MEG
Mu-E-Gamma Collaboration

The MEG II experiment in search of $\mu \to e\gamma$

Y. Uchiyama (The University of Tokyo)
on behalf of MEG II collaboration

The APS Division of Particles & Fields Meeting
July 29th, 2019 @ Northeastern University

東京大学
THE UNIVERSITY OF TOKYO

ICEPP
The University of Tokyo

研究拠点形成事業
Core-to-Core Program

2019 DPF
Northeastern

MEG II: in search of $\mu^+ \to e^+\gamma$

- An intensity frontier experiment
- Upgraded from MEG experiment
- To get definitive evidence for BSM

UTokyo KEK	PSI ETHZ	INFN Genoa INFN Lecce INFN Pavia INFN Pisa INFN Roma	BINP JINR	UC Irvine

~60 physicists

MEG result (2016)

$$B(\mu^+ \to e^+\gamma) < 4.2 \times 10^{-13}$$

@90% C.L.

(while 5.3×10^{-13} expected)

×2 intensity muon beam

×2 resolution everywhere

×2 efficiency

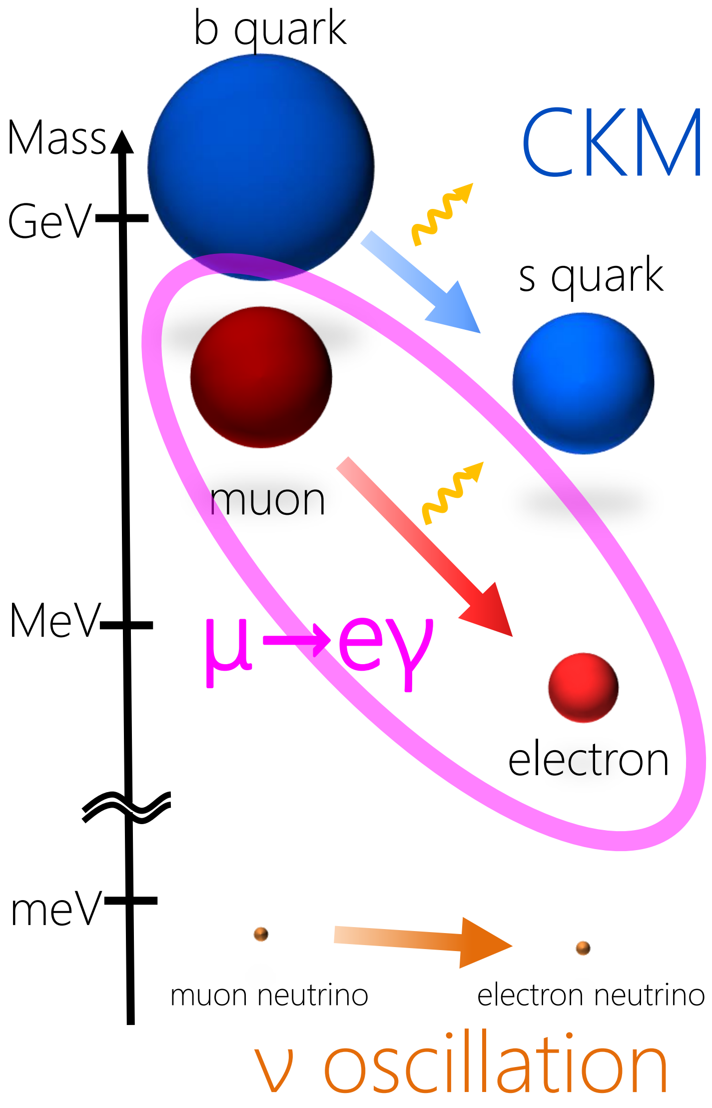
Search for $\mu^+ \to e^+\gamma$ down to

$$6 \times 10^{-14}$$

(90% C.L. sensitivity)

Physics of $\mu^+ \rightarrow e^+\gamma$

- Charged Lepton Flavor Violation
  - ☐ Practically **forbidden in SM** by tiny neutrino masses.
  - ☐ Never observed yet.
- But we know 'flavors' **are** violated in SM.
- Why not in physics beyond SM?
  1. Generally no reason to be conserved.
  2. Even with some symmetry, contribution from the known FV is unavoidable via radiative corrections in the new physics.
- Why charged lepton?
  1. No SM contribution, no theoretical uncertainty.
  2. Probably, connected to the mystery of neutrino.
- Many theoretical predictions are within experimental reach



Ultra-high scale

GUT

Force unification
Matter unification
Charge quantization

Seesaw

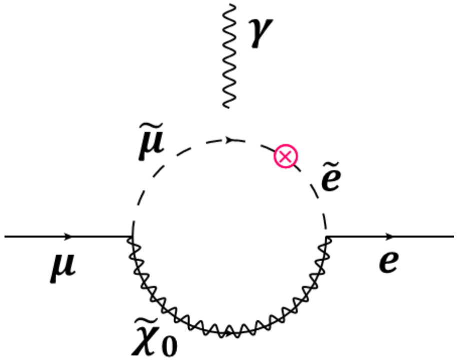
Neutrino mass
Leptogenesis

Flavor violation from quark Yukawa

Flavor violation from neutrino Yukawa

SUSY

TeV scale



Spacetime–internal sym. unification
Darkmatter?
Solution for hierarchy problem?

LFV

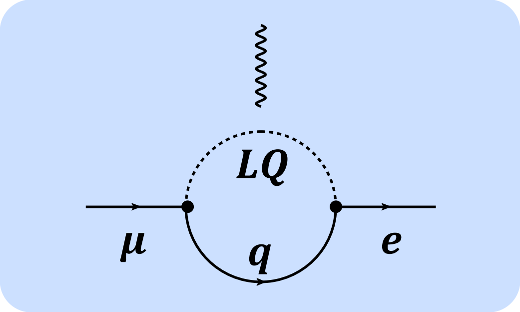
Lepton flavor violation

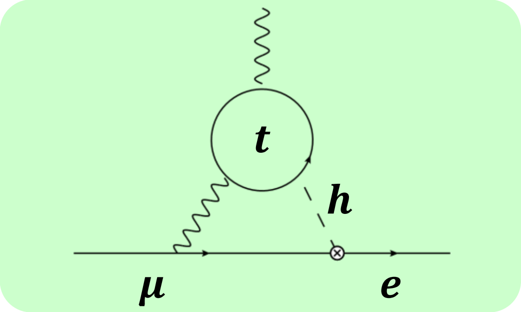
$B(\mu \to e\gamma) \sim 10^{-11} - 10^{-14}$

