Lepton Flavor Violation: present and future experiments - 1

LNF- May, 11ht 2008

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First experiment: E.P.Hincks and B. Pontecorvo (1948)

- At that time the motivation for a such searches was motivated by the general study of μ decay
- $\nu_{e,}$ ν_{μ} and *e* spectrum not discoverd
- μ was supposed to decay in *e* + ν_e (Yukawa)

neutrino hypothesis,[3] a direct experiment to test an alternative hypothesis—*that the decay process consists of the emission of an electron and a photon, each of about 50 Mev*—has been performed.

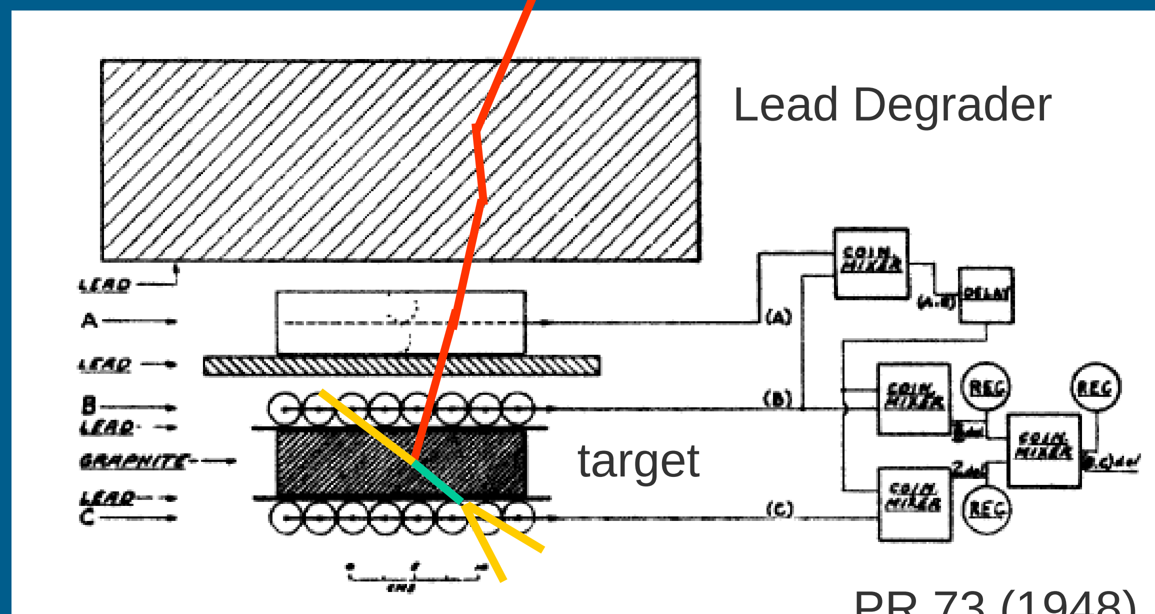
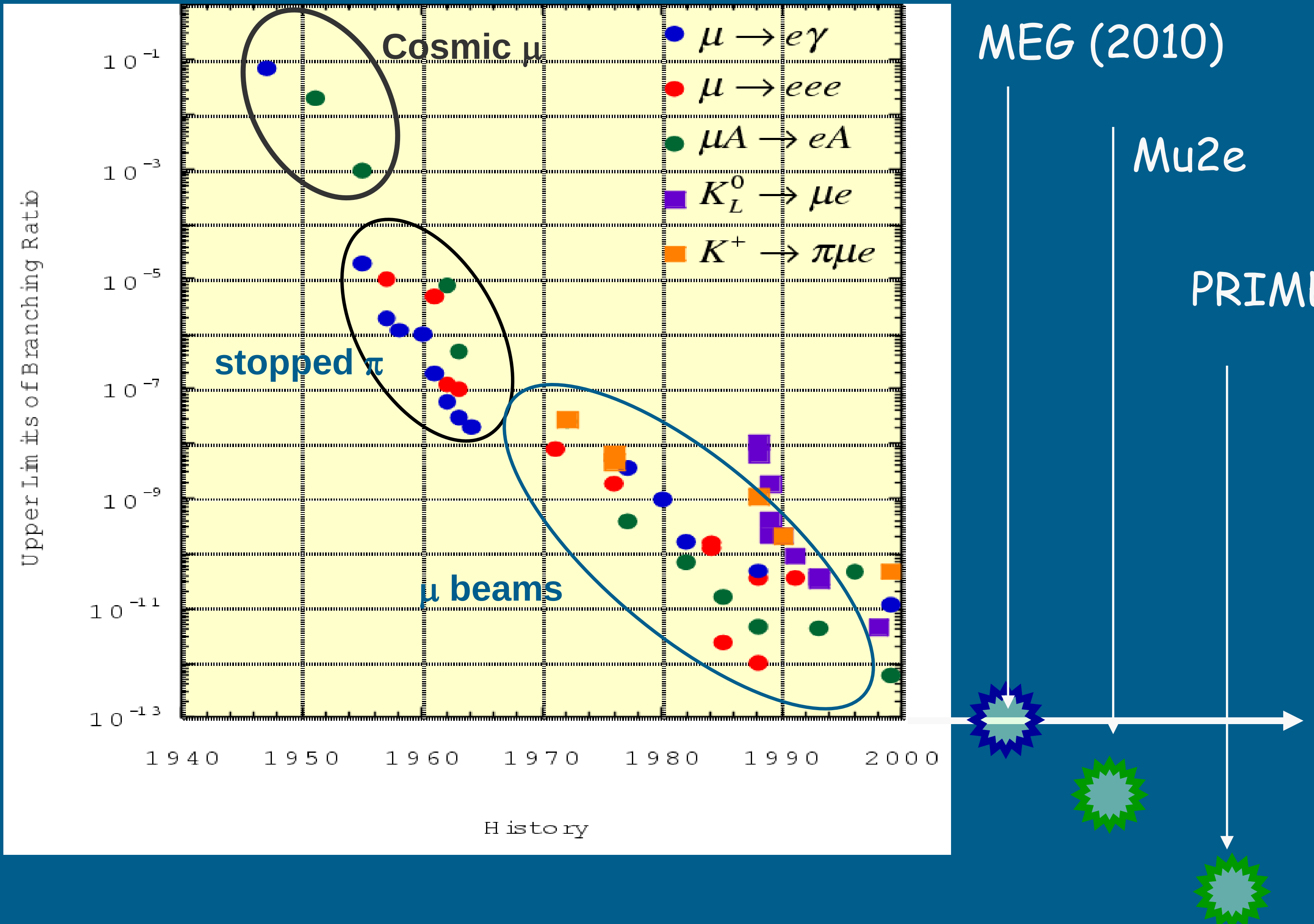


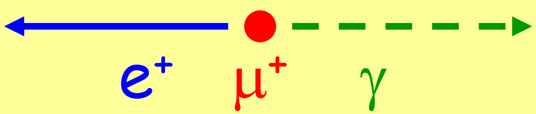
FIGURE 1 - ARRANGEMENT OF APPARATUS

History and future of FLV
μ decay searches



signal

$\mu \to e\,\gamma$



$\theta_{e\gamma} = 180°$

$E_e = E_\gamma = 52.8$ MeV

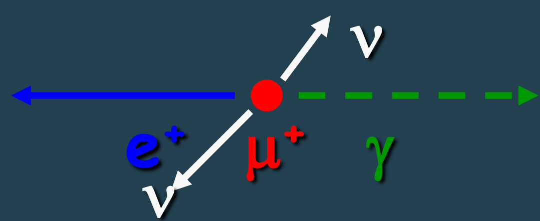
$T_e = T_\gamma$

background

physical

$\mu \to e\,\gamma\,\nu\,\nu$

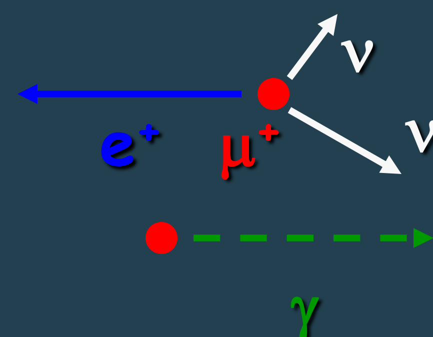
(<u>radiative decay</u>)



accidental

$\mu \to e\,\nu\,\nu$

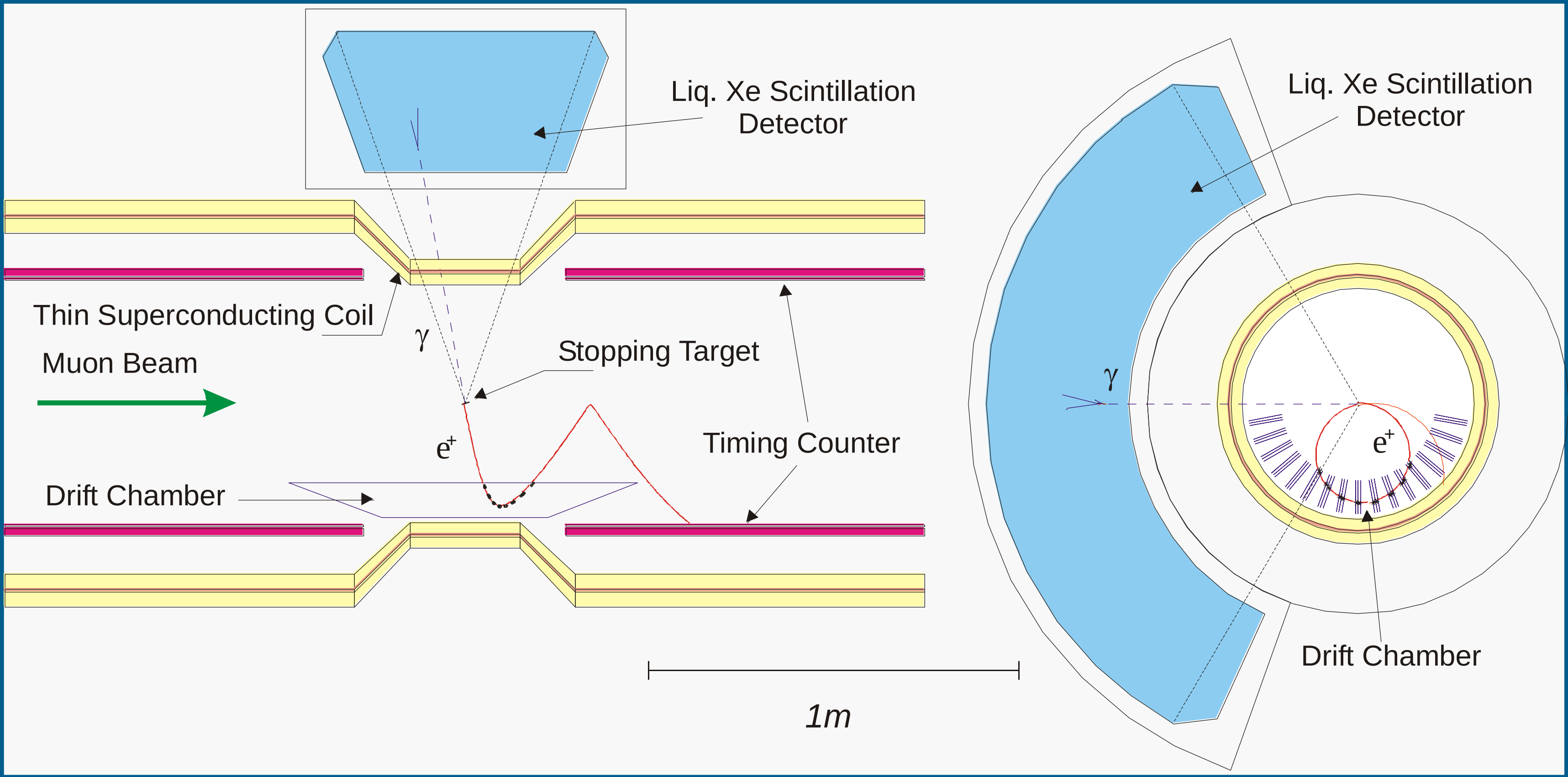
$\left\{ \begin{array}{l} \mu \to e\,\gamma\,\nu\,\nu \\ ee \to \gamma\,\gamma \\ eZ \to eZ\,\gamma \end{array} \right.$



The last of a series

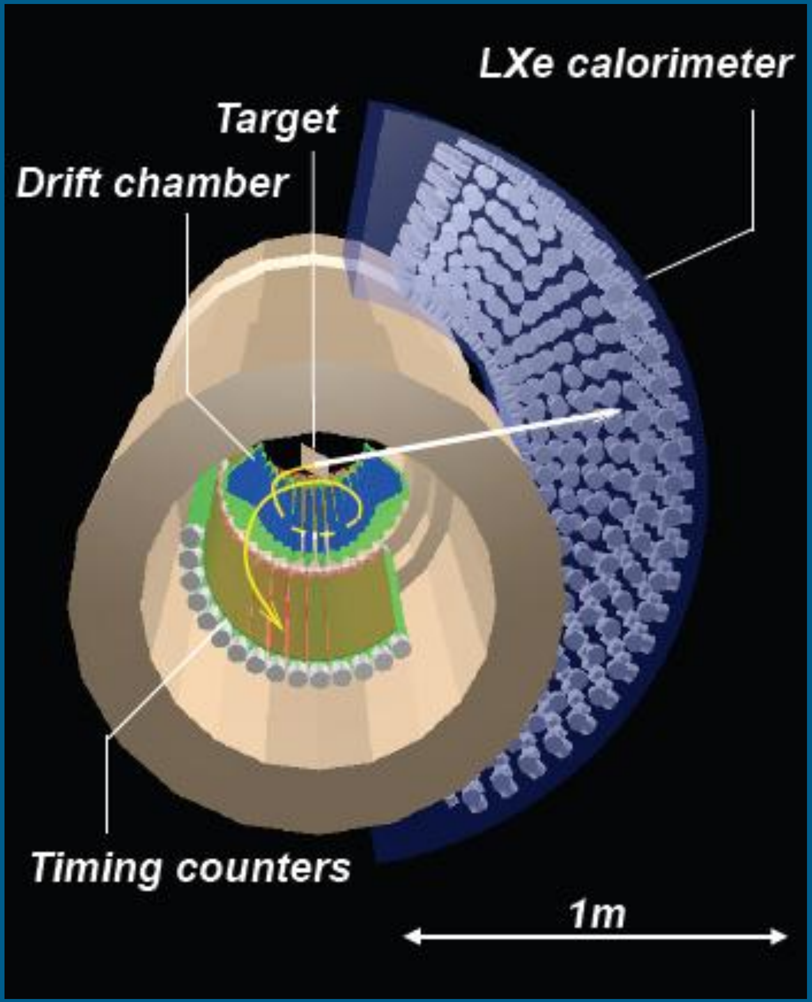
Exp./Lab	Year	DE_e/E_e (%)	DE_g/E_g (%)	Dt_{eg} (ns)	Dq_{eg} (mrad)	Stop rate (s^{-1})	Duty cyc.(%)	BR (90% CL)
SIN	1977	8.7	9.3	1.4	-	5×10^5	100	3.6×10^{-9}
TRIUMF	1977	10	8.7	6.7	-	2×10^5	100	1×10^{-9}
LANL	1979	8.8	8	1.9	37	2.4×10^5	6.4	1.7×10^{-10}
Crystal Box	1986	8	8	1.3	87	4×10^5	(6..9)	4.9×10^{-11}
MEGA	1999	1.2	4.5	1.6	17	2.5×10^8	(6..7)	1.2×10^{-11}
MEG	2010	**0.8**	**4**	**0.15**	**19**	**2.5×10^7**	**100**	**1×10^{-13}**

Conceptual design of MEG



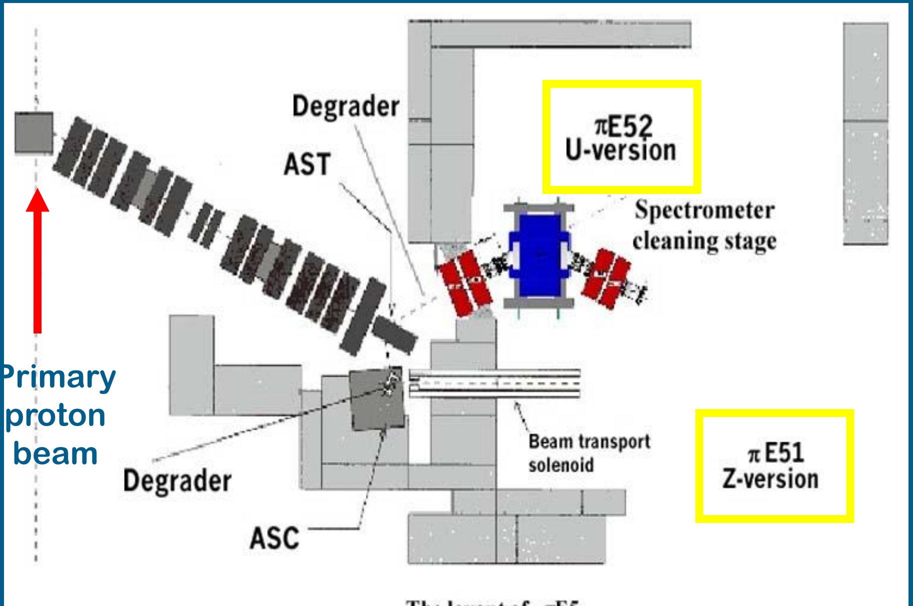
Actual MEG configuration

- Liquid Xenon Calorimeter
- Drift Chambers
- Timing counters
- COBRA Magnet



PSI-beam

- The most powerful continuous machine in the world;
- Proton energy **590 MeV**;**Power 1.1 MW**;n ominal operational current **2.0 mA.**
- **27.7 MeV/c muons** from π stop at rest (**surface muons**);
- Provides a DC beam of $\approx$ **10^8 m/s**.

