New experimental concepts for μ→eγ search

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on behalf of the authors of:

«The quest for μ→eγ and its experimental limiting factors at future high intensity muon beams» Eur. Phys. J. C (2018) 78: 37

« A new experiment for the μ→eγ search» LOI RF5_RF0 067

μ→eγ event kinematic

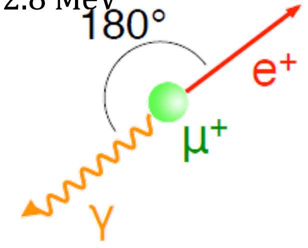
Low momentum (28 MeV/c) muons are stopped on a thin target

Signal

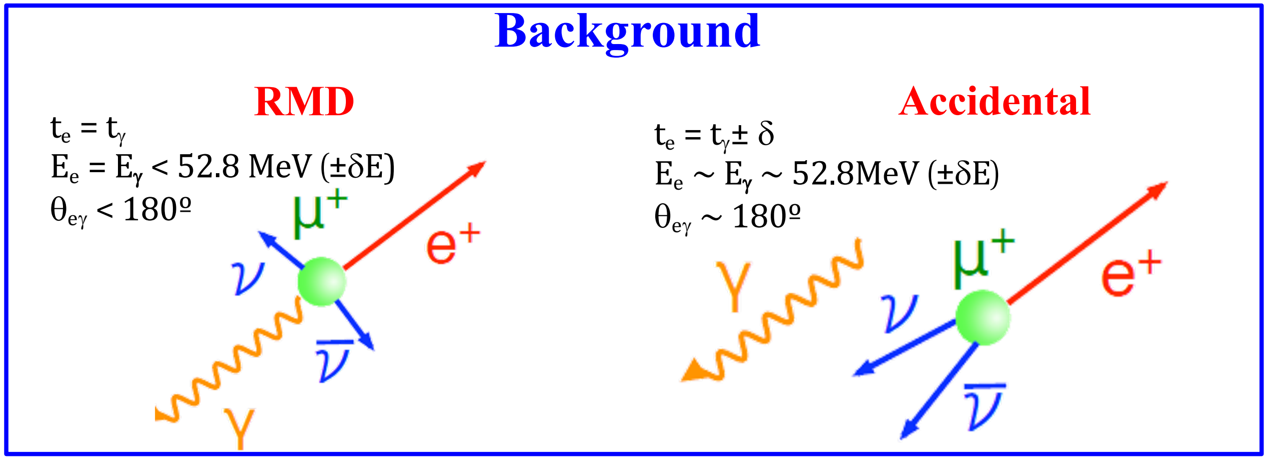
$t_e = t_\gamma$

$E_e = E_\gamma = 52.8$ MeV

$\theta_{e\gamma} = 180º$



Background



RMD

$t_e = t_\gamma$

$E_e = E_\gamma < 52.8$ MeV ($\pm\delta E$)

$\theta_{e\gamma} < 180º$

Accidental

$t_e = t_\gamma \pm \delta$

$E_e \sim E_\gamma \sim 52.8$MeV ($\pm\delta E$)

$\theta_{e\gamma} \sim 180º$

- radiative decay $\mu\to e\nu\nu\gamma$: two neutrinos have low energy and γ and *e* emitted back-to-back with high energy
- "accidental": *e* and γ from different sources but with compatible kinematics to the $\mu\to e\gamma$ (e.g. e^+ from Michel decay, γ from RMD, e^+e^- annihilation…)

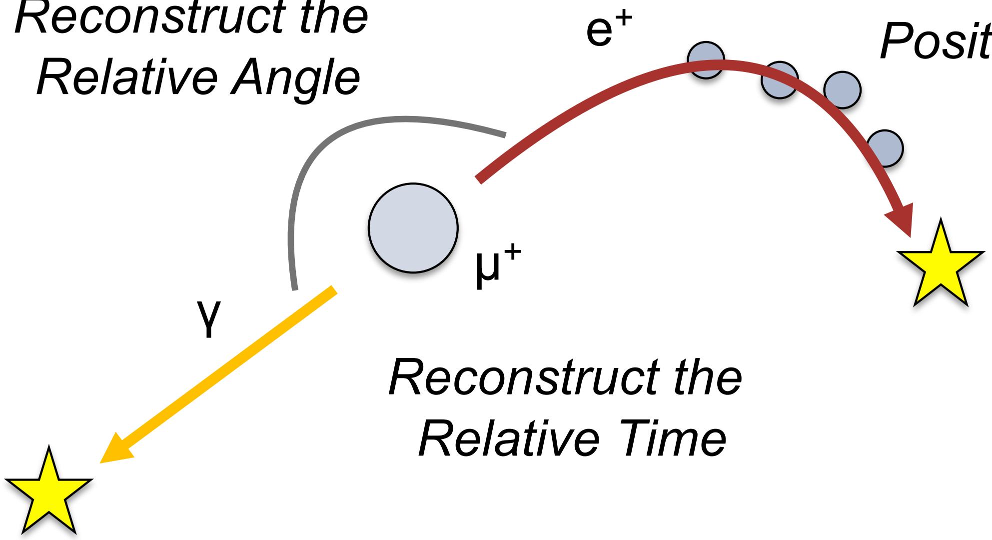
Accidental background is **dominant** and determined by **beam rate** and **resolutions**:

$$N_{sig} = \Gamma_\mu \cdot T \cdot \Omega \cdot BR \cdot \varepsilon_\gamma \cdot \varepsilon_{e^+} \cdot \varepsilon_s$$

$$N_{acc} \propto \Gamma_\mu^2 \cdot \Delta E_\gamma^2 \cdot \Delta p_{e^+} \cdot \Delta\Theta_{e^+\gamma}^2 \cdot \Delta t_{e^+\gamma} \cdot T$$

