Low-mass trackers for muon decay experiments

yesterday, today and (maybe) tomorrow

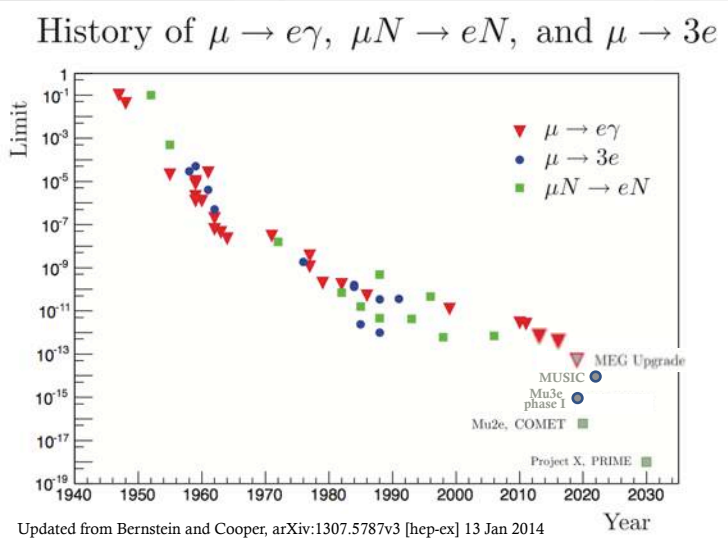
F. Grancagnolo – INFN Lecce

CPAD Instrumentation Frontier Meeting 2016:
NEW TECHNOLOGIES FOR DISCOVERY II
Caltech, 8-10 October 2016

Outline

- The updated world best limit on $\mathcal{B}(\mu^+ \rightarrow e^+ + \gamma)$
- The **MEG** drift chambers
- The **MEG2** experiment
- The new **MEG2** drift chamber
- The **Mu3e** experiment: HV-MAPS tracker
- An ambitious proposal at a very early embryonic state: **CIRCE** and its tracker

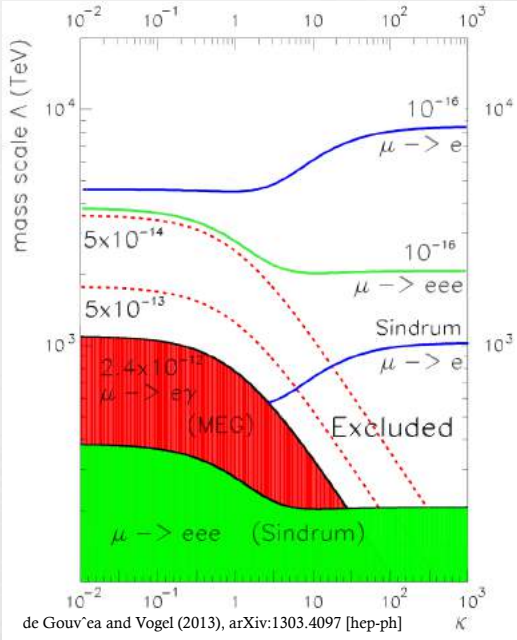
Charged Lepton Flavor Violation



$$\mu \to e\gamma$$

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

$$\mathcal{L}_{\rm CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \text{h.c.} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L \gamma_\mu e_L (\bar{e}\gamma^\mu e) + \text{h.c.}$$



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

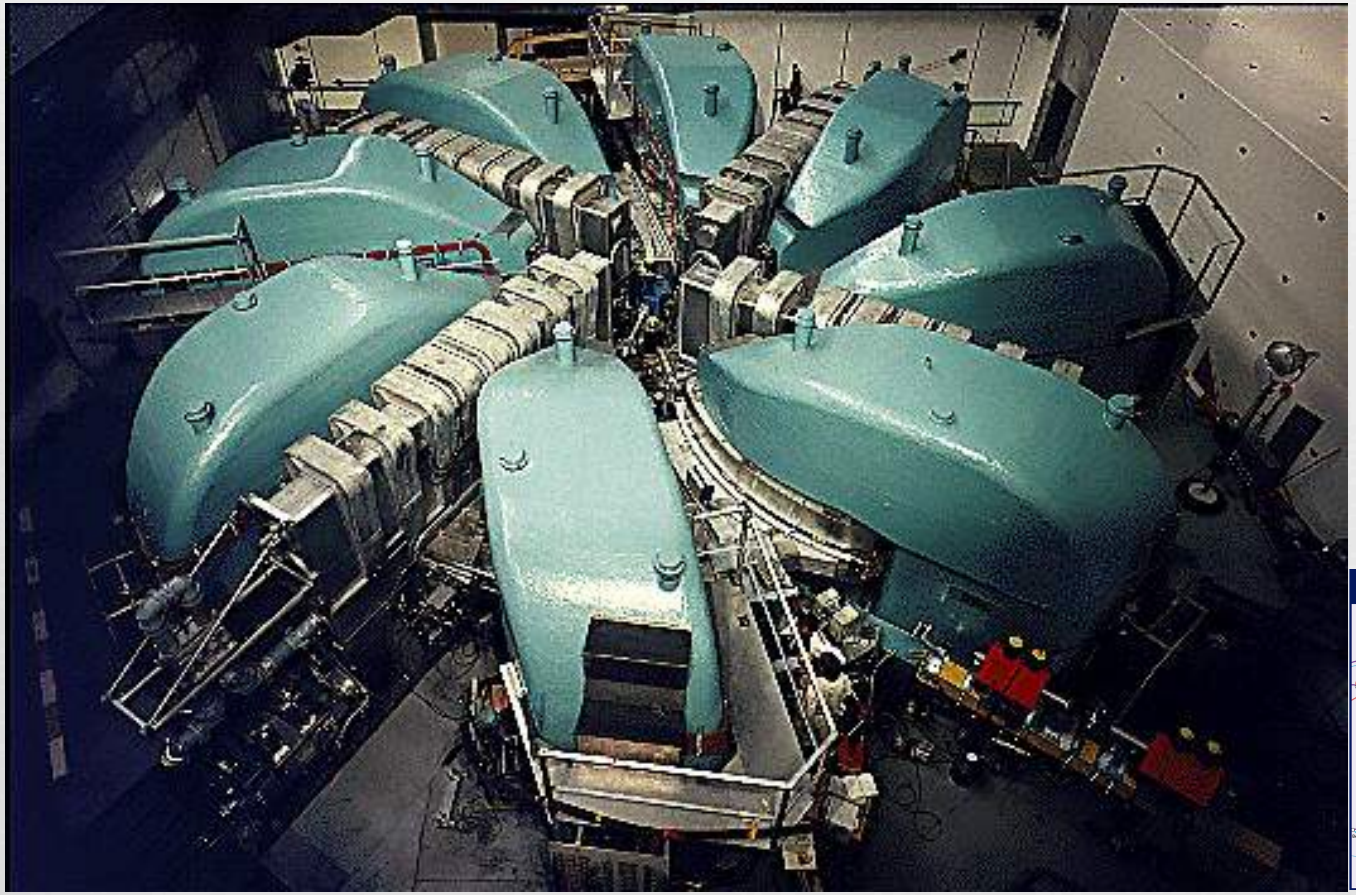
[Eur. Phys. J. C (2016) 76:434]

For a comprehensive and updated review on the subject, see:

1st Conference on Charged Lepton Flavor Violation - 6÷8 May 2013, Lecce (Italy) [Nucl. Phys. B Suppl., 248-249, April 2014]

2nd Conference on Charged Lepton Flavor Violation - 20÷22 June 2016 Charlottesville, Virginia (USA) [to be pub.]

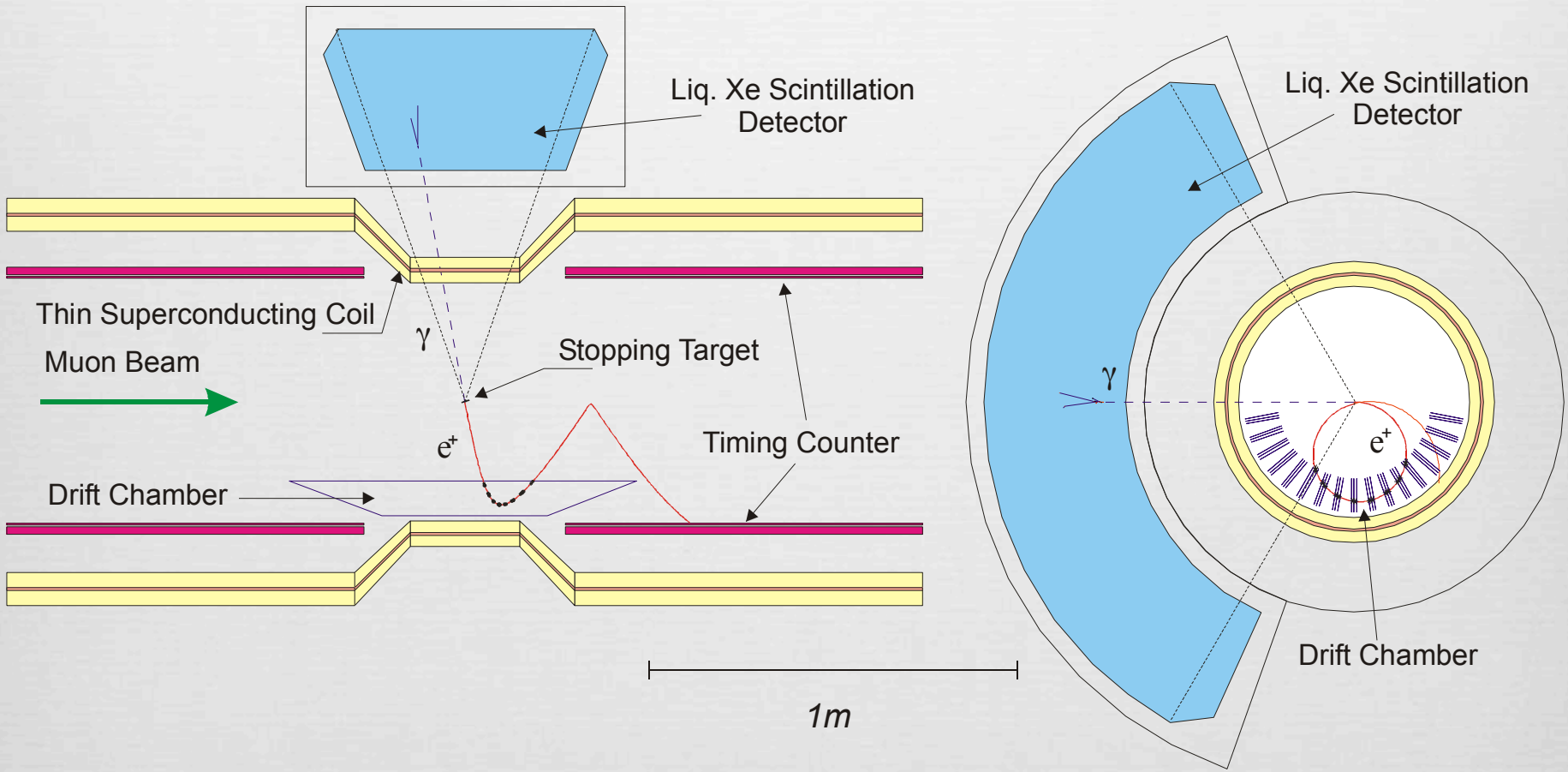
1.4 MW Proton Cyclotron at PSI



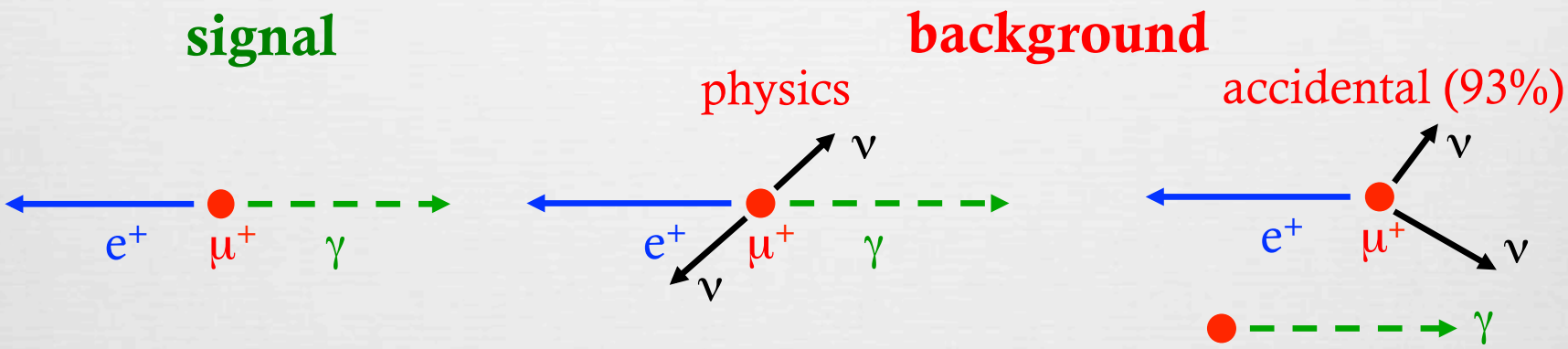
Unique facility for μ physics at PSI

provides world's most powerful DC muon beam > 10^8/s

The MEG experiment at PSI



The MEG experiment at PSI



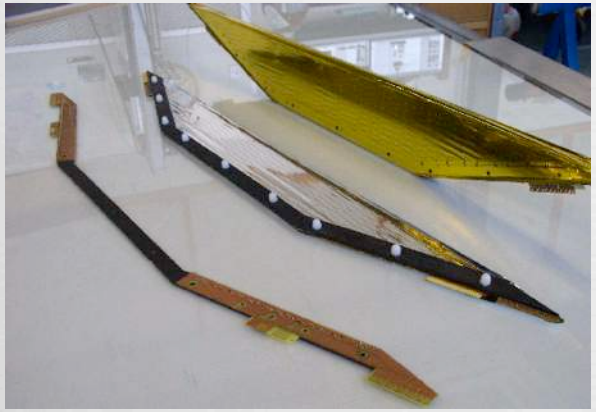
$$N_{\text{sig}} = R_\mu \times T \times \Omega \times \mathcal{B} \times \epsilon_\gamma \times \epsilon_e \times \epsilon_s$$

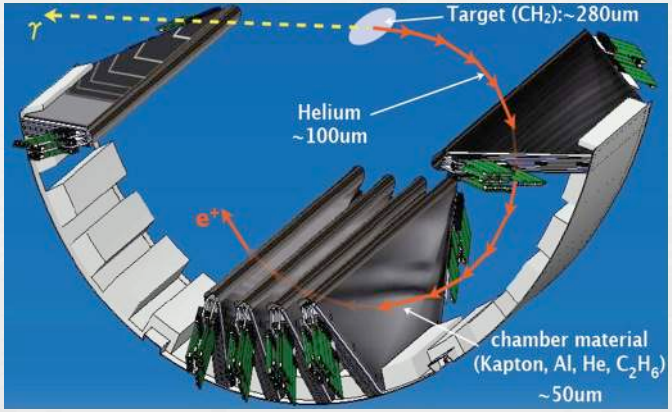
$$N_{\text{acc}} \propto R_\mu^2 \times \Delta E_\gamma{}^2 \times \Delta P_e \times \Delta\Theta_{e\gamma}^2 \times \Delta t_{e\gamma} \times T$$

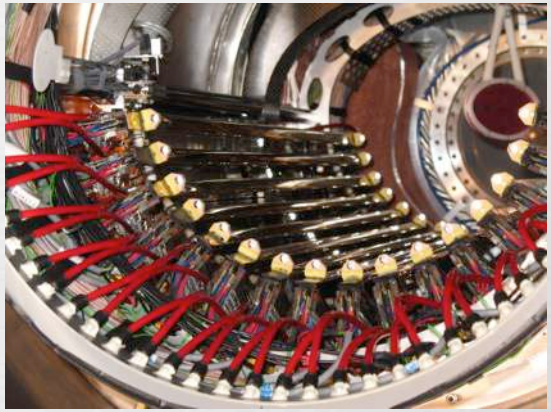
$$\mathcal{B}(\mu^+ \to e^+\gamma) < 4.2 \times 10^{-13} \text{ @ 90\% CL}$$

based on 7.5×10^{14} stopped muons on target (full data set: 2009-2013)

