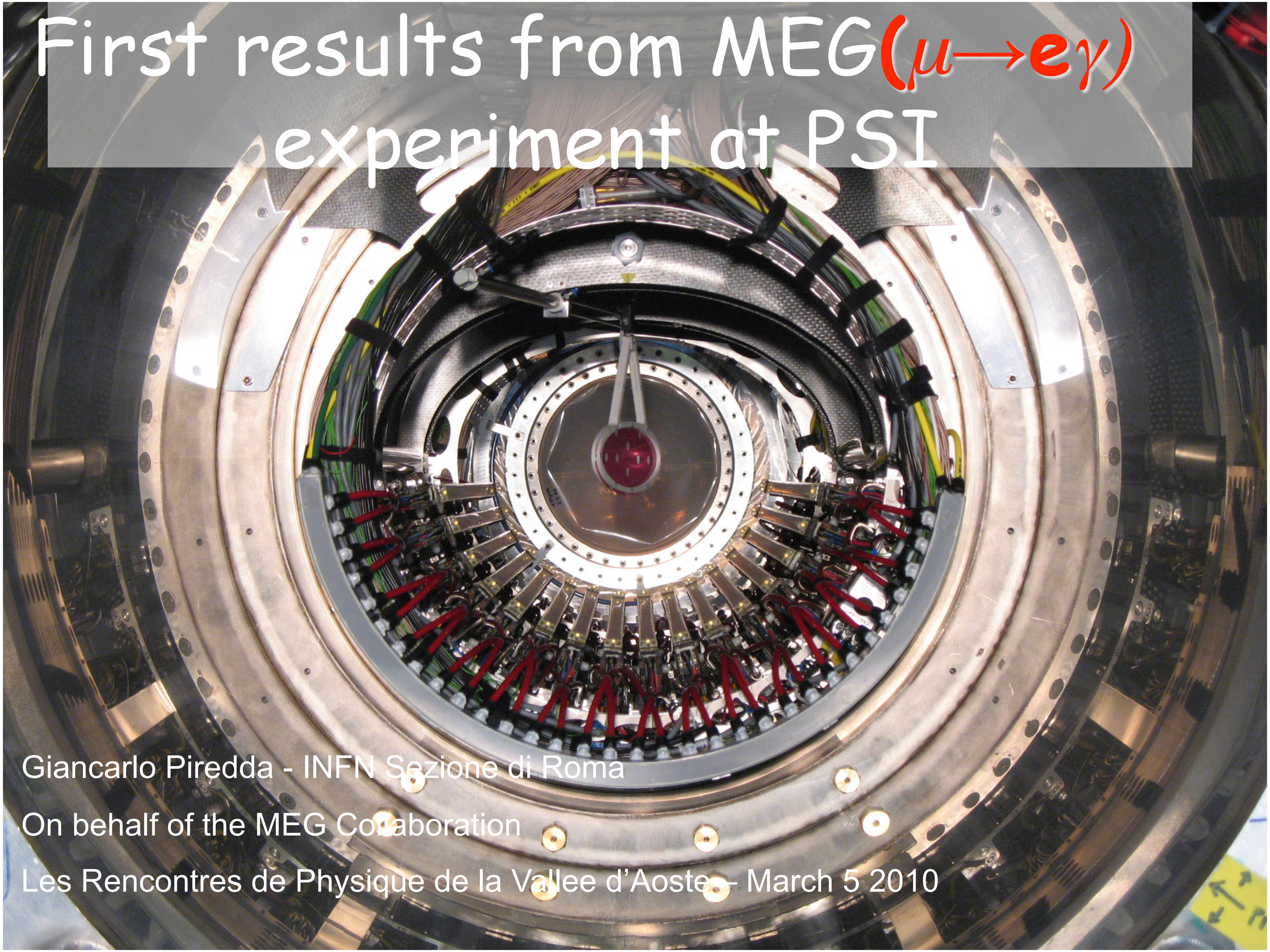
First results from MEG($\mu \rightarrow e\gamma$) experiment at PSI



Giancarlo Piredda - INFN Sezione di Roma

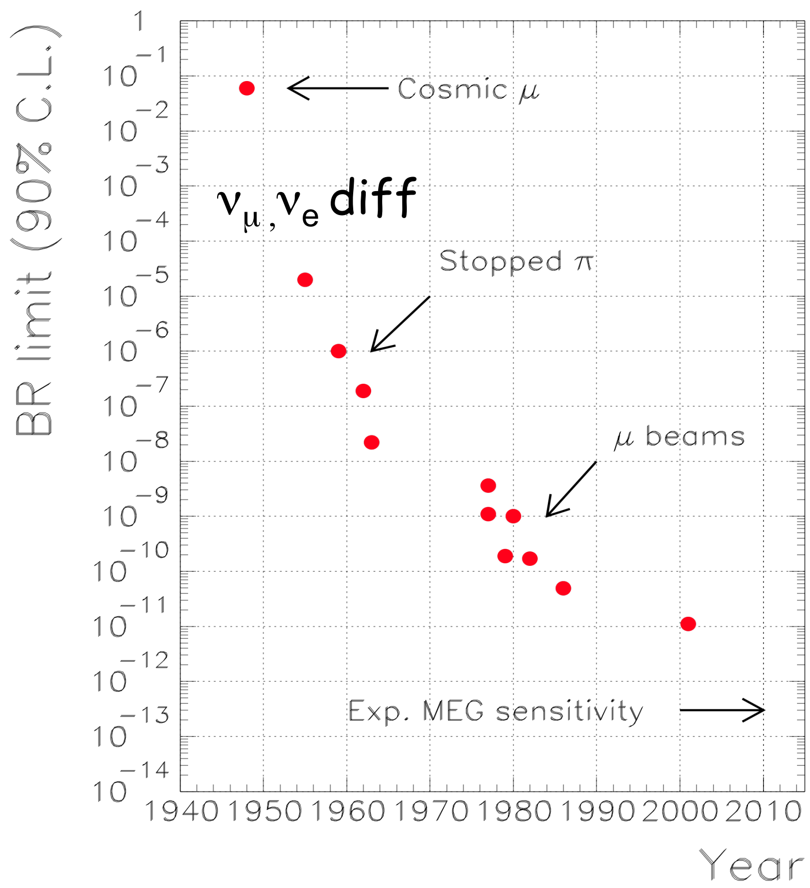
On behalf of the MEG Collaboration

Les Rencontres de Physique de la Vallee d'Aoste – March 5 2010

Outline

- Motivation for searching $\mu \to e\gamma$
  - (see A.Ibarra on Neutrino and LFV Session at this conference)
- The MEG detector
- Calibration
- The 2008 Data taking and result
- The 2009 run
- Conclusions and Perspectives

$\mu \rightarrow e\gamma$ A long Quest



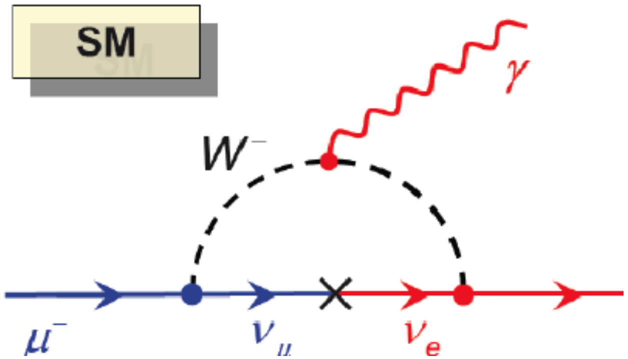
- Step forward in sensitivity linked to technology upgrades!
- Current upper limit on BF

$<1.2 \cdot 10^{-11}$ @90%C.L. MEGA

MEG plans to improve two order of magnitudes the current best limit

The lack of signal in the 60ies→clear evidence of two neutrino species!

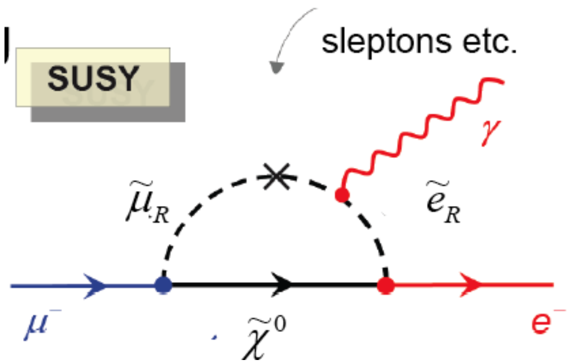
No possible in the SM!



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

$$\approx \frac{G_F^2 m_\mu^5}{192\pi^3}\left(\frac{\alpha}{2\pi}\right)\sin^2 2\theta_\odot\left(\frac{\Delta m^2}{M_W^2}\right)^2,$$

Relative probability ~ 10^{-55}

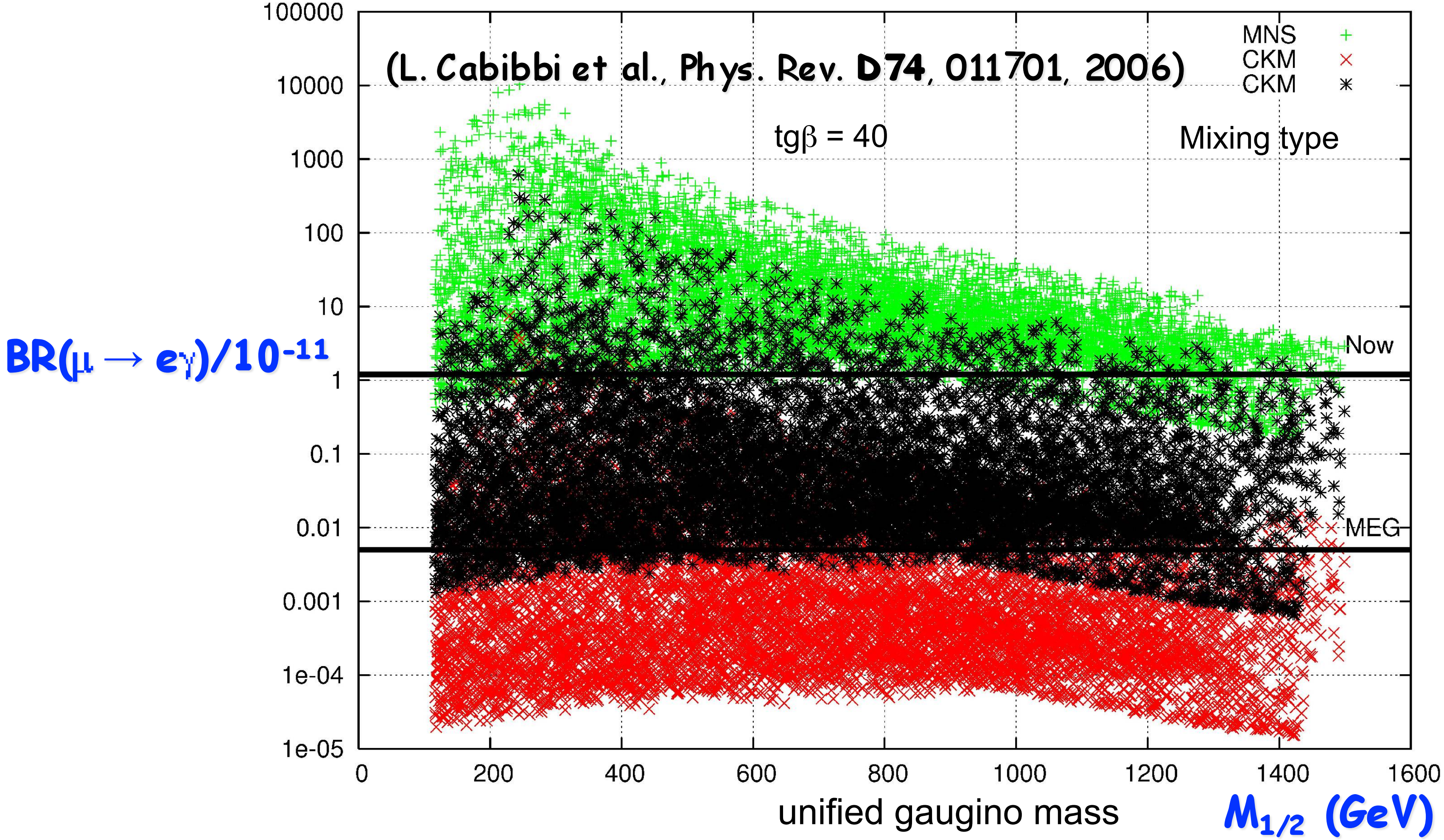


Standard Model extensions have a mechanisms to enhance the rate!

Observation is a clear indication of New Physics

Among recent Predictions

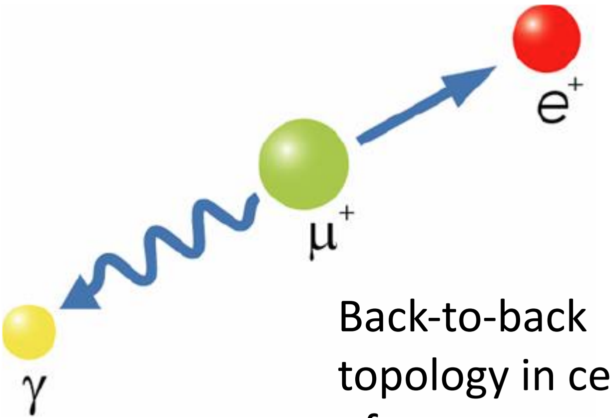
in SUSY-GUT models



In the LHC accessible region

The Signature

$$E_e \cong E_\gamma = 52.8\ MeV$$



Back-to-back topology in center of mass

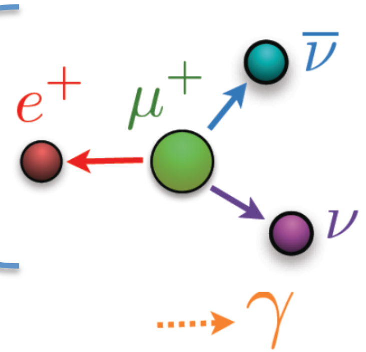
$$\vartheta_{e\gamma} = 180^\circ \qquad t_{e\gamma} = 0$$

- Two-body process
  - Well-defined photon and positron energy
- Resolutions and efficiency should be optimized
  - Background rejection at the lowest cost…
- Huge amount of muon decays
  - High beam rate to be effective

EASY. JUST measure E_e, E_γ, , $\theta_{e\gamma}$, $t_{e\gamma}$ and have a very intense muon beam!

