The MEG experiment at PSI: search for the $\mu^+ \rightarrow e^+ \gamma$ decay

Giovanni Signorelli
INFN Pisa and Pisa University (Italy)
for the MEG collaboration

NEW TRENDS IN HIGH ENERGY PHYSICS

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Outline

- Physics motivation for a $\mu \rightarrow e\gamma$ experiment
- The $\mu \rightarrow e\gamma$ decay
- The detector
  - Beam line & target
  - Spectrometer
  - Timing Counter
  - LXe calorimeter
  - Calibrations
  - Electronics
- Status
- Future

The SM. And beyond...

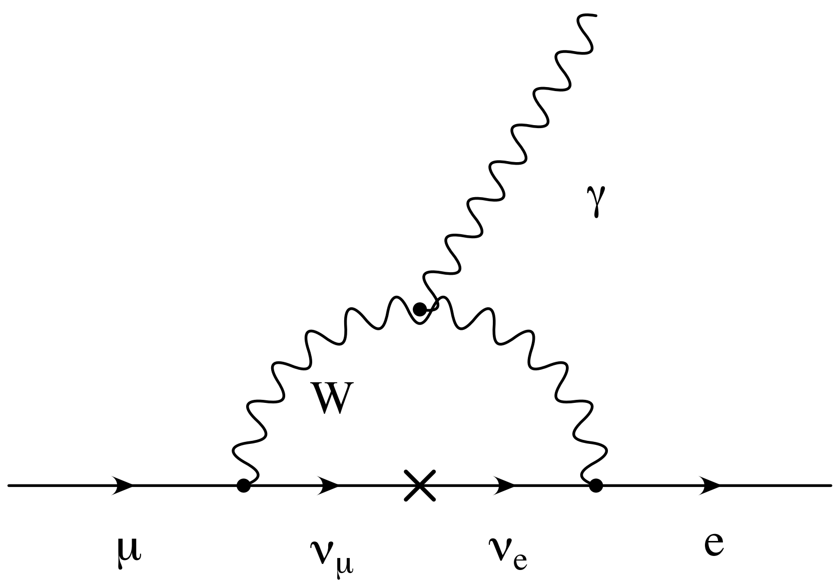
- The Standard Model is made of particles + interactions + symmetries
    - Phyisics symmetries
    - Gauge symmetries
    - Accidental symmetries

B	L	L_i
baryon number	lepton number	lepton family number
$p \rightarrow e^- \pi^0$	ν masses	$\mu \rightarrow e\gamma$

- These symmetries are called accidental because there is no general rule that imposes them - they just "happen" to be in the SM
- The research for the failure of one of these symmetries could shed new light on particle physics
- Three complementary searches to probe the Standard Model.

The μ→eγ decay

- The μ→eγ decay is forbidden in the SM because of the (accidental) conservation of lepton family numbers
- The introduction of neutrino masses and mixings induces μ→eγ radiatively, but at a negligible level

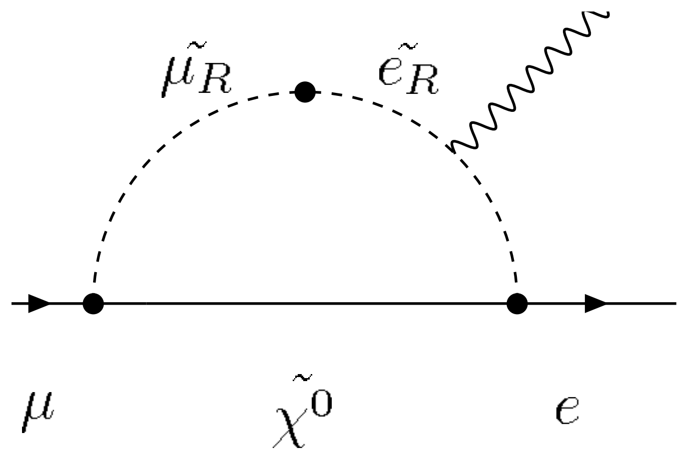


$$\Gamma(\mu \to e\gamma) \approx \underbrace{\frac{G_F^2 m_\mu^5}{192\pi^3}}_{\mu-\text{decay}} \underbrace{\left(\frac{\alpha}{2\pi}\right)}_{\gamma-\text{vertex}} \underbrace{\sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2}{M_W^2}\right)}_{\nu-\text{oscillation}}$$

$$\approx 10^{-53}$$

- All SM extensions enhance the rate through mixing in the high energy sector of the theory

For instance... predictions



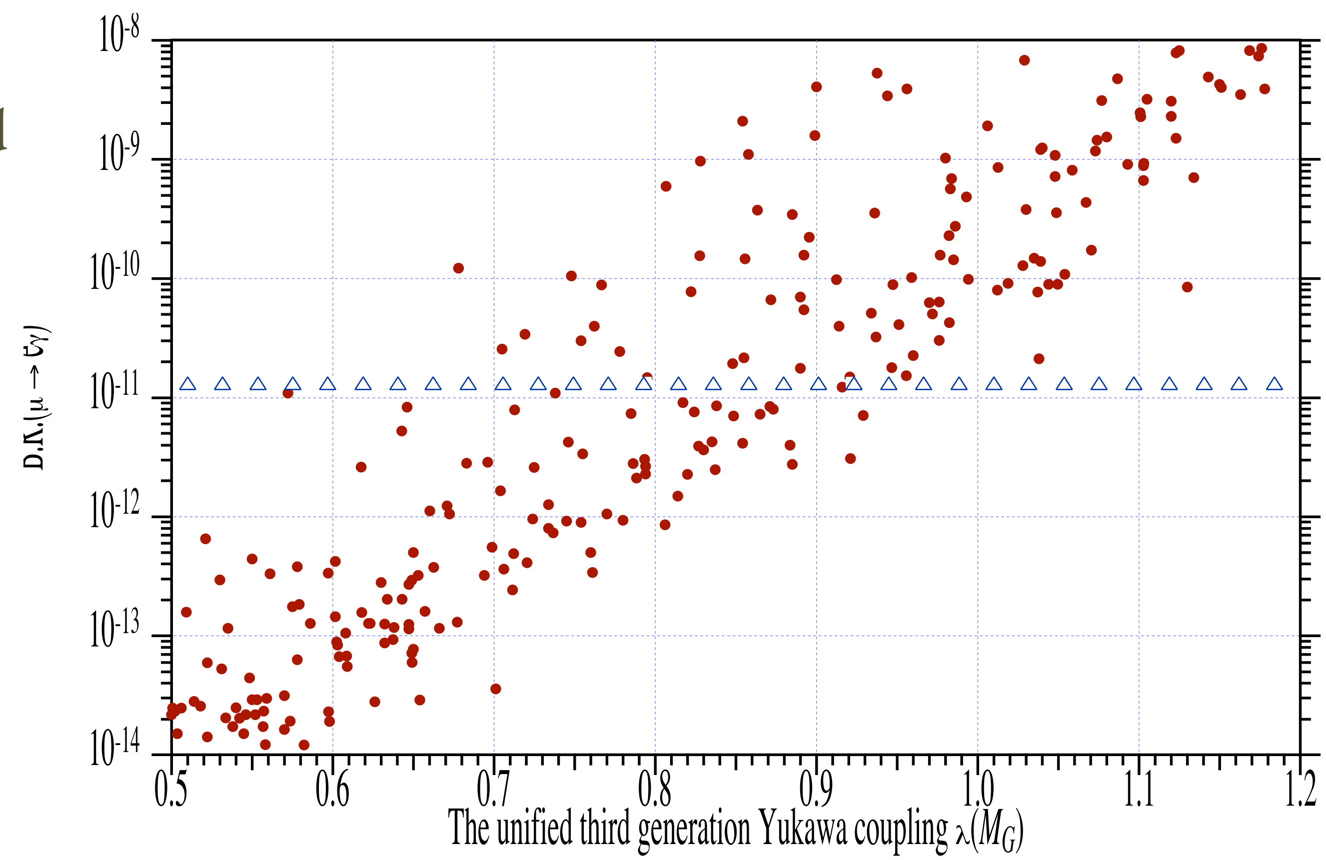
R. Barbieri et al.,Nucl. Phys. B445(1995) 215

J.Hisano et al.,Phys. Lett. B391 (1997) 341

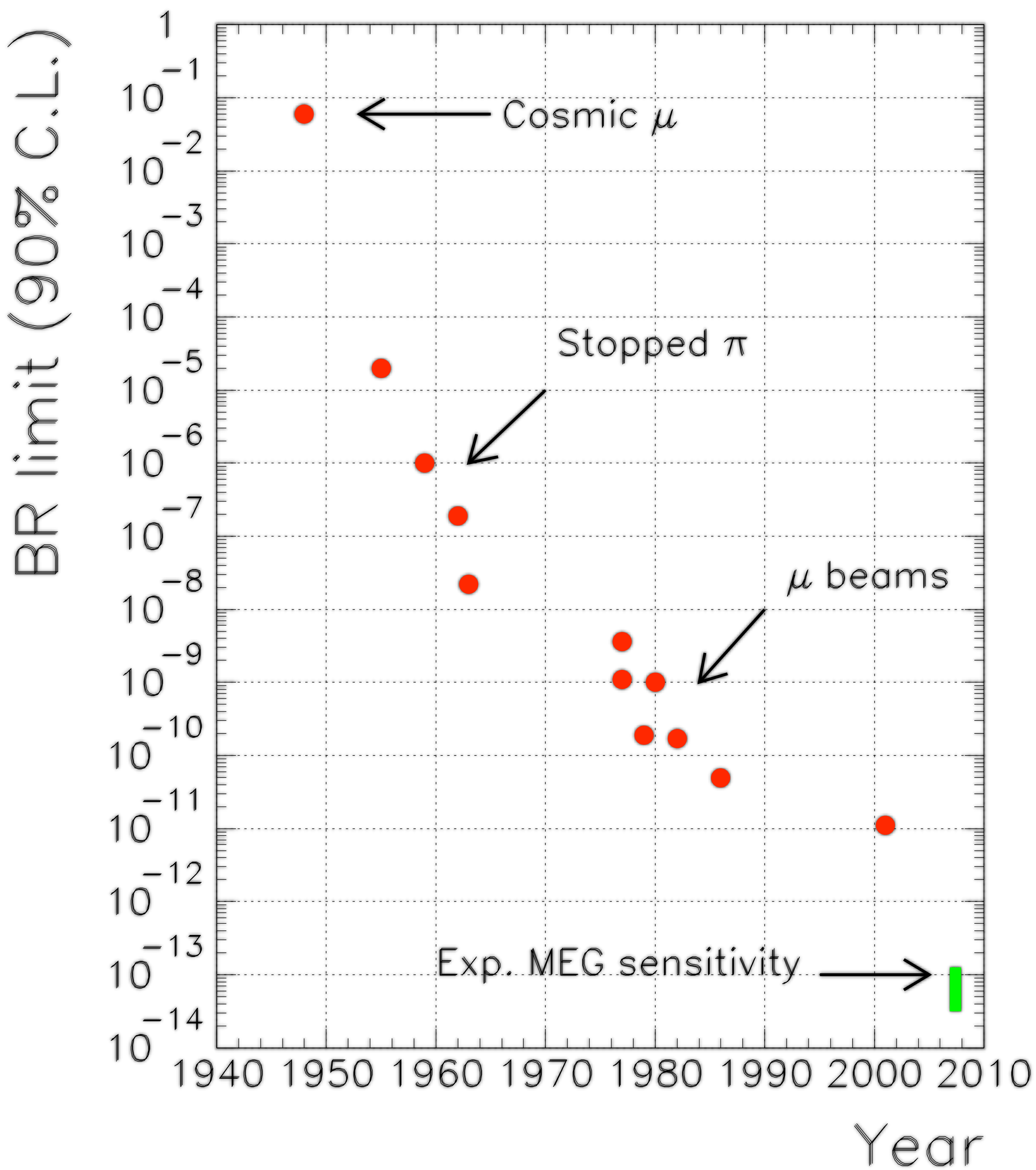
R. Ciafaloni, A. Romanino, A. Strumia, Nucl. Phys. B458 (1996)

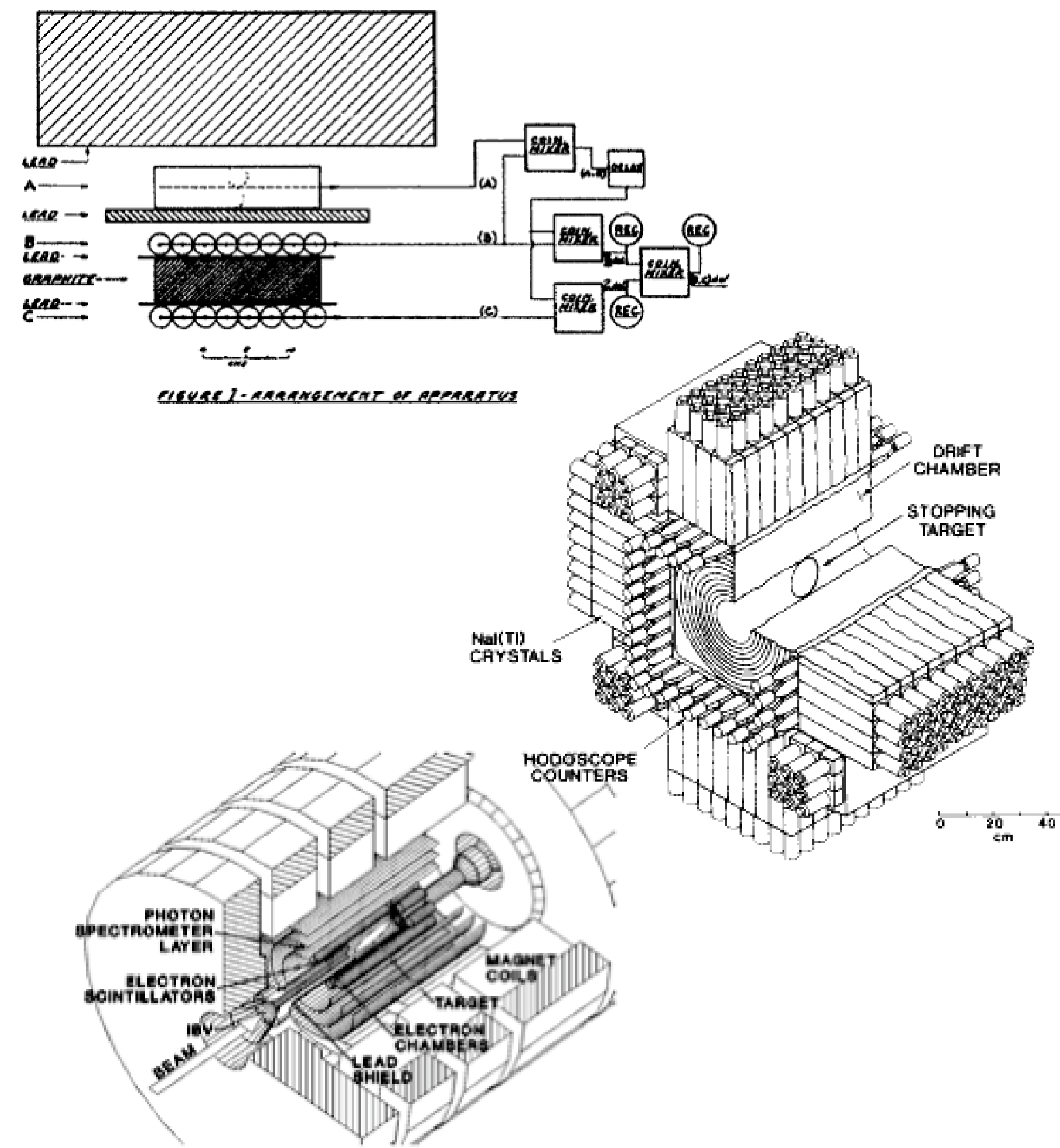
J. Hisano, N. Nomura, Phys. Rev. D59 (1999)

- SUSY SU(5) predictions: LFV induced by finite slepton mixing through radiative corrections. The mixing could be large due to the top-quark mass at a level of 10^{-12} - 10^{-15}
- SO(10) predicts even larger BR:
  - m(τ)/m(μ) enhancement
- Models with right-handed neutrinos also predict large BR
- ⇒ clear evidence for physics beyond the SM.



Historical perspective



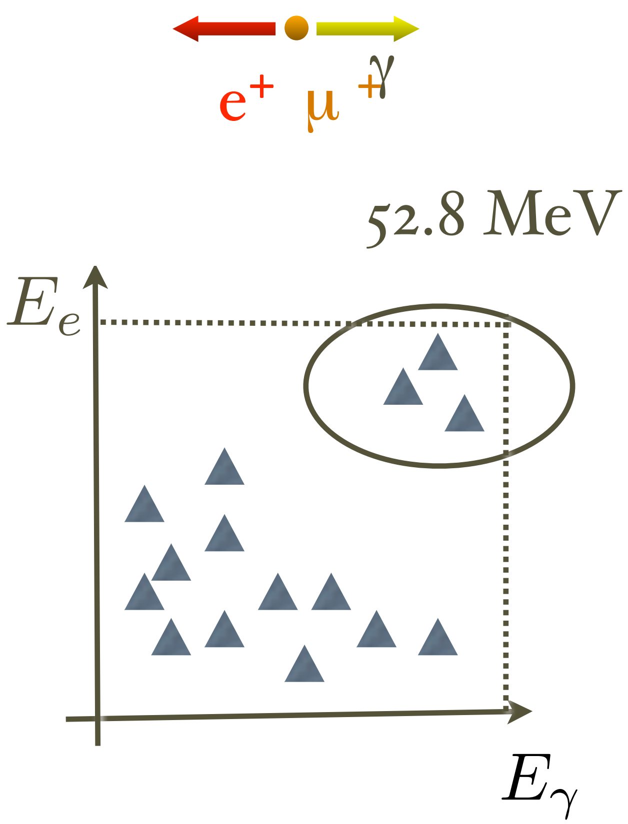


Each improvement linked to an improvement in the technology

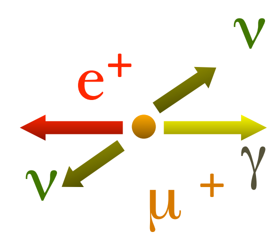
$$N_{\rm sig} = R_\mu T \frac{\Delta\Omega}{4\pi} \epsilon_\gamma \epsilon_e \epsilon_{\rm cut} B_{\mu\to e\gamma}$$

Signal and Background

"Signal"

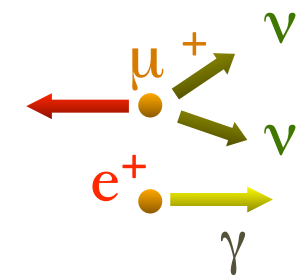


"Prompt"



$$\mu \rightarrow e\bar{\nu}\nu\gamma$$

"Accidental"



$$e^+e^- \rightarrow \gamma\gamma$$
$$\mu \rightarrow e\bar{\nu}\nu\gamma$$
$$e\mathcal{N} \rightarrow e\mathcal{N}\gamma$$

$$\mu \rightarrow e\bar{\nu}\nu$$

$$B_{\text{prompt}} \approx 0.1 \times B_{\text{acc}}$$

$$B_{\text{acc}} \approx R_\mu \Delta E_e \Delta E_\gamma^2 \Delta\theta^2 \Delta t$$

The accidental background is dominant and it is determined by the experimental resolutions

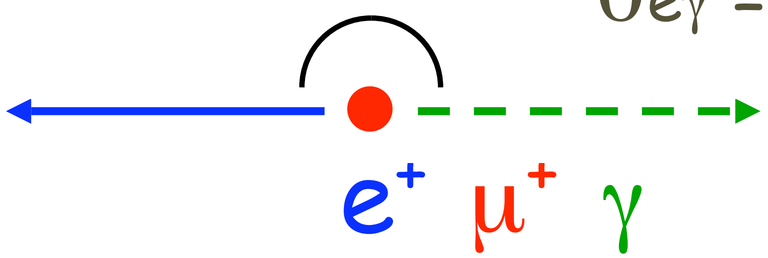
Exp./Lab	Year	ΔEe/Ee (%)	ΔEγ /Eγ (%)	Δteγ (ns)	Δθeγ (mrad)	Stop rate (s^{-1})	Duty cyc. (%)	BR (90% CL)
SIN	1977	8.7	9.3	1.4	-	5×10^5	100	3.6×10^{-9}
TRIUMF	1977	10	8.7	6.7	-	2×10^5	100	1×10^{-9}
LANL	1979	8.8	8	1.9	37	2.4×10^5	6.4	1.7×10^{-10}
Crystal Box	1986	8	8	1.3	87	4×10^5	(6..9)	4.9×10^{-11}
MEGA	1999	1.2	4.5	1.6	17	2.5×10^8	(6..7)	1.2×10^{-11}
MEG	2006	0.8	4	0.15	19	2.5×10^7	100	1×10^{-13}