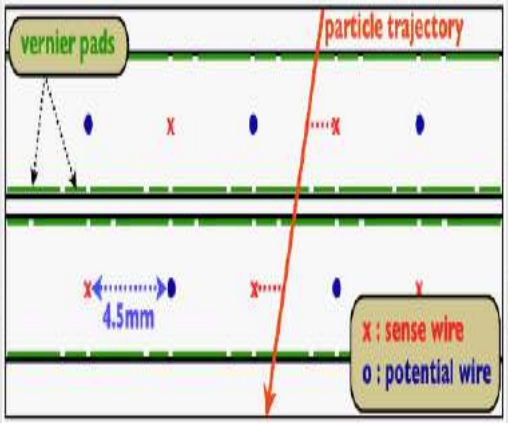
MEG Drift Chambers

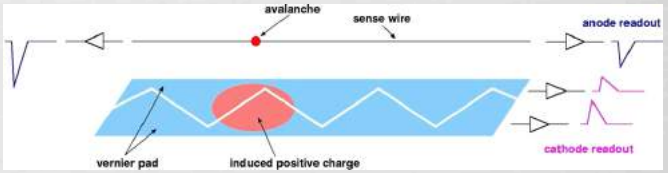




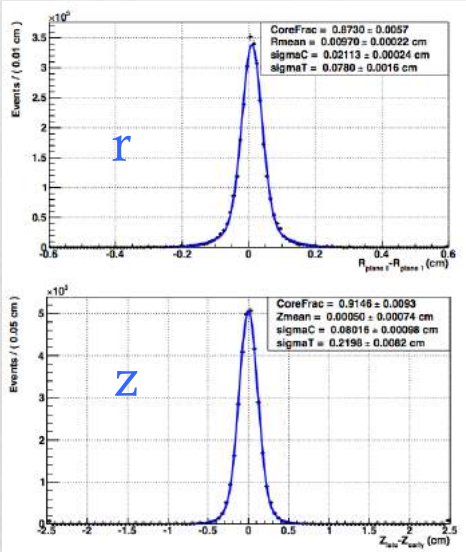


- 16 chambers
- Each chamber is composed of
  - 4 x12 μm of kapton (cathodes)
  - 50 μm BeCu cathode wires
  - 25 μm NiCr anode wires
  - 2 x 7 +3 mm He:C_2H_6 (50/50)
- Single chamber ~ 2.3 10^{-4} X_0
- Full e+ turn : ~ 1.7 10^{-3} X_0





MEG DC Performance

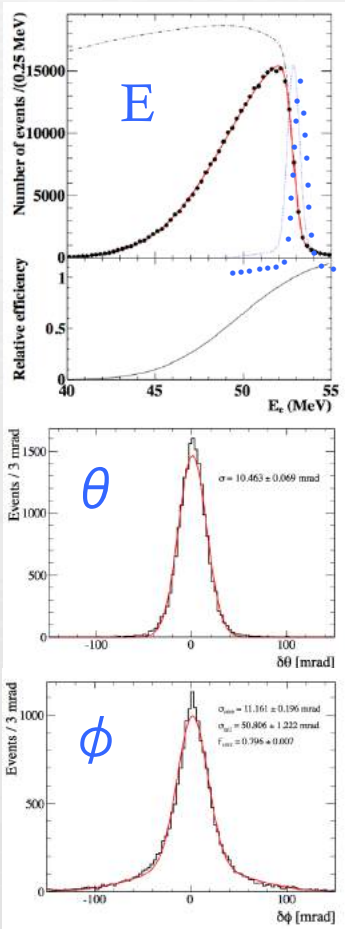


radial coordinate resolution

$\sigma_{r,core}$ = 210 μm
$\sigma_{r,tail}$ = 780 μm
frac. = 87%
$\sigma_{r,design}$ = 200 μm

longitudinal coordinate resolution

$\sigma_{z,core}$ = 800 μm
$\sigma_{z,tail}$ = 2100 μm
frac. = 91%
$\sigma_{z,design}$ = 300 μm



positron energy resolution

$\sigma_{E,core}$ = 330±16 keV
$\sigma_{E,tail}$ = 1.13±0.12 MeV
frac. = 82%
$\sigma_{r,design}$ = 180 keV

polar angular resolution

σ_{θ} = 9.4±0.5 mrad
$\sigma_{\theta,design}$ = 5.0 mrad

azimuth angular resolution

$\sigma_{\phi,core}$ = 8.4±1.4 mrad
$\sigma_{\phi,tail}$ = 38±6 mrad
frac. = 80%
$\sigma_{\phi,design}$ = 5.0 mrad

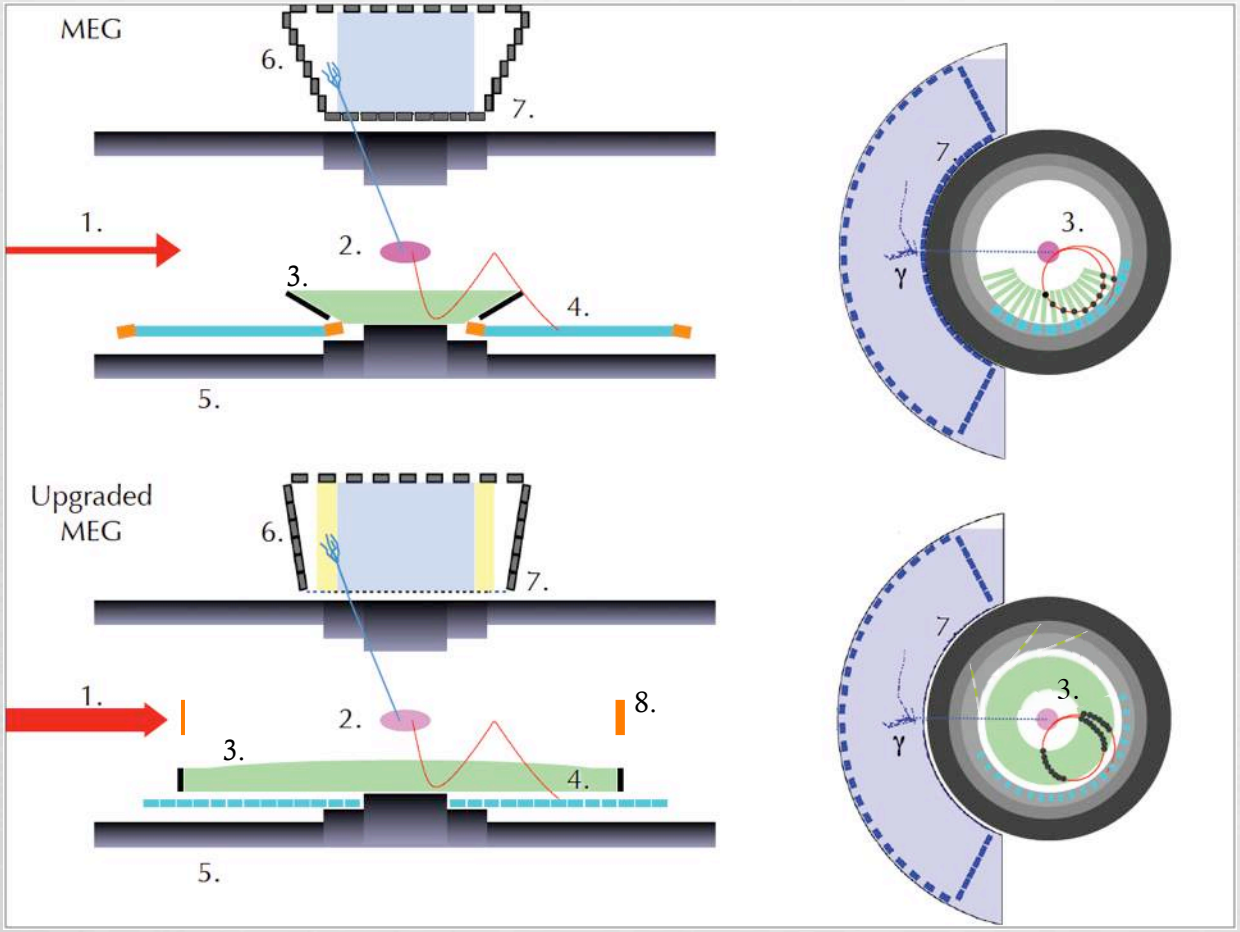
DC - TC matching efficiency

$\varepsilon_{DC\text{-}TC}$ = 41%
$\varepsilon_{DC\text{-}TC,design}$ = 90%

vertex resolution

$\sigma_{y,core}$ = 1.1±0.1 mm
$\sigma_{y,tail}$ = 5.3±3.0 mm
frac. = 87%
σ_{z} = 2.5±1.0 mm
$\sigma_{y,z,design}$ = 1.0 mm

The MEG upgrade (MEG2)

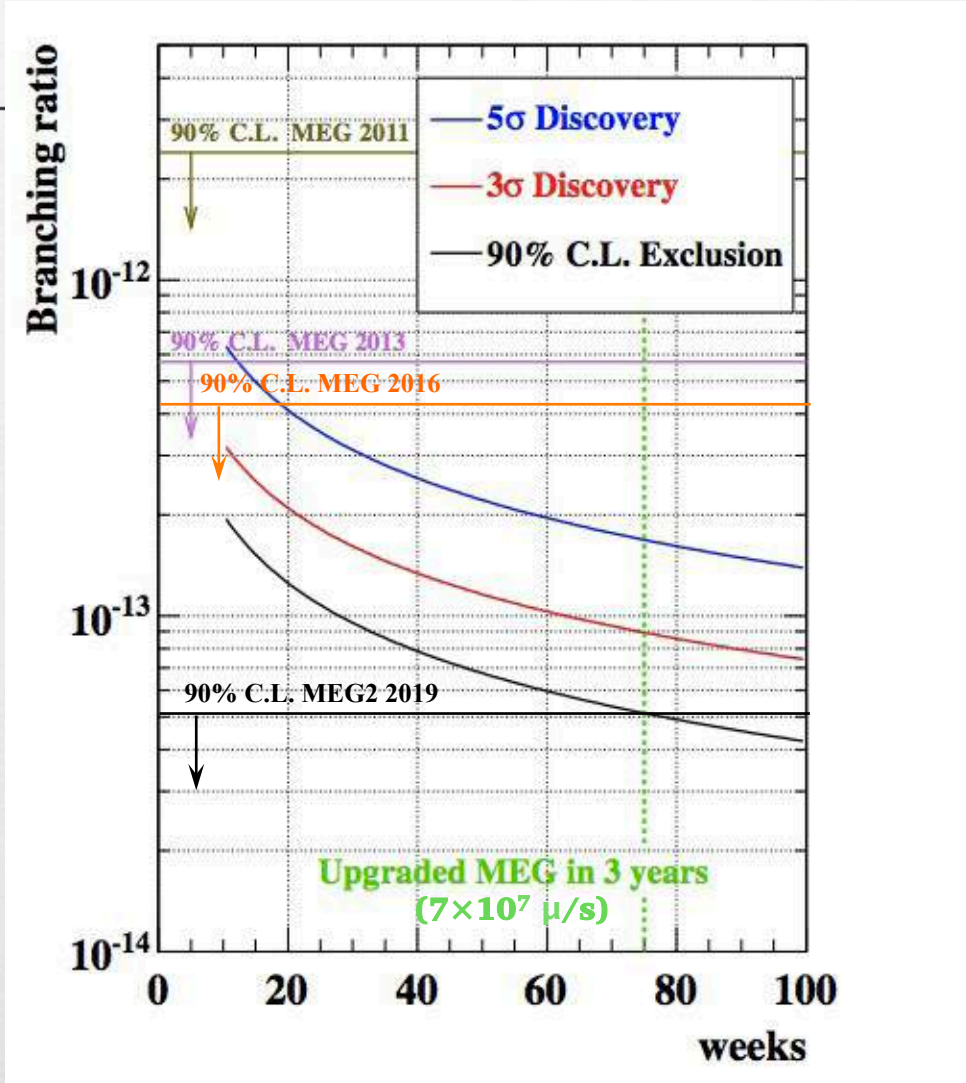


1. Increase the number of stopped muons on target
2. Reduce the target thickness
3. Reduce the tracker radiation length and improve on granularity, resolution and efficiency
4. Improve matching DC-TC
5. Improve timing counters granularity
6. Extend calorimeter acceptance
7. Improve photon energy, position and timing resolution for shallow events
8. New RMD conters
9. New DAQ for higher bandwidth

The MEG upgrade (MEG2)

TABLE XI: Resolution (Gaussian σ) and efficiencies for MEG upgrade

PDF parameters	Present MEG	Upgrade scenario
e^+ energy (keV)	306 (core)	130
e^+ θ (mrad)	9.4	5.3
e^+ ϕ (mrad)	8.7	3.7
e^+ vertex (mm) Z/Y(core)	2.4 / 1.2	1.6 / 0.7
γ energy (%) (w <2 cm)/(w >2 cm)	2.4 / 1.7	1.1 / 1.0
γ position (mm) $u/v/w$	5 / 5 / 6	2.6 / 2.2 / 5
γ-e^+ timing (ps)	122	84
Efficiency (%)		
trigger	≈ 99	≈ 99
γ	63	69
e^+	40	88



MEG2 DC layout

- Full stereo cylindrical d. ch. with large stereo angles **(102÷147 mrad)**
- Redundant **(N_{hit} ≈ 60 on signal track)**
- Small square cells **(5.8÷7.8 mm at z=0, 6.7÷9.0 at z=±L/2)**
- High ratio of field/sense **(5 : 1)** wires
- Light mechanical structure **(Peek end-plates, C-fiber outer cyl., Mylar inner cyl.)**
- Innovative wiring procedure **(feed-through-less)**
- Light gas mixture **(85% He – 15% iC_4H_{10})**
- Cluster Timing readout capabilities **(high bandwidth, high sampling rate)** for improved spatial resolution

Active length L	1960	mm
N. of layers	10	
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

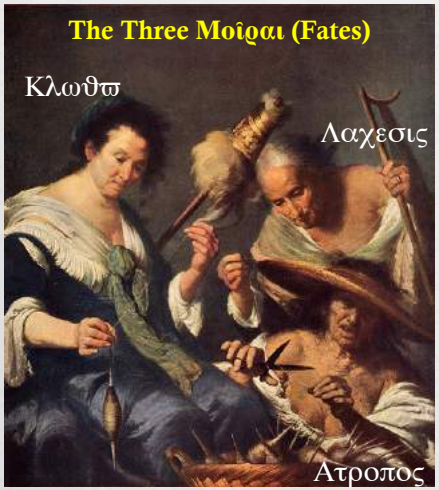
Radii	z = 0	z = ±L/2	
Guard wires layer	170.7	197.1	mm
First active layer	174.5	201.5	mm
Last (10th) active layer	242.0	279.5	mm
Guard wires layer	246.0	284.0	mm

MEG2 DC wiring

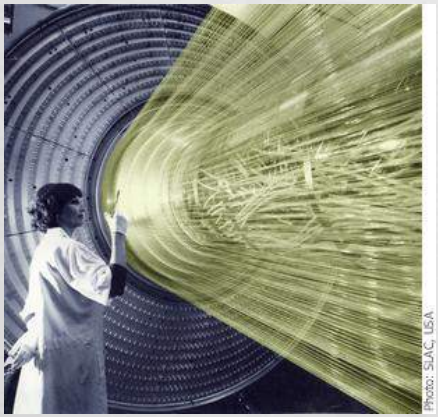
- A larger field to sense wires ratio (5 : 1) allows for thinner field wires, thus reducing the **wire contribution to multiple scattering** and the **total wire tension** on the the end-plates.
- **Large field to sense wires ratios** and **small cells**, on the other end, imply high wire densities and, because of the reduced wire spacing, prevent the use of feed-through.
- Large number of wires, anyway, require complicated and time consuming **assembly procedures** and, therefore, they need a **novel approach** to the problem

