The MEG experiment at PSI

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for the MEG collaboration

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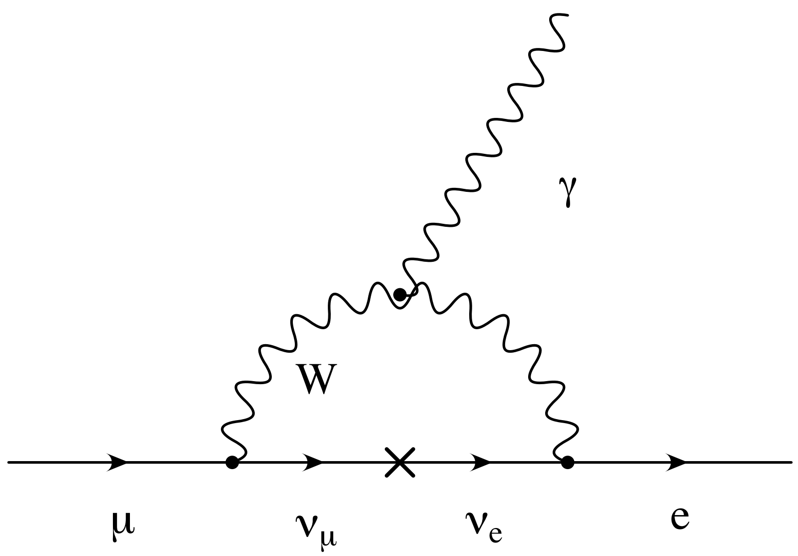
Outline

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

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

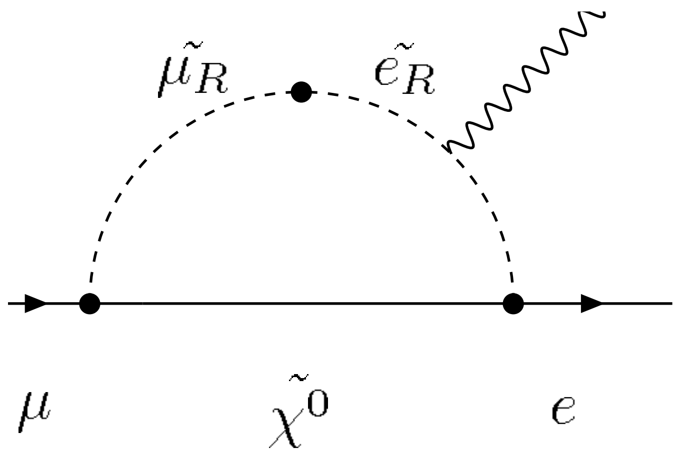


$$\Gamma(\mu \to e\gamma) \approx \frac{G_F^2 m_\mu^5}{192\pi^3}\left(\frac{\alpha}{2\pi}\right)\sin^2 2\theta sin^2\left(\frac{1.27\Delta m^2}{M_W^2}\right)$$

BR~ 10^{-55}

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

For instance... predictions



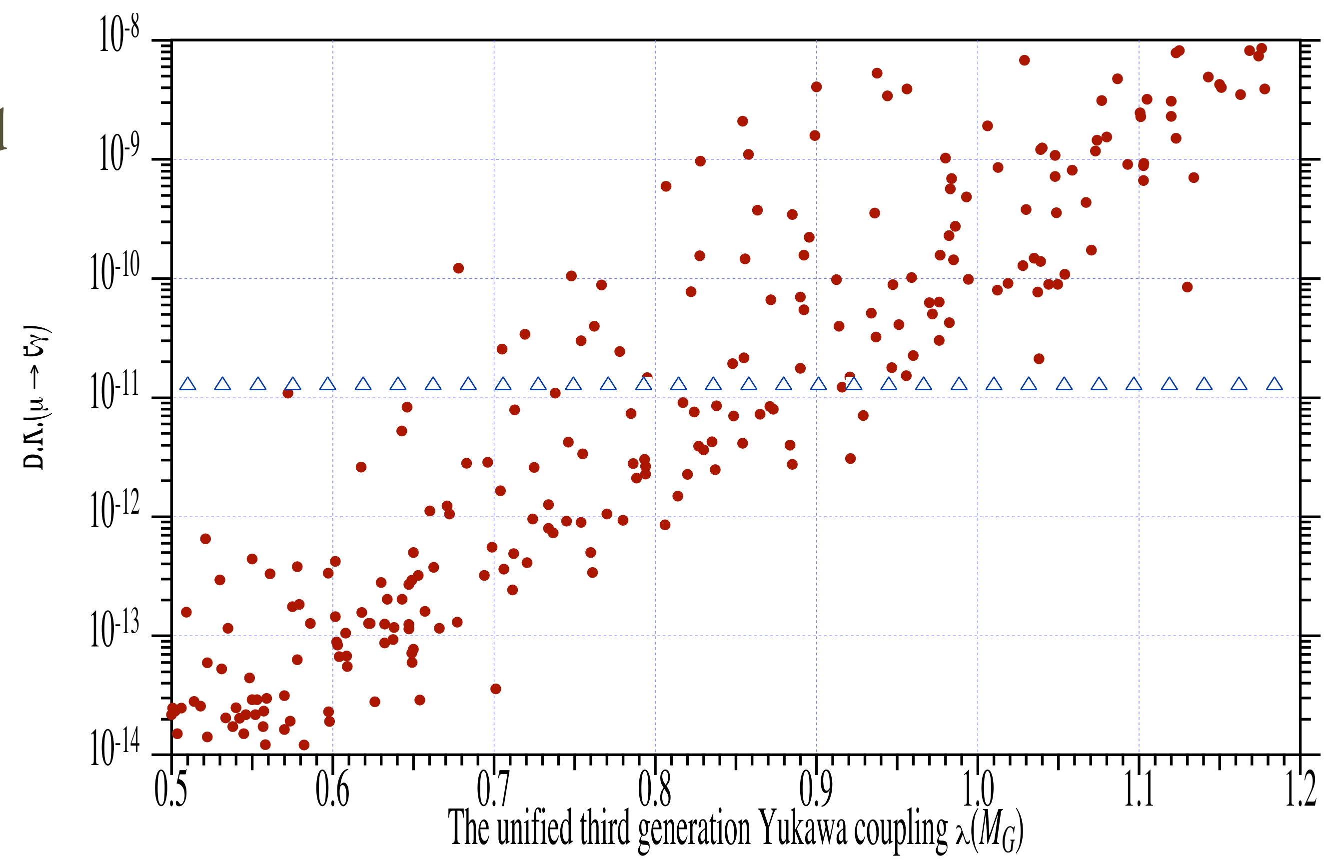
R. Barbieri et al.,Nucl. Phys. B445(1995) 215

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

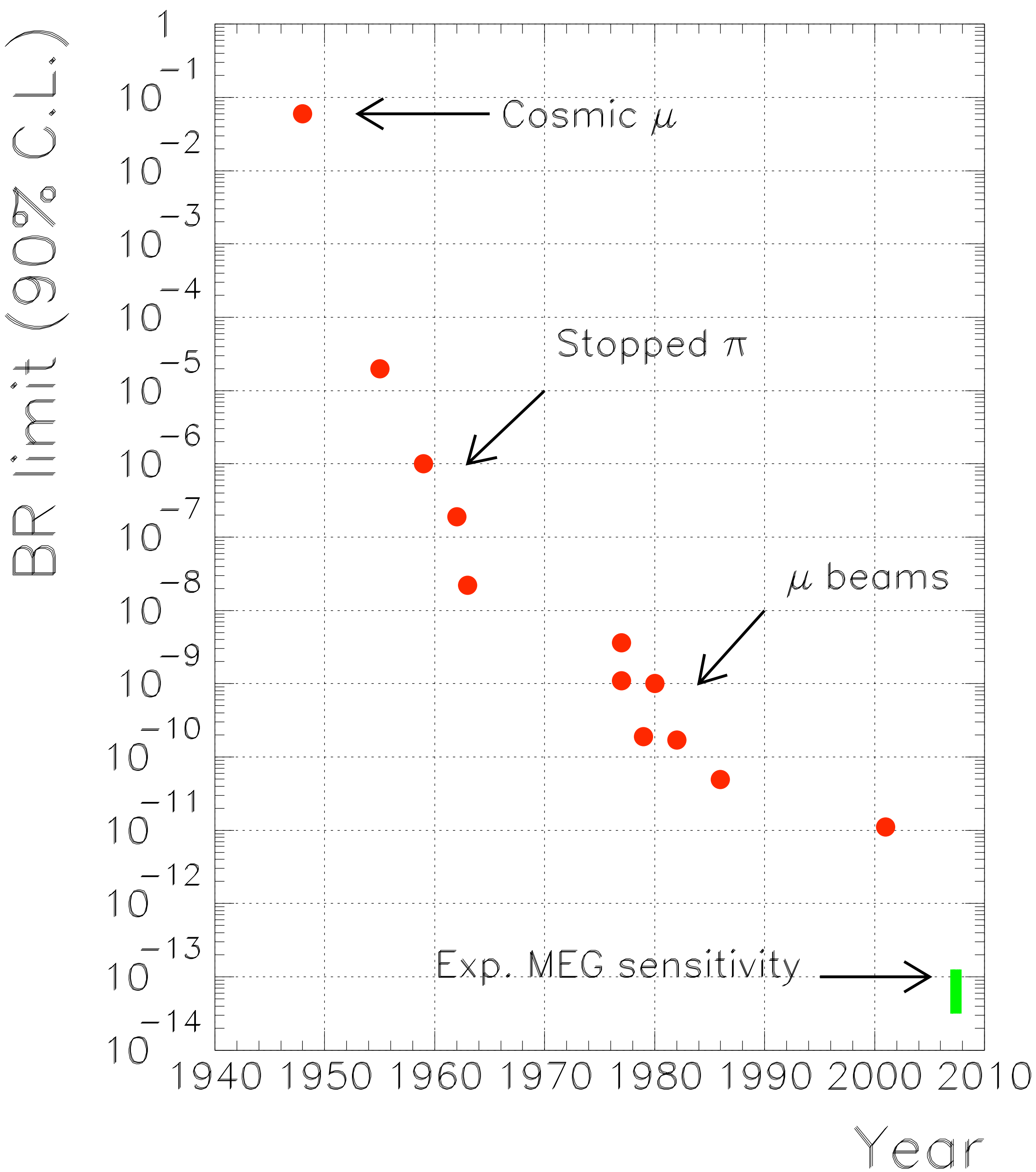
R. Ciafaloni, A. Romanino, A. Strumia, Nucl. Phys. B458 (1996)

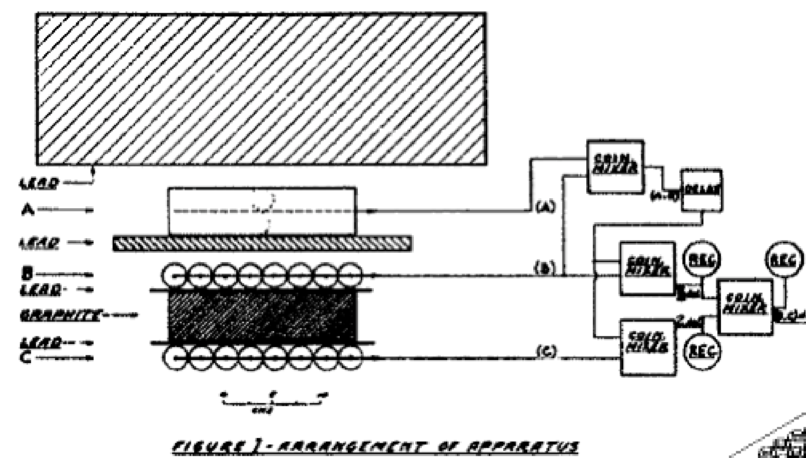
J. Hisano, N. Nomura, Phys. Rev. D59 (1999)

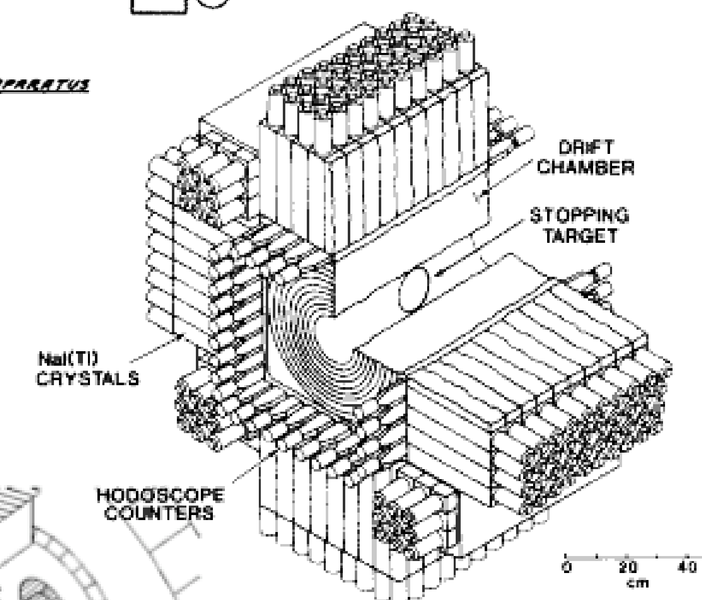
- SUSY SU(5) predictions: LFV induced by finite slepton mixing through radiative corrections. The mixing could be large due to the top-quark mass at a level of 10-12 10-15
- SO(10) predicts even larger BR:
  - m(τ)/m(μ) enhancement
- Models with right-handed neutrinos also predict large BR
- ⇒ clear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

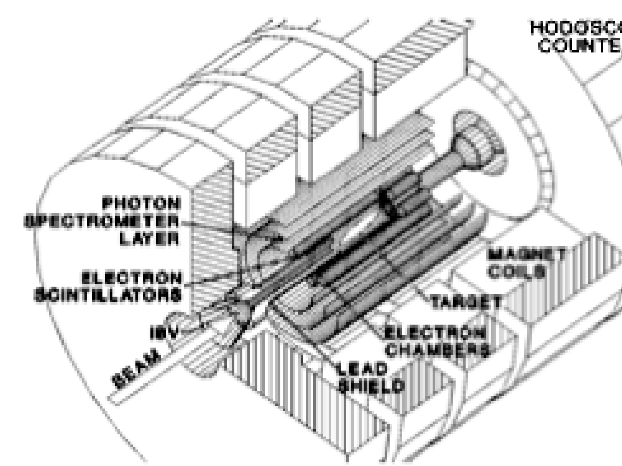


Historical perspective





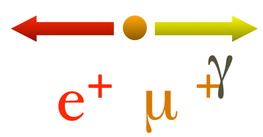


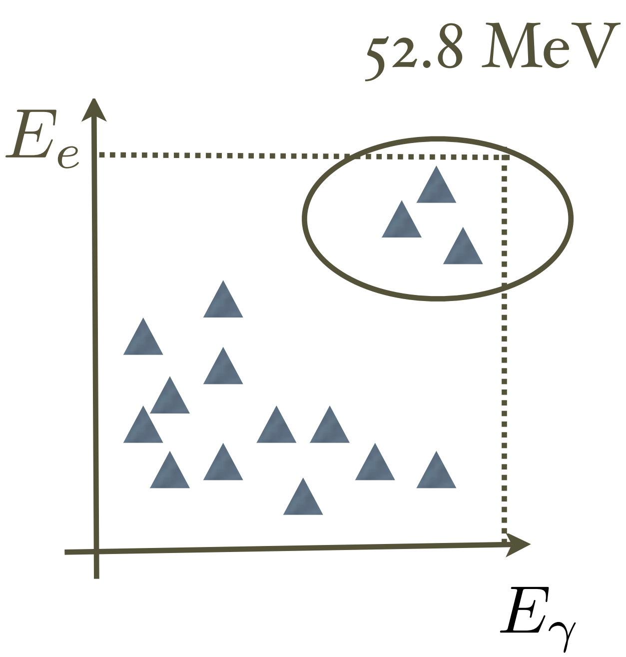


Each improvement linked to an improvement in the technology

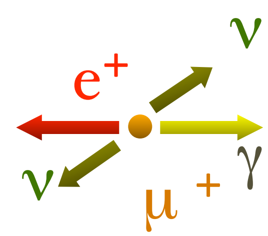
Signal and Background

"Signal"



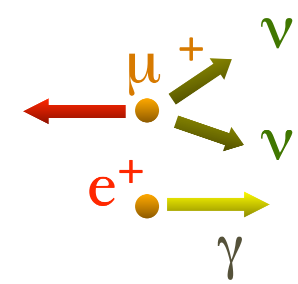


"Prompt"



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

"Accidental"



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

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

$e\mathcal{N} \to e\mathcal{N}\gamma$

$e^+e^- \to \gamma\gamma$

$B_{Prompt} \sim 0.1 * B_{acc}$ $\quad$ $B_{acc} \sim R_\mu \, \Delta E_e \, \Delta E_\gamma^2 \, \Delta\theta^2 \, \Delta t$

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

Required Performances

- To achieve such a stringent limit the performance of each subdetector must be pushed to the limit

		FWHM						
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 x 105	100	3.6 x 10-9
TRIUMF	1977	10	8.7	6.7	-	2 x 105	100	1 x 10-9
LANL	1979	8.8	8	1.9	37	2.4 x 105	6.4	1.7 x 10-10
Crystal Box	1986	8	8	1.3	87	4 x 105	(6..9)	4.9 x 10-11
MEGA	1999	1.2	4.5	1.6	17	2.5 x 108	(6..7)	1.2 x 10-11
MEG	2006	0.8	4	0.15	19	2.5 x 107	100	1 x 10-13