FWHM

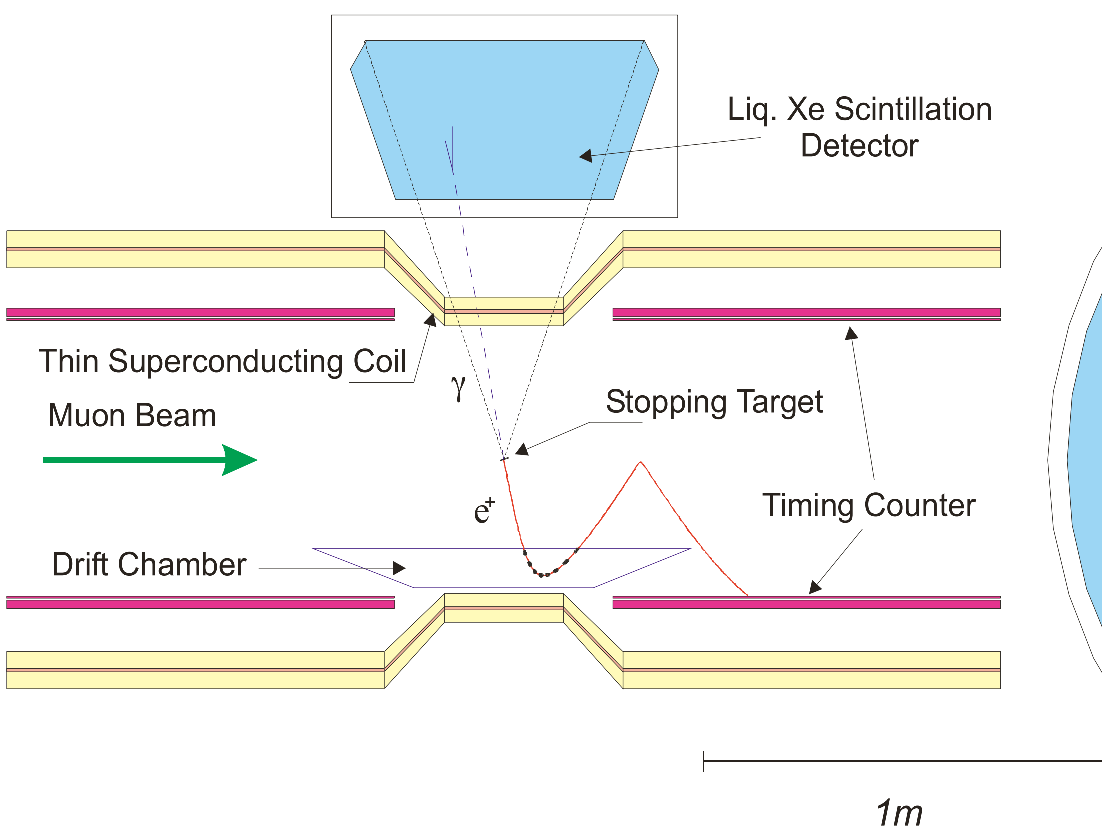
MEG experimental method

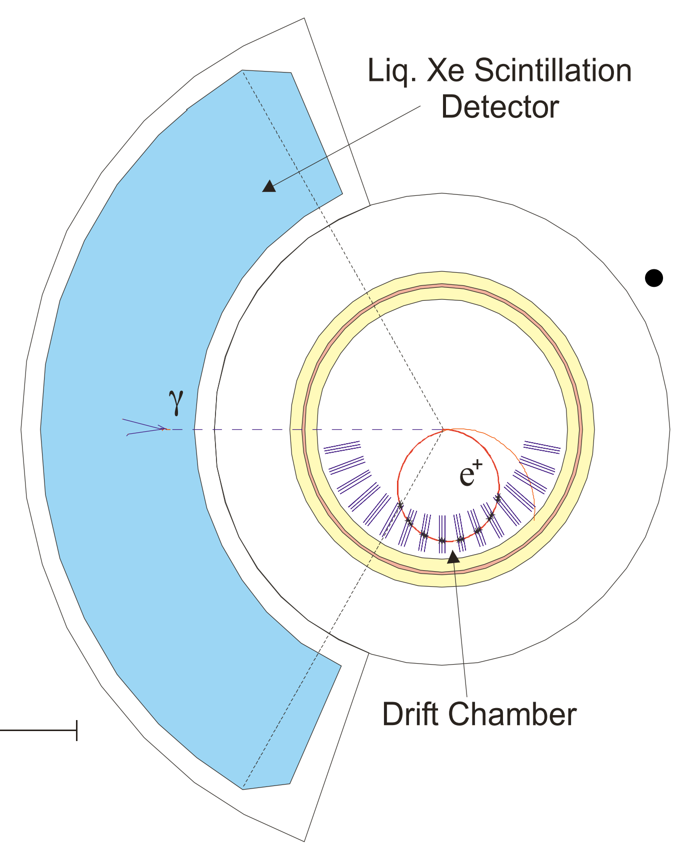
Easy signal selection with μ^+ at rest

$\theta_{e\gamma} = 180°$



$E_e = E_\gamma = 52.8$ MeV



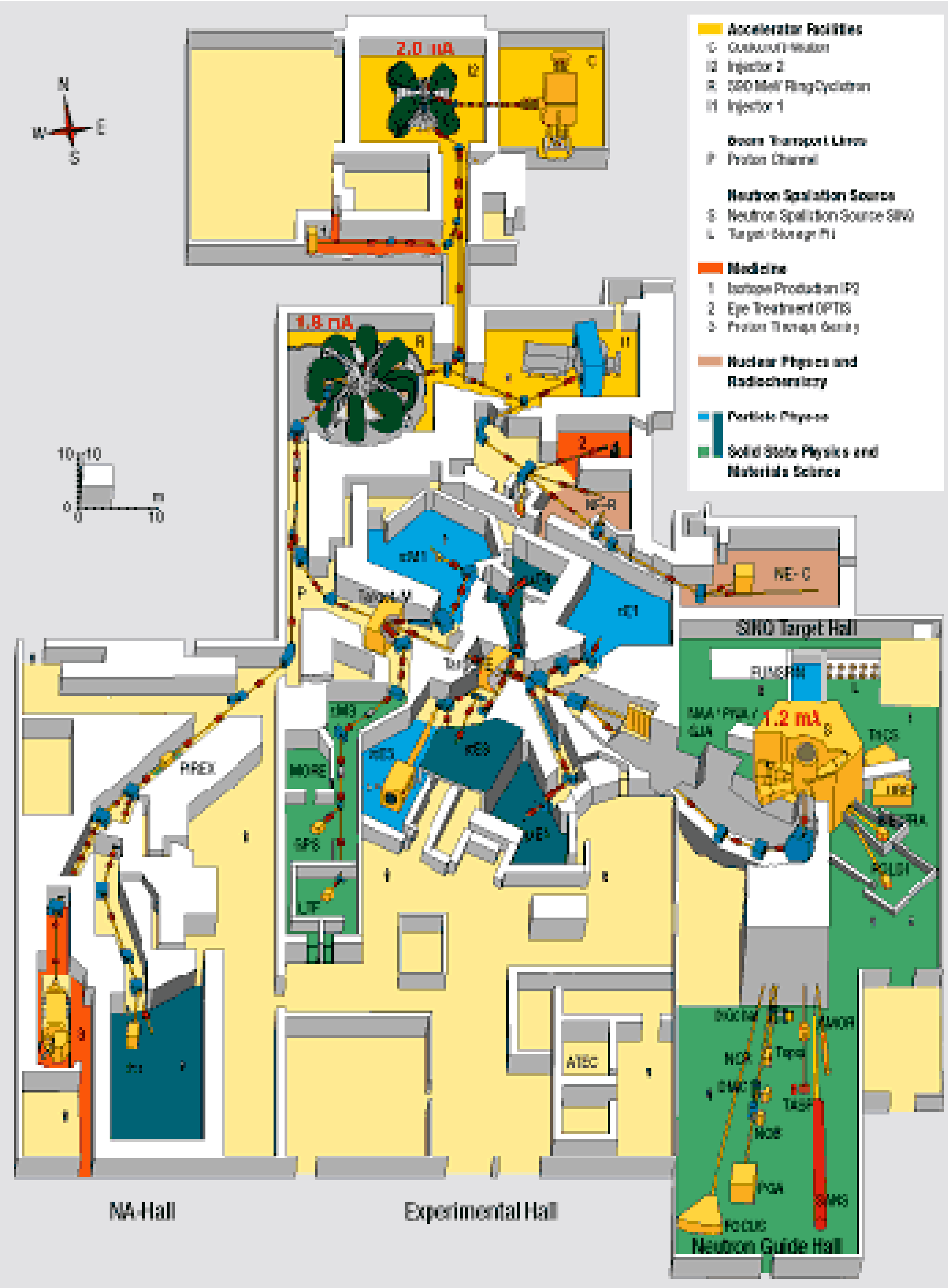


- Stopped beam of $>10^7$ μ /sec in a 150 μm target
- γ detection

  Liquid Xenon calorimeter based on the scintillation light
  - fast: 4 / 22 / 45 ns
  - high LY: ~ 0.8 * NaI
  - short X_0: 2.77 cm
- e^+ detection

  magnetic spectrometer composed by solenoidal magnet and drift chambers for momentum

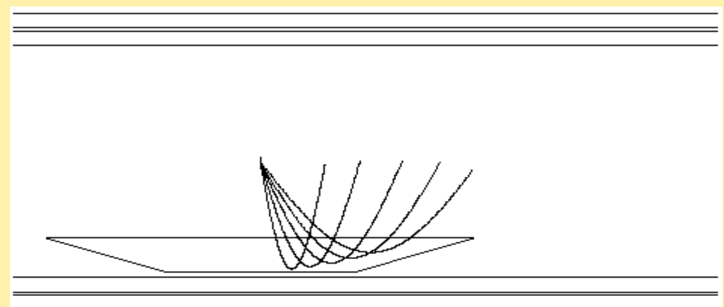
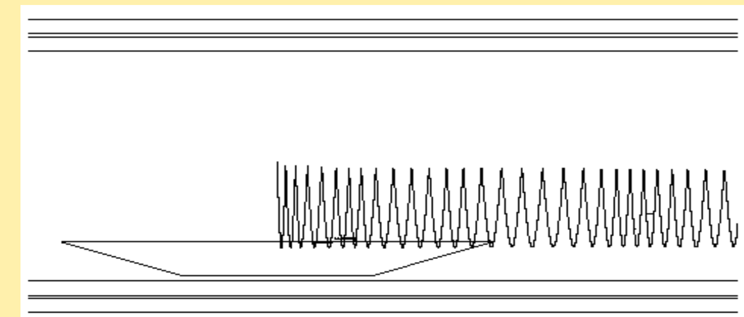
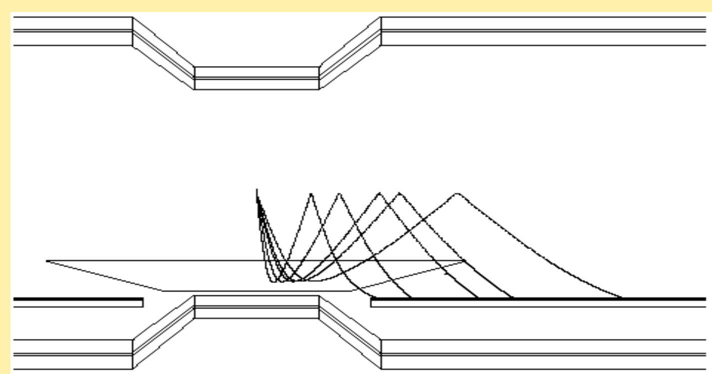
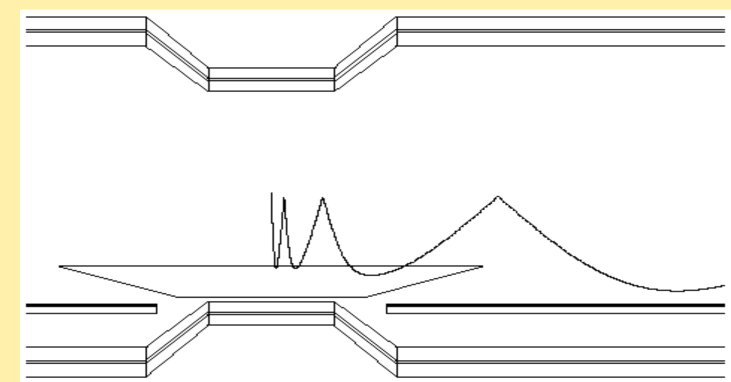
  scintillation counters for timing



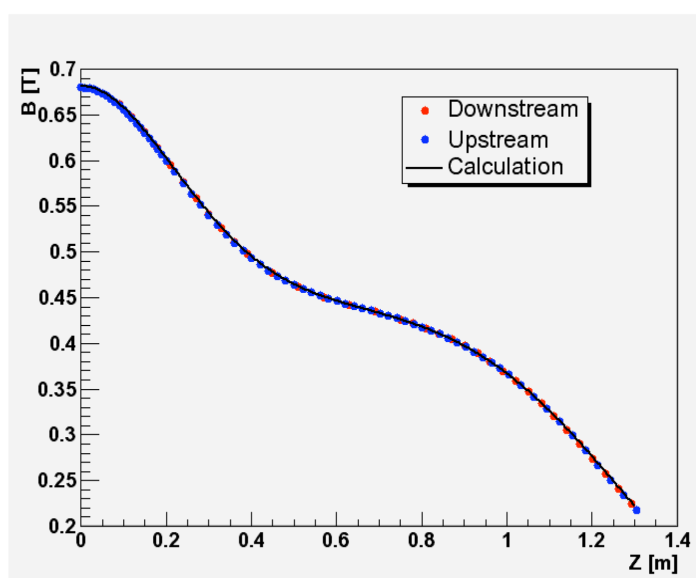
2.0 mA
1.8 mA
1.2 mA
Accelerator Facilities
Injector 2
Injector 1
Beam Transport Lines
Proton Channel
Neutron Spallation Source
Medicine
Nuclear Physics and Radiochemistry
Particle Physics
Solid State Physics and Materials Science
SINQ Target Hall
NE-C
PIREX
NA-Hall
Experimental Hall
Neutron Guide Hall

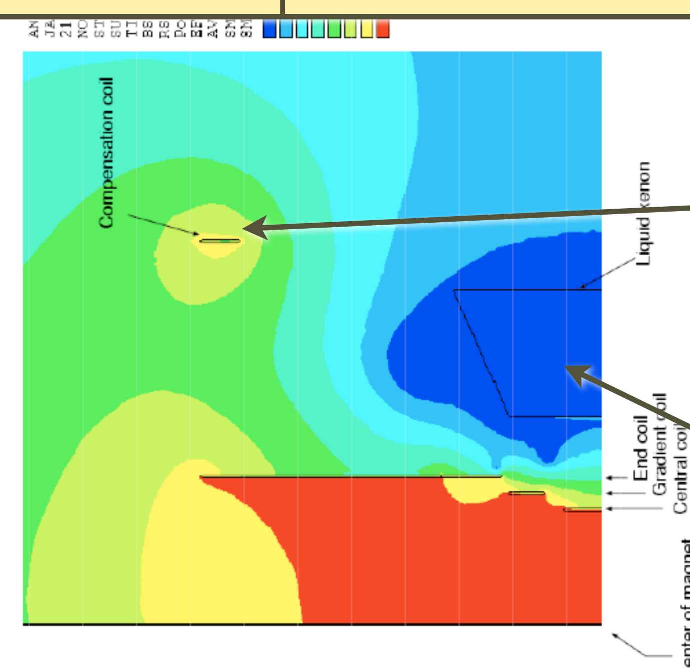
AUSTRIA
ITALY
Bern
Zürich

COBRA spectrometer

	Constant $|p|$ track	High p_T track
Uniform field		
CoBRa: Constant bending quick sweep away		

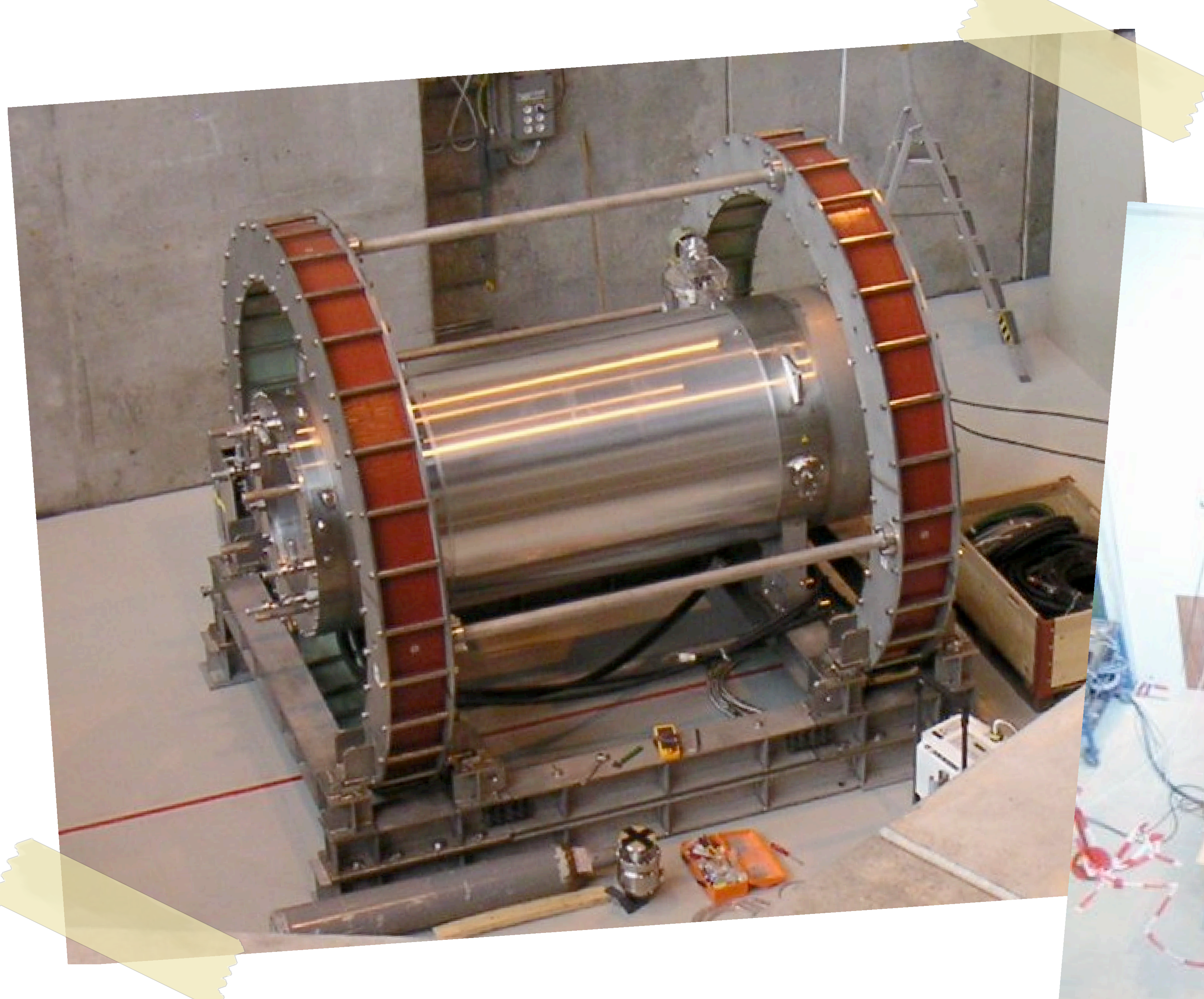
Non uniform magnetic field decreasing from the center to the periphery

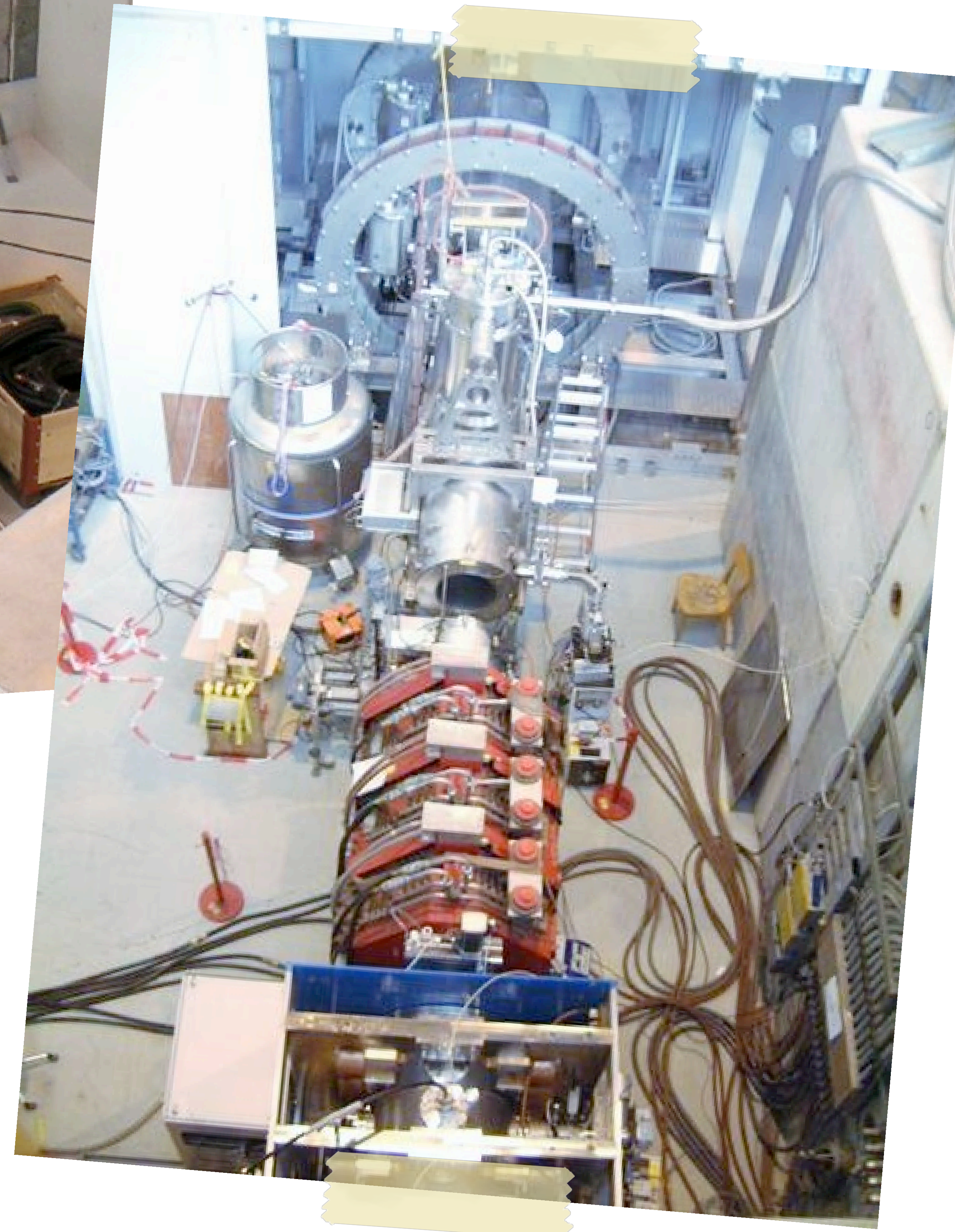




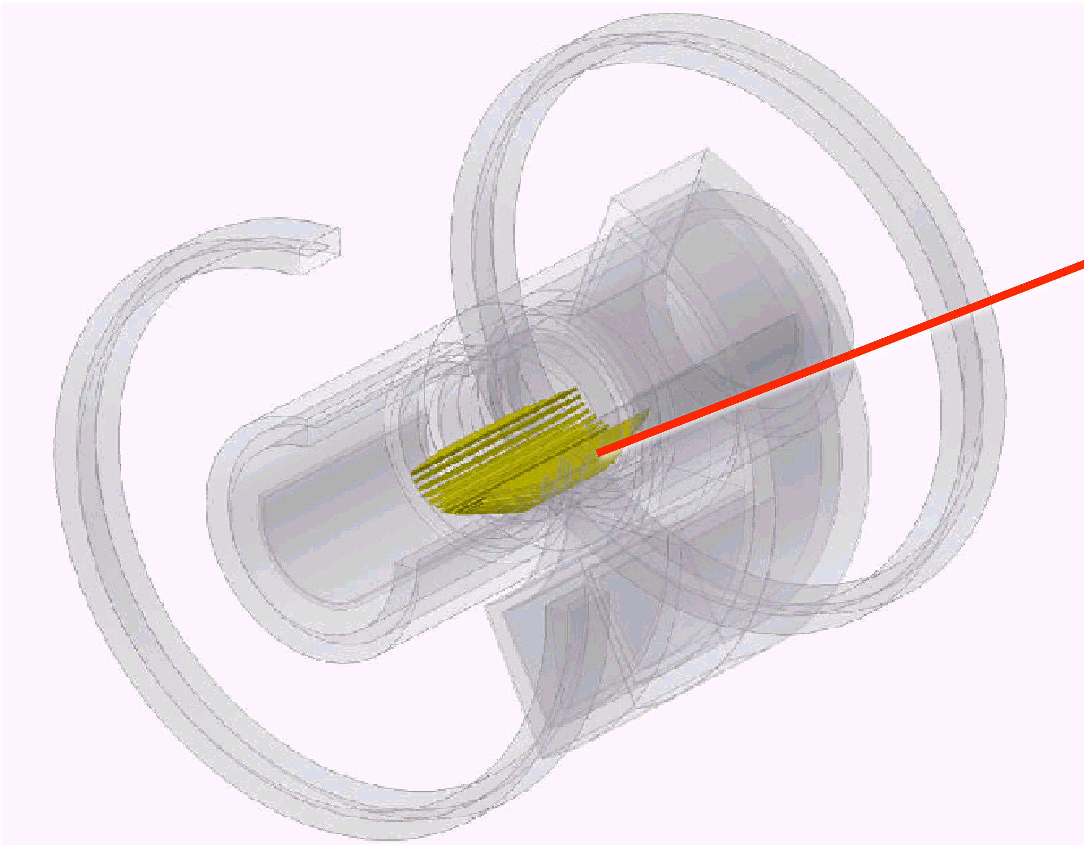
Compensation coil for LXe calorimeter

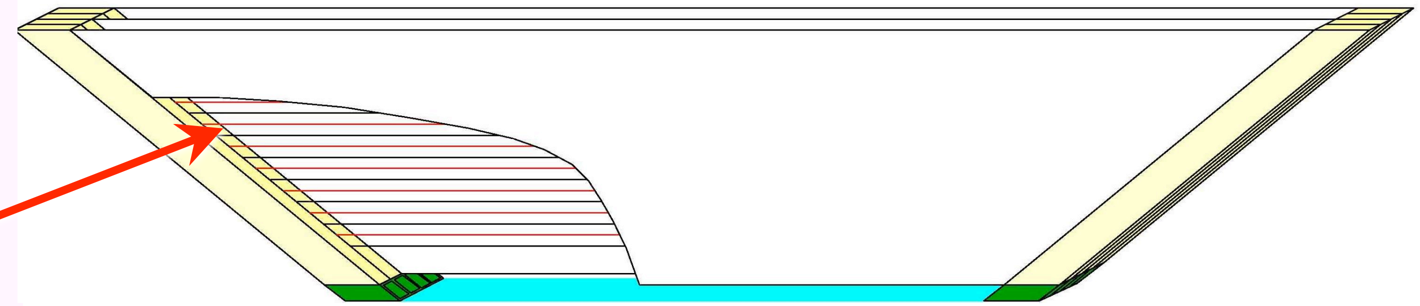
$|\vec{B}| < 50\ G$





Positron Tracker





- 16 chambers radially aligned with 10°intervals
- 2 staggered arrays of drift cells
- 1 signal wire and 2 x 2 vernier cathode strips made of 15 μm kapton foils and 0.45 μm aluminum strips
- Chamber gas: He-C_2H_6 mixture

transverse coordinate (t drift)

