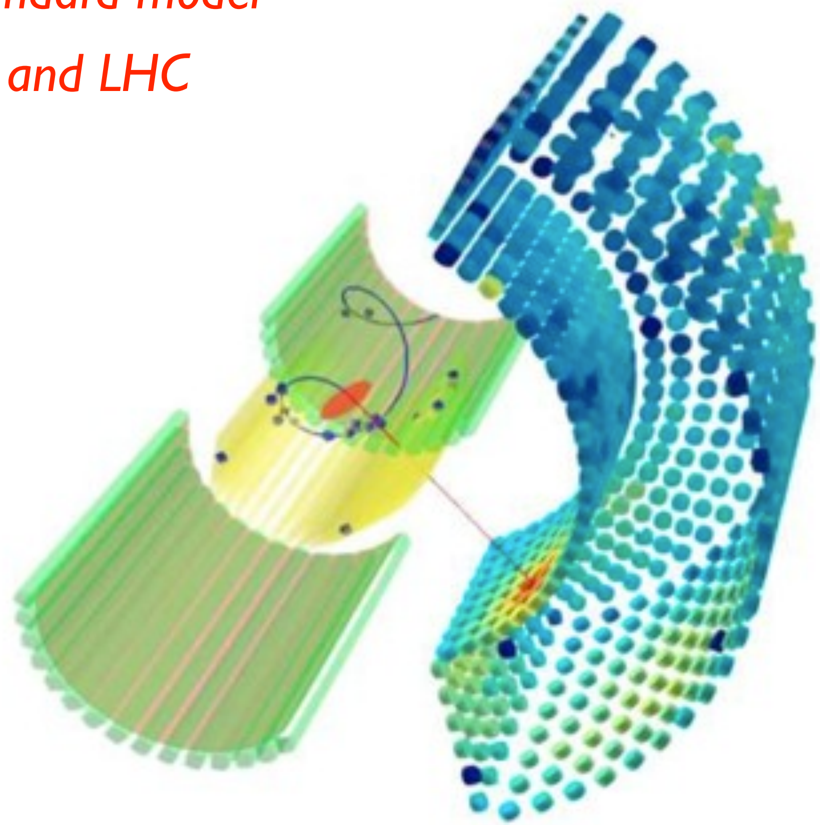
The MEG experiment: recent result and upgrade

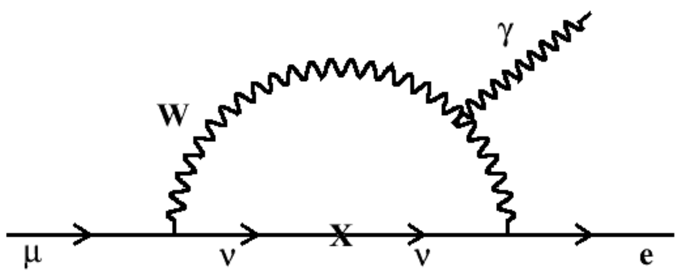
- Theoretical motivations
  - *μ→eγ decay probe of physics beyond standard model*
  - *comparison with other cLFV experiments and LHC*
- Experiment overview
  - *Signal and background*
  - *The detector*
- Latest result
  - *Improvements in data analysis*
  - *Result*
- The upgrade
  - *Design and R&D*
  - *Perspectives*



Luca Galli, Paul Scherrer Institut and INFN Pisa

Charged Lepton Flavor Violation in SM

- **cLFV forbidden** in the **Standard Model** with **vanishing neutrino masses**
- **extremely suppressed** in the SM extension with **neutrino oscillation**
  - *example:* ***BR(μ→eγ) ≈ 10^{-50} not measurable*** *by any experiment*



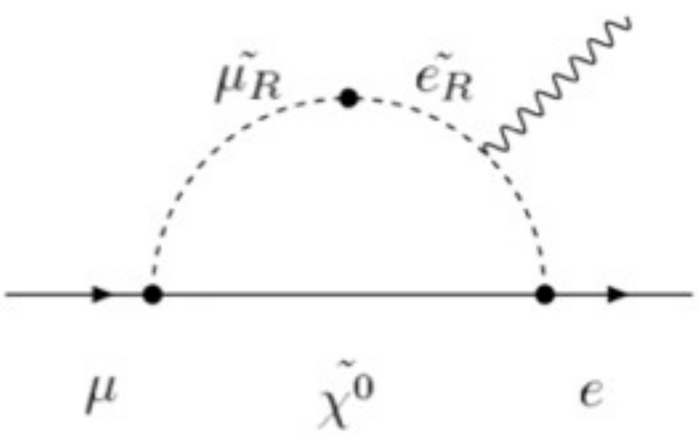
$$\Gamma(\mu \to e\gamma) \approx \underbrace{\frac{G_F^2 m_\mu^5}{192\pi^3}}_{\mu-\text{decay}} \underbrace{\left(\frac{\alpha}{2\pi}\right)}_{\gamma-\text{vertex}} \underbrace{\sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2}{M_W^2}\right)}_{\nu-\text{oscillation}}$$

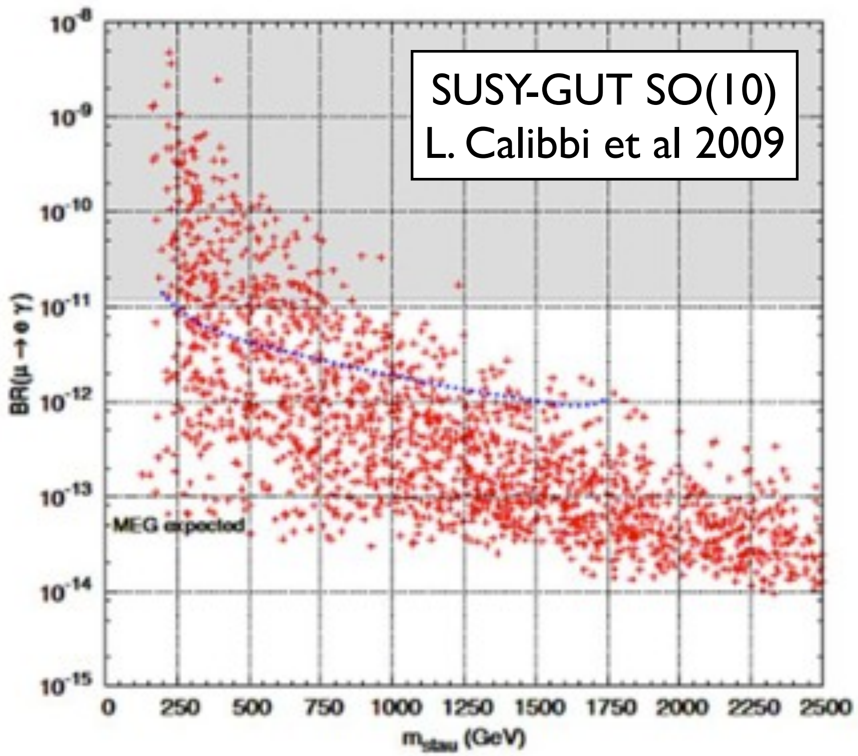
$$\approx \frac{G_F^2 m_\mu^5}{192\pi^3} \frac{3\alpha}{32\pi} \left(\frac{\Delta m_{23}^2 s_{13} c_{13} s_{23}}{M_W^2}\right)^2$$

➡ **μ→eγ** as a **clean probe** of **new physics** beyond the Standard Model

cLFV beyond the SM

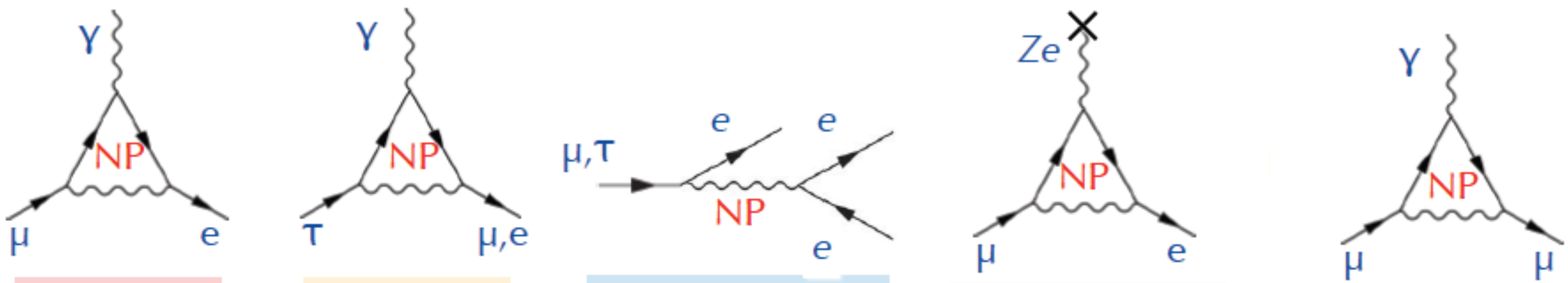
- **Huge enhancement** in several **beyond** the **SM** in particular in **Supersymmetric and Grand Unification Theories**
  - ***B(μ→eγ) ≈ (10^{-14} ÷ 10^{-12})*** *experimentally* ***accessible****!!*
  - *New physics* ***discovery*** *or* ***tight limits*** *on their parameters*





cLFV zoology

Several **cLFV processes sensitive** to **New Physics**



$\mu \to e\gamma$

$\tau \to \mu\gamma$
$\tau \to e\gamma$

$\mu \to eee$

$\mu^- \mathcal{N} \to e^- \mathcal{N}$

$(g-2)_\mu$

Lepton anomalous decay

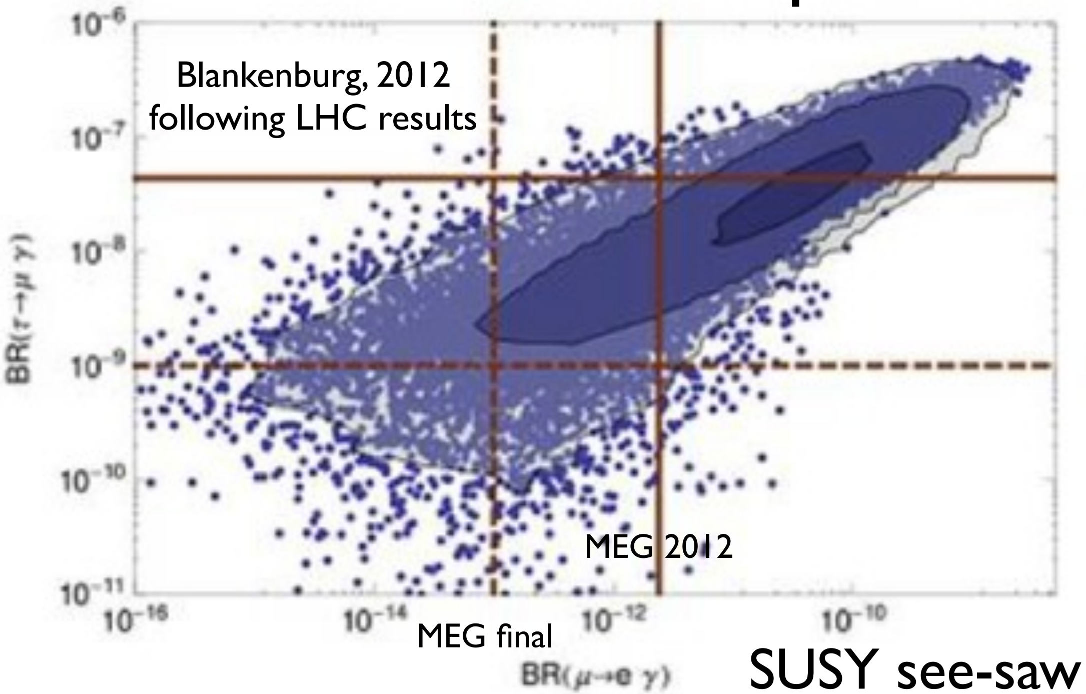
μ→e conversion in nuclei

Anomalous magnetic moment

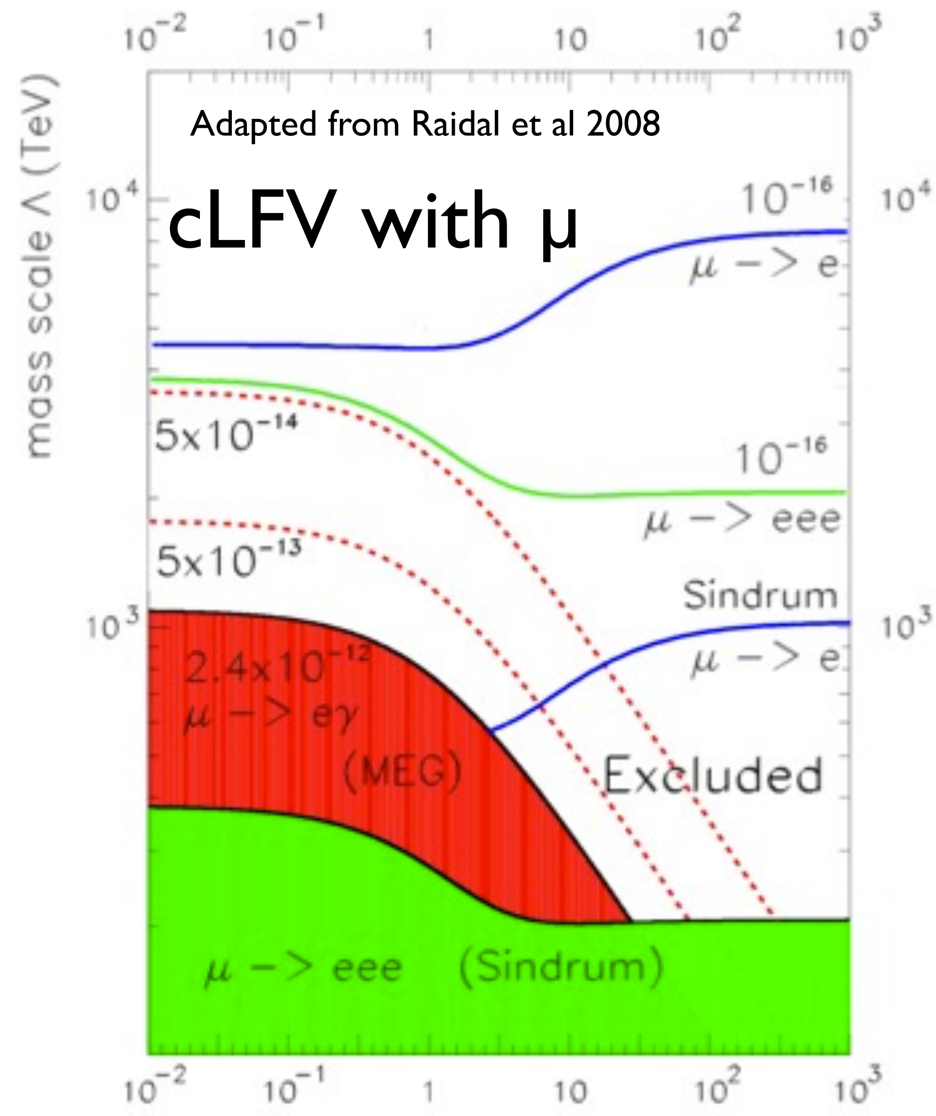
complementary processes to **define** the **nature** of NP

cLFV violation prediction comparison

cLFV in τ and μ

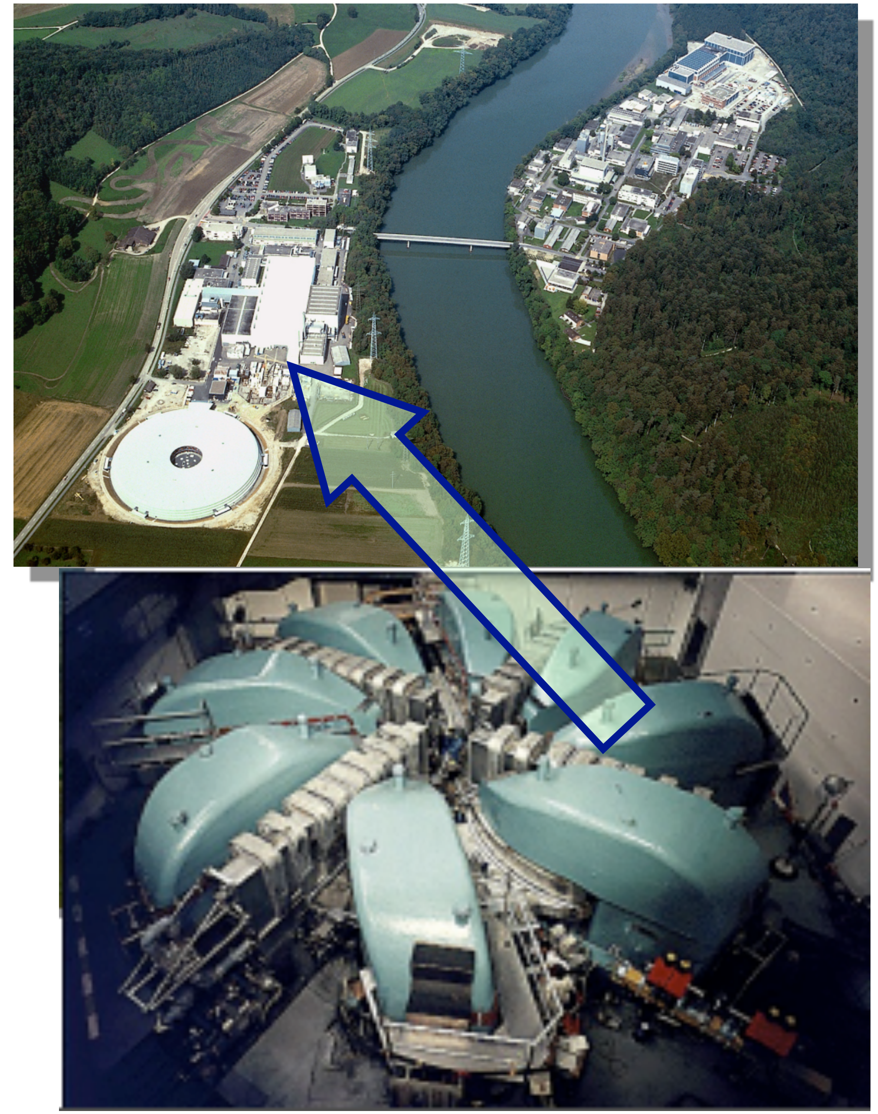


Relative probability as a **function** of **many parameters**



Effective lagrangian: Λ **energy scale**, κ **coupling** to 4 fermions diagram

The MEG experiment at PSI

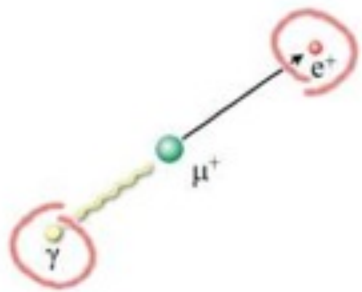


<u>Why PSI?</u>

. The **most powerful continuous** machine in the world
. Proton energy **590 MeV**
. Power **1.2 MW**
. Nominal operational current **2.4 mA**
. **μ beam** up to **10^8 μ/sec, more than needed**

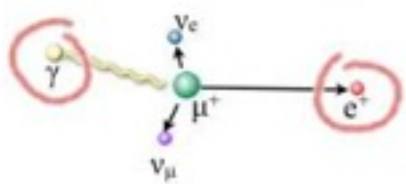
Signal and background

Signal



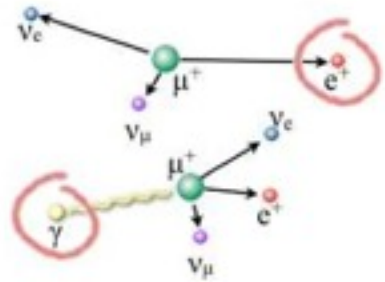
$E_\gamma = 52.8$ MeV
$E_{e^+} = 52.8$ MeV
$\Theta_{e\gamma} = 180°$
$T_{e\gamma} = 0$ s

Radiative Muon Decay



$E_\gamma < 52.8$ MeV
$E_{e^+} < 52.8$ MeV
$\Theta_{e\gamma} < 180°$
$T_{e\gamma} = 0$ s

Accidental



$E_\gamma < 52.8$ MeV
$E_{e^+} < 52.8$ MeV
$\Theta_{e\gamma} < 180°$
$T_{e\gamma} \Rightarrow$ flat

Accidental bkg is **dominant** and determined by **beam rate** and **resolutions**

$$B_{acc} \propto R_\mu \Delta E_e \Delta E_\gamma^2 \Delta\Theta_{e\gamma}^2 \Delta t_{e\gamma}$$

$$B_{RMD} \approx 0.1 \cdot B_{acc}$$

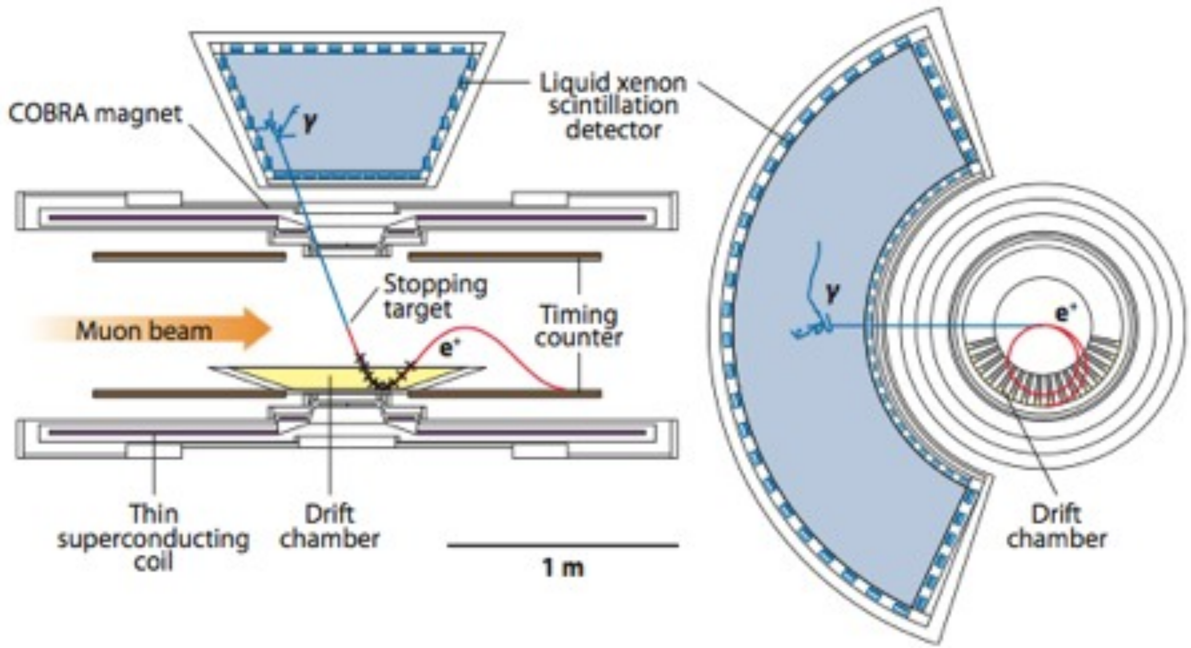
Exp./Lab	Year	ΔEe/Ee (%)	ΔEγ /Eγ (%)	Δteγ (ns)	Δθeγ (mrad)	Stop rate (s^{-1})	Duty cyc.(%)	BR (90% CL)
SIN	1977	8.7	9.3	1.4	-	5×10^5	100	3.6×10^{-9}
TRIUMF	1977	10	8.7	6.7	-	2×10^5	100	1×10^{-9}
LANL	1979	8.8	8	1.9	37	2.4×10^5	6.4	1.7×10^{-10}
Crystal Box	1986	8	8	1.3	87	4×10^5	(6..9)	4.9×10^{-11}
MEGA	1999	1.2	4.5	1.6	17	2.5×10^8	(6..7)	1.2×10^{-11}
MEG	2008 - x	1	4.5	0.15	19	3×10^7	100	5×10^{-13}

The MEG detection technique

MEG keywords:
1) **thin** → "low" energy
2) **fast** → high rate → intensity frontier
3) **stable** → precision measurement → background rejection

. **μ beam stopped** on a 205μm polyethylene target (1)
. **non uniform** solenoidal **magnetic** field (2)
. tracking with **ultra-thin DC** (1) and timing with **plastic scintillators** (2)
. γ detection with **LXe scintillator** (1+2)
. **complete** and **redundant calibration** techniques (3)

The MEG detector

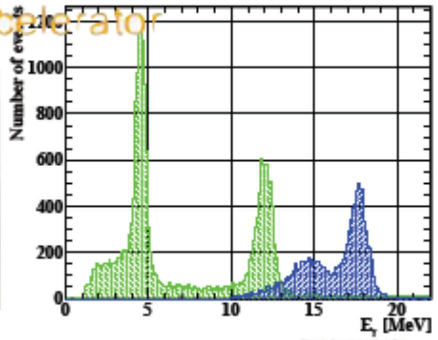


Detector OUTLINE

- **μ decay** at **rest**
  - *Beam rate:* ***3×10⁷ μ/s***
  - *μ stopped in* ***205 μm target***
- γ detection
  - ***Liquid Xenon*** *calorimetry with* ***scintillation light***
    - **fast**: 4/22/45 ns
    - **high LY**: ~0.8 NaI
    - **short X_0**: 2.77 cm
- e^+ detection
  - ***magnetic spectrometer***
    - **non-uniform B field → constant bending radius** and **e^+ swept rapidly away**
    - **ultra-thin drift chambers** to **limit matter effects (X_0 ~ 0.0003 per module)**
  - ***TC detector***
    - **time of flight** with **plastic scintillator counters**
    - **transverse scintillation fibers → hit position**

Calibration system (a subset!)