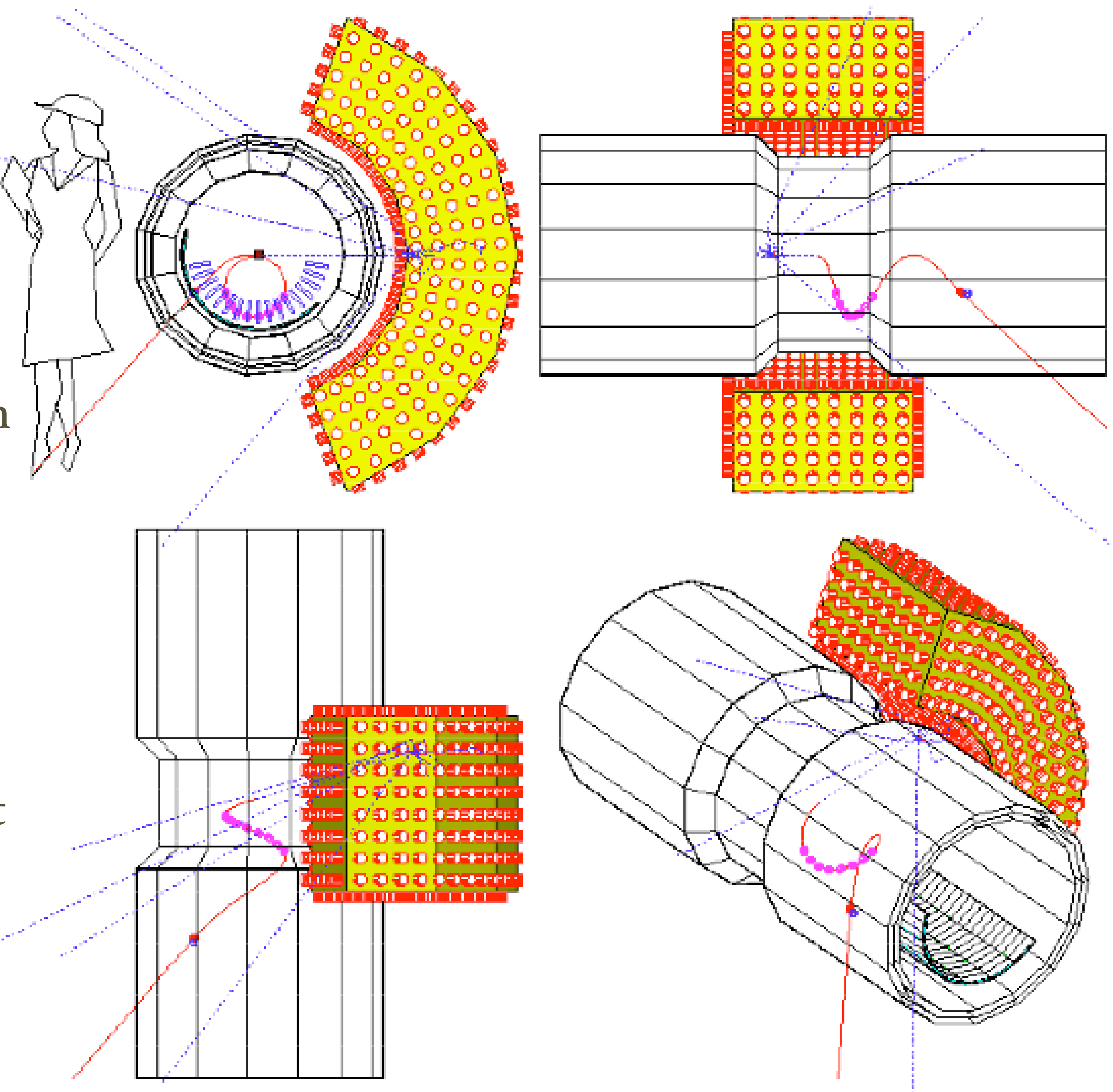
Stopped μ-beam: up to 10^8 μ /sec

The presently most intense continuous muon beam in the world, PSI (CH) is brought to rest in a 100 μm mylar target

Solenoid spectrometer & drift chambers

Timing Counter for e+ timing

Liquid Xenon calorimeter for γ detection (scintillation)

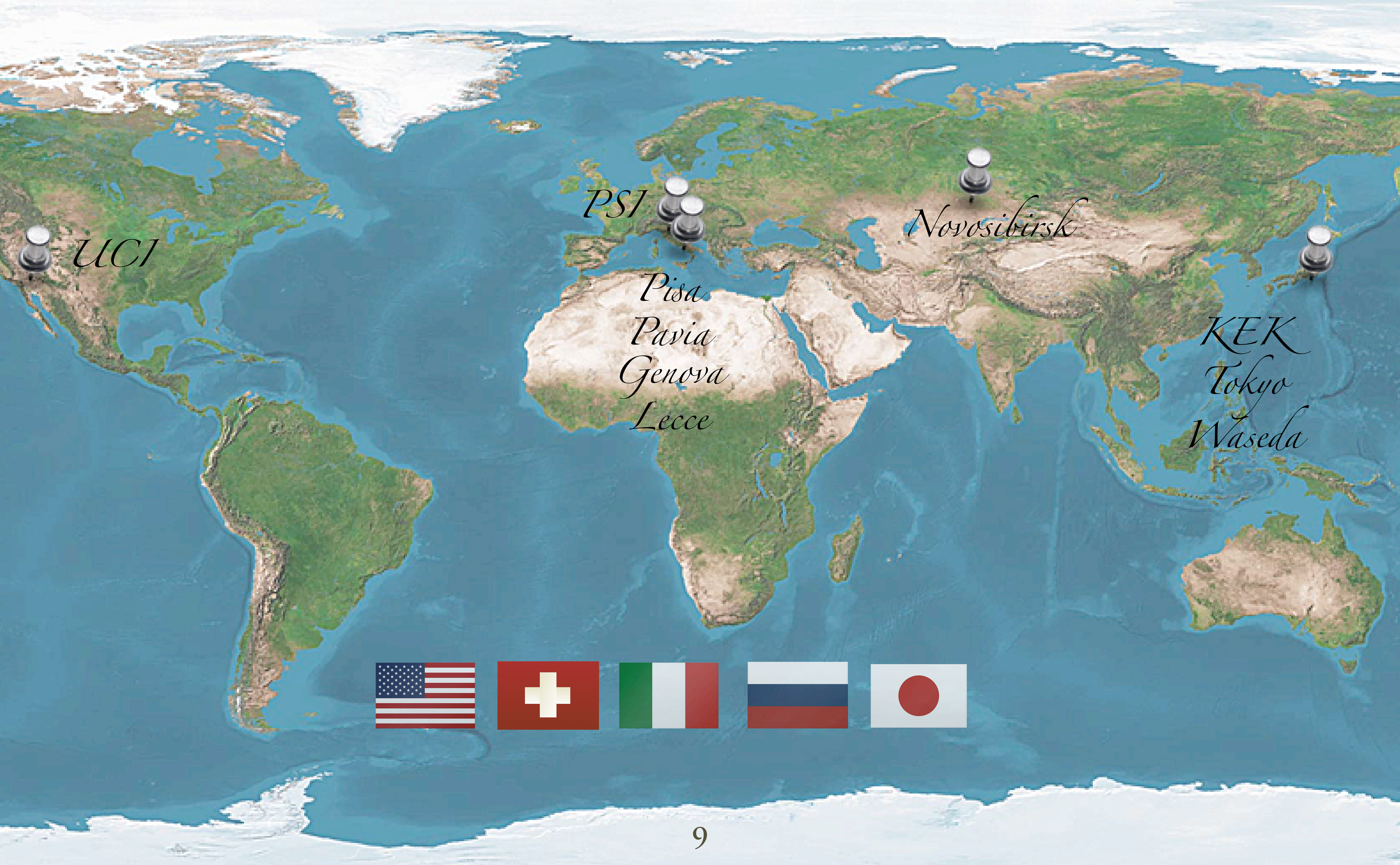


View of a Monte Carlo simulated event: the photons enters the LXe calorimeter and the positron is measured by the drift chambers + timing counters.

Positron: energy, Momentum and timing

Photon: energy, direction and timing

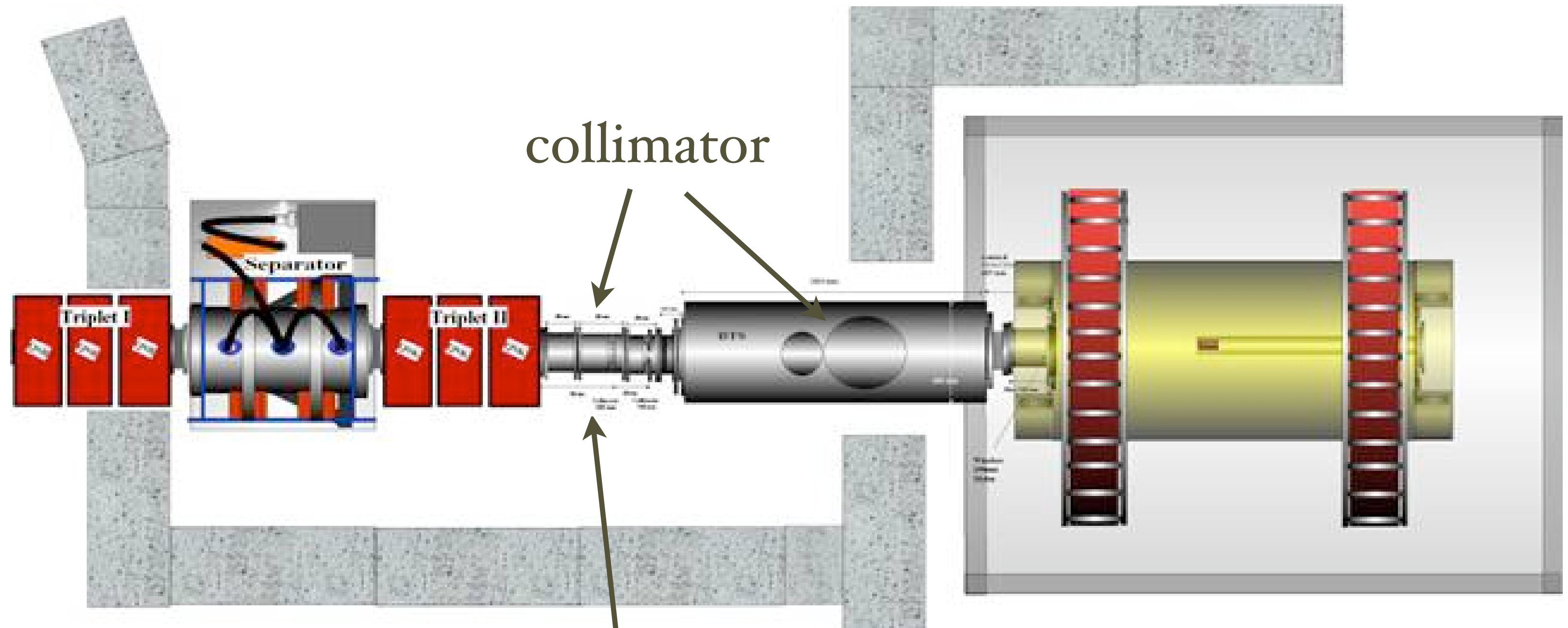
The MEG Collaboration



Beam line & target

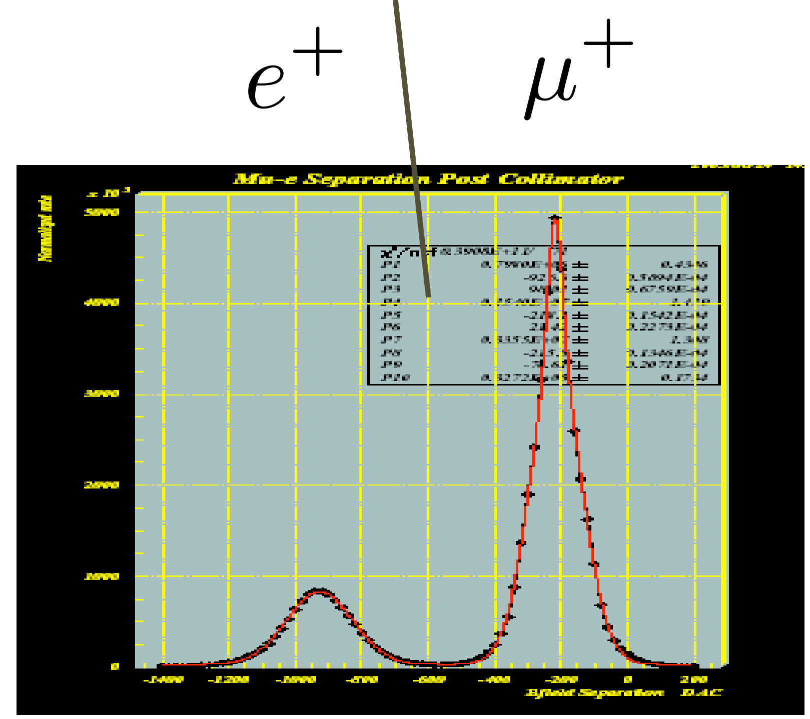
Optimisation of the beam elements:

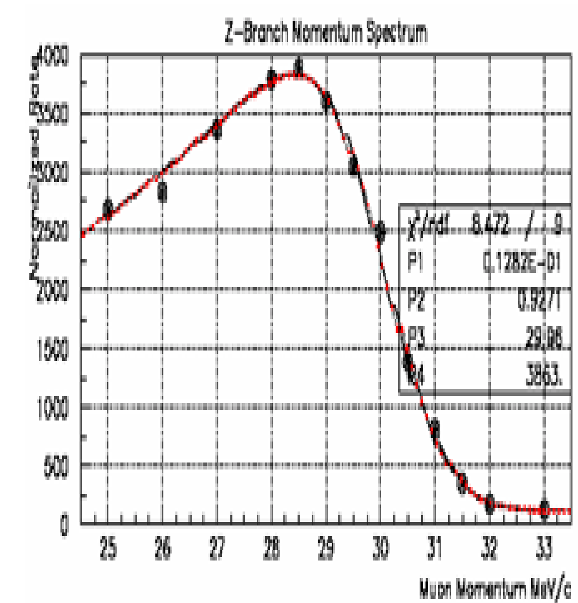
- Muon momentum ~ 29 MeV/c
- Wien filter for μ/e separation
- Solenoid to couple beam and spectrometer
- Degrader to reduce the momentum for a 150 μm target



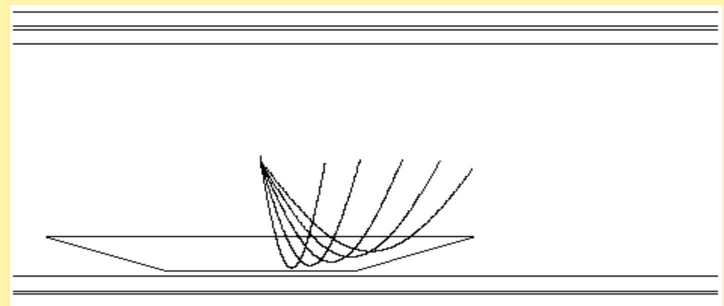
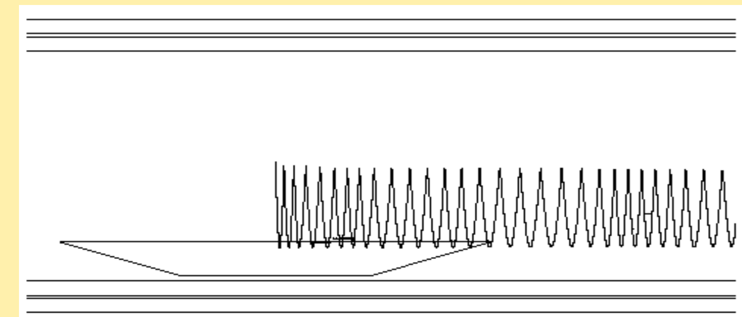
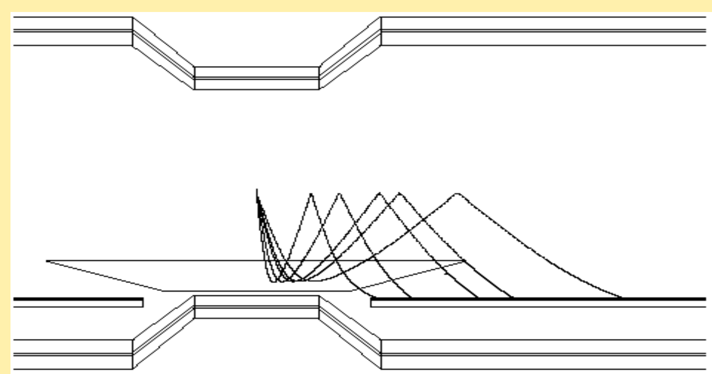
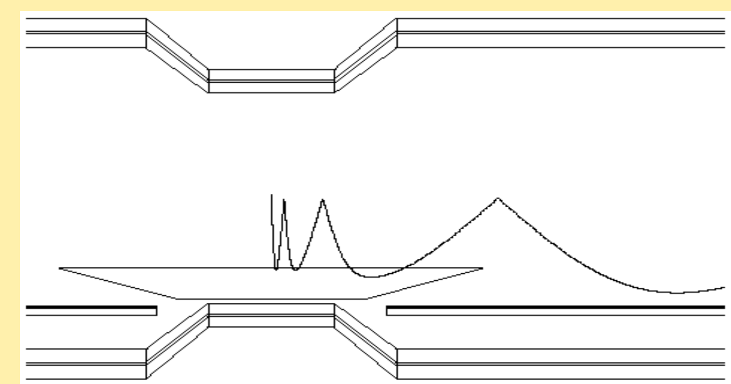
Present results (1.8 mA):

- Rμ (total) 1.3*10^8 μ$^+$/s
- Rμ (after Triplet 2) 9.4*10^7 μ$^+$/s
- μ/e separation 11.8 cm (7.2 σ)
- Rμ (exp. on target) 6.4*10^7 μ$^+$/s
- μ spot (exp. on target) $\sigma_V \approx \sigma_H \approx$ 10 mm

