$\mu^+ \to e^+ \gamma$ 探索実験 MEG II

現状と今後の見込み

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on behalf of MEG II collaboration

日本物理学会2019年秋季大会
令和元年9月19日＠山形大学

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

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

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

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

~60 physicists

MEG result (2016)

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

@90% C.L.

(while 5.3×10^{-13} expected)

- ×2 intensity muon beam
- ×2 resolution everywhere
- ×2 efficiency

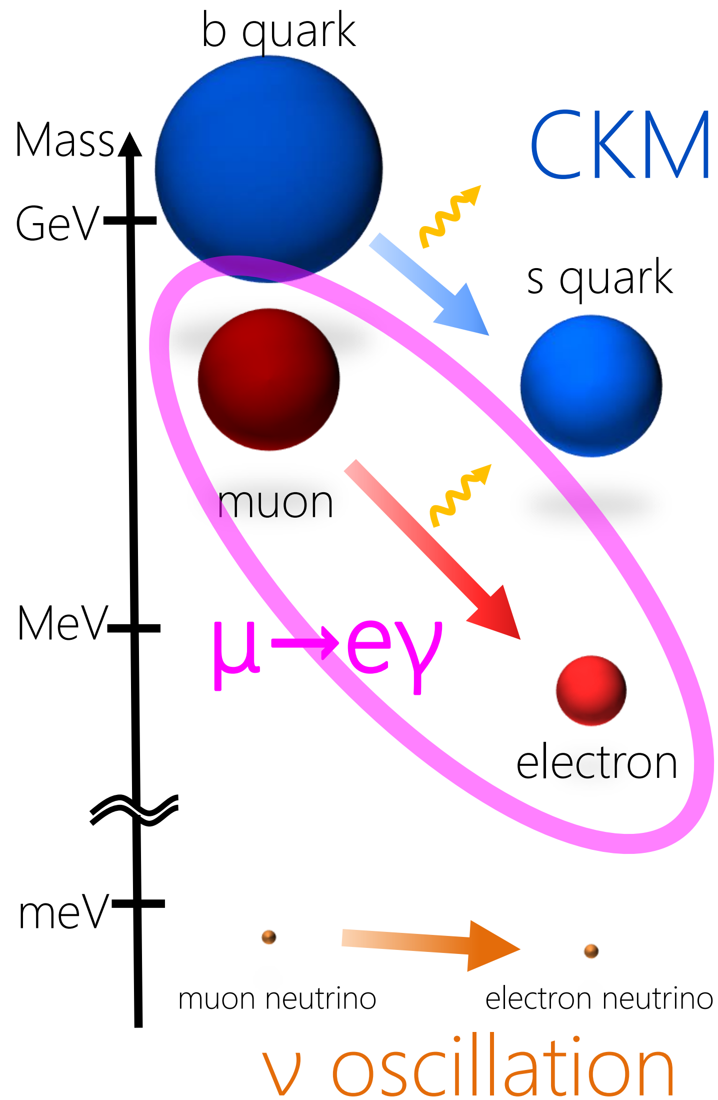
Search for $\mu^+ \rightarrow e^+\gamma$ down to

6×10^{-14}

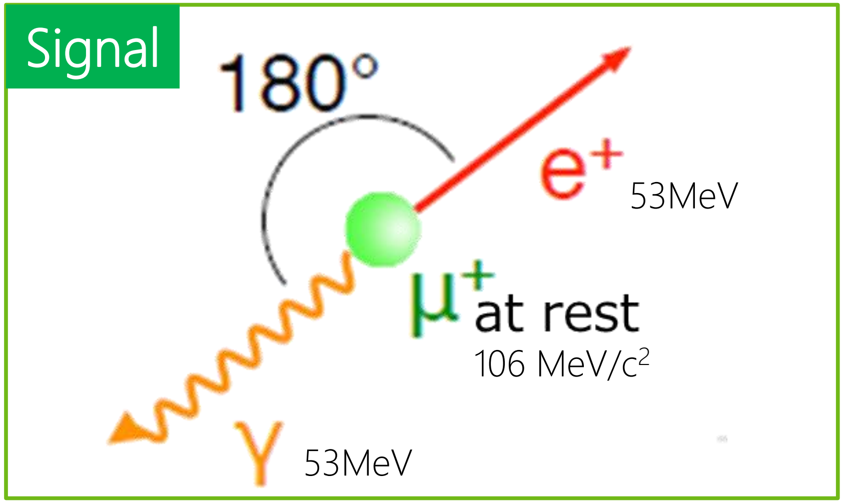
(90% C.L. sensitivity)

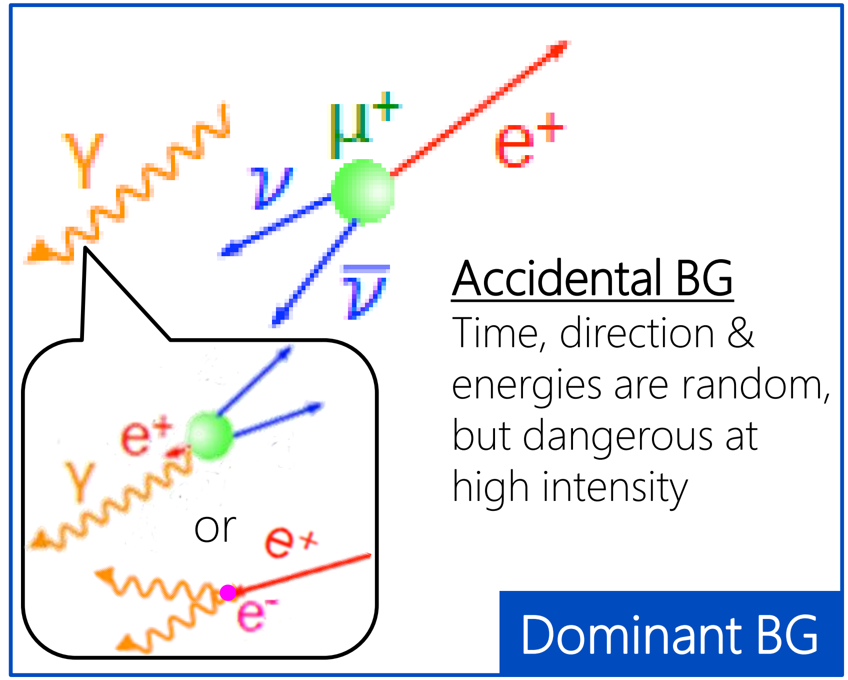
Physics of $\mu^+ \rightarrow e^+\gamma$

- **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. No reason to be conserved.
  2. 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
  - SUSY-GUT, SUSY-seesaw, leptoquarks, etc.