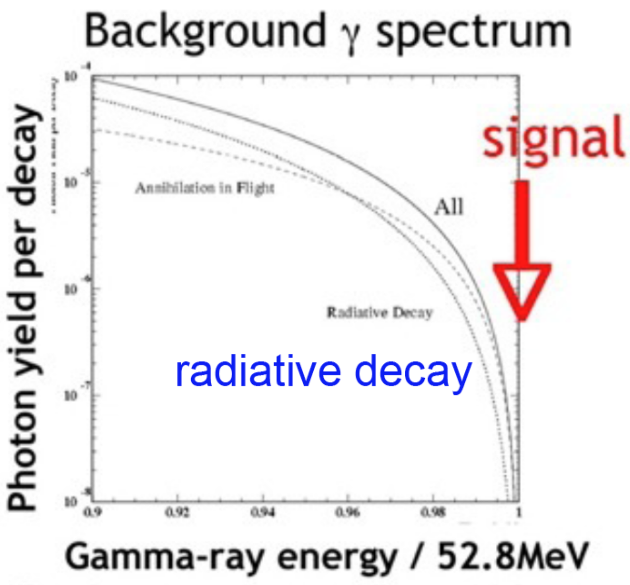
The Accidental Background

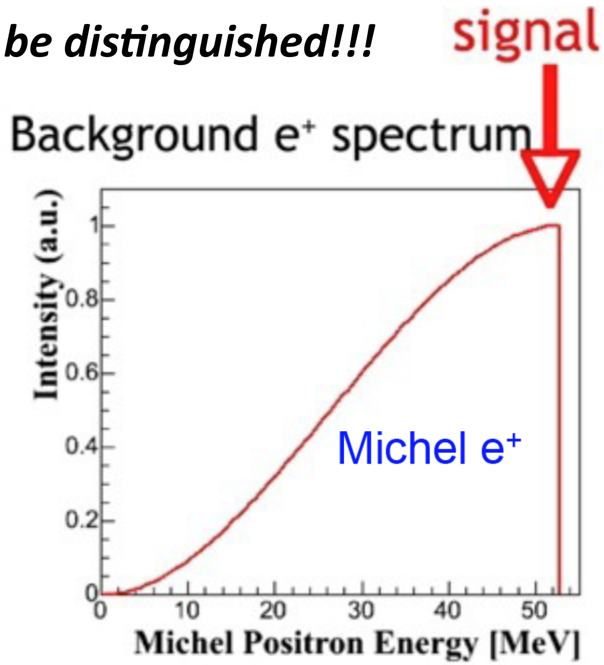
Positron from Michel decay



– Photon from
  - » Radiative Michel $\mu \rightarrow e\nu\overline{\nu}\gamma$
  - » Annihilation in flight $e^+e^- \rightarrow \gamma\gamma$
  - » Bremsstrahlung $e^+N \rightarrow e^+N\gamma$

So close in time they cannot be distinguished!!!





Required Performances

To reach BR ($\mu \to e\gamma$) ≈ 10^{-13}

- $N_{signal} = R_\mu * BR(\mu \to e\gamma)$
- $N_{RD} = R_\mu * BR(\mu \to e\nu\nu\gamma)$
- $N_{acc} \propto (R_\mu)^2 * (\Delta\Theta)^2 * (\Delta E_\gamma)^2 * \Delta t_{e\gamma} * \Delta E_e$

need the following resolutions

FWHM

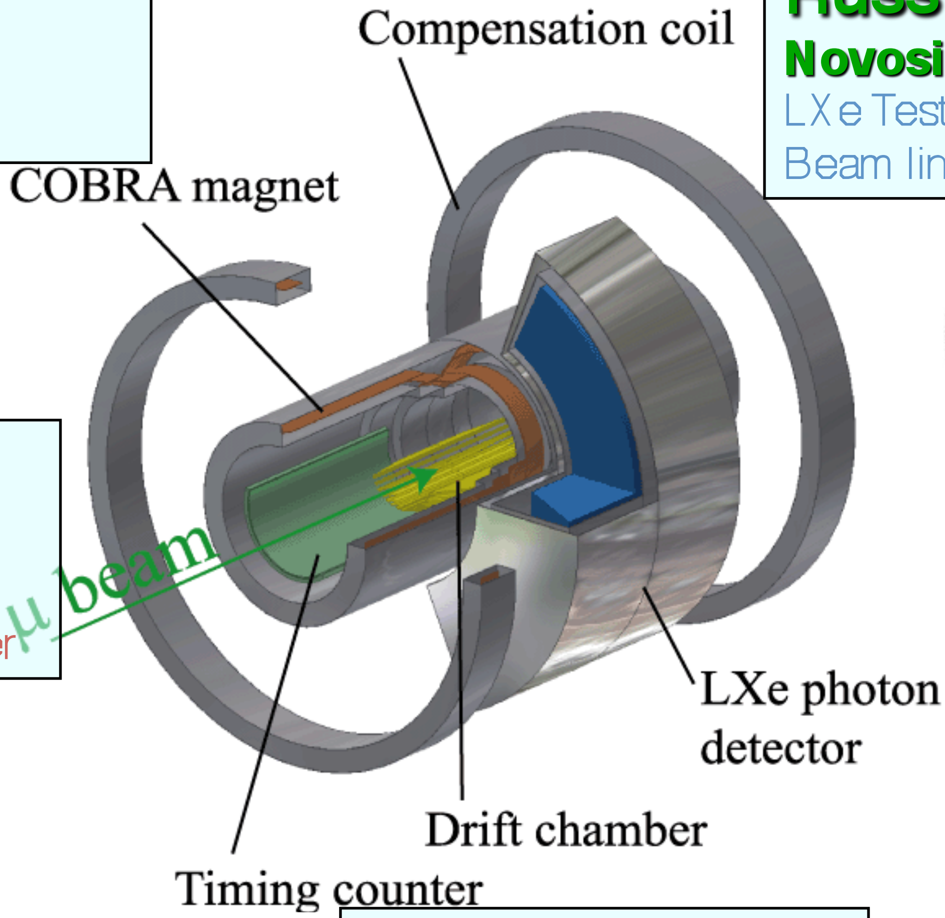
Exp./Lab	Year	$\Delta E_e/E_e$ (%)	$\Delta E_\gamma/E_\gamma$ (%)	$\Delta t_{e\gamma}$ (ns)	$\Delta\theta_{e\gamma}$ (mrad)	Stop rate (s^{-1})	Duty cyc.(%)	BR (90% CL)
SIN	1977	8.7	9.3	1.4	-	5×10^5	100	3.6×10^{-9}
TRIUMF	1977	10	8.7	6.7	-	2×10^5	100	1×10^{-9}
LANL	1979	8.8	8	1.9	37	2.4×10^5	6.4	1.7×10^{-10}
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

The MEG Collaboration

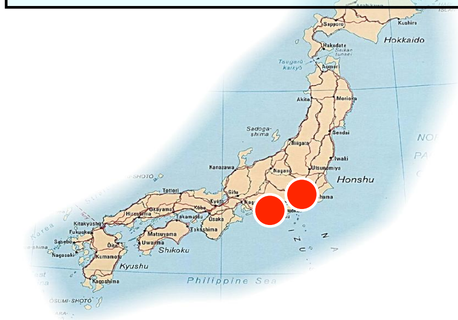
Switzerland (PSI)
Drift Chambers
Beam Line DAQ

Italy (GE, LE, PV, PI, RM)
e+ counter
Trigger LXe Calorimeter



Russia (Dubna, Novosibirsk)
LXe Tests
Beam line

Japan (Kek, Tokyo, Waseda)
LXe Calorimeter,
Spectrometer's magnet



USA (UC Irvine)
Calibrations/Target/DC pressure system

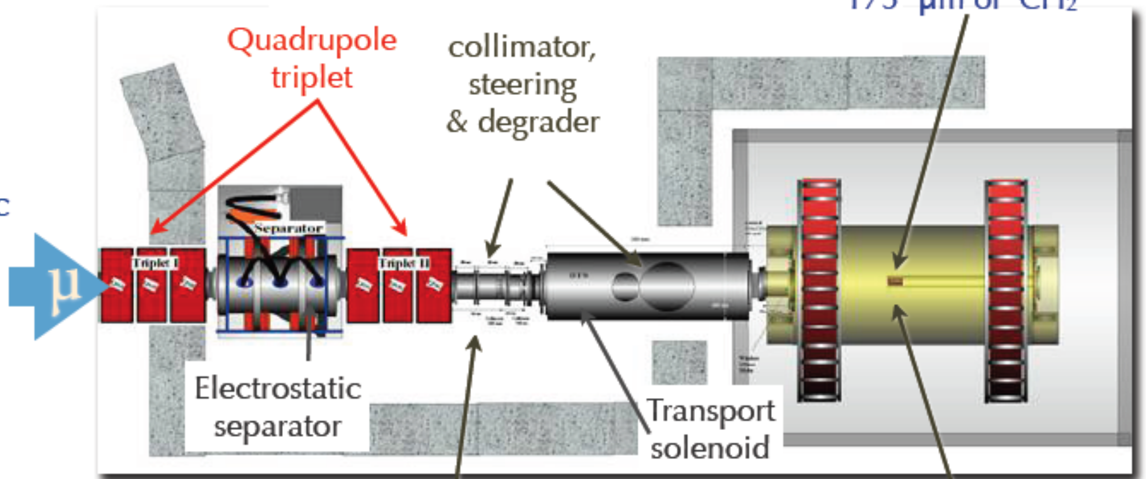
The Beam Line

1.2 MW proton cyclotron at PSI

πE5 beam line at PSI

Optimization of the beam elements:

- Muon momentum ~ 29 MeV/c
- Wien filter for μ/e separation
- Solenoid to couple beam and spectrometer (BTS)
- Degrader to reduce the momentum for a 175 μm target

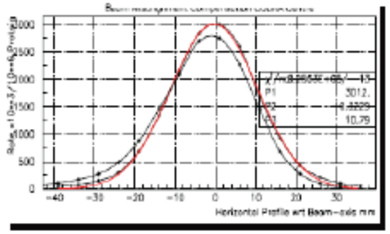


μ/e separation 11.8 cm (7.2 σ)

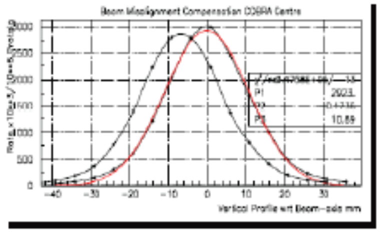
R_μ (exp. on target) >6 10^7 μ^+/s

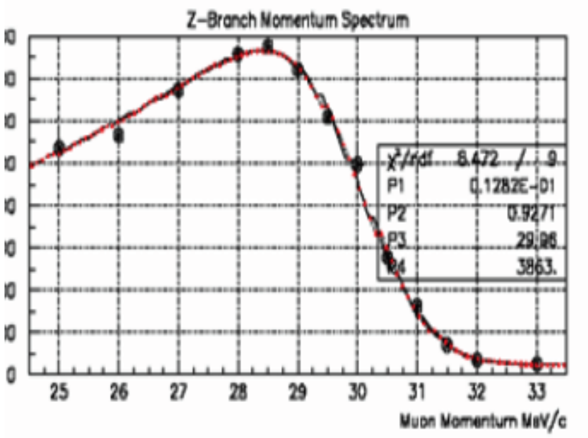
μ spot (exp. on target) $\sigma_V \approx \sigma_H \approx$ 11 mm