Low scale

top-down

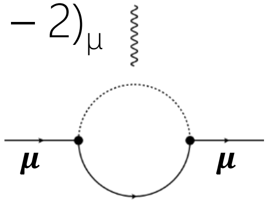
Other reasons



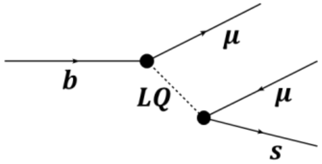


two-loop

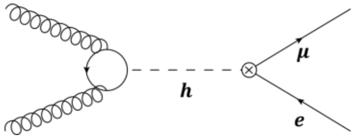
$(g-2)_\mu$



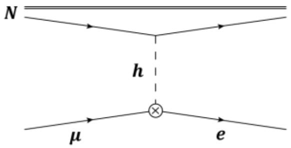
LHCb



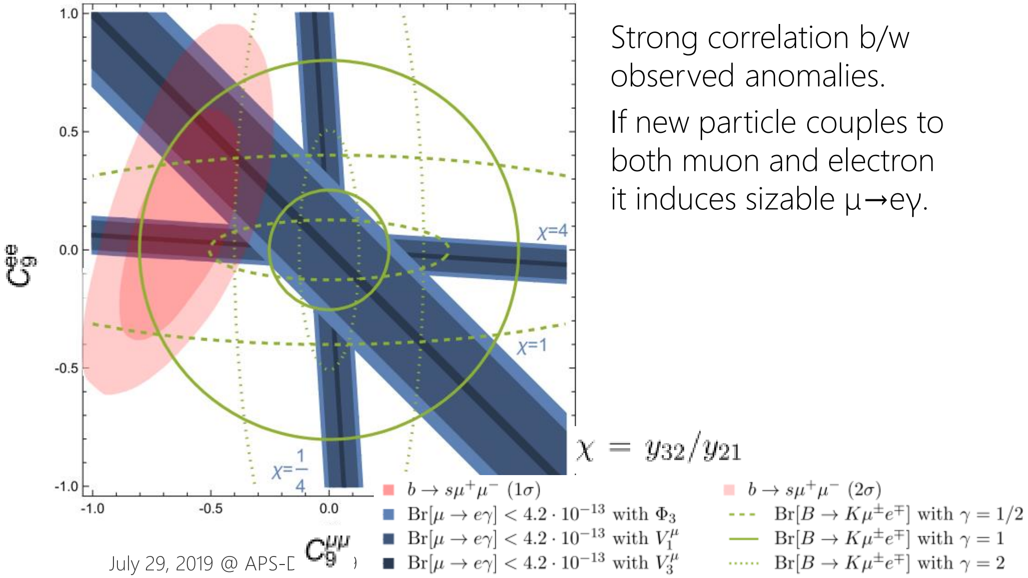
CMS



mu2e/COMET



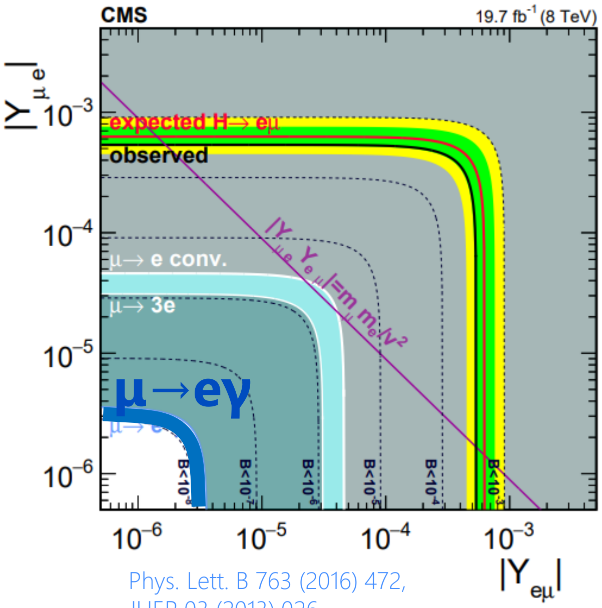
tree



Phys. Rev. D 97 (2018) 015019

Strong correlation b/w observed anomalies.

If new particle couples to both muon and electron it induces sizable μ→eγ.

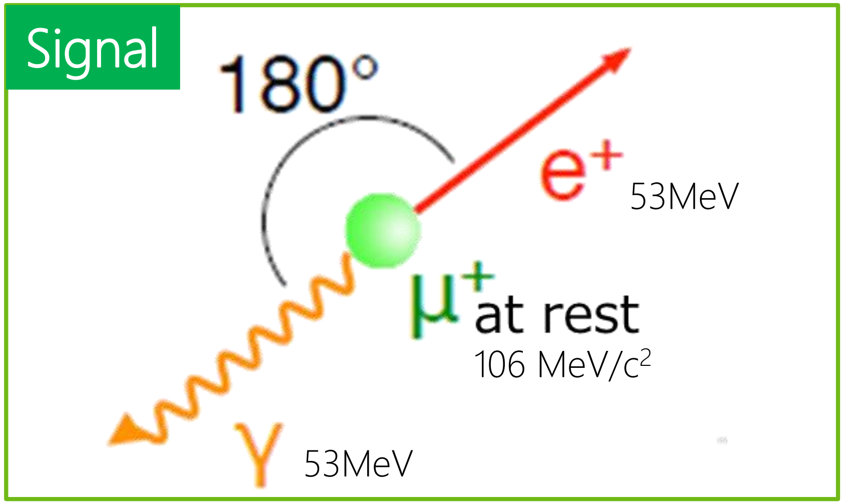


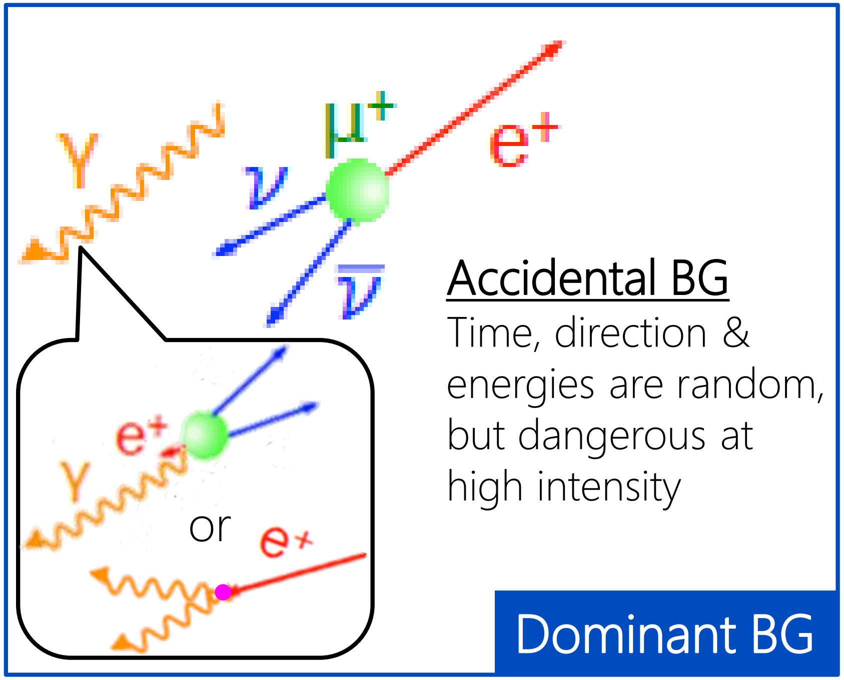
Phys. Lett. B 763 (2016) 472,
JHEP 03 (2013) 026

Limit on μ→eγ provides the most stringent limit on the LFV Higgs decay
BR(h→μe) $\lesssim 10^{-8}$

(CMS limit:
BR(h→μe) < 3.5 × 10^{-4})

Experimental requirements





Accidental BG

Time, direction & energies are random, but dangerous at high intensity

$$R_{BG} \propto R_{\mu}^{2} \cdot \delta E_{e} \cdot (\delta E_{\gamma})^{2} \cdot \delta\omega/4\pi \cdot \delta t$$

accidentally back-to-back

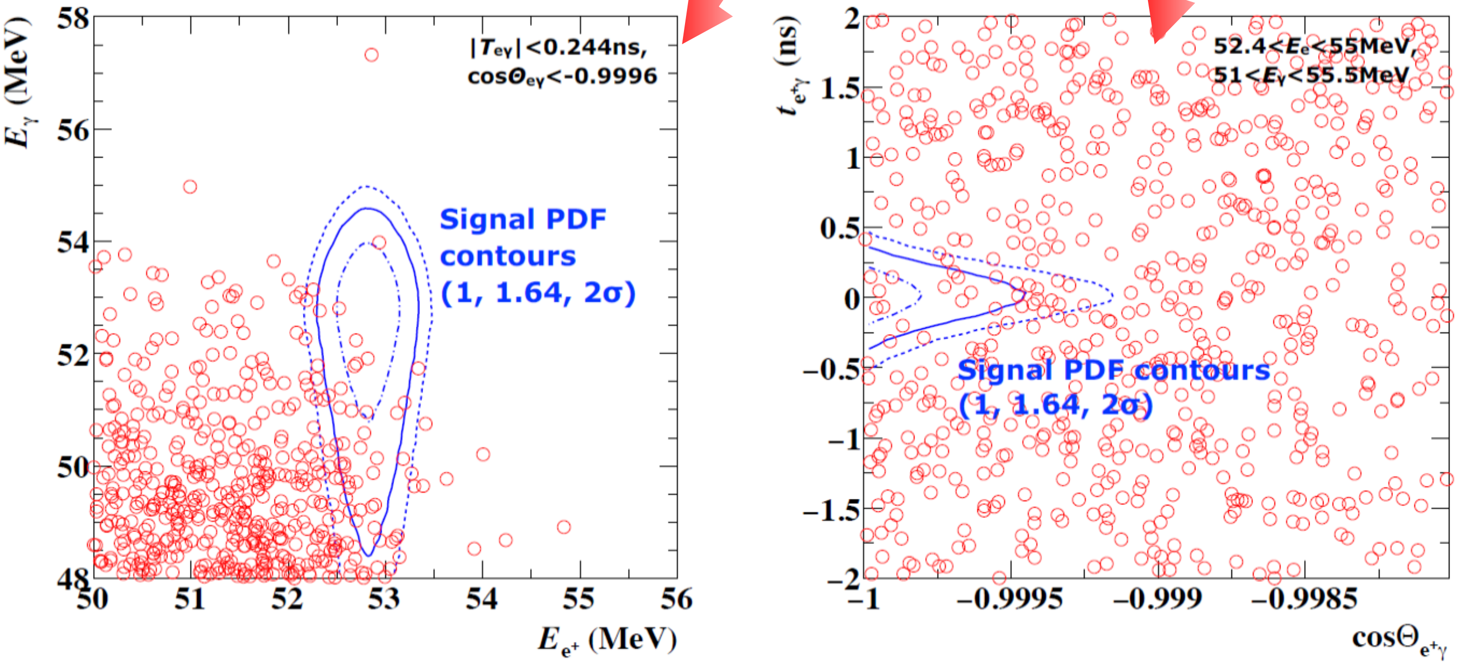
accidentally coincident

- High intensity **DC** μ^+ beam
- High resolution detector for energy, timing, and direction of γ & e^+.