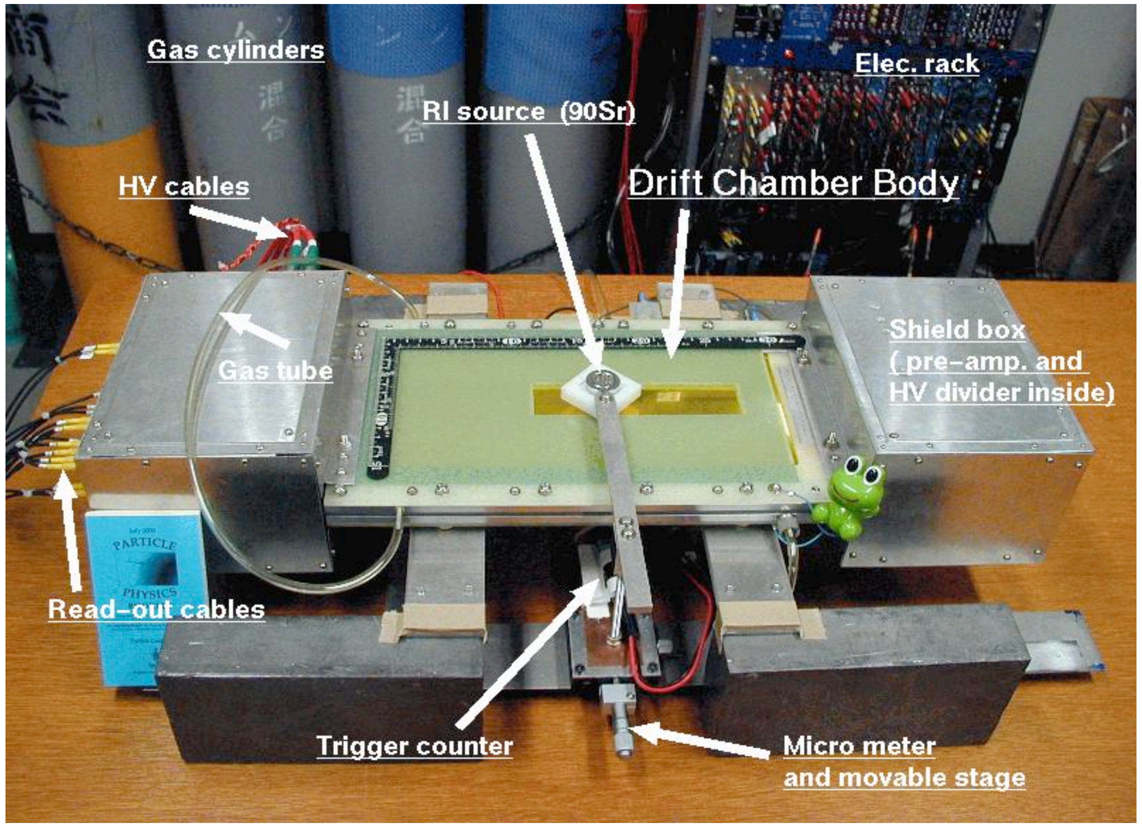
longitudinal coordinate (charge division)

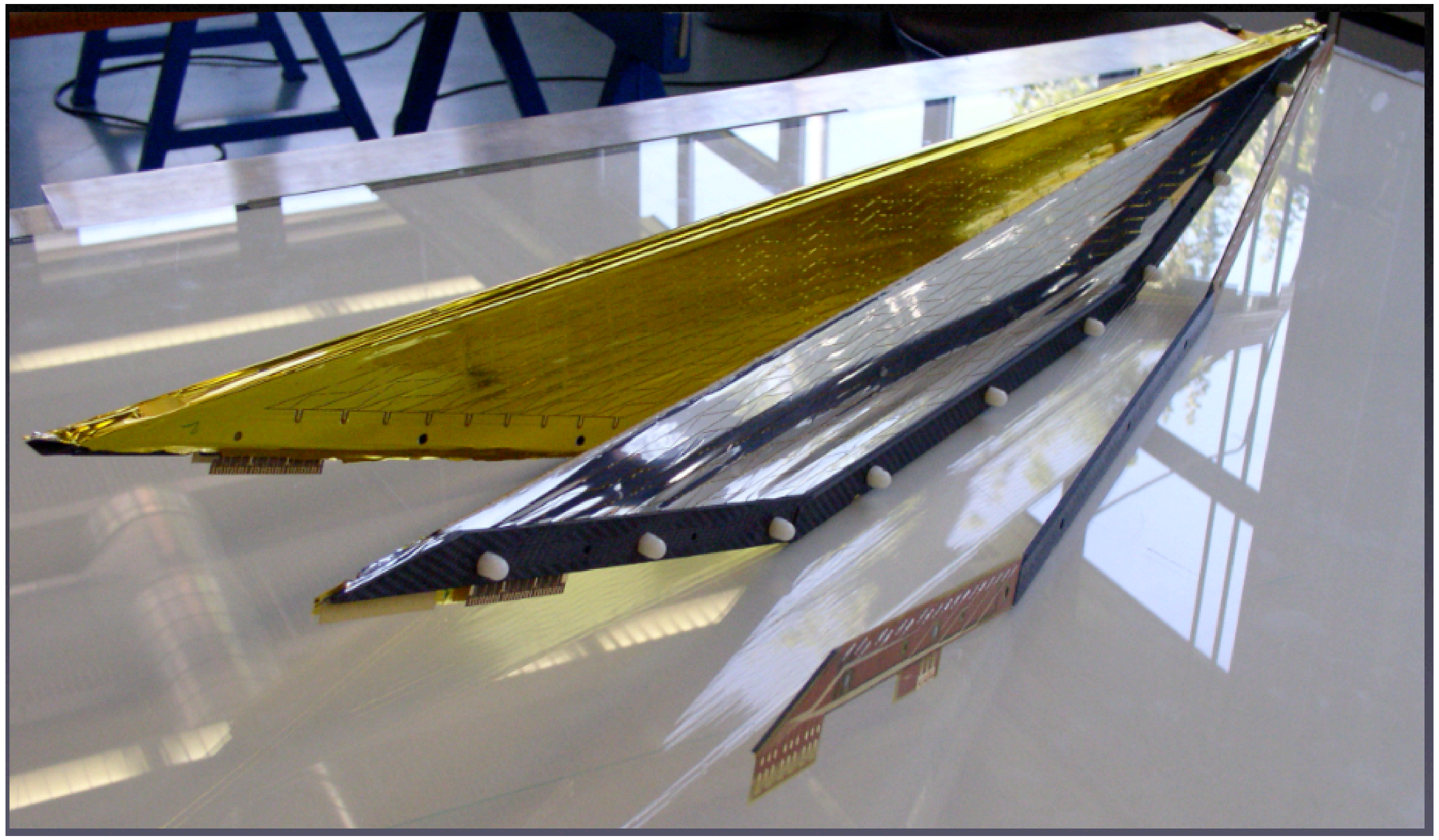
Measurements at Tokyo University:

$$\sigma_R = 93 \pm 10 \mu m$$

$$\sigma_Z = 425 \pm 7 \mu m$$

Drift chambers





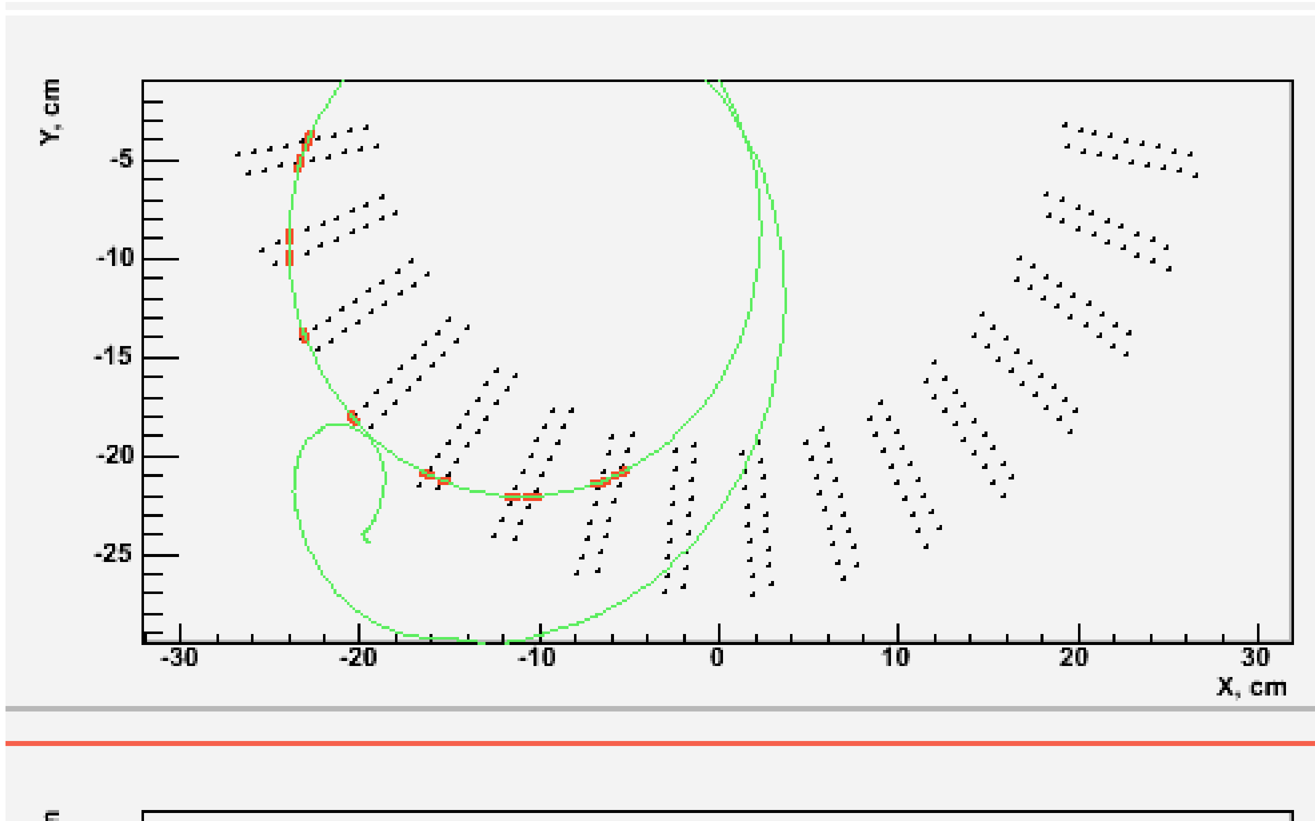
- Full scale test in November
- Summary of Drift Chamber simulation

FWHM

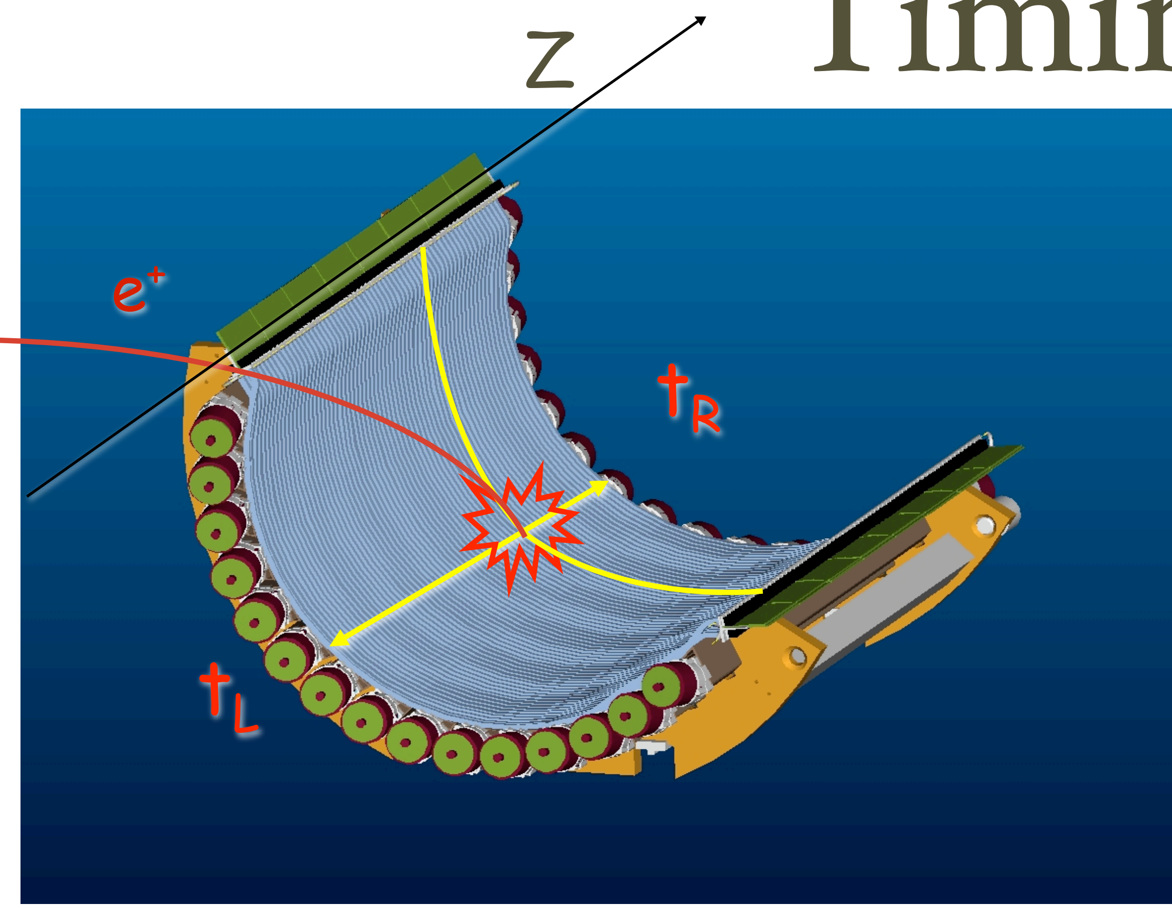
$$\delta P_{e^+} / P_{e^+} = 0.7 \div 0.9\%$$

$$\delta\theta_{e^+} = 9 \div 12\, mrad$$

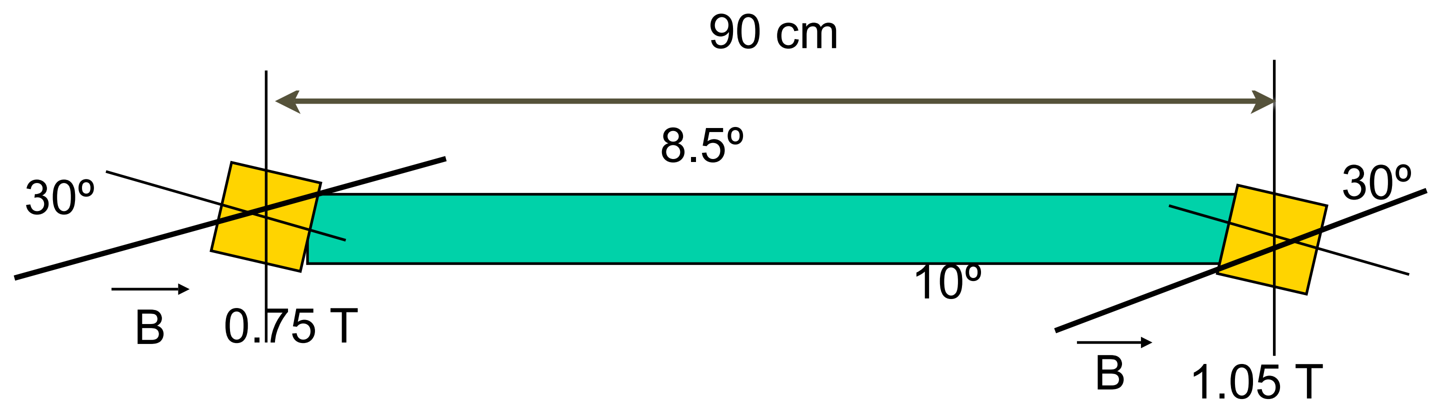
$$\delta x_{orig} = 2.1 \div 2.5\, mm$$

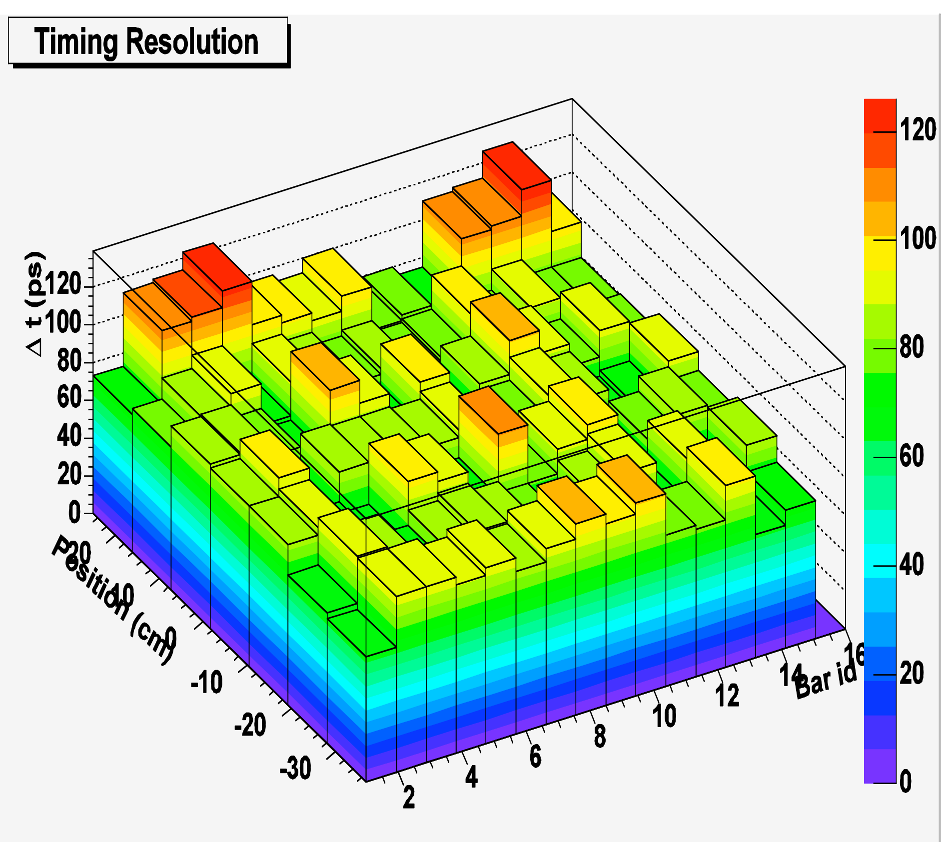


Timing Counter



- Two layers of scintillators:
  - Outer layer, read out by PMTs: timing measurement
  - Inner layer, read out with APDs at 90°: z-trigger
- Obtained goal σ_{time}~ 40 psec (100 ps FWHM)





Exp. application (*)	Counter size (cm) (T x W x L)	Scintillator	PMT	λ_{att} (cm)	σ_t(meas)	σ_t(exp)
G.D.Agostini	3x 15 x 100	NE114	XP2020	200	120	60
T. Tanimori	3 x 20 x 150	SCSN38	R1332	180	140	110
T. Sugitate	4 x 3.5 x 100	SCSN23	R1828	200	50	53
R.T. Gile	5 x 10 x 280	BC408	XP2020	270	110	137
TOPAZ	4.2 x 13 x 400	BC412	R1828	300	210	240
R. Stroynowski	2 x 3 x 300	SCSN38	XP2020	180	180	420
Belle	4 x 6 x 255	BC408	R6680	250	90	143
MEG	**4 x 4 x 90**	**BC404**	**R5924**	**270**	**38**	

Best existing TC

Timing Counter

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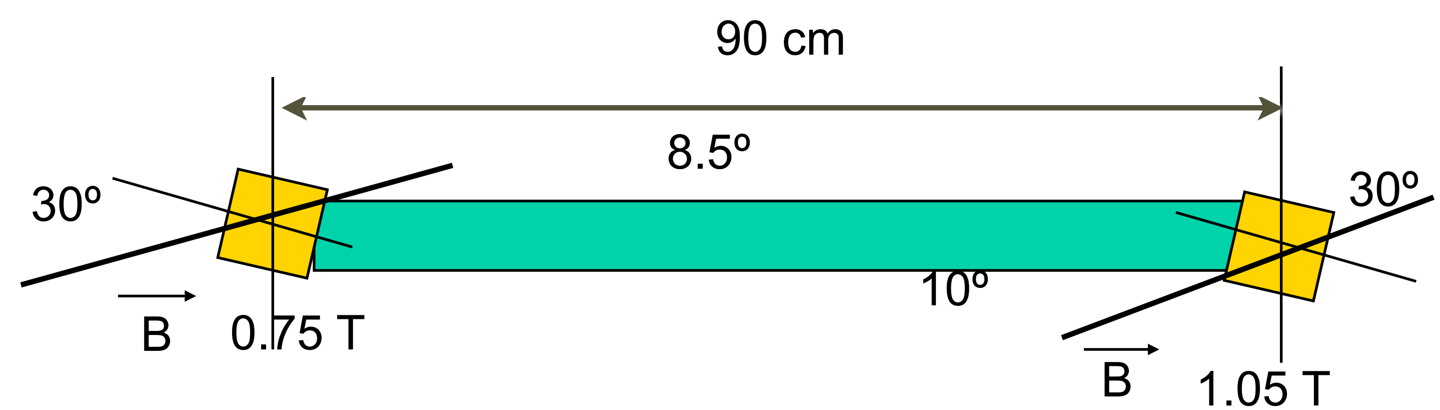