$$N_{RMB} \sim 0.1 \cdot N_{acc}$$

Ingredients for a search of μ→eγ



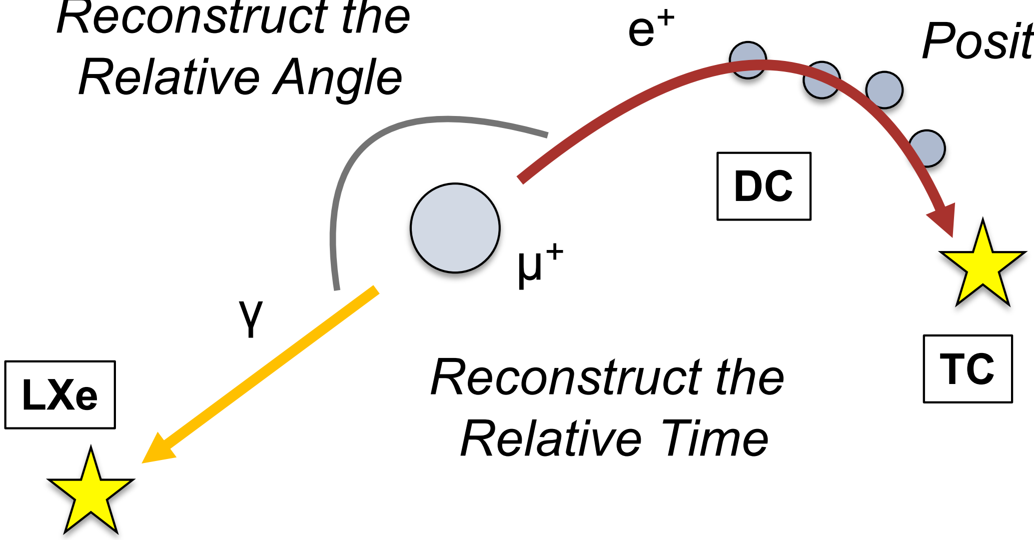
Reconstruct the Relative Angle

Reconstruct the Positron Energy

Reconstruct the Relative Time

Reconstruct the Photon Energy

Ingredients for a search of μ→eγ



Reconstruct the Relative Angle

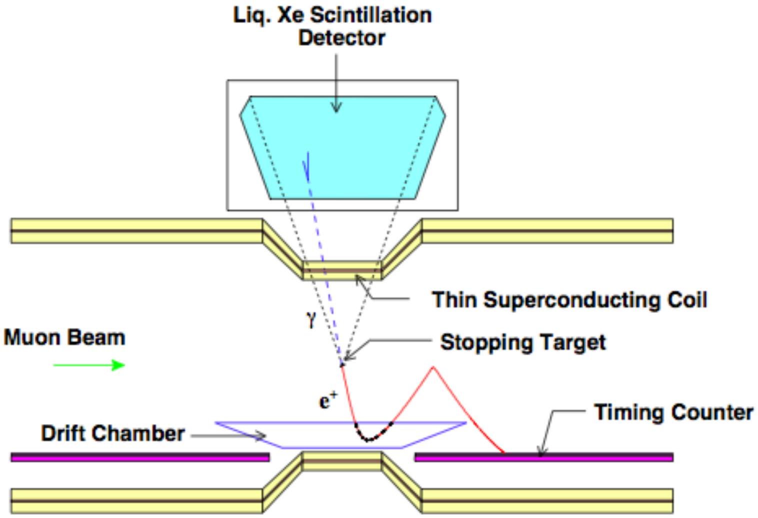
Reconstruct the Positron Energy

Reconstruct the Relative Time

Reconstruct the Photon Energy

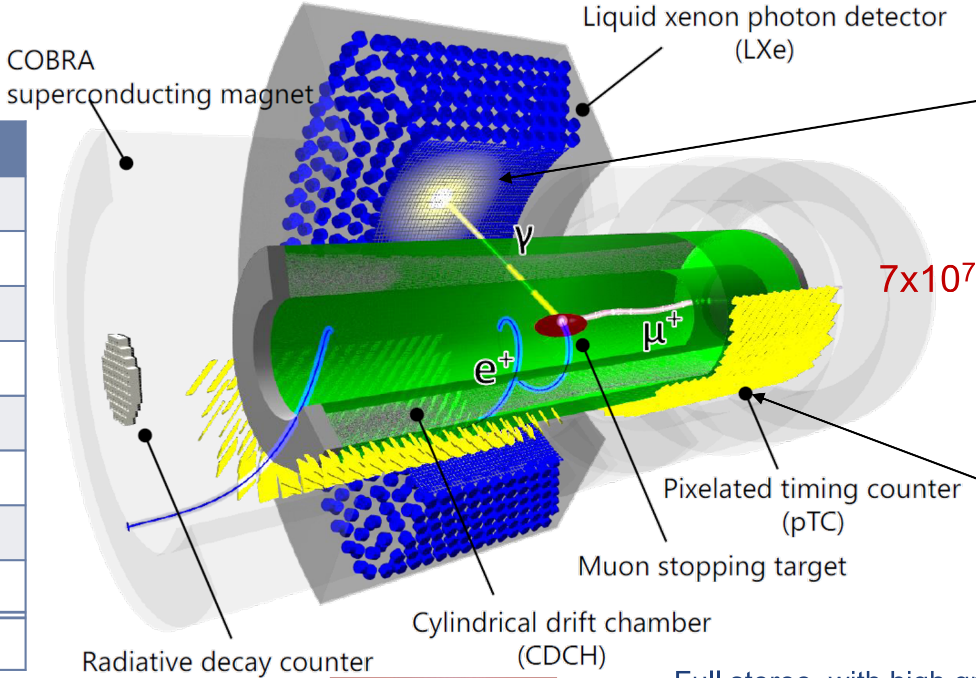
7.5 x 10^{14} μ on target

BR(μ -> e γ) < 4.2 x 10^{-13} @ 90% C.L.

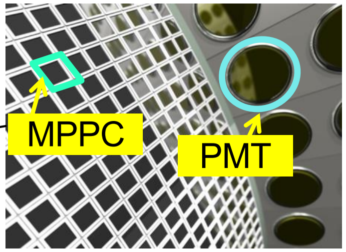


The state of the art: MEG II Experiment

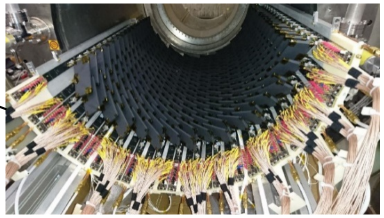
	expected
Δp_{e+} (keV)	130
$\Delta\theta_{e+}$ / $\Delta\varphi_{e+}$ (mrad)	5.3 / 3.7
$\Delta Z_{e+}/\Delta Y_{e+}$ (mm) *core*	1.6 / 0.7
ΔE_γ (MeV)	~1.1/1.0
Δu_γ, Δv_γ, Δw_γ (mm)	2.6 / 2.2 / 5
$\Delta t_{e+\,\gamma}$ (ps)	84
Ω (%)	11
ε_γ	69
ε_{e+} (trac.×matc.)	70



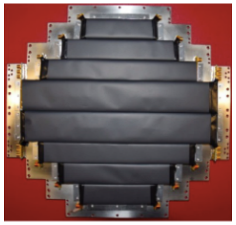
$7\text{x}10^7$ μ/s



Better uniformity w/ VUV-sensitive $12\text{x}12\text{mm}^2$ SiPM



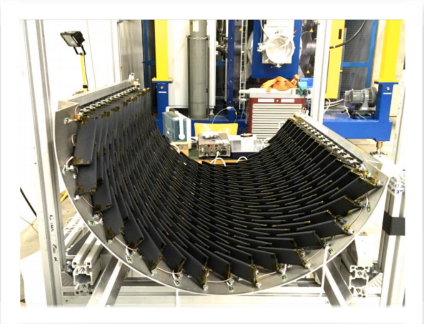
LYSO crystals + plastic scintillators (Further reduction of radiative BG)