DC stringing: the old way

The Old Way

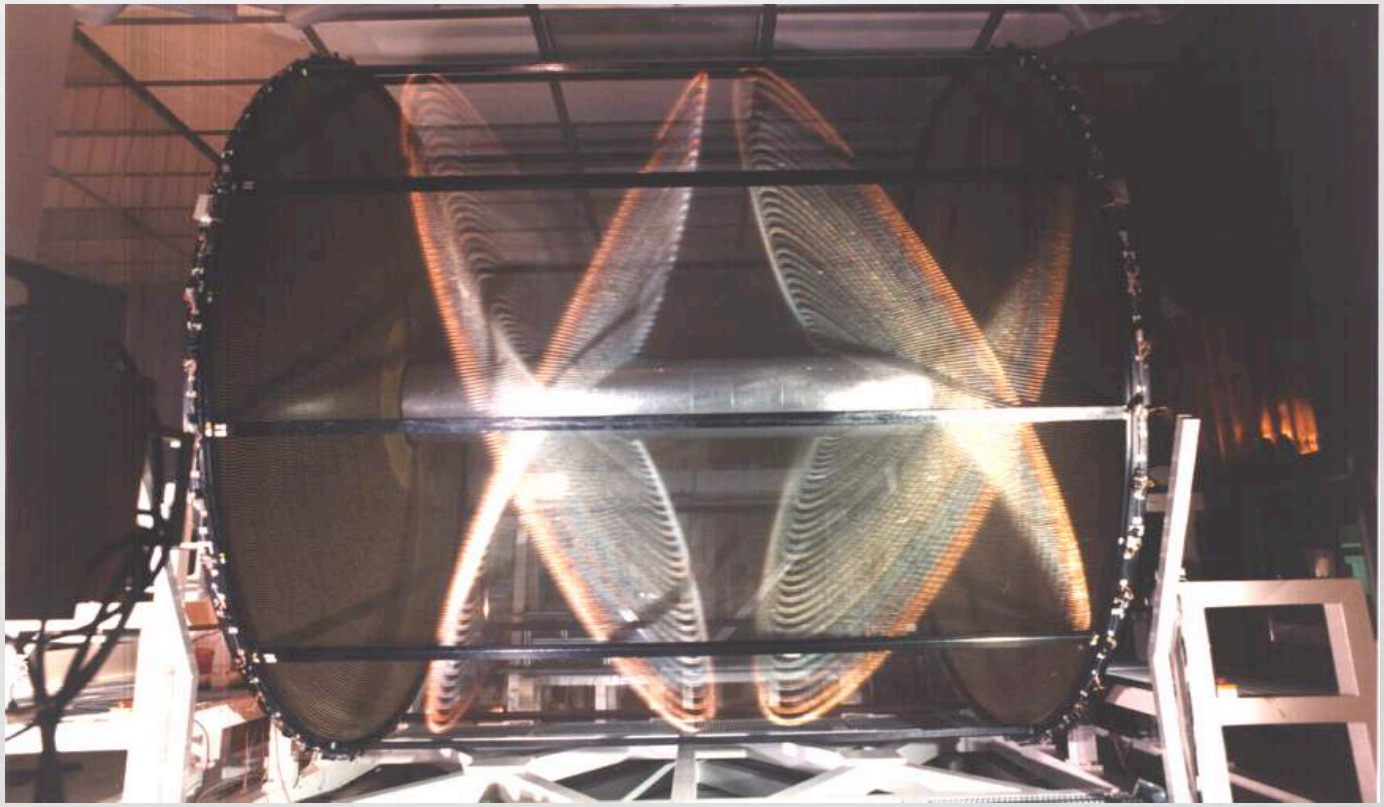


Bernardo Strozzi – Le tre Parche – Venezia, circa 1620

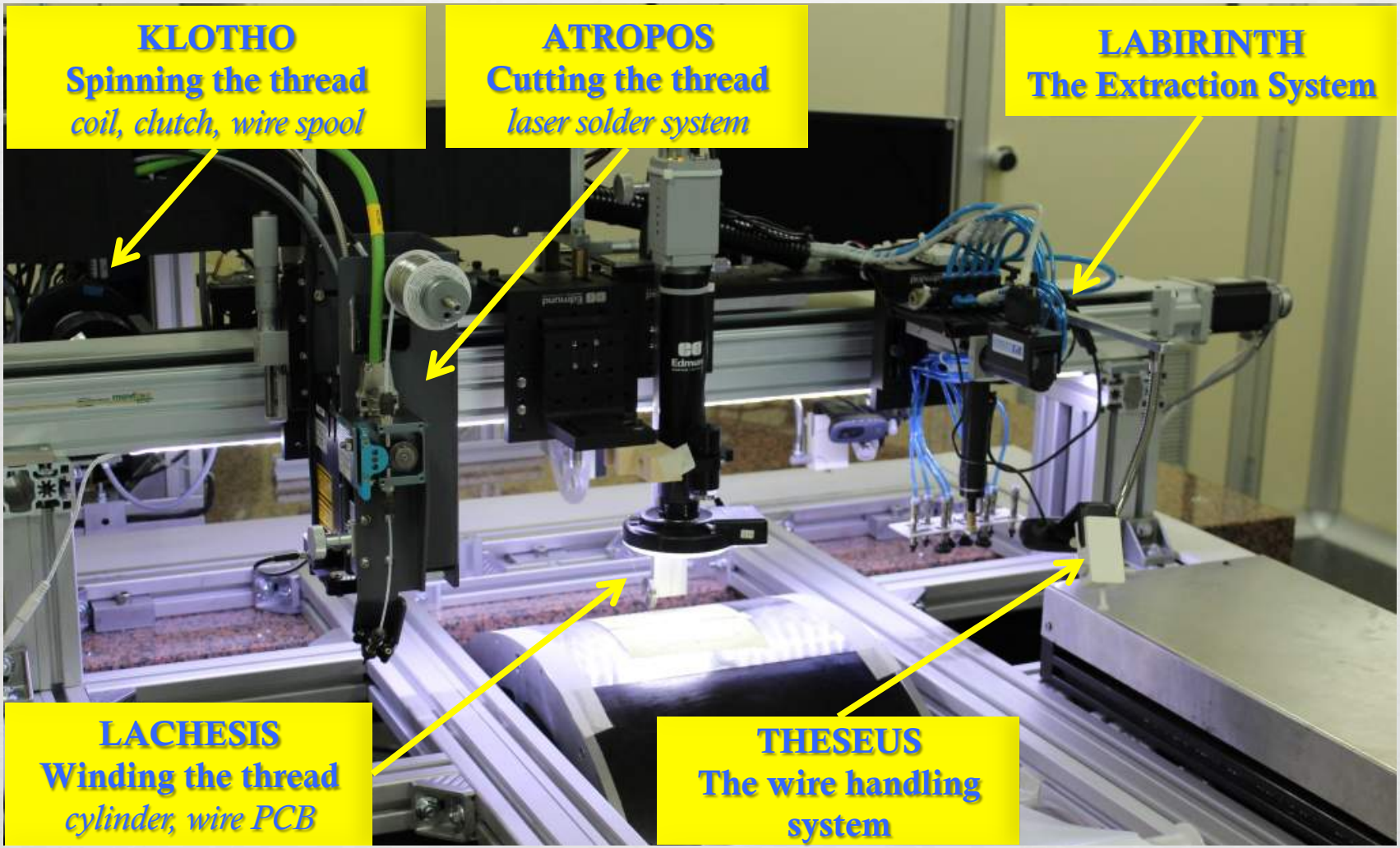


The KLOE Drift Chamber

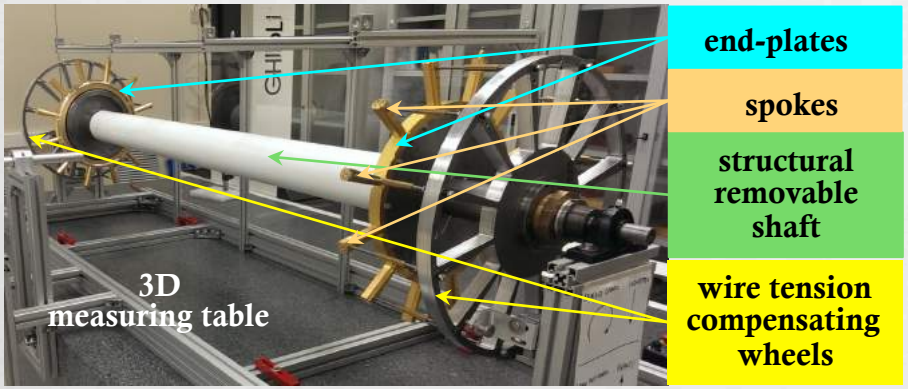
45 m^3 > 52,000 wires He/iC_4H_{10}



DC stringing: the novel way



MEG2 DC EndPlates

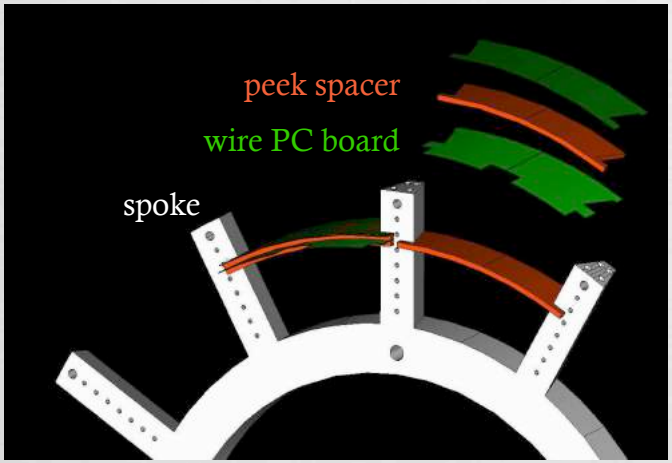


end-plates

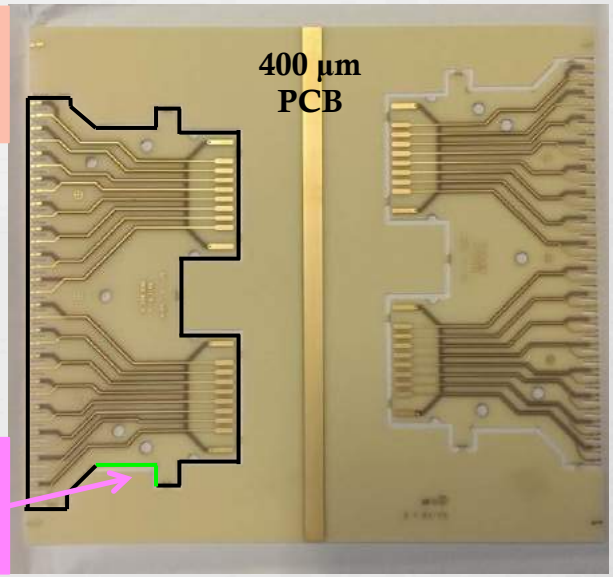
spokes

structural removable shaft

wire tension compensating wheels



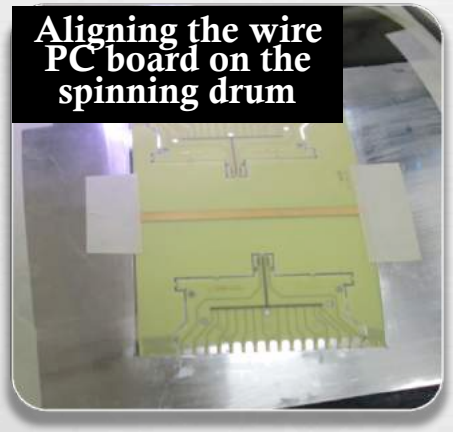
sense wires PC boards (16 cells)

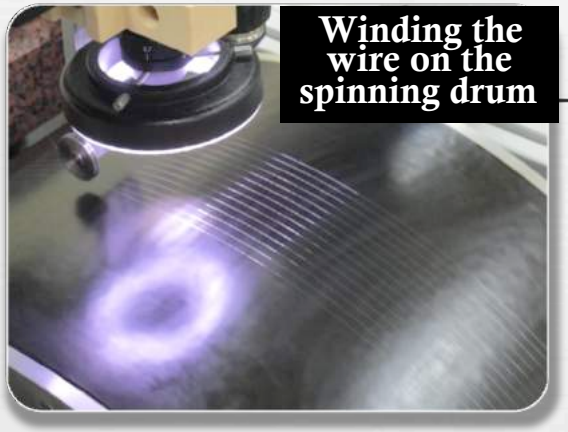


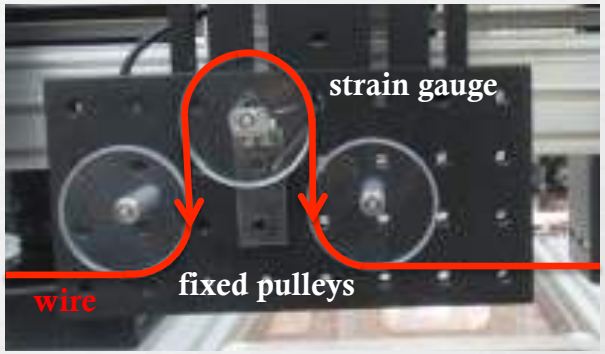
fiducial reference edge

NC machined peek spacer (½ cell thick 1 sector wide)

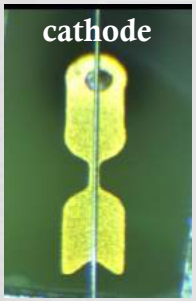
MEG2 DC Wiring

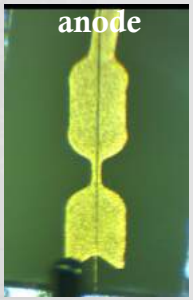


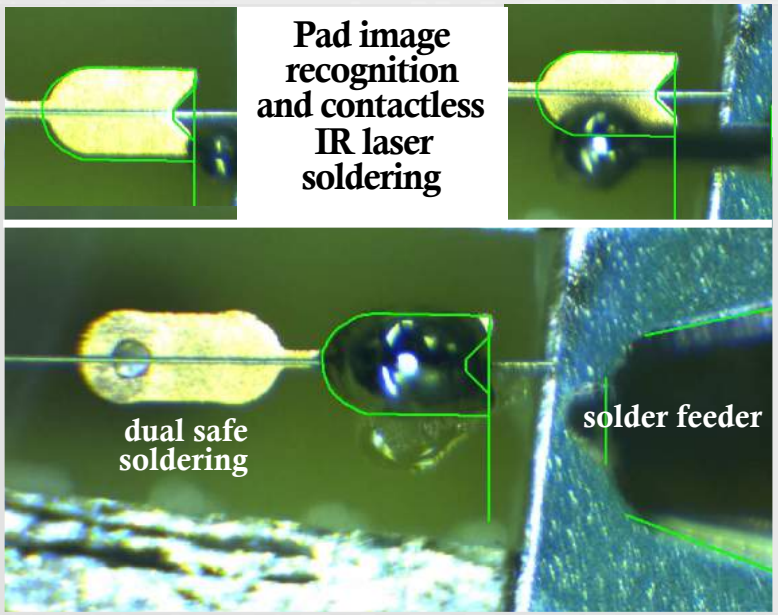


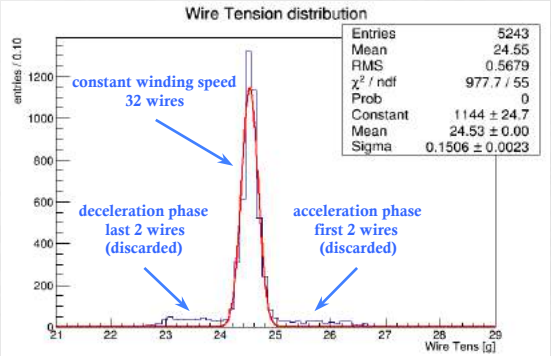


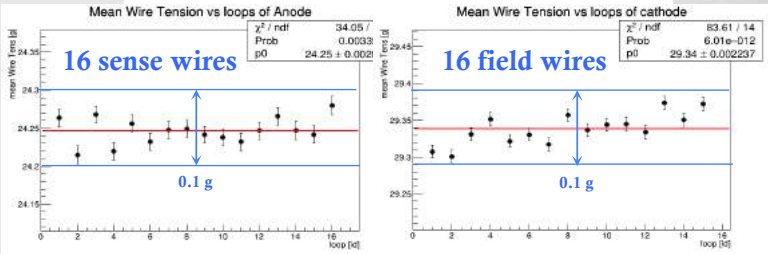
Wire tension set up with a real time strain gauge feedback system on the spooling el. mag. clutch