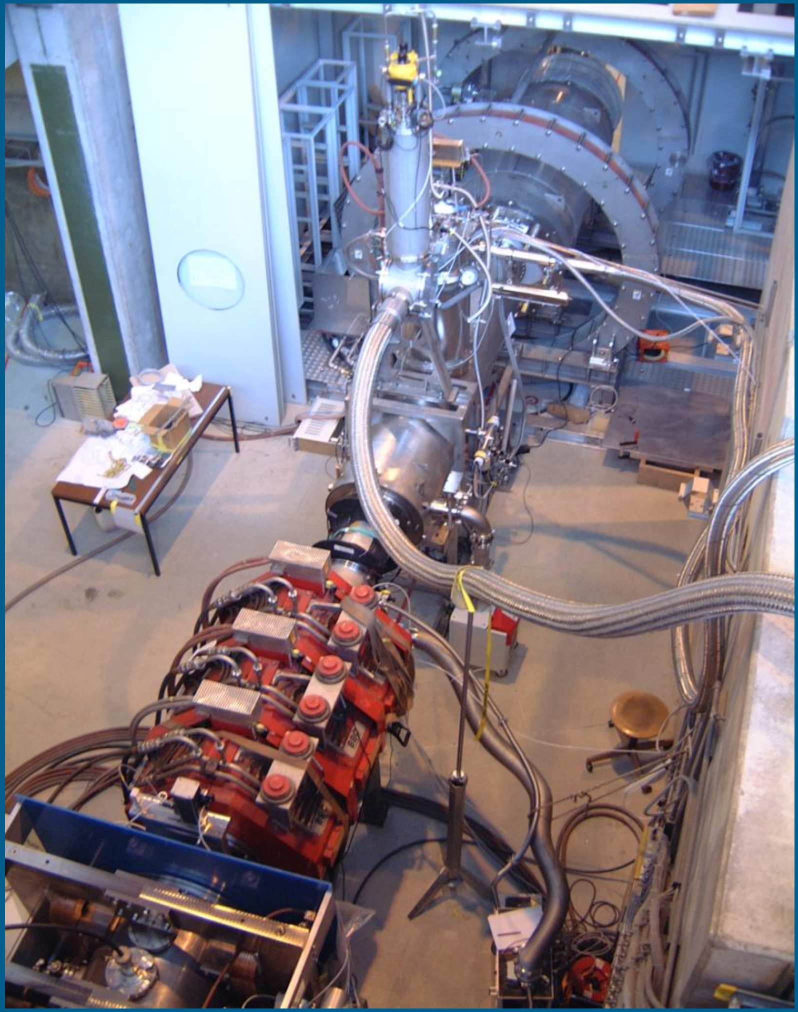


The layout of πE5

PSI-Beam

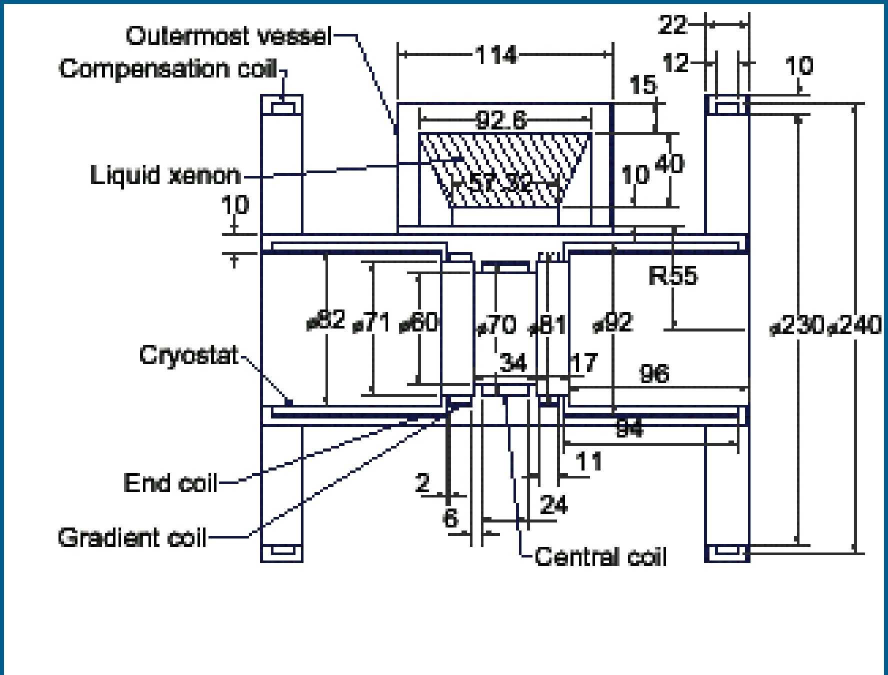
- The beam elements:
  - Wien filter for μ/e separation
  - Degrader to reduce the momentum stopping in a 150 μm CH2 target
  - Transport Solenoid to couple beam with COBRA spectrometer
- Rμ (total) 1.3*108 μ^+/s
- Rμ (after W.filter & Coll.) 1.1*10^8 μ^+/s
- Rμ (stop in target) 6*10^7 μ^+/s
- Beam spot (target) $\sigma \approx 10$ mm
- μ/e separation 7.5 σ (12 cm)

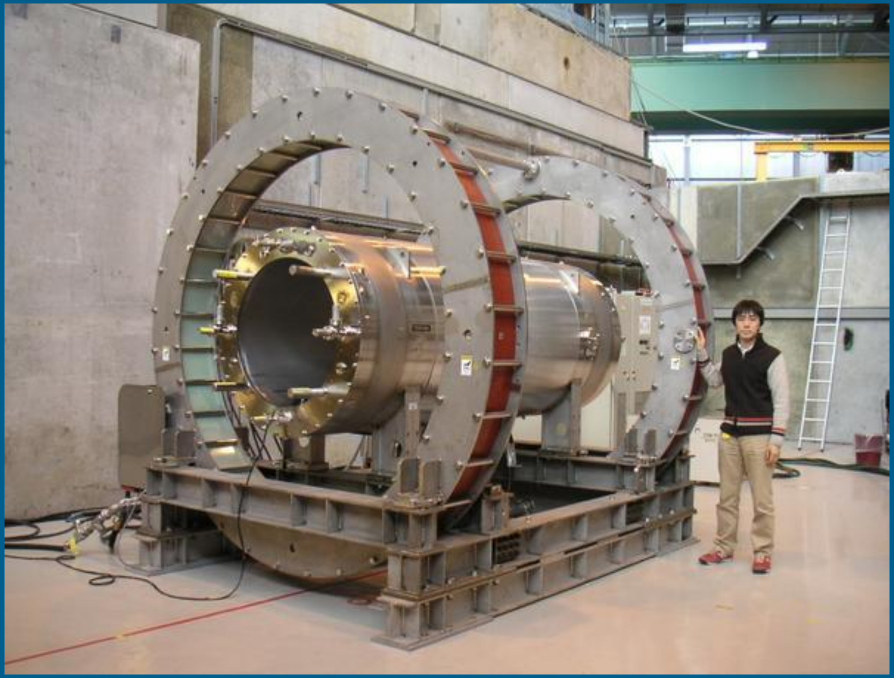
- <u>Maximum beam stop rate ≈ 10^8 μ/s, but we will use only 3 x 10^7 because of accidental background (proportional to (muon rate)^2)</u>



COnstant Bending RAdius- COBRA- magnet

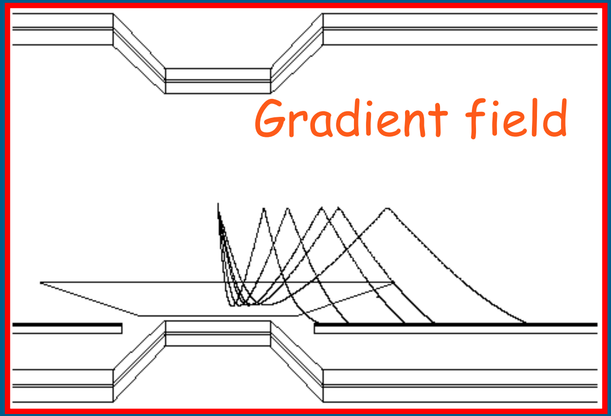
COBRA spectrometer was designed to provide a graded magnetic field whose flux lines have large divergence also in the center (1.27 T at the center and 0.49 T at both ends). Positrons with the same absolute momentum follow trajectories with a constant projected bending radius, independent on the emission angles over a wide angular range

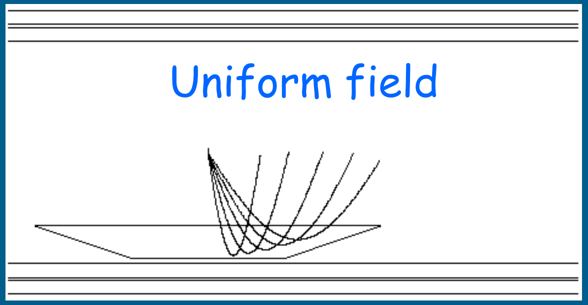




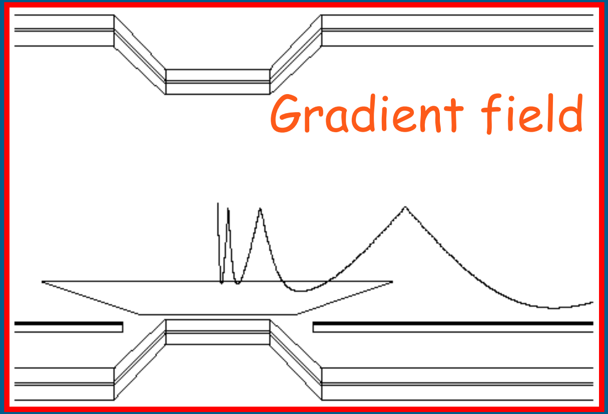
COBRA-magnet

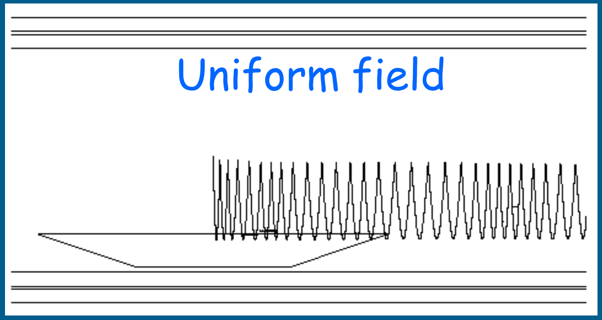
- Constant bending radius independent of emission angles