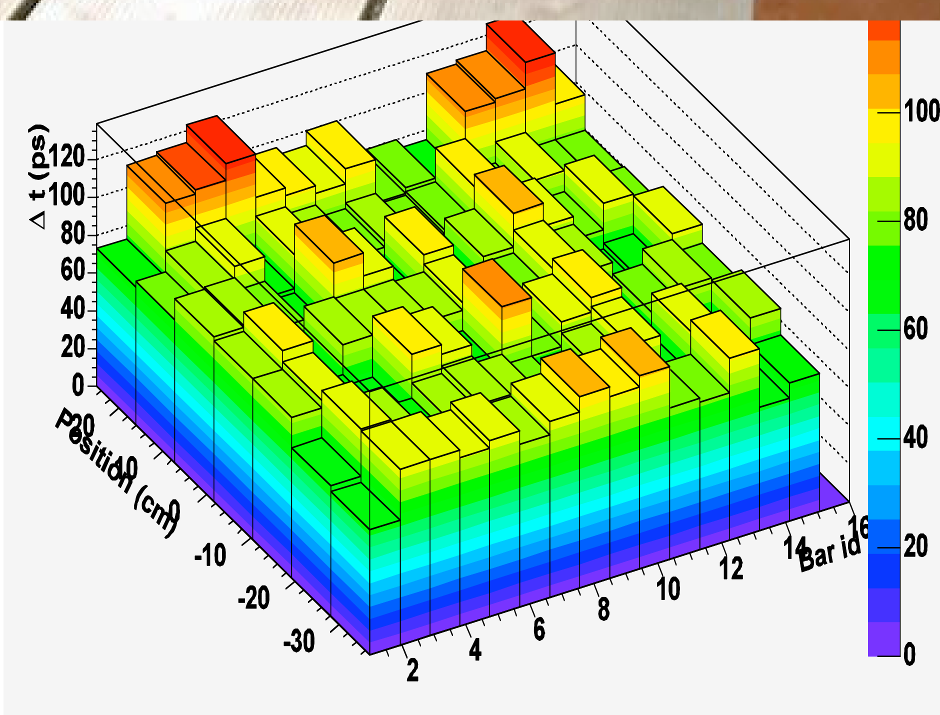

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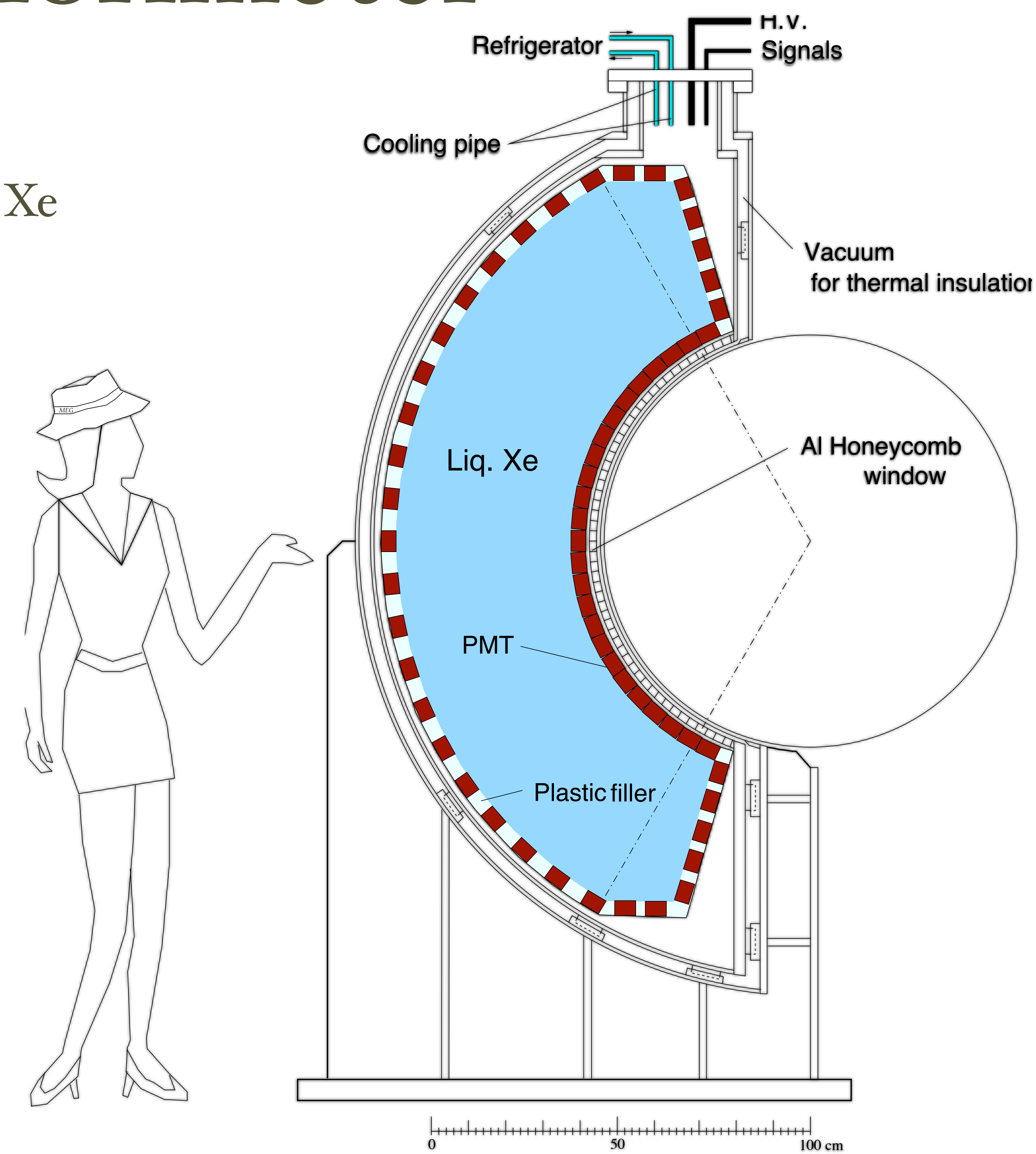
Best existing TC

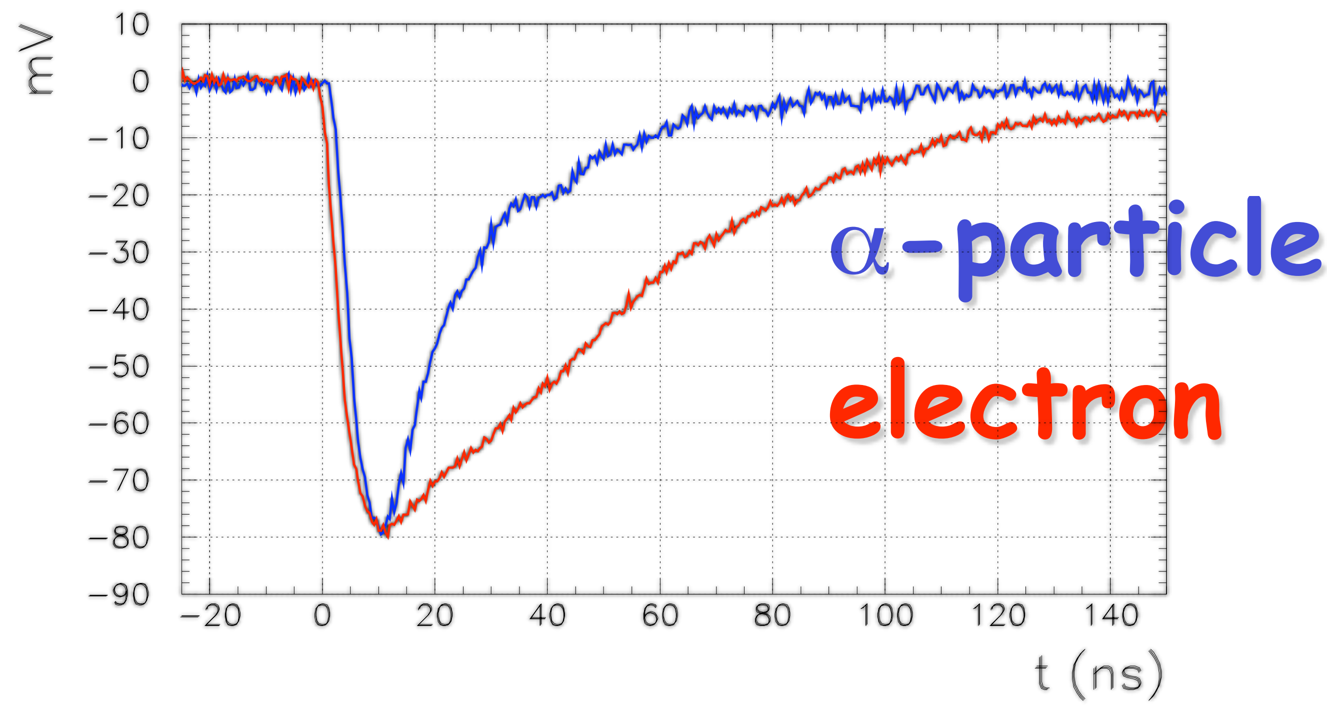
The calorimeter

- γ Energy, position, timing
- Homogeneous 0.8 m^3 volume of liquid Xe
  - 10 % solid angle
  - 65 < r < 112 cm
  - |cosθ| < 0.35 |φ| < 60o
- Only scintillation light
- Read by 848 PMT
  - 2” photo-multiplier tubes
  - Maximum coverage FF (6.2 cm cell)
  - Immersed in liquid Xe
  - Low temperature (165 K)
  - Quartz window (178 nm)
- Thin entrance wall
- Singularly applied HV
- Waveform digitizing @2 GHz
  - Pileup rejection



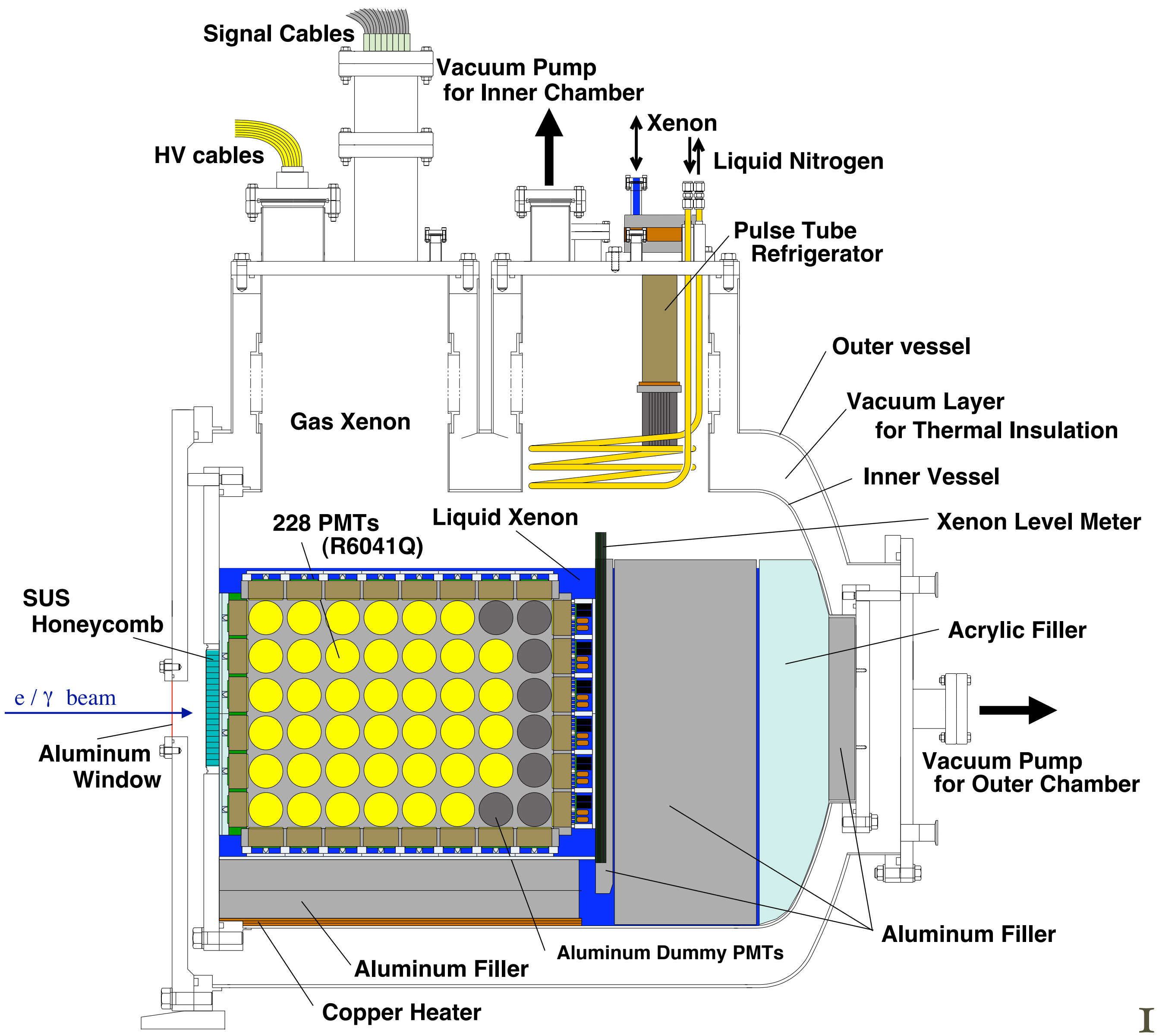
Liquid Xe properties

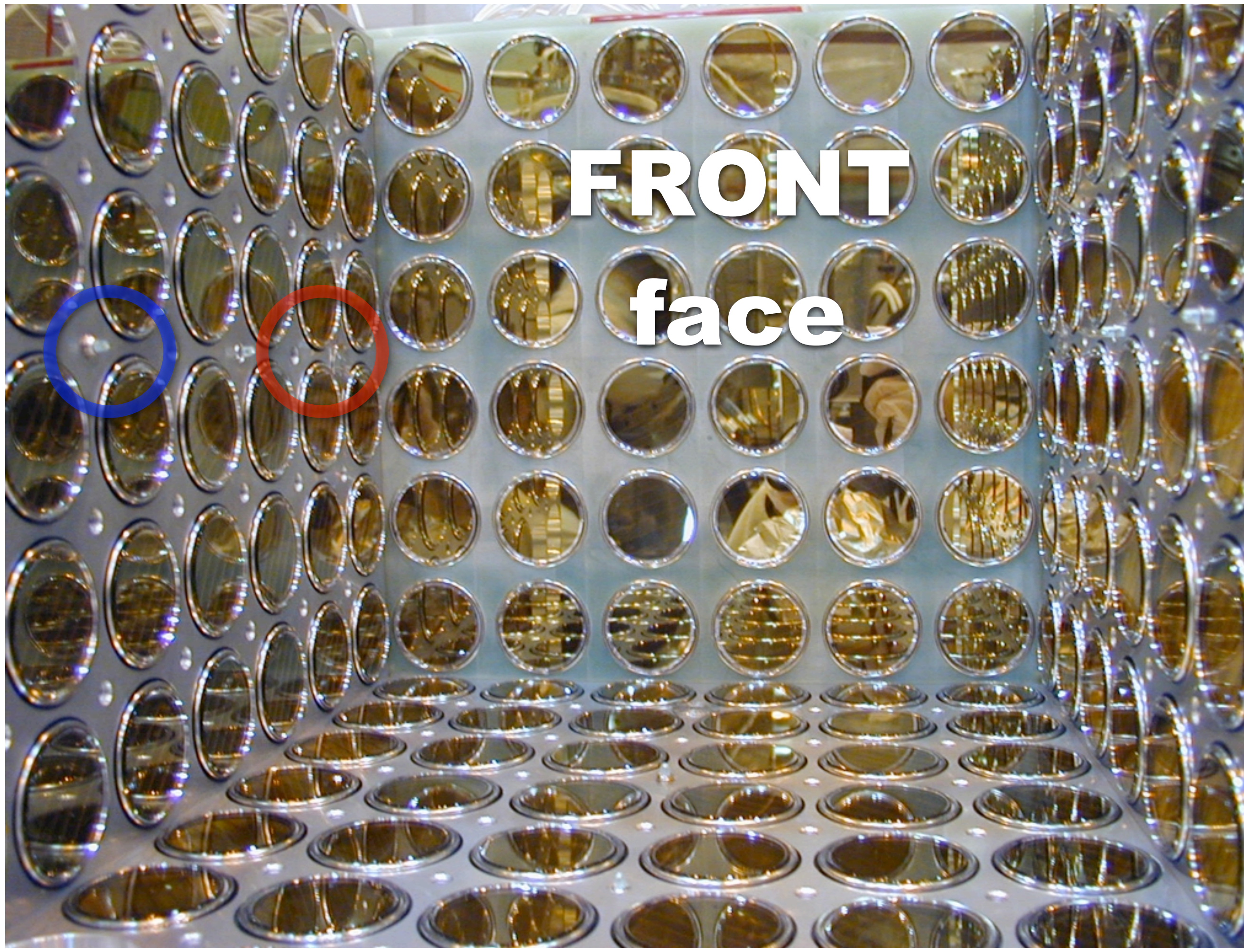
- Fast
  - $\tau_{singlet}$= 4.2 ns
  - $\tau_{triplet}$= 22 ns
  - τ_{recomb}= 45 ns
- Particle ID
  - LY alpha = 1.2 x LY gamma/e
- High LY (≈ NaI)
  - 40000 phe/MeV
- n = 1.65
- Z=54, ρ=2.95 g/cm^3 (X_o=2.7 cm), R_M=4.1 cm
- No self-absorption ($\lambda_{Abs}=\infty$)



The LXe calorimeter prototype

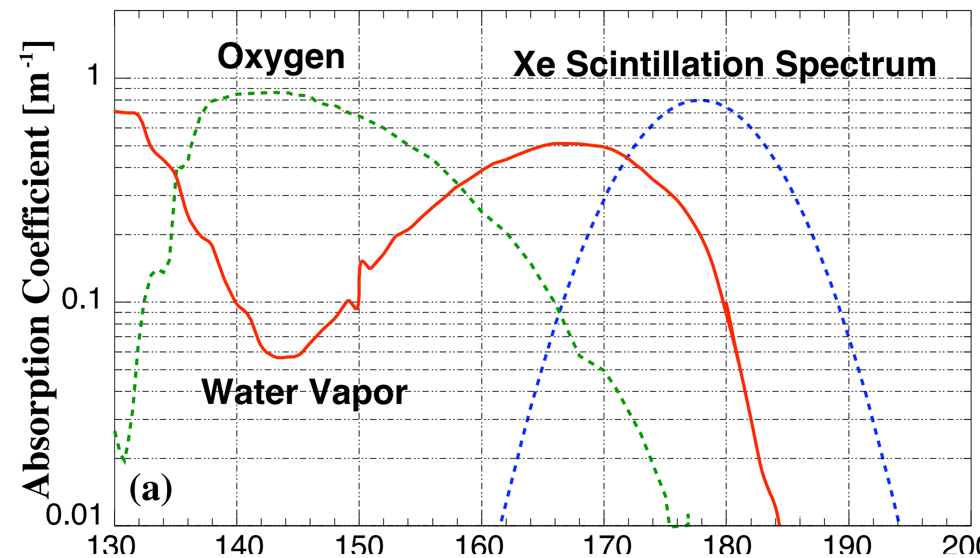
- A 100 liters, 240 PMTs large prototype was built and exensively tested to demonstrate the calorimeter performance
- α-sources and LEDs used for PMT calibrations and monitoring

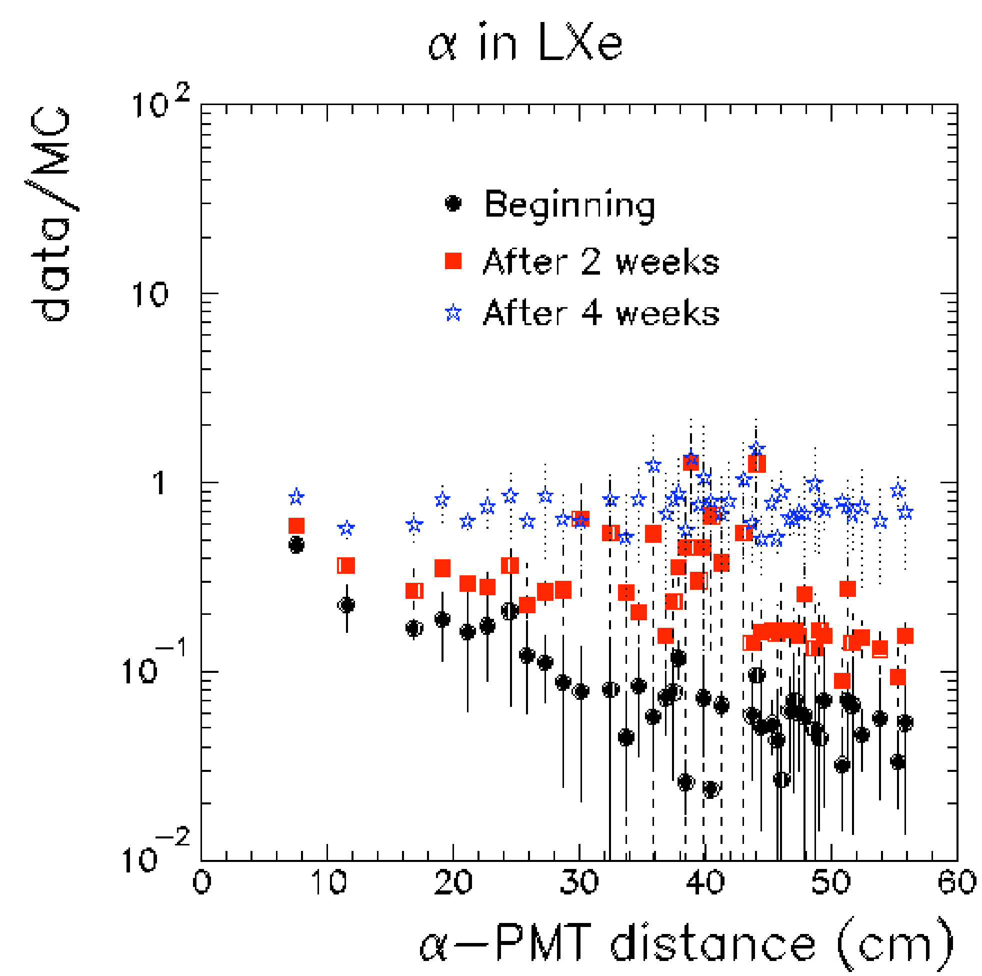


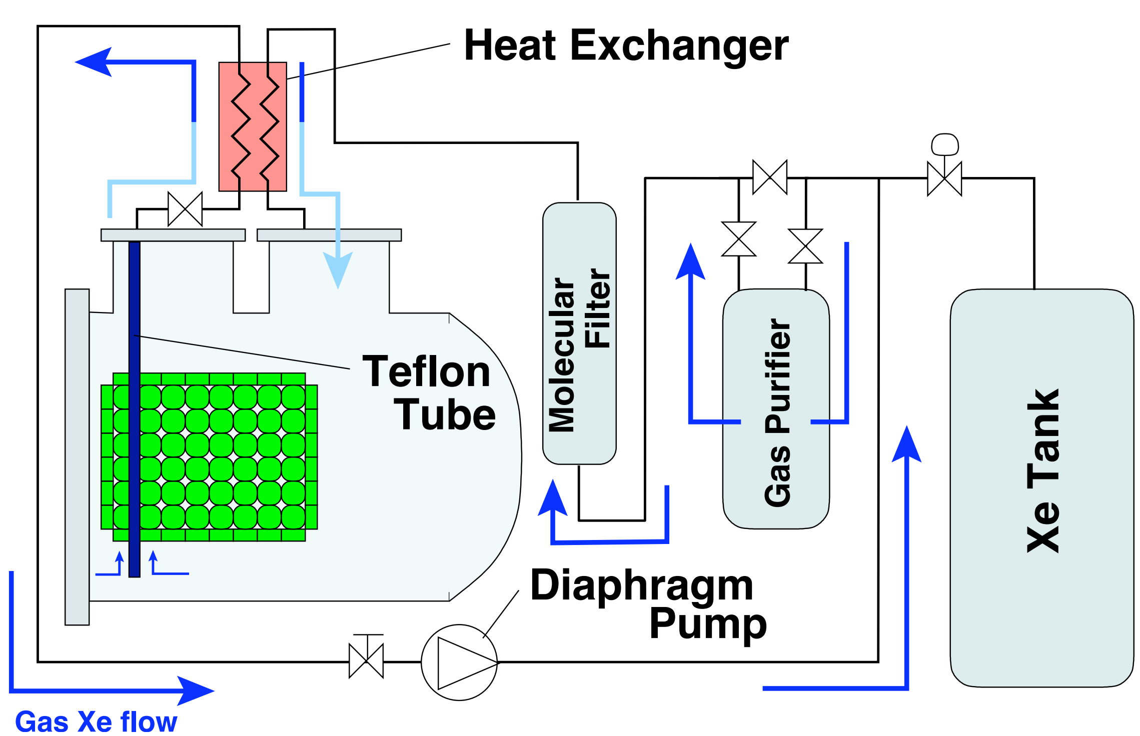


Xenon purity

- Energy resolution strongly depends on absorption
- We developed a method to measure the absorption length with alpha sources
- We added a purification system (molecular sieve + gas getter) to reduce impurities below ppb