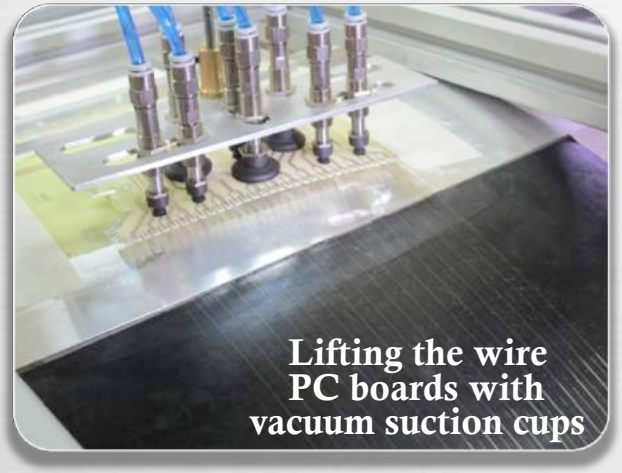


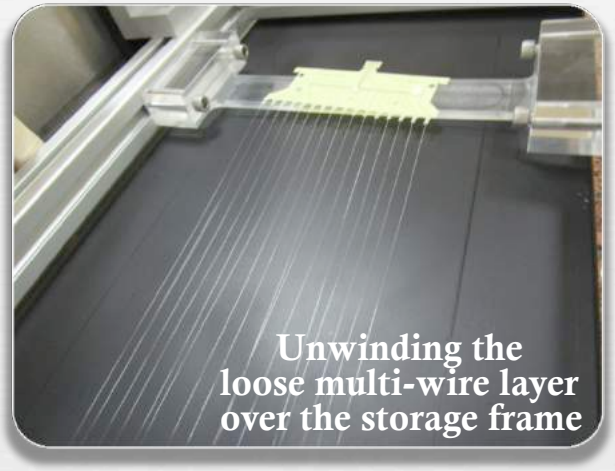


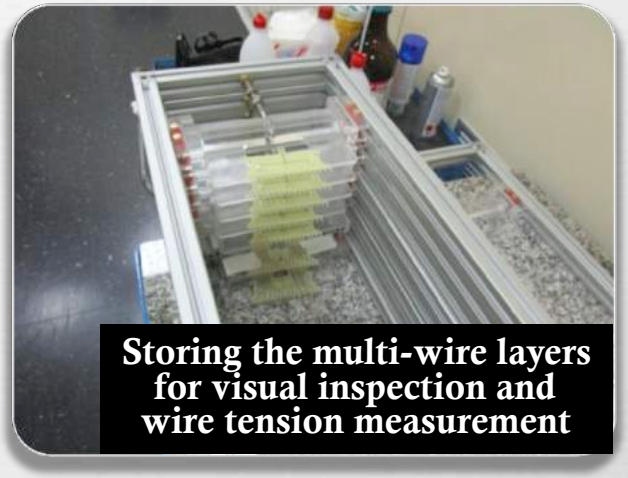


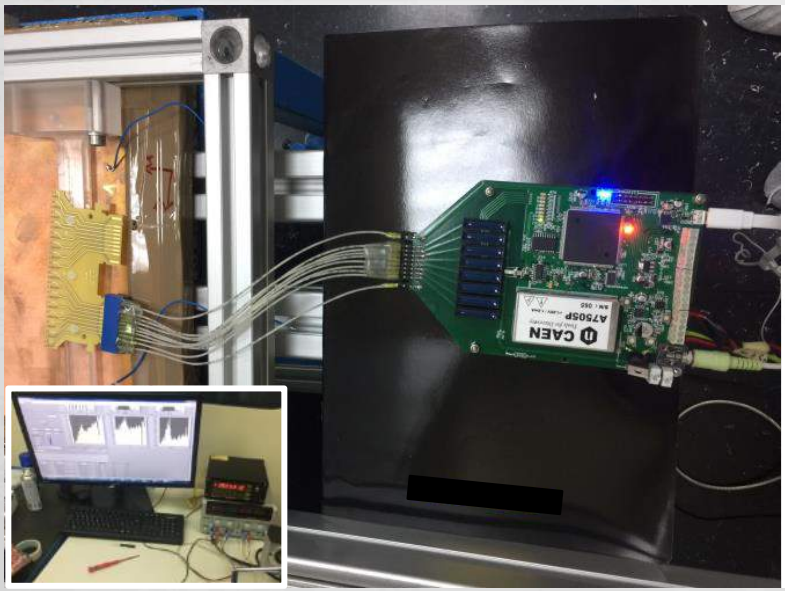


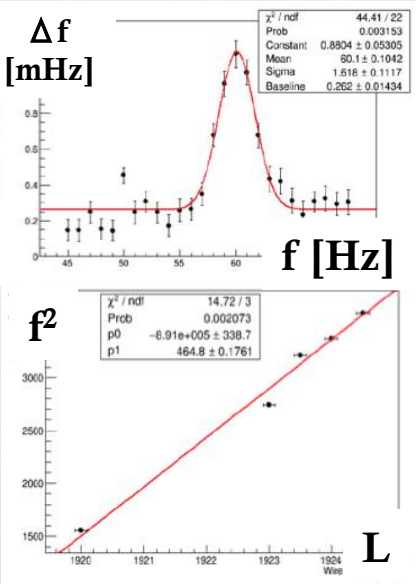
MEG2 DC Wiring







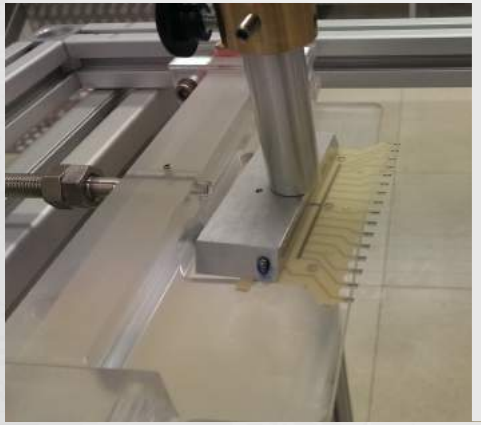




Chamber accuracy

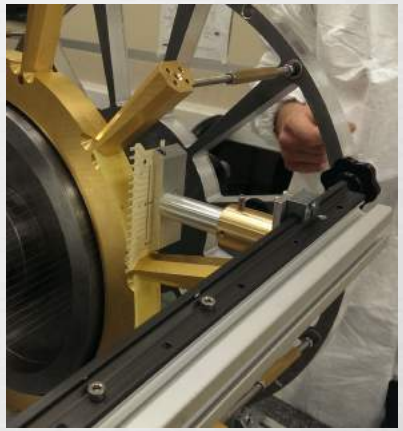
stereo angle	<	35 µrad
wire position on PCB pad	<	25 µm
cell width (wire pitch)	<	1 µm
cell height (spacer)	<	50 µm
wire tension	<	0.1 g
PCB offset vs spoke	<	50 µm
chamber length	<	200 µm

MEG2 DC Assembly



wire PC Boards are lifted up by adjustable arm ...

... and presented to the end plates moved closer by a few mm



A pressure sensitive tape holds them in the correct position above the peek spacer.

At completion of each layer (12 sectors), the end plates are moved away to the nominal length. The layer radial coordinates and the tension of all wires are then measured.

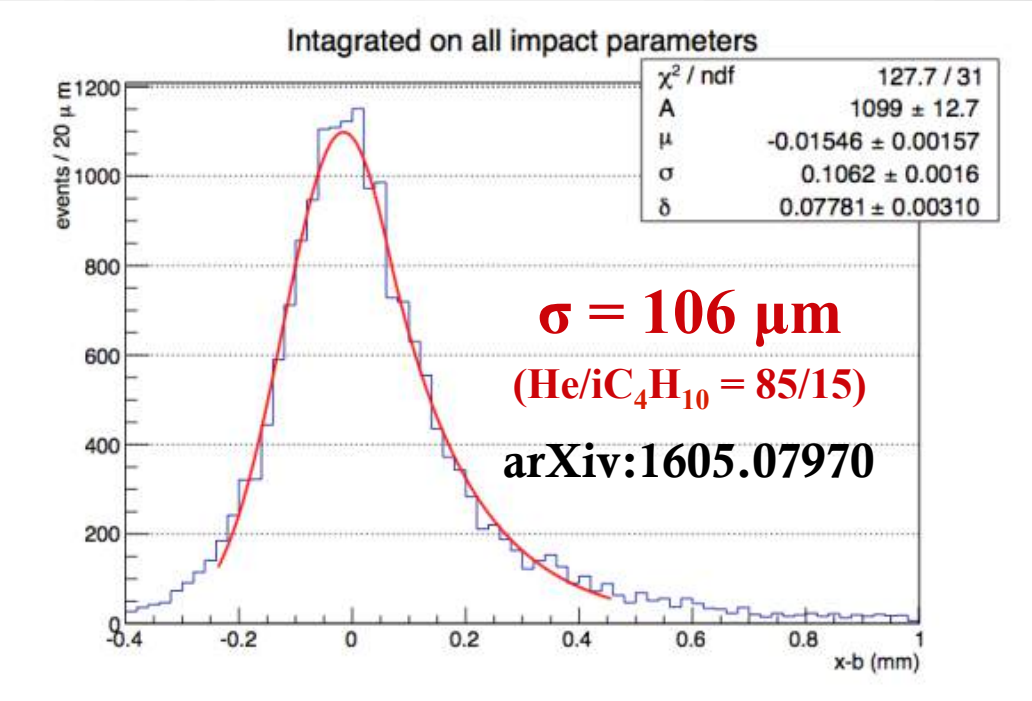
After last layer has been mounted, the outer structural carbon fiber cylindrical shell is placed and the inner shaft is removed. The end plates are sealed, the inner mylar cylinder is mounted, together with the extensions for the FEE

MEG2 DC Spatial resolution

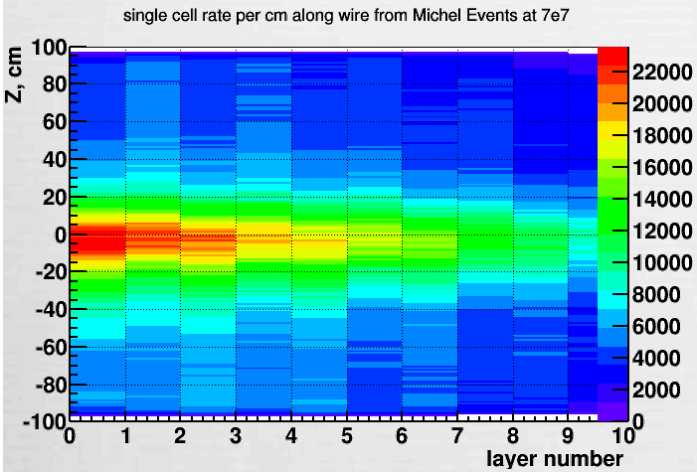
Single-hit resolution **measured** with three different prototypes.

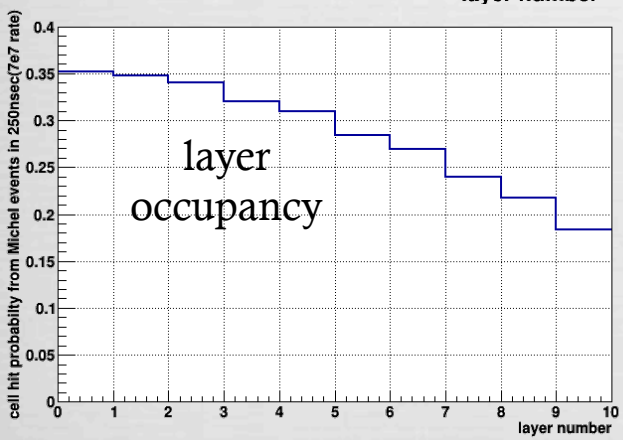
Results are all in agreement, yielding a resolution of about 110 μm averaged throughout the cell.

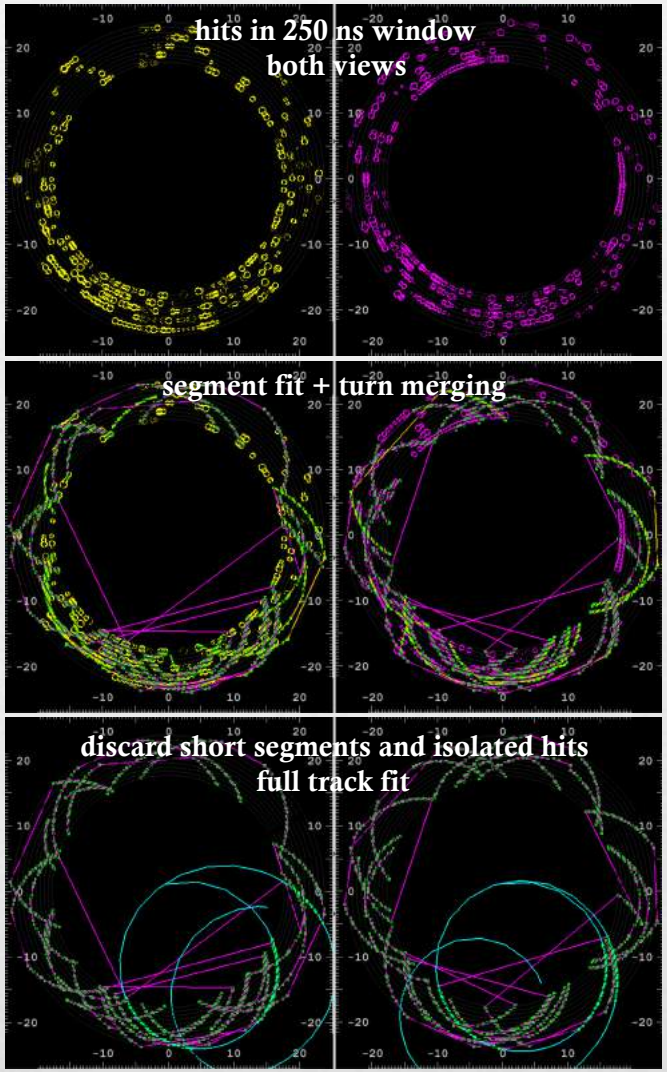
Further improvements expected thanks to the implementation of a wide bandwidth front end electronics allowing for the exploitation of the **cluster timing** technique.



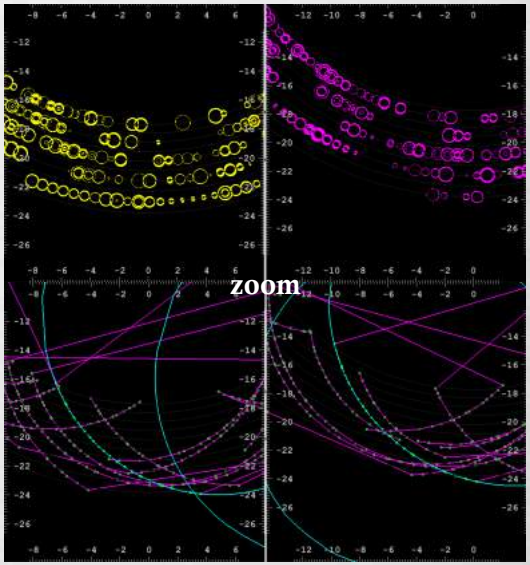
MEG2 DC Expected Perf.