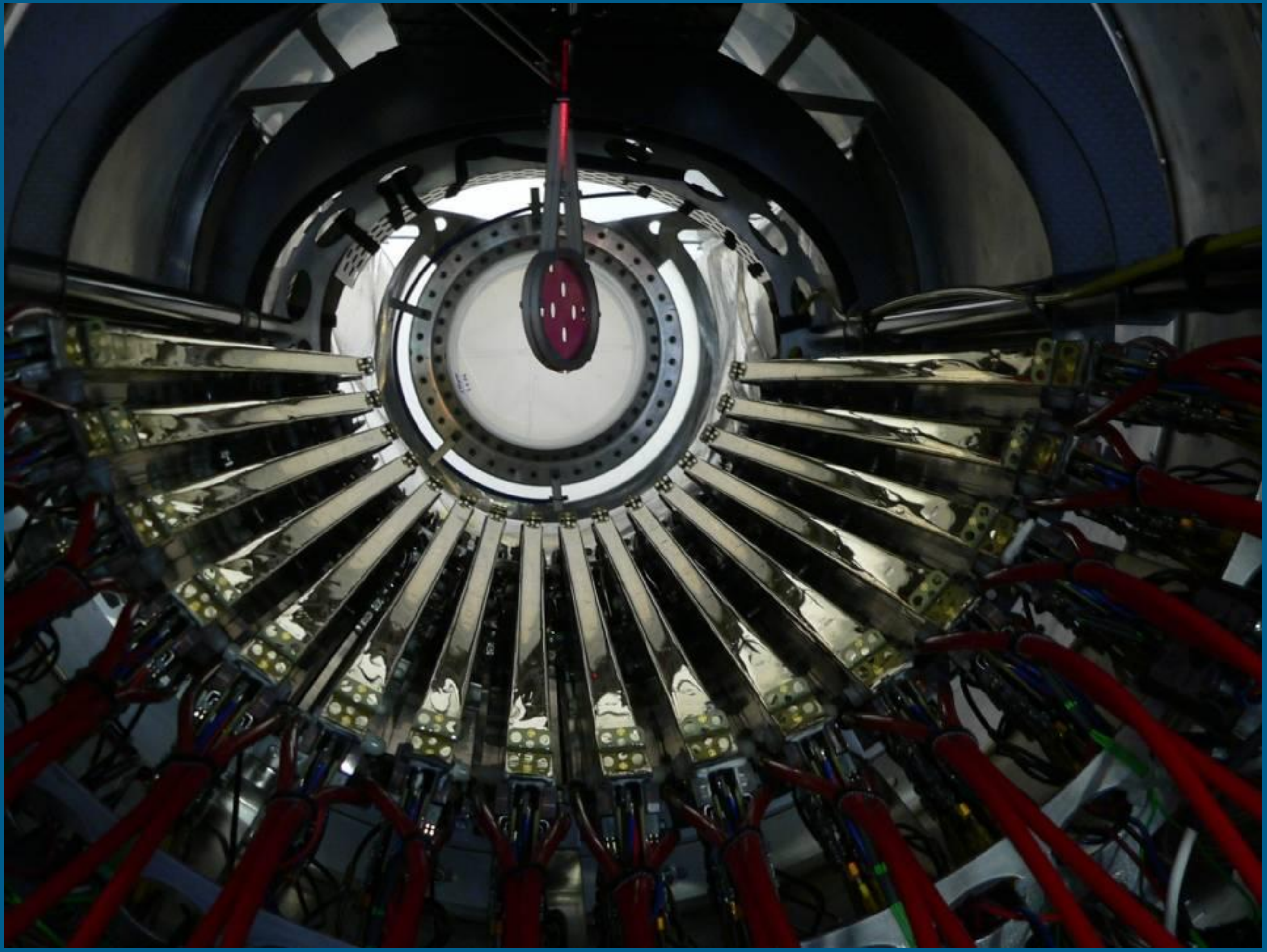


- High p_T positrons quickly swept out



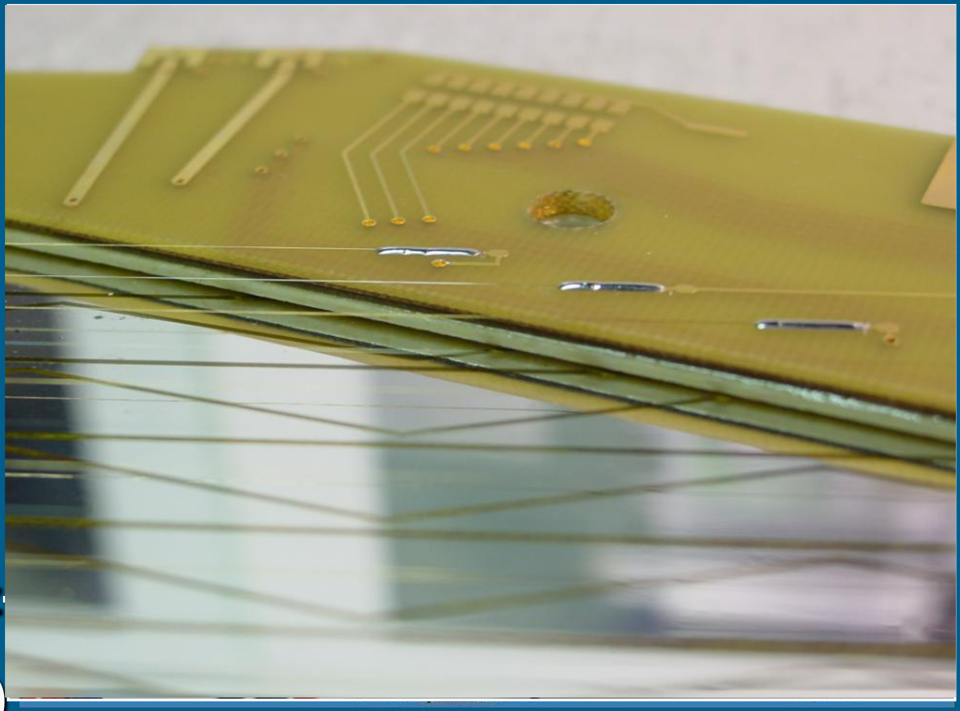


Target and positron tracking

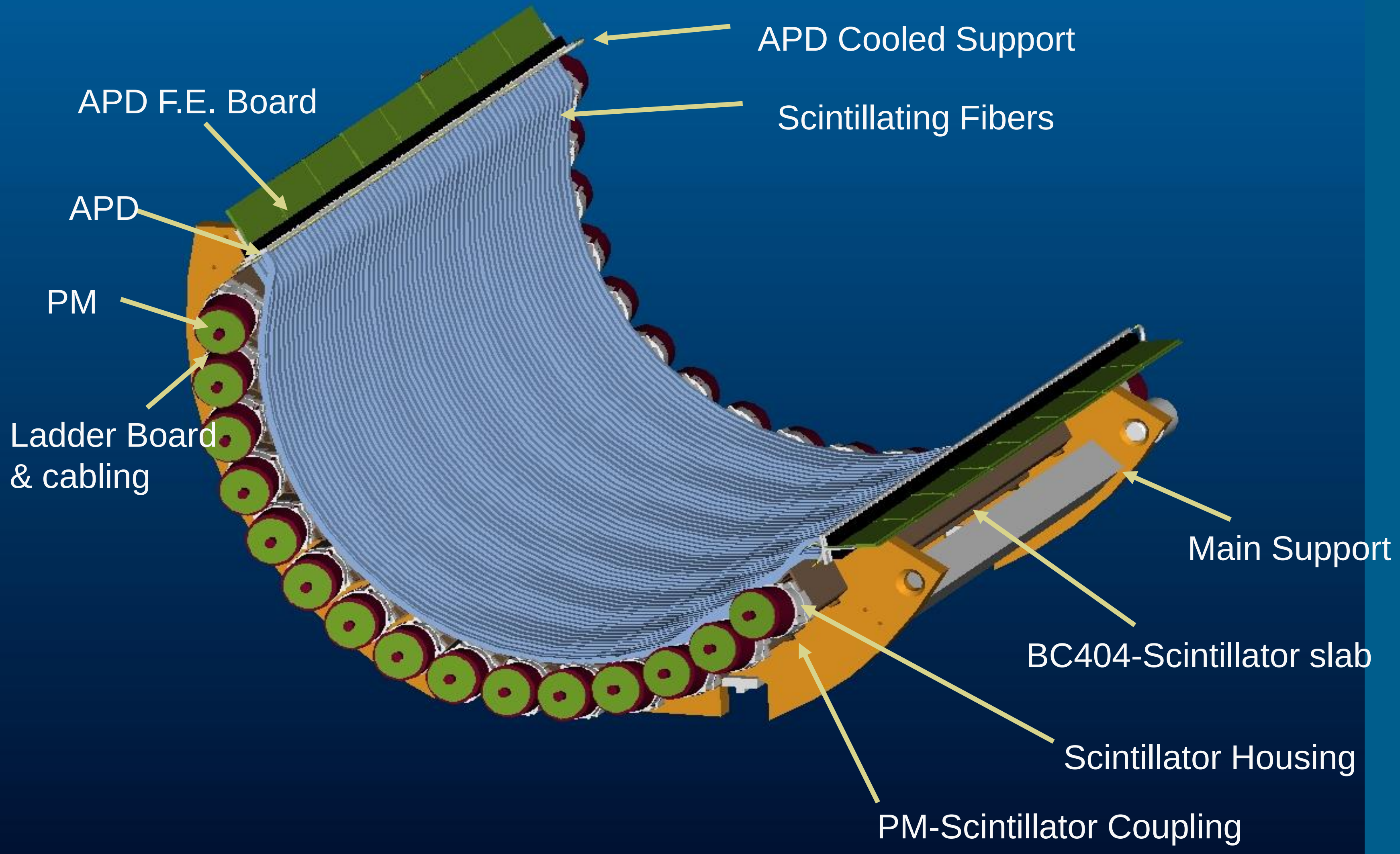


Positron Tracking

- Sixteen drift chambers (ten degrees interval), each one equipped with 18 staggered wires and cathodic kapton foils.
- Wires: r , ϕ coordinates
- Cathode: z coordinate
- $\sigma(X,Y) \sim 200\ \mu m$
- Chamber gas: He-C_2H_6 mixture
- Vernier pattern to measure z-position made of 15 μm kapton foils(charge division)
- $\sigma(Z) \sim 300\ \mu m$



Positron timing- Timing Counter

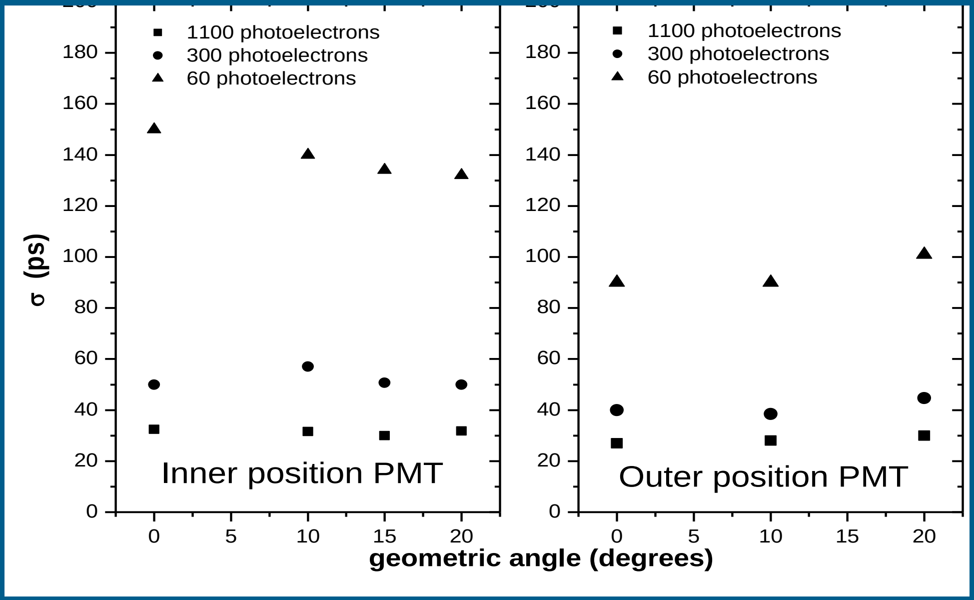


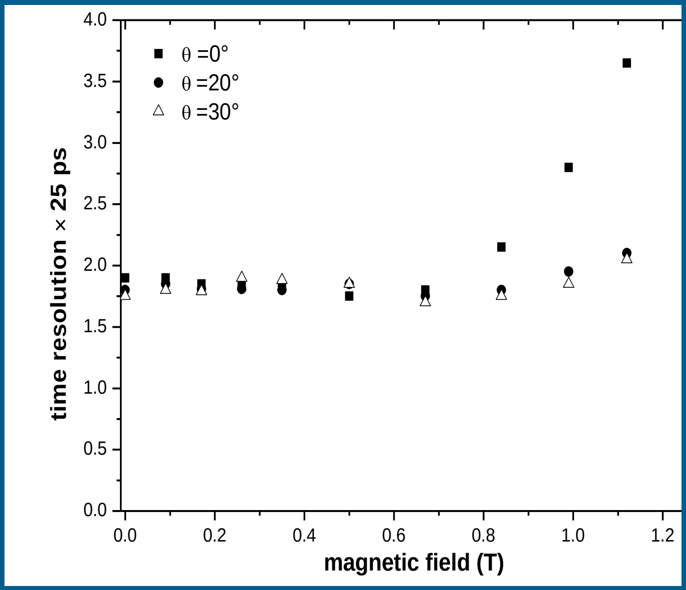
Positron timing- Timing Counter

- Two layers of scintillation counters placed at right angles with each other.
- Outer layer: scintillator bars, mainly devoted to timing measurement.
- Two sections of 15 bars each, read by PMTs, before and after DCH system.
- Inner layer: scintillating fibres, devoted to provide trigger and z information.
- 5 x 5 mm2 fibres, read by APDs.
- Measurements of TC bars timing resolution in dedicated test beams at several positions and impact angles at BTF in Frascati

Limitations due to the B field

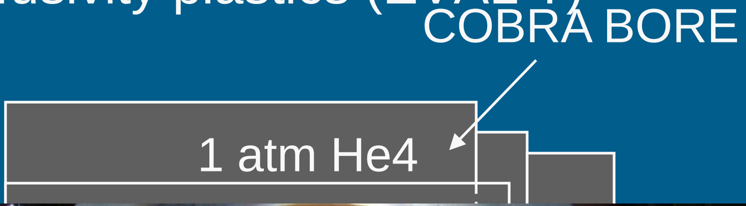
- PMT TTS, gain as a function of magnetic field and orientation angles
- Scintillation time, attenuation length, PMT-bar coupling
- Fine-mesh PMTs show good timing properties even in magnetic field up to 1 Tesla
- Gain behaviour is related to the orientation angle – best for q = 20-30°
- A high number of photoelectrons is necessary to be in a 100 ps resolution range

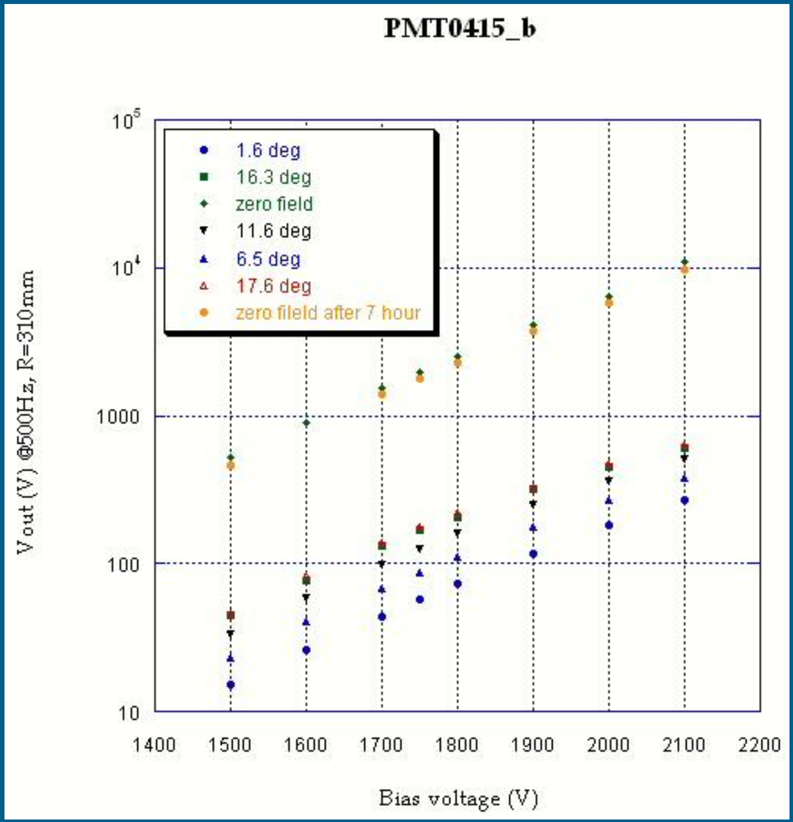


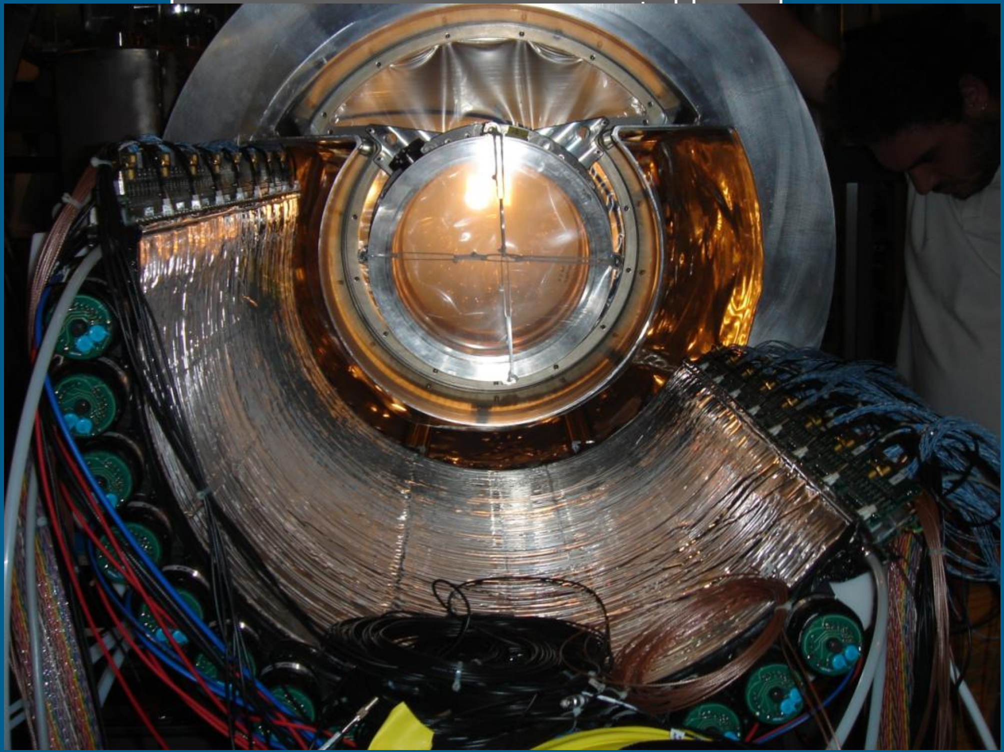


B field and He atmosphere

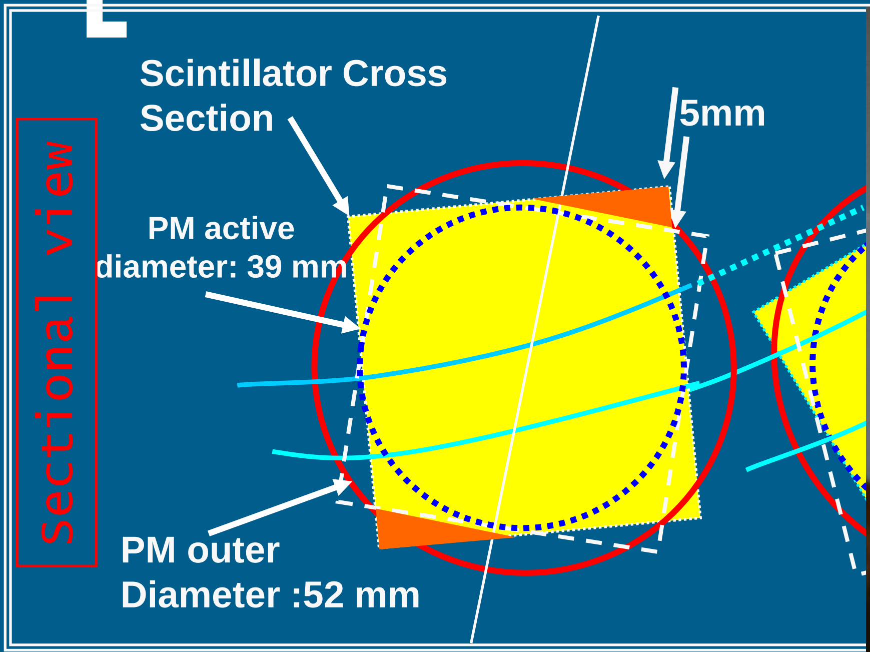
- Optimization of angular position of PMs
- Protecting Bag with thin low diffusivity plastics (EVAL T)