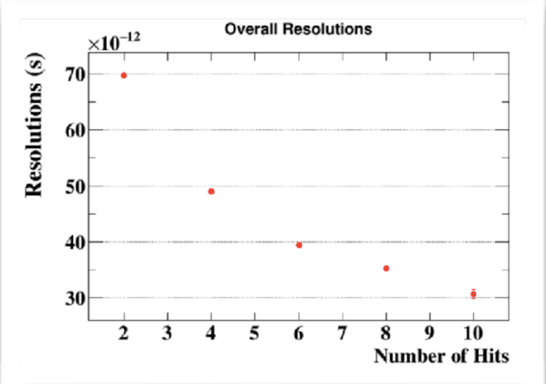


Full stereo, with high granularity and high transparency ($\sim1.6\cdot10^{-3}$ X_0) Drift Chamber (improve tracking performance and minimizing the background sources)

A new experiment for the μ→eγ search

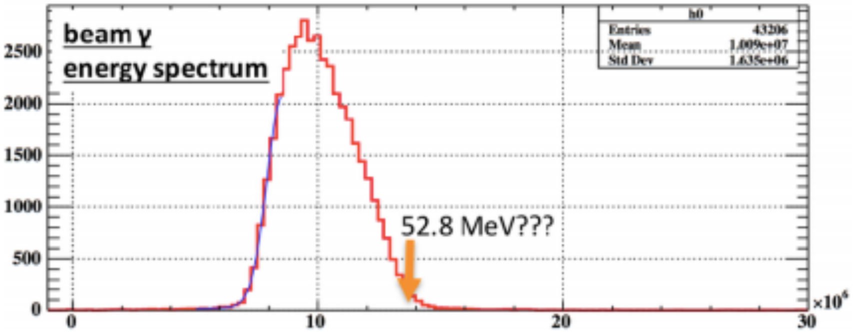
MEG II status

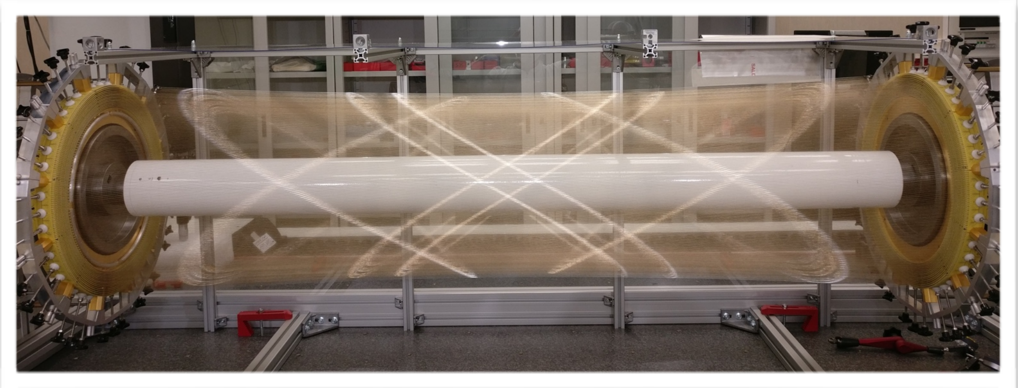




TC built and commissioned
in 2016-2017
$\sigma_T \sim 35$ ps

First photons in the upgraded
XEC in 2017
$\sigma_E \sim 1\%$ @ 52.8 MeV





New DC under
commissioning

Expected to be fully
operational in 2021

$\sigma_E \sim 130$ keV

A new experiment for the μ→eγ search

MEG II sta

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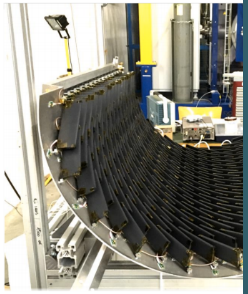
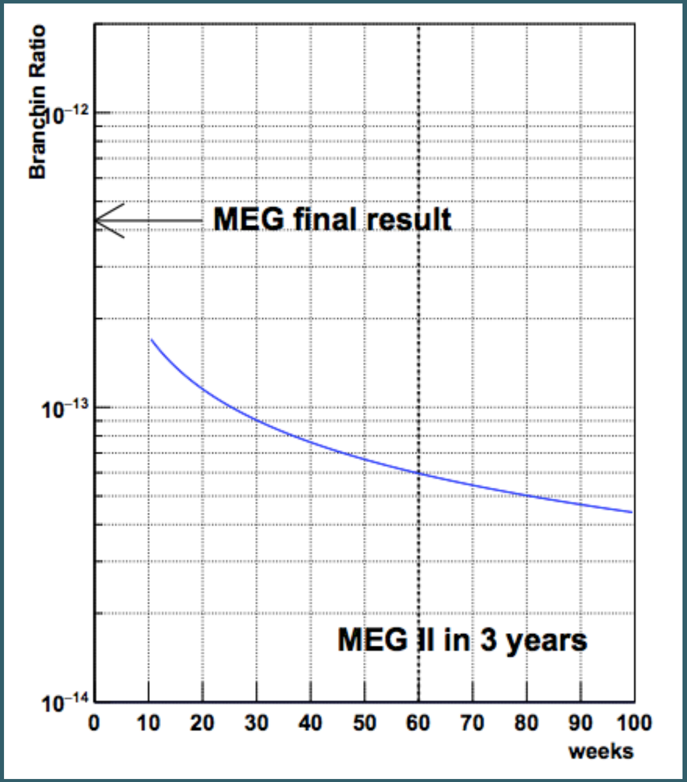


TC

First physics run in 2021

Expected UL $\sim 6 \times 10^{-14}$ in a 3-year run



What next?

Ingredients for a search of μ→eγ

Beam:

- **positive** (*to avoid capture by nuclei in the stopping target*) muon
- continuous (*to reduce max rate capability*)
- ~ 10^8 μ/s available at PSI now
- PSI is considering a beamline with > ~ 10^9 μ/s
- prospects for very high intensity DC muon beams at PIP-II (Fermilab) are under study

Ingredients for a search of μ→eγ

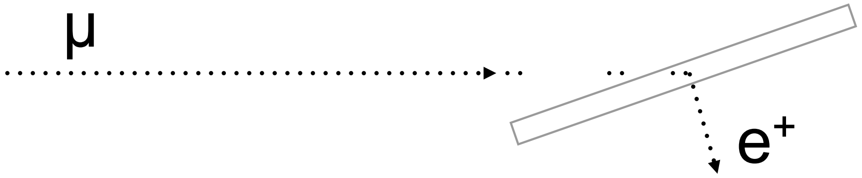
Requirements for positron reconstruction:

- Magnetic spectrometer to get the best resolutions;
- 52.8 MeV/c → large Multiple Scattering → very low material budget
- The target itself contribute significantly to the angular resolution
  (target as thin as possible → *low momentum beam, as monochromatic as possible*)
- MS makes useless an extreme position resolution (e.g. silicon detectors) and plays in favor of light gaseous detectors, but would a gaseous detector be able to cope with the very high occupancy at > 10^9 μ/s?
  Solutions for a gaseous detector with high rate capabilities are also under study (new geometries, optical readout,…)

Ingredients for a search of μ→eγ

- The target plays a crucial role in determining the positron angular resolution, due to the Multiple Coulomb Scattering (***target must be as thin as possible***)

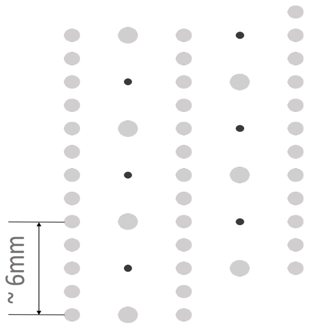
- In order to stop a relevant fraction of muons, it must be at the Bragg peak (***muons not stopped by the target are stopped in the gas right after, giving background without contributing to the signal***)
  → enough thickness to stop ~ all muons



Optimal target
Be, 90 μm
θMS(e+) ~ 2.5 - 3 mrad

- The expected MEG II positron momentum resolution should be adequate, but the rate capability of its innermost layers needs to be improved at level ~MHz/cm^2 for Γ_μ up to 10^{10} μ/s. Fluxes ≳200 kHz/cm^2 could be sustained by a drift chamber, similar to the MEG II one, but with shorter cells arranged orthogonally to the beam;

- A light Si based or MPGD detector could be used in the hottest part close to the target but the MS effects has to be evaluated carefully.