Experimental requirements





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

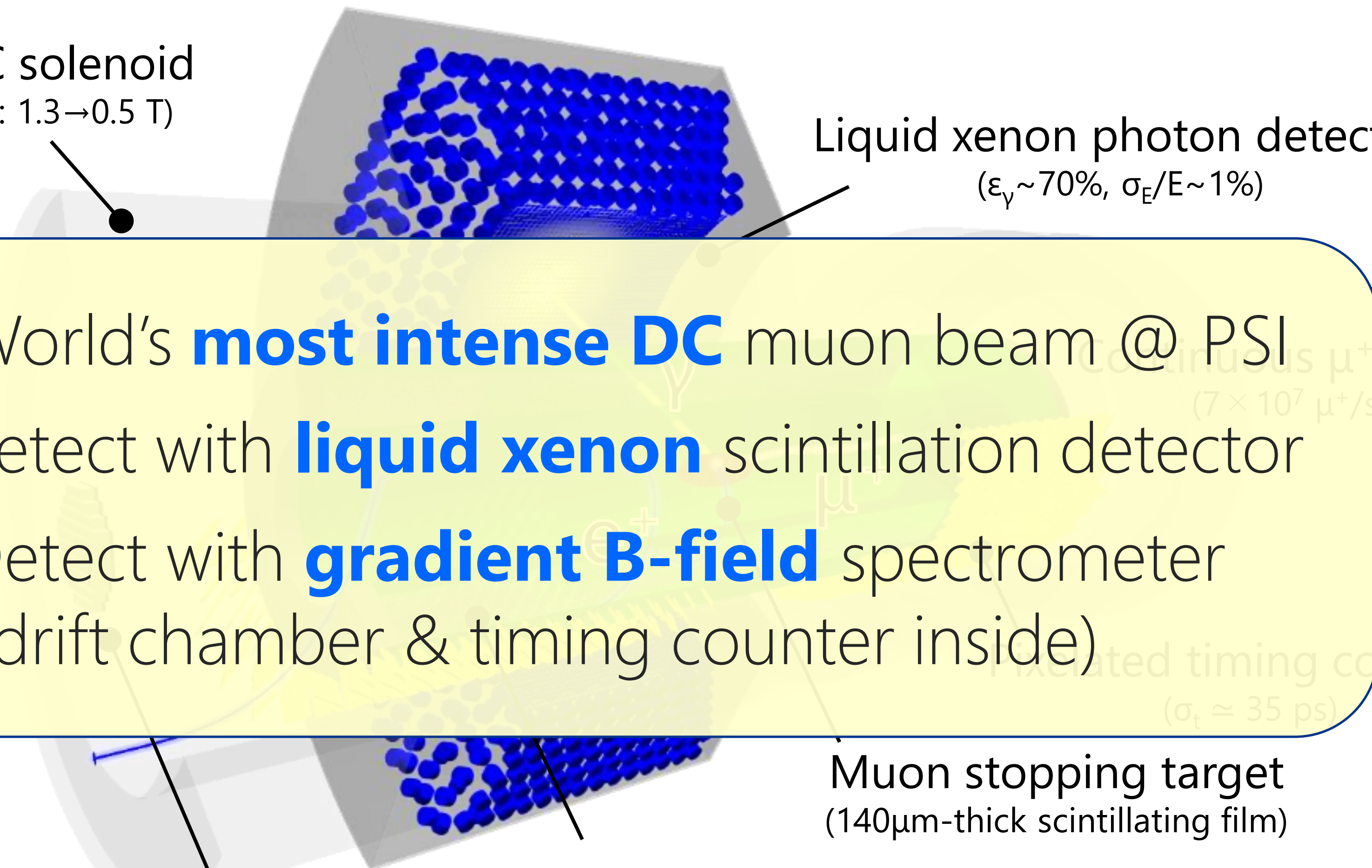
accidentally back-to-back

accidentally coincident

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

MEG II

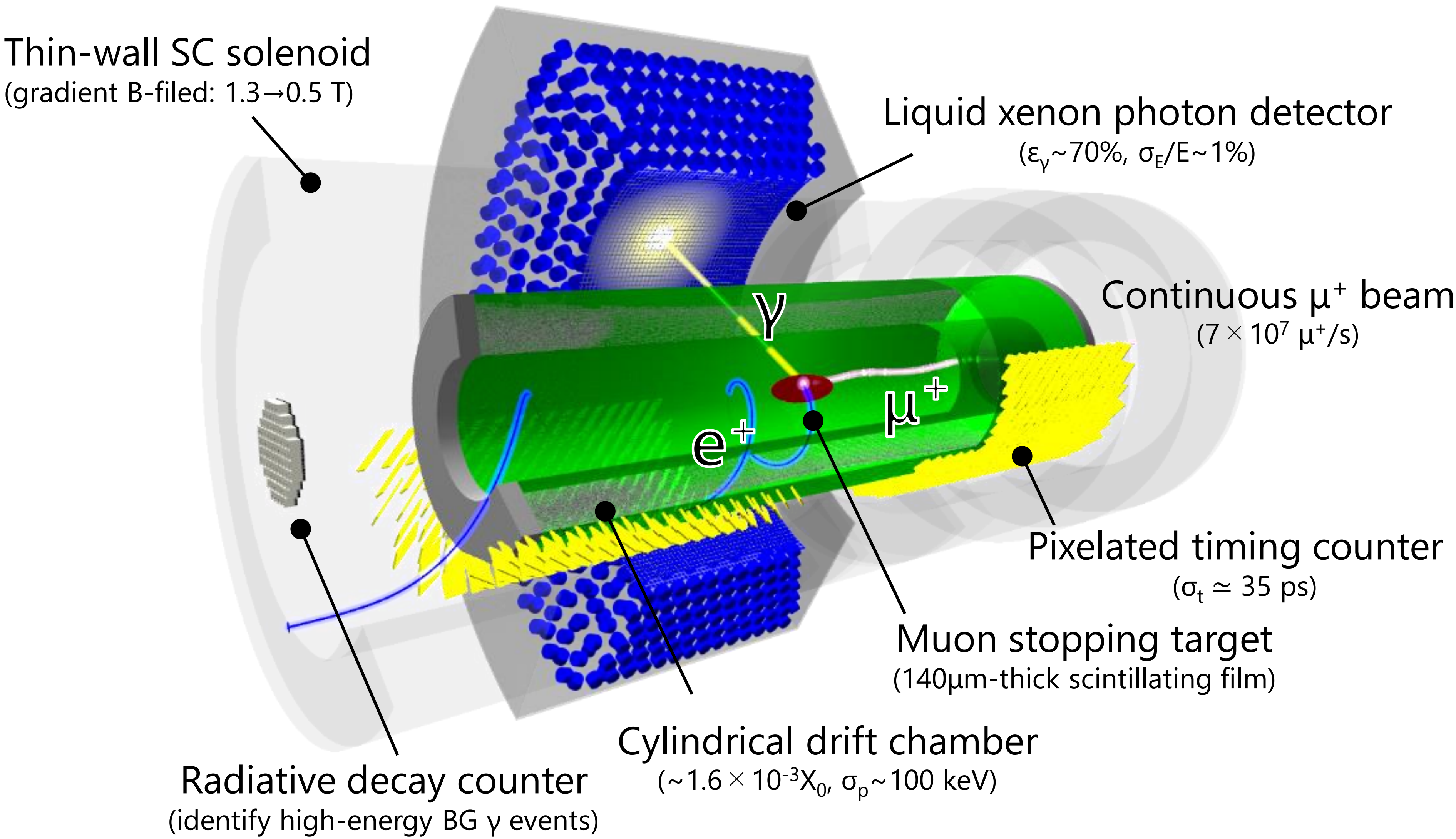
EPJ-C 78 (2018) 380



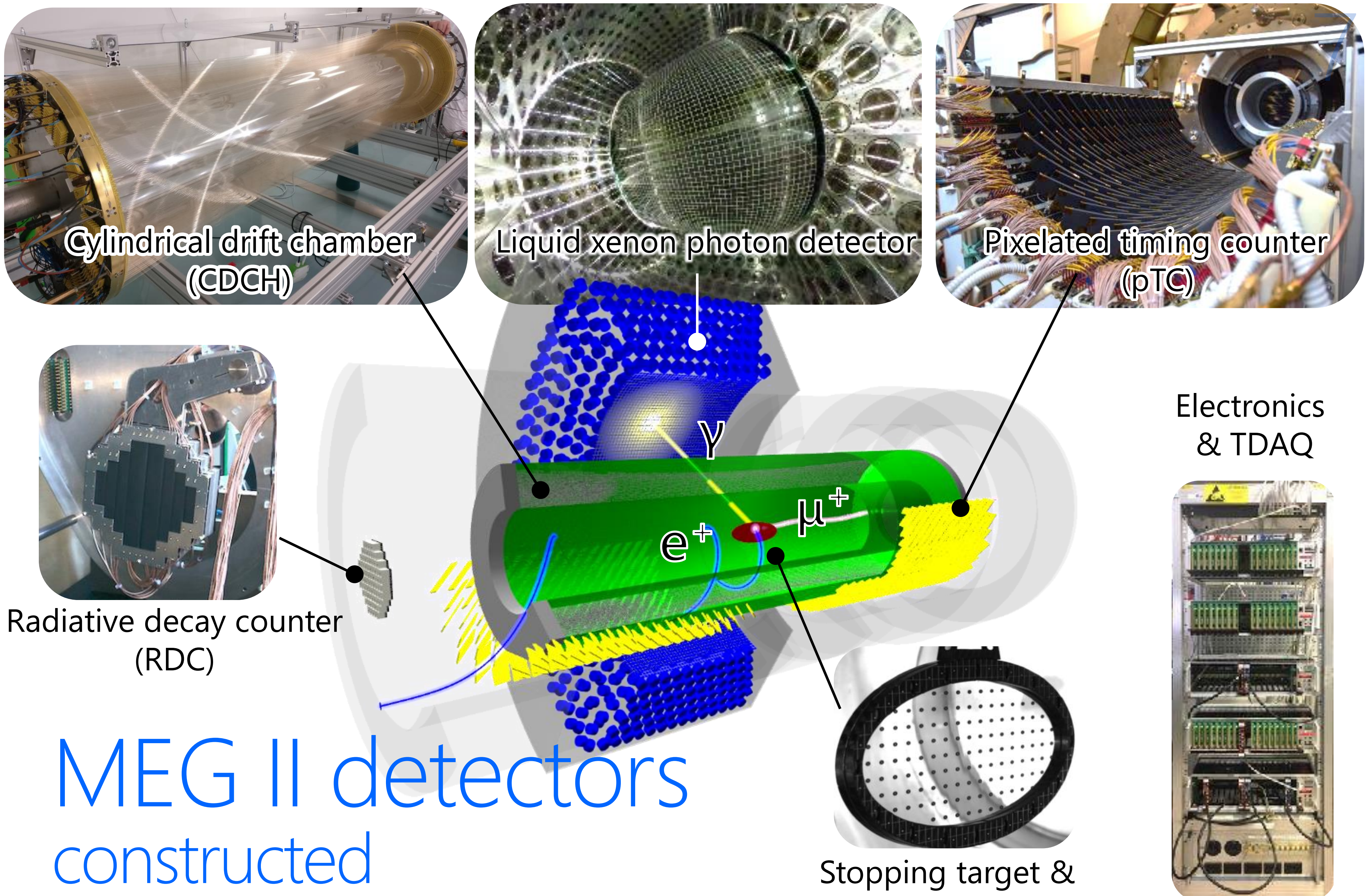
- μ^+: World's **most intense DC** muon beam @ PSI
- γ : Detect with **liquid xenon** scintillation detector
- e^+: Detect with **gradient B-field** spectrometer
  (drift chamber & timing counter inside)

