Status of MEG: an experiment to search for the $\mu^+ \to e^+ \gamma$ decay

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Réunions plénières du GDR NEUTRINO - SESSION 2009

LPNHE - Univ. Pierre et M. Curie Paris 6 et Denis Diderot Paris 7

Paris, 27~28 Avril 2009

The MEG collaboration

Tokyo U.
Waseda U.
KEK

INFN & U Pisa
INFN & U Roma
INFN & U Genova
INFN & U Pavia
INFN & U Lecce

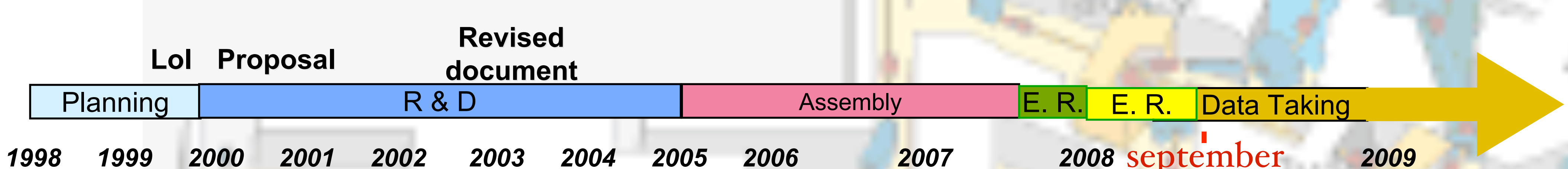
PSI

UCIrvine

JINR Dubna
BINP Novosibirsk

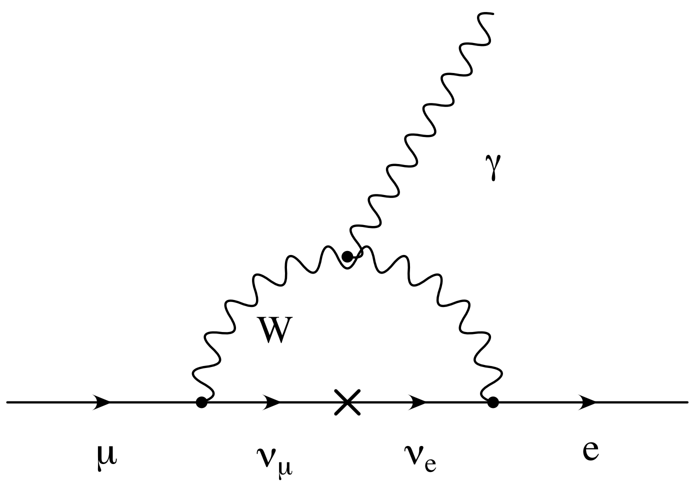
Outline

- Physics motivation for a $\mu \to e\gamma$ experiment
- The μ $e\gamma$ decay
- The detector
  - Overview of sub-detectors
  - Calibration methods
- Status
  - Run 2008
- Next year(s)



The μ→eγ decay

- The theoretical framework has been thoroughly covered by the previous speaker;
- The μ→eγ decay in the SM is radiatively induced by neutrino masses and mixings at a negligible level

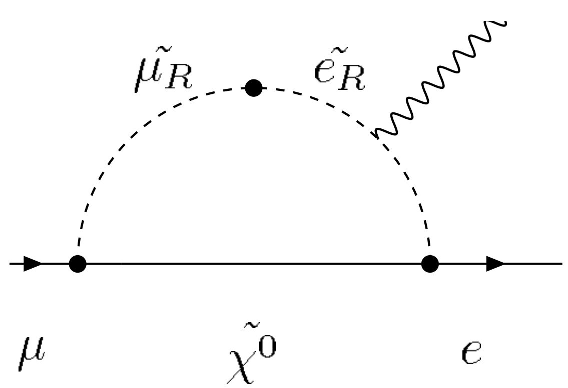


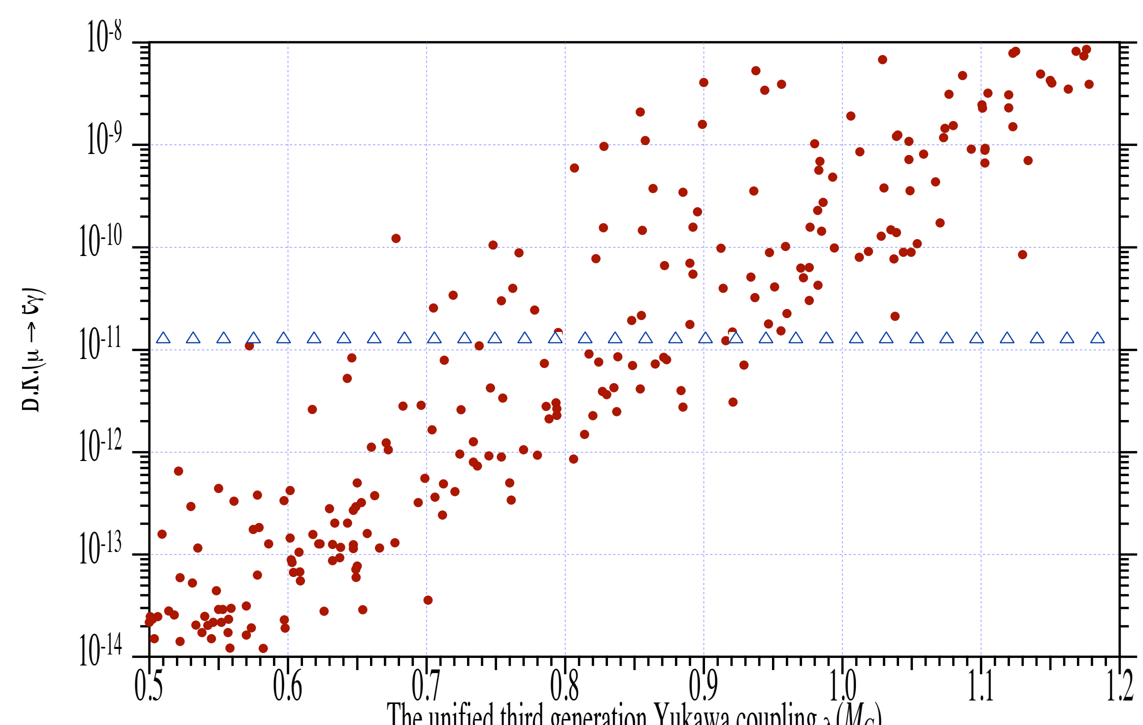
$$\Gamma(\mu \to e\gamma) \approx \underbrace{\frac{G_F^2 m_\mu^5}{192\pi^3}}_{\mu-\text{decay}} \quad \underbrace{\left(\frac{\alpha}{2\pi}\right)}_{\gamma-\text{vertex}} \quad \underbrace{\sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2}{M_W^2}\right)}_{\nu-\text{oscillation}}$$

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

Relative probability ~ 10^{-55}

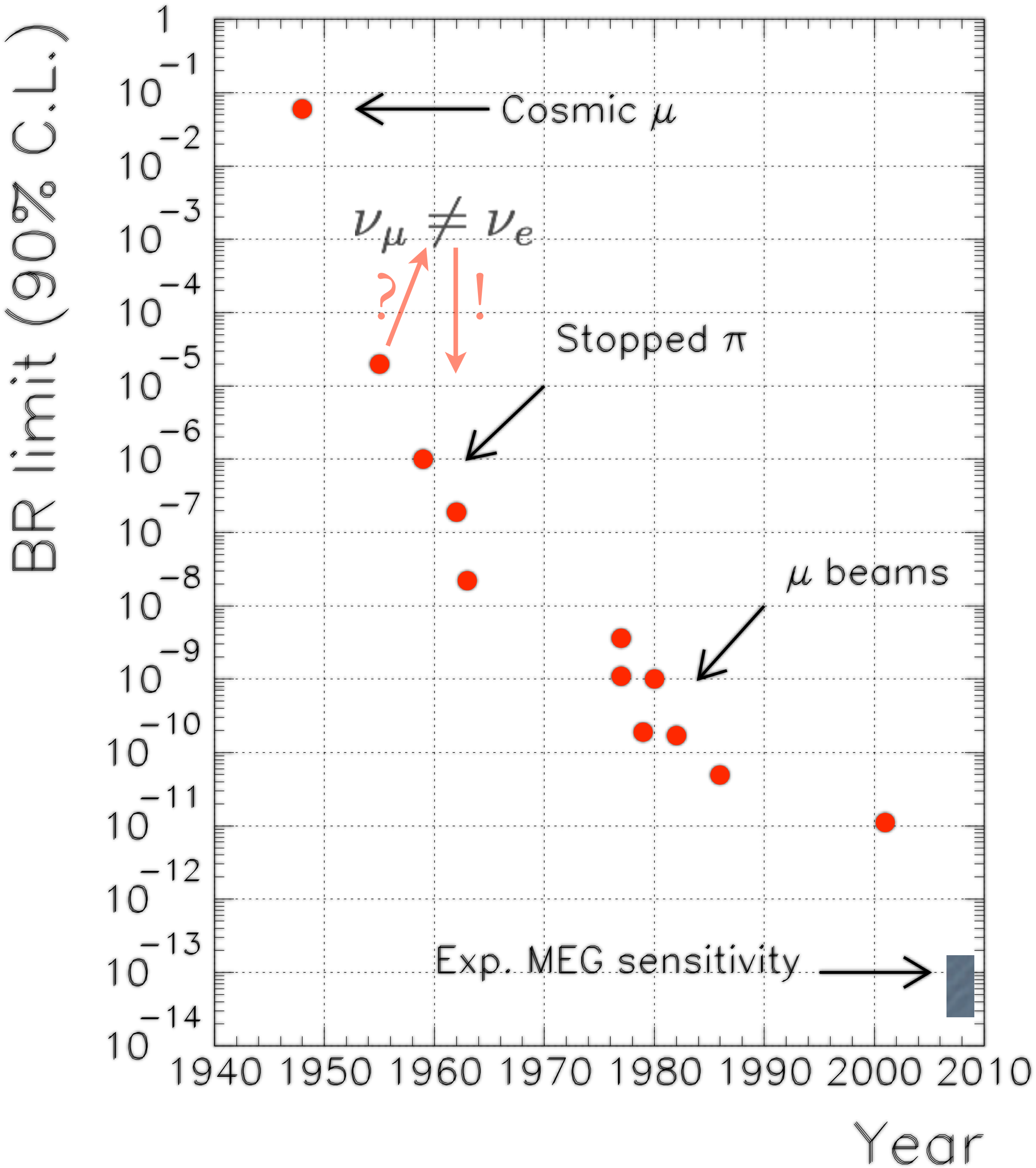
- All SM extensions enhance the rate through mixing in the high energy sector of the theory (other particles in the loop...)



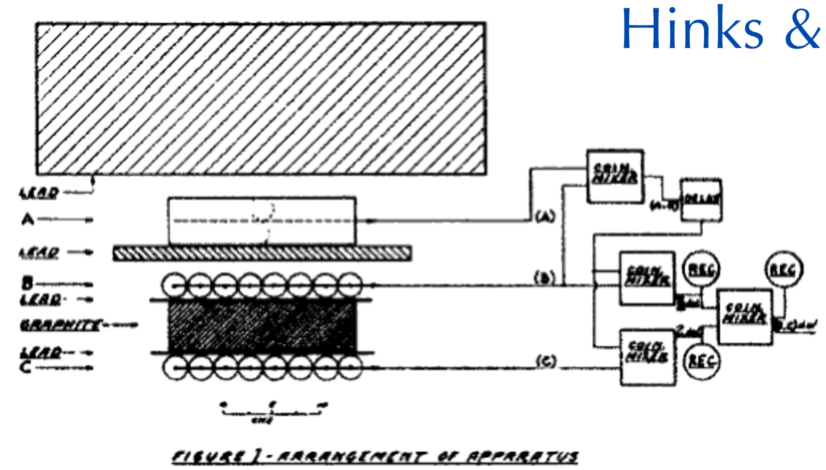


- Clear evidence for physics beyond the SM
  - (SU(5), SU(10), SUSY...)

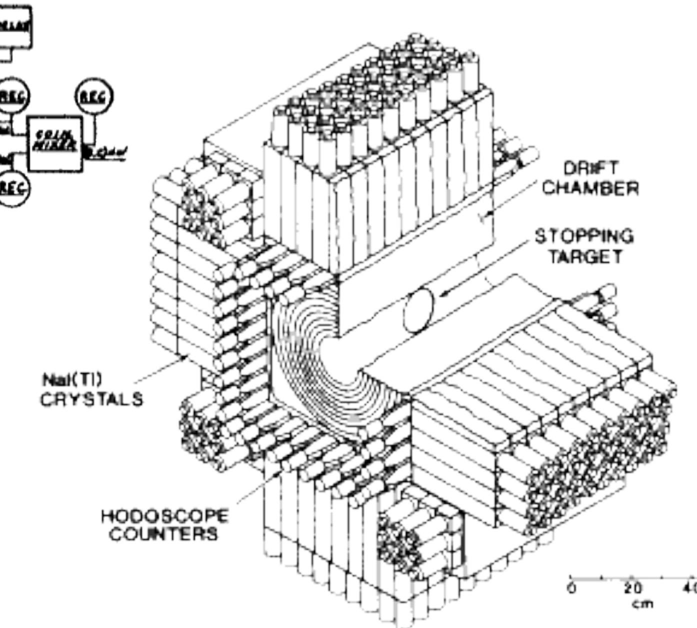
Historical perspective

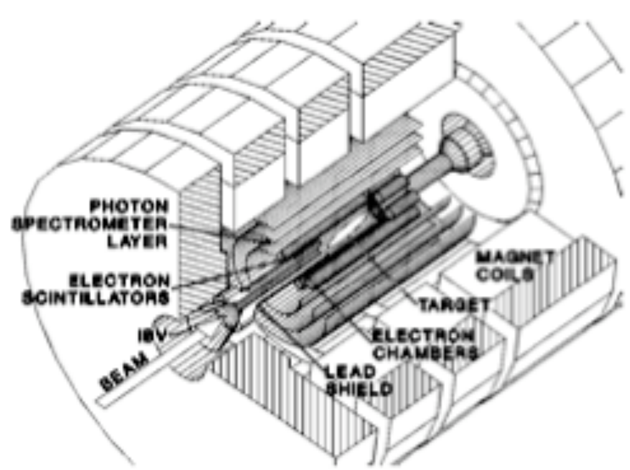


Hinks & Pontecorvo

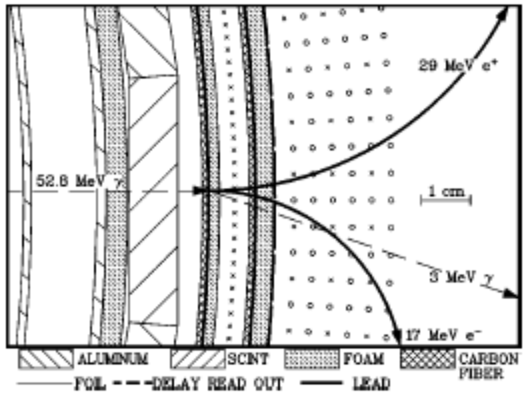


Crystal Box





MEGA



Each improvement linked to the technology either in the beam or in the detector

Always a trade-off between various elements of the detector to achieve the best "sensitivity"

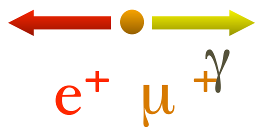
Signal and Background

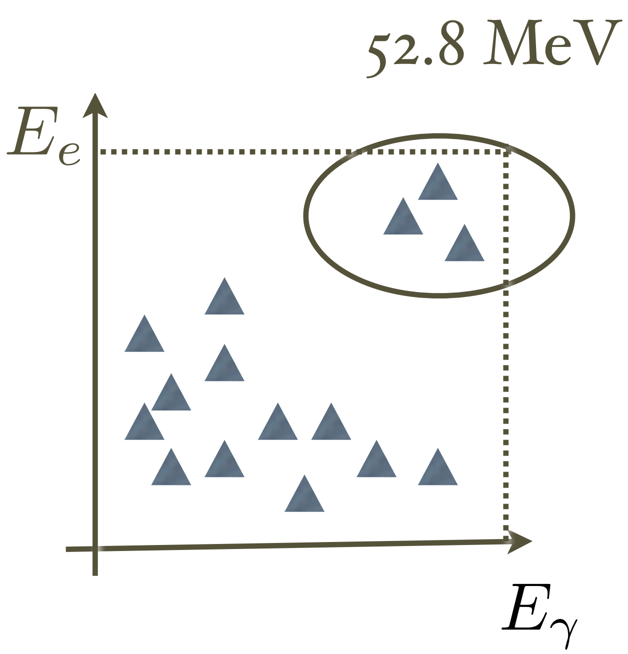
- Connection with neutrino physics was apparent at the beginning of the $\mu \to e\gamma$ search
- Looking at LFV under a different angle

- To better understand why MEG was designed the way it is we have to understand exactly:
    - what are we searching for? signal
    - in which environment? background
- which handles can we use for discrimination?

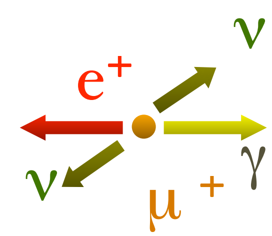
Signal and Background

"Signal"



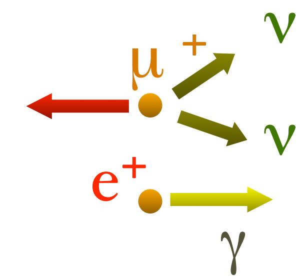


"Prompt"



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

"Accidental"



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

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

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

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

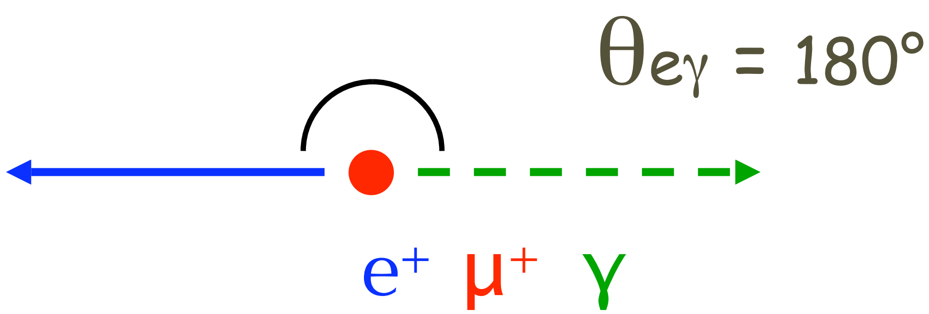
The accidental background is dominant and it is determined by the experimental resolutions

Exp./Lab	Year	ΔEe/Ee (%)	ΔEγ /Eγ (%)	Δteγ (ns)	Δθeγ (mrad)	Stop rate (s^{-1})	Duty cyc. (%)	BR (90% CL)
SIN	1977	8.7	9.3	1.4	-	5×10^5	100	3.6×10^{-9}
TRIUMF	1977	10	8.7	6.7	-	2×10^5	100	1×10^{-9}
LANL	1979	8.8	8	1.9	37	2.4×10^5	6.4	1.7×10^{-10}
Crystal Box	1986	8	8	1.3	87	4×10^5	(6..9)	4.9×10^{-11}
MEGA	1999	1.2	4.5	1.6	17	2.5×10^8	(6..7)	1.2×10^{-11}
MEG	2009	1	4.5	0.15	19	3×10^7	100	2×10^{-13}

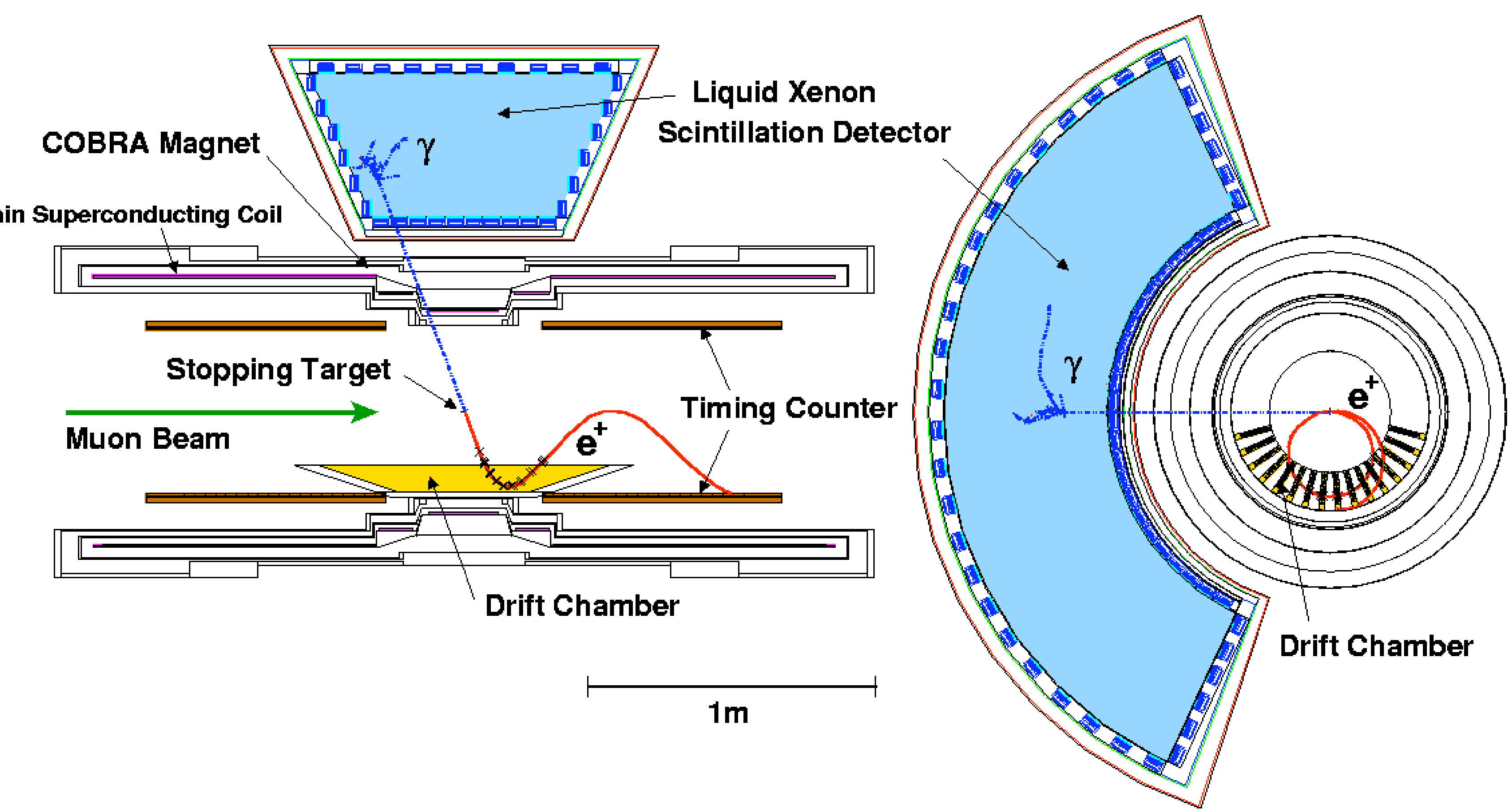
FWHM

MEG experimental method

Easy signal selection with μ^+ at rest



$E_e = E_\gamma = 52.8$ MeV



- μ: stopped beam of $>10^7$ μ /sec in a 175 μm target
- e^+ detection

  magnetic spectrometer composed by solenoidal magnet and drift chambers for momentum

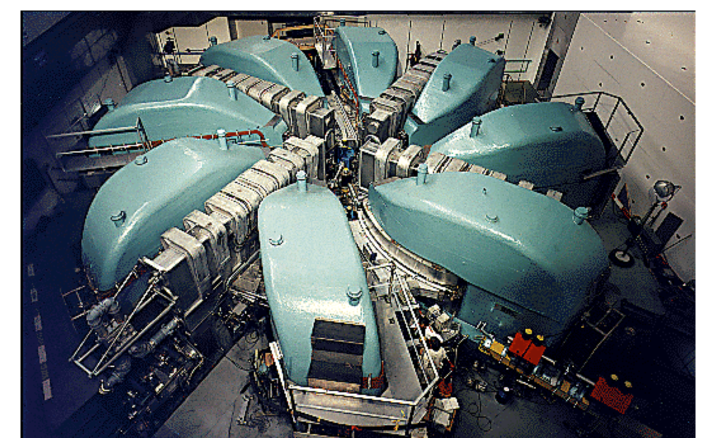
  plastic counters for timing
- γ detection

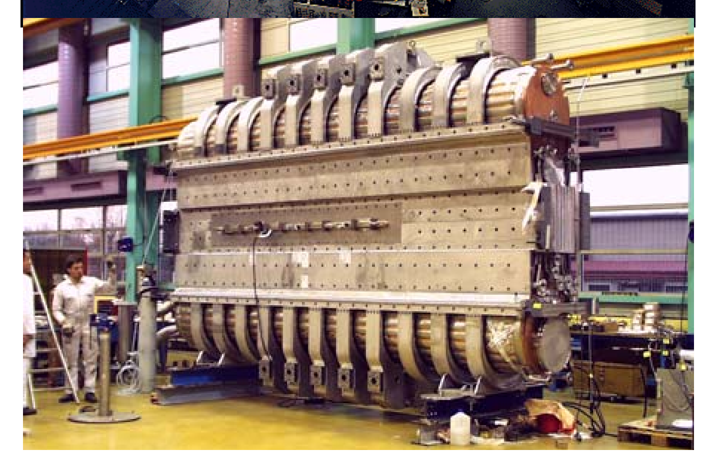
  Liquid Xenon calorimeter based on the scintillation light

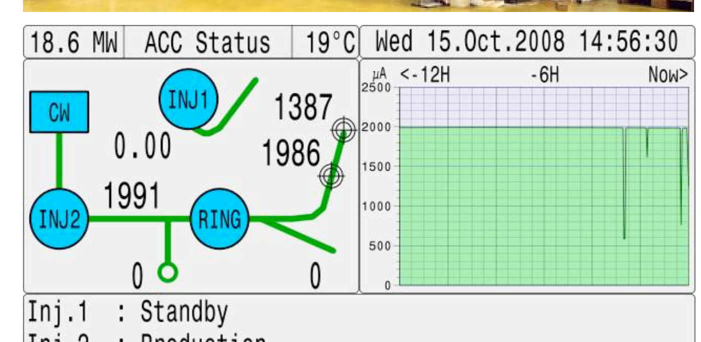
  - fast: 4 / 22 / 45 ns
  - high LY: ~ 0.8 * NaI
  - short X_0: 2.77 cm

Machine

- "Sensitivity" proportional to the number of muons observed
- Find the most intense (continuous) muon beam: Paul Scherrer Institut (CH)
- 1.6 MW proton accelerator
  - 2 mA of protons - towards 3 mA (replace with new resonant cavities)!
  - extremely stable
  - $> 3 \times 10^8$ muons/sec @ 2 mA





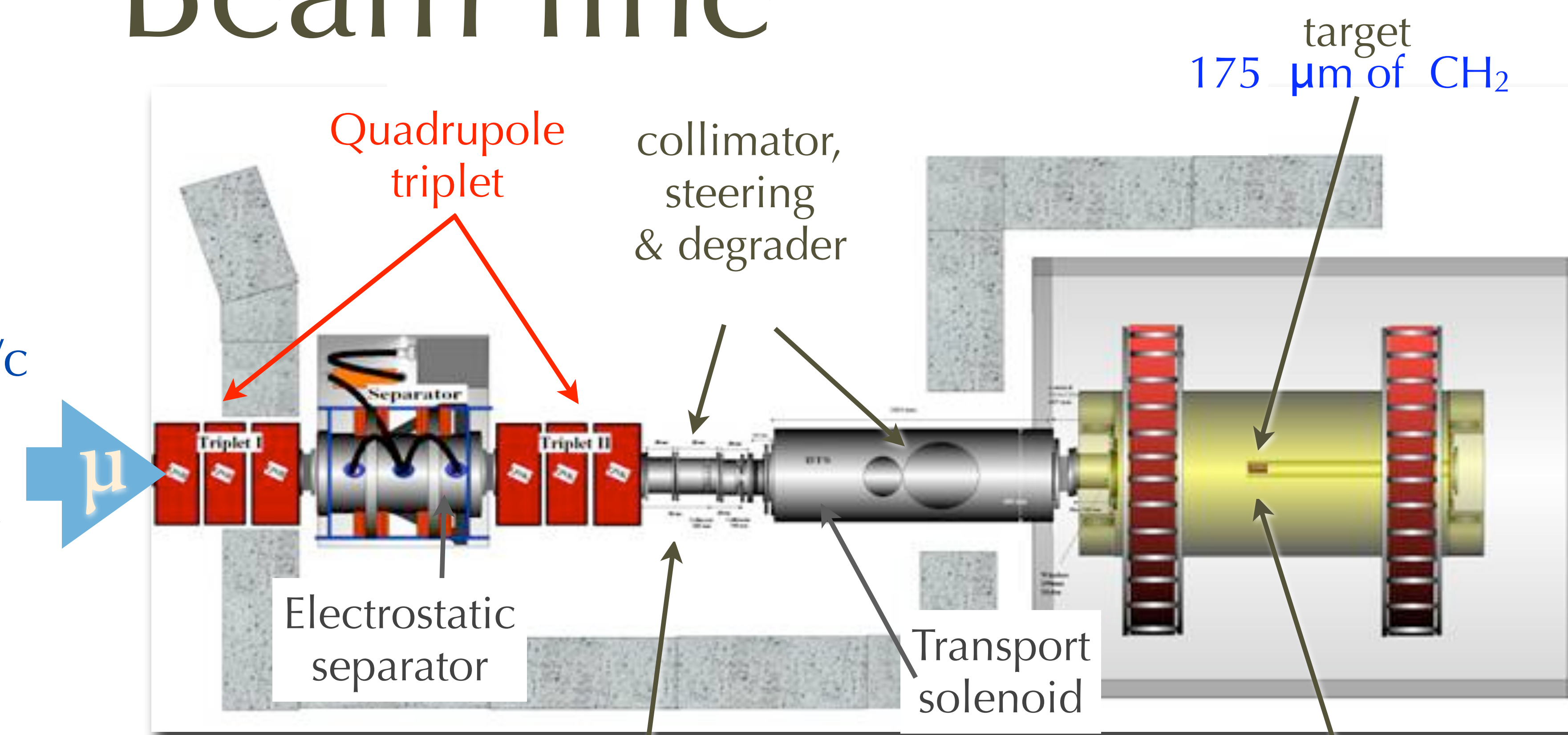


Beam line

πE5 beam line at PSI

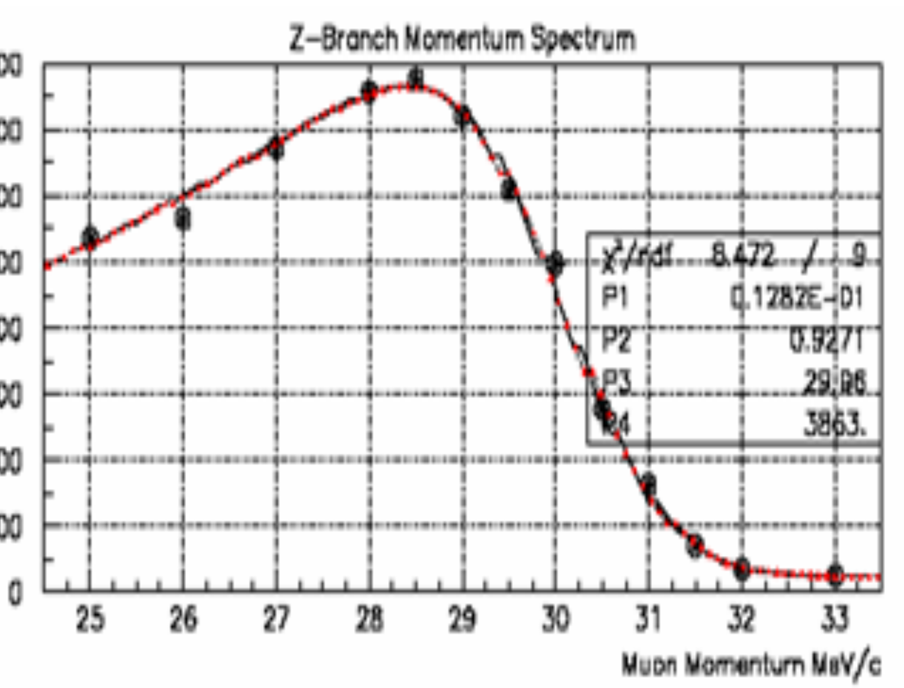
Optimization of the beam elements:

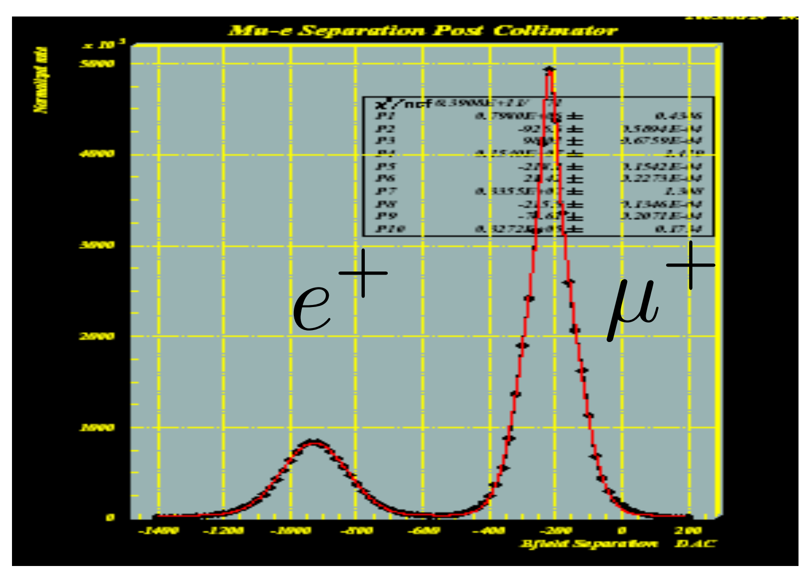
- Muon momentum ~ 29 MeV/c
- Wien filter for μ/e separation
- Solenoid to couple beam and spectrometer (BTS)
- Degrader to reduce the momentum for a 175 μm target



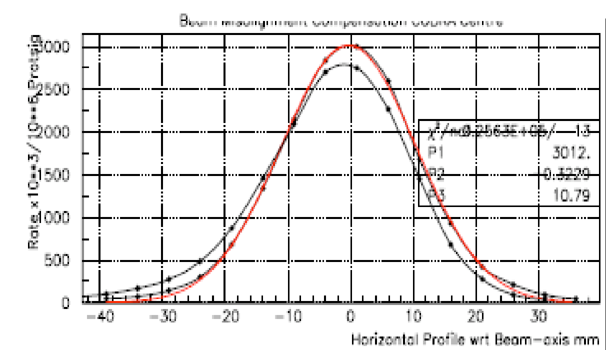
μ/e separation 11.8 cm (7.2 σ)

R_μ (exp. on target)	$>6\ 10^7\ \mu^+/s$
μ spot (exp. on target)	$\sigma_V \approx \sigma_H \approx 11$ mm