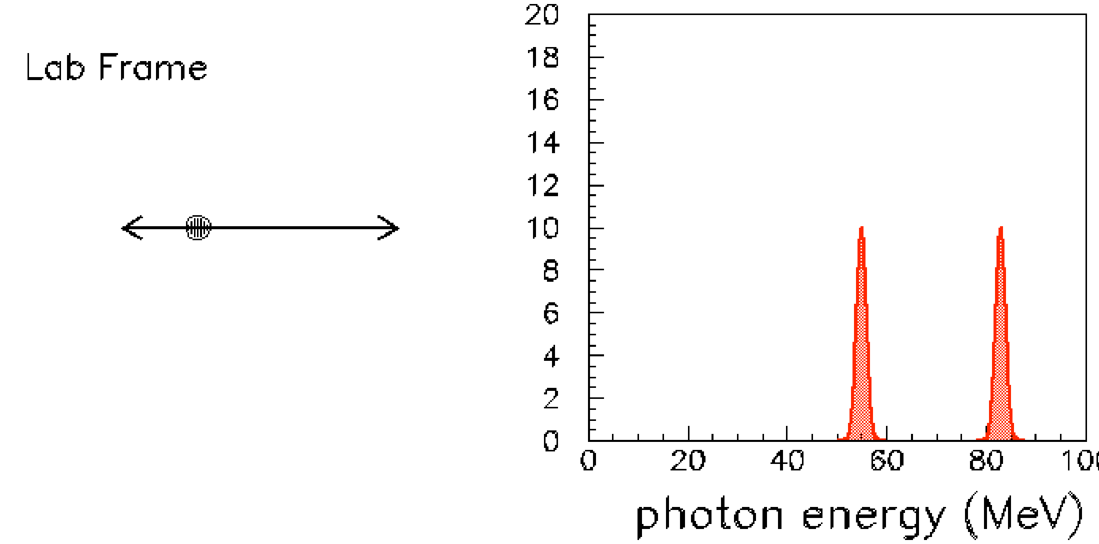






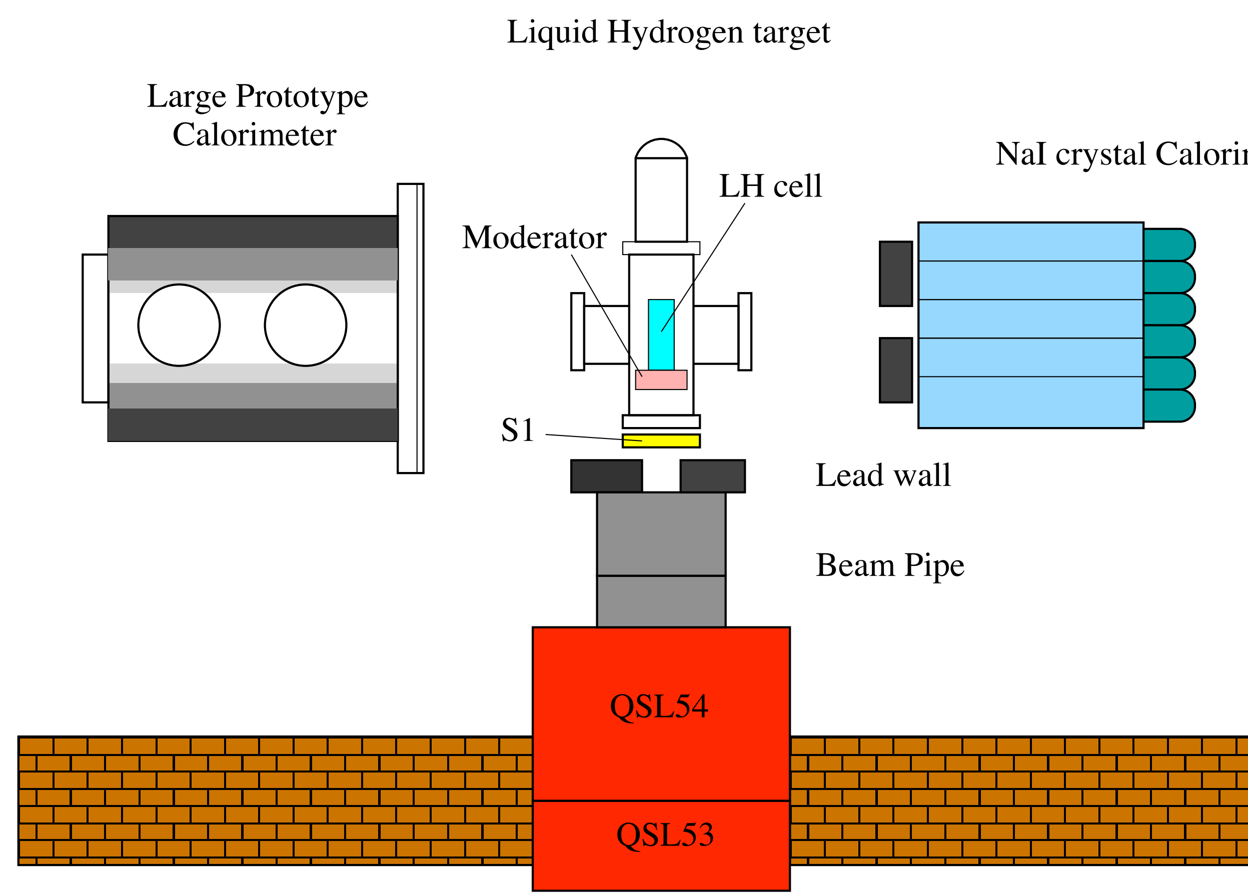
Energy resolution measurement

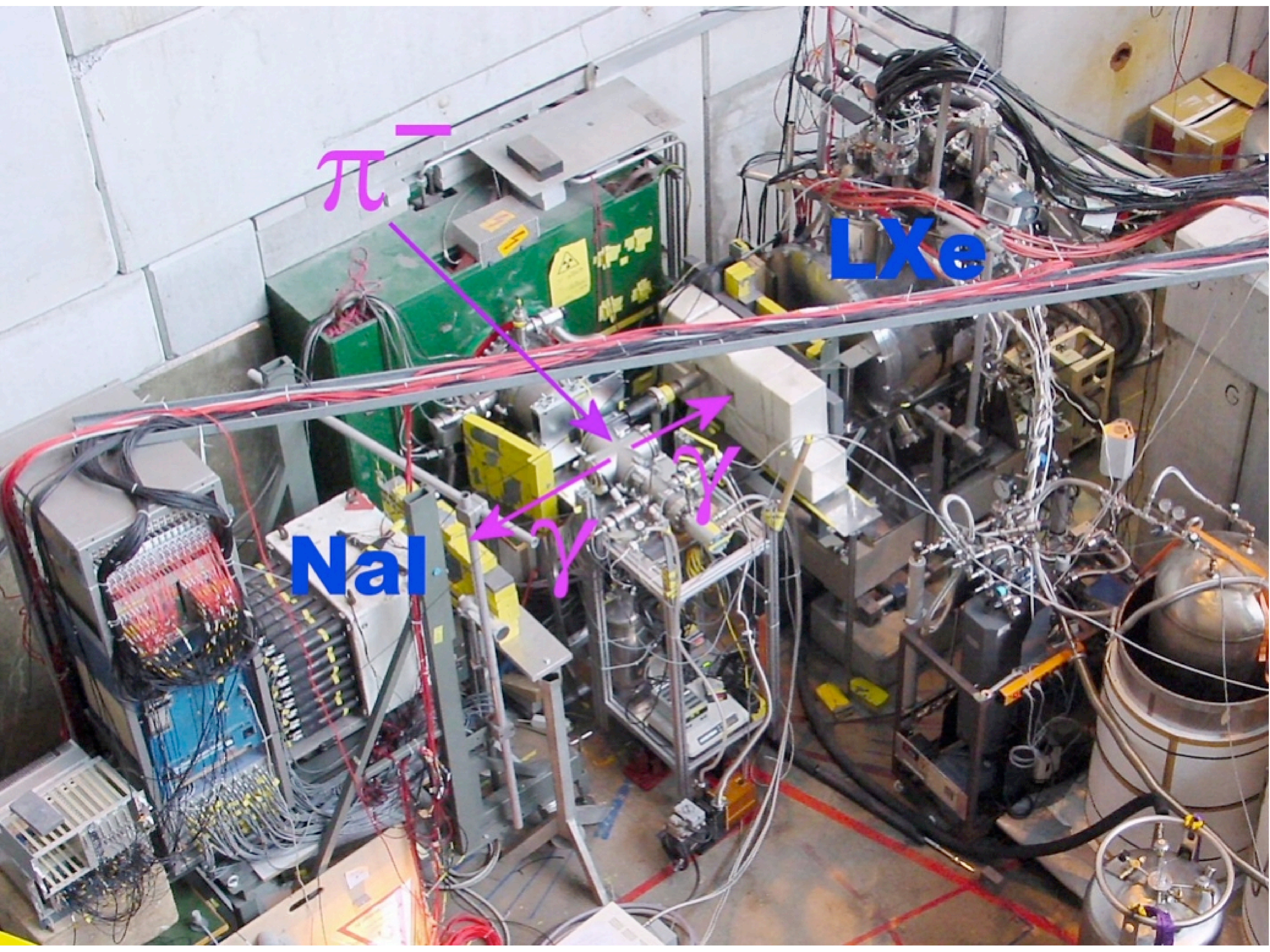
$$\pi^- p \rightarrow \pi^0 n$$
$$\pi^0 \rightarrow \gamma\gamma$$



- The monochromatic spectrum in the pi-zero rest frame becomes flat in the Lab
- In the back-to-back configuration the energies are 55 MeV and 83 MeV

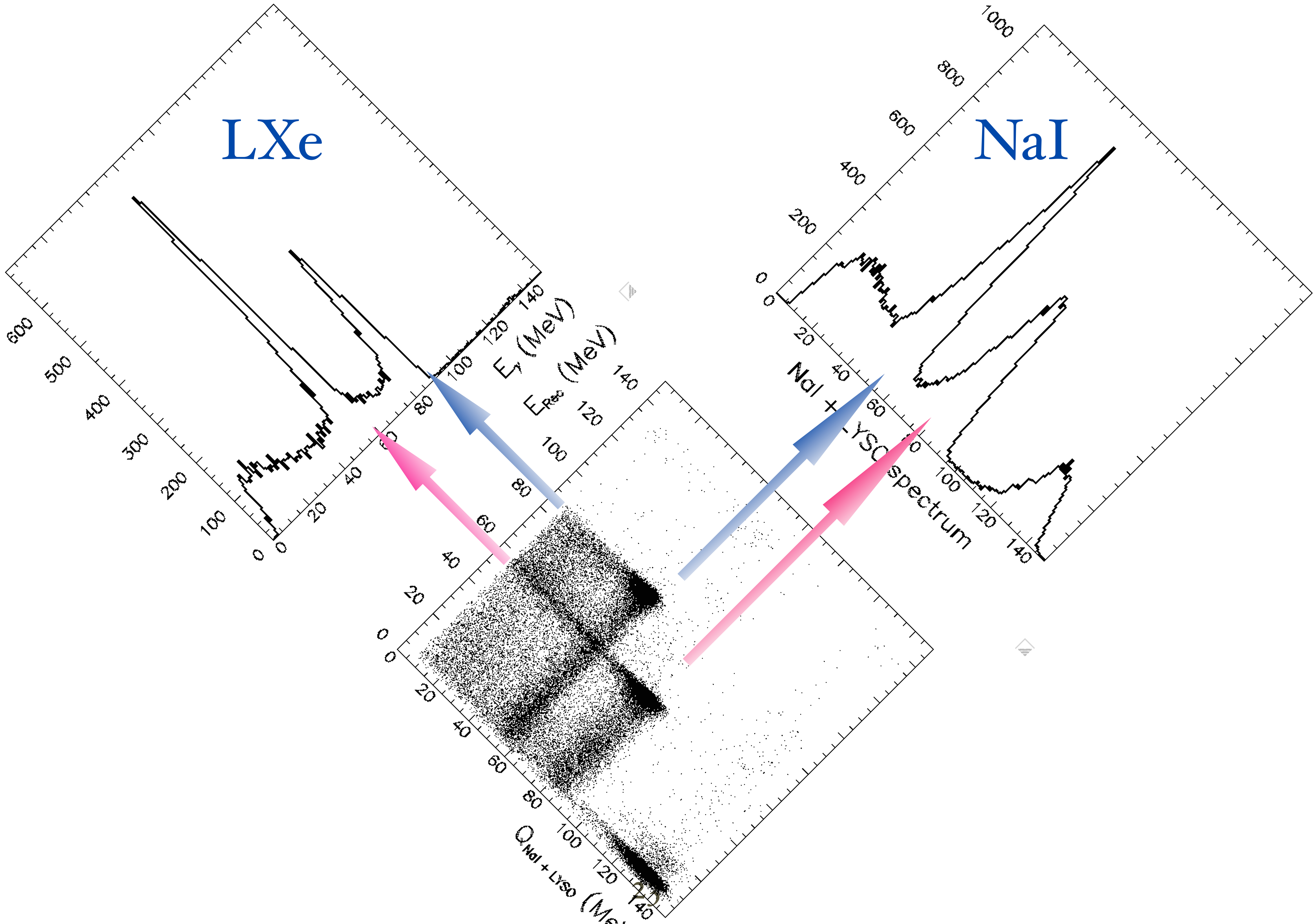
- Even a modest collimation guarantees a sufficient monochromaticity
- Liquid hydrogen target to maximize photon flux
- An "opposite side detector" is needed (NaI array)





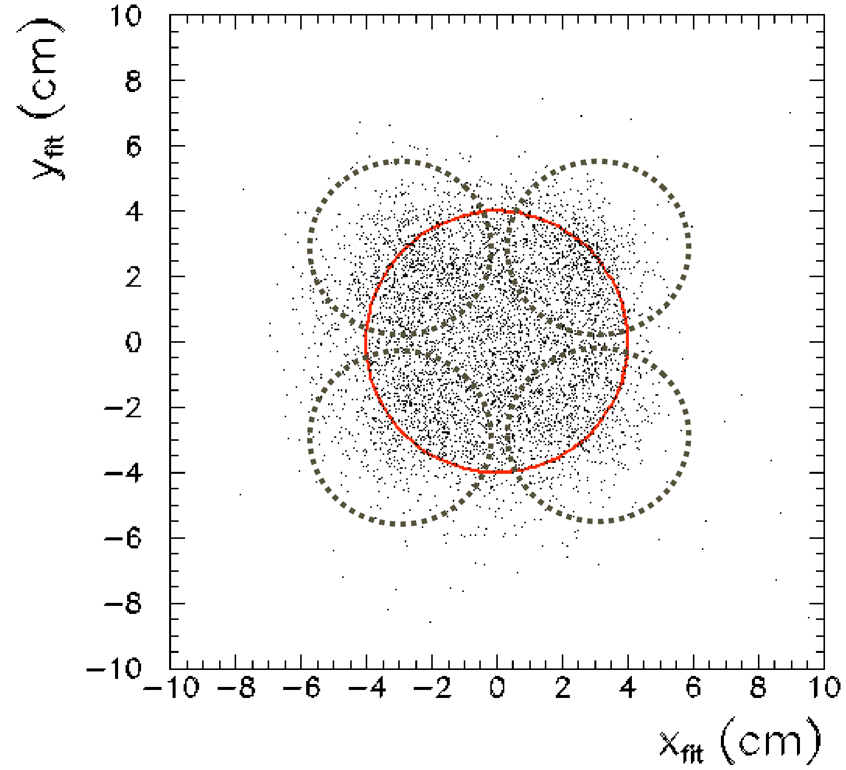
π⁻
LXe
γ
γ
NaI

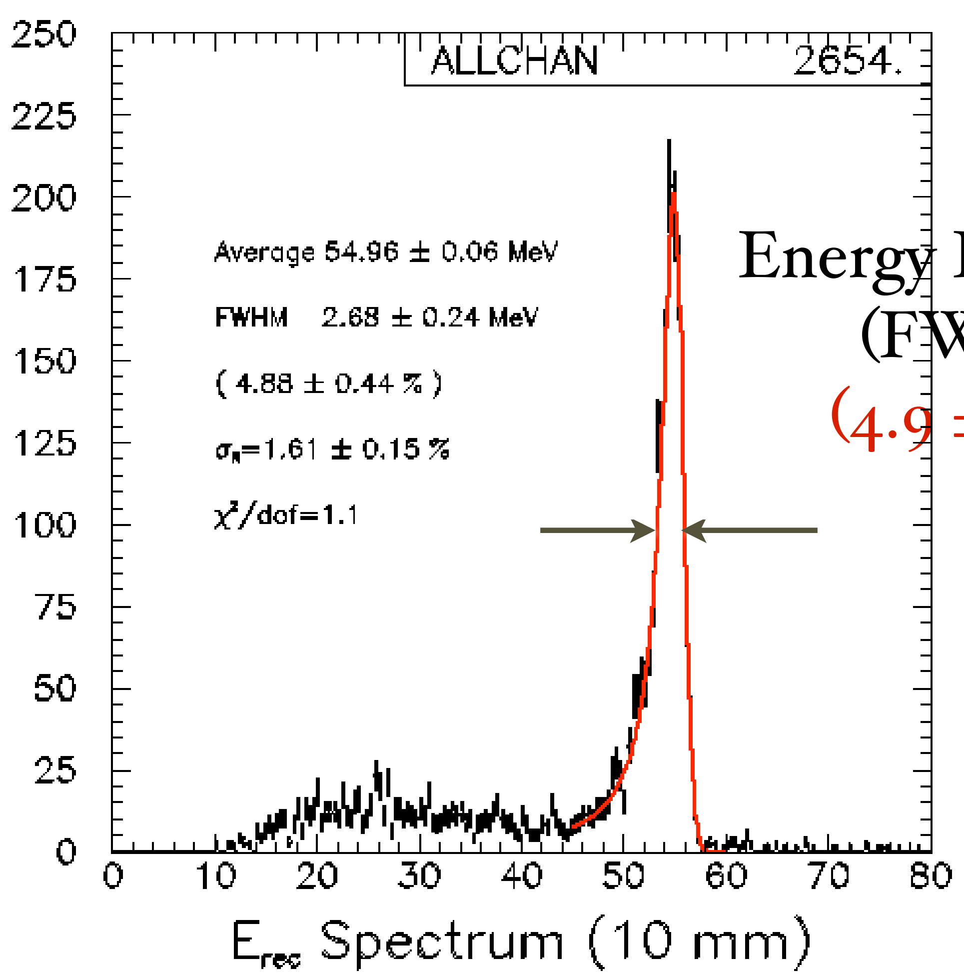
- In the back-to-back raw spectrum we see the correlation
  - 83 MeV ⇔ 55 MeV
  - The 129 MeV line is visible in the NaI because Xe is sensitive to neutrons (9 MeV)



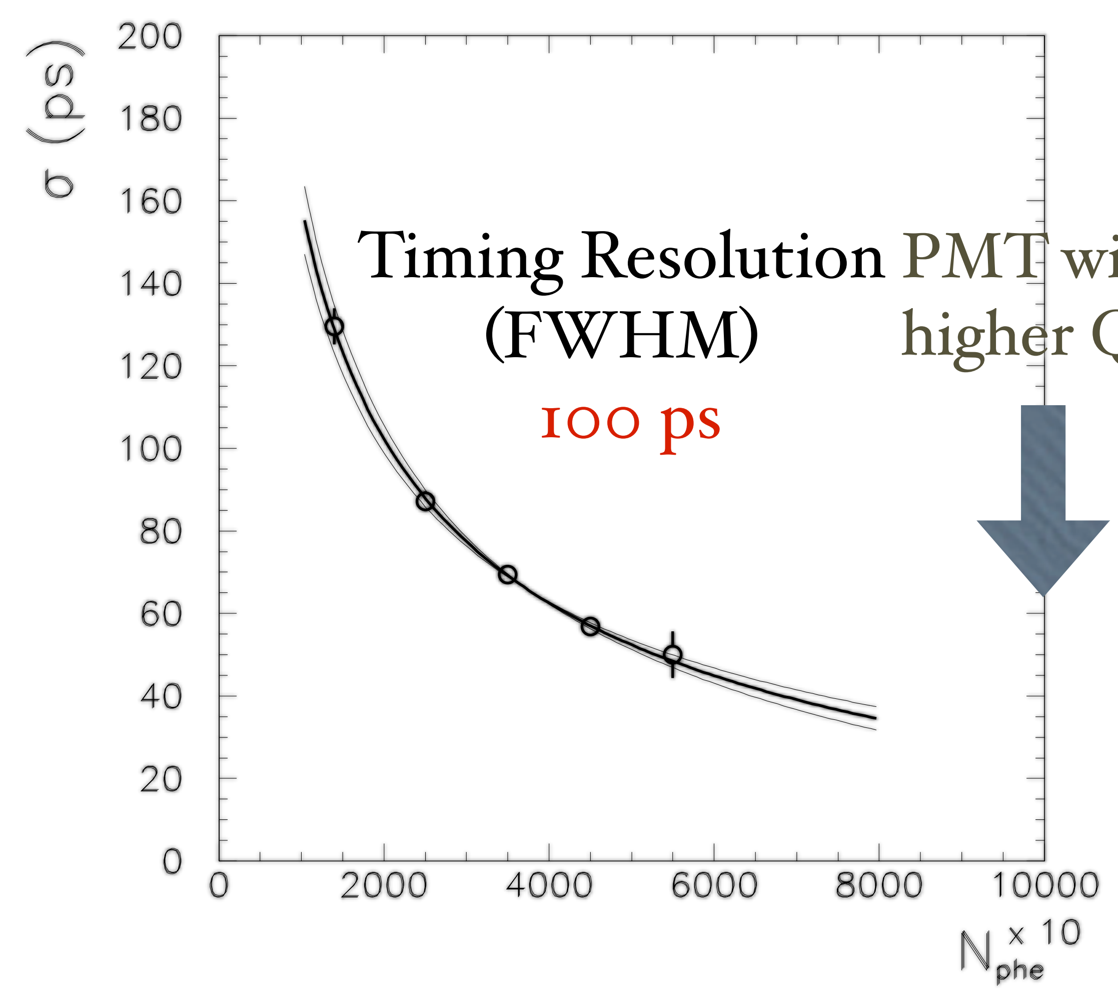
Resolutions @ 55 MeV

- Select negative pions in the beam
- 65 MeV < E(NaI) < 95 MeV
- Collimator cut (r < 4 cm)