Proton Accelerator



Li(p,γ)Be

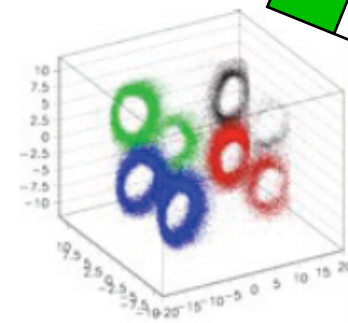
LiF target at COBRA center

17.6MeV γ

~daily calib.

also for initial setup

Alpha on wires

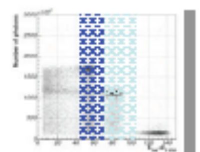


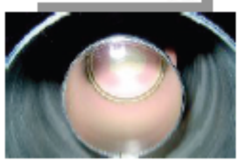
PMT QE & Att. L

Cold GXe

LXe

$\pi^0 \to \gamma\gamma$



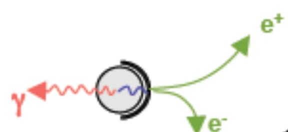


$\pi^- + p \to \pi^0 + n$

$\pi^0 \to \gamma\gamma$ (55MeV, 83MeV)

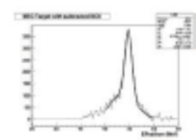
$\pi^- + p \to \gamma + n$ (129MeV)

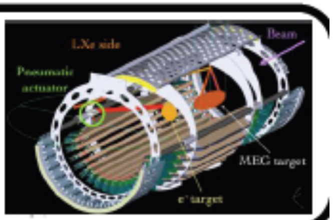
LH_2 target



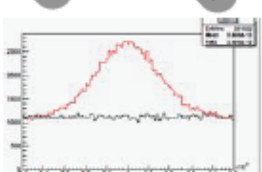
Detector Calibration

Mott e+ scattering





μ radiative decay

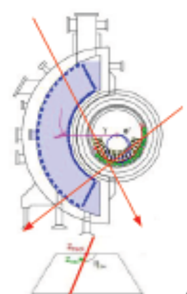


Lower beam intensity < 10^7

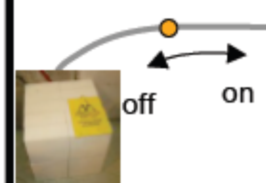
Is necessary to reduce pile-ups

A few days ~ 1 week to get enough statistics

Cosmic ray alignment

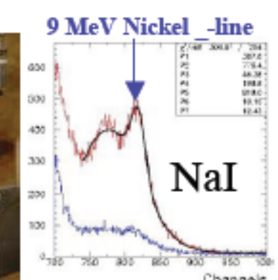


Nickel γ Generator



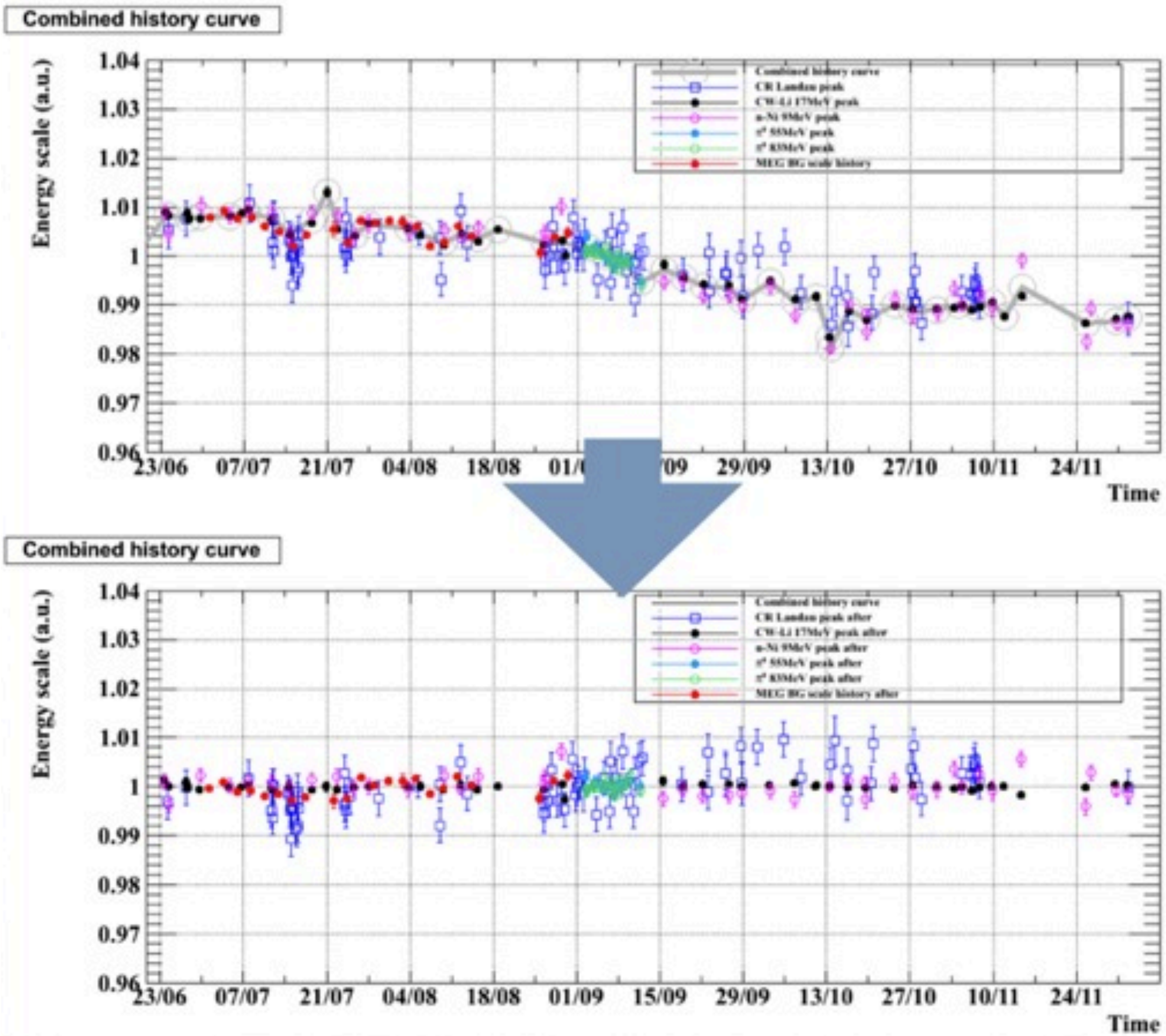
Illuminate Xe from the back

Source (Cf) transferred by comp air → on/off



Passed down to MEGUP!!!

Relevant example: LXe energy scale

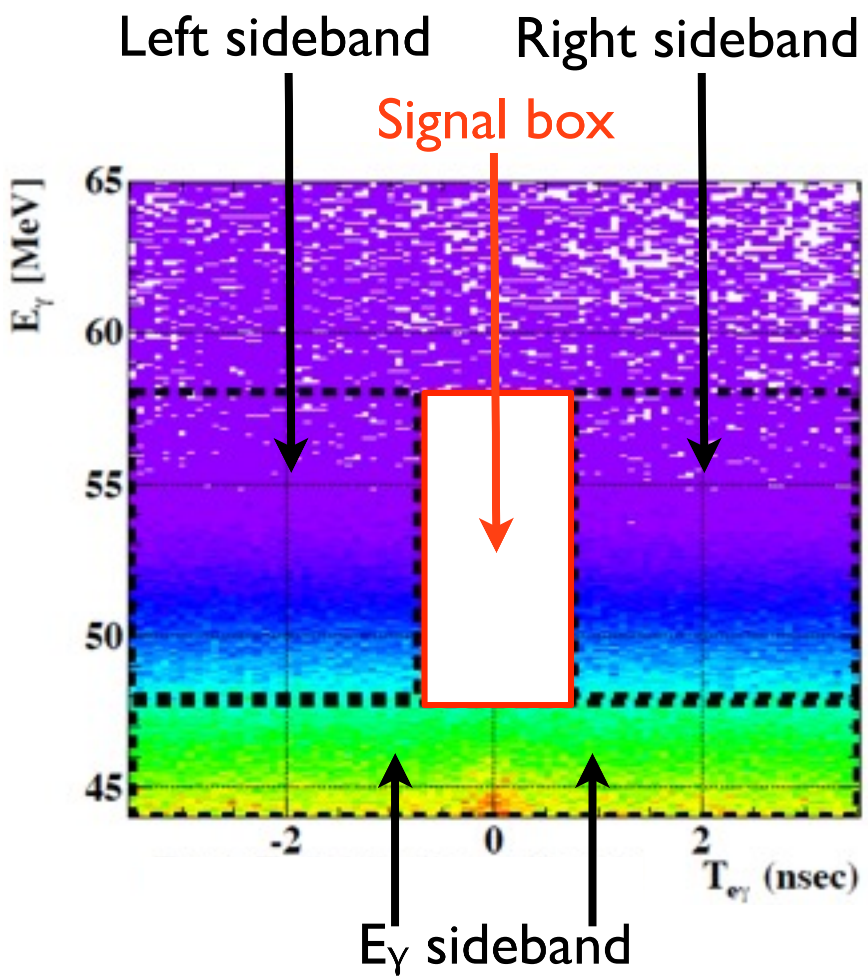


γ energy scale **before** and **after** calibration

uncertainty less than 0.5%

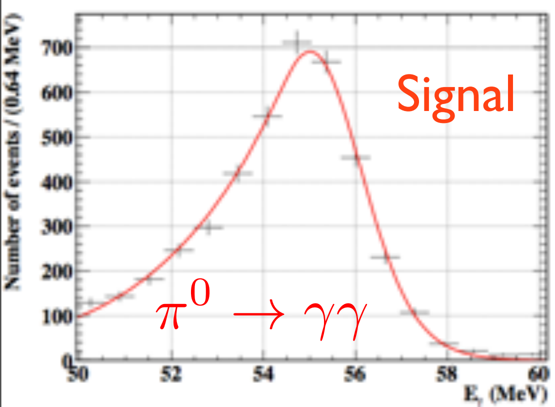
Analysis strategy

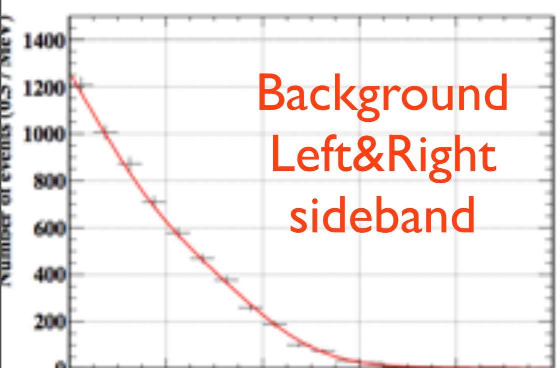
- Decided to extract **CL to B(μ→eγ)** from a **likelihood analysis** in a **wide signal box**
- Each **event** is described in terms of **5 kinematic variables**
  - $x_i = (E_\gamma, E_e, t_{e\gamma}, \varphi_{e\gamma}, \theta_{e\gamma})$
- **resolutions** and **PDFs** evaluated **on data outside the signal box**
  - *signal box* ***closed*** *until* ***analysis is fixed***
- Use of **sidebands**
  - ***accidental background*** *from* ***Left and Right sidebands***
  - ***Radiative Muon Decay*** *(RMD) studied in the* ***E_γ sideband***



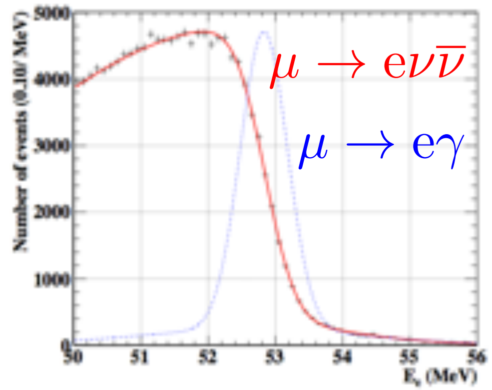
Probability density functions

Photon

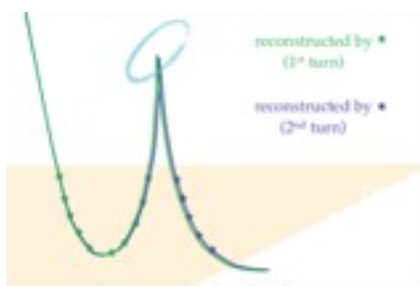




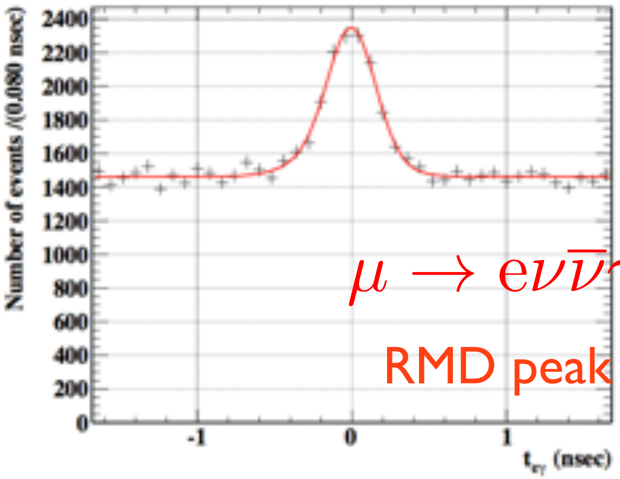
Positron



Resolutions from Michel edge and double turns method



Relative timing



Variable	Foreseen	Obtained
ΔE_γ (%)	1.2	1.7
Δt_γ (psec)	43	67
γ position (mm)	4(u,v),6(w)	5(u,v),6(w)
γ efficiency (%)	> 40	63
ΔP_e (KeV)	200	306
e^+ angle (mrad)	$5(\phi_e),5(\theta_e)$	$8.7(\phi_e),9.4(\theta_e)$
Δt_{e^+} (psec)	50	107
e^+ efficiency (%)	90	40
$\Delta t_{e\gamma}$ (ps)	65	122

Likelihood function

- **Likelihood** function in terms of **S**ignal, **R**adiative muon decay, and accidental **B**ackground **number of events** and **PDFs**

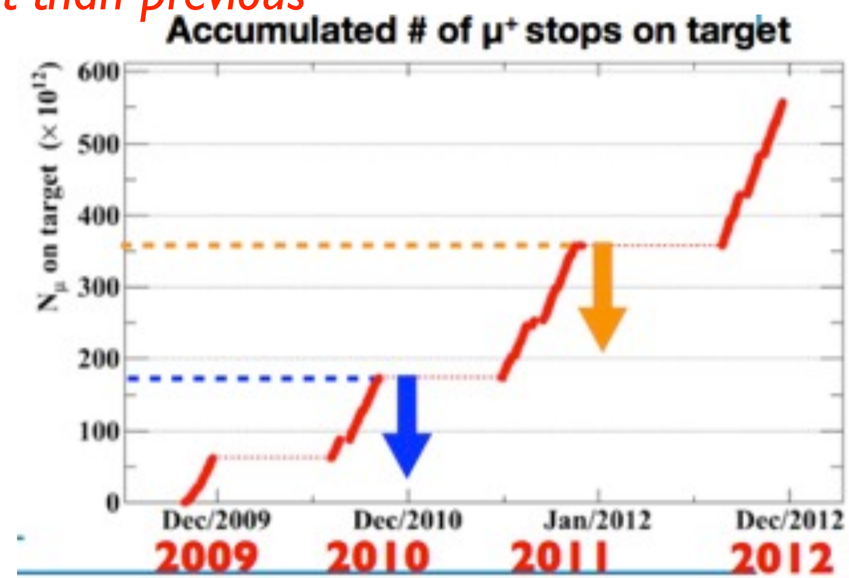
$$\mathcal{L}(N_{\rm sig}, N_{\rm RMD}, N_{\rm BG}) = \frac{e^{-N}}{N_{\rm obs}!} \boxed{e^{-[(N_{\rm RMD}-\langle N_{\rm RMD}\rangle)^2/2\sigma^2_{\rm RMD}]}}$$
$$\times \boxed{e^{-[(N_{\rm BG}-\langle N_{\rm BG}\rangle)^2/2\sigma^2_{\rm BG}]}} \prod_{i=1}^{N_{\rm obs}} [N_{\rm sig} S(\vec{x}_i)$$
$$+ N_{\rm RMD} R(\vec{x}_i) + N_{\rm BG} B(\vec{x}_i)],$$

Number of background events constrained with side bands

- **N$_S$**, **N$_R$**, **N$_B$** measured **simultaneously** with an **un-binned** Likelihood fit in the **analysis box**
- **B(μ→eγ) C.L.** with **Feldman and Cousins**
- Cross-check:
  - ***two*** *independent* ***frequentistic analysis*** *with* ***different PDFs***
    - **Analysis A:** separated angles **(θeγ, φeγ)** and **event by event PDFs**
    - **Analysis B**: stereo angle **Θeγ constant PDF**
  - ***third*** *analysis based on* ***Bayesian statistics***

MEG history

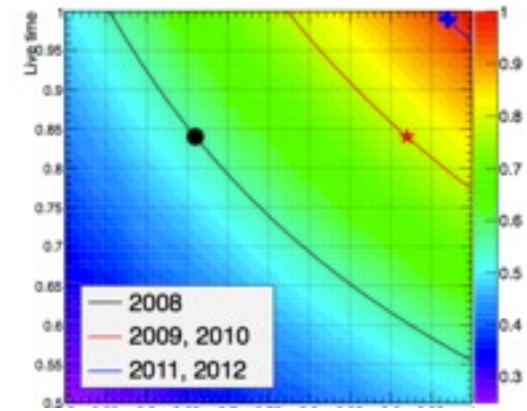
- **1999:** approved at PSI
- **2007:** Detector construction /commissioning/engineering run
- **2008:** DAQ started
- **2010:** Preliminary result based on low quality 2008 data
- **2011:** Published analysis result with 2009-2010 dataset (1.65 x 10^{14} μ^+)
  - ***BR<2.4 x 10^{-12} (90% C.L.)*** *(x5 more stringent than previous experiment)*
- **2013:** New result (this seminar)
  - *combined analysis 2009-2011 (3.6 x 10^{14} μ^+)*



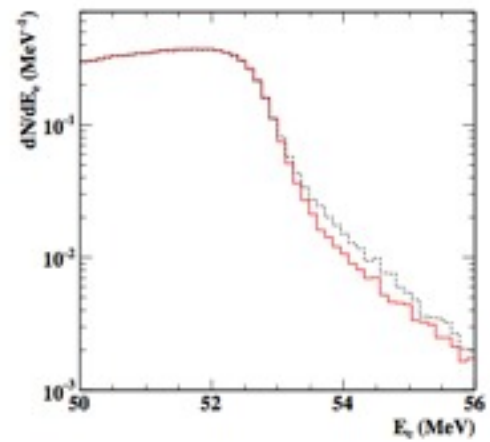
- **Last MEG run 2013 ready to start!**

What's new in the last result?

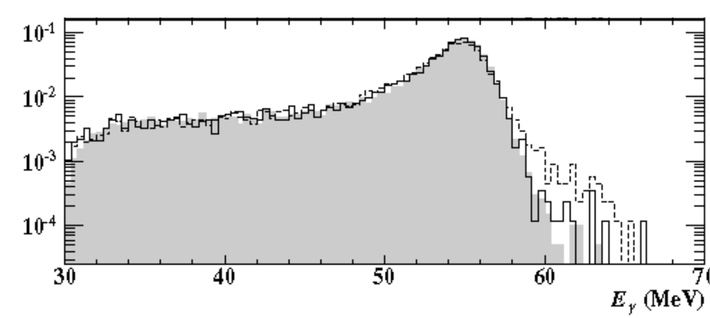
- Hardware
  - ***Multiple buffer** read out → **DAQ efficiency = 96%***



- Software
  - *e^+ side:*
    - new DC-waveform **noise filtering** → **improved resolution**
    - **new Kalman filter** implementation → **higher efficiency** and **reliable** per event track **fit uncertainties**
      - ***per event PDFs***



  - *γ-detector side:*
    - **improved pile up rejection** algorithm → **steeper background spectrum** close to signal region



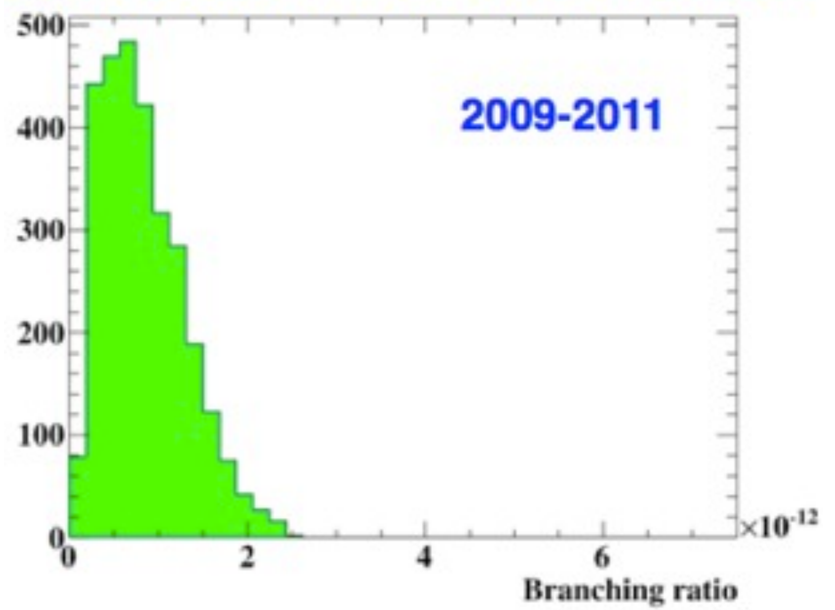
Sensitivity

- **Sensitivity**: **90% C.L.** upper limit **averaged** over **pseudo-experiments** based on **null-signal hypothesis** with **expected** rates of RMD and accidental BG.
- **~20% improvements** in the same sample 2009-2010 in total with the **new algorithms**
- **Now** MEG is in the **B≈10^{-13} region**!

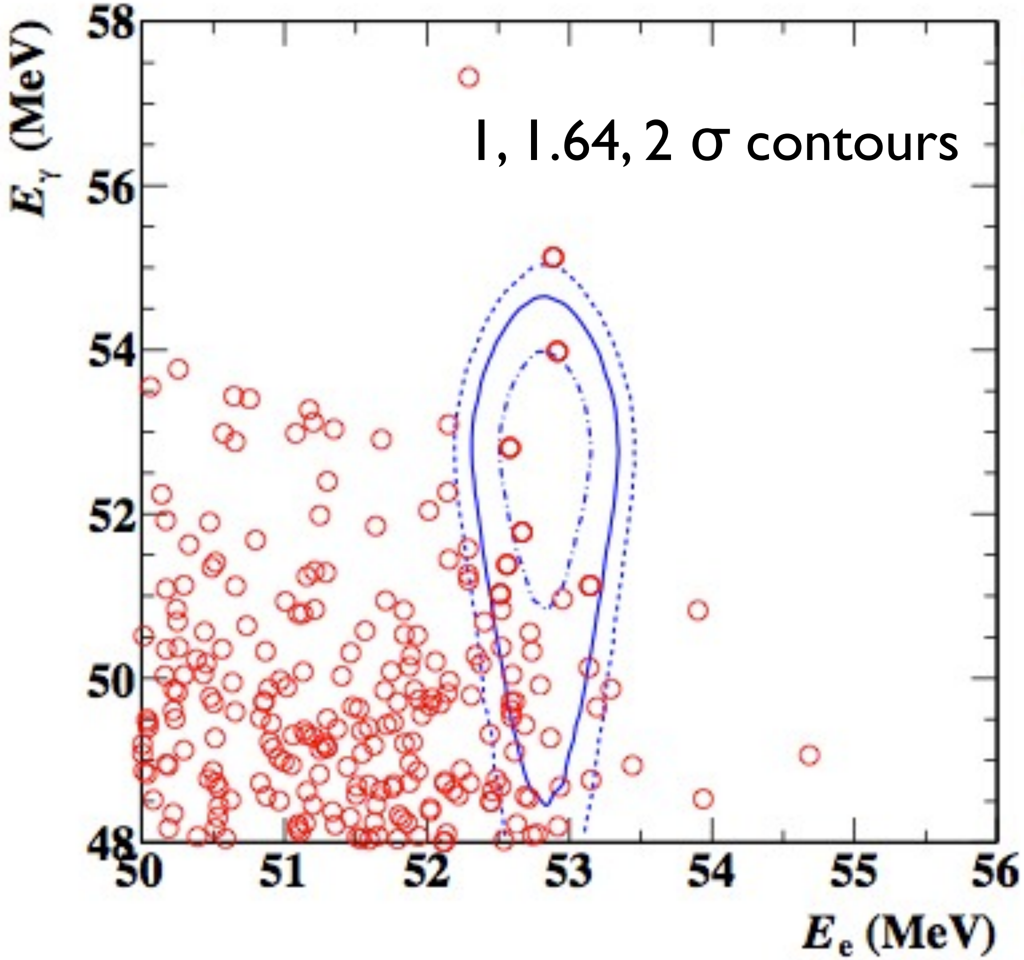
	μ^+ stops	Sensitivity
2009-2010	1.75×10^{14}	1.3×10^{-12}*
2011	1.85×10^{14}	1.1×10^{-12}
2009-2011	3.60×10^{14}	7.7×10^{-13}

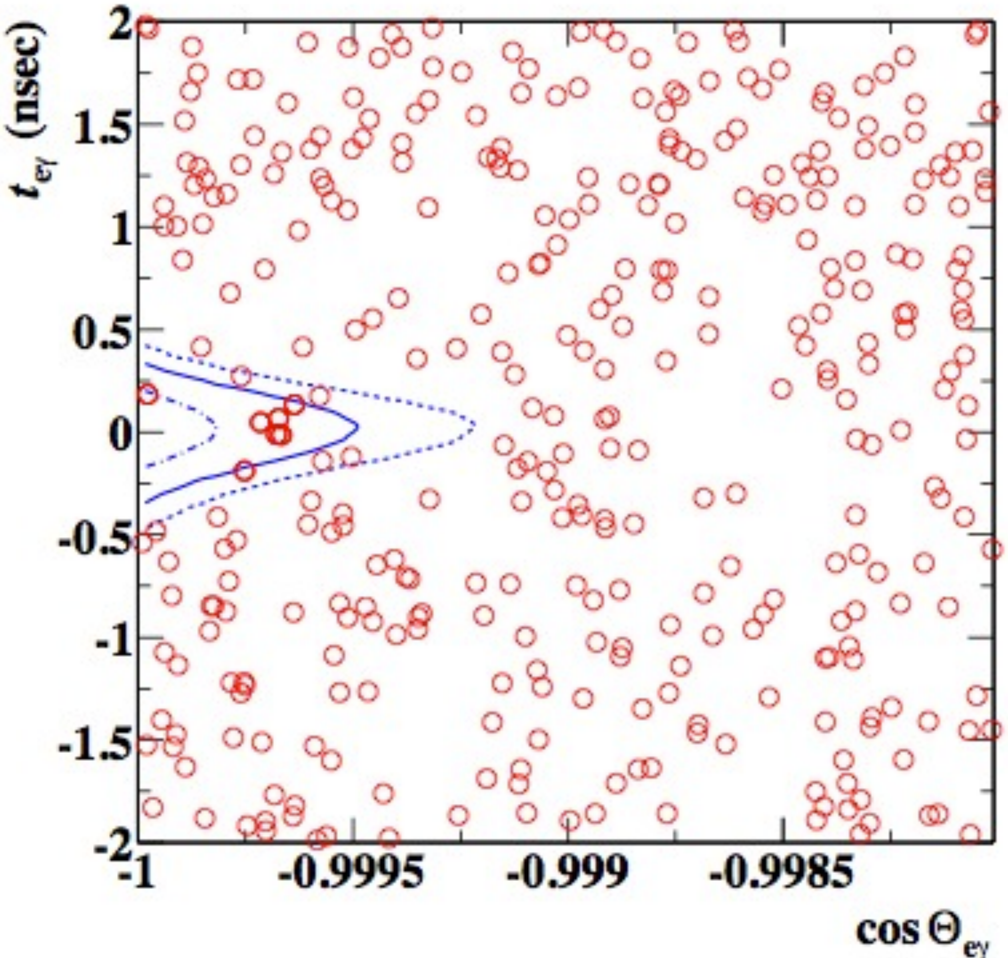
* 1.6×10^{-12} in previous analysis

Distribution of 90%UL in pseudo exp.