MEG result (2009 – 2013)

Eur. Phys. J. C (2016) **76**:434

$$R_{BG} \propto R_\mu{}^2 \cdot \delta E_e \cdot (\delta E_\gamma)^2 \cdot \delta\omega/4\pi \cdot \delta t$$



- Search for $\mu^+ \to e^+\gamma$ in 1.7×10^{13} muon decays.
- No excess was found, and new upper limit was set:

$$\mathbf{B(\mu^+ \to e^+\gamma) < 4.2 \times 10^{-13}} \text{ (90\% C.L.)}$$

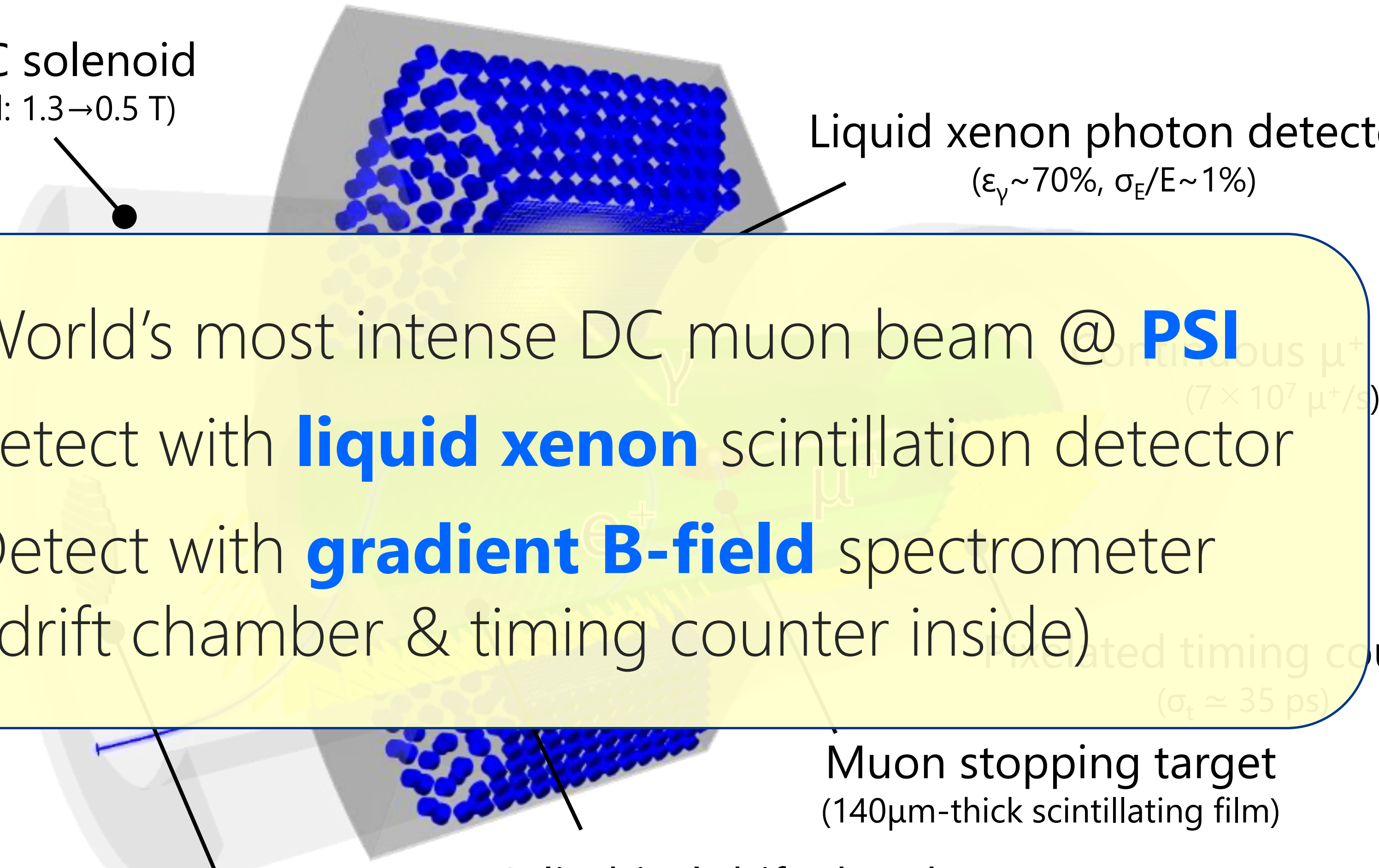
(while 5.3×10^{-13} expected)

×30
improvement from
the prev. experiment

This is the tiniest upper limit for any particle's BR.

MEG II

EPJ-C **78** (2018) 380



Thin-wall SC solenoid
(gradient B-filed: 1.3→0.5 T)

Liquid xenon photon detector
(ϵ_γ~70%, σ_E/E~1%)

ontinuous μ^+ beam
(7×10^7 μ^+/s)

ixelated timing counter
($\sigma_t \simeq 35$ ps)

Muon stopping target
(140μm-thick scintillating film)

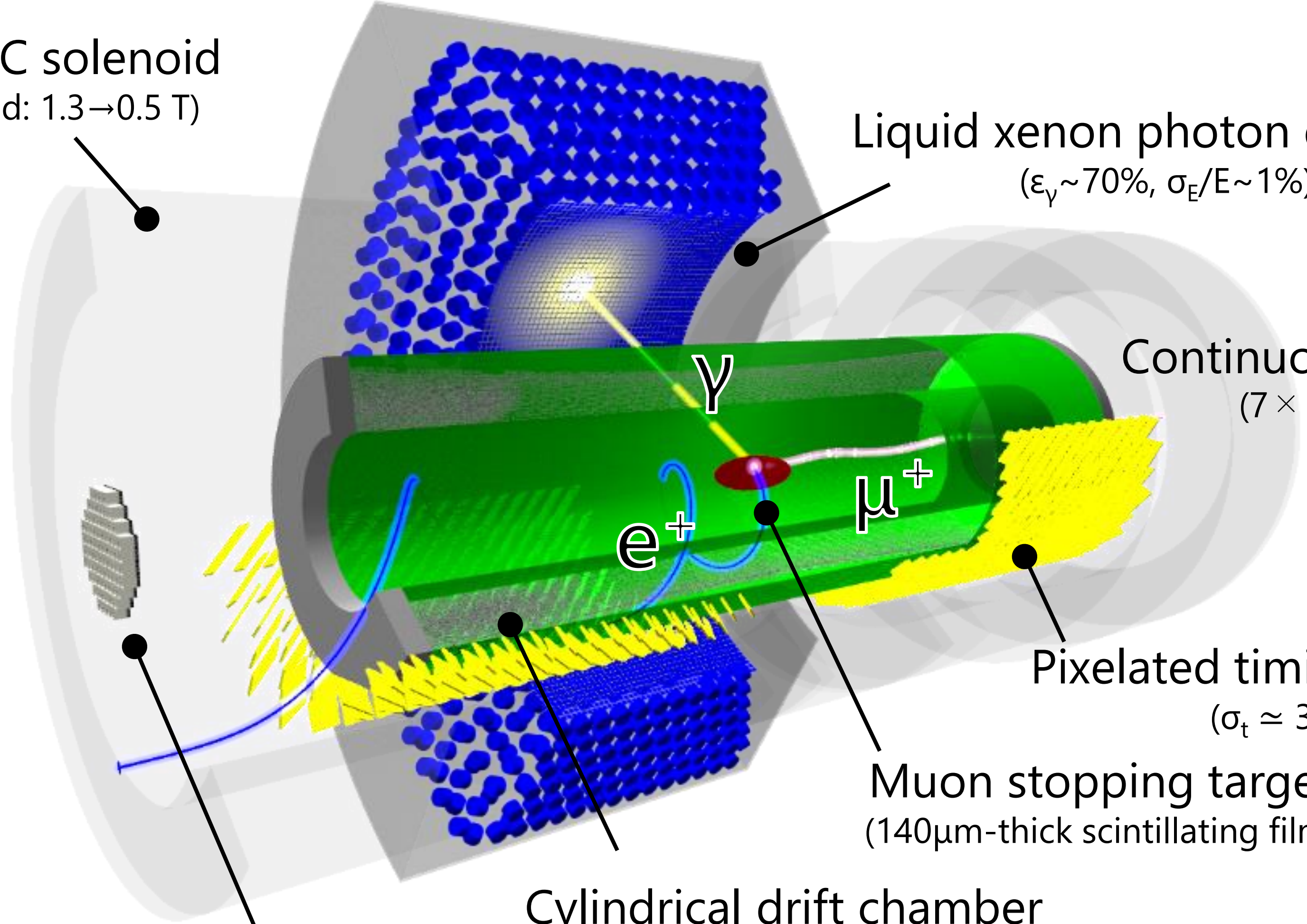
Cylindrical drift chamber
(~$1.6 \times 10^{-3} X_0$, σ_p~100 keV)