Energy Resolution (FWHM)
(4.9 ± 0.4) %

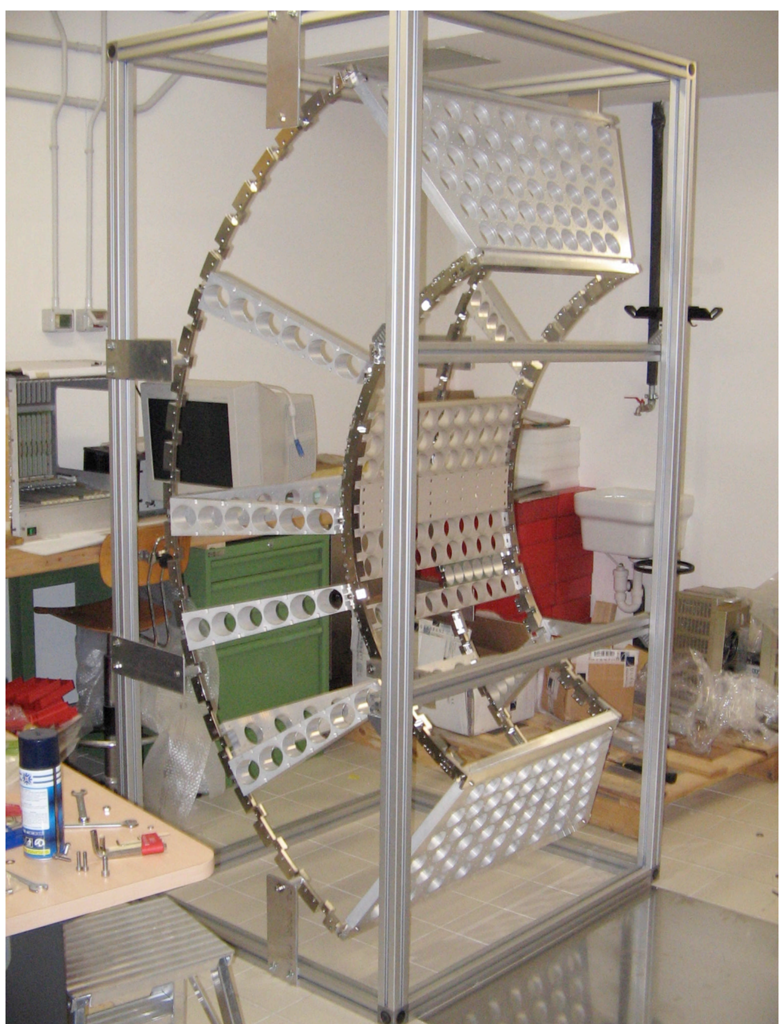


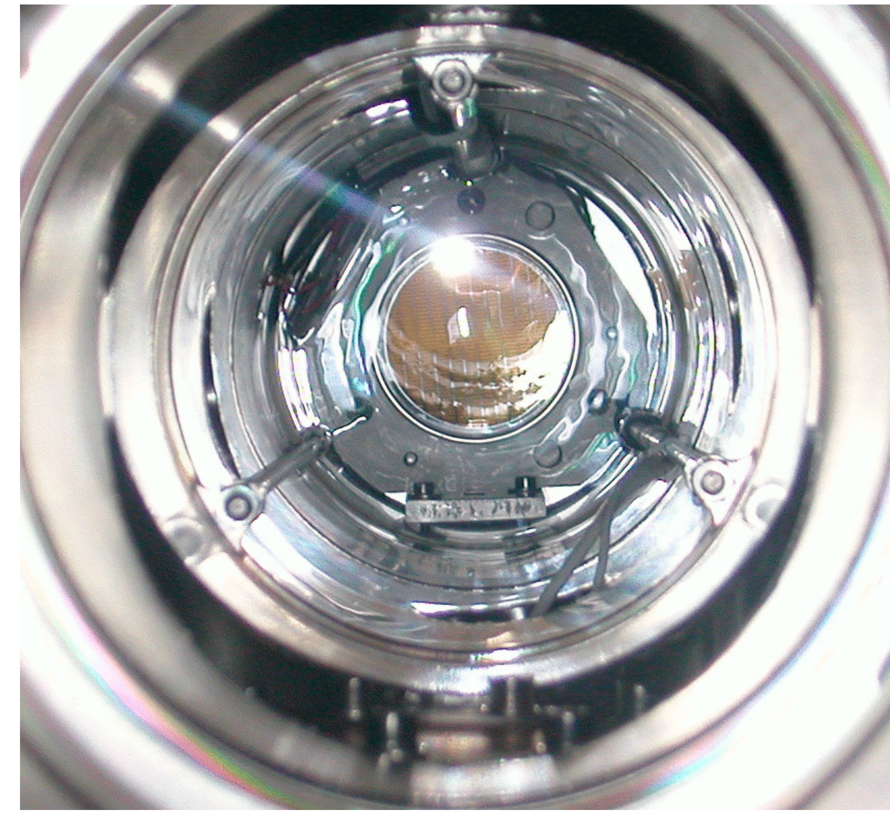
Timing Resolution (FWHM)
100 ps

PMT with higher QE

Status of the calorimeter

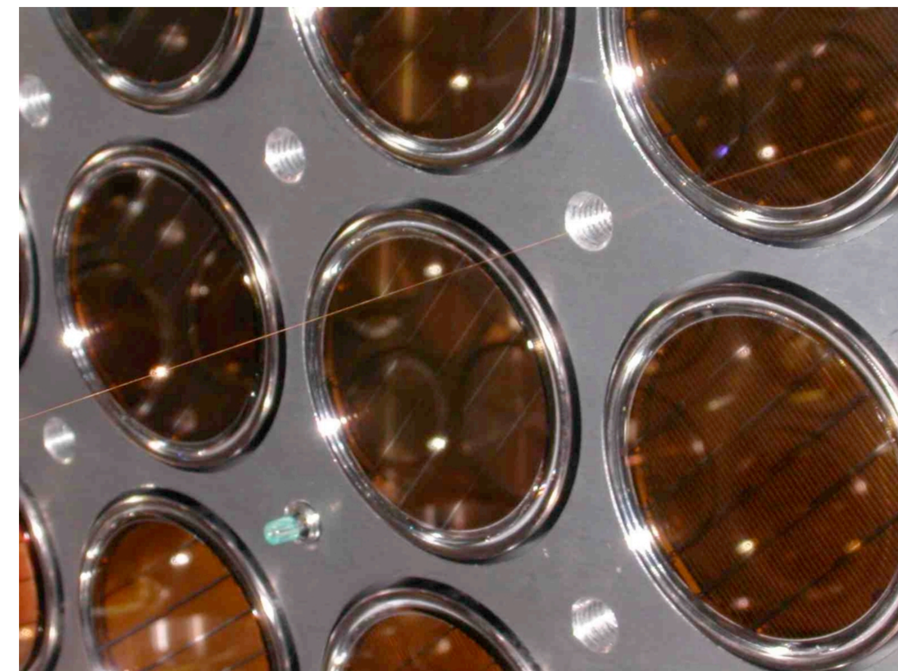
- All > 900 PMTs tested at Pisa and PSI
- PMT support structure: ready
- Warm vessel: ready
- Cold vessel: under completion





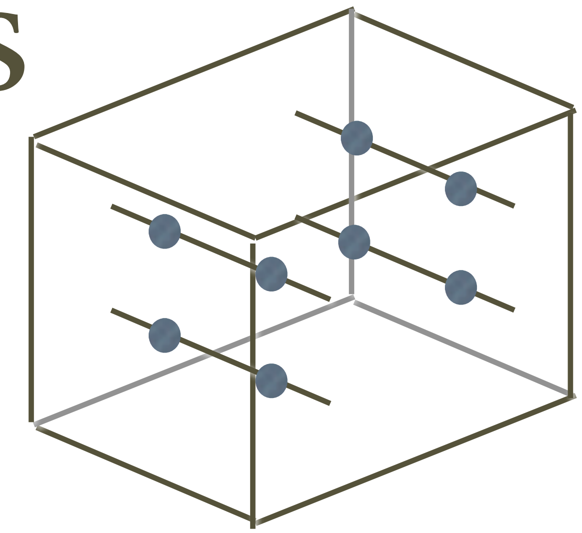
MEG (LXe) calibrations

- A reliable result depend on a constant calibration and monitoring of the apparatus
  - Charge exchange reaction (Panofsky) $\pi^- p \to \pi^0 n$, $\pi^0 \to \gamma\gamma$
  - alpha Sources (on wires and wall)
  - Proton accelerator $^7\mathrm{Li}(p, \gamma_{17.6})^8\mathrm{Be}$
  - Neutron capture $^{58}\mathrm{Ni}(n, \gamma_9)^{59}\mathrm{Ni}$
- Calibration frequency is different

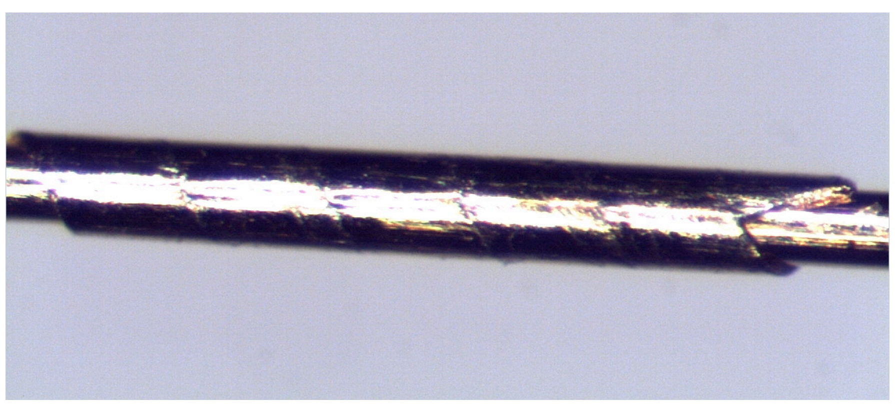


500 keV Cockroft-Walton

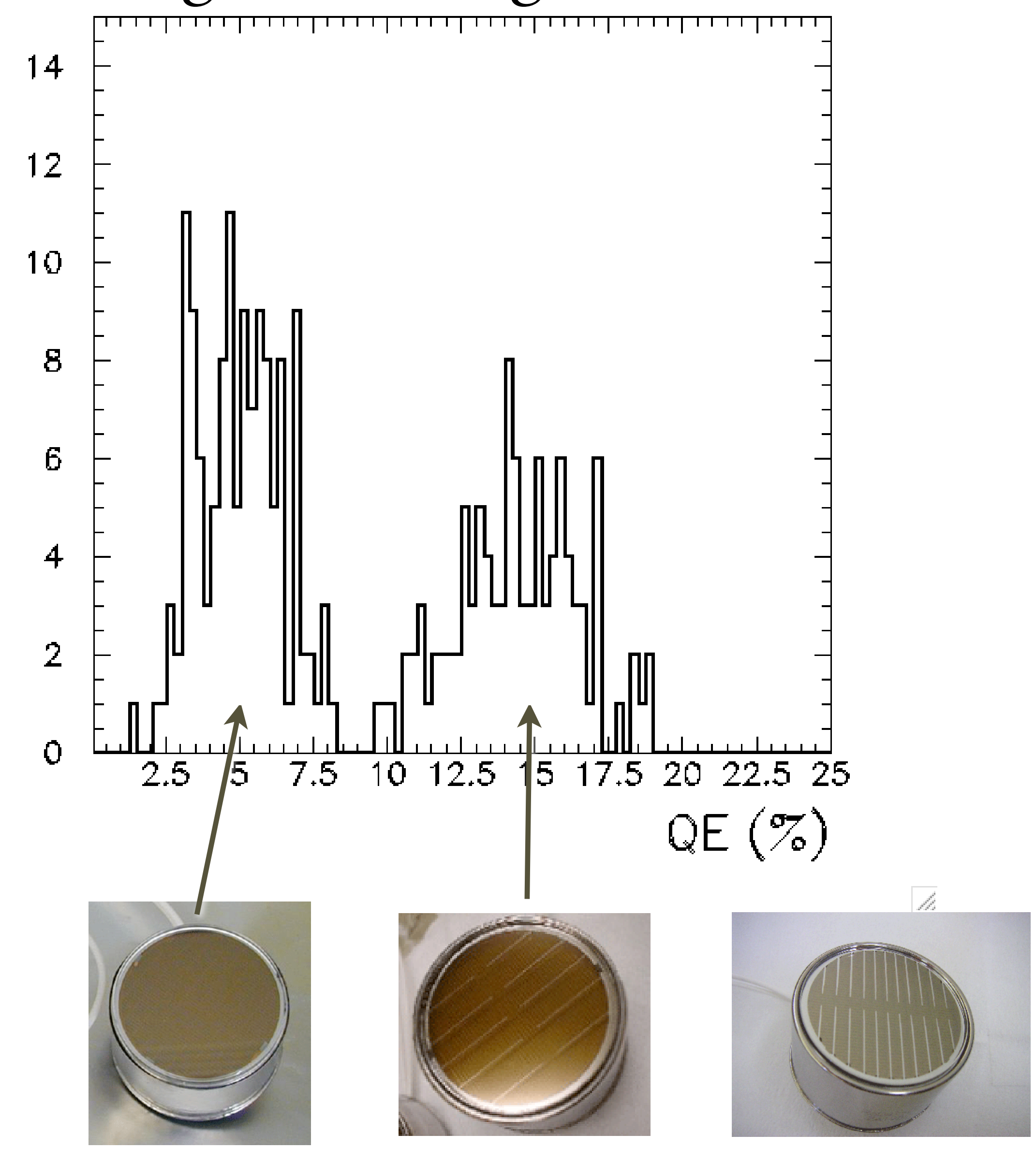
Alpha sources



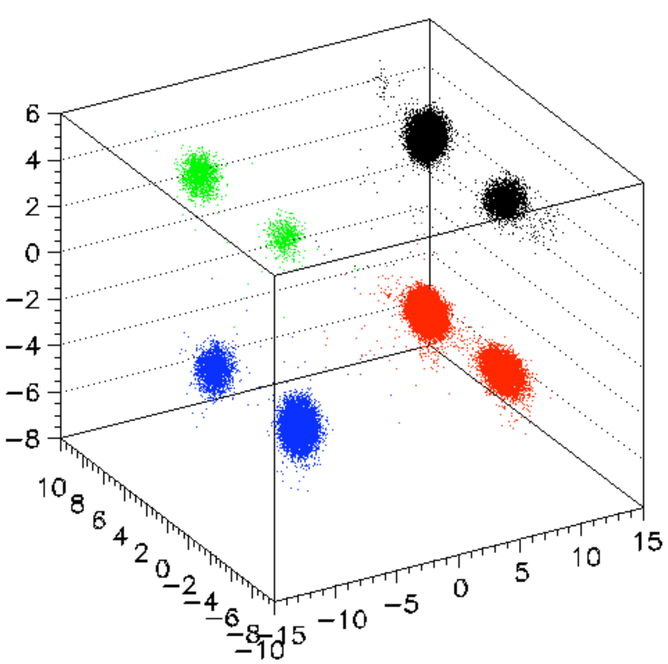
- 4 W wires suspended inside the liquid xenon
  - unique to liquid
  - Po and Am sources
- QEs determined by comparison of alpha source signal in cold gaseous xenon and MC determined at a 10% level

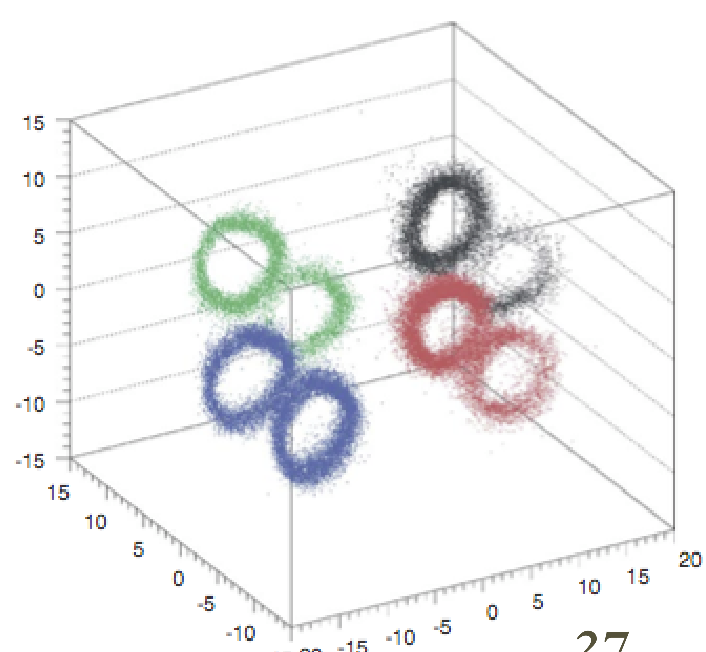


ø 100 μm

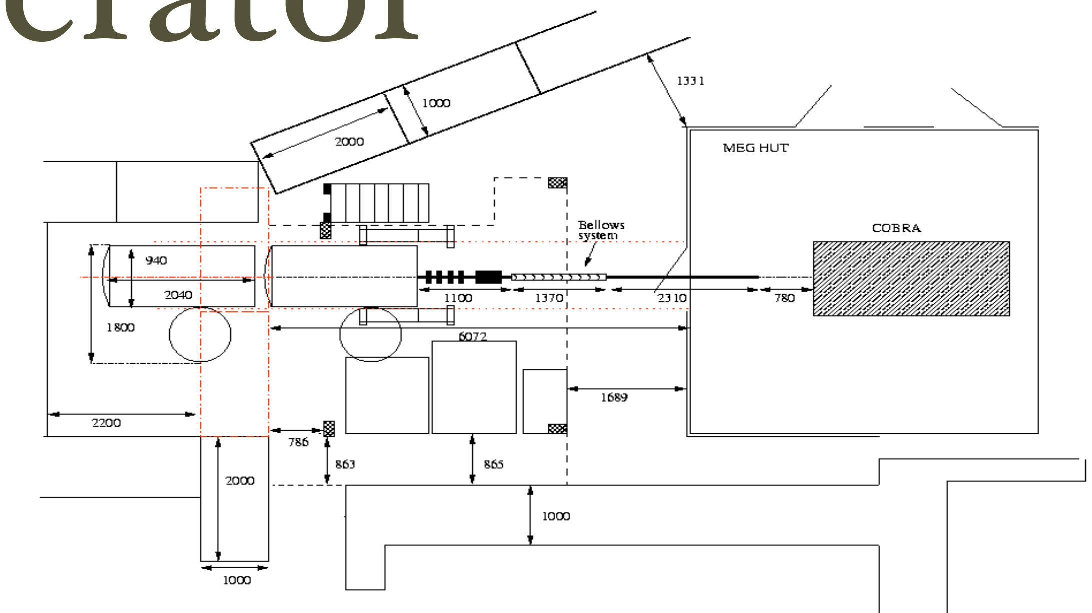


First Ver. Second Ver. Final Ver.



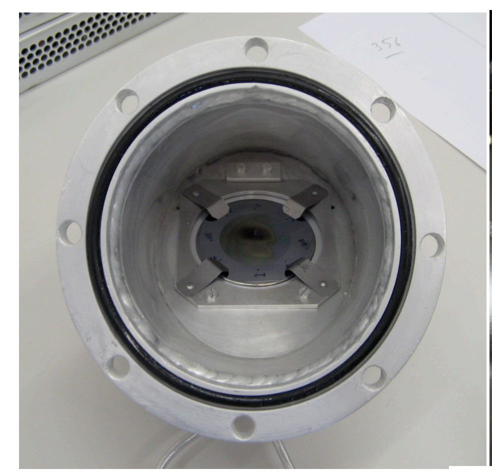


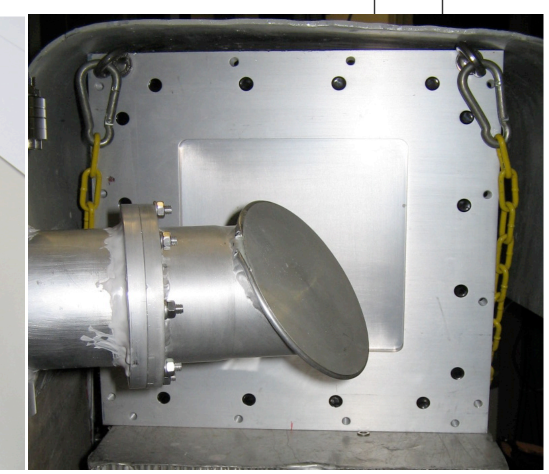
Proton accelerator



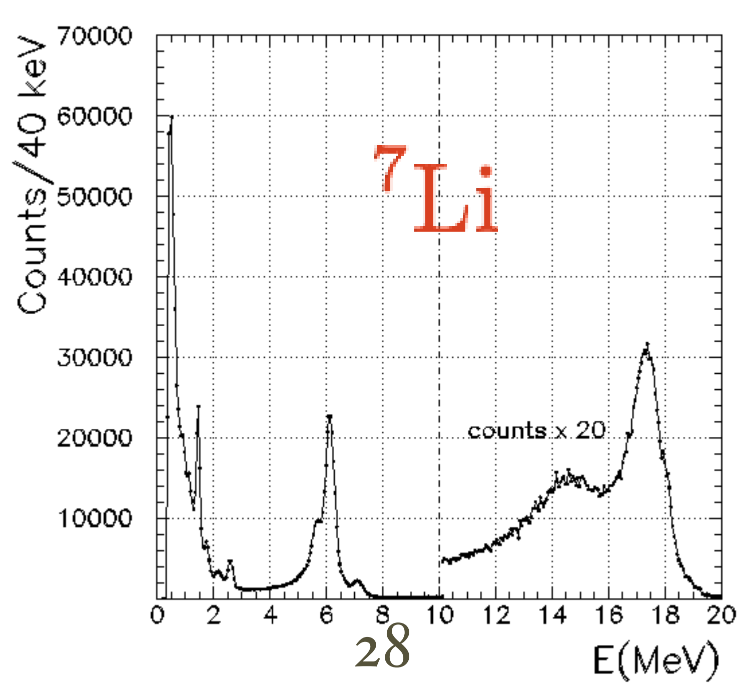
- Positioned opposite to the muon beam
- Essentially two reactions

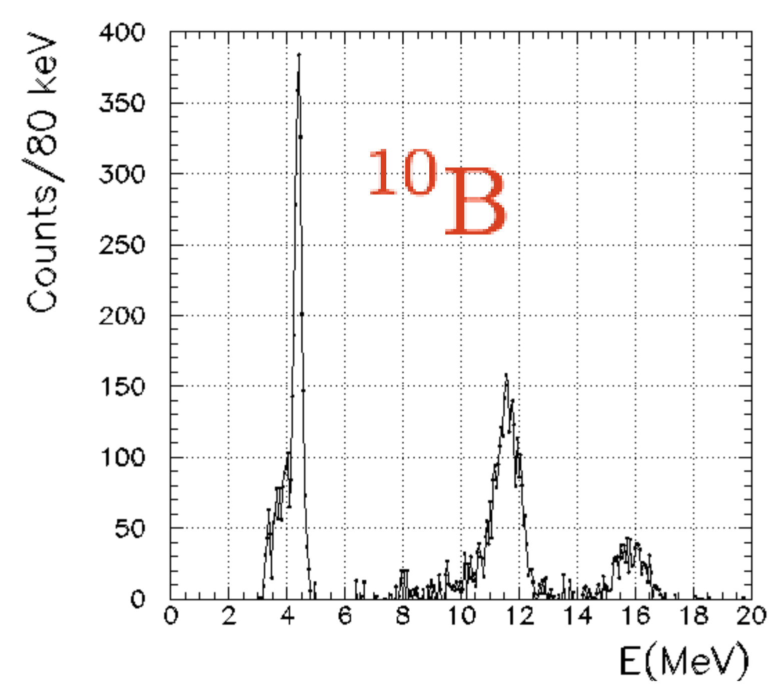
Reaction	*Resonance energy*	σ peak	γ-lines
Li(p,γ)Be	*440 keV*	5 mb	17.6 MeV, 14.6 MeV
B(p,γ)C	*163 keV*	$2\ 10^{-1}$ mb	4.4 MeV, 11.7 MeV, 16.1 MeV





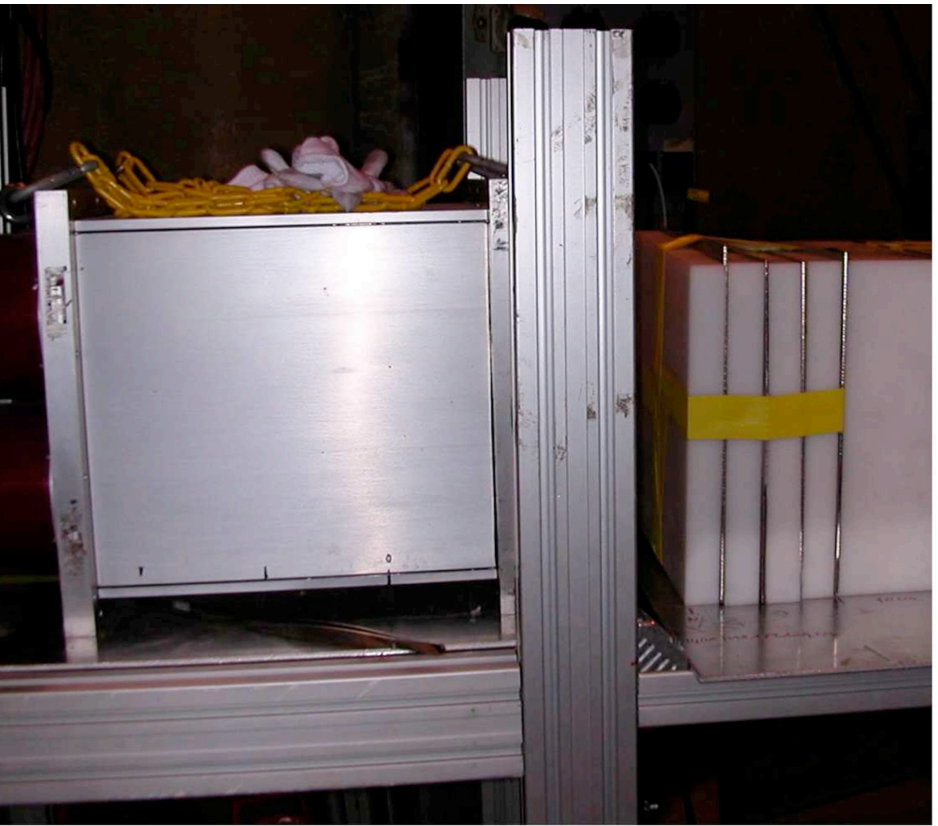
- tested at Legnaro (Italy) van de Graaf with a large NaI