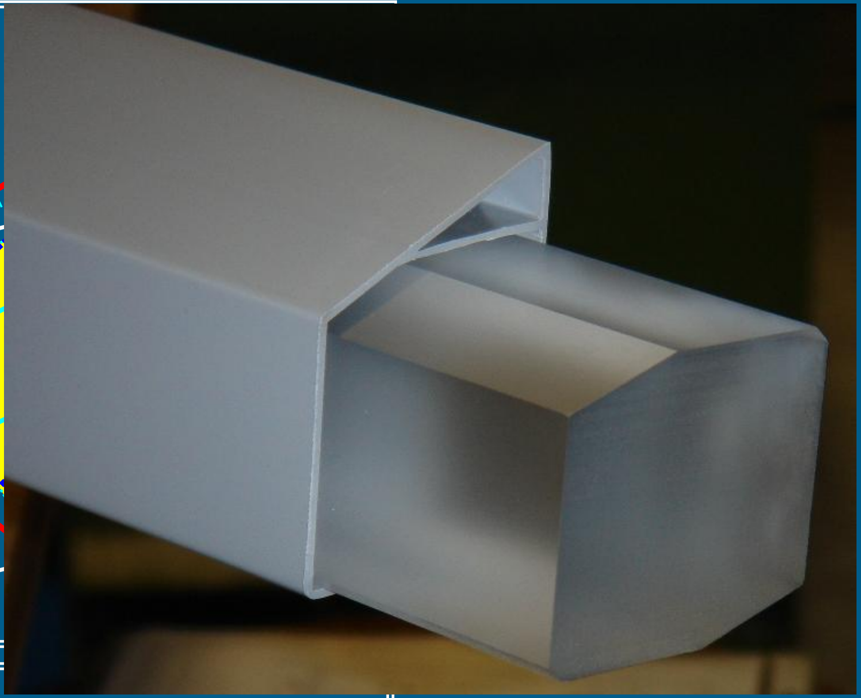


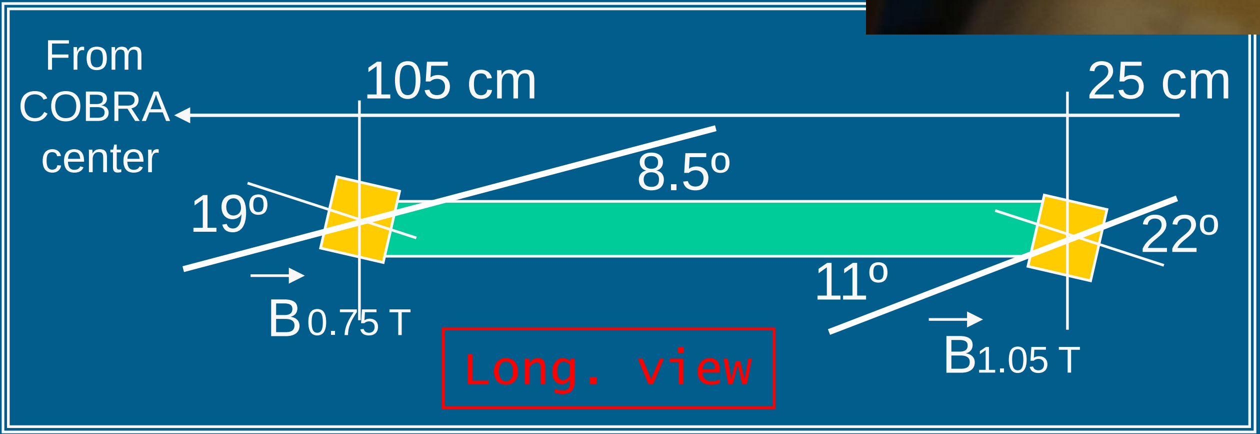




Experimental constraints: re-shaping the TC elements

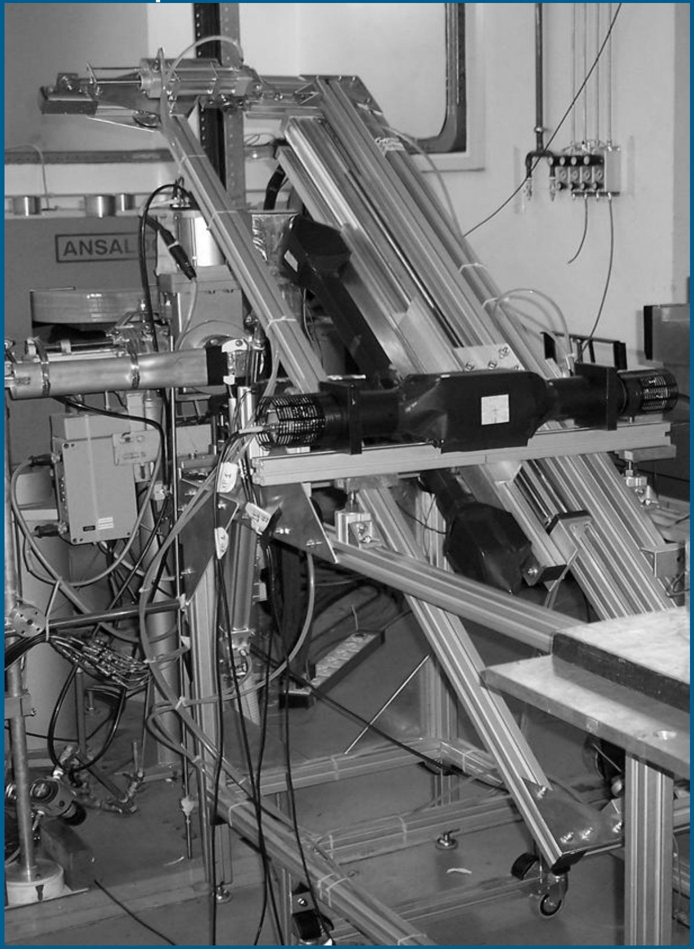




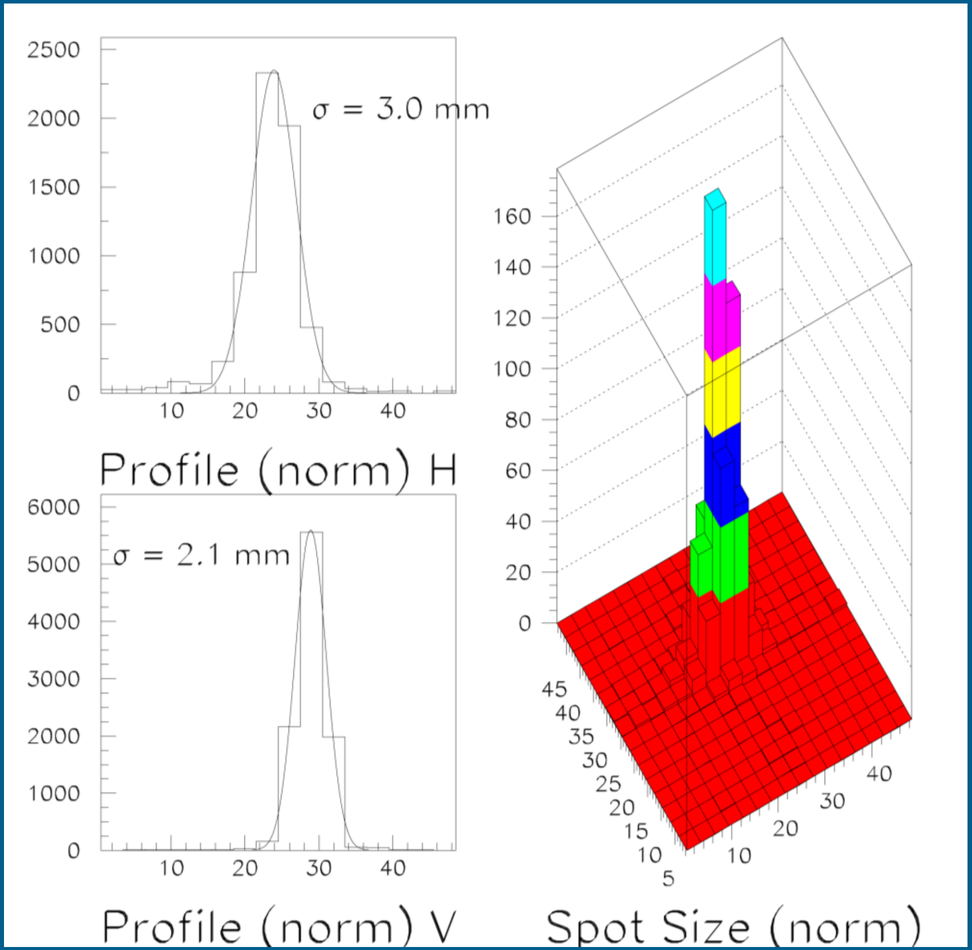


Testing single element at Beam Test Facility (LNF)

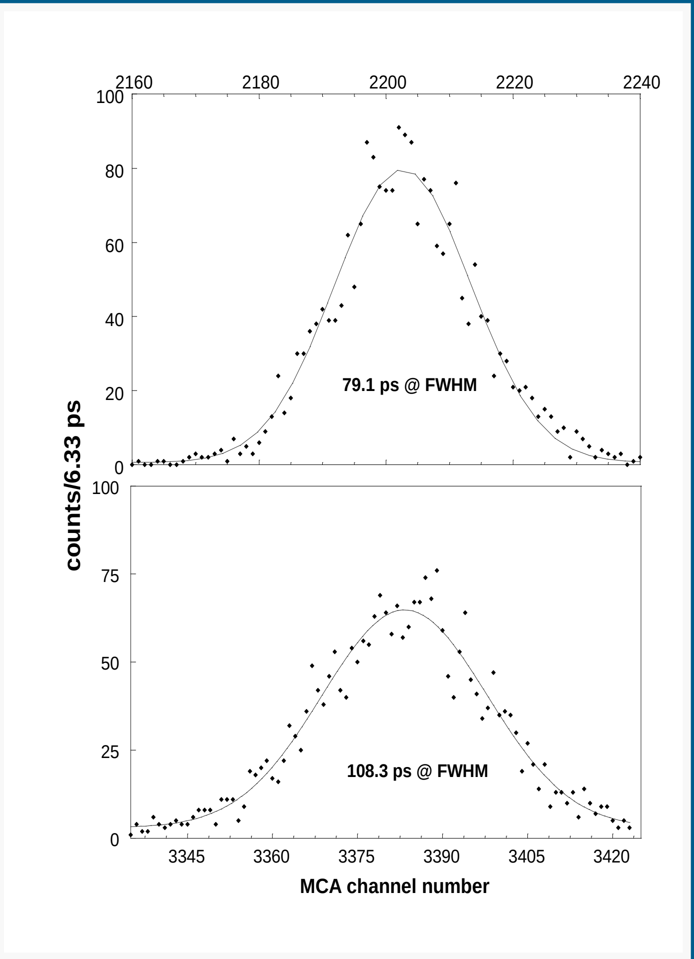
Apparatus for 2-axis + longitidinal sample movements

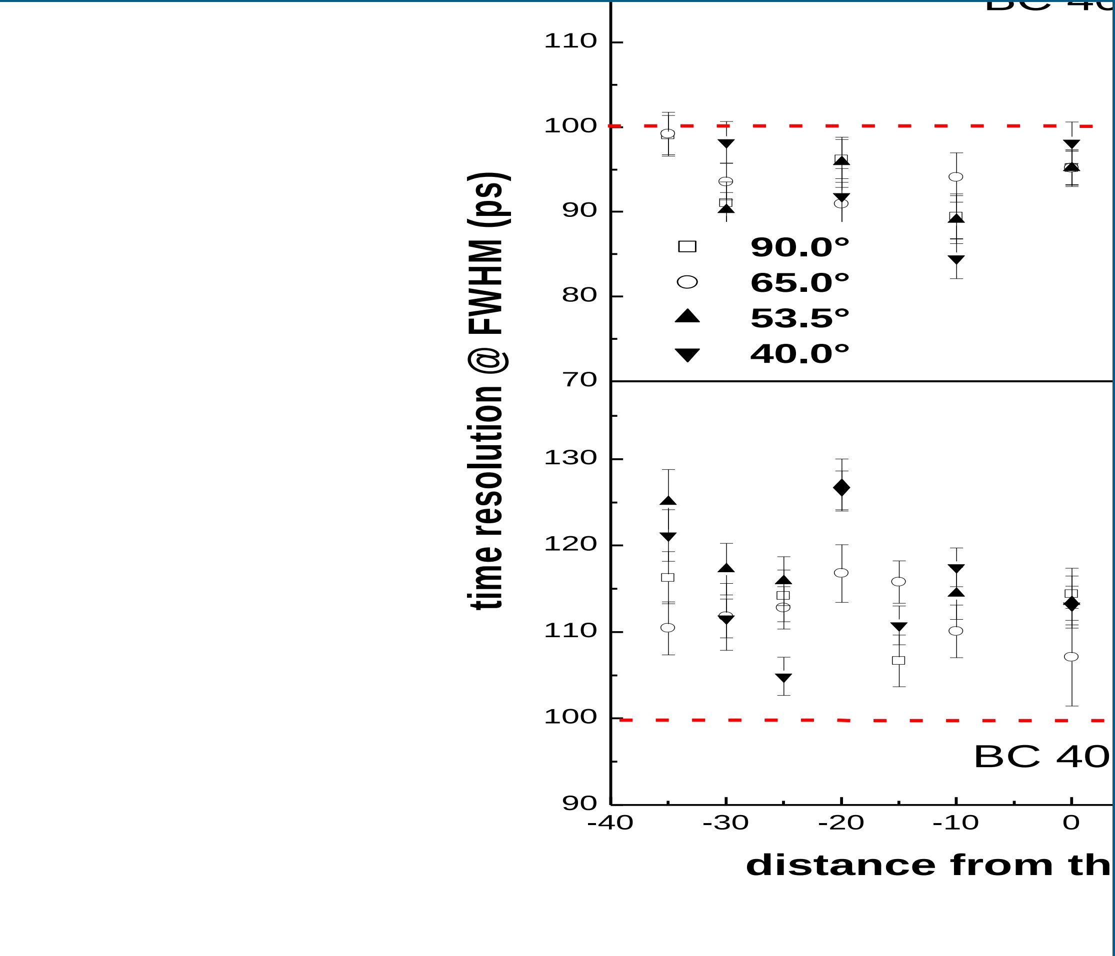


Typical BTF beam performance



Single element timing resolution



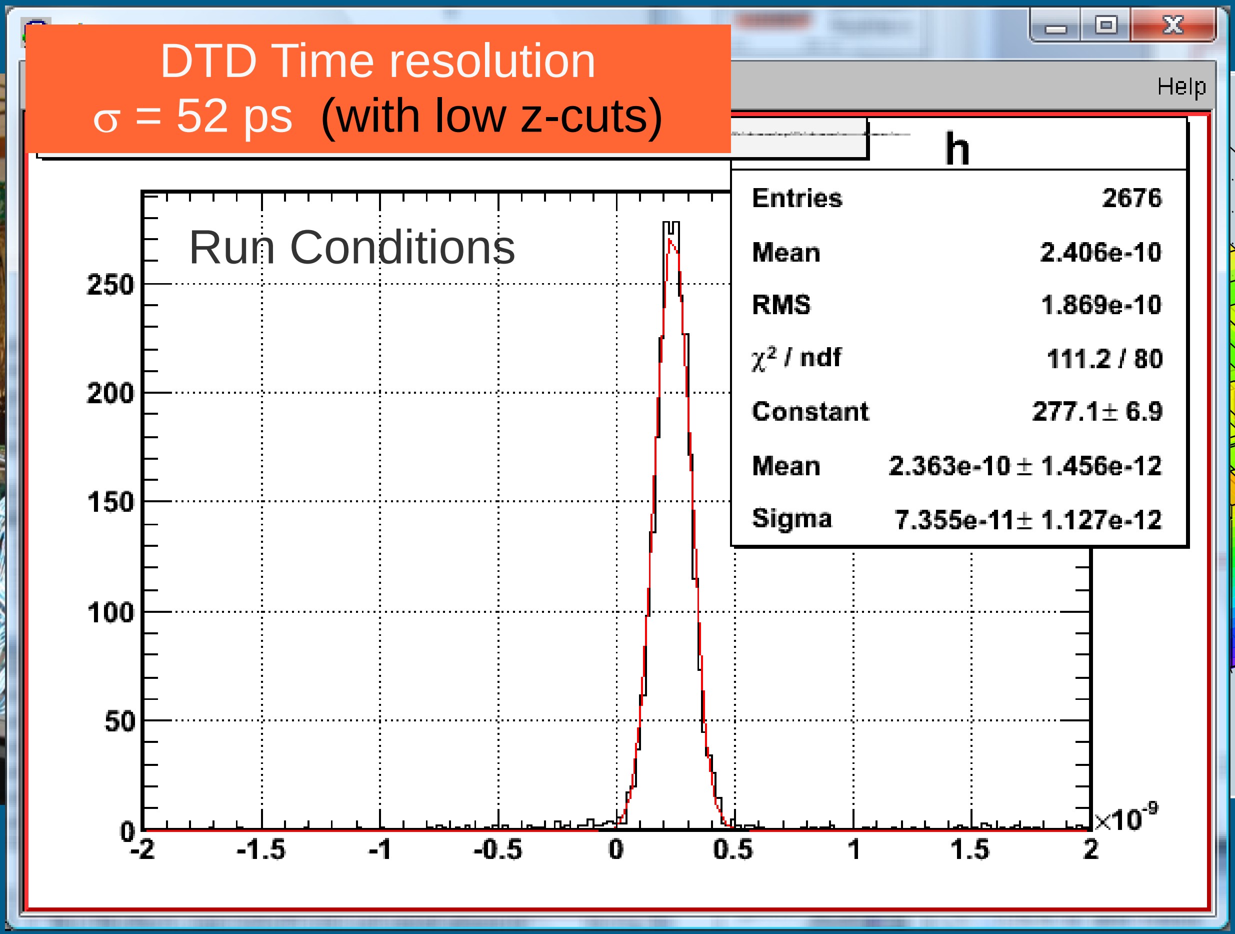


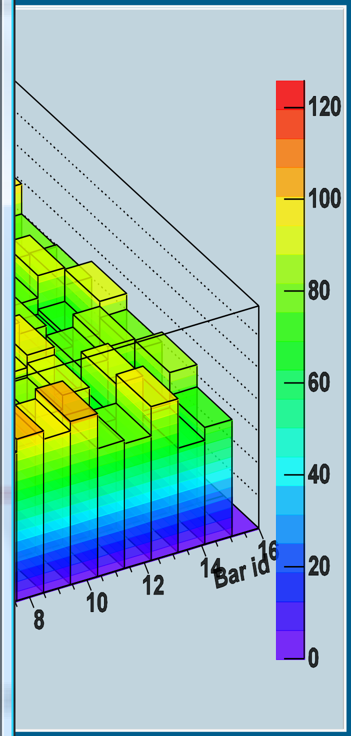
Timing performance with some other ToF

Scintil. type	PMT	LxWxT (cm)	σ (ps)	Ref
BC420	R1828-01	40x7x2.2	123	1
BC408	R3478	12-48x1-1.25x1.5-2.4	80	2
BC408	H1949	200x8.5x5	110	3
BC408	XP2020	180-250x21x2.5	160	4
BC408	XP2020	280x10x5	139	5
NE110†	XP2020	210-300x21x2	300	6
NE110†	XP2020	300x9.3x4	170	7
BC408	XP2020	305x10x5	110	8
NE Pilot F‡	XP2020	317.5x15.6x5.1	170	9
BC408	XP43132B/D1	32-450x15-22x5.1	163	10
BC404	R5924	80x4x4	40	our

- 1. B. Adeva *et al.*, *Nucl. Instr. and Meth* **A 491** (2002) 41.
- 2. G. Palla *et al.*, *Nucl. Instr. and Meth.* **A 451** (2000) 406.
- 3. V. Sum *et al.*, *Nucl. Instr. and Meth. A* **326** (1993) 489.
- 4. M. Baldo-Ceolin *et al., Nucl. Instr. and Meth. A* **532** (2004) 548.
- 5. Y. Kubota *et al.*, *Nucl. Instr. and Meth. A* **320** (1992) 66.
- 6. M. Baldo Ceolin *et al.*, *Nuovo Cimento* **105A** (1992) 1679.
- 7. G.C. Bonazzola *et al.*, *Nucl. Instr. and Meth.* **A 356** (1995) 270.
- 8. S. Benerjee *et al.*, *Nucl. Instr. and Meth.* **A 269** (1988) 121.
- 9. E.S. Smith *et al.*, *Nucl. Instr. and Meth* **A 432** (1999) 265
- 10 J.S. Brown *et al.*, *Nucl. Instr. and Meth.* **221** (1984) 503.