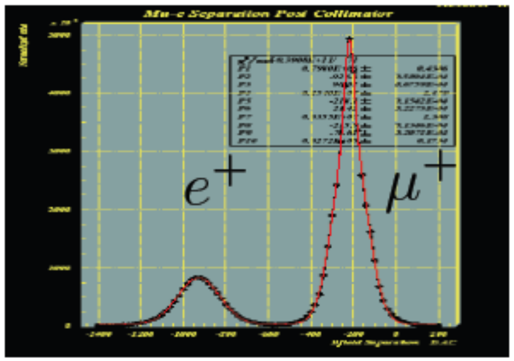
σ_x = 11 mm



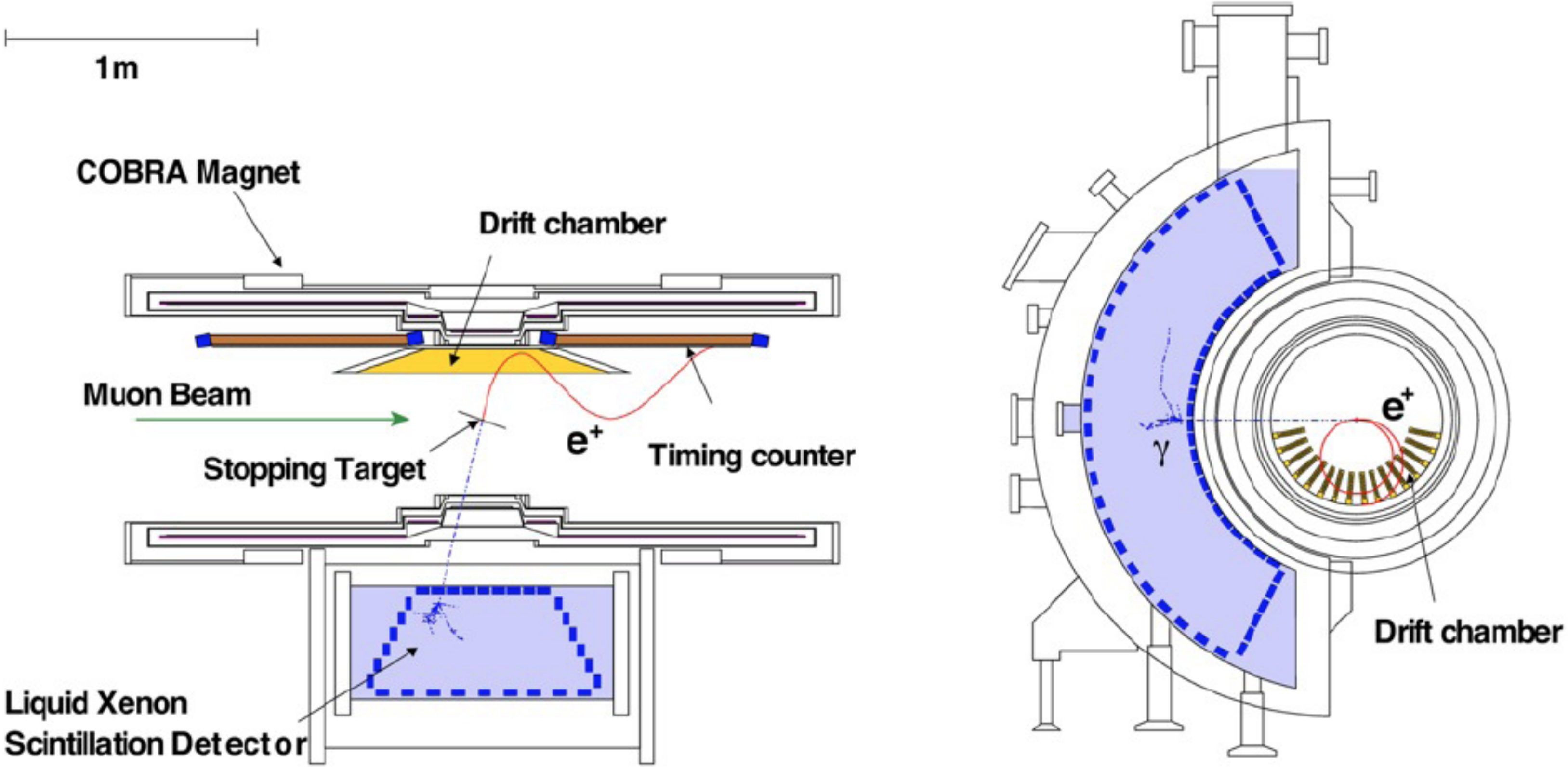
σ_y = 11 mm







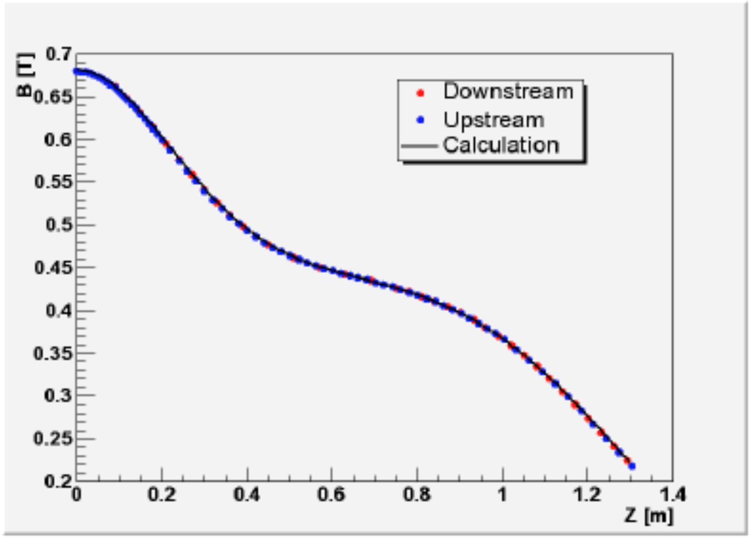
A dedicated Detector

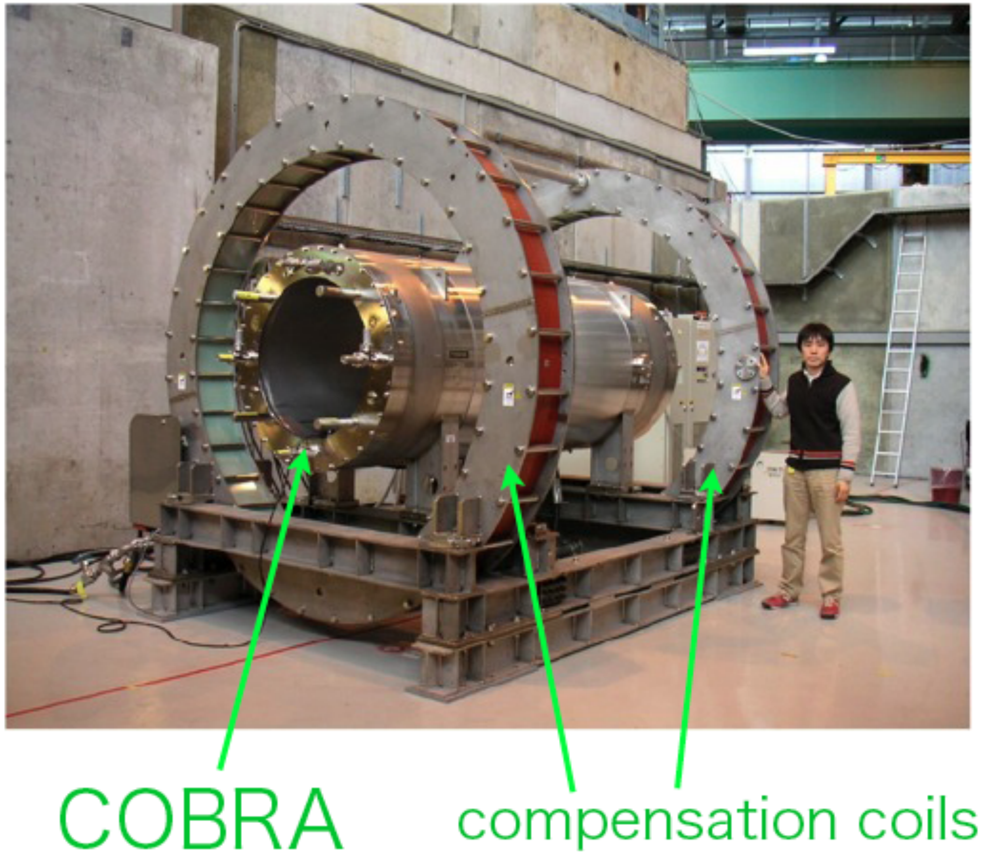


- Asymmetric coverage. Minimum material in front of calorimeter: high photon detection efficiency!!!

The Magnet

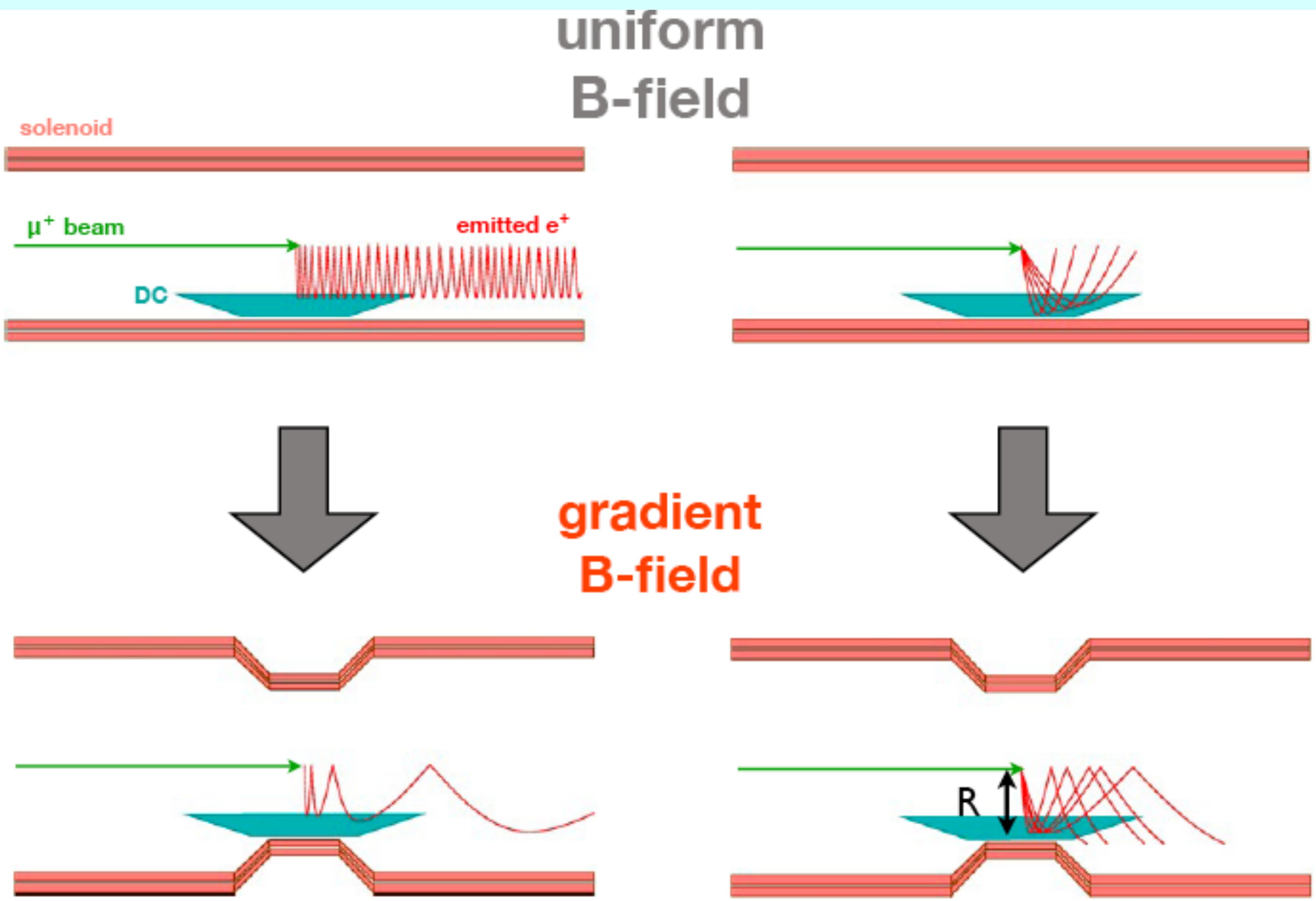
- thin-walled SC solenoid with a gradient magnetic field: 1.27 - 0.49 Tesla





COnstant Bending RAdius

The Advantage of COBRA

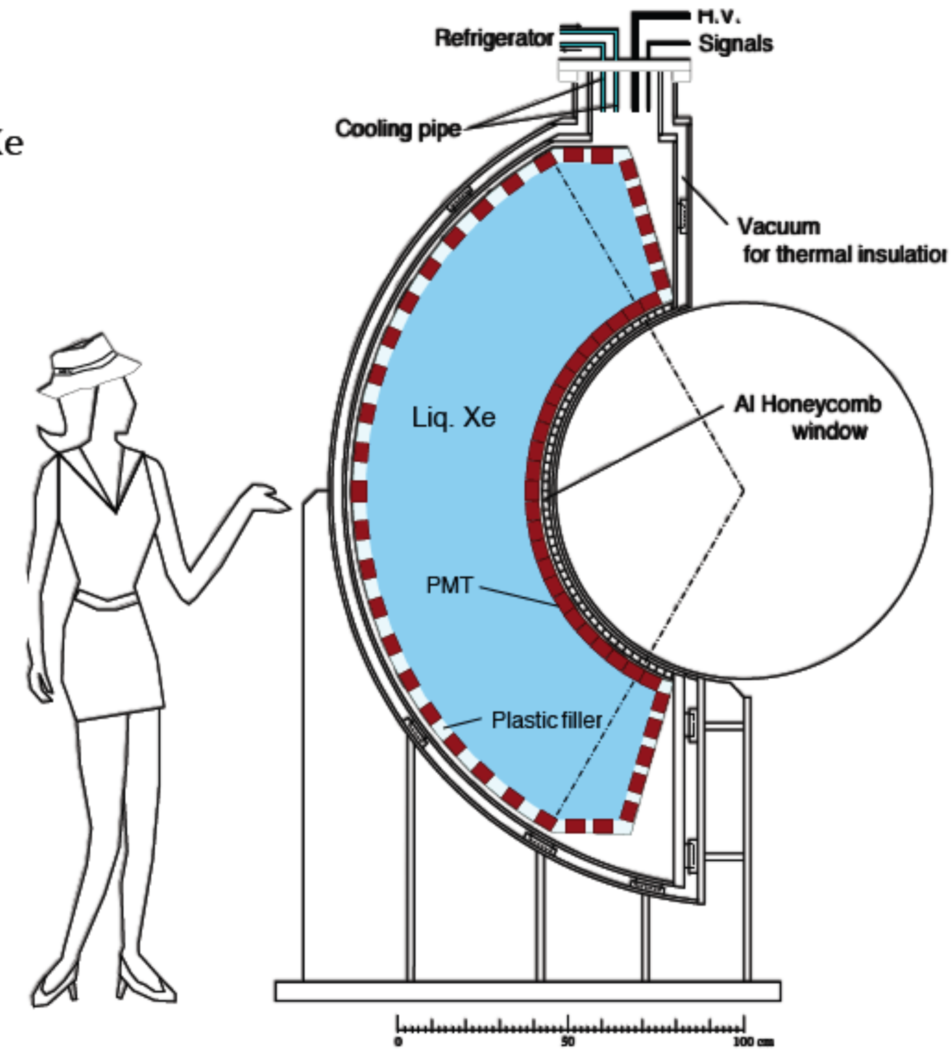


Low energy positrons quickly swept out

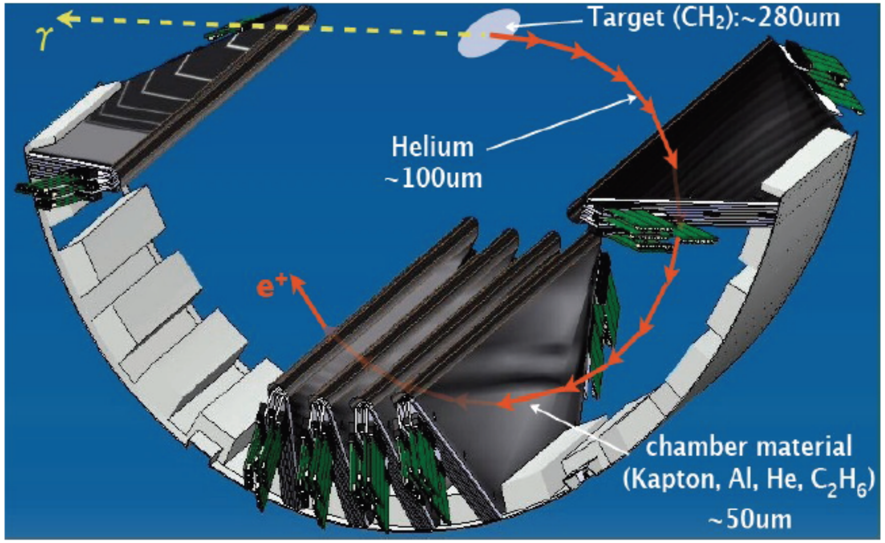
Constant bending radius independent of emission angles

The liquid Xe Calorimeter

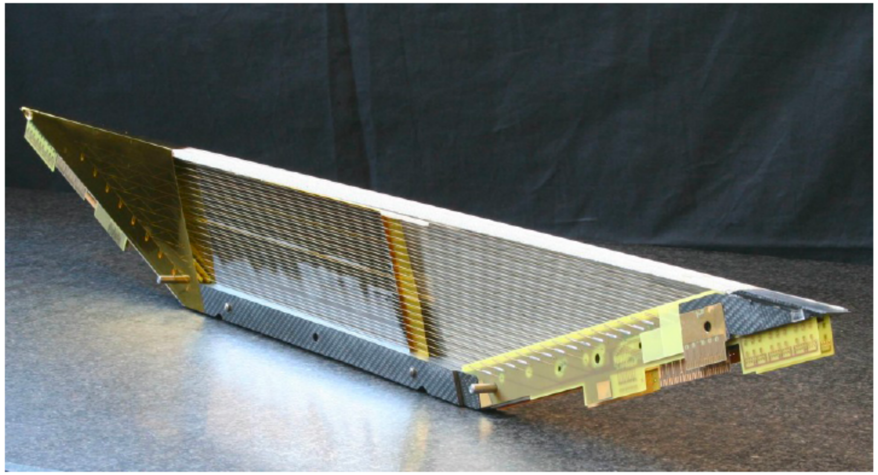
- γ Energy, position, timing
- Homogeneous 0.8 m^3 volume of liquid Xe
  - 10 % solid angle
  - $65 < r < 112$ cm
  - $|\cos\theta| < 0.35$ $|\phi| < 60^o$
- Only scintillation light
- Read by 848 PMT
  - 2'' photo-multiplier tubes
  - Maximum coverage FF (6.2 cm cell)
  - Immersed in liquid Xe
  - Low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

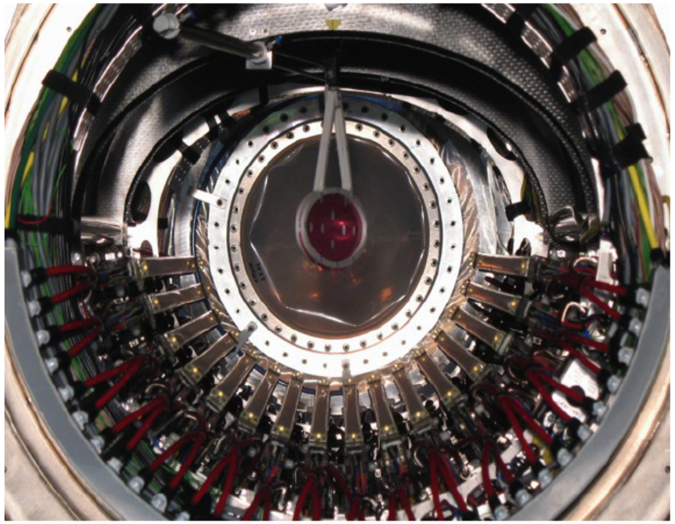


Low Mass Drift Chambers



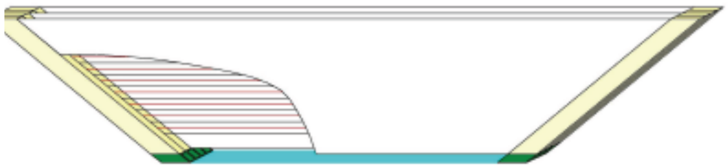
A DC Module





- Only $2x10^{-3}$ X_0 along track
- Operated with 50:50 He:ethane mixture
- Installed in a He-filled bag inside COBRA

