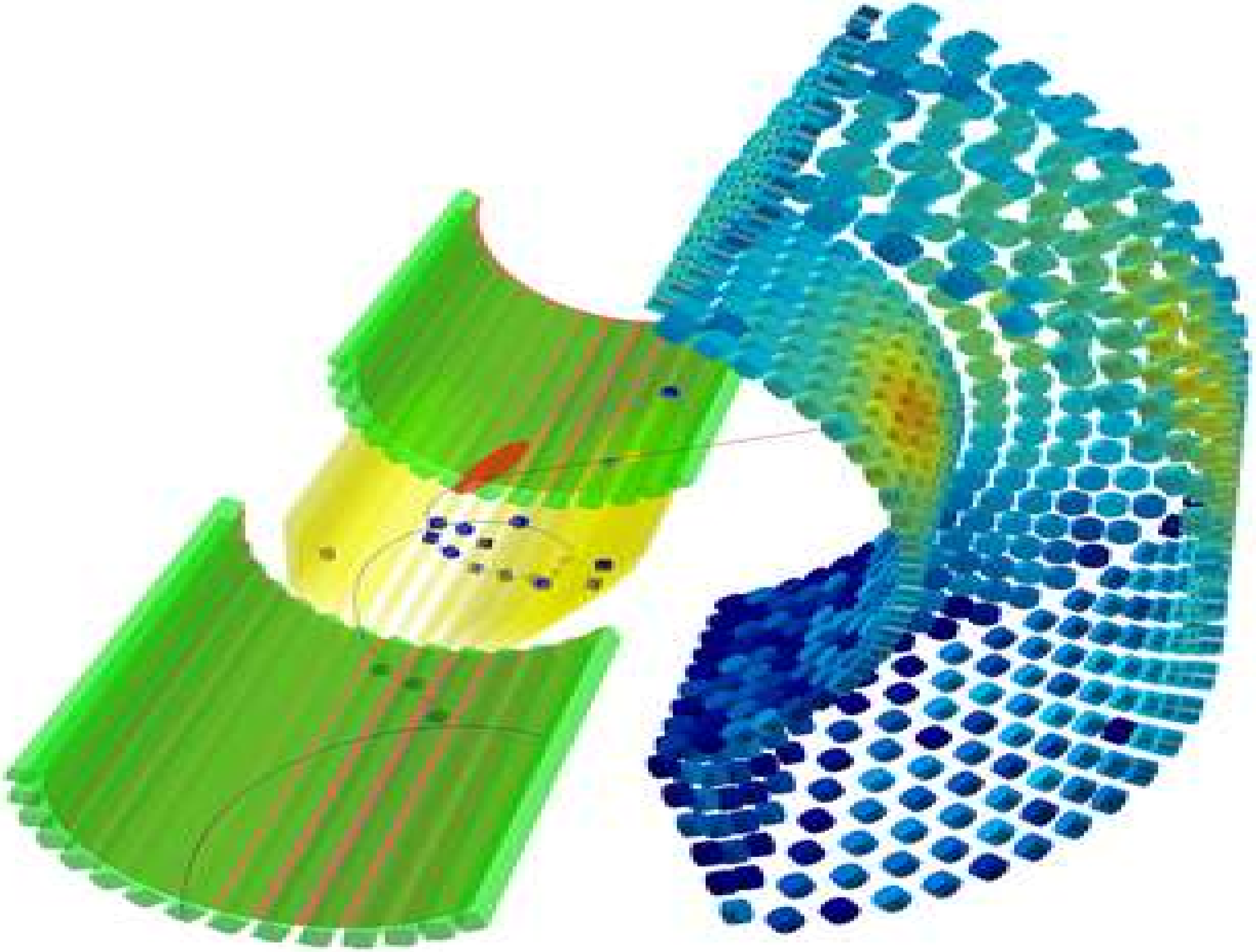
First results from the MEG experiment: $\mu \to e\gamma$

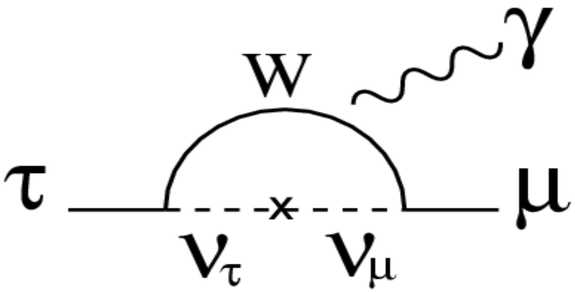
Paolo Walter Cattaneo, INFN Pavia, Italy, 18-11-2009

International conference on Neutrino Physics in the LHC Era, Luxor, Egypt

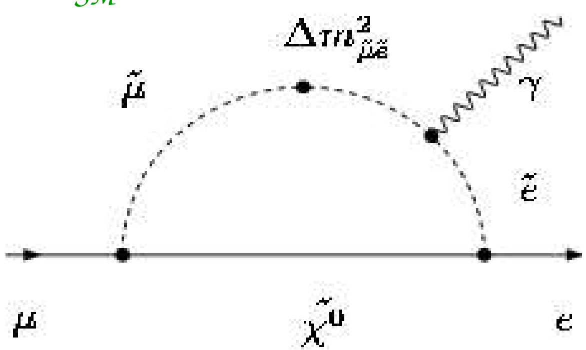


The $\mu \rightarrow e\gamma$ decay

SM with massive ν



BR$_{SM}$*(*$\mu \rightarrow e\gamma$*)* $\approx$ *10-14 ÷ 10-13*



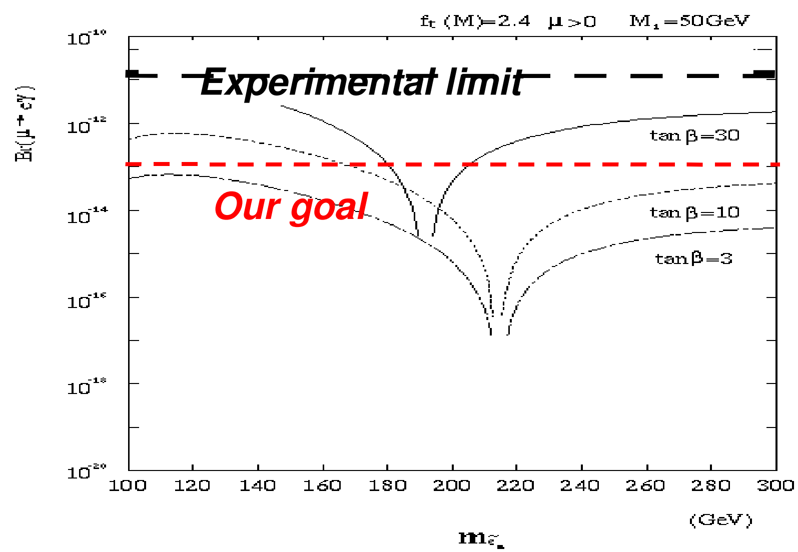
LFV induced by slepton mixing

R. Barbieri et al., Phys. Lett. B338(1994) 212

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

- *SUSY SU(5)* *BR* $(\mu \rightarrow e\gamma) \approx 10^{-14} \div 10^{-13}$
- *SUSY SO(10)* $BR_{SO(10)} \approx 100\ BR_{SU(5)}$

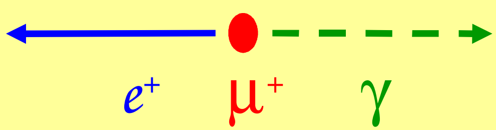
Lab.	Year	Upper limit	Experiment or Auth.
PSI	1977	$< 1.0 \times 10^{-9}$	A. Van der Schaaf *et al.*
TRIUMF	1977	$< 3.6 \times 10^{-9}$	P. Depommier *et al.*
LANL	1979	$< 1.7 \times 10^{-10}$	W.W. Kinnison *et al.*
LANL	1986	$< 4.9 \times 10^{-11}$	Crystal Box
LANL	1999	$< 1.2 \times 10^{-11}$	MEGA
PSI	~2011	$\sim 10^{-13}$	*MEG*



Signal and background

signal

$\mu \rightarrow e\gamma$



$\theta_{e\gamma} = 180°$

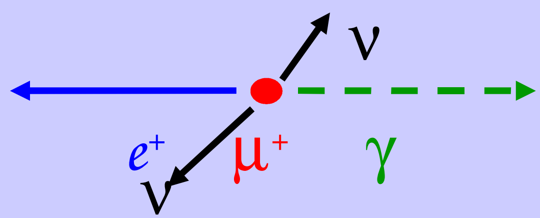
$E_e = E_\gamma = 52.8\ MeV$

$T_e = T_\gamma$

background

physical

$\mu \rightarrow e\gamma\nu\nu$



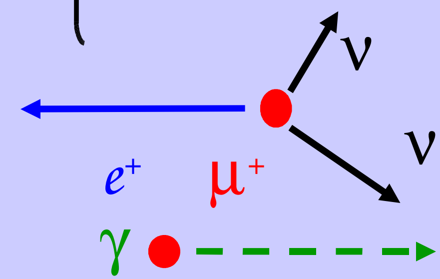
accidental

$\mu \rightarrow e\nu\nu$

$\mu \rightarrow e\gamma\nu\nu$

$ee \rightarrow \gamma\gamma$

$eZ \rightarrow eZ\gamma$



Need μ^+ to avoid muonic atoms

The sensitivity is limited by the accidental background

$$n_{sig} \propto R_{\mu} T \quad n_{phys,b} \propto R_{\mu} T \quad n_{acc,b} \propto R_{\mu}^2 T$$

The n. of acc. backg events ($n_{acc.b.}$) depends quadratically on the muon rate R_{μ} and on the quality of the measurement of the experimental quantities:

e-γ relative timing and angle, positron and photon energy

$$BR_{acc} \propto R_{\mu} \times \Delta t_{e\gamma} \times \Delta\theta^2_{e\gamma} \times \Delta E_e \times \Delta E_{\gamma}^2$$

DC beam, rather than pulsed beam, give lowest instantaneous rate R_{μ} and thus lowest background

Required Performances

$BR(\mu \to e\gamma) \approx 10^{-13}$ reachable

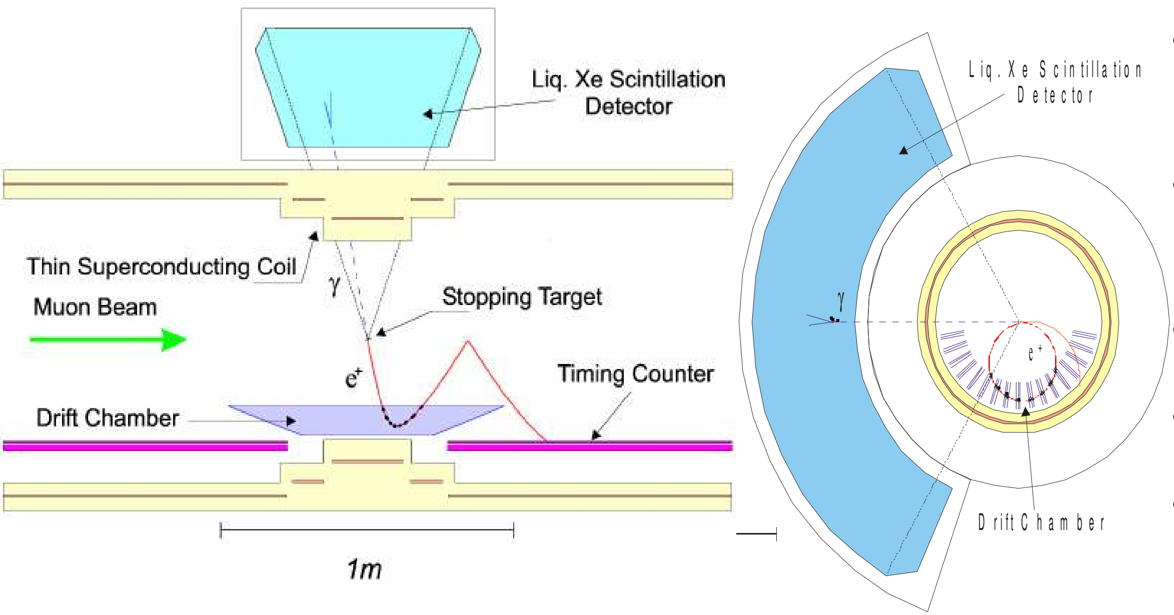
$BR_{acc.b} \approx 2\ 10^{-14}$ and $BR_{phys.b} \approx 0.1\ BR_{acc,b}$ with the following resolutions

FWHM (applies to $\Delta E_e/E_e$, $\Delta E_\gamma/E_\gamma$, $\Delta t_{e\gamma}$, $\Delta\theta_{e\gamma}$)

Exp./Lab	Year	$\Delta E_e/E_e$ (%)	$\Delta E_\gamma/E_\gamma$ (%)	$\Delta t_{e\gamma}$ (ns)	$\Delta\theta_{e\gamma}$ (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	2011	0.8	4	0.15	19	2.5×10^7	100	1×10^{-13}

Need of a DC muon beam

Experimental method



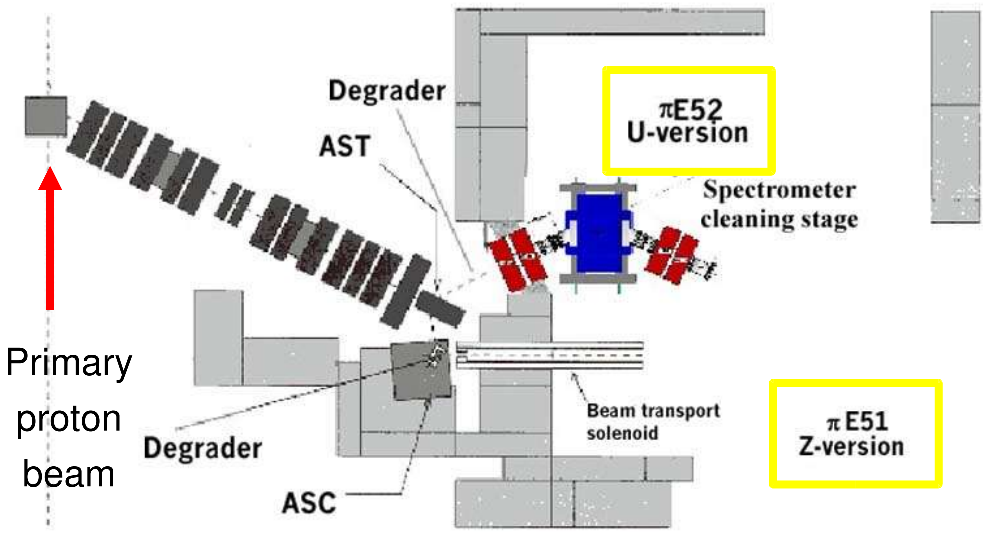
Detector outline

- *Stopped beam of 3 10^7 μ /sec in a 205 μm target*
- *Solenoid spectrometer & drift chambers for e^+ momentum*
- *Scintillation counters for e^+ timing*
- *Scintillating fiber for e^+ z position*
- *Liquid Xenon calorimeter for γ detection (scintillation)*

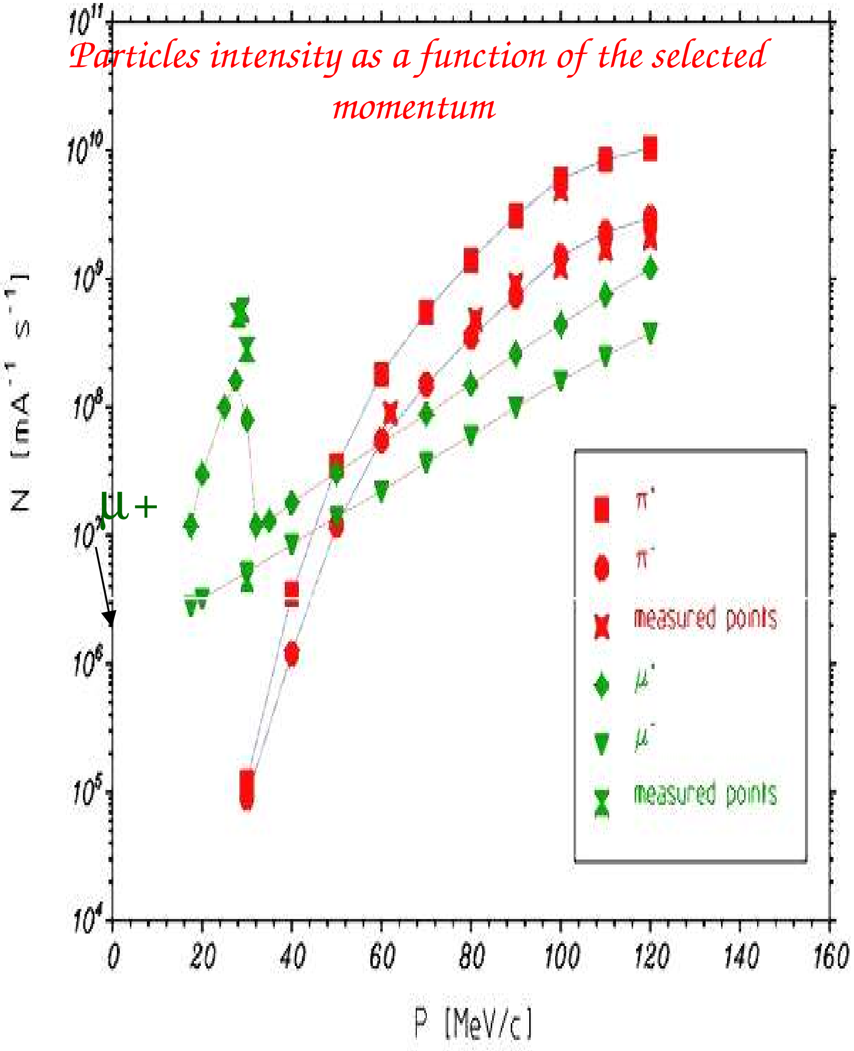
MEG proposal: September 2002: 10^{-13} goal: A. Baldini and T. Mori et al.,

Italy, Japan, Switzerland, Russia

The PSI πE5 DC beam



The layout of πE5

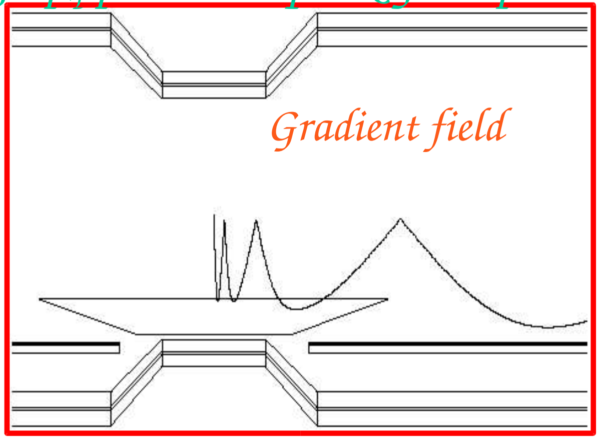


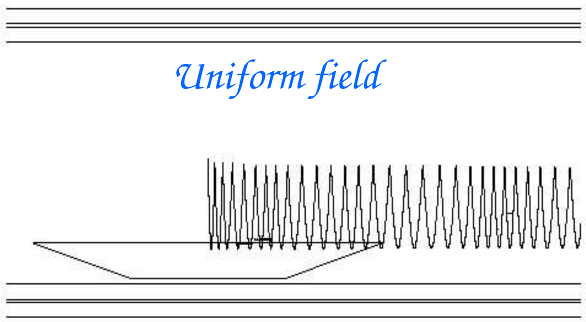
- **1.8 mA of 590 MeV/c protons (most intense DC beam in the world)**
- **29 MeV/c muons from decay of π stop at rest: fully polarized**

The positron spectrometer: COBRA spectrometer

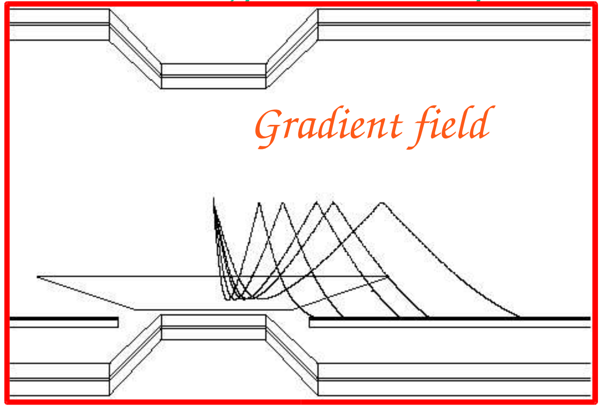
COnstant Bending RAdius (COBRA) spectrometer

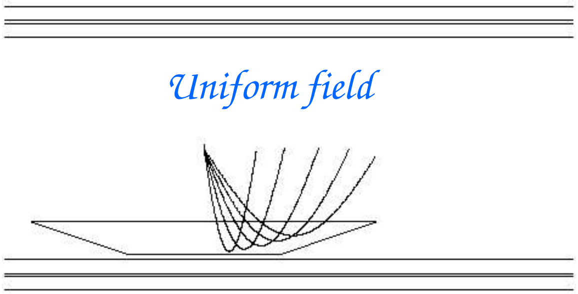
- High p_T positrons quickly swept out: reduced #DCH hits



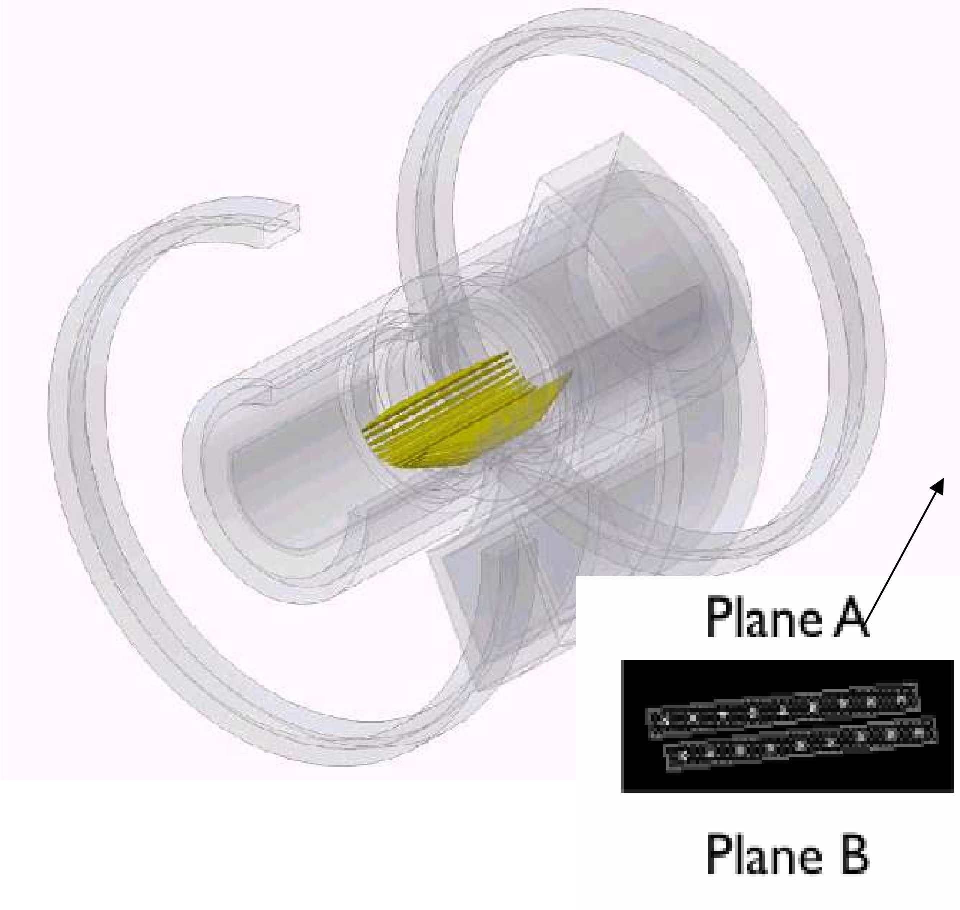


- Constant bending radius independent of emission angles: ease of treigger



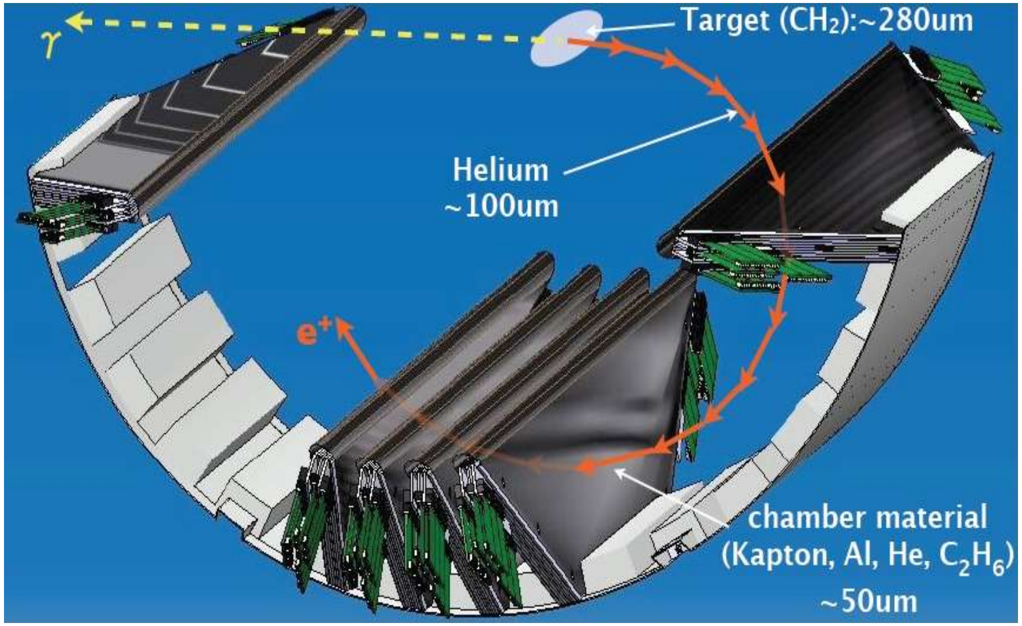


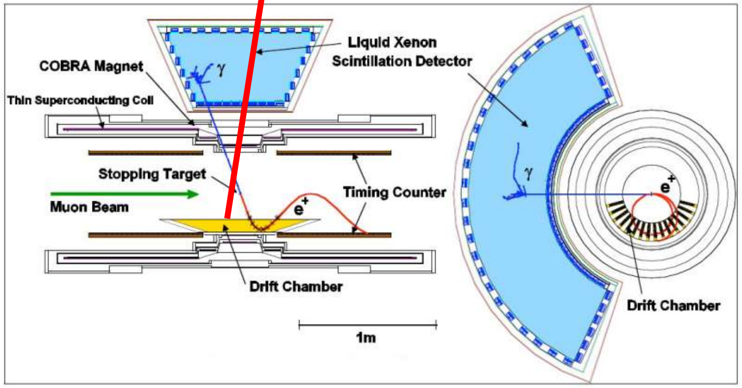
The drift chambers

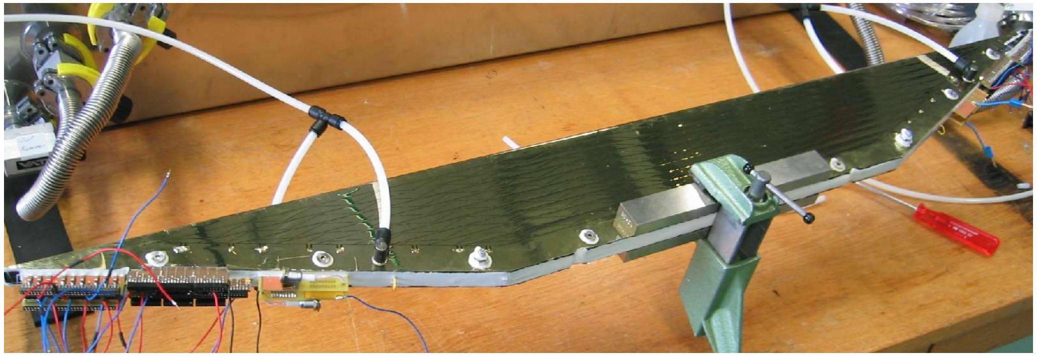


- *16 chamber sectors aligned radially with 10°intervals*
- *Two staggered arrays of drift cells*
- *Chamber gas: He-C_2H_6 mixture*
- *Vernier pattern to measure z-position made of 15 µm kapton foils*
- *Embedded in He gas to reduce MS*
- *Elliptic thin target slanted ~ 20^0 to reduce MS*