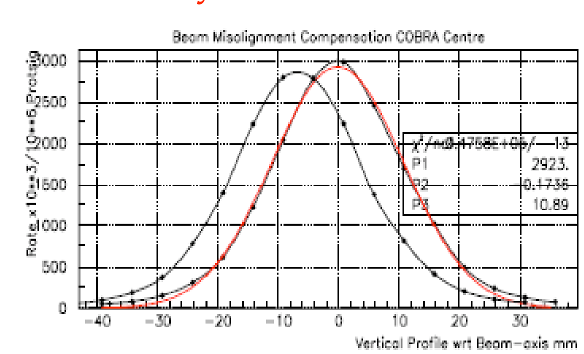




$\sigma_x = 11$ mm

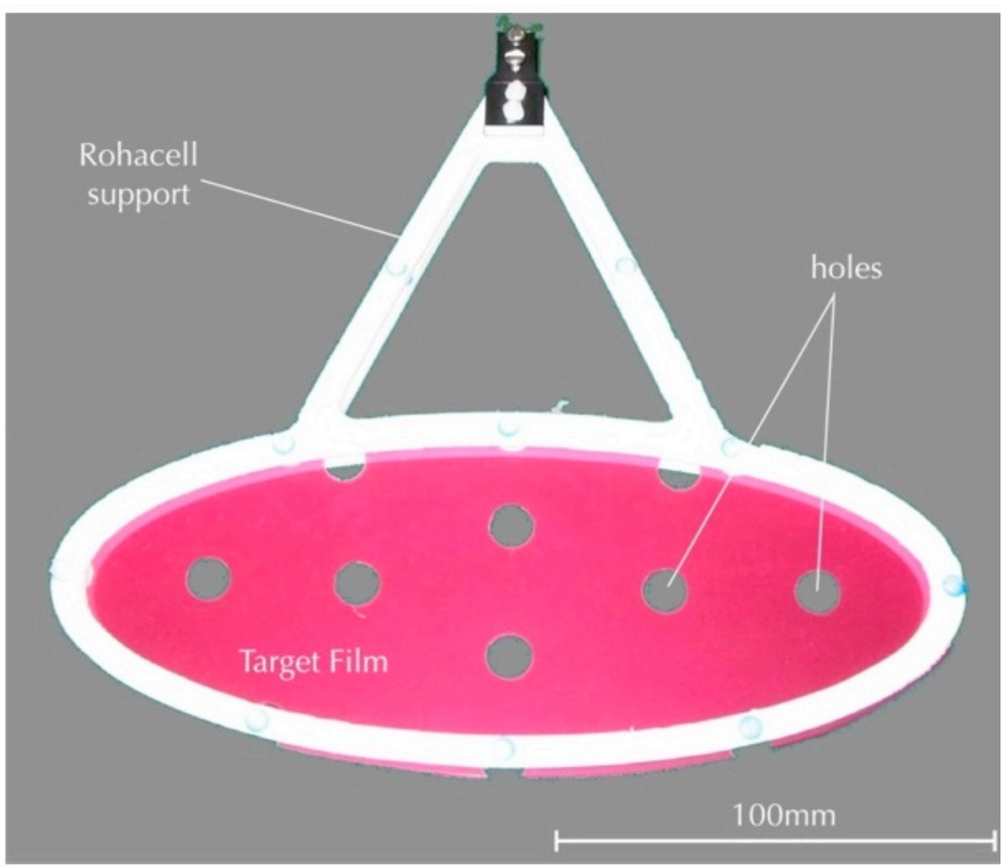


$\sigma_y = 11$ mm



Target

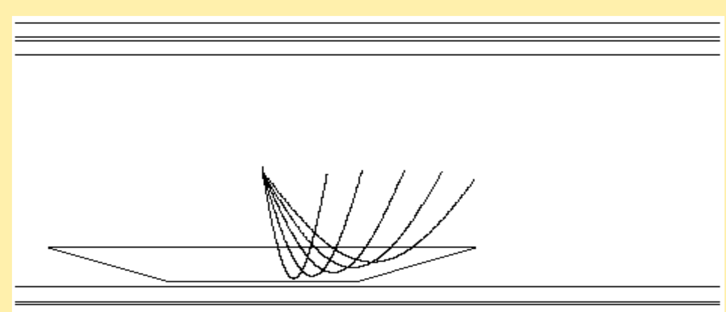
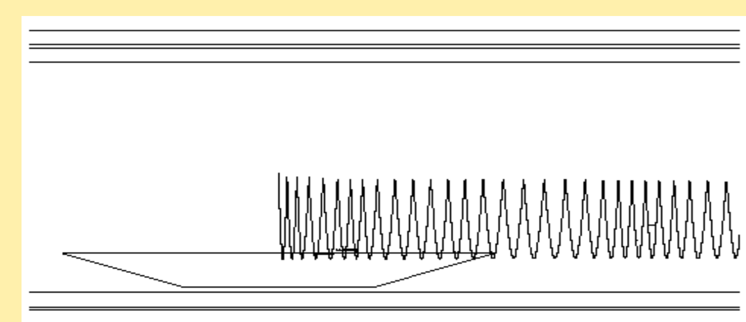
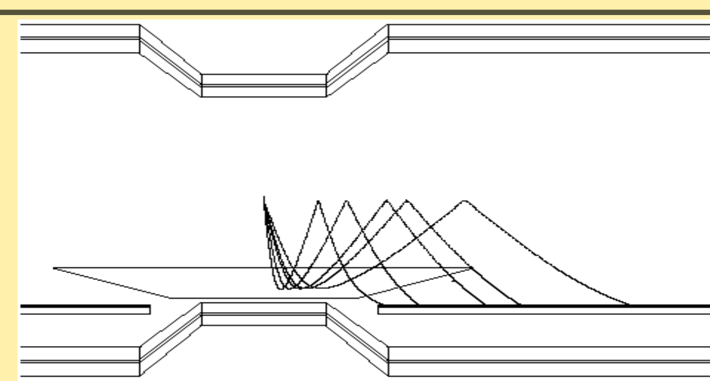
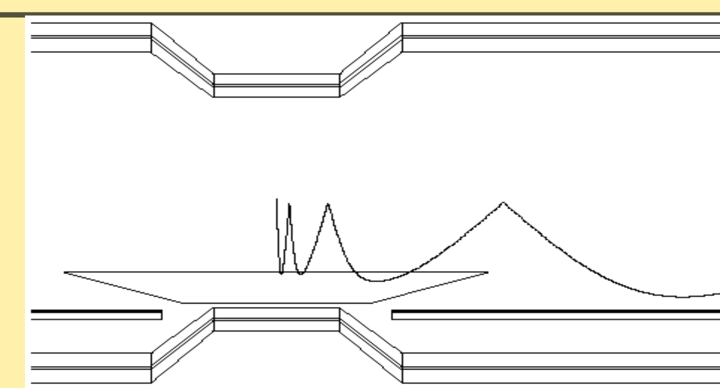
- Stop muons on the thinnest possible target 175 μm CH_2:
  - need low energy muons (lots of multiple scattering) but...
  - the MS of the decaying positron is minimized: precise direction/timing
  - bremsstrahlung reduced
  - the conversion probability of the photon in the target is negligible



Holes to study position reconstruction resolution

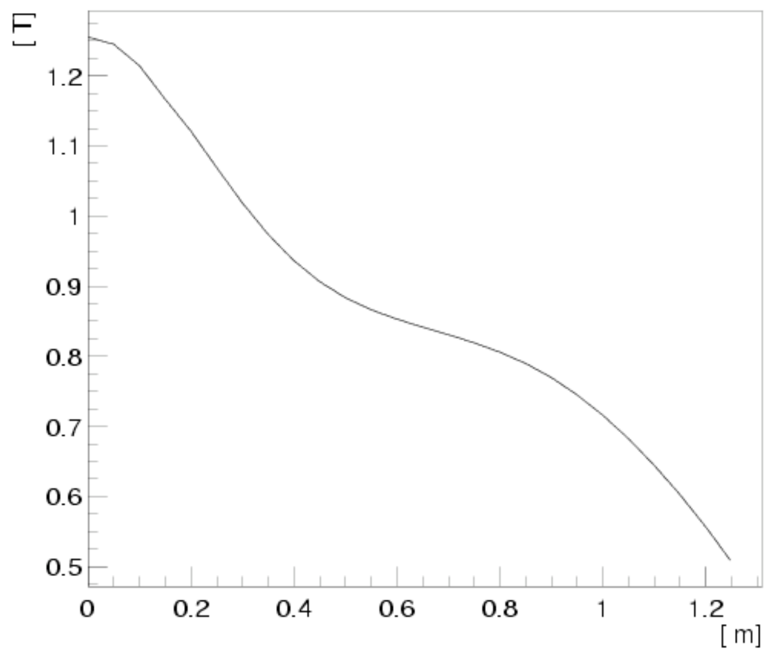
COBRA spectrometer

- The emitted positrons tend to wind in a uniform magnetic field
  - the tracking detector becomes easily “blind” at the high rate required to observe many muons
- A non uniform magnetic field solves the rate problem
- As a bonus: COnstant Bending RAdius

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

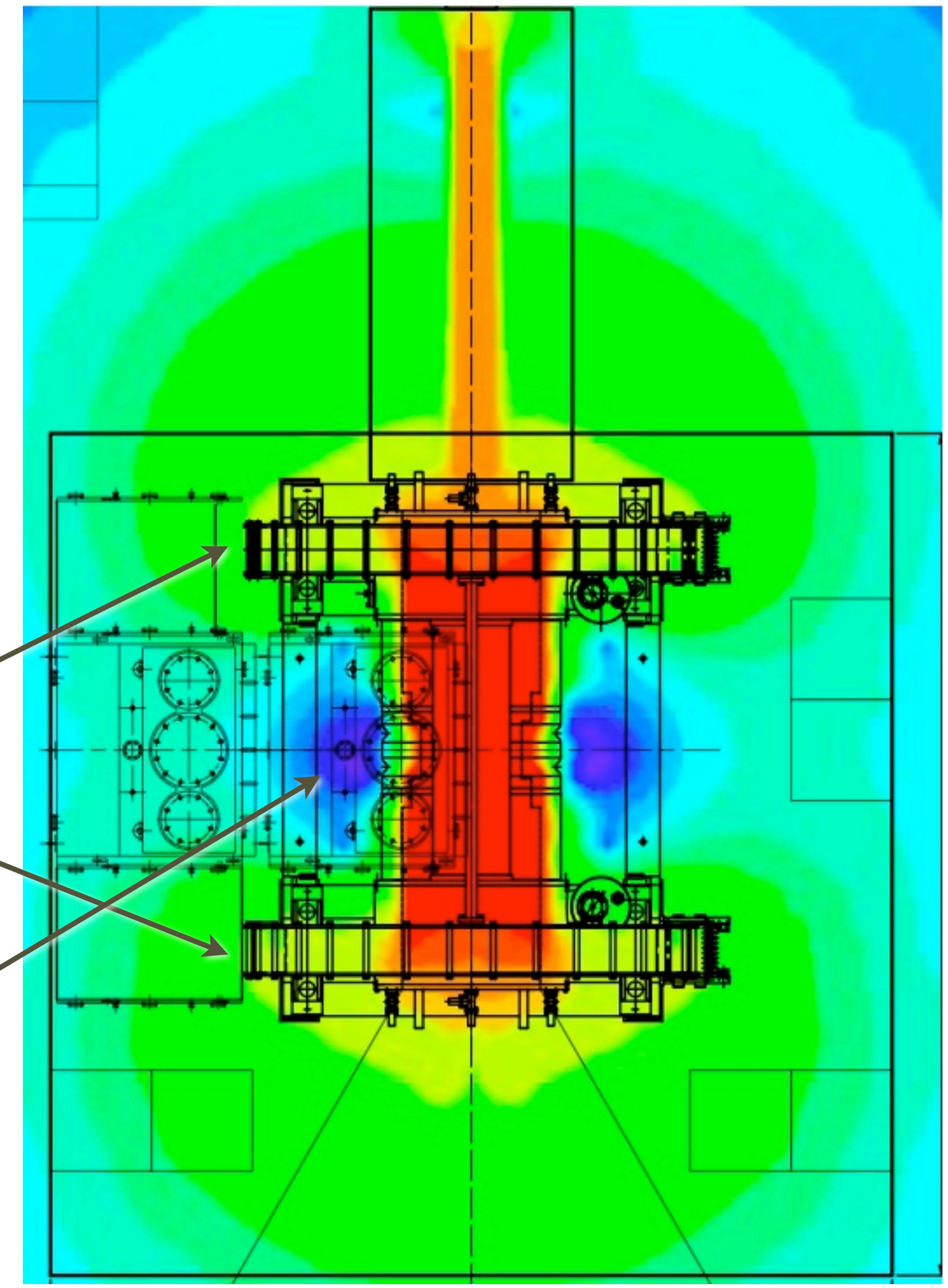
COBRA spectrometer

Non uniform magnetic field decreasing from the center to the periphery

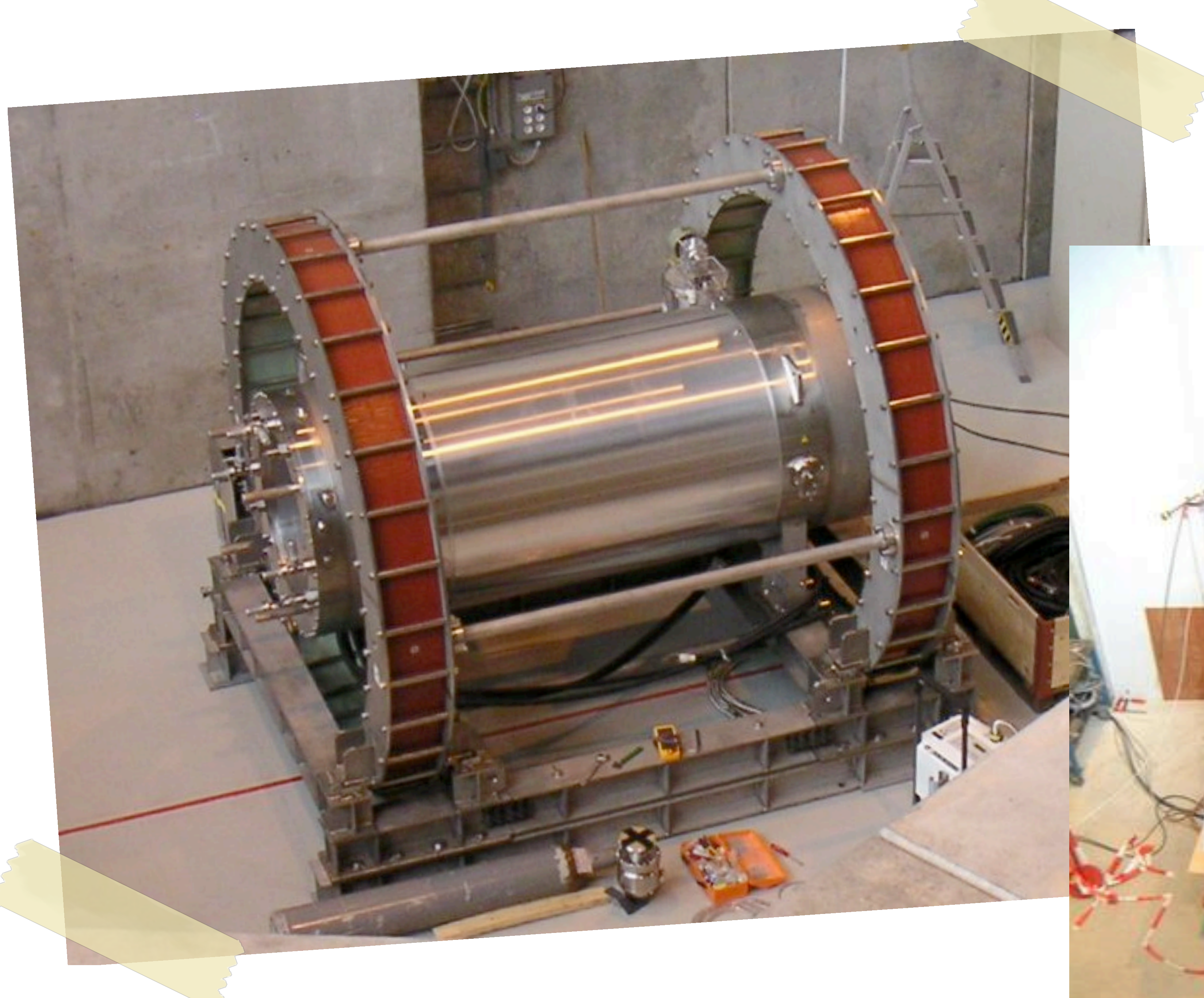


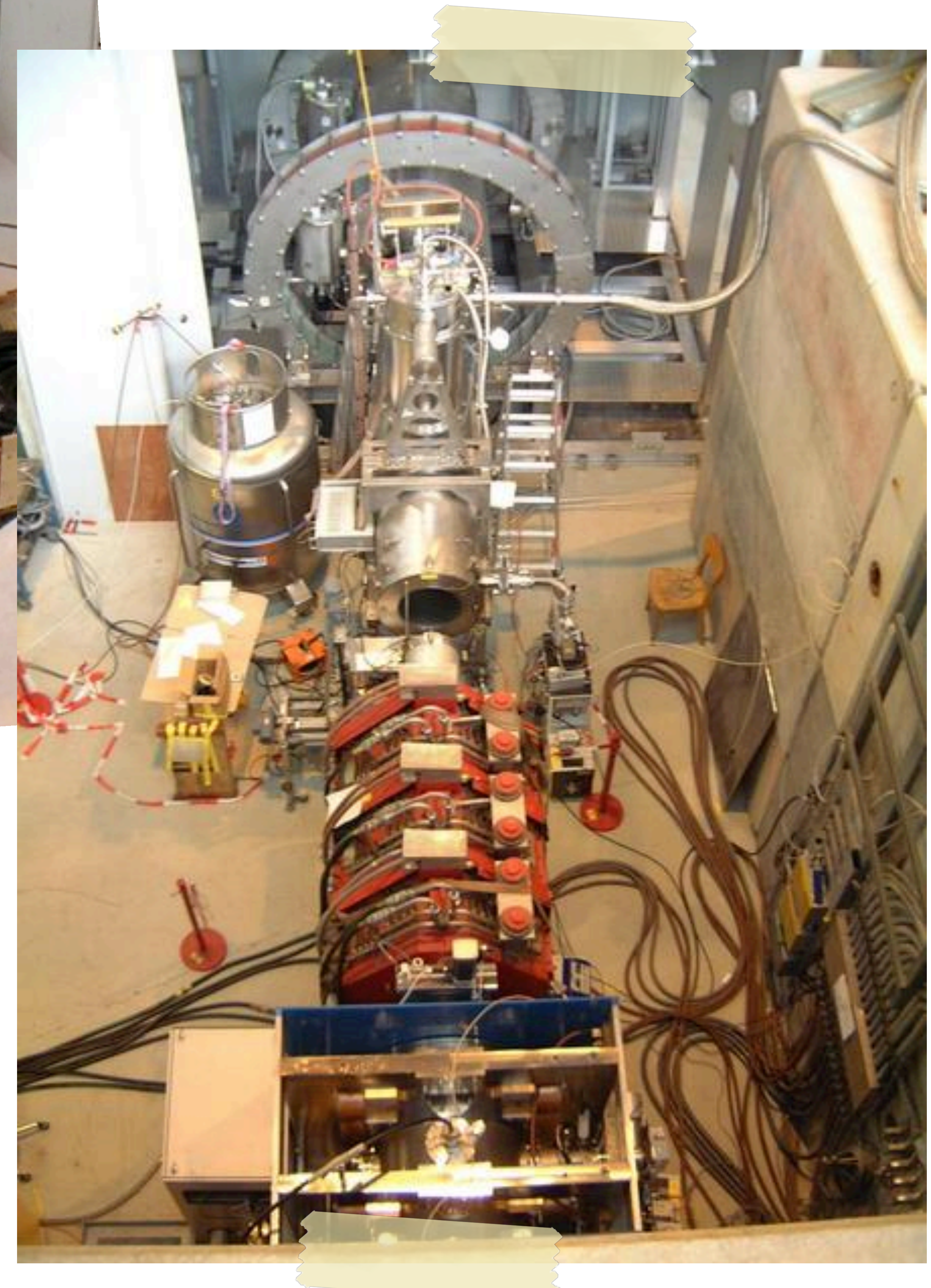
Compensation coil for LXe calorimeter

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



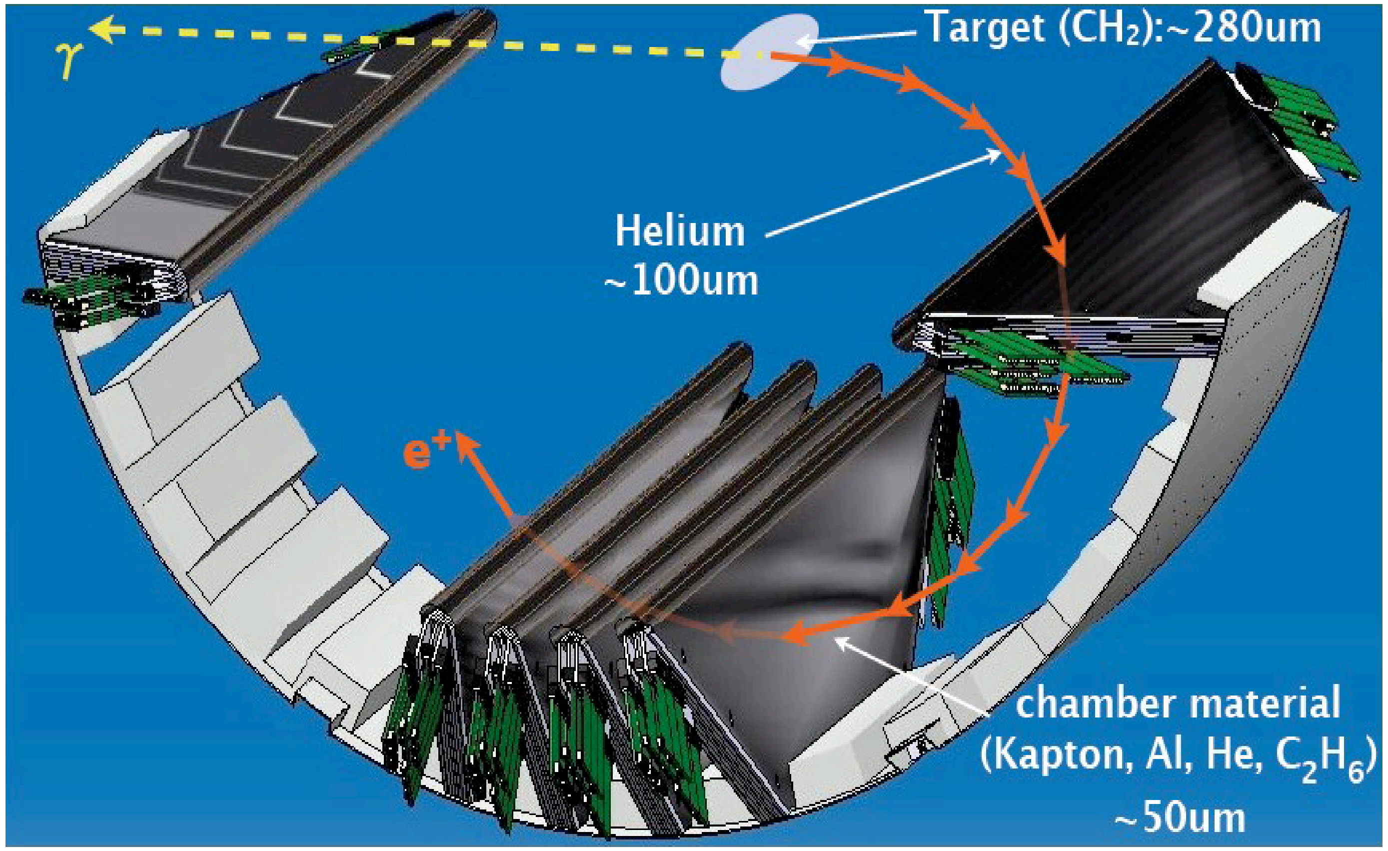
- The superconducting magnet is very thin (0.2 X_0)
- Can be kept at 4 K with GM refrigerators (no usage of liquid helium)



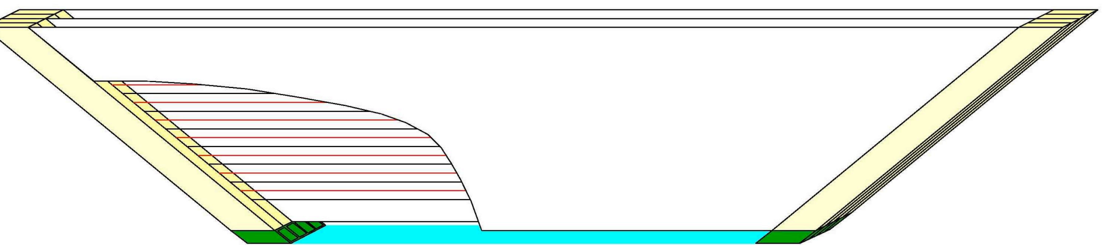


Positron tracker

- Excellent momentum resolution at ~50 MeV
- The energy is very low hence the multiple scattering is important
  - we tend to loose position/energy resolution
  - MS ~ σ
- The volumes of the chambers are independent
  - too much high-Z gas otherwise (He/C_2H_6 vs He)
  - find a clever way for a good *z*-reconstruction

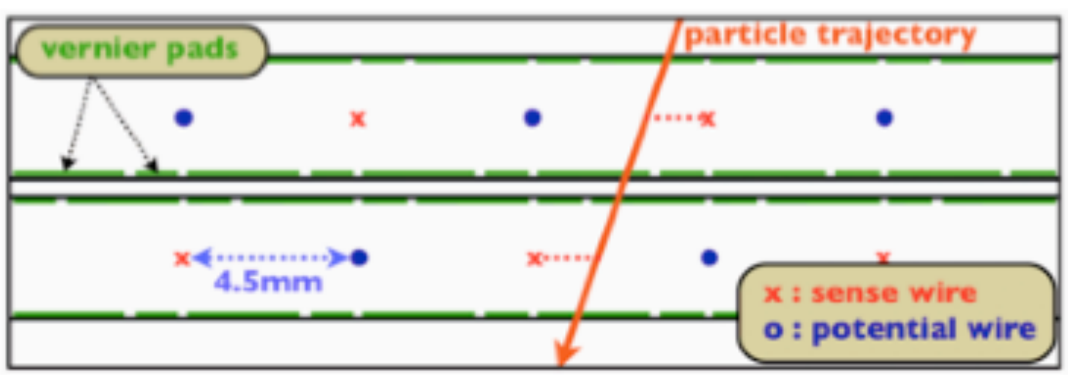


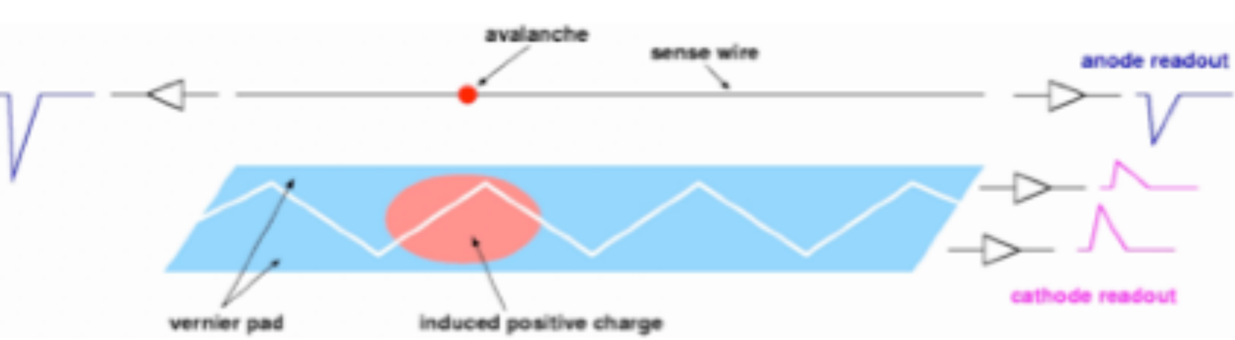
Positron Tracker



- 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

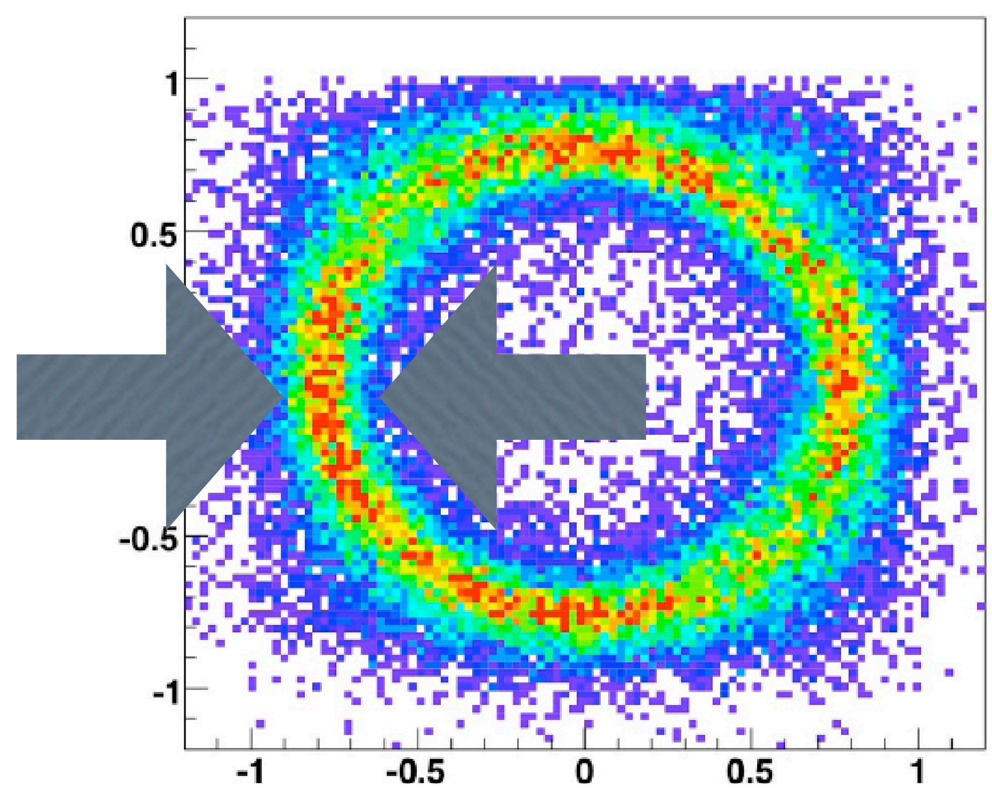
transverse coordinate (t drift)



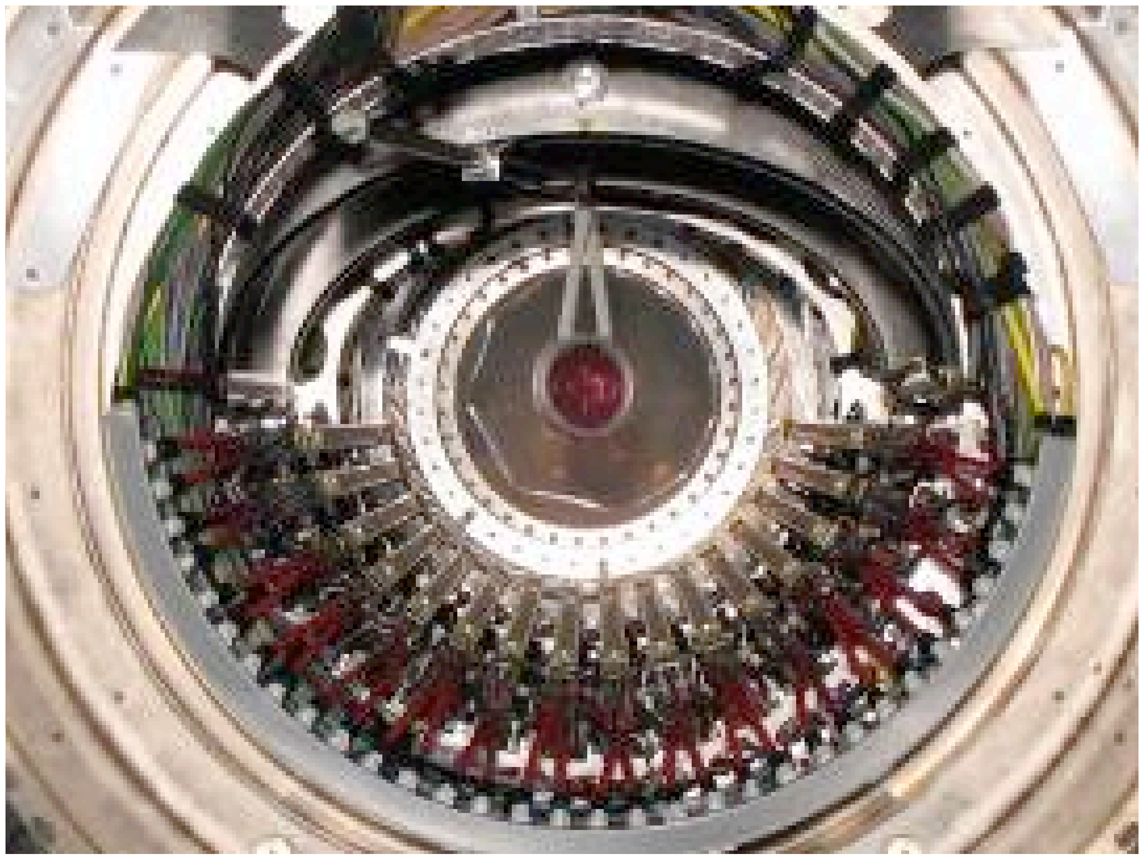


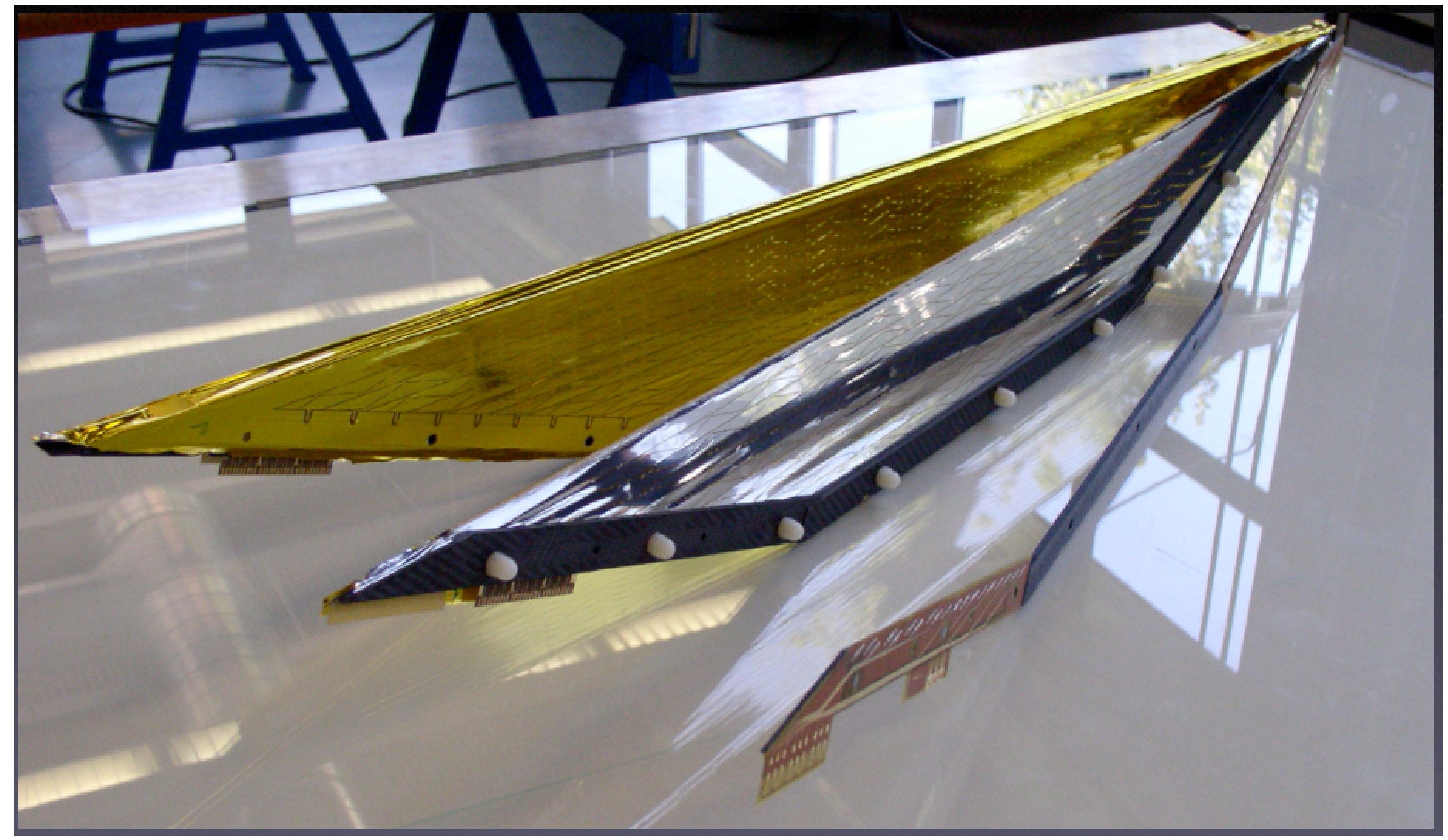
longitudinal coordinate (charge division + Vernier)

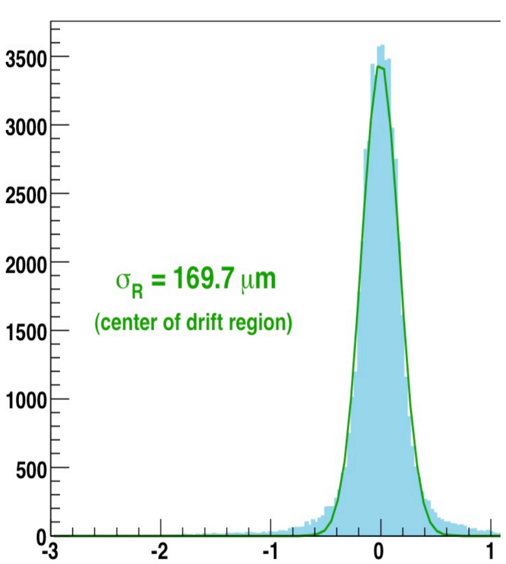
- Within one period, fine structure given by the Vernier circle