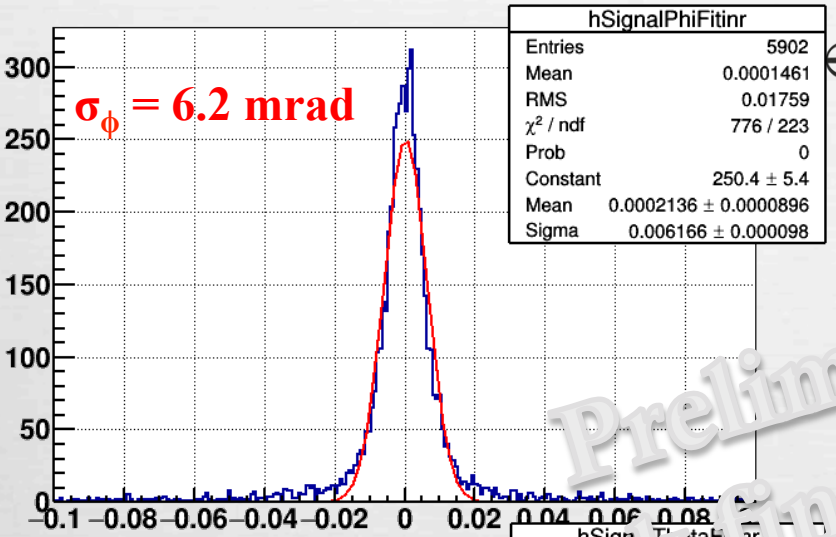


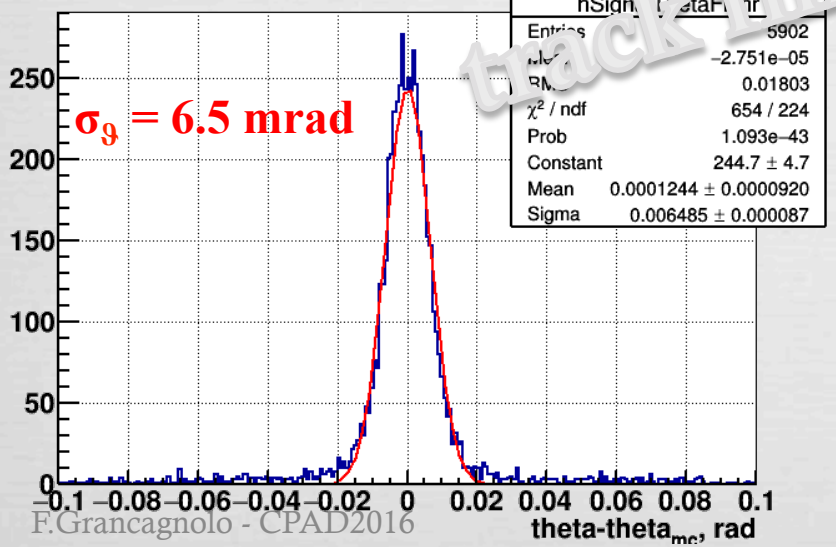
3D track finding and fit

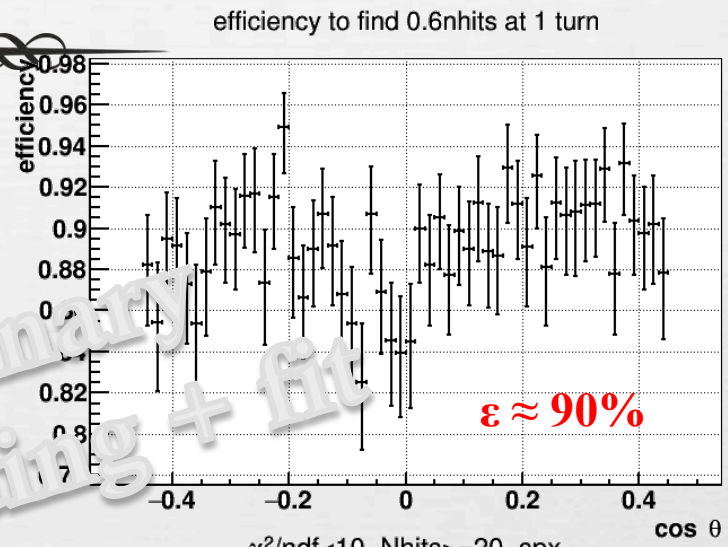


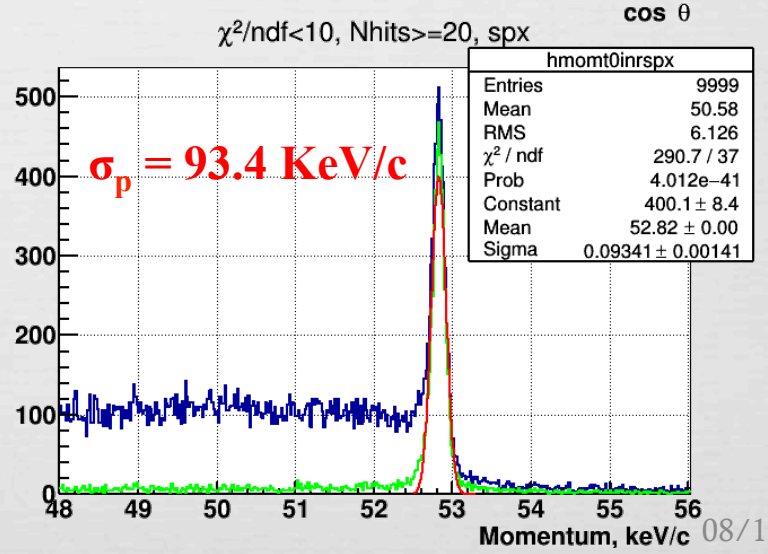
michel tracks
signal track

MEG2 DC Expected Perf.









Preliminary
track finding + fit

MEG2 DC summary

	MEG	MEG2
single hit contribution to m.s.	2.3×10^{-4} X_0	4.6×10^{-5} X_0
transverse position resolution	210 μm	106 μm
e^+ momentum resolution	330 KeV/c	*94 KeV/c*
e^+ θ angle	9.4 mrad	*6.2 mrad*
e^+ ϕ angle	8.4 mrad	*6.5 mrad*
e^+ y vertex	1.6 mm	0.9 mm
e^+ z vertex	2.5 mm	1.1 mm
DC–TC matching efficiency	41%	89%

remember!

$$N_{\rm sig} = R_\mu \times T \times \Omega \times \mathcal{B} \times \epsilon_\gamma \times \epsilon_{\rm e} \times \epsilon_{\rm s}$$

$$N_{\rm acc} \propto R_\mu^2 \times \Delta E_\gamma{}^2 \times \Delta P_{\rm e} \times \Delta\Theta_{{\rm e}\gamma}^2 \times \Delta t_{{\rm e}\gamma} \times T$$

Slides from Andre Shoening

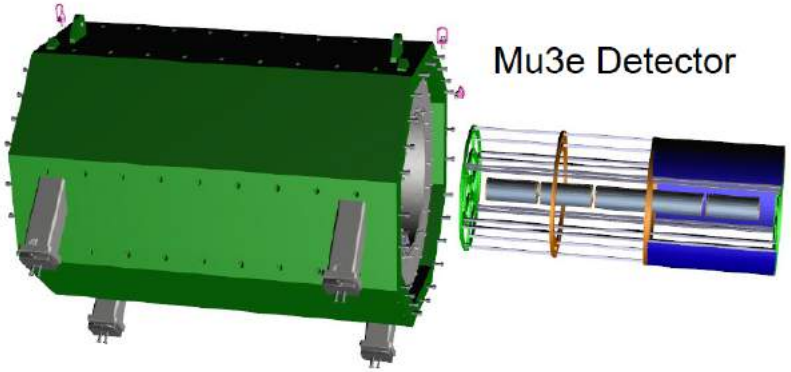
Mu3e Experiment at PSI

Mu3e Research Proposal, A.Blondel et al., arXiv:1301.6113

Search for lepton flavor violating decay

- $BR(\mu^+ \rightarrow e^+ e^+ e^-) < 10^{-12}$ (SINDRUM 1986)
- **$BR(\mu^+ \rightarrow e^+ e^+ e^-) < 10^{-15}$** (phase I, PiE5 beamline)
- $BR(\mu^+ \rightarrow e^+ e^+ e^-) < 10^{-16}$ (phase II, High Intensity Muon beamline)

Mu3e Solenoid B=1 Tesla

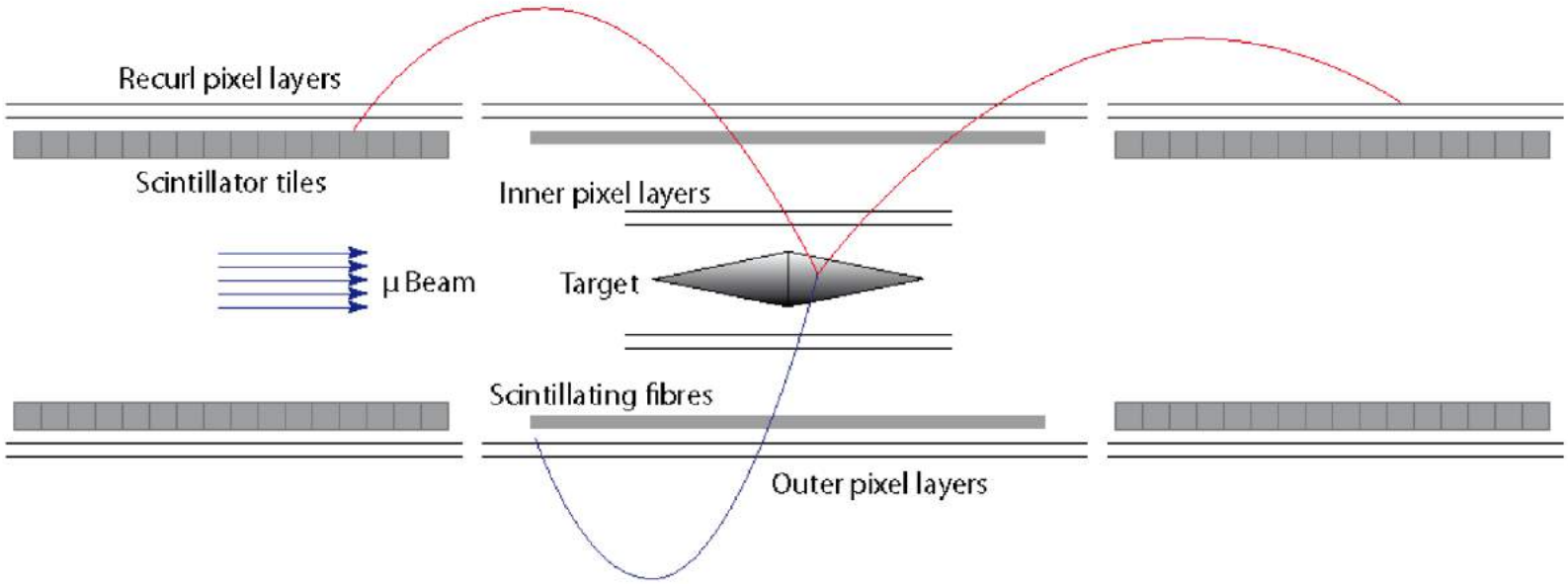


Requirements:

- $10^8 – 10^9$ muon stops / second
- electron energies < 53 MeV
  - multiple scattering dominated
- high precision silicon pixel tracker
  - relative momentum resolution < 1%
- scintillating timing detectors
  - 100-500 ps resolution

Slides from Andre Shoening

Mu3e Design



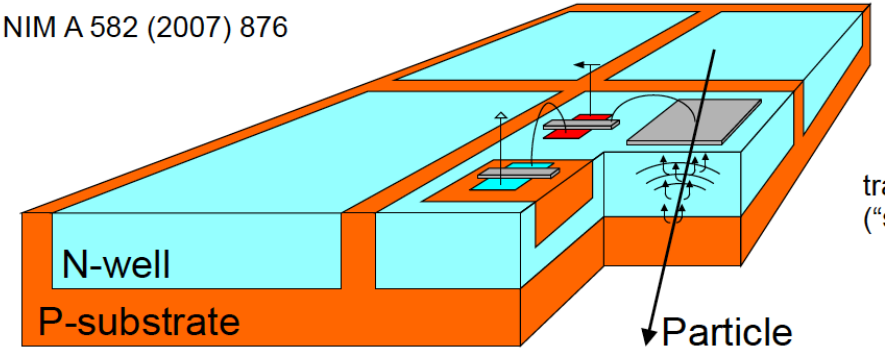
Main technological Challenges

- Large area (1m^2) monolithic pixel detectors with X/X_0 = 0.1% per tracking layer
- Novel helium gas cooling concept
- Thin scintillating fiber detector with ≤ 1mm thickness
- Timing resolution 100-500 ps
- Filter farm reconstructing and processing 10^8-10^9 tracks per second

High Voltage Monolithic Active Pixel Sensors (HV-MAPS)

Slides from Andre Shoening

I.Peric, et al., NIM A 582 (2007) 876



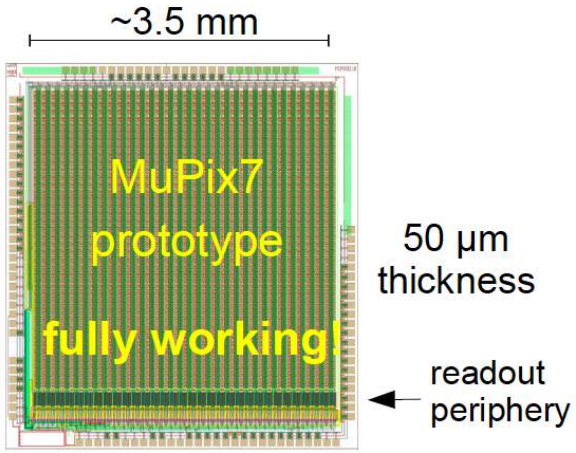
transistor logic embedded in N-well
("smart diode array")

MuPix HV-MAPS for Mu3e

- **active sensor → hit finding + digitisation + zero suppression + readout**
- high precision → pixels 80 x 80 μm^2
- total thickness ~50 μm (~ 0.0005 X_0)
- standard HV-CMOS process, 60-120 V → low production costs
- continuous and fast readout (serial link) → online reconstruction

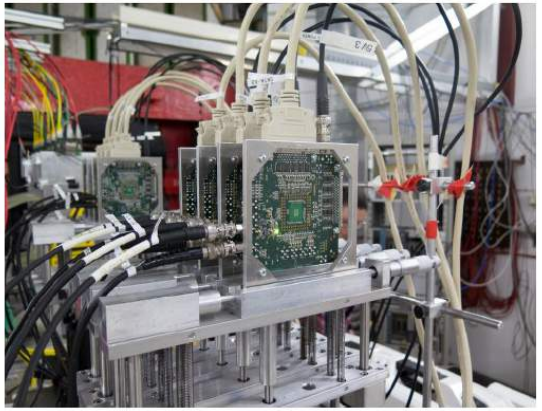
Slides from Andre Shoening

HV-MAPS Beam Test Results

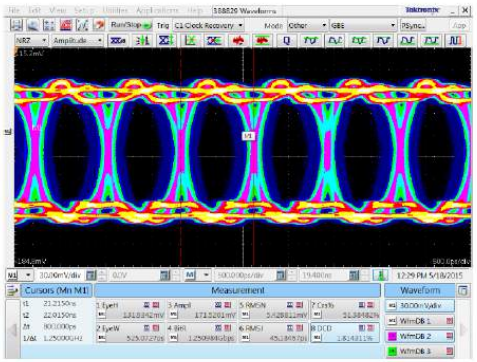


Test beams performed at:

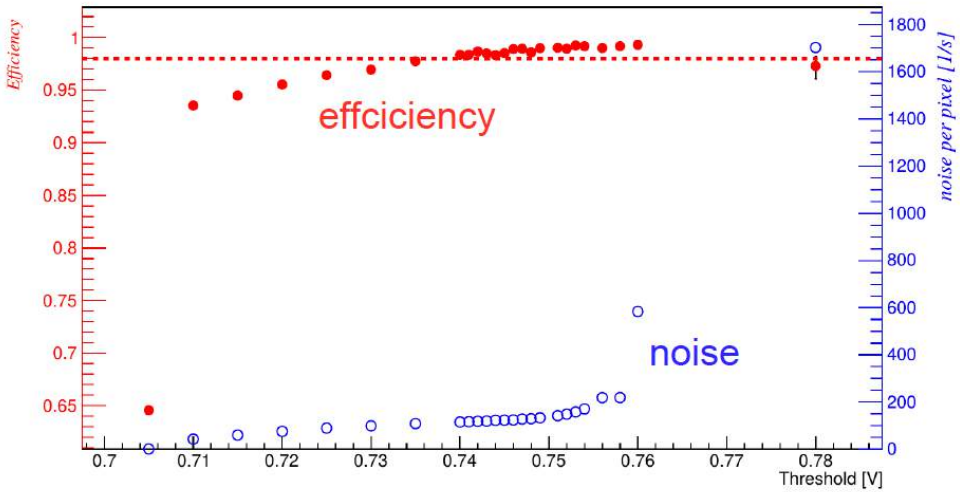
- CERN
- PSI
- DESY
- MAMI



- continuous readout
- serial link: 1.25 Gbit/s
- up to 33 Mhits / s



Efficiency and noise



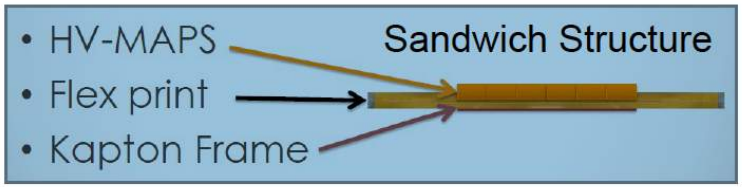
Slides from Andre Shoening

Prototypes for Pixel Tracker

Ultra-thin mechanical mockup:

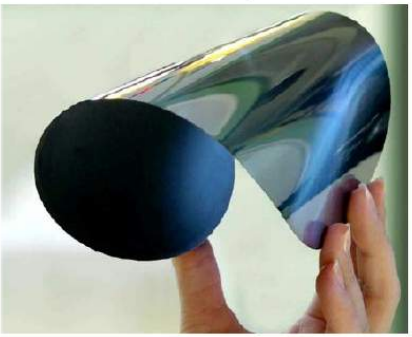
- sandwich of 25 µm Kapton®
- here 50 µm glass (instead of Si)

Layout of module:



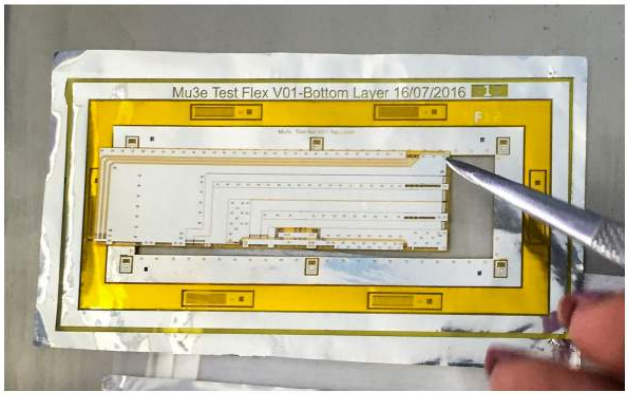
X ≤ 0.1% X_0 per layer possible

Silicon wafer of 50 µm thickness



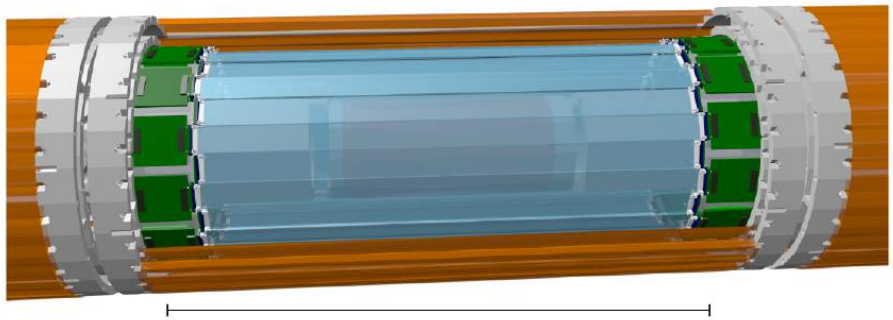
Flexprint by LTU Limited (Ukraine)

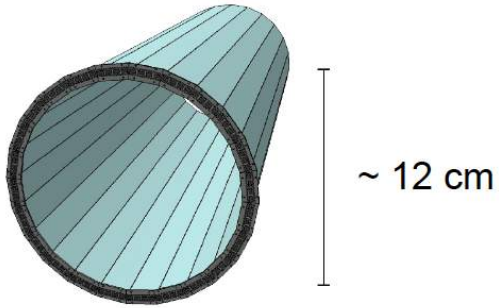
- thin two layer aluminum/kapton compound



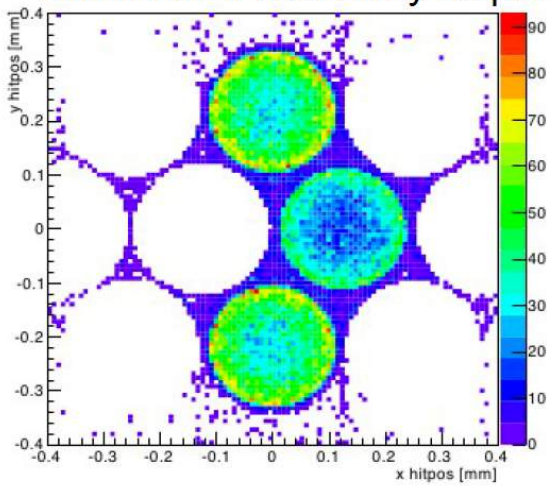
Slides from Andre Shoening

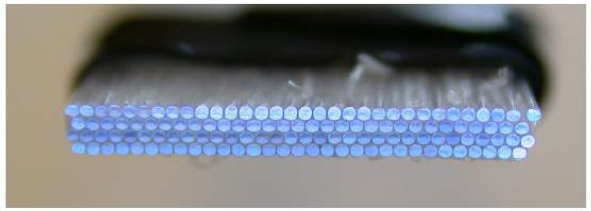
Scintillating Fiber Tracker





Simulation if fiber array response

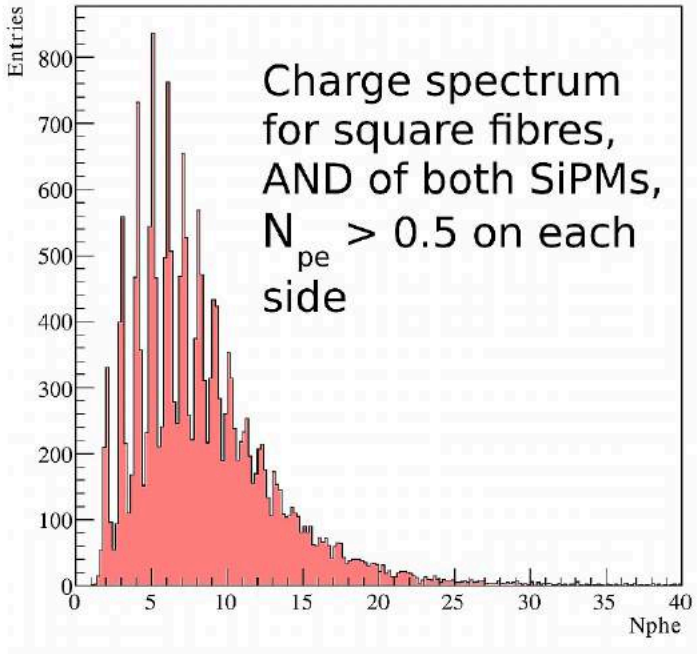




- 2-3 layers of scintillating fibers Ø = 250 μm
  - Readout by SiPM arrays (Hamamatsu) and custom made ASICs (MuSTic chip)
  - 100 nm Al coating by evaporation method (no TiO_2 to reduce radiation length)

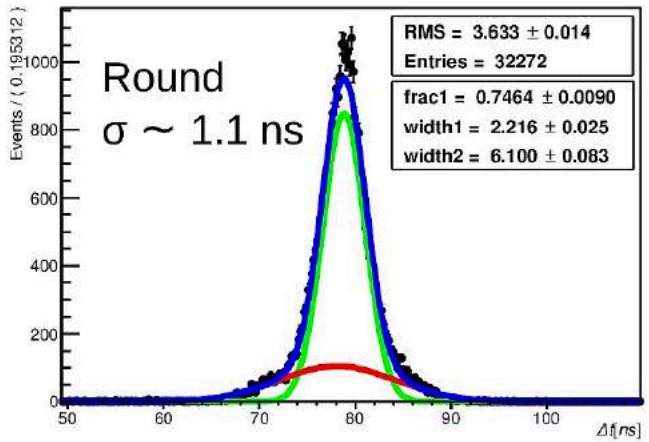
Mu3e Sci-Fi Results from Prototypes

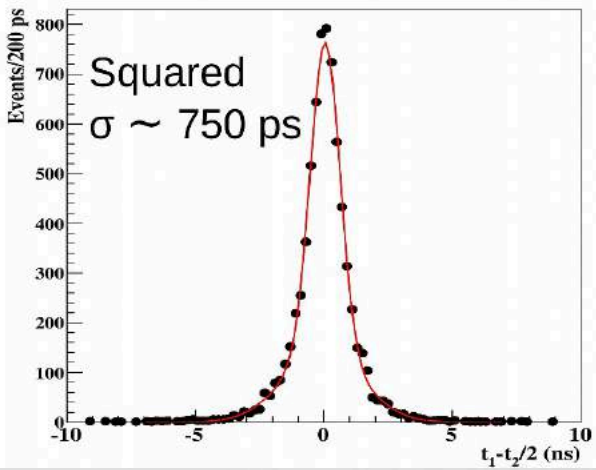
Slides from Andre Shoening



Double layer square fibres, AND configuration, N_{pe} > 0.5: 93 % efficiency

Single fiber time resolutions



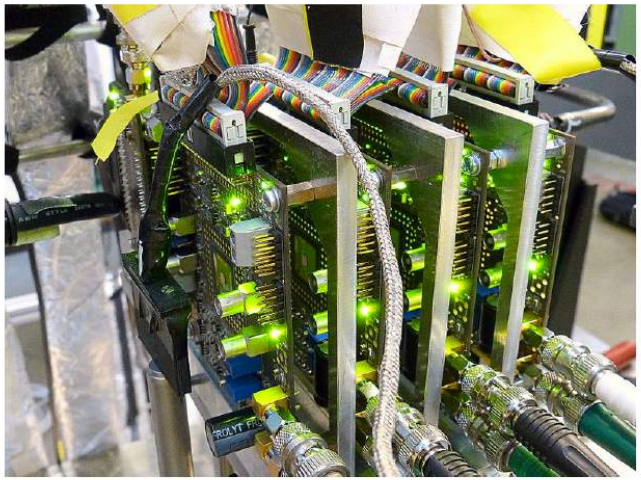


Slides from Andre Shoening

Mu3e Experimental Status

- Technical Design Report end of 2016
- Detector construction will start in 2017
- Delivery of solenoid magnet mid 2018 (Danfysik, Denmark)
- Commissioning of two inner HV-MAPS pixel layers in 2018
- First physics data (Phase I) in 2019

Mupix beam telecope in July 2014 at PSI



How to improve?

$$N_{\rm sig} = R_\mu \times T \times \Omega \times \mathcal{B} \times \epsilon_\gamma \times \epsilon_{\rm e} \times \epsilon_{\rm s}$$

$$N_{\rm acc} \propto R_\mu^2 \times \Delta E_\gamma{}^2 \times \Delta P_{\rm e} \times \Delta\Theta_{{\rm e}\gamma}^2 \times \Delta t_{{\rm e}\gamma} \times T$$

Variable	Design	Monte Carlo	Obtained
Resolutions			
Positron (e)			
σ_{E_e} (keV)	200	315	306
σ_{ϕ_e,θ_e} (mrad)	$5(\phi_e)$, $5(\theta_e)$	$8(\phi_e)$, $9(\theta_e)$	$9(\phi_e)$, $9(\theta_e)$
σ_{z_e,y_e} (mm)	1.0	$2.9(z_e)/1.0(y_e)$	$2.4(z_e)/1.2(y_e)$
σ_{t_e} (ps)	50	65	102
Photon (γ)			
σ_{E_γ} (%)	1.2	1.2	1.7
σ_{t_γ} (ps)	43	69	67
$\sigma_{(u_\gamma,v_\gamma)}$ (mm)	4	5	5
σ_{w_γ} (mm)	5	6	5
Combined (e–γ)			
$\sigma_{t_{e\gamma}}$ (ps)	66	95	122
$\sigma_{\Theta_{e\gamma}}$ (mrad)	11	16	17
Efficiencies			
ϵ_e (%)	90	40	40
ϵ_γ (%)	60	63	63
$\epsilon_{\rm trg}$ (%)	100	99	99

Eur. Phys. J. C (2013) 73:2365

$R_\mu = 3.3 \times 10^7\ \mu^+/s$

→ $\Omega = 11\ \%$

$\varphi \in (2/3\pi, 4/3\pi)$

$|\cos\theta| < 0.35$

→ $\varepsilon_\gamma = 63\%$

→ $\varepsilon_e = 40\%$

$\varepsilon_s = 65\%$

based on 2009-2011 data: $\mathcal{B}(\mu^+ \to e^+ + \gamma) < 5.7 \times 10^{-13}$

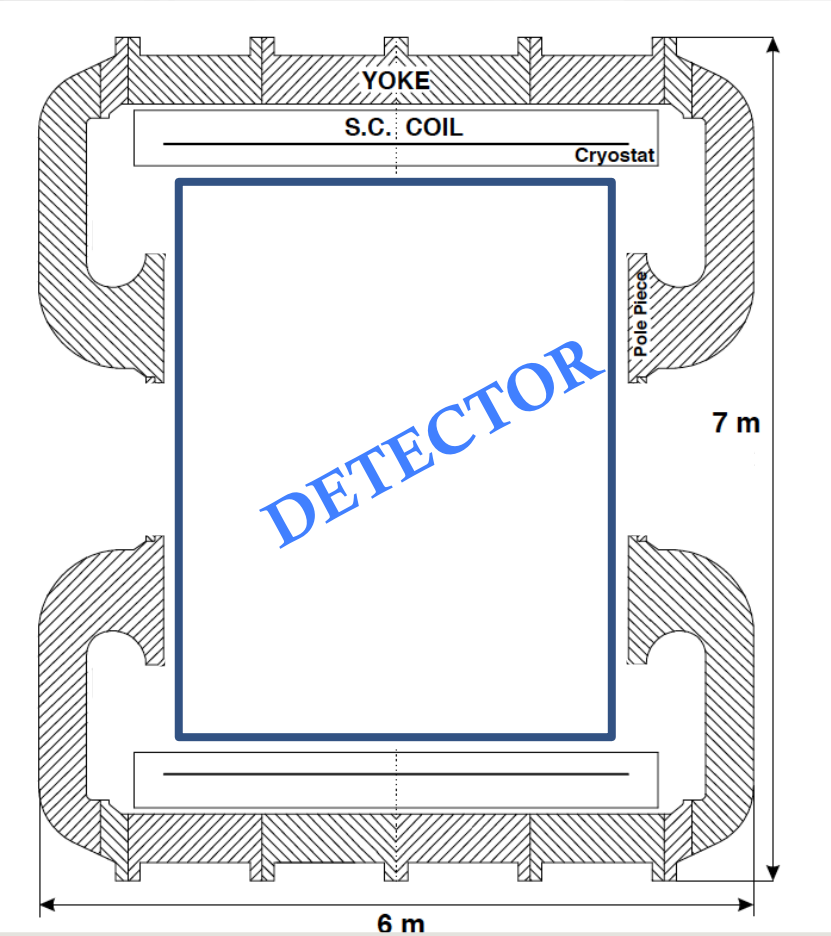
→ $\Delta E_\gamma = 1.7\% = 900$ KeV

→ $\Delta P_e = 306$ KeV

→ $\Delta\Theta_{e\gamma} = 17$ mrad

→ $\Delta t_{e\gamma} = 122$ ns

A suggestion: CIRCE



Consider a large volume solendoidal magnet, such as the **KLOE coil** (active volume 2.45 m radius, 3.8 m length) run at 0.6T.

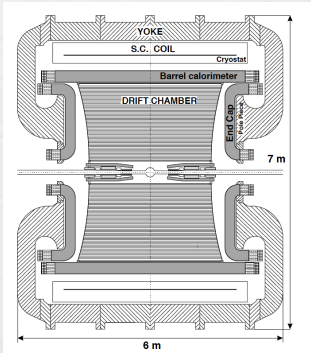
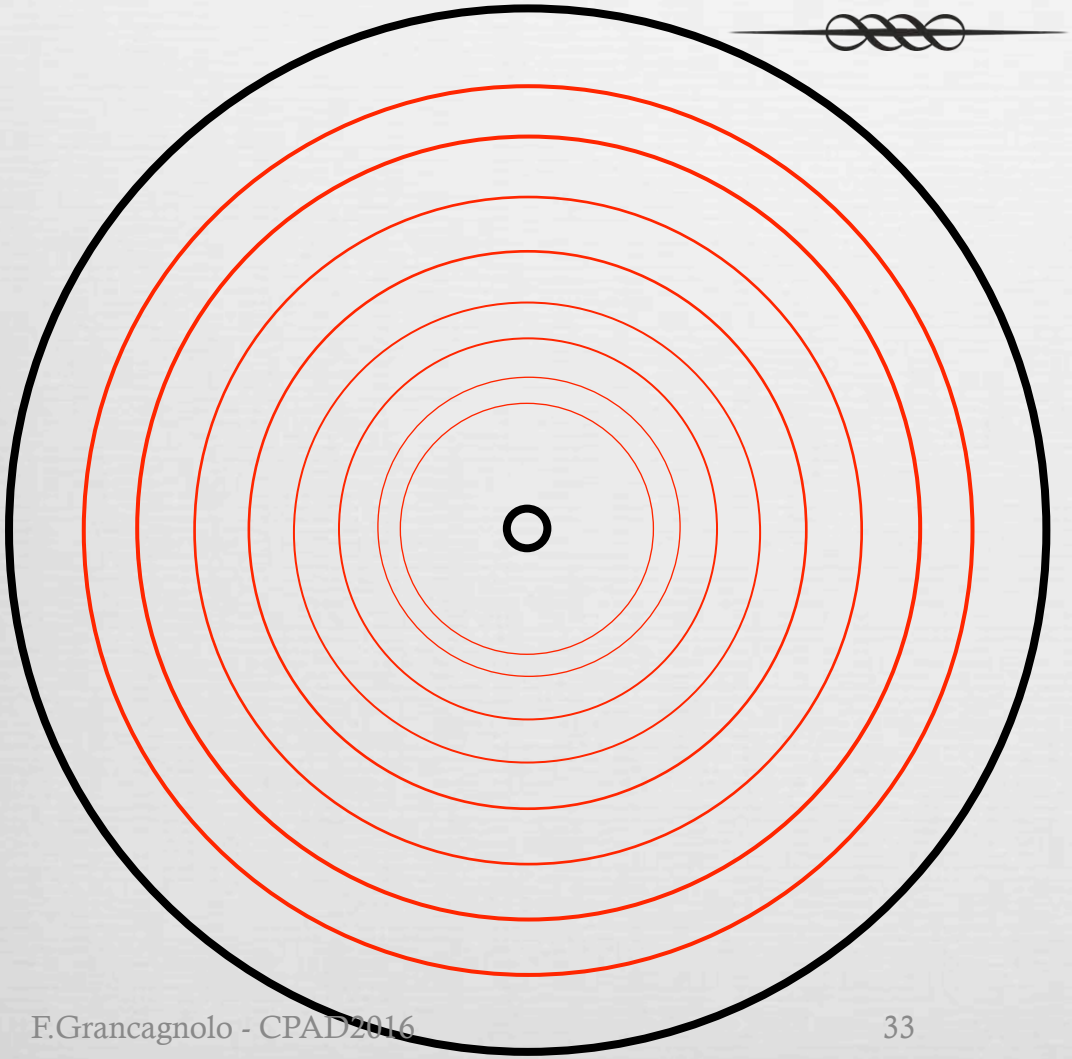


Fig. 1. Vertical cross-section of the KLOE detector along the beam line.