Final detector, test at BTF (LNF) and run performance

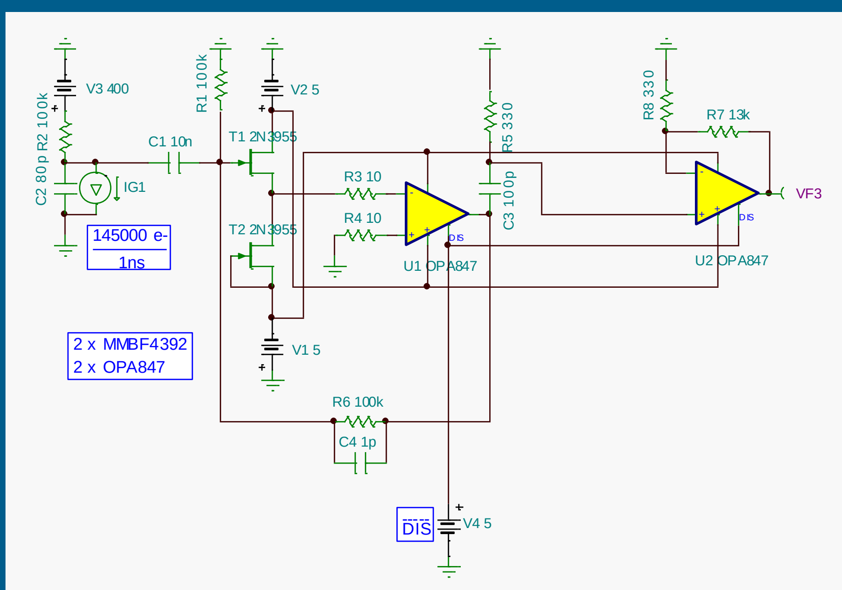


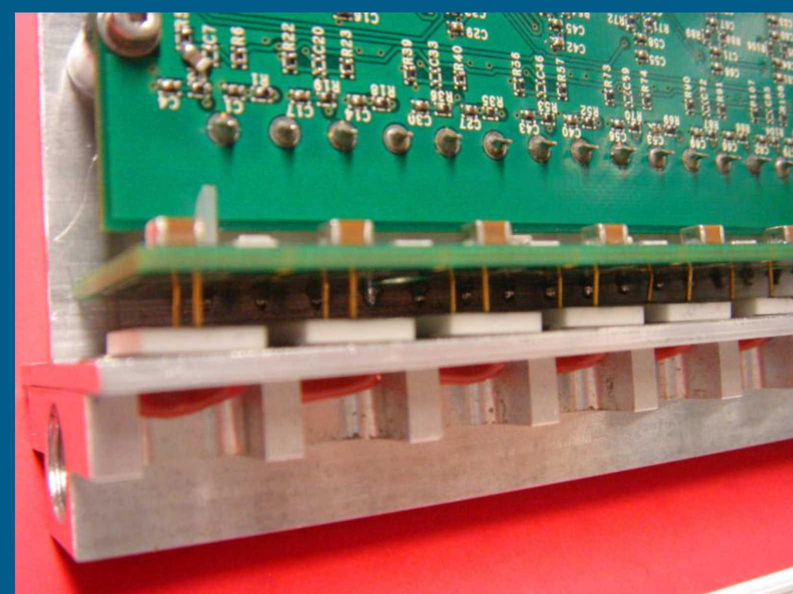


APD readout of scintillating fibers detectors

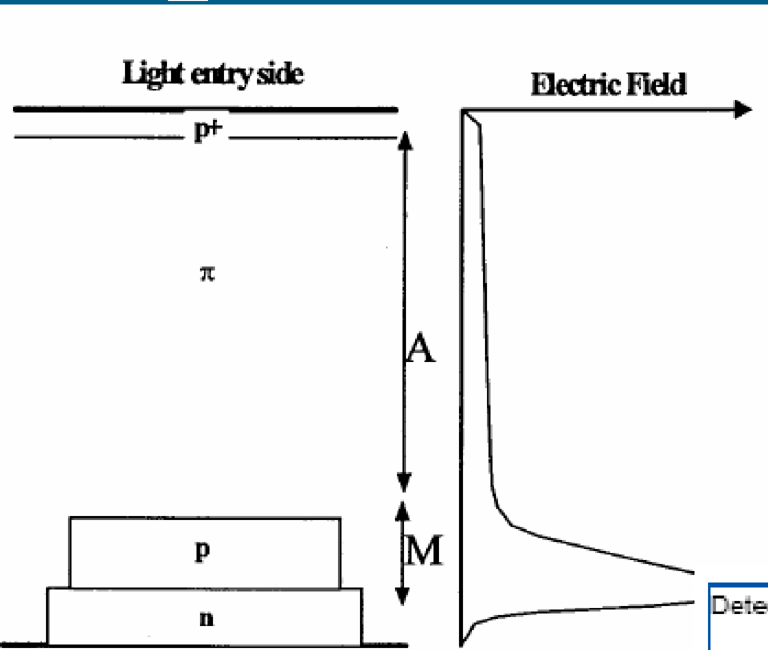
New solution with APD and scintillating fibers:

1. High QE of APD
2. Good performances, not influenced by magnetic field
3. Optimum matching APD-fiber
4. Better spatial resolution (5mm)
5. Lower cost per channel (total 512 channels)
6. Fast - Low noise electronics for analog signals (ENC = 1500e) custom made
7. Digital output with hitmap encoding





Avalanche Photo-Diodes (APD)



$$i_n = \left[2 \cdot q \cdot \left(I_{DS} + I_{DB} \cdot M^2 \cdot F\right) \cdot B\right]^{0.5}$$

Dark noise

$$i_n = \left[2 \cdot q \cdot \left(I_{DS} + \left(I_{DB} \cdot M^2 + R_0(\lambda) \cdot M^2 \cdot P_s\right) \cdot F\right) \cdot B\right]^{0.5}$$

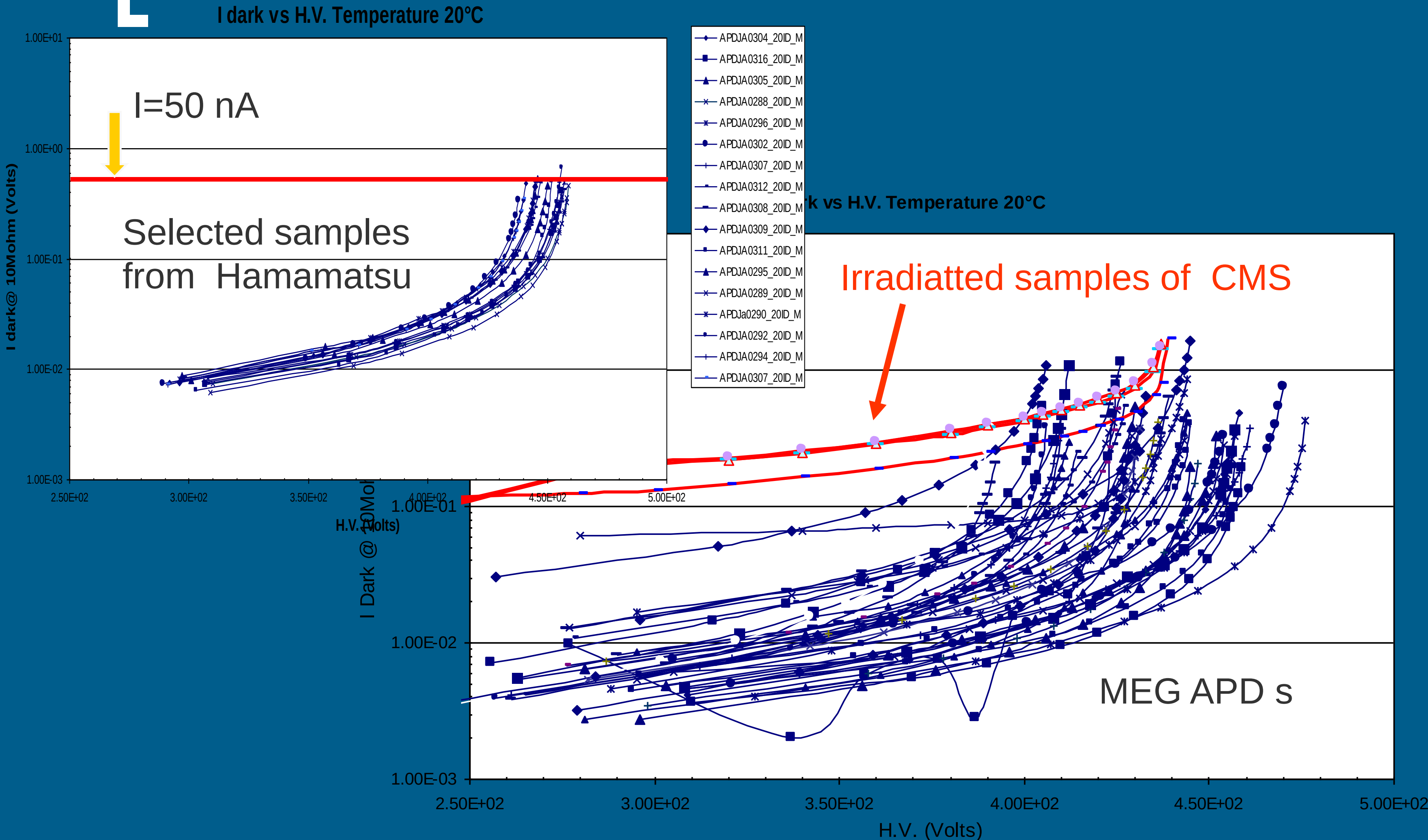
Total noise of illuminated APD including
Shot niose, excess noise, photon noise

$$F = M^x$$

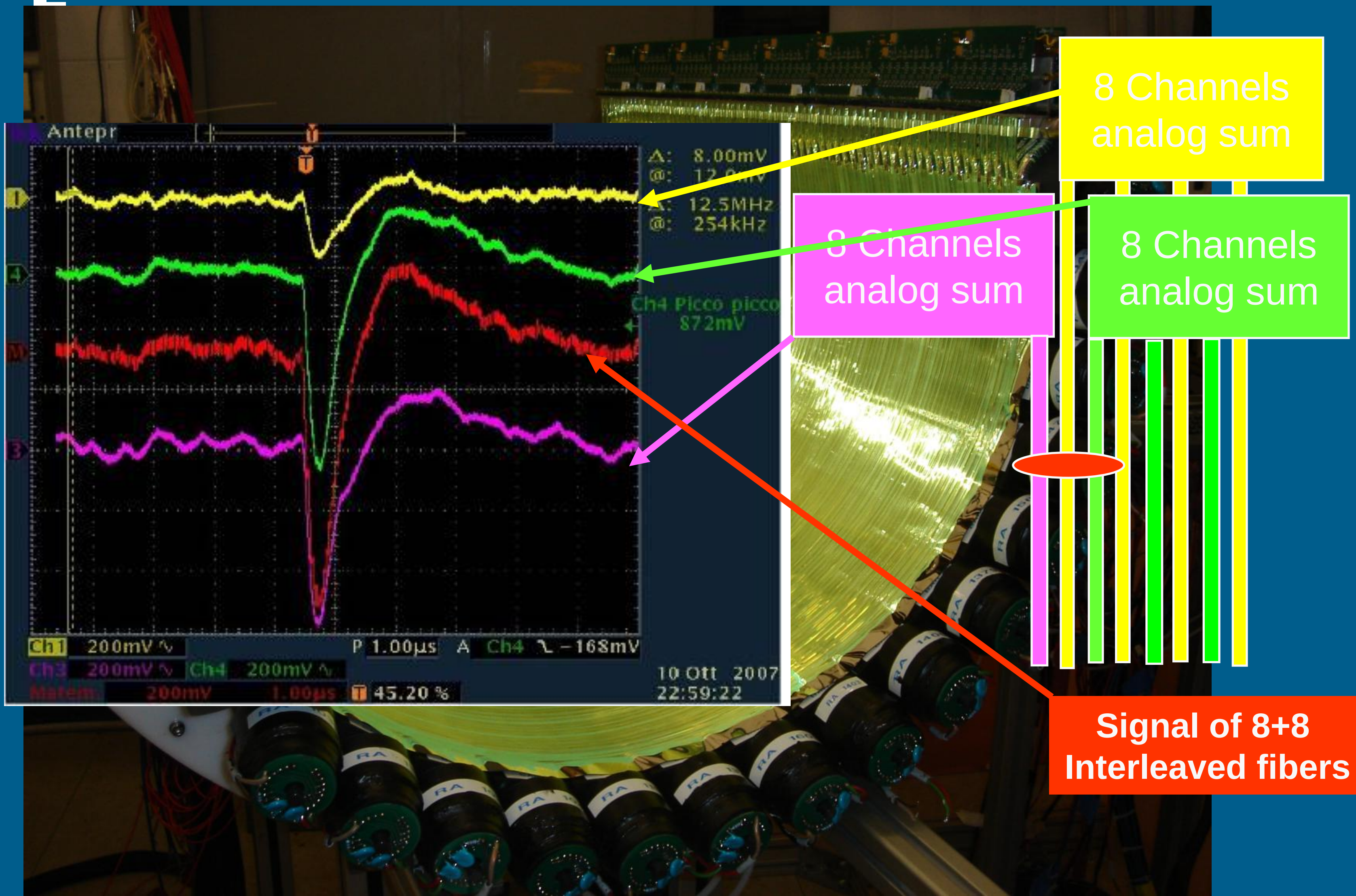
Excess noise factor
at M=500 x= 0.5

Detector Type	Ionization Ratio	X-Factor	Typical Gain	Excess Noise Factor (at typical gain)
	(k)	-	(M)	(F)
Silicon ("reach-through" structure)	0.02	0.3	150	4.9
Silicon Epitaxial APDs	0.06	0.45	100	7.9
Silicon (SLiK™ low-k structure)	0.002	0.17	500	3.0
Germanium	0.9	0.95	10	9.2
InGaAs	0.45	0.7- 0.75	10	5.5