Ingredients for a search of μ→eγ

Requirements for photon reconstruction:

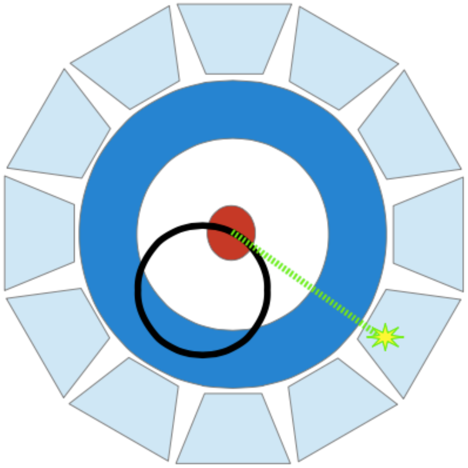
- N_{acc} depends on the $\Delta E_{\gamma}^{2} \cdot \Delta \Theta_{e^{+}\gamma}^{2}$ → improvements on the photon detection have more relevant effects on the sensitivity limitations
- the Energy resolution has to be <1MeV
- the angle of photon vertex resolution has to be improved
  - the measurement of the photon direction should reduce the accidental coincidences!
- timing also plays a crucial role in μ → e γ searches (accidental coincidences!!!) → need a very good photon timing too
- try to increase the acceptance

Ingredients for a search of μ→eγ

Calorimetry

LiBr3(Ce) based

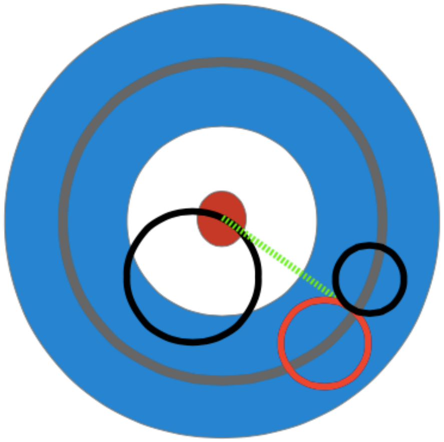
High efficiency
Good resolutions
Low acceptance
(MEG: LXe calorimeter 10% acceptance)



Photon Conversion

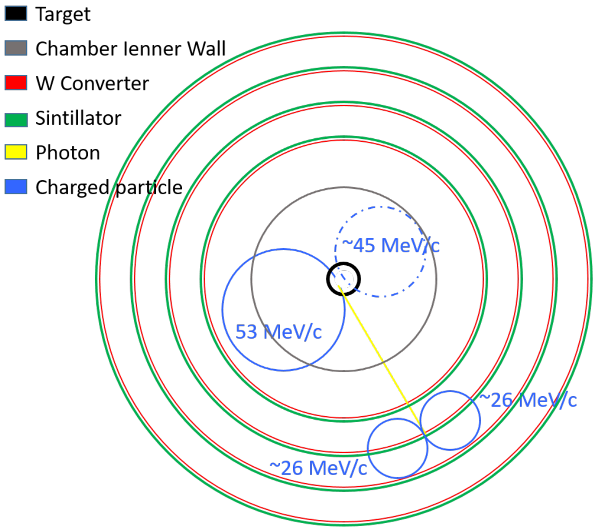
Option A

Low efficiency
Extreme resolution
Middle acceptance



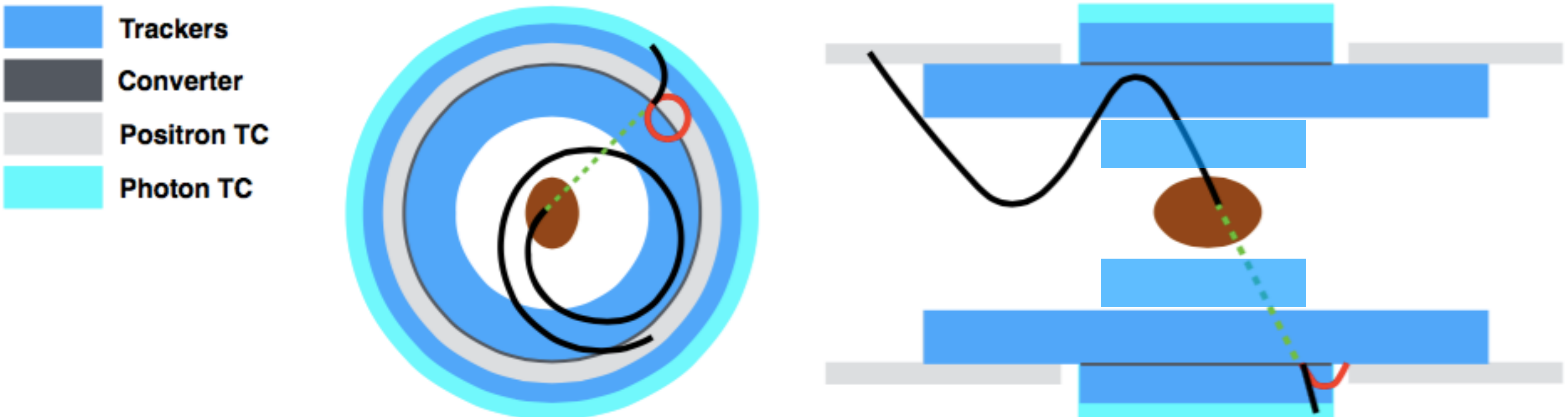
Option B

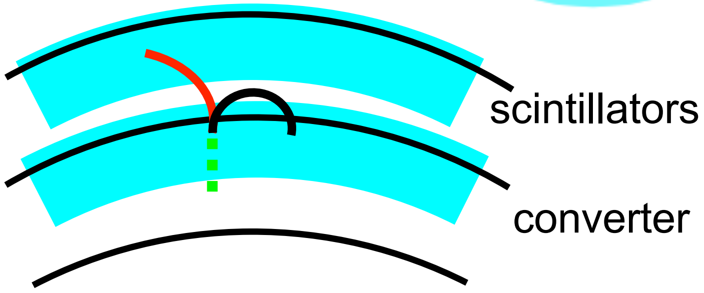
reasonable efficiency
Good/extreme resolution
Large acceptance