MEG II

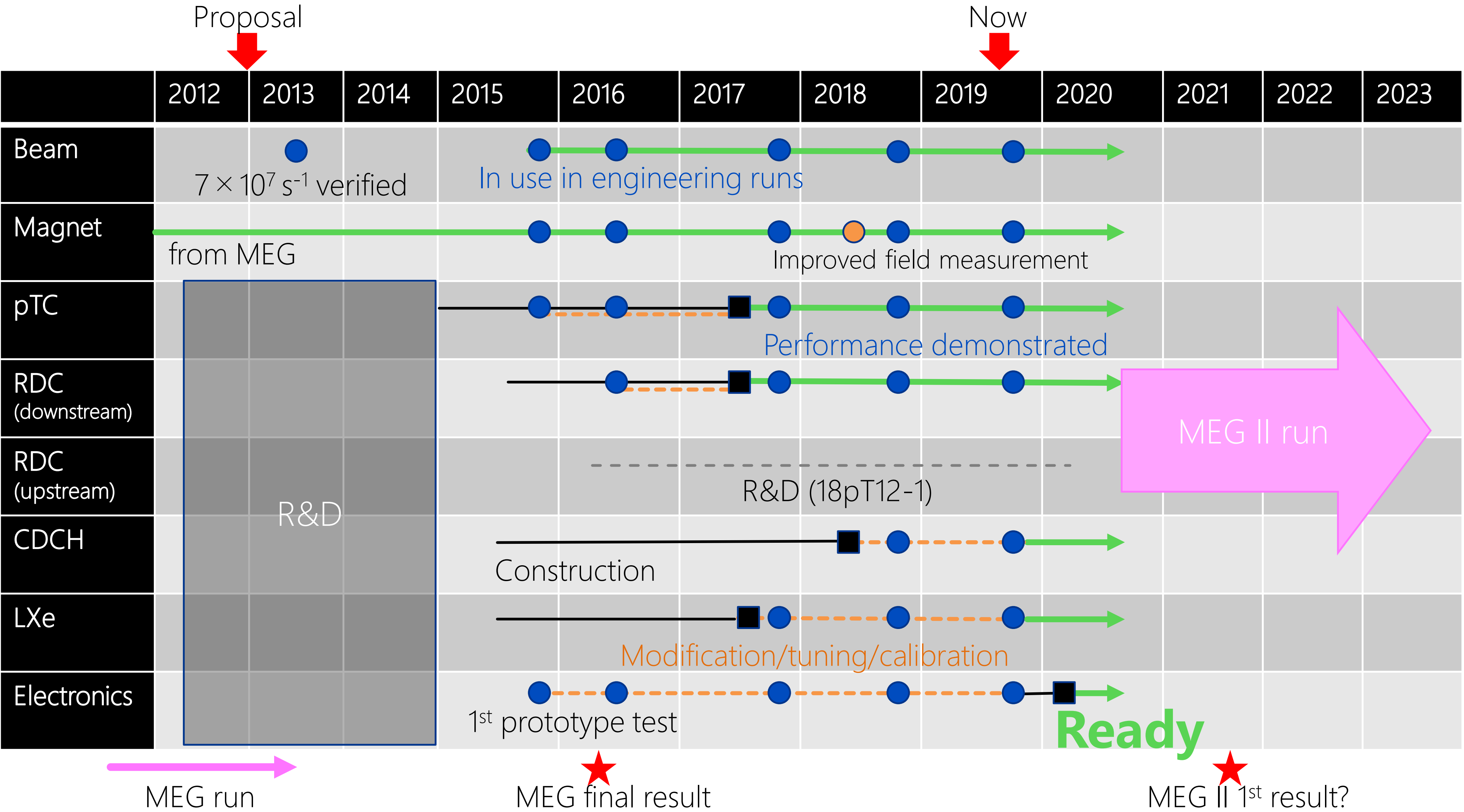
EPJ-C 78 (2018) 380



MEG II detectors constructed



MEG II timeline



2018 run & issues

- We performed a successful engineering run in Oct. – Dec. 2018 with all the detectors & MEG II intensity beam.

Major issues

- Drift chamber
  - Severe problem in the electrostatic stability → only 3 outer-most layers were operational.
  - Critical problem of wire breaking happened again.
- LXe detector
  - Performance (especially the energy resolution) has not yet be demonstrated.
  - Unexpectedly large degradation of photo-sensors (MPPC & PMT) observed in beam.
- Electronics
  - Schedule delay → only limited number of channels were available.
  - Noise reduced version (final version) not yet tested.

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Focus in this talk

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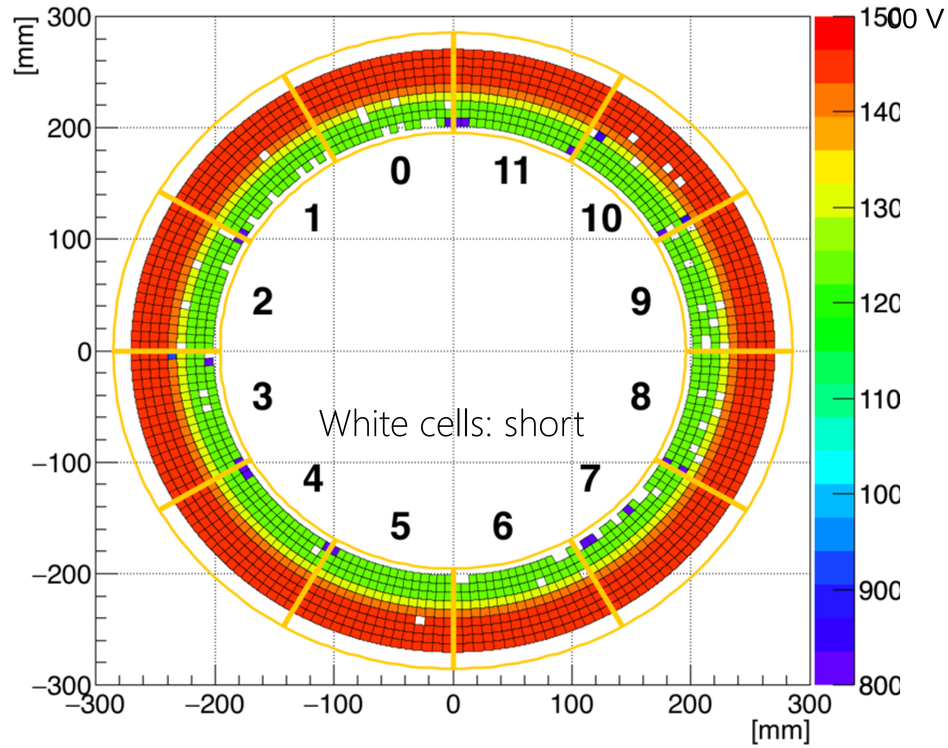
→ See 17aT12-4,5 19pT14-6,7,8

Drift chamber HV

After closing chamber, we tested HV.

- During HV ramp-up, currents oscillate → sometimes permanent short.
- Inner layers cannot reach the nominal voltage.
- Wire tension was not enough.
  - Tension is controlled by the length of wires.
  - We set **+3.8 mm** elongation (40% of elastic limit) in assembly (2018)
  - relatively weak tension to suppress *wire breaking*.