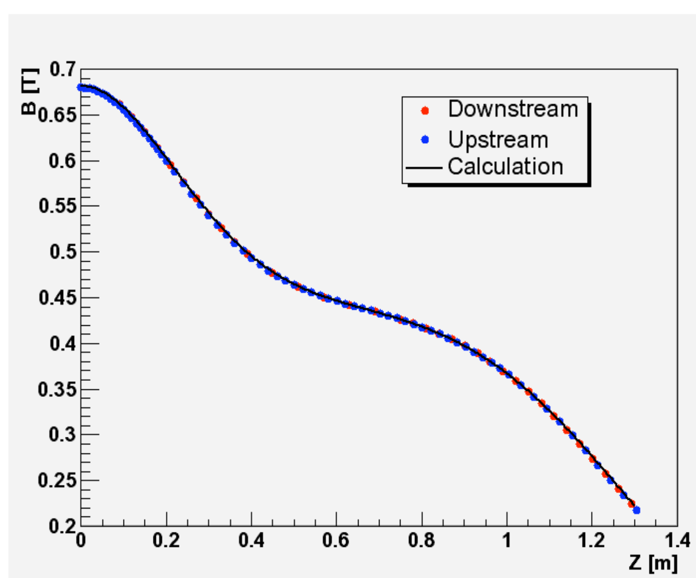


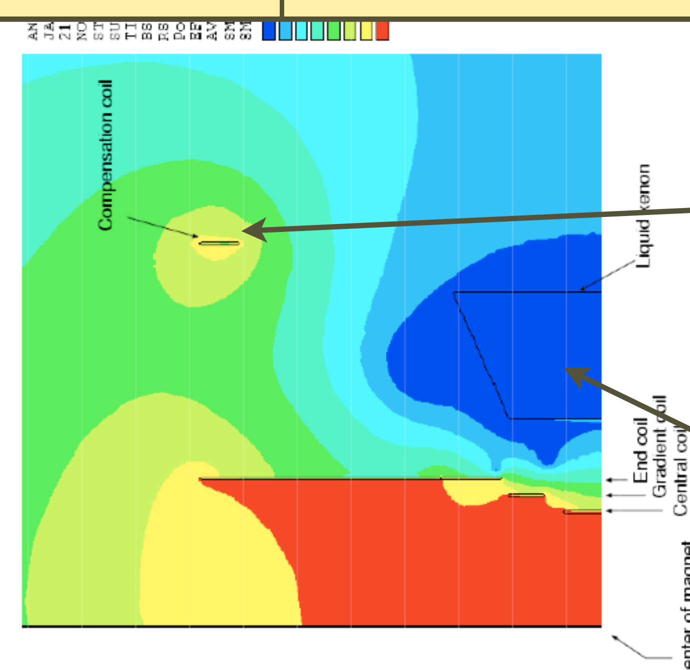


COBRA spectrometer

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

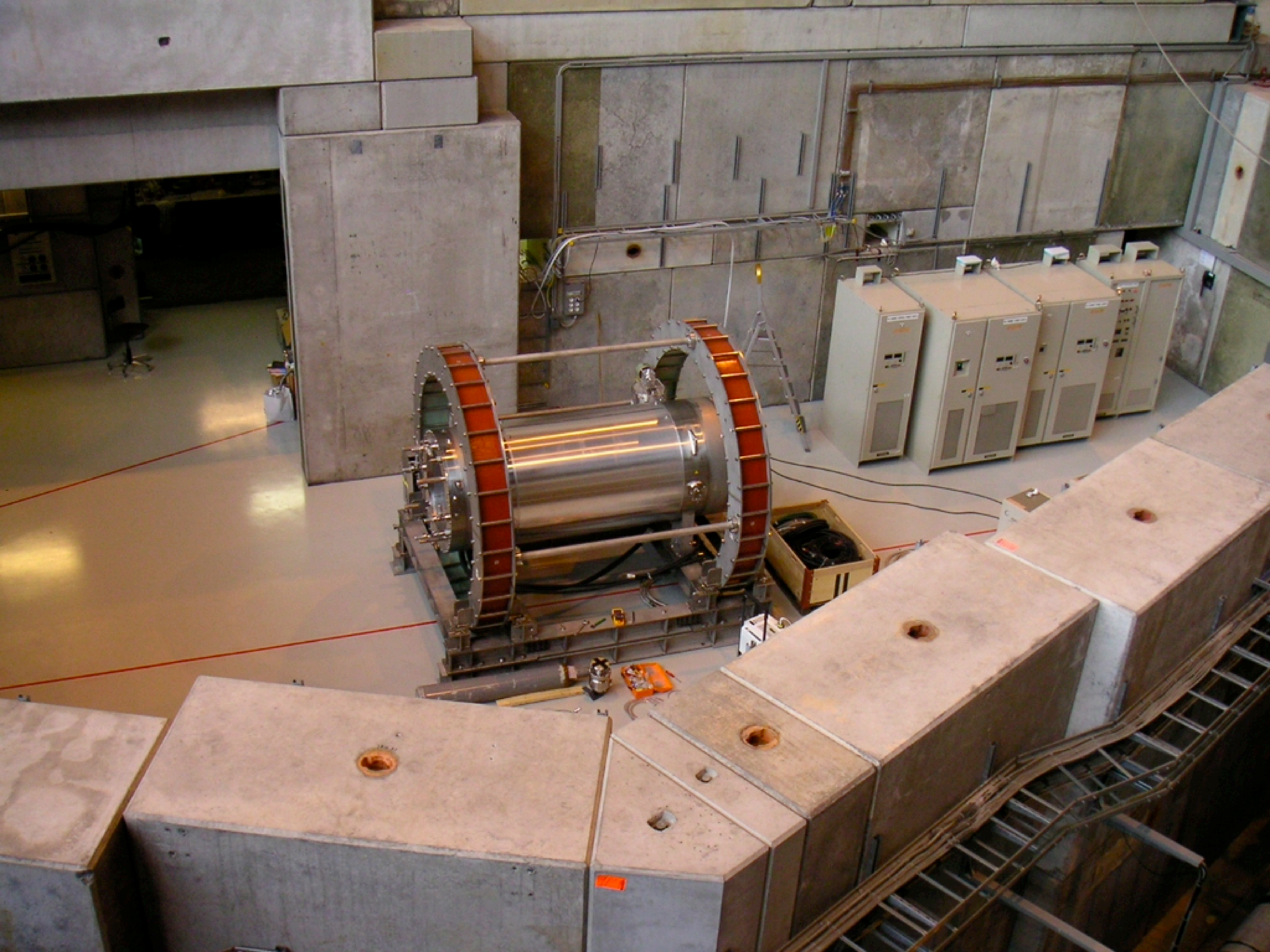
Non uniform magnetic field decreasing from the center to the periphery



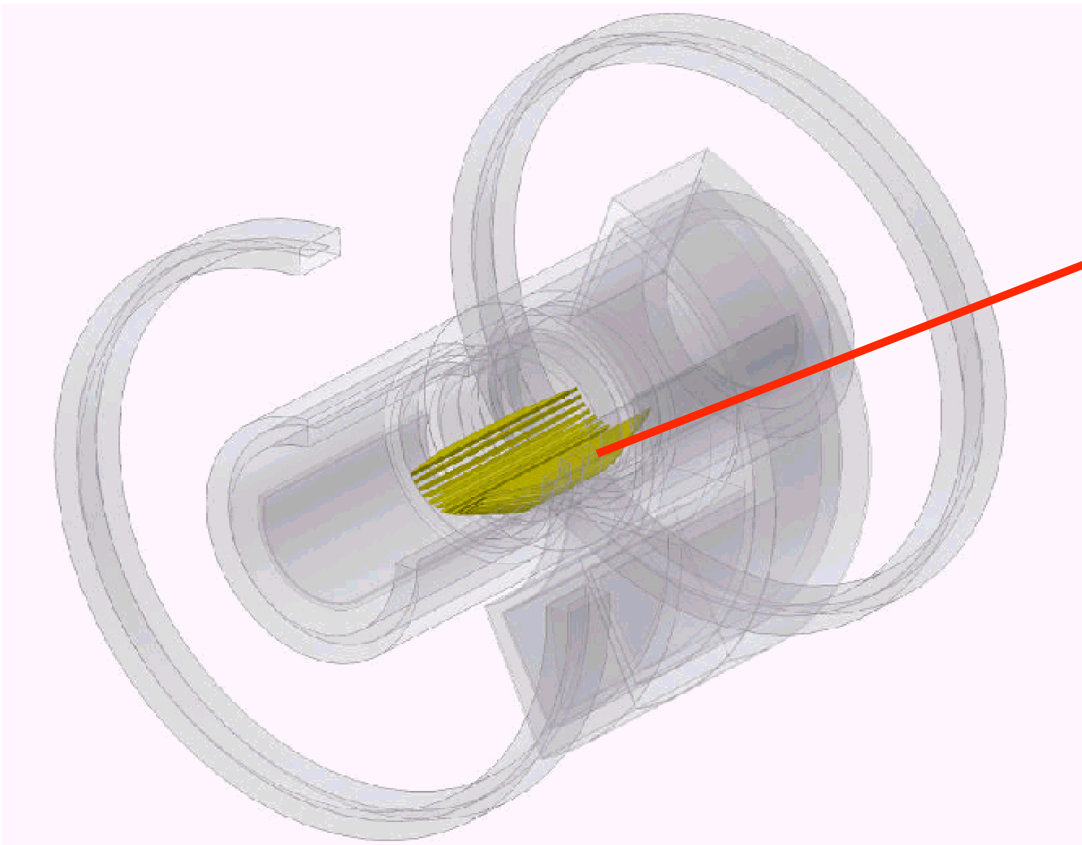


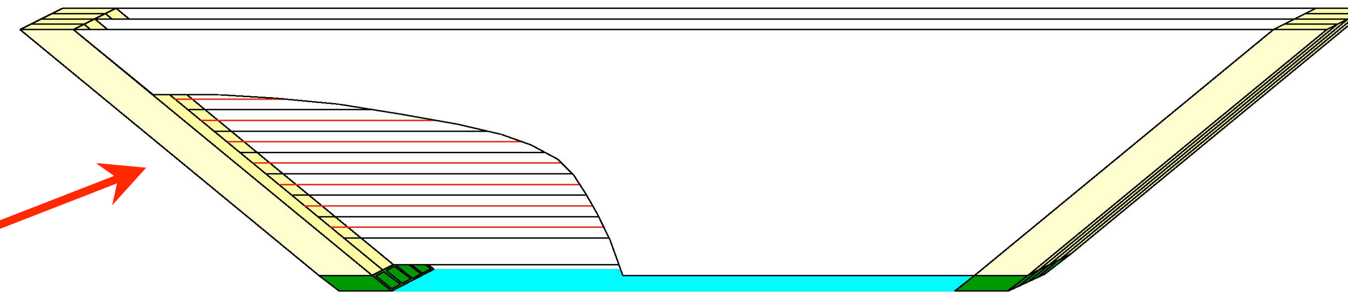
Compensation coil for LXe calorimeter

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



Positron Tracker

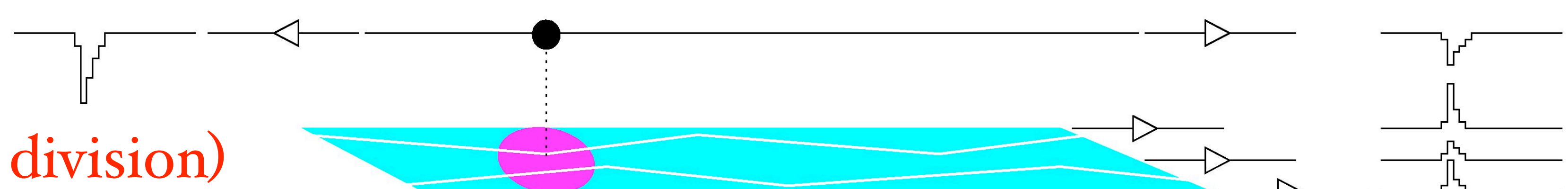




- 16 chambers radially aligned with 10°intervals
- 2 staggered arrays of drift cells
- 1 signal wire and 2 x 2 vernier cathode strips made of 15 μm kapton foils and 0.45 μm aluminum strips
- Chamber gas: He-C_2H_6 mixture

transverse coordinate (t drift)

longitudinal coordinate (charge division)

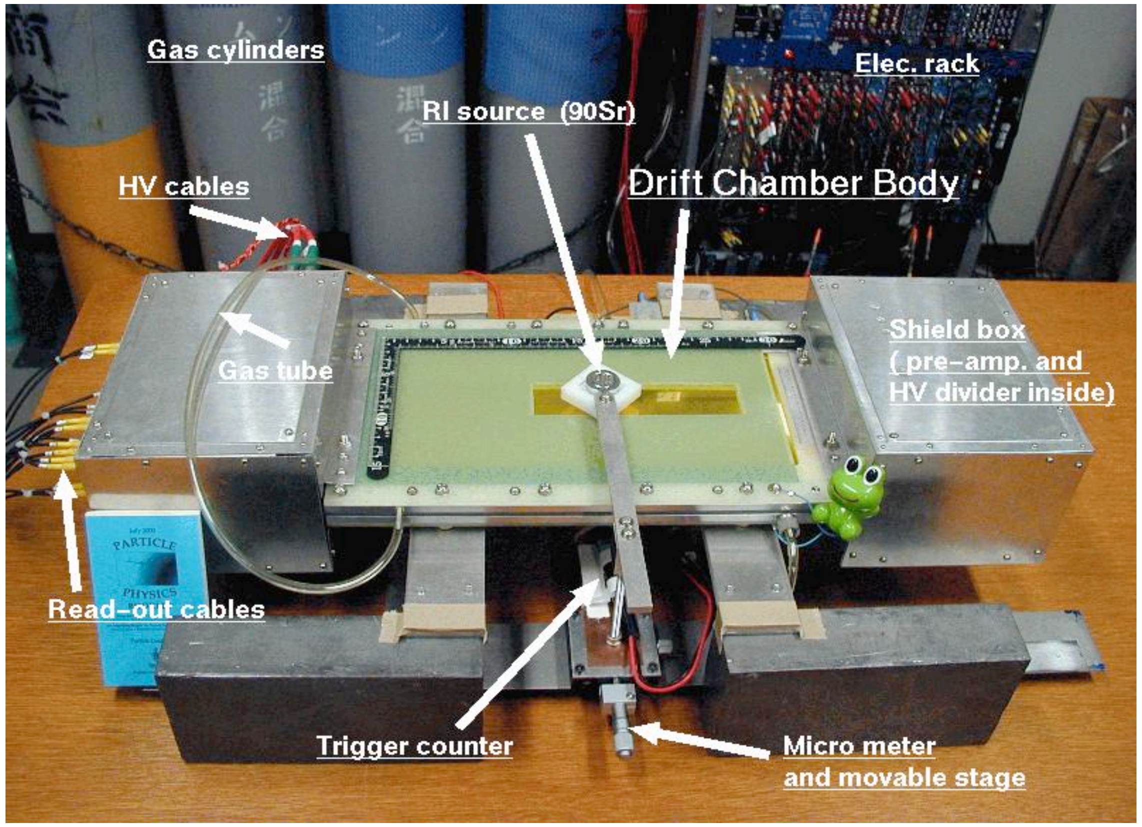


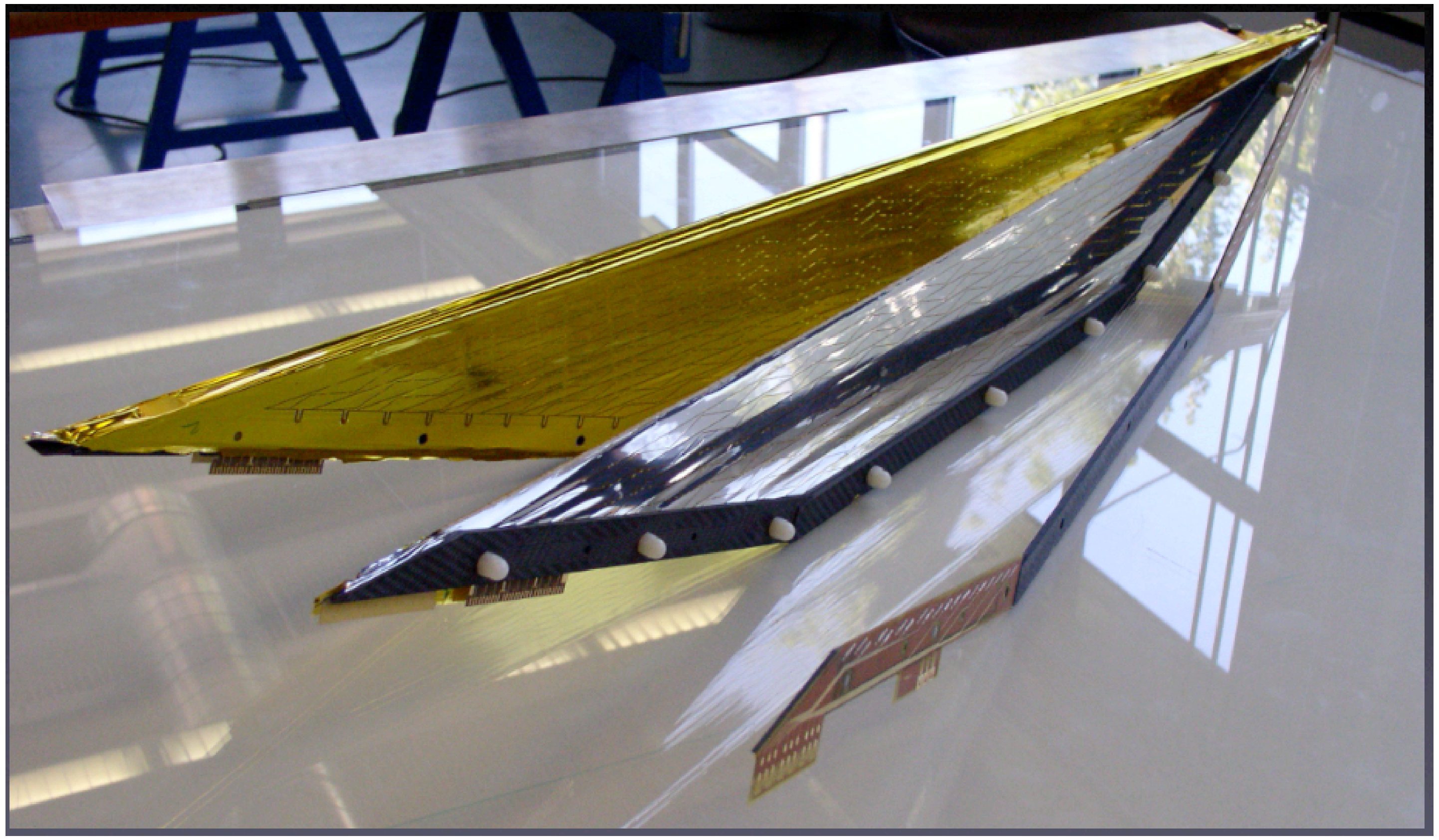
Measurements at Tokyo University:

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

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

Drift chambers





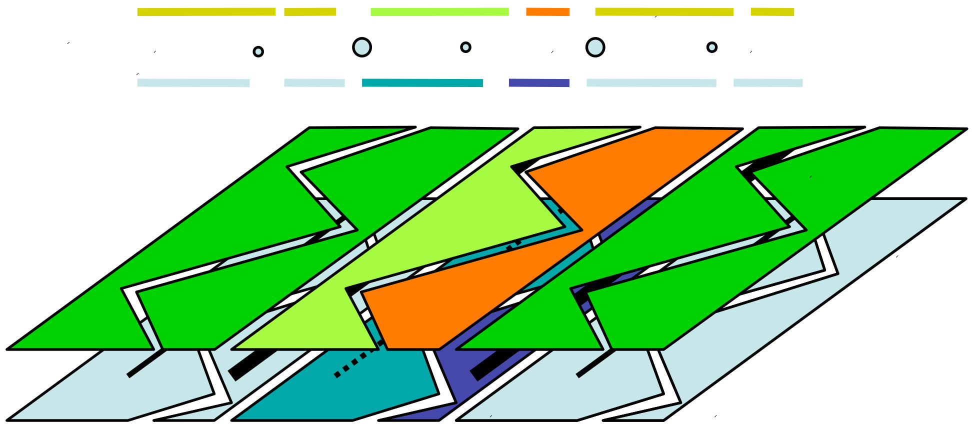
- Full scale test in November
- Summary of Drift Chamber simulation