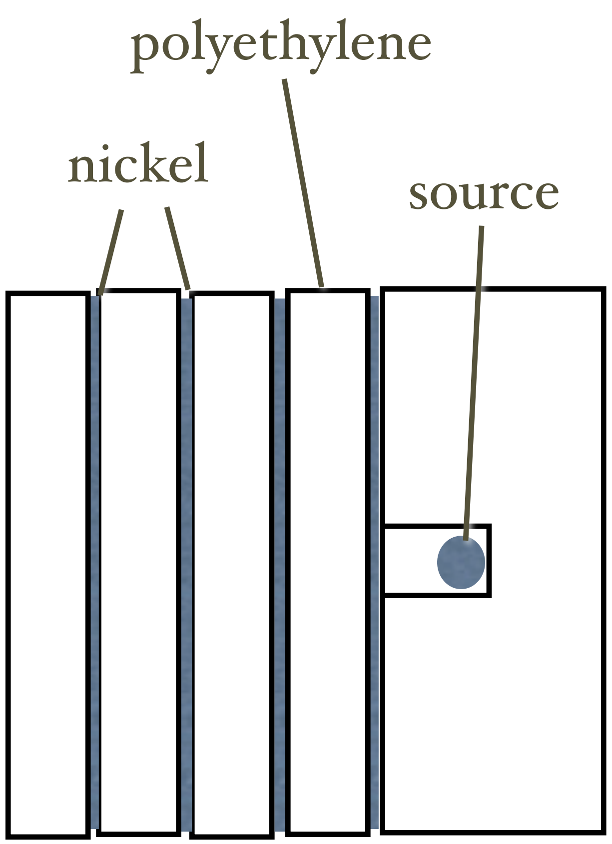


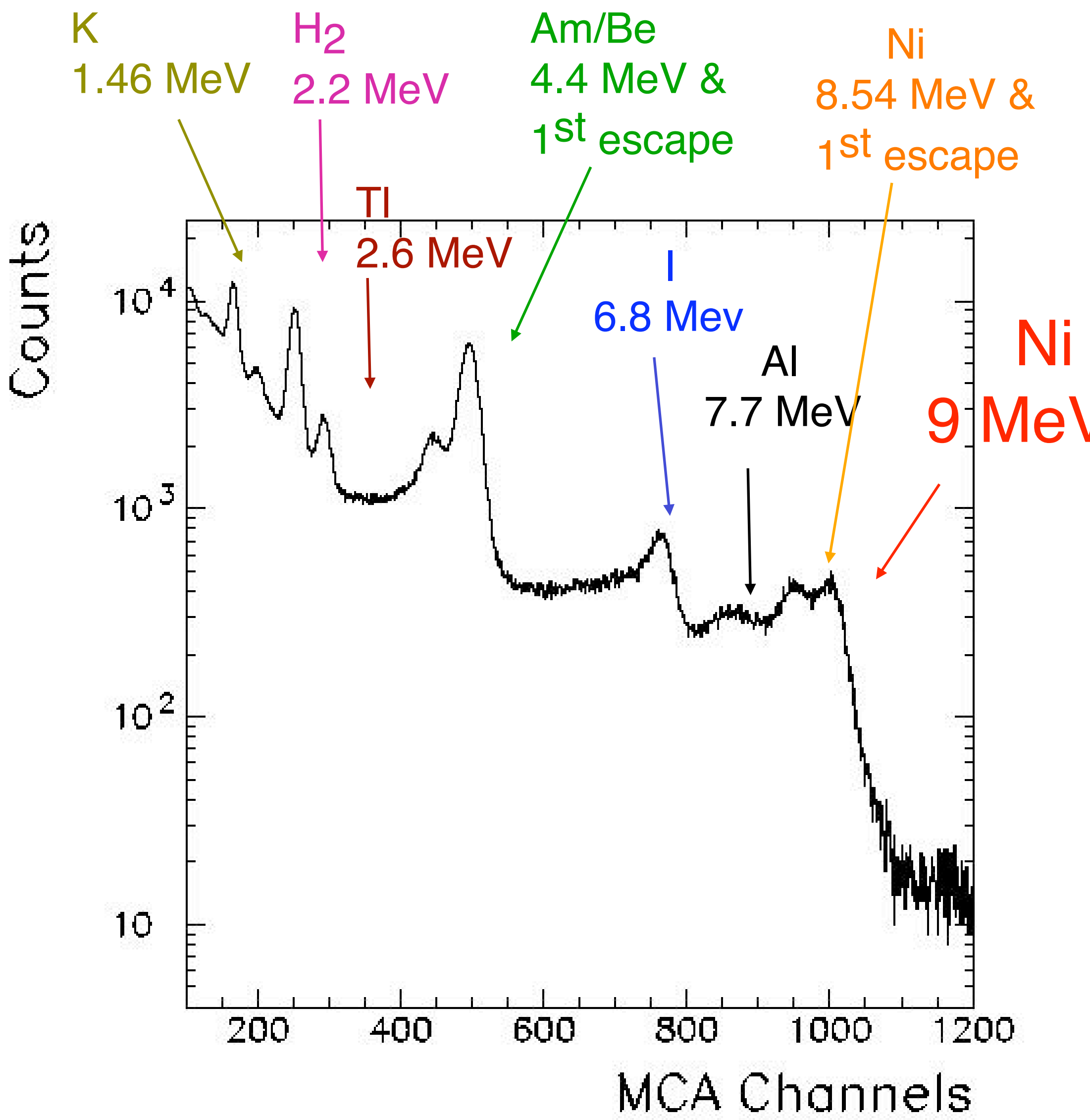


Neutron/Ni γ-line

- Reaction of thermal neutrons on Ni
- AmBe source inside a polyethylene/nickel sandwich (Cf)
- Tested with large NaI
- Will be placed behind the calorimeter







MEG sensitivity

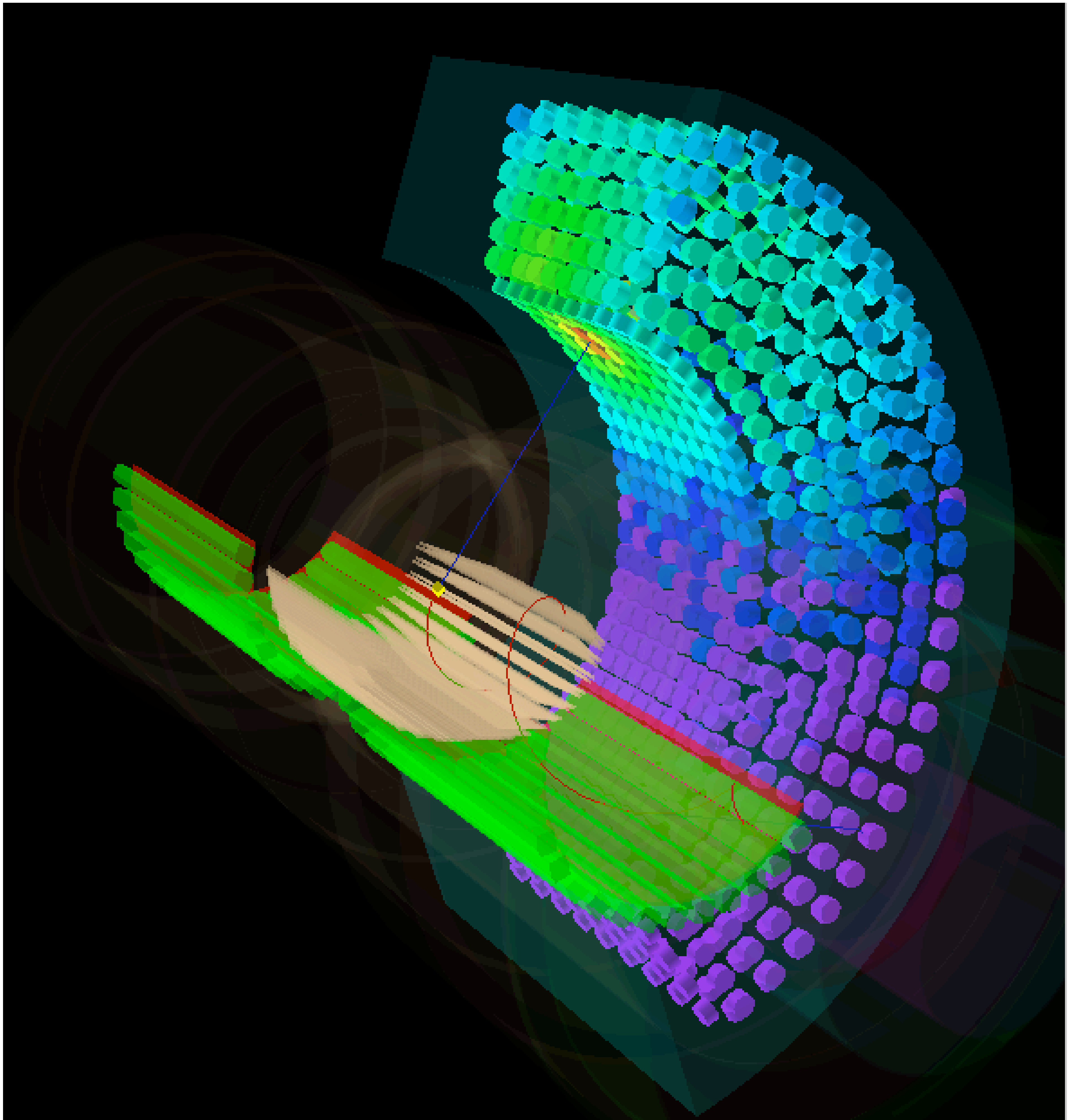
- Computation of the sensitivity based on the measured resolutions

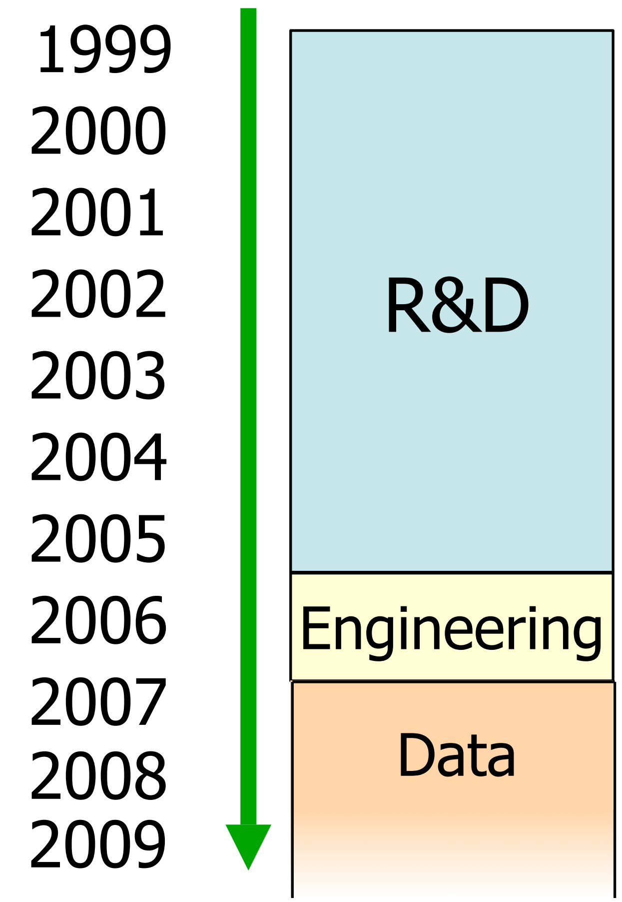
FWHM E_γ/E_γ	5 %
FWHM E_e/E_e	0.9 %
$\delta t_{e\gamma}$	105 ps
$\delta\theta_{e\gamma}$	23 mrad

- The resolutions determine the accidental background
- For a given background we choose R(μ) and running time.
  - BG = 0.5 events
  - R(μ) = 1.2 10^7 μ/sec
  - T = 3.5 10^7 sec (2 years running time)
  - ⇒SES = 6 10^{-14} (1.7 10^{13} muons observed)
- NO candidate ⇒ BR(μ→eγ) < 1.2 10^{-13} @ 90% CL
- Unlikely fluctuation (4 events) ⇒ BR(μ→eγ) ≈ 2.4 10^{-13}

Summary and Time Scale

- The experiment may provide a clean indication of New Physics or a strong constrain on SM extensions, complementary to proton decay searches
- Measurements and detector simulation make us confident that we can reach the SES of 6×10^{-14} to $\mu \rightarrow e\gamma$ (BR = $1.2\ 10^{-13}$)
- Final prototypes of all sub-detectors were measured
  - Liquid Xe calorimeter Large Prototype
  - Chambers
  - Timing counters
  - Trigger/DAQ
- Detector assembly during end 2006 engineering run end 2006 - beg. 2007





Plans

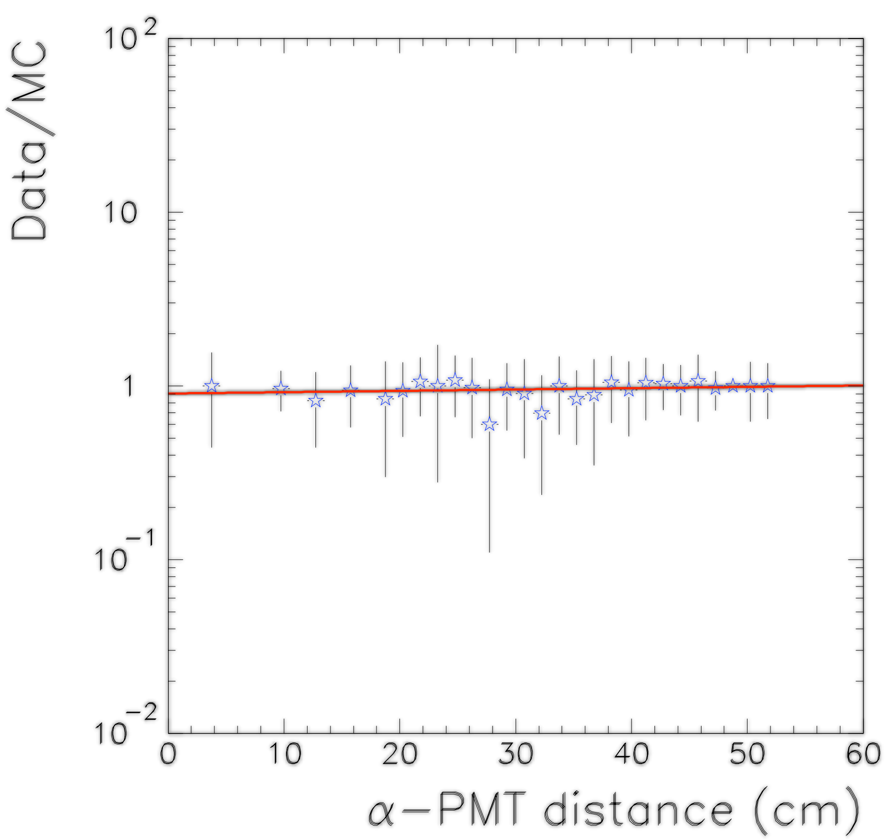
- Data taking from 2007 on to reach 10^{-13} sensitivity (90% CL)
- Obtain a “significant” result before the LHC era
- Eventual reach 10^{-14} during LHC era

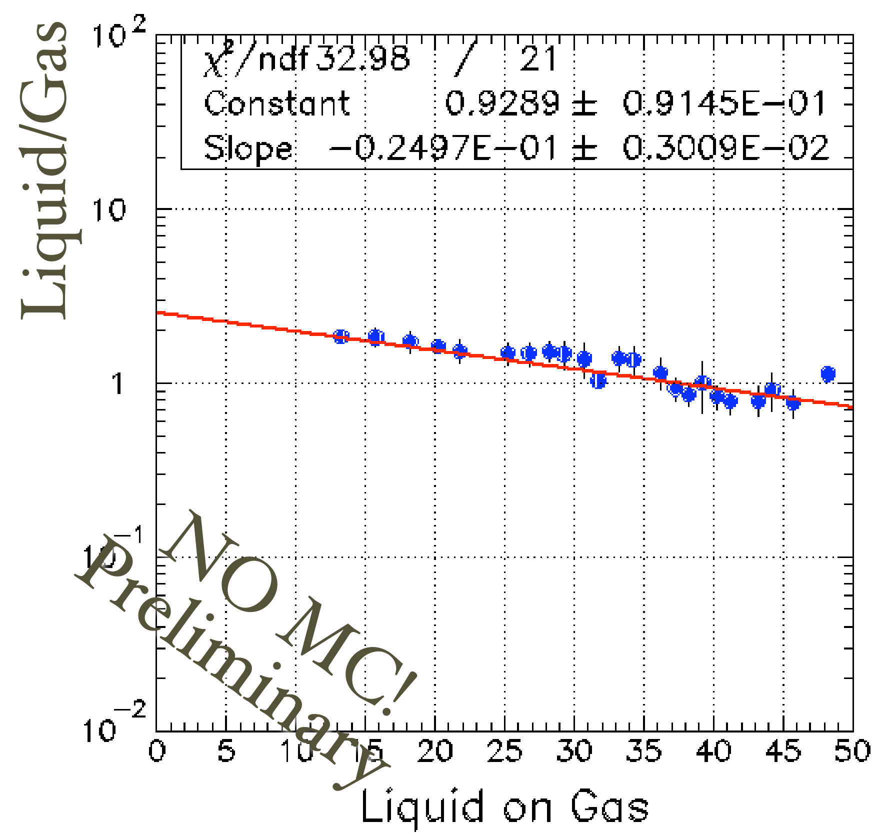
Back-up slides

- LP Energy resolution as a function of the position
- LP position resolution
- Xe scintillation mechanism
- Xe absorption
- Xe lambda Abs measurement
- Liquid phase purification
- DAQ, DRS
- Trigger

λ_{Abs} measurement

- It is possible to estimate a lower limit on the xenon absorption length
- Typical plots shown
  - $\lambda_{Abs} > 125$ cm (68% CL) or $\lambda_{Abs} > 95$ cm (95 % CL)
  - LY ~ 37500 scintillation photons/MeV (0.9 NaI)





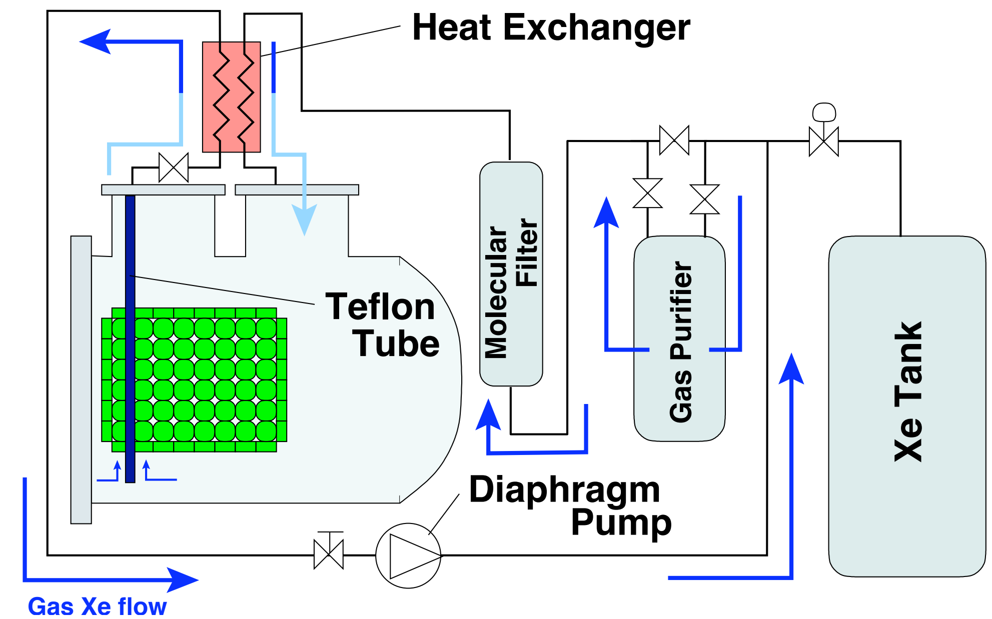
Attenuation = Rayleigh

$\lambda_{Att} \sim 40$ cm

L.Y.(liquid) $\sim 3 \times$ L.Y.(gas)