Event distribution





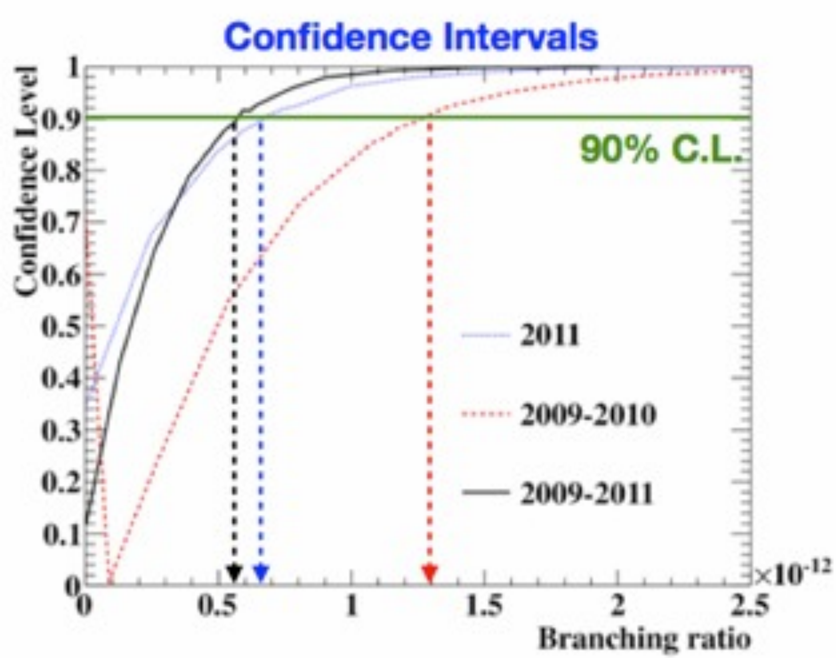
Cut on time and angle:
$|t_{e\gamma}| < 0.244$ ns
$\cos\theta_{e\gamma} < -0.9996$

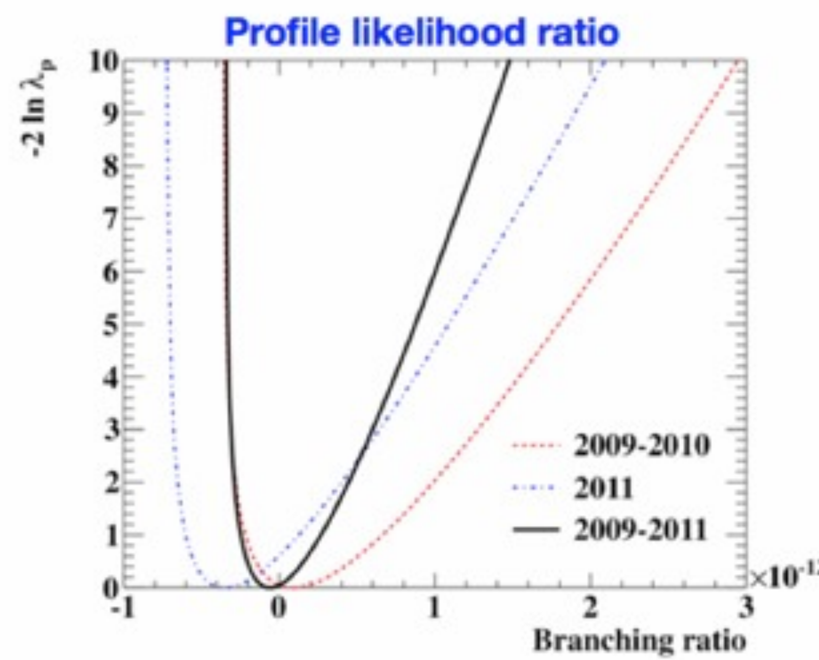
Cut on energies:
$52.4 < E_e < 55$MeV
$51 < E_\gamma < 55.5$MeV

Confidence interval

- **Confidence interval** calculated with **Feldman-Cousins** method + **profile likelihood** ratio ordering
- **Consistent** with **null-signal** hypothesis
- **Confirmed** by **other analyses**

BR < 5.7 10^{-13}





CL curve: Allowed region of branching ratio can be read at given confidence level.

N.B. likelihood curves are not directly used in confidence interval calculation

For more details

- arXiv: 1303.0754 (approved by PRL)

New constraint on the existence of the $\mu^+ \to e^+\gamma$ decay

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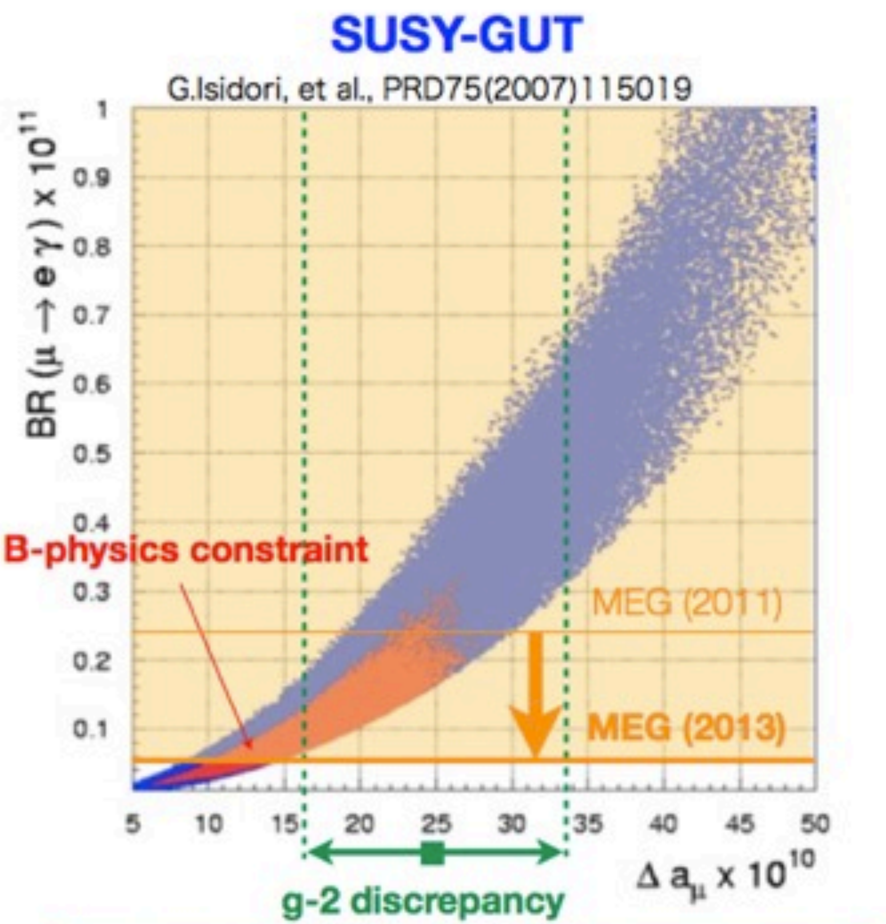
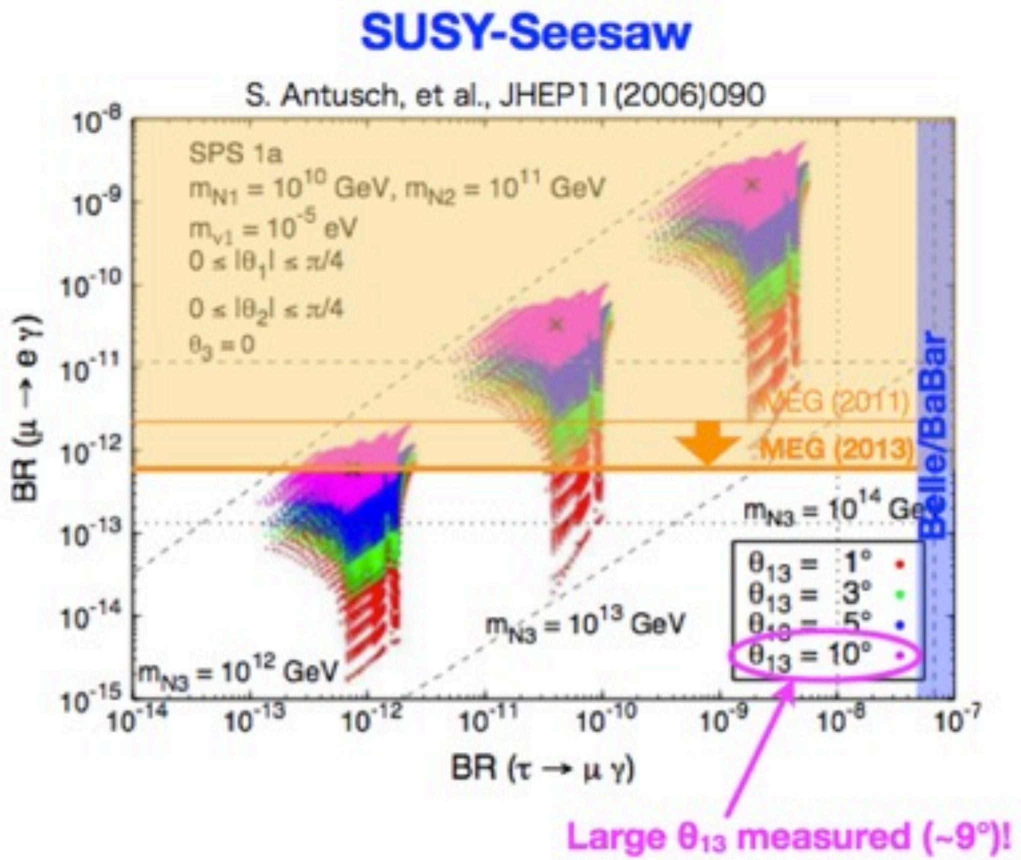
(Dated: March 4, 2013)

The analysis of a combined dataset, totaling 3.6×10^{14} stopped muons on target, in the search for the lepton flavour violating decay $\mu^+ \to e^+\gamma$ is presented. The data collected by the MEG experiment at the Paul Scherrer Institut show no excess of events compared to background expectations and yield a new upper limit on the branching ratio of this decay of 5.7×10^{-13} (90% confidence level). This represents a four times more stringent limit than the previous world best limit set by MEG.

Constraints on New Physics, two examples





Inconsistency arising... compatibility with LHCb

Willing for one more order of magnitude!!!!

MEG perspectives

- The **2012 run already performed**
  - ***10% more statistics*** *w.r.t.* ***2011*** *run,* ***analysis ongoing***
- The **2013 run ready** to start in the **middle of May** until to **end of August, together** with **2012** will **double** this **seminar statistics**
  - ***Detector*** *already under* ***preliminary calibrations***

Data statistics will be doubled with 2012+2013 (est.)

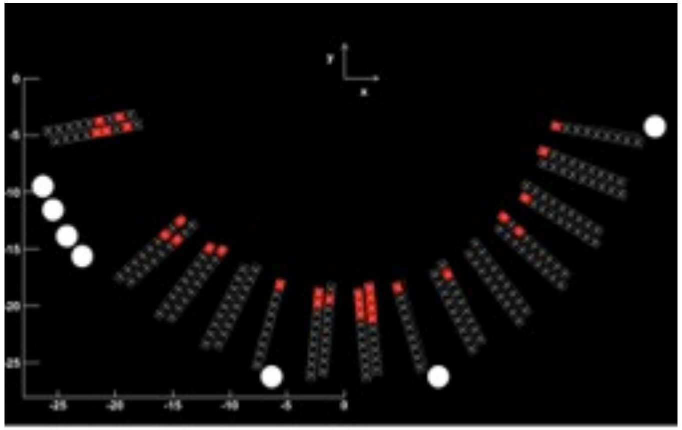
Final MEG S = 5 10^{-13}

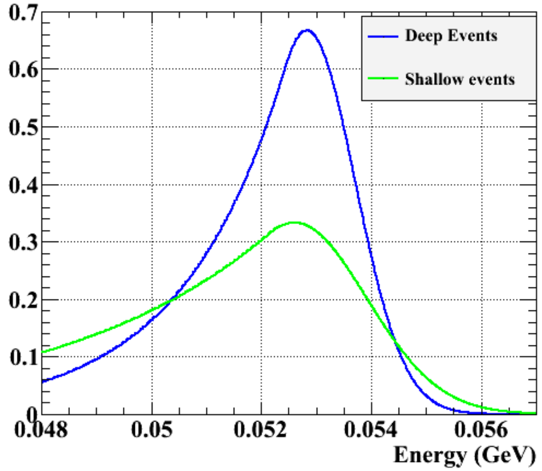
Waiting for even more...

Why an upgrade?

- The **resolution** are **NOT** at the **proposal level** in particular in the **positron side**
  - ***DC hit resolution worse*** *than expected and* ***HW*** *and* ***design inefficiencies***
  - ***Problems*** *with* ***shallow events*** *in* ***LXe detector***

Variable	Foreseen	Obtained
ΔE_γ (%)	1.2	1.7
Δt_γ (psec)	43	67
γ position (mm)	4(u,v),6(w)	5(u,v),6(w)
γ efficiency (%)	> 40	63
ΔP_e (KeV)	200	306
e^+ angle (mrad)	$5(\phi_e),5(\theta_e)$	$8.7(\phi_e),9.4(\theta_e)$
Δt_{e^+} (psec)	50	107
e^+ efficiency (%)	90	40
$\Delta t_{e\gamma}$ (ps)	65	122

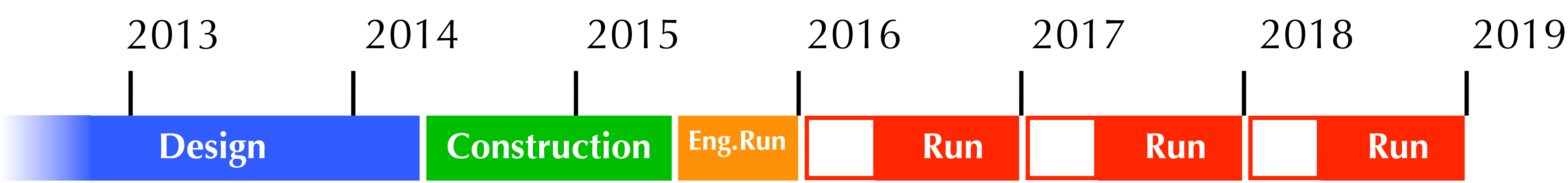




MEG Upgrade

- It is an **upgrade**, **NOT** a **new experiment**!
  - ***improving*** *the final MEG sensitivity* ***by an order of magnitude ~ 5x10^{-14}***
- Limited to a **reasonable time span**
- Make the **best usage** of existing
  - ***infrastructures***
    - **beam line, magnet, cryostat, calibrations** (CW)
  - ***knowledge*** *accumulated in these 12 years*
  - ***expertise*** *inside the collaboration*

- **MEG^{UP} approved and financed** by **INFN** and also in **Japan** and **Switzerland**



The MEG$^{\mathrm{UP}}$ collaboration

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JINR Dubna
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Key elements to MEG^{UP}

μ

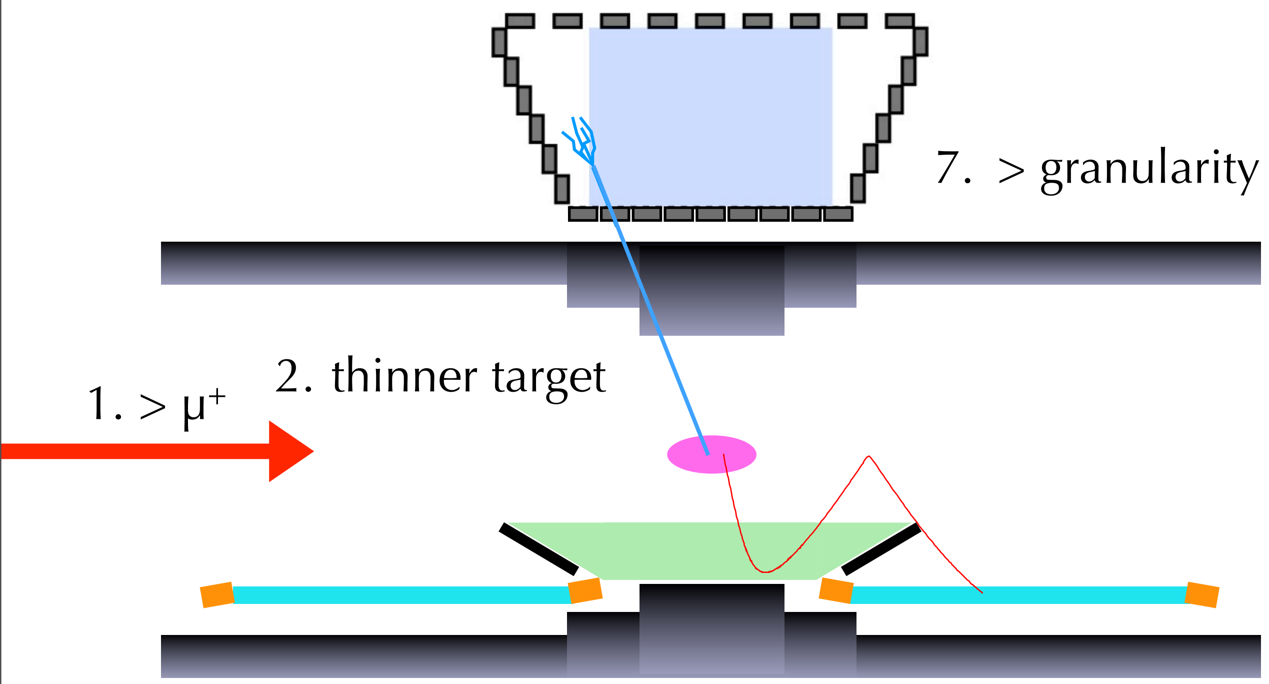
e

γ

1. **Increasing μ^+-stop** on target
2. **Reducing** target **thickness** to minimize e^+ MS & brehmsstrahlung (**or** replace it with an **active target**)
3. **Replacing** the **e^+ tracker** reducing its radiation length and **improving** its **granularity** and **resolution**
4. **Improving** the **timing counter granularity** for **better timing** and **reconstruction**
5. **Improving** the **e^+ tracking-timing integration** by measuring the e^+ trajectory up to the TC interface
6. **Extending γ-ray** detector **acceptance**
7. **Improving** the **γ-ray energy** and **position resolution** for **shallow** events
8. **Integrating splitter, trigger and DAQ** maintaining high bandwidth

