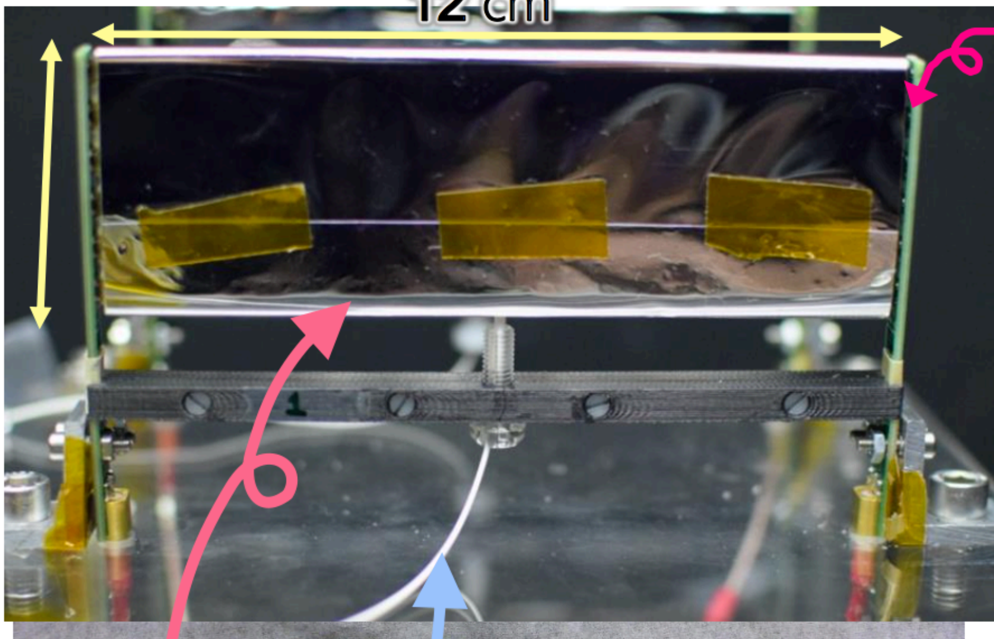
- Final choice is given by optimization between
  - Single counter resolution (small size)
    and
    Hit multiplicity & efficiency (larger size)
  - Performance of SiPMs
    and
    Number of SiPMs (cost)



Final Design

12 cm

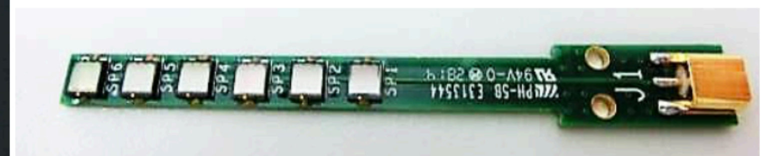
4 cm or 5 cm



6 SiPMs in series at the both ends

AdvanSiD **3x3** mm², **50x50** μm² pixels

$V_{breakdown}$ ~ 24 V (145 V for 6 series)