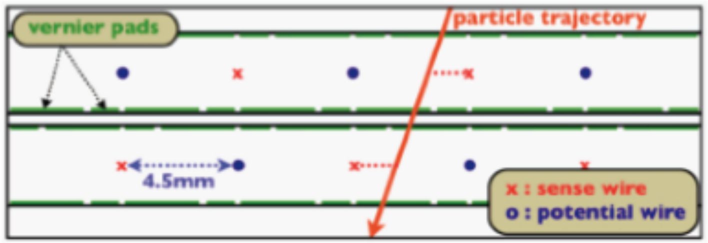
Drift Time & Charge Division

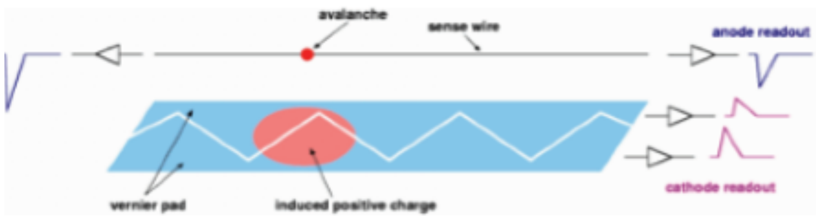


- 16 chambers radially aligned with 10° intervals
- 2 staggered arrays of drift cells
- 1 signal wire and 2 x 2 vernier cathode strips made of 15 μm kapton foils and 0.45 μm aluminum strips
- Chamber gas: He-C_2H_6 mixture

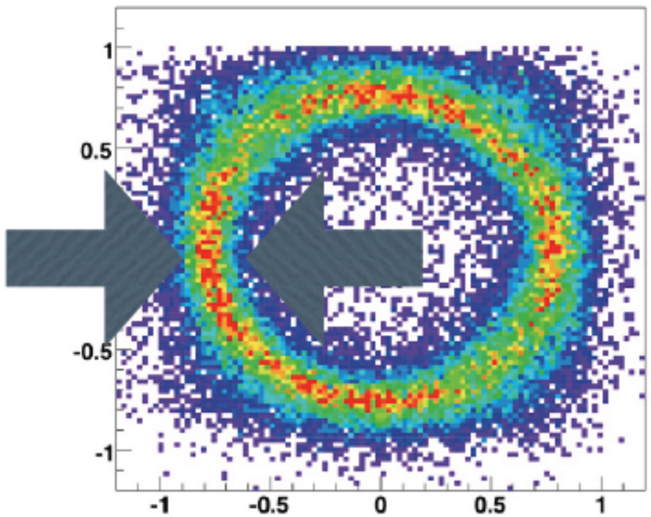
- Within one period, fine structure given by the Vernier circle

transverse coordinate (t drift)



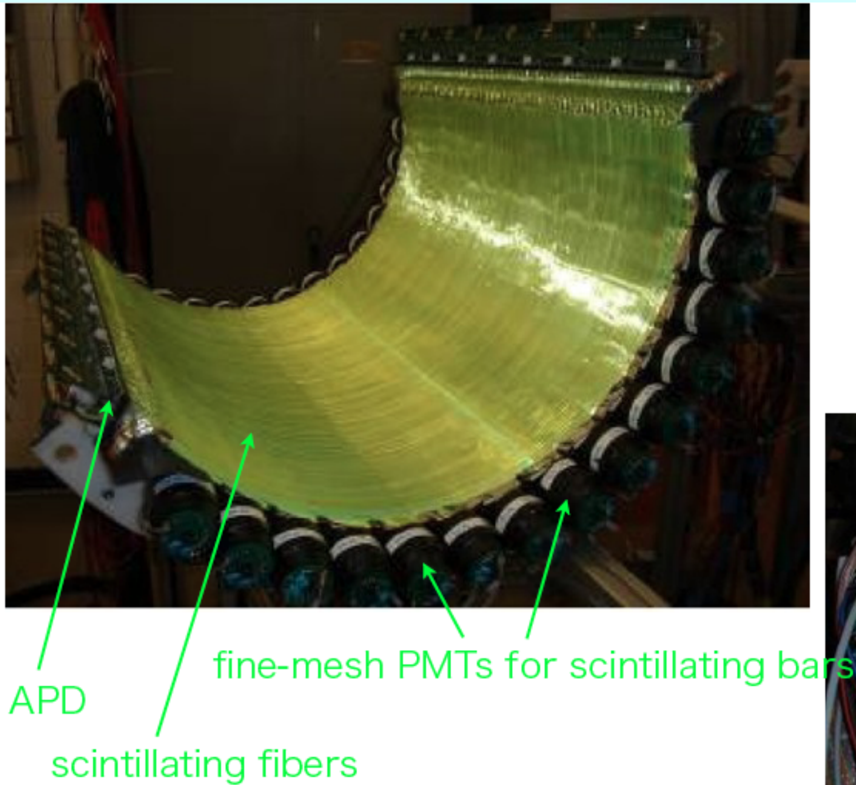


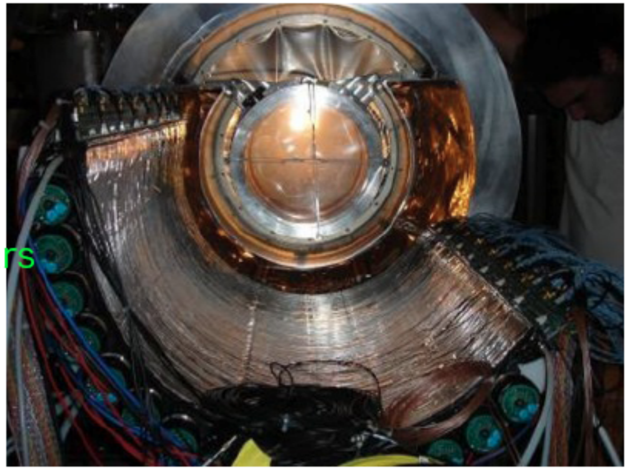
longitudinal coordinate (charge division + Vernier)



Positron Timing Counters

- Scintillator arrays placed at each end of the spectrometer
- Measures the impact point of the positron to obtain precise timing

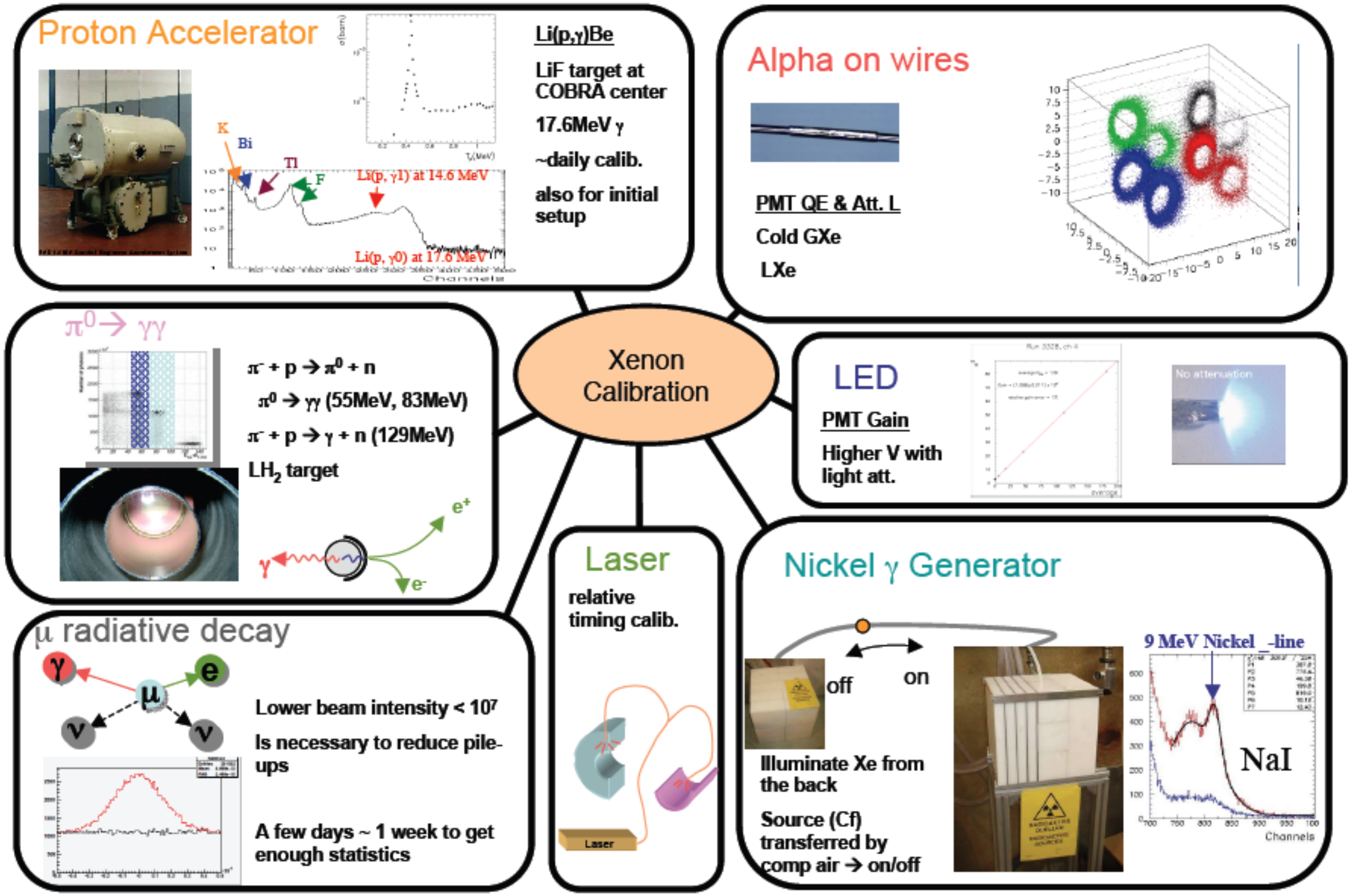




installing inside COBRA

- Critical for triggering (time coincidence with calorimeter and rough positron direction)

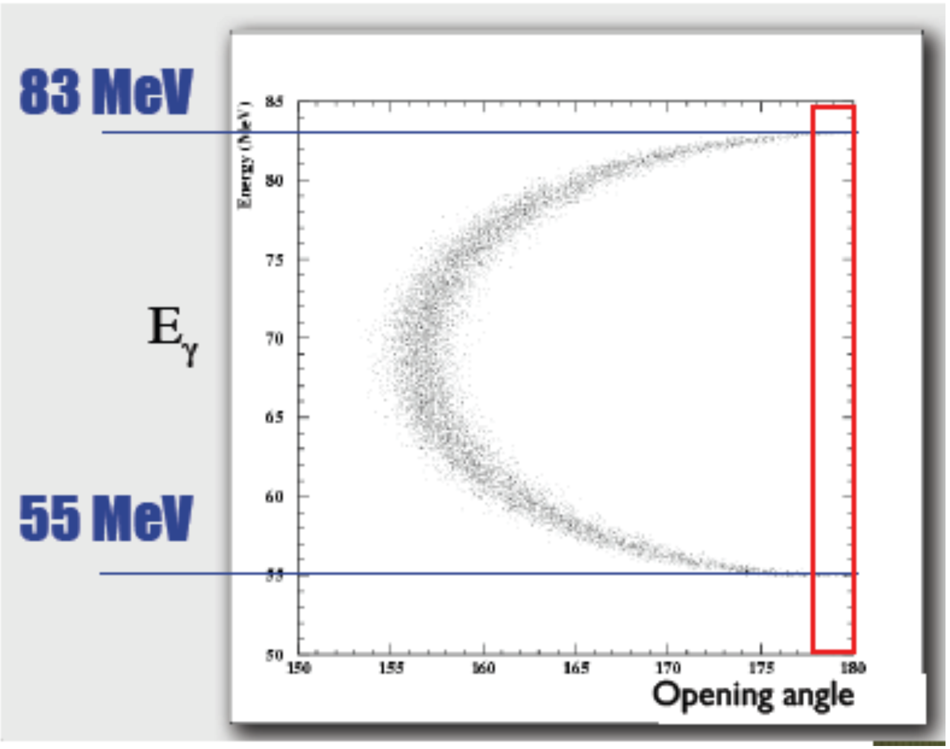
LXe Calibration Overview



Finding the Energy scale

- Charge-exchange process used to find the absolute scale of LXe (in a region close to signal energy)
- Hydrogen target in COBRA volume in special runs

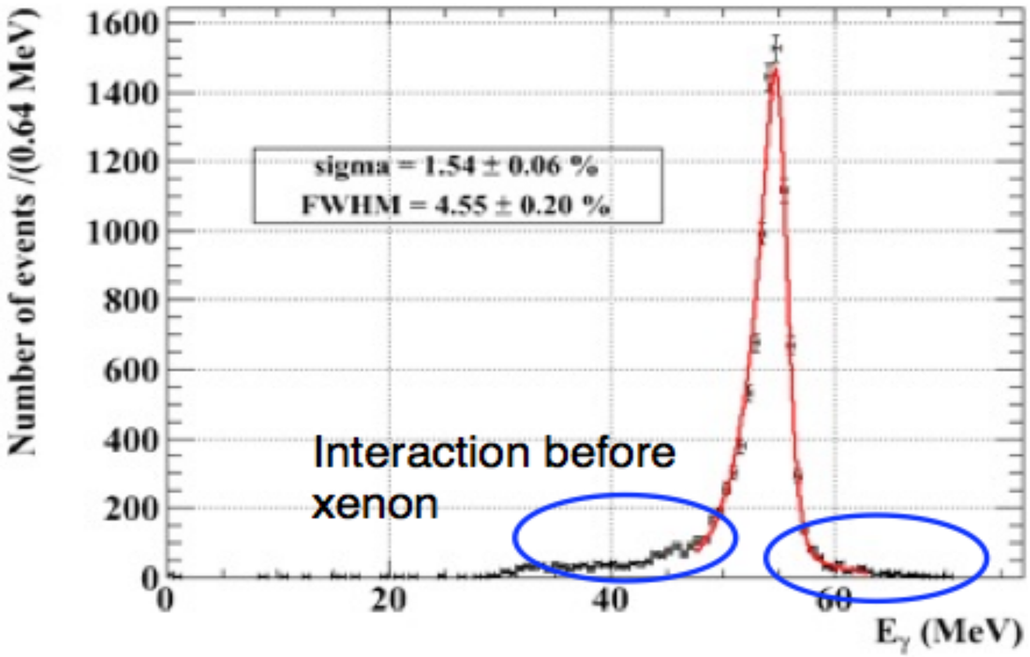
$$\pi^- p \rightarrow \pi^0 n \rightarrow \gamma\gamma n$$