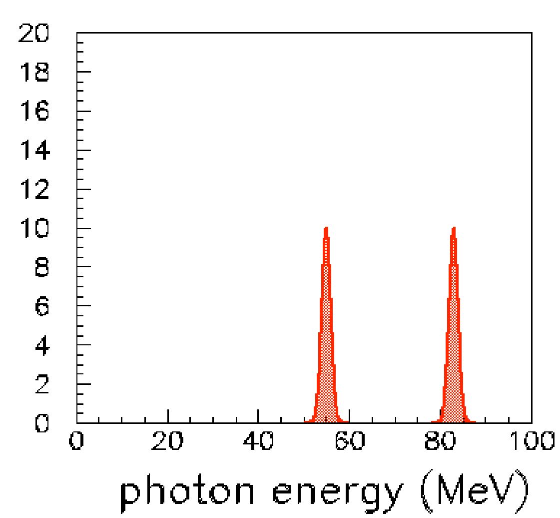
LXe calorimeter R&D

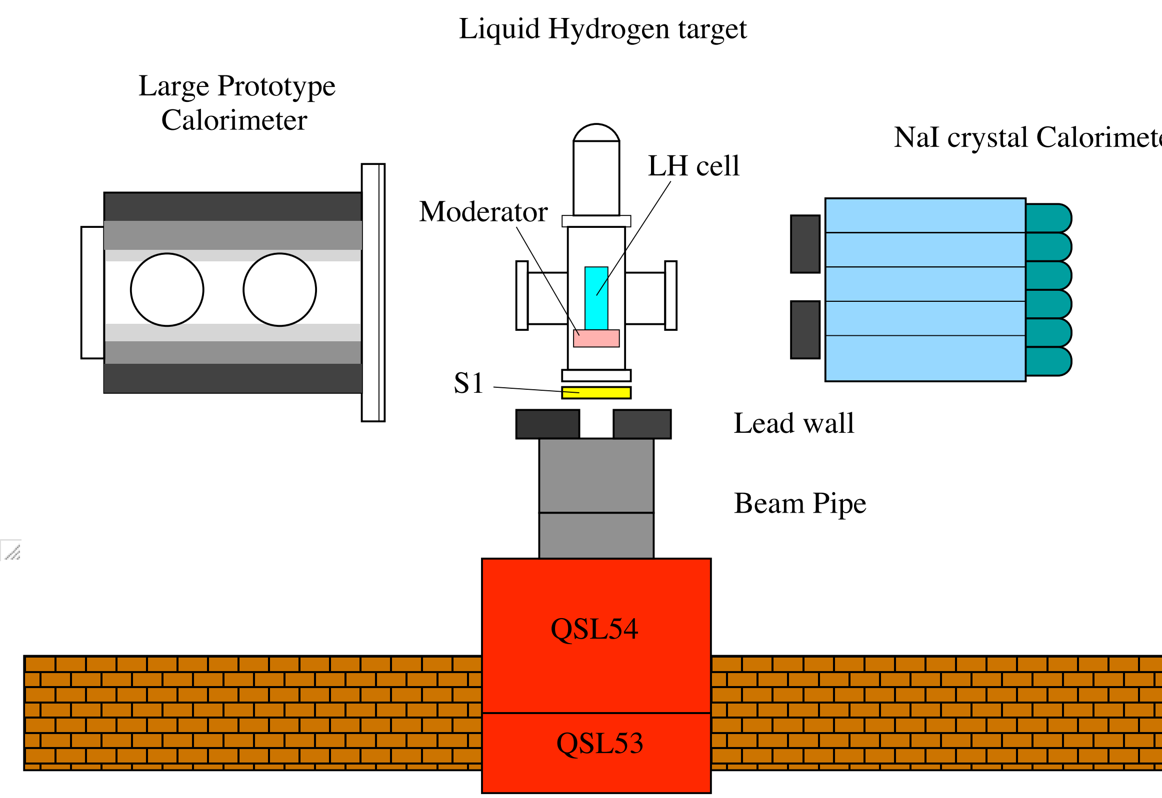
- Energy resolution strongly depends on absorption. A long R&D to insure L(Abs)>3 m with a circulation/purification system
- Measurement of energy and timing resolution with high energy photons: 55 MeV photons from pion charge exchange reaction



$$\pi^- p \rightarrow \pi^0 n$$
$$\pi^0 \rightarrow \gamma\gamma$$

Lab Frame

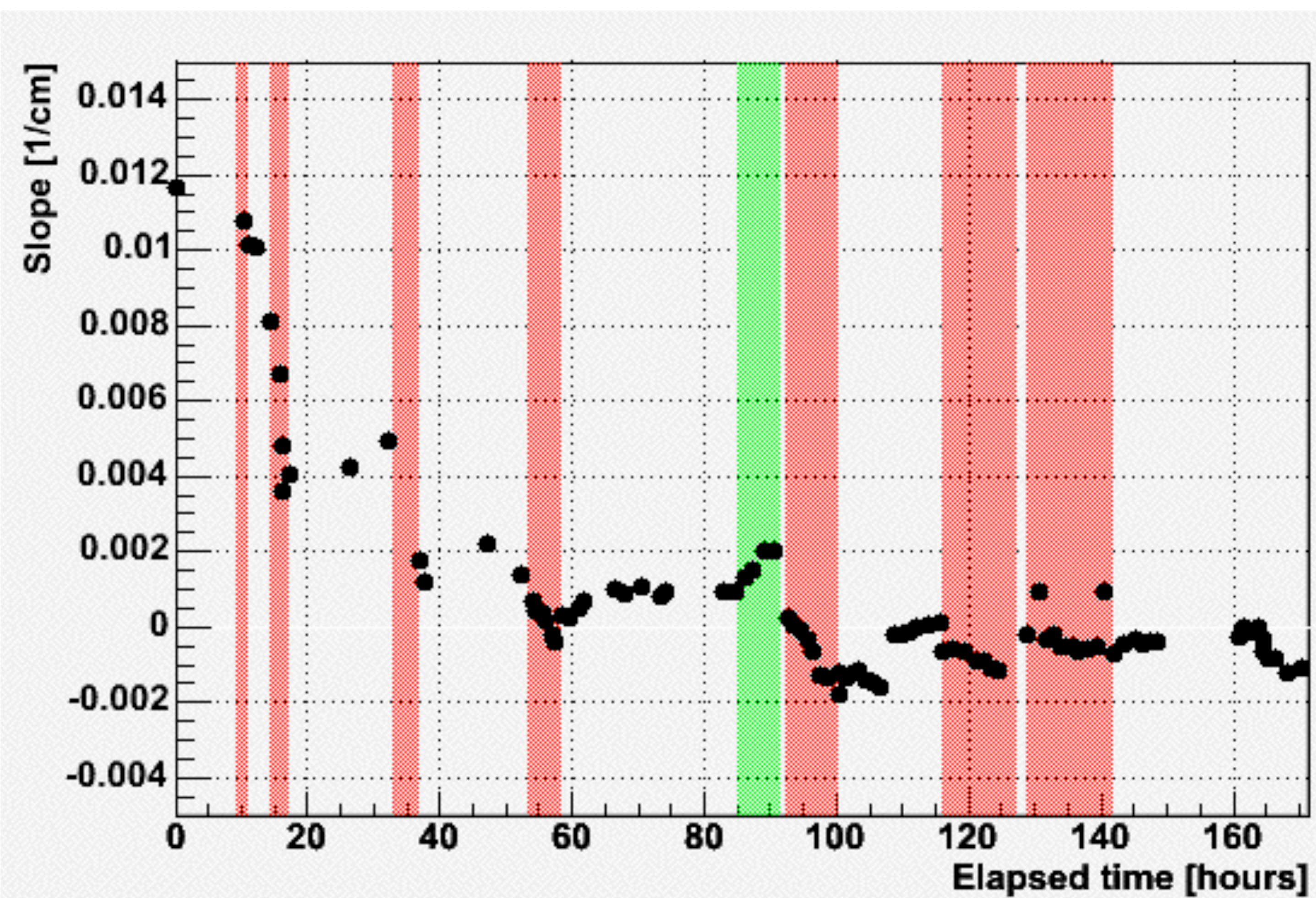


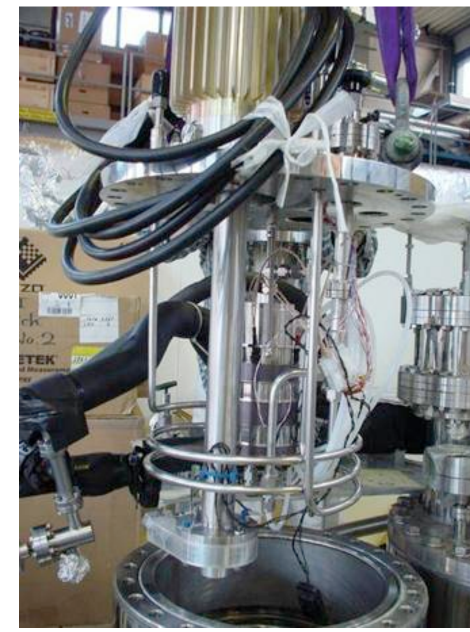


Two tests in 2003 and 2004 demonstrated the calibration procedure and the resolutions

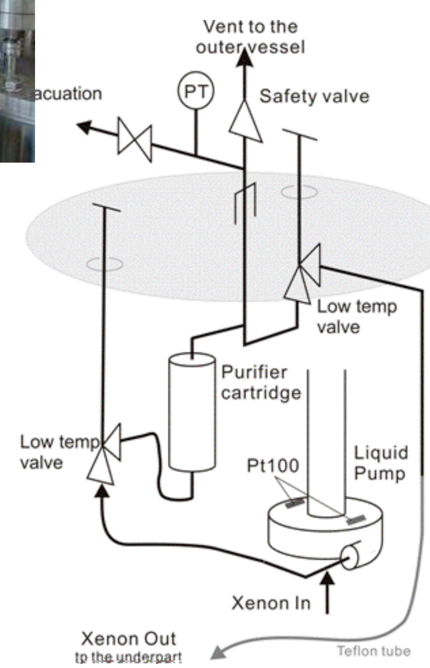
Liquid phase purification

- Xenon circulation in liquid phase.
- Impurity (water) is removed by a purifier cartridge filled with molecular sieves.
- 100 l/hour circulation.





molecular sieve 13X
25g water

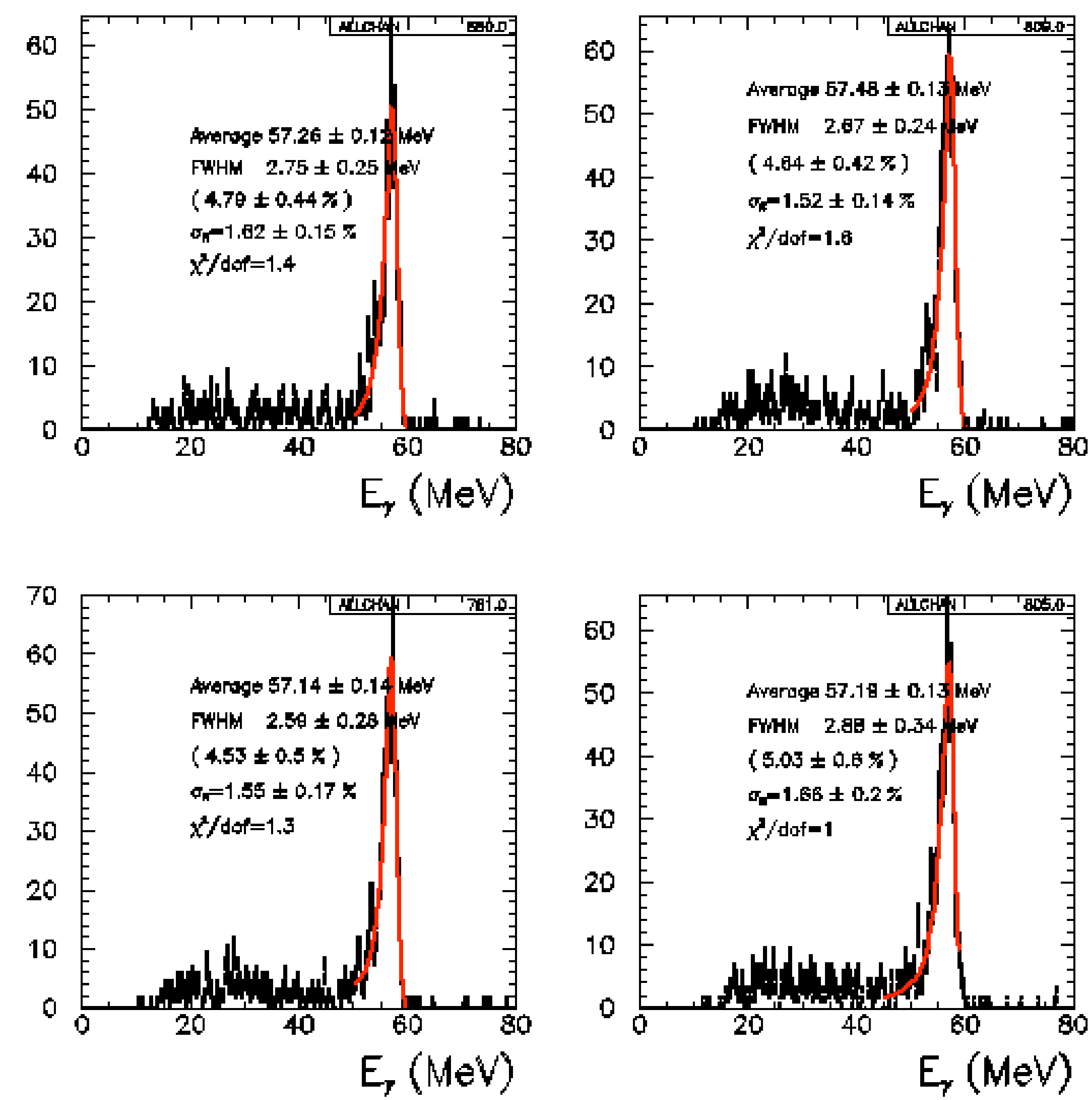


- Cryogenic fluid pump
  - Barber-Nicols BNCP-62-000
  - Flow rate: 100L/hr in liquid (design)
  - Rot. speed: 3175rpm

Position dependence

- small FWHM residual dependence
- no significant peak shift
- The resolution is always better than 5% FWHM

4.8%	4.6%
4.5%	5.0%



Trigger Electronics

- 100 MHz waveform digitizer on VME boards that perform online pedestal subtraction
- Uses :
  - γ energy
  - e^+ - γ time coincidence
  - e^+ - γ collinearity
- Built on a FADC-FPGA architecture
- More performing algorithms could be implemented

❖ Beam rate $10^8\ s^{-1}$

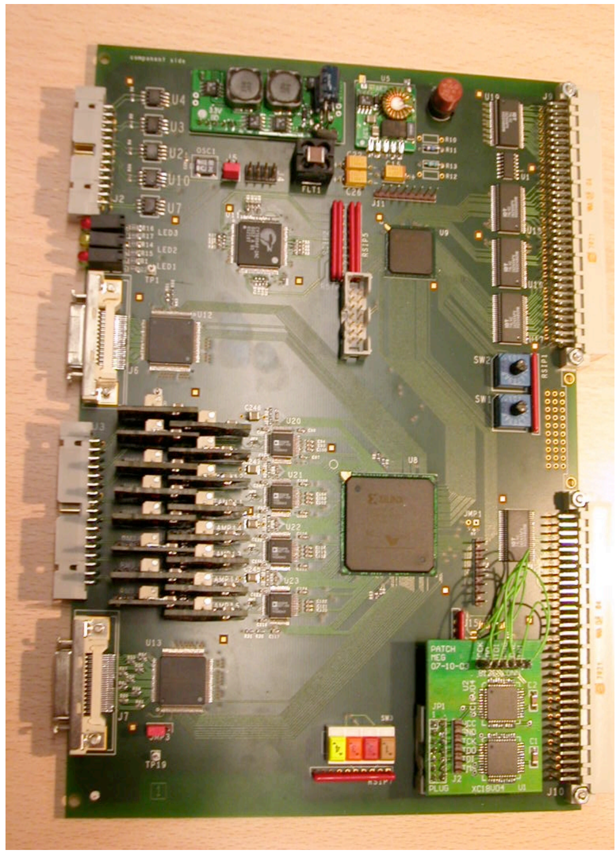
❖ Fast LXe energy sum > 45MeV $2\times10^3\ s^{-1}$

gamma interaction point (PMT of max charge)

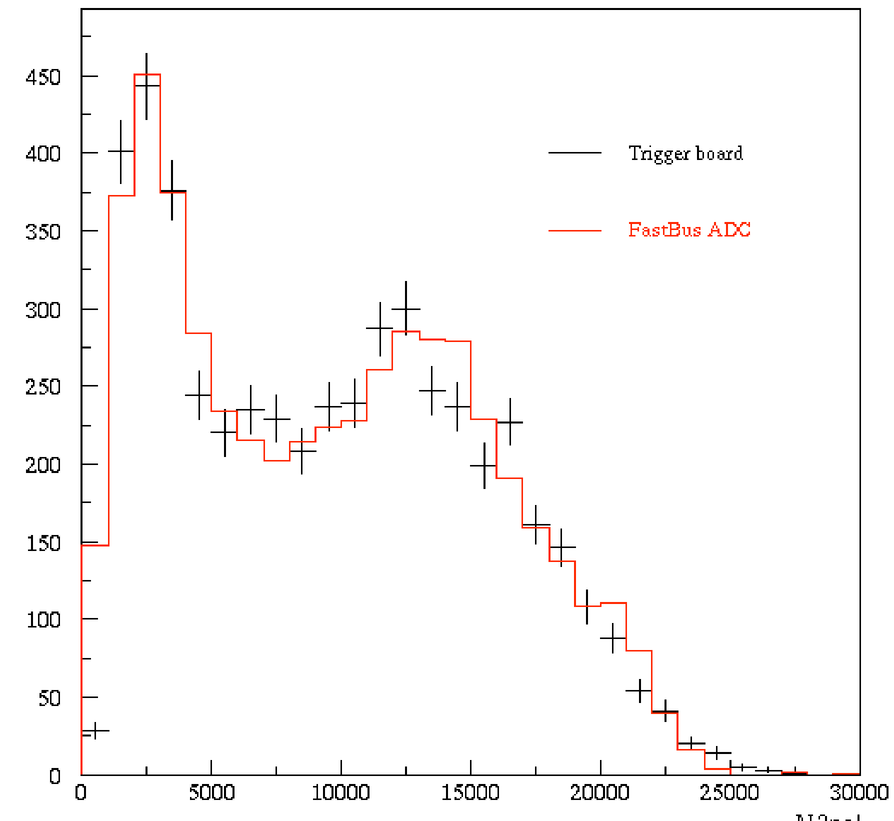
e^+ hit point in timing counter

❖ time correlation γ – e^+ 200 s^{-1}

❖ angular correlation γ – e^+ 20 s^{-1}

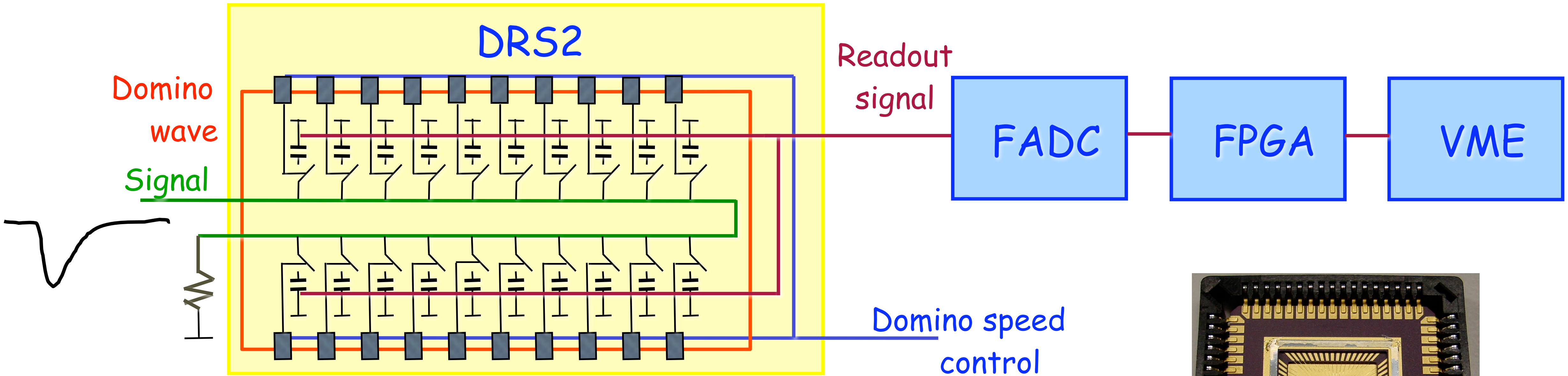


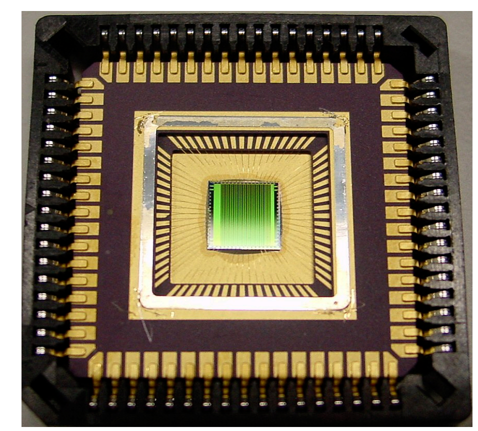
- Prototype system has been successfully tested on the LP
- Design of the final system is in progress
- π° data
- Charge spectrum
- Only 32 PMT



Readout electronics

2.5 GHz Waveform digitization for all channels

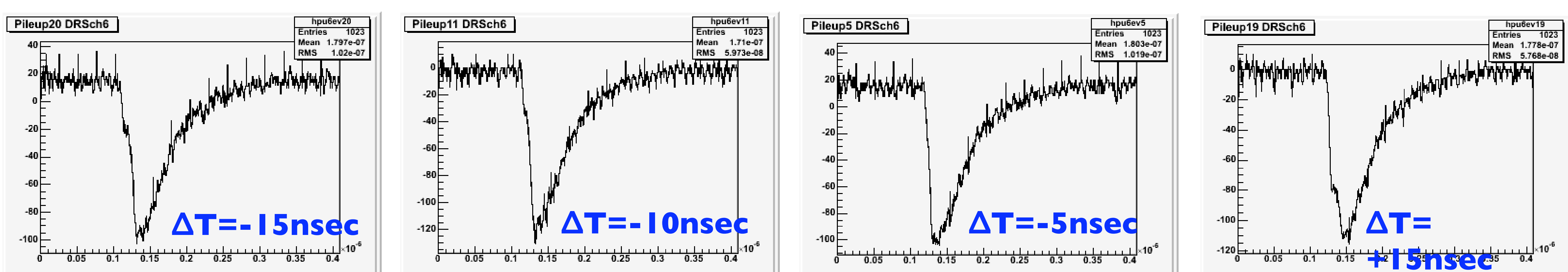




DRS2 chip (Domino Ring Sampler)

- Custom sampling chip designed at PSI
- 2.5 GHz sampling speed @ 40 ps timing resolution
- Sampling depth 1024 bins for 8 channels/chip
- Data taken in charge exchange test to study pile-up rejection algorithms

Original



Scintillation process in Xe

Xe + radiation

excitation → Xe^*

ionization → Xe^+

Xe^+ + Xe

recombination

$Xe_2^+ + e^-$

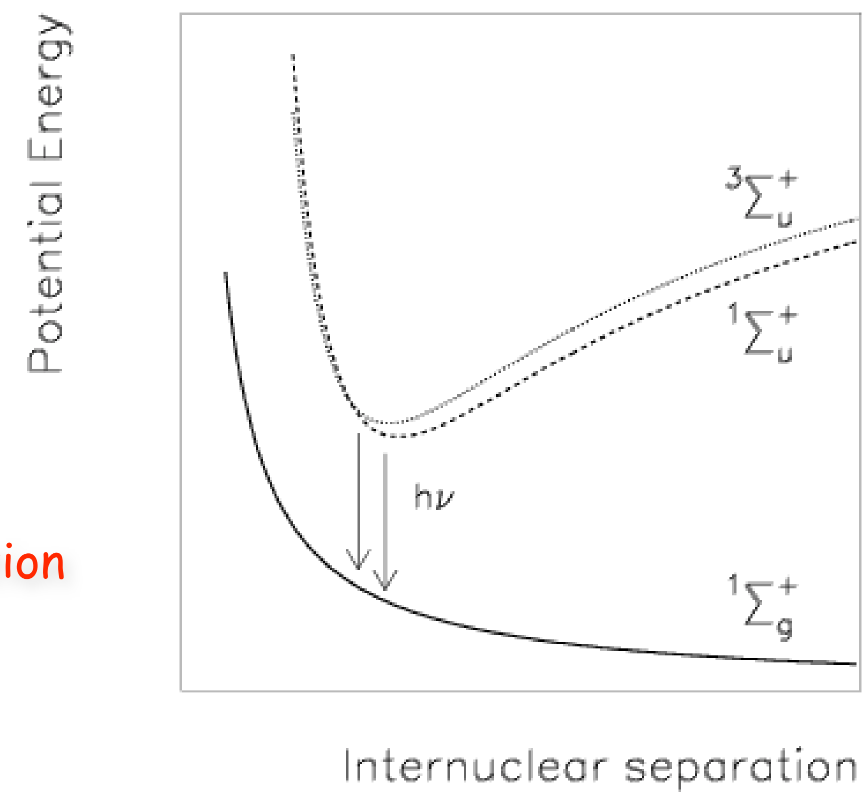
Xe + Xe^{**}

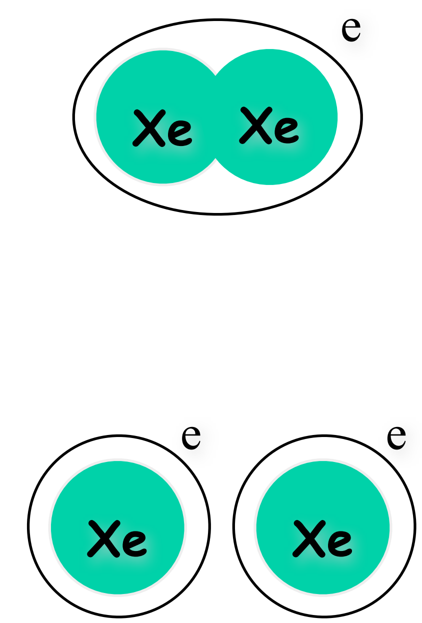
$Xe^{**} \rightarrow Xe^*$

Xe^* + Xe

excimer Xe_2^* scintillation photon (175 nm, 14 nm FWHM)

2Xe + hv





$\tau_{singlet}$= 4.2 ns

$\tau_{triplet}$= 22 ns

τ_{recomb}= 45 ns

Position resolution