Fast Plastic Scintillator

BC422

wrapped in ESR2 film

Optical Fiber

Inter-counter time calibration with laser

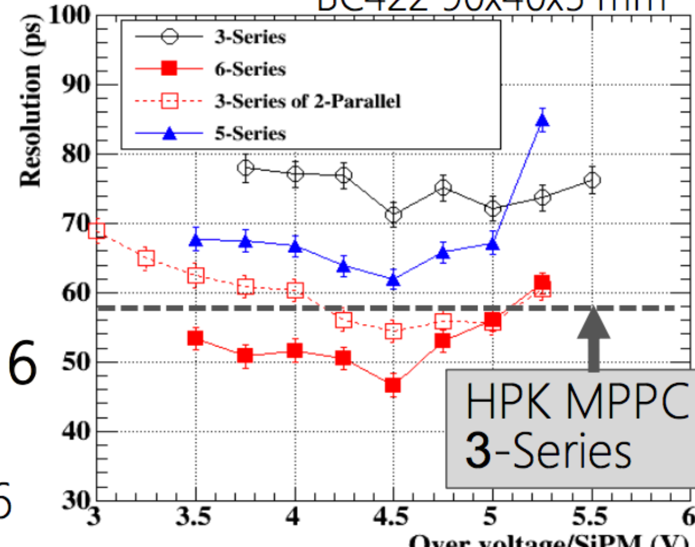
Resolution

HPK ×3 > AdvanSiD ×6

Cost

HPK ×3 ≈ AdvanSiD ×6

BC422 90x40x5 mm³



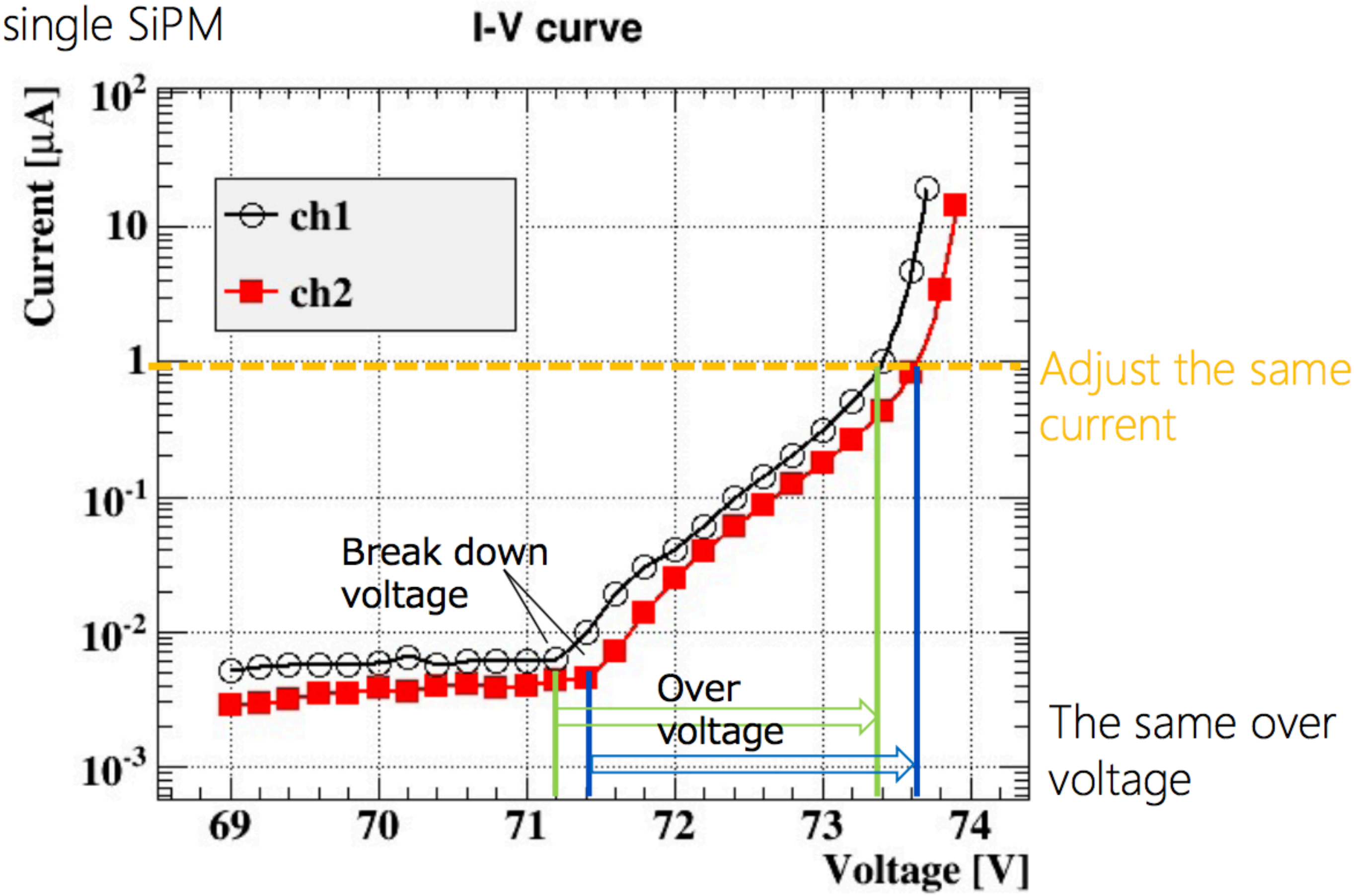
We decided to employ AdvanSiD SiPM

February 15, 2016
YUSUKE UCHIYAMA

Bias Voltage

Slide from Y. Uchiyama in VCI2016

I-V curve of single SiPM



<u>Shape of I-V curve is almost same for every SiPM.</u>

Only break down changed for each SiPM.

⇒ If the current is the same for SiPMs, their over-voltages are adjusted to be same automatically.