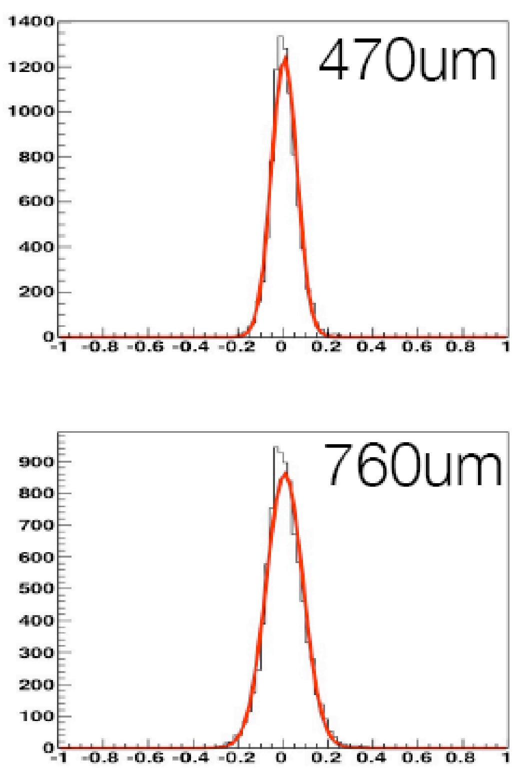


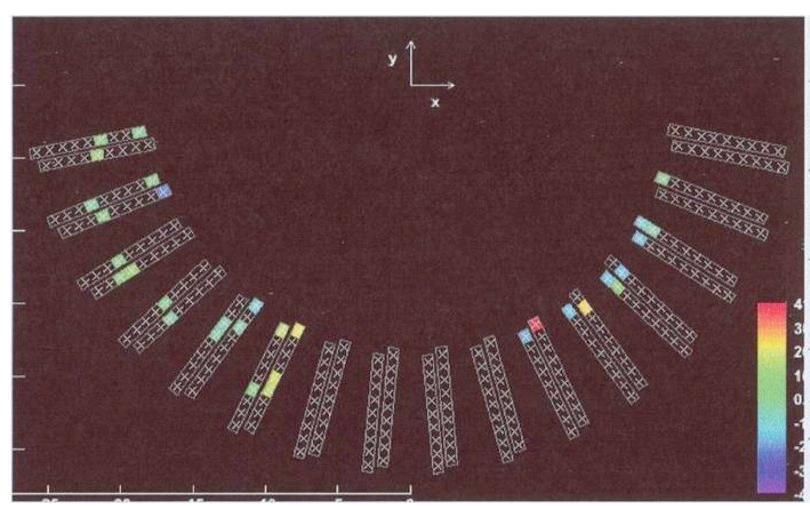
Drift chambers

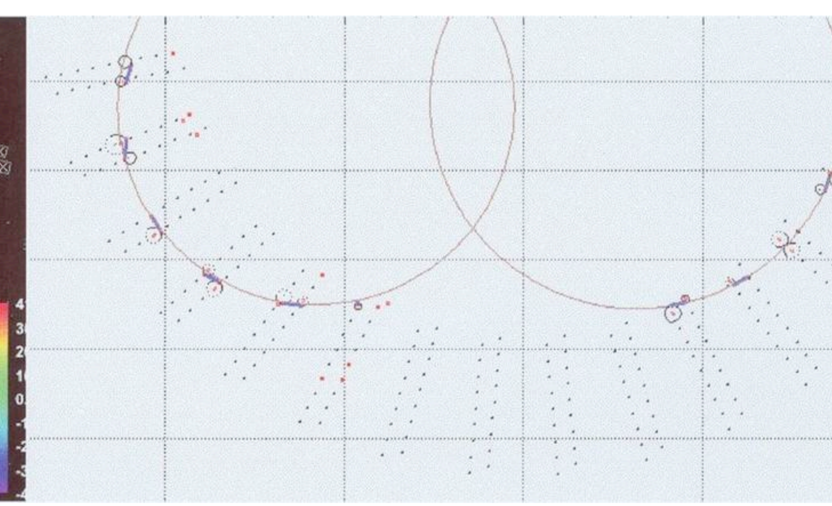




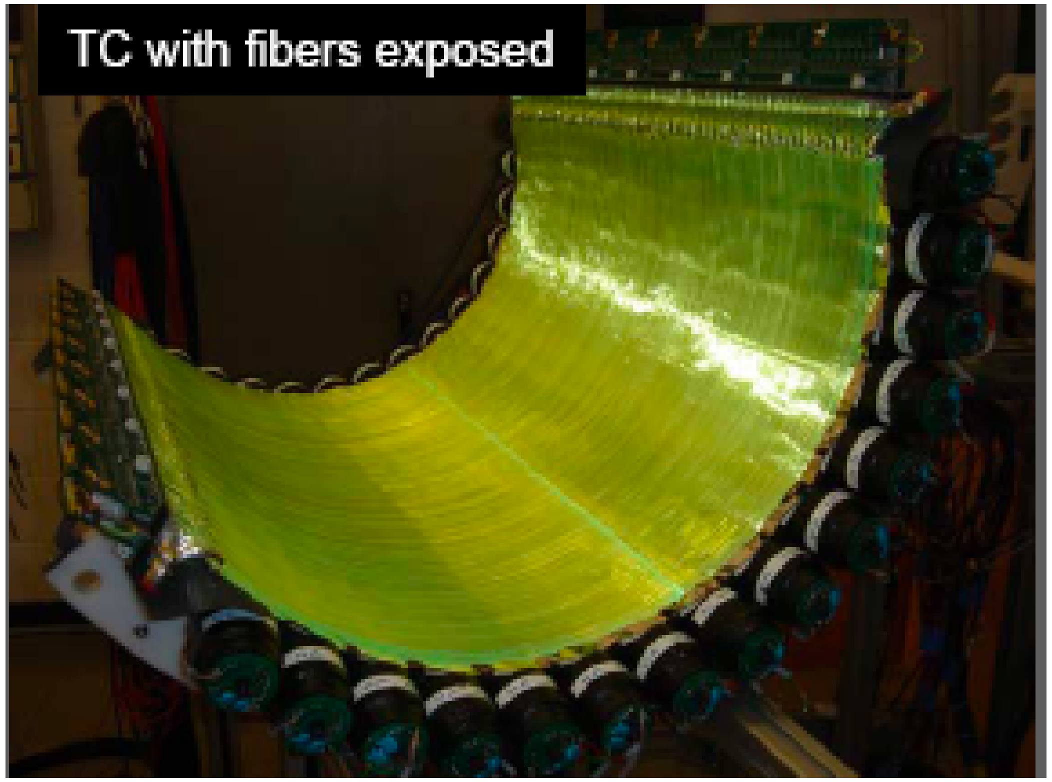




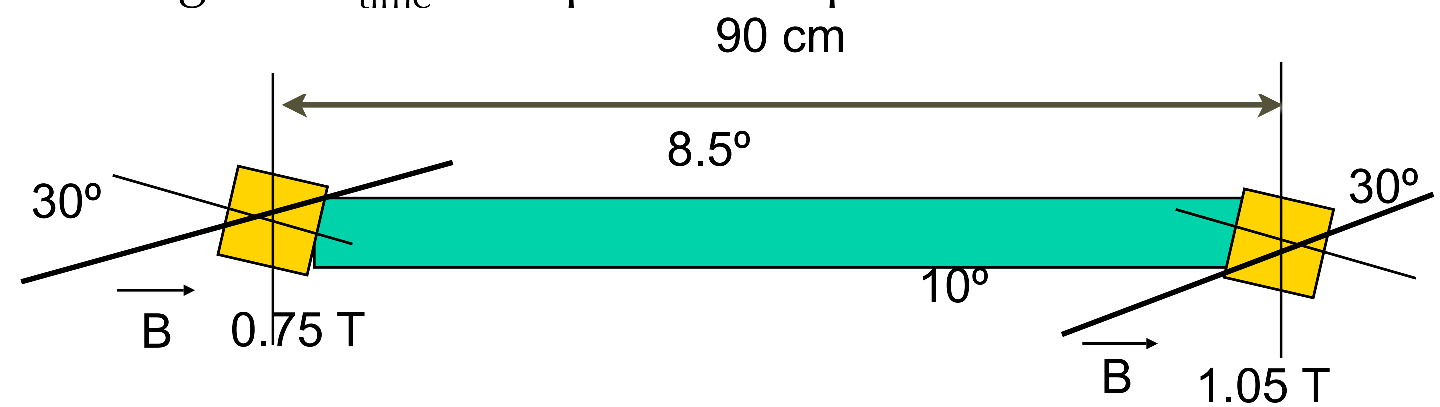


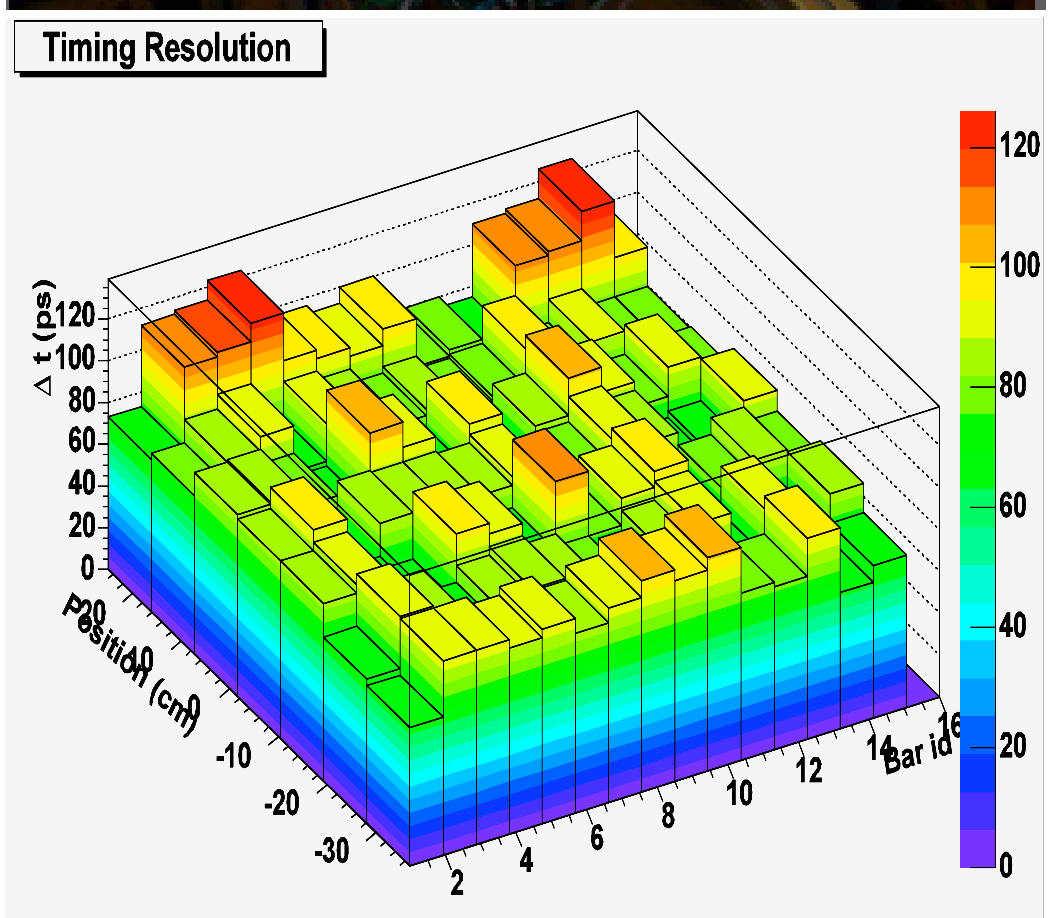


Timing Counter



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



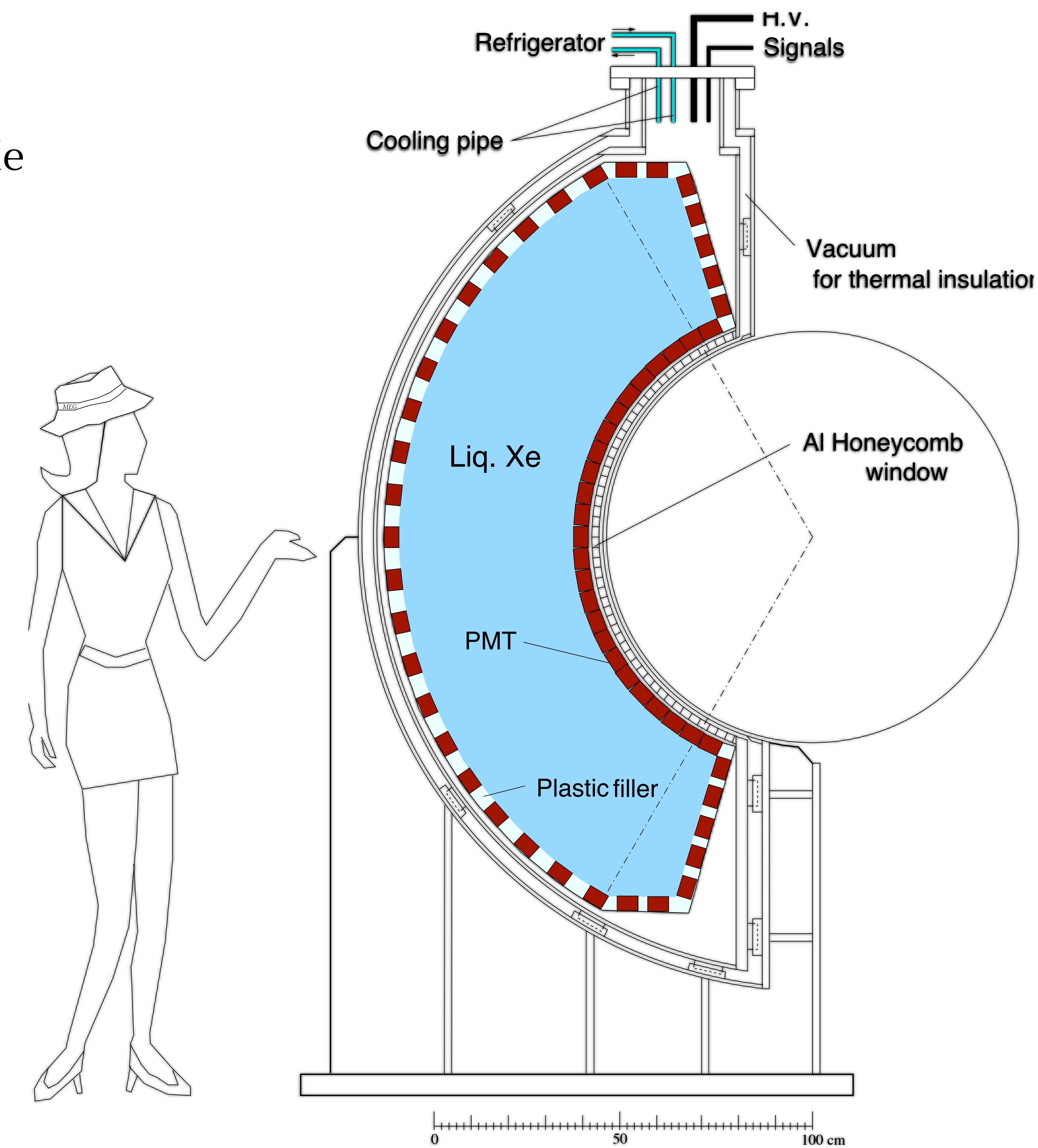


Exp. application (*)	Counter size (cm) (T x W x L)	Scintillator	PMT	λ_{att} (cm)	σ_t(meas)	σ_t(exp)
G.D.Agostini	3x 15 x 100	NE114	XP2020	200	120	60
T. Tanimori	3 x 20 x 150	SCSN38	R1332	180	140	110
T. Sugitate	4 x 3.5 x 100	SCSN23	R1828	200	50	53
R.T. Gile	5 x 10 x 280	BC408	XP2020	270	110	137
TOPAZ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

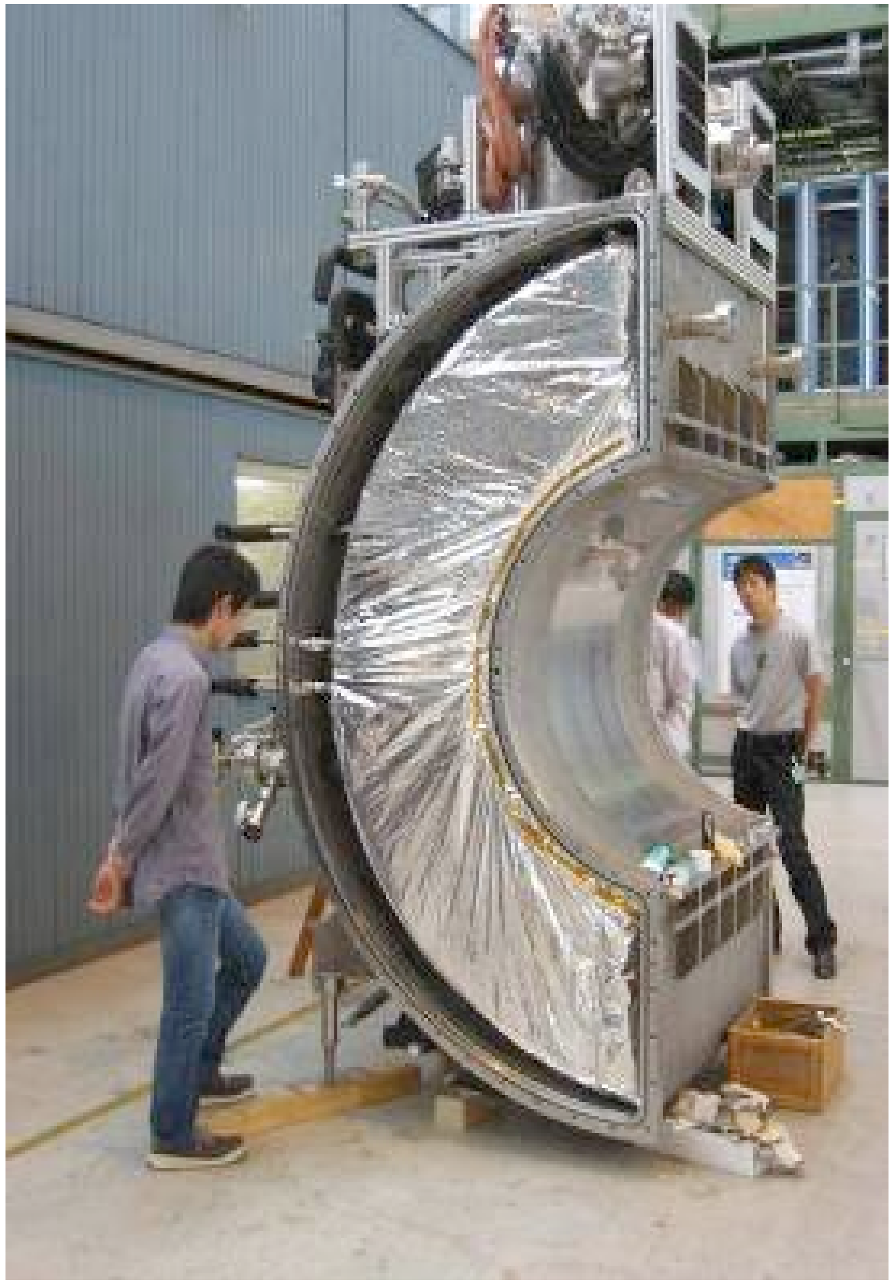
Best existing TC

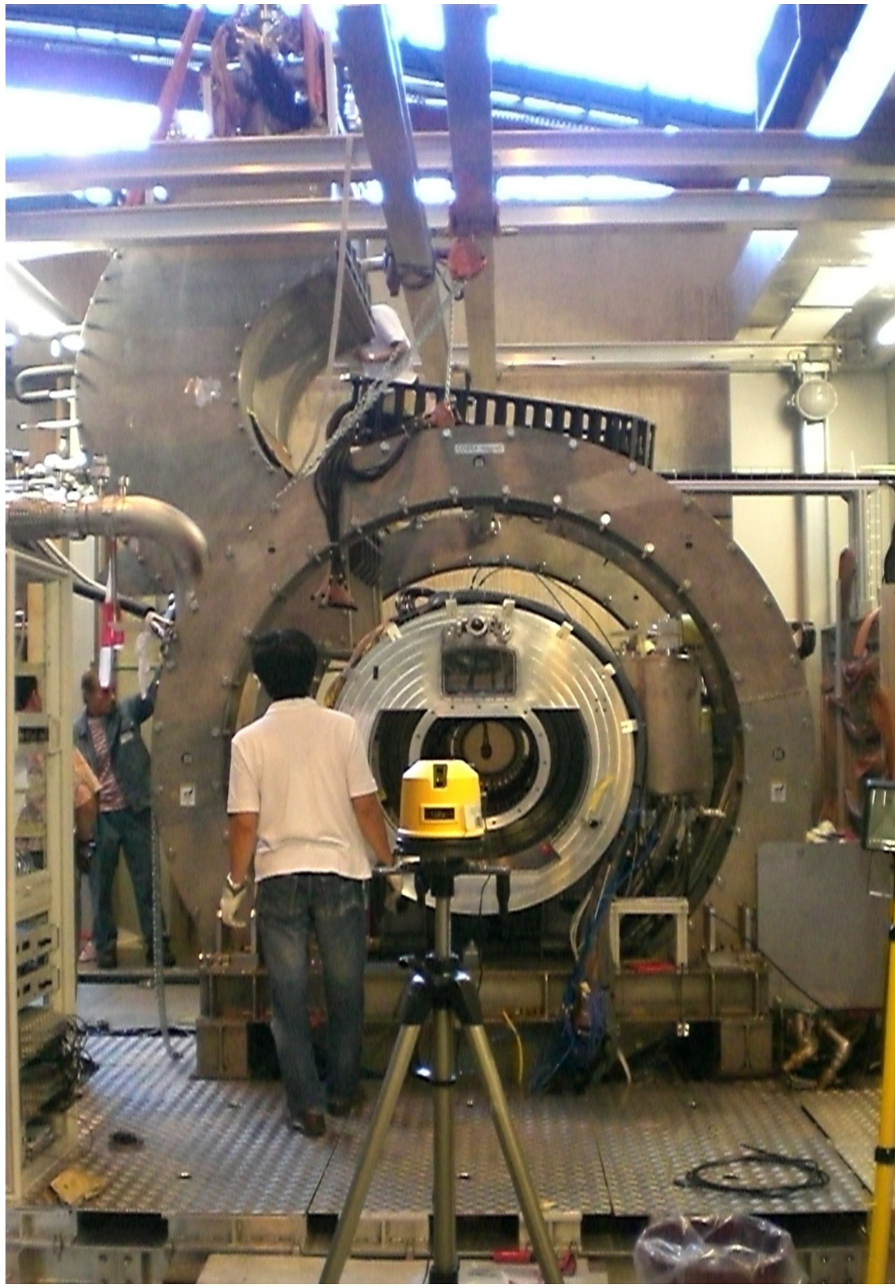
The calorimeter

- 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



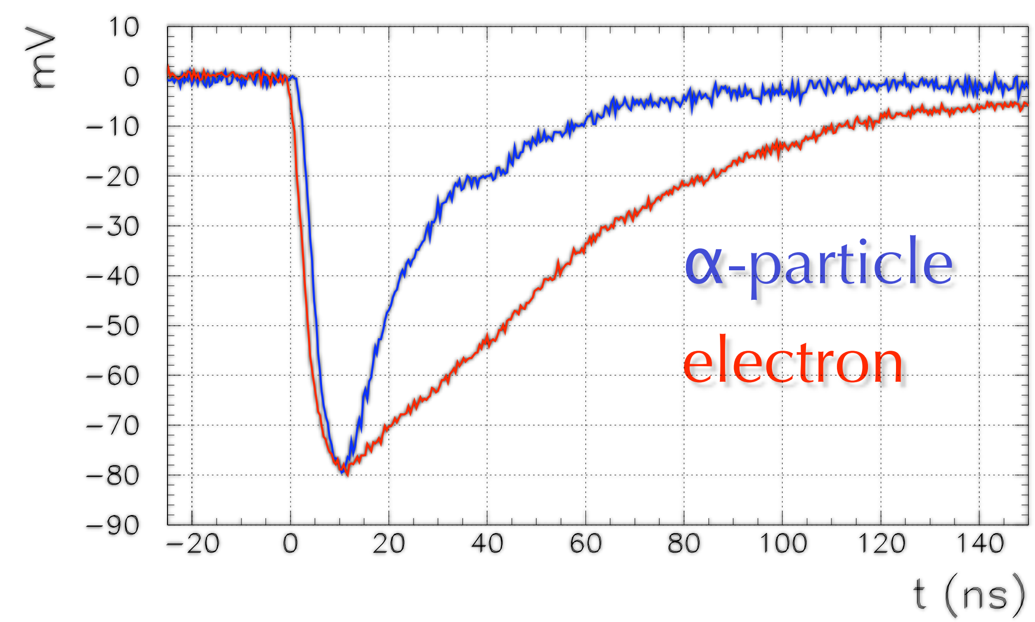
Calorimeter construction

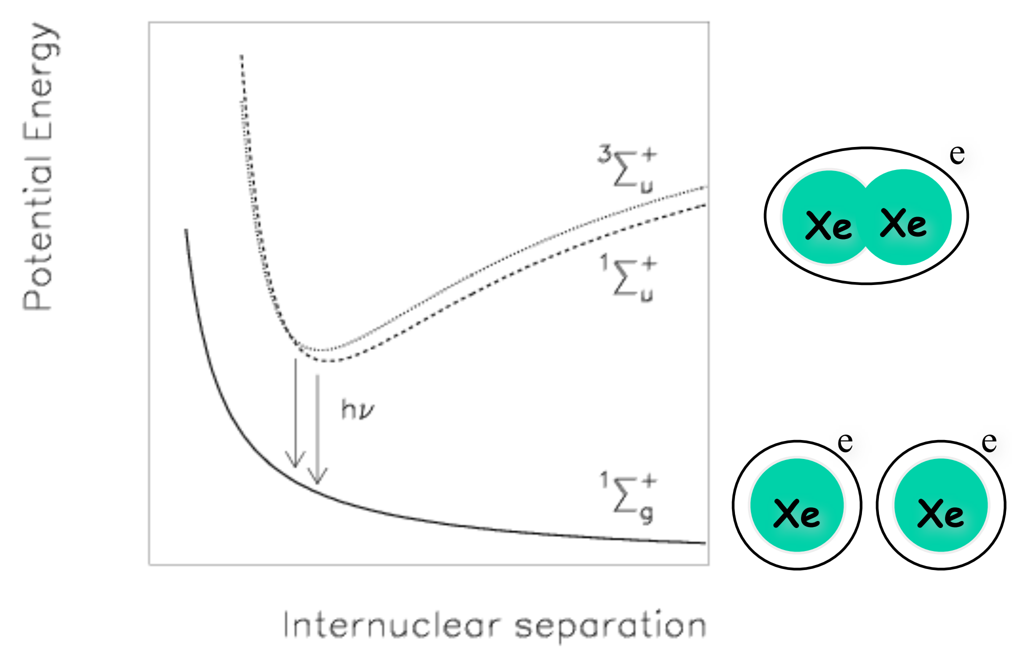




Xe properties

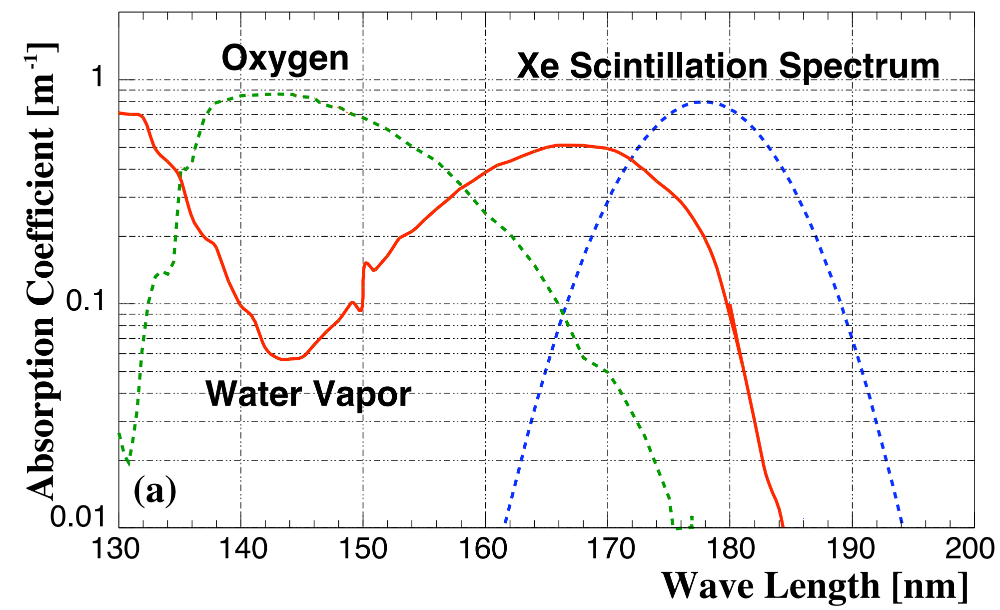
- Liquid Xenon was chosen because of its unique properties among radiation detection active media
- Z=54, ρ=2.95 g/cm^3 (X_0=2.7 cm), R_M=4.1 cm
- High light yield (similar to NaI)
  - 40000 phe/MeV
- Fast response of the scintillation decay time
  - $\tau_{singlet}$= 4.2 ns
  - $\tau_{triplet}$= 22 ns
  - τ_{recomb}= 45 ns
- Particle ID is possible
  - α ~ singlet+triplet, γ ~ recombination
- Large refractive index n = 1.65
- No self-absorption (λ_{Abs}=∞)

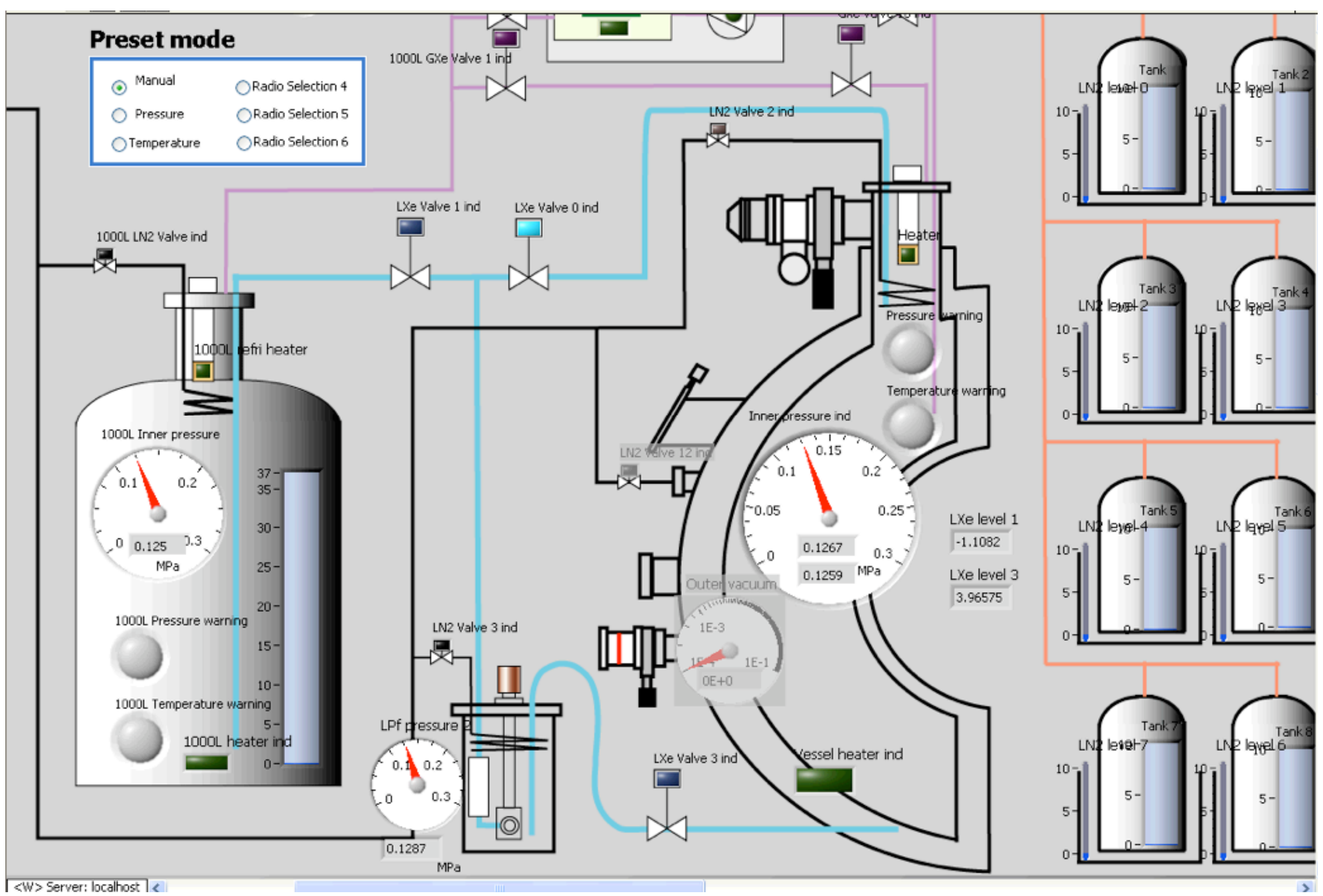


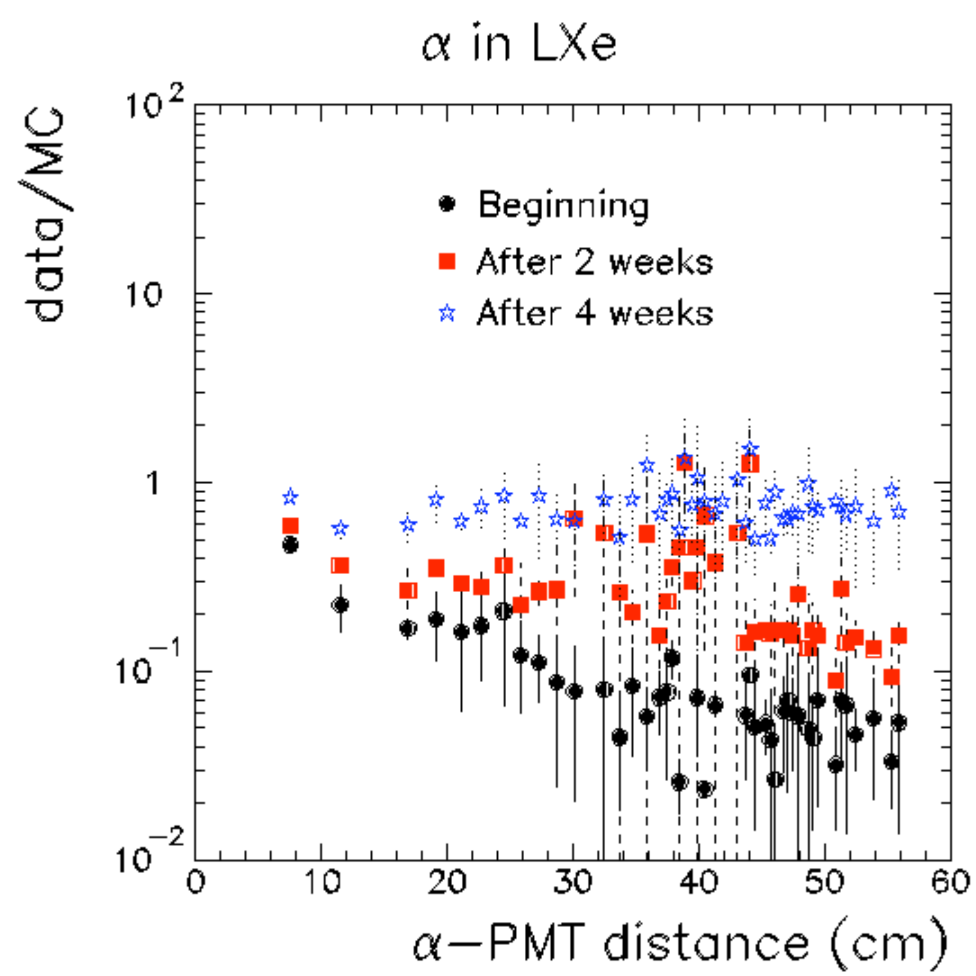


Xenon purity

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







Trigger

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

✴Beam rate ~ $3\ 10^7\ s^{-1}$

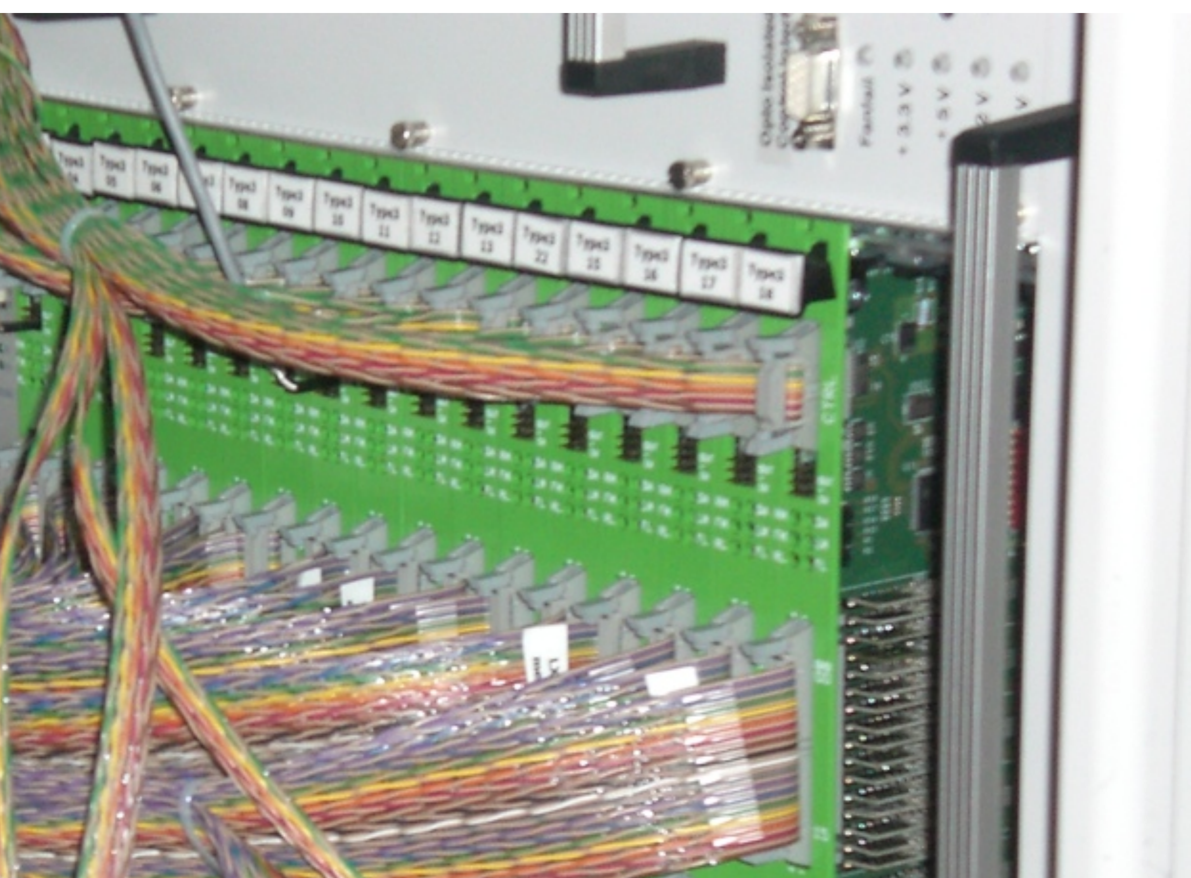
✴Fast LXe energy sum > 45MeV $2\times10^3\ s^{-1}$