MEG^{UP} at a glance

6. > LXe acceptance



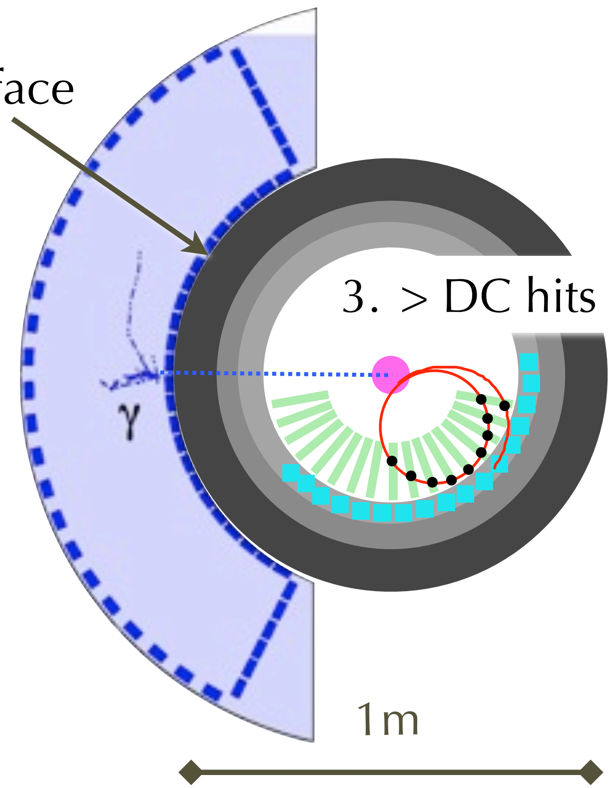
7. > granularity on front face

2. thinner target

1. > μ^+

5. > TC granularity

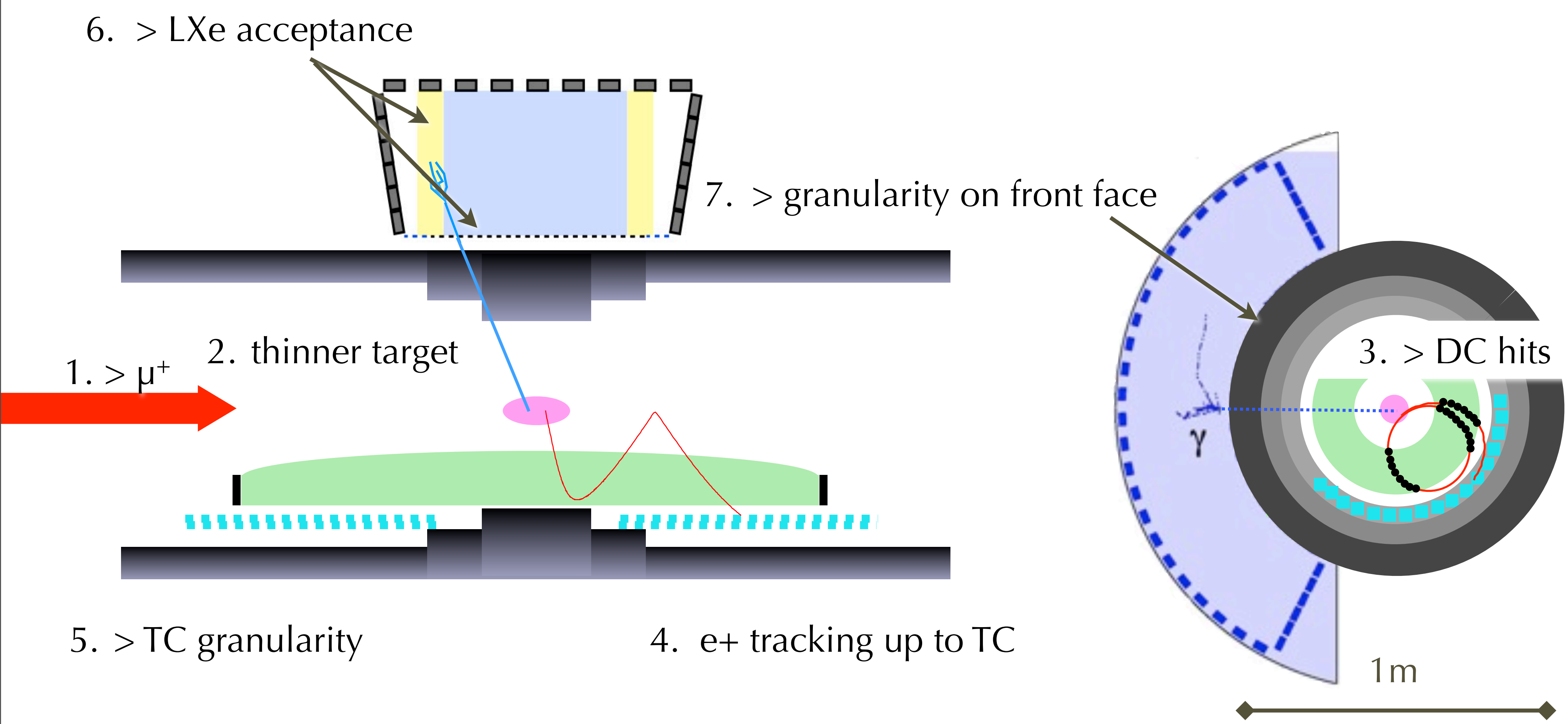
4. e+ tracking up to TC



3. > DC hits

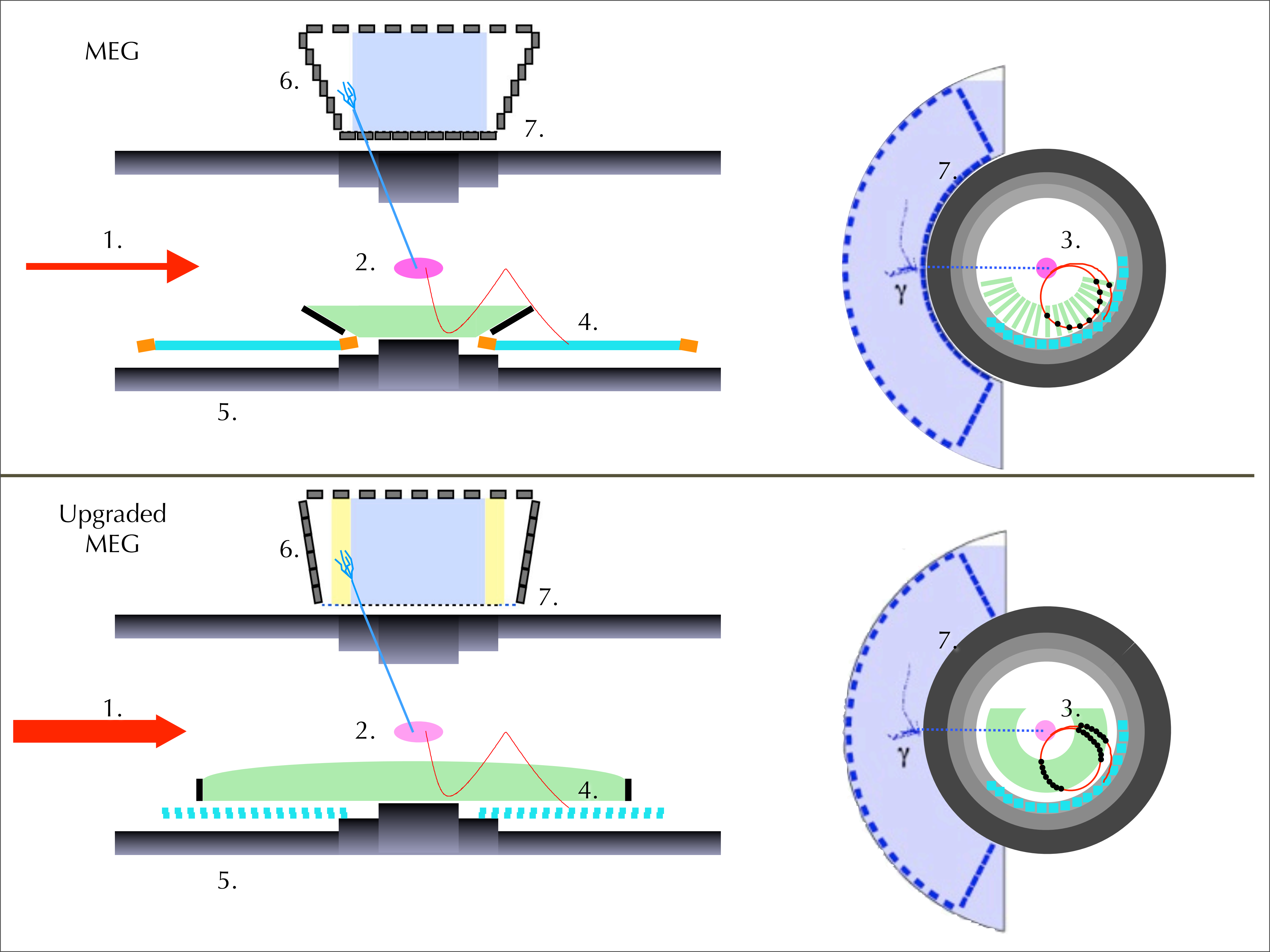
3. < Multiple scattering

MEG^{UP} at a glance



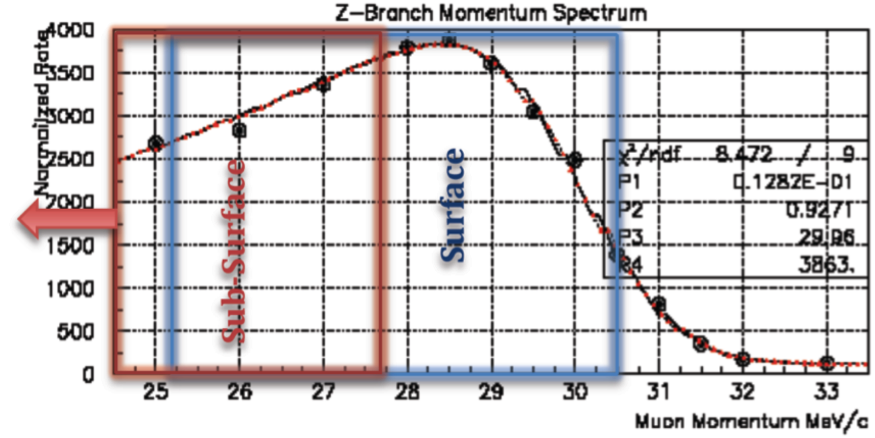
PMTs → SiPM / MPPC

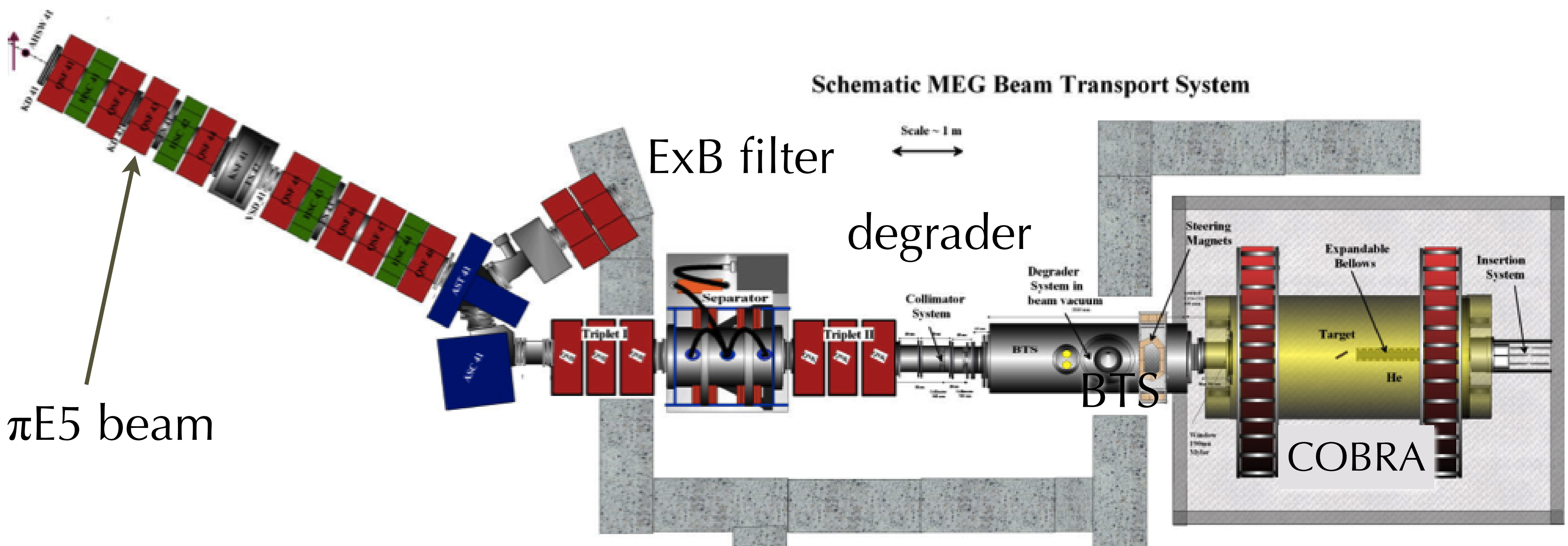
3. < Multiple scattering


MEG
6.
7.
1.
2.
4.
5.
7.
3.
γ
Upgraded MEG
6.
7.
1.
2.
4.
5.
7.
3.
γ

Beam line

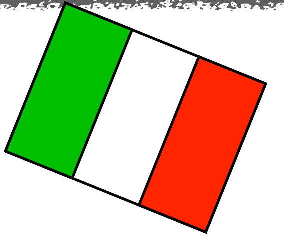
- PSI **πe5 beam line**
  - ***> 10^8 μ⁺/sec***
- **Surface** (p=28 MeV/c) **muon beam**
  - ***residual range*** *~ 120 mg/cm²*
  - ***thinner target 140μm*** *[205]* → placed at **15°** [22°]
  - **7x10⁷ μ⁺/sec**, 8.1 σ e/μ separation
  - **$\sigma_x \sim \sigma_y$ = 9 mm**

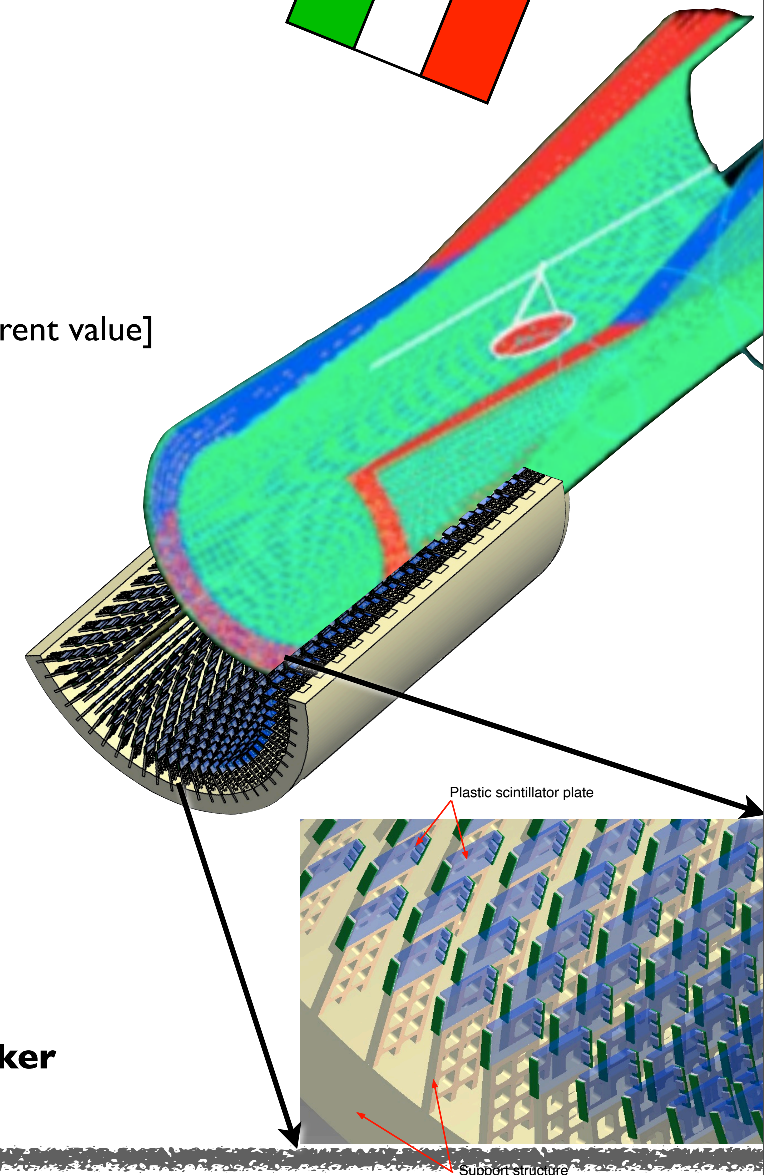




Positron Tracker

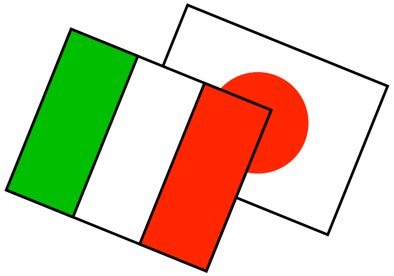
- **single volume, low mass, stereo drift chamber + multi tile scintillation timing counter** inside COBRA magnet
  - *Drift chamber*
    - **Single volume** gas detector
    - **U-V stereo reconstruction** (8°) → hyperbolic DC
    - **low mass** (90:10 He:iC_4H_{10}) → Low X_0 <1.7 x 10^{-3} per track [similar to current value]
    - **>80% transparency** towards **TC** [40 %]
    - **Ultra-fast electronics** for cluster timing, ~1GHz bandwidth
  - *performance from MC*
    - **> 40 hits/track** [10-16]
    - single hit resolution **<=120μm** [210]
    - Momentum resolution **~150 keV** [~310]
    - Angular resolution **~5-7 mrad** [9-10]



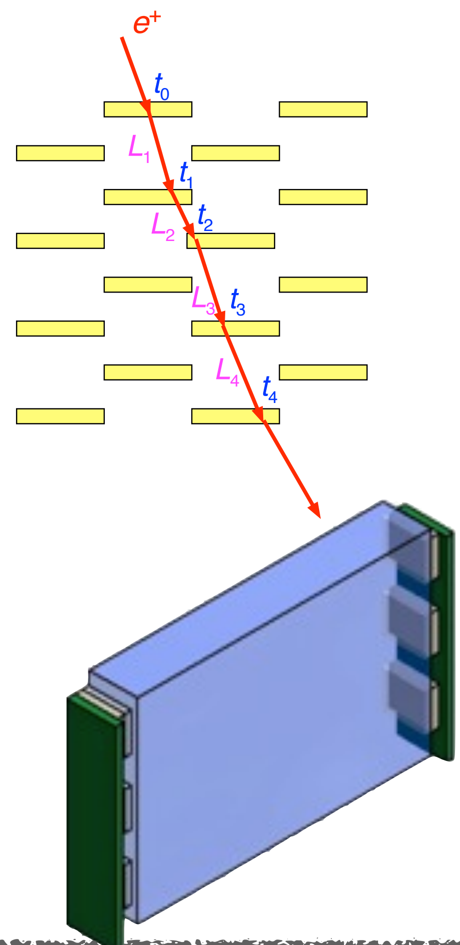


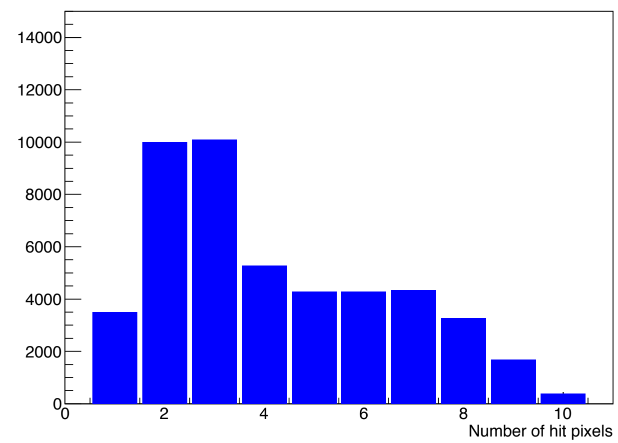
- **INFN takes the full responsibility of the construction of the new tracker**

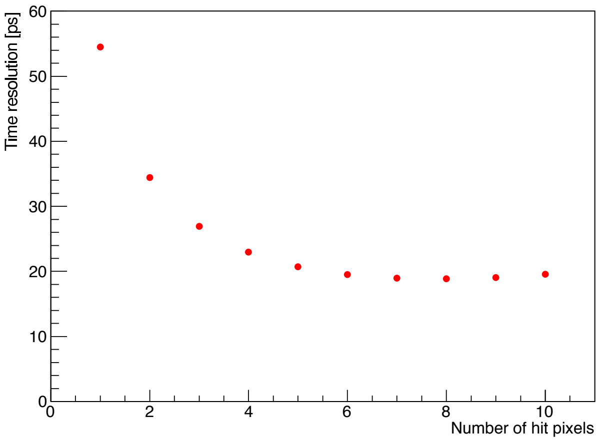
Timing Counter

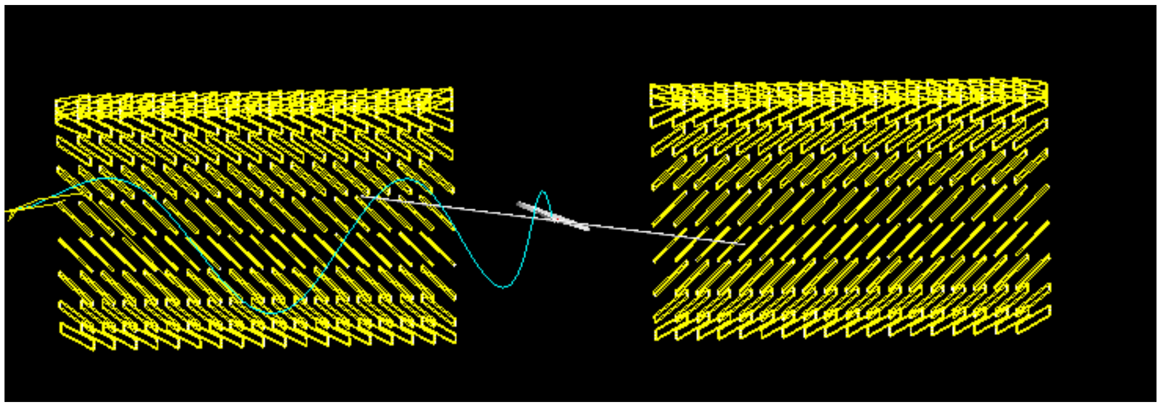


- **increased muon flux → reduce hit-rate and pile-up**
- (3 x 9 x 0.5) cm^3 plastic **scintillator tiles**, read by **MPPC**
- **improve timing resolution** by combining several tiles



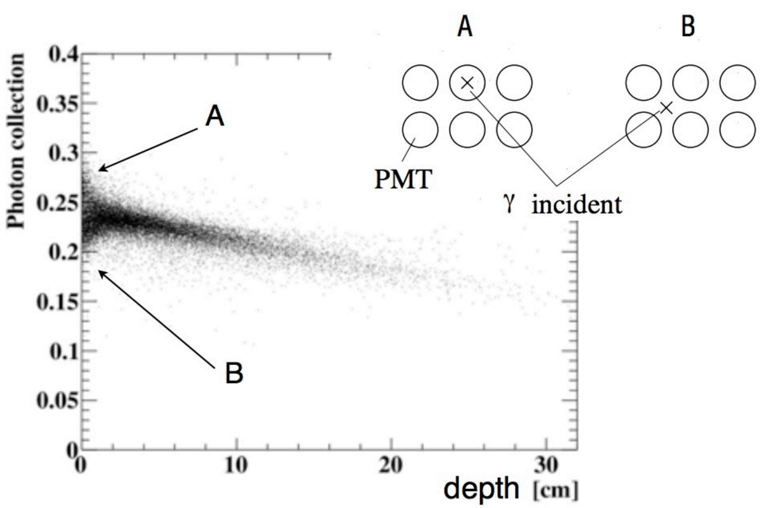


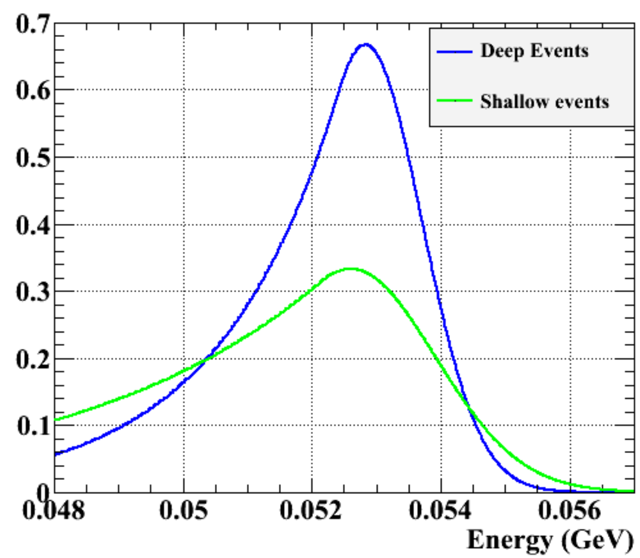


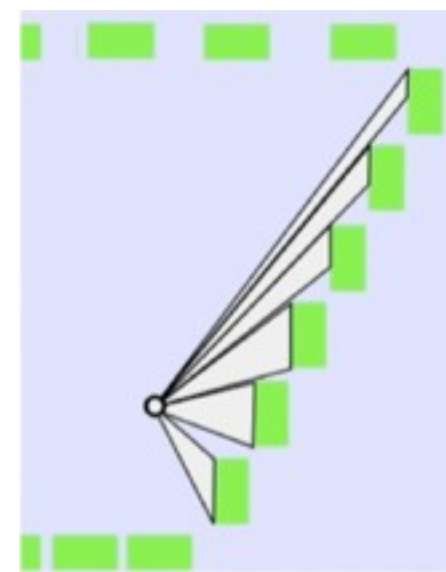


The photon detector

- The γ-detector **almost met its design** requirements
  - ***largest, best performant Xe detector to date***
- **800 liters LXe, 848** VUV **PMTs**
  - ***216*** *on the* ***entrance face****,* ***6.2 cm granularity***
- **Non-optimal** reconstruction of γ-rays that **convert close** to the detector **entrance face**
  - ***worse*** *energy and position* ***resolution*** *for* ***shallow events***
- **Non-uniform** light transmission for events **close** to the **lateral surfaces**
  - ***reduced acceptance*** *at the edges*

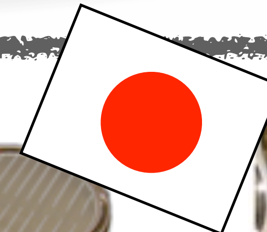


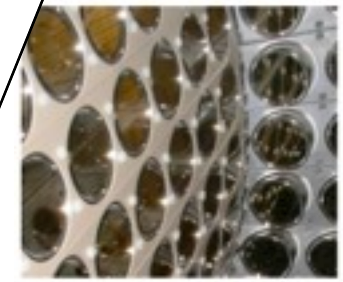


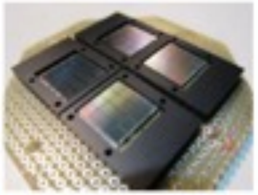


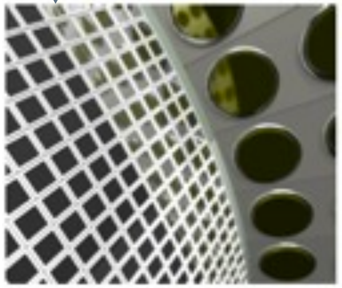
γ-detector improvement

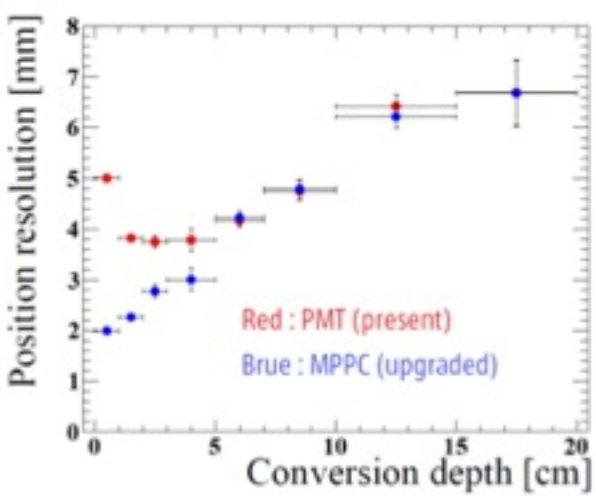
- Use the **same cryostat**, most **mechanics**, + **620 PMTs**
- Use of **SiPM** (MPPC) **12x12 mm²**
  - ***~3500*** *sensors*
  - ***+9%*** *detector* ***transparency*** *to 52.8 MeV γ-rays*
  - ***Better granularity*** *for* ***depth reconstruction/pile-up rejection***
    - **position reconstruction**
    - **timing**
- Difference **geometry** for the **lateral faces**
  - ***+10% acceptance***