PDE Comparison

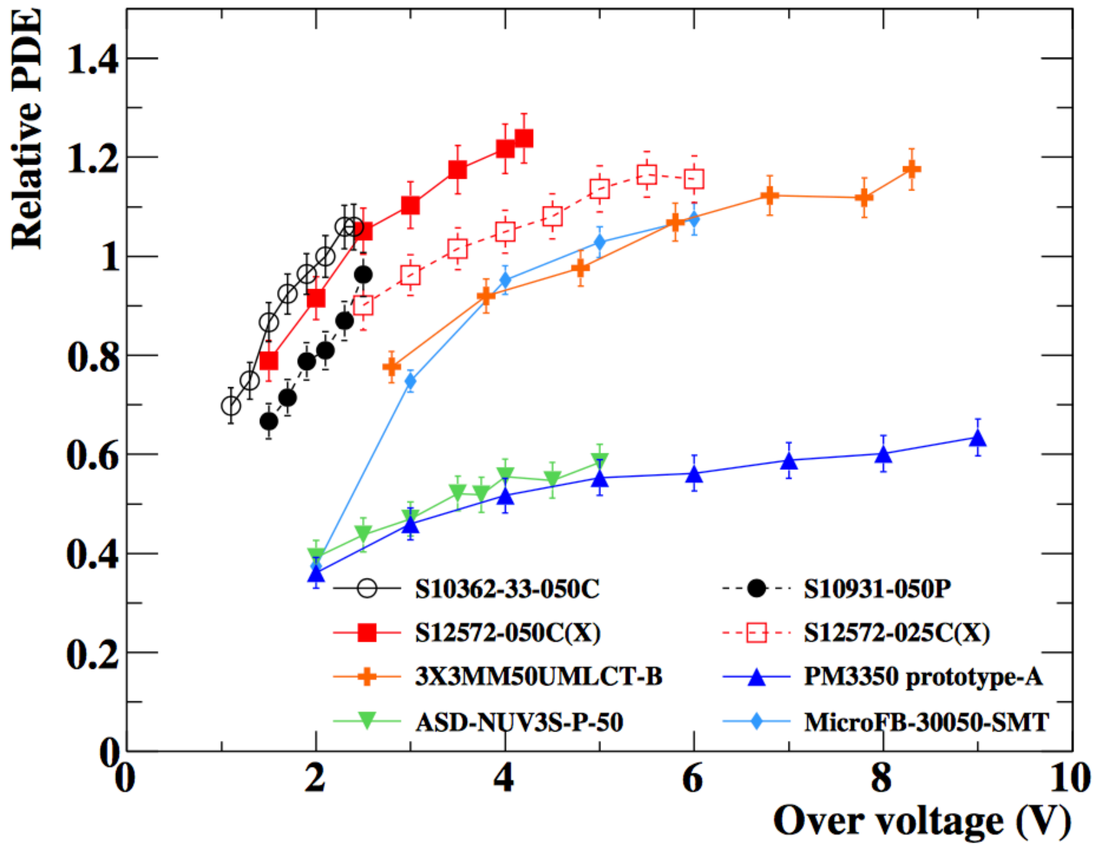
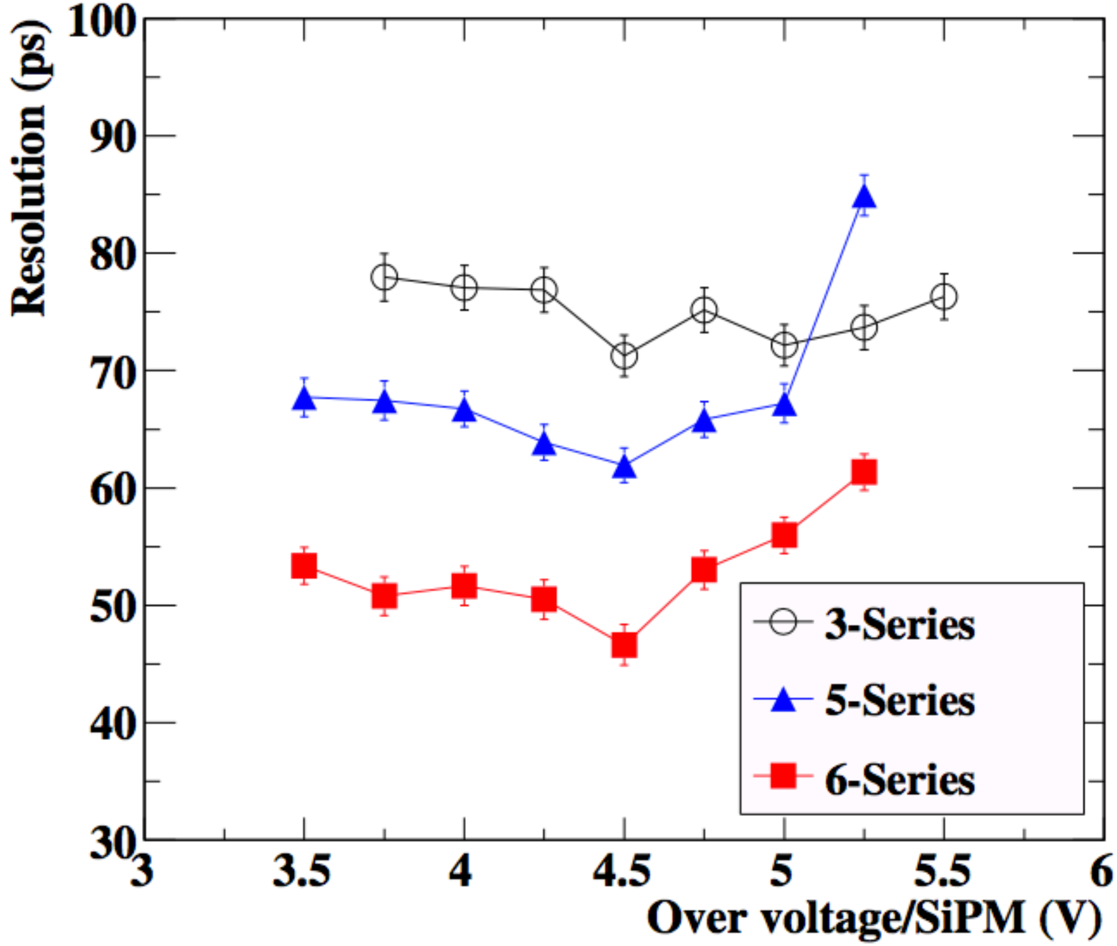