FWHM

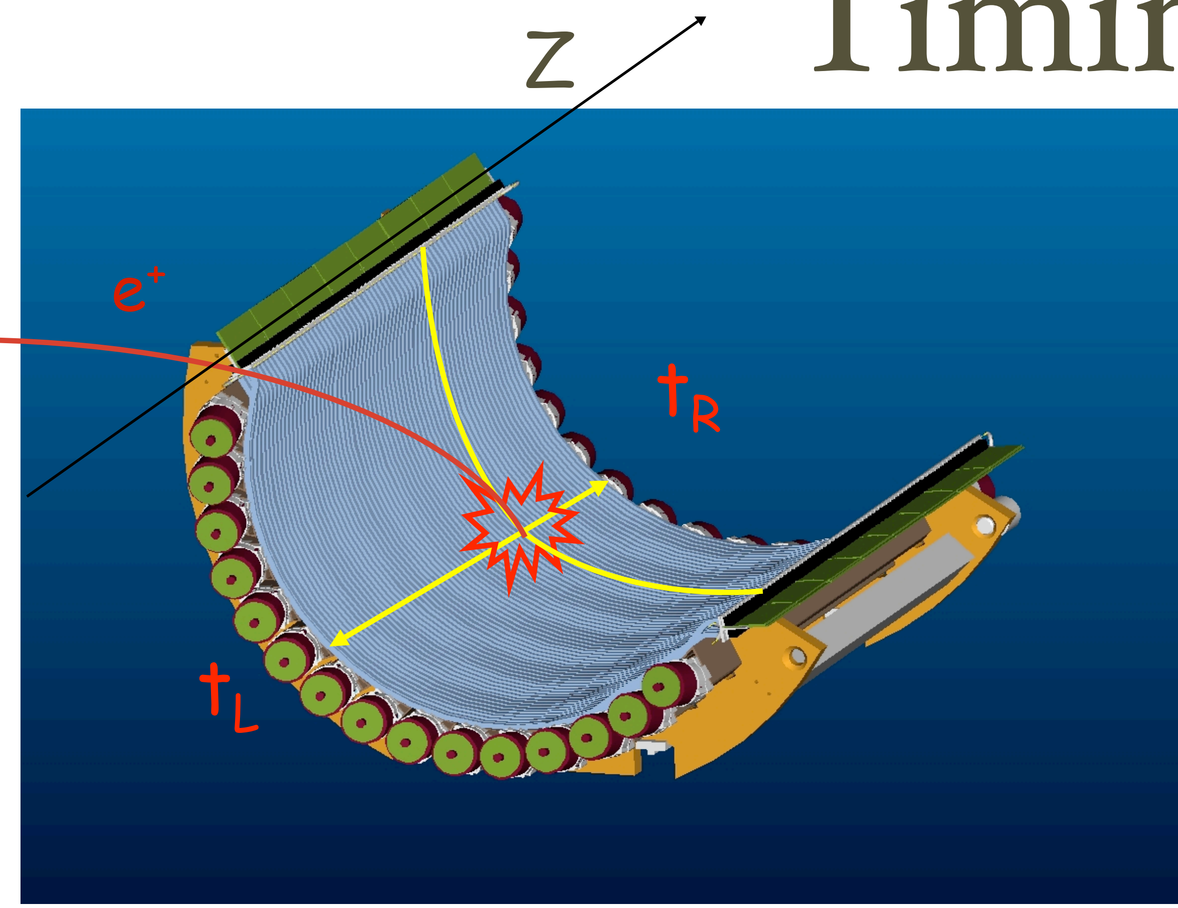
$$\delta P_{e^+} / P_{e^+} = 0.7 \div 0.9\%$$

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

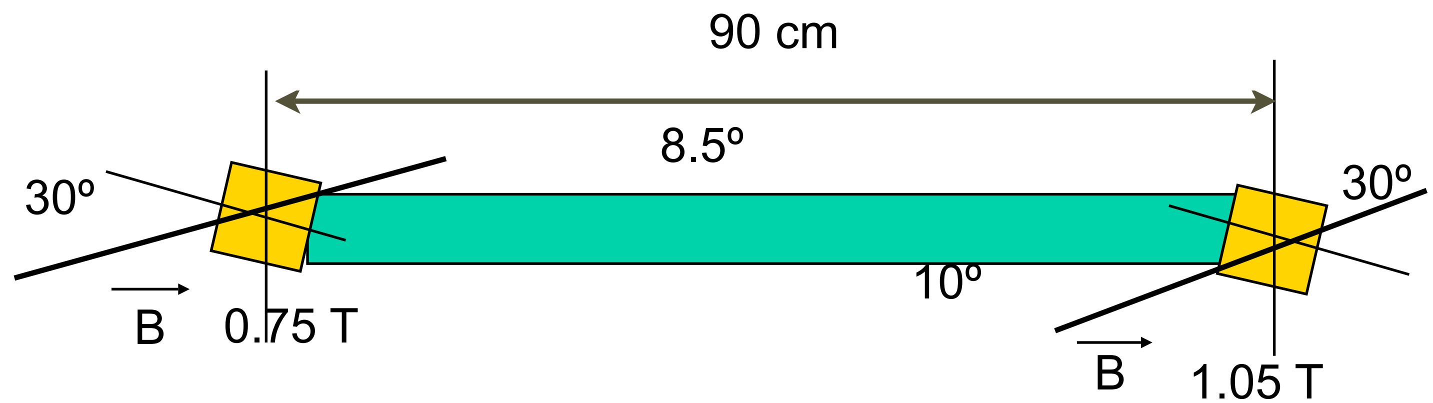
$$\delta x_{orig} = 2.1 \div 2.5\, mm$$

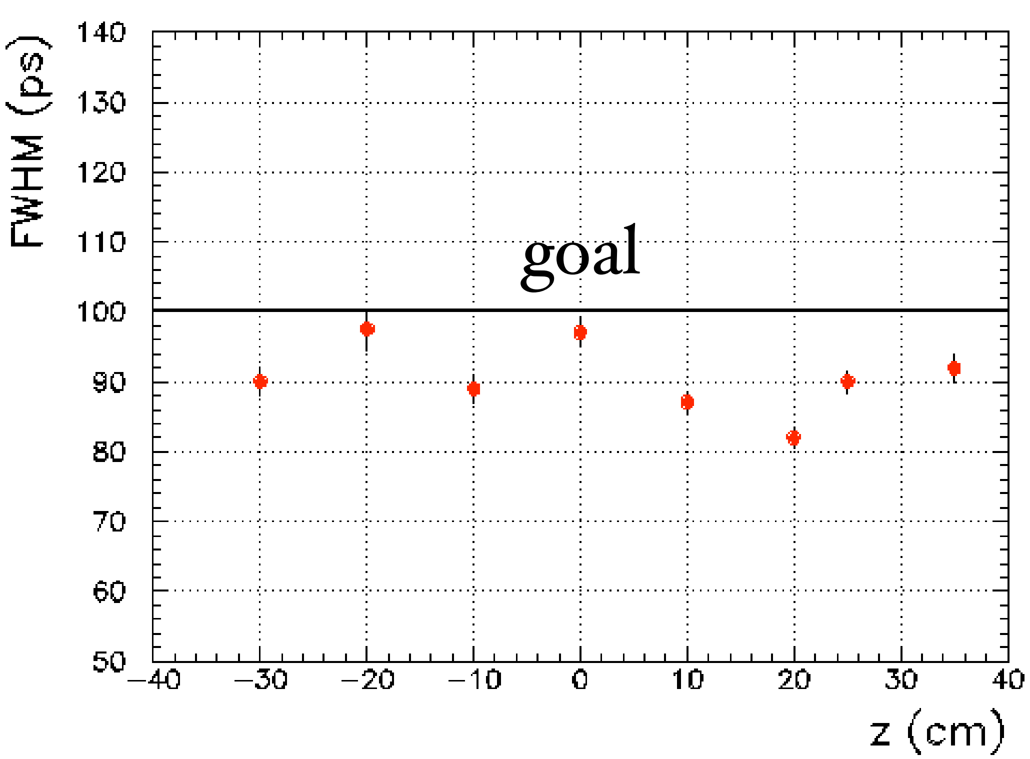


Timing Counter



- 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)

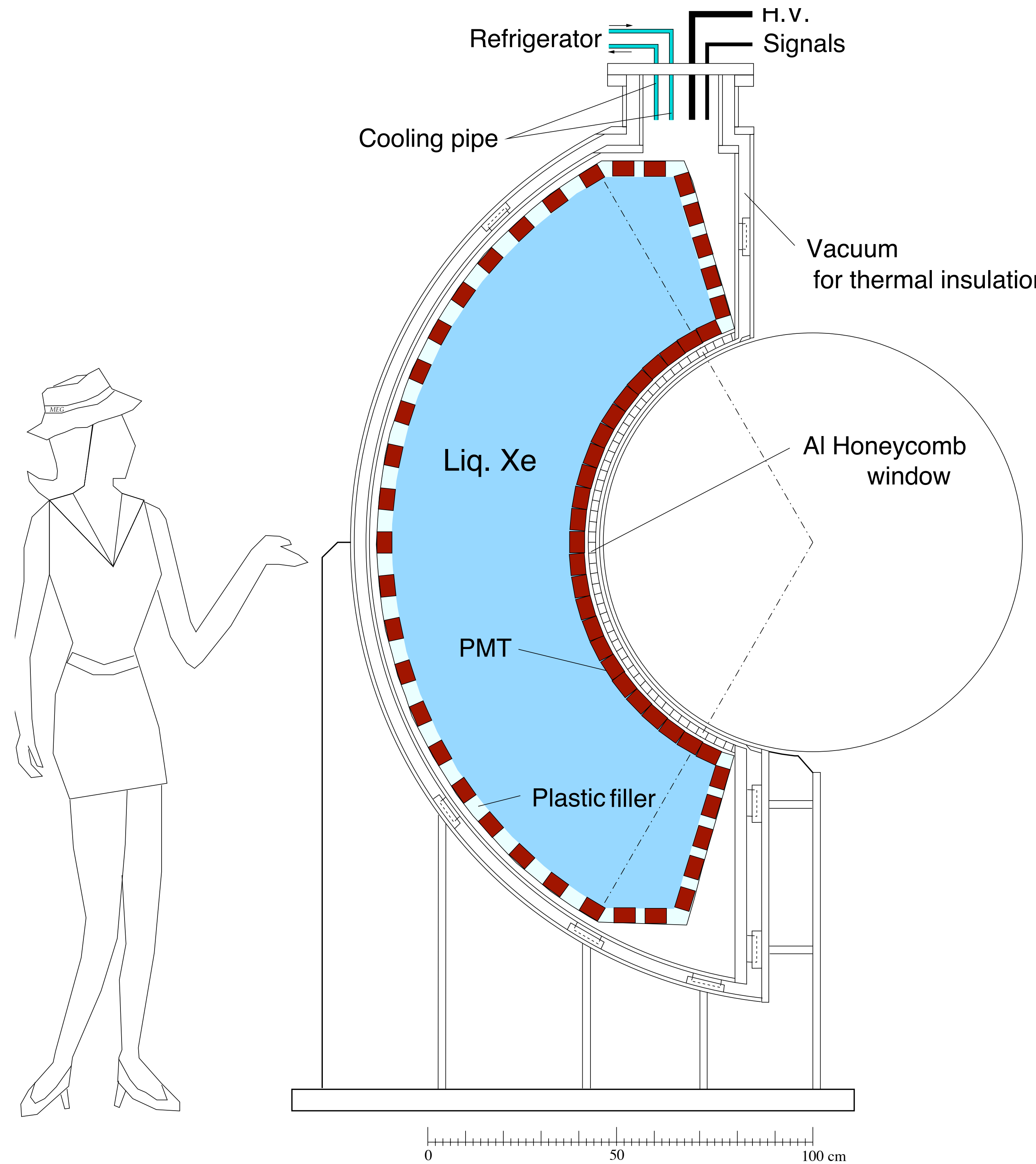




Exp. application (*)	Counter size (cm) (T x W x L)	Scintillator	PMT	λ_{att} (cm)	σ_t(meas)	σ_t(exp)
G.D.Agostini	3x 15 x 100	NE114	XP2020	200	120	60
T. Tanimori	3 x 20 x 150	SCSN38	R1332	180	140	110
T. Sugitate	4 x 3.5 x 100	SCSN23	R1828	200	50	53
R.T. Gile	5 x 10 x 280	BC408	XP2020	270	110	137
TOPAZ	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**	

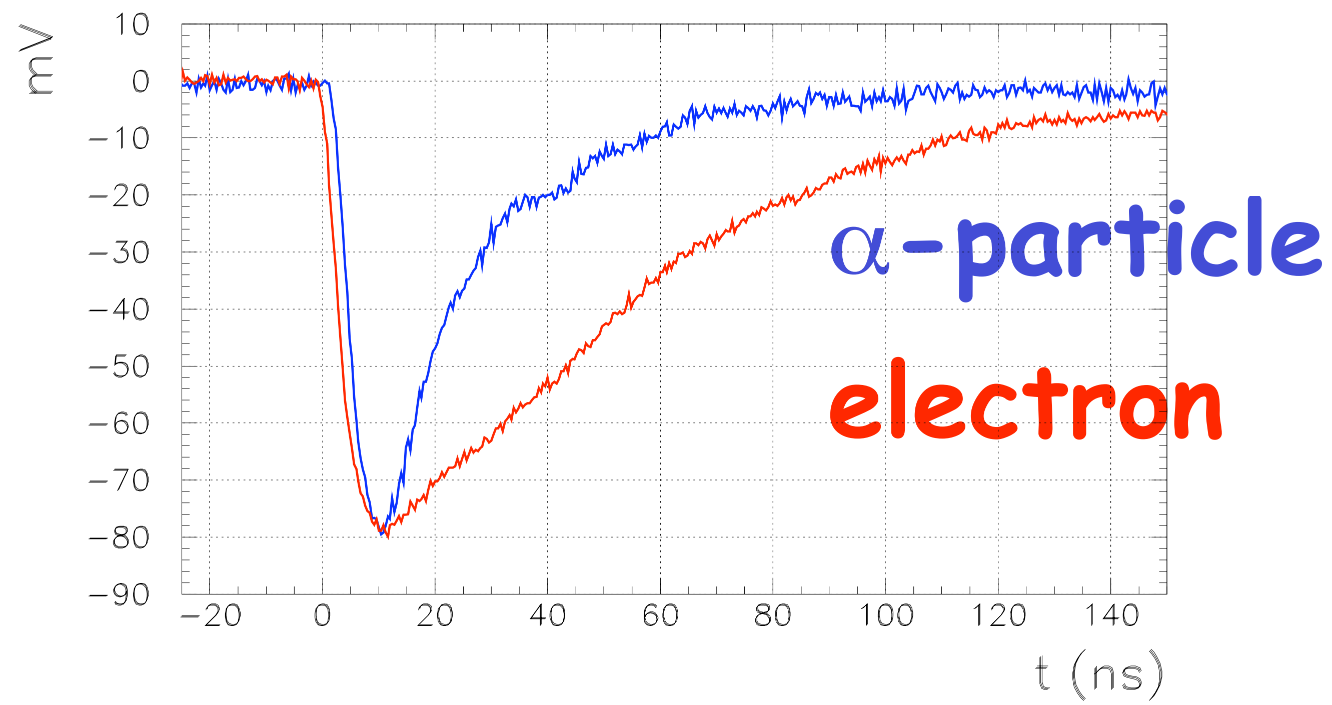
The calorimeter

- γ Energy, position, timing
- Homogeneous 0.8 m^3 volume of liquid Xe
  - 10 % solid angle
  - 65 < r < 112 cm
  - |cosθ| < 0.35 |φ| < 60°
- 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 (175 nm)
- Thin entrance wall
- Singularly applied HV
- Waveform digitizing @2 GHz
  - Pileup rejection



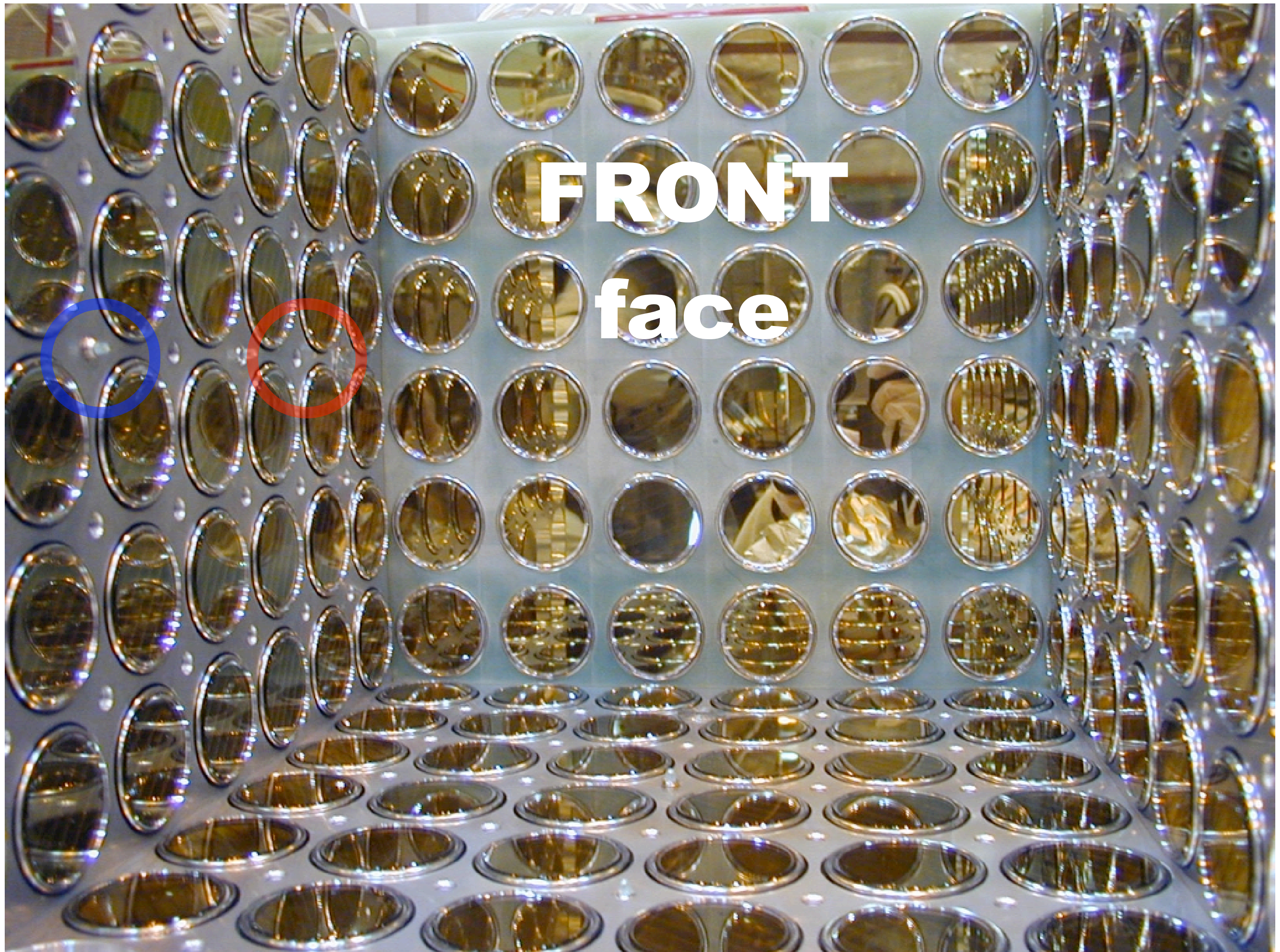
Xe properties

- 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 ($\lambda_{Abs}=\infty$)