2018 after assembly



~1450V is required to get G~5×10^5

Drift chamber HV

After the commissioning,

- Outer layers of several sectors showed bunch of short circuits.

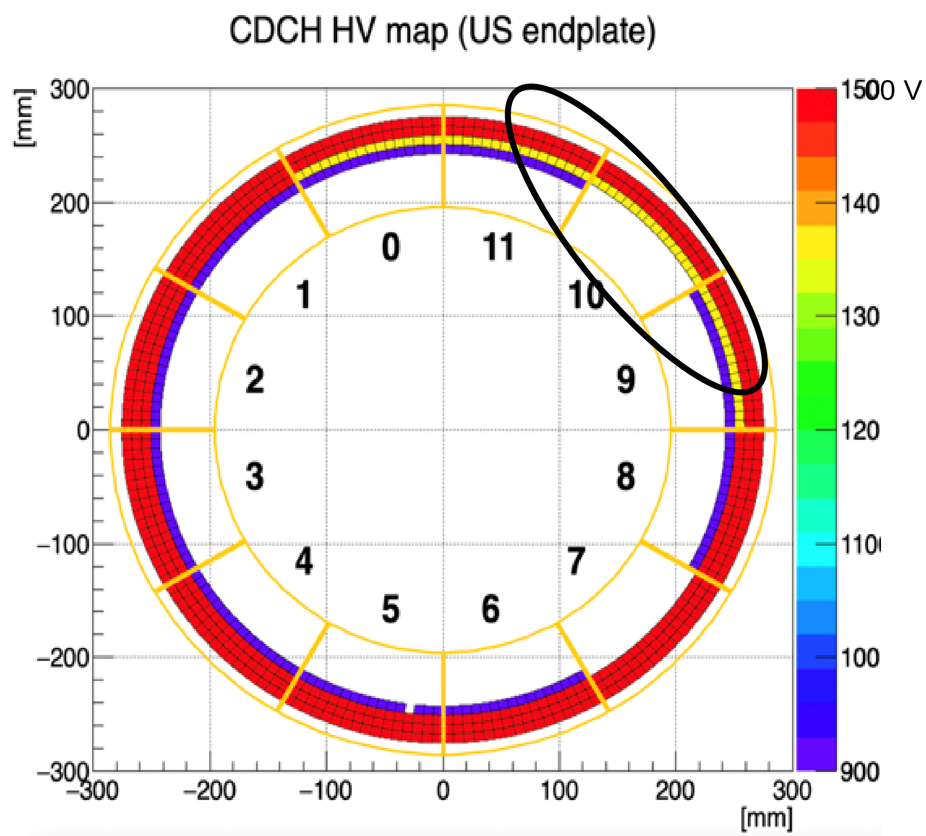
⇒ 2 cathode wires broke!

- **First breaking since 2017 Aug.**
- **Even in dry environment**

During the run

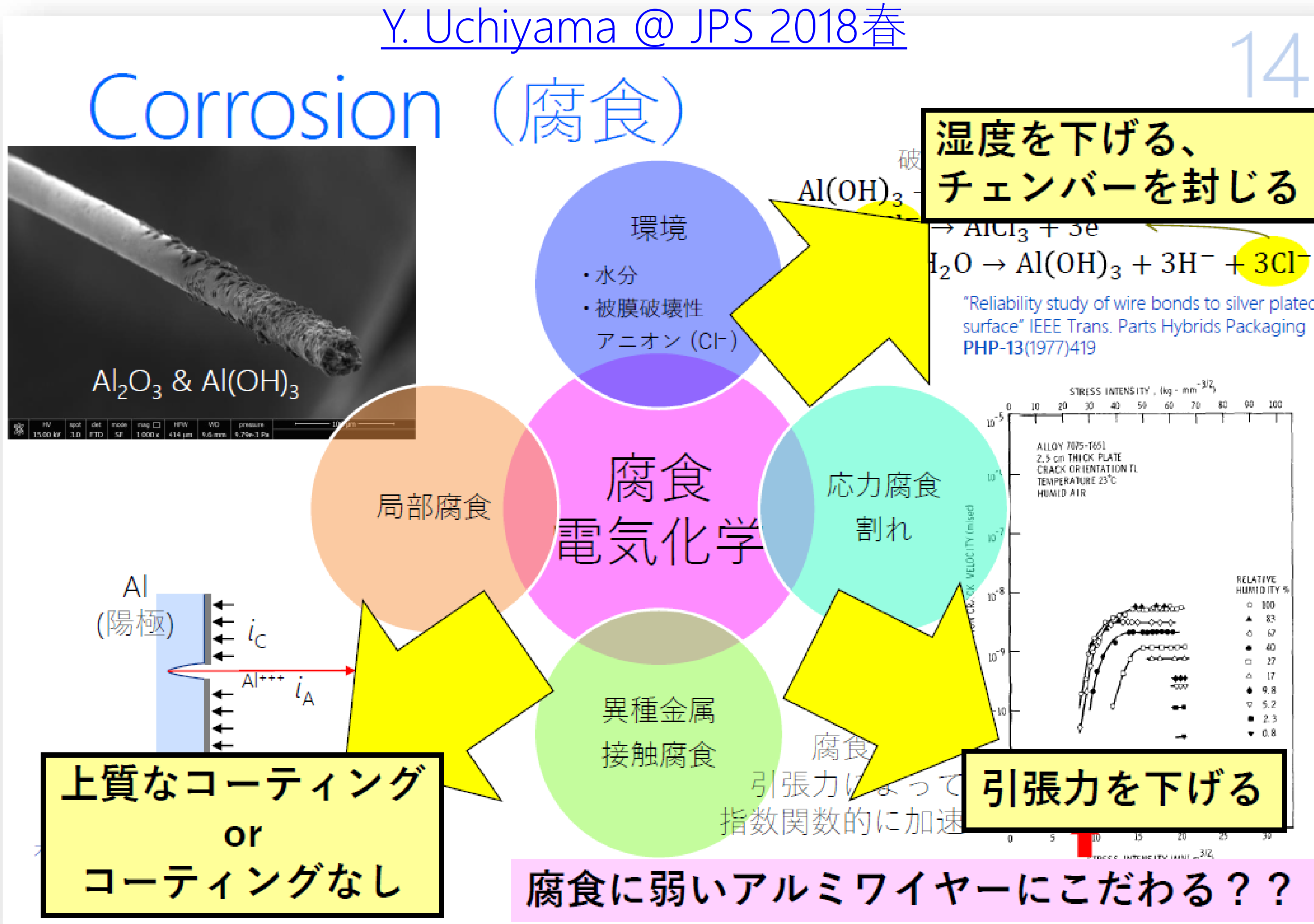
- we can apply HV only to outer 3 layers.

2018 run



~1450V is required to get $G \sim 5 \times 10^5$

The fundamental problem is still the wire-breaking



- アルミと銀の境界　＋　水分　＋　張力　＝　腐食による断線
  - 陰極ワイヤ：40 or 50 μm 銀コーティングアルミニウムワイヤ
  - チェンバーを封じ，張力も抑えたからもう起きないと期待していた。

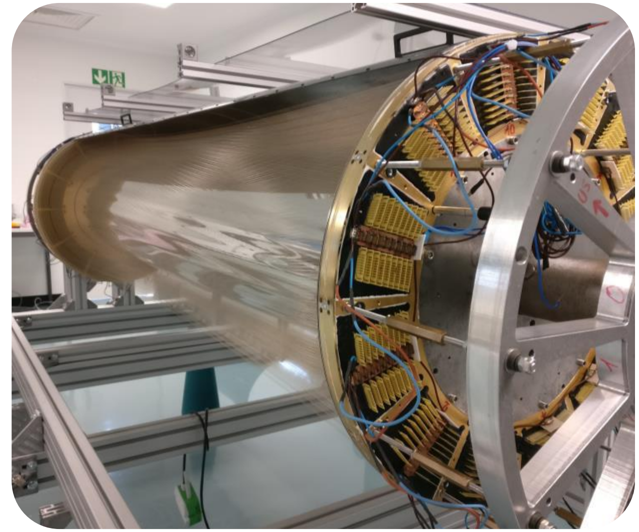
Strategy & measures (1)

- Short term (for this year)

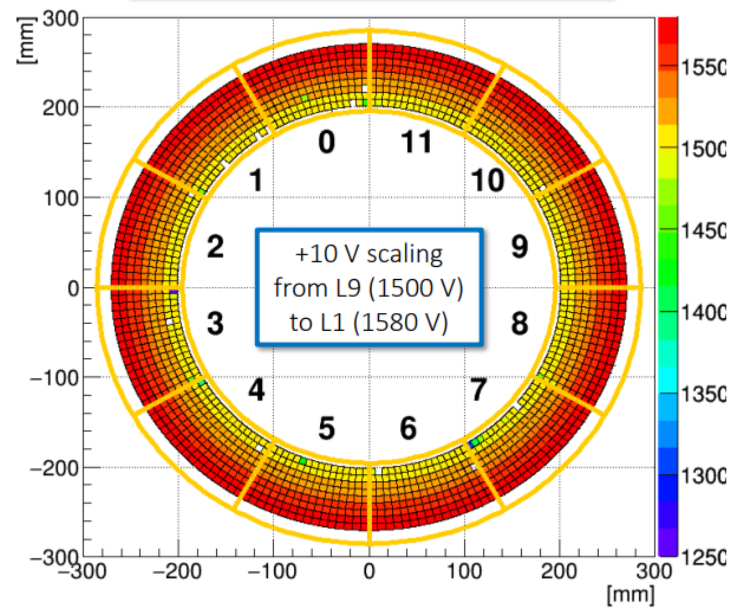
1. Open the chamber and remove the broken wires.
2. Stretch the chamber to get the electrostatic stability at nominal HV.
3. Stretch more to let weak wires break.