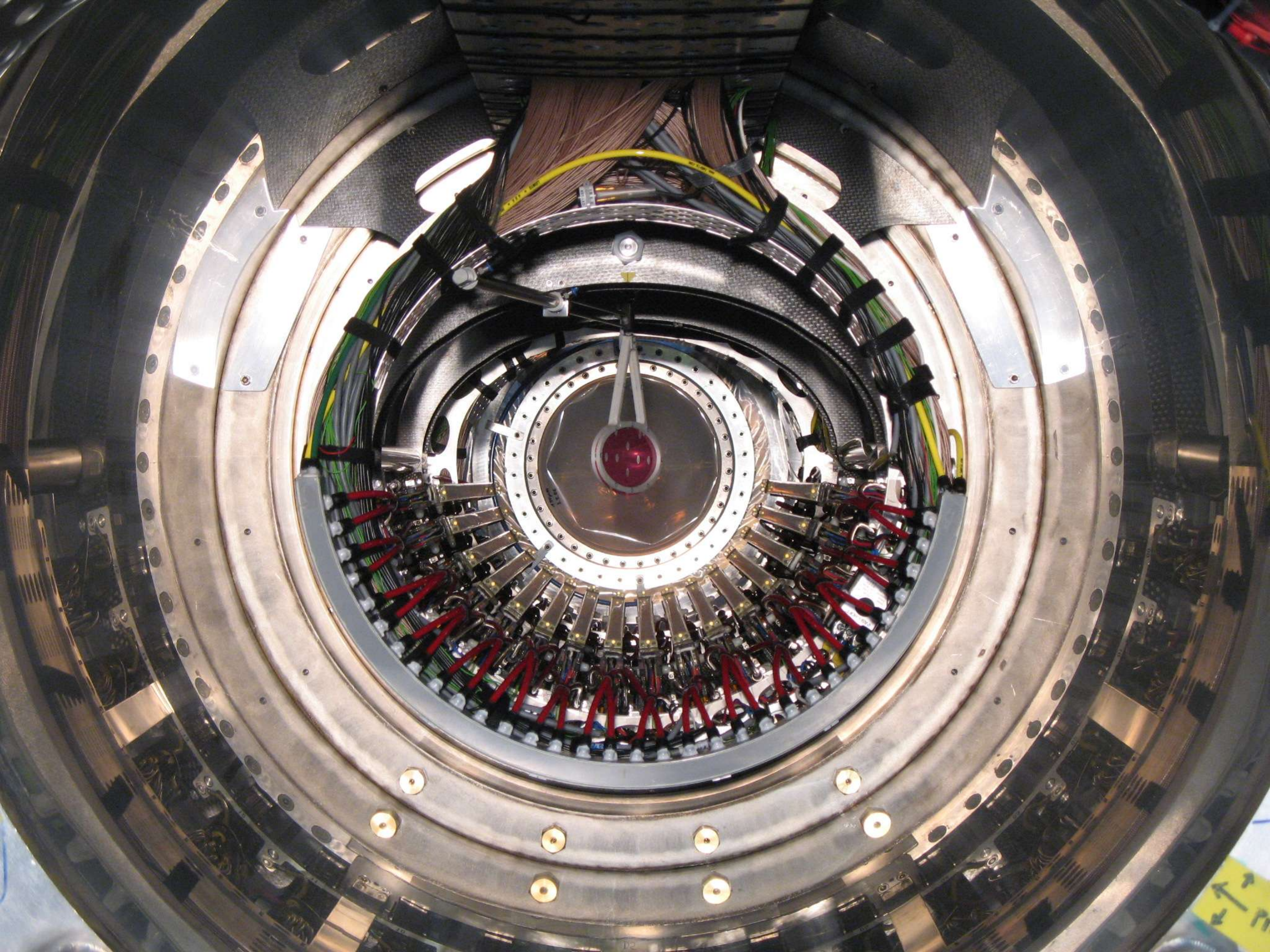
Goals:
σ(X,Y) ~200 µm (drift time)
σ(Z) ~ 300 µm (charge division vernier strips)
σ(p) ~ 0.4%



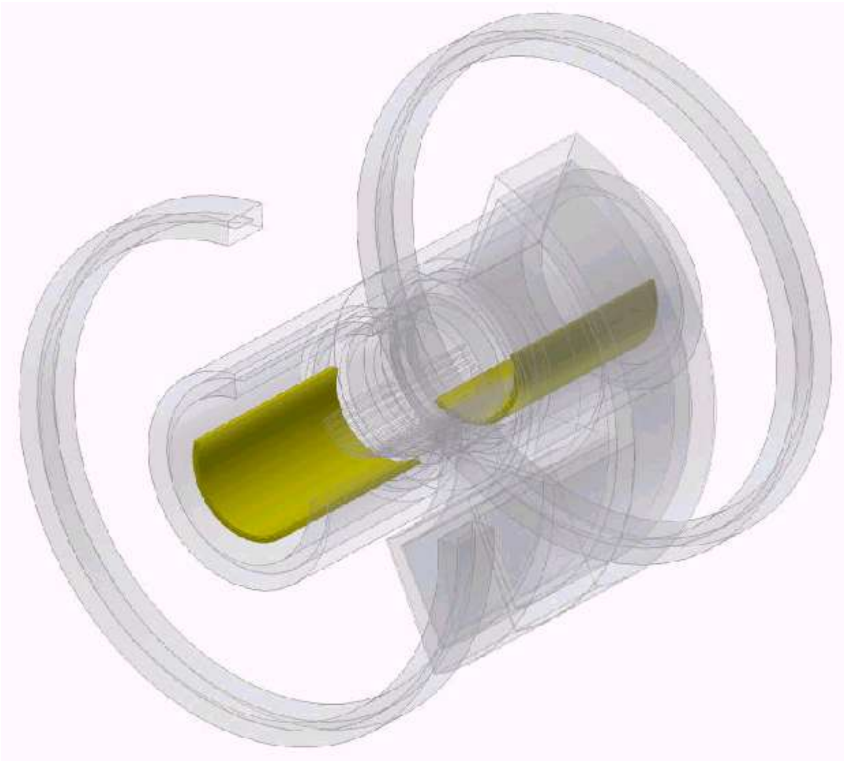


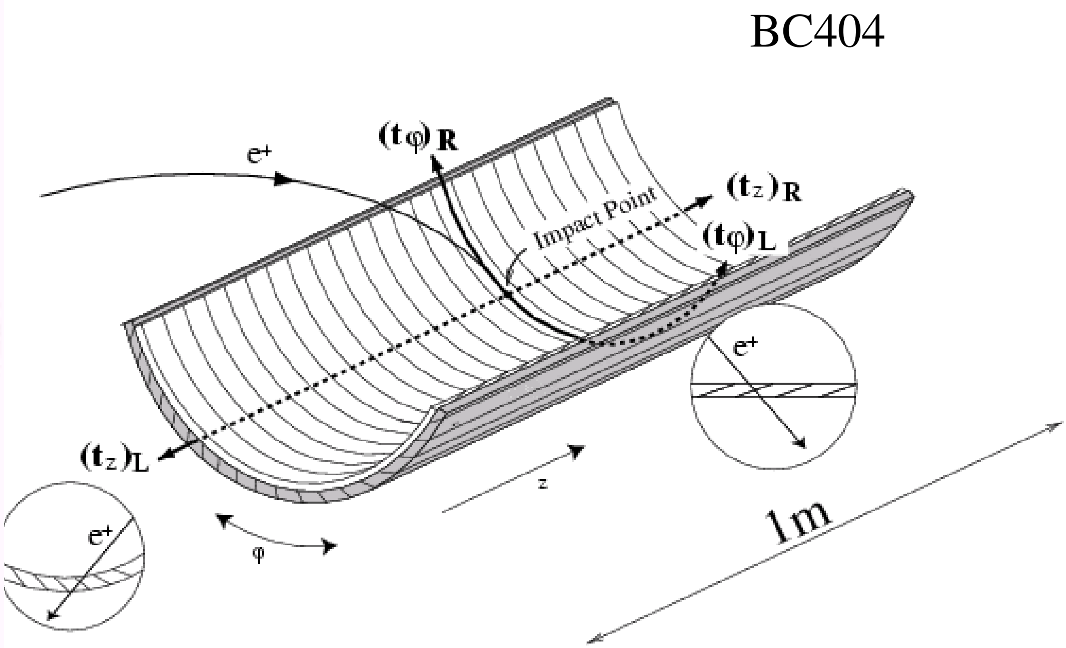


2 10^{-3} X_0 along e^+ trajectory

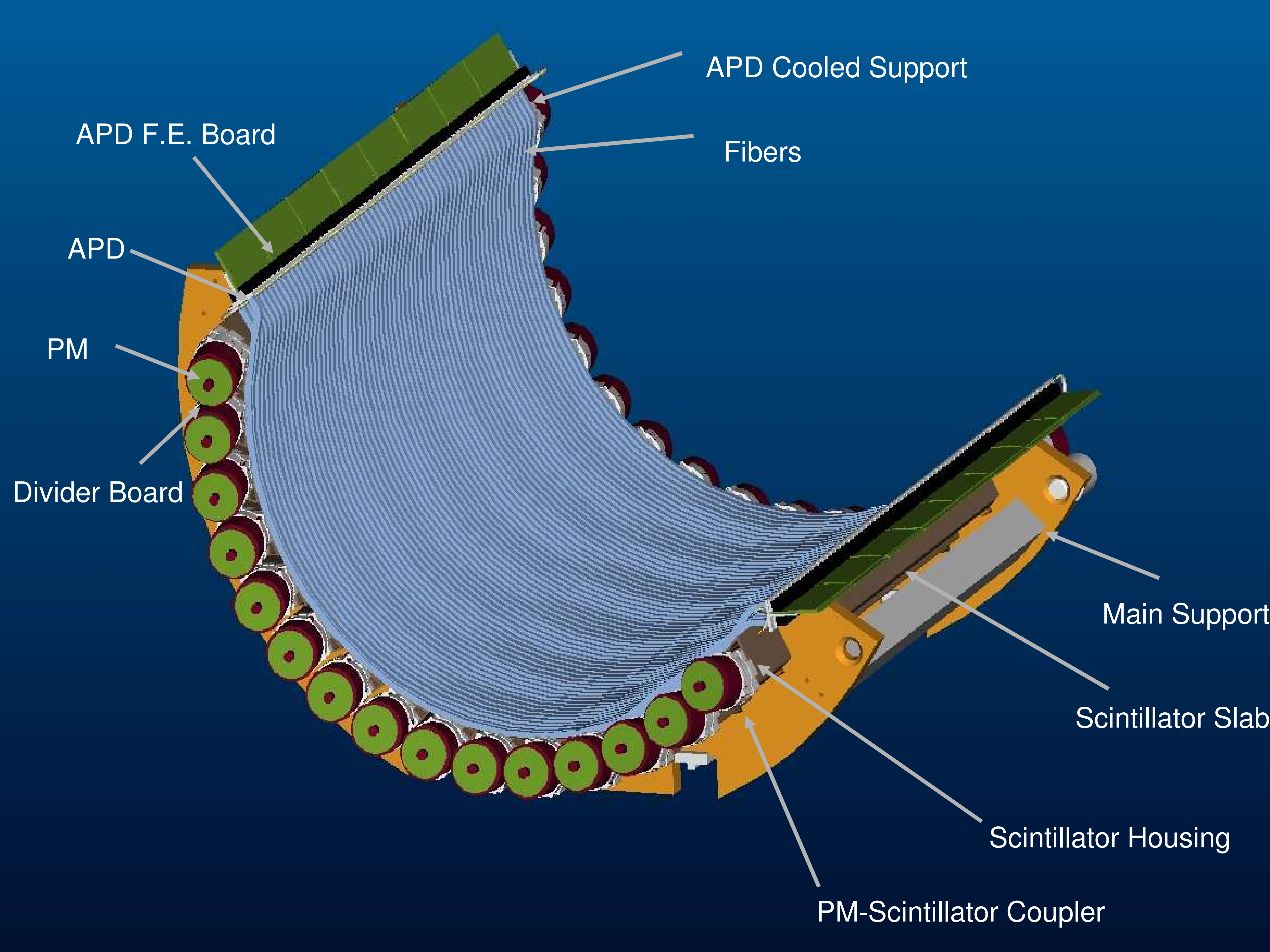


The Timing Counter





- One (outer) layer of scintillating bars read by PMTs : e^+ timing
One inner layer of scintillating fibers read by APDs: e^+ z for trigger and analysis (longitudinal position is needed for a fast estimate of the e^+ direction)
- Goal σ_{time}~ 40 ps (100 ps FWHM) σ_z~ 2 mm

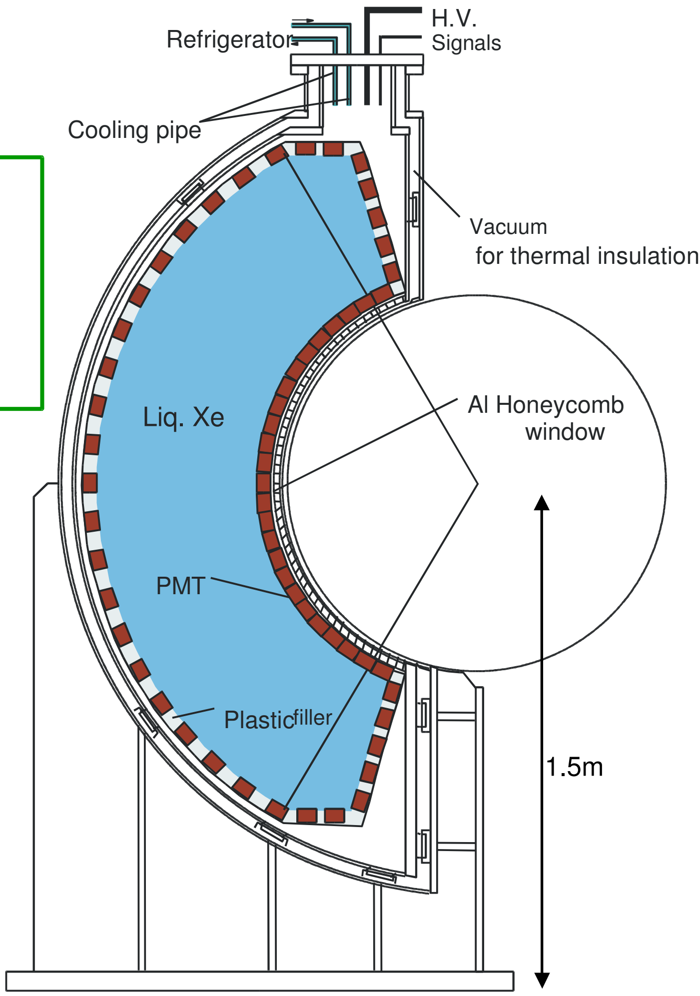

APD Cooled Support
Fibers
APD F.E. Board
APD
PM
Divider Board
Main Support
Scintillator Slab
Scintillator Housing
PM-Scintillator Coupler

The Liquid Xe calorimeter

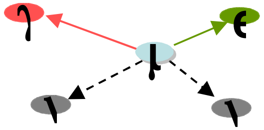
- 800 l of Liquid Xe
- 848 PMT immersed in LXe
- Only scintillation light
- High luminosity
- Unsegmented volume

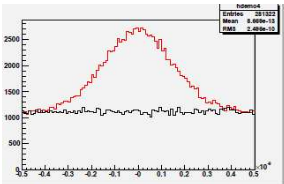
Experimental check
In a Large Prototype

Density		2.95 g/cm^3
Boiling and melting points	→	165 K, 161 K
Energy per scintillation photon	→	24 eV
Radiation length	→	2.77 cm
Decay-time	→	4.2 nsec, 22 nsec 45 nsec
Scintillation light wave length	→	175 nm
Scintillation absorption length		> 100 cm
Attenuation length (Rayleigh scattering)		30 cm
Refractive index		1.74



μ radiative decay





Lower beam intensity < 10^7

Is necessary to reduce pile-ups

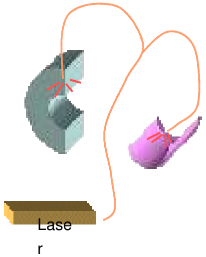
Better σ_t, makes it possible to take data with higher beam intensity

A few days ~ 1 week to get enough statistics

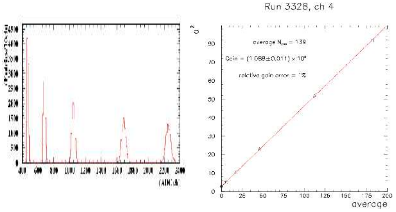
Laser

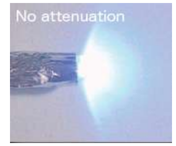
(rough) relative timing calib.

< 2~3 nsec



LED

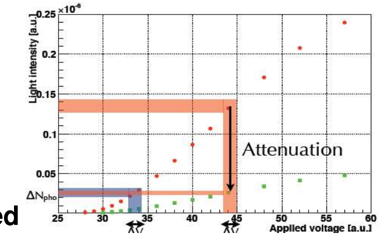




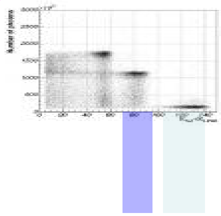
PMT Gain

Higher V with light att.

Can be repeated frequently



$\pi^0 \rightarrow \gamma\gamma$



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

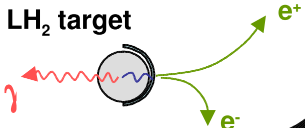
$\pi^0 \rightarrow \gamma\gamma$ (55MeV, 83MeV)

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

10 days to scan all volume precisely

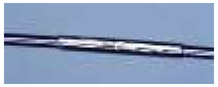
(faster scan possible with less points)

LH_2 target



Xenon Calibration

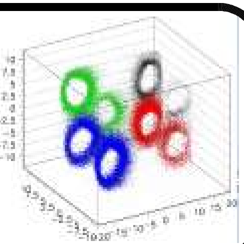
alpha



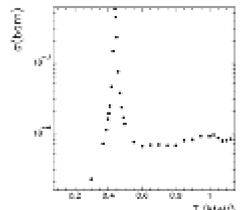
PMT QE & Att. L

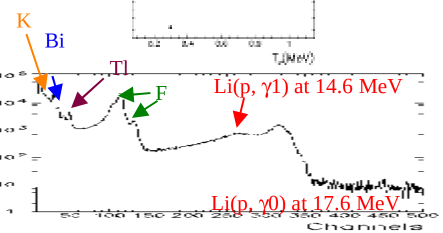
Cold GXe

LXe



Proton Acc





Li(p,γ)Be

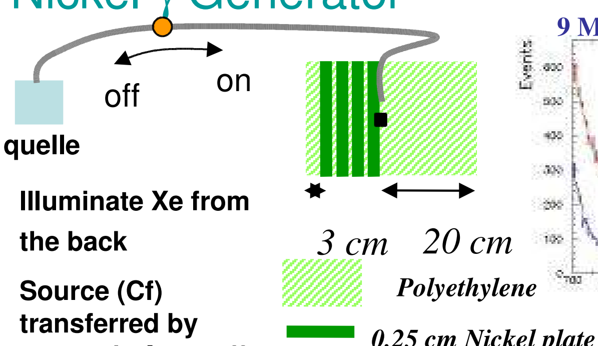
LiF target at COBRA center

17.6MeV γ

~daily calib.

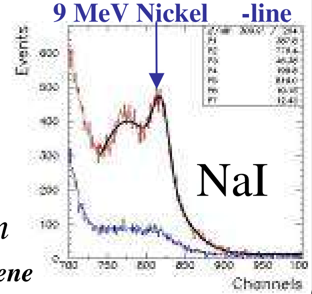
Can be used also for initial setup

Nickel γ Generator



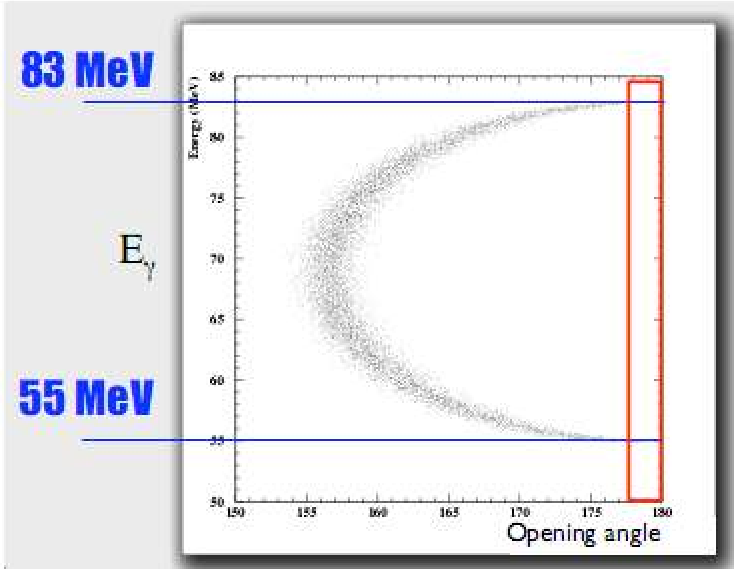
Illuminate Xe from the back

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

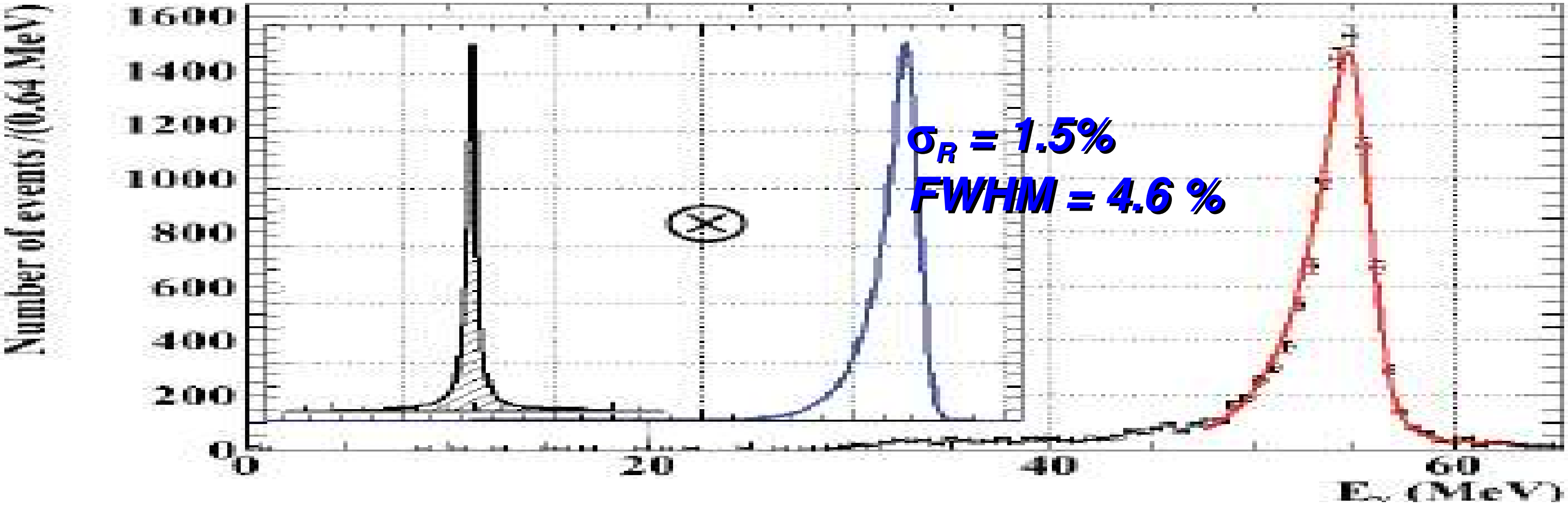


Calorimeter energy Calibration by Charge Exchange Reactions (CEX)

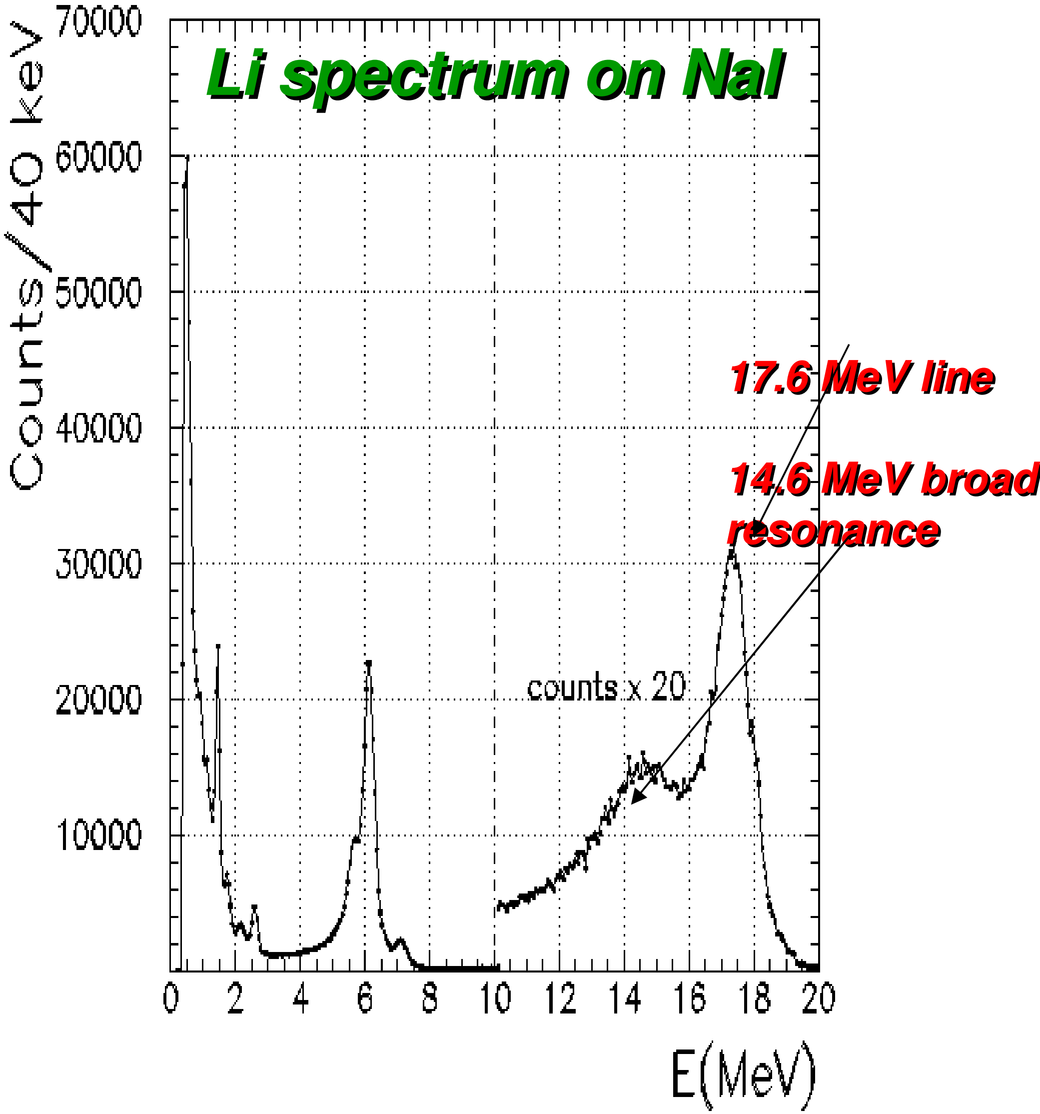
$$\pi^- p \rightarrow \pi^0 n \rightarrow \gamma\gamma n$$



- π^- stopped in liquid H_2 target
- Tagging γ at 180^0 provides monochromatic γ
- NaI crystal array to tag the other γ
- Dalitz decay π^0-> $\gamma\, e^+e^-$ to study $e^+\gamma$ synchronization and time resolution



Monochromatic Photons from Nuclear Reactions



- Sub-Mev proton beam by a Cockcroft-Walton (CW) impinge on a $Li_2B_3O_7$ target
- 17.6 MeV from ^{7}Li
- 2 coincidence γ (4.4, 11.6) MeV from ^{11}B: synchronization of LXe and TC
- Short runs thrice a week

DAQ: trigger

Uses easily quantities:

- e^+ - γ coincidence in time and direction
- γ energy
- Built on a **FADC-FPGA** architecture
- More complex algorithms implementable

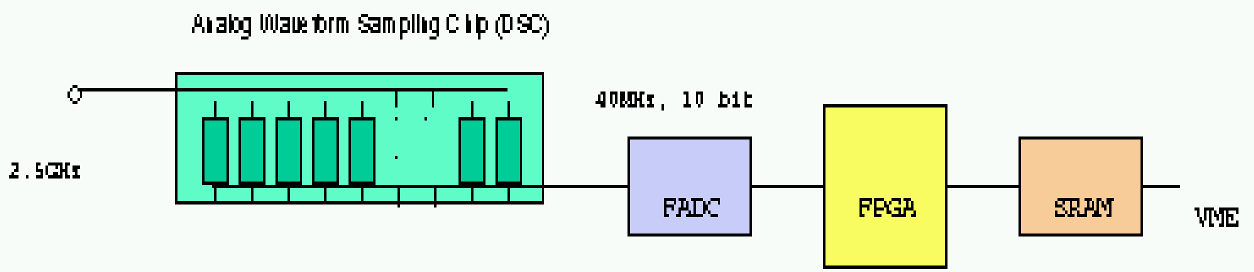
❖ Beam rate	10^8 s^{-1}
❖ Fast LXe energy sum > 45MeV	2×10^3 s^{-1}
γ interaction point (PMT of max charge)	
e^+ hit point in TC	
❖ time correlation γ – e^+	200 s^{-1}
❖ angular correlation γ – e^+	20 s^{-1}
❖ ~5 Hz trigger rate in 2008 data taking	

Trigger:

Signals from Calorimeter and TC bar are sampled at 100 MHz with separate ADC

Several trigger combinations available to study trigger and detector efficiency for all subdetectors

Readout electronics: the Domino Principle



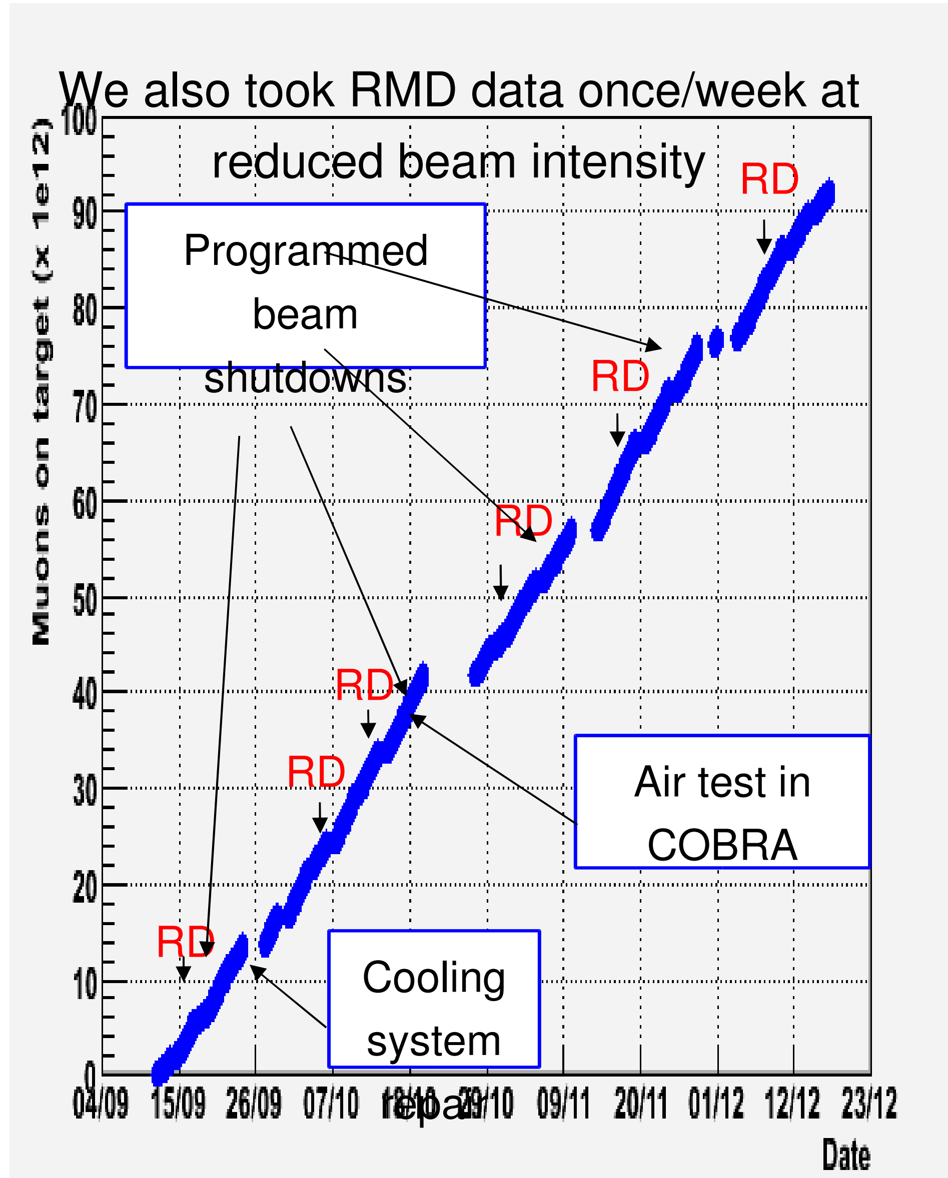
- ***Waveform digitizing for all channels (pile-up rejection);***
- ***Custom sampling chip*** **Domino Ring Sampler** ***(DRS) designed at PSI;***
- ***2.5 GHz sampling speed @ 40 ps timing resolution;***
- ***Sampling depth 1024 bins;***
- ***Readout similar to trigger;***
- ***Trigger:***

Signals from Calorimeter and TC bar are sampled at 100 MHz with separate ADC

Several trigger combinations available to study trigger and detector efficiency for all subdetectors

The 2008 Physics run

- Long calibration run in summer with π charge exchange (CEX)
- First 3 months physics data taking (september-december 2008)
- During physics run, frequent calibration runs (CW, RMD) were conducted frequently
- Another CEX run performed at end of run



Drift chamber instability

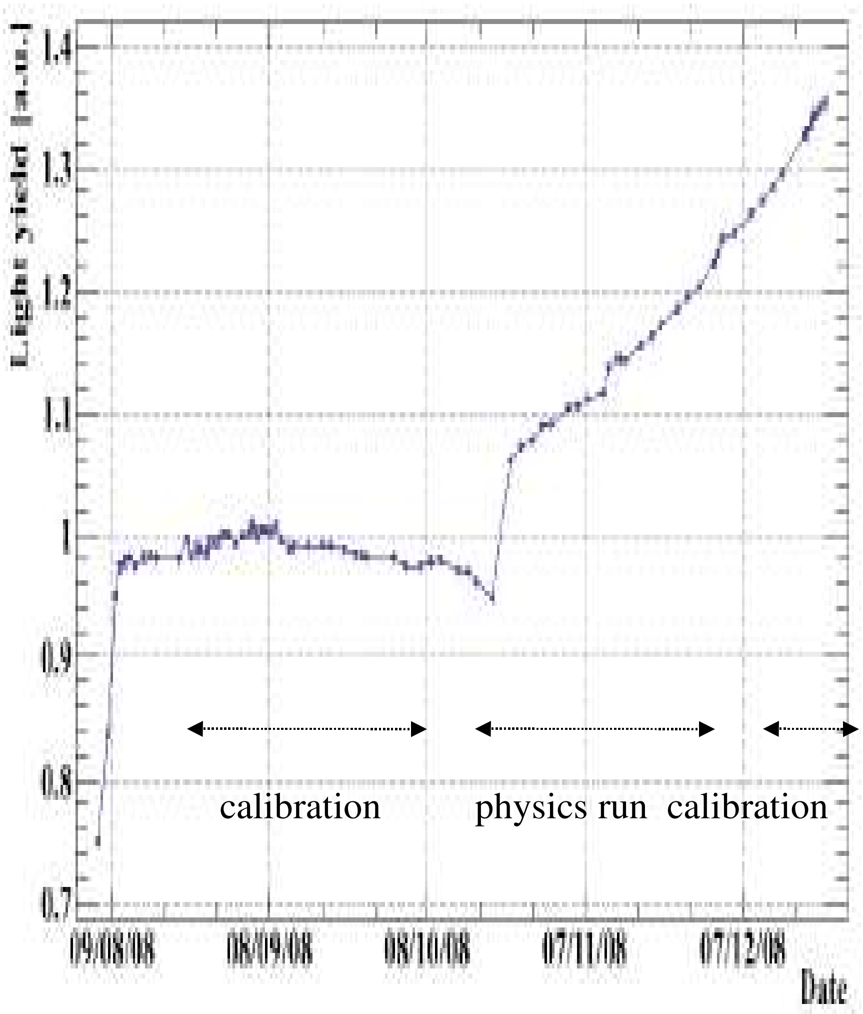
- DC showed frequent HV trips after 2-3 months of operation
- Increased #DCs had to be operated with reduced HV
- Reduced efficiency and resolution for e^+ measurement
- Problem related to lomg term exposure to He
- The DC instability uncertainty cancels out in the $\mu^+ \to e^+\gamma$ analysis: BR = $\#\mu^+ \to e^+\gamma / \#$ Michel
- DC modules are now modified and runs without problems in the laboratory and in the experiment since several months.

Light yield of LXe calorimeter

• LXe has been purified durng the run monitoring the increase of the light yield with calibration tools (CW, alpha, LED, cosmic rays)

•Overall energy scale uncertainty during the whole run period: ~0.4%

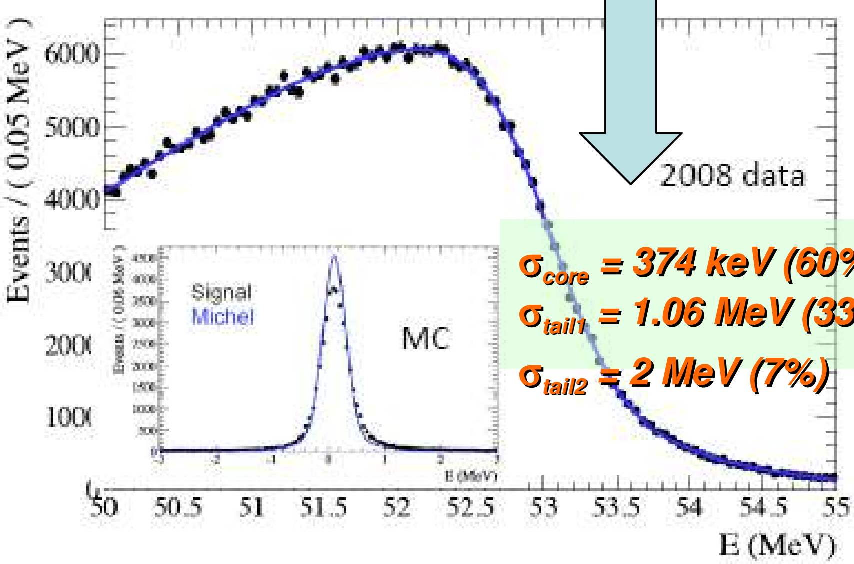
•The light yield at the end of the run was 70% of the expectation



DCH resolutions from 2008 data

Tracks with two turns in the spectrometer are used to estimate theangular resolutions

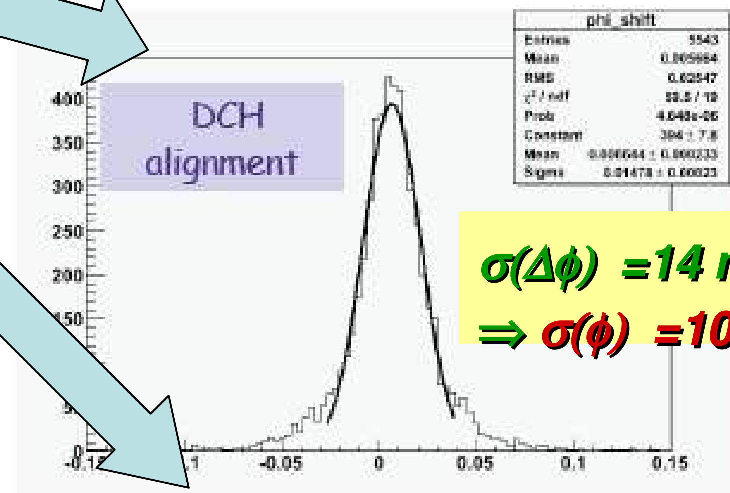
The edge of Michel positrons used to determine momentum resolution



σ_{core} = 374 keV (60%)

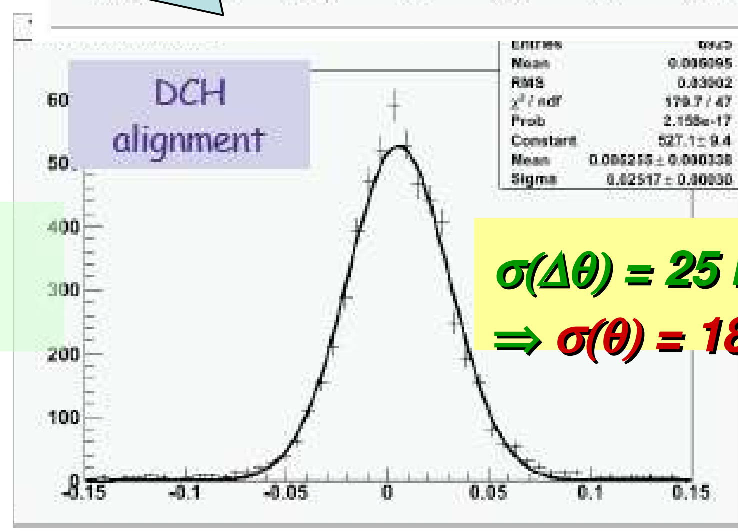
σ_{tail1} = 1.06 MeV (33%)

σ_{tail2} = 2 MeV (7%)



$\sigma(\Delta\phi)$ =14 mrad

$\Rightarrow \sigma(\phi)$ =10 mrad

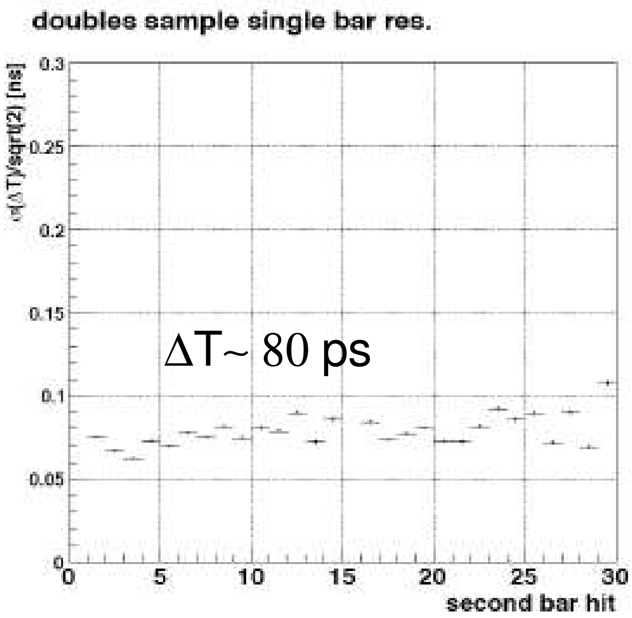


$\sigma(\Delta\theta)$ = 25 mrad

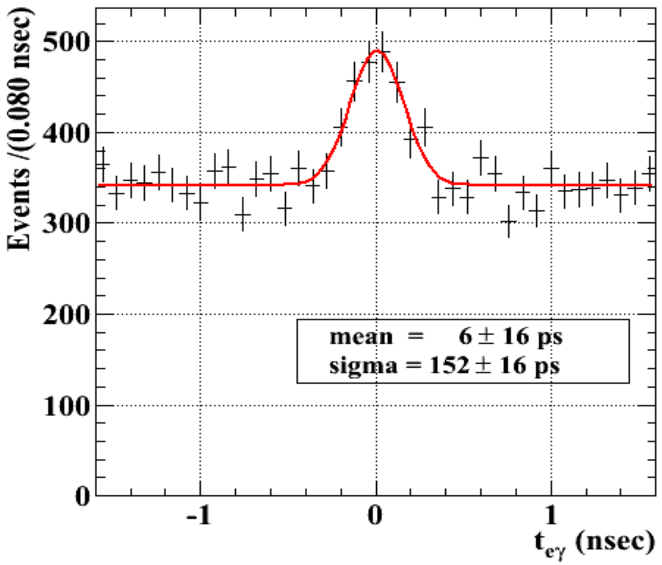
$\Rightarrow \sigma(\theta)$ = 18 mrad

γ-e^+ Timing resolutions from 2008 data

Intrinsic timing resolution using e^+ hitting several bars



γ-e^+ timing resolution by using Radiative Muon Decay



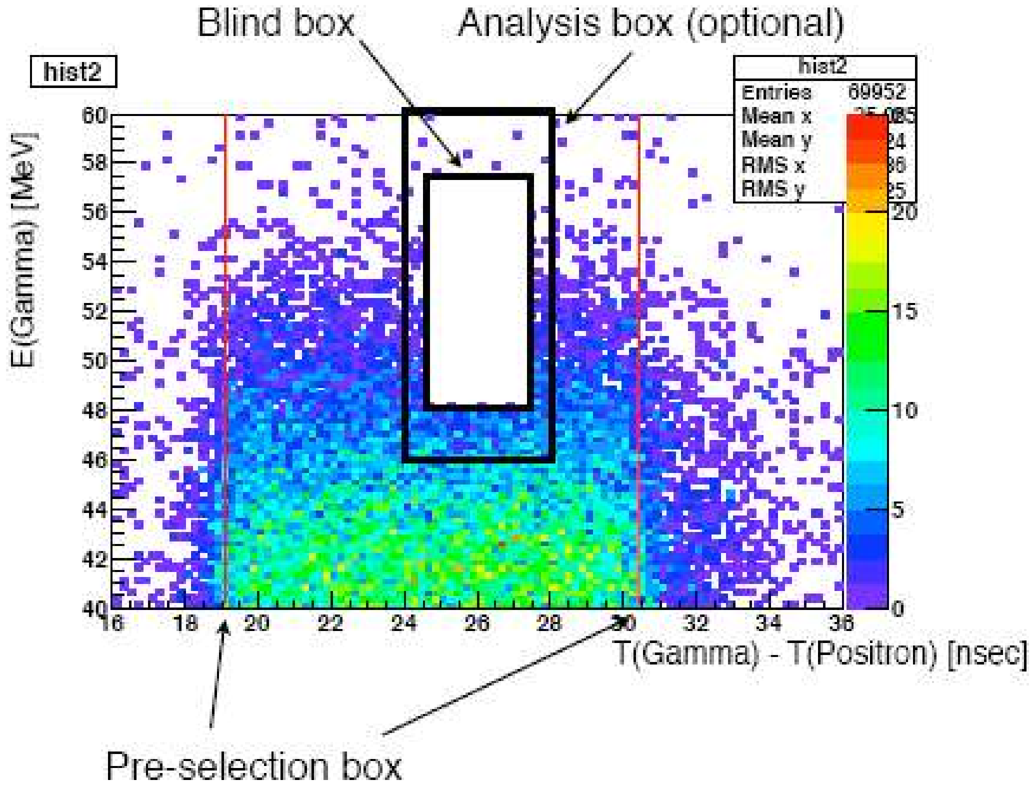
Corrected by small energy dependence:

$\sigma(t_{e\gamma}) = 148 +- 17$ ps

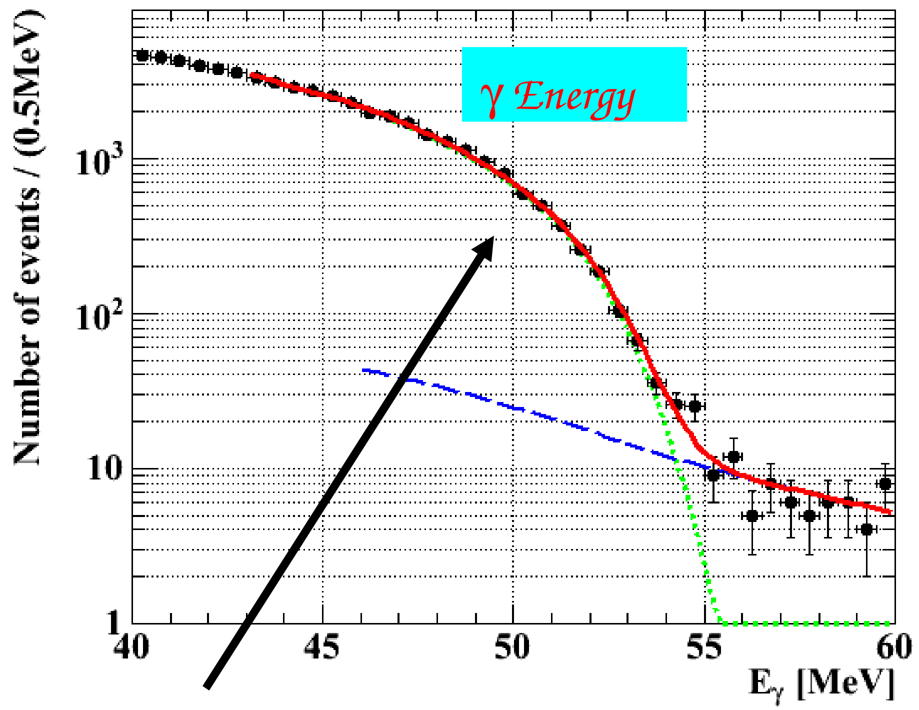
e^+ time hit measured by TC corrected by ToF (DCH trajectory) to target

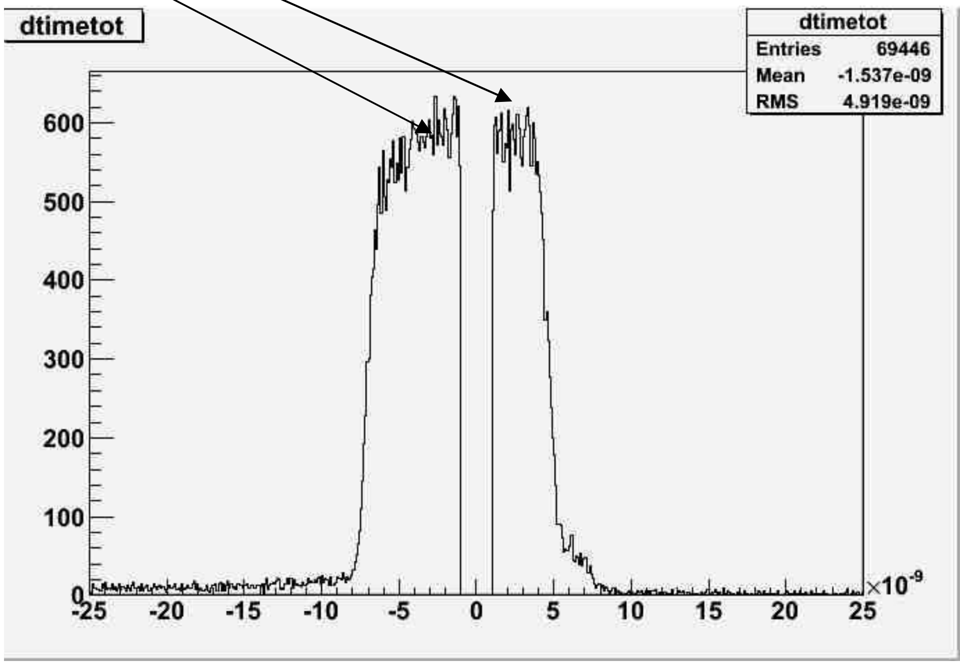
LXe corrected by ToF from target to conversion point

Blind analysis: E_γ vs $\Delta t_{\gamma e}$ window



Sidebands (|ΔTeγ| > 1 ns) are used to measure accidental background distributions



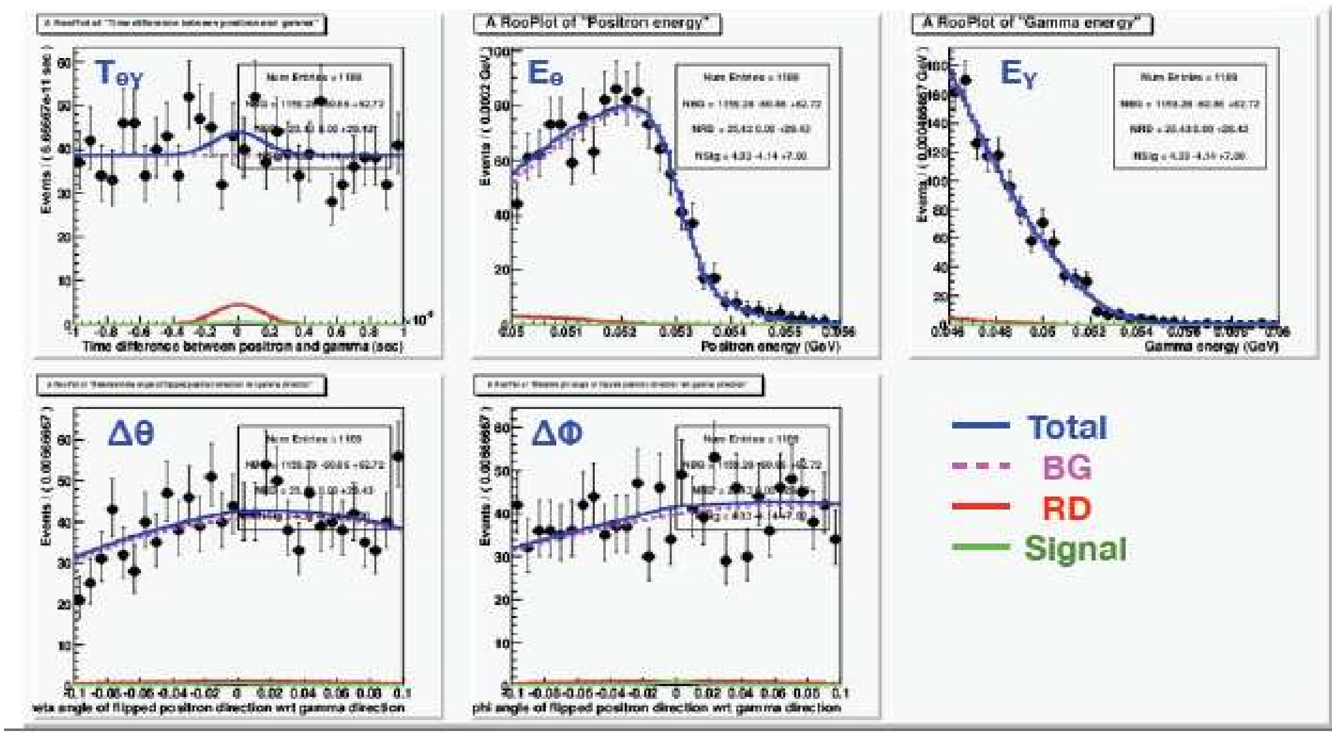


Radiative decay + In flight positron annihilation + resolution + pileup: in agreement with MCs

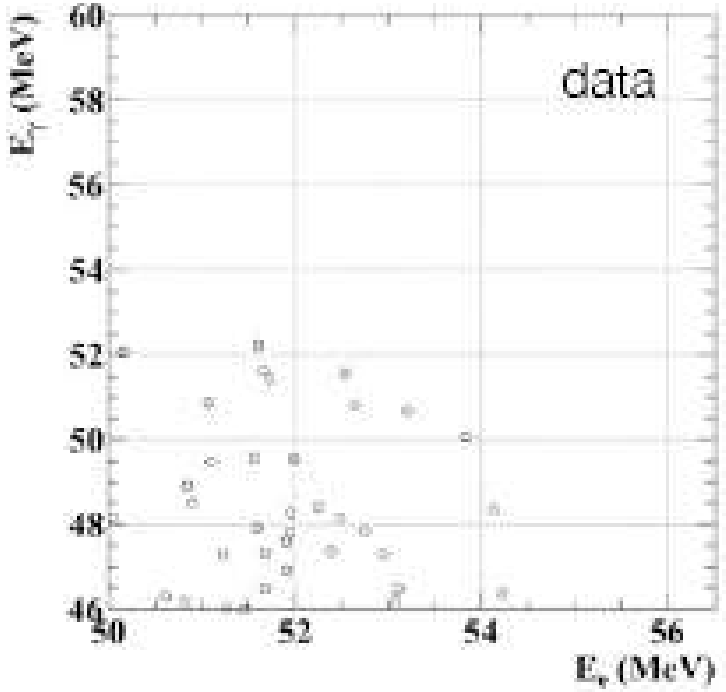
Likelihood analysis: accidentals + radiative + signal PDFs to fit data + Feldman Cousins