Radiative decay counter
(identify high-energy BG γ events)

- μ^+: World's most intense DC muon beam @ **PSI**
- γ : Detect with **liquid xenon** scintillation detector
- e^+: Detect with **gradient B-field** spectrometer
  (drift chamber & timing counter inside)

MEG II

EPJ-C 78 (2018) 380



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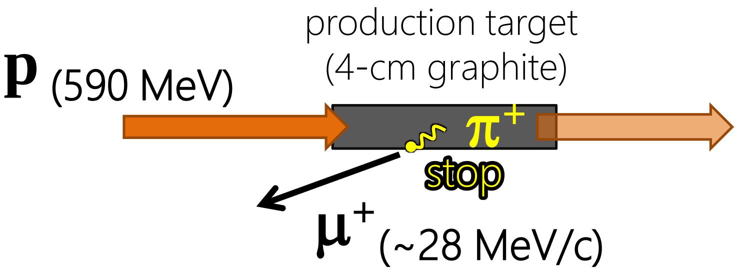
Muon beam



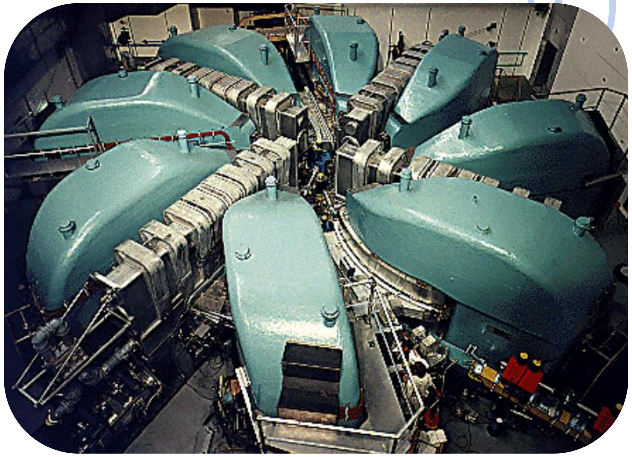
production target
(4-cm graphite)

p (590 MeV)

π^+ stop

μ^+ (~28 MeV/c)

'Surface muon beam'
= fully polarized low-momentum positive muon beam

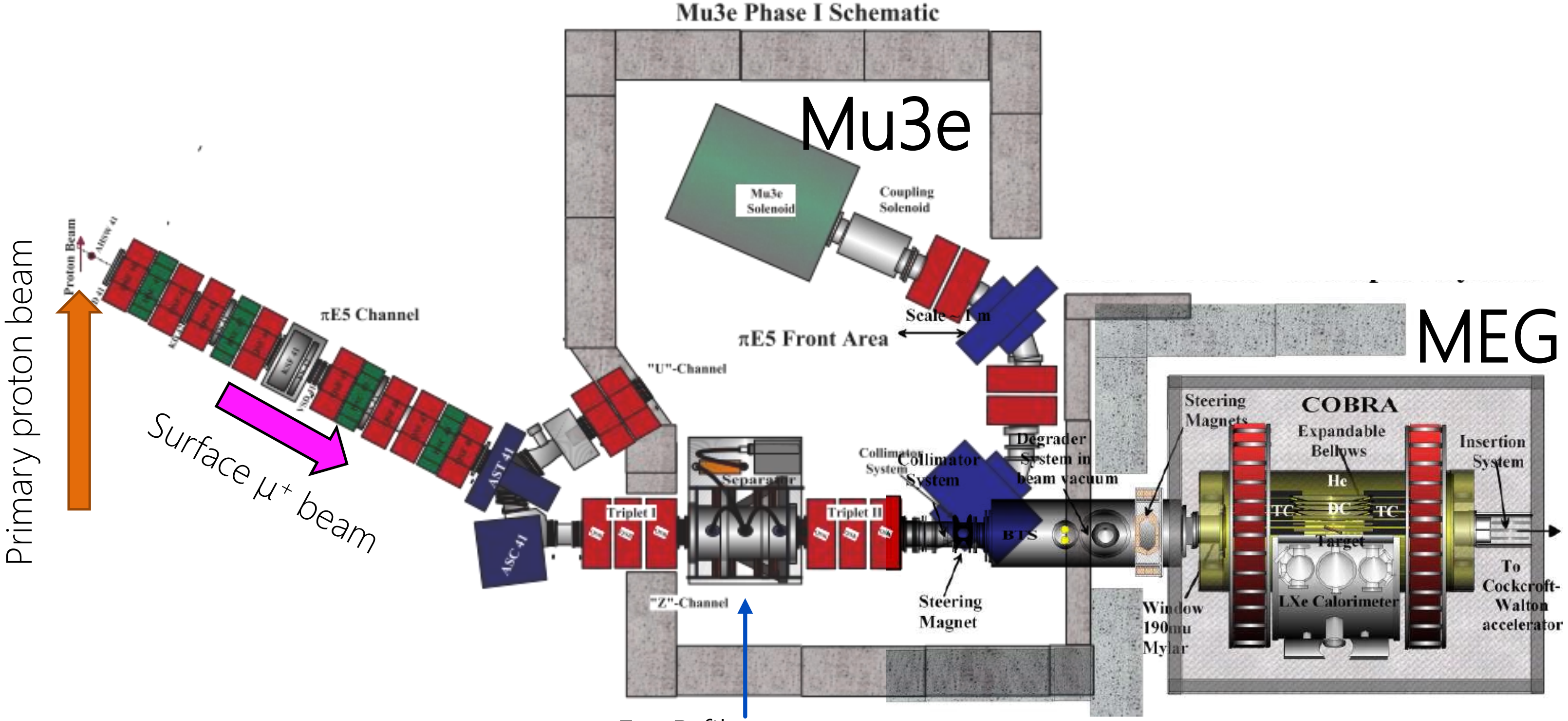


PSI 1.4 MW ring cyclotron
590 MeV, optimal to surface muon production

- World's most intense DC (50MHz) low-momentum muon beam
  - Unique location to perform $\mu^+ \rightarrow e^+\gamma$ experiments with ~10^8 μ^+/s.
  - New production target will be tested this year to increase surface muon yield by 30–50%.
- Polarization is important to discriminate physics behind, after the discovery of $\mu^+ \rightarrow e^+\gamma$.
  - Residual polarization measured : $P_\mu = 0.86$ (EPJ-C 76 (2016) 223)

See A. Papa's talk on 31 Jul.
"The High Intensity Muon Beam project at PSI"