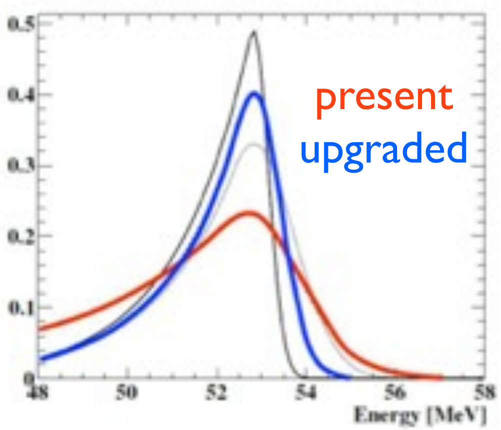


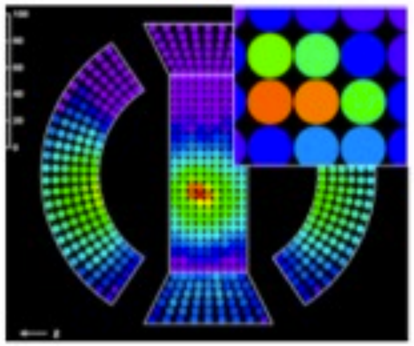


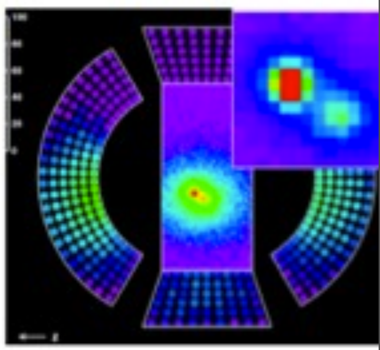






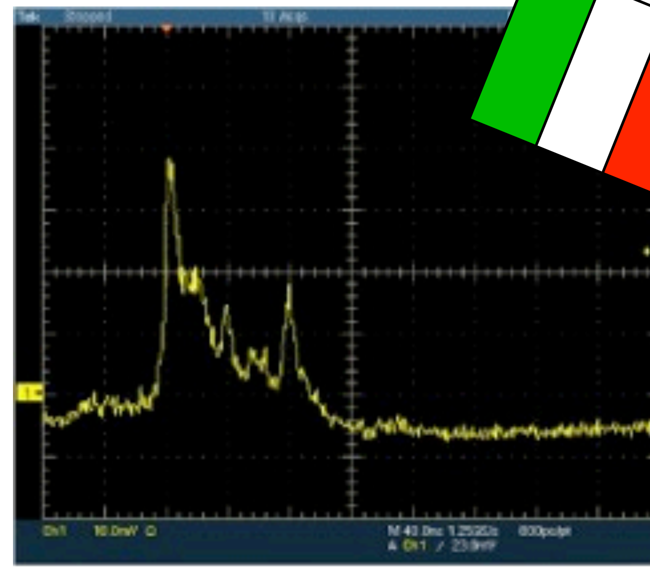


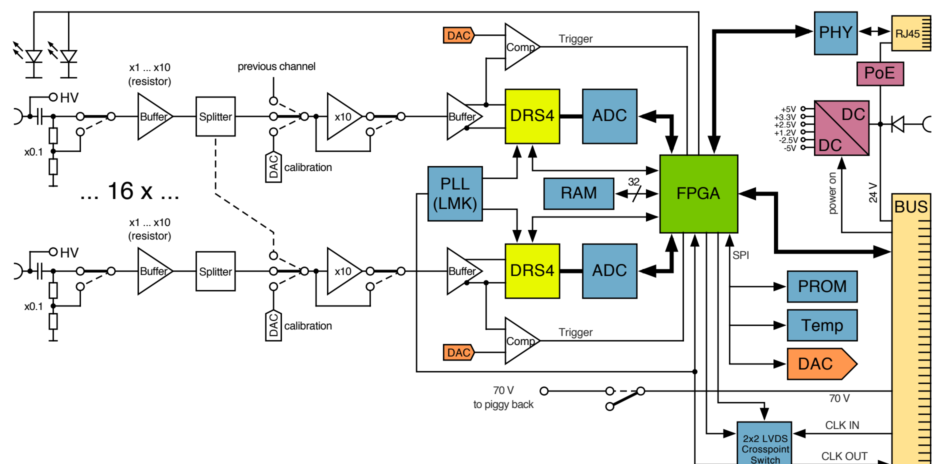




Trigger & DAQ

- **Increased number** of **channels** (DC +1000, LXe +3000, TC +200)
  - ***higher bandwidth*** *for timing, DC cluster recognition*
- **2 GHz waveform digitizer** for **all signals**
- **WaveDREAM board**
  - ***General purpose*** *board*
  - ***DRS4*** *waveform digitizing technology*
  - ***splitter + trigger***
  - *dedicated* ***fast comparator*** *for* ***self trigger*** *and* ***FPGA*** *for* ***complex algorithms***
  - ***improved*** *clock* ***synchronization*** *→* ***timing***



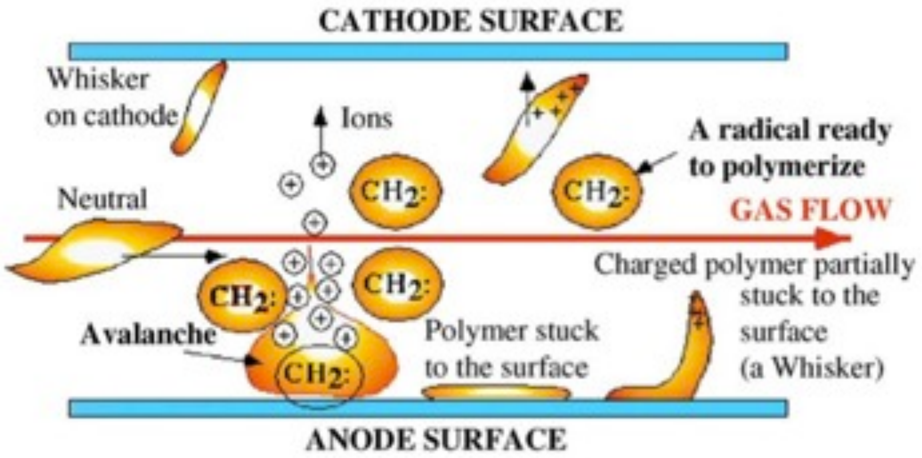


- **Trigger** algorithm **the same** as **MEG**!!!!
  - *trigger* ***responsibility*** *confirmed to* ***INFN Pisa***

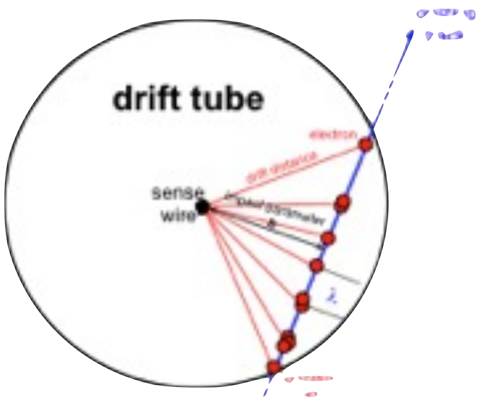
Drift Chamber R&D

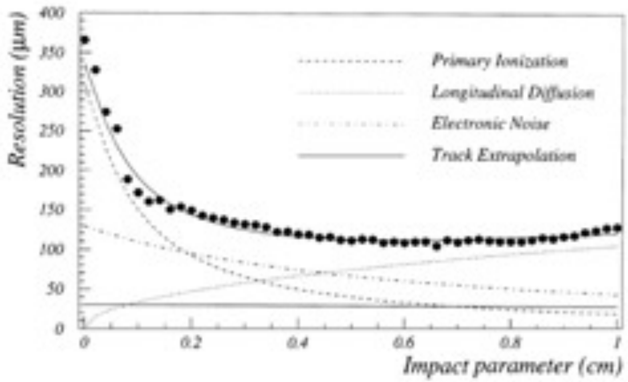
Pisa
Lecce
Roma

- **Chamber** behavior in MEG^{UP} **high rate environment**
  - *Under a* ***harsh environment*** *the DC is subject to* ***aging effects***
    - **gain loss**
      - ***worse energy resolution***
    - **excessive chamber current**
    - **self-sustained discharges**
    - **high voltage instability**
    - **wire corrosion, swelling, rupture**
  - ***Accelerate aging test***



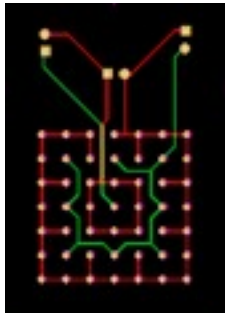
- Single **hit resolution**
  - ***Light gas*** *(He:iC$_4$H$_{10}$)*
    - **low multiple scattering**
    - **lower number** of **clusters**
    - **large** impact parameter **fluctuations**
    - **count/time individual clusters** on anode wire (cluster timing)

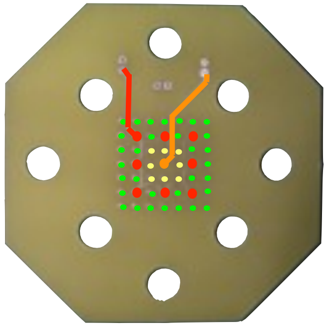


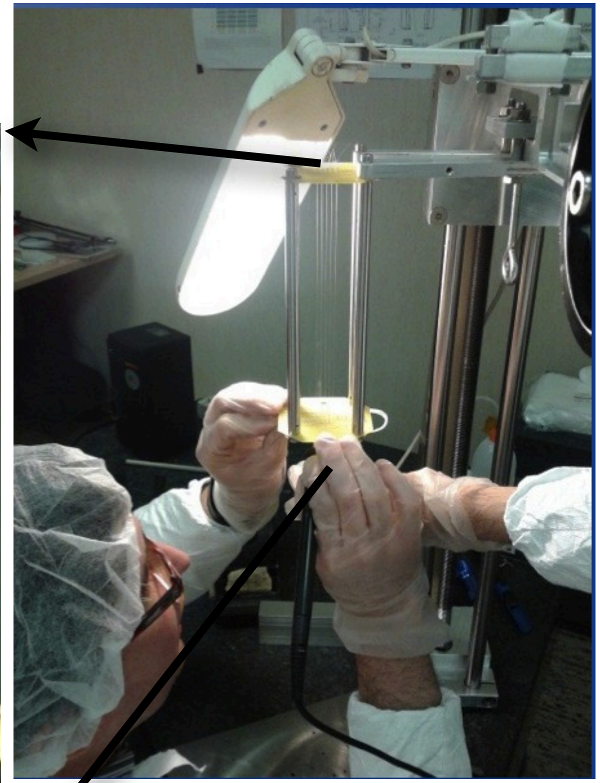


Aging DC prototype @INFN Pisa

- **Realistic prototype** from the point of view of
    - ***field configuration***
    - ***decision*** *on* ***materials***
- Prototype feature
    - ***1 complete cell*** *(20 cm length)* + ***guard field***
    - ***Gold-plated tungsten wires***
        - **~4μm** plating
        - **sense** wire **25μm**, **field+shape 80μm**
    - ***~1 kBq alpha-source*** *at* ***the center***
    - *Assembled in* ***clean room***
- Work done **@INFN Pisa**
    - ***1 prototype assembly*** *in* ***2 working days***

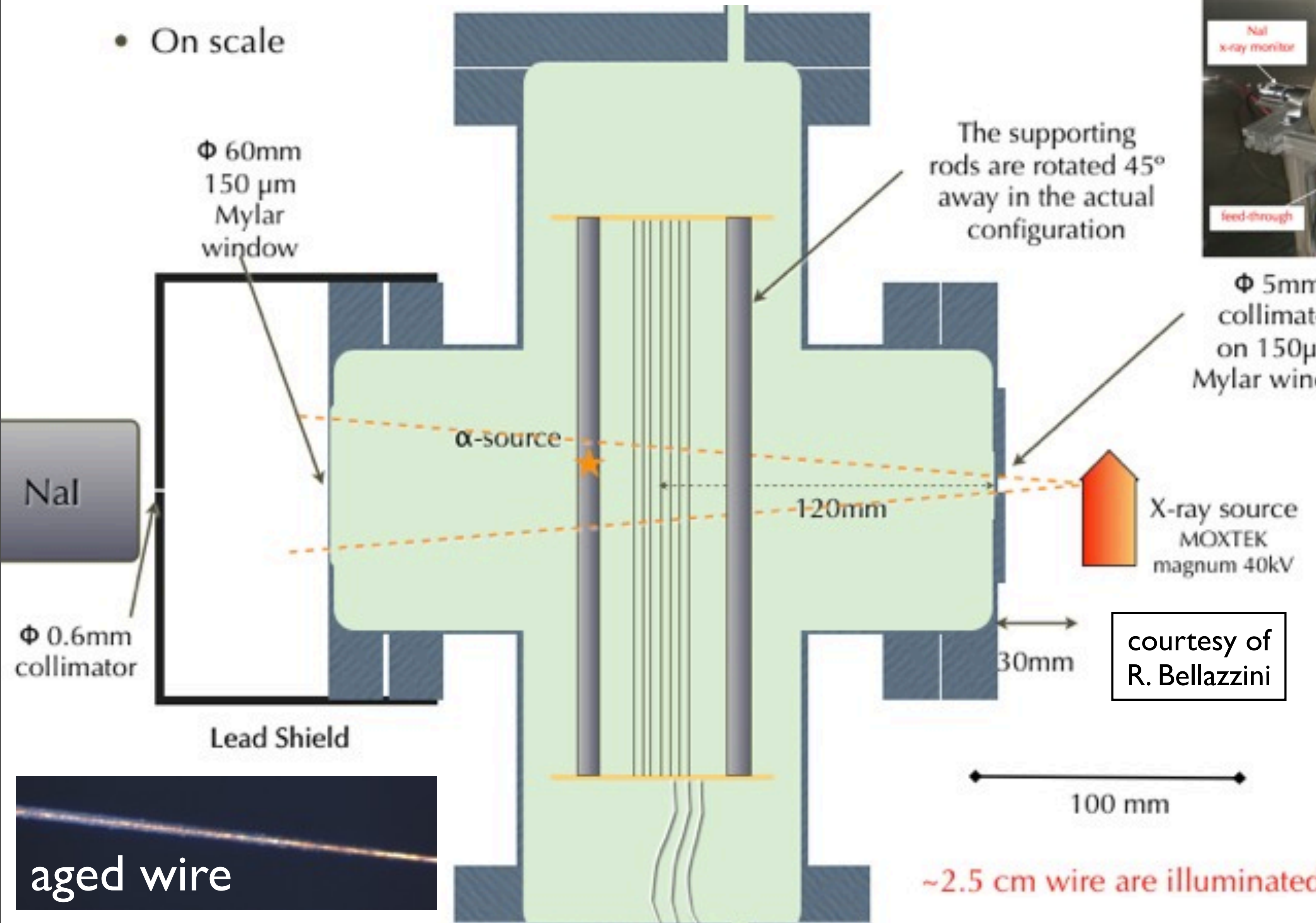


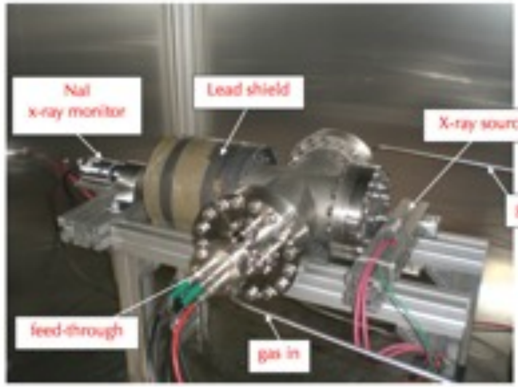




Measuring configuration

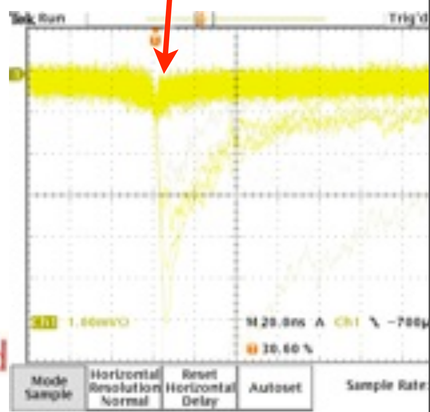
- On scale





courtesy of
R. Bellazzini

α-particles and
X-rays from source

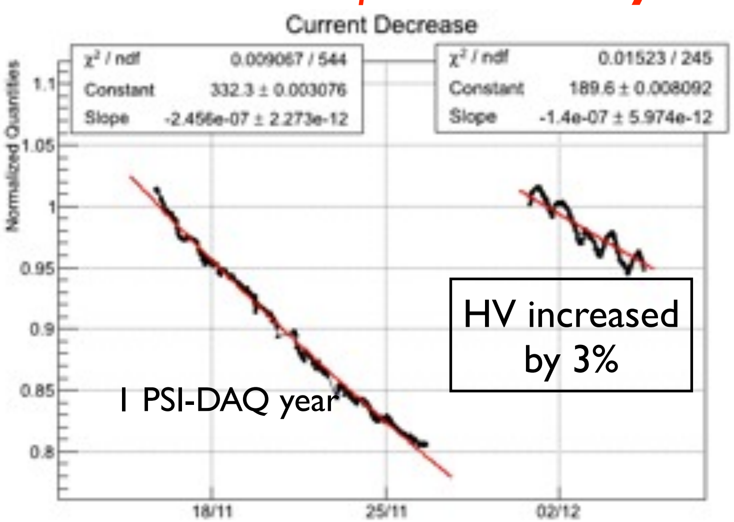


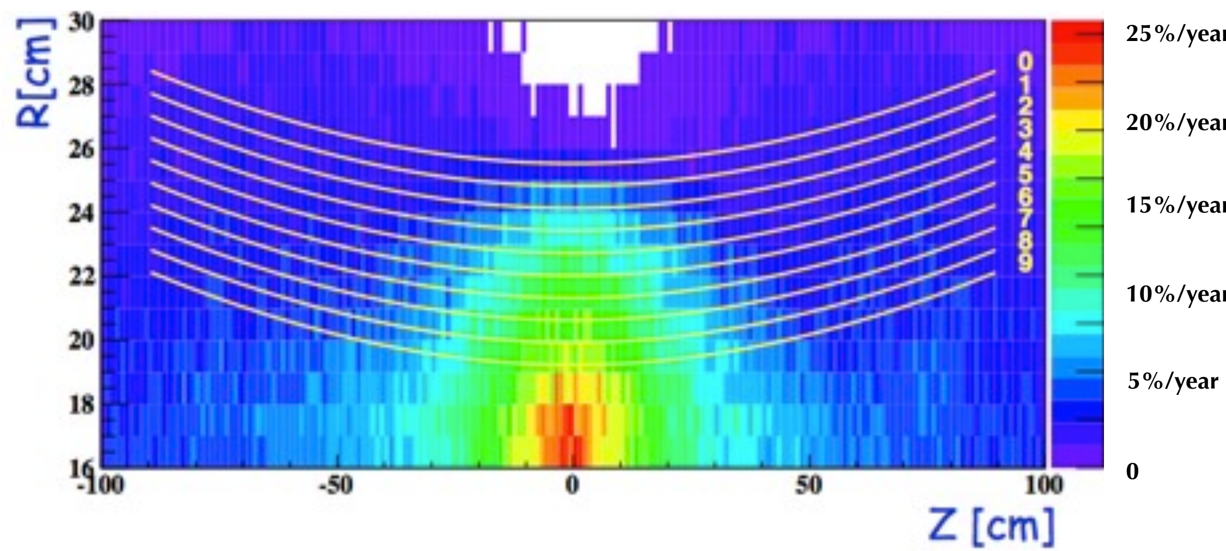
First results

- **Aging** is measured as the **gain drop** as a function of the **collected charge**

$$R = -\frac{1}{G_0}\frac{\mathrm{d}G}{\mathrm{d}Q}\left(\frac{\%}{\mathrm{C/cm}}\right)$$

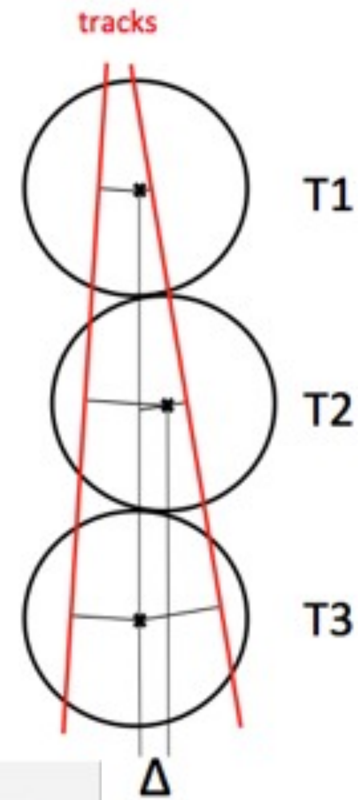
- **Accelerated irradiation** (20x aging), **accelerated gas flow**
- The **current drop** is nicely fitted with an **exponential function** over > 10 days
  - *Actualized **time constant = 945 days***
  - *Gain drop **0.11%/day** on the central wire, **NOT** a serious **problem** for MEG^{UP}*

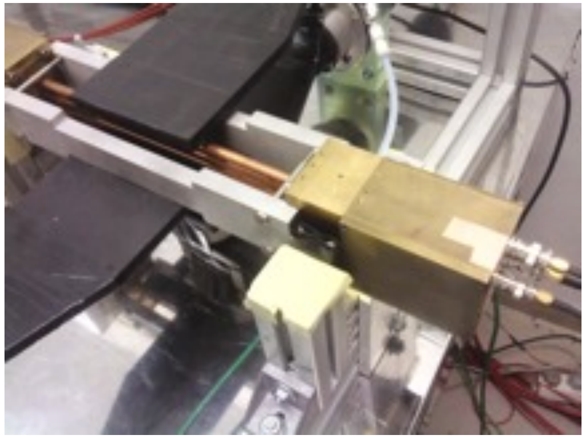


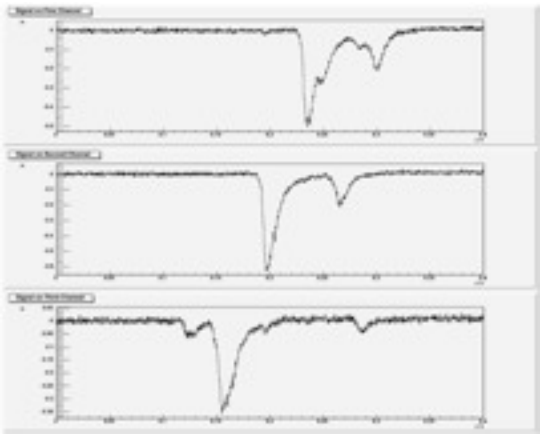


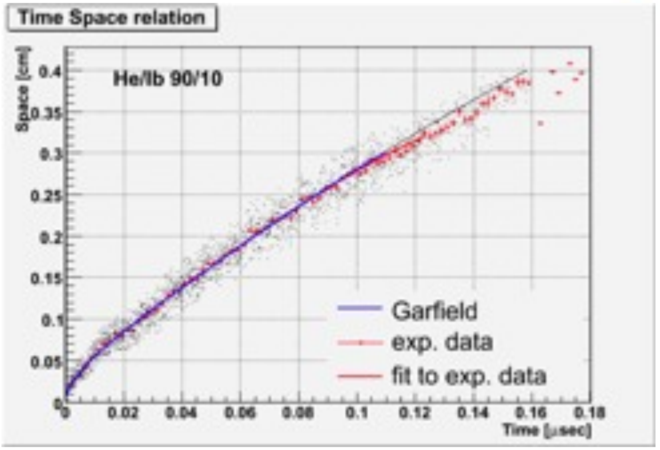
Single hit resolution measurement

- Measurements with **three Cu drift-tubes + 20μm W(Au) wires**
  - ***200 μm thin wall***
- For **vertical tracks**: $\frac{d_1+d_3}{2}-d_2=\pm\Delta$ and $\sigma_\Delta \cong \sqrt{\frac{3}{2}}\,\sigma_d$
- Measurement done **@INFN Lecce**
  - *various* ***He:iC₄H₁₀ mixture*** *(95:5* → 50:50)
  - **high bandwidth** commercial **amplifier** (Phillips 775)
  - use the arrival **time** of the **first cluster** + **x-t relation**
  - **custom pre-amp** prototype **produced @INFN Lecce**