Photon Conversion

For photon conversion, need to detect e+ or e- in a fast detector





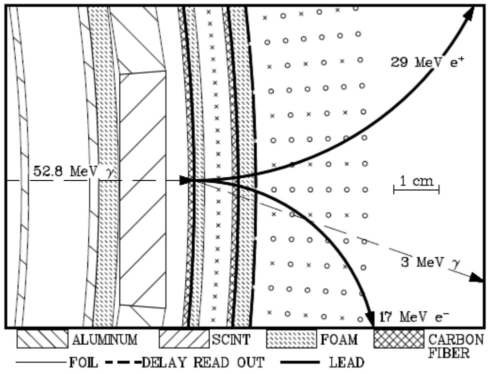
Effective converter material with lower Z

Worse compromise of efficiency vs. resolution

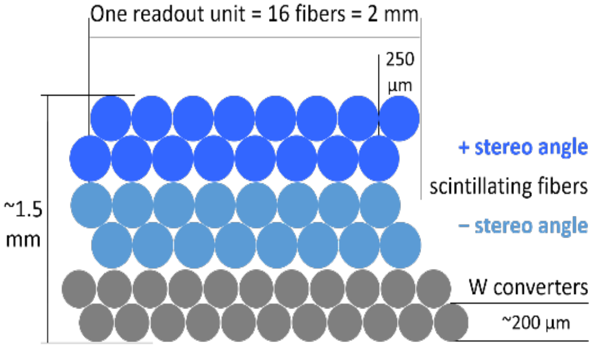
How to improve the photon detection and resolutions

An alternative way to identify and measure the 52.8 MeV photon with improved energy and angular resolutions relies on a precise reconstruction of the electron and positron tracks from its conversion.

- This approach was used by the MEGA experiment using a lead foil of 0.045 X_0 equivalent thickness preceded by a scintillator layer for timing and followed by 4 layers of drift cells to measure the emerging charged tracks. (ΔE_γ ~1.7 MeV, $\Delta\theta_\gamma$ ~ 180 mrad, $\Delta t_{e+\gamma}$ ~ 1.6 ns);



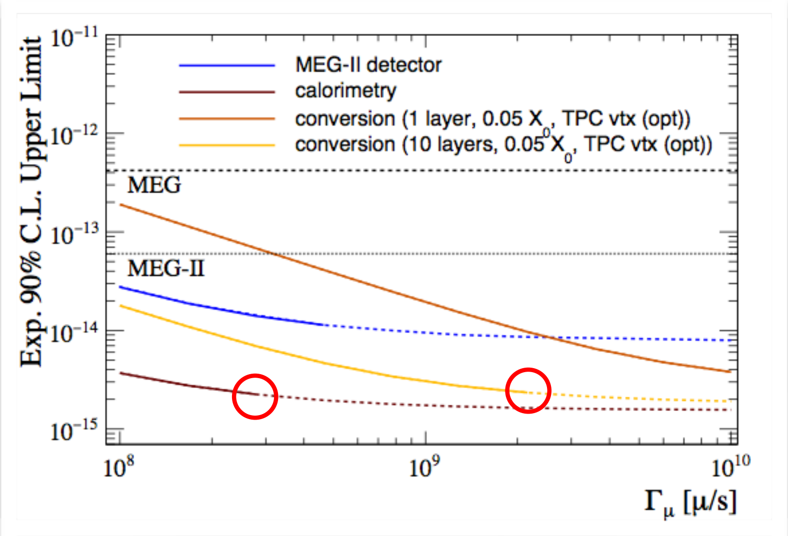
- by using tungsten (W) wires to create a thin, ~0.1 X/X_0, conversion layer followed by a layer of scintillating fibres, it should be possible to reach (ΔE_γ ~0.3 keV, $\Delta\theta_\gamma$ ~ 8 mrad, $\Delta t_{e+\gamma}$ ~ 50 ps);
- a possible construction strategy could be to insert the radiator shells in the drift chamber volume, without creating dead regions, by placing bundles of W wires at the same stereo angle as the drift chamber layers.

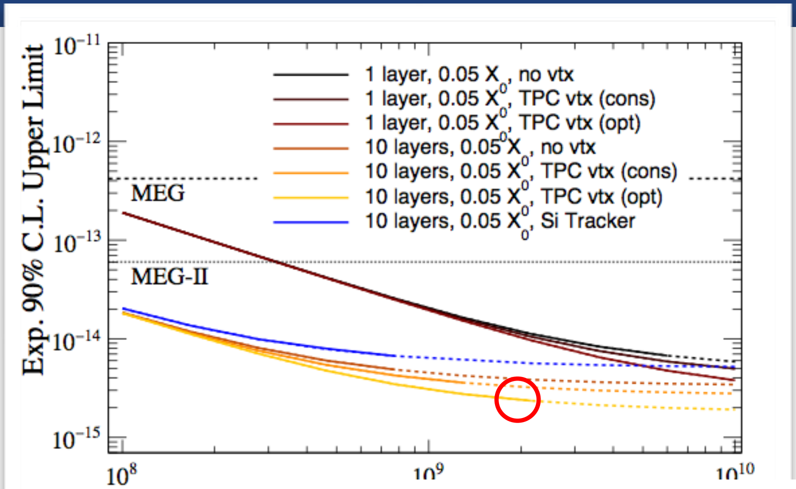


A possible new experiment

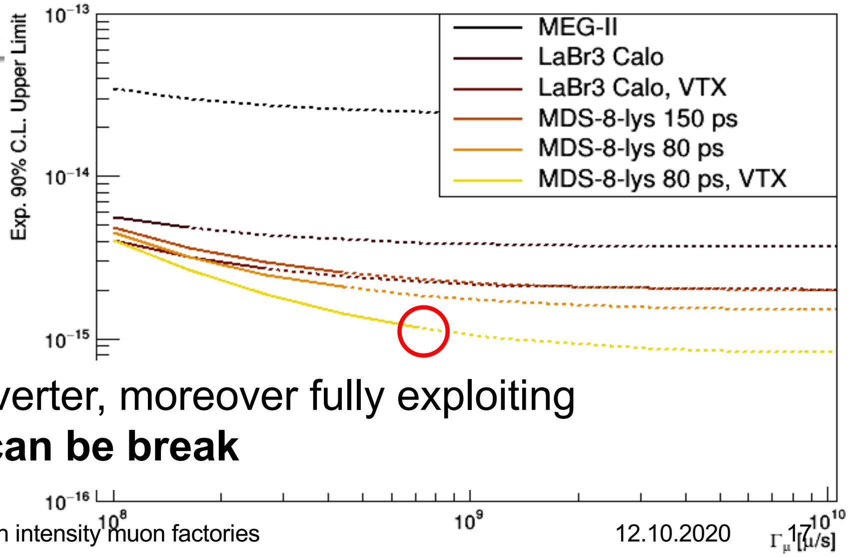
- A central low mass tracker system (a drift chamber and, eventually, a vertex detector) surrounds the stopping target.
- The inner and outer radii of the tracker are chosen to cut off all the positron tracks with momenta <45 MeV/c, and fully contain those with momenta of 52.8 MeV/c.
- The tracker is surrounded by a sequence of co-axial cylindrical photon spectrometers (as described before).
- A sufficient number of alternating sign stereo layers (about 12-16) of 1cm square drift cells can be located between two radiator shells in order to efficiently and precisely reconstruct the looping electron-positron pairs.
- A geometrical acceptance of $\Omega \sim 90\%$ is feasible with a $\varepsilon_\gamma > 50\%$
- The accidental background could be relatively reduced due to:
  - measurements of the photon vertex and direction;
  - reduction of the photon overlap contribution