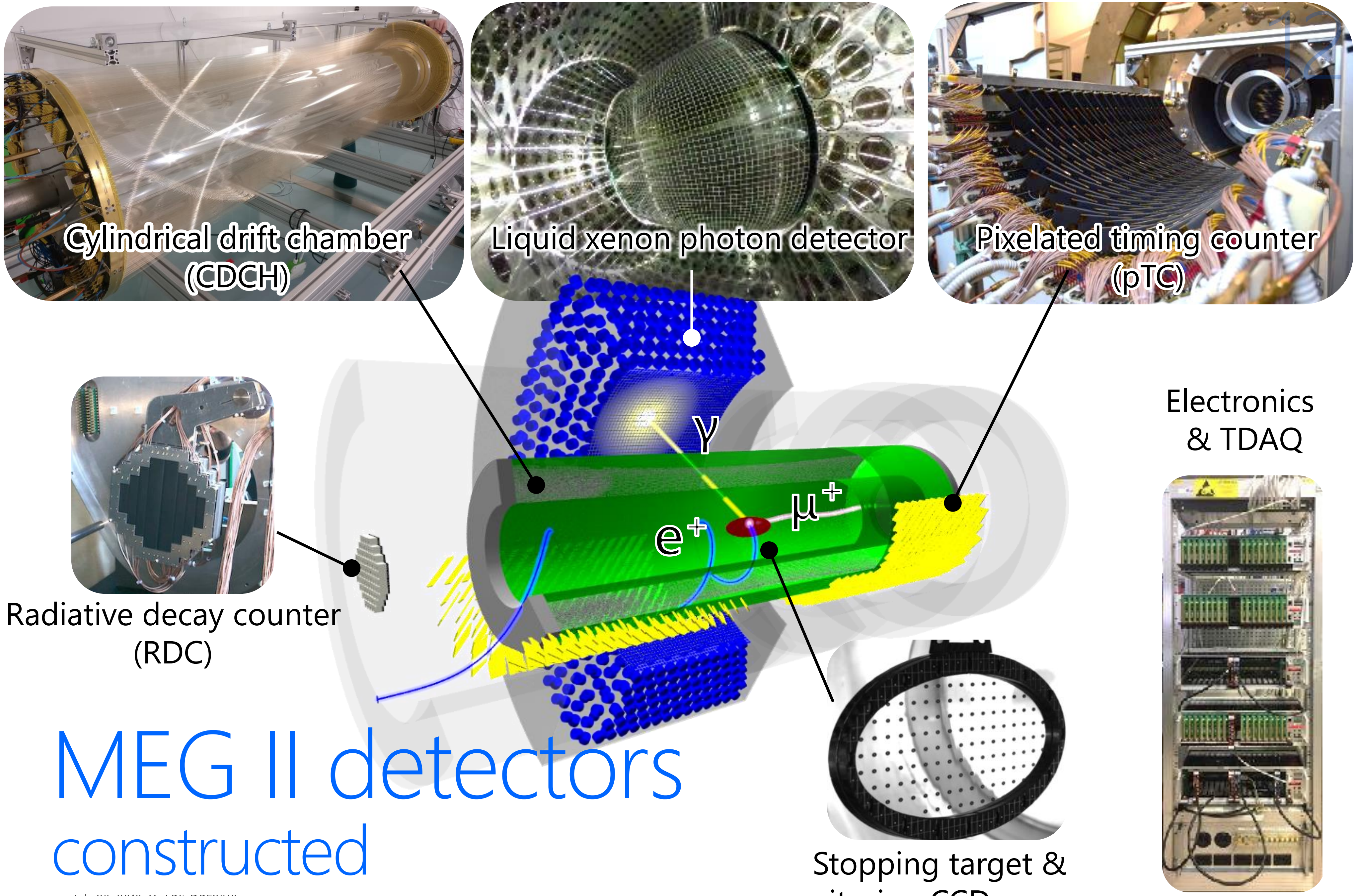
The piE5 beam line



E × B filter
to eliminate e^+ contamination
(renewed this year)

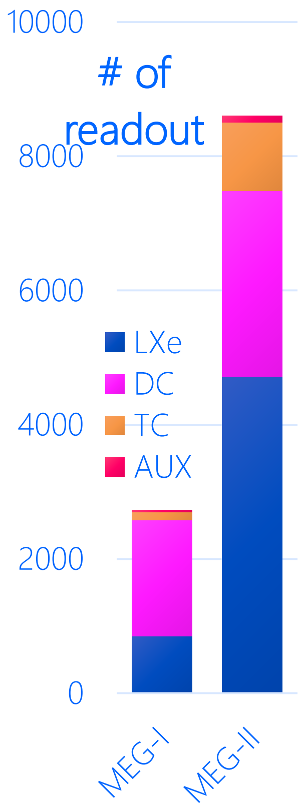
- Will be shared with Mu3e experiment.
  - ☐ Two experiments are not able to run in parallel.
  - ☐ Mu3e won't start at least until 2021.

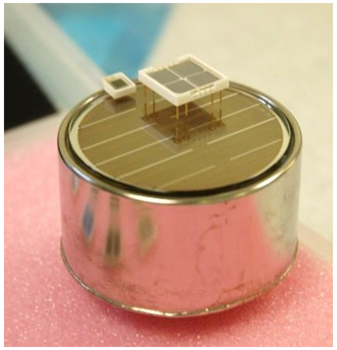
MEG II detectors constructed



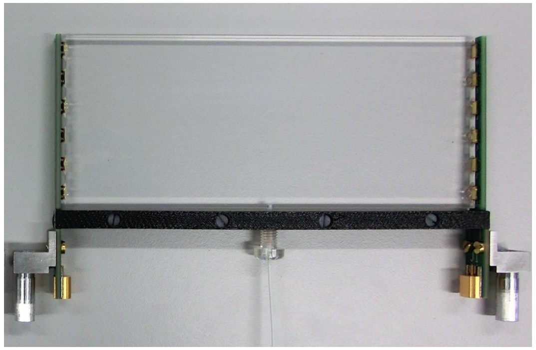
Detector technologies

- Large-area VUV sensitive SiPM
  - for 3-ton LXe detector (wavelength 175 nm)
  - Significantly improve resolutions with higher granularity
- 35 ps precision time measurement
  - with fast plastic scinti. & SiPMs
- Low-mass long drift chamber
  - 0.0016 X_0 for a particle with extremely thin wires (20um W(Au) + 40-50um Al(Ag))
  - High granularity cells (6 × 6 mm^2)
- Compact, dense, multi functional DAQ system
  - To deal with increased channels
  - GHz waveform digitization & 1st level trigger in one board



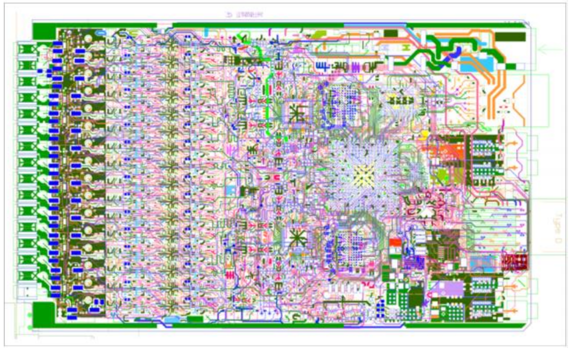


12 × 12 mm^2 VUV MPPC & 2-inch VUV PMT



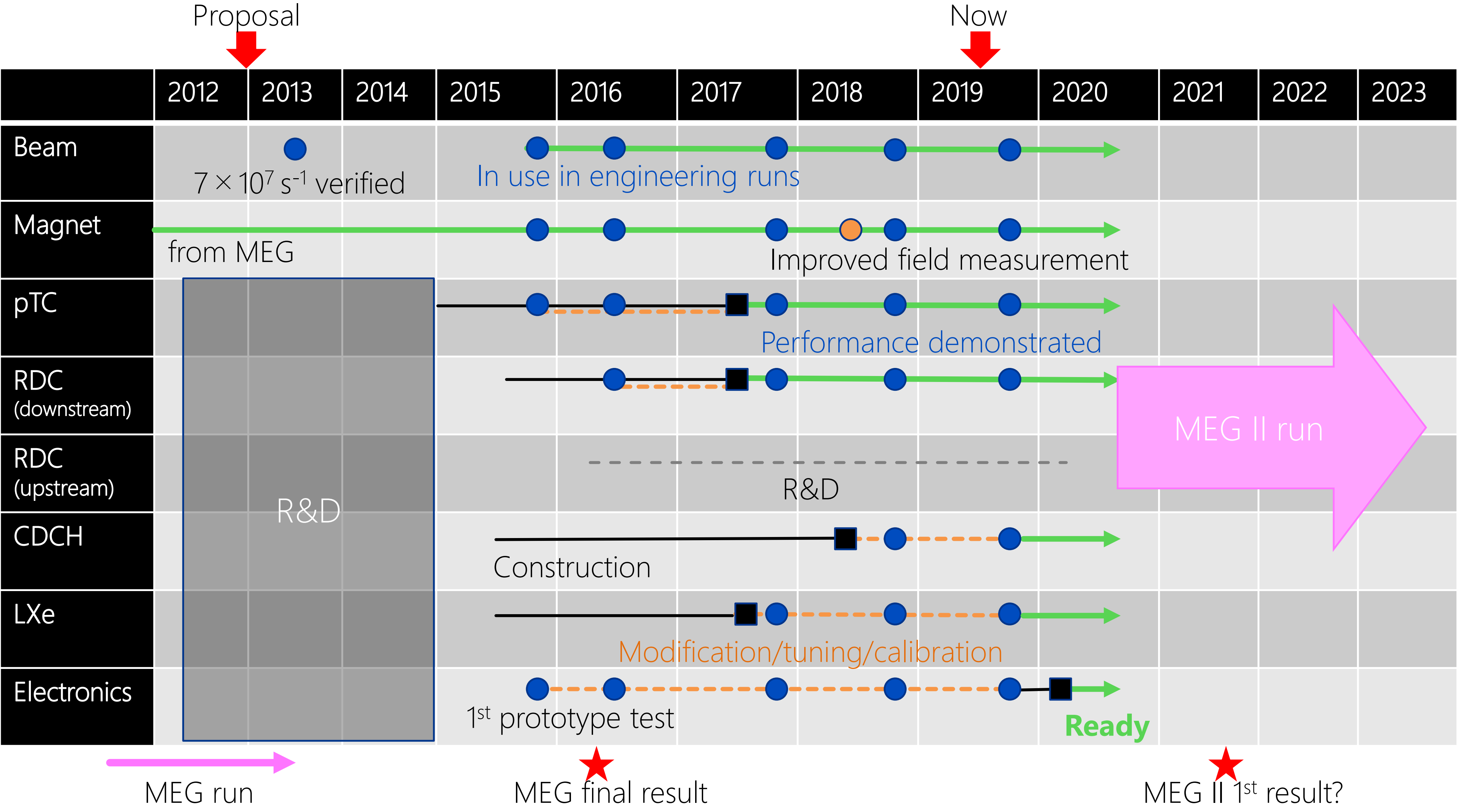
A scintillator counter readout with 6-series SiPM chain at both ends

Highly granular drift cells formed by thin wires soldered on PCBs (no feedthrough & crimping)