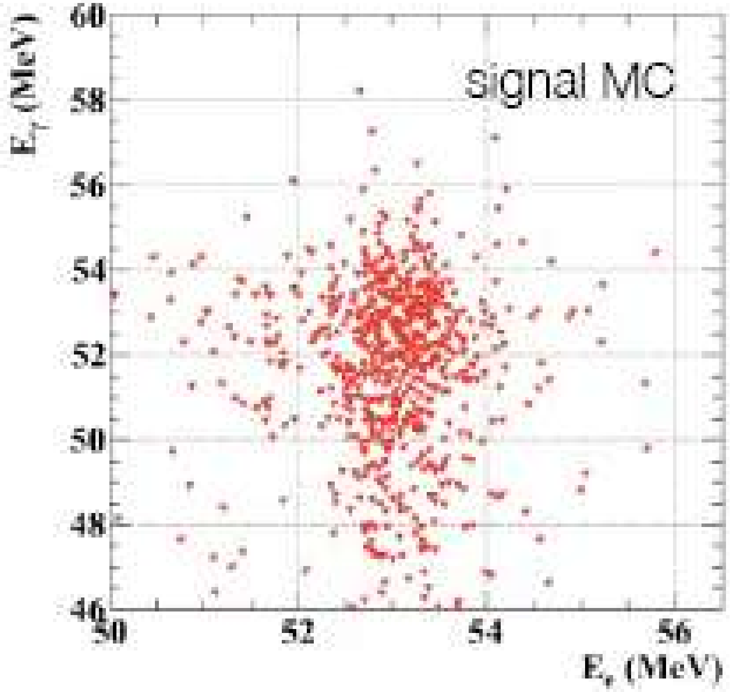
Best fit in the signal region

$$0 \leq N_{Sig} \leq 14.6$$



E_γ vs E_{e+}





Note: all the other parameters are cut to select ~90% of signal events in these plots

Normalization with Michel events measured simultaneously with the MEG trigger

$$N_{e\gamma} = BR(\mu^+ \longrightarrow e^+\gamma) \times k$$

dove:

$$k \equiv N_e \times \left[\frac{f_S}{f_M}\right] \times \left[\frac{\varepsilon(TRG=MEG|e^+)}{\varepsilon(TRG=Michel|_{track} \cap e^+_m \cap TC)}\right] \times A(\gamma|track) \cdot \varepsilon(\gamma) \cdot Psc(_{Michel})$$

pre-scaling 10^7

$$f_S = \mathcal{A}(\mathcal{DC}) \times \varepsilon\,(\text{track}, p_e > 50\text{MeV} \mid \text{DC}) \times \varepsilon\,(\text{TC} \mid p_e > 50\text{MeV})\Big|_S$$

$$f_M = \ldots\Big|_M$$

-Independent of instantaneous beam rate

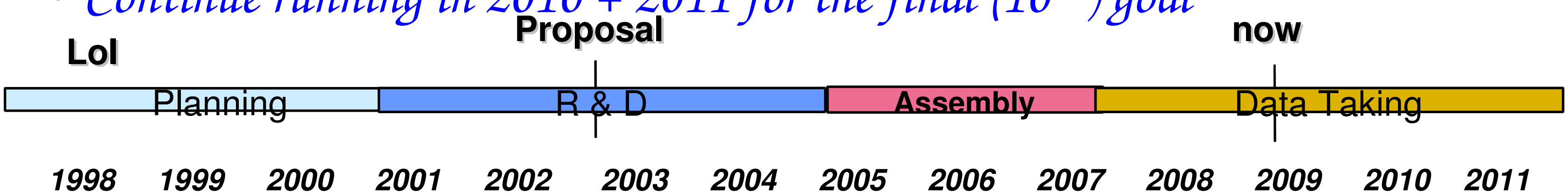
-Nearly insensitive to e^+ acceptance and efficiency factors related to DCH and TC

90% CL limit

- 90% C.L. N_{sig} <= 14.6 corresponds to $BR(\mu \to e\gamma) \leq 3.0 \times 10^{-11}$
- Computed sensitivity 1.3×10^{-11}
- Statistical fluctuation 5%
- From sidebands analysis we expected 0.9 (left) and 2.1 (right) $\times 10^{-11}$
- Bad luck

Future prospects

- *Re-start of data taking in october, until december (as in 2008)*
- *Instabilities eliminated: DRS2→DRS4 (timing improvement + noise reduction)*
- *Data taking and trigger efficiencies: 3-4 factor improvement*
- *Corresponding improvement in sensitivity: 3-4 $* 10^{-12}$ for 2009 run*
- *Continue running in 2010 + 2011 for the final (10^{-13}) goal*

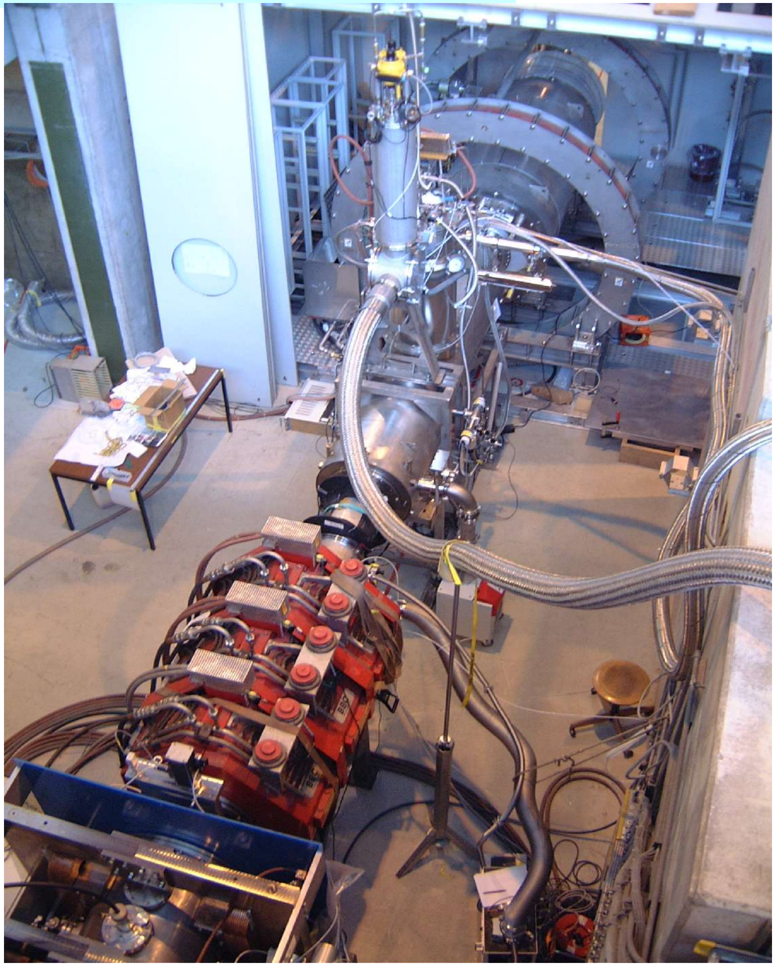


More details at

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

Backup Slides

Beam studies



Optimization of the beam elements:

- Wien filter for μ/e separation
- Degrader to reduce the momentum stopping in a 205 μm CH_2 target
- Solenoid to couple beam with COBRA spectrometer

Results (4 cm target):

	Z-version
• Rμ (total)	$1.3*10^8$ 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

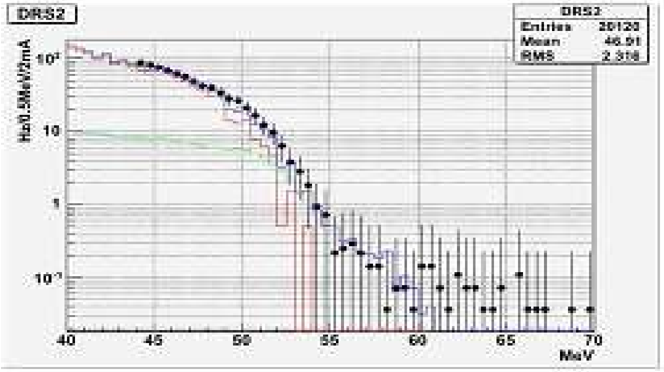
∀ μ/e separation (at collimator) 7.5 σ (12 cm)

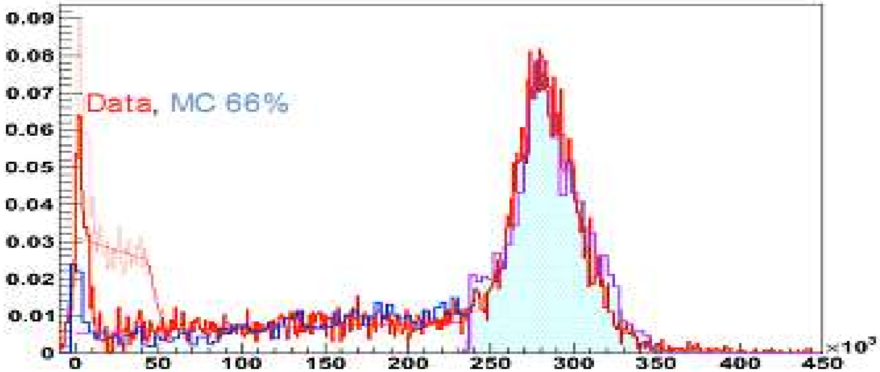
10^8 μ/s could be stopped in the target but only $3x10^7$ are used because of accidental background

Detection efficiency

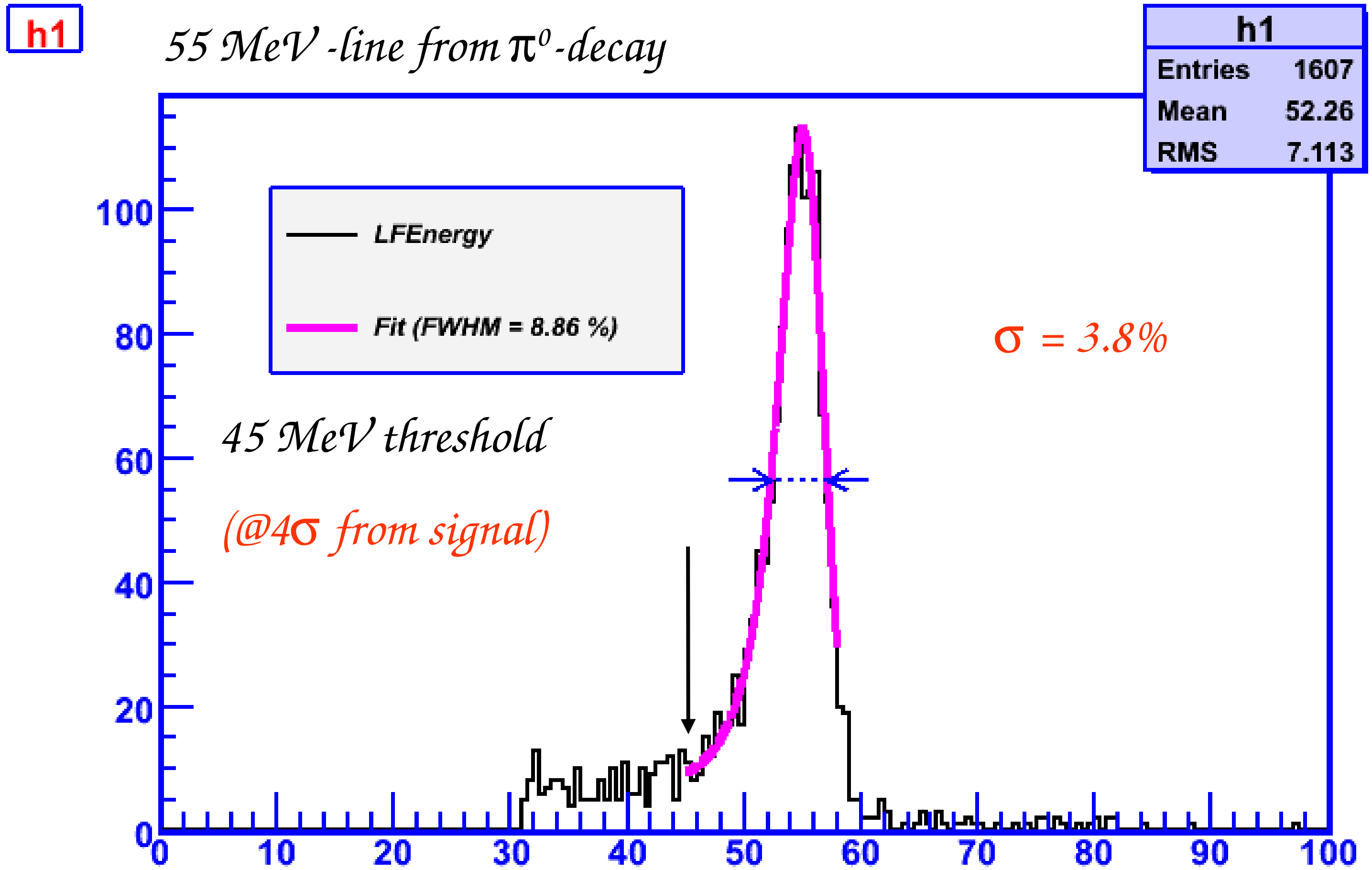
Detection efficiency

- The probability to detect a signal γ-ray within the detector acceptance is computed using the Monte Carlo simulation;
- The probability that the energy of a 52.8 MeV γ-ray is reconstructed >46 MeV (0.66) is corrected by taking into account
  - position resolution smearing for the acceptance;
  - positron direction smearing;
- $\varepsilon_{(\gamma)} = 0.61 \pm 0.03$
  - confirmed by π^0 and RD spectra





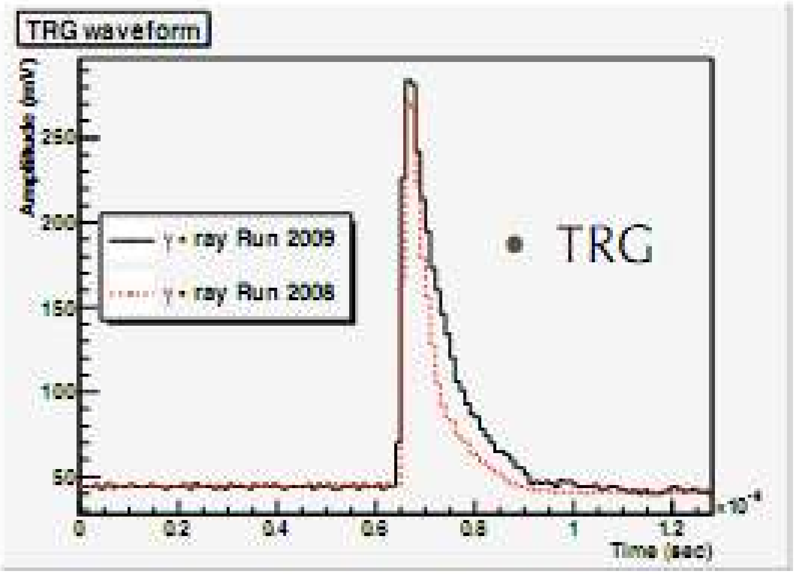
On-line E_γ resolution

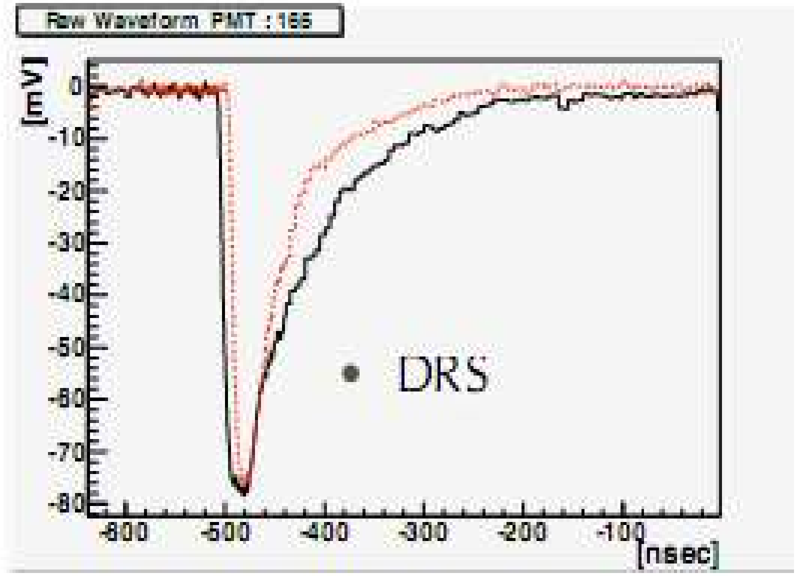


Liquid xenon: waveforms: 2 digitizers

Trigger@100 MHz

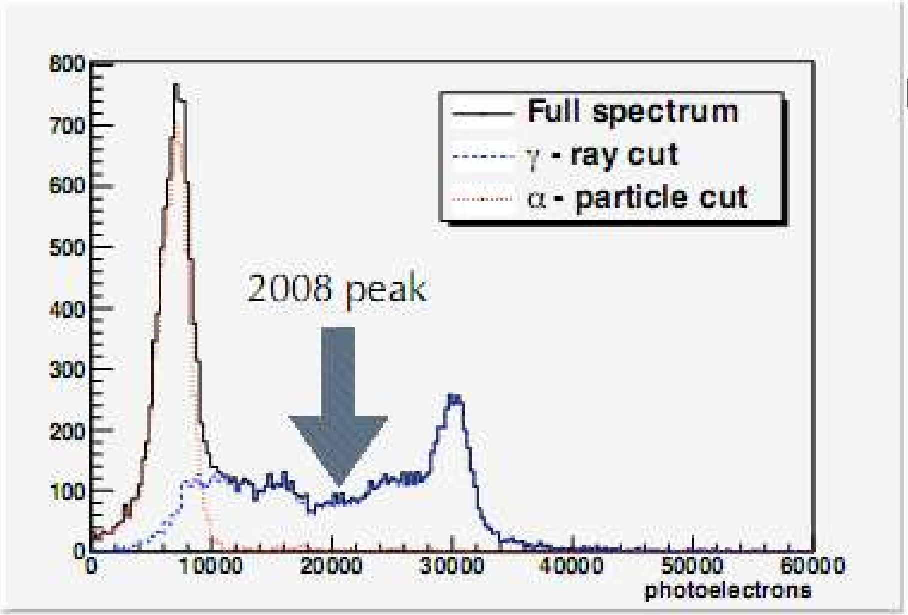
DRS2 @ 500 MHz or 2 GHz





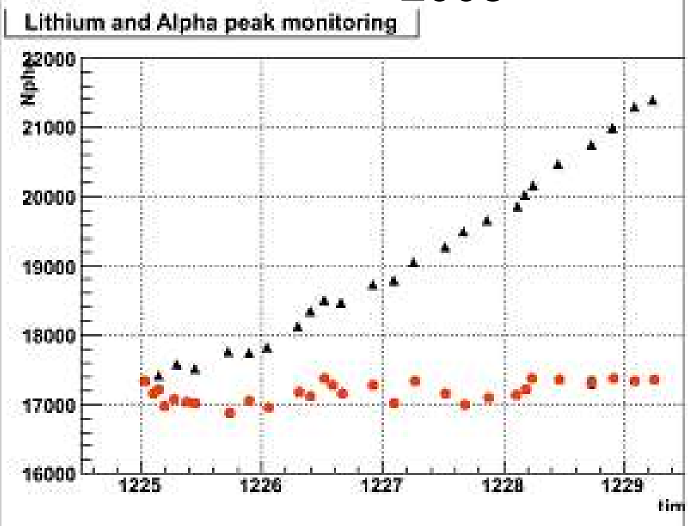
α-source and Li line

- The position of the α-source peak is ~the same as year 2008
- The Li peak (17.6 MeV) is higher!
  - around ~ 30k phe
  - it was at < 22k phe
  - integration still not optimized for this year's waveform



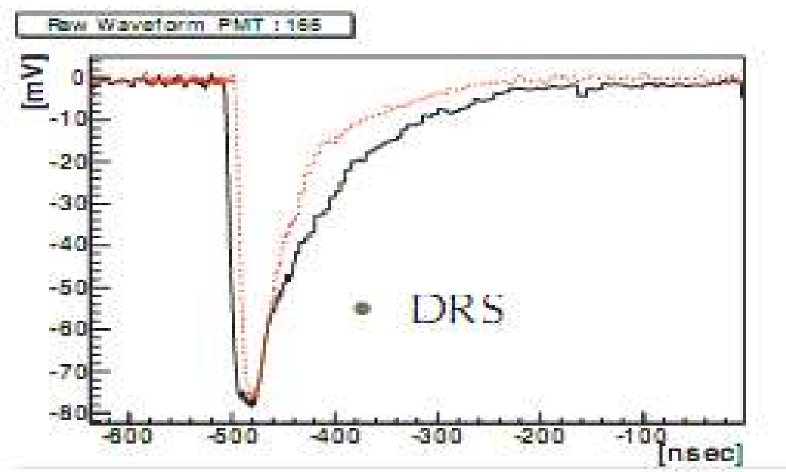
2009

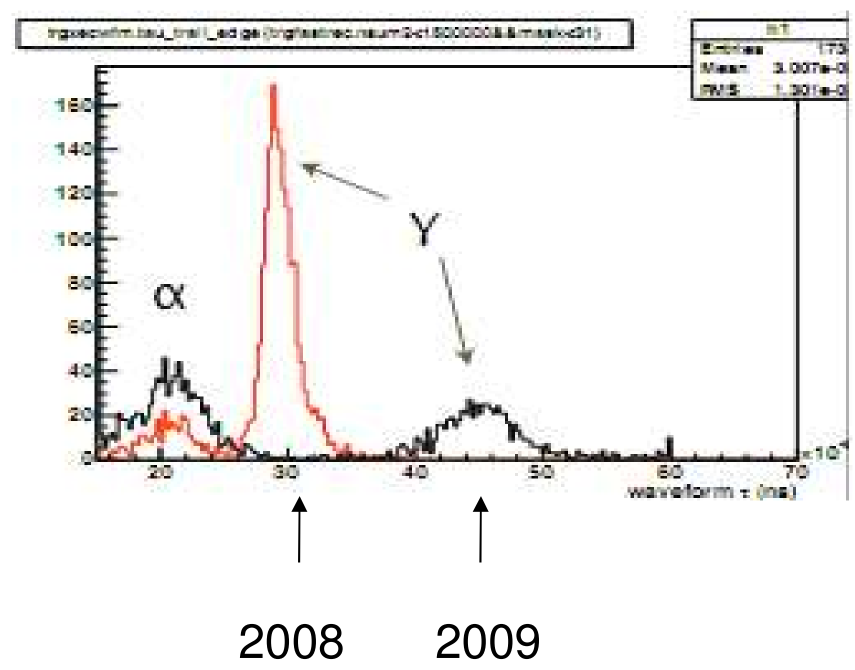
2008



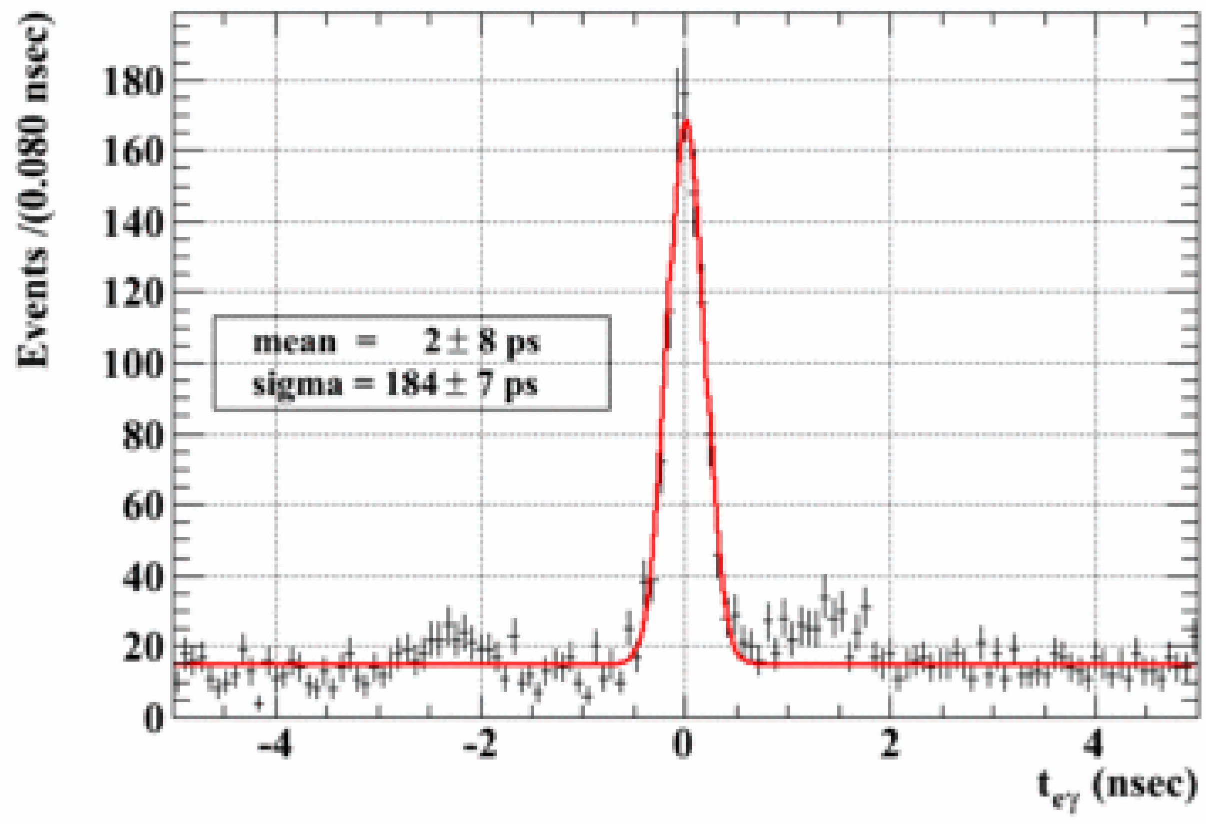
Xenon waveforms in 2009

In 2009 xenon scintillation waveforms have the right time decay constant: longer for gammas