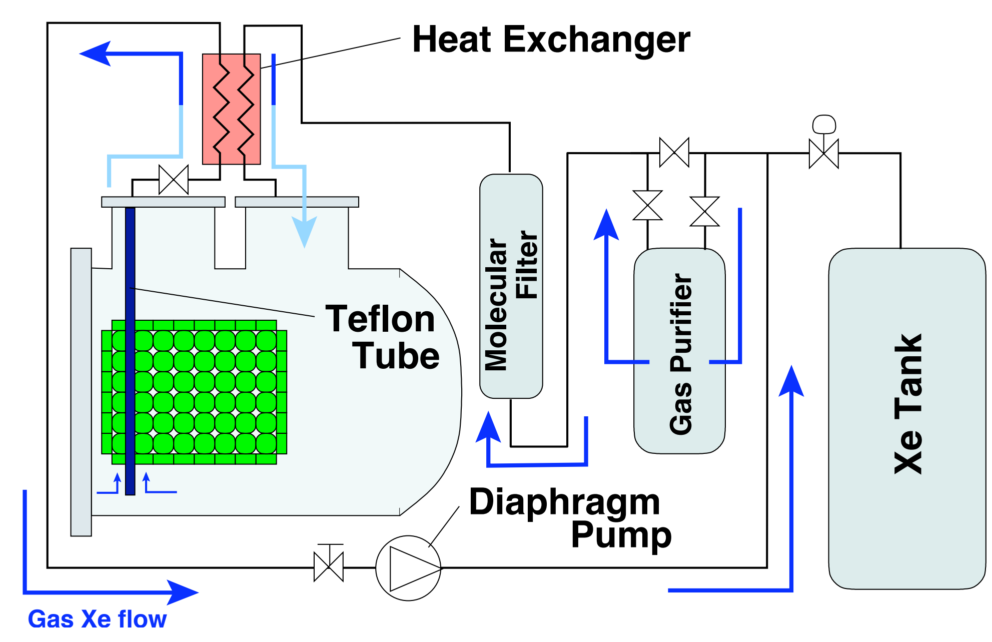
The LXe calorimeter prototype

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



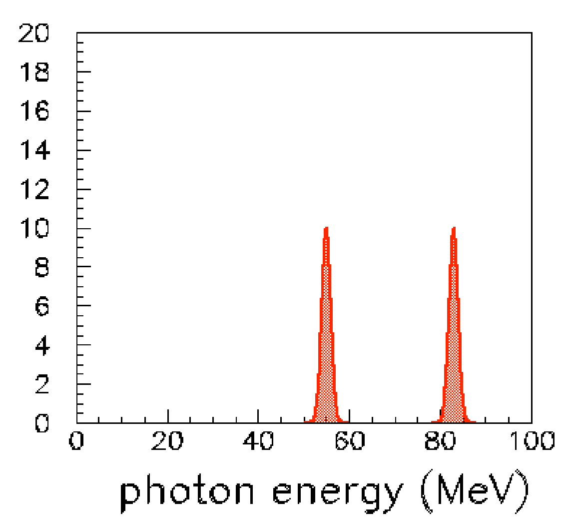
LXe calorimeter R&D

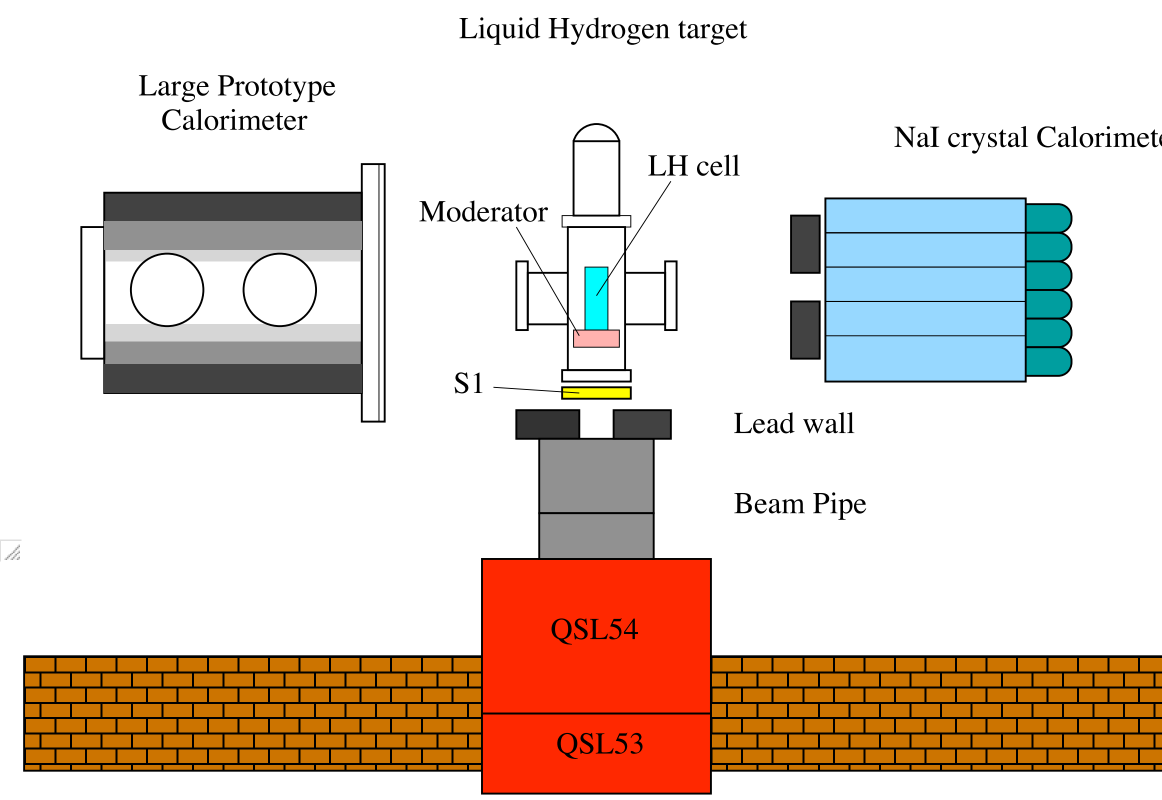
- Energy resolution strongly depends on absorption. A long R&D to insure L(Abs)>3 m with a circulation/purification system
- Measurement of energy and timing resolution with high energy photons: 55 MeV photons from pion charge exchange reaction



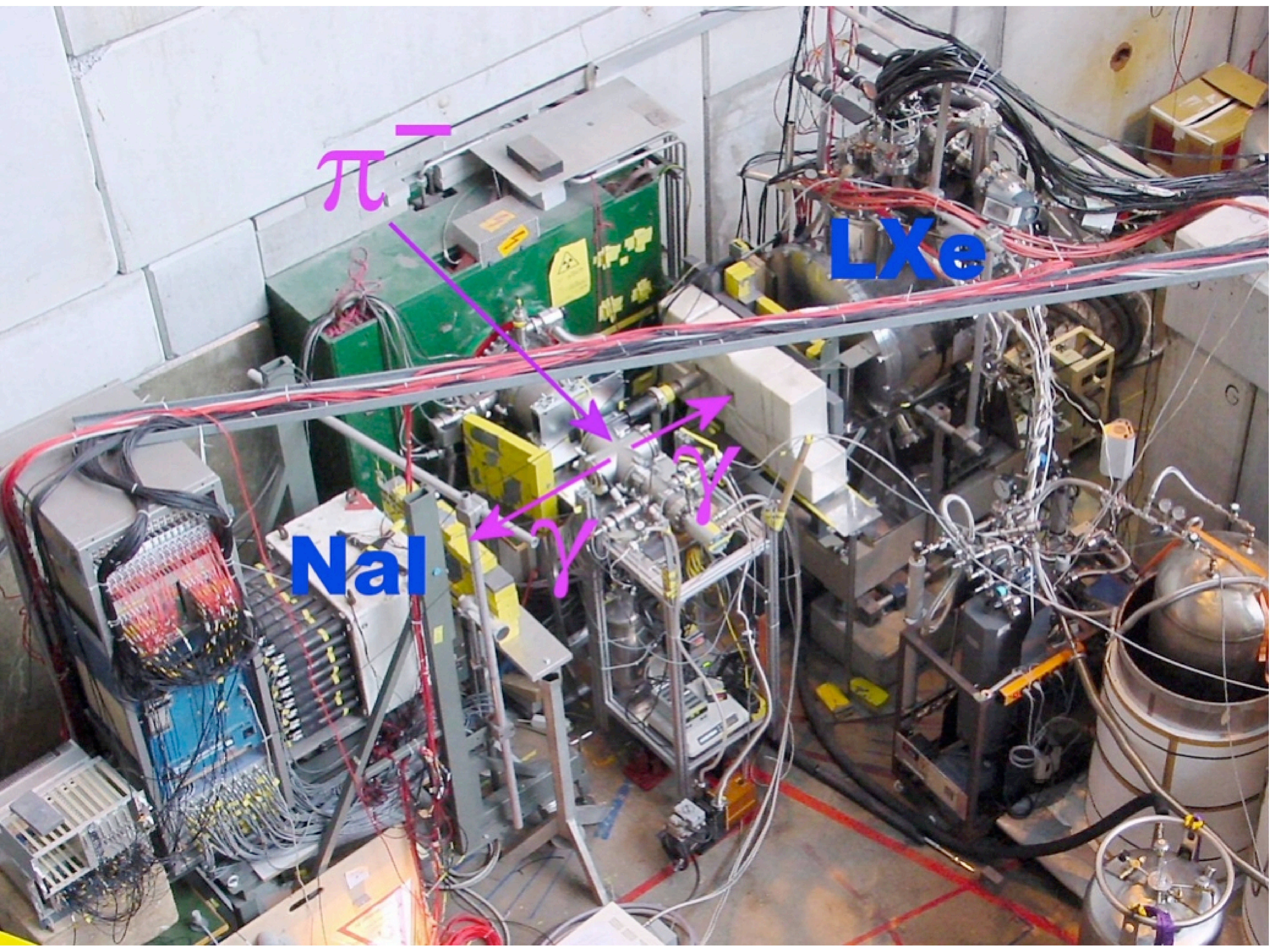
$$\pi^- p \rightarrow \pi^0 n$$
$$\pi^0 \rightarrow \gamma\gamma$$

Lab Frame

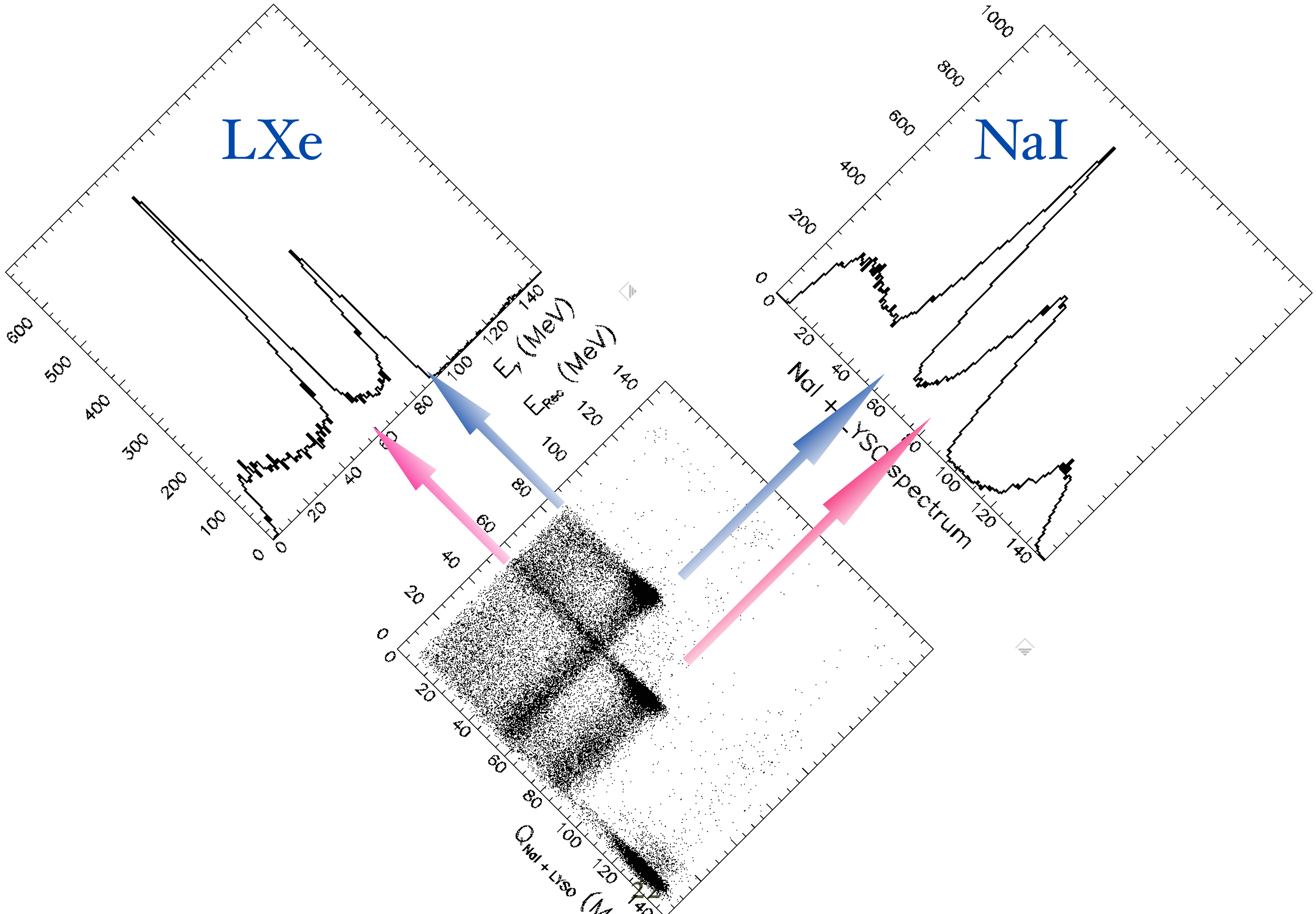




Two tests in 2003 and 2004 demonstrated the calibration procedure and the resolutions

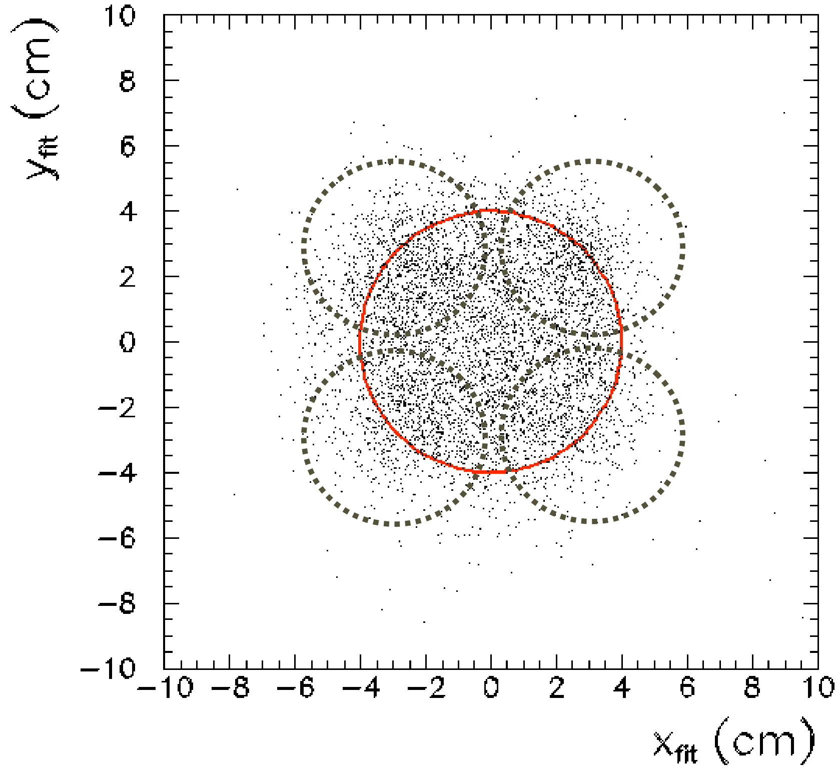

π⁻
LXe
γ
γ
NaI

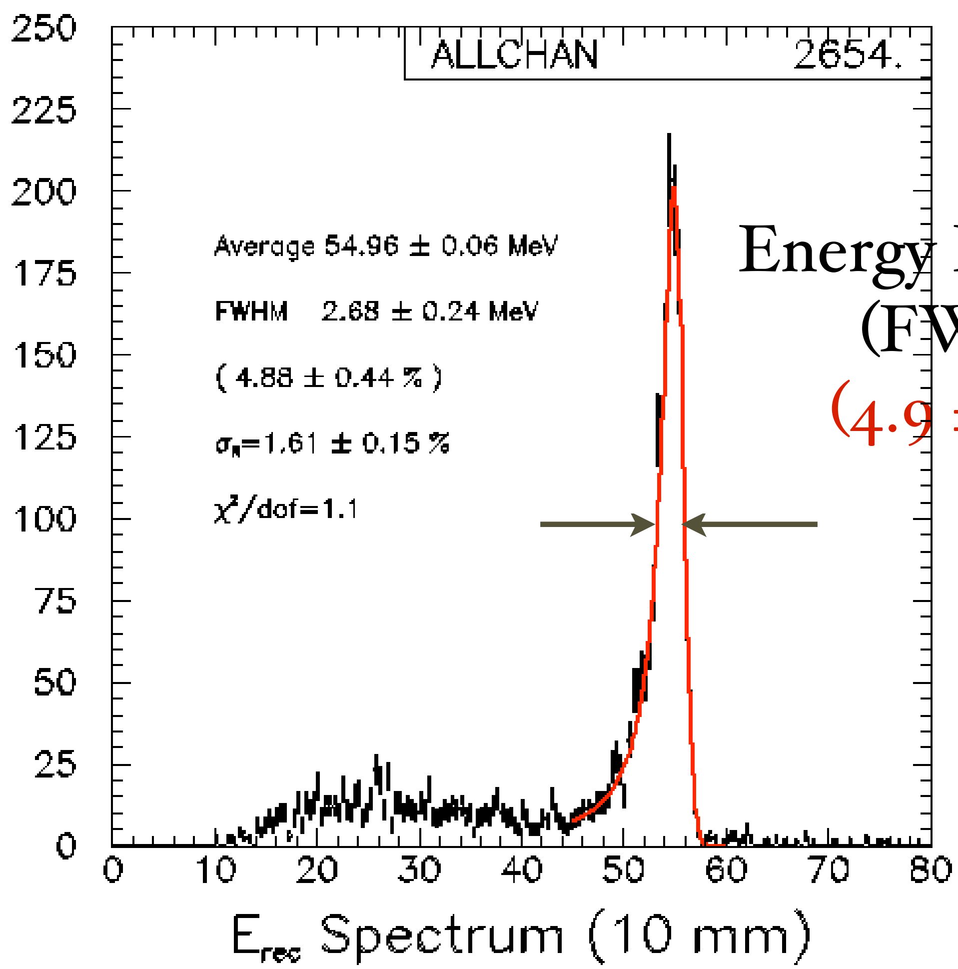
- In the back-to-back raw spectrum we see the correlation
  - 83 MeV ⇔ 55 MeV
  - The 129 MeV line is visible in the NaI because Xe is sensitive to neutrons (9 MeV)