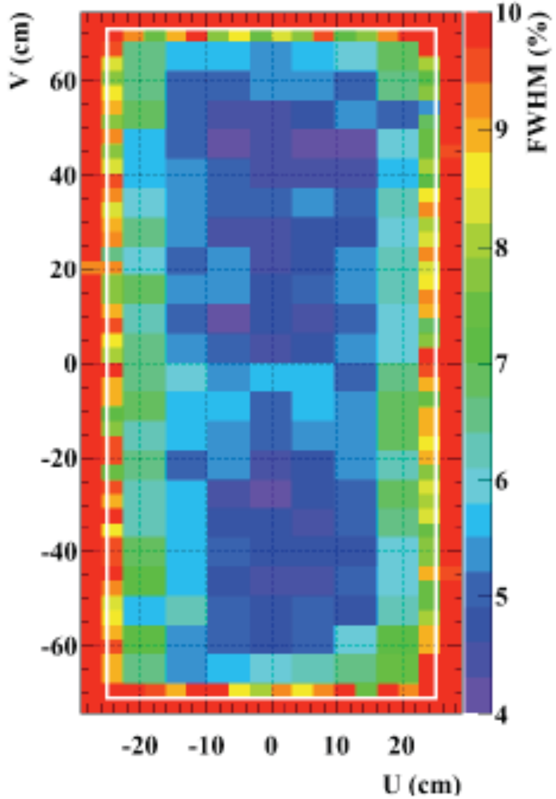


"opposite" side crystal NaI calorimeter to measure the other photons

Photon Energy Resolution

σ_R = 1.5%
FWHM = 4.6 %



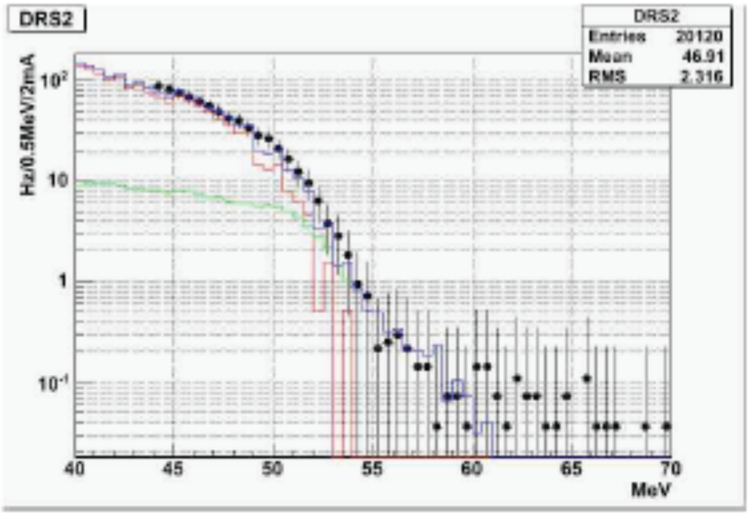


Correct for different pedestal (pile-up) conditions in pion vs muon beam

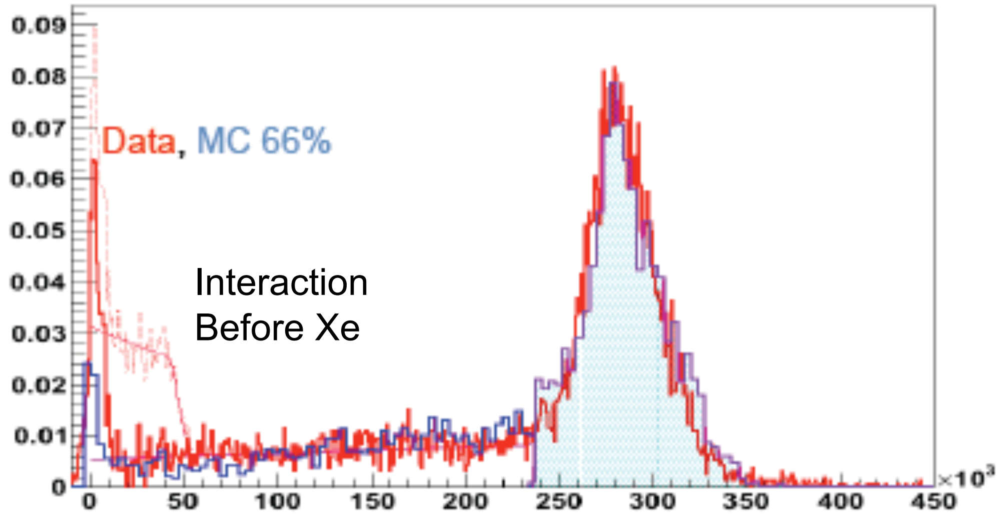
Uniformity of photon Energy resolution vs. Photon impact point

XEC efficiency

Detection efficiency of LXe
(normalized to detector fiducial volume)



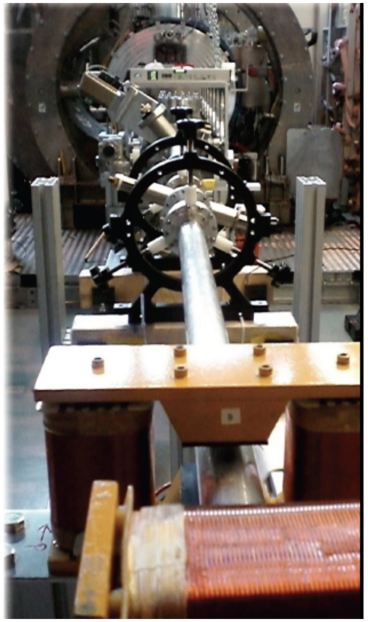
Photon spectrum from MC compared
with data background photon
(normalized according to muon rate)



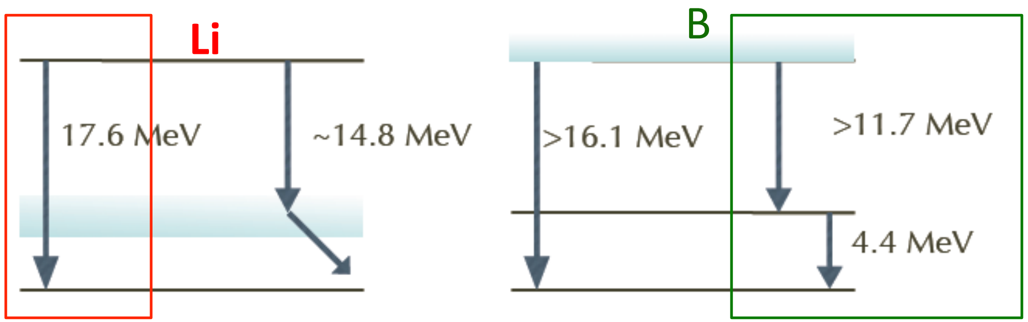
Data/MC comparison for 55 MeV photon

A special Accelerator

(NIM paper in progress)



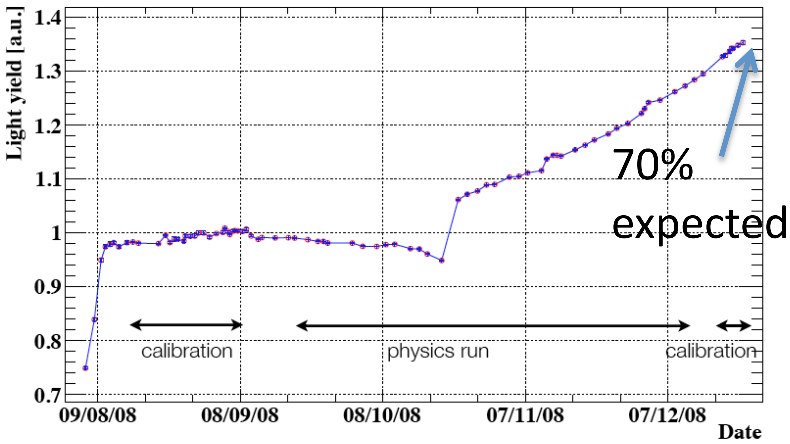
Reaction	Peak energy	σ peak	γ-lines
Li(p,γ)Be	440 keV	5 mb	(17.6, 14.6) MeV
B(p,γ)C	163 keV	$2\ 10^{-1}$ mb	(4.4, 11.7, 16.1) MeV

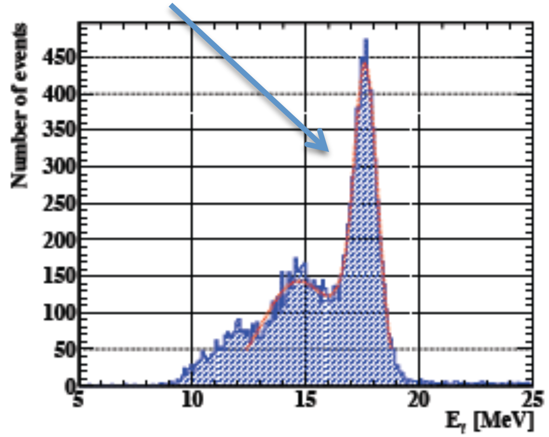


- A Cockroft-Walton accelerator accelerates protons up to ~1 MeV hitting a special target ($Li_2B_4O_7$) to produce monochromatic photons
- Reaction with one or two (coincident) photons to calibrate and monitor LXe energy measure and LXe-TC relative timing

Lxe Light Yield and Linearity

Monitoring with 17.6 MeV Lithium line

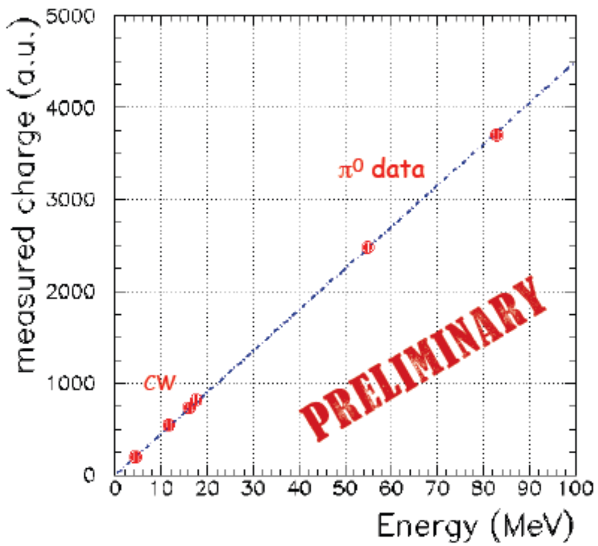




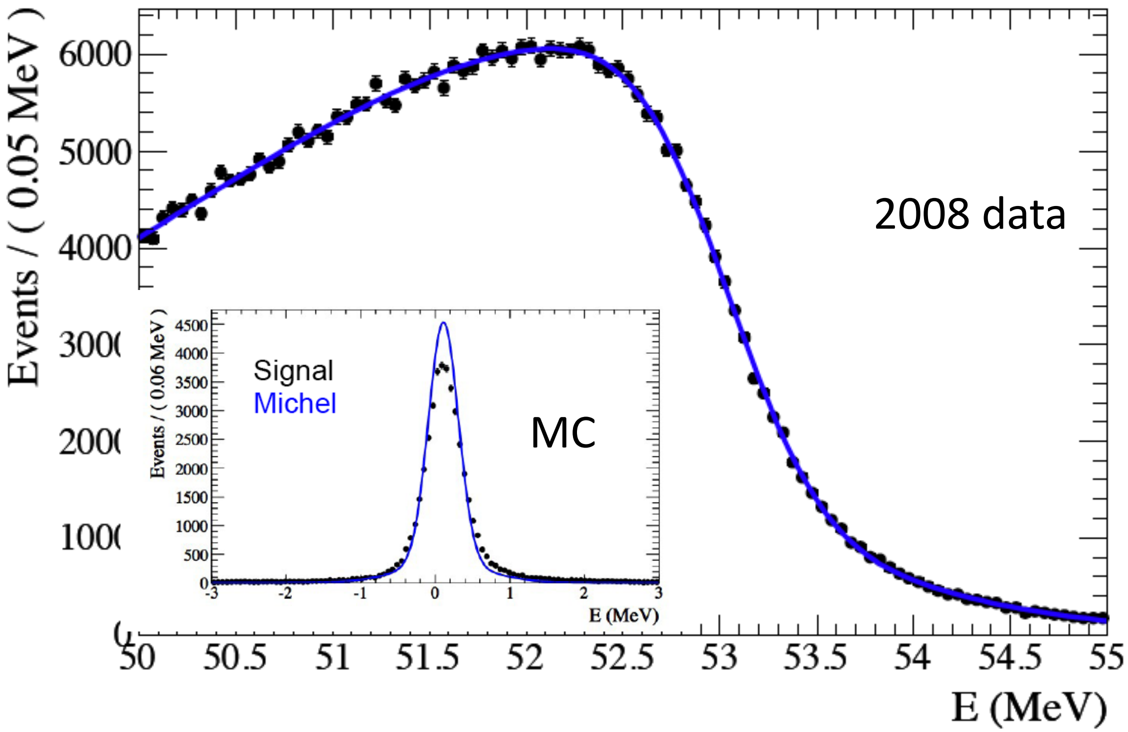
LY increasing due to increasing Xe purity

Connect CW calibration
("low" energy) with
pion calib ("high" E)

Linearity better than 1%



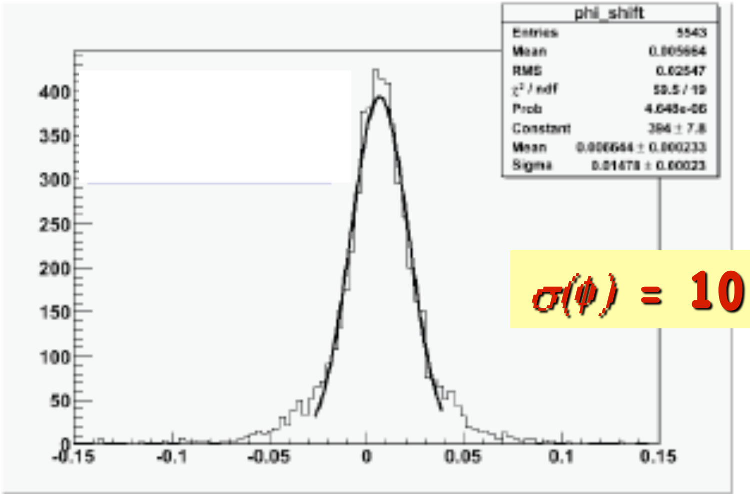
e+ Momentum Resolution



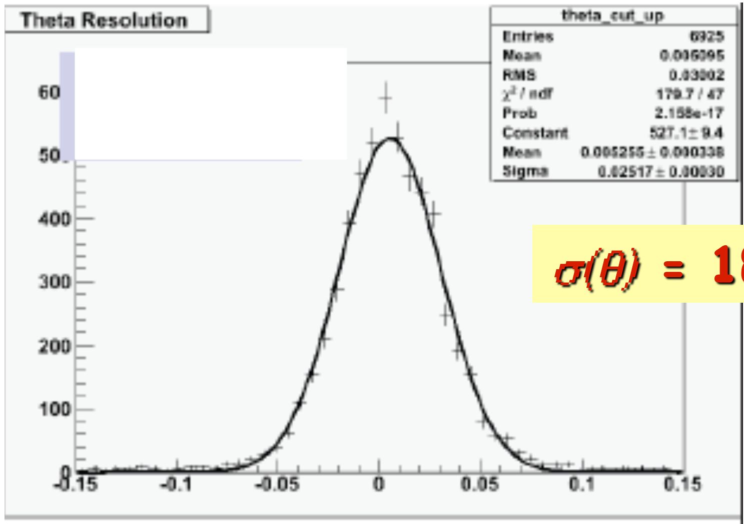
- Positron energy scale and resolution are evaluated by fitting the kinematic edge of the Michel positron spectrum at 52.8MeV
- Resolution function of core and tail components:
  core = 374keV (60%)
  tail = 1.06MeV (33%),
  2.00MeV (7%)

Given the fewer hits-on-track due to HW problem still not at the desired level (250 KeV)

e+ Angle Resolution



$\sigma(\phi)$ = 10 mrad



$\sigma(\theta)$ = 18 mrad

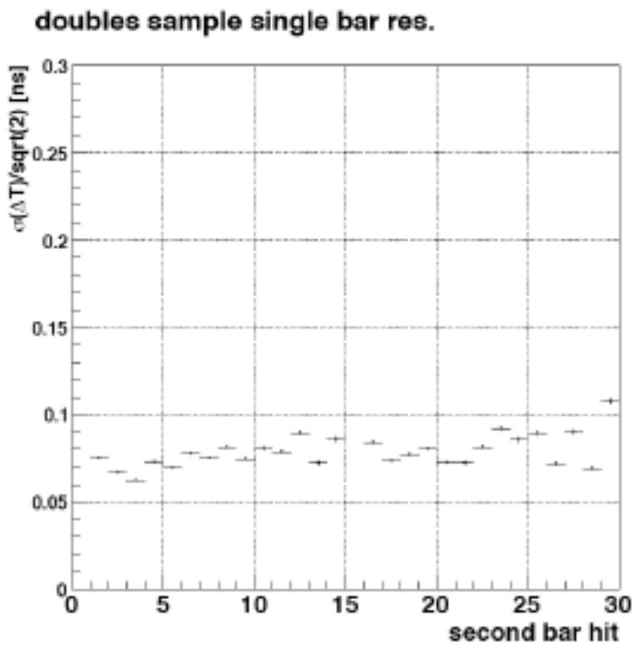
Use “looper” tracks: fit separately two sub-segments of track.
Propogate them to the same point (close to beam axis).
Compare track parameter at the same point.