Fig. 10. Results of relative PDE measurements in the NUV region using a UV-LED.

arXiv:1402.1404

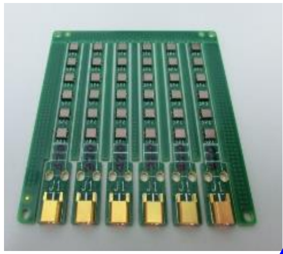
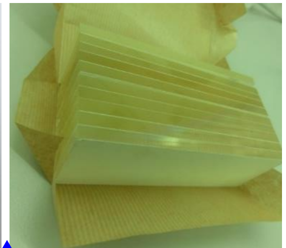
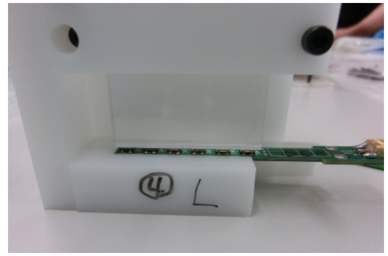
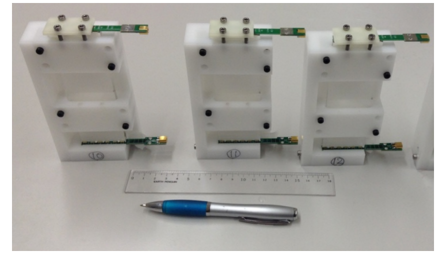
Increasing the number of SiPMs



PoS(PhotoDet 2015)011, Moscow, Russia, (2016)

Construction

SiPMs on PCB & Scintillators → Couple scintillators and arrays w/ optical cement → Hole making

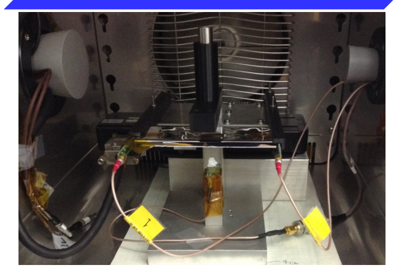






BC600

- SiPMs, SiPM-Arrays, scintillators are tested at each step.