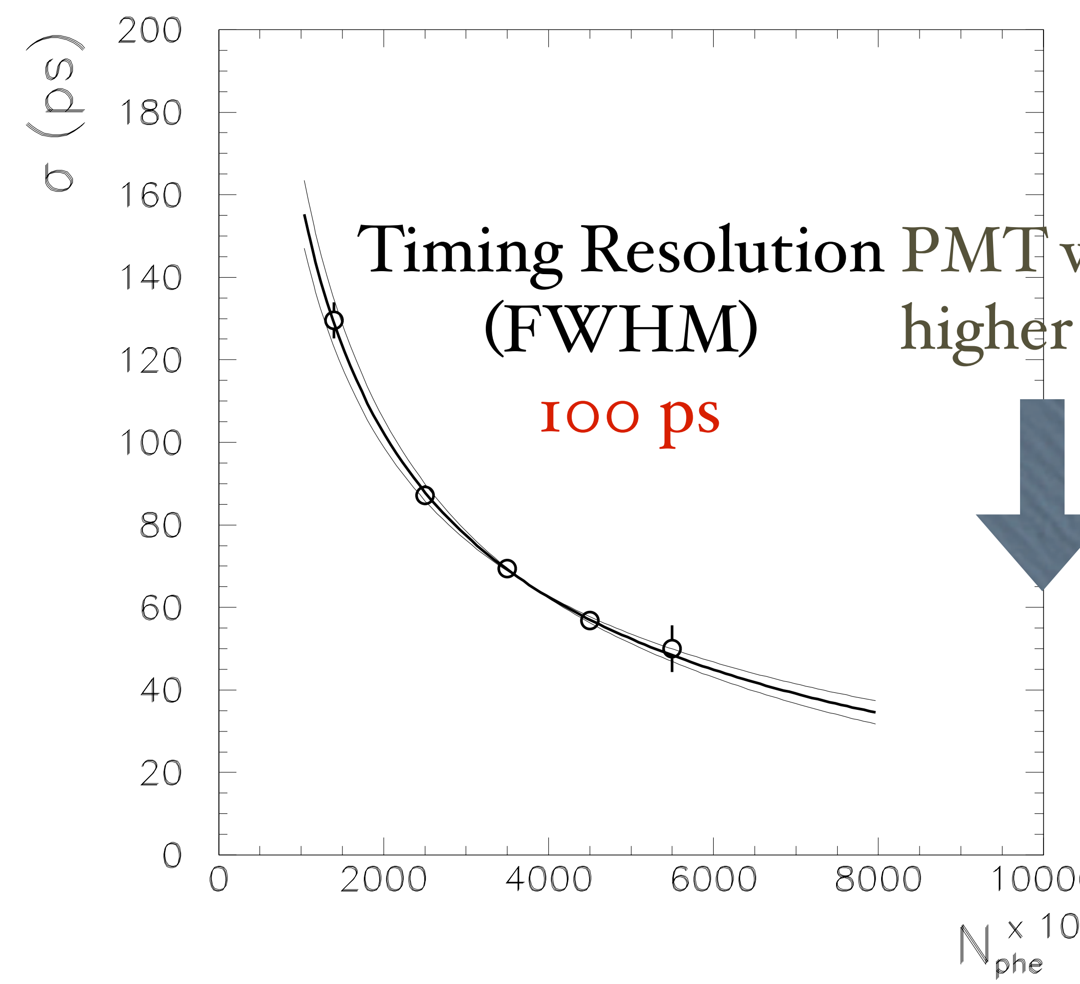
Resolutions @ 55 MeV

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





Energy Resolution (FWHM)
(4.9 ± 0.4) %

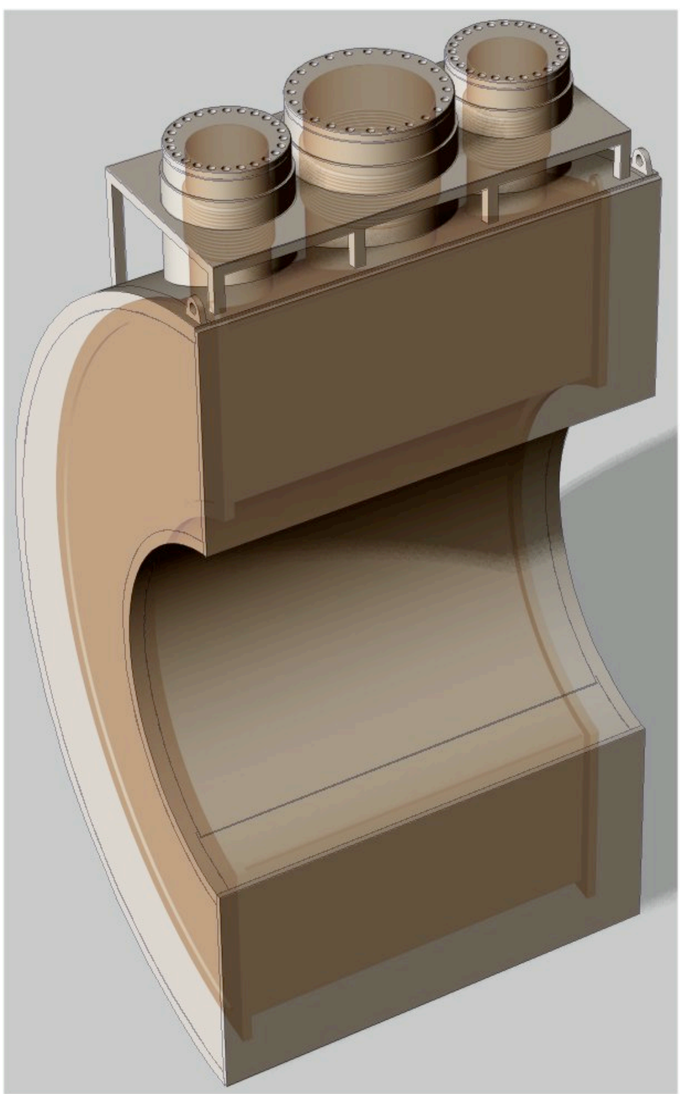


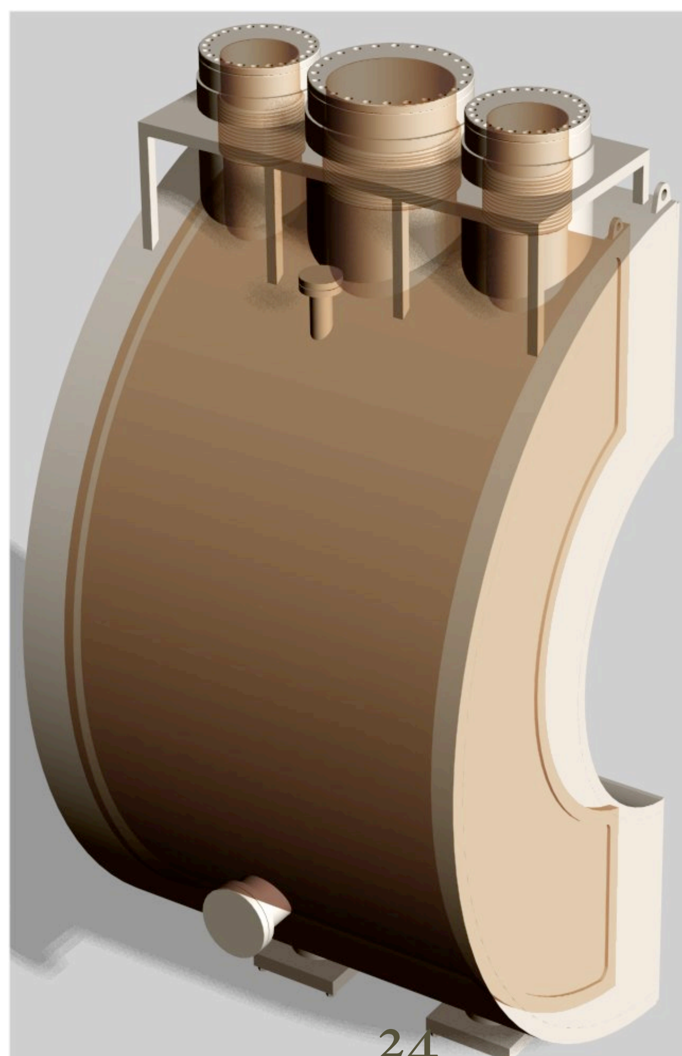
Timing Resolution (FWHM)
100 ps

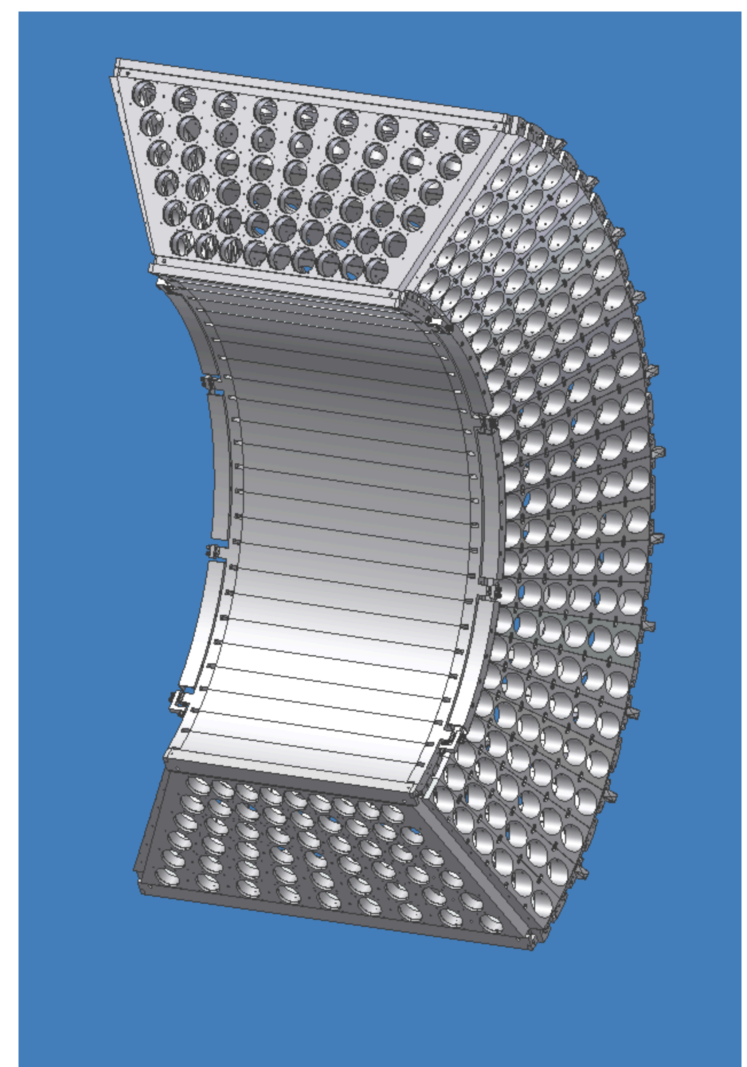
PMT with higher QE

Calorimeter construction

- Built by SIMIC (Italy) on a japanese-italian project
- Low magnetic permeability stainless steel
- Delivery January 2006 @ PSI
- Test of all the >800 PMTs in Pisa and at PSI

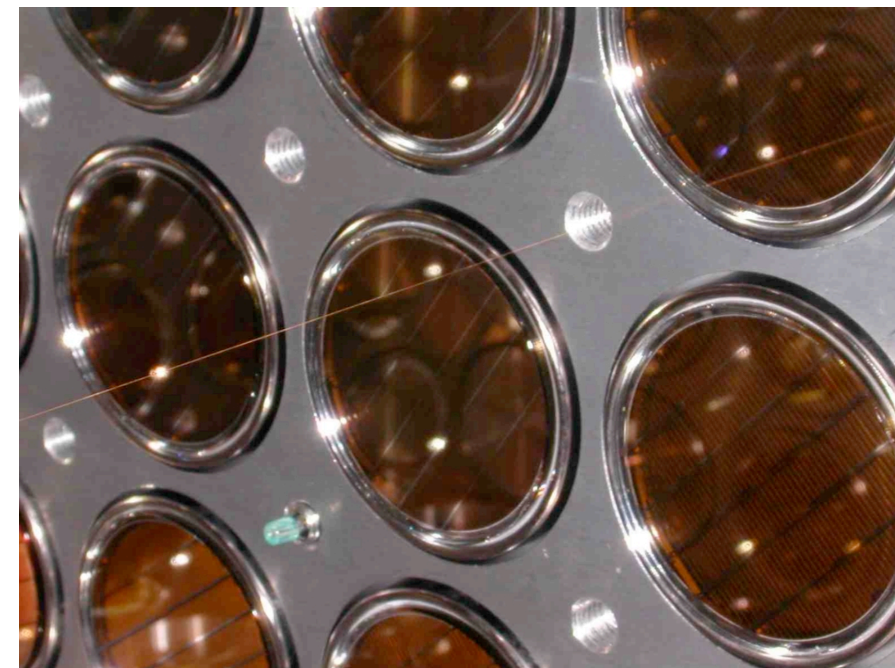






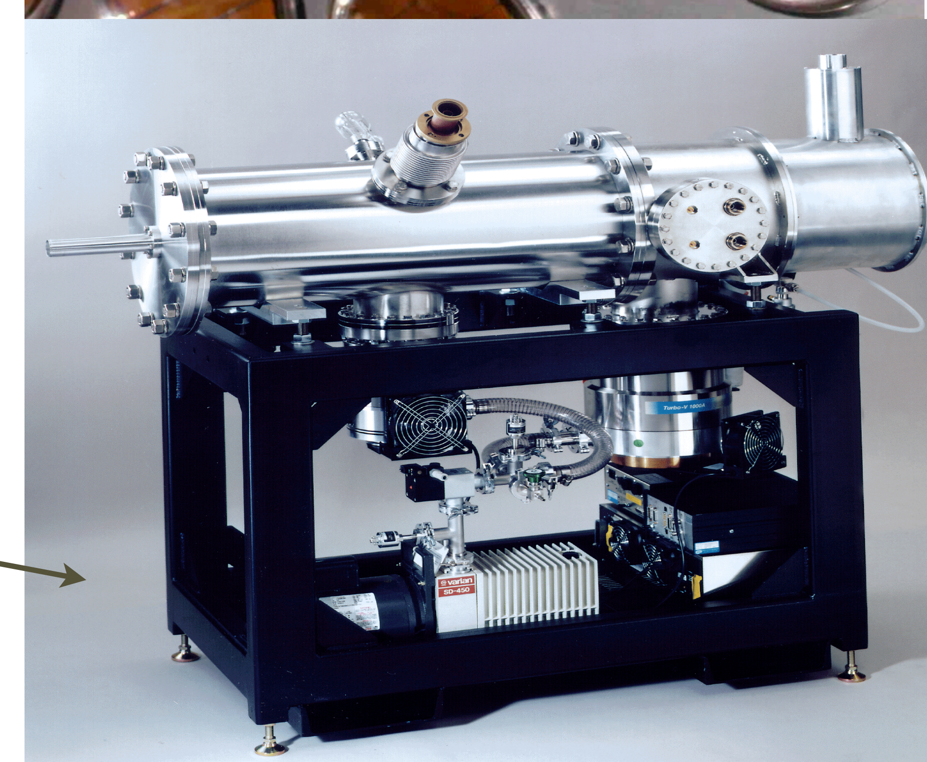
MEG calibrations

- A reliable result depend on a constant calibration and monitoring of the apparatus
  - alpha Sources (on wires and wall)
  - Proton accelerator $^{7}\text{Li}(p, \gamma_{17.6})^{8}\text{Be}$ design under way
  - Neutron generator $^{58}\text{Ni}(n, \gamma_{9})^{59}\text{Ni}$
  - Charge exchange reaction (Panofsky) $\pi^{-}p \rightarrow \pi^{0}n$ $\pi^{0} \rightarrow \gamma\gamma$



500 keV Cockroft-Walton

500 keV RFQ



Trigger Electronics

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

❖ Beam rate $10^8\ s^{-1}$

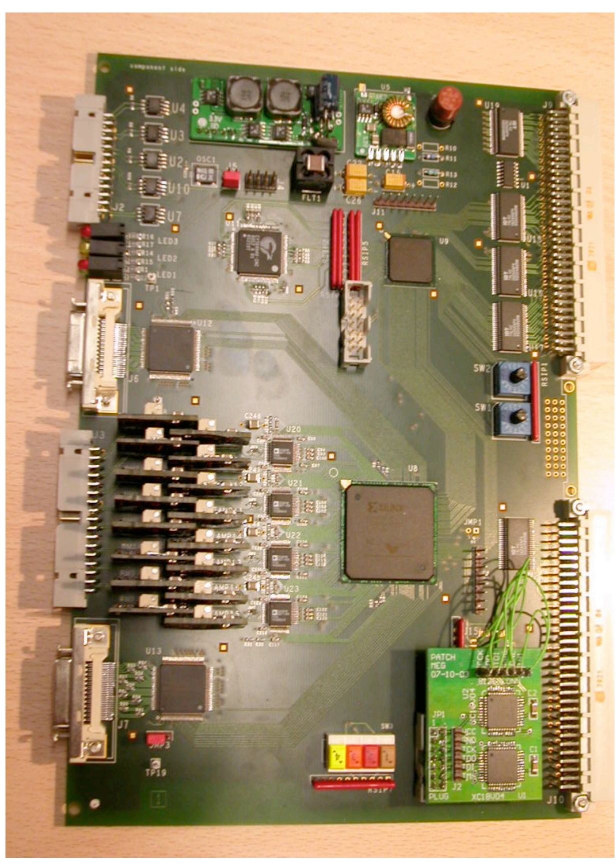
❖ Fast LXe energy sum > 45MeV $2\times10^3\ s^{-1}$

gamma interaction point (PMT of max charge)