Expected Sensitivity (Toy MC)





A few (2-3) 10^{-15} seems to be within reach for a 3-year run at ~ 10^{8} μ/s with calorimetry (*expensive*) or ~ 10^{9} μ/s with Si based conversion (*cheaper*)

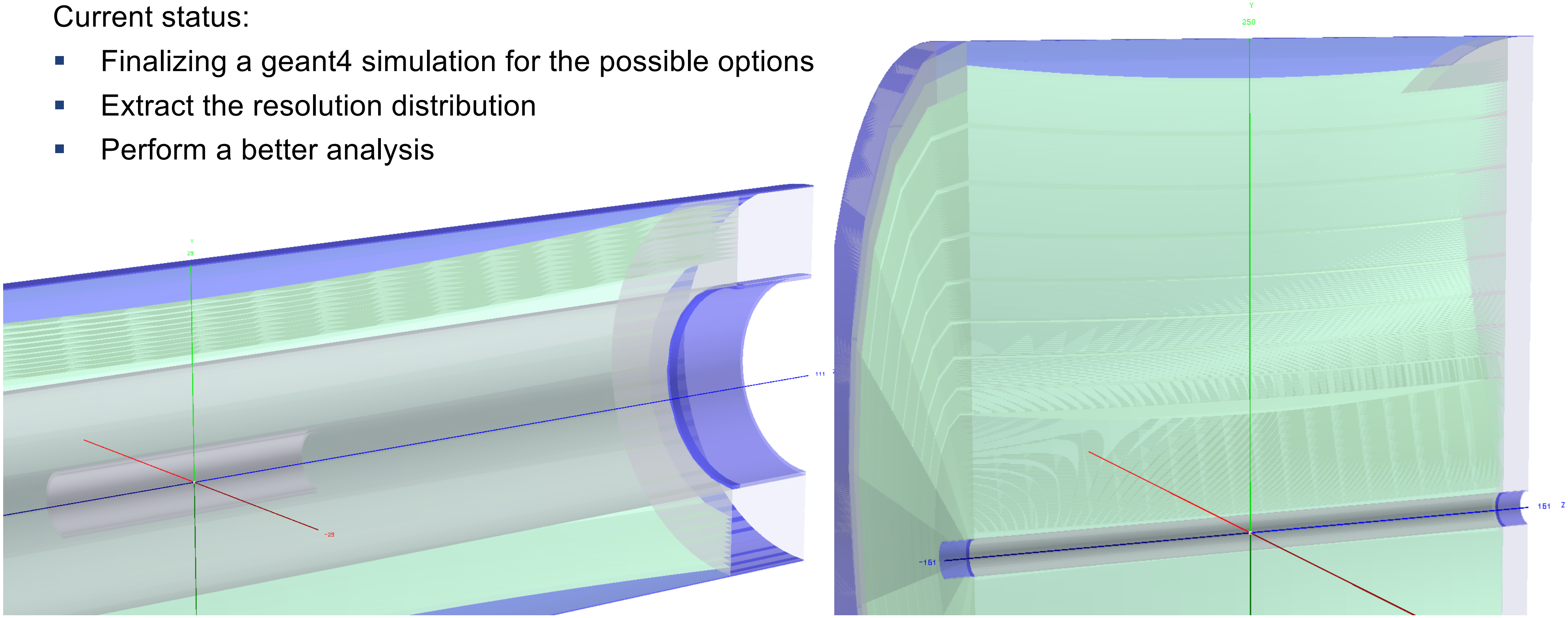


$1\cdot10^{-15}$ seems can be reach with the large area photon converter, moreover fully exploiting 10^{10} μ/s capability and photon pointing capability the **10^{-15} can be break**

Root to contributed paper

Current status:

- Finalizing a geant4 simulation for the possible options
- Extract the resolution distribution
- Perform a better analysis

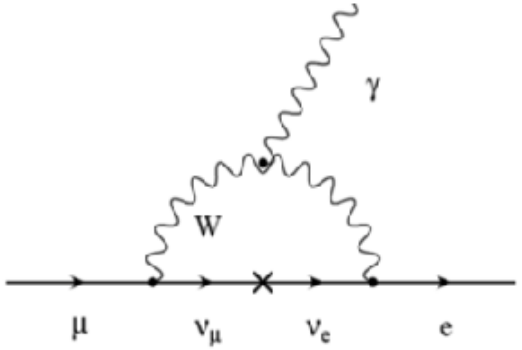


Summary

- Preliminary studies show that an experiment for the $\mu^+ \to e^+\gamma$ with a sensitivity of ~10^{-15} can be envisioned;
- The main construction peculiarities don't seem to be a showstopper;
- Significant work is needed and is ongoing to have the right tools to prove it;
- By exploiting the potential of the PIP II at Fermilab, as well as increasing the accidental background rejection and optimizing the photon reconstruction strategy, branching ratios down to O(10^{-16}) could be reach;
- Investigation on the possibility to perform the μ→eee search with the same experiment will performed too
- More collaborators are welcome to join it;
- We hope that the SnowMass process can speed up the studies for the mu e gamma search at 10^{-16} level and promote the R&D to develop the needed technologies.

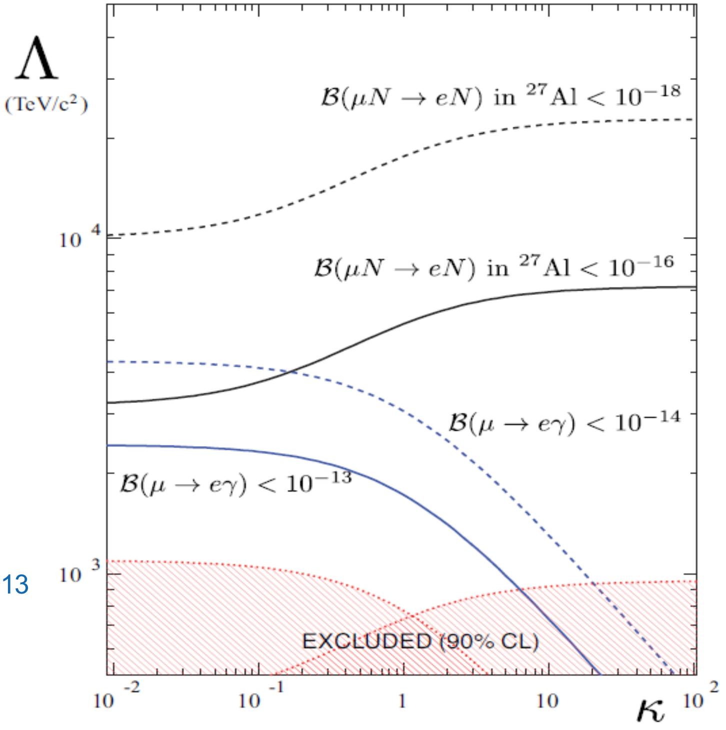
backup

Mu e gamma search



$$\mathcal{L}_{cLFV} = \frac{m_\mu}{(k+1)\Lambda^2}\mathcal{L}_{loop} + \frac{k}{(k+1)\Lambda^2}\mathcal{L}_{contact} + h.c.$$