- Results
  - ☐ Good stability achieved by elongation of 1.8 mm (+5.6 mm from no-tension length, 70% of elastic limit)
  - ☐ Further 30 cathode wires broke during the additional stretch
    3 weeks at +6 mm
    In total ~65 cathode wires have broken
  - ☐ Simulation study shows no impact on chamber performance.

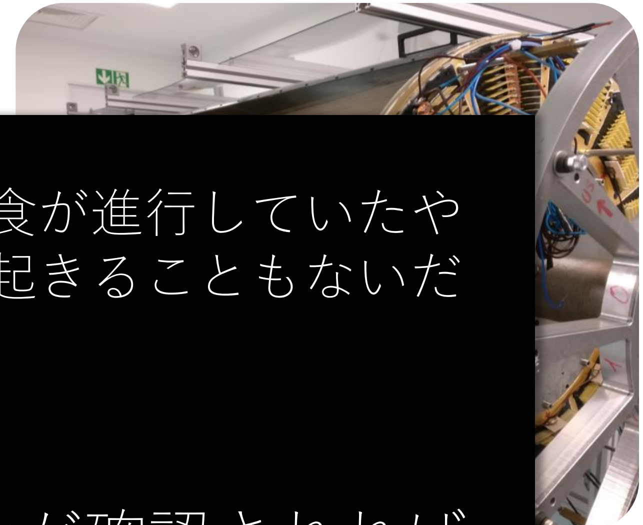
The operation took 5 months



FINAL LENGTH @ +5.6 mm CONFIRMED



Strategy & measures (1)



- Sh
1.
2.
3.

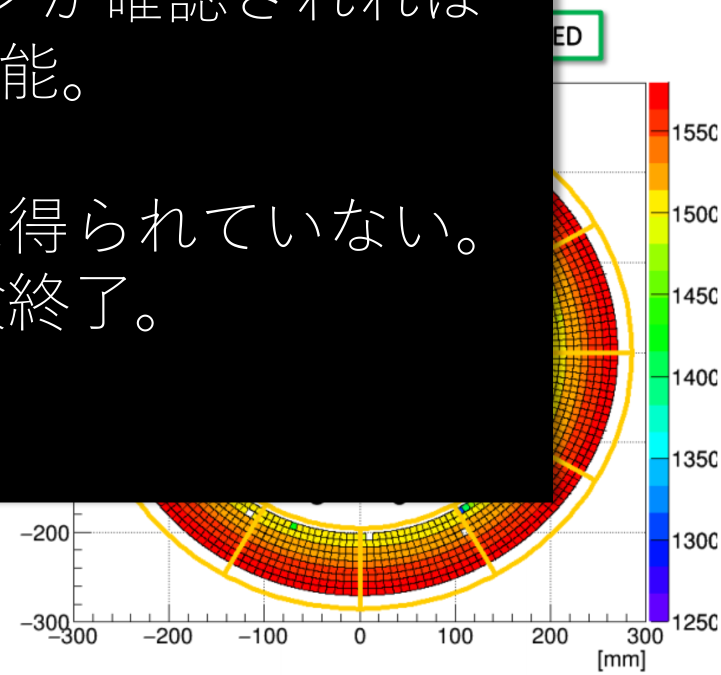
- 切れるやつはもう全部切った（建設時に腐食が進行していたやつ）。これ以上腐食が進むことも，断線が起きることもないだろう。
- HV問題も解決した。

今年のランで安定したオペレーションが確認されれば
このままMEG IIに使用可能。

一方，１００％断線が起きない確証は得られていない。
一本断線が起きたら，実験終了。
リスクが大きすぎる

- Re

The operation took 5 months



Strategy & measures (2)

- Long term risk hedge

Build another chamber with different cathode wire

- ☐ It takes at least ~**2 years** → start as soon as possible, otherwise useless.
- ☐ Revisiting design requires further R&D, too late.
- ☐ Only way to go is just changing cathode wire.

今始めて2021半ば

- A review meeting was held with PSI/INFN joint review committee (by gas-detector experts incl. Uno-san from KEK) in 5-6th Sep.
- About to submit budget request to INFN

Alternative wires?

- Several candidates have been investigated.
- From performance point of view, Al is still preferable.
- The committee suggests to expand the candidates, incl. back-up of back-up

- Present first candidate: **bare aluminum wire**
  - The main issue is soldering (tension is supported by soldering in our chamber)
  - "**C-SOLDER**™" shows good quality of soldering on Al.
    C-Solder is new tin-based soldering alloys which enable the joining of various carbon materials (carbon fibers or carbon nanotube fibers), ceramics, and aluminum.

Further tests from various viewpoints are necessary before final decision, but looks promising!