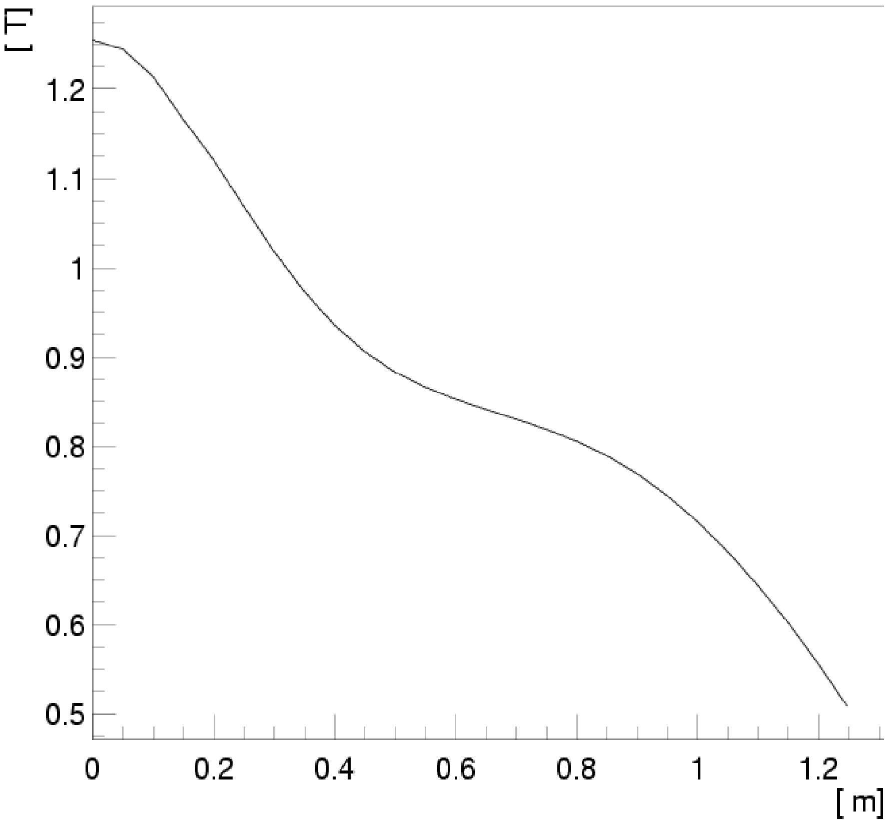
Dedicated RMD runs at lower thresholds

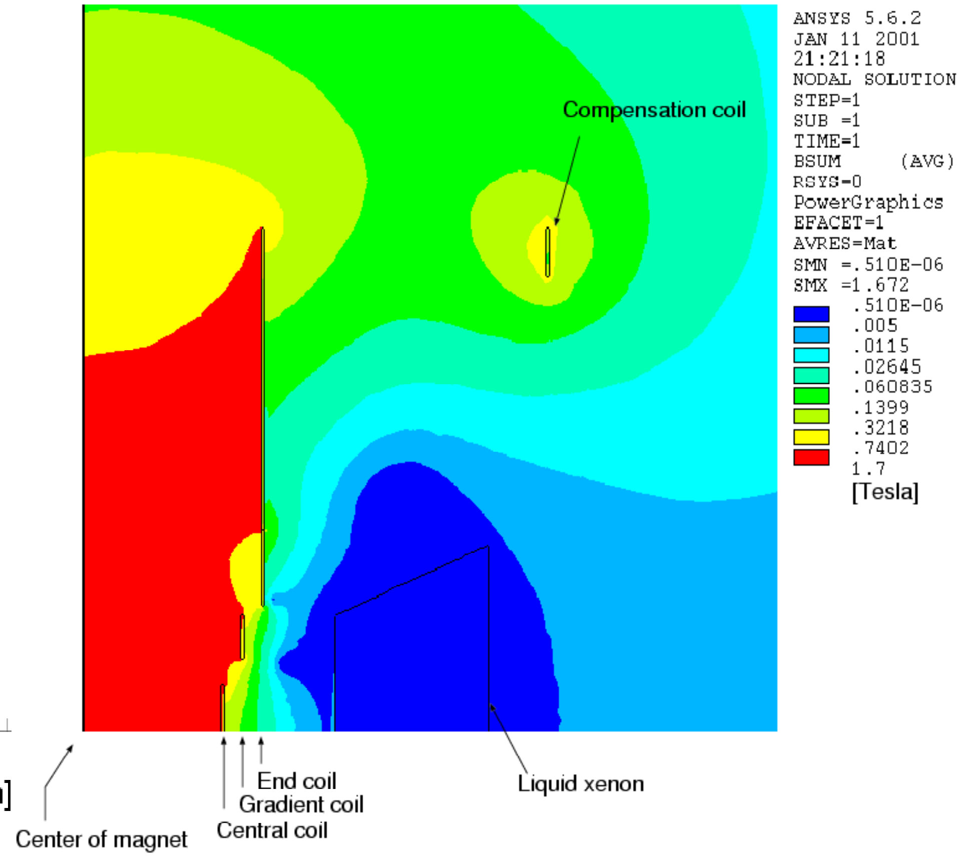


The magnet

- $\mathcal{B}_c$ = *1.26T* *current = 359A*
- *Five coils with three different diameters*
- *Compensation coils to suppress the stray field around the LXe detector*
- *High-strength aluminum stabilized superconductor*

  ⇒ *thin magnet* (**1.46 cm Aluminum**, **0.2 X_0**)





Background and Sensitivity

	“ Goal “ Measured/ Simulated
Gamma energy %	*5.0*
Gamma Timing (ns)	*0.15*
Gamma Position (mm)	*4.5 – 9.0*
Gamma Efficiency (%)	*>40*
e^+ Timing (ns)	*0.1*
e^+ Momentum (%)	*0.8*
e^+ Angle (mrad)	*10.5*
e^+ Efficiency (%)	*65*
Muon decay Point (mm)	*2.1*
Muon Rate (10^8/s)	*0.3*
Running Time (weeks)	*100*
Single Event Sens (10^{-13})	*0.5*
Accidental Rate (10^{-13})	*0.1 – 0.3*
# Accidental Events	*0.2 - 0.5*
90% CL Limit (10^{-13})	*1.7*

1 week = 4 x 10^5 s

Single Event Sensitivity

Limited by Accidental Background

hence Detector Performance

$$BR(\mu\to e\gamma) = (R_\mu \cdot T \cdot \Omega/4\pi \cdot \varepsilon_e \cdot \varepsilon_\gamma \cdot \varepsilon_{sel})^{-1} \cong 5\cdot10^{-14}$$

Prompt Physics Background (Radiative)

$$BR_{pr} \cong < 3\cdot10^{-15}$$

Accidental Background

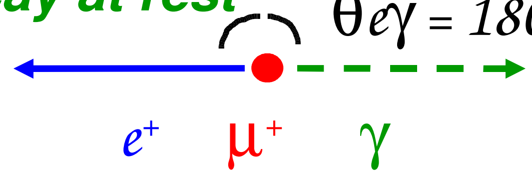
$$BR_{acc} \propto R_\mu \cdot \Delta E_e \cdot \Delta t_{e\gamma} \cdot (\Delta E_\gamma)^2 \cdot (\Delta\theta_{e\gamma})^2 \to 3\cdot 10^{-14}$$

Upper Limit at 90% C.L. for BR $(\mu\to e\gamma) \approx 1\cdot 10^{-13}$

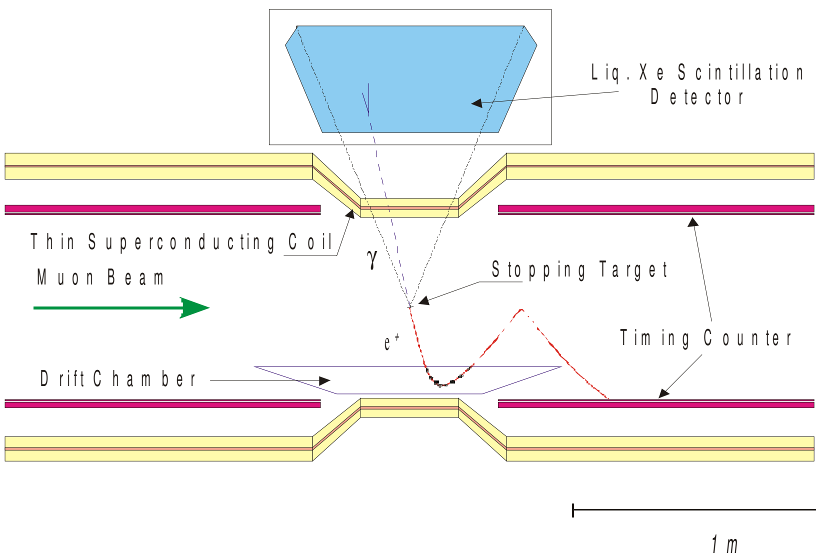
** The muon rate can be optimized to improve the limit*

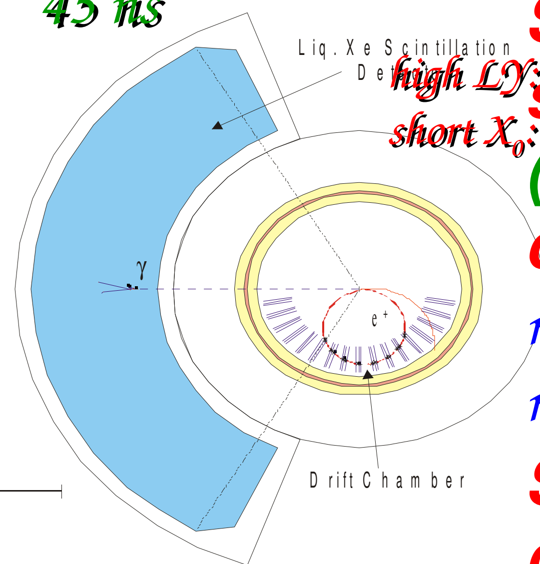
MEG detection concept

μ^+ decay at rest $\theta_{e\gamma} = 180°$



$E_e = E_\gamma = 52.8$ MeV





Stopped beam of 3×10^7 μ/sec in a 205 μm target

Liquid Xenon calorimeter for γ detection (scintillation): fast: 4 / 22 / 45 ns

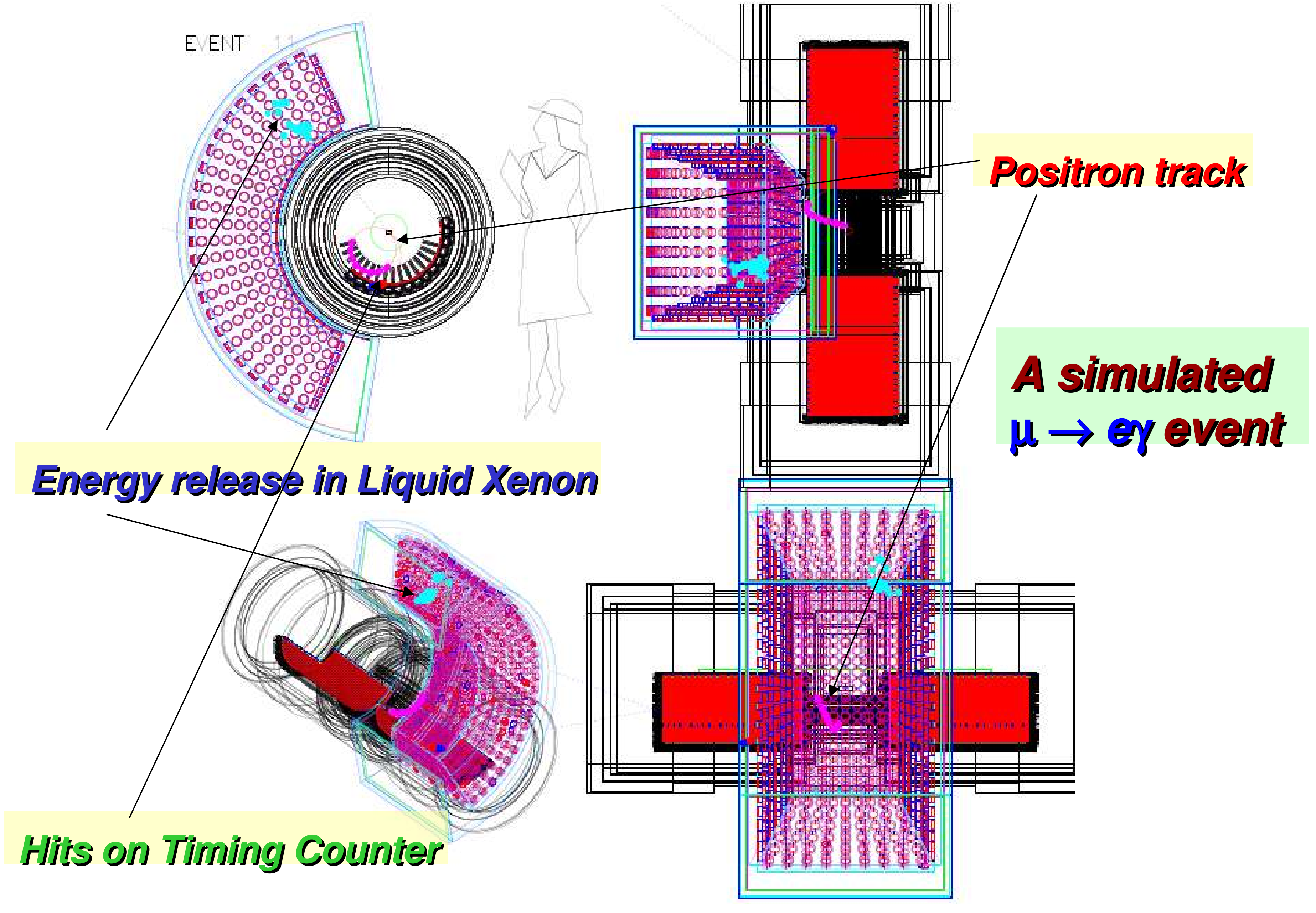
high LY: ~ 0.8 * NaI

short X_0: 2.77 cm

Solenoid spectrometer (COBRA) & drift chambers for e+ momentum measurement

Scintillation counters for e+ timing

More on Lxe Calorimeter in R. Sawada talk


EVENT
Positron track
A simulated
μ → eγ event
Energy release in Liquid Xenon
Hits on Timing Counter

Timing Counter 2)

Two sectors upstream and downstream the target

Two layers of scintillation counters placed at right angles with each other.

Outer layer: scintillator bars devoted to **trigger, ϕ and time measurement**.

Two sectors of 15 bars each, read by 2 PMTs, on the inner and outer sides

Full PMT waveforms read out for dedicated charge and time analysis

Inner layer: scintillating fibres ... **information**

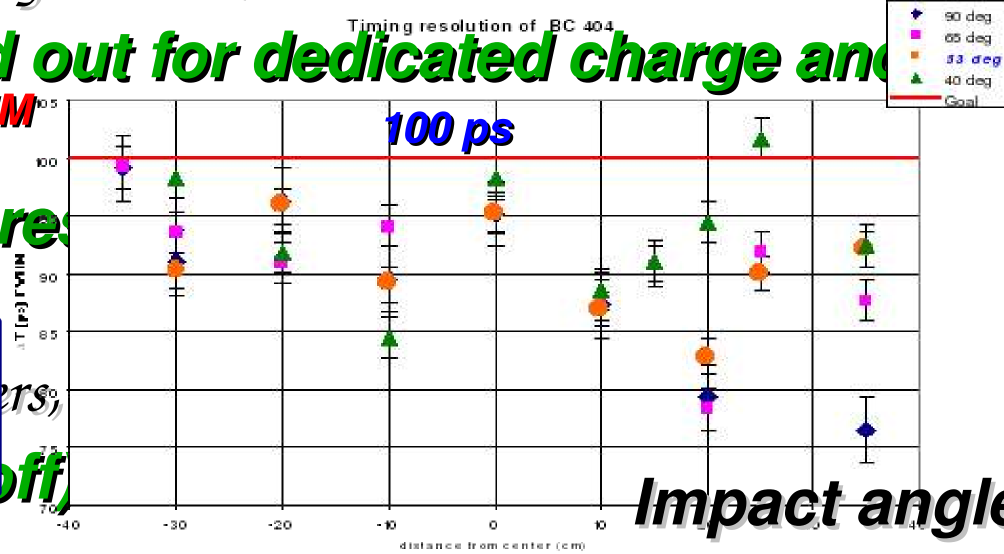
Two sectors of 15 5×5 mm² fibers,

Only digital signals (on/off)

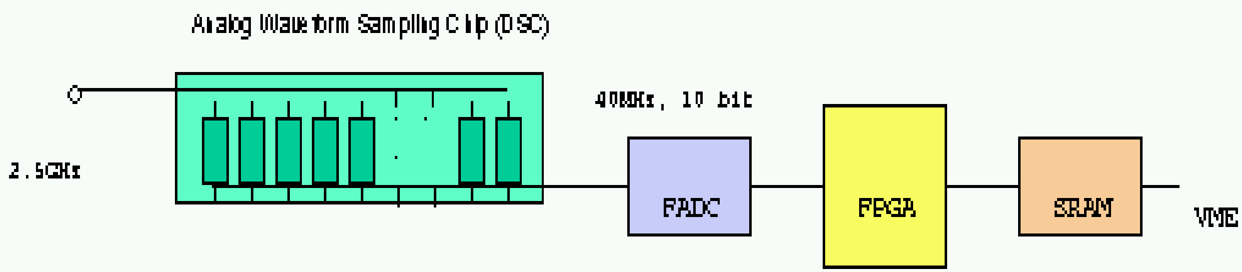
Measurements of **TC bars timing resolution** in dedicated test beams at **several positions** and **impact angles**

FWHM(T) = 91 ps (±5%)

MEG Goal 100 ps



Readout electronics



- ***Waveform digitizing for all channels (pile-up rejection);***
- ***Custom domino sampling chip (DRS) designed at PSI;***
- ***2.5 GHz sampling speed @ 40 ps timing resolution;***
- ***Sampling depth 1024 bins;***
- ***Readout similar to trigger;***
- ***Trigger:***

Signals from Calorimeter and TC bar are sampled at 100 MHz with separate ADC

Several trigger combinations are available to study trigger and detector efficiency for all subdetectors

Spectrometer calibration

- MEG is a precision experiment
- High experimental resolutions to reject background
- Stable for a ~ 4 year scale

PMT time walk correction	⟷	Michel
Same bar PMT time offset	⟷	Cosmics,Laser
Interbar time offset	⟷	Boron,Laser,Dalitz
XEC-TC time offset	⟷	Dalitz
Bar V_{eff}	⟷	Cosmics

Tc-LXe calibration with Cockroft-Walton accelerator

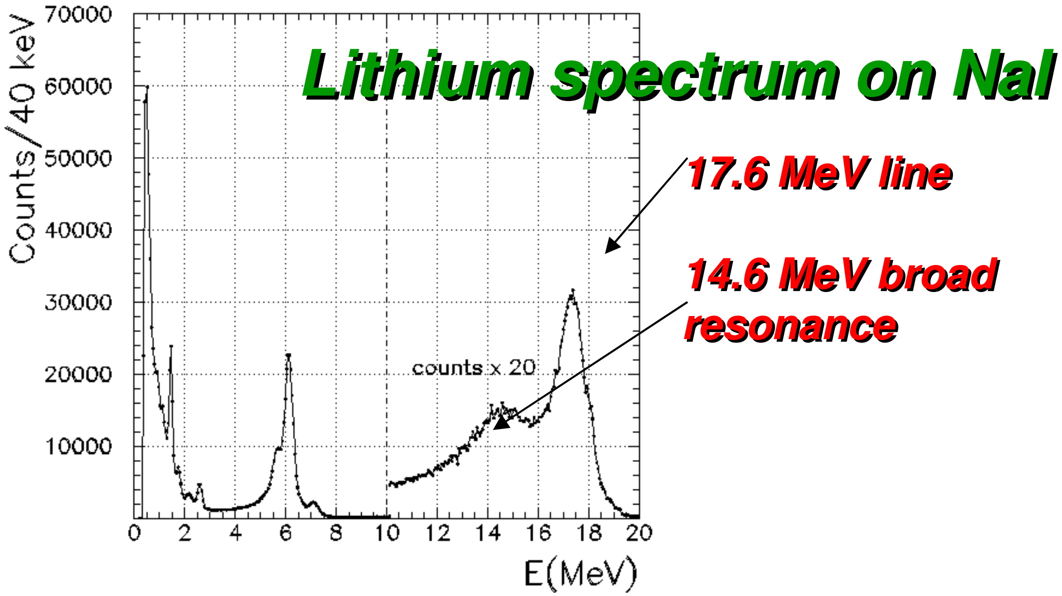
Reactions induced by Cockroft-Walton protons (E ~ 1 MeV) on Li and B targets

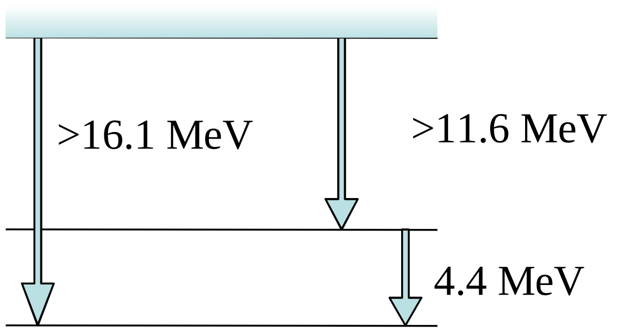
Reactio	Peak energy	σ peak	γ-lines
Li(p,γ)Be	440 keV	5 mb	(17.6, 14.6) MeV
B(p,γ)C	163 keV	2 10^{-1} mb	(4.4, 11.6, 16.1) MeV

Boron target:

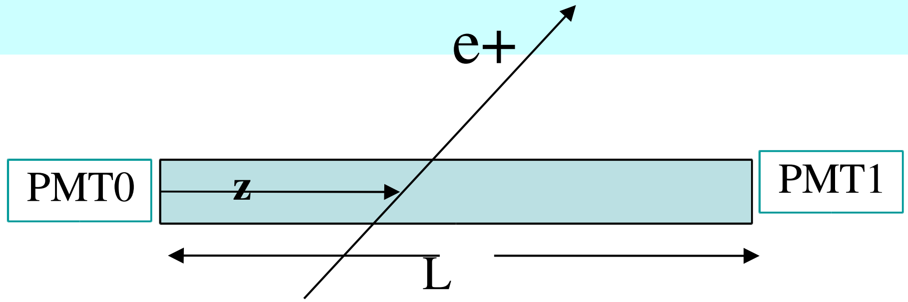
- Lower cross section
- **Two gamma's emitted simultaneously** ⇒ tool for **relative timing calibration**

Lithium spectrum on NaI





TC bar measurements



$$t_0 = T + \frac{z}{v_{eff}} + b_0 + \frac{c_0}{\sqrt{A_0}}$$

$$t_1 = T + \frac{L - z}{v_{eff}} + b_1 + \frac{c_1}{\sqrt{A_1}}.$$

amplitude of PMT signal

effective velocity

T : time of e^+ at the impact point on first hit bar

z : impact point along bar length

b_{01} PMT time offsets

c_{01} PMT Time Walk coefficients

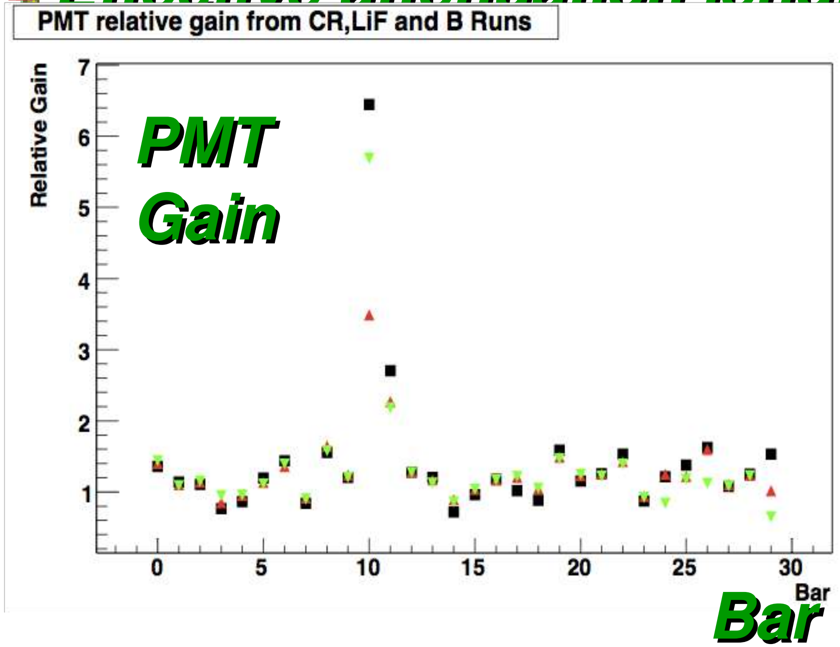
Detector calibration and performances: TC 1)

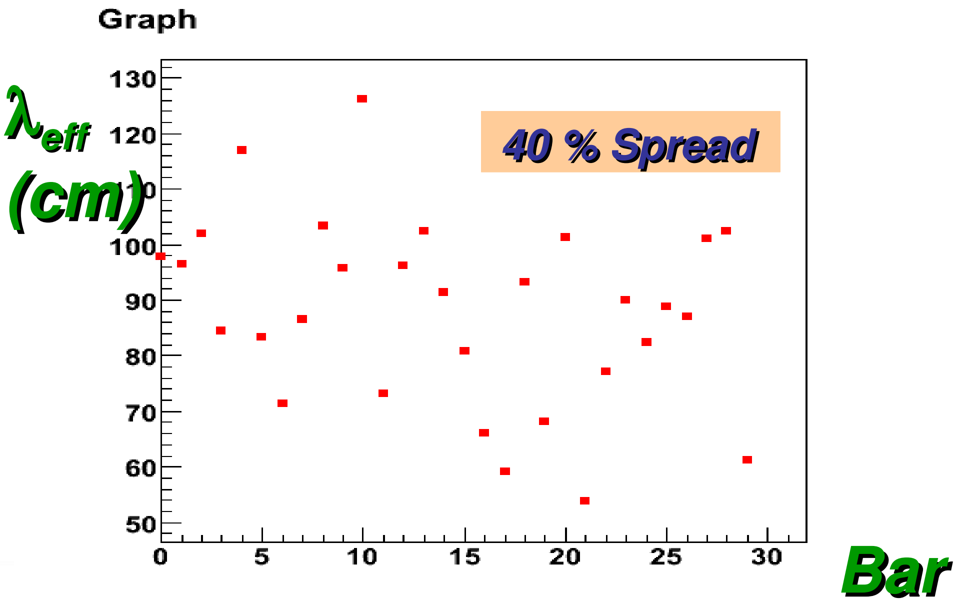
Timing counter parameters:

$$z = \frac{v_{eff} \cdot (t_0 - t_1)}{2} \qquad T = \frac{t_1 + t_0}{2} - \frac{L}{2 v_{eff}}$$

- *PMT* **Gain** → *charge response*
- **Effective velocity v_{eff}**
- **Effective attenuation length λ_{eff}**

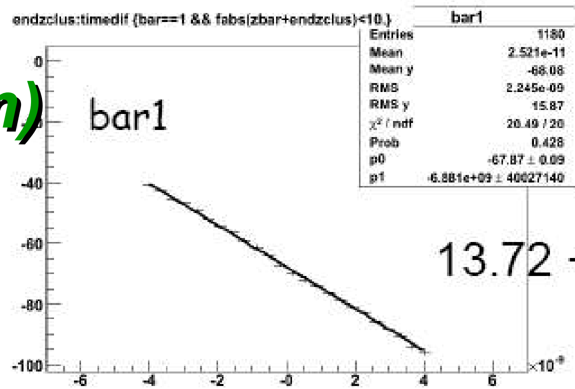
$$\ln\left(\frac{Q_1}{Q_0}\right) = \ln\frac{G_1}{G_0} + \frac{2z}{l_{eff}}$$



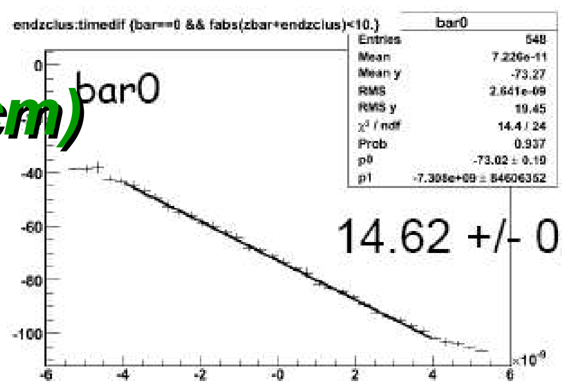


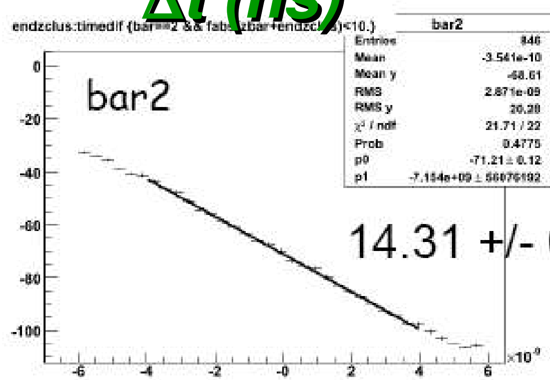
Effective velocity measurement (cm/ns)