Fill it with **a low mass cylindrical drift chamber**, subdivided in concentric **stereo super-layers** separated from each other by a thin shell of **photon converter** made of Tungsten.

The drift chamber



Inner chamber radius = 10 cm
(p_{tmin} = 9 MeV/c)
to allow for vertex detector

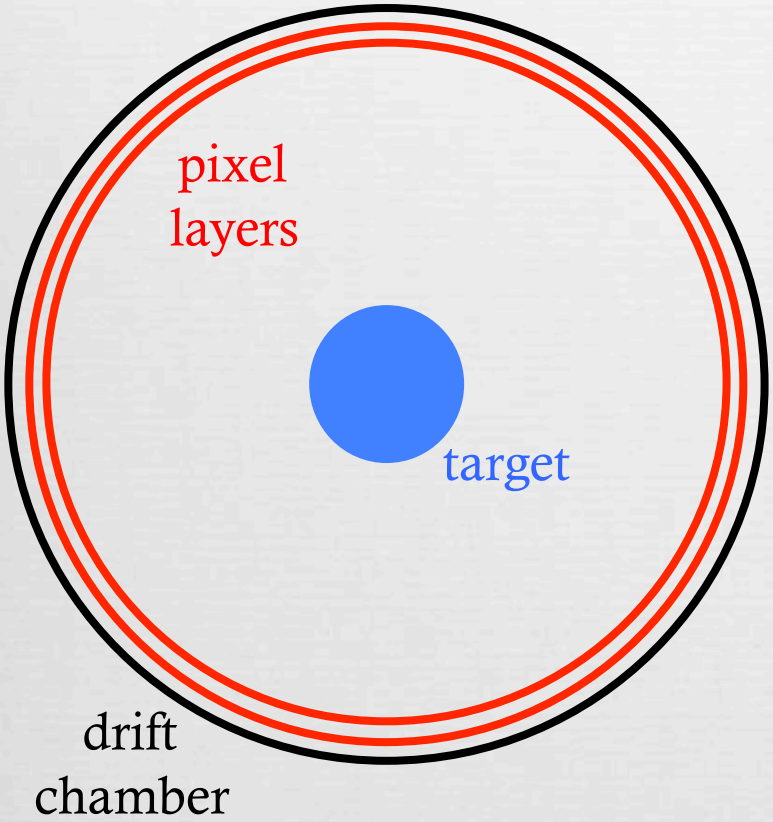
Outer radius R = 245 cm

1st super-layer up to R = 60 cm
to fully contain $p_t \leq 53$ MeV/c
100 ± stereo layers radially

Successive super-layers of
16 stereo layers of increasing
cell size (from 0.8 to 2.2 cm)
separated by a radiator shell
to track electron pairs from
photon conversion

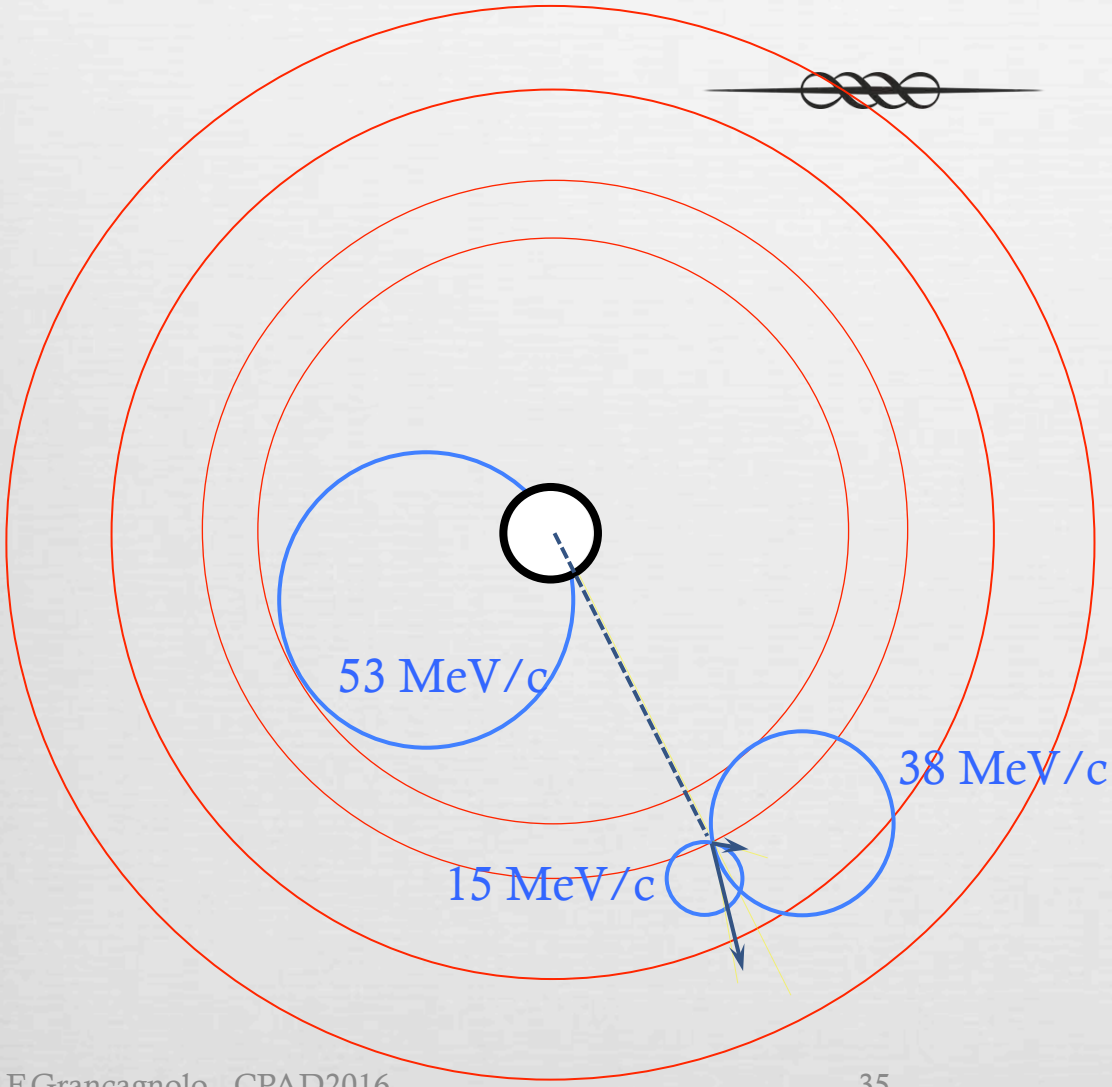
Length to be optimized to
minimize
occupancy of inner layers

The vertex detector (Mu3e like)



- 80 μm × 80 μm
  (occ. < 0.5% for 10^9 μ/s at 10 cm)
  (3 μs double pulse resolution)
- Only 2 layers:
  no standalone tracking required.
- 16 cm long:
  to match drift chamber acceptance.
- 7×10^5 pixels/layer
  no standalone tracking required.
- Total of 2×10^{-3} X_0.

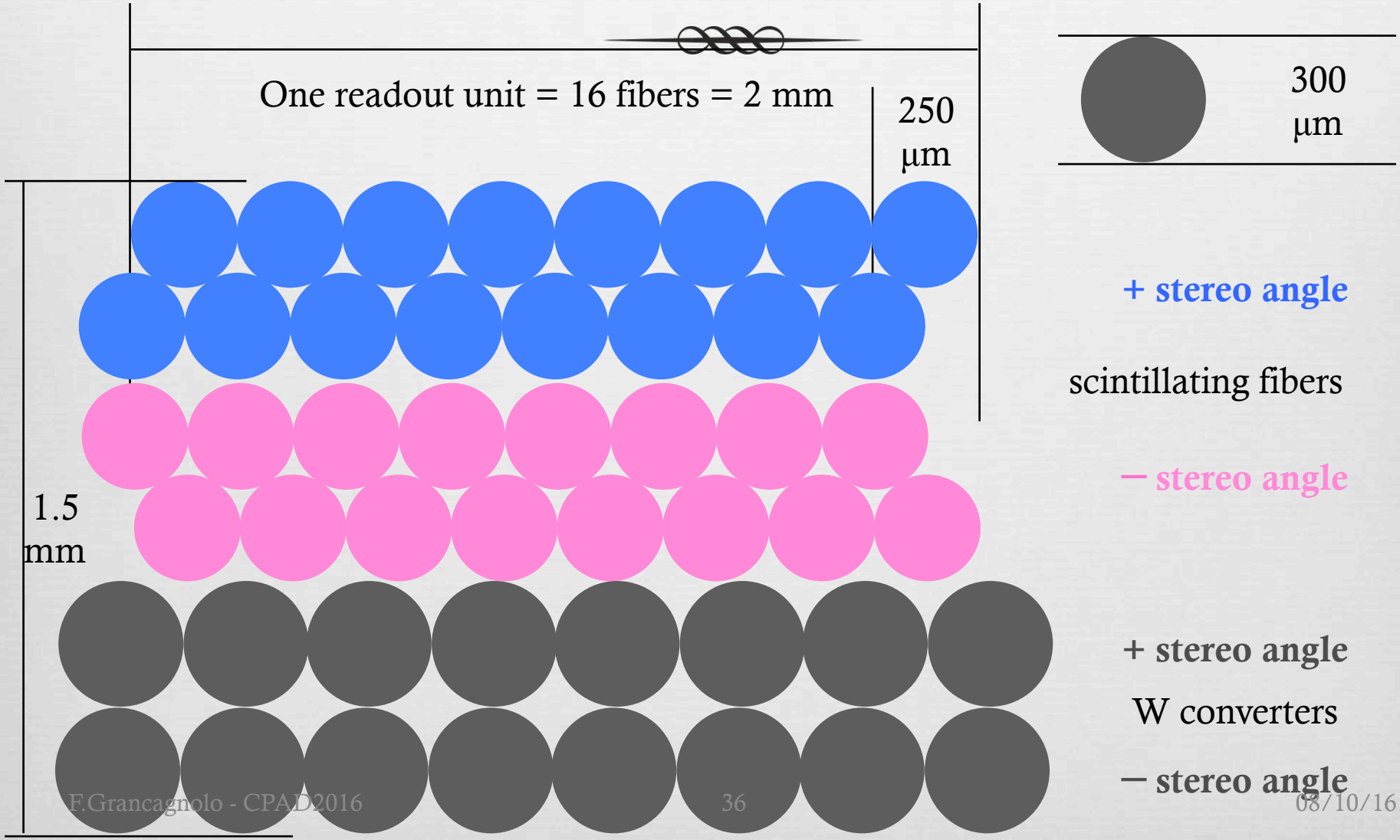
The photon converter



A 53 MeV/c p_t track leaves
> 400 hits per turn
in the first super-layer
Momentum resolution
dominated by mult. scatt.
$\Delta p_t/p_t \approx 2\times10^{-4}$

Many kinematical constraints:
$\Delta e_\gamma \approx 300$ **KeV**
(to be checked by MC)

The scintillating fibers



Expected performance

$$N_{sig} = R_\mu \times T \times \Omega \times B_r \times \varepsilon_\gamma \times \varepsilon_e \times \varepsilon_s$$

$$N_{bkg} \propto R_\mu^2 \times \Delta E_\gamma^2 \times \Delta P_e \times \Delta\Theta_{e\gamma}^2 \times \Delta t_{e\gamma} \times T$$

MEG	CIRCE
$R_\mu = 3.3 \times 10^7\ \mu^+/s$	$R_\mu = 3 \times 10^8\ \mu^+/s$
$\Omega = 11\ \%$	$\Omega = 90\ \%$
$\varepsilon_\gamma = 63\%$	$\varepsilon_\gamma = 80\%$
$\varepsilon_e = 40\%$	$\varepsilon_e = 90\%$
$\varepsilon_s = 65\%$	$\varepsilon_s = 65\%$
$\Delta E_\gamma = 1.7\% = 900\ KeV$	$\Delta E_\gamma = 0.6\% = 300\ KeV$
$\Delta P_e = 306\ KeV$	$\Delta P_e = 150\ KeV$
$\Delta\Theta_{e\gamma} = 17\ mrad$	$\Delta\Theta_{e\gamma} = 2\ mrad$
$\Delta t_{e\gamma} = 122\ ns$	$\Delta t_{e\gamma} = 200\ ns$

Expected performance

$$N_{sig} \times 200$$

$$N_{bkg} \times (0.05\ (uncorr.) + 0.30\ (corr.))$$

Sensitivity, in principle, can be improved by almost 3 orders of magnitude down to

$$2 \times 10^{-15}$$

with a ×3 less background.

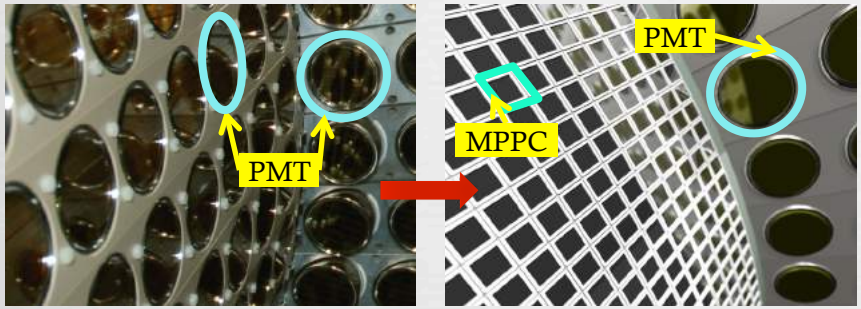
Conclusions

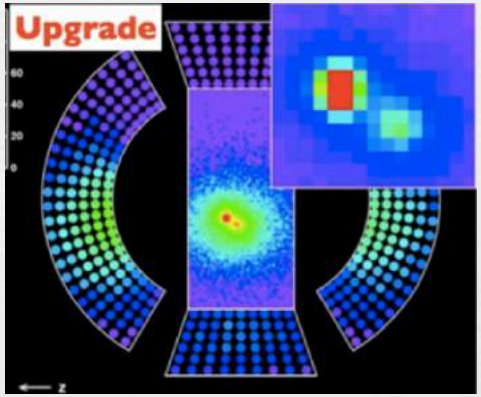
- Strong motivations for an upgraded MEG experiment aiming at setting an upper limit $\mathcal{B}(\mu^+ \longrightarrow e^+ + \gamma) < 5 \times 10^{-14}$.
- The design and the performance of the new tracking system, among the other subsystems, are crucial to reaching this goal.
- On the same beam line at PSI Mu3e experiment is being ready to demonstrate its capabilities.
- A new approach at improving the sensitivity for $\mu^+ \longrightarrow e^+ + \gamma$ has been presented.

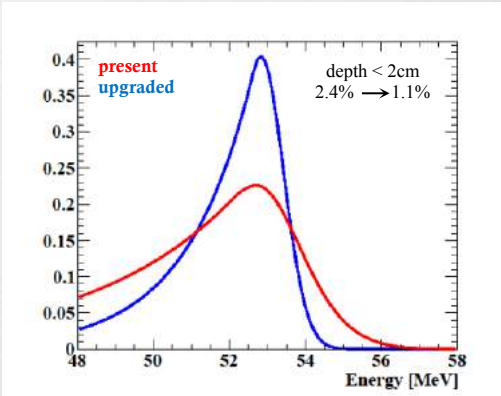
Additional slides

MEG2: Liquid Xe Cal.