$\sigma(\phi) = \sigma(\Delta\phi)/sqrt(2)$;
$\sigma(\theta) = \sigma(\Delta\theta)/sqrt(2)$

Still far from design resolution
Improvement in DCH z resolution for 2009 runs foreseen

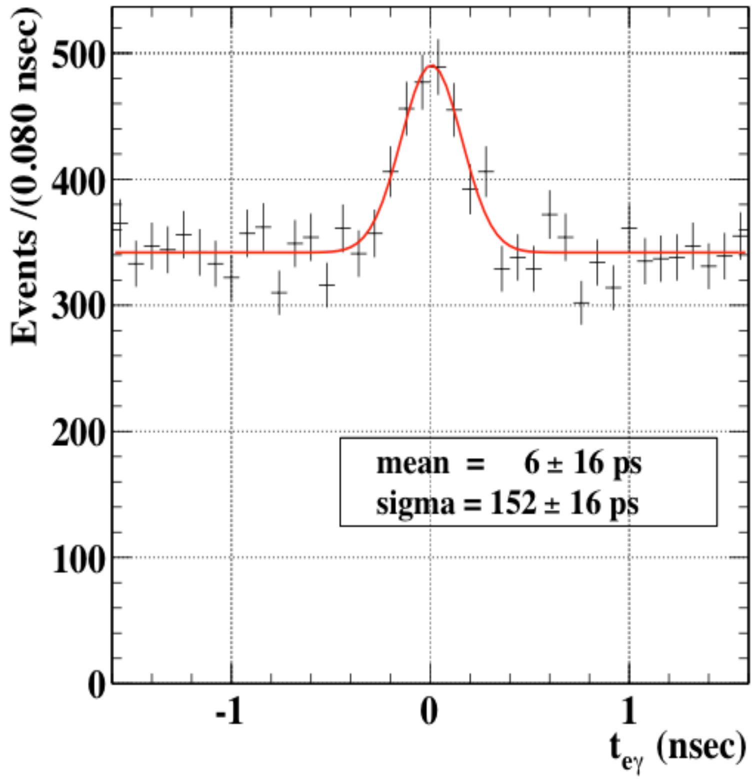
Time Resolution

Intrinsic time resolution of TC bars
(compare time measure in two adjacent bar hit by the same positron)



60-90 ps

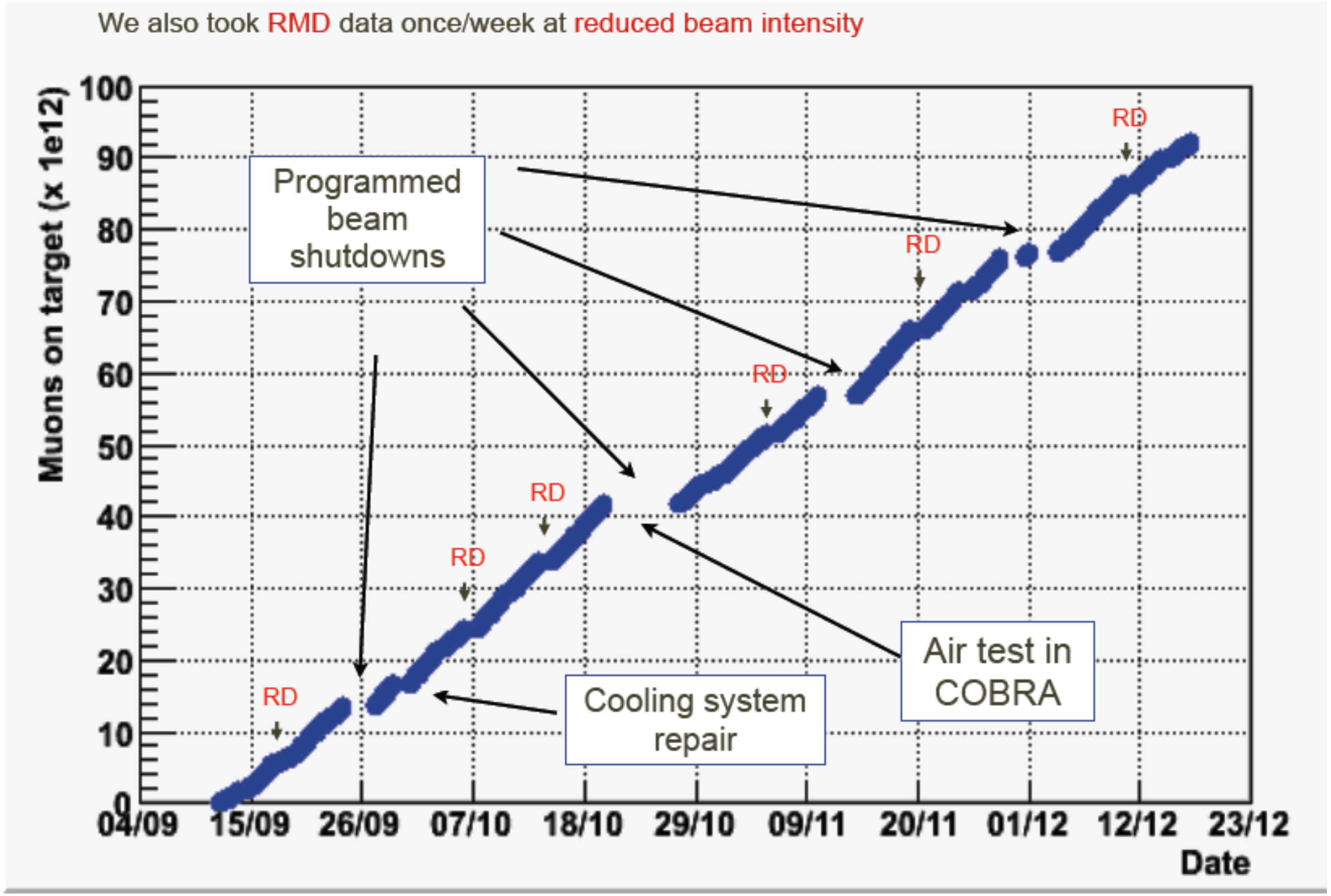
Prompt radiative decay events



Time-of-flight correction needed:
Positron tracklength and photon line of flight length
(to be improved with better DCH operation in 2009)

2008 Data Taking

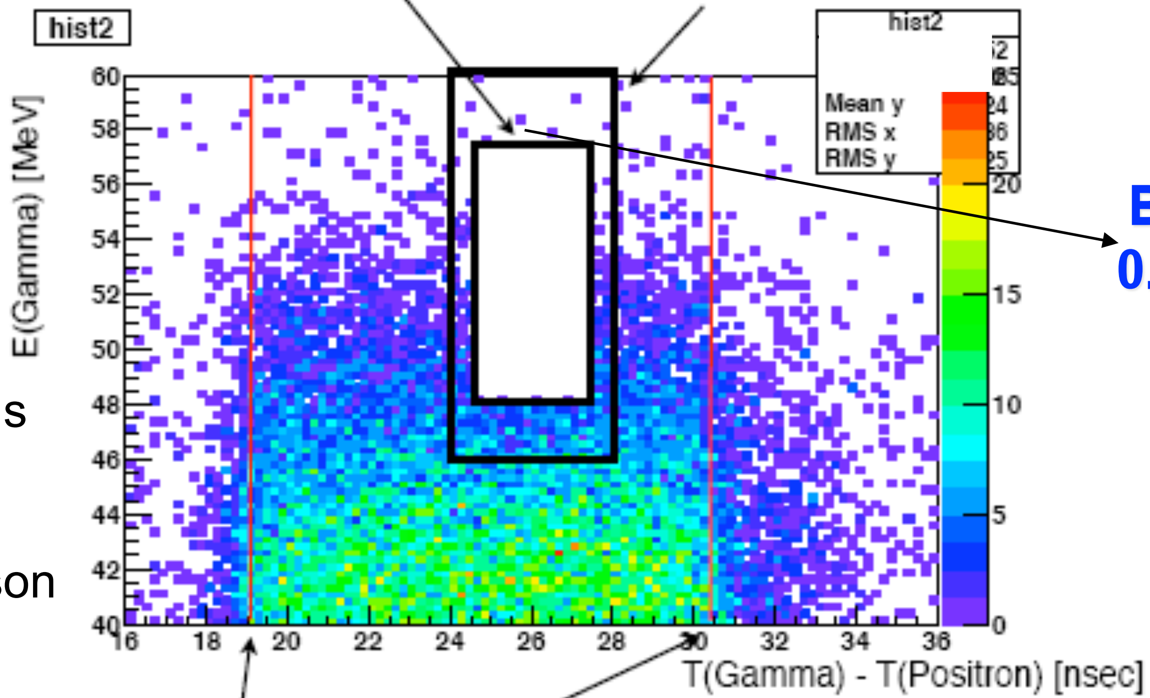
(the PSI muon beam performs like a swiss watch!)



10^{14} muons on target !!!

Blinding Box

Blind box   Analysis box (optional)



Keep sidebands for analysis comparison

Blinded files: 0.2%

Pre-selection box → **Open files: 16 %**

Time offset determined in Dalitz pion decays $\pi^0 \rightarrow e^+(e^-)\gamma$

Analysis box for the final maximum likelihood fit (three indep. tool with slightly different selections)

$$\mathcal{L}(N_{\rm sig}, N_{\rm RMD}, N_{\rm BG}) = \frac{N^{N_{\rm obs}} \exp^{-N}}{N_{\rm obs}!} \prod_{i=1}^{N_{\rm obs}} \left[\frac{N_{\rm sig}}{N} S + \frac{N_{\rm RMD}}{N} R + \frac{N_{\rm BG}}{N} B \right]$$

Probability Density Functions

Four(five) obervables

- SIGNAL

E_γ: from full signal MC (or from fit to endpoint)
E_e: 3-gaussian fit on data
$\theta_{e\gamma}$: combination of e and gamma angular resolution from data
$t_{e\gamma}$: single gaussian from MEG trigger Radiative Decay (no cut on $E\gamma$)

- RADIATIVE

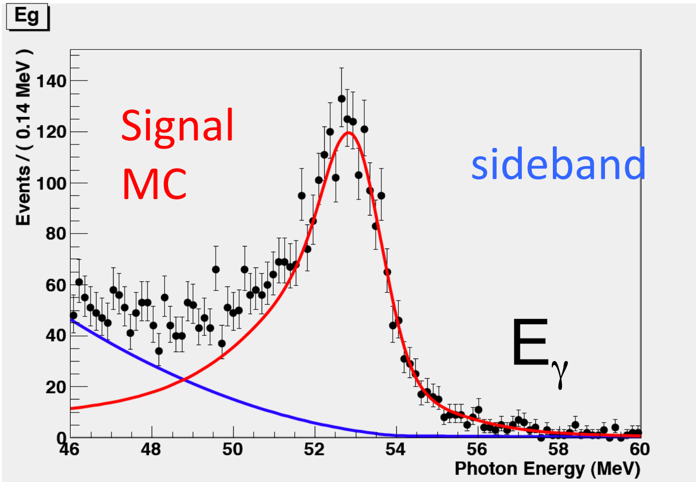
E_e,E_γ,$\theta_{e\gamma}$: 3D histo PDF from toy MC that smears and weighs Kuno-Okada distribution taking into account resolution and acceptance
$t_{e\gamma}$: single gaussian with same resolution as signal

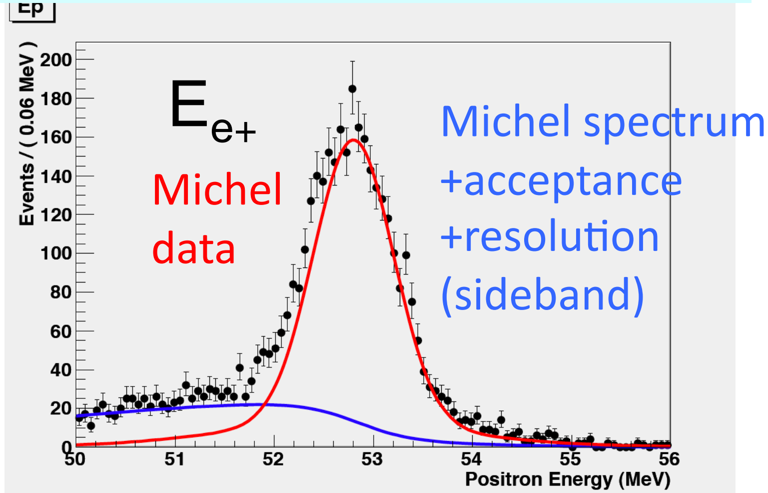
- ACCIDENTAL

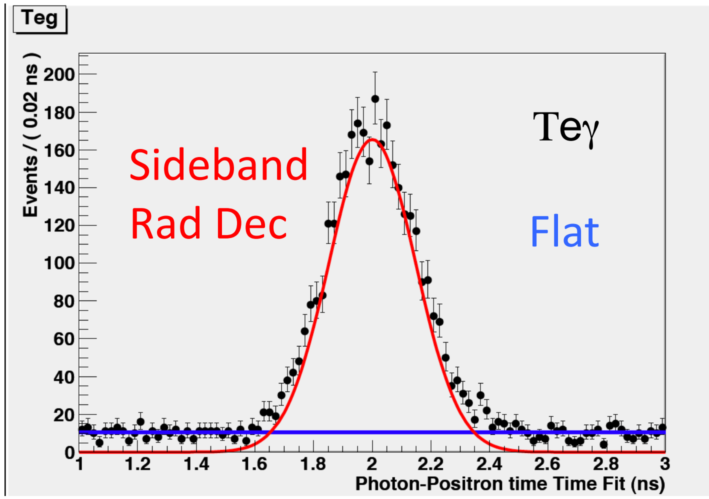
E_γ: from fit to $t_{e\gamma}$ sideband
E_e: from data
$\theta_{e\gamma}$: from fit to $t_{e\gamma}$ sideband
$t_{e\gamma}$: flat

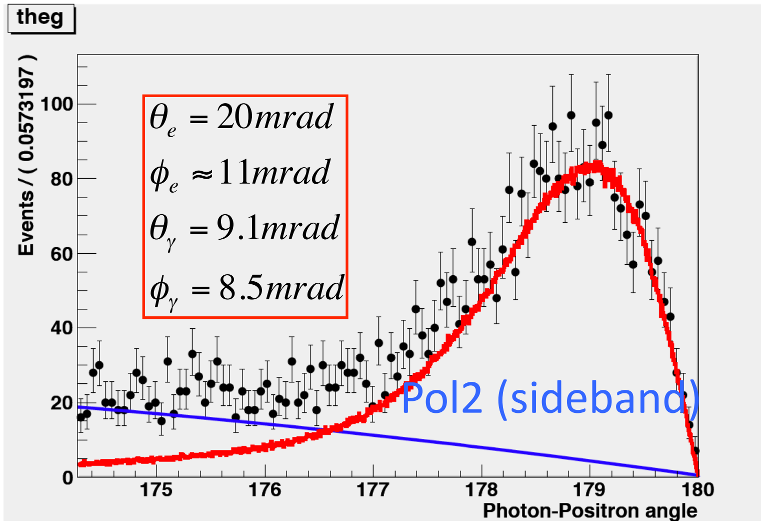
Alternative observables definition
1) different algorithm for LXe Timing
2) Trigger LXe waveform digitizing electronics (E_γ)