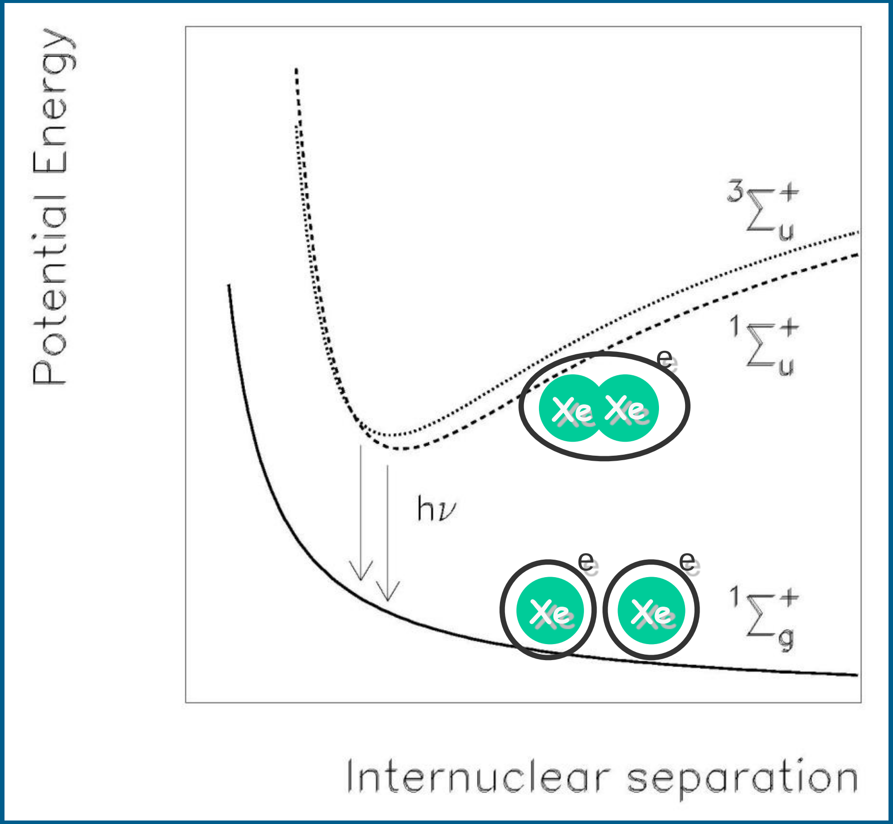
APDs production

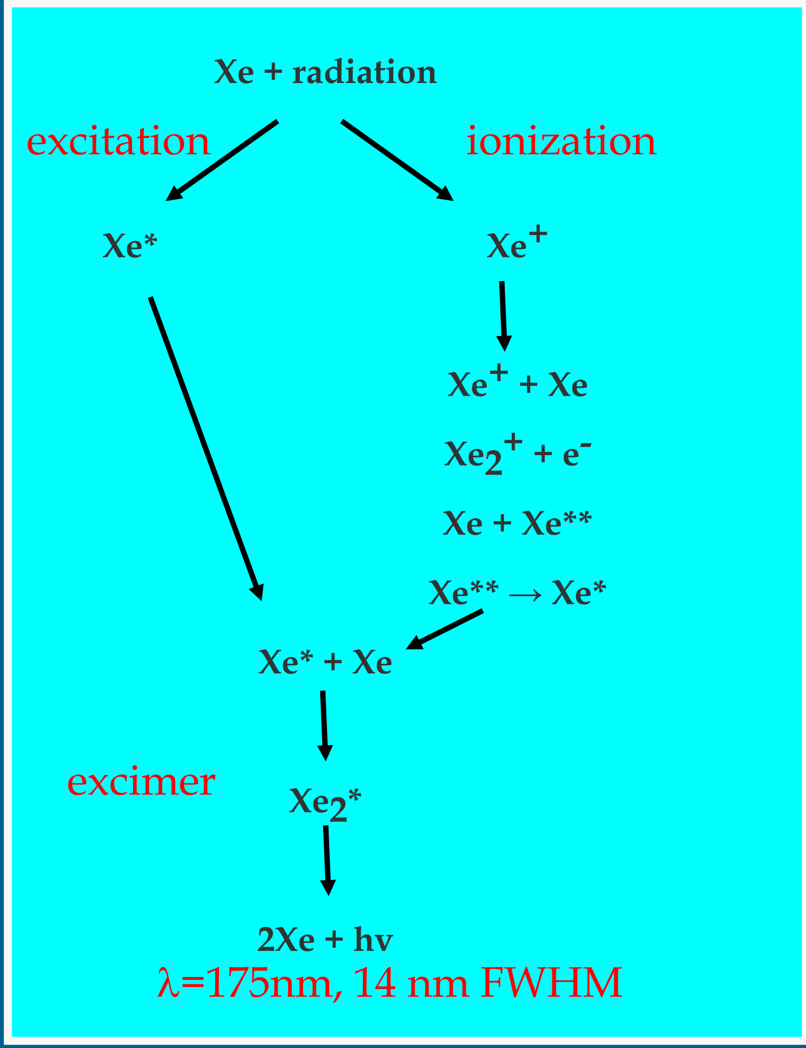


Fiber detector under run consitions



Liquid Xe Calorimeter -XEC





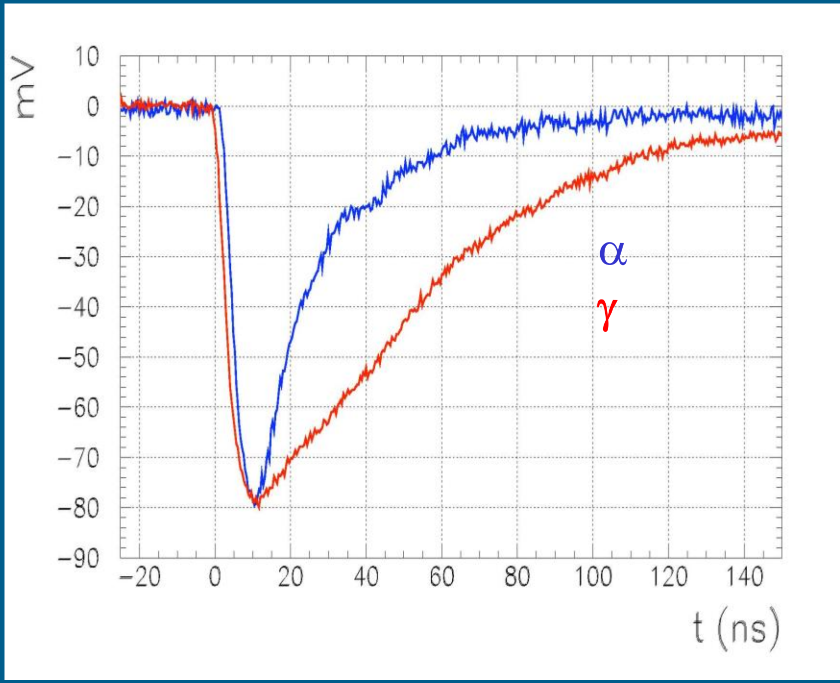
XEC

- Compact
  - Z=54, ρ=2.95 g/cm^3 (X_0=2.7 cm), R_M=4.1 cm @ T=165 K
- High light yield
  - L.Y.=42000 phe/MeV ≈ 0.7 LY(NaI) for m.i.p.'s
- Fast
  - t_1=4ns, t_3=22ns, t_{rec}=45ns
- Particle ID
  - $\tau_\gamma \approx 2\ \tau_\alpha$
  - L.Y.$_\alpha$= 1.2 x LY_{mip}
- n = 1.65 (≈ n_{quartz})

  ➔ good optical coupling with PMTs
- No self-absorption (λ_{Abs}=∞)

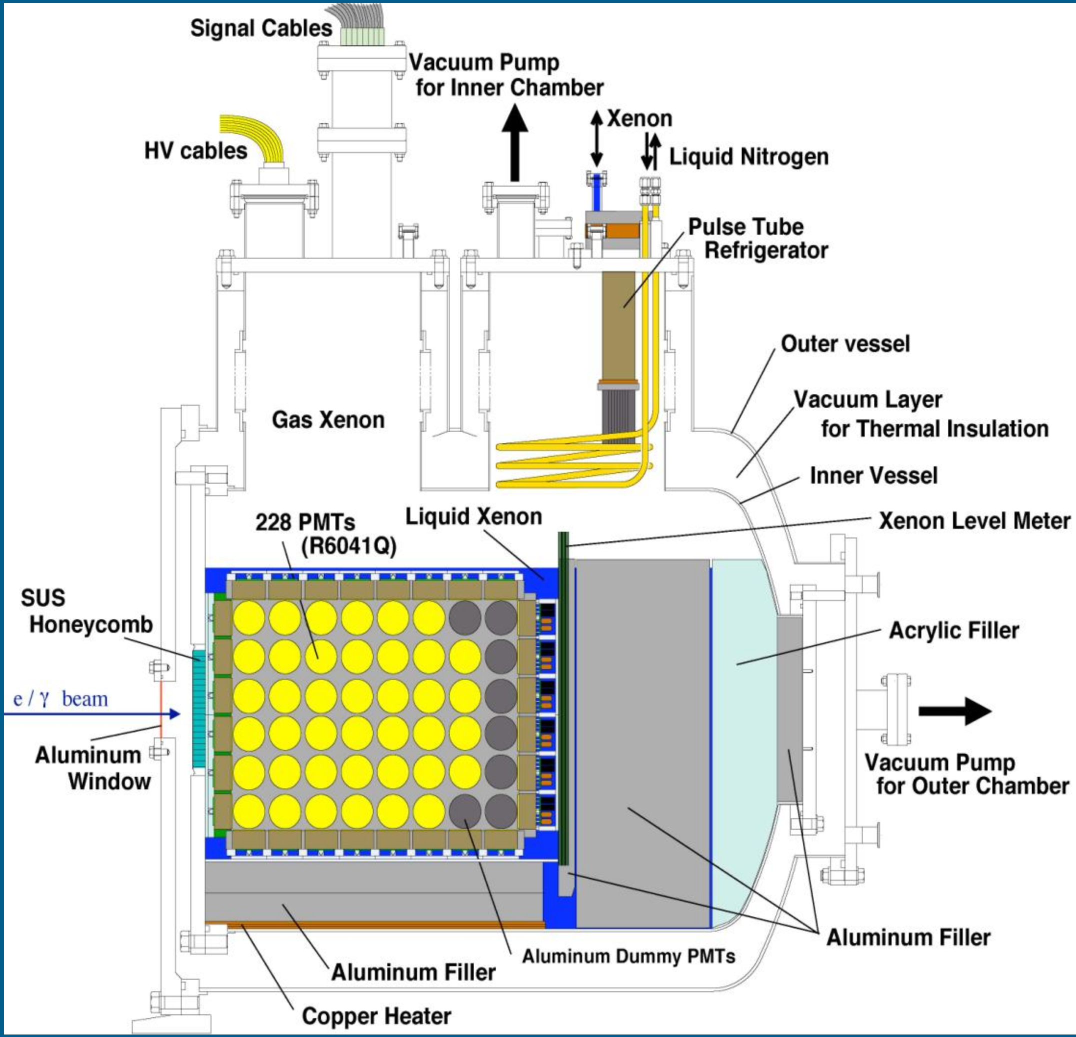
  ➔ position-independent energy response

  ➔ homogeneous calorimeter



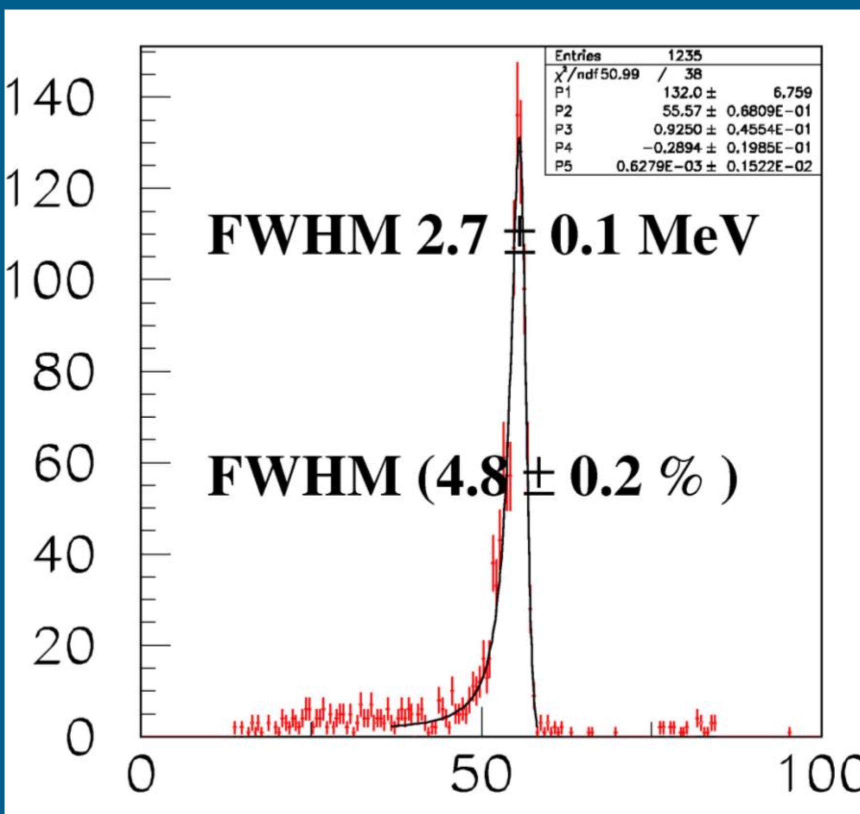
First test made in 100l prototype

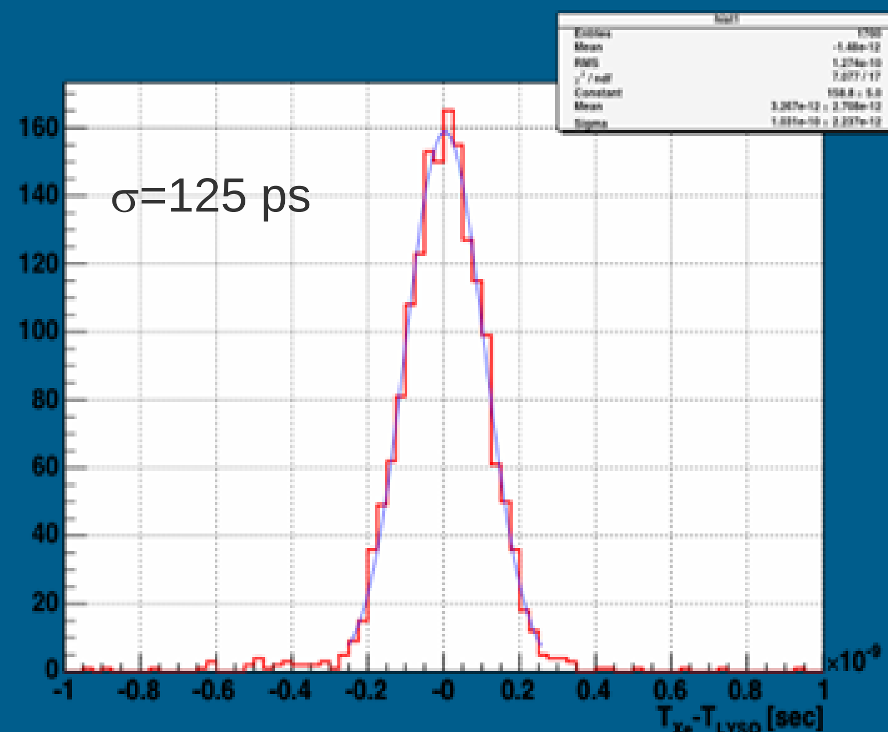
- 40 x 40 x 50 cm3, 100 l LXe
- (same depth, 1/10 of the final volume)
- the world-wide largest at that time
- Equipped with 240 PMTs
  - (HAMAMATSU R6041+R9288TB)
  - - K-Cs-Sb photocathode
  - - Quartz window (suited for VUV)
- Gas purification system
- (getter+Oxysorb) to keep impurity
- content < 1ppb



100 l prototype

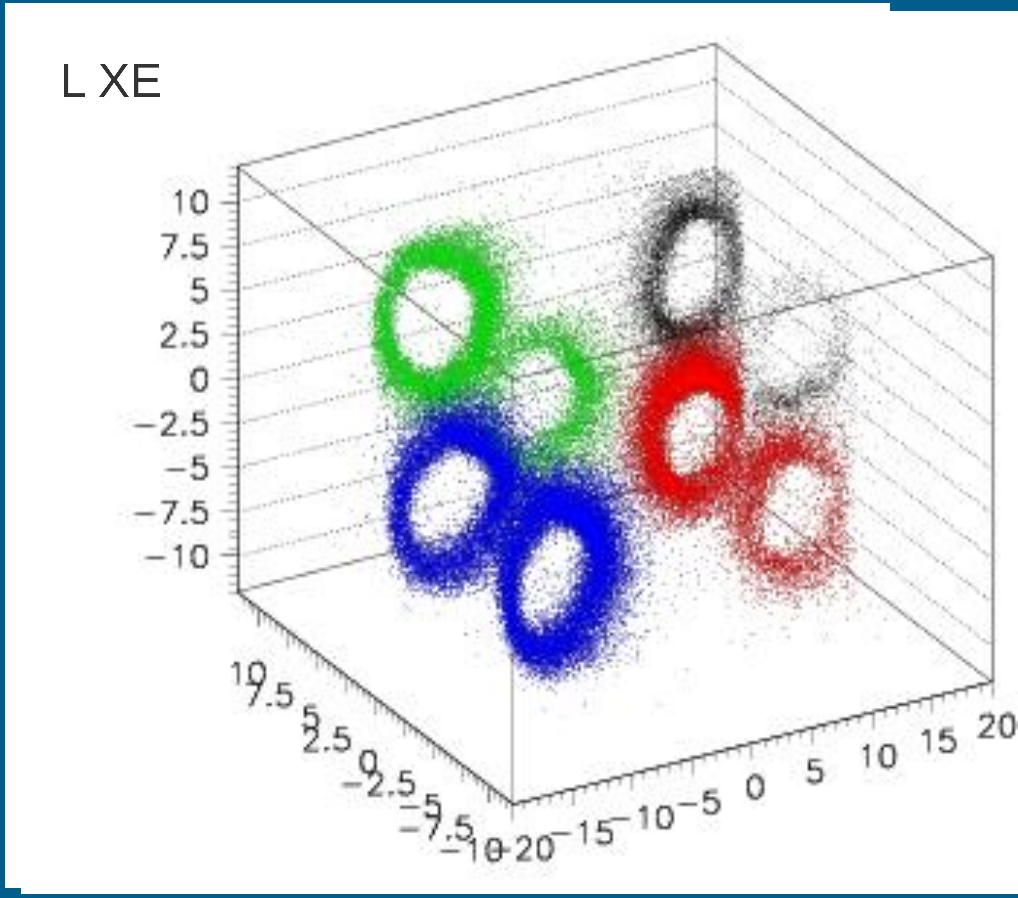
- Demonstrated: high energy and timing resolution and absorption length >> 1m



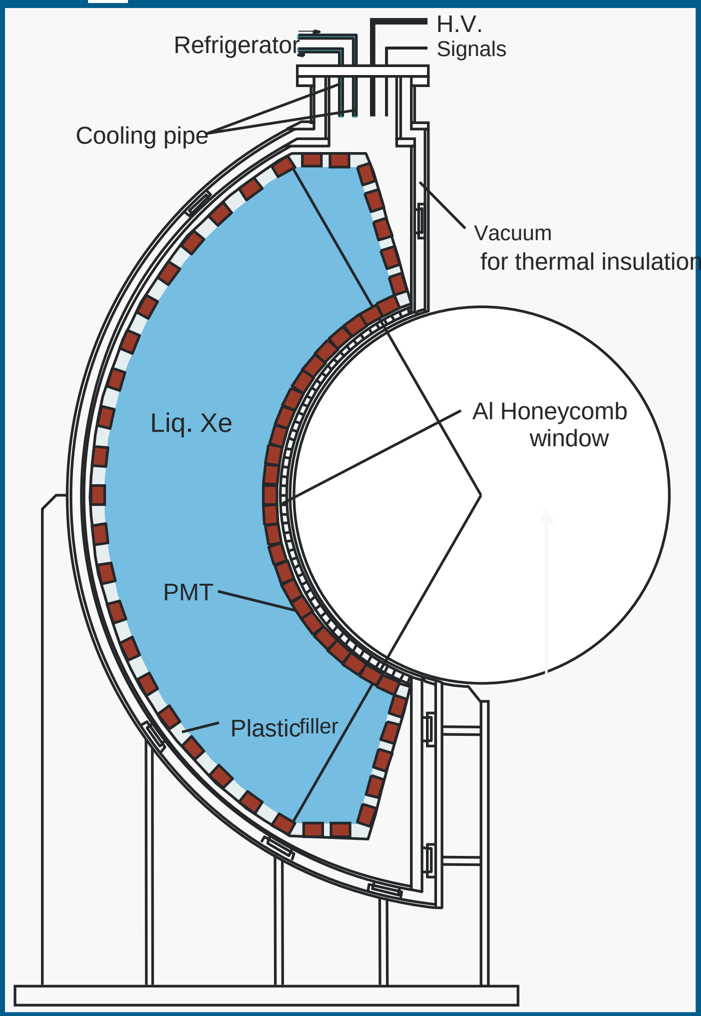


Calibration of position reconstruction

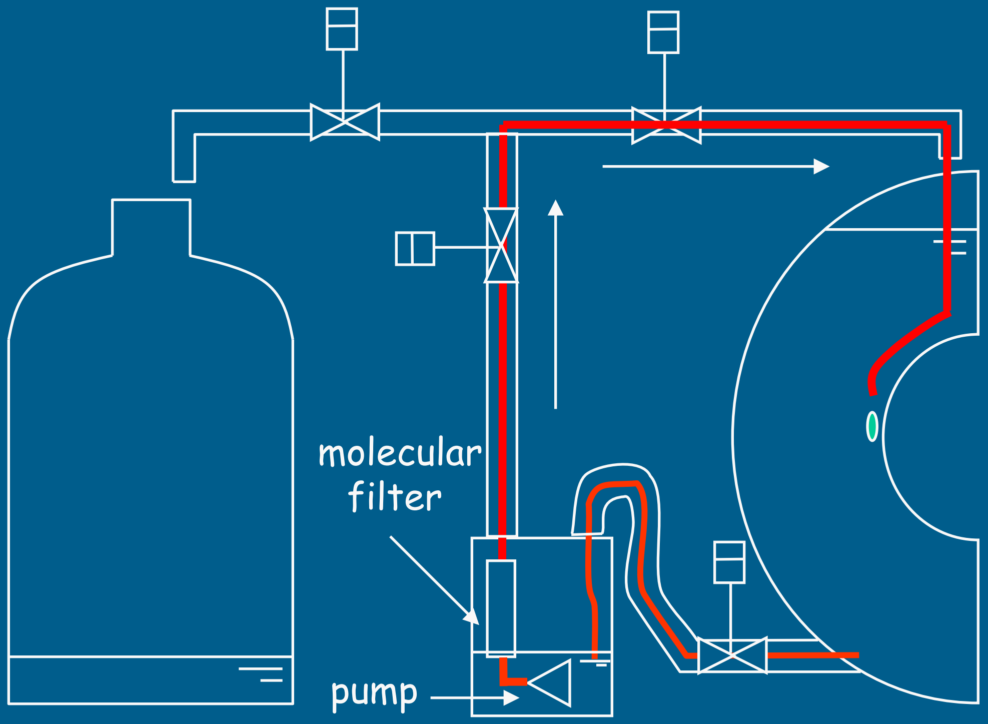
- Alpha sources electroplated onto 50 um wire → alpha rings