Events with
|Δz|<10



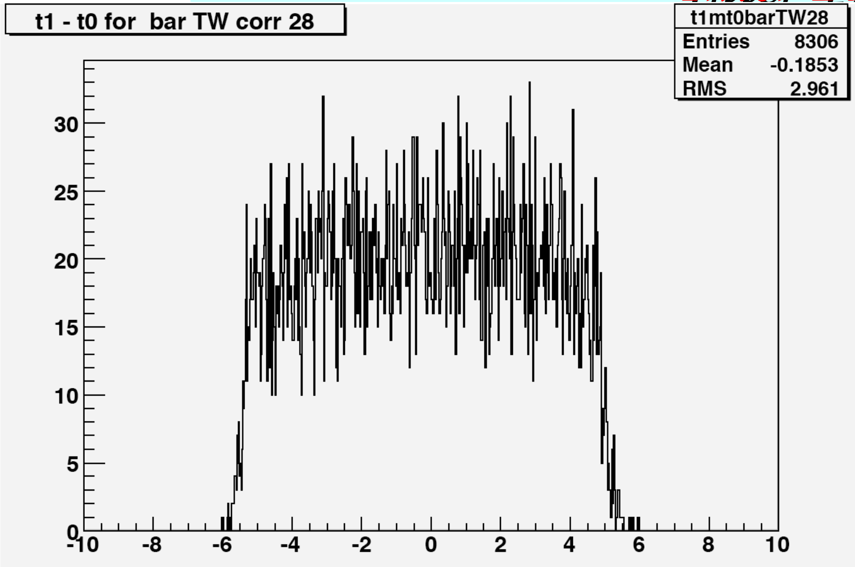
V_{eff} *determined with* **< 1% precision** *by using* **bar and fibre information simultaneously**



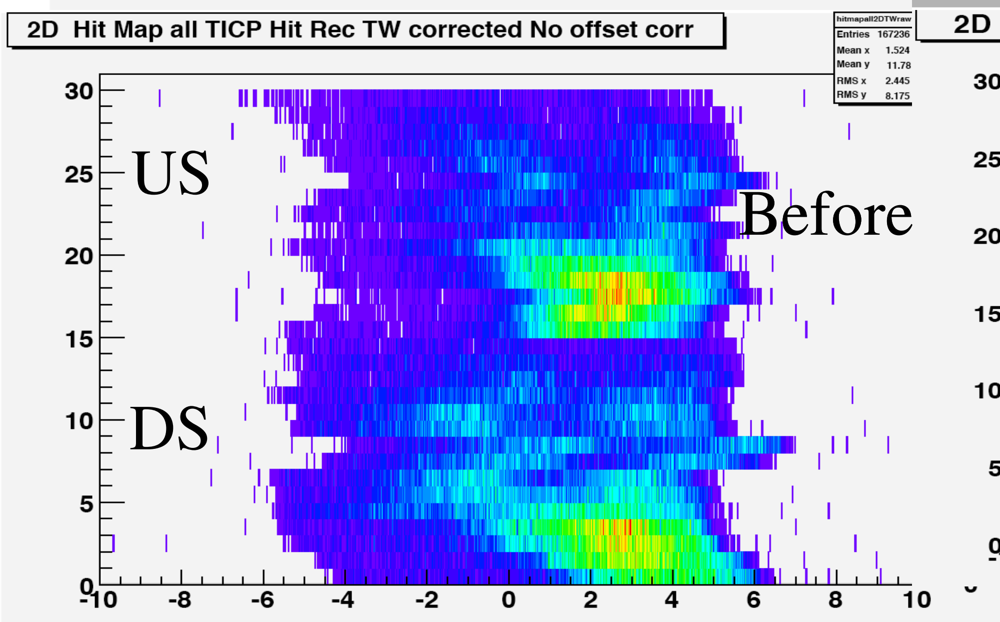


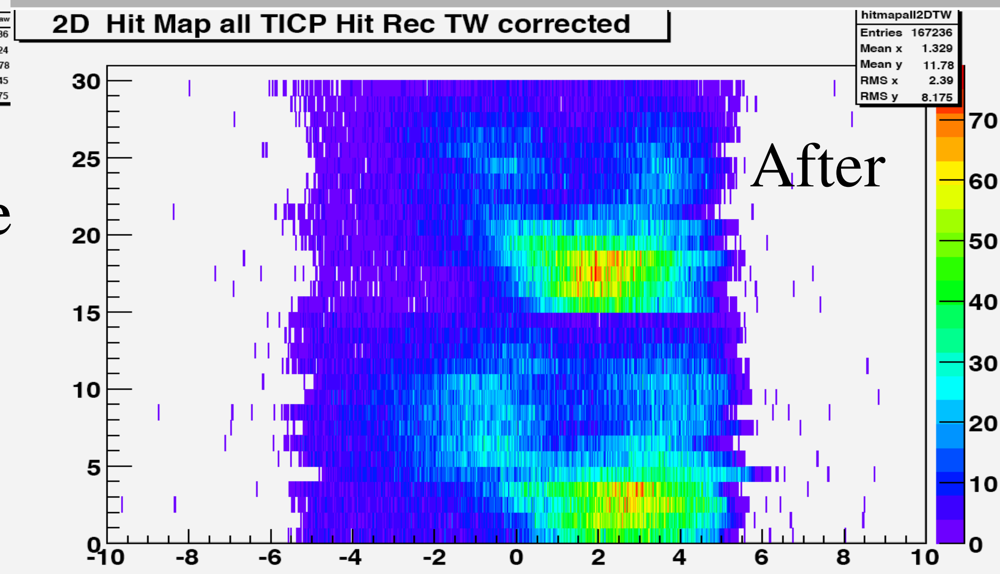
Inter-PMT offsets

Average Δt is PMT offset in cosmic runs



MEG physics runs TC hitmap





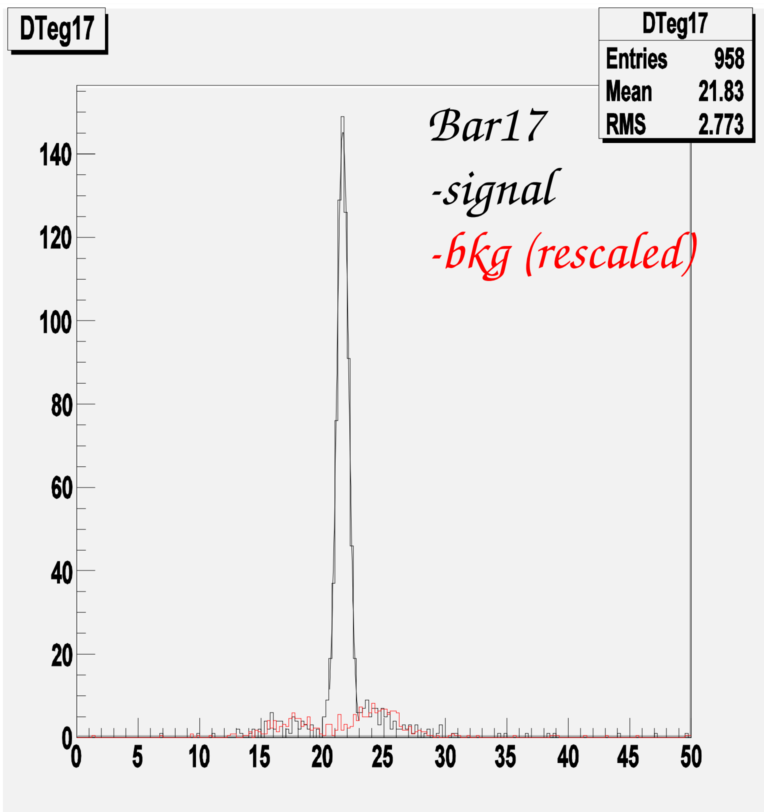
t_1-t_0 [ns]

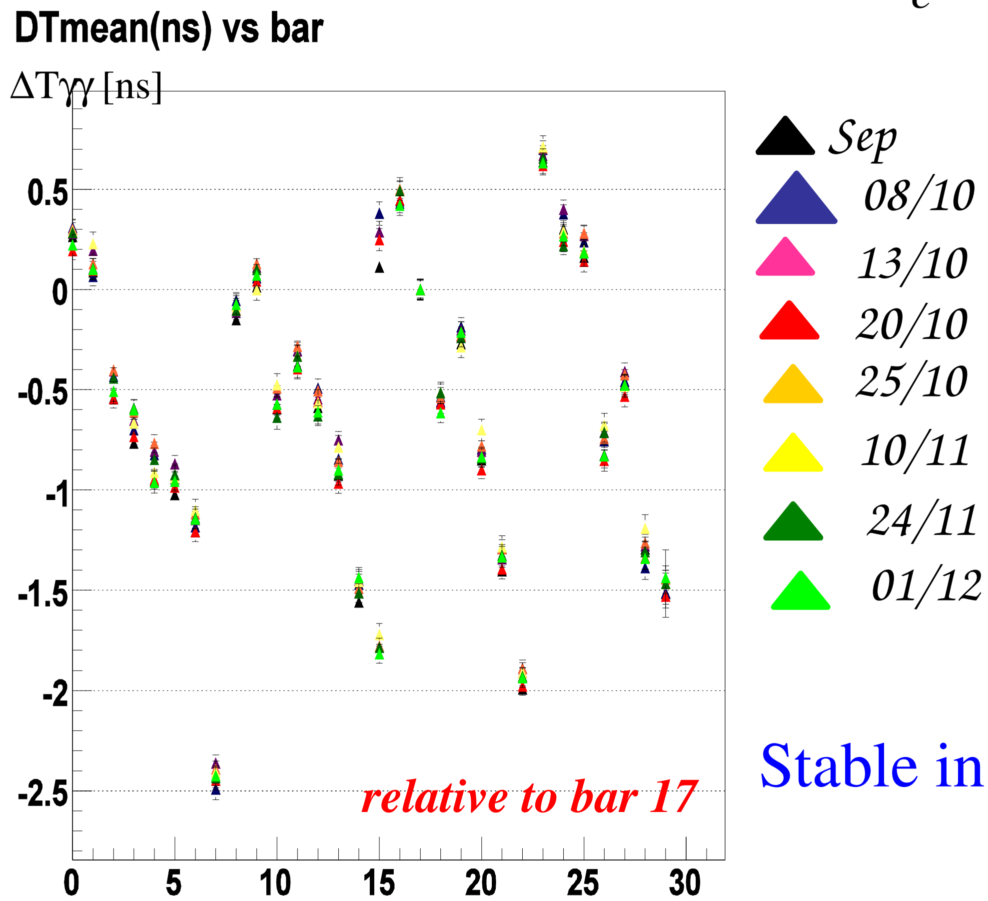
t_1-t_0 [ns]

Inter-bar offset extraction

Boron 4.4MeV (XEC) and 11.7MeV(TC)

$$DT_{gg} = \left(T_{XEC} - \frac{L_g^{XEC}}{c} \right) - \left(\frac{t_0 + t_1}{2} - \frac{L_g^{TC}}{c} \right)$$

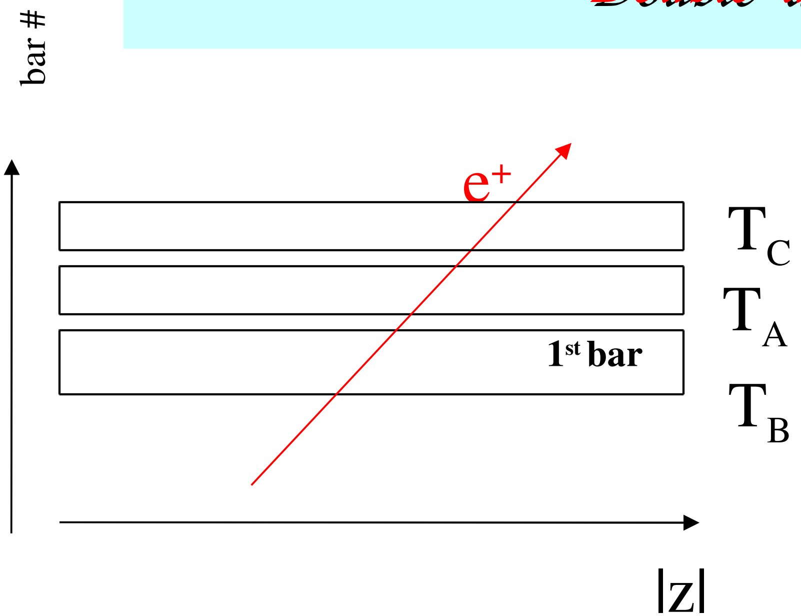




Stable in time!

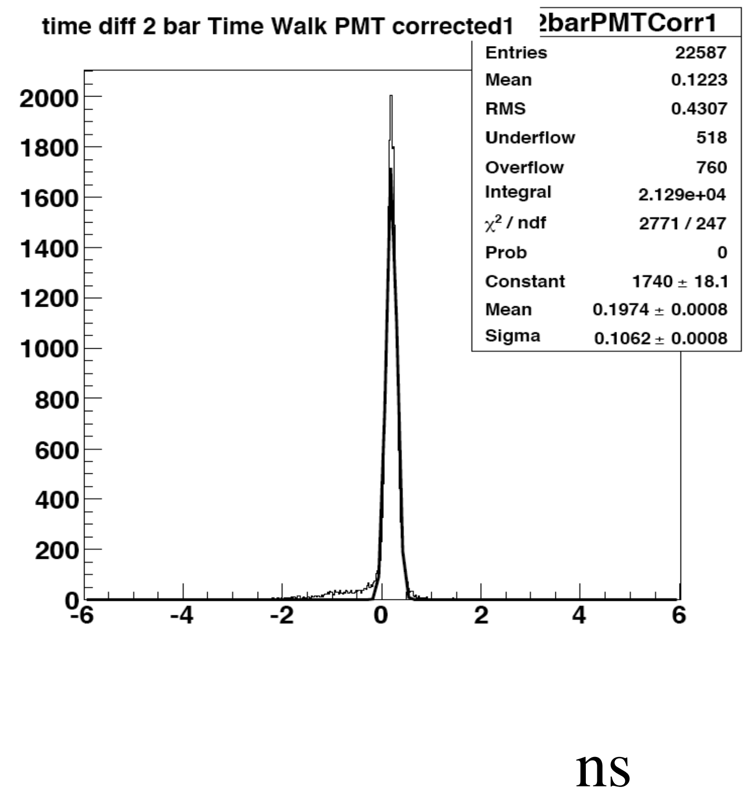
ΔTγγ[ns]

'Double' and 'triple' hit events



On events with three adjacent hit bars (triples)
minimize the differences (for all the bars)

$$\frac{t_{0C}+t_{0B}}{2} - t_{0A} - \left[\frac{1}{2}\left(\frac{c_{0C}}{\sqrt{A_{0C}}}+\frac{c_{0B}}{\sqrt{A_{0B}}}\right) - \frac{c_{0A}}{\sqrt{A_{0A}}}\right].$$

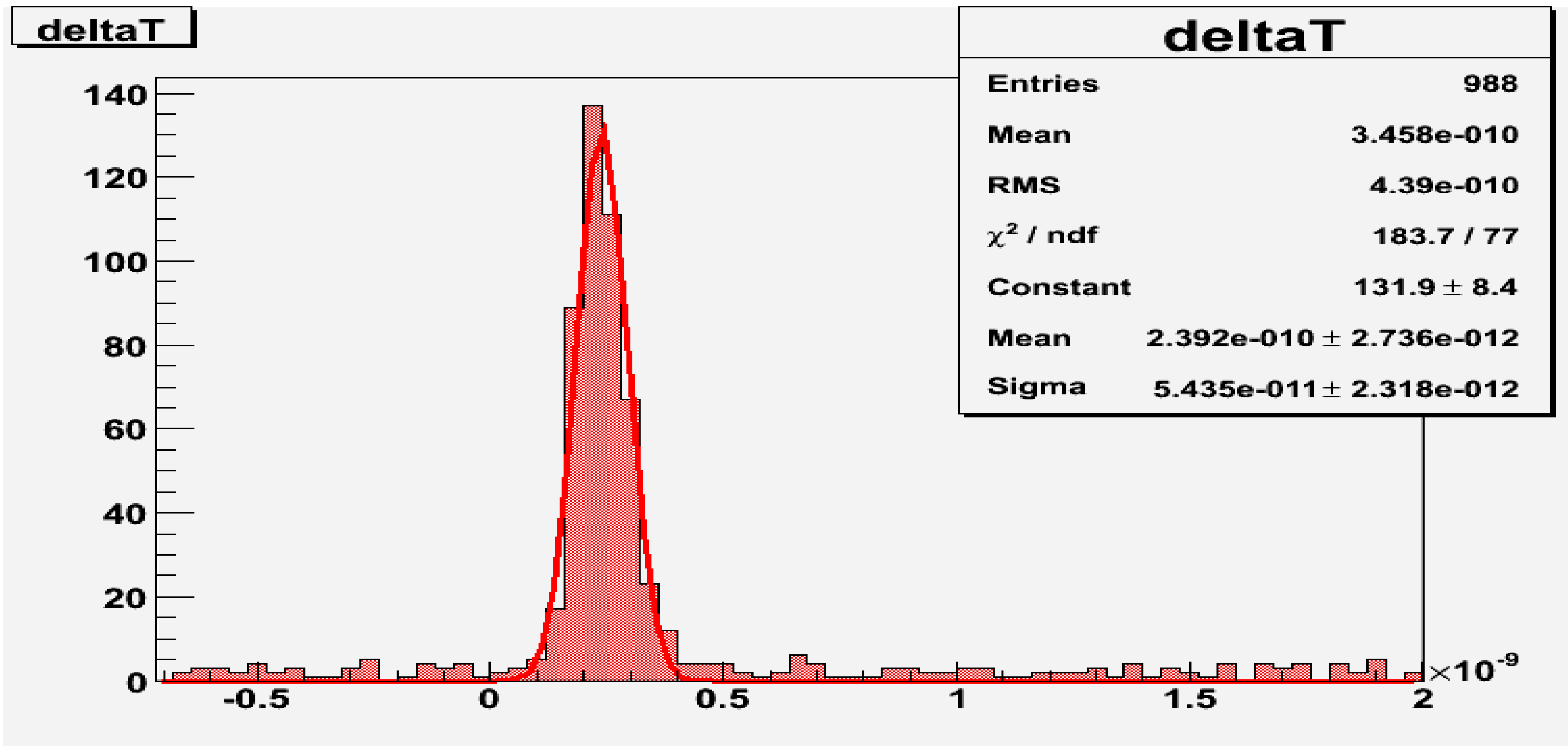


On sample of two hit adjacent bars ('doubles') **test** time walk correction (c_0 and c_1)

$$DT = T_A - T_B$$

Detector calibration and performances: TC resolution

Timing resolution *(timing difference between adjacent bars)*



$\sigma_T \approx$ 54 ps, *close to project goal (100 ps FWHM)*

MEG absolute time offset

Dalitz π^0 events $\pi^0 \rightarrow \gamma\, e^+e^-$

- Same topology as signal !
- Gamma/positron energy range (can be chosen) same as for signal
- Worse resolution due to LH_2 target

  Comparison with signal is not exact

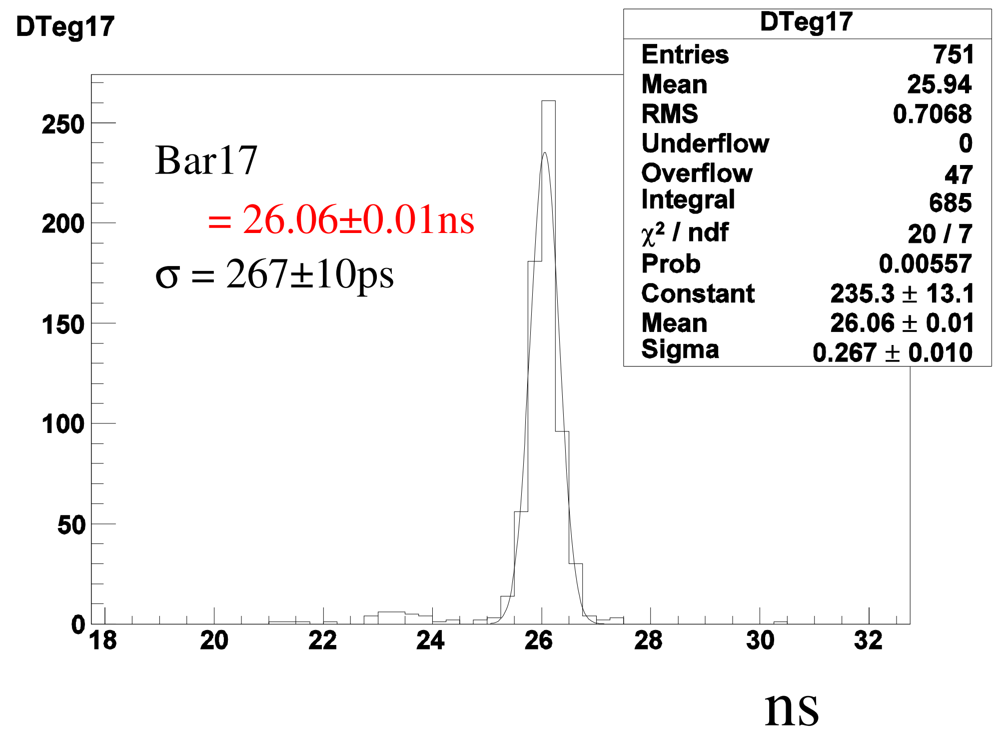
$$DT = \left(T_{XEC} - \frac{L_g^{XEC}}{c}\right) - \left(T - \frac{L_e^{TC}}{c}\right)$$

Centre of signal window

Control sample

(flight length correction)

MC validation



DCH Tracking efficiency

Tracking efficiency in the Drift Chamber was severely limited by HV trips

A substantial and growing with time number of DCH planes had low or no efficiency

More details in the dedicated talk on Drift Chambers

- In spite of that DCH were adequate for many studies

Highly pre-scaled TC trigger ~ 6000 C total live protons on target 2.8 x 10^7 μ/s/2mA

Implies ~ 8400 x 10^{10} total muon stops

$N_{\mu\to e\nu\nu}$ = 11895 satisfying selection cuts

= 8.4x10^{13} Number of muon stops calculated

X 10^7 prescale factor known

X 0.30 TIC acceptance x efficiency for Michel measured

X 0.182 fraction of Michel spectrum > 48 MeV calculated

X (0.92-1.0) conditional trigger efficiency for TIC measured*

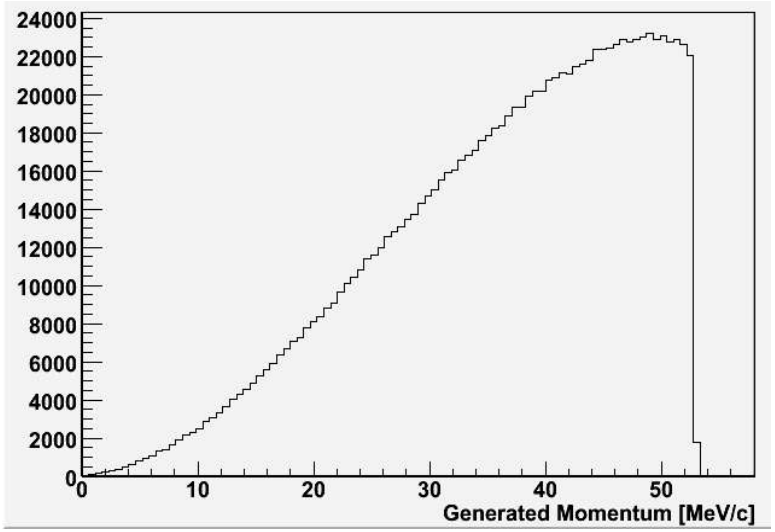
X 0.091 Michel geometric acceptance assumed

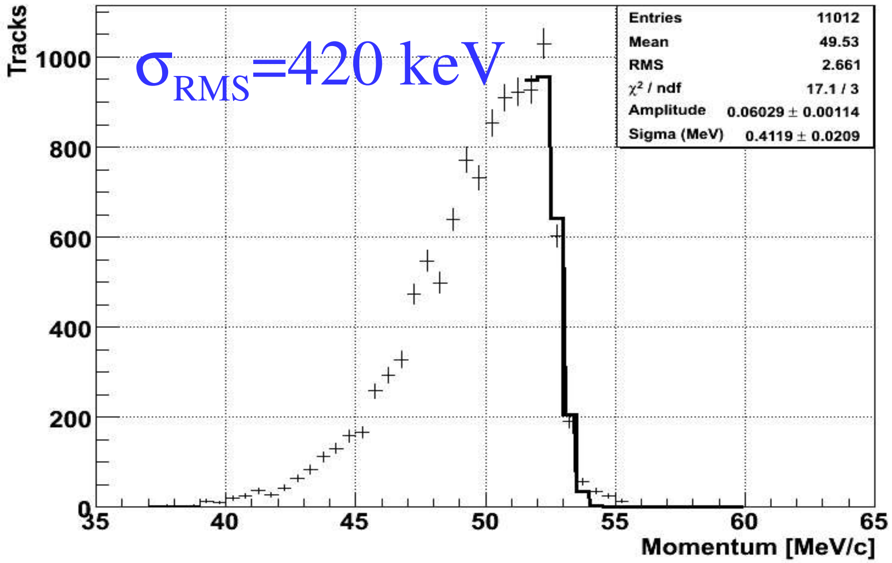
X ε_{DCH} drift chamber reconstruction & cuts unknown

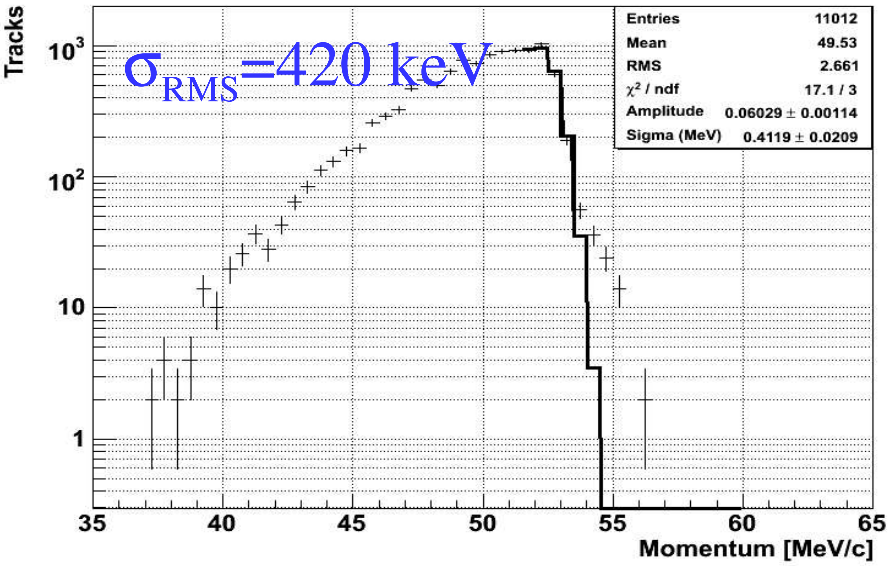
ε_{DCH} = 11895 x 10^7 / 0.3 / 0.182 / 0.92 / 0.091 / 8.4 / 10^{13} = 0.28-0.31

Momentum resolution from MC

- No source of fixed momentum particles – fit to edge of Michel spectrum
- Generate Michel spectrum without inefficiencies
- Fit convolution of generated MC spectrum with Gaussian to reconstructed MC spectrum
  - Fit range (51.5-54.0) MeV/c
  - Done for "tight cuts"
- Resolution worse than original MEG predictions: DRS noise + ?
- Tails from large angle scattering, pattern recognition?, others?