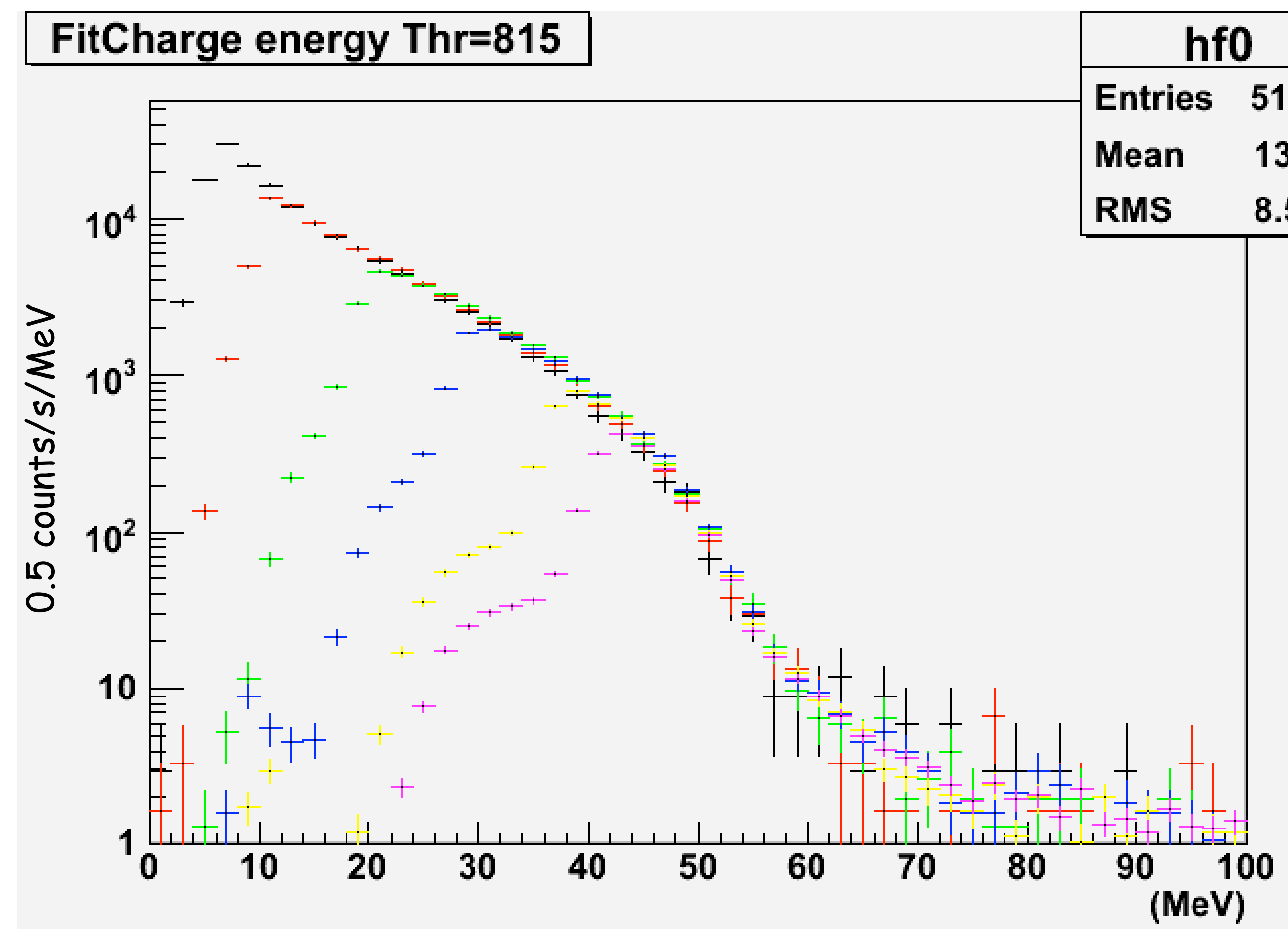
 ✴gamma interaction point (PMT charge)

 ✴e^+ hit point in timing counter

✴time correlation $\gamma - e^+$ $100\ s^{-1}$

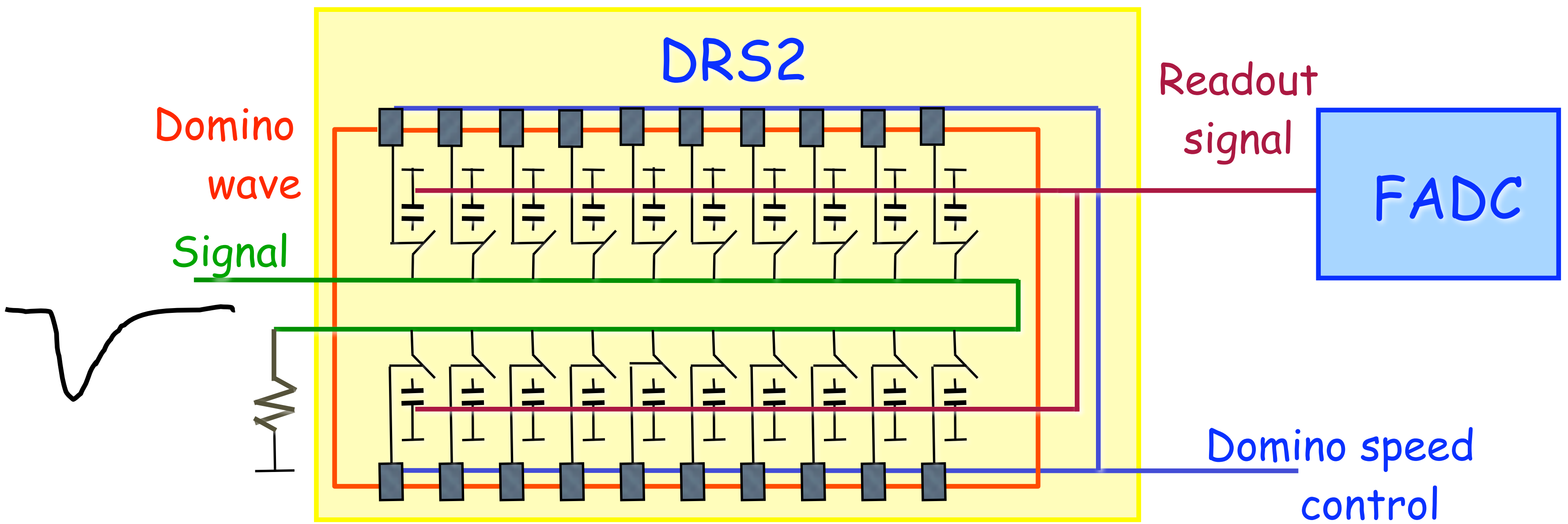
✴angular correlation $\gamma - e^+$ $10\ s^{-1}$





Readout electronics

2 GHz waveform digitization for all channels

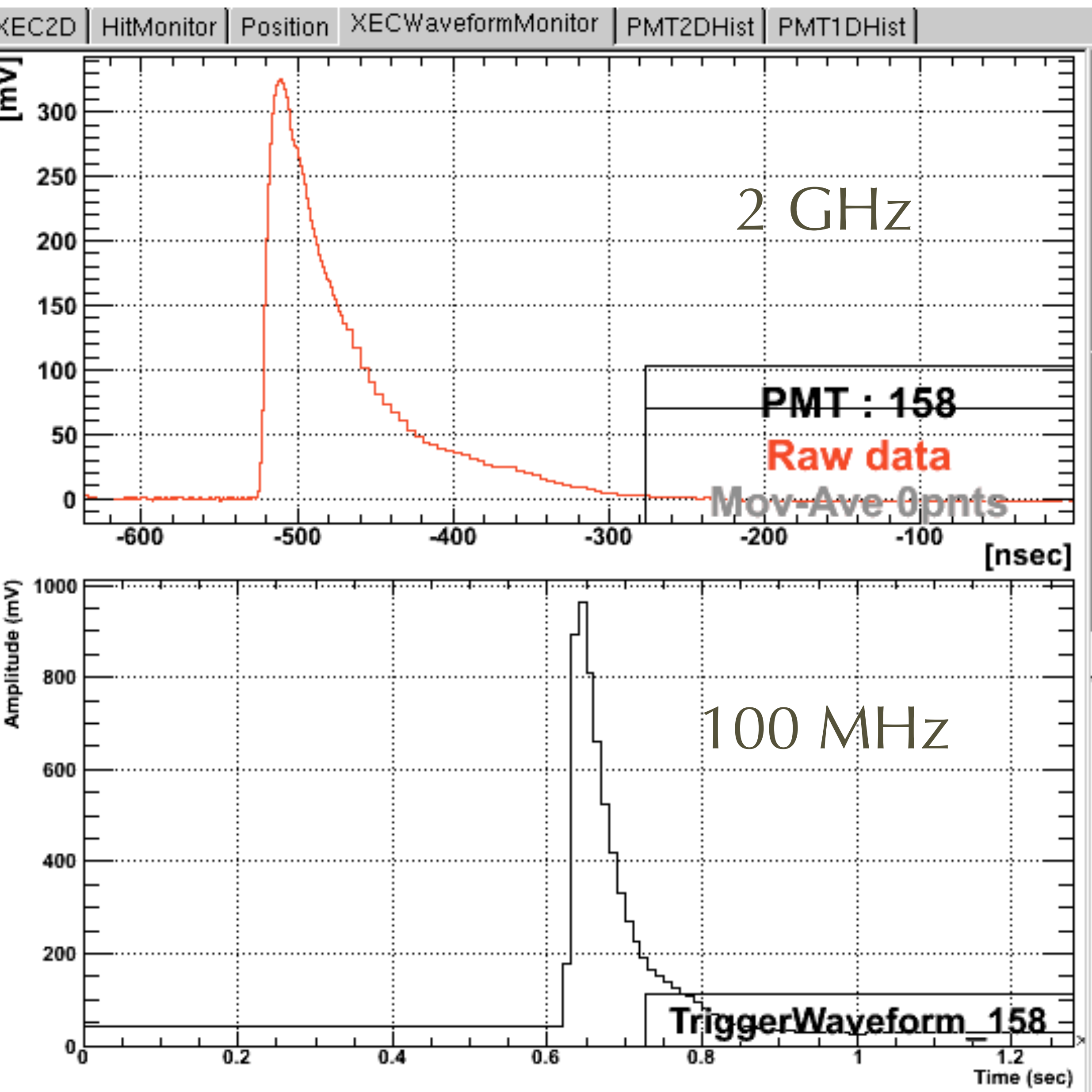


DRS chip (Domino Ring Sampler)

- 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

TRG + DAQ example

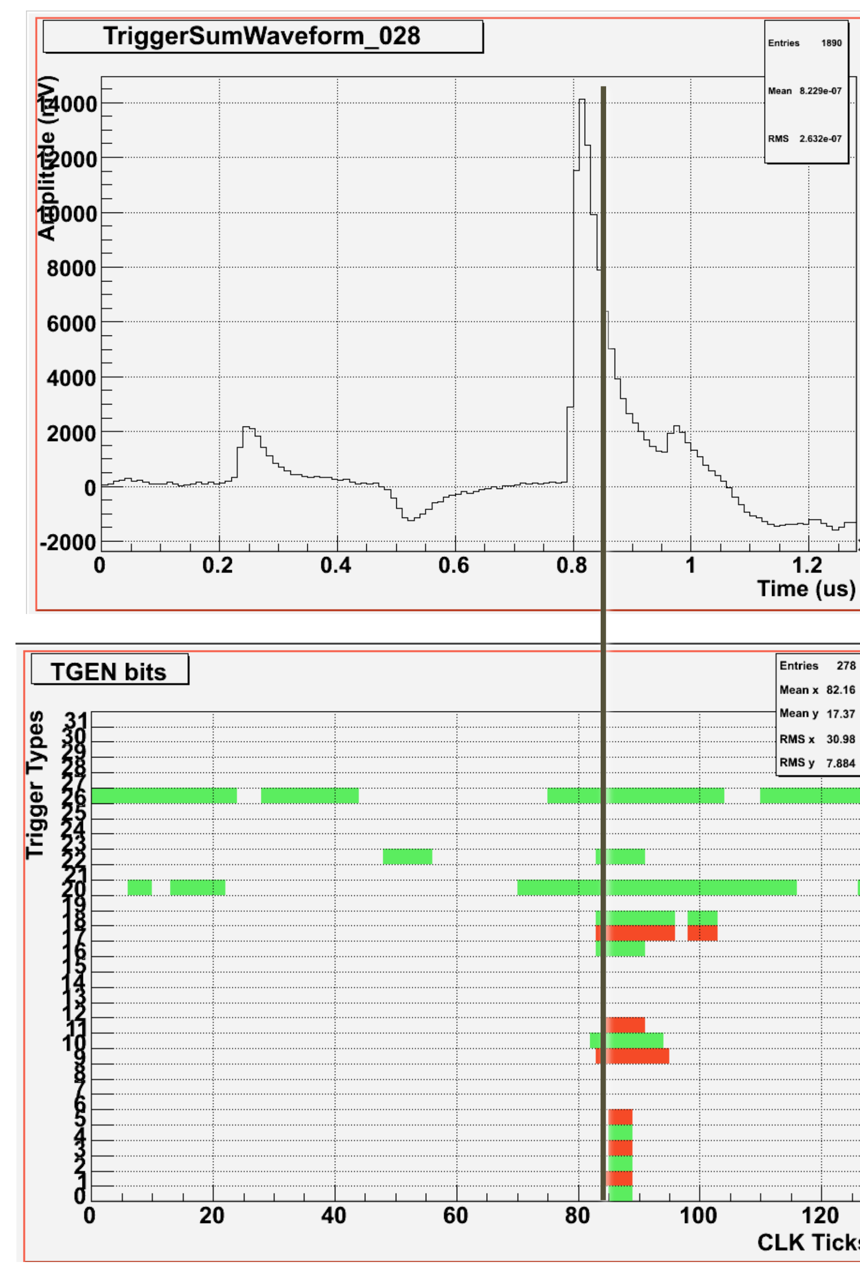
- For (almost) all channels, for each sub-detector we have two waveform digitizers with complementary characteristics



online pedestal subtraction for LXe

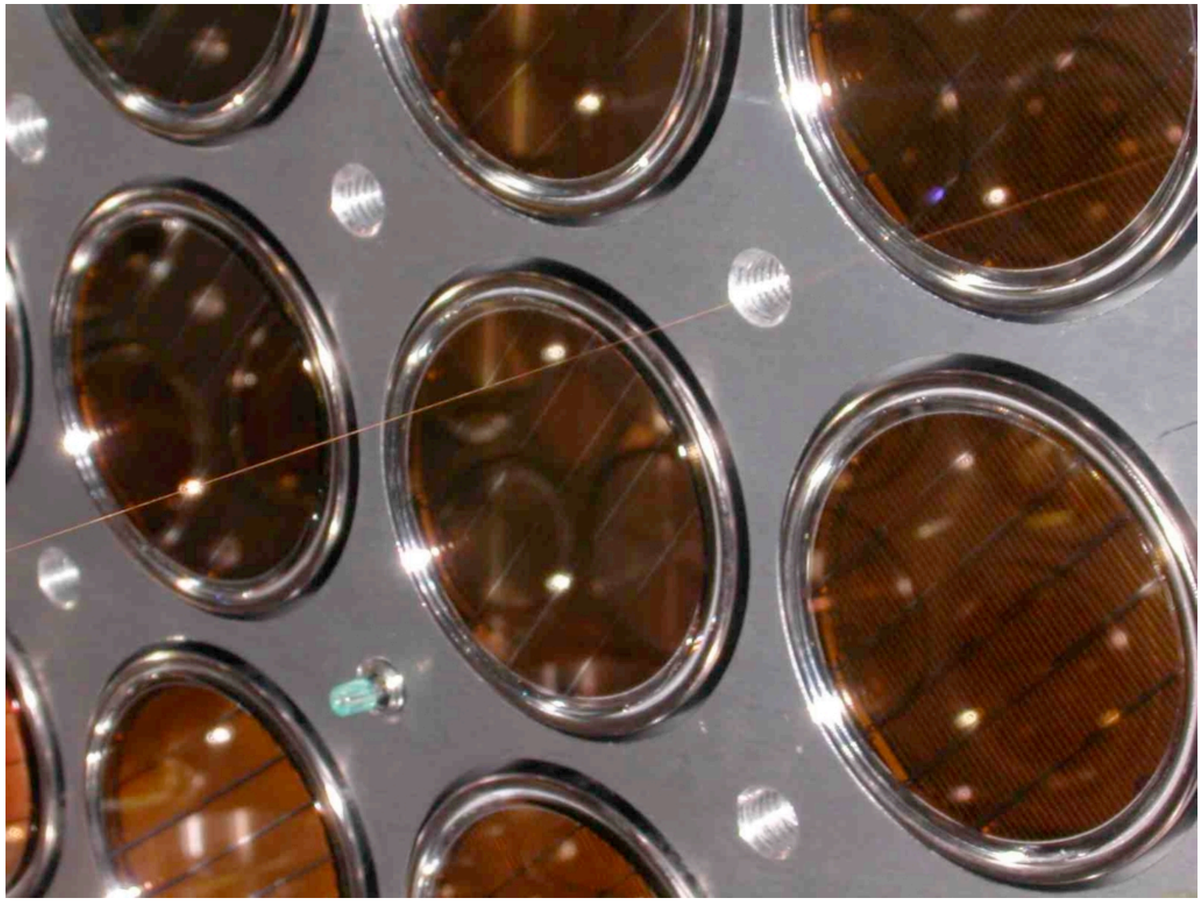
info from all subdetectors is combined

Trigger!



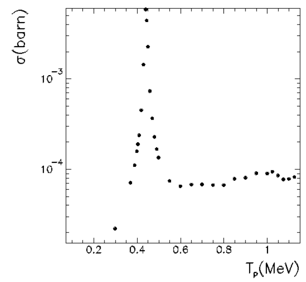
Calibrations

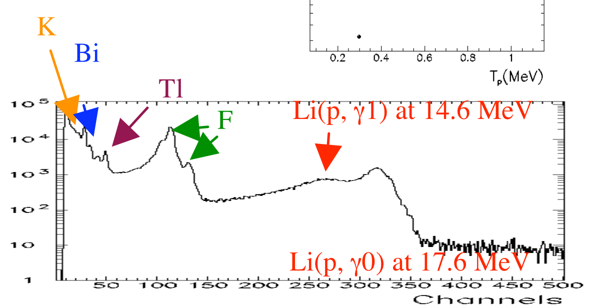
- It is understood that in such a complex detector a lot of parameters must be constantly checked
- We are prepared for redundant calibration and monitoring
- Single detector
  - PMT equalization for LXe and TIC
  - Inter-bar timing (TIC)
  - Energy scale
- Multiple detectors
  - relative timing



Calibrations

Proton Accelerator





Li(p,γ)Be

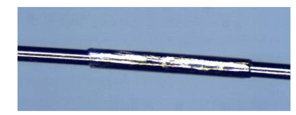
LiF target at COBRA center

17.6MeV γ

~daily calib.

also for initial setup

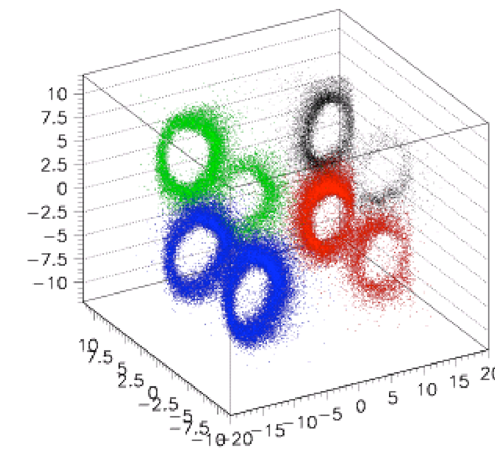
Alpha on wires



PMT QE & Att. L

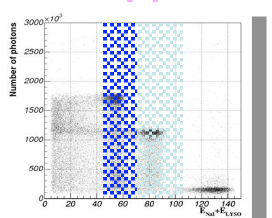
Cold GXe

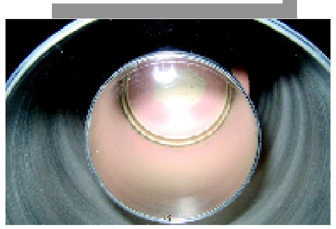
LXe



Xenon Calibration

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



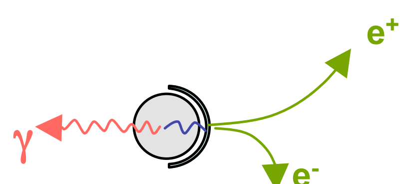


$\pi^- + p \rightarrow \pi^0 + n$

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

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

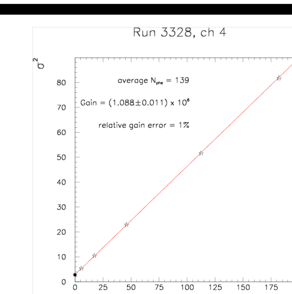
LH_2 target



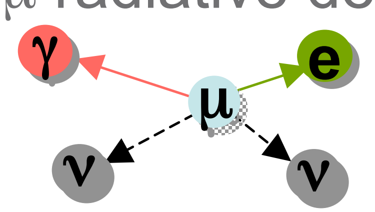
LED

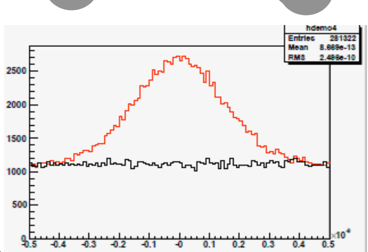
PMT Gain

Higher V with light att.



μ radiative decay





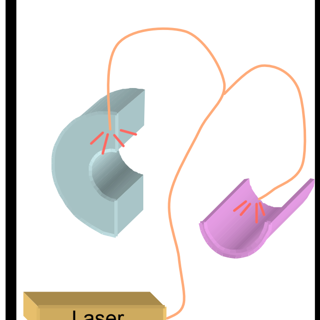
Lower beam intensity < 10^7

Is necessary to reduce pile-ups

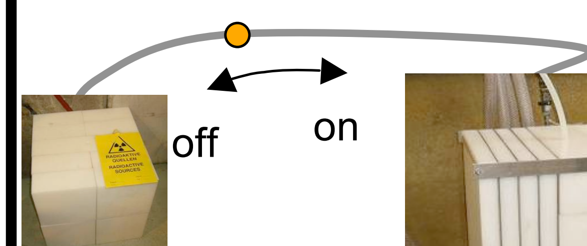
A few days ~ 1 week to get enough statistics

Laser

relative timing calib.

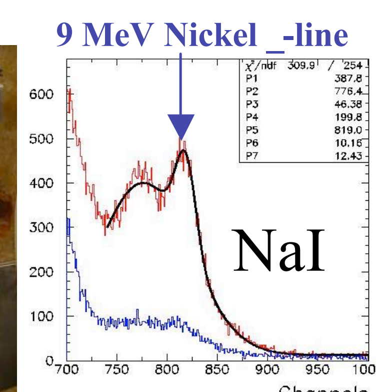


Nickel γ Generator



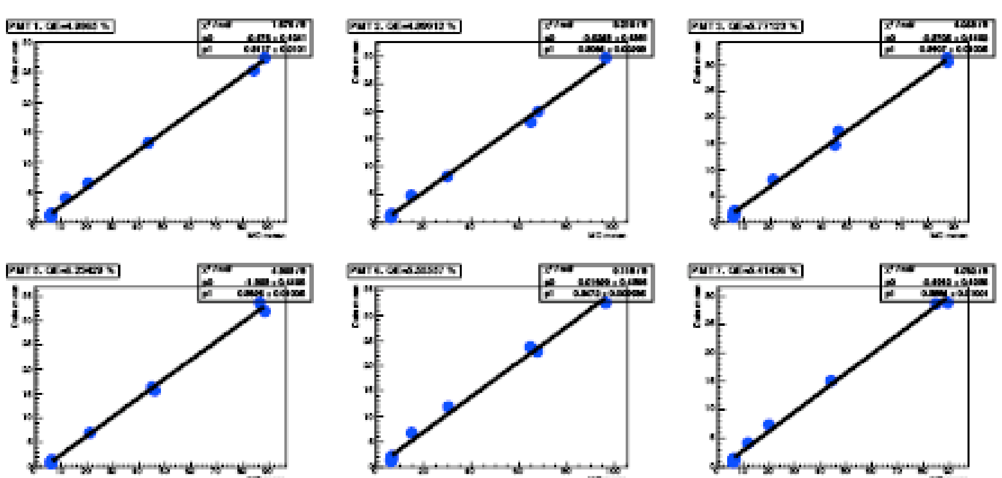
Illuminate Xe from the back

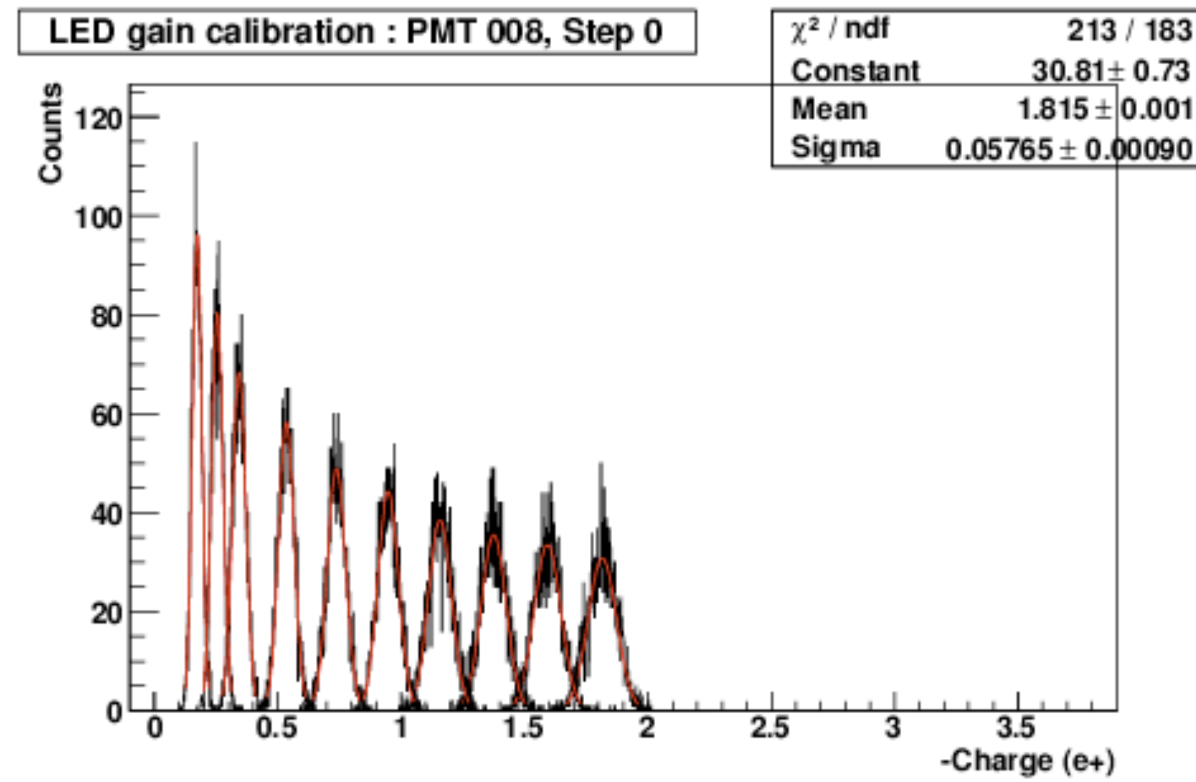
Source (Cf) transferred by comp air → on/off

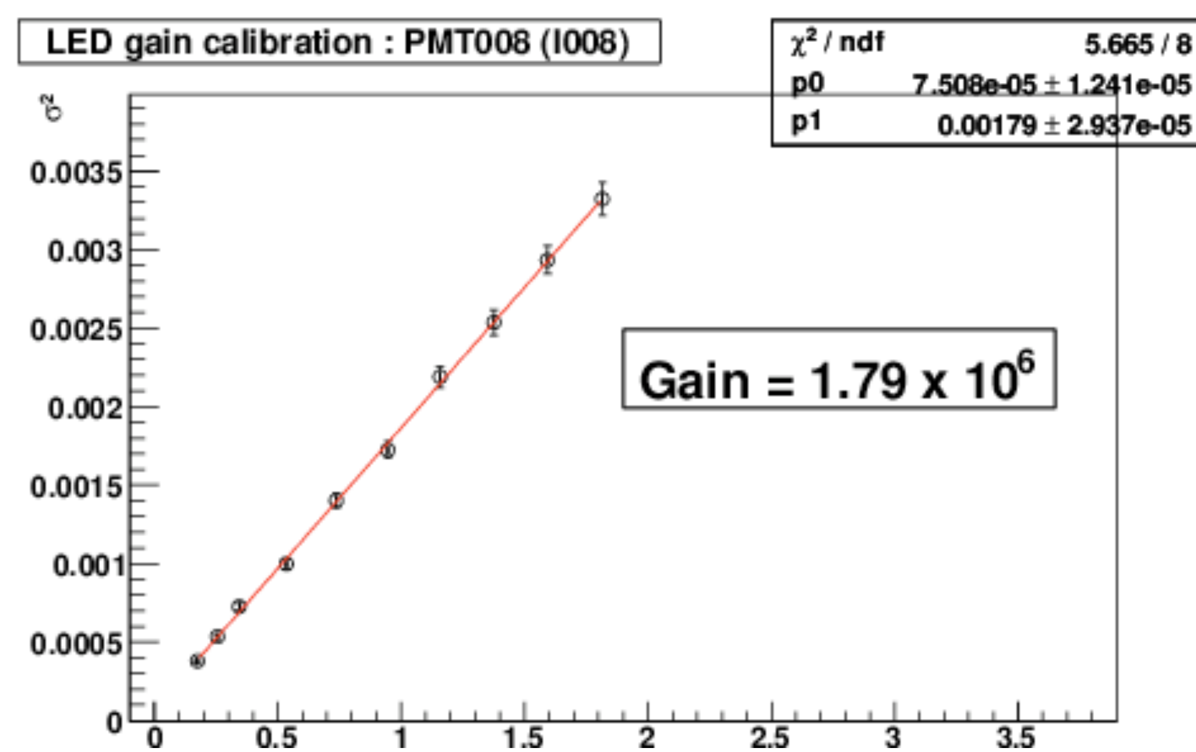


LXe: *g* and QE

- The calorimeter is equipped with blue LEDs and alpha sources
- Measurements of light from LEDs:
  - $\sigma^2 = g\,(q - q_0) + \sigma_0^{\,2}$
  - Absolute knowledge of the GAIN of ALL PMTs within few percents
  - $g = 10^6$ for a typical HV of 800 V
- QEs determined by comparison of alpha source signal in cold gaseous xenon and MC determined at a 10% level

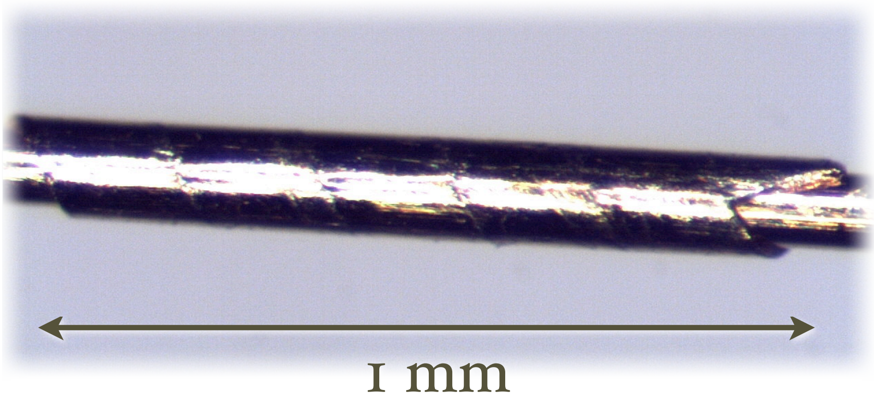


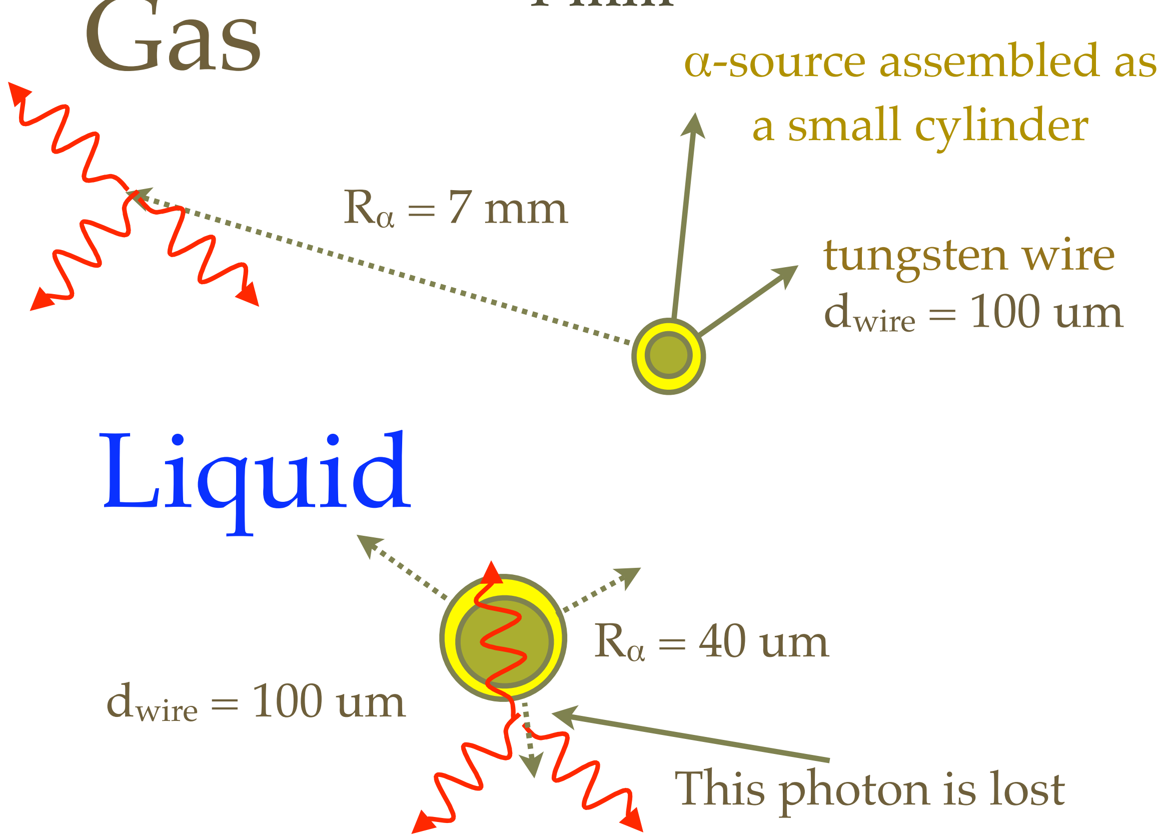


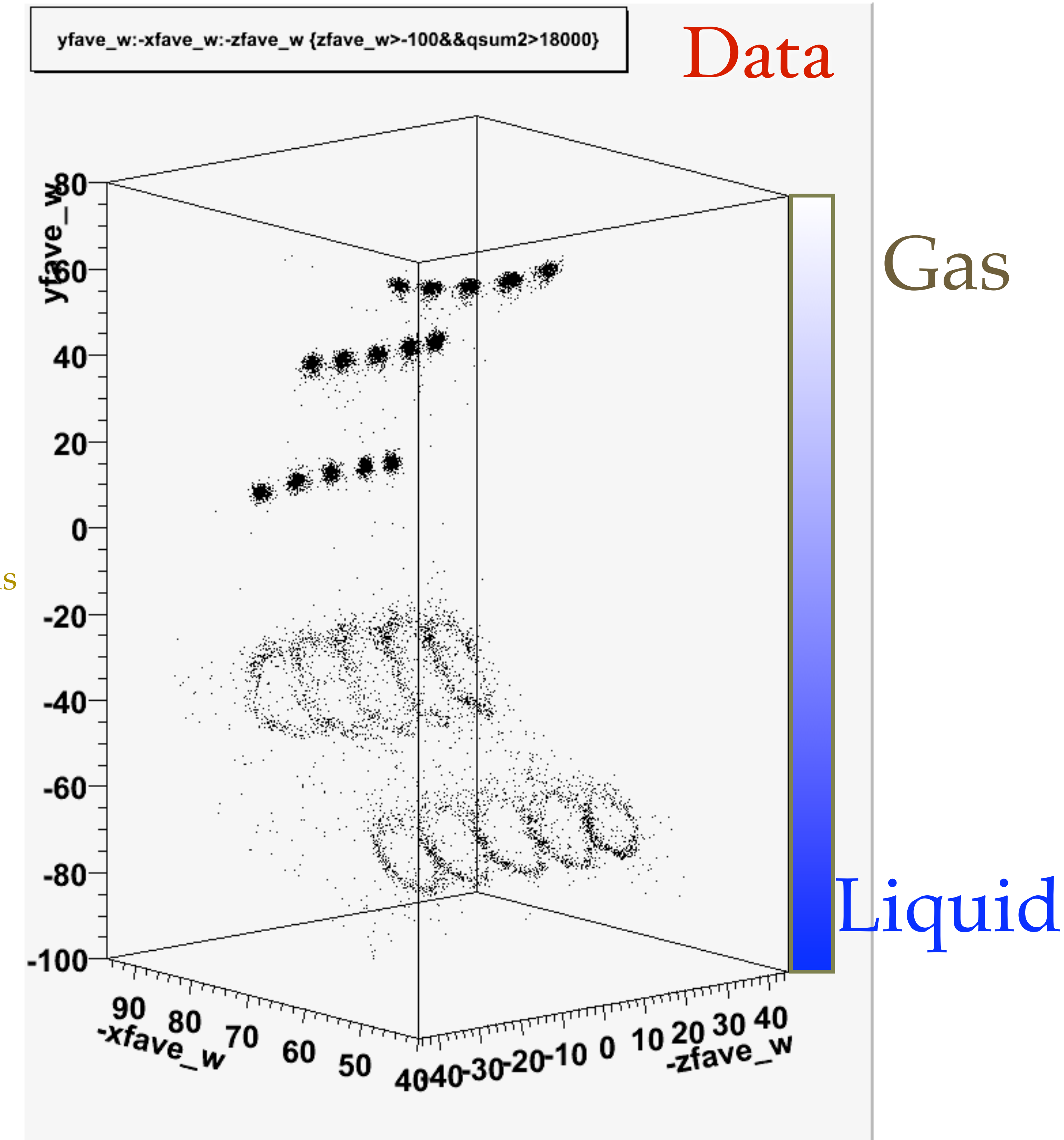


α-sources in Xe

- Specially developed Am sources:
  - 5 dot-sources on thin (100 μm) tungsten wires
  - SORAD Ltd. (Czech Republic)