Mass scale inaccessible to direct search



SM extension + ν oscillations

- **but not experimentally observable**: m_ν small → **BR<10^{-50}**

Beyond SM theories (SUSY-GUT) predict cLFV interactions rare but enhancement up to an observable level (BR($\mu^+ \to e^+\gamma$)≈$10^{-(14\text{-}15)}$)

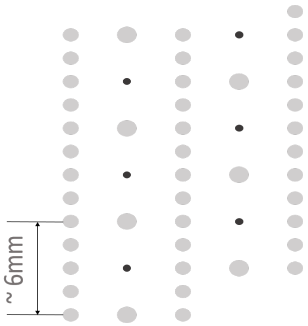
In this context the MEG experiment represents the state of the art in the search for the CLFV $\mu^+ \to e^+\gamma$ decay

Final results exploiting the full statistics collected during the 2009-2013 data taking period at Paul Scherrer Institute (PSI) BR($\mu^+ \to e^+\gamma$) < $4.2 \cdot 10^{-13}$ (90% C.L.) world best upper limit

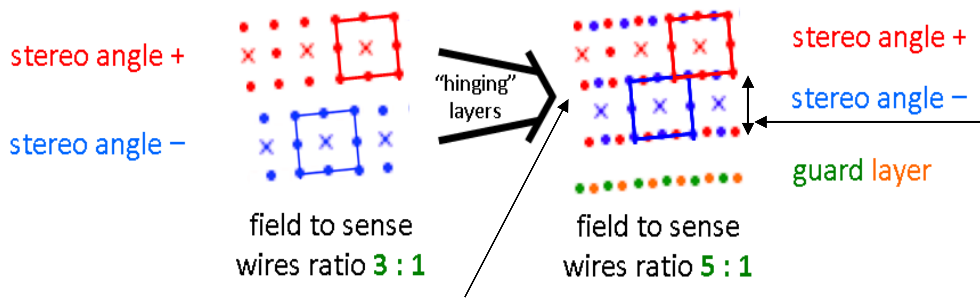
Strategy to improve the sensitivity by at least one order of magnitude

Theoretical speculations, driven by the formulas:

- The beam rate ($\boldsymbol{\Gamma}_{\mu}$) has to be increased but the detector resolutions limits the available max usable beam rate in order to keep a reasonable signal to background ratio;
- $\boldsymbol{N_{acc}}$ depends on the $\boldsymbol{\Delta E_{\gamma}^{2} \cdot \Delta\Theta_{e^{+}\gamma}^{2}}$ ⇨ improvements on the photon detection have more relevant effects on the sensitivity limitations
- The expected MEG II positron momentum resolution should be adequate, but the rate capability of its innermost layers needs to be improved at level ~MHz/cm^2 for $\boldsymbol{\Gamma}_{\mu}$ up to 10^{10} μ/s. Fluxes ≳200 kHz/cm^2 could be sustained by a drift chamber, similar to the MEG II one, but with shorter cells arranged orthogonally to the beam;
- A light Si based or MPGD detector could be used in the hottest part close to the target but the MS effects has to be evaluated carefully.



MEG II Drift chamber: design



The wire net created by the combination of + and – orientation generates a more uniform equipotential plane

Full stereo cylindrical DC with large stereo angles (102÷147 mrad)
Small square cells
(5.8÷7.8 mm at z=0, 6.7÷9.0 at z=±L/2)
(~ 12 wires/cm^2)

Active length L	1932	mm
N. of layers	9	
N. of stereo sectors	12	
N. of cells per layer	192	
N. of cells per sector	16	
Cell size (at z=0)	5.8 ÷ 7.8	mm
Twist angle	±60°	
Stereo angle	102 ÷ 147	mrad
Stereo drop	35.7 ÷ 51.4	mm

sense wires:	20 μm diameter W(Au)	=>	1728 wires
field wires:	40 μm diameter Al(Ag)	=>	7680 wires
f. and g. wires:	50 μm diameter Al(Ag)	=>	2496 wires

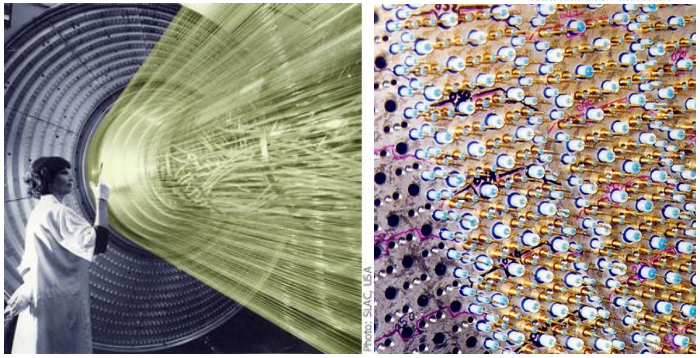
11904 wires in total

High wire densities, anyway, require complex and time consuming assembly procedures and need novel approaches to a feed-through-less wiring

MEG II Drift chamber: The novel approch

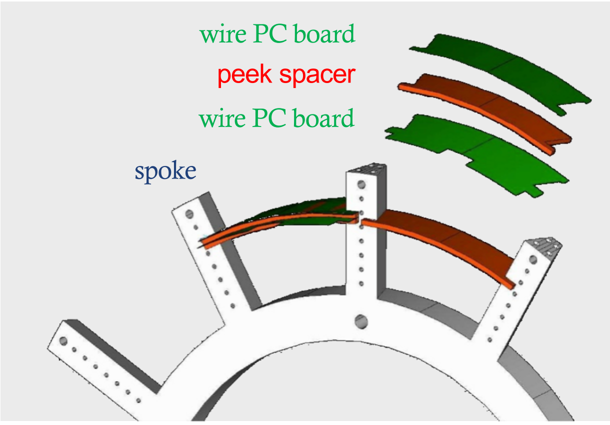
- Separate the end-plate function: mechanical support for the wires and gas sealer;
- Find a feed-trough-less wiring procedure.