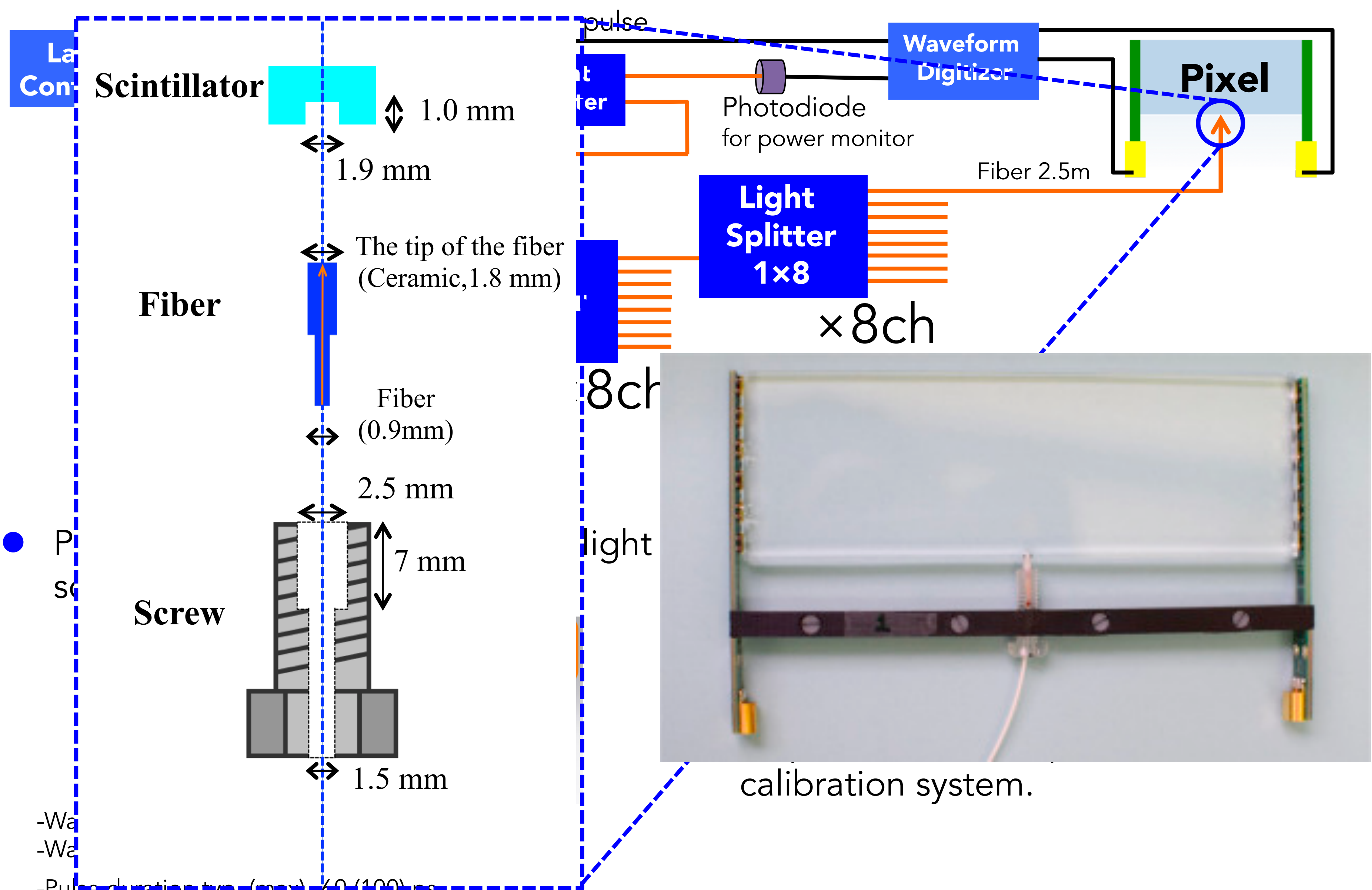
Wrap pixel with reflector → Pixel Test → Shielding → Finish!!