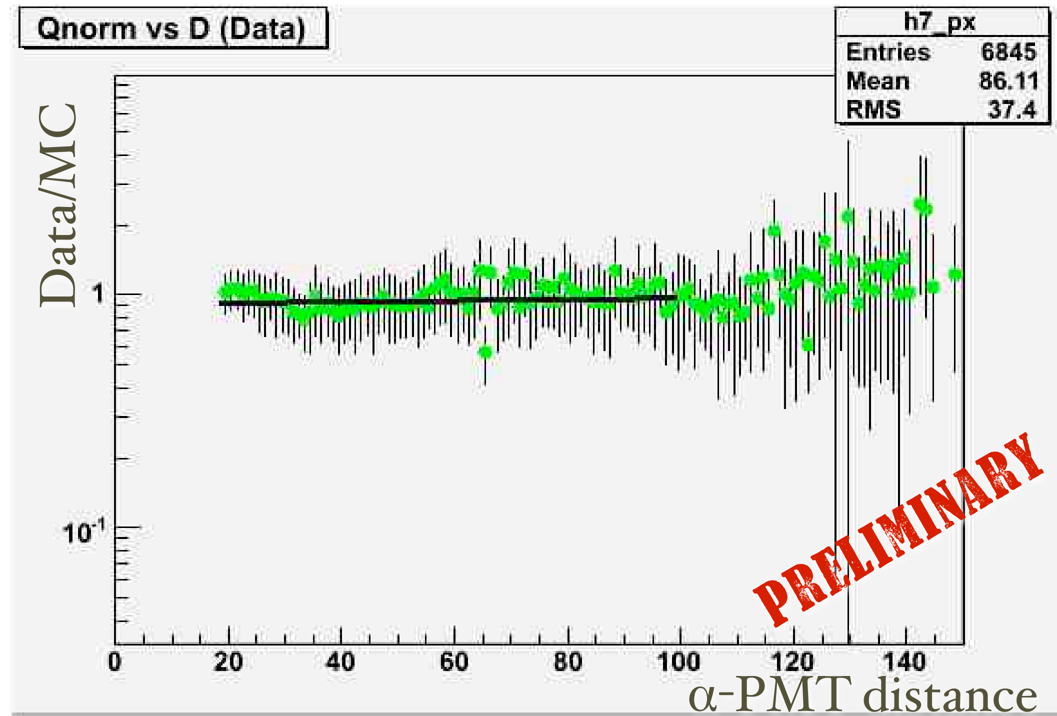






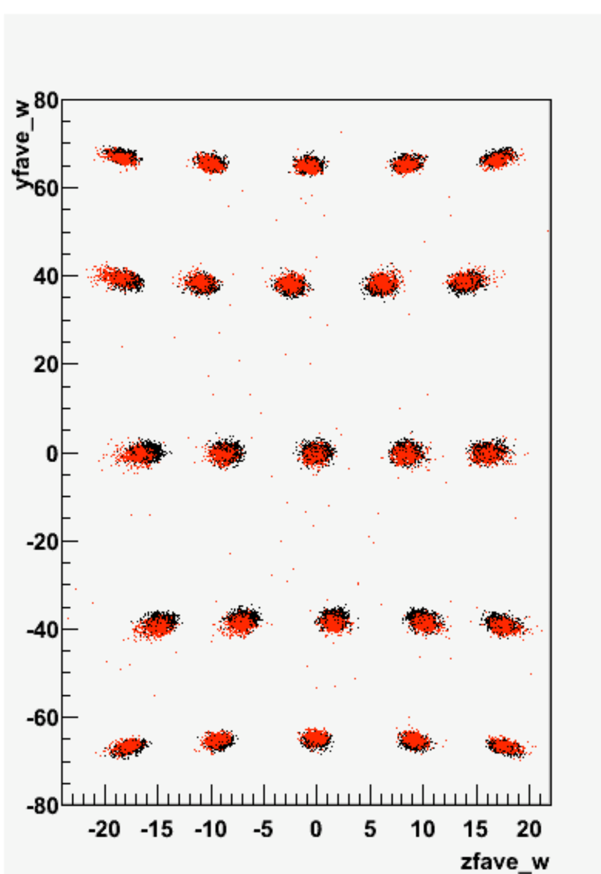
α-sources in Xe

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

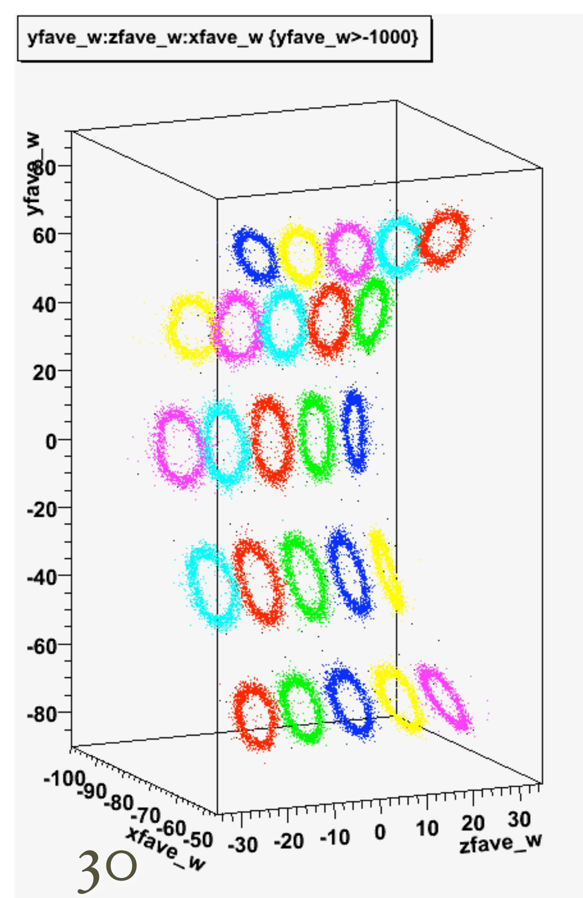


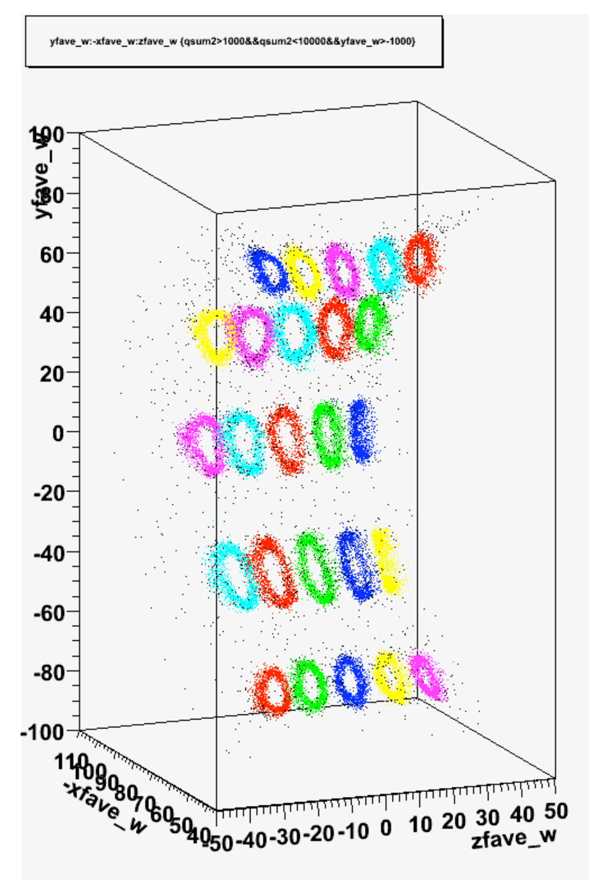
$\lambda_{Abs} > 300$ cm

GXe: MC & data



LXe: MC & data

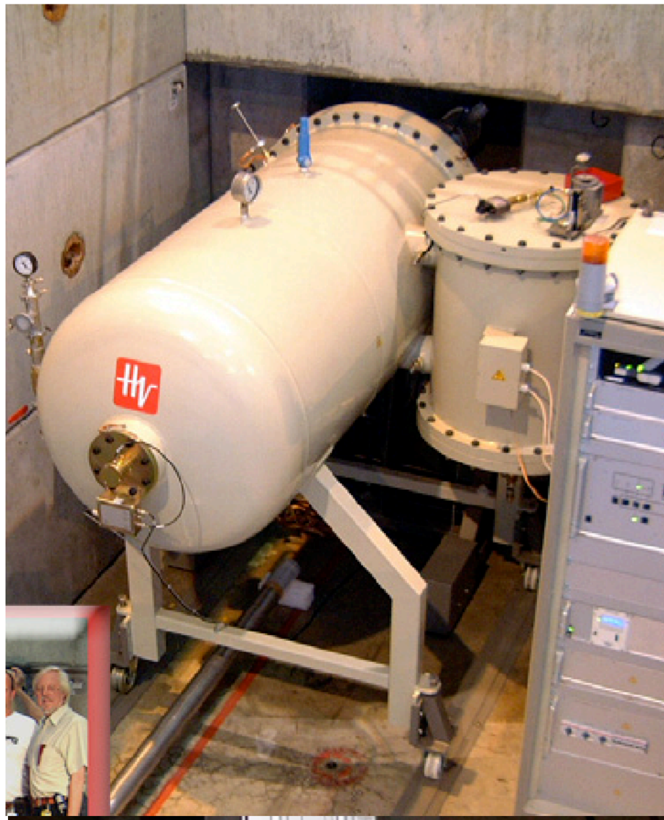




Energy scale calibrations

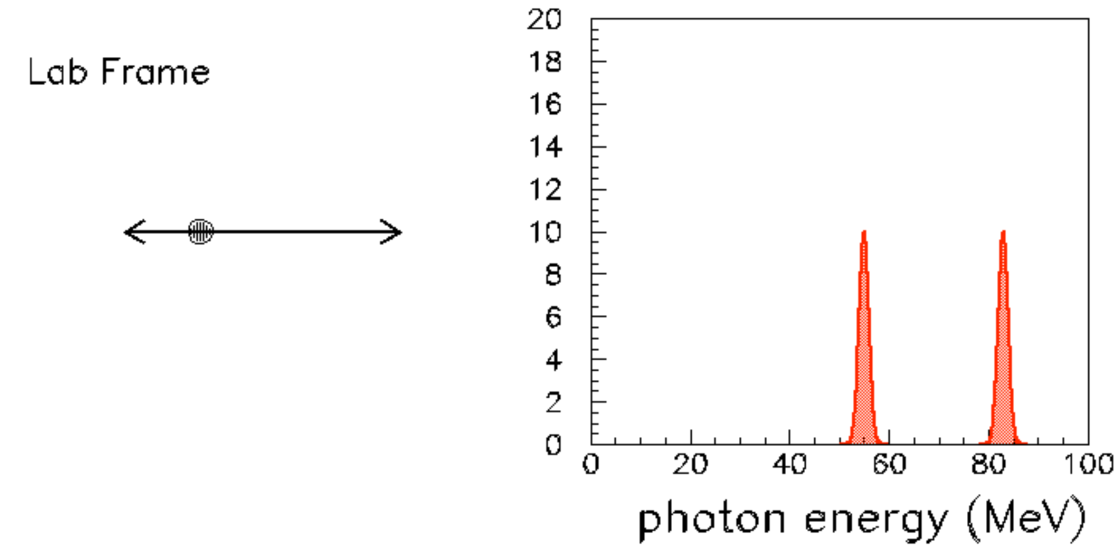
- A reliable result depend on a constant calibration and monitoring of the apparatus
- We are prepared for continuous and redundant checks
  - different energies
  - different frequency

Process		Energy	Frequency
Charge exchange	$\pi^- p \rightarrow \pi^0 n$ $\pi^0 \rightarrow \gamma\gamma$	55, 83, 129 MeV	year - month
Proton accelerator	${}^7\mathrm{Li}(p, \gamma_{17.6})^8\mathrm{Be}$	14.8, 17.6 MeV	week
Nuclear reaction	${}^{58}\mathrm{Ni}(n, \gamma_9)^{59}\mathrm{Ni}$	9 MeV	daily
Radioactive source	${}^{60}\mathrm{Co}, \quad \mathrm{AmBe}$	1.1 -4.4 MeV	daily

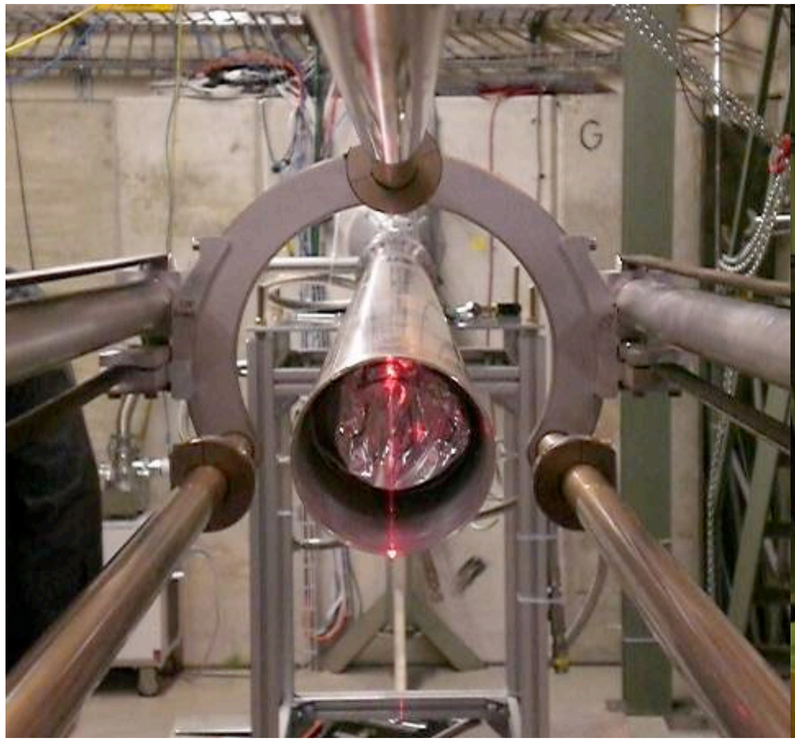


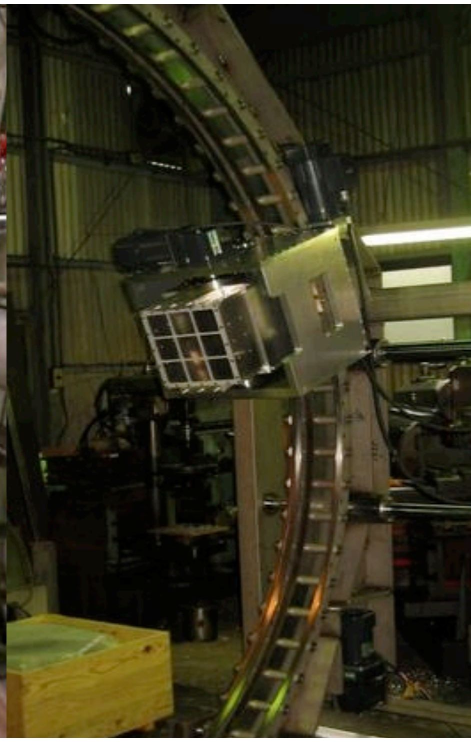
CEX measurement

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



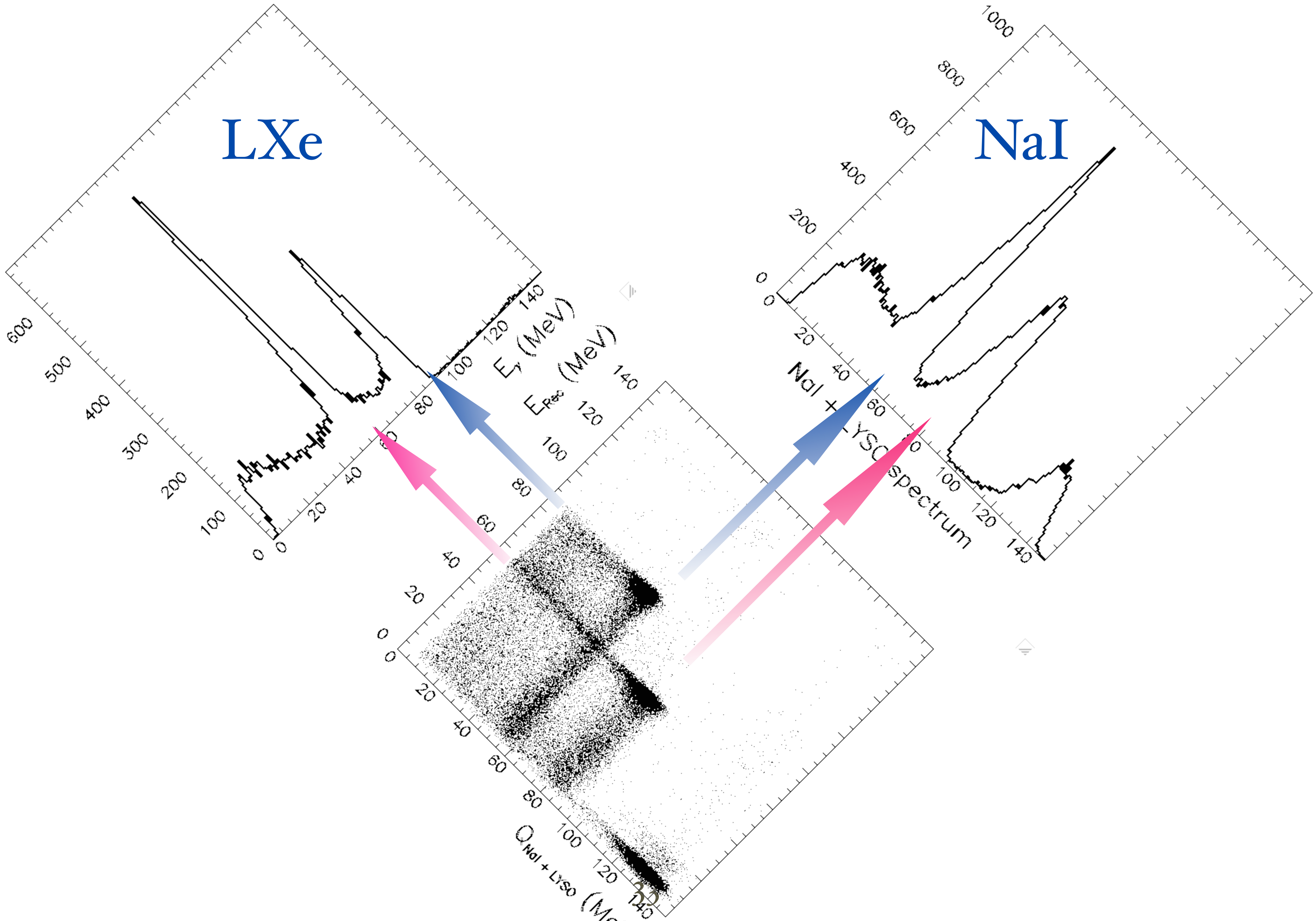
- The monochromatic spectrum in the pi-zero rest frame becomes flat in the Lab
- In the back-to-back configuration the energies are 55 MeV and 83 MeV



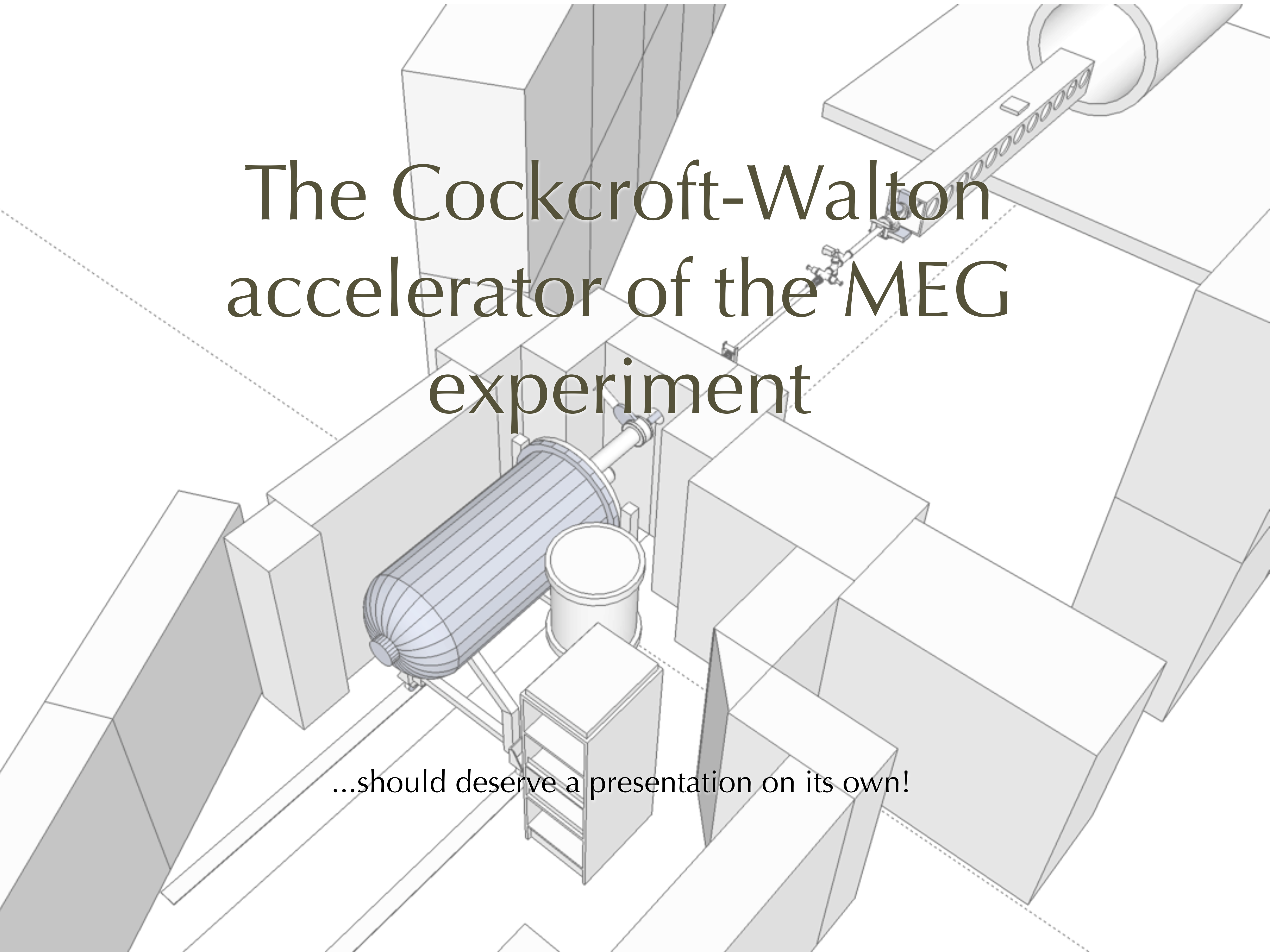


- Even a modest collimation guarantees a sufficient monochromaticity
- Liquid hydrogen target to maximize photon flux
- An "opposite side detector" is needed (NaI array)

- 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)



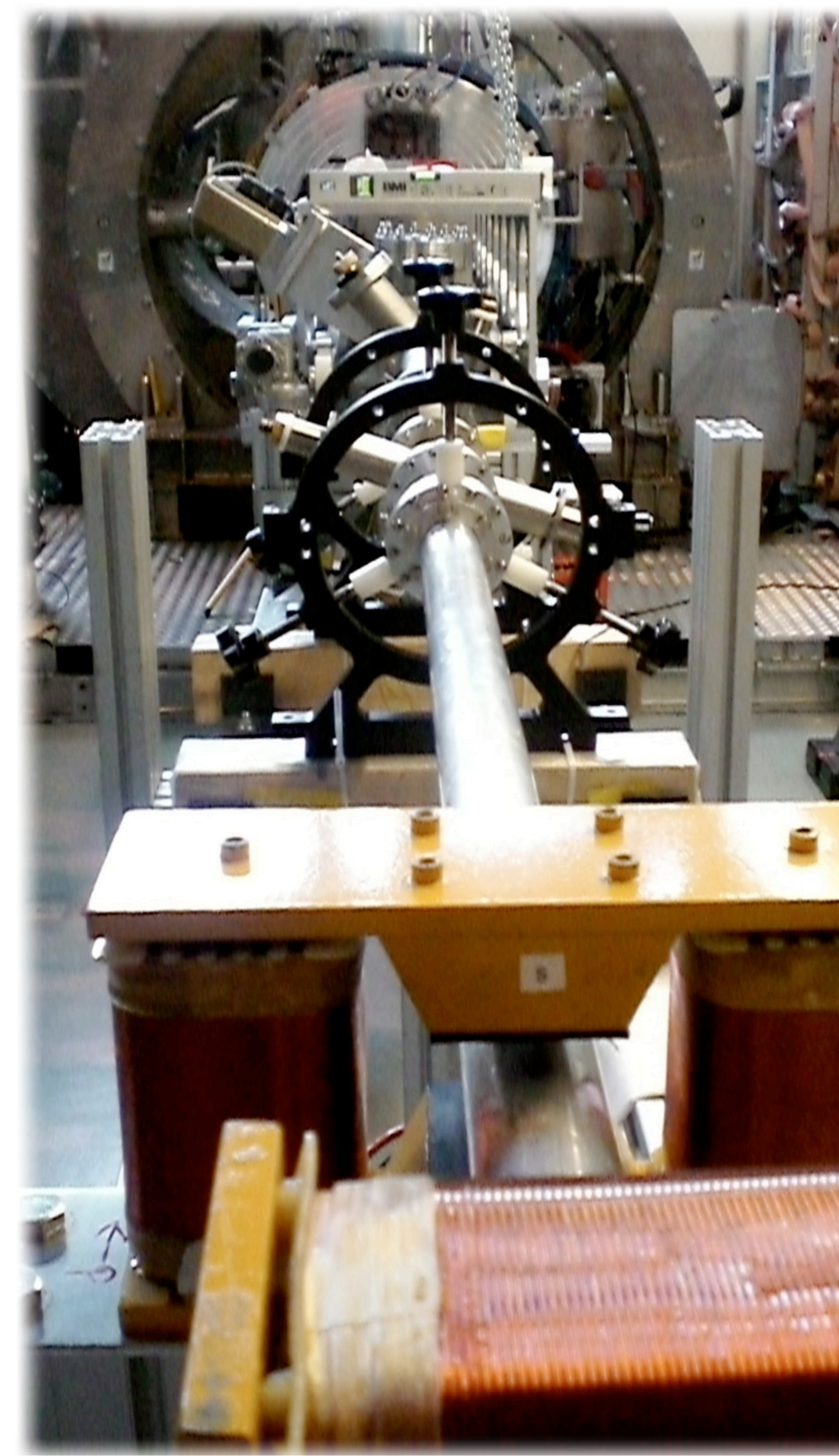
The Cockcroft-Walton accelerator of the MEG experiment



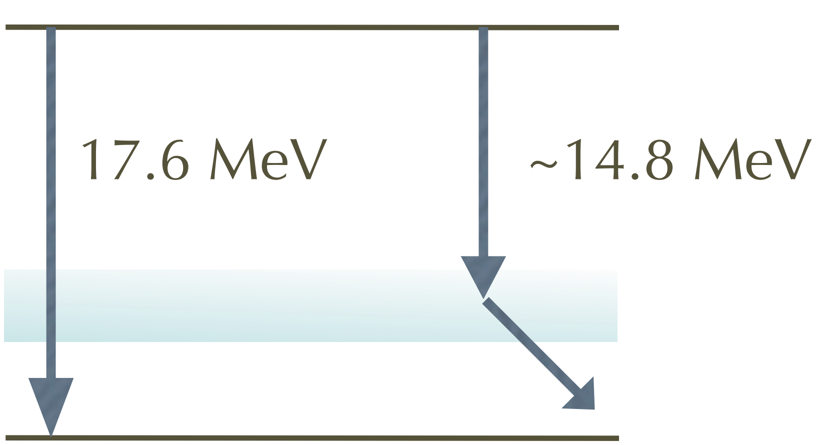
...should deserve a presentation on its own!

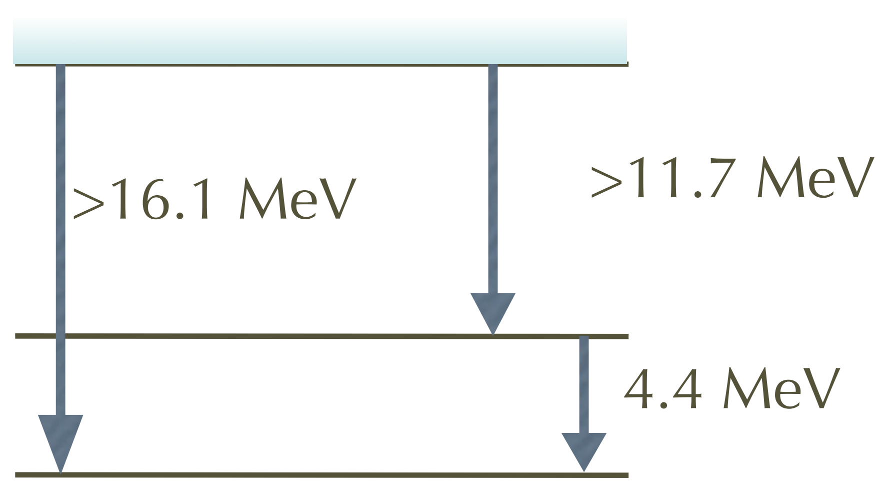
Intro & reactions

- The Cockcroft-Walton is an extremely powerful tool, installed for monitoring and calibrating *all* the MEG experiment
- Protons of up to 1 MeV on Li or B
  - Li: high rate, higher energy photon
  - B: two (lower energy) time-coincident photons



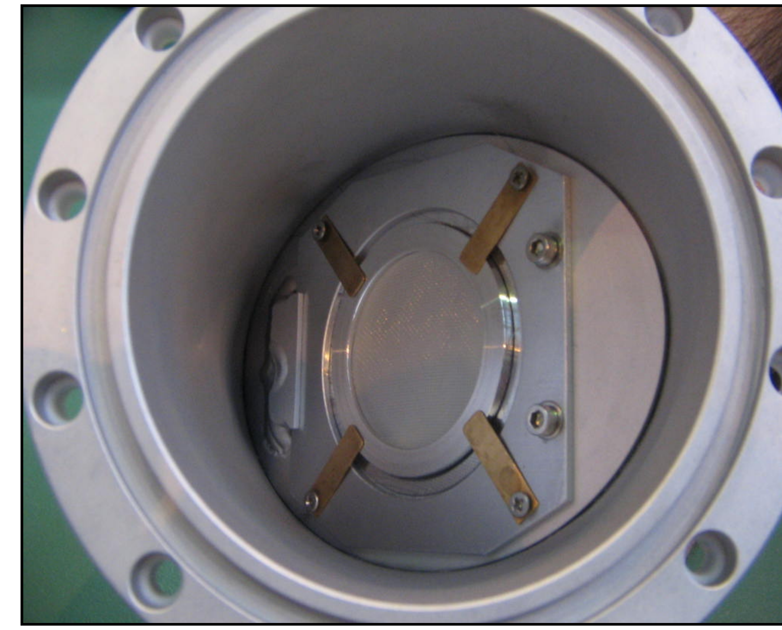
Reaction	Peak energy	σ peak	γ-lines
Li(p,γ)Be	440 keV	5 mb	(17.6, 14.6) MeV
B(p,γ)C	163 keV	$2\ 10^{-1}$ mb	(4.4, 11.7, 16.1) MeV

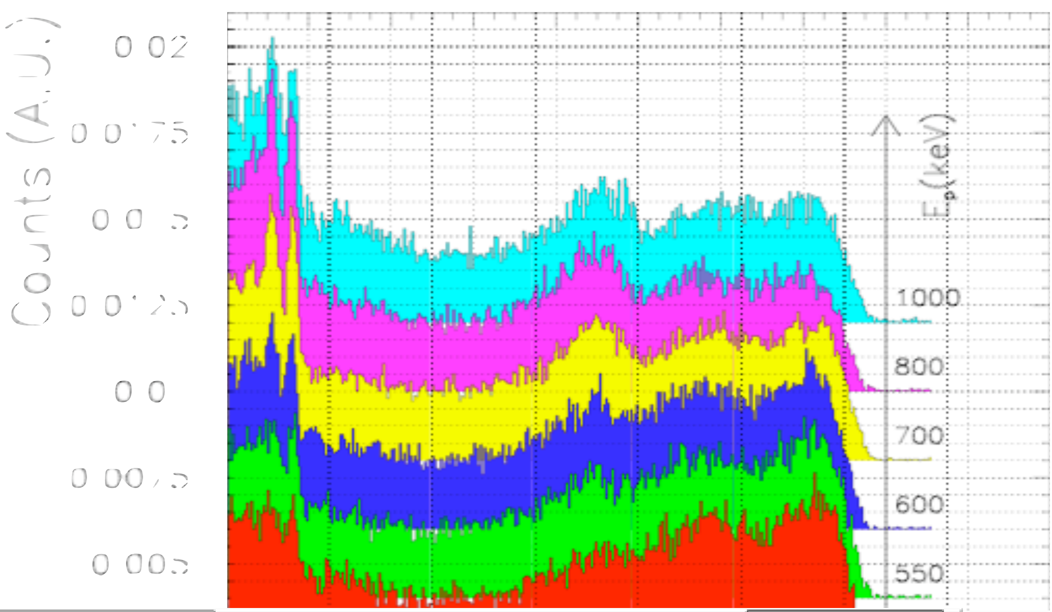




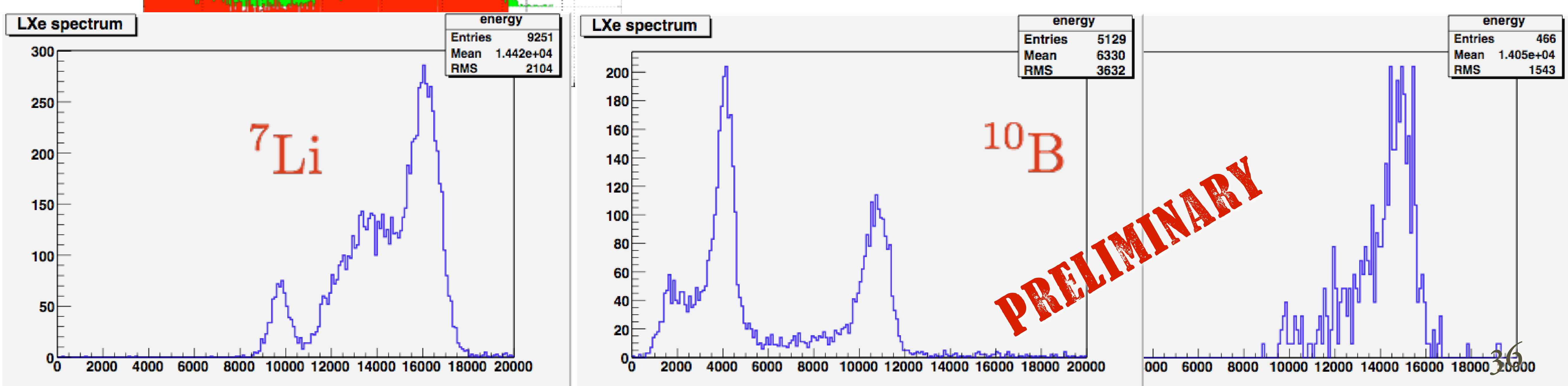
CW - daily calibration

- This calibration is performed every other day
  - Muon target moves away and a crystal target is inserted
- Hybrid target ($Li_2B_4O_7$)
  - Possibility to use the same target and select the line by changing proton energy