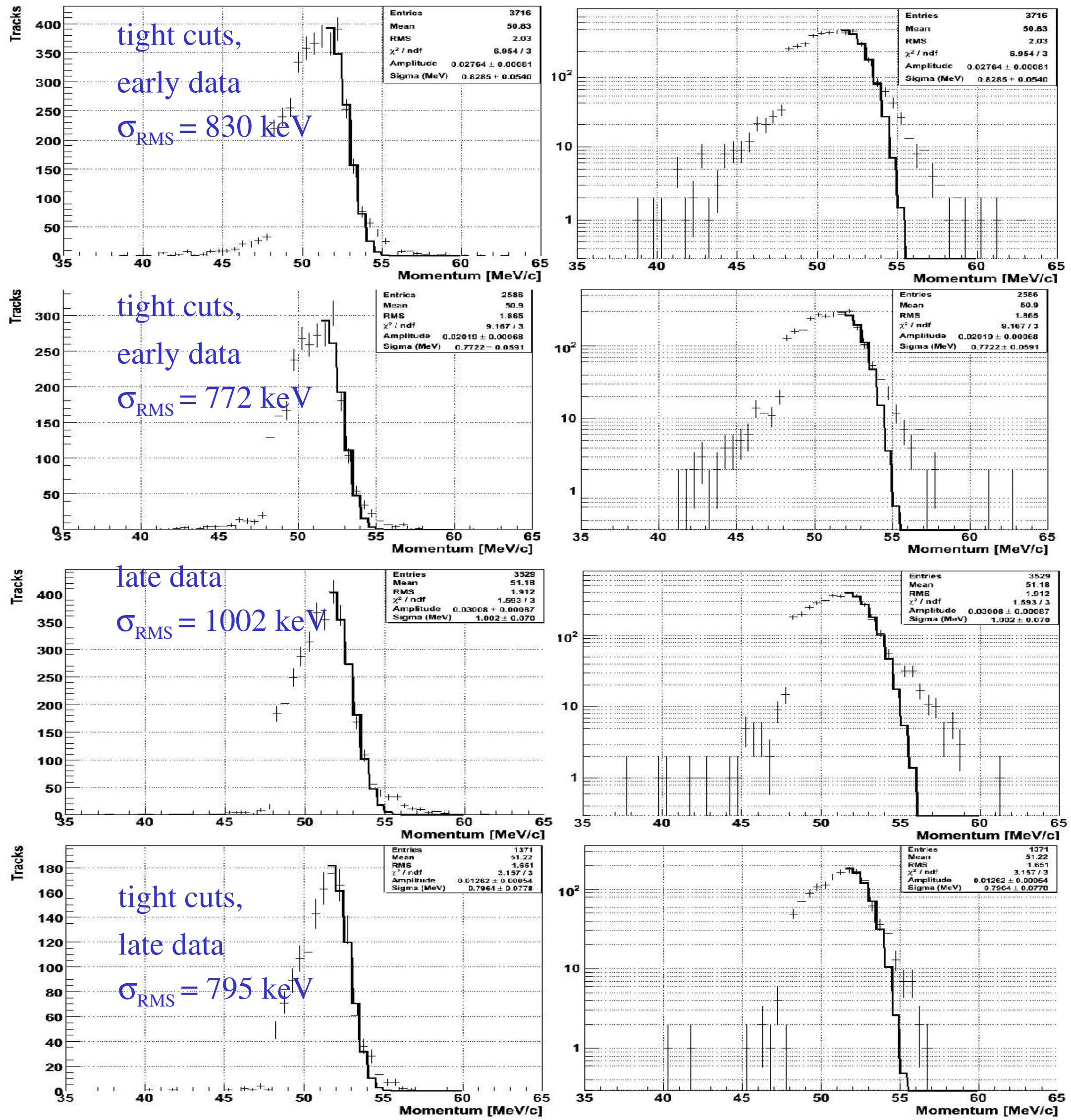






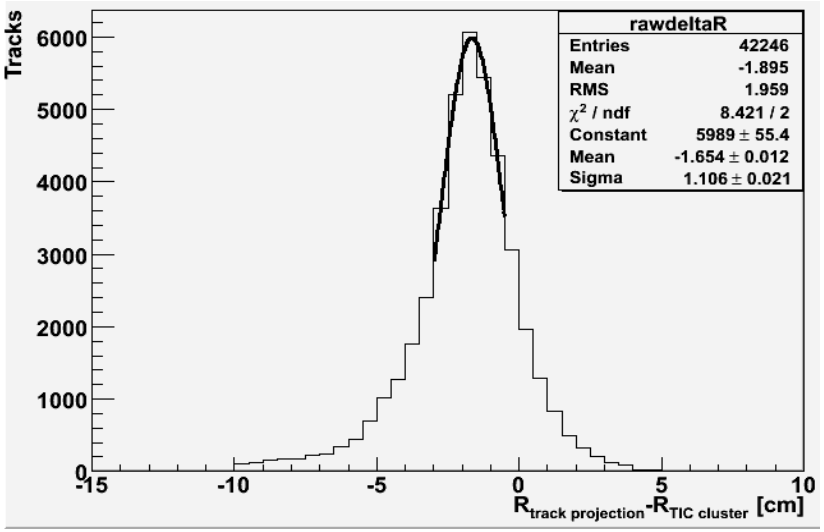
Momentum resolution from data

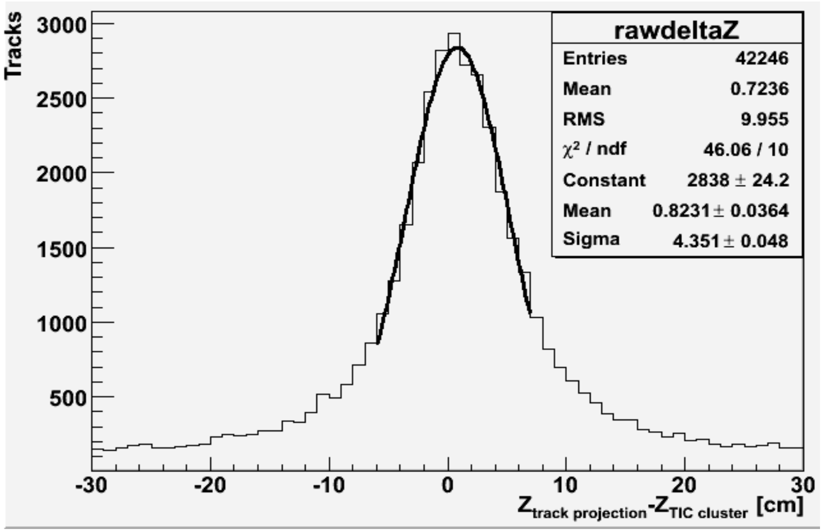
- No fixed momentum particles to measure response function
- Fit to edge of Michel spectrum to demonstrate resolution
  - Edge of spectrum most sensitive to Gaussian part of resolution function – fit of high energy tail very dependent on model for tail in resolution function
  - Currently worse than MC by a factor of 2, but inefficiencies not yet in MC resolution



Track TC Match and Propagation time

- Need to correct for track propagation delay to precision of 50 ps ⇒ track length to 1.5 cm
- Trajectory known from target plane through spectrometer to very good precision
- Projection to TIC complicated by material after spectrometer causing scattering, energy loss
- Currently, project to fixed ϕ of timing counter with using propagation of Kalman state vector
  - No correction for mismatch with reconstructed position in timing counter
  - Typical propagation distance is of order 1 m
  - Systematic uncertainties in dR, dZ seen, of order 1 cm

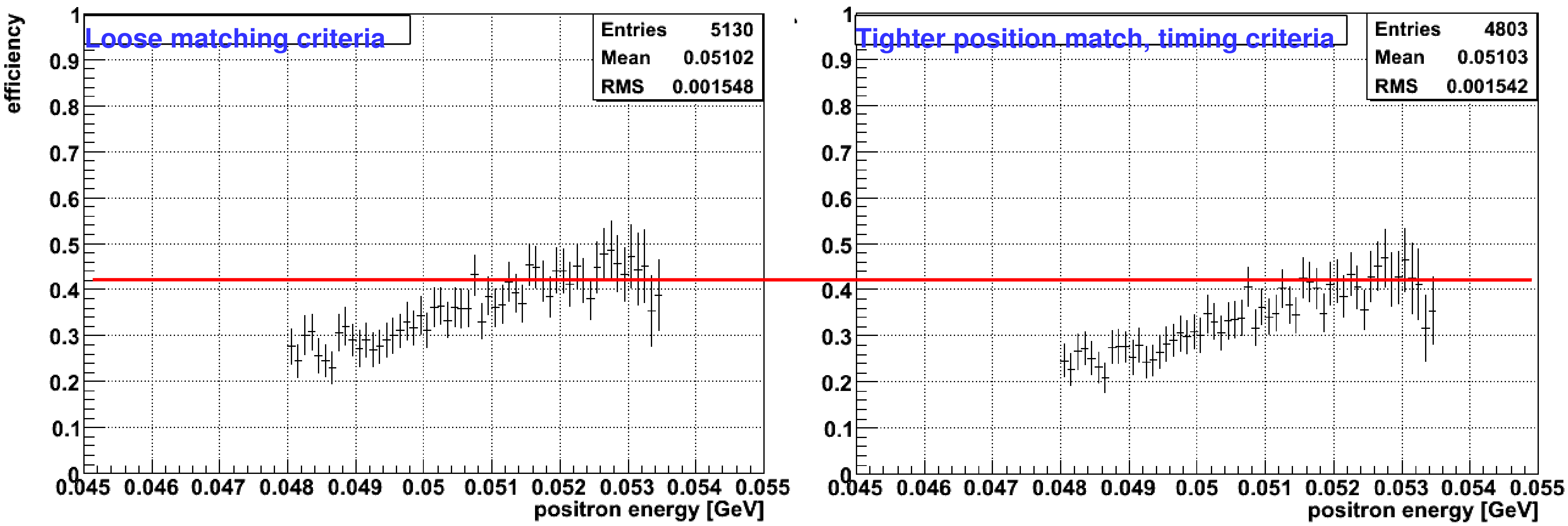




- Fully corrected photon-positron timing difference currently at level of 150 ps in RD signal with photon energy above 40 MeV

Using DCH to Study Timing Counter

- Use DCH trigger data
  - Require 4 hits in 5 contiguous chambers
  - Run standard analysis, positron selection criteria
  - Measure probability of having a TIC hit



RD detection

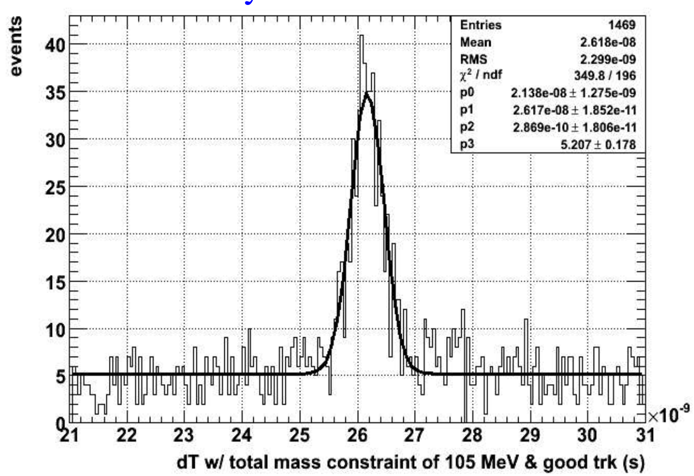
Radiative Decay peak is searched in:

- Dedicated Low Intensity run
- Standard Intensity

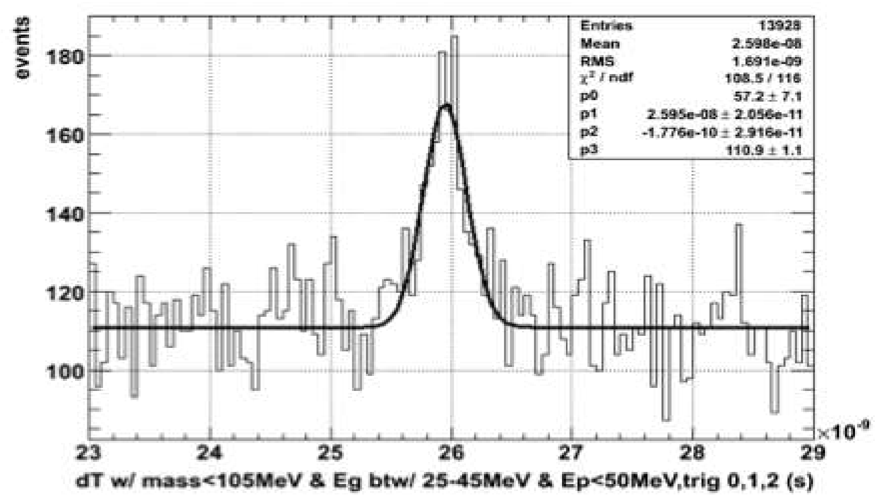
The distribution T_{e+}-T_{γ} shows a clear peak!!

Selecting high Eγ time resolution is close to design value !!

Low intensity runs



Standard runs



Conclusions

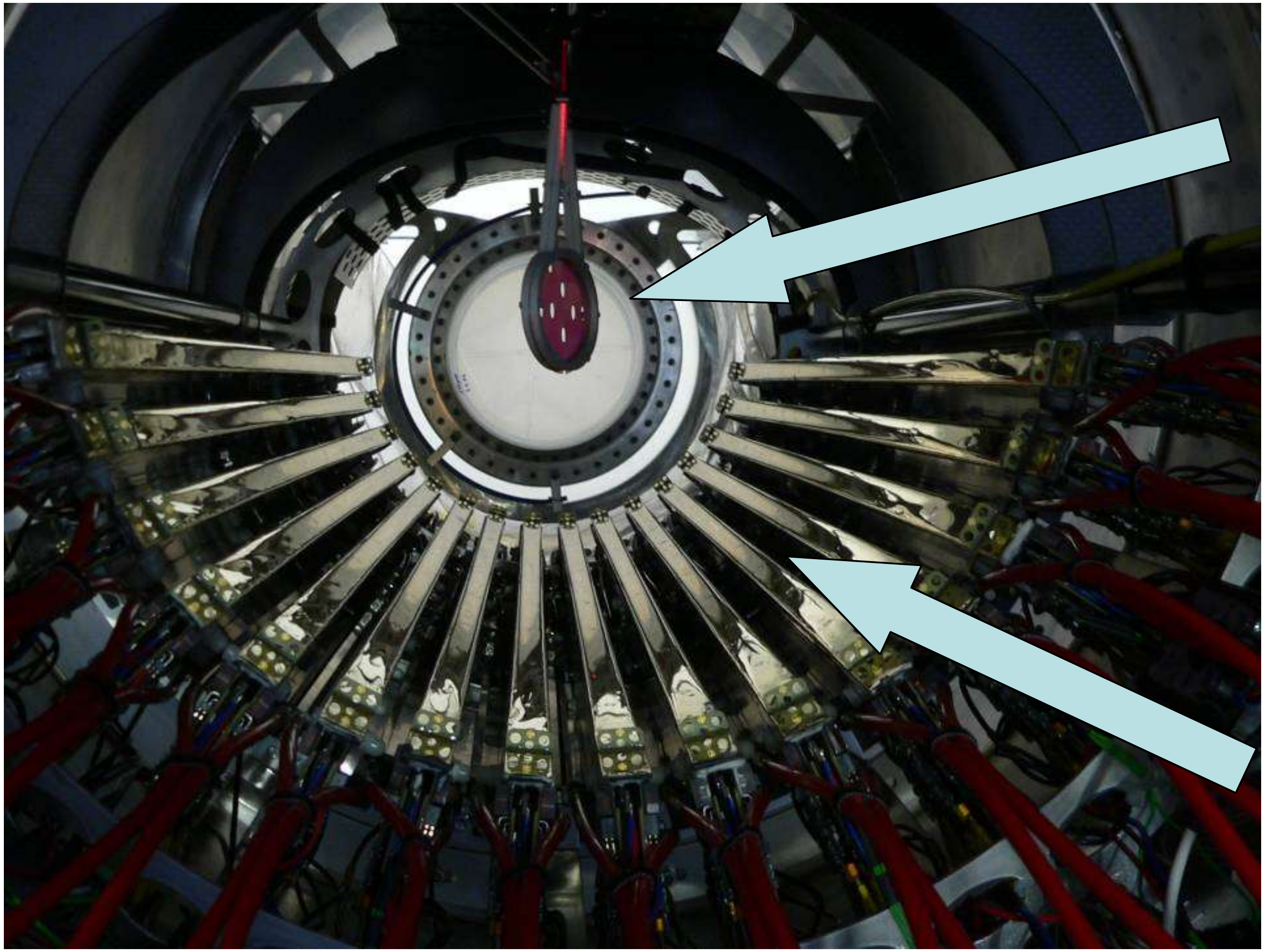
- Tracking efficiency in current run is poor, mostly due to DCH performance
- Momentum resolution not yet corresponding to MC (Inefficiency?)
- TC fibre performance limited by malfunctioning digital electronics, adequate otherwise
- TC bar performance in line with design parameters
- Radiative Decay peak cleanly detected with good time resolution
- Analysis currently adequate for data with MEG sensitivity of order few x 10^{-12}
- Significant improvement in MEG sensitivity per day can be achieved
  - Replacing TC fibre electronics
  - Improvements in DCH resolution function
    - improved chamber efficiency (hardware)
    - Improved noise performance (hardware)
    - some tuning (software)

$\Rightarrow$ increase in sensitivity per day by 3

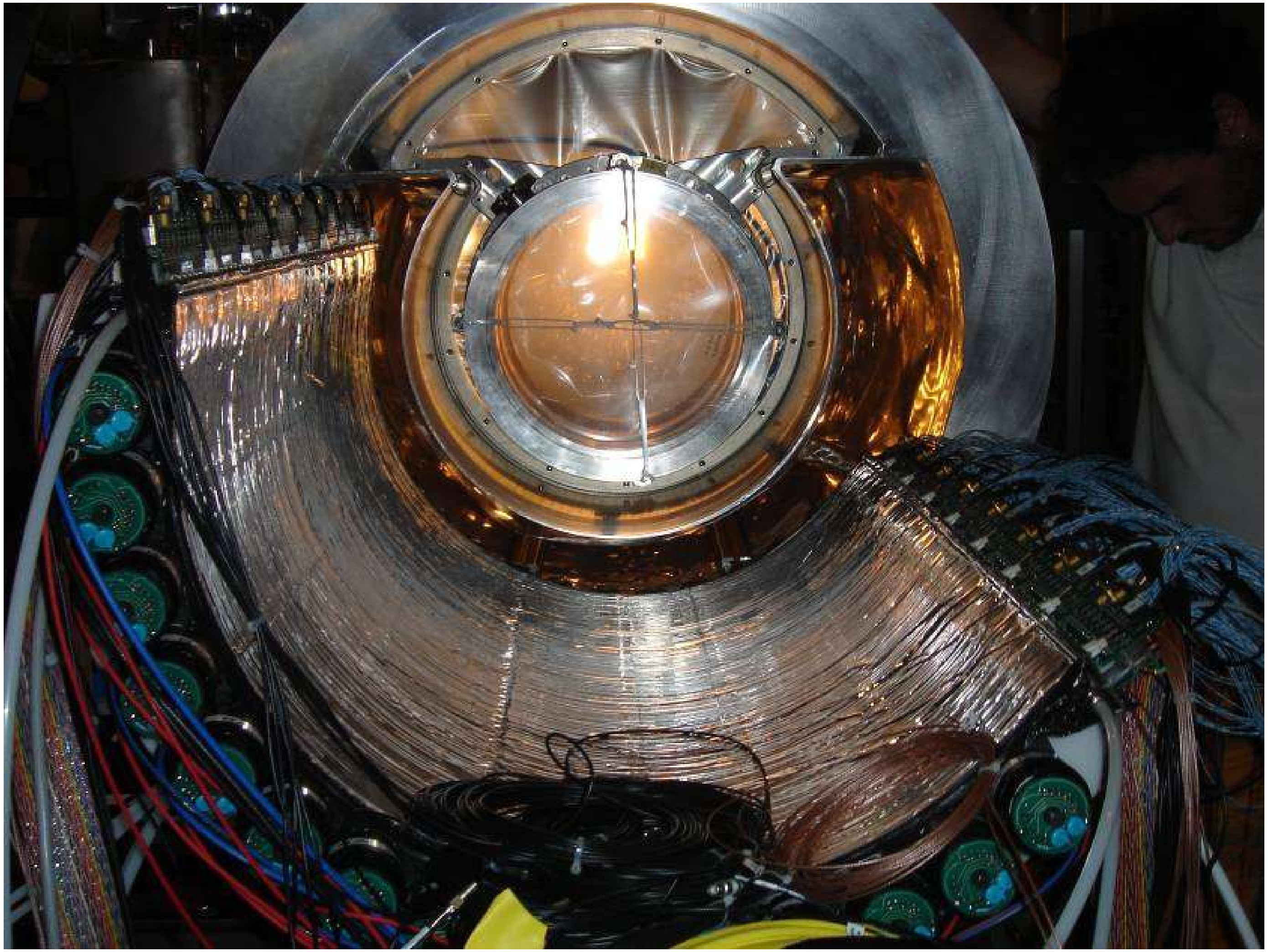
Design sensitivity is within reach in three years data taking !

Backup slides

Drift Chambers 1)



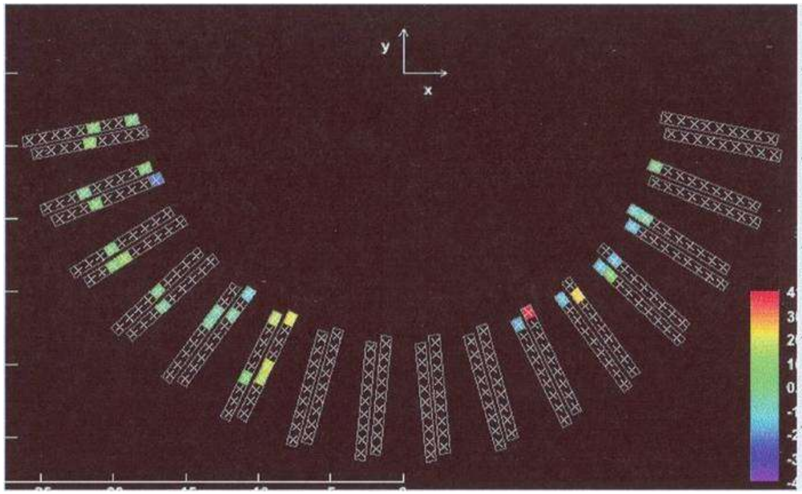
Timing Counter 3)

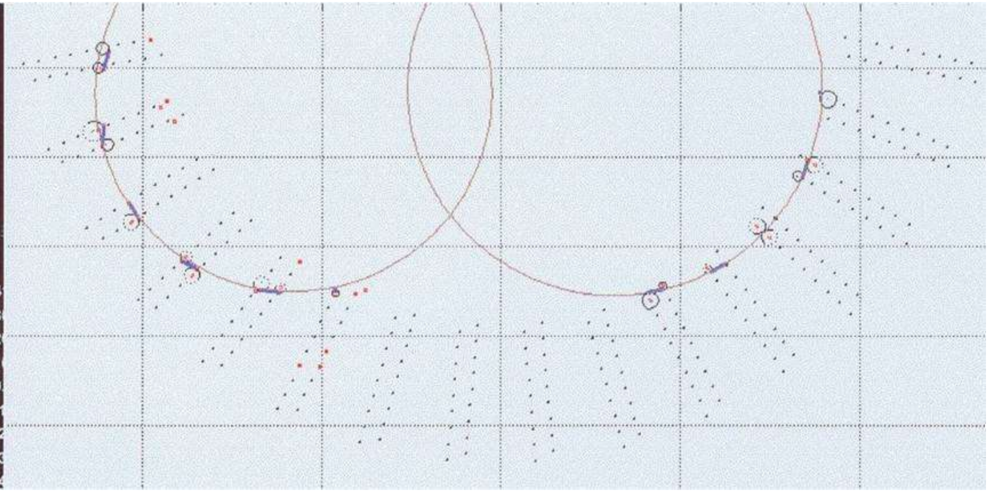


TC after installation in MEG

Detector calibration and performances: DC & target

- Target position and drift chambers alignment checked by optical survey. Target orientation known within 0.2°.
- Final alignment based on **tracks**:
  - **cosmic rays**;
  - **Michel positrons** → x-t calibration, algorithm refinement

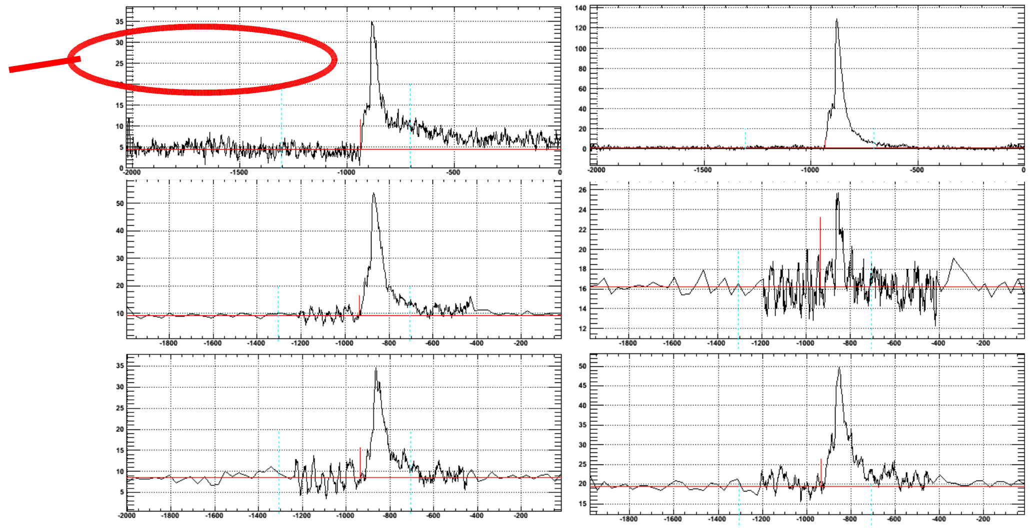




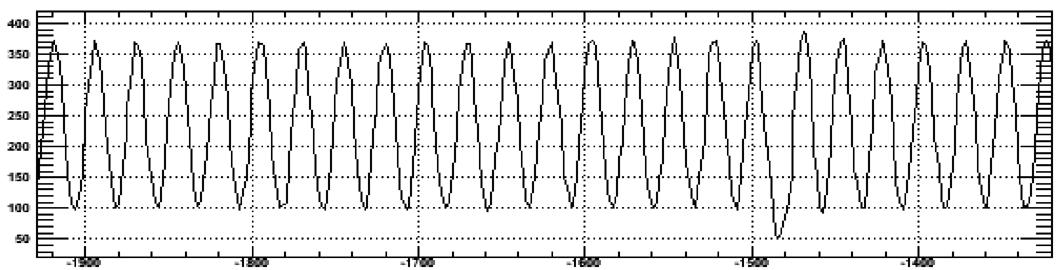
Waveform analysis

- Based on waveforms on 2 *anode* ends and 4 *pads* associated with each *cell*

waveform noise limits resolution



Waveform Analysis

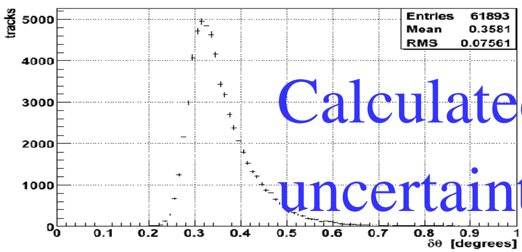


hardware improvements anticipated

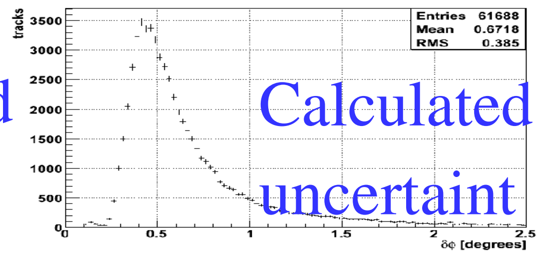
– Improvement in noise level would significantly improve resolution

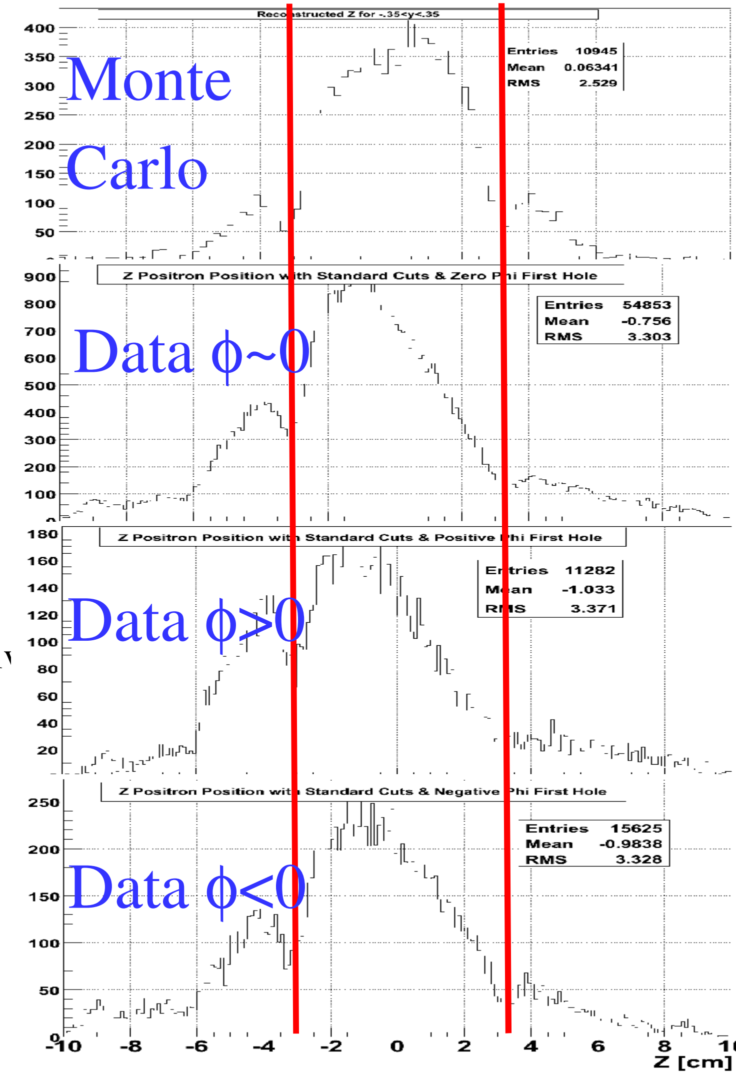
Check of Angular Resolution

- No source of positrons of known direction
- Fitting provides event-by-event estimate of $\delta\theta$, $\delta\phi$