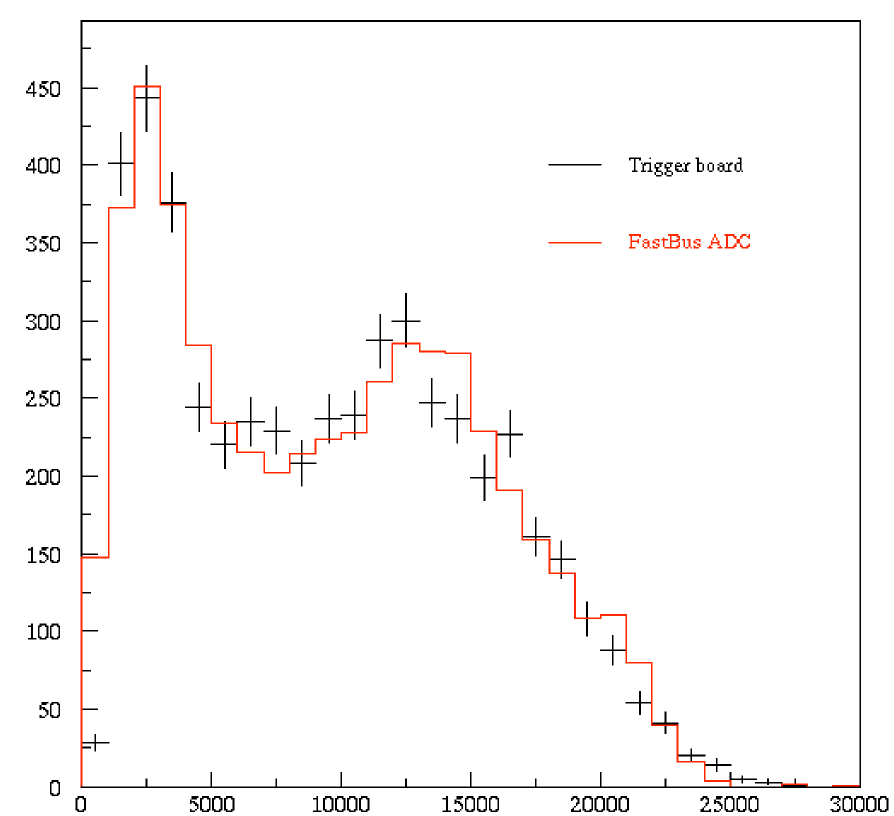
e^+ hit point in timing counter

❖ time correlation γ – e^+ 200 s^{-1}

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

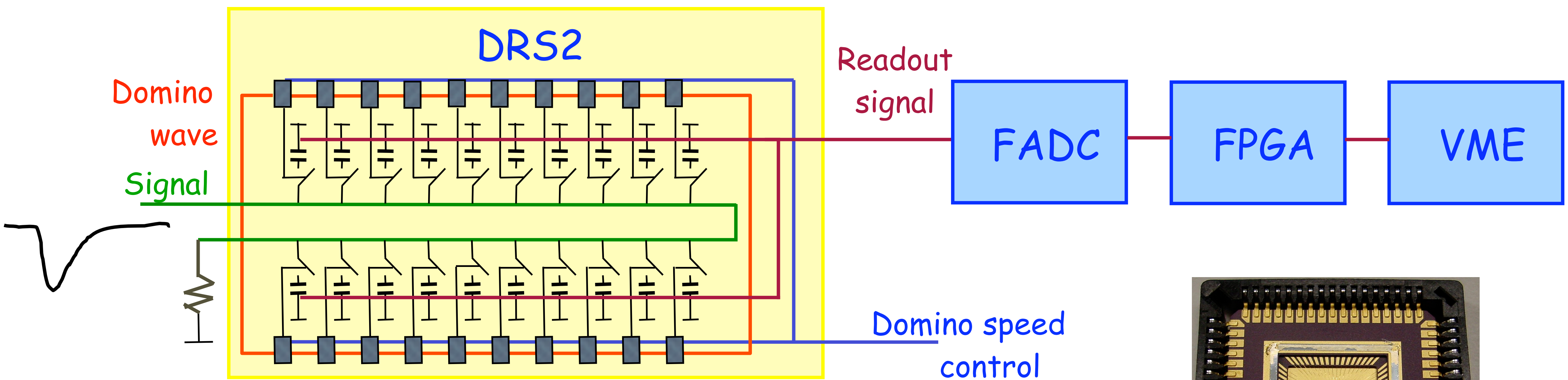


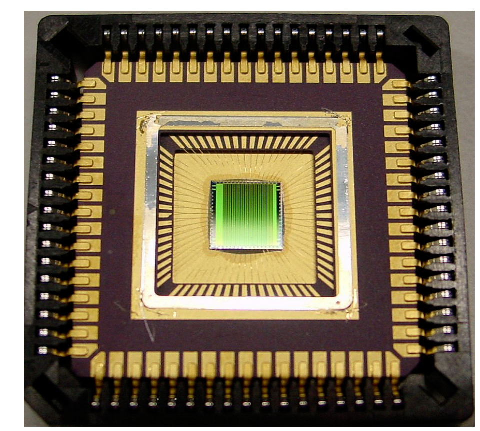
- Prototype system has been tested successfully on the LP
- Design of the final system is in progress
- π^0 data
- Charge spectrum
- Only 32 PMT



Readout electronics

2.5 GHz Waveform digitization for all channels

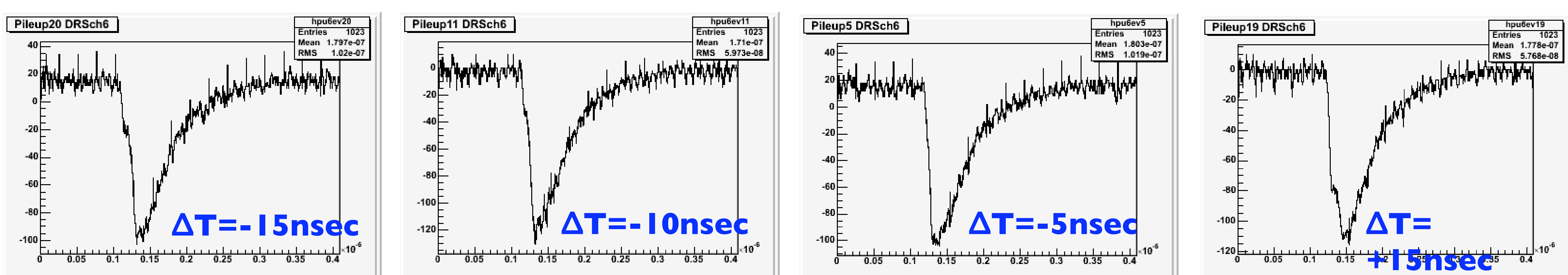




DRS2 chip (Domino Ring Sampler)

- 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



MEG sensitivity

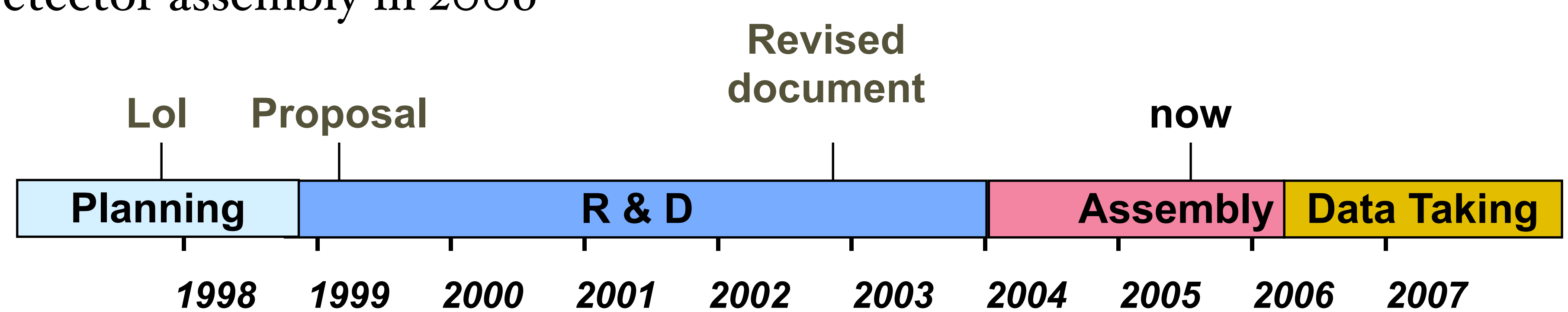
- Computation of the sensitivity based on the measured resolutions

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
- 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 af (almost) all subdetectors were measured
  - Liquid Xe calorimeter Large Prototype
  - Timing counters
- Detector assembly in 2006



More details at

http://meg.psi.ch
http://meg.pi.infn.it
http://meg.icepp.s.u-tokyo.ac.jp

Conclusion

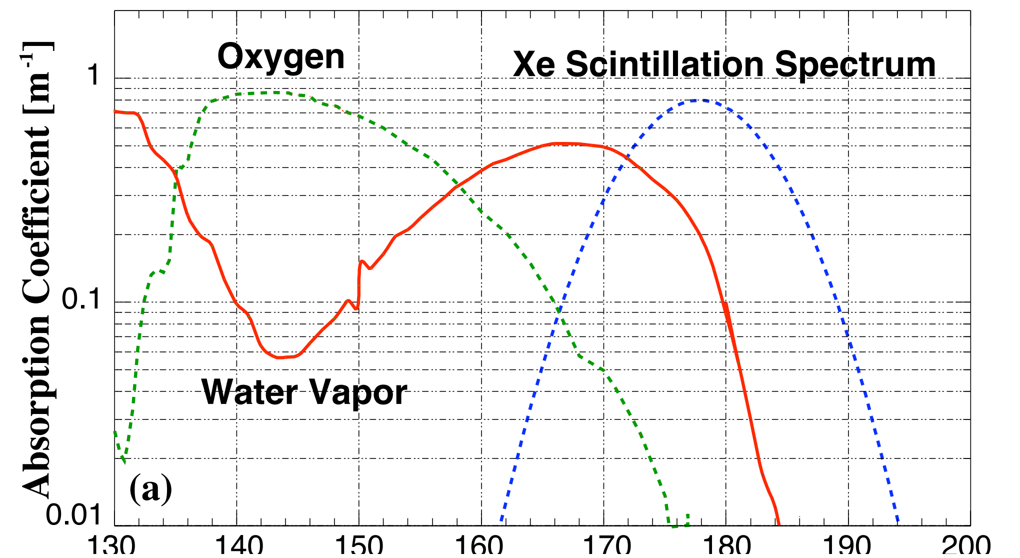
- The MEG experiment is expected to start engineering run in 2006
- Tests of the most advanced sub-detector were shown
  - Absorption length > 100 cm
  - Energy resolution < 5% FWHM at 55 MeV
  - Timing resolution < 90 ps (remeasured in 2004)
  - Importance of PMT and energy calibration and monitoring
- Expected sensitivity at a level of 10^{-13}
- Space (and time) for improvements!

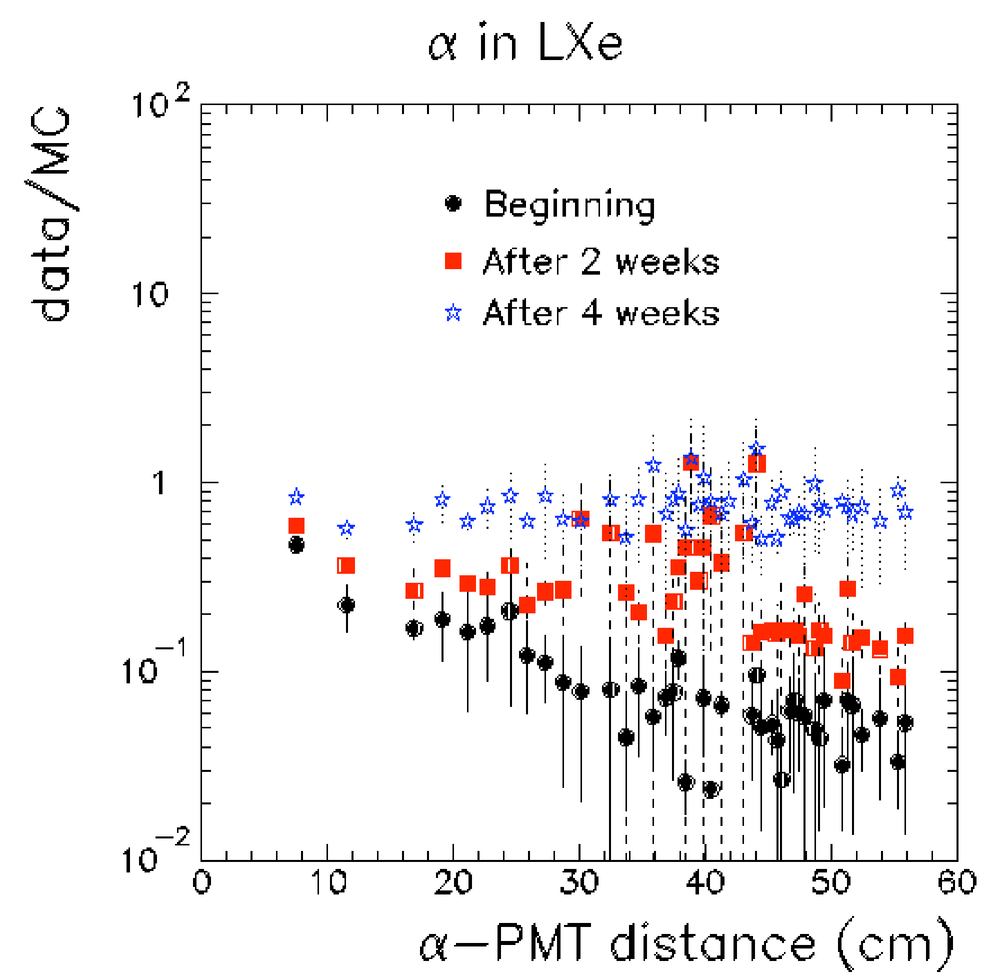
PMT support design (Tokyo)

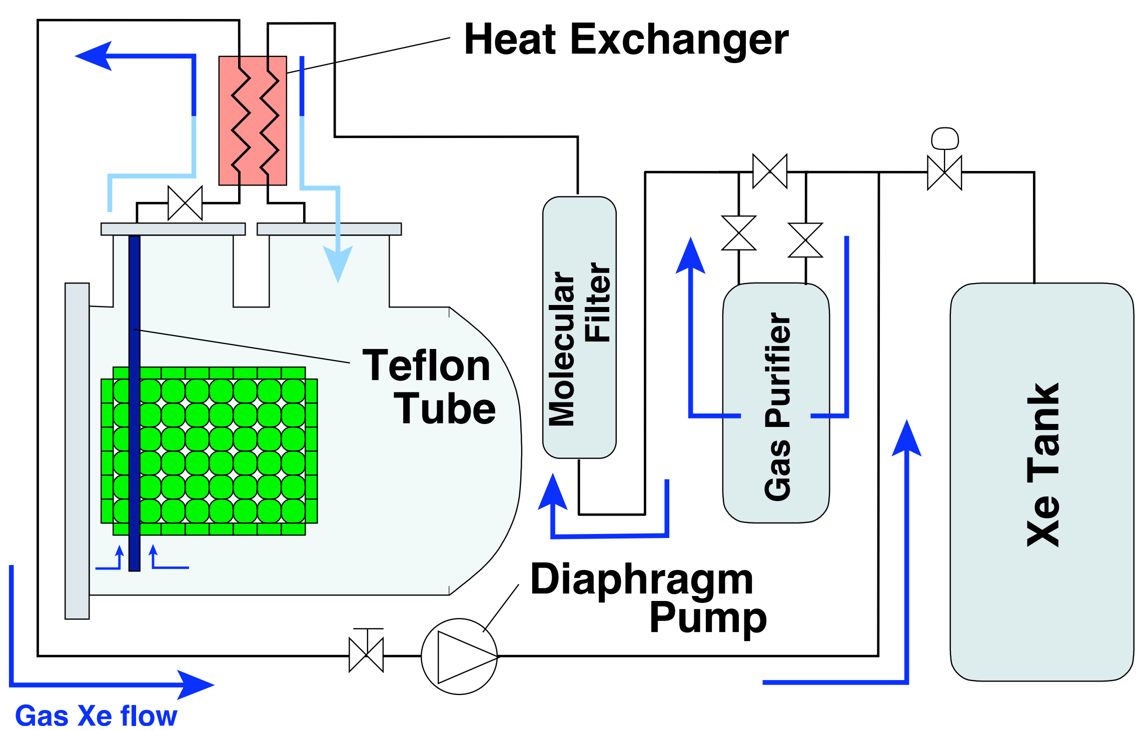
- Inner and outer faces 2x9x24=432
- Side faces 2x6x24=288
- Front faces 2x9x6=108
  - Total =432+288+108=828 PMTs

Measurement of absorption

- 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

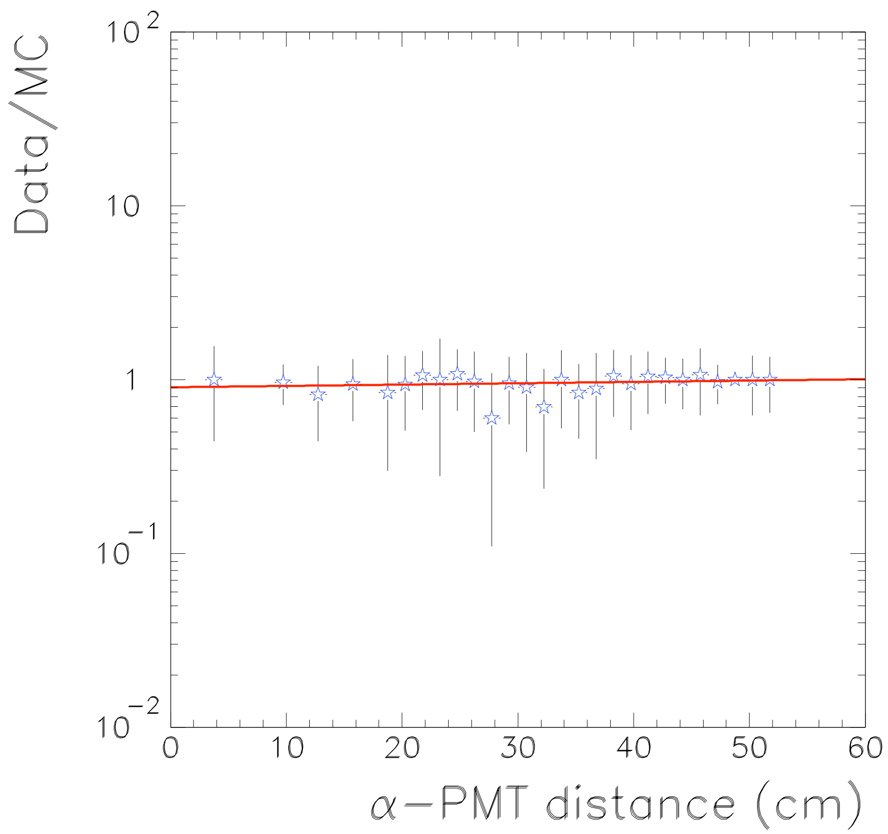


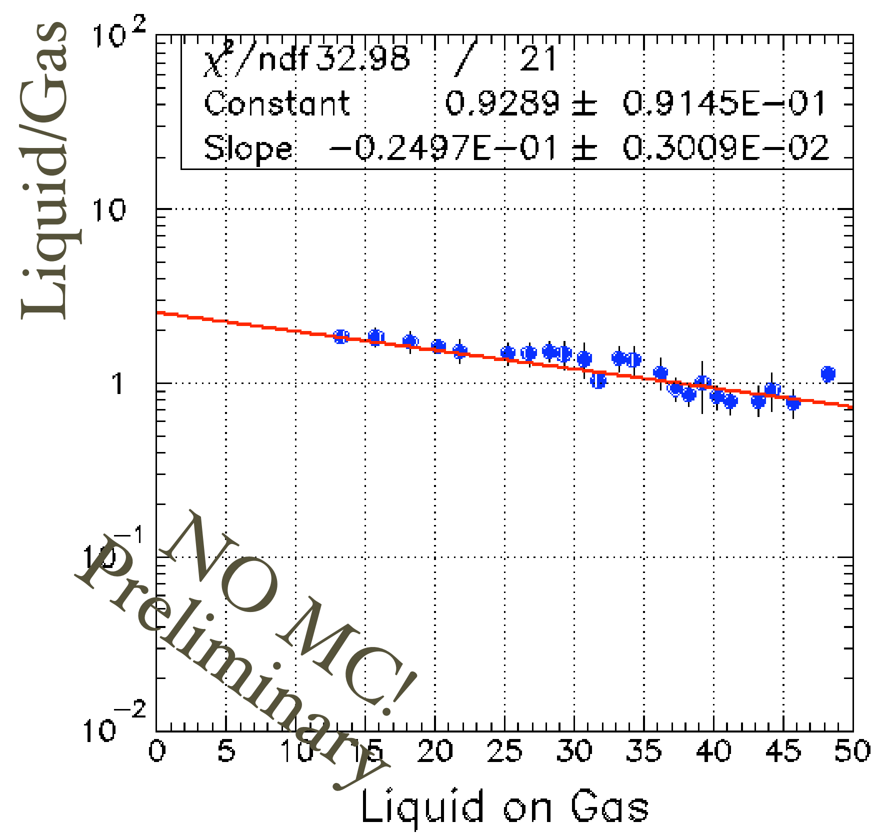




λ_{Abs} measurement

- 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)