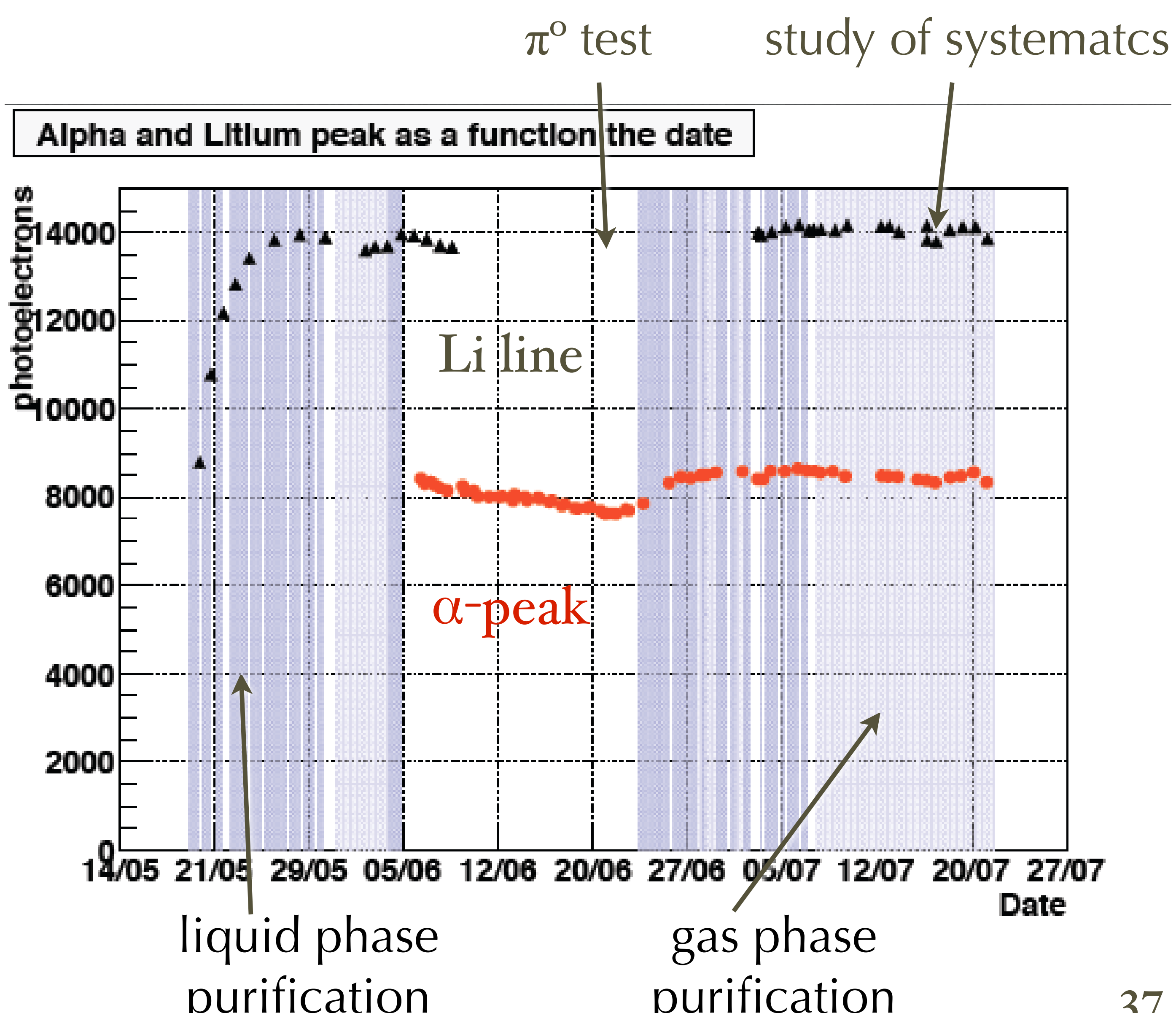
When p energy increases B lines appear

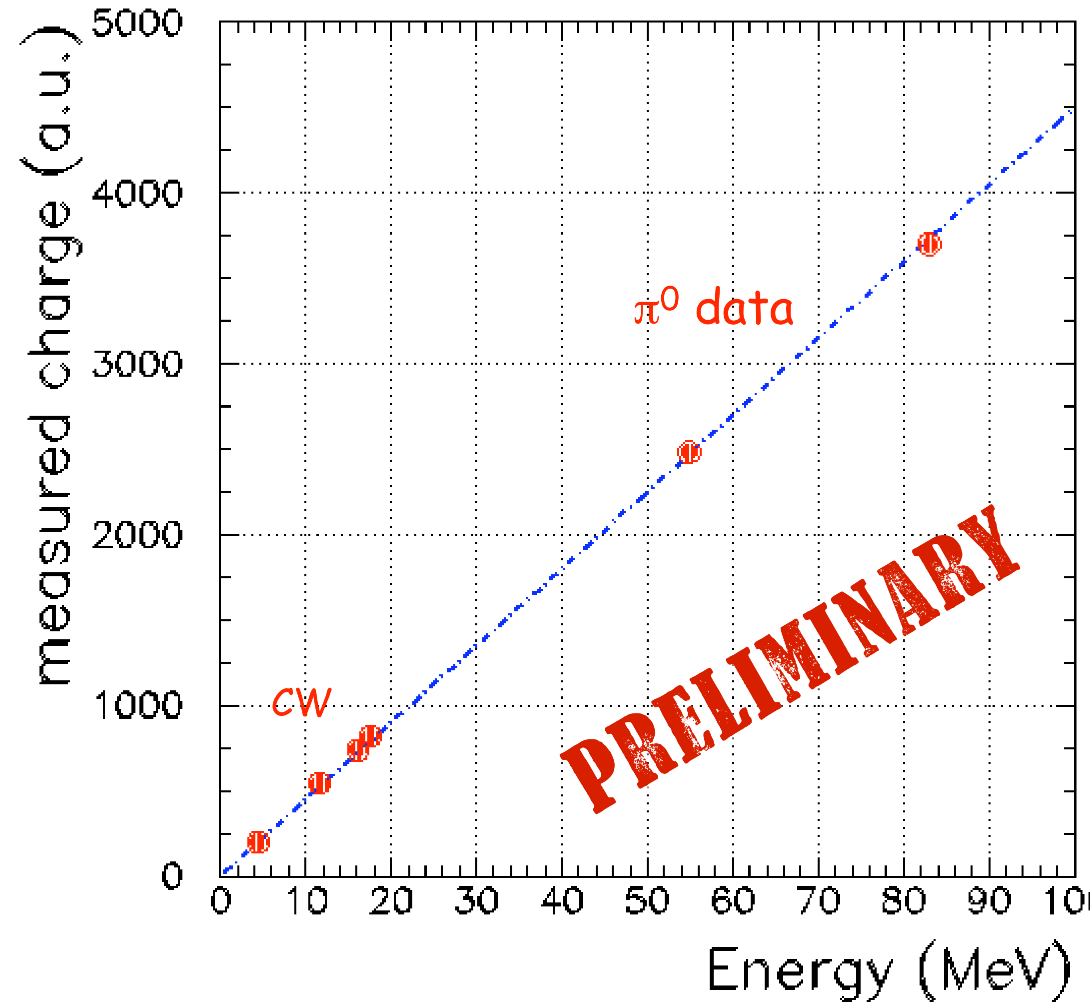


Daily monitoring

- Monitor Xe light yield
  - liquid/gas purification studies
  - stability studies

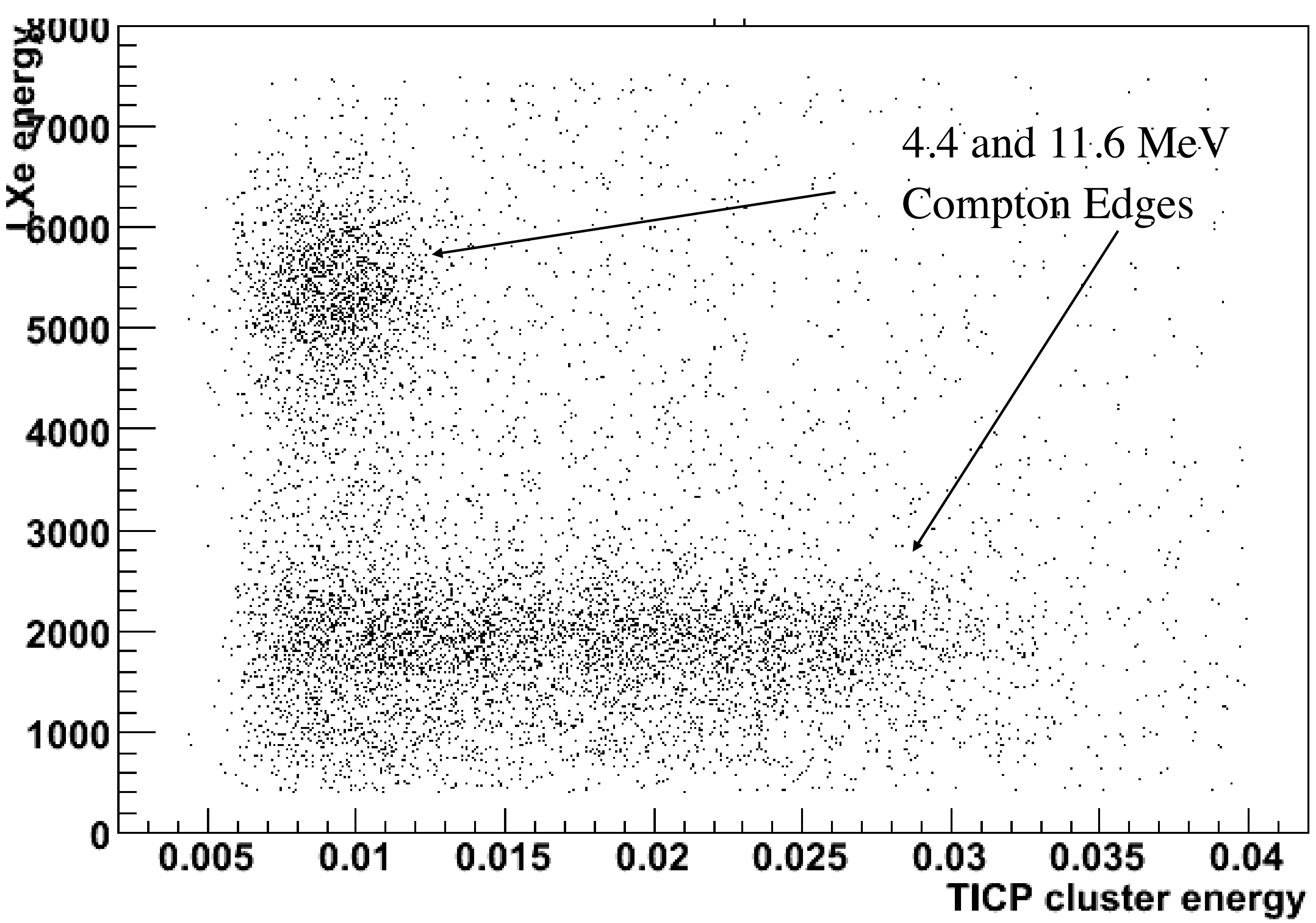
< 1% knowledge of l.y. and energy scale

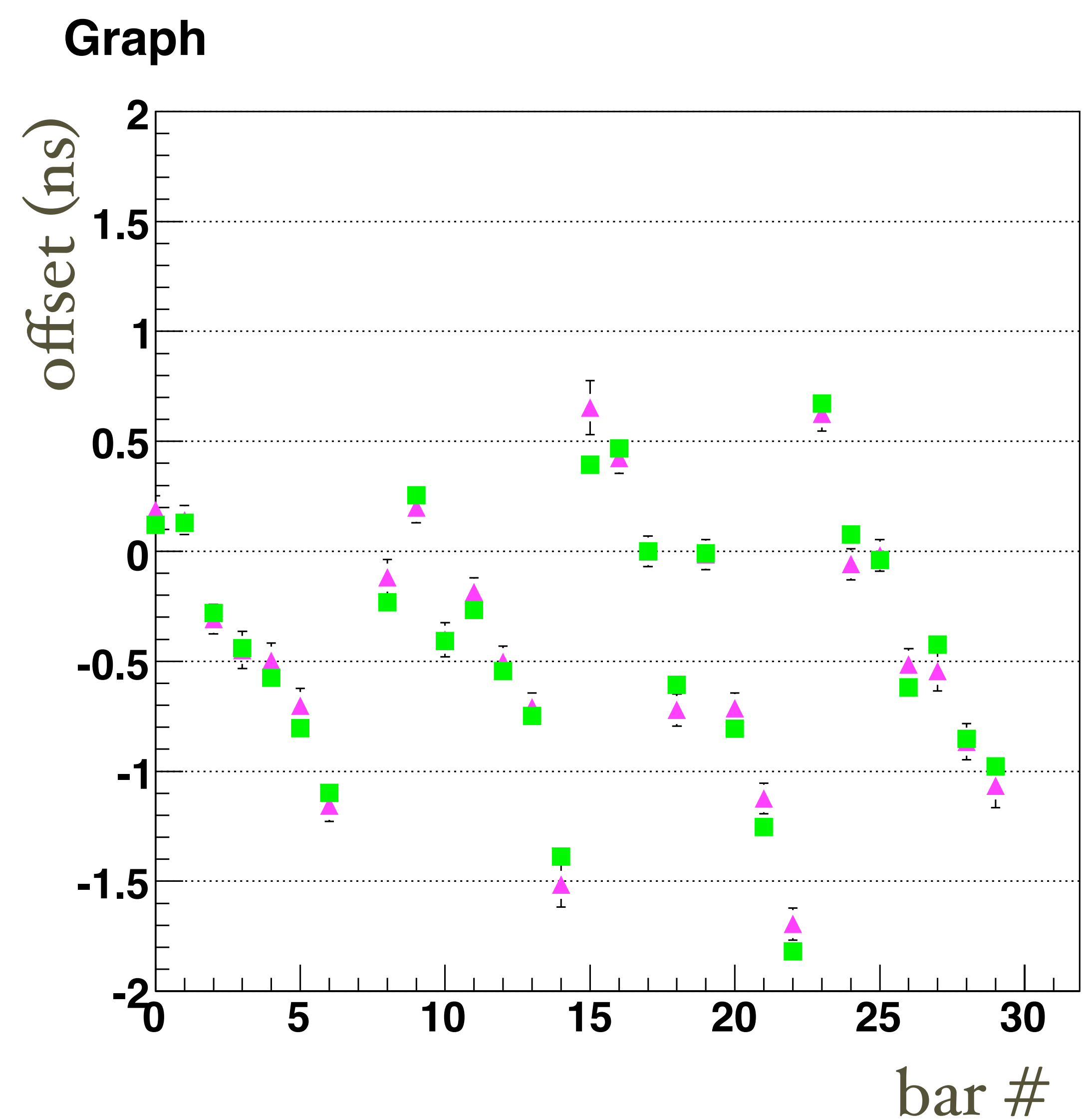




CW and timing counter

- The simultaneous emission of two photons in the Boron reaction is used to
  - determine relative timing between Xe and TIC
  - Inter-calibrate TIC bar (LASER)





2008: First run of the experiment

(... after a short engineering run in 2007)

Time shedule

Winter - Spring

- detector dismantling
- improvement (after run 2007)
- re – installation

Spring - Summer

- LXe purification
- CW and π^0 calibration
- beam line setup

September – December

- MEG run
- short π^0 calibration

Running conditions

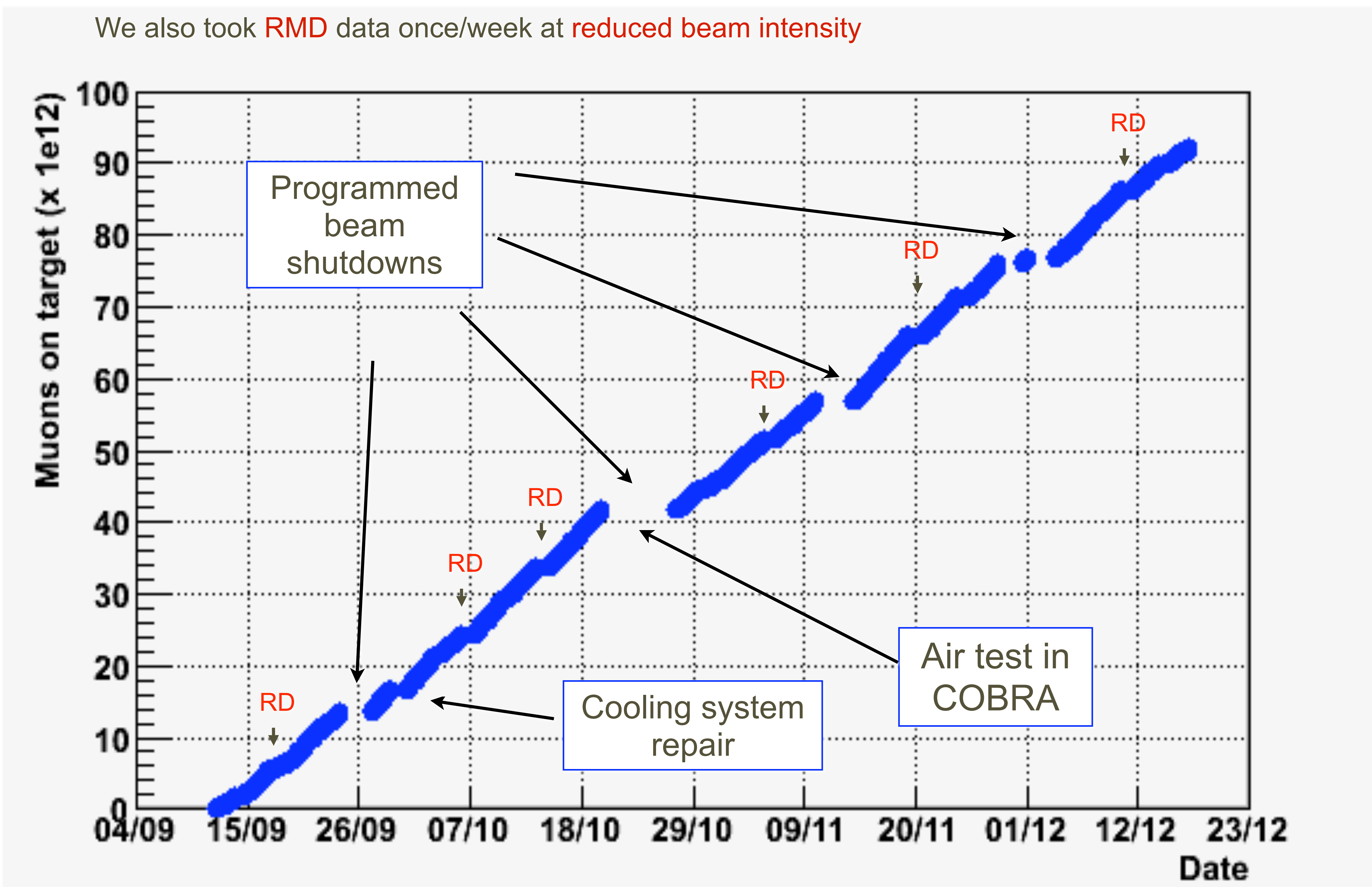
MEG run period

– Live time ~50% of total time
– Total time ~ 7×10^6 s
– μ stop rate: 3×10^7 μ/s
– Trigger rate 6.5 ev/s ; 9 MB/s

The missing 50% is composed of:

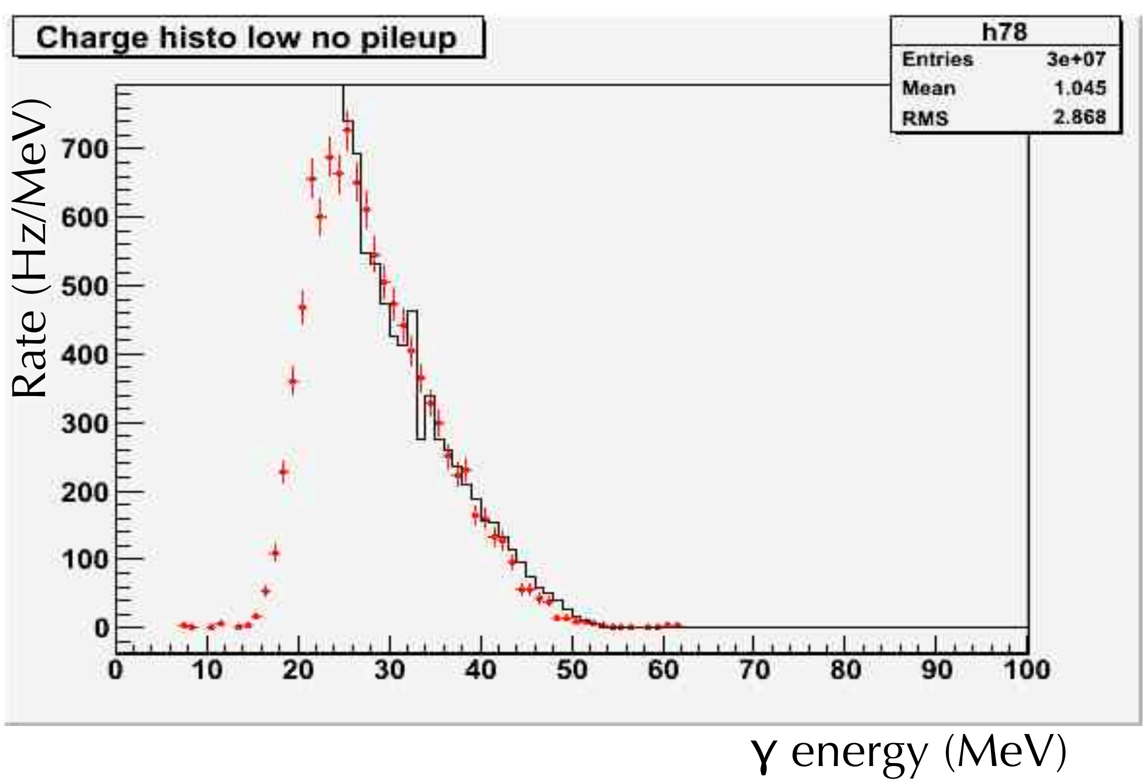
– 17% DAQ dead time
– 14% programmed beam shutdowns
– 7% low intensity Radiative muon decay runs (RMD)
– 11% calibrations
– 2% unforeseen beam stops

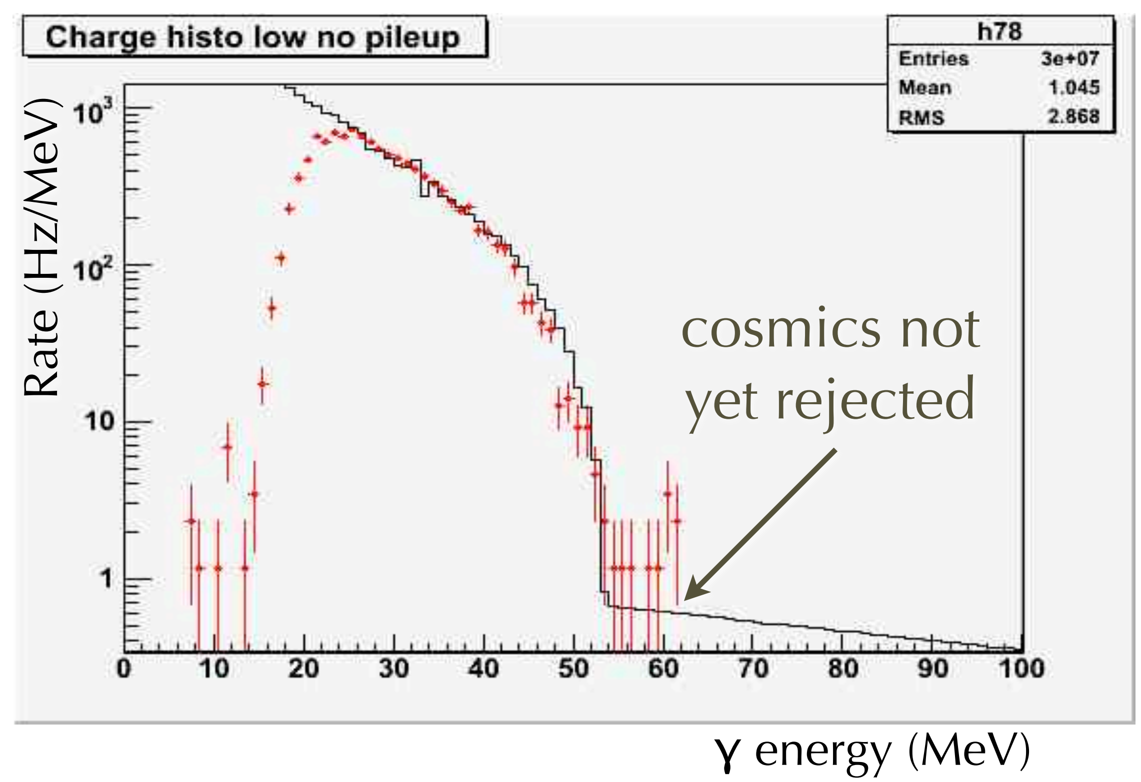
Muons on target



LXe Energy spectrum

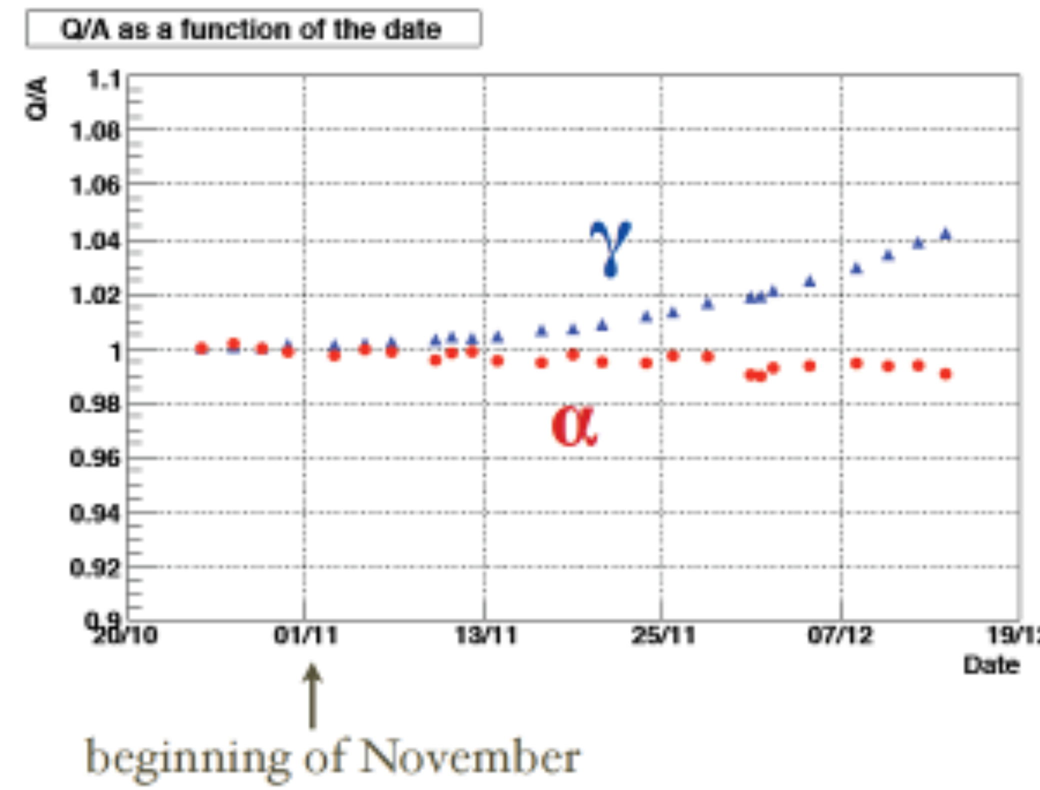
- From the LXe single event trigger we do not observe any unforeseen background in the μ-beam.
- Both the spectrum shape and the absolute rate are correctly reproduced
  - 3 x 10^7 μ^+/s stopping rate
- the γ detection efficiency is understood
- cosmic muons and event pile-up are under control

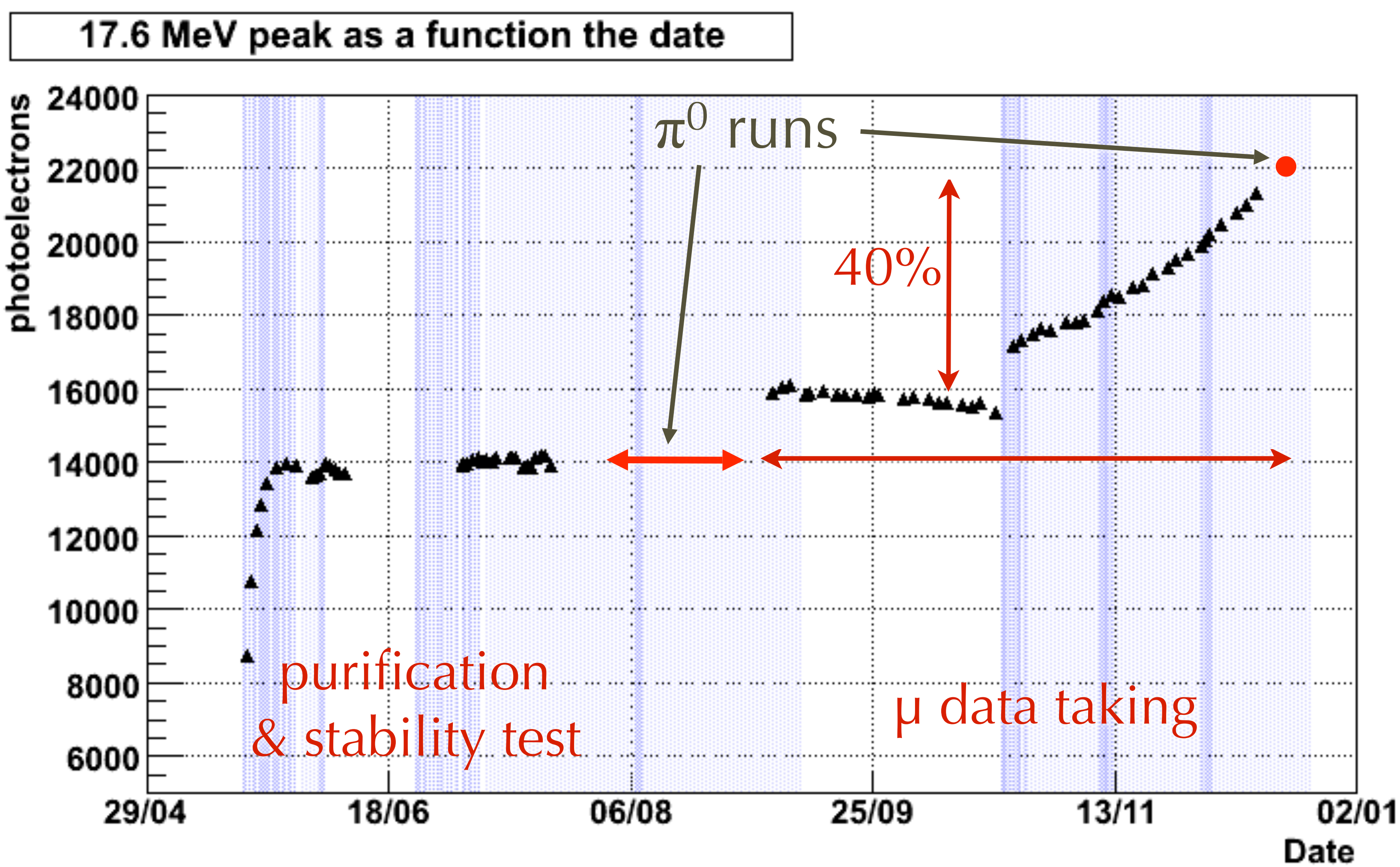




Xe light yield

- Large light yield increase (40%) during MEG run
- Approaching the expected 27000 ph.el.
- LY change monitored with the calibration system
- Different time constants for α and γ scintillation pulses (as it should be)



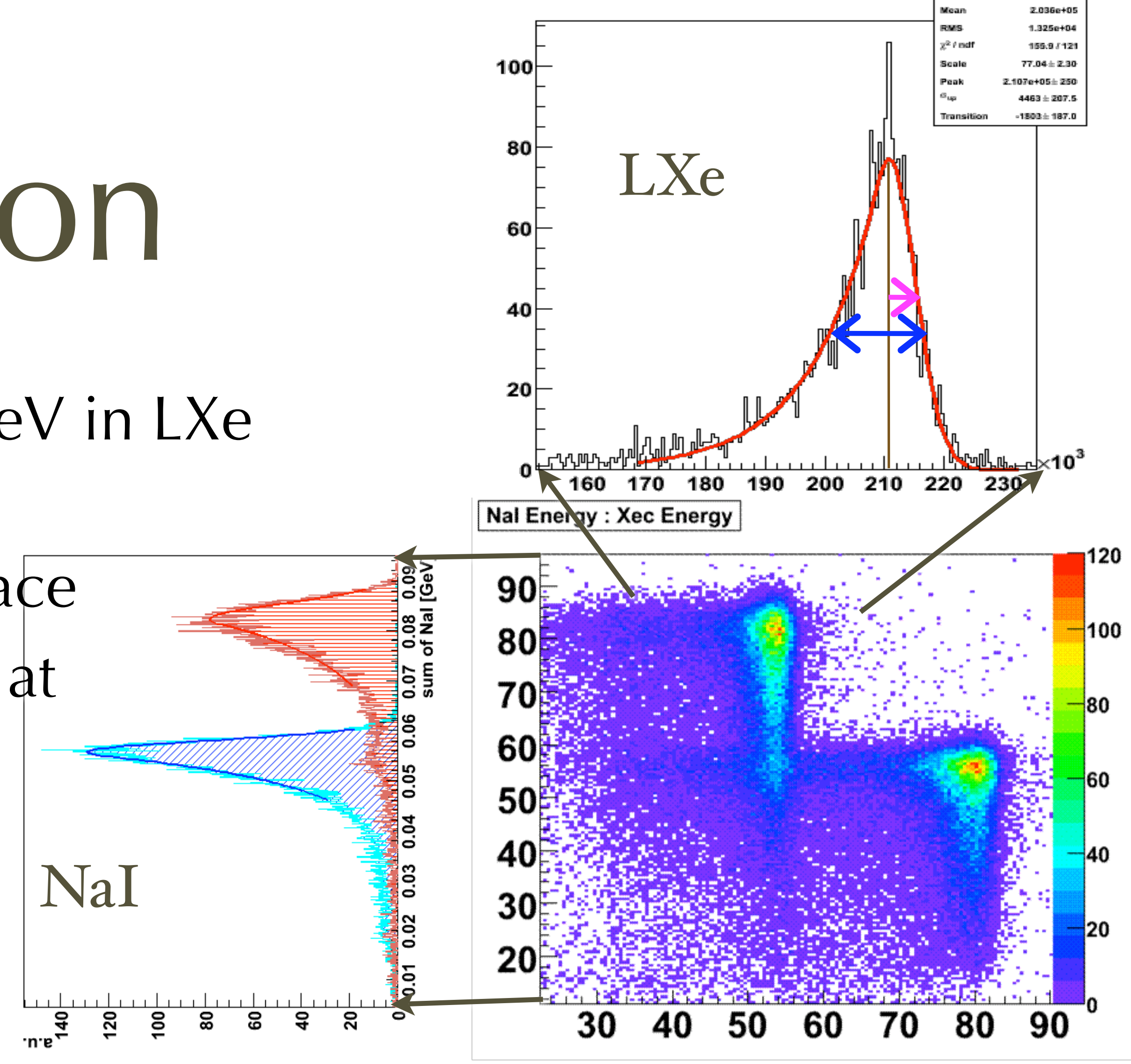


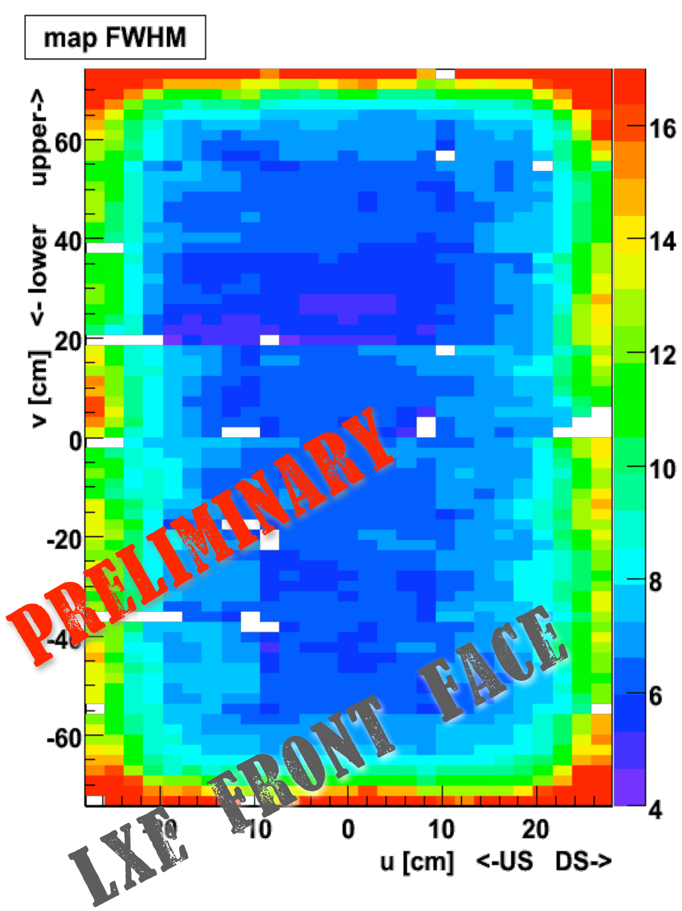
= liq.phase purif.