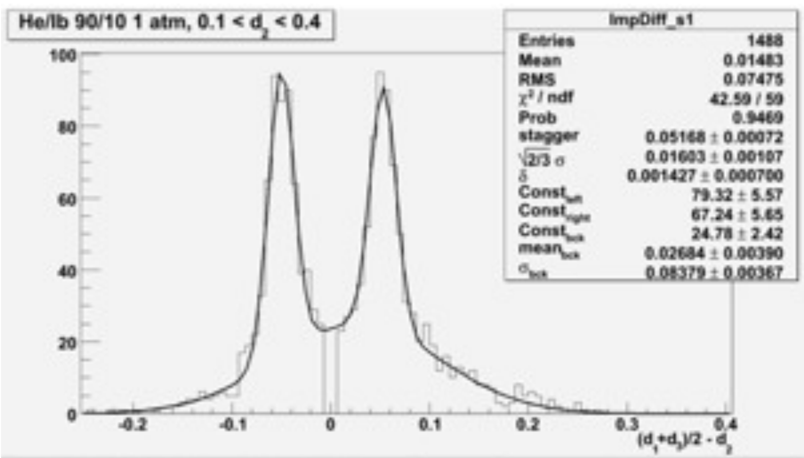


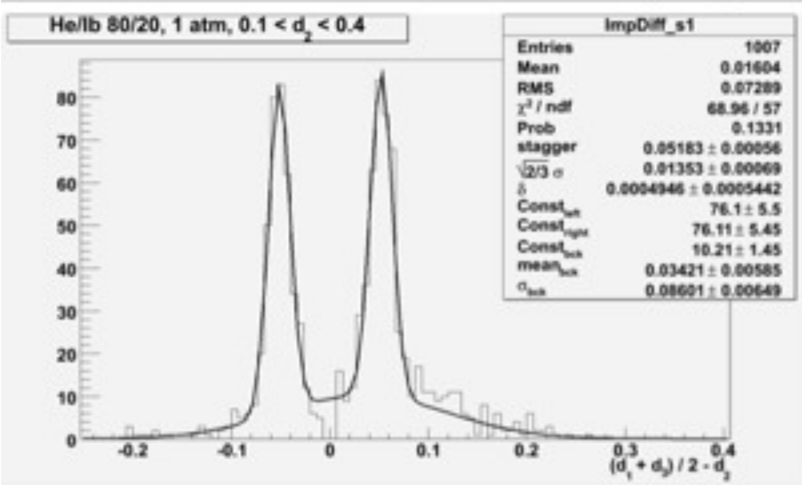


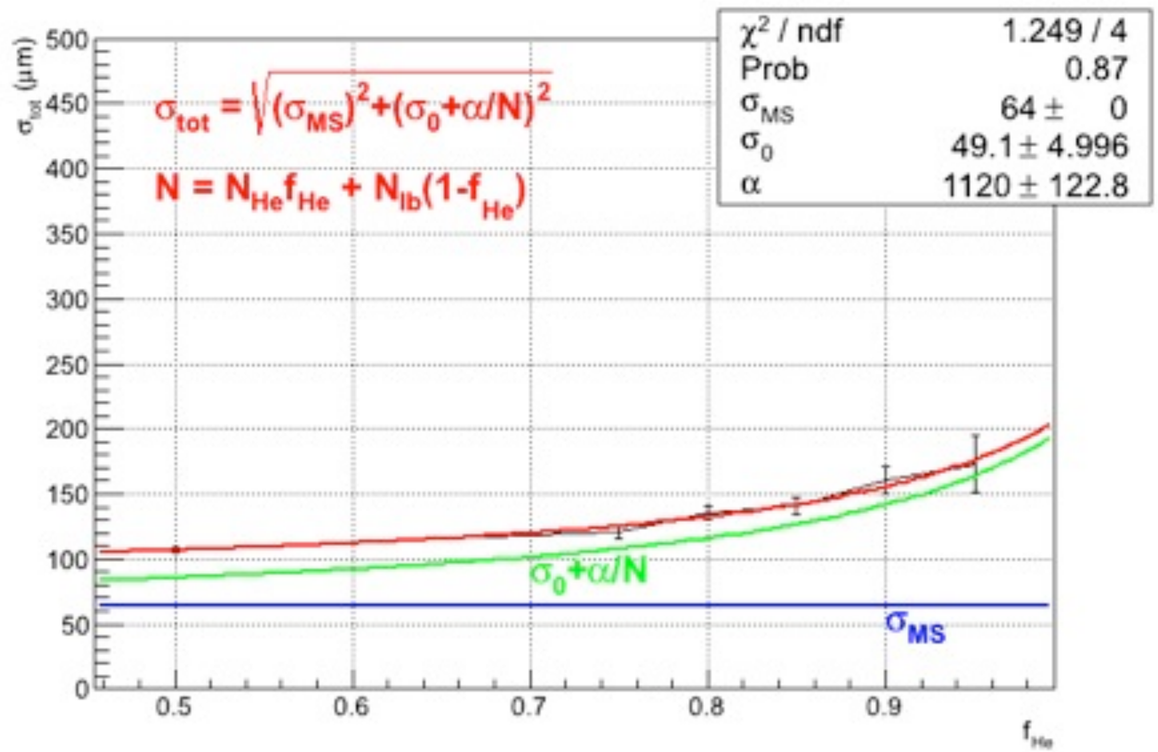
Three-tubes results

- Contains the **contribution** of **CR** muons **multiple scattering**
  - *When **MS removed σ<120 μm** already for **(15:85)***

Mixture ($He{:}iC_4H_{10}$)	Resolution (μm)
5:95	330
10:90	160
15:85	140
20:80	135
25:75	120
50:50	110

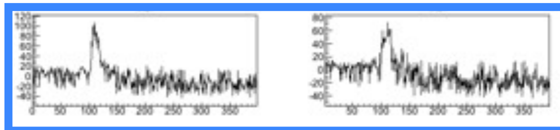


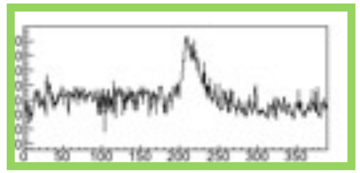


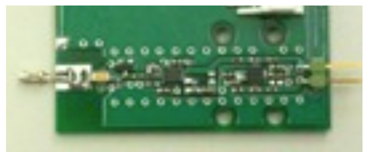


Hit resolution with cluster timing

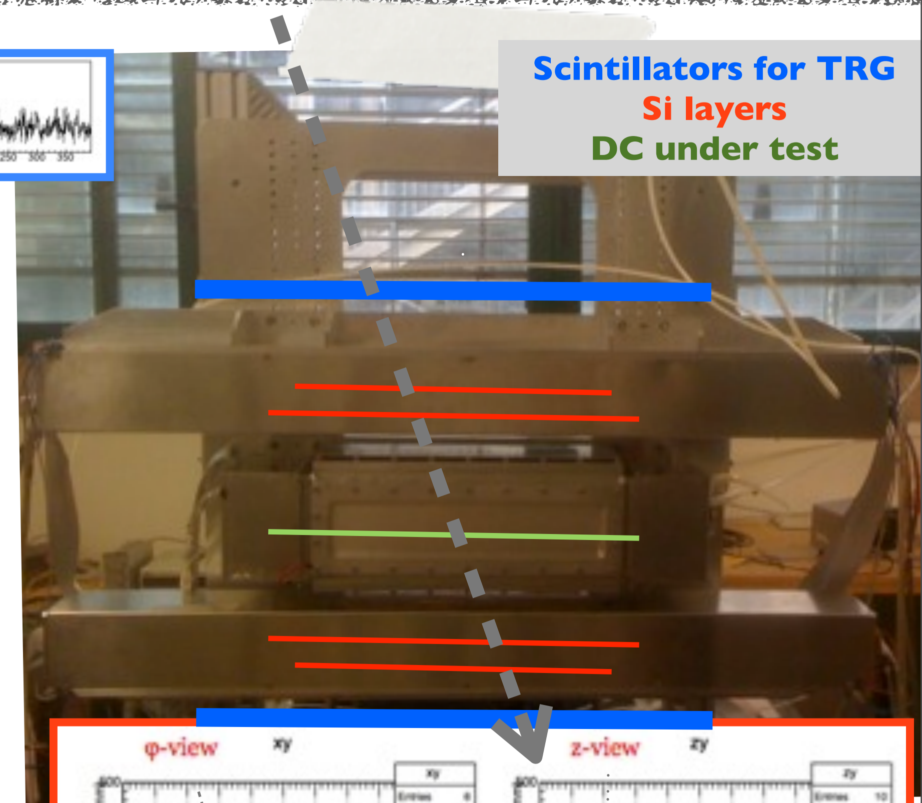
- Large **prototype** built **@INFN Roma**
  - ***8x8 cells*** *(7x7 mm²)*
  - ***50 cm*** *long wires*
    - **80 μm W(Au) field wires**
    - **25 μm W(Au) sense wires**
  - ***No stereo angles***
  - ***custom pre-amp (INFN Lecce)***

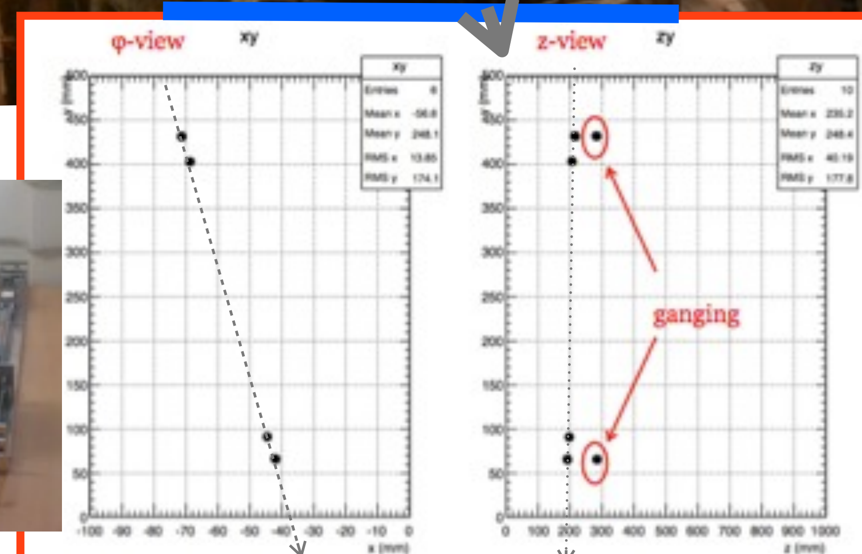


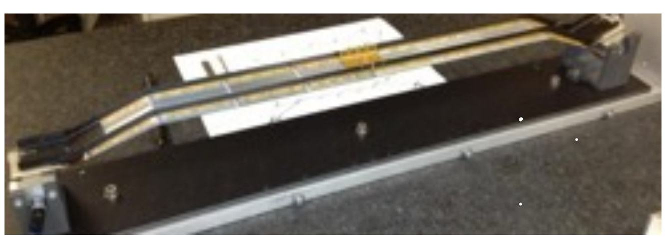


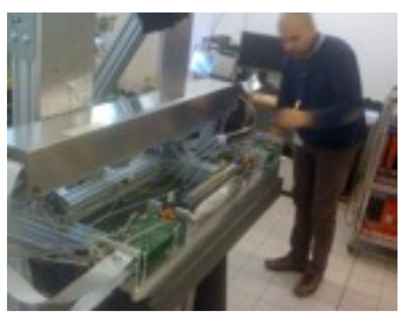


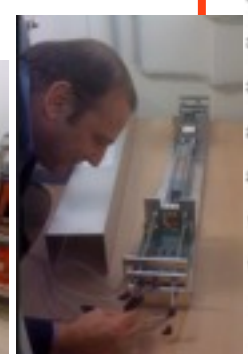
- **Silicon cosmic ray telescope** assembled **@INFN Pisa** as a **section facility**
  - ***BaBar SVT*** *spare**, new electronics** designed for **supply and read out***
    - **support from "servizio alte tecnologie" and "servizio progettazione elettronica"**
  - ***20μm resolution*** *on **straight tracks***
  - ***DUT in a sandwich*** *within **4 layers** of **Si detectors***





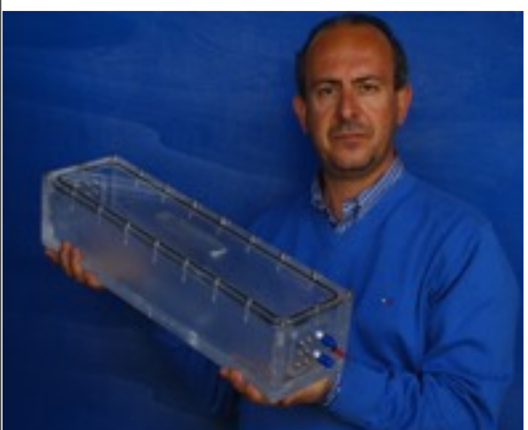


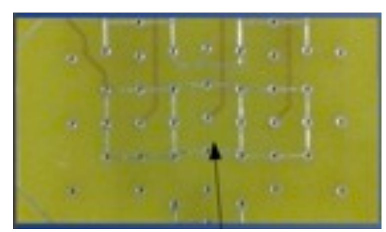




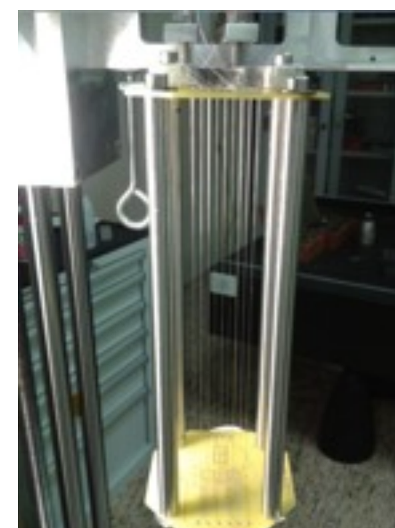
Measurements schedule

- **Preliminary resolution** measurements with three-tubes are **very promising**
- **To be confirmed** with **intensive** measurement **campaign** with the **silicon telescope** to test reconstruction/cluster timing (chronological order)
  - ***Roma prototype***
  - ***Lecce three-tubes*** *in the telescope*
  - ***Pisa new prototype*** *in configuration with* ***stereo wires***
  - ***Pisa and Lecce full scale prototype*** *(mechanics and read out)*
    - last one maybe **not only telescope** but **beam**...





500µm offset

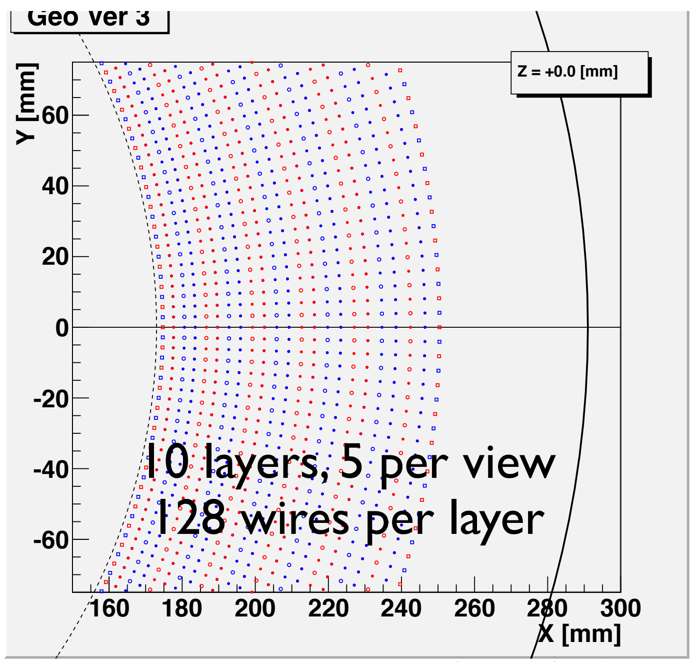


DC mechanics

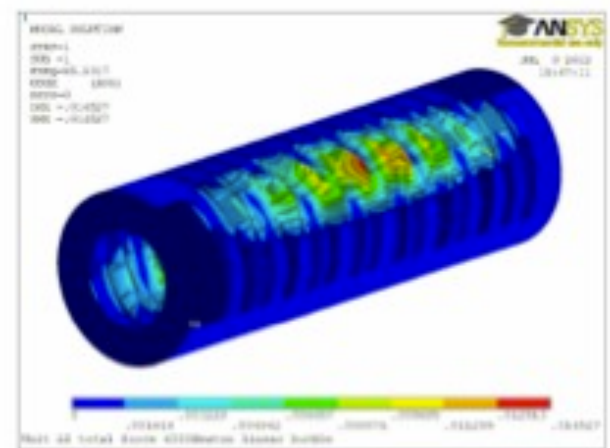
Item	Description	Thickness ($10^{-3}X_0$)
Target	(140 μm Polyethilene)	0.21
Sense wires	(25 μm Ni/Cr)	0.16
Field wires	(40 μm Al)	0.38
Protective foil	(20 μm Kapton)	0.14
Inner gas	(Pure He)	0.06
Tracker gas	He/iBut. 85:15 (90:10)	0.50 (0.36)
Total	One full turn w/o target	1.24 (1.10)

Assembly procedure under **test** with long **prototypes**

Support structure and **assembly @INFN Pisa clean room**

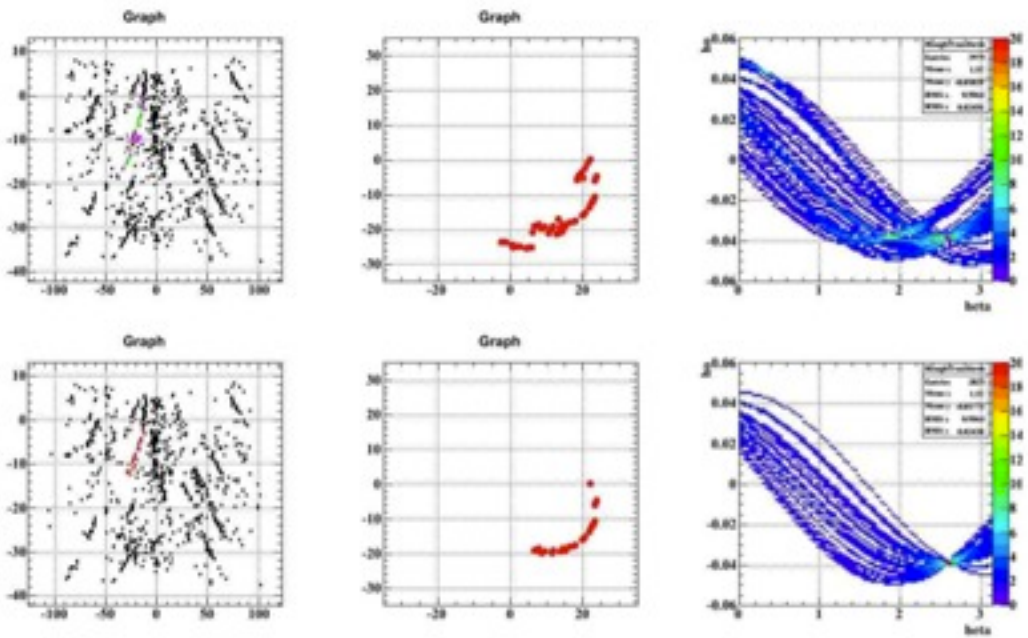


Wire geometry choice: **projective** cells along **r** slightly **trapezoidal cell but unmodified** along **z**
~7x7 mm²
~210° coverage in **φ** at the **center**



External carbon fiber buckling simulation

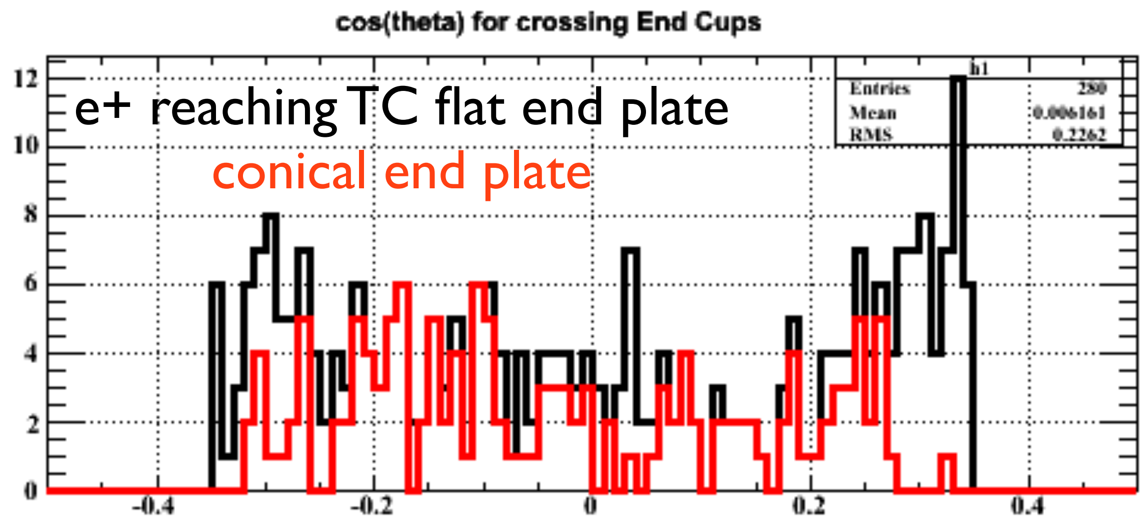
Reconstruction and optimization



Track finder:
lots of **tracks** and **hits**
>90% track finding efficiency,
resistive wires possibility under study

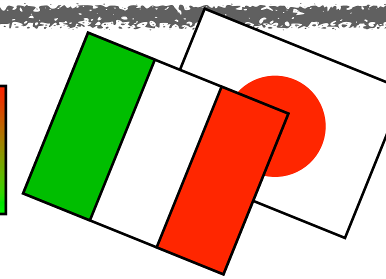
Track fit: same MEG algorithm

End plate geometry:
flat → >90% transparency to **TC**
(**76%** with **conical** one)
work ongoing...



Timing Counter R&D

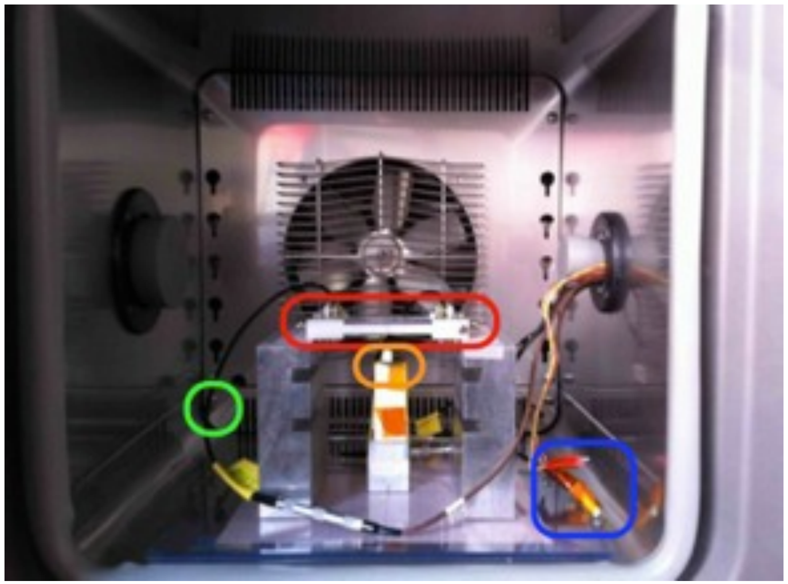
Genova
Pavia

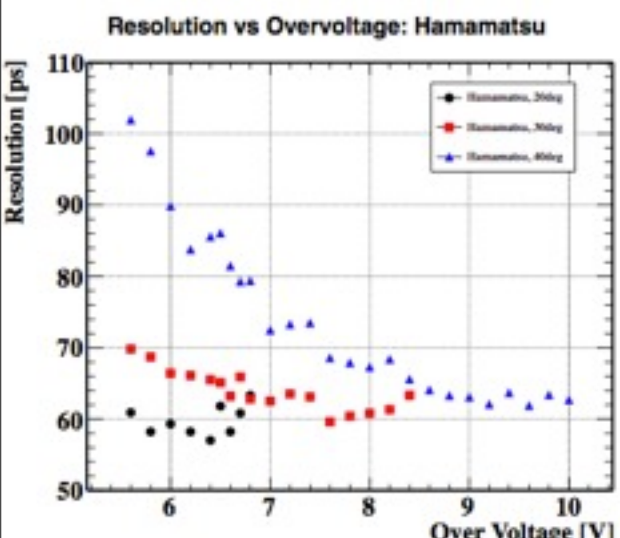


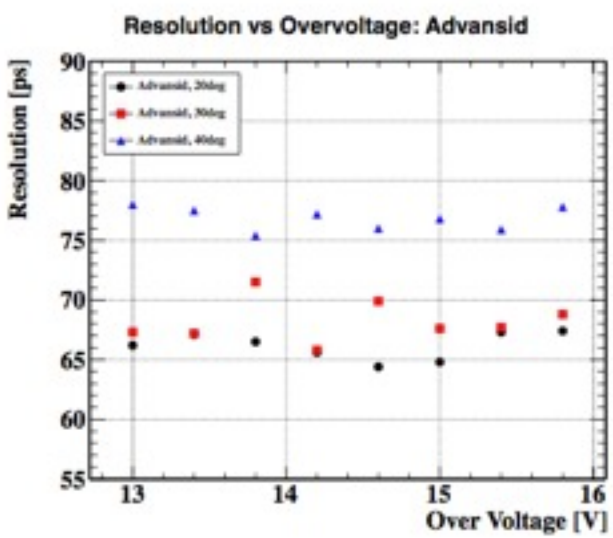
- **Several** prototype **tiles** built to test
  - ***different scintillators*** *(BC422, BC418, BC420)*
  - ***different wrapping*** *material/techniques (Al Mylar, Teflon, M3 reflector tape)*
  - ***different*** *tiles* ***dimension*** *to optimize*
    - **resolution** vs **efficiency** vs **number** of **channels** vs ...
  - ***different sensors*** *(Hamamatsu, Advancid, Ketek)*
    - **time resolution** and **temperature** dependence
  - ***Different pre-amplifiers***