XEC

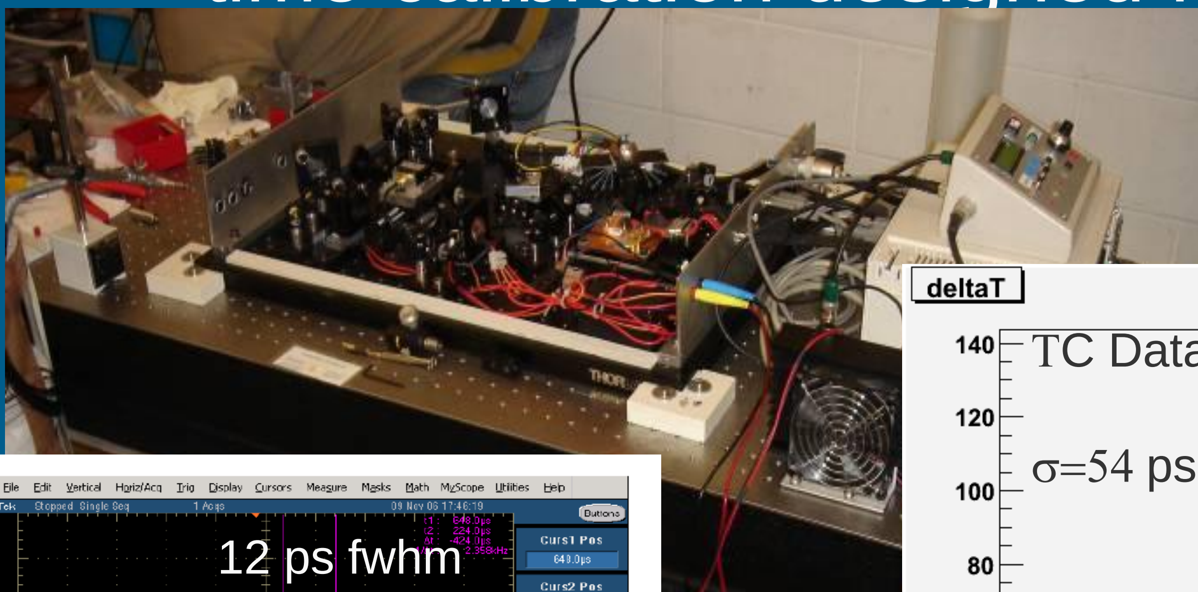


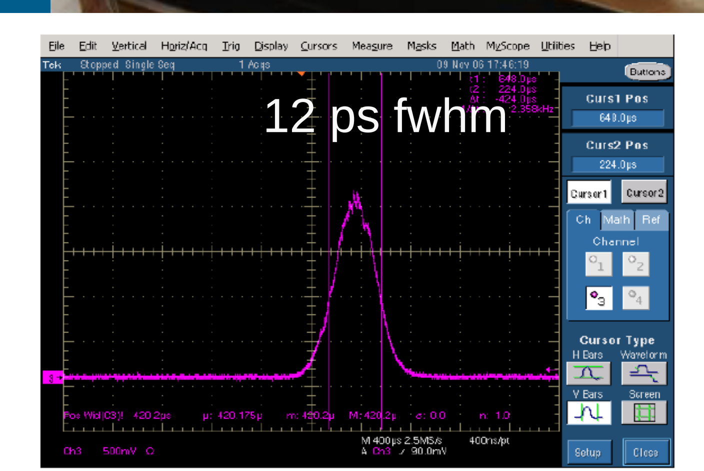
- 800 l of Liquid Xenon equipped with 846 PMTs; 9% $\Omega/4\pi$;
- Only scintillation light;
- 19 X_0 depth and 0.4X_0 of front material.
- PMT quartz windows to match LXe scintillation UV spectrum

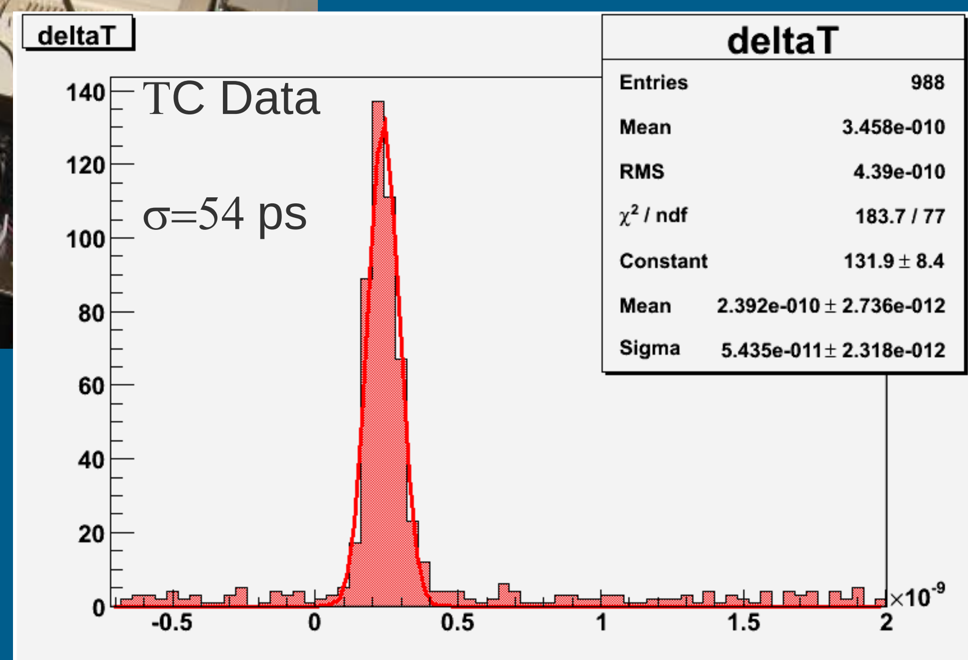


TC calibration with 12 ps laser

- 12 ps fwhm NYVO laser for TC-XEC time calibration designed for MEG







Calibration with (p,γ)

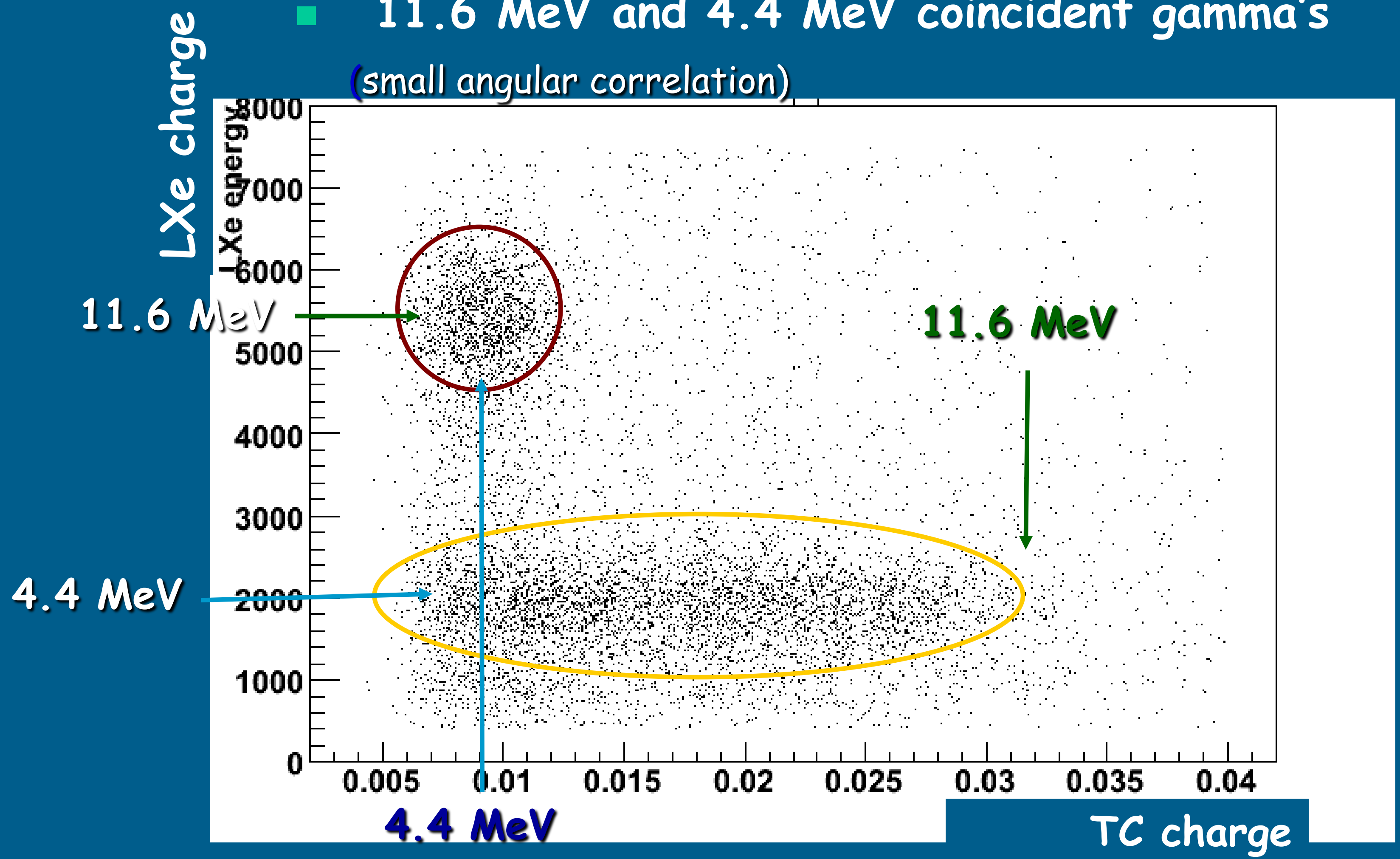
- 500 KeV CW generator excite Boron or Li target at COBRA center,

Reaction	*Peak energy*	σ peak	γ-lines
Li(p,γ)Be	***440 keV***	5 mb	(17.6, 14.6) MeV
B(p,γ)C	***163 keV***	2 10^{-1} mb	(4.4, 11.6, 16.1) MeV

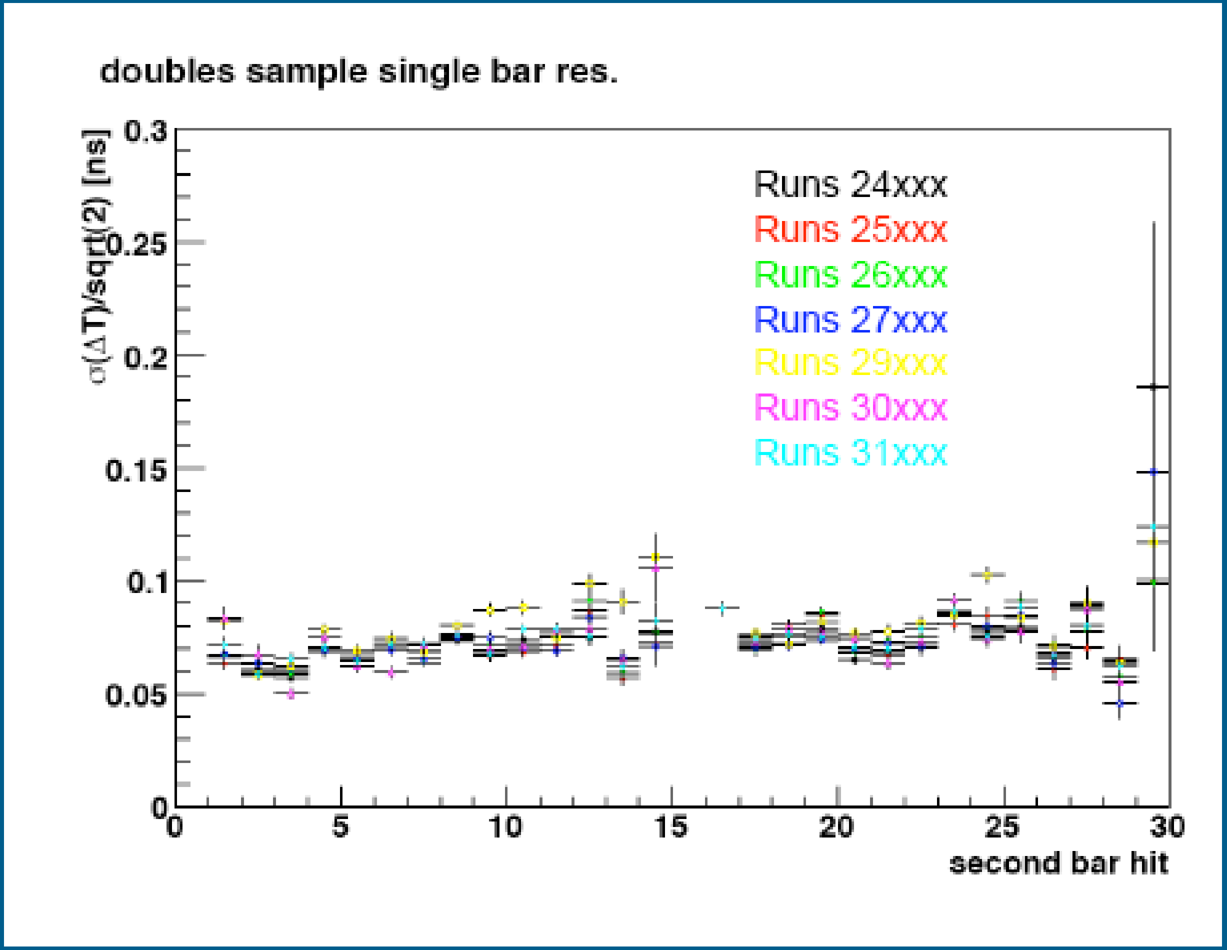
TC-DC time relative timing

- **11.6 MeV and 4.4 MeV coincident gamma's**

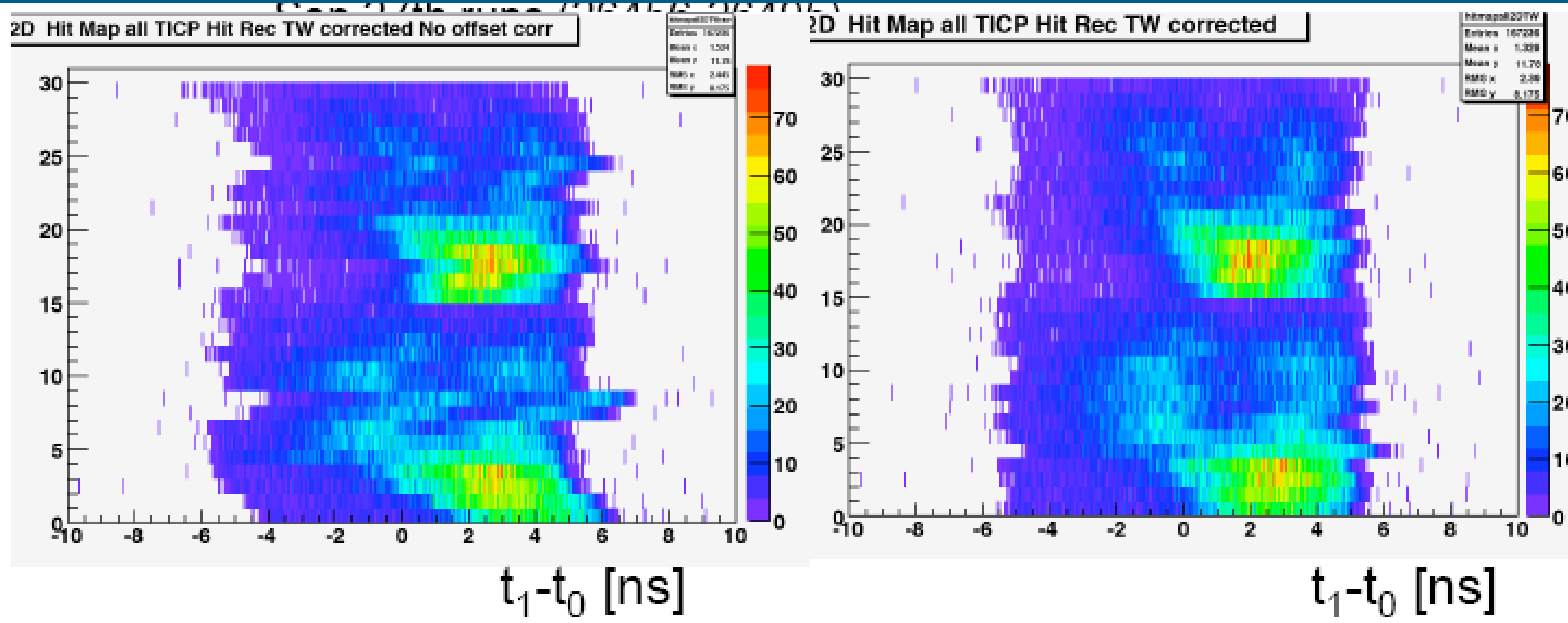
(small angular correlation)