(**~ 12 wires/cm^2**) can't be built with feedthrough



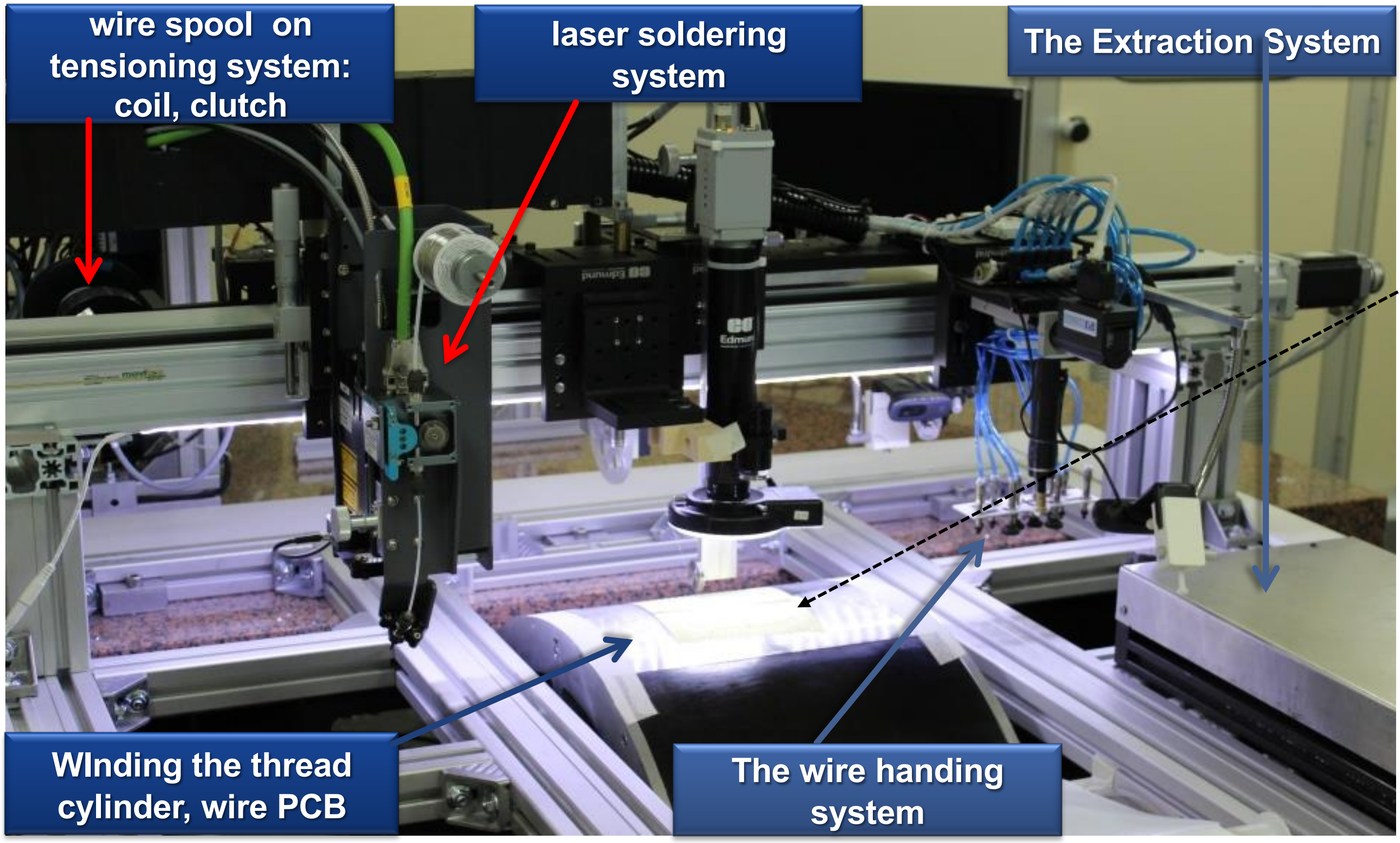
The solution found for MEG II:

- end-plates numerically machined from solid Aluminum (mechanical support only);
- Field, Sense and Guard wires placed azimuthally by Wiring Robot with better than one wire diameter accuracy;
- wire PC board layers (green) radially spaced by numerically machined peek spacers (red) (accuracy < 20 μm);
- wire tension defined by homogeneous winding and wire elongation (ΔL = 100μm corresponds to ≈ 0.5 g);
- Drift Chamber assembly done on a 3D digital measuring table;
- build up of layers continuously checked and corrected during assembly
- End-plate gas sealing will be done with glue.



see poster 91: NEW CONCEPTS FOR LIGHT MECHANICAL STRUCTURES OF CYLINDRICAL DRIFT CHAMBERS

MEG II Drift chamber: Wiring procedure



wire spool on tensioning system: coil, clutch

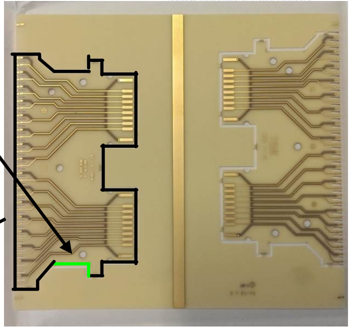
laser soldering system

The Extraction System

WInding the thread cylinder, wire PCB

The wire handing system

reference edge for alignment



The main tasks of the wiring robot are:

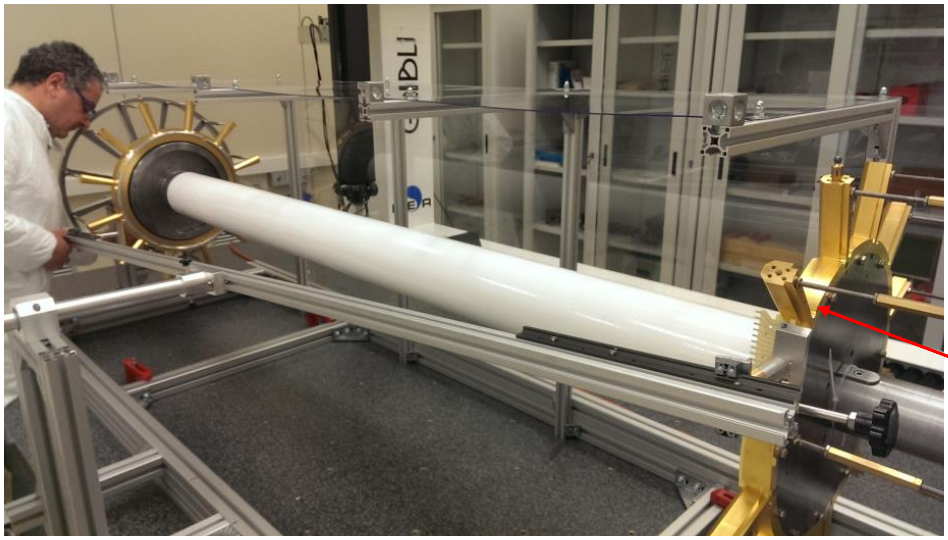
- the wiring of a multiwire layer made of 32 parallel wires;
- settable wire tension (±0.05g);
- 20μm of accuracy on wire position;
- anchor the wires using a contact-less technique

see poster 11: An automatic system for the construction of Drift Chambers for modern High Energy Physics experiments

MEG II Drift chamber: Assembling

Procedure:

- The mounting arm (with the multi-wire layer) is then placed next to the end plates for the engagement procedure
- The mounting arm is fixed to a support structure to prevent damaging the wires
- This structure transfers the multi-layer wire on the end plates between two spokes
- Spacers, to separate the successive layer, are pressed and glued in position



Spacer

Spoke used as reference for the alignment of the pcb