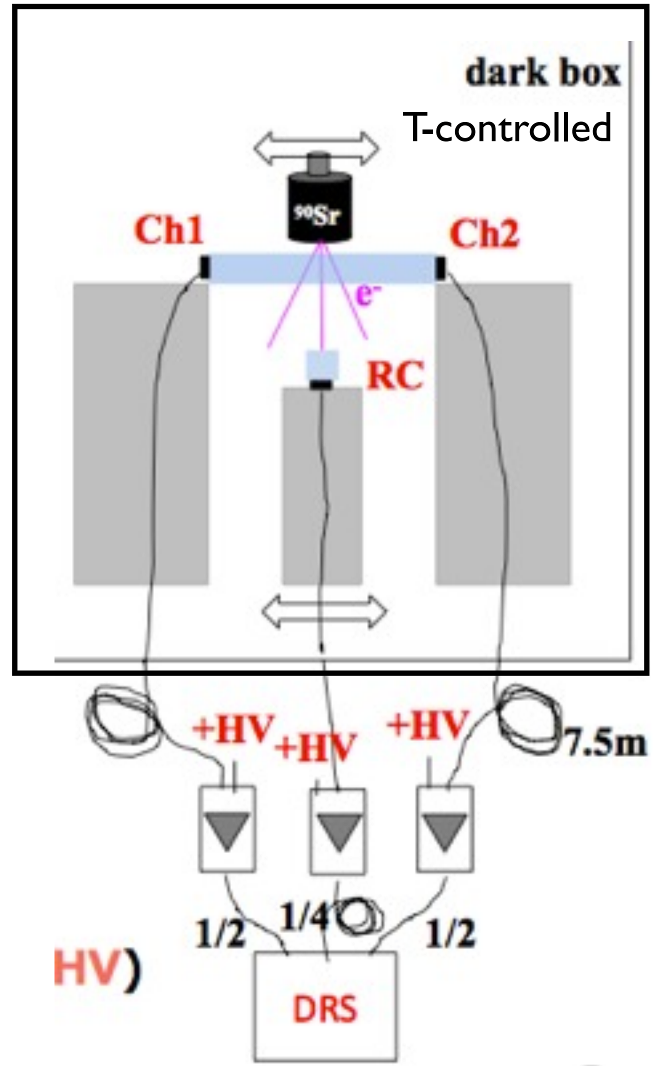
- R&D @PSI by **INFN Genova** and **INFN Pavia** + **Tokyo University**
  - ***Thermalized chamber*** *for test* ***@PSI***
  - ***Beam tests @Frascati*** *this summer*

Measurements





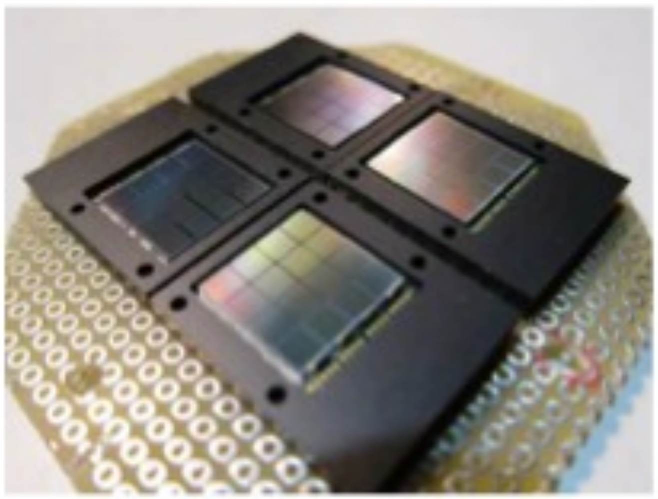


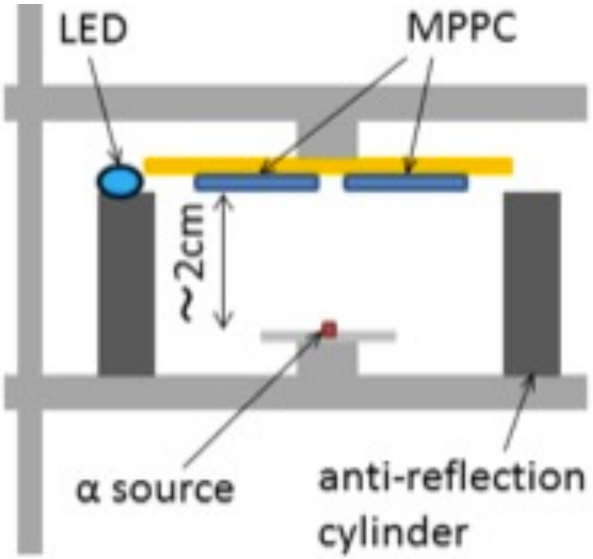


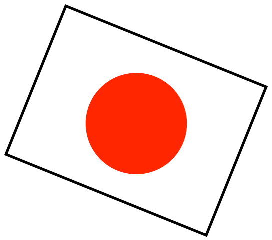
Tail **time resolution better** than **60ps**

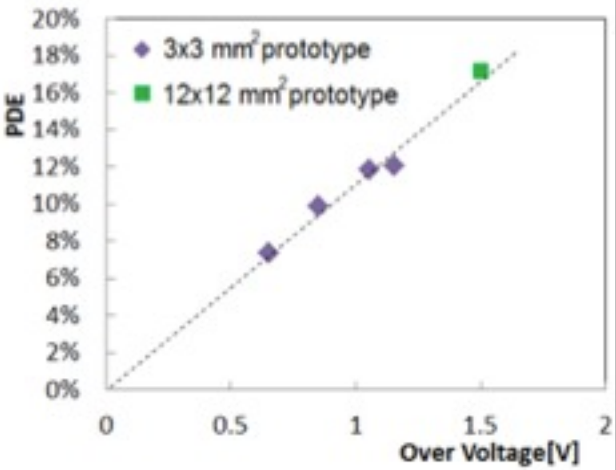
γ-detector R&D

- Development of **UV-sensitive MPPC** in **collaboration** with **Hamamatsu photonics**



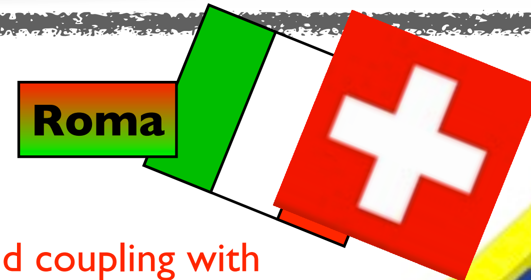




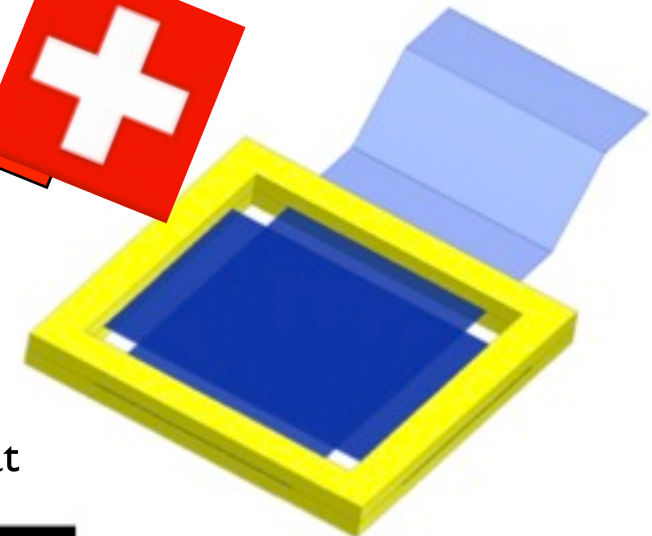


- ~**18% P**hoton **D**etection **E**fficiency **measured**
- R&D ongoing for **read-out of multiple channels** with
  - ***realistic cable configuration***
  - ***noisy environment***
  - ***vacuum feed-through tests with many signals***

An active target for MEG^{UP}



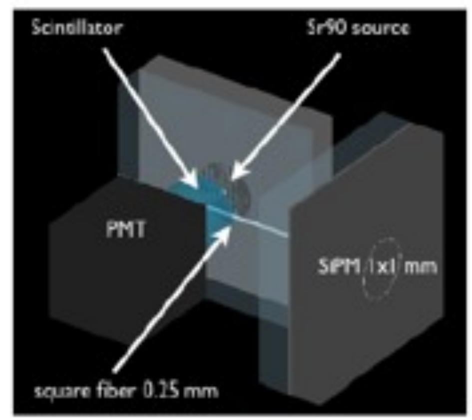
- Detect the **positron emerging** from the **target**
  - *array of* ***250μm scintillating fibers*** *read out by* ***SiPM***
  - *weak signal from* $e^+ \rightarrow$ R&D on fiber polishing, wrapping and coupling with sensors
- **Decay point** → e^+ **momentum** and **angular** resolution improvement
- **Independent** measurement of the **beam shape** and **intensity** at the **COBRA center**

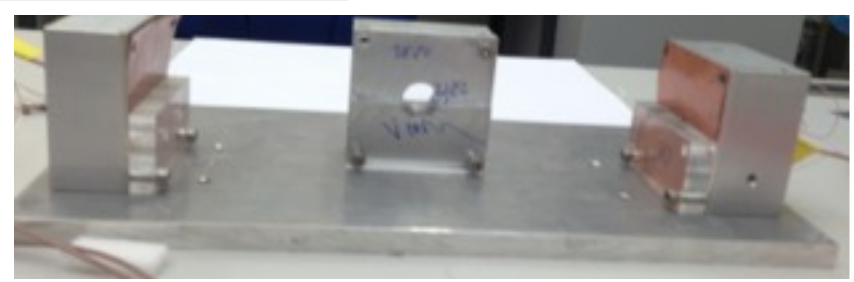


$\sigma_p < 100$ keV
$\sigma_\varphi < 5$ mrad

- R&D **@PSI** by **PSI** and **INFN Rome**

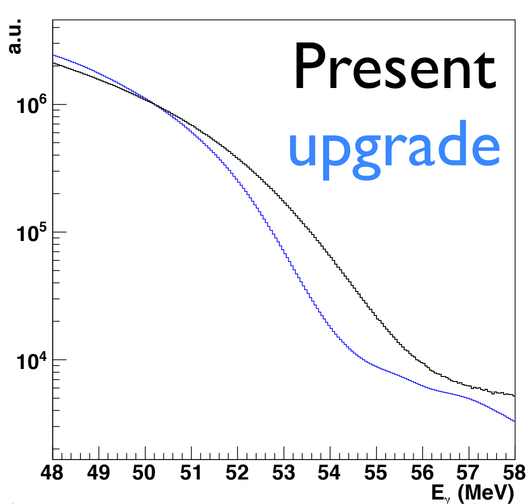
Target/ Spectrometer	thickness (μm)/ angle (deg)	σ_p (keV)	σ_ϕ (mrad)	σ_θ (mrad)	comment
Passive/old	205/ 20.5	320	11.7	9.8	measured
Passive/new	205/ 20.5	110	6.3	5.3	simulated
Passive/new	140/ 15	110	5.3	4.8	simulated
Active/new	250/ 20.5	90	4.7	5.1	simulated

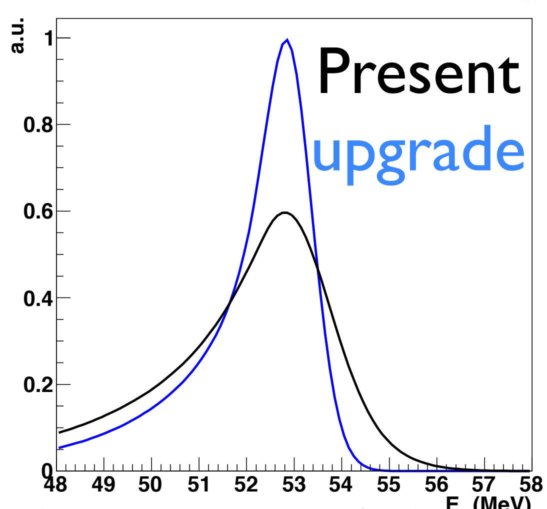


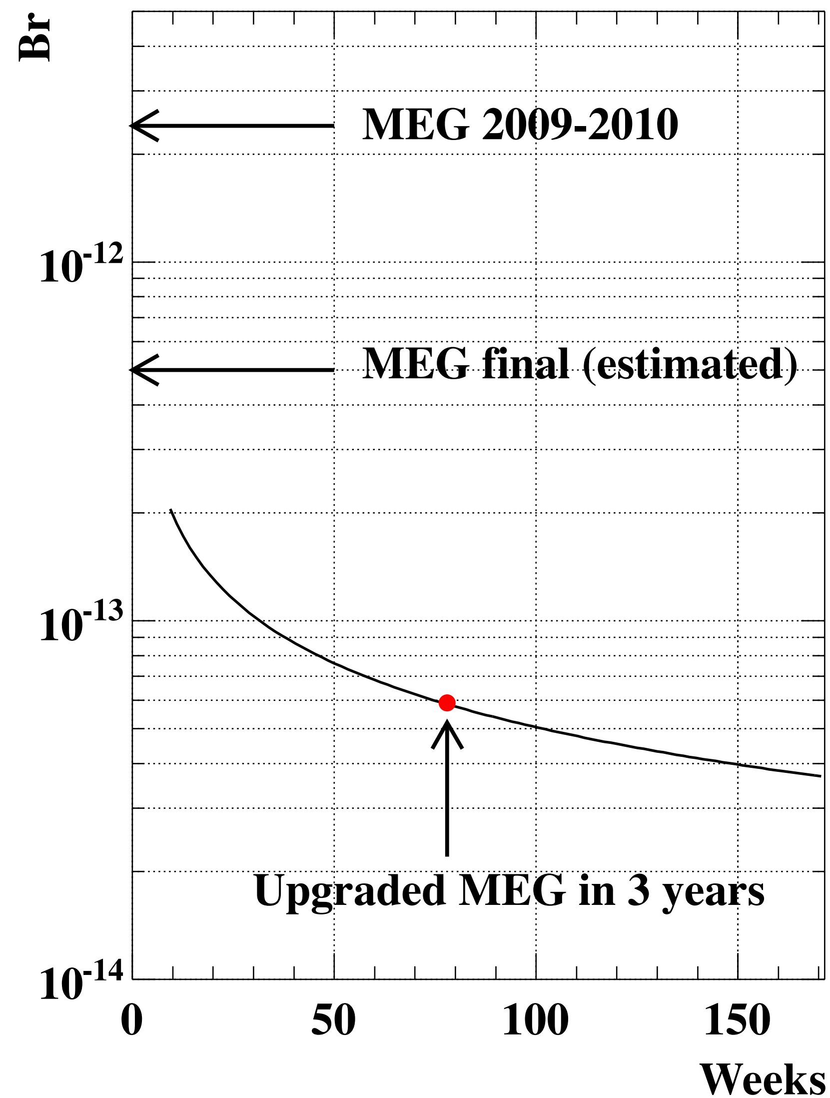


Expected sensitivity

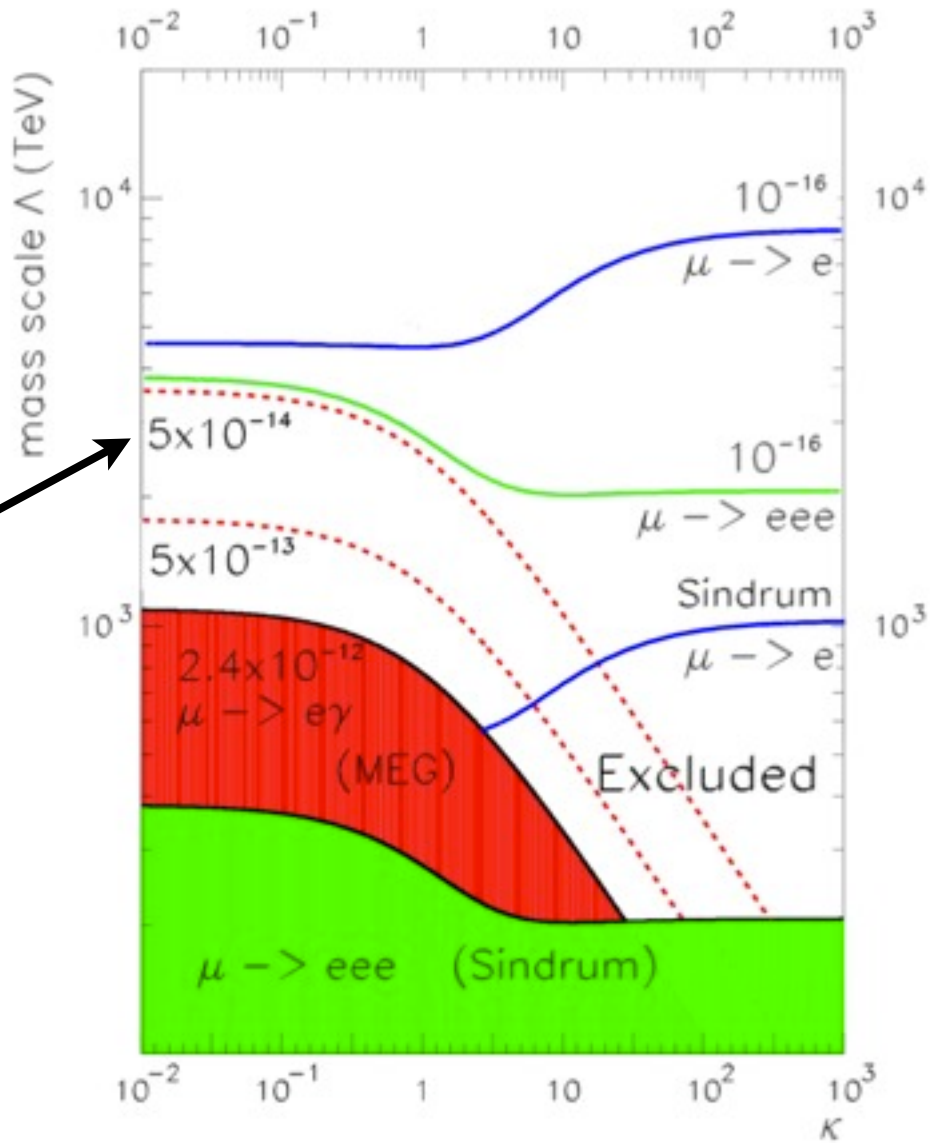
PDF parameters	Present MEG	Upgrade scenario
$\sigma_{E_{e^+}}$ (keV)	380	110
e^+ σ_θ (mrad)	9	5
e^+ σ_ϕ (mrad)	11	5
e^+ σ_Z / σ_Y(core) (mm)	2.0/1.0	1.2/0.7
$\frac{\sigma_{E_\gamma}}{E_\gamma}$ (%) w>2 cm	1.6	1.0
γ position at LXe $\sigma_{(u,v)}$-σ_w (mm)	4	2
γ-e^+ timing (ps)	120	80
Efficiency (%)		
trigger	≈ 99	≈ 99
γ reconstruction	60	60
e^+ reconstruction	40	95
event selection	80	85







Comparison with other projects

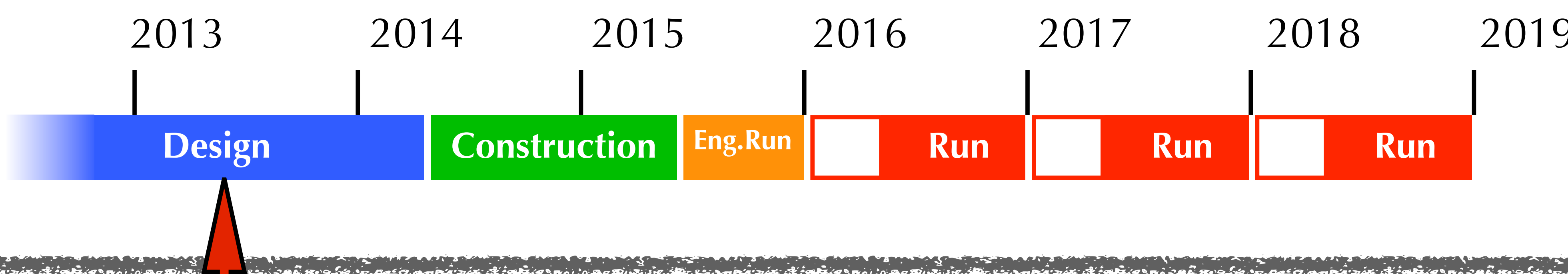


MEG^{UP}

MEG^{UP} **competitor** in a **large phase space region** with **other projects** as **mu2e, *COMET*, μ→eee** *that* ***will follow***

Conclusions

- **Physics case** of cLFV in $\mu \to e\gamma$ channel
- **Last MEG result**
  - ***BR<5.7 10^{-13}*** *(sensitivity 7.7×10^{-13})*
  - *Expected MEG final sensitivity ~5×10^{-13} (**statistics doubled** w.r.t. this **seminar**)*
- **From MEG → MEG^{UP}**
  - ***upgrade*** *in a relative* ***short*** *amount of* ***time****, make* ***best use*** *of the* ***present technology*** *available*
- aiming at a sensitivity ~ **5×10^{-14}**
  - ***R&D*** *on* ***new/refurbished sub-detectors***
- The **upgrade schedule** is **well defined** and up to now ***on schedule***



Thanks for you attention

PAUL SCHERRER INSTITUT

PSI

INFN

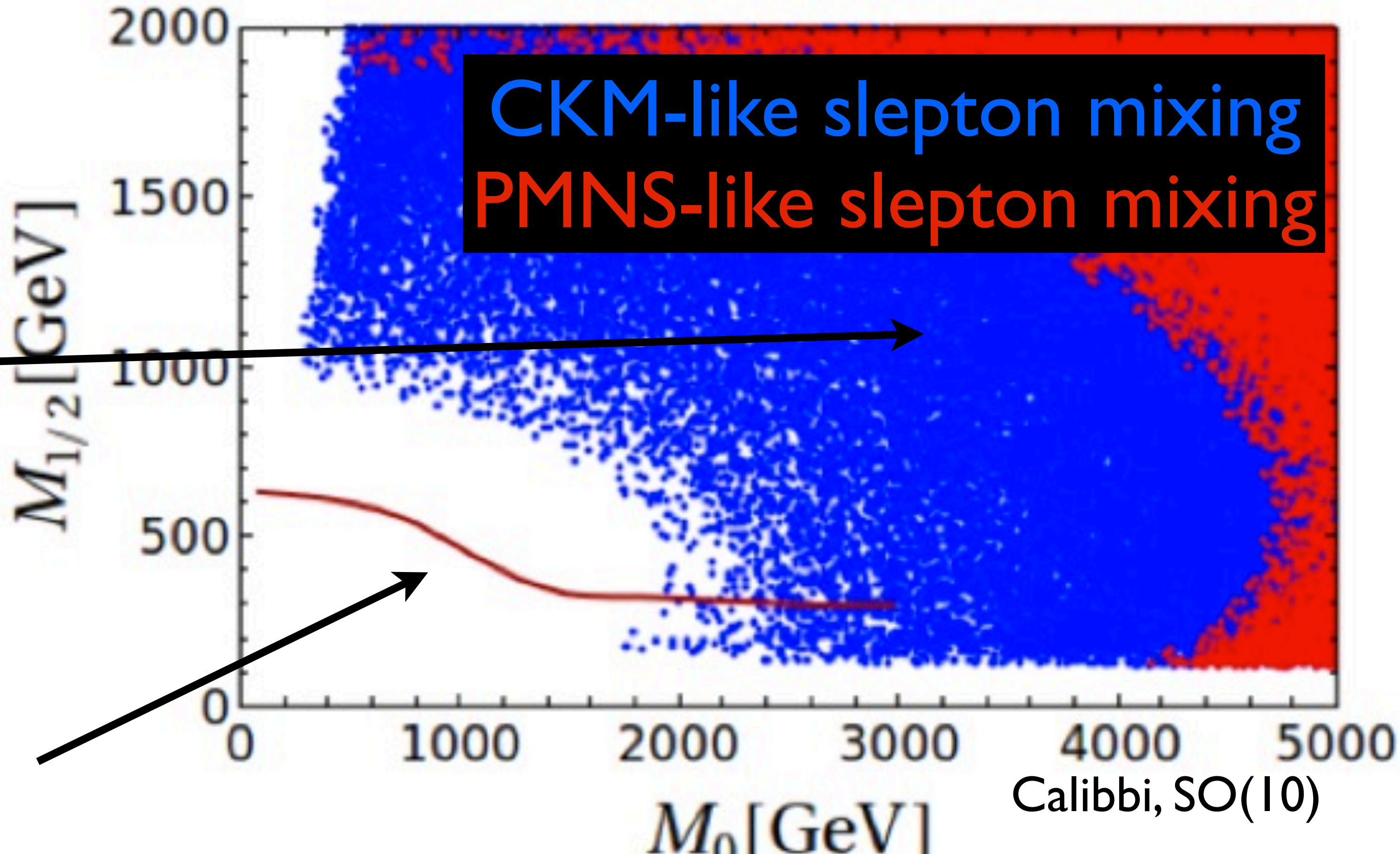
backup

Direct and indirect search

NP **indirect** search via cLFV is sensible to **higher energy scale w.r.t. to direct** search at LHC

MEG allowed by **last result** (2.4×10^{-12})

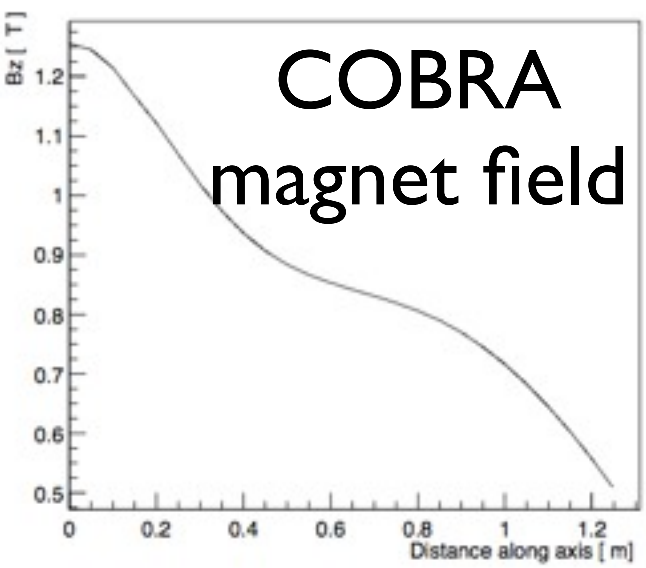
LHC upper **bound** in sensitivity



Calibbi, SO(10)