SiPM bias voltage, amplifier & shaper, waveform digitizer (DRS4), discriminator, ADC, FPGA on a board (16 channels)

MEG II time line



Recent activities

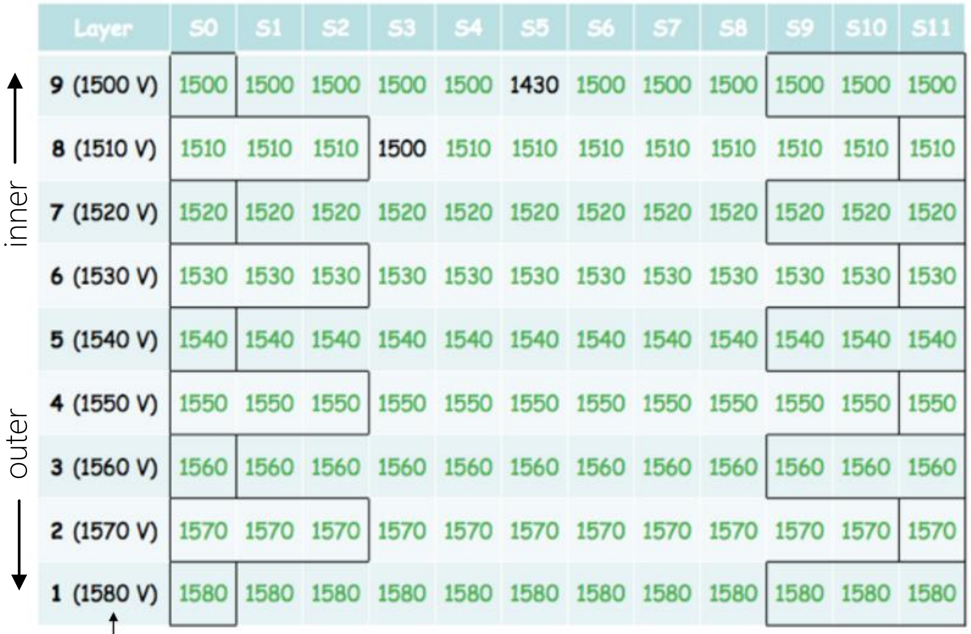
Highlights

Drift chamber

- Electrostatic stability problems in 2018 run
  ⇒ inner layers could not reach the working point
- Wire elongation in spring 2019 (up to 70% of elastic limit).
- Remove broken wires.
- New HV tests show that all the layers can be operated at the working point with 100 V safety margin
- Will be tested in beam in Oct. – Dec.

- In parallel, continue the study for more robust chamber (against wire breaking).


The chamber was opened



Layer	S0	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11
9 (1500 V)	1500	1500	1500	1500	1500	1430	1500	1500	1500	1500	1500	1500
8 (1510 V)	1510	1510	1510	1500	1510	1510	1510	1510	1510	1510	1510	1510
7 (1520 V)	1520	1520	1520	1520	1520	1520	1520	1520	1520	1520	1520	1520
6 (1530 V)	1530	1530	1530	1530	1530	1530	1530	1530	1530	1530	1530	1530
5 (1540 V)	1540	1540	1540	1540	1540	1540	1540	1540	1540	1540	1540	1540
4 (1550 V)	1550	1550	1550	1550	1550	1550	1550	1550	1550	1550	1550	1550
3 (1560 V)	1560	1560	1560	1560	1560	1560	1560	1560	1560	1560	1560	1560
2 (1570 V)	1570	1570	1570	1570	1570	1570	1570	1570	1570	1570	1570	1570
1 (1580 V)	1580	1580	1580	1580	1580	1580	1580	1580	1580	1580	1580	1580

Working point + 100V
(Gain=5×10^5)

green = goal reached

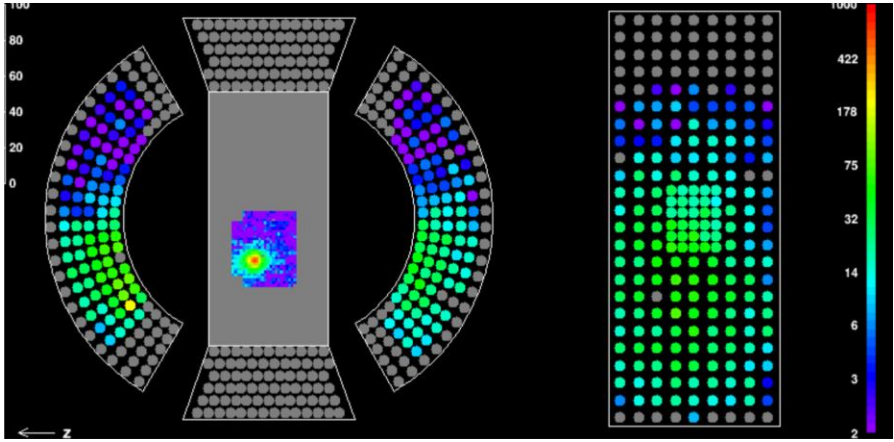
Recent activities

Highlights

LXe detector

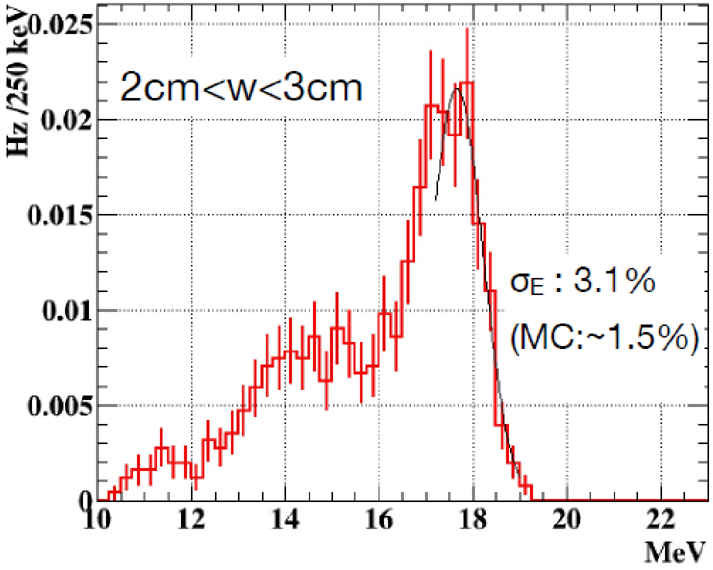
- Detailed calibration ongoing
  - ☐ Light yield, absorption, reflectance, etc.
  - ☐ Photo sensors (MPPC + PMT) response (gain, PDE)
- Performance study
  - ☐ Good timing & position resolutions achieved.
  - ☐ Energy resolution not yet reach the design value.

17.6 MeV γ from Li(p,γ)Be



Only limited region readout

- Performance evaluation with 55 MeV photons from pi0 decay is planned in this winter.



Next step

Engineering run this autumn – winter

- Final tests of detector stability/performance with limited number of electronics.
  - ☐ CDCH test in beam at nominal HV
  - ☐ LXe detector with 55 MeV γ from pi0
  - ☐ Test final design electronics in beam → mass production
- Test new production target
  - ☐ 30 – 50% surface muon yield increase

Very important step to start physics run from next year

On-going activities Highlights

R&D of upstream RDC detector (optional detector)

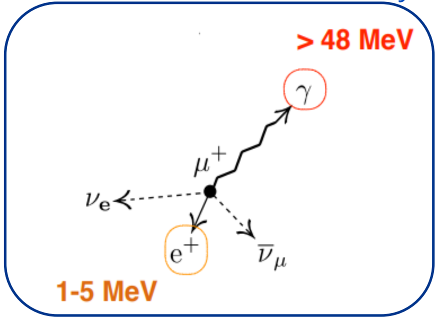
- Detect low-momentum e^+ emitted with high-energy photon.
- The detector has to be placed on beam axis.
  - ☐ **Downstream side**: newly introduced in MEG II, already constructed.
  - ☐ **Upstream side**: muon beam has to pass through the detector → difficult
    - ■ Several designs have been considered and tested

Scintillating fibers ☹ radiation hardness

Thin silicon/diamond sensors ☹ signal-to-noise ratio

Resistive plate chamber ⬅

radiative muon decay

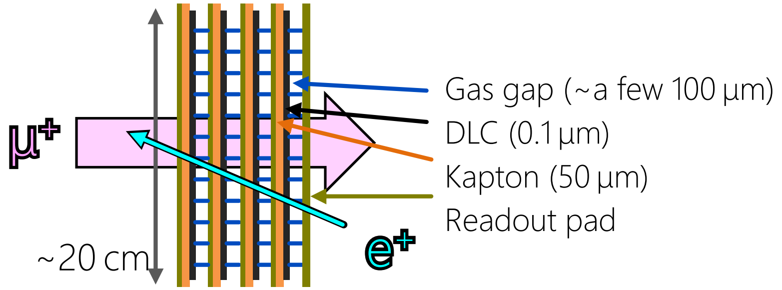


Requirements

☐	High rate capability	(4 MHz/cm^2)
☐	Radiation hardness	(~1 MGy)
☐	Low material budget	(<0.1% X_0)
☐	Time resolution	< 1 ns
☐	90% efficiency for e^+	(40% each layer)

⇨ improve sensitivity by 10%

Resistive plates of diamond like carbon (DLC)



Low material budget and adjustable surface resistance

200μm-gap single-layer prototype shows

- 360 ps time resolution
- 23% detection efficiency
  → test lager gap to improve efficiency
- ☐ Rate capability to be tested

Summary & prospects

- All the detectors were upgraded from MEG
  - ☐ to make maximum use of the highest intensity DC muon beam to date.
  - ☐ Full engineering run this year.
    - Still have to fight with a few issues: demonstrate CDCH stability, LXe energy resolution, finalize electronics.
- Physics data acquisition from 2020 for (at least) 3 years to reach a sensitivity 6×10^{-14}.
  - ☐ MEG limit will be exceeded in a few months.