TC timing resolution stable over the full run

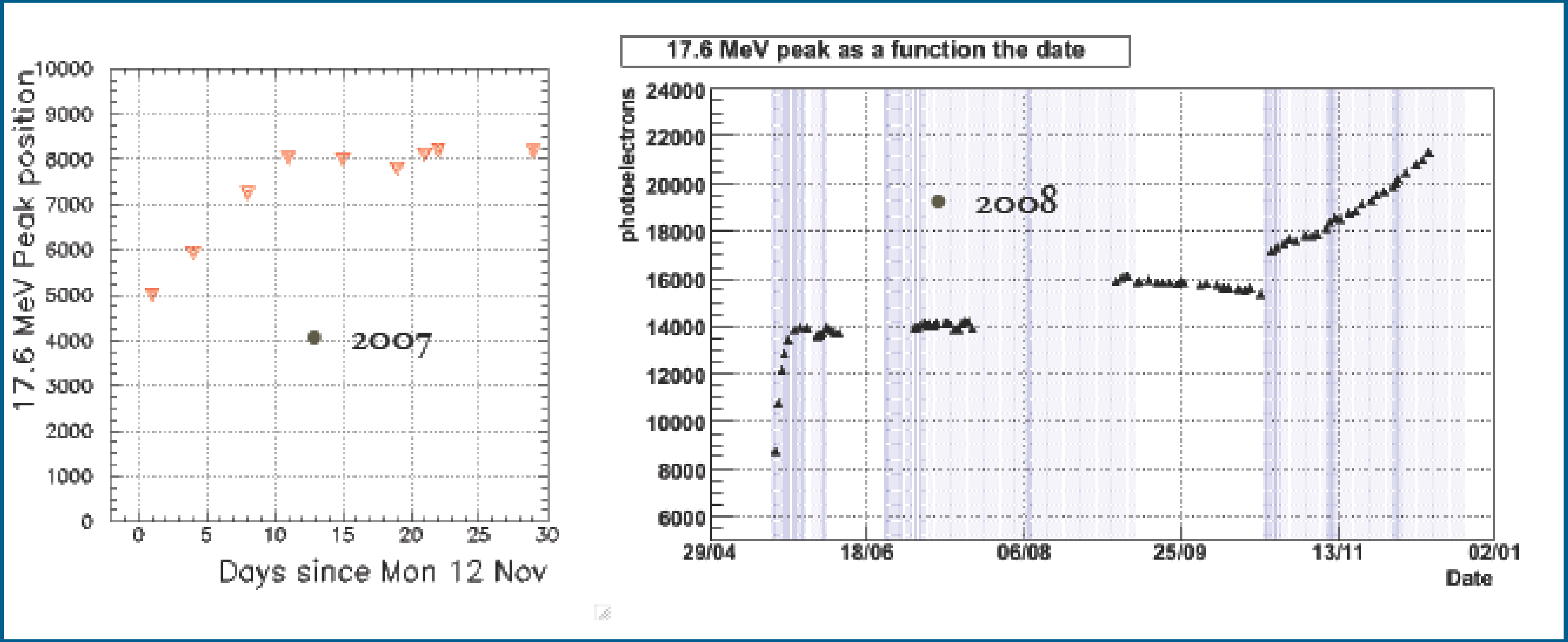


TC – hit map before and after calibration

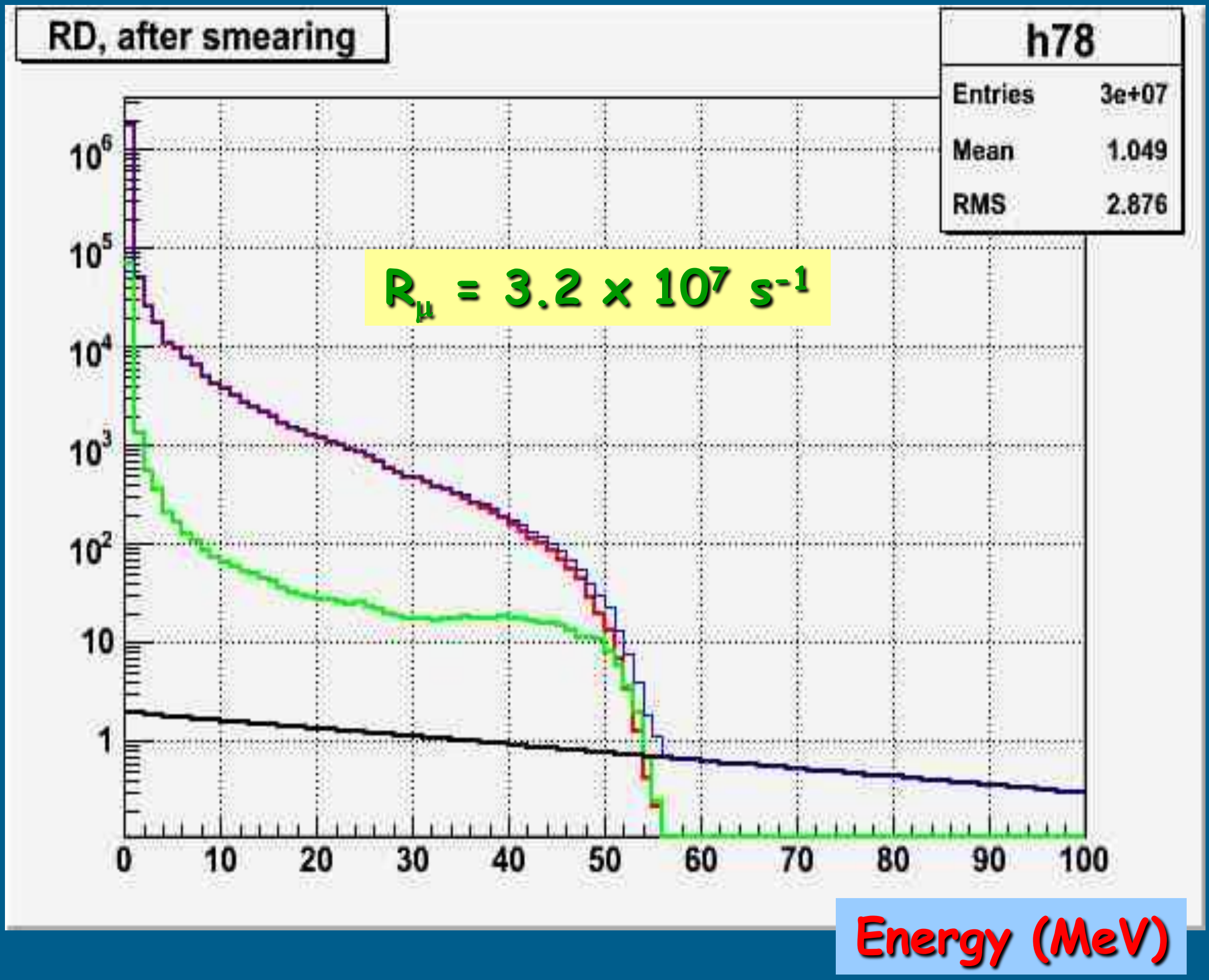


XEC L.Y. increased over the RUN

- Continuous improvement of XEC L.Y. (expected value 26.000 phe at 17.5 MeV)



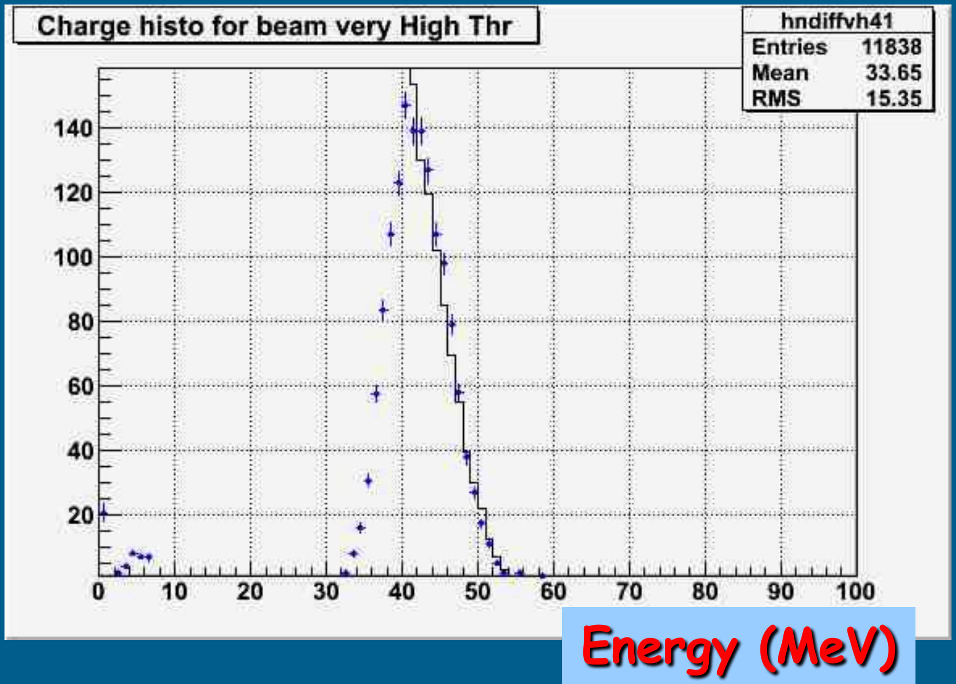
MC of gamma spectrum

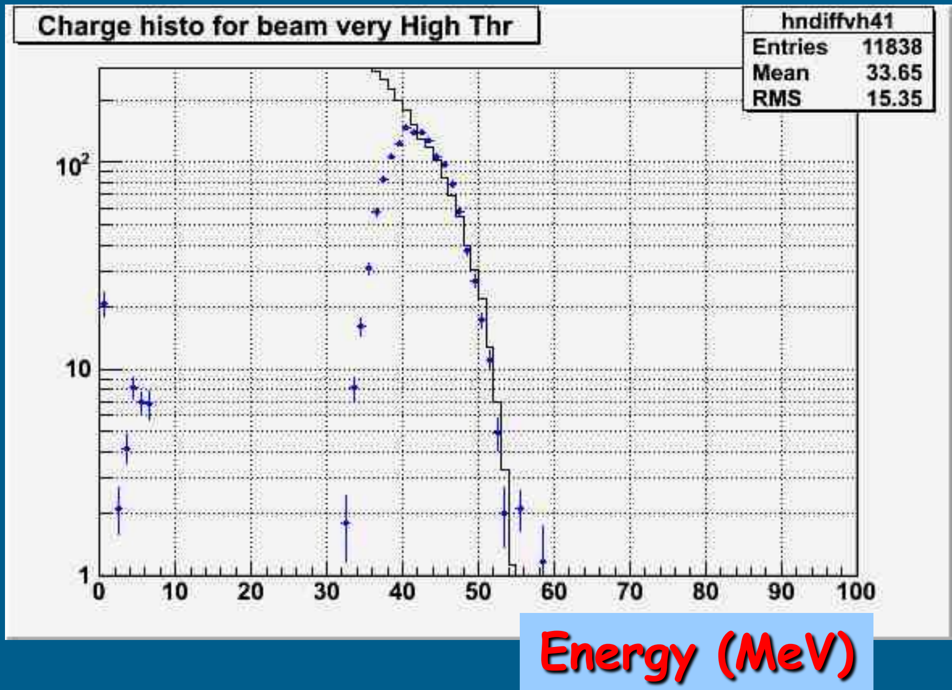


- **Red: Radiative decay**
- **Green: Annihilation In Flight**
- **Black: Cosmics**
- **Blue: Total** (including pile-up)

Data-MC

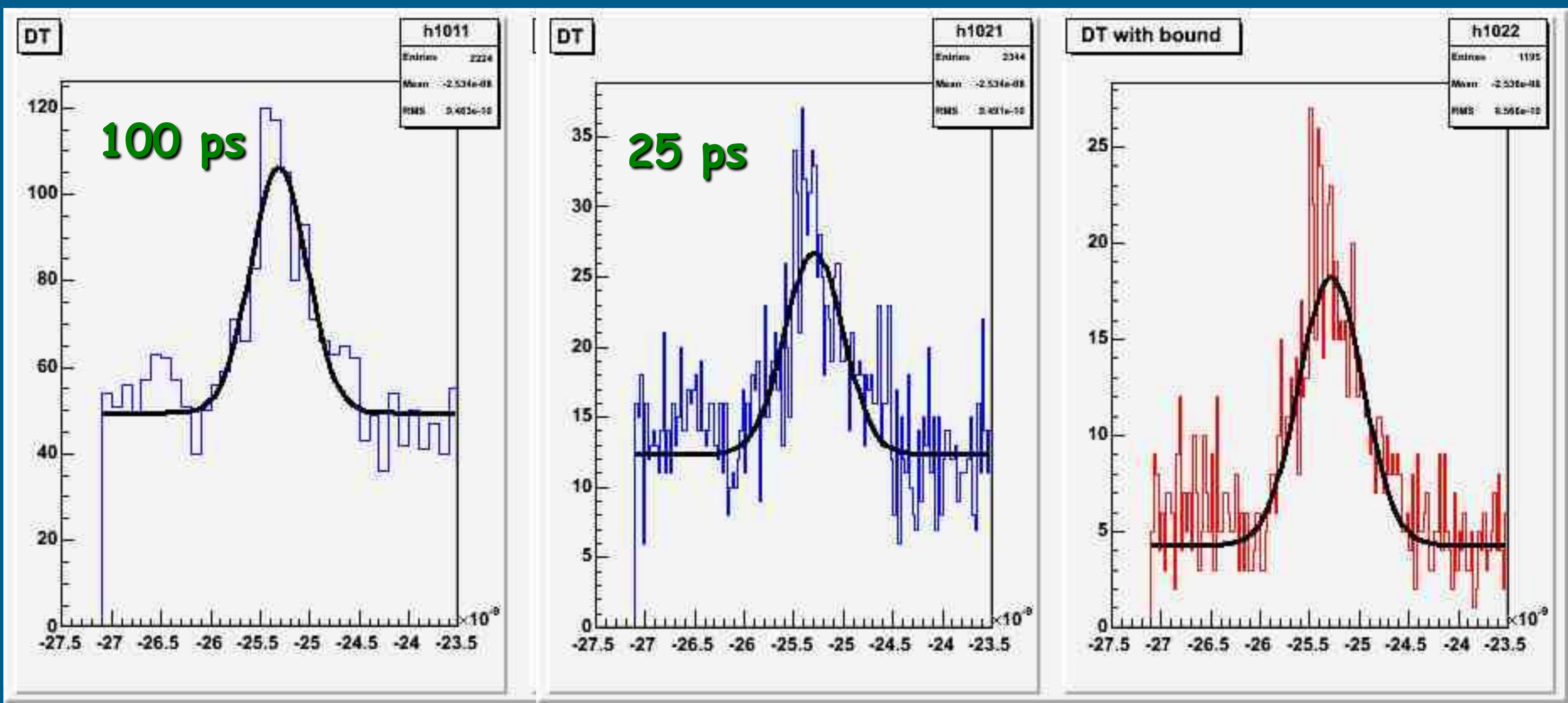
- Data (Blue Points): **Beam @ 3.2 x 107 m s-1, threshold ≈ 45 MeV**
- MC (Black line): **full background simulation. Absolute rate reproduced**
- Pile-up subtracted by charge distribution; cosmics rejected.
- Final pile-up rejection by using waveforms (not here).





Radiative Decay in the timing sginal

- Blue: no kinematical bound; Red: kinematical bound applied.
- **Kinematical bound has no effect on signal and a factor 2.5 reduction on bck**



MEG expectations

Detector parameters	$\varepsilon_e \approx 0.9$ $\varepsilon_{sel} \approx (0.9)^3 = 0.7$ $\varepsilon_\gamma \approx 0.6$ $T = 2.6 \cdot 10^7 s$ $R_\mu = 0.3 \cdot 10^8 \,\mu/s$ $\frac{\Omega}{4\pi} = 0.09$
Signal	Cuts at 1,4×FWHM $N_{sig} = BR \cdot T \cdot R_\mu \cdot \frac{\Omega}{4\pi} \cdot \varepsilon_e \cdot \varepsilon_\gamma \cdot \varepsilon_{sel}$
Single Event Sensitivity	$SES = \left(T \cdot R_\mu \cdot \frac{\Omega}{4\pi} \cdot \varepsilon_e \cdot \varepsilon_\gamma \cdot \varepsilon_{sel} \right)^{-1} \approx 4 \times 10^{-14}$
Backgrounds	$BR_{acc} \propto R_\mu^2 \times \Delta E_e \times \Delta E_\gamma^2 \times \Delta\theta_{e\gamma}^2 \times \Delta t_{e\gamma} \approx 3 \times 10^{-14}$ $BR_{corr} \approx 3 \times 10^{-15}$
Upper Limit at 90% CL	$BR\,(\mu \to e\gamma) \approx 1 \times 10^{-13}$
Discovery	4 events (P = 2×10^{-3}) correspond $BR = 2 \times 10^{-13}$