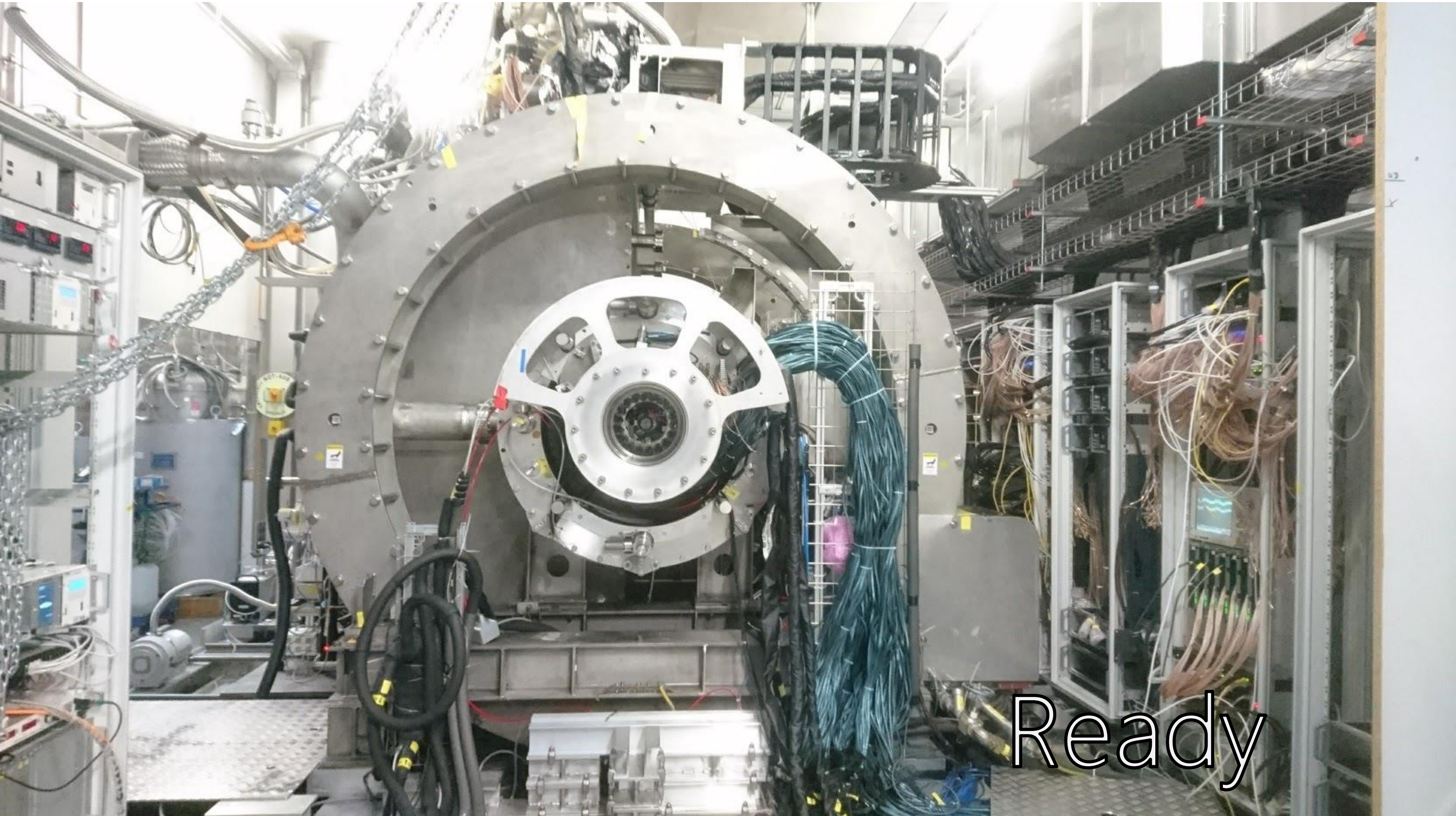
Next step

Engineering run this autumn – winter

- Final tests of detector stability/performance with (still) limited number of electronics.
  - ☐ Drift chamber test in beam at nominal HV
  - ☐ LXe detector detailed sensor tests and performance test with 55 MeV γ from pi0
  - ☐ Test final design electronics in beam → mass production by next summer
- Test new production target
  - ☐ 30 – 50% surface muon yield increase

Very important step to start physics run from next year

Status



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.
- Build another more robust drift chamber by 2021.

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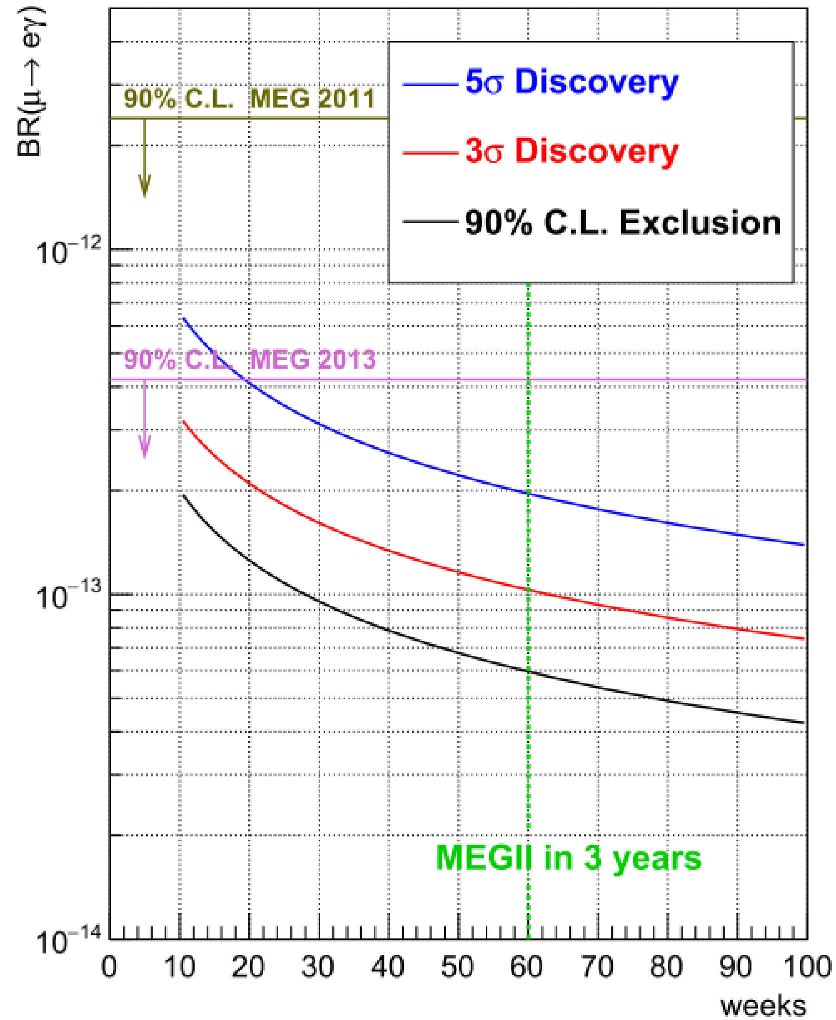


Low-mass drift chambers

	Gas	Cell size	Sense wire	Field wire	
CLEO II	Ar:C_2H_6 50:50	14 mm	20-μm Au-W	110-μm Au-**Al**, 110-μm Cu/Be	Crimp
BESIII	He:C_3H_8 60:40	12–16.2 mm	25-μm Au-W	110-μm Au-**Al**	Crimp
Belle II	He:C_2H_6 50:50	6–18 mm	30-μm Au-W	126-μm **Al**	Crimp
COMET-Phase I	He:iC_4H_{10} 90:10	16–16.8 mm	25-μm Au-W	126-μm **Al**	Crimp
KLOE	He:iC_4H_{10} 90:10	20–30 mm	25-μm Au-W	81-μm Ag-**Al**	Crimp
MEG II	He:iC_4H_{10} 85:15	6.6–9 mm	20-μm Au-W	40-μm Ag-**Al**	Solder

- **KLOE** used same type of wire without any problem for **>10 years**
  Constructed under 50% R.H., never observed salt formation

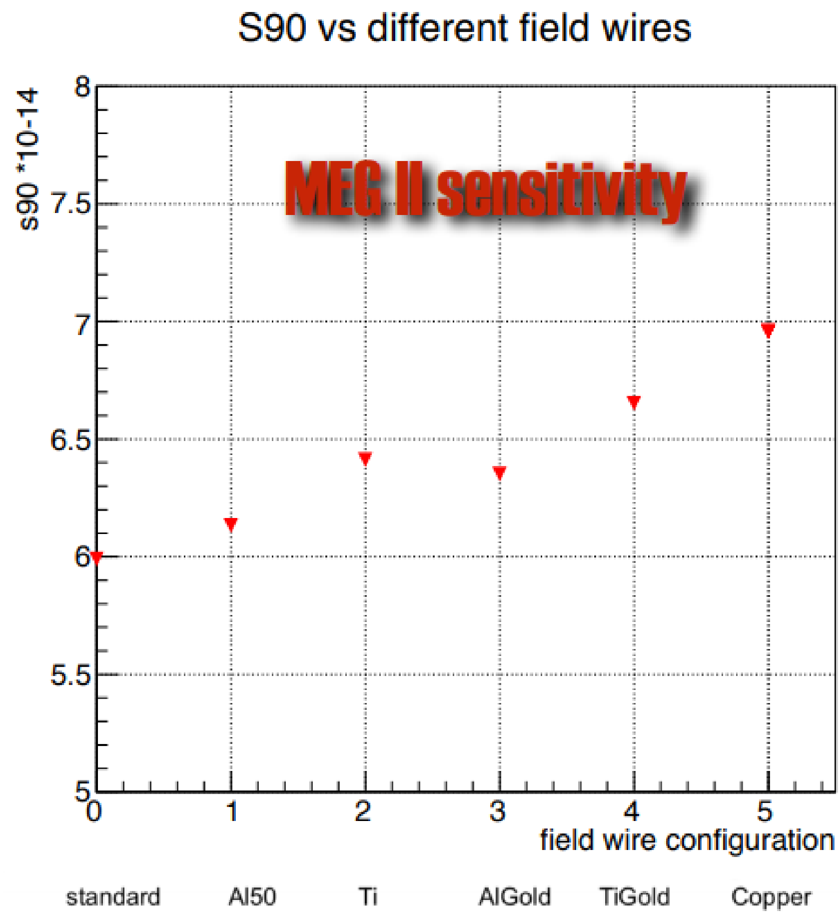
Type	X_0 (mm)	$\langle X\rangle^{wires}$ (10^{-3} X_0)	$\langle X\rangle^{tot}$ (10^{-3} X_0)	θ_{MCS}^{wires} (mrad)	θ_{MCS}^{tot} (mrad)
Al (5056)	89	0.72	1.5	5	7.6
Ti	36	1.26	2.1	6.8	9
CuBe	14.7	2.58	3.4	10.1	11.7
Stainless Steel (302)	17.8	2.2	3	9.3	11

Other material than Al is **not acceptable** from the resolution point of view.