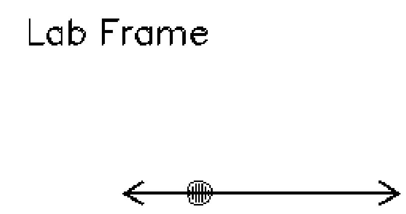
Attenuation = Rayleigh

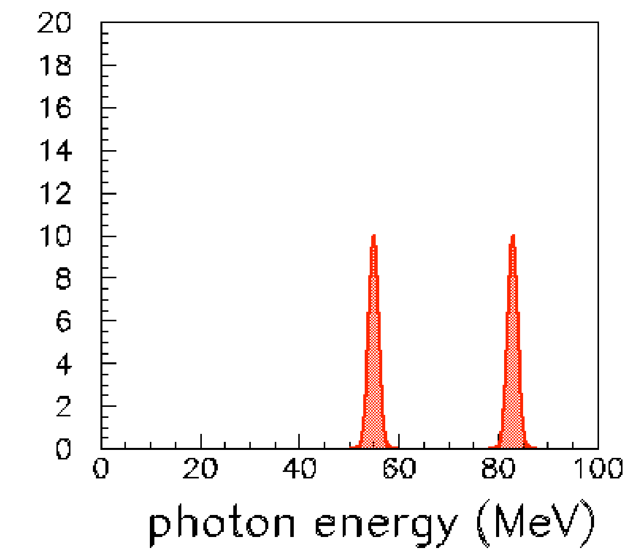
$\lambda_{Att} \sim 40$ cm

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

Energy resolution measurement

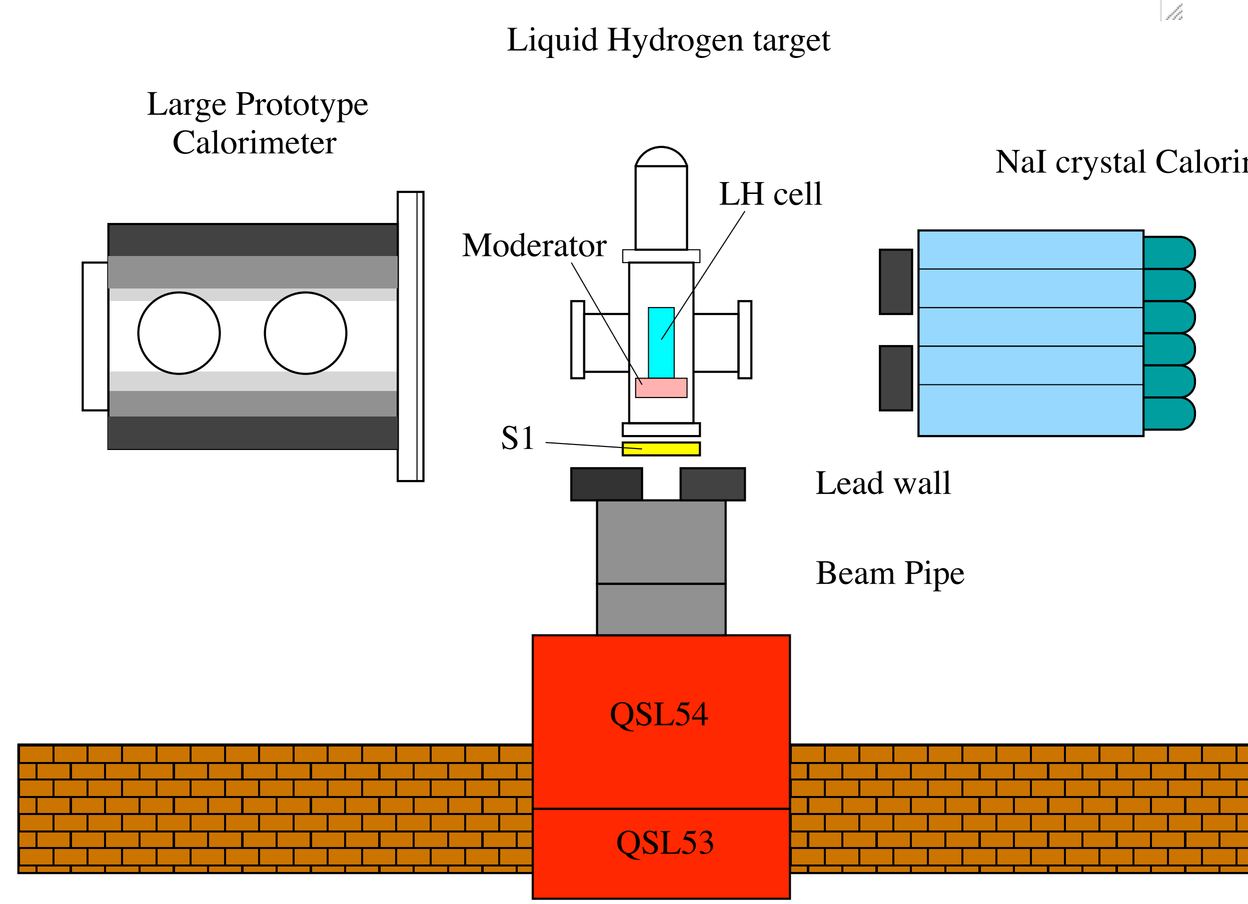
$$\pi^- p \to \pi^0 n$$
$$\pi^0 \to \gamma\gamma$$





- 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

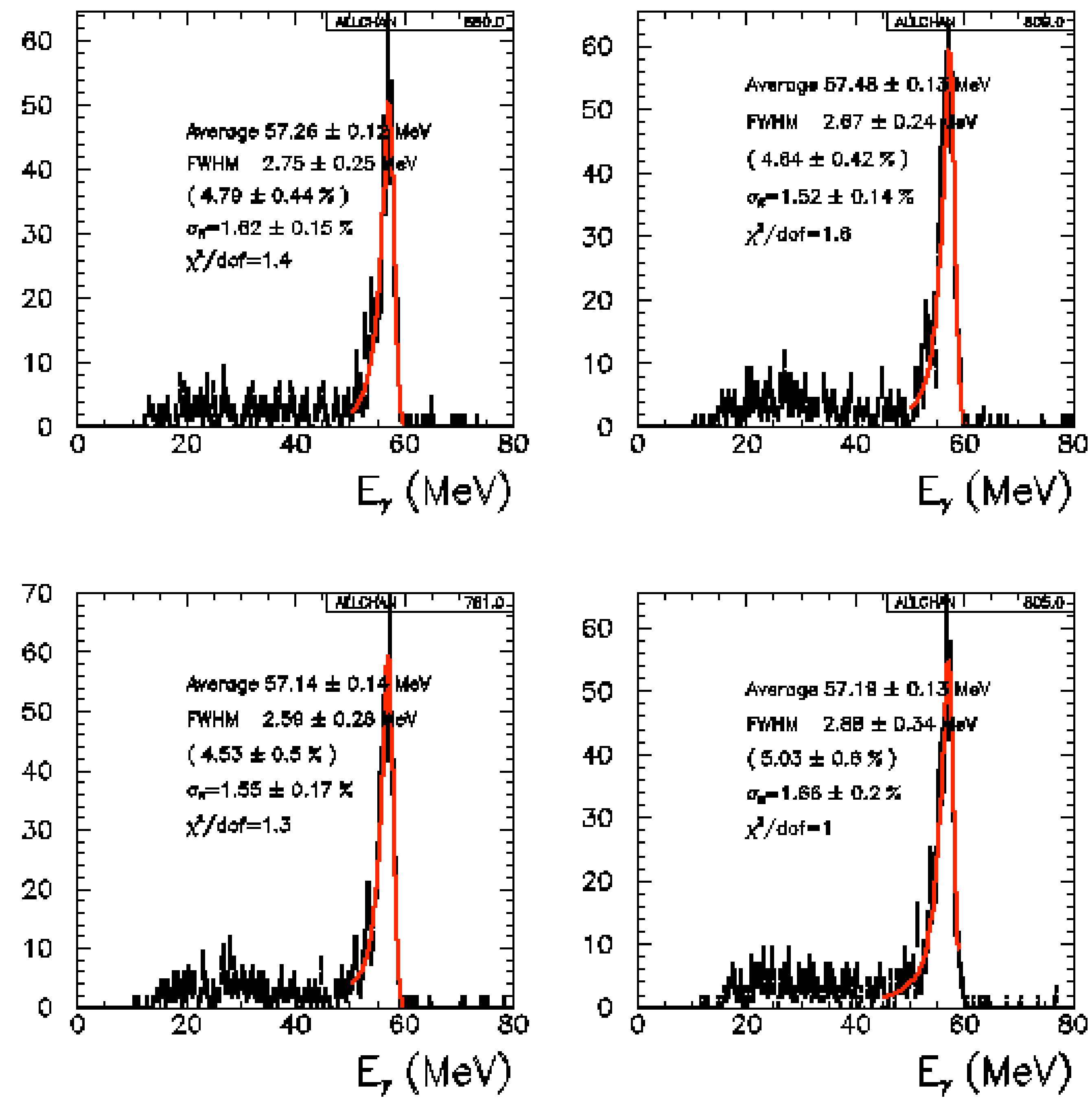
- Even a modest collimation guarantees a sufficient monochromaticity
- Liquid hydrogen target to maximize photon flux
- An "opposite side detector" is needed (NaI array)



Position dependence

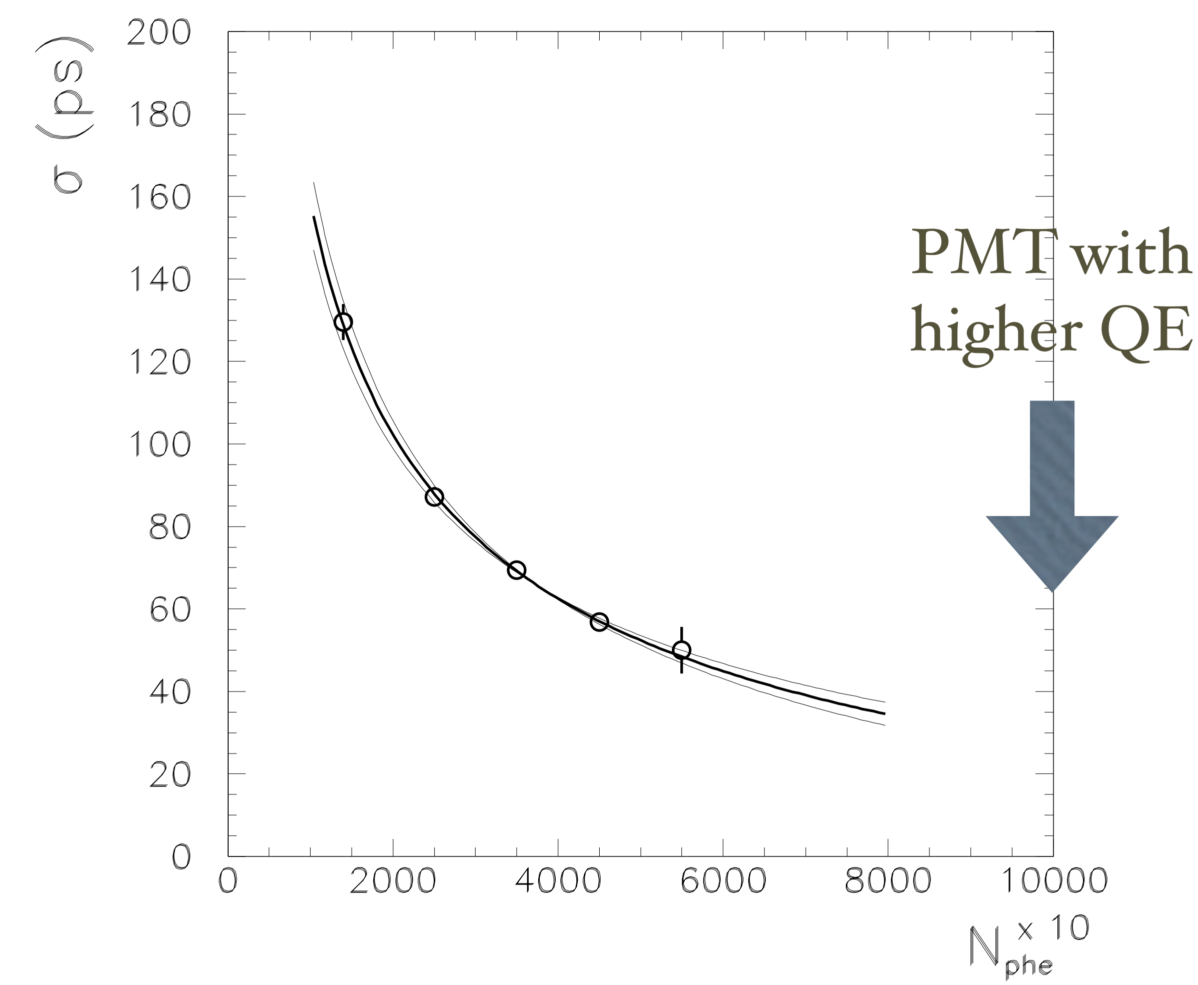
- small FWHM residual dependence
- no significant peak shift
- The resolution is always better than 5% FWHM

4.8%	4.6%
4.5%	5.0%



Intrinsic resolution (2003)

- Does not include the fluctuations of the photon conversion
- Divide the PMTs in two groups (LEFT and RIGHT)
  - $$T_{L,R} = \frac{\sum_{i\in\{L,R\}} T_i/\sigma_i^2}{\sum_{i\in\{L,R\}} 1/\sigma_i^2}$$
  - $$T_{\text{intr}} = \frac{1}{2}\left(T_L - T_R\right)$$



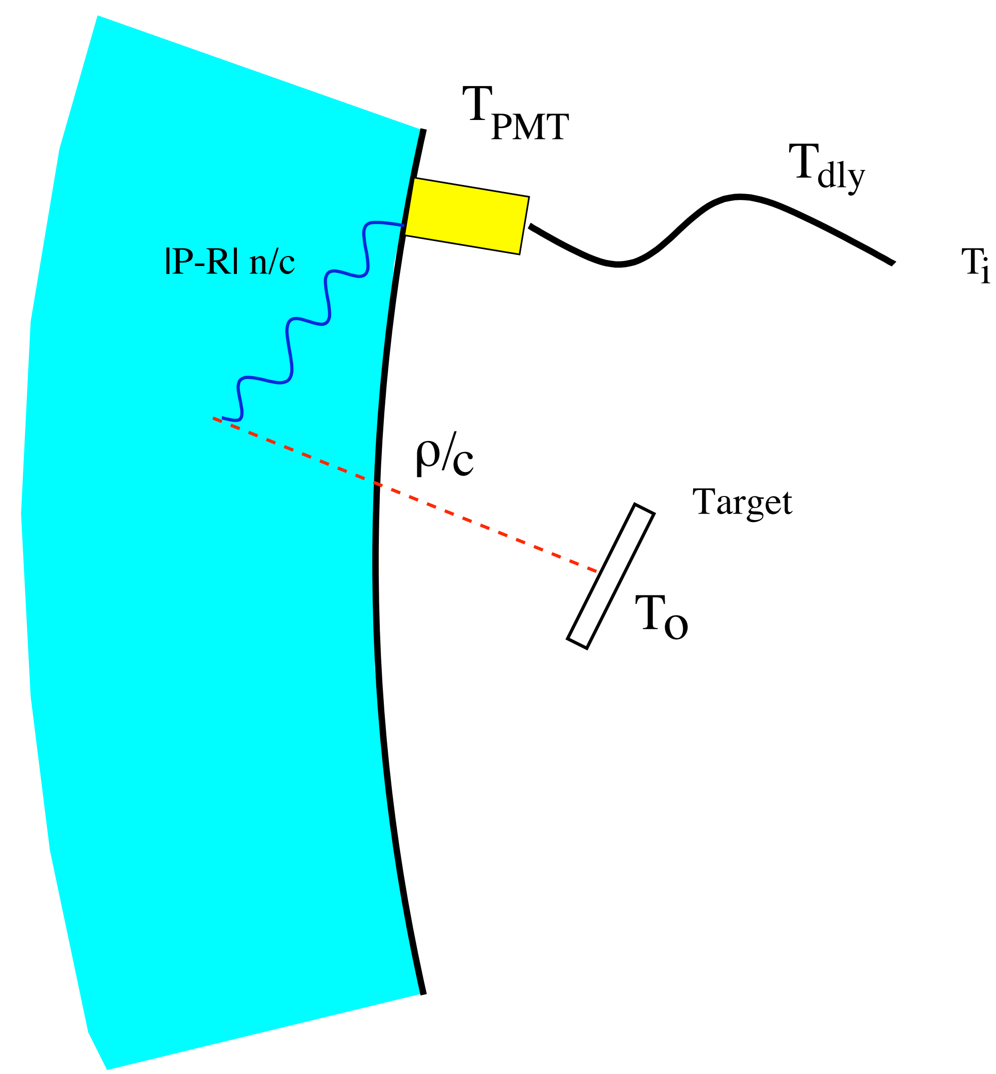
- Studied as a function of N(phe)
- Extrapolation: (30±10) ps @ 100000 phe

Calibrations

Timing resolution

- We have to determine the time of the photon production in the target

$$T_0 = T_i^{tw} - \frac{\rho_{\rm int}}{c} - \frac{|\vec{R}_{\rm int} - \vec{P}_i| n_{\rm Xe}}{c} - T_{\rm PMT} - T_{\rm dly}$$



- The fluctuation on To is the sum of all the fluctuations of the various terms
- We distinguish two "types" of resolution:
  - Intrinsic resolution
  - Absolute resolution
- Skip 3