= gas purif.

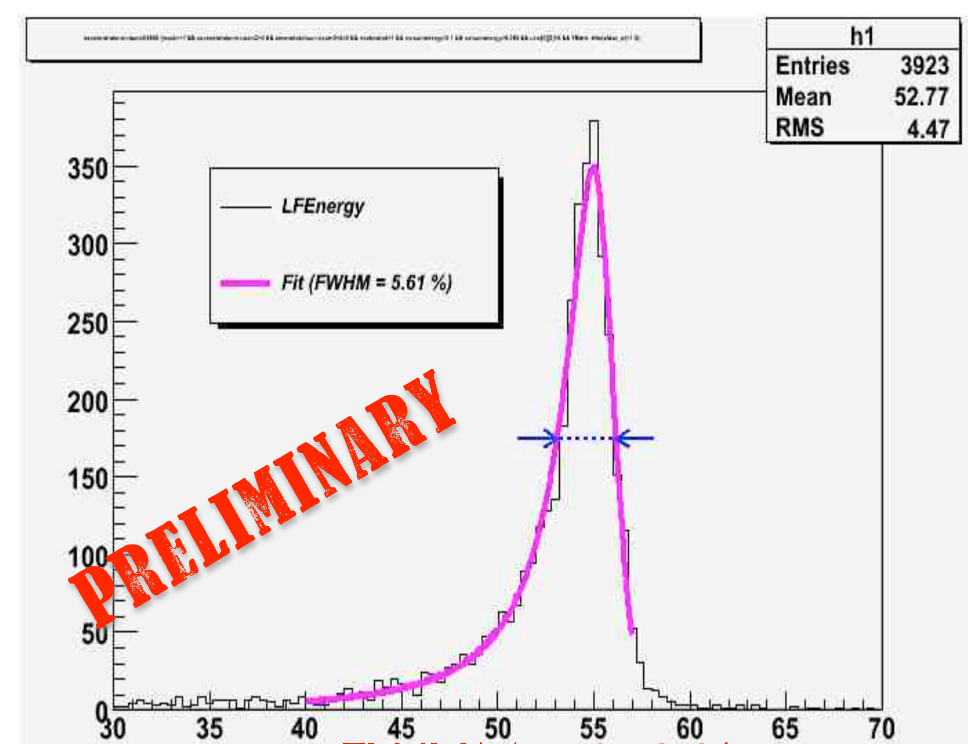
Energy resolution

- 180° coincidence selects 55 MeV and 83 MeV in LXe and NaI
- Resolution evaluated on all calorimeter surface
- Not yet as expected but we are improving it at analysis level
- Background level quite different from $\mu \to e\gamma$
  - pile-up





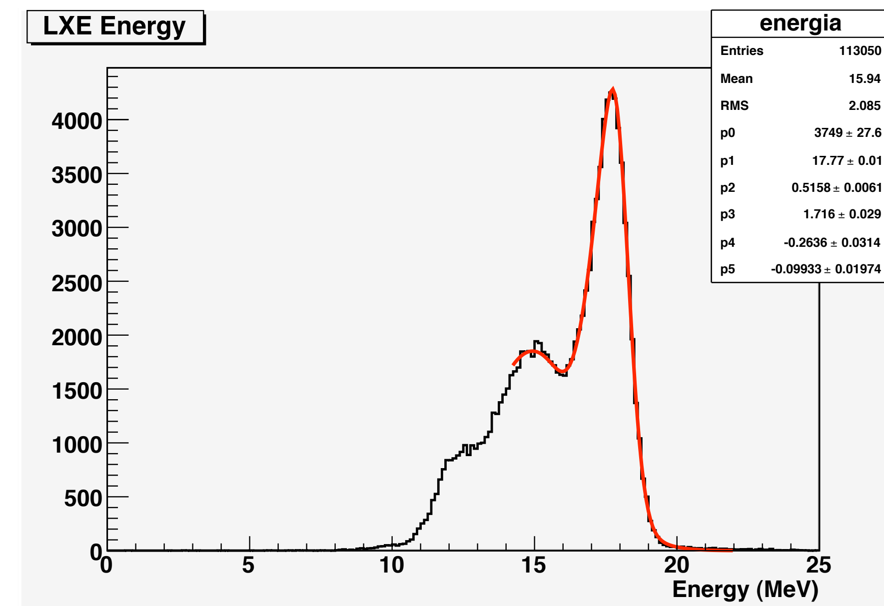
⟨FWHM⟩ = 5…6%



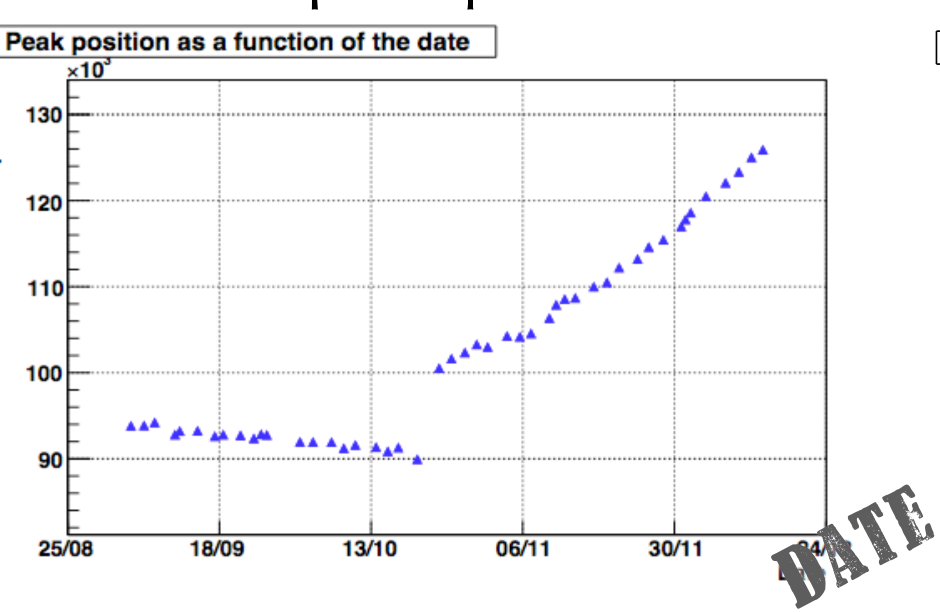
FWHM = 5.6 %

In-run changes

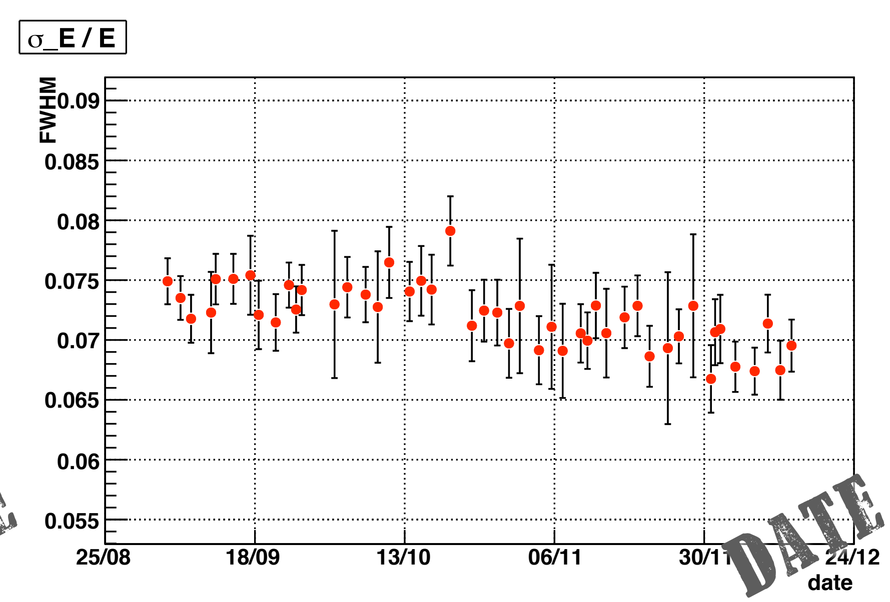
- Despite the continuous change in LXe light yield we could follow
  - how the performance changes during the run
  - the energy resolution as a function of the time
  - the efficiencies
- Information to extract systematics
  - rescale all runs
- Refinements in progress



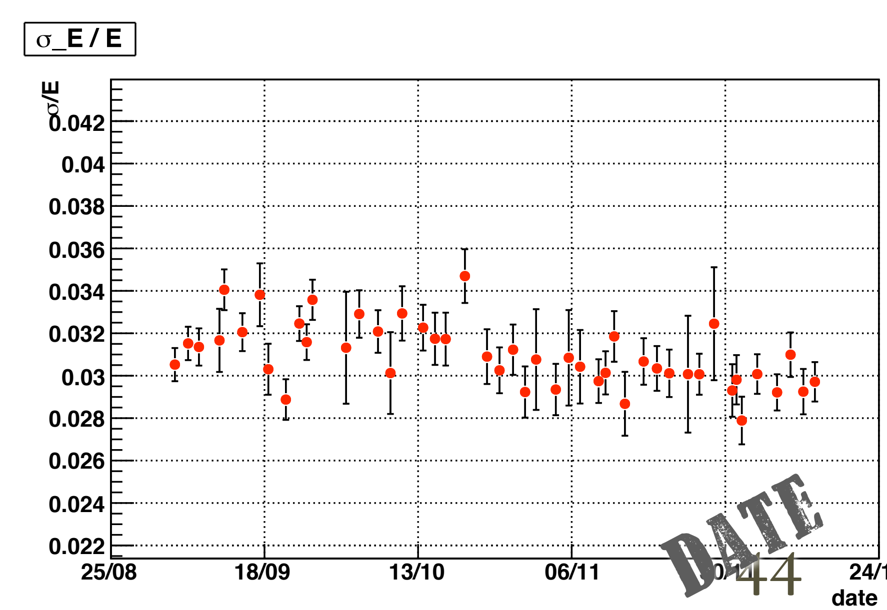
Li peak position



FWHM ~ 7%

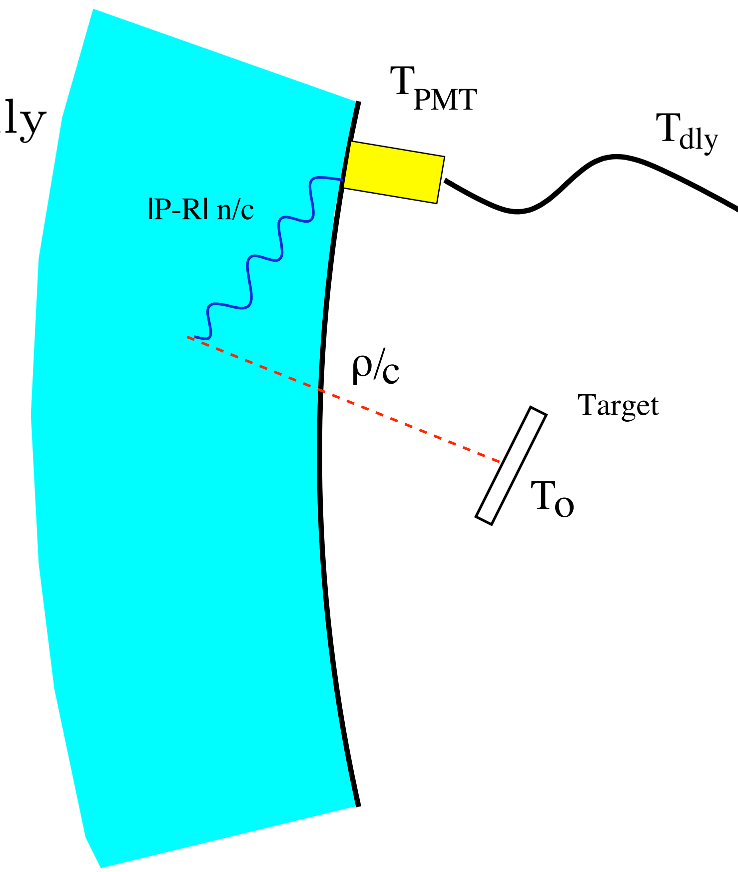


σ_R~ 3%

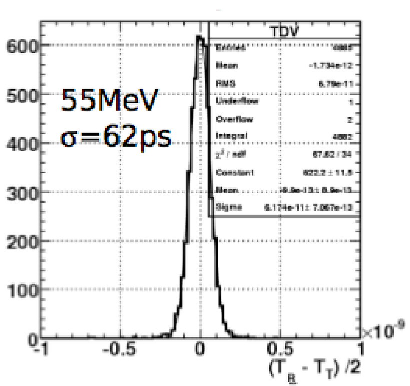


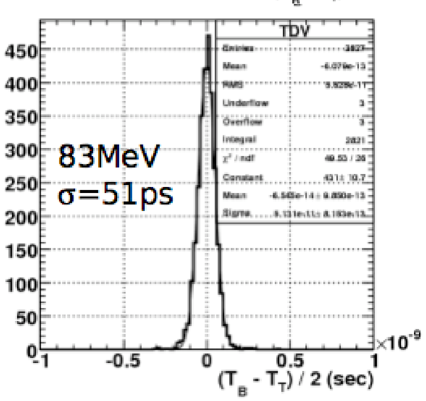
Intrinsic time resolution

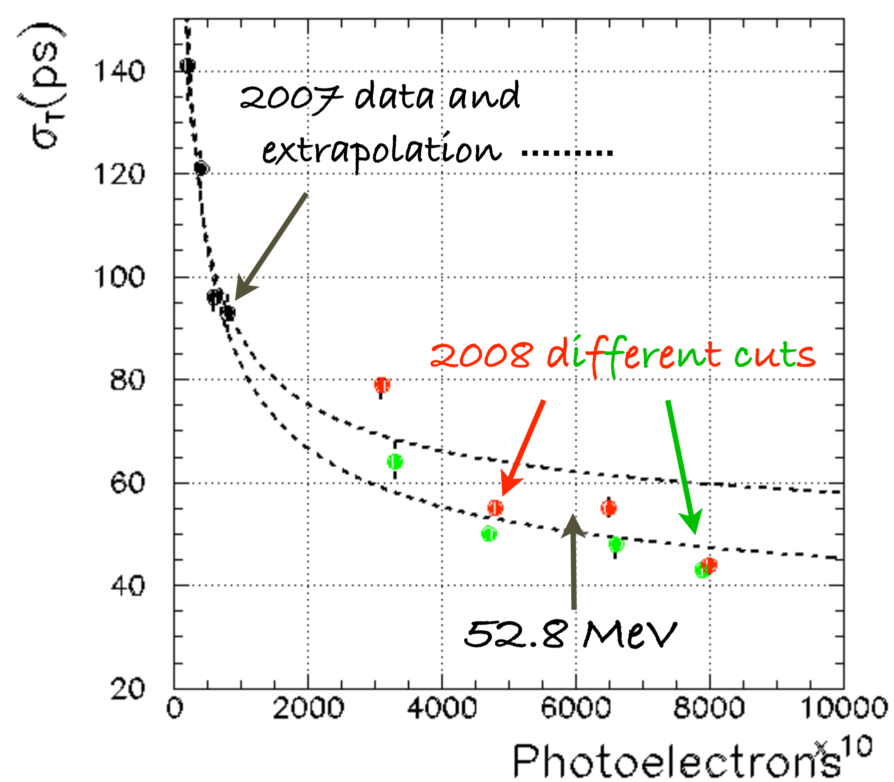
$$T_0 = T_i^{tw} - \frac{\rho_{\rm int}}{c} - \frac{|\vec{R}_{\rm int} - \vec{P}_i| n_{\rm Xe}}{c} - T_{\rm PMT} - T_{\rm dly}$$

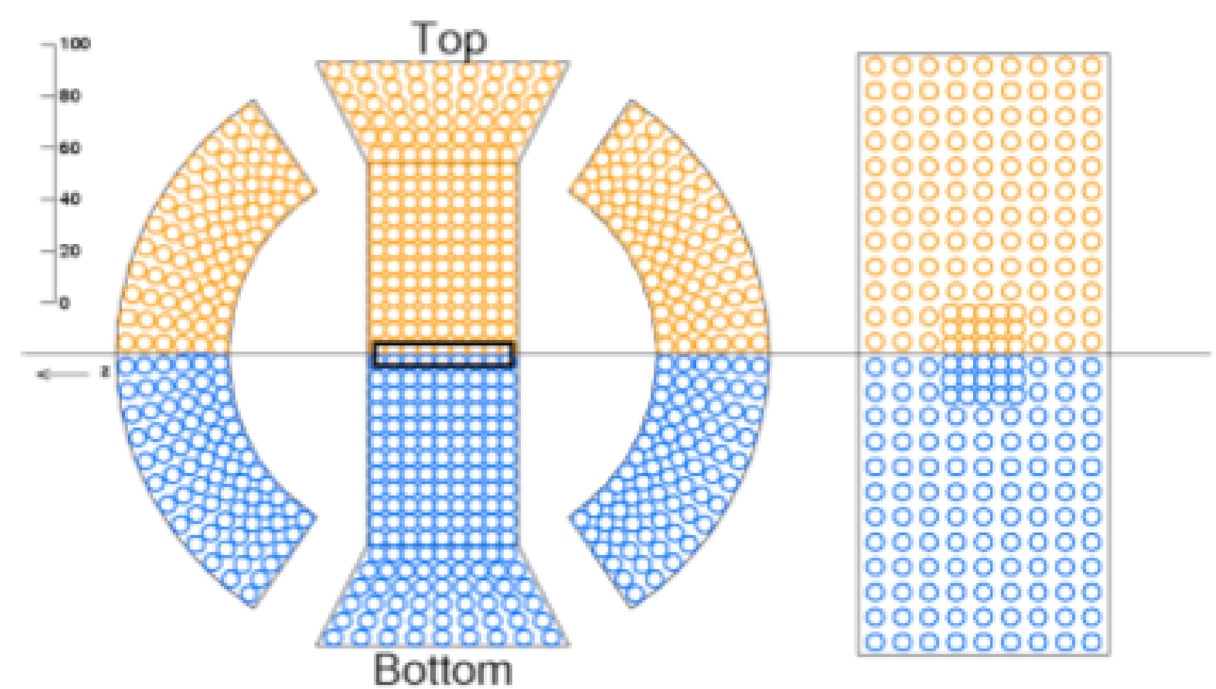


- Divide the PMTs in two groups
  - Odd / Even
  - Top / Bottom
- $t_a = \Sigma\, t_{2k} Q_{2k} / \Sigma Q \quad t_b = \Sigma t_{2k+1} Q_{2k+1} / \Sigma Q$
  - $\sigma_t = \mathrm{VAR}(½(t_a - t_b))$
- The two analyses agree well
  - σ_t(intrinsic) ~ 50 – 60 ps @ 52.8 MeV
  - still some dependence on cuts, geometry...



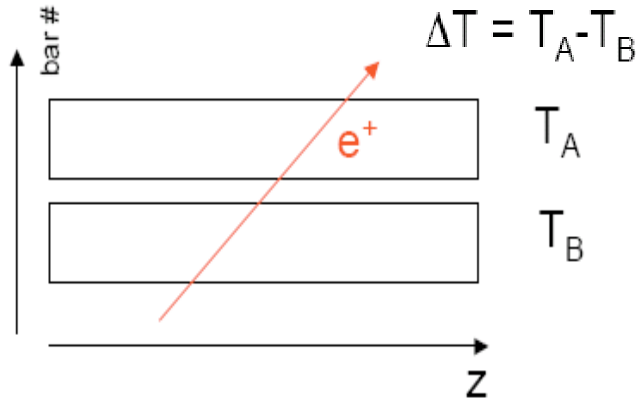


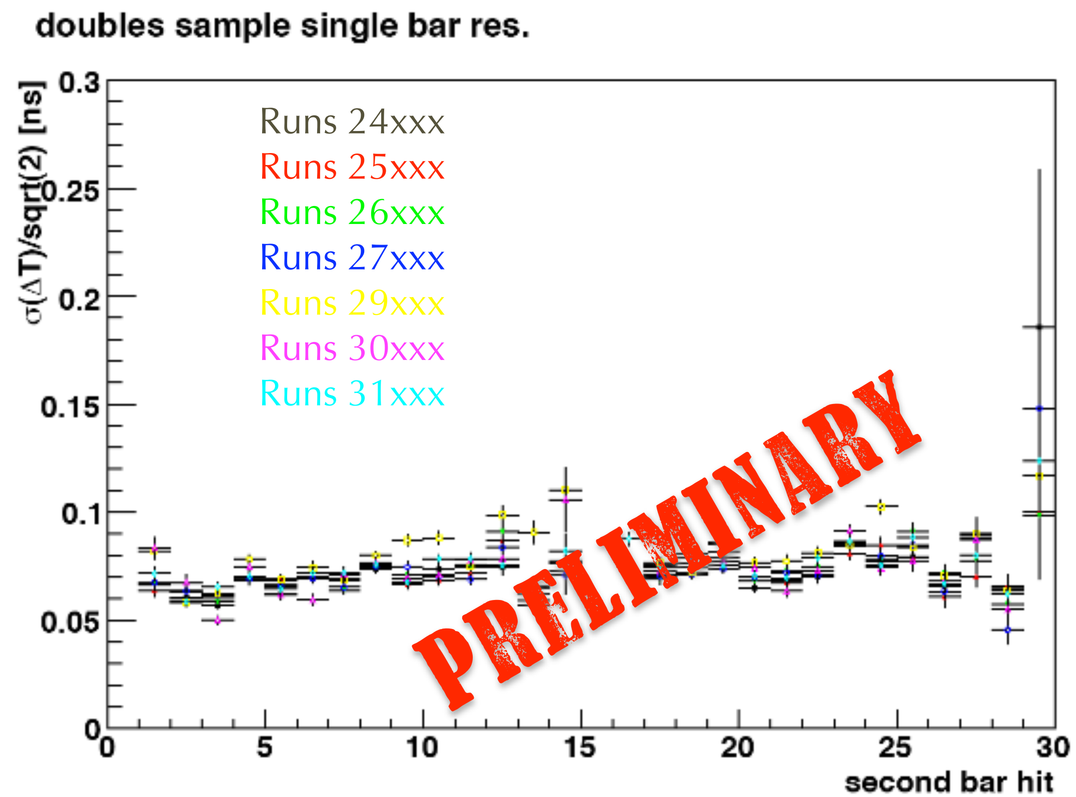




TC time resolution

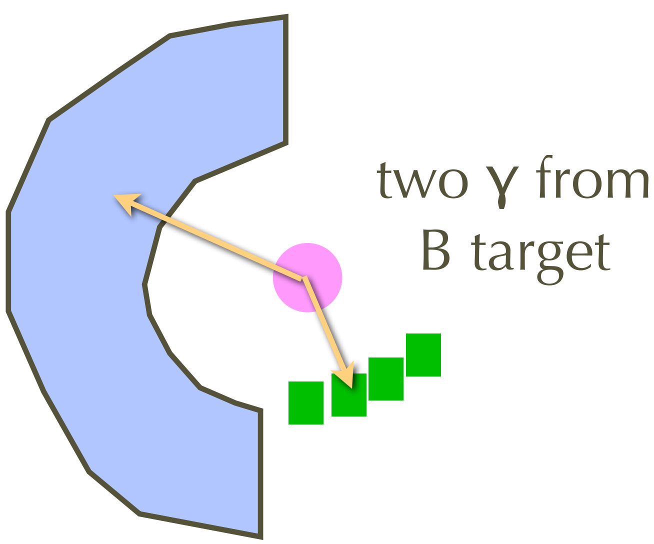
e^+

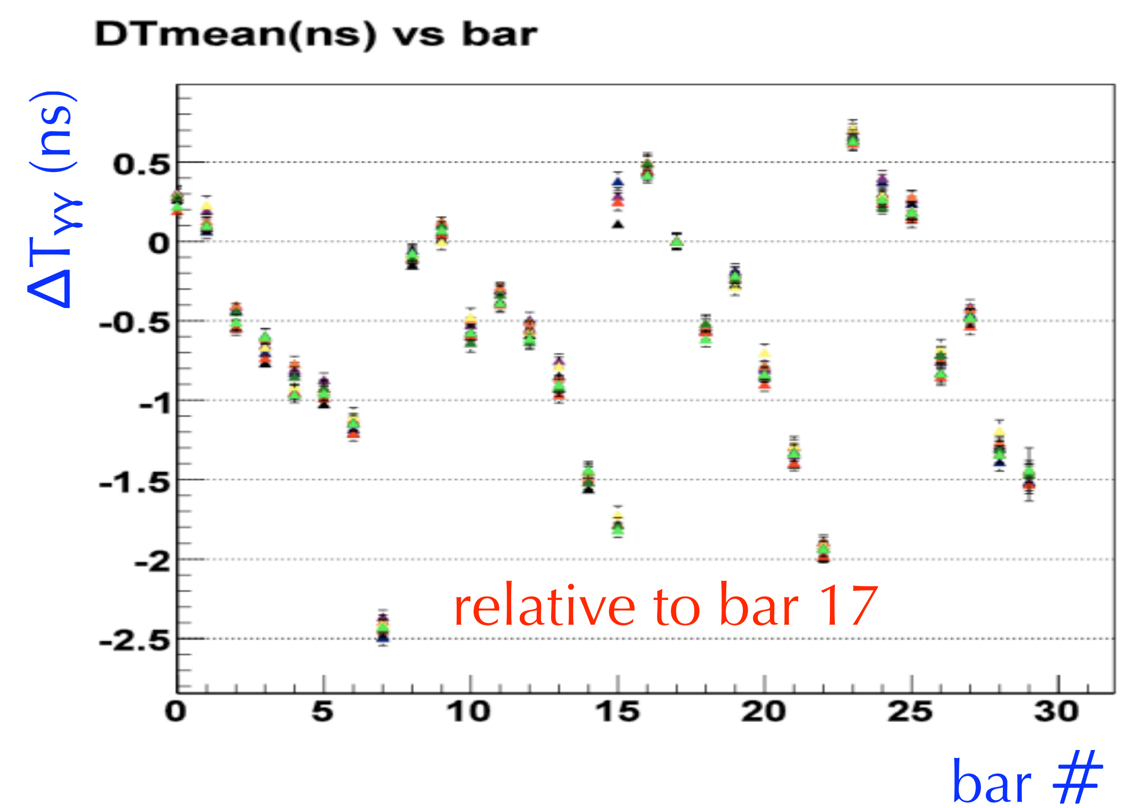




- Not yet corrected for positron track length
- Upper limits on $\sigma \sim$ 60-90 ps
- Time-walk correction applied

γγ

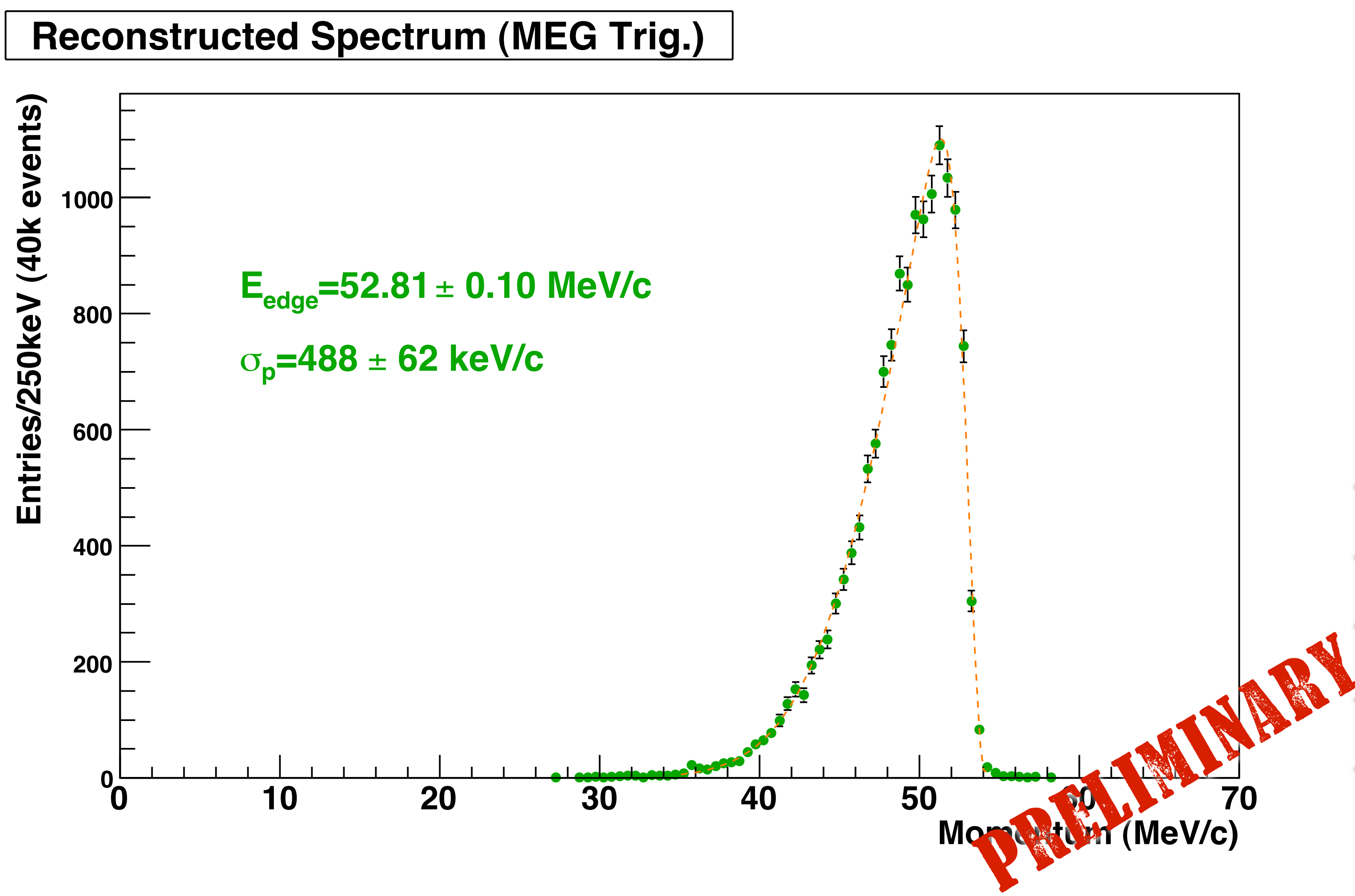


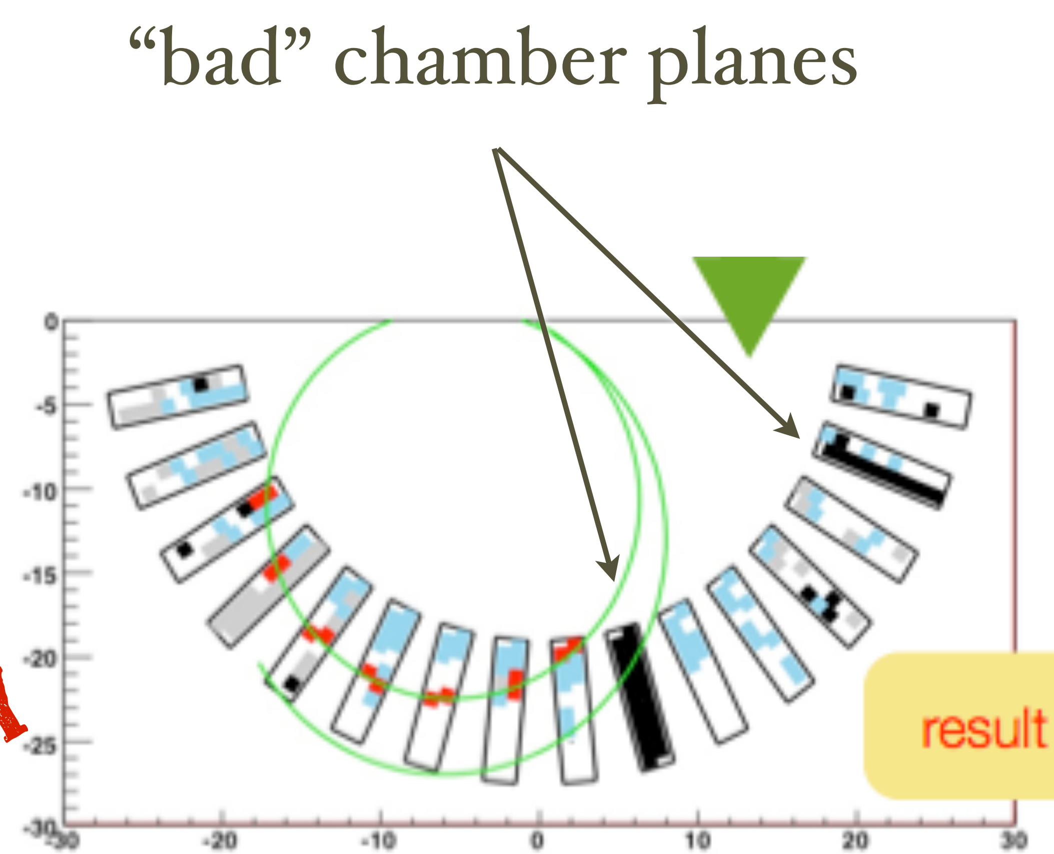


- Stability over the run period
- Further improvement in 2009 with the new digitizers (DRS4)

DCH performance

- Few DCH experienced high voltage (HV) *trips*
  - The tracking efficiency & resolution were not optimal
  - Resolution evaluated on the edge of the positron (Michel) spectrum





DCH HV performance

- The chambers are operated in He/ethane 50%/50% mixture
- They are immersed in He atmosphere

- In June-July the situation was ok:
  - 30 / 32 planes >1800 V
  - 2 planes showed problems right from the beginning

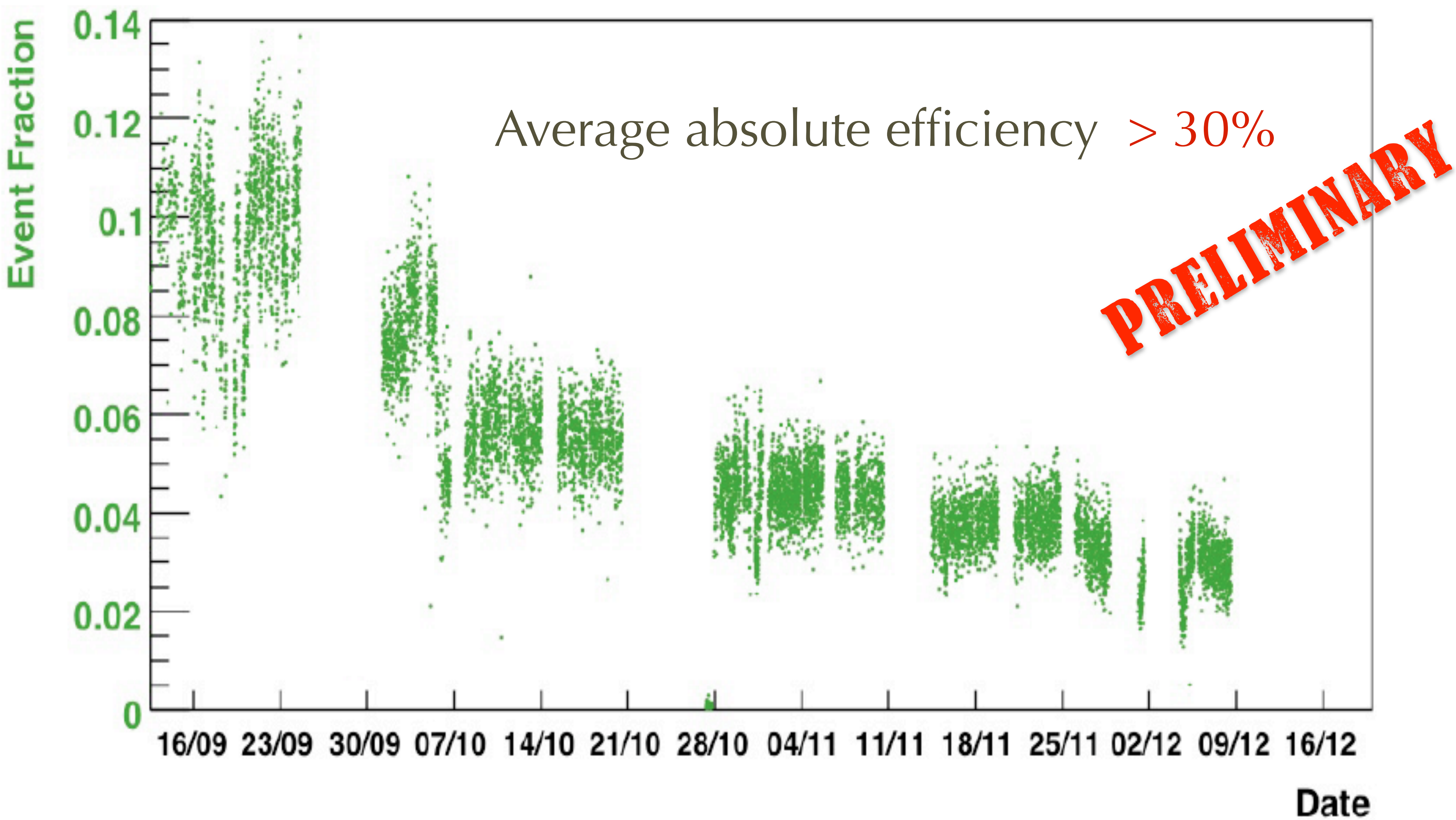
- In September, after the π^o calibration, the situation started to deteriorate but we decided to start anyhow data taking (September 12th)