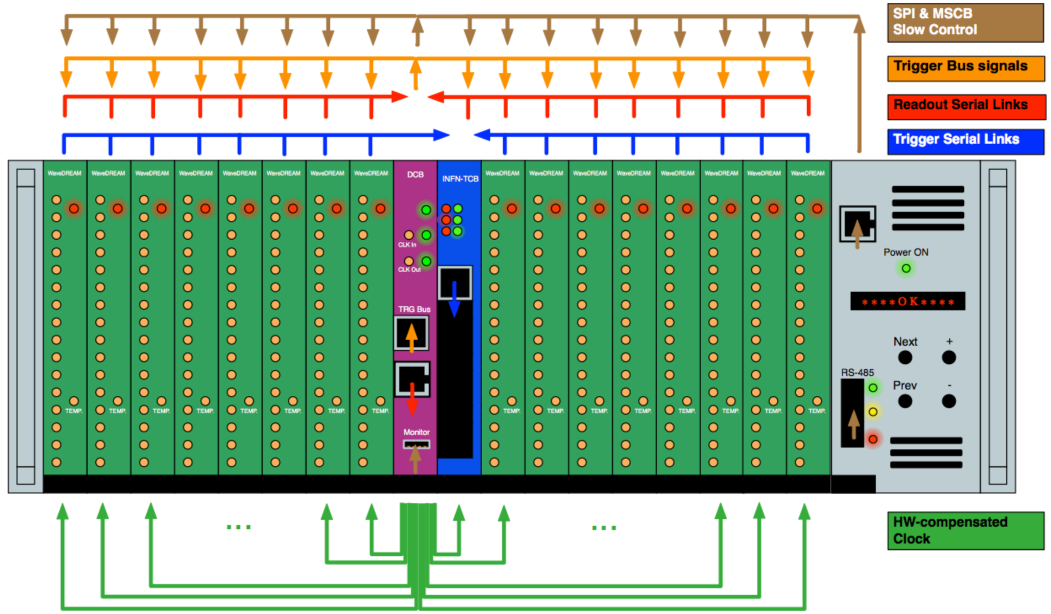
32 μm-thick ESR2

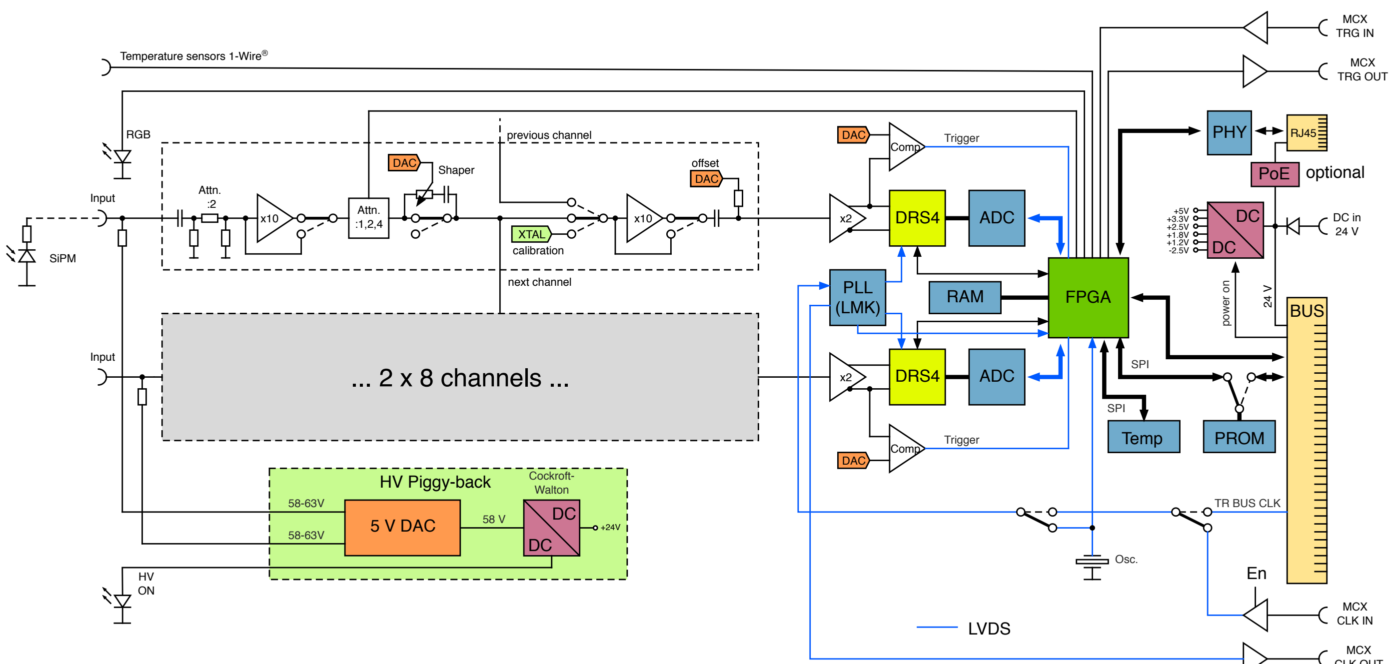



25 μm-thick Tedlar®

Time Calibration: Laser-based

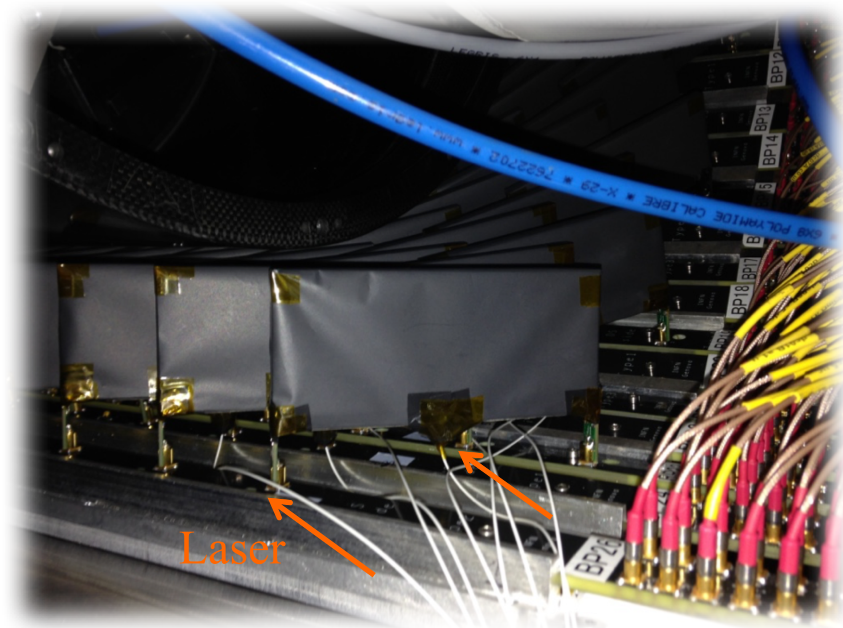


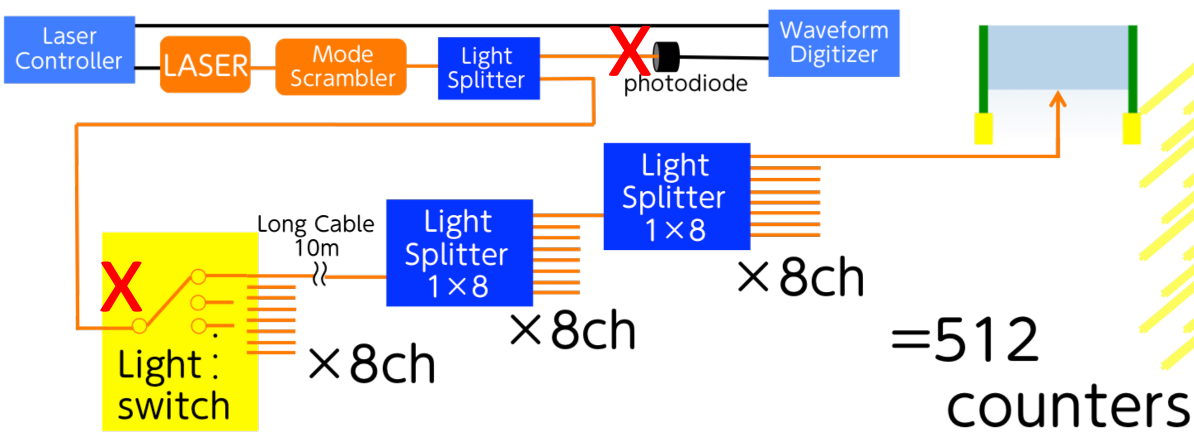

SPI & MSCB Slow Control
Trigger Bus signals
Readout Serial Links
Trigger Serial Links
HW-compensated Clock
WaveDREAM
DCB
INFN-TCB
CLK In
CLK Out
TRG Bus
Monitor
TEMP
Power ON
****OK****
Next
Prev
RS-485