Calculated uncertainty in θ, data 6 mrad

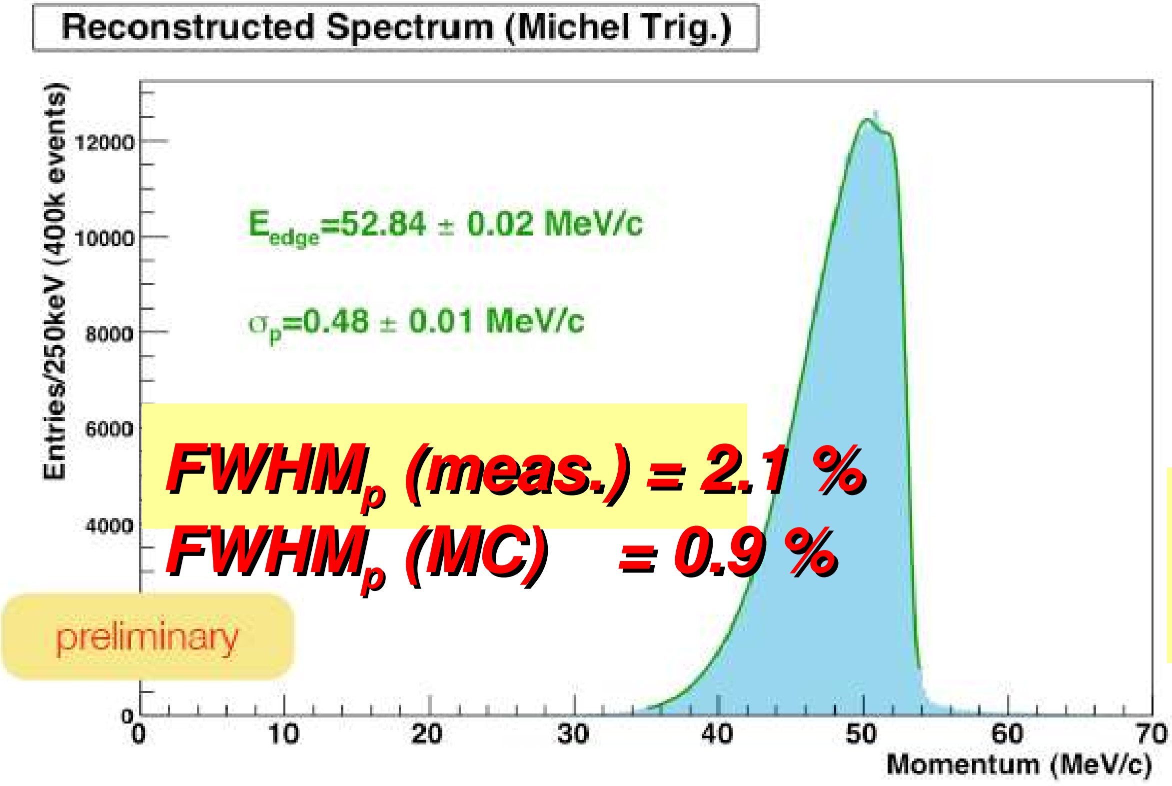




- Target designed with holes to test of resolution in projection to the target $\Rightarrow$ infer $\delta\theta$, $\delta\phi$
- Take slice in target projection around hole, try to match depth of dip data to MC
- Position of hole vs. angle of track with respect to target normal sensitiv to target position
- Difficult to quantitatively match distributions
  - Beam spot has different shape
  - Hole on falling distribution
  - Work in progress
  - First try requires increasing resolution in δZ, δY by 50%
- Position of hole good to at least 1 mm – neglibible contribution to $\theta_{e\gamma}$ uncertainty

Detector calibration and performances: DC resolution

DC performances: momentum resolution



$FWHM_p$ (meas.) = 2.1 %

$FWHM_p$ (MC) = 0.9 %

Expected improvements in:

- *detector resolution*
- *tracking efficiency*

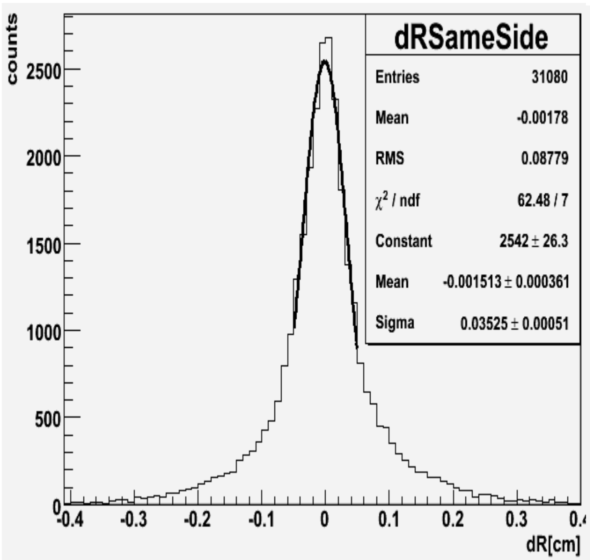
Decay vertex resolution

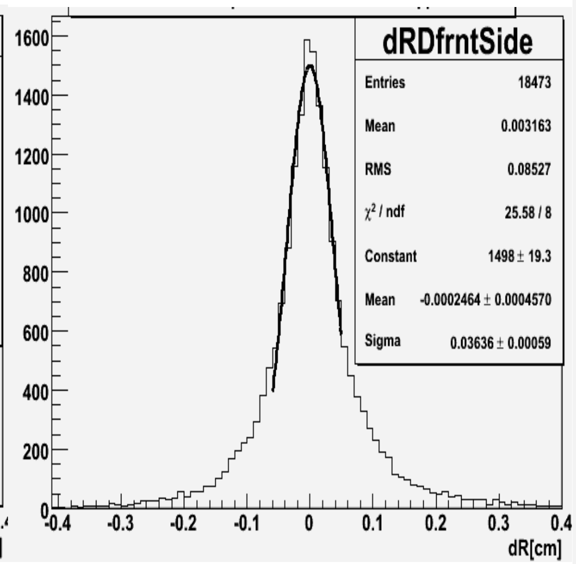
$\sigma_V \approx 1$ mm

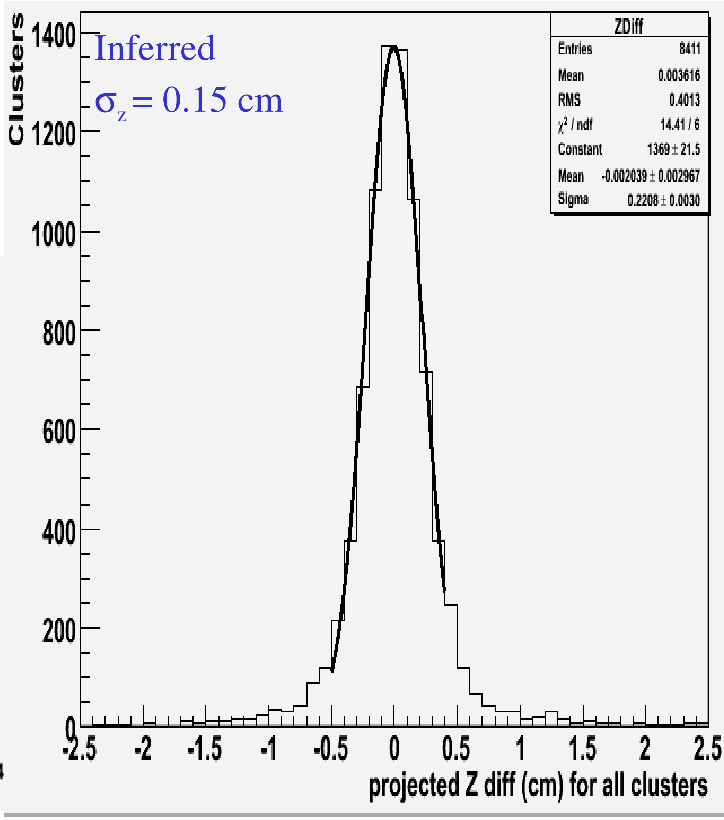
as required (holes on target)

Drift Chamber Performance from Tracking

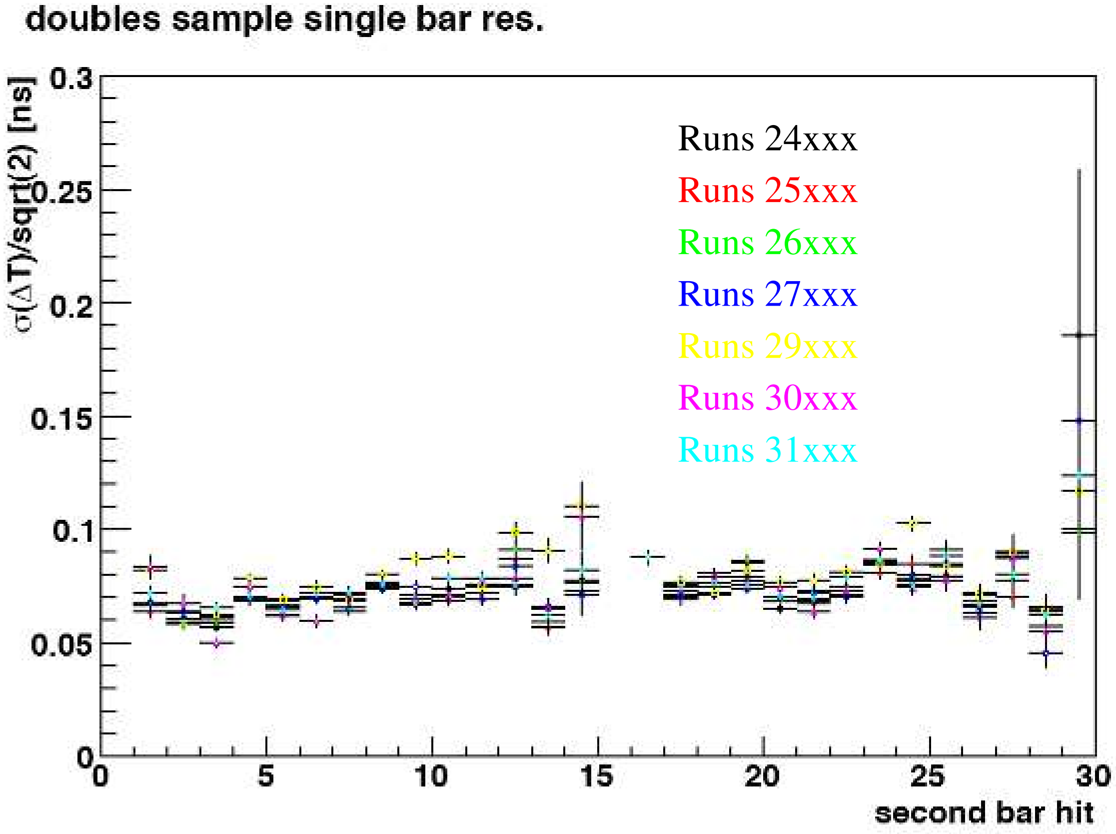
- Rφ position resolution
  - Look at difference in hits in 2 planes in chamber projected to central plane using trajectory information: insensitive to multiple scattering
  - Typical spatial resolution of 260 microns
  - Systematic effects with drift distance and angle – ad-hoc corrections applied
- Z position resolution
  - Similar technique to that for Rφ resolution







TC time resolution stability

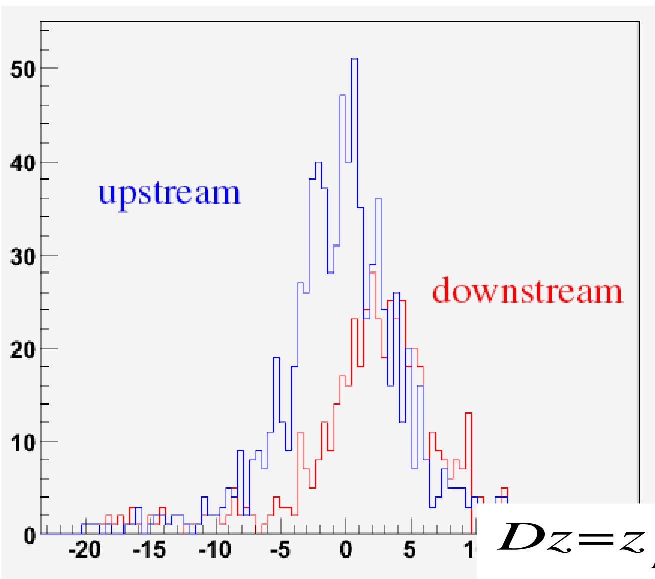


- Same TW calibration constants
- Stable over time
  no need of different
  sets of constants

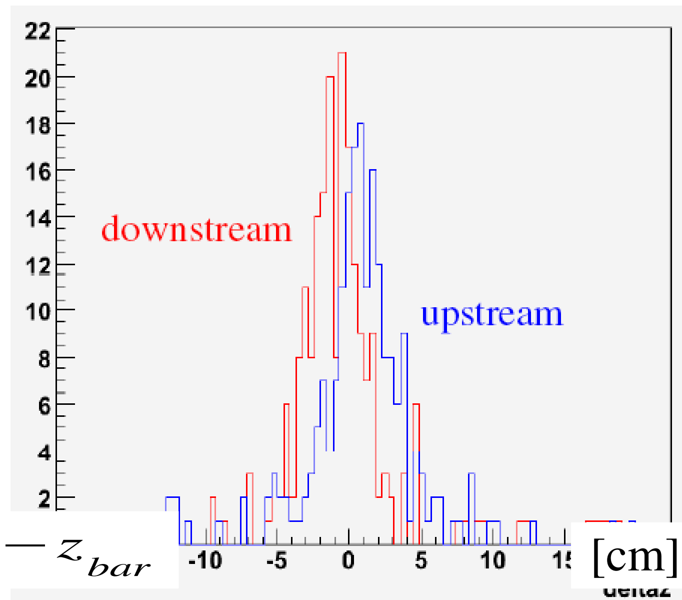
DCH-TC match hitmap

Extrapolate tracks from DCH to TC bars

DATA



MC

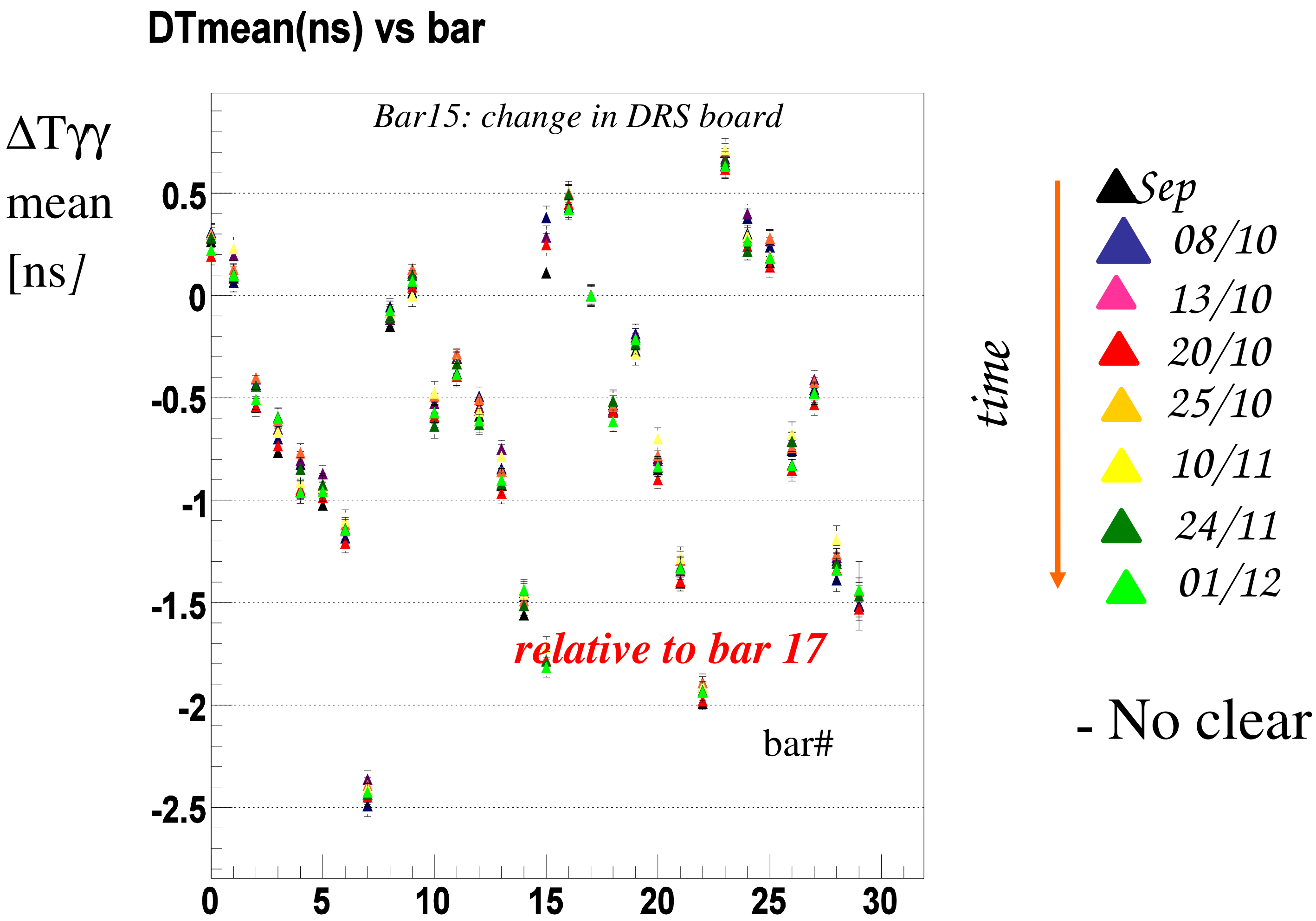


$Dz = z_{DCH} - z_{bar}$ [cm]

Given a track **and** a TC bar hit matching efficiency is 91%

Some data/MC discrepancy

Inter-bar offsets monitoring



Weekly monitoring (periodic DB updates)

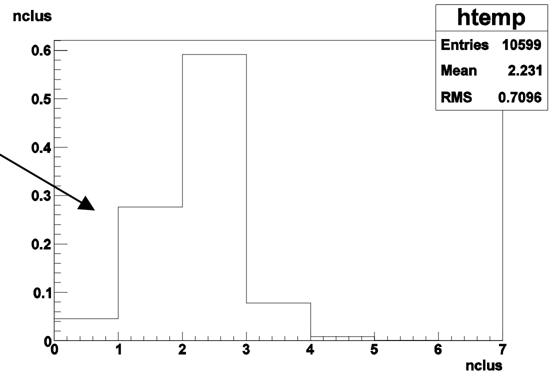
- No clear trend vs time

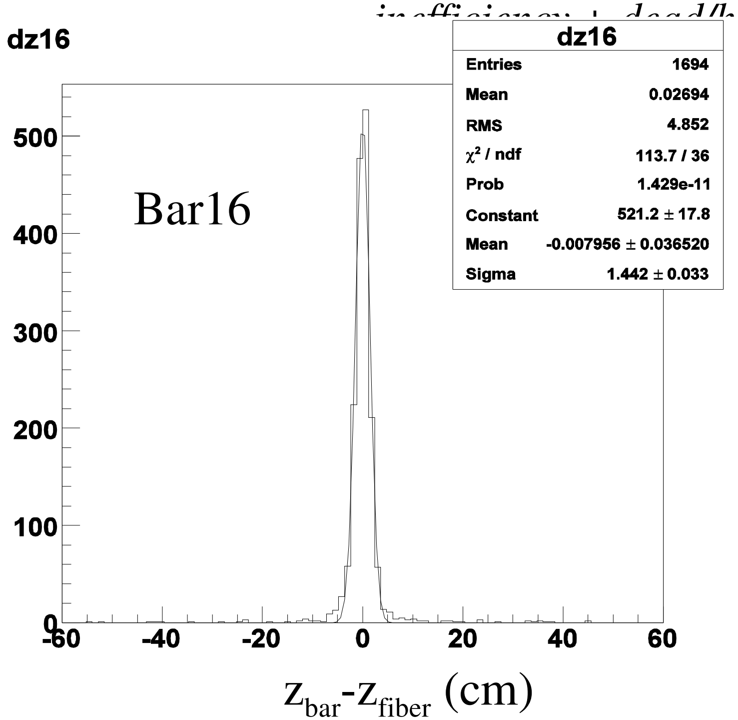
Effective velocity with TICZ

Pass-thru cosmics, 2 hit fibers (clusters) expected

Single-cluster inefficiency: 27%

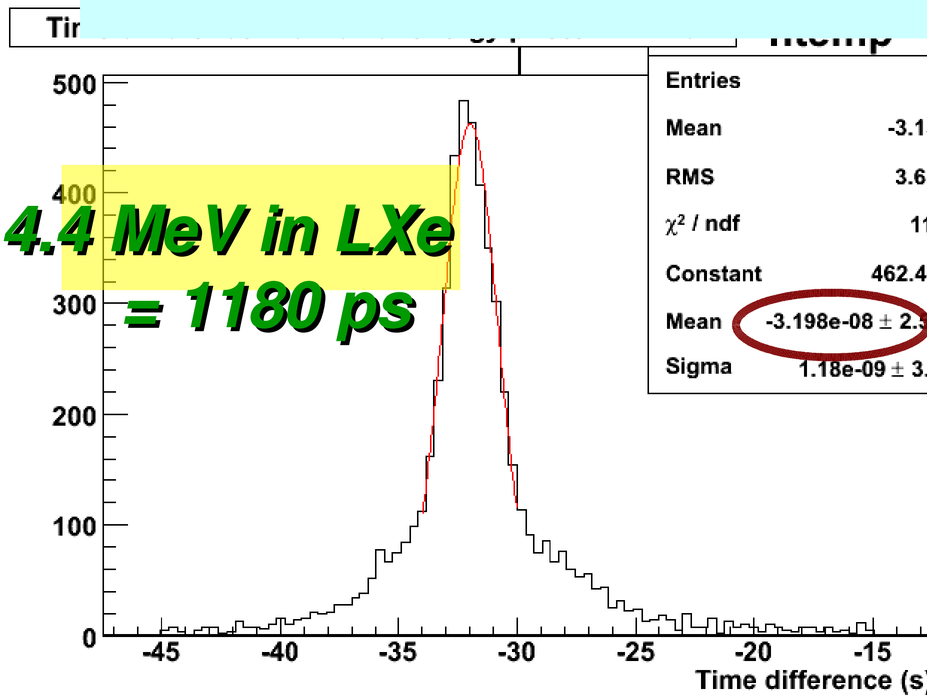
due to cosmics geometrical inefficiency + dead/hot fibers (5%)





Using $z_{fiber} = \frac{1}{2} v_{eff} \cdot (t_1 - t_0)$

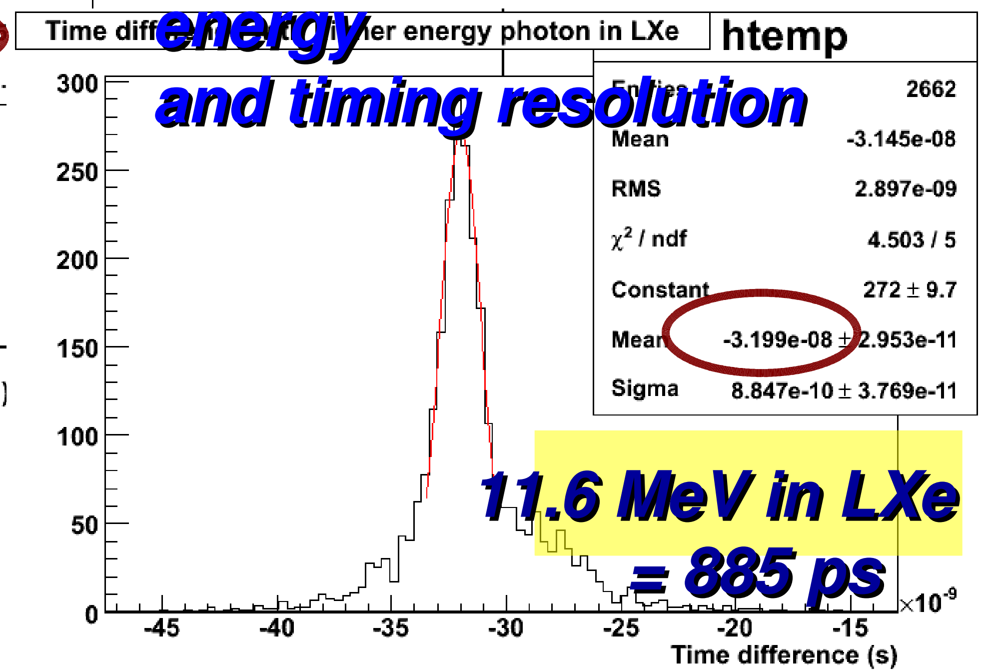
TC – LXe relative timing calibration with Boron



4.4 MeV in LXe = 1180 ps

TC-LXe timing difference at target

Correlation between energy and timing resolution



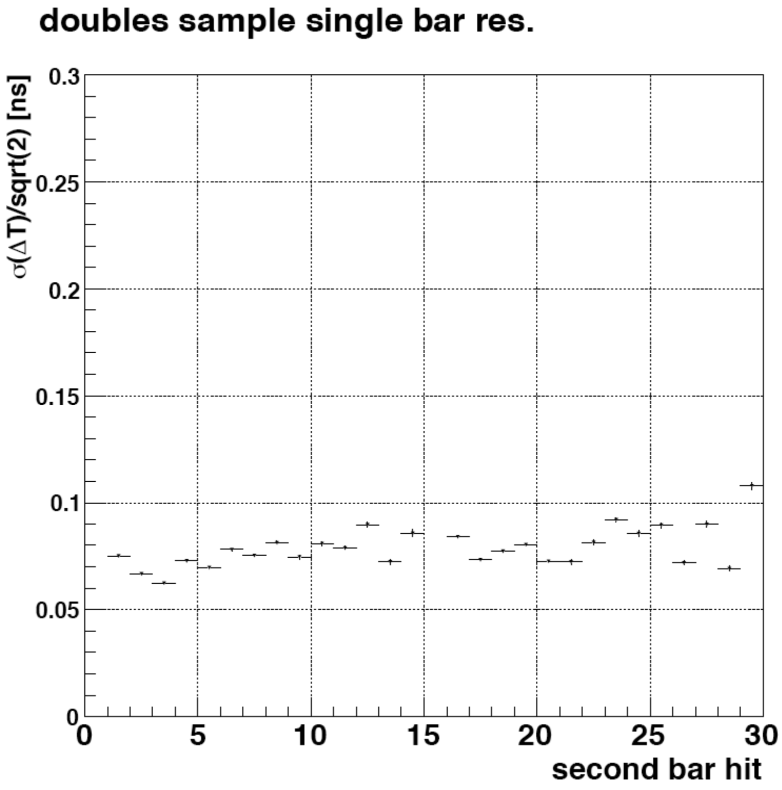
11.6 MeV in LXe = 885 ps

For coincident gamma's at the target

T_{TC}-T_{LXe} = -32 ns

TC time resolution

$\frac{\sigma_{\Delta T}}{\sqrt{2}}$ **Estimate** of single bar time resolution
Assuming the two bars to have
the same intrinsic time resolution



Upper limit on average time resolution (σ) in 60-90ps range

Includes effect of DRS digitization (~10 ps)