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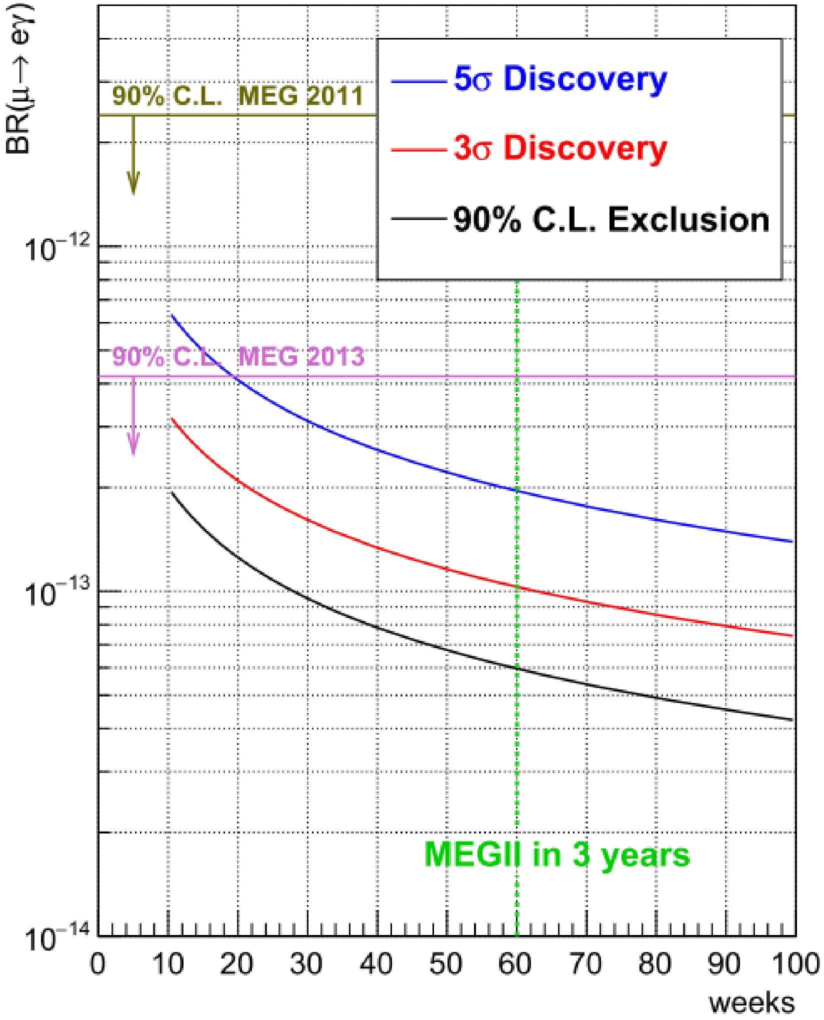
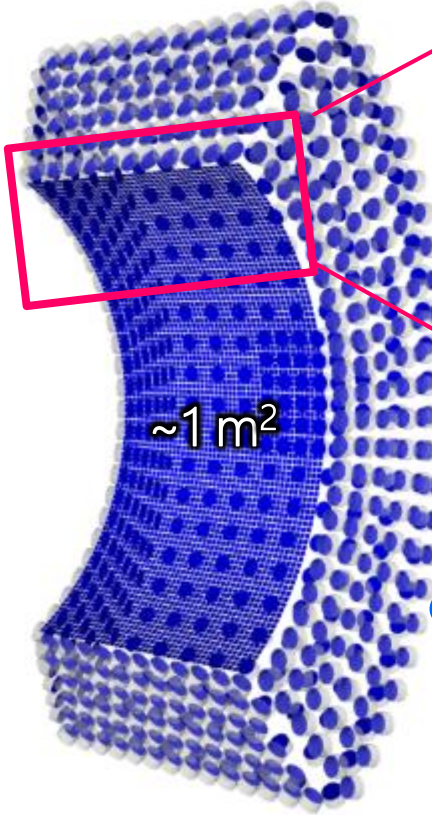
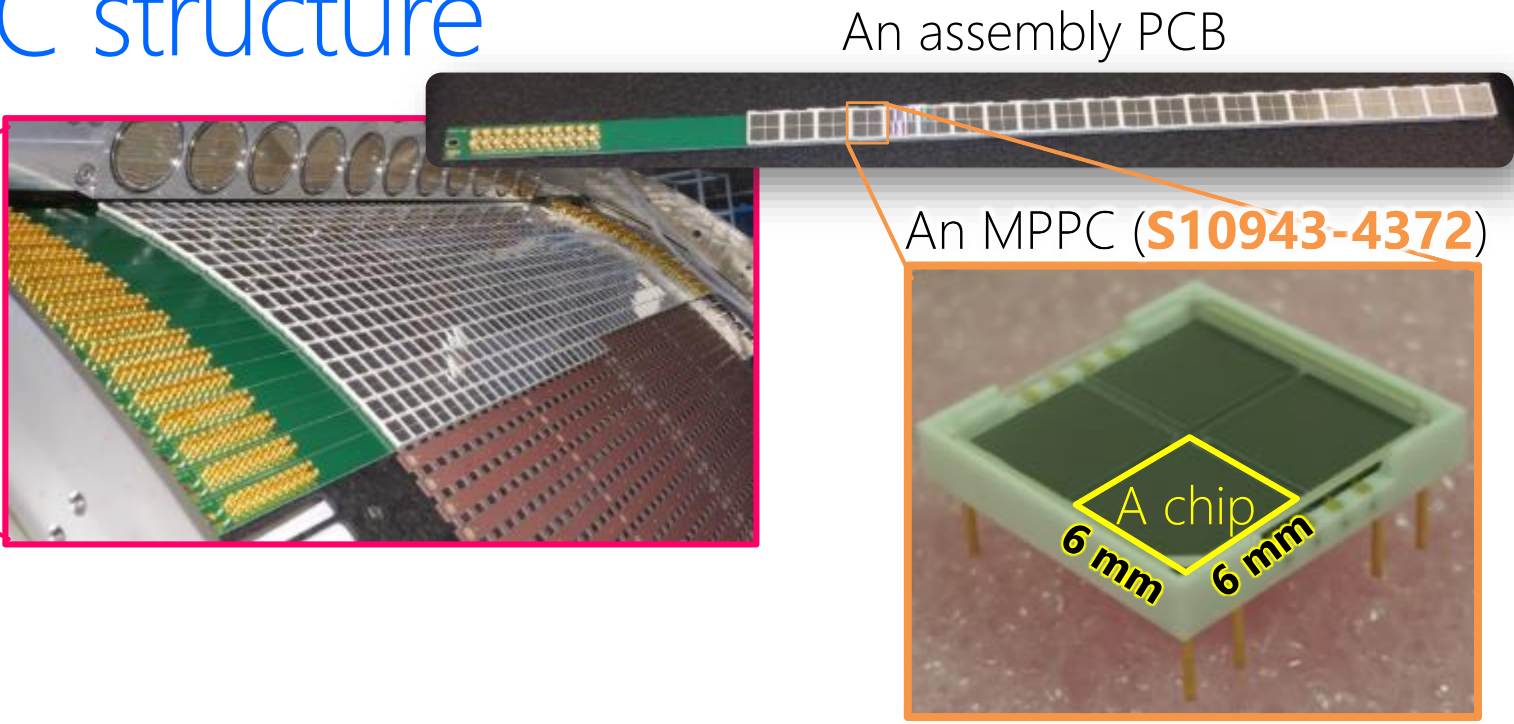


Beyond MEG II?