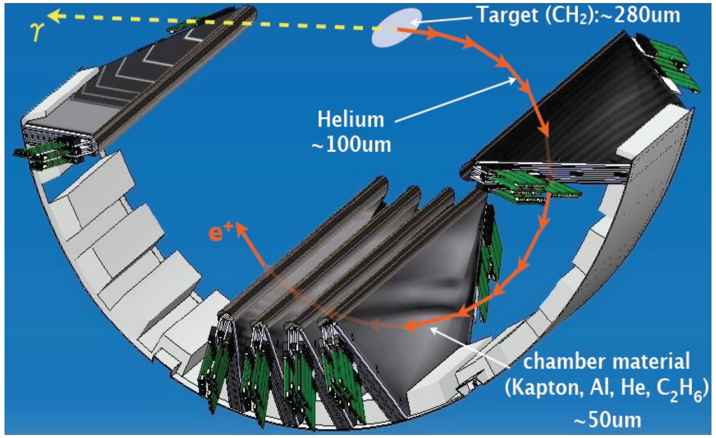
Spectrometer

COBRA magnet field



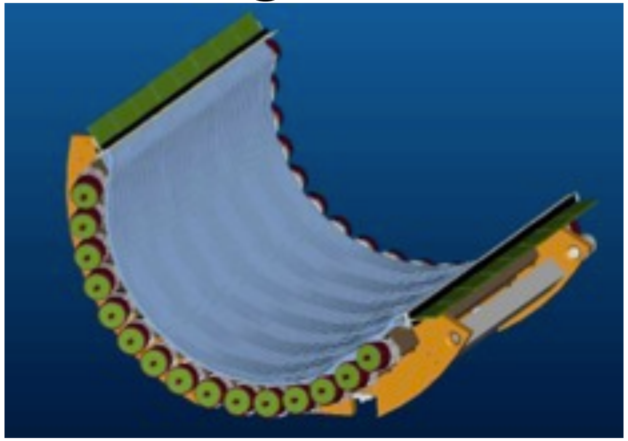
- Non uniform field: positron emitted almost perpendicular w.r.t beam axis swapped away rapidly
- bending radius almost independent w.r.t. emission angle

Drift chambers



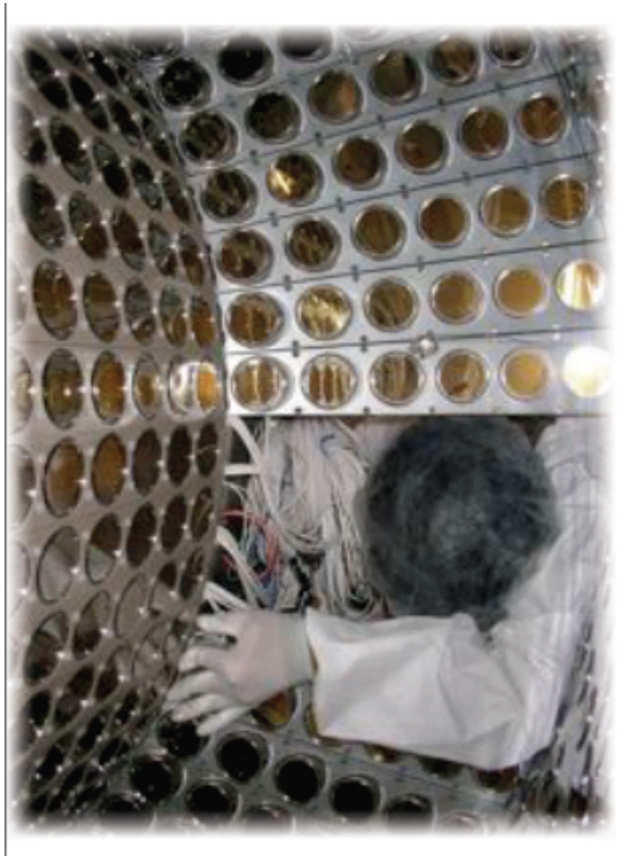
- 16 ultra thin modules
  - 0.0003 X_0 per module
  - two staggers planes with 9 wires each
  - cathode foils for longitudinal information

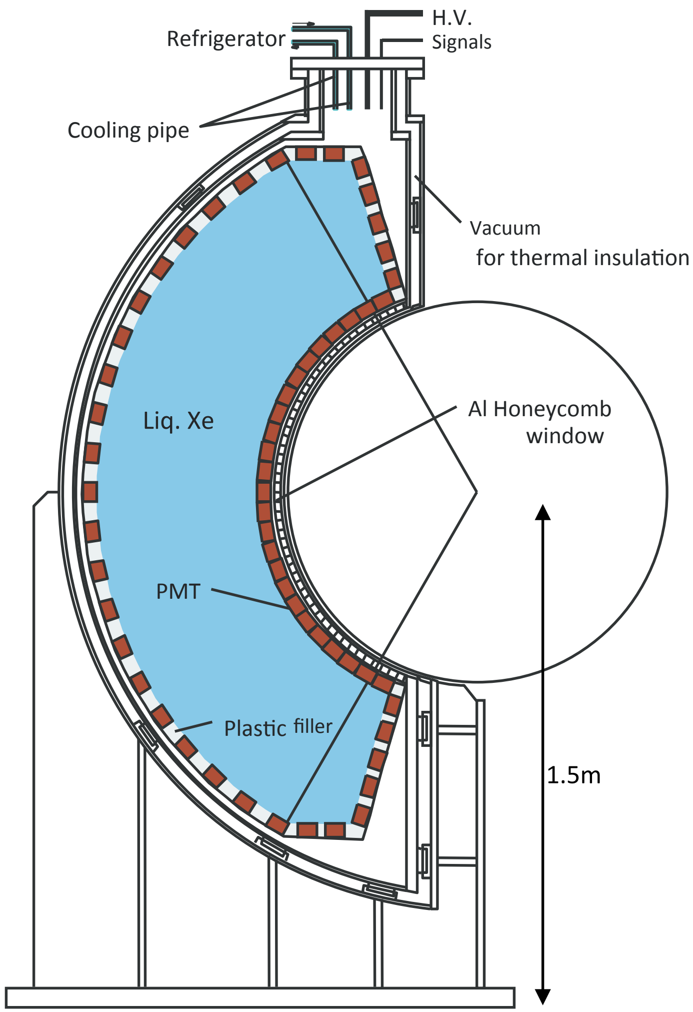
Timing counter



- Two identical sectors of 15 scintillation bars read by fine mesh PMTa
- Transverse scintillation fibers read by APDs for longitudinal hit reconstruction

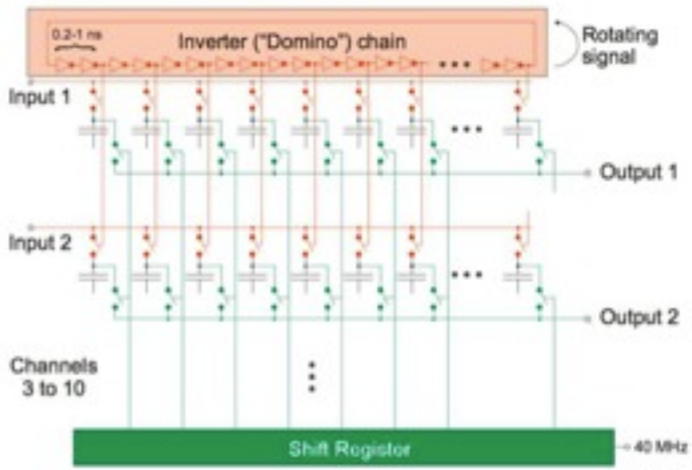
γ-detector

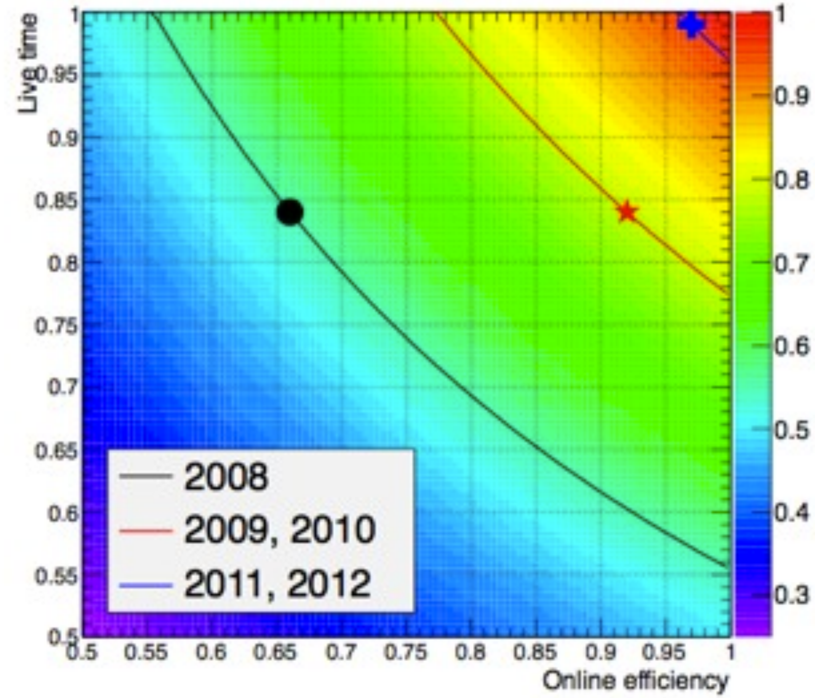




- 900 liters of LXe detector with 846 PMTs to collect scintillation light
- Large LY and fast response (4, 22 and 45 ns)
- LXe purification system in gaseous and liquid phase to remove impurities

Trigger and DAQ

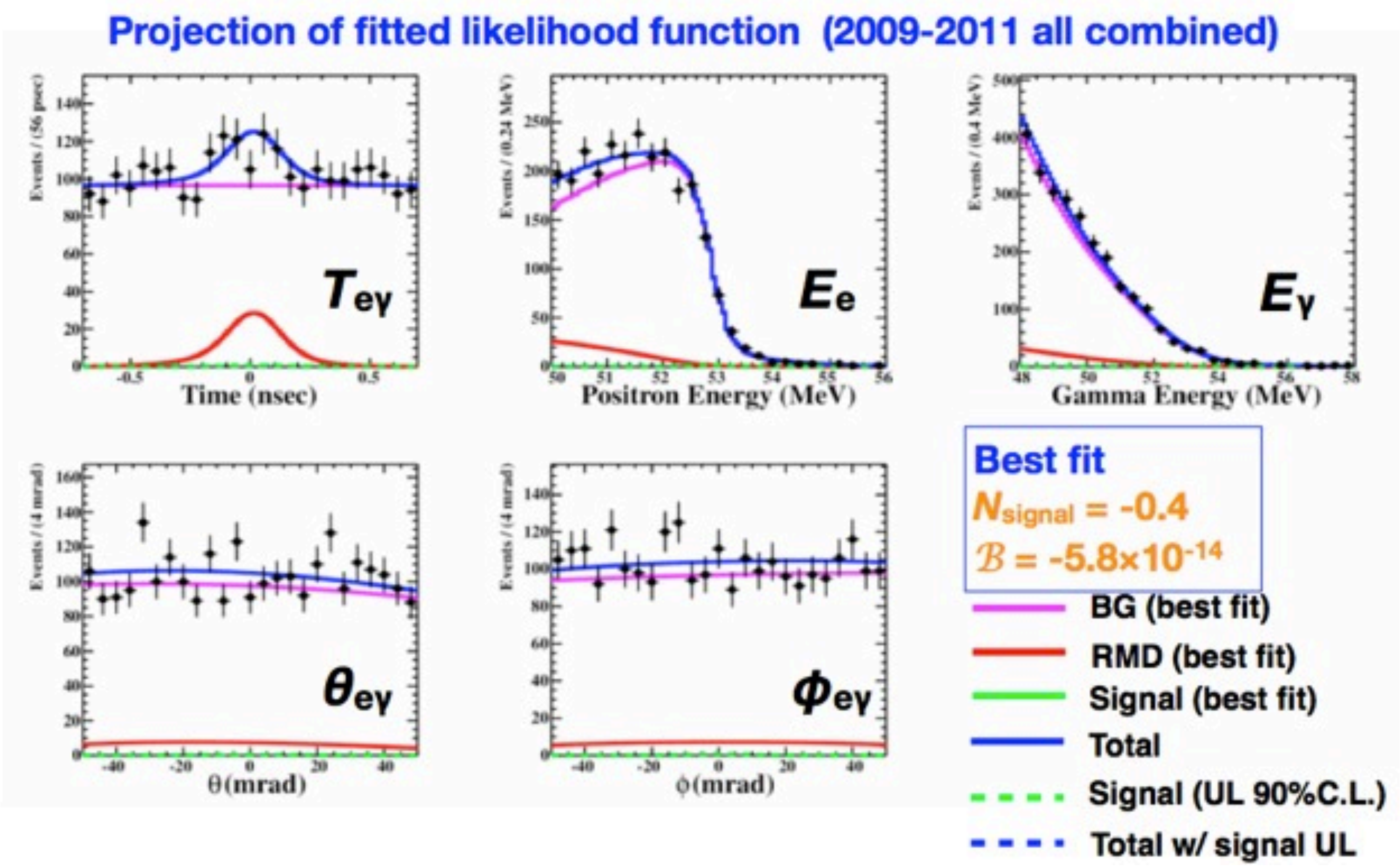




- Trigger algorithms implemented on FPGA: fast, efficient and flexible to experimental needs
- Use of DRS waveform digitizer: optimum timing and energy reconstruction and pile up rejection
- DAQ efficiency ≈ 1 for the bulk of the statistics

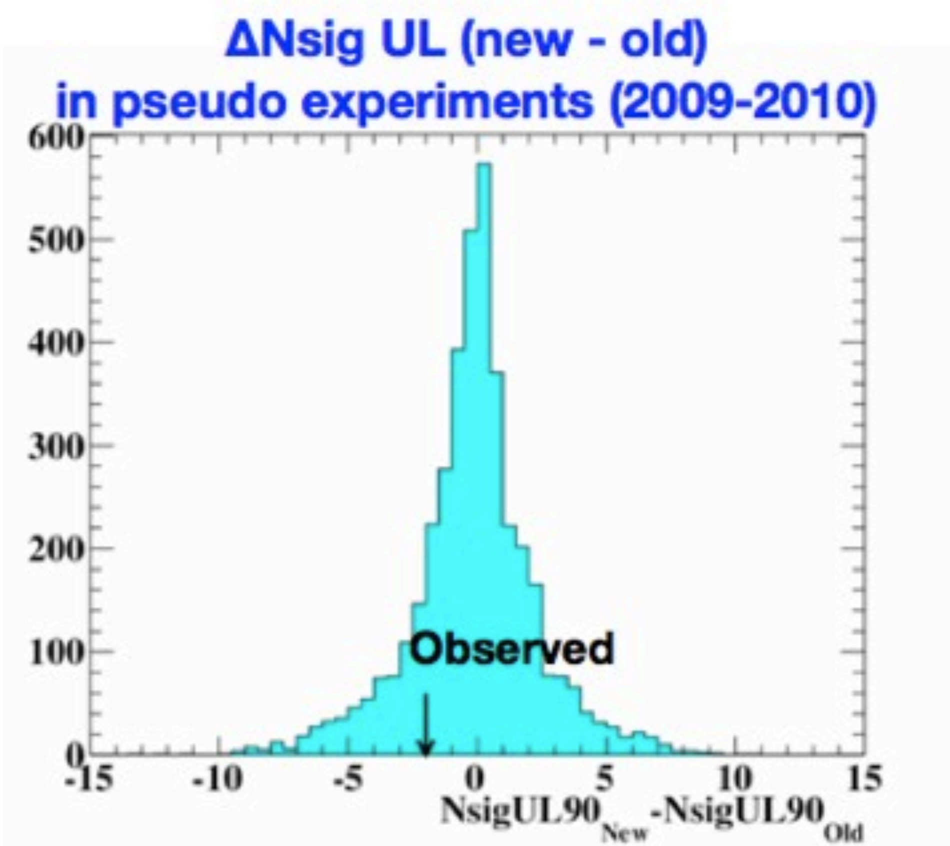
Likelihood fit

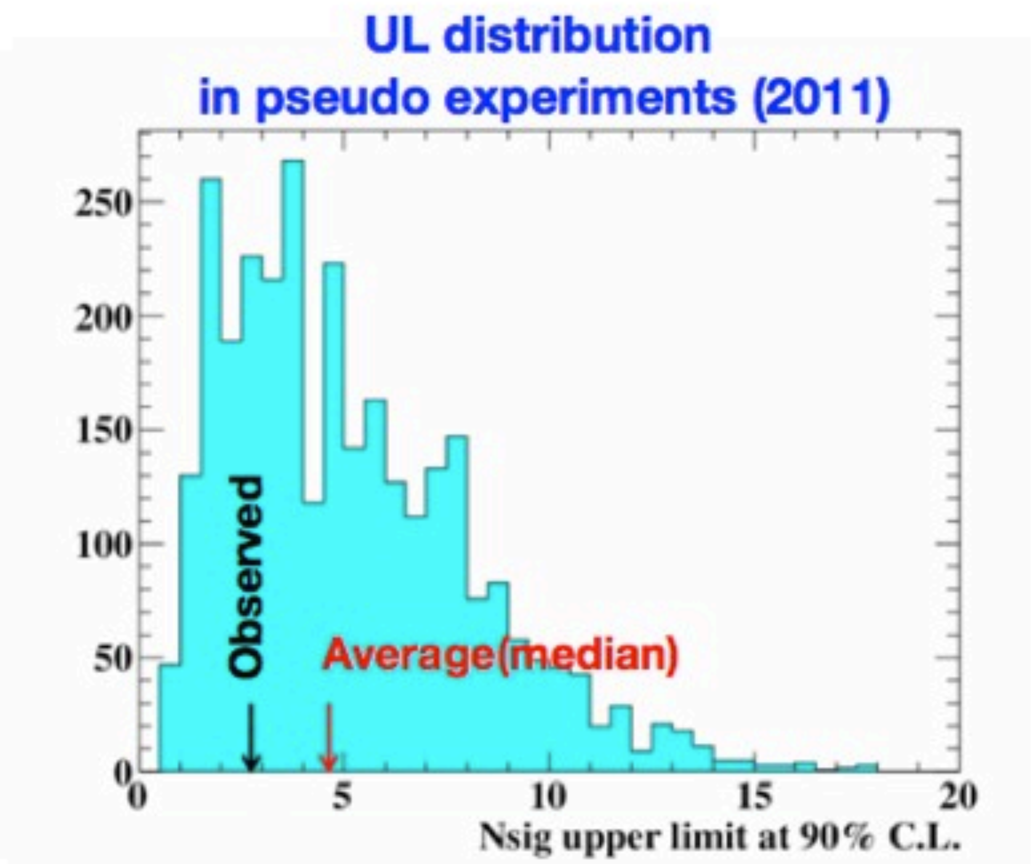
No excess over expected background is **observed** in data set



Consistency check

- Compatibility between old and new analysis: 31%
- Probability to observe UL equal or lower than observed: 24%





Systematics

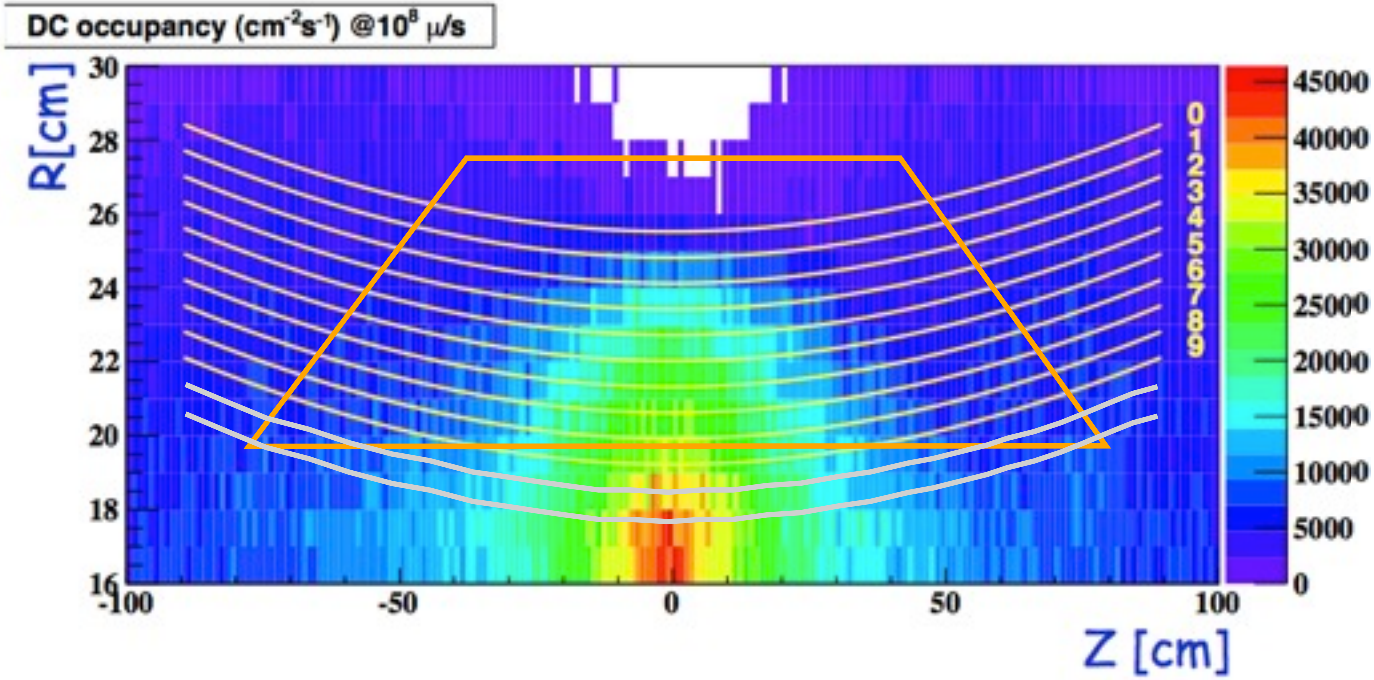
- 1% uncertainty on upper limit value

Effect on UL (change in ΔNLL)

Center of $\theta_{e\gamma}$ and $\phi_{e\gamma}$	0.18
Positron correlations	0.11
E_γ scale	0.07
E_e bias	0.06
$t_{e\gamma}$ signal shape	0.06
$t_{e\gamma}$ center	0.05
Normalization	0.04
E_γ signal shape	0.03
E_γ BG shape	0.03
Positron angle resolutions (θ_e, ϕ_e, z_e, y_e)	0.03
γ angle resolution (u_γ, v_γ, w_γ)	0.03
E_e BG shape	0.01
E_e signal shape	0.01
Angle BG shape	0.00
Total	0.25

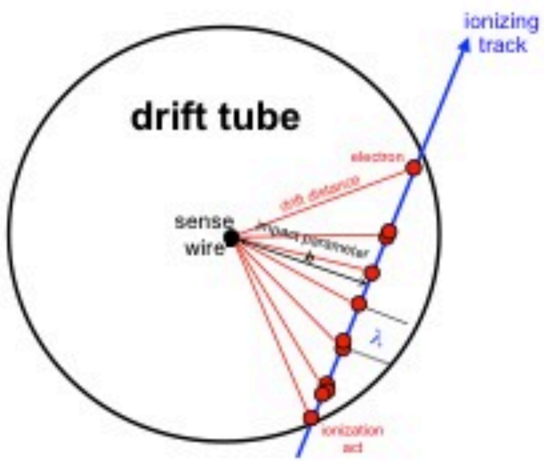
Positron hit rate density

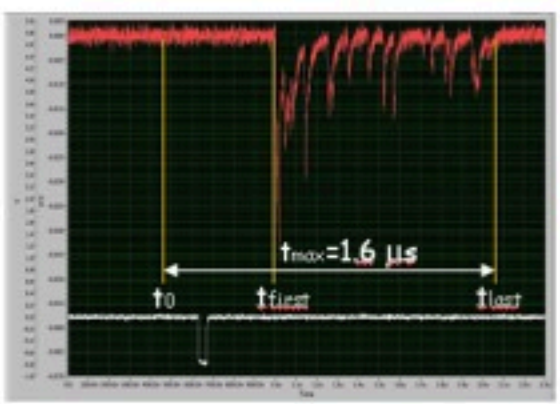
- Necessary to take into account the **specific ionization inside the detector**
  - ***31.5 kHz/cm^2*** *on the* ***innermost wire @ 7x10^7 μ/sec***
    - **6 nA/cm @10^5 gain**, for 90:10 He:iC_4H_{10}
    - **0.32 C/cm** on wire **integrated in 3 years** of DAQ (7 mm cell)
  - ***New DC*** *at center* ***17.6 cm*** *[19.3 cm in present config]*



Cluster timing

Cluster Counting/Timing in pillole





$t_0 = t_{last} - t_{max}$	gives the trigger time
$b_f = \int_{t_0}^{t_{first}} v(t)\, dt$	first approx. of impact parameter b
$(c/2)^2 = r^2 - b_f^2$	length of chord
$N_{cl} = c\,/(\lambda(\beta\gamma) \times \sin\theta)$	expected number of cluster
$N_{ele} = k \times N_{cl}$	expected number of electrons
$\{t_i\}$ and $\{A_i\}$, $i=1,N_{ele}$	ordered sequence of electron drift times and amplitudes
$P(i,j)$, $i=1,N_{ele}$, $j=1,N_{cl}$	probability i-th ele. $\in$ to j-th cl.

$$D_i^{Ncl}(x) = \frac{N_{cl}!}{(N_{cl}-i)!\,(i-1)!}(1-x)^{N_{cl}-i}\, x^{i-1}$$

probability density function of ionization along track