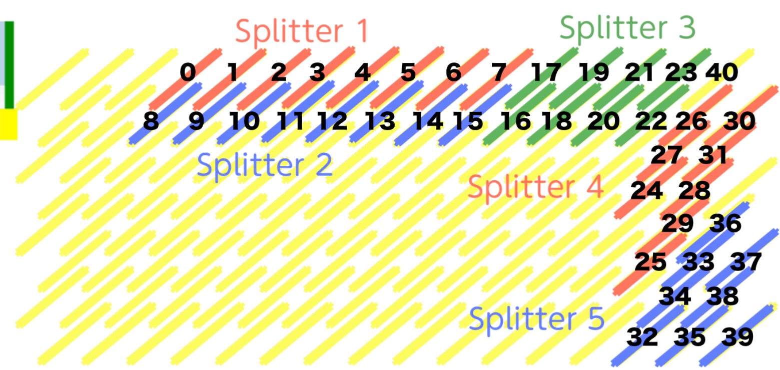

Temperature sensors 1-Wire®
RGB
Input
SiPM
Attn. :2
x10
Attn. :1,2,4
DAC
Shaper
previous channel
offset
XTAL
calibration
next channel
... 2 x 8 channels ...
HV Piggy-back
Cockroft-Walton
58-63V
5 V DAC
58 V
DC
+24V
HV ON
x2
Comp
Trigger
DRS4
ADC
PLL (LMK)
RAM
FPGA
PHY
RJ45
PoE
optional
+5V
+3.3V
+2.5V
+1.8V
+1.2V
-2.5V
DC in 24 V
power on
24 V
BUS
SPI
Temp
PROM
TR BUS CLK
Osc.
En
LVDS
MCX TRG IN
MCX TRG OUT
MCX CLK IN
MCX CLK OUT