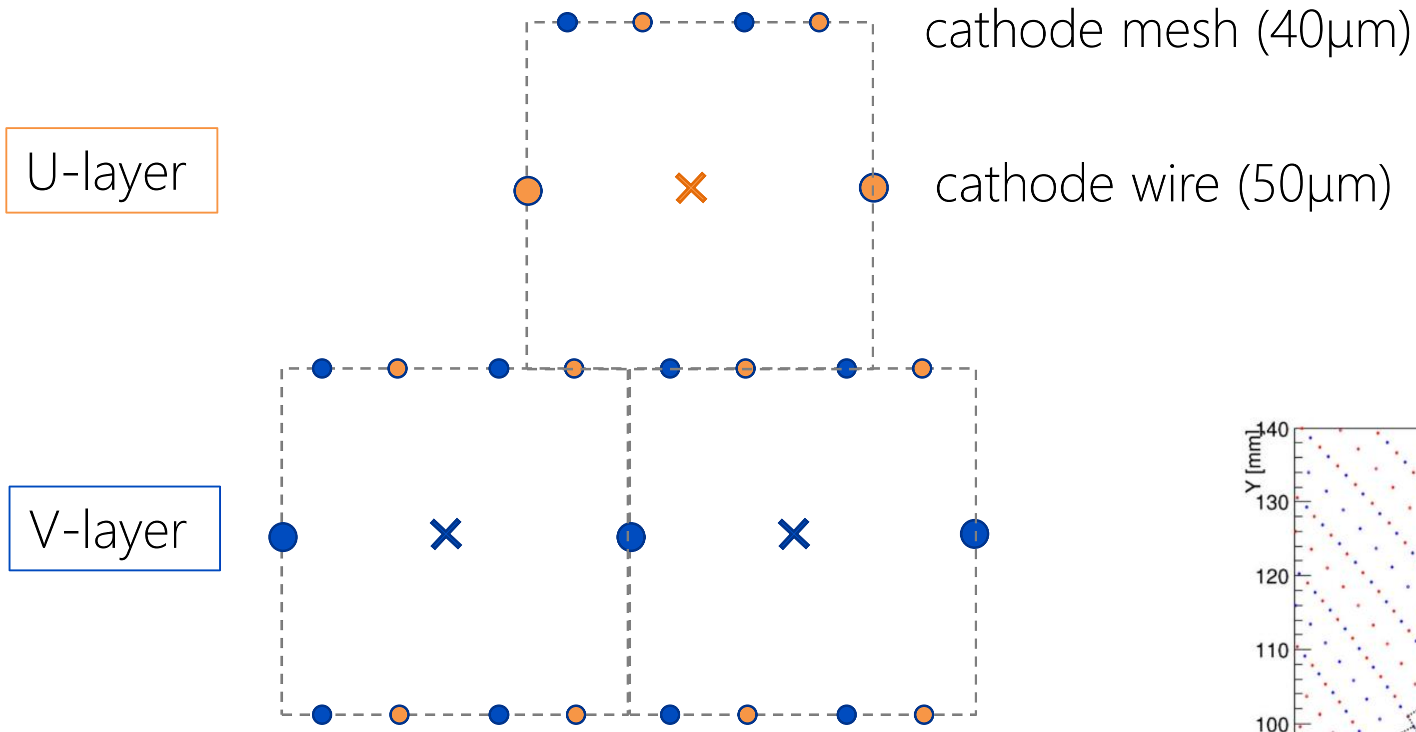
- **Bare Al wire** could be a better alternative, but difficulty in soldering.
  (Naturally coated by Al_2O_3)

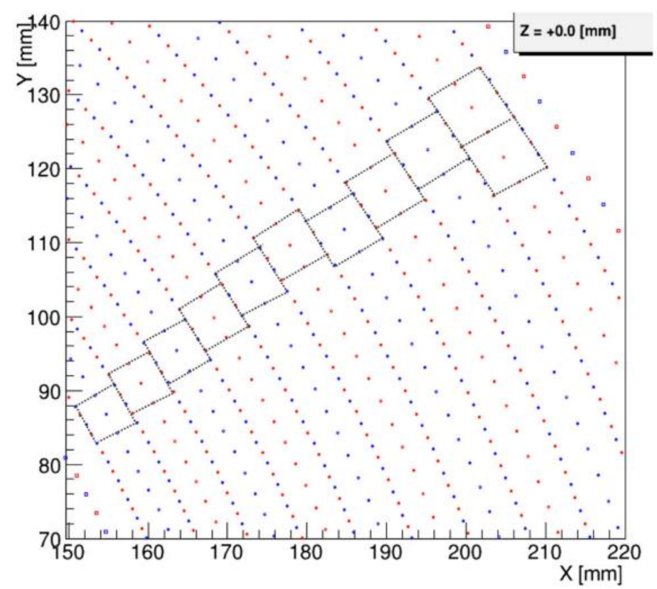
Possibilities

- Al/Au 40 and 50µm
  - ***requirement:*** *only if* ***insensitive*** *to* ***humidity***
- Al or Ti 50µm
  - ***requirement:*** *effective* ***soldering*** *or* ***gluing*** *procedure*
- Ti/Au 50µm
  - ***not*** *yet* ***found*** *a good* ***producer***
    - **DISCARDED**
- Cu 40 and 50µm
  - *pros:* ***standard*** *use in other* ***chambers***
  - *cons:* ***large impact*** *on experiment* ***sensitivity***
    - **DISCARDED**



Drift cell configuration





Ultra-high scale

GUT

Force unification
Matter unification
Charge quantization

Seesaw

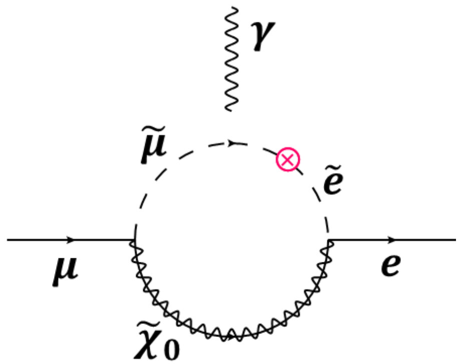
Neutrino mass
Leptogenesis

Flavor violation from quark Yukawa

Flavor violation from neutrino Yukawa

SUSY

TeV scale



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

LFV

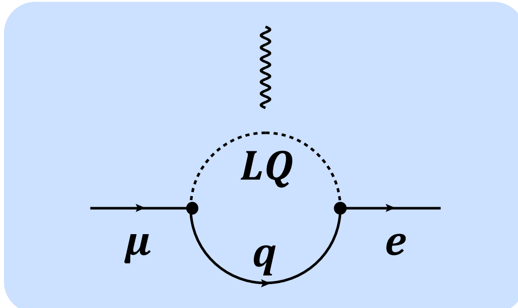
Lepton flavor violation

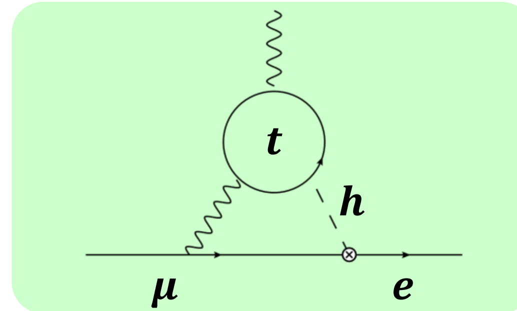
$B(\mu \to e\gamma) \sim 10^{-11} - 10^{-14}$