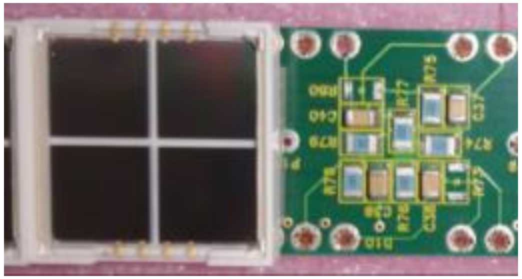
- To go beyond MEG II requires
  - A new higher intensity muon beam line
  - A new concept of experiment
  - ☐ HiMB project at PSI will offer 10^{10} μ/s.
    - As a part of the project, a new production target, increasing μ yield 30-50%, is going to be tested at the MEG II beam line this year.
    - See A. Papa's talk on 31 Jul. "The High Intensity Muon Beam project at PSI"
  - ☐ Concept & detector technologies are under investigation aiming for a sensitivity of O(10^{-15}).
- Once we discover it, measurement of angular distribution w.r.t. muon polarization becomes important.
  - ☐ MEG setup is not optimum from this aspect. Wider acceptance is beneficial.

LXe-MPPC structure



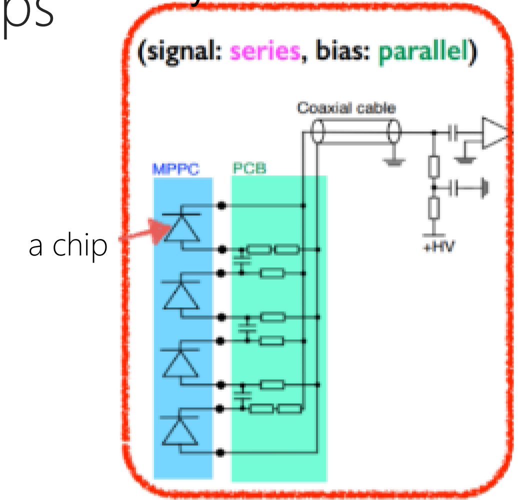


- A **VUV-sensitive large-area MPPC** consists of 4 independent SiPM chips
  - ☐ Chips with similar V_{bd} are selected.
  - ☐ Able to readout individually.
  - ☐ We connect them on the assembly PCB

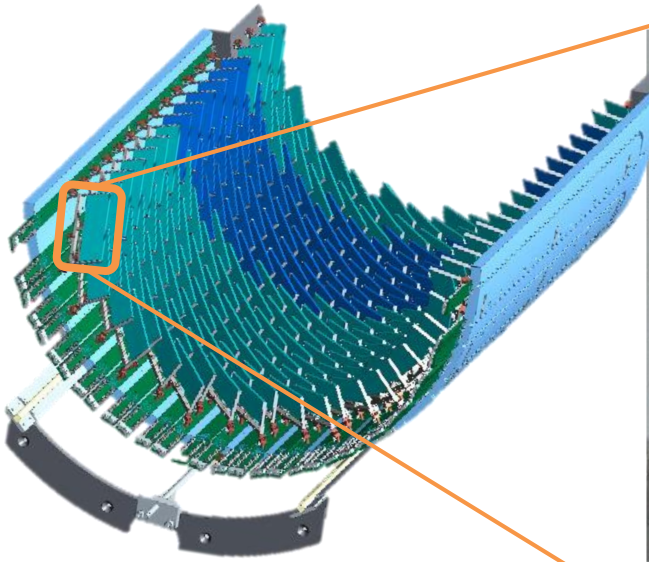


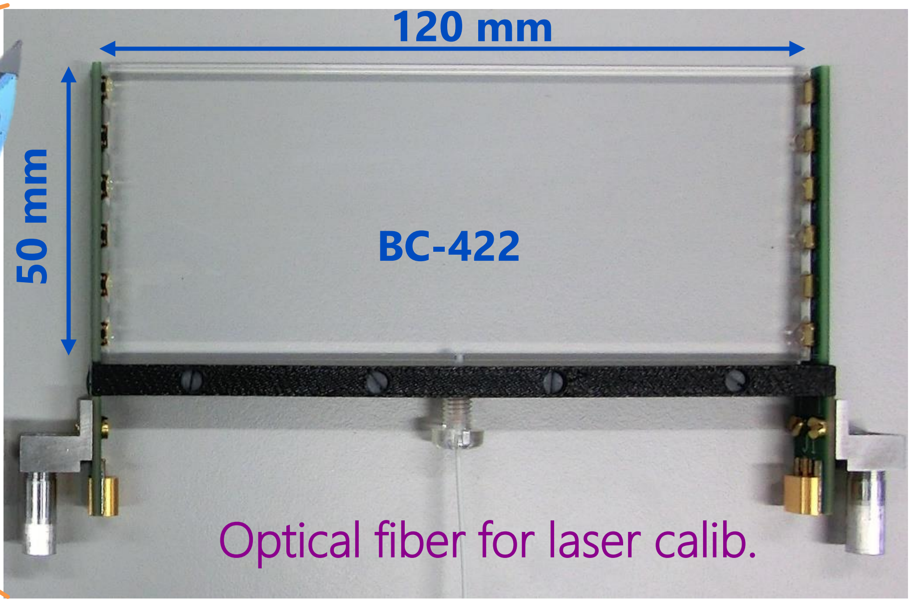
‘Hybrid’ connection

(signal: series, bias: parallel)



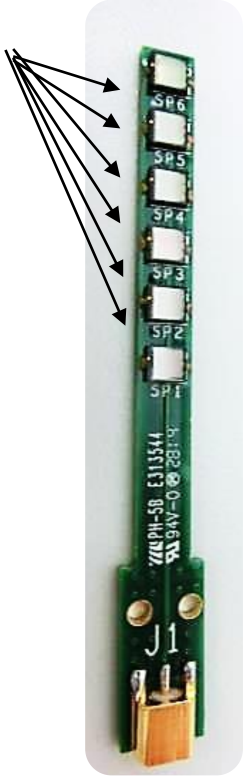
Counter structure





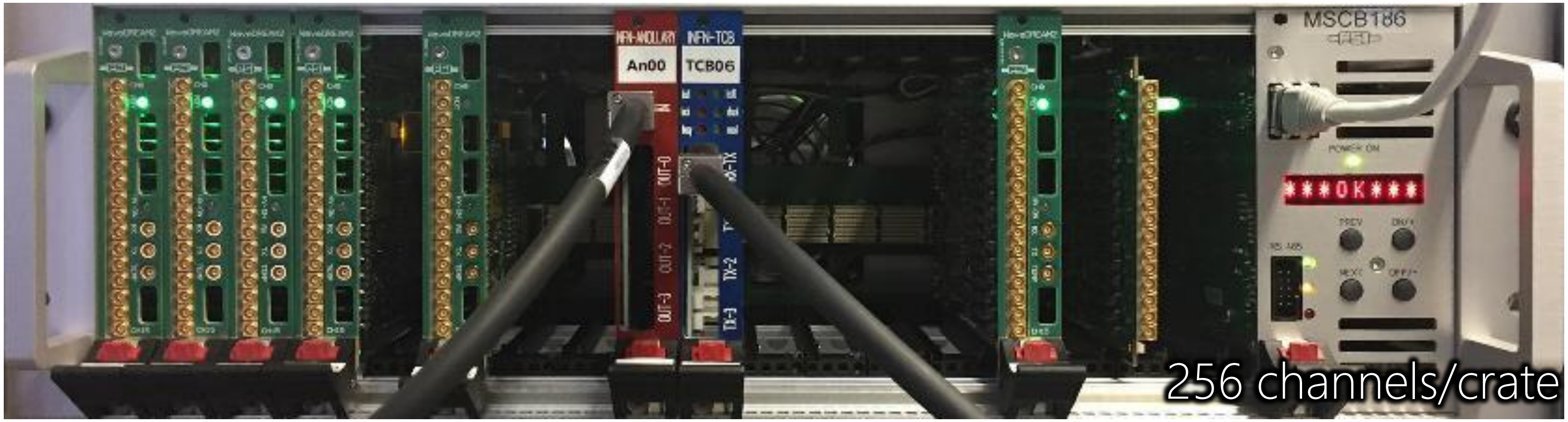
6 SiPMs
connected in series

A SiPM-array
(a readout ch)



- SiPM: **ASD-NUV3S-P High-Gain (MEG)**
  - 3 × 3 mm^2, 50 μm pixel pitch
  - Breakdown voltage: 24 V
  - Operational range: V_{over}=2 – 3.5 V
  - Peak sensitivity: 420 nm
  - Temperature coeff. V_{BD}: 26 mV/℃
  - Production in 2014

Readout electronics



256 channels/crate

- New DAQ/Trigger system being developed: WaveDAQ system
  - Used for all MEG-II detectors in common
  - Dense & compact system to cope with increased # of channels. Away from VME crates
  - No pre-amplifier at detector side
  - Custom multi-functional readout board: **WaveDREAM** *Analog FE (programmable shaper & amplifier), SiPM bias-voltage supply, waveform sampling (DRS4), digitization, discriminator, FPGA-based trigger in one module*
  - Synchronization accuracy **< 20 ps** (over different crate modules)

16 channels/module