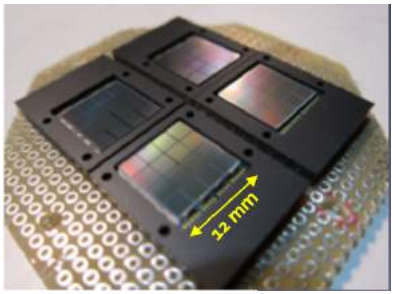
higher granularity in front face: => finer resolution, higher pile-up rejection





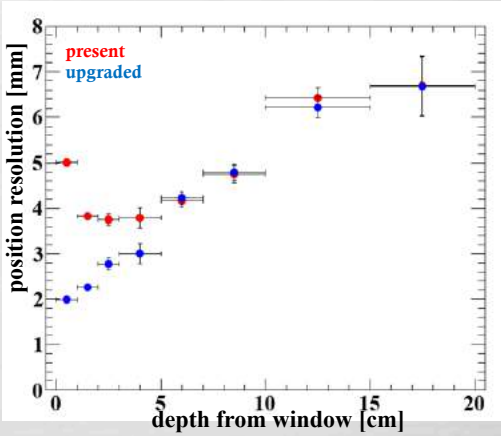


Large UV-ext SiPM



Developed UV sensitive MPPC (vacuum UV 12x12mm^2 SiPM)

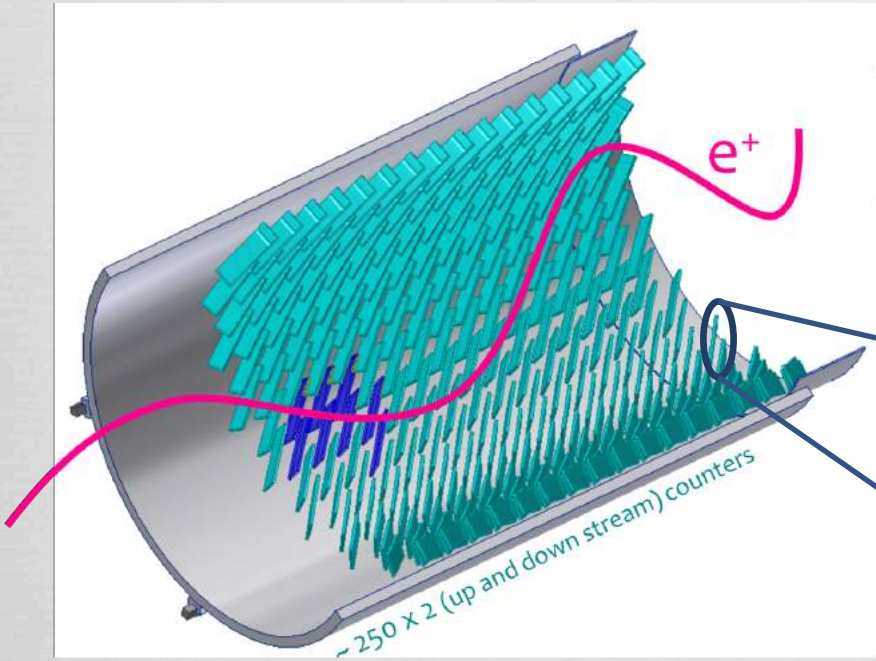
Detector under commissioning (calibrations by end of 2016)

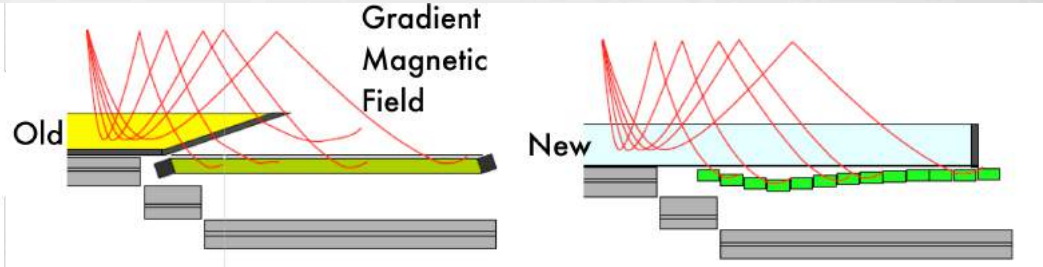


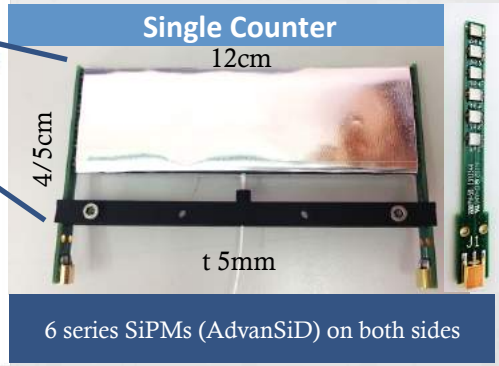
MEG2: Timing Counters

Hit time measurement with multiple hits in segmented timing counter (SiPM readout)

High rate tolerance, better timing resolution $\sigma \sim 30$ps

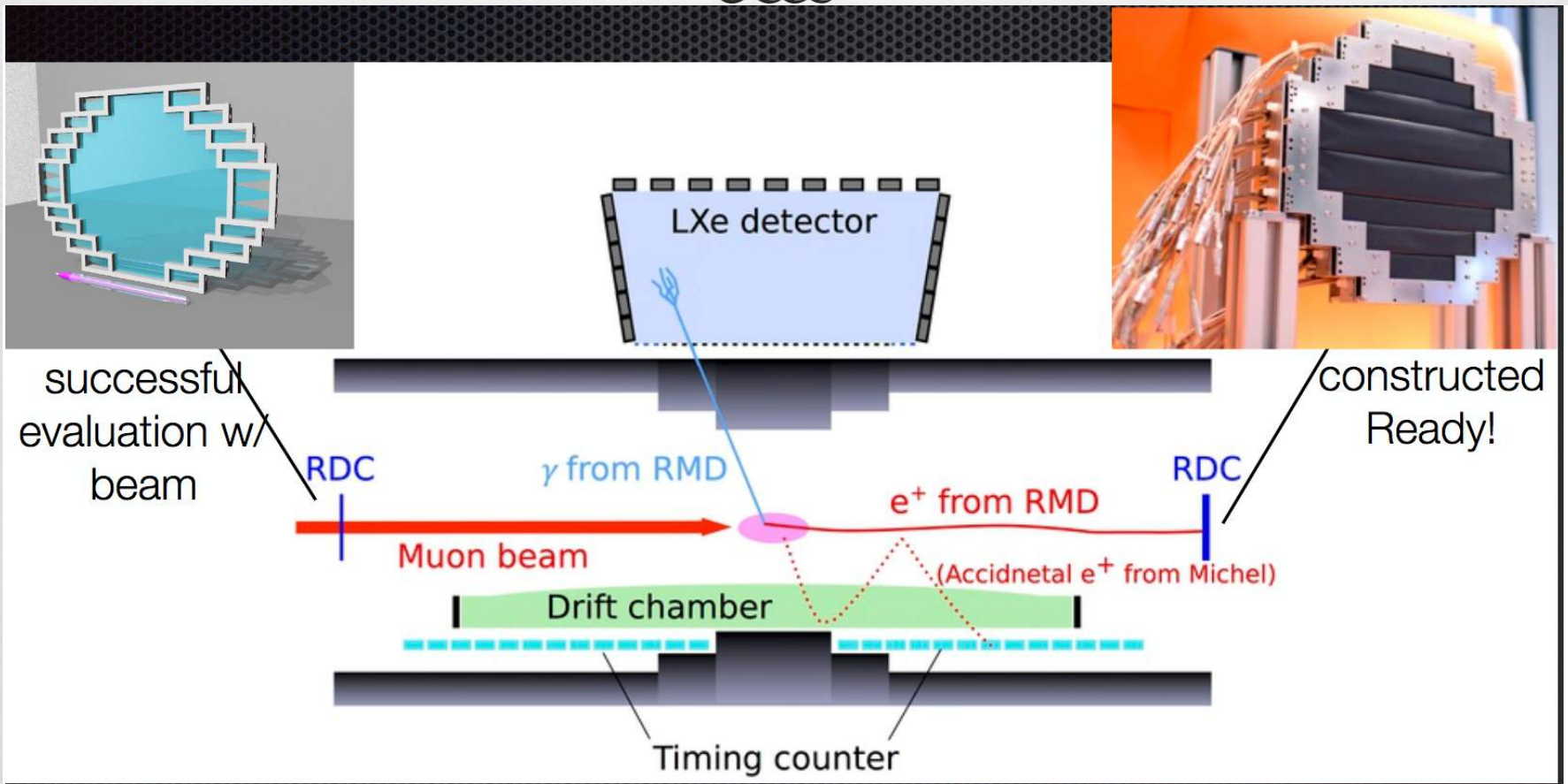






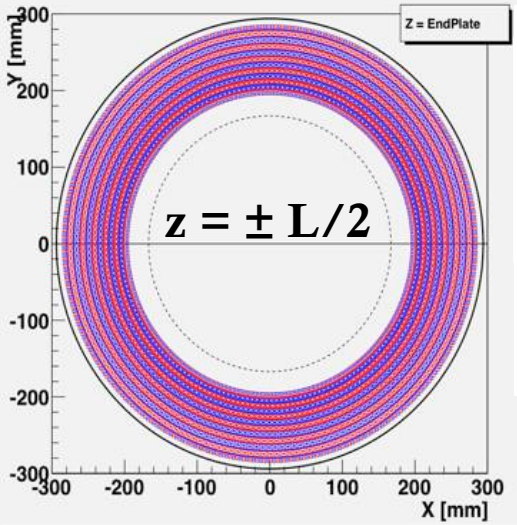
Installation completed by end of 2016

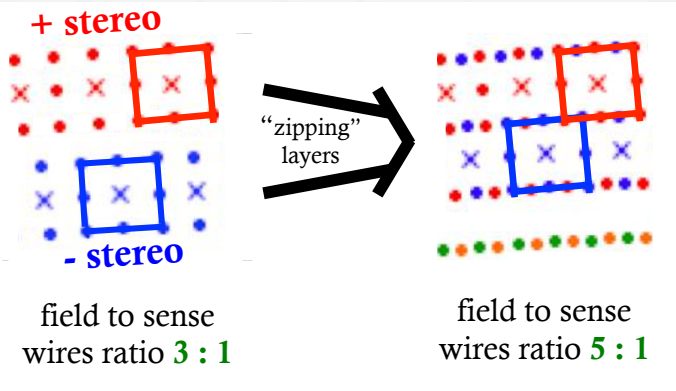
MEG2: RMD Counter

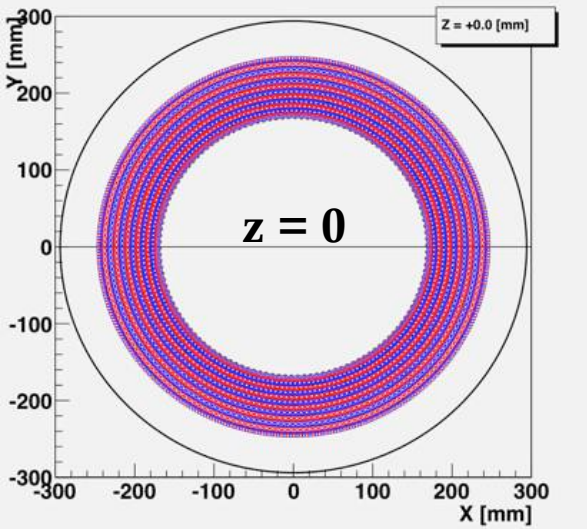


~28% sensitivity improvement by tagging gamma-rays from radiative decays

MEG2 DC layout

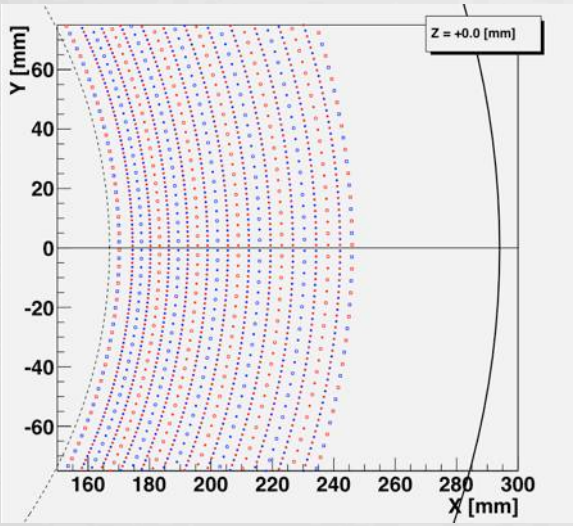


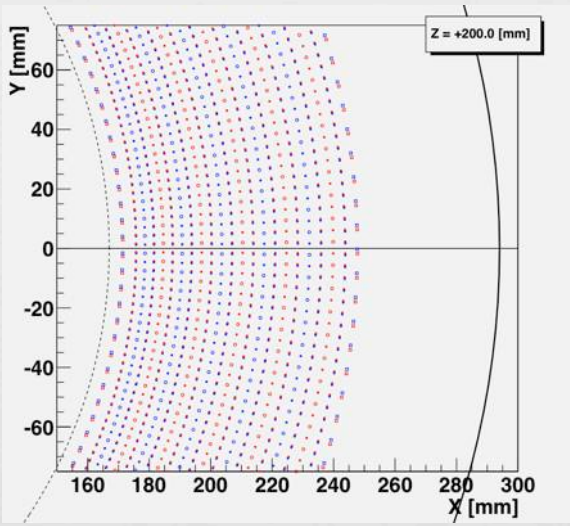


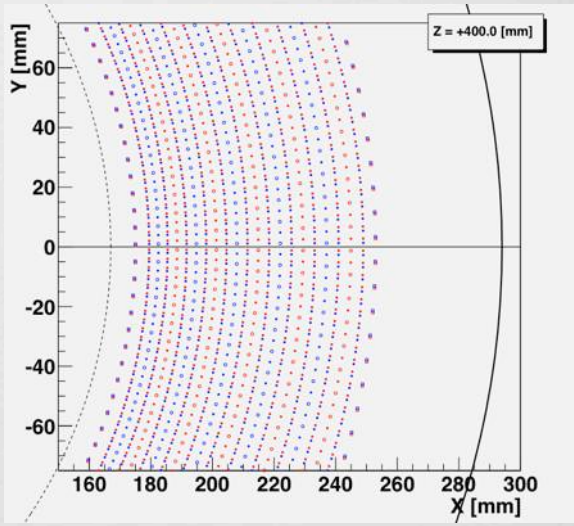


sense wires:	20 μm diameter W(Au)	=> 1920 wires
field and guard wires:	40 μm diameter Al(Ag)	=> 8448 wires
potential wires:	50 μm diameter Al(Ag)	=> 1920 wires

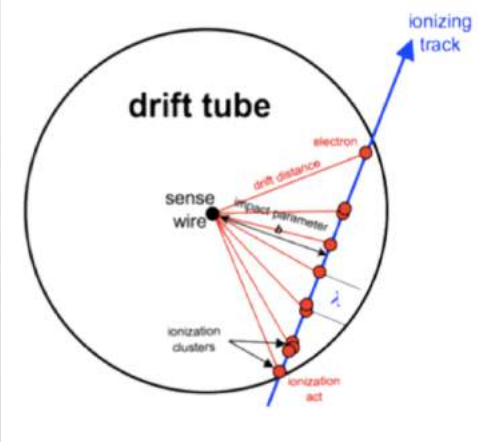
12,288wires in total



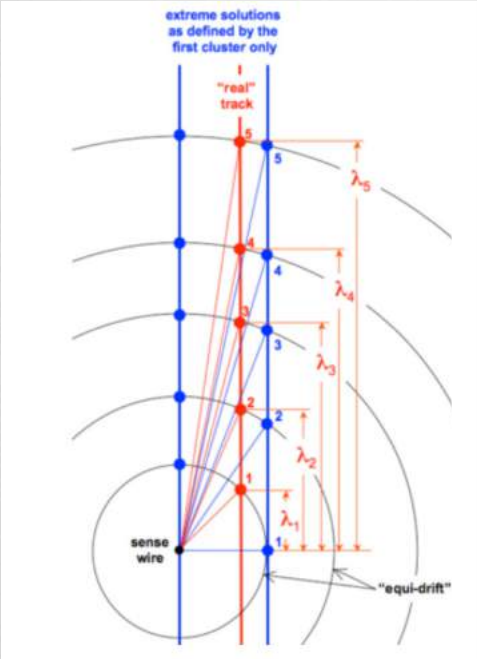




MEG2 DC Cluster Timing



From the **ordered sequence of the electrons arrival times**, considering the average time separation between clusters and their time spread due to diffusion, **reconstruct the most probable sequence of clusters drift times:** $\left\{t_i^{cl}\right\} \quad i = 1, N_{cl}$



For any given first cluster (**FC**) drift time, the **cluster timing technique** exploits the drift time distribution of all successive clusters to determine the most probable impact parameter, thus reducing the **bias** and the average **drift distance resolution** with respect to what is obtained from with the FC only.