SIG and BKG PDF





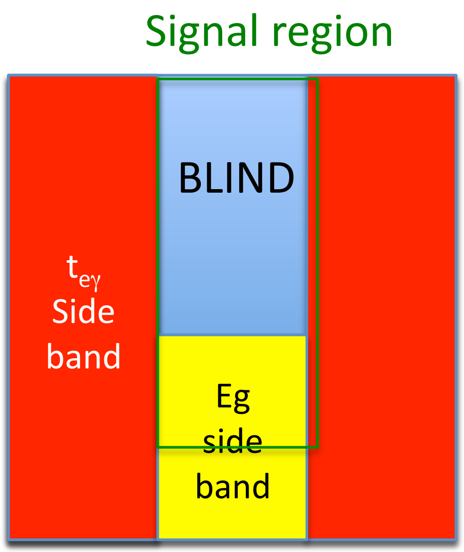




Dots are some of the two pdf's

The Final Selection…

Region	Events
Signal region ($\|t_{e\gamma}\|$<1ns)	1007
-2.5< $t_{e\gamma}$ < -1.5 ns	1004
1.5< $t_{e\gamma}$ < 2.5 ns	1060



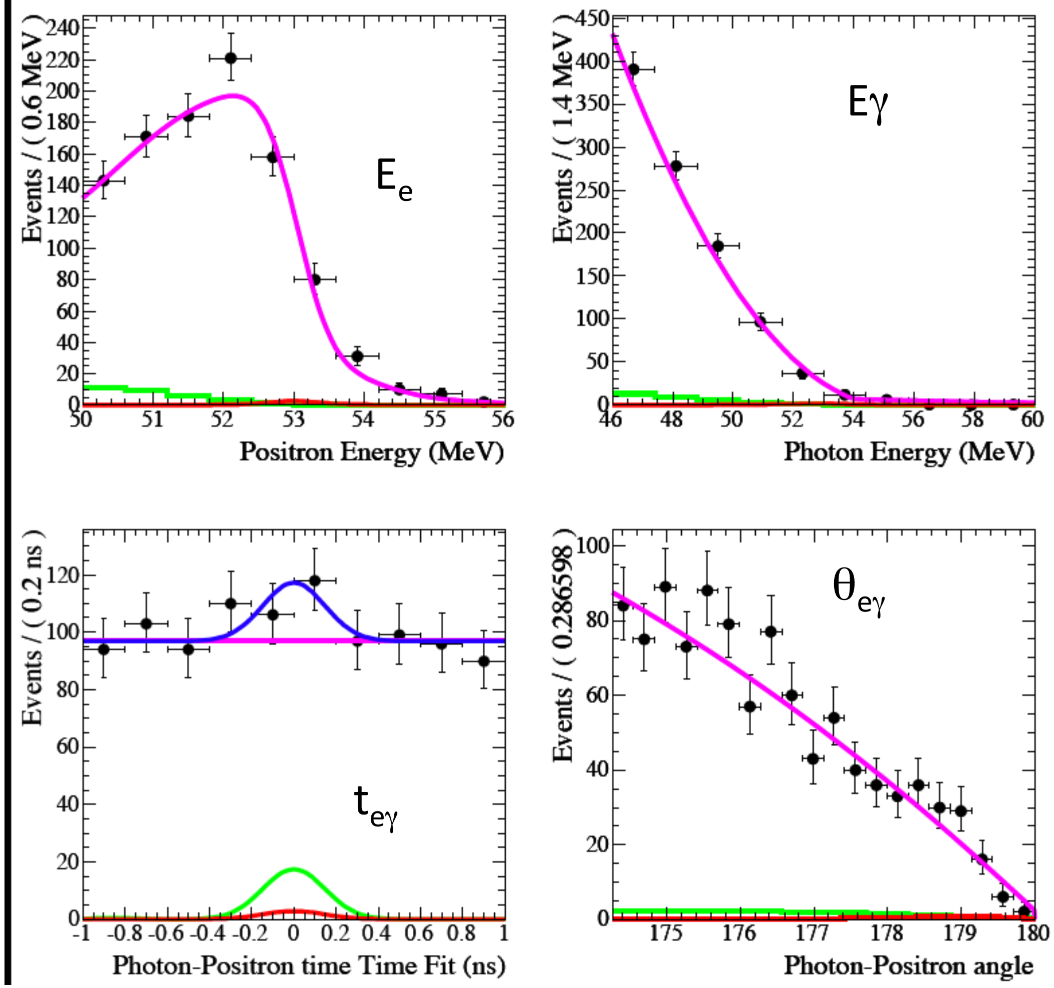
…and Normalization

$$\mathrm{BR}(\mu^+ \to \mathrm{e}^+\gamma) = \frac{N_{\mathrm{sig}}}{N_{e\nu\bar{\nu}}} \times \frac{f^E_{e\nu\bar{\nu}}}{P} \times \frac{\epsilon^{trig}_{e\nu\bar{\nu}}}{\epsilon^{trig}_{e\gamma}} \times \frac{A^{TC}_{e\nu\bar{\nu}}}{A^{TC}_{e\gamma}} \times \frac{\epsilon^{DC}_{e\nu\bar{\nu}}}{\epsilon^{DC}_{e\gamma}} \times \frac{1}{A^{LXe}_{e\gamma}} \times \frac{1}{\epsilon^{LXe}_{e\gamma}}$$

Nsig normalized to Michel positrons counted simultaneously with the signal.
Independent of instantaneous beam rate and insensitive to positron acceptance and efficiency

Expected sensitivity in absence of signal:
average 90% C.L UL on BF evaluated on toyMC : 1.3 10^{-11}

Signal Region Fit



ACC BKG

Rad Muon Decay

SIG

Fit with alternative observable definition gives very compatible results

Highly non Gaussian likelihood for signal:
frequentist Feldman Cousins and Bayesian approaches to quote 90% C.L. UL on BF

Upper limit B.R.($\mu \rightarrow e\gamma$)

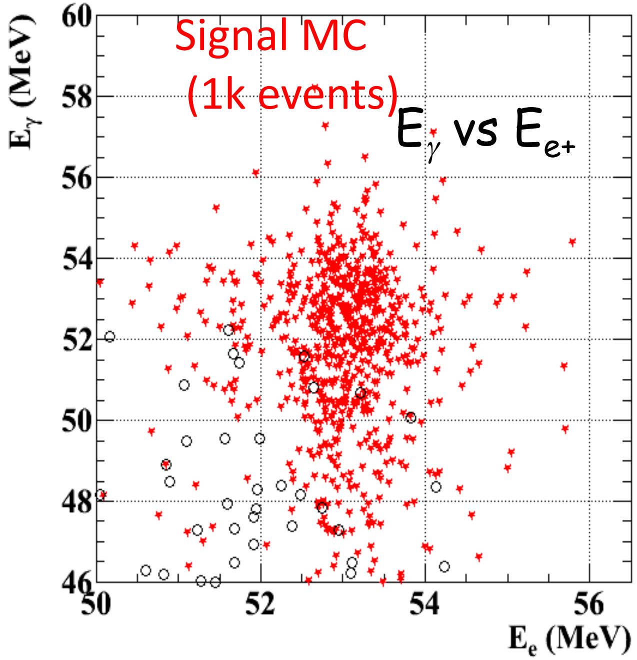
The upper limit at 90 % C.L evaluated with F-C prescription (likelihood ratio) on the number of events is Nsig<14.7 corresponding to

BR($\mu \rightarrow e\gamma$) ≤ 2.8 x 10^{-11}

normalization factor 5.2x10^{11}

This includes systematics effects evaluation.
About two times worse than expected sensitivity.
Bad luck!

Data selected with 90% efficient cuts on $t_{e\gamma}$ and $\theta_{e\gamma}$



On t_{eg} sidebands we find "**B.R.($\mu \rightarrow e\gamma$)**" ≤ **(0.9 ÷ 2.1) x 10^{-11}**

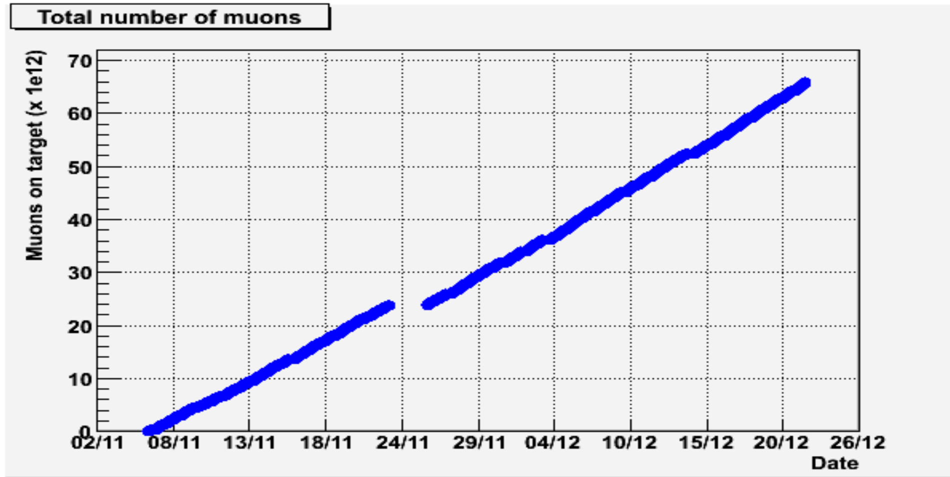
Statistical fluctuation at the level (3-5)% evaluated with different techniques.

Results available on **arXiv:0908.2594(LP 2008), Paper to be submitted soon**

The 2009 Run

(ended Dec 23rd)

Short run, but very smooth
Improved tracking and trigger efficiency
Light yield in LXe good since the beginning. No additional purification needed.



- More than 6×10^{13} muons
- Expect a sensitivity of few 10^{-12}
- Result ready for Summer Conferences
- Detector ready for long run 2010-2011
- **MEG only user of muon beam**

Conclusions

First Physics Data taken in 2008

Detector not at the design level

DCH instabilities largely reduced MEG sensitivity

Low efficiency and worse resolution

DCH layers refurbished and proved to work in 2009 run

Upper limit at 90% C.L. BR($\mu \rightarrow e\gamma$) $\leq$ 2.8 x 10^{-11}

Successful run in 2009

Physics Analysis in progress

Expected sensitivity **of few 10^{-12}**

Planning	R & D	Assembly	Data Taking
1998 1999 2000	2001 2002 2003 2004	2005 2006 2007	2008 2009 2010 2011

•Two more years of data-taking to reach 10^{-13} sensitivity

Back-up slides

The Final Selection

» Good quality track selection
 (good chi2, projection to target)

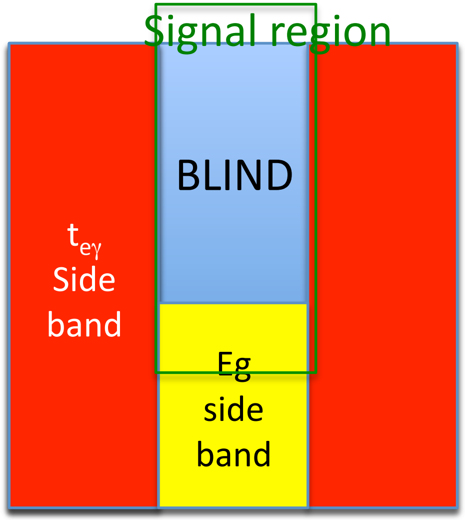
» Track projected to TC with good match

» Events with pile-up photon accepted
 (energy correction)

» Cosmic ray rejection

 » Inner/Outer face charge

$E\gamma$ = [46, 60] MeV
E_e= [50,56] MeV
$\theta_{e\gamma}$> acos(-0.995)



Region	Events
Signal region ($\|t_{e\gamma}\|$<1ns)	1007
-2.5< $t_{e\gamma}$ < -1.5 ns	1004
1.5< $t_{e\gamma}$ < 2.5 ns	1060

Expected sensitivity in absence of signal:
average 90% C.L UL on BF evaluated on toyMC : 1.3 10^{-11}

Present: 2009 analysis

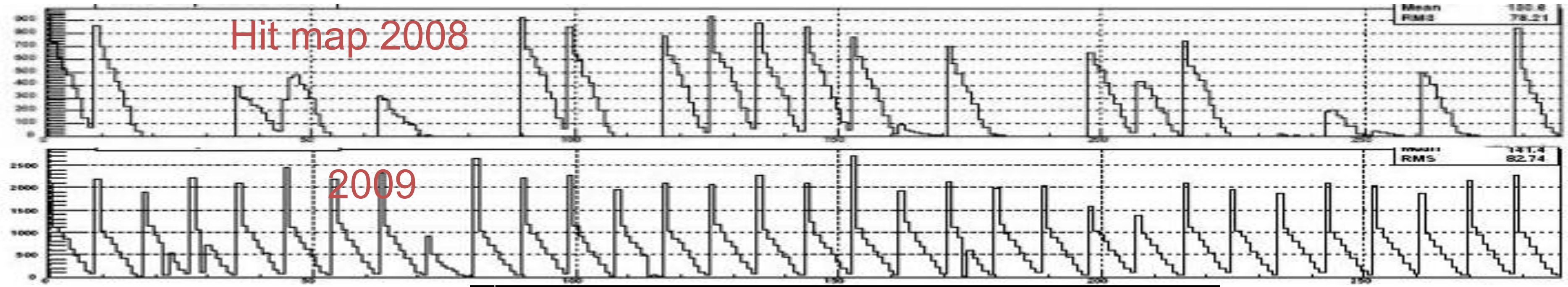
	2008	2009 (preliminary)	"Goal"
Gamma Energy (%)	2.0(w>2cm)	←	1.2
Gamma Timing (psec)	80	>67	43
Gamma Position (mm)	5(u,v)/6(w)	←	3.8(u,v)/5.9(w)
Gamma Efficiency (%)	63	←	60
e^+ Timing (psec)	<125	←	50
e^+ Momentum (%)	1.6	0.85	0.3-0.38(100%)
e^+ Angle (mrad)	10(ϕ)/18(θ)	8(ϕ)/11(θ)	3.8-5.1
e^+ Efficiency (%)	14	40	90
e^+-gamma timing (psec)	148	<180	64
Muon Decay Point (mm)	3.2(R)/4.5(Z)	2.2(R)/3.1(Z)	0.9-1.1
Trigger efficiency (%)	66	88	100
Stopping Muon Rate (sec^{-1})	3×10^7 (300μm)	2.9×10^7 (300μm)	3×10^7
DAQ time/Real time (days)	48/78	35/43	300/-
S.E.S @90% box	5×10^{-12}	2.3×10^{-12}	3.8×10^{-14}
Expected N_{BG}	0.5	0.7	0.5
Sensitivity	1.3×10^{-11}	6.6×10^{-12}	1.0×10^{-13}
BR upper limit (obtained)	2.8×10^{-11}	-	-