Low scale

top-down

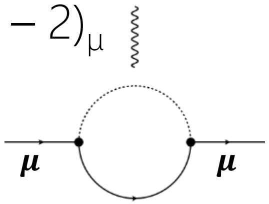
Other reasons



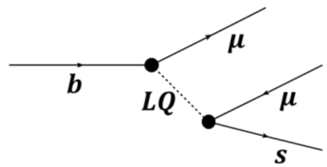


two-loop

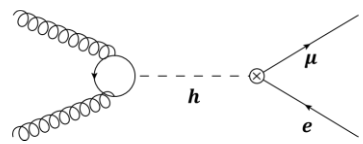
(g – 2)$_\mu$



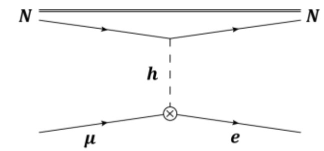
LHCb



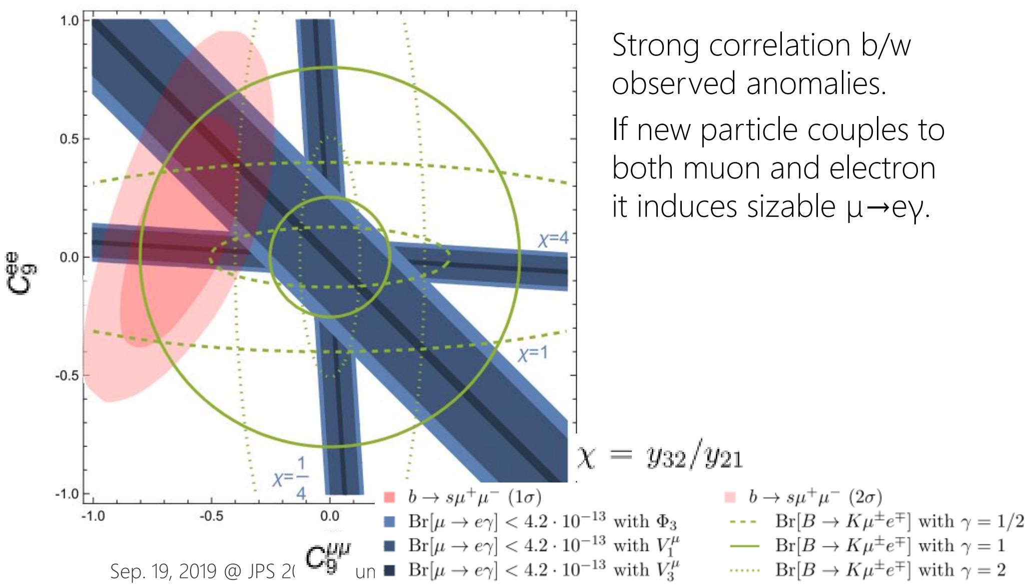
CMS



mu2e/COMET



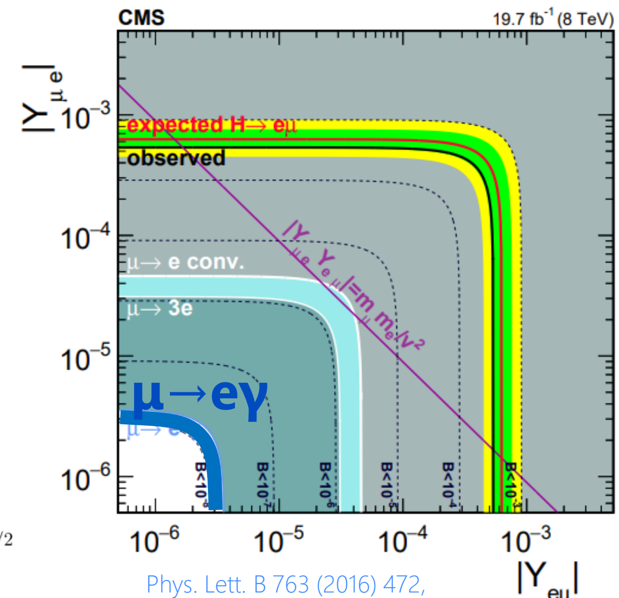
tree



Strong correlation b/w observed anomalies.

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

Phys. Rev. D 97 (2018) 015019



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) $\lesssim 10^{-8}$

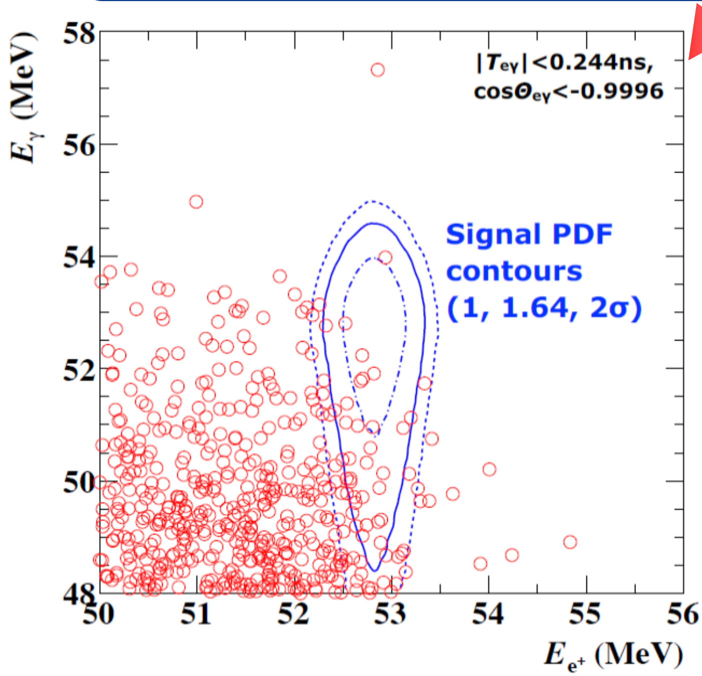
(CMS limit:

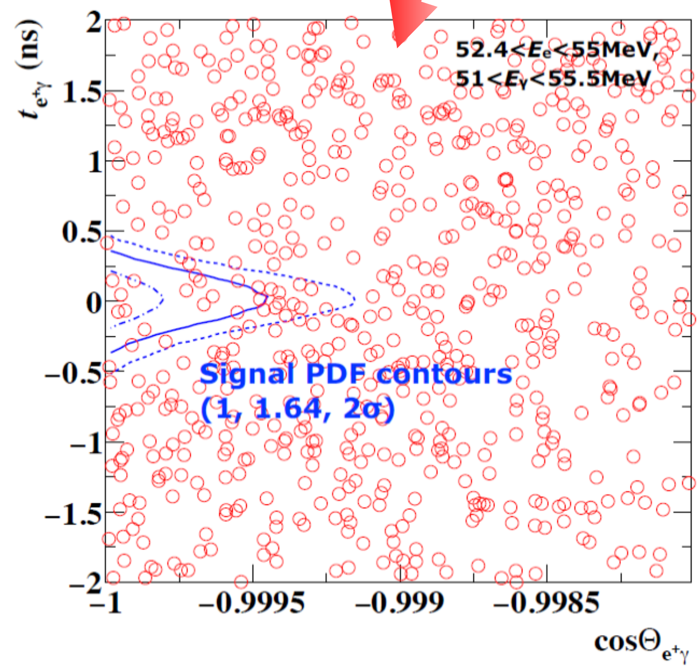
BR(h→μe) < 3.5×10^{-4})

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:

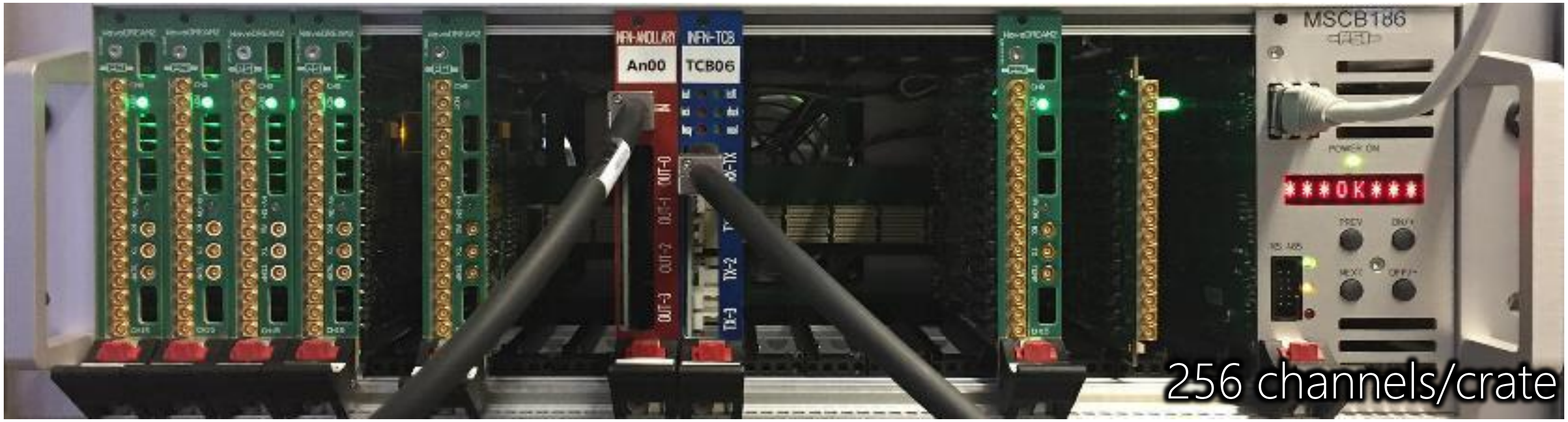
$$\mathbf{B(\mu^+ \to e^+\gamma) < 4.2 \times 10^{-13}} \text{ (90\% C.L.)}$$

(while 5.3×10^{-13} expected)

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

×30
improvement from the prev. experiment

Readout electronics



- 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)