Laser Calibration Setup in Pilot Run 2016

- Laser system was successfully installed into 40 counters out of 128 counters.
- Signal is divided by means of optical splitters.
- Relative time-offset = difference from first counter



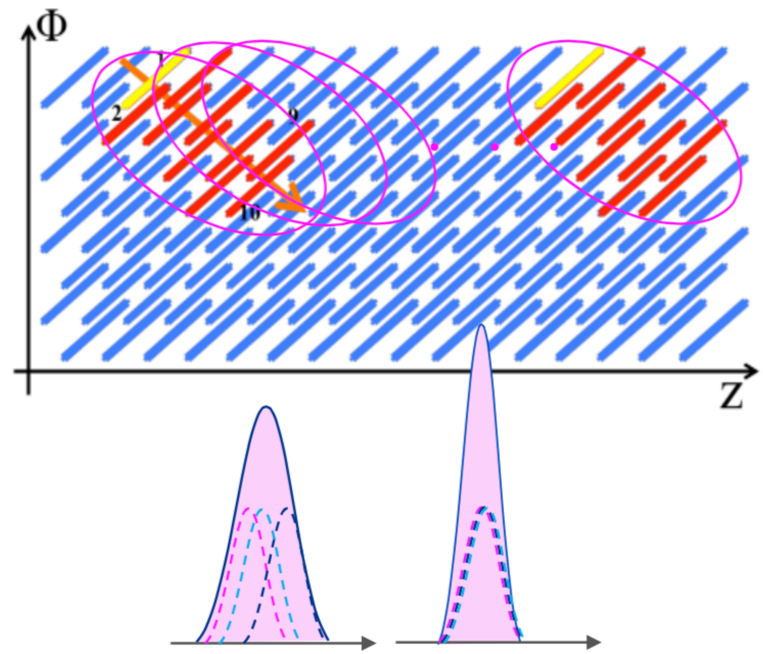


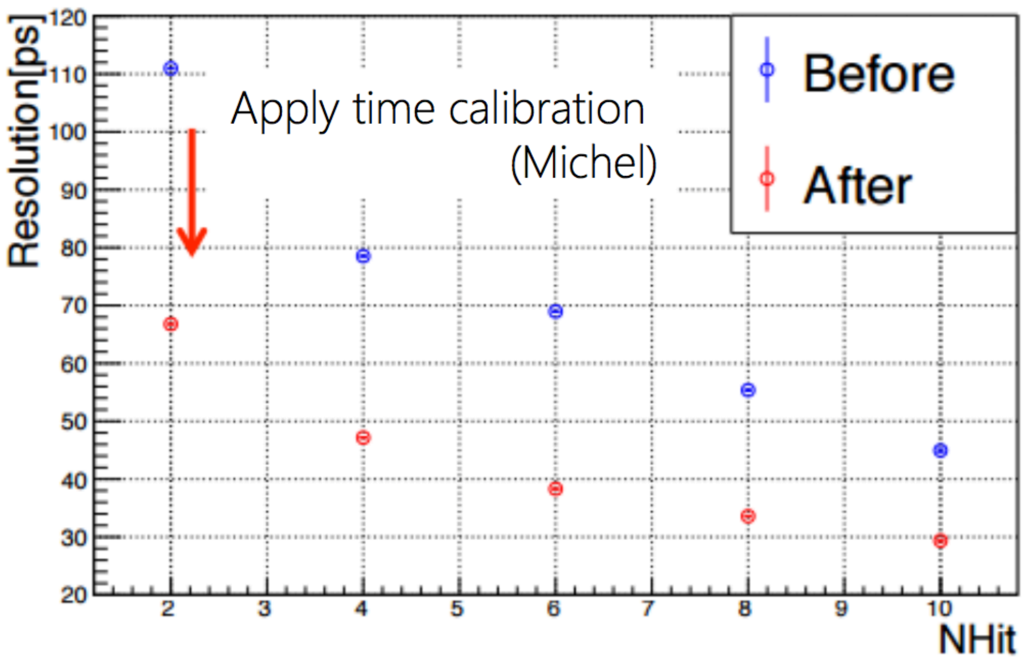


40 counters(5 splitters)

Resolution incl. time calibration

- Even – odd analysis is insensitive to time offset when testing a given combination
- Select 22 10-counter combinations
  - Different combinations have different center for *T*(even – odd) if time offset is not calibrated.
  - Accumulate *T*(even – odd) for all the combinations





- No degradation
- Validation of a good time calibration
- Achieved $\sigma(N=8)$ = 34 ps including time calibration contribution

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Time Calibration w/ Other Detrctors