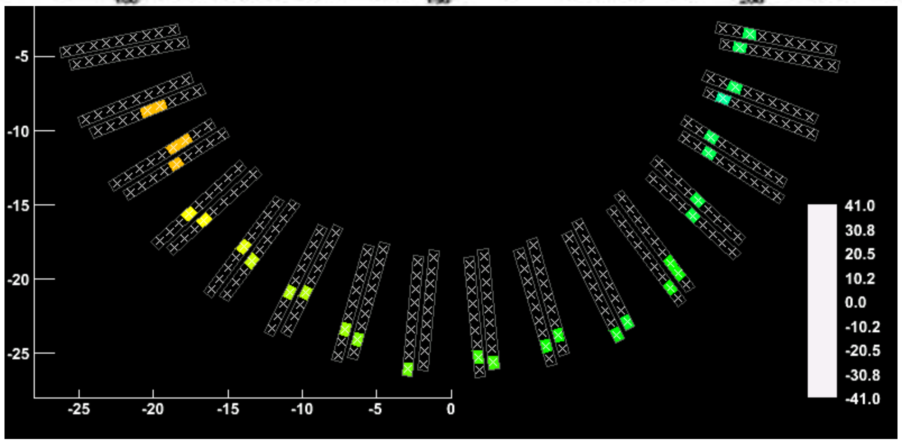
Likelihood analysis

Past: february - august 2009

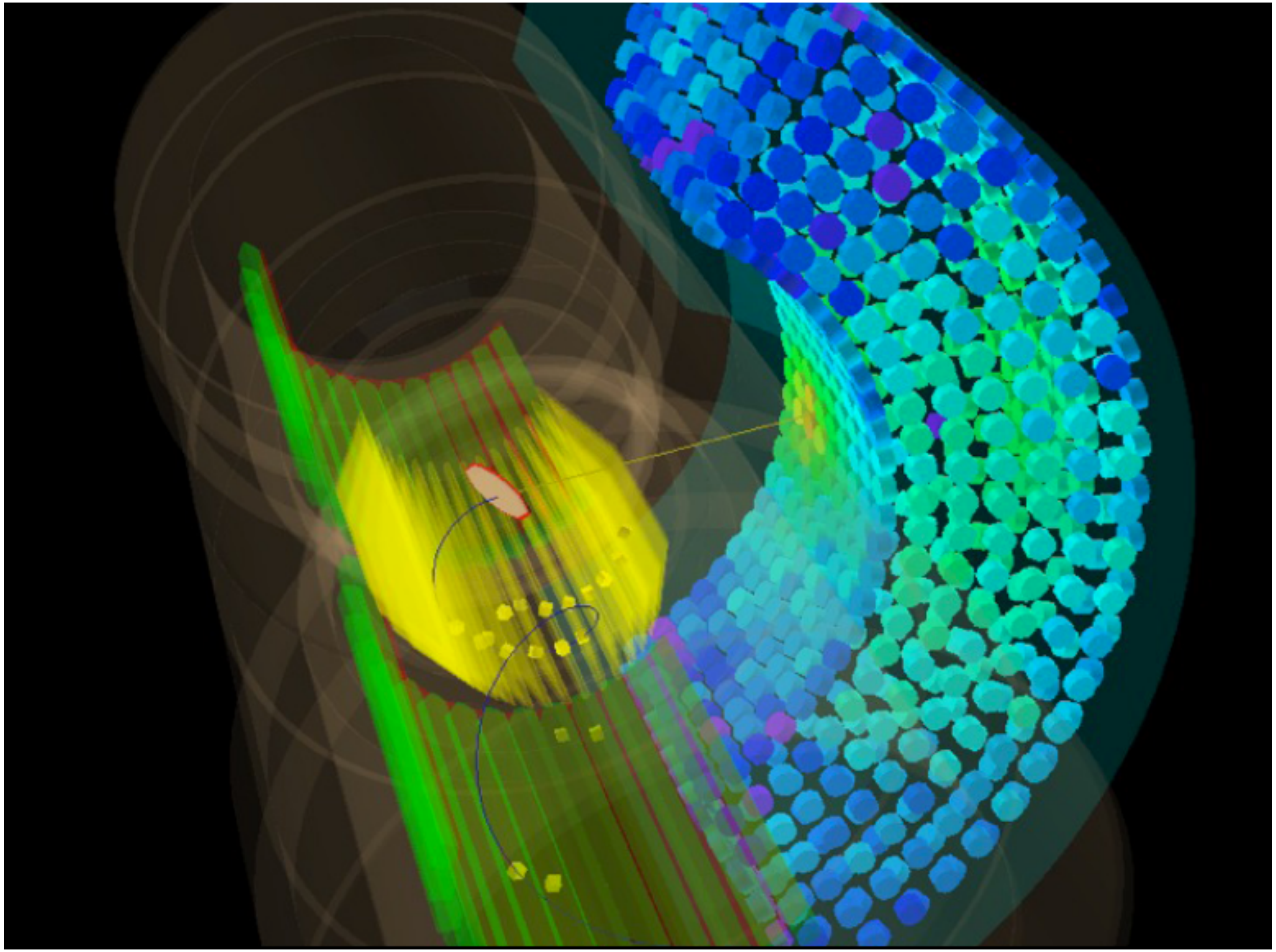
- Intensive work on understanding instability problem on DCHs – finally found problem in HV distribution cards

- All chambers repaired before start of 2009 beam time: MH



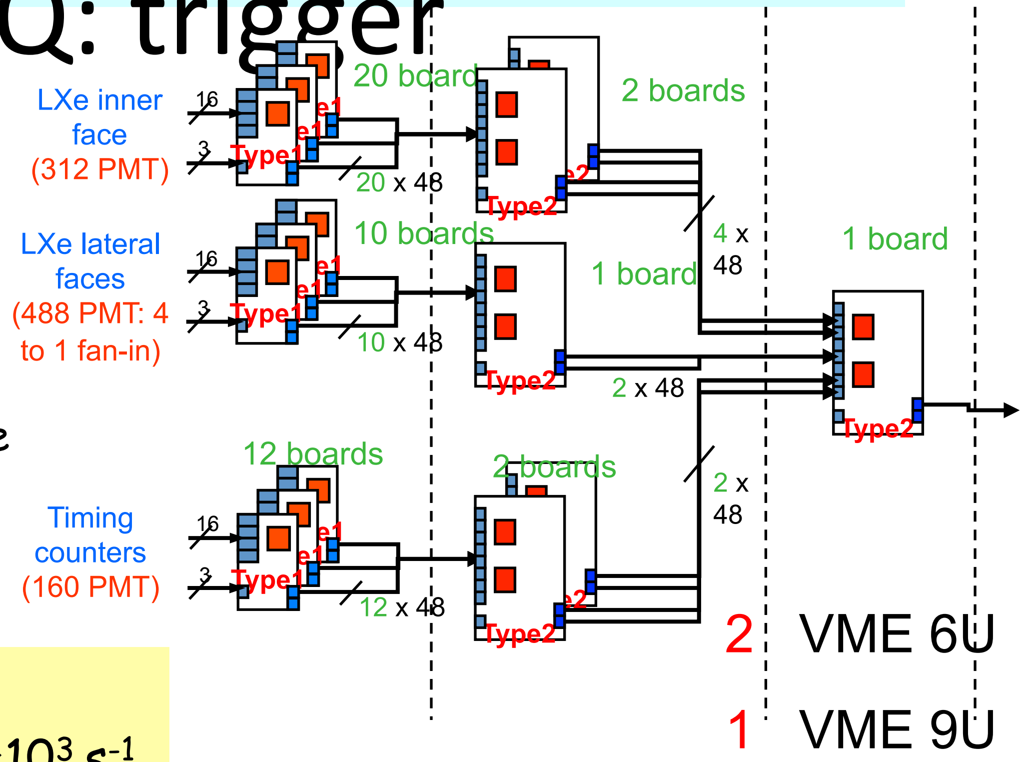


A MEG-like event



4) DAQ: trigger

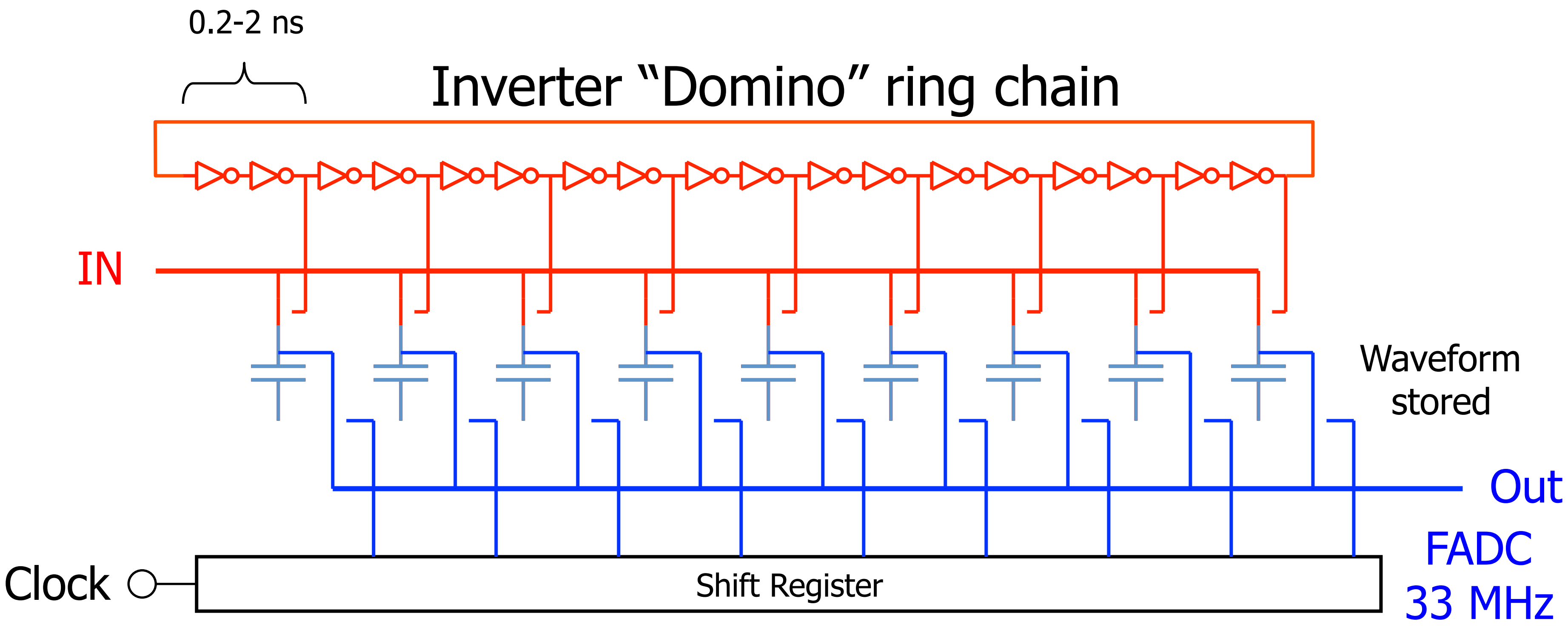
- Uses easily quantities:
  - γ energy
  - Positron- γ coincidence in time and direction
- Built on a **FADC-FPGA** architecture
- More complex algorithms implementable



- Beam rate $10^8\ s^{-1}$
- Fast LXe energy sum > 45MeV $2\times10^3\ s^{-1}$
  - g interaction point (PMT of max charge)
  - e^+ hit point in timing counter
- time correlation $\gamma - e^+$ $200\ s^{-1}$
- angular correlation $\gamma - e^+$ $20\ s^{-1}$

~ 5 Hz in 2008 data taking

DAQ: readout The Domino Principle



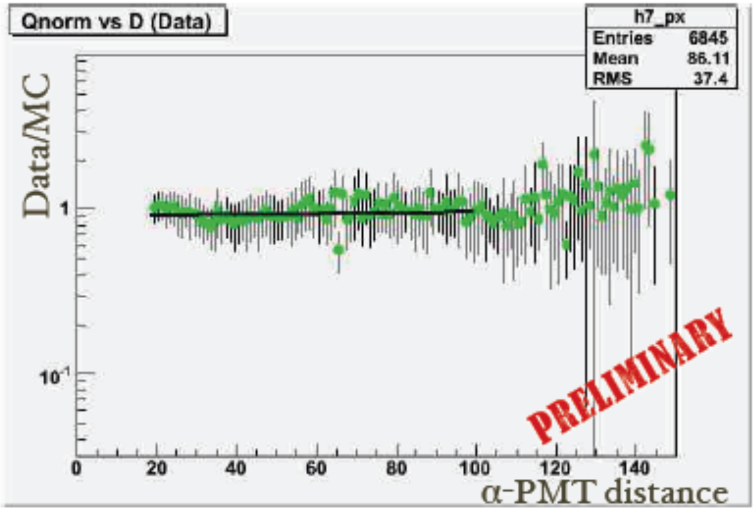
"Time stretcher" GHz → MHz

Keep Domino wave running in a circular fashion and stop by trigger → Domino Ring Sampler (DRS)

Low cost ➔One "oscilloscope" per channel

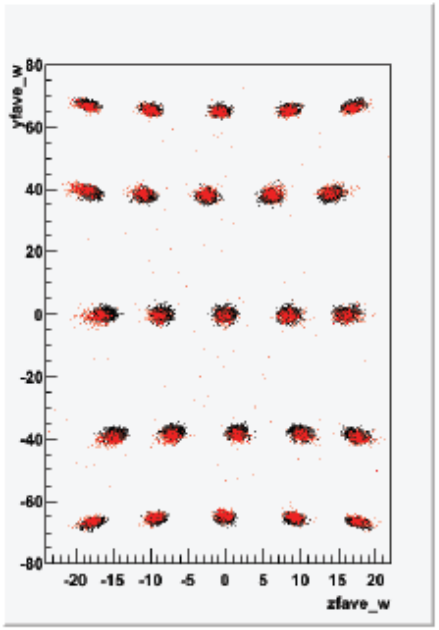
α-sources in Xe

- Used to
  - QE determination
  - Monitor Xe stability
  - Measure absorption
  - Measure Rayleigh scattering

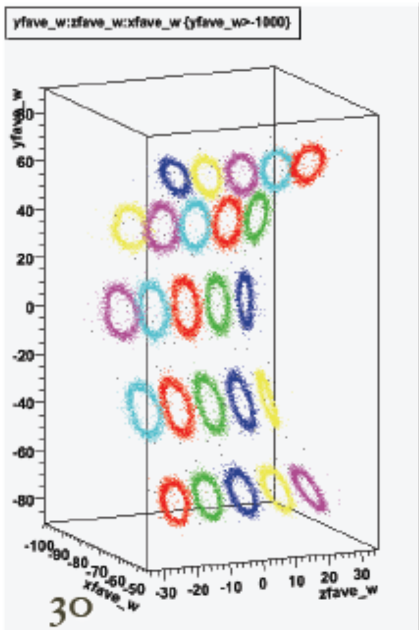


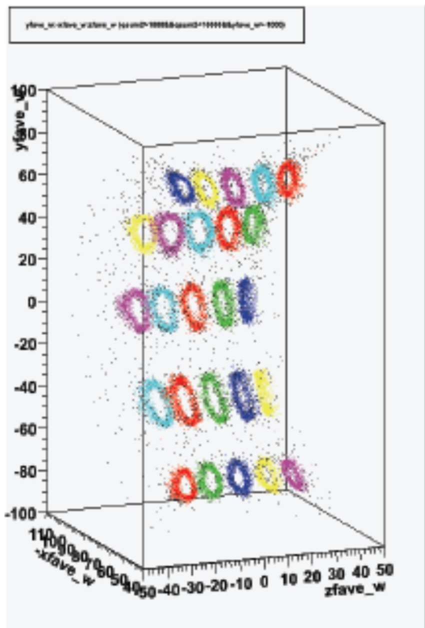
$\lambda_{Abs} > 300$ cm

GXe: MC & data



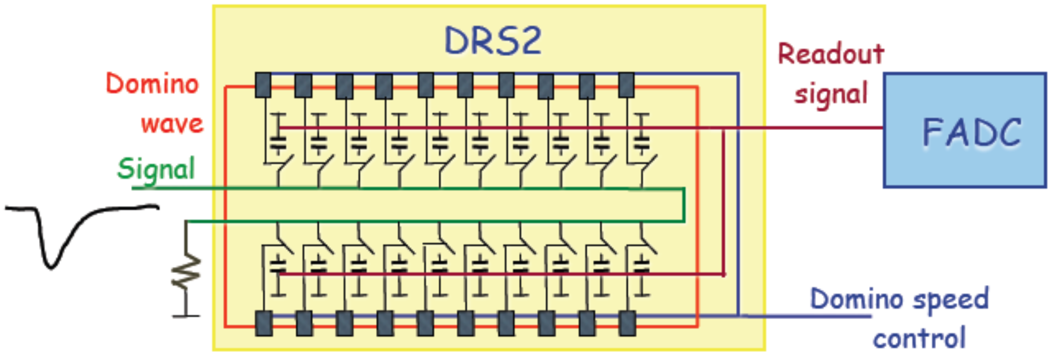
LXe: MC & data





Custom read-out electronics

2 GHz waveform digitization for all channels



DRS chip (Domino Ring Sampler)

- Custom sampling chip designed at PSI
- 2 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