- During MEG run (September – December):
  - further deterioration of HV performance
- At the end of MEG run
  - 11 / 32 planes >1800 V
  - 7 / 32 planes 1700-1800 V

- The problem is tricky because it does not show up immediately but only after some time: helium penetration in HV distribution

DCH efficiency

- The fraction of events with at least one reconstructed track at high momentum is a measure of relative (not absolute) tracking efficiency

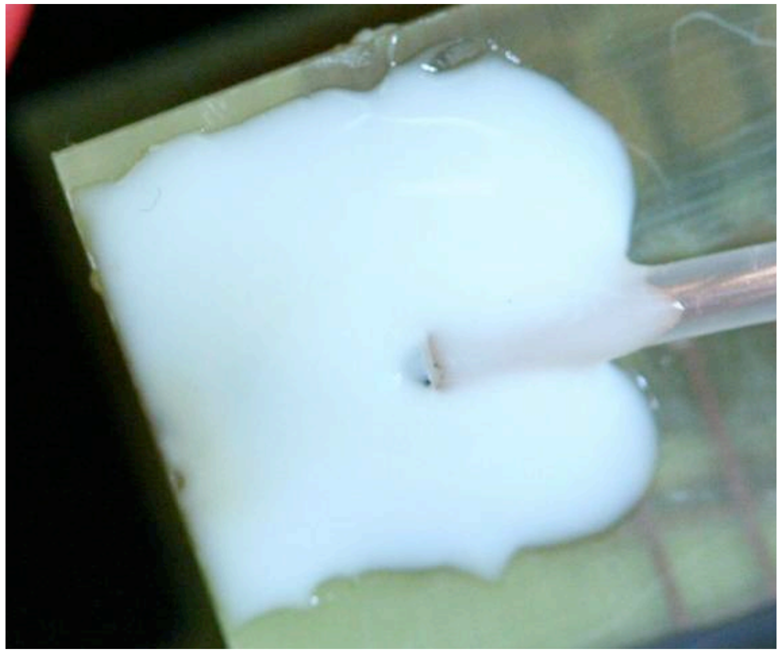


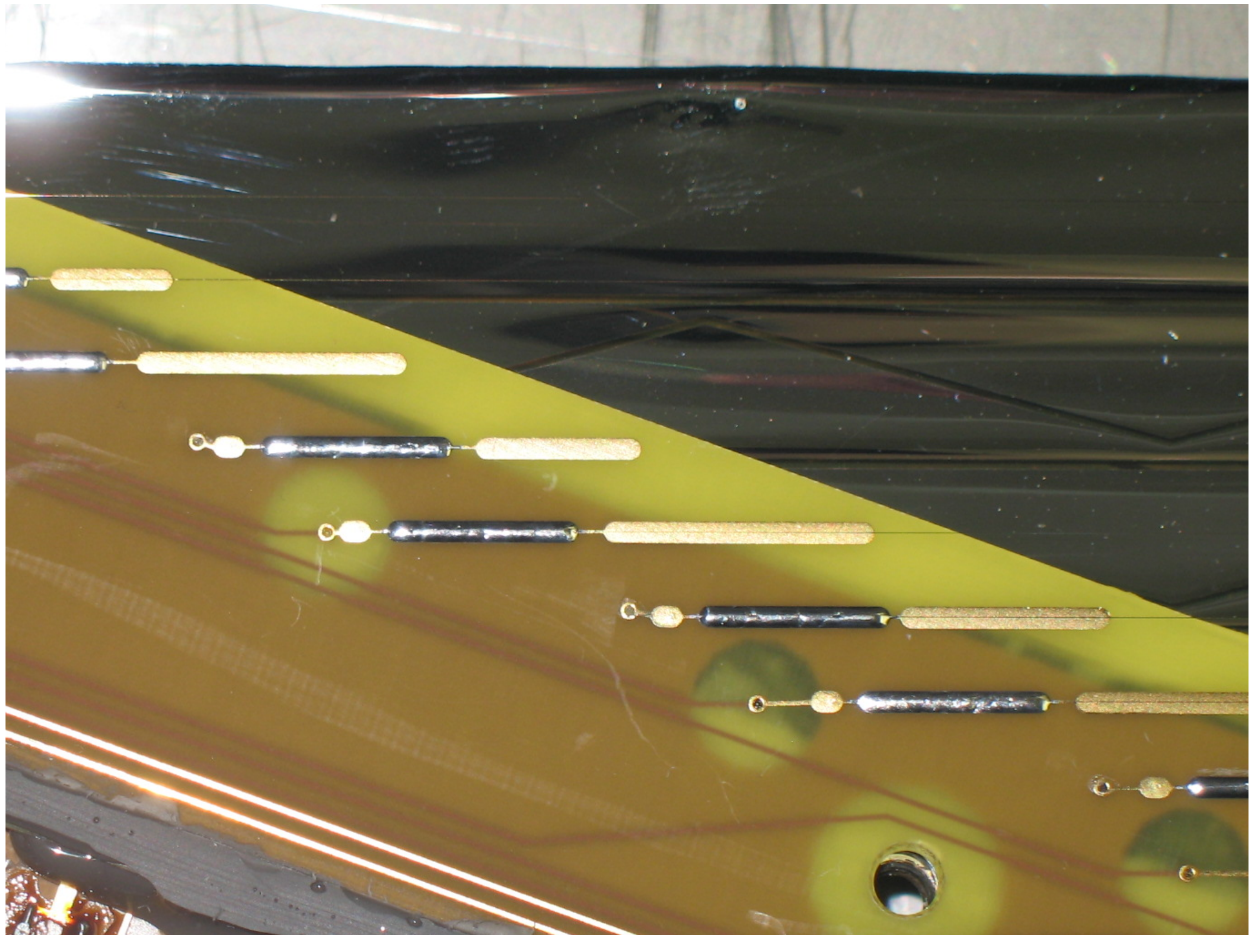
DCH repair

1) The chambers are dismounted and operated in laboratory in He atmosphere

2) The potting glue for the HV protection was inadequate: change on all chamber to epoxy glue

3) The PCB has vias close to ground plane, partially filled with araldite to fix PCB to the Carbon fiber frame: new PCB design





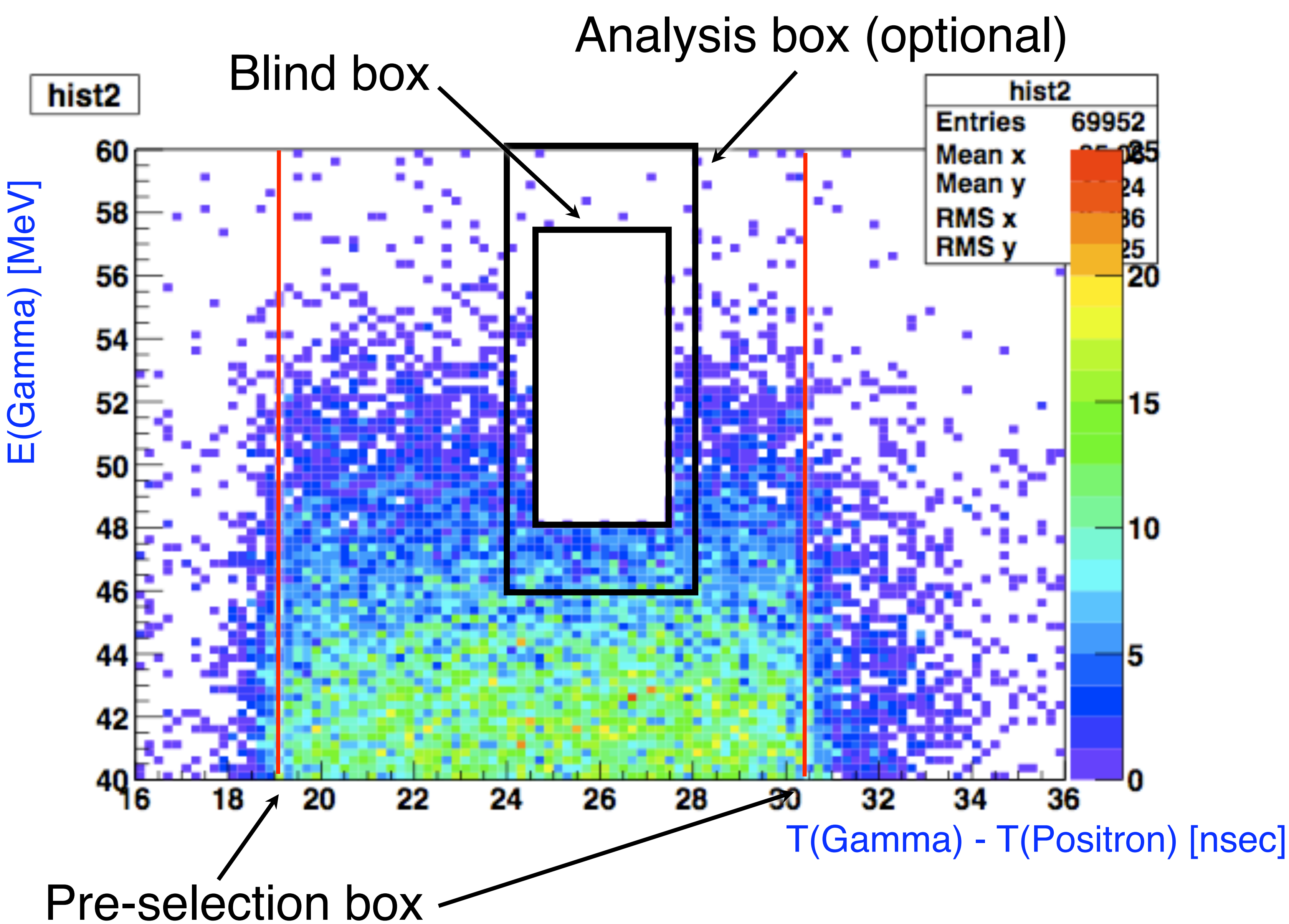
4) Open all chambers, replace the PCB and the wires, saving the cathodes

5) Test of the chambers in laboratory as soon as they are ready

Estimated time: ready to mount in August

Analysis

- We decided to adopt a blind-box likelihood analysis strategy
- The blinding variables are E_γ and $\Delta t_{e\gamma}$
- Usage of the sidebands justified by the fact that our main background comes from accidental coincidences



PDF

Signal: from detector resolutions

Accidental background: from data

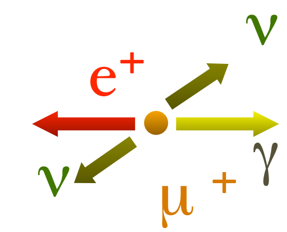
Prompt background: from simulation and from RMD data sample

Radiative decay signal

The radiative μ-decay events are:

- good sample to check the LXe-TC timing
- good sample to control the efficiencies
- the second source of background: we want to validate our pdf

Search in dedicated low μ-beam intensity runs



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

Event selection

1. Reject cosmic muons
2. Reconstructed track matching the TC
3. LXe energy >30 MeV

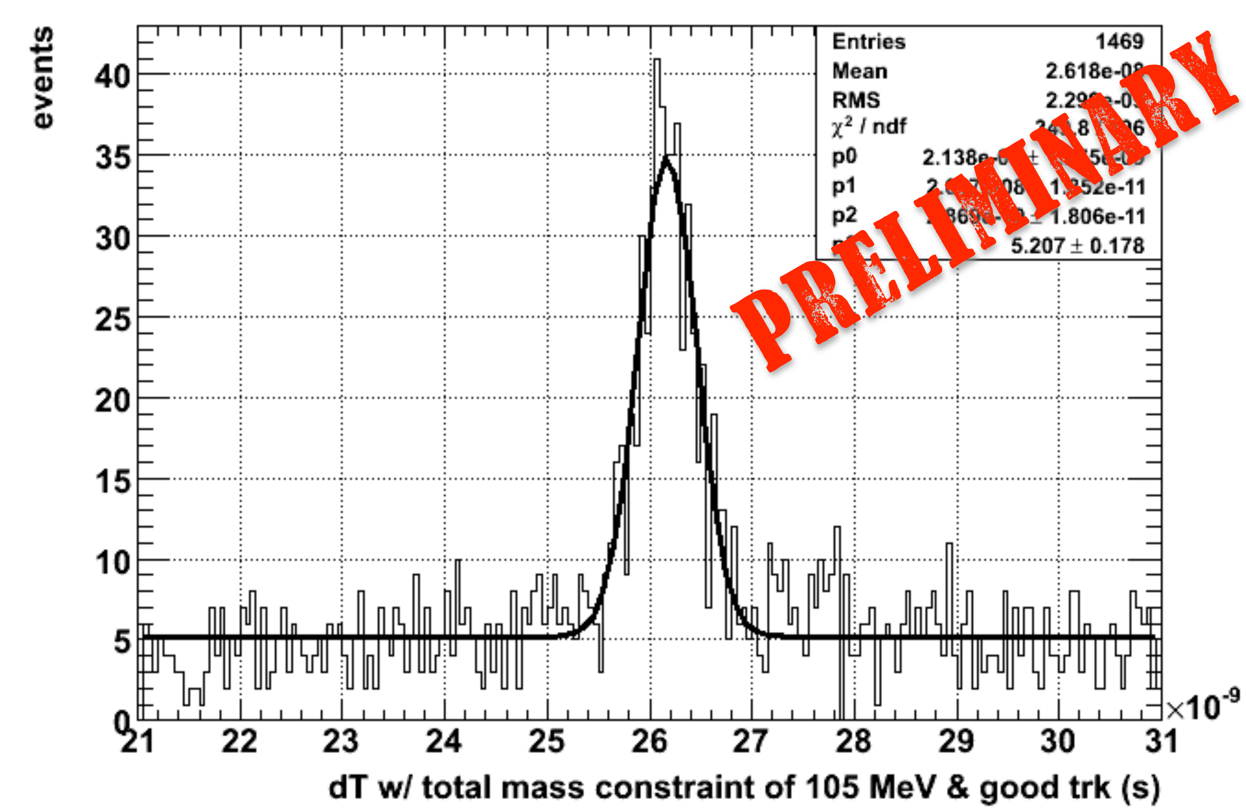
S/N ratio = 0.8

4. Kinematical constraint

S/N ratio = 2.8

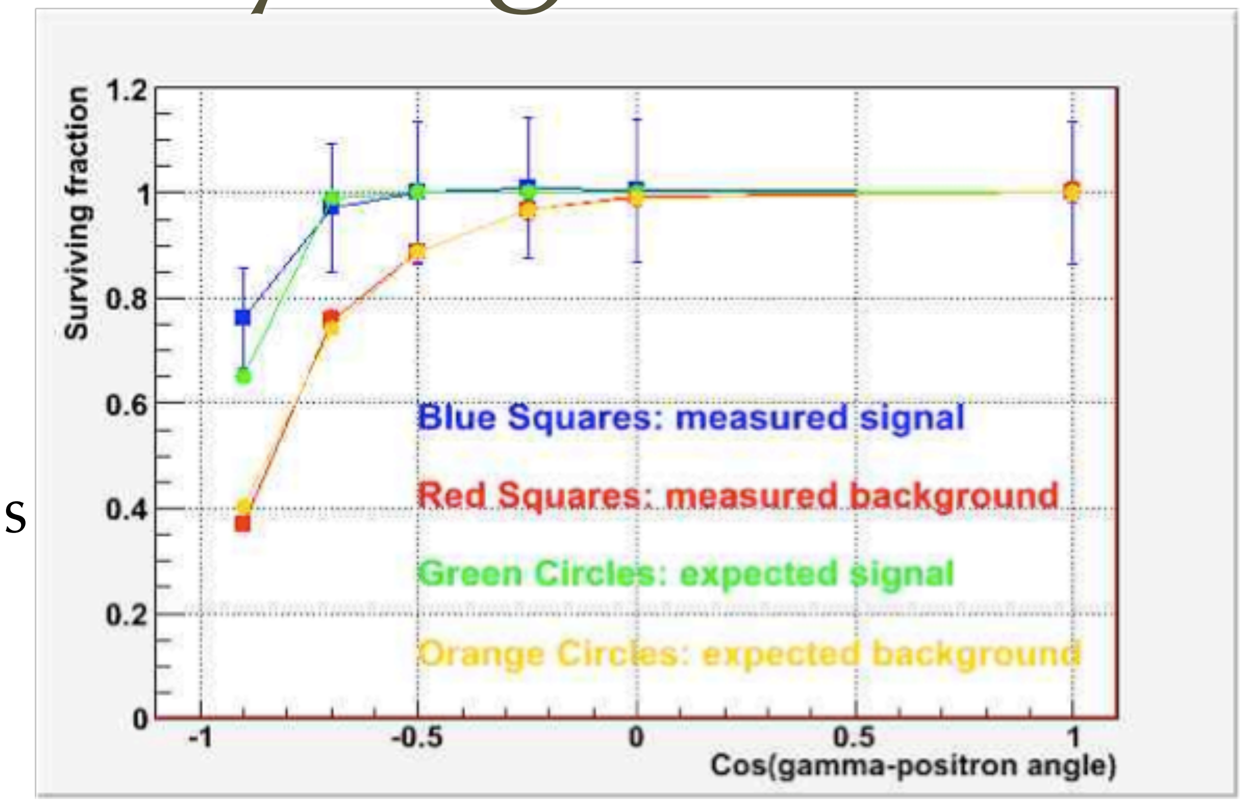
$$
\begin{aligned}
M_{2\nu}^2 &= E_{2\nu}^2 - \vec{p}_{2\nu}^2 = (M_\mu - E_e - E_\gamma)^2 - (\vec{p}_e + \vec{p}_\gamma)^2 \\
&\approx M_\mu^2 - 2(E_e + E_\gamma)M_\mu + 2E_eE_\gamma \sin^2(\vartheta/2) \geq 0 \\
&\Rightarrow xy\sin^2(\vartheta/2) \geq x + y - 1
\end{aligned}
$$

428 events



Radiative μ-decay signal

- The observed number is compatible with the estimated detectors efficiencies
- The measured angular dependence of e+ γ pair is in agreement with the expectations



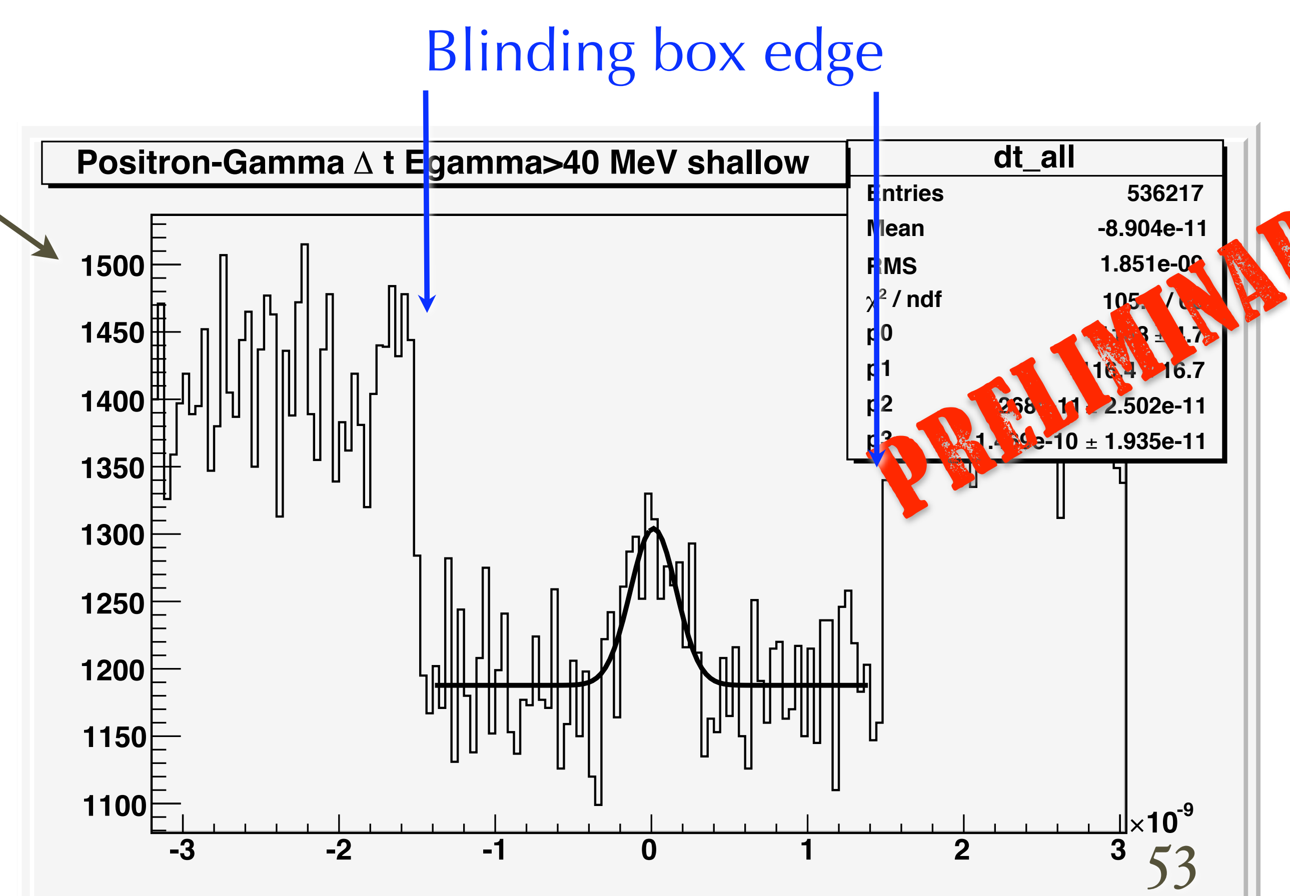
Search in normal MEG runs

1. Reject cosmic muons
2. Reconstructed track matching the TC
3. Kinematical constraint
4. LXe energy >30 MeV

$\sigma(\Delta t)$ = 178±29 ps

LXe energy >40 MeV

$\sigma(\Delta t)$ = 114±30 ps



Sensitivity for 2008 run

CAUTION: All 2008 numbers are provisional

Still lots of things to learn from the data

Efficiencies

- Blue numbers likely to change - Grey numbers may vanish

(%)	"Goal"	2008 Provisional Lower Limits	2009 Provisional Prospects
Gamma	> 40	> 50 x (65 x 85) (depth, pileup)	> 50 x 90
e+	65	30 x 40 (DC, DC-TC)	85 x 50
Trigger	100	100 x 99 x 80 (energy, time, direction)	> 99
Selection	$90^4 = 66$	$90^3 \times 95 = 69$	69
DAQ	(> 90)	> 80 x 93 (live, run transition)	> 90 x 99
Calibration Run etc	(> 95)	~70	90
Running Time (week)	100*	11.5**	11.5
Single Event Sensitivity (10^{-13})	0.5	< 30 - 50	< 3 - 5

* 1 week = 4×10^5 sec (66%) ** CEX runs not included

Resolutions for 2008 run

CAUTION: All 2008 numbers are provisional

Resolutions

Resolutions are improving as we understand the detectors better.

(in sigma)	"Goal"	2008 Provisional	2009 Provisional Prospects
Gamma Energy (%)	1.2 - 1.5	< 2.3	< 1.7
Gamma Timing (ps)	65	< 100*	< 80
Gamma Position (mm)	2 - 4	5 - 6.5	5
e+ Momentum (%)	0.35	1.5 - 2.0	0.7 - 0.8
e+ Timing (ps)	45	< 60 - 90	60
e+ Angle (mrad)	4.5	9 - 18	11
mu Decay Point (mm)	0.9	3 - 4	2
Gamma - e+ Timing (ps)	80	150	100
Background (10^{-13})	0.1 - 0.3	-	< 0.6 - 3

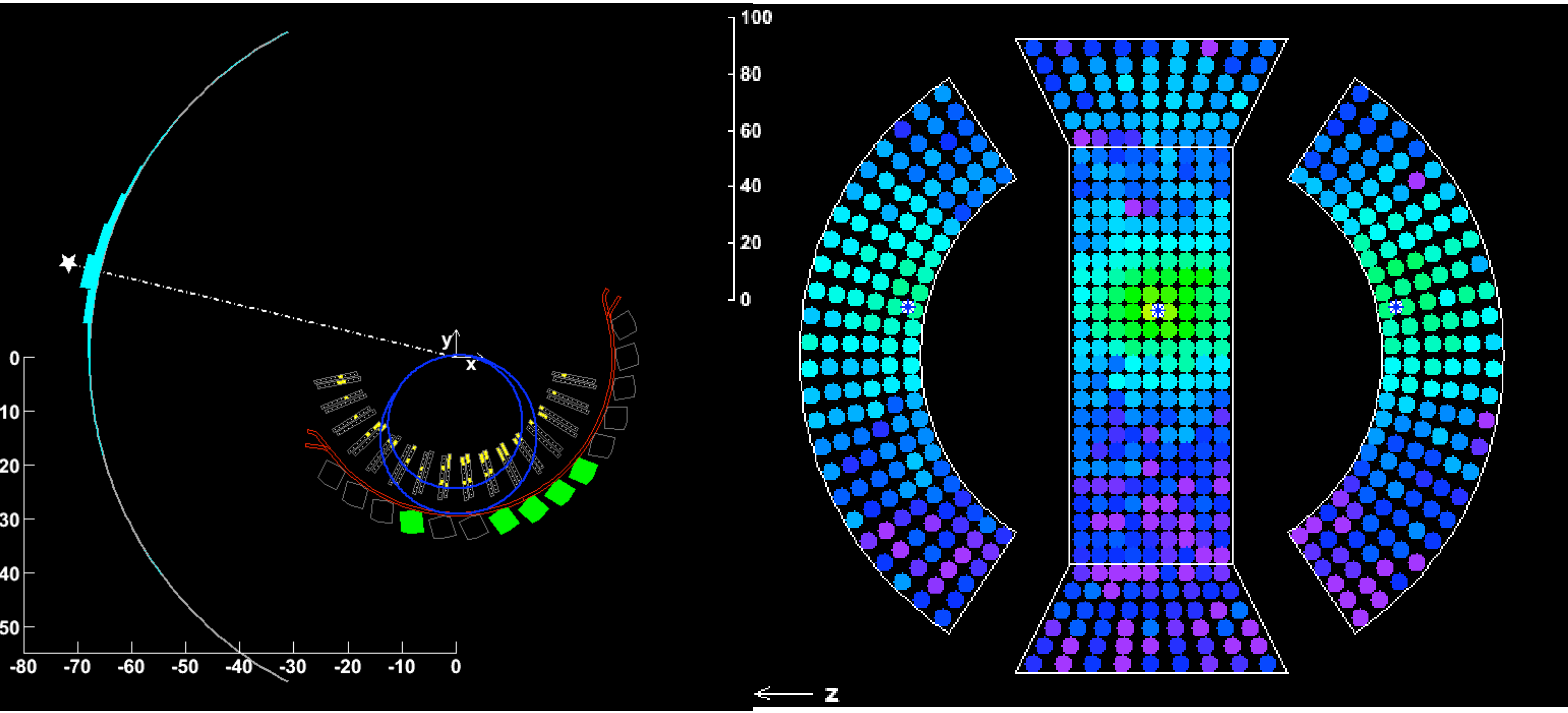
* clock error of ~60ps included

Conclusion

- Despite 2008 run suffered from detector instabilities we demonstrated our ability in seeing $\mu \to e\,\gamma$ events (IB process observed in normal data taking)
- We are gaining better knowledge of our detectors systematics: resolutions are (almost daily) improving
- We are working to have analysis results on 2008 data ready by this summer
- We are making all efforts to reach stable DCH operation for the 2009 run: we believe the strategy presented will eliminate HV discharges
- We will need to run until the end of 2011 for reaching the target sensitivity

A 2008 candidate event

- A good hint for this year!

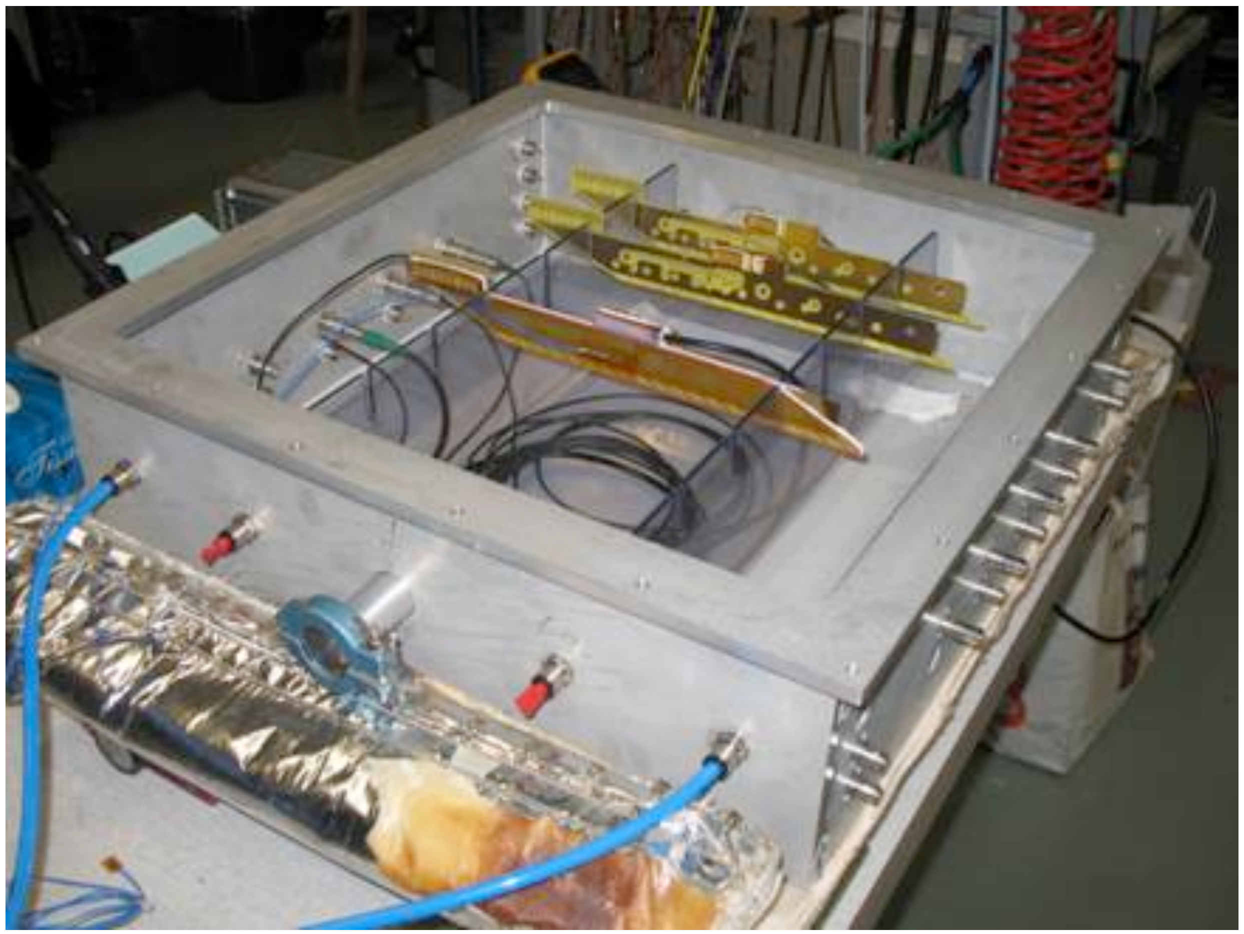


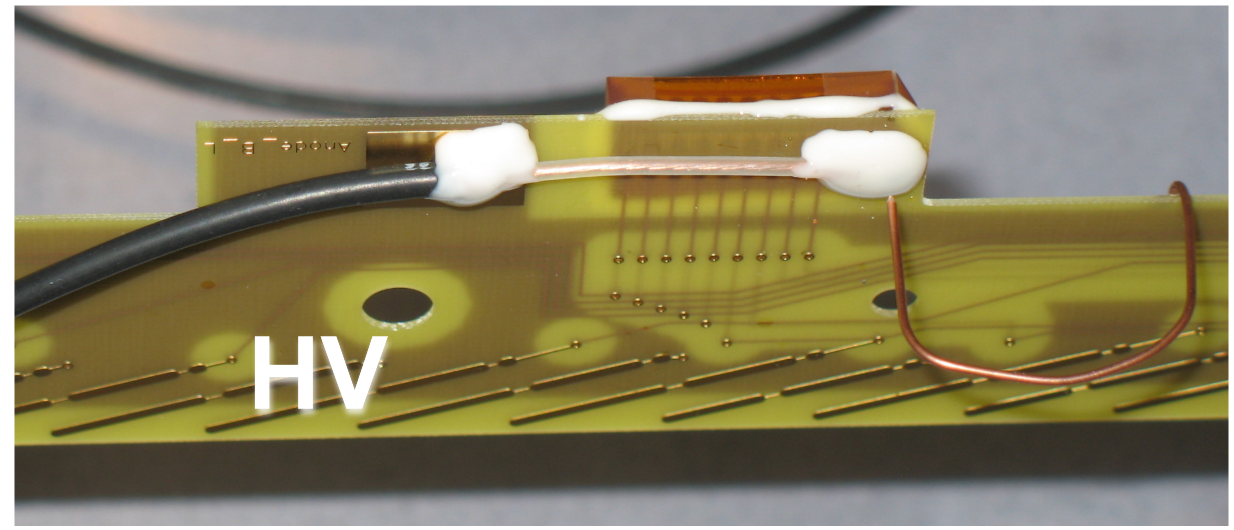
Thanks

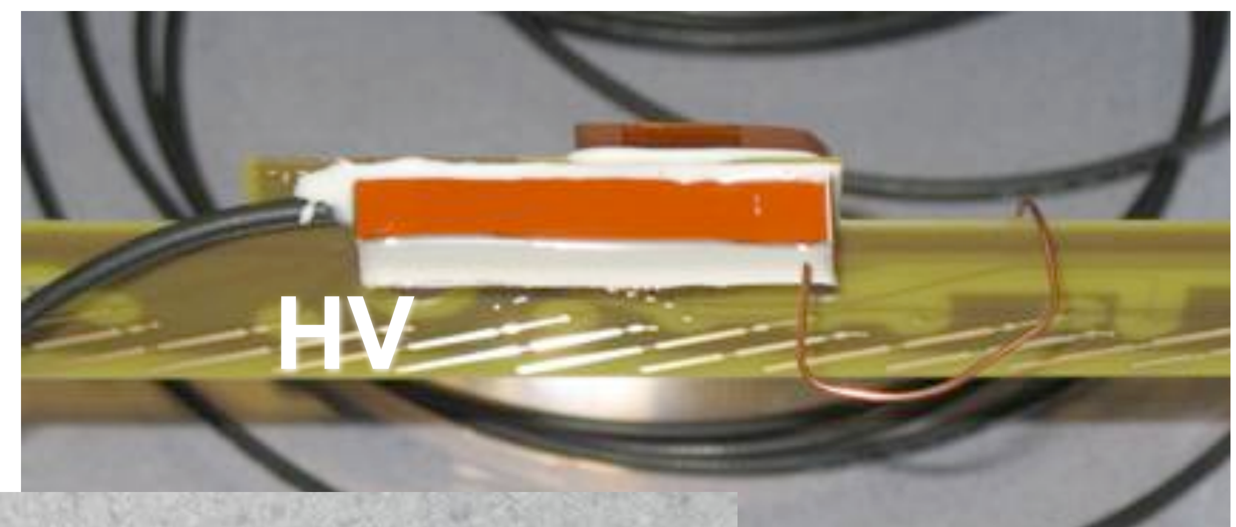
Back-up

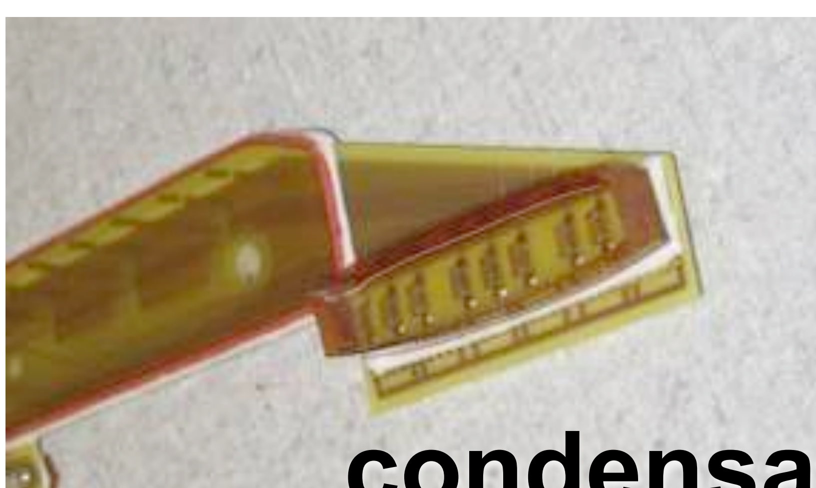
DC: PCB nella testbox

since Fri nov 7th: HV in helium atmosphere (~99% from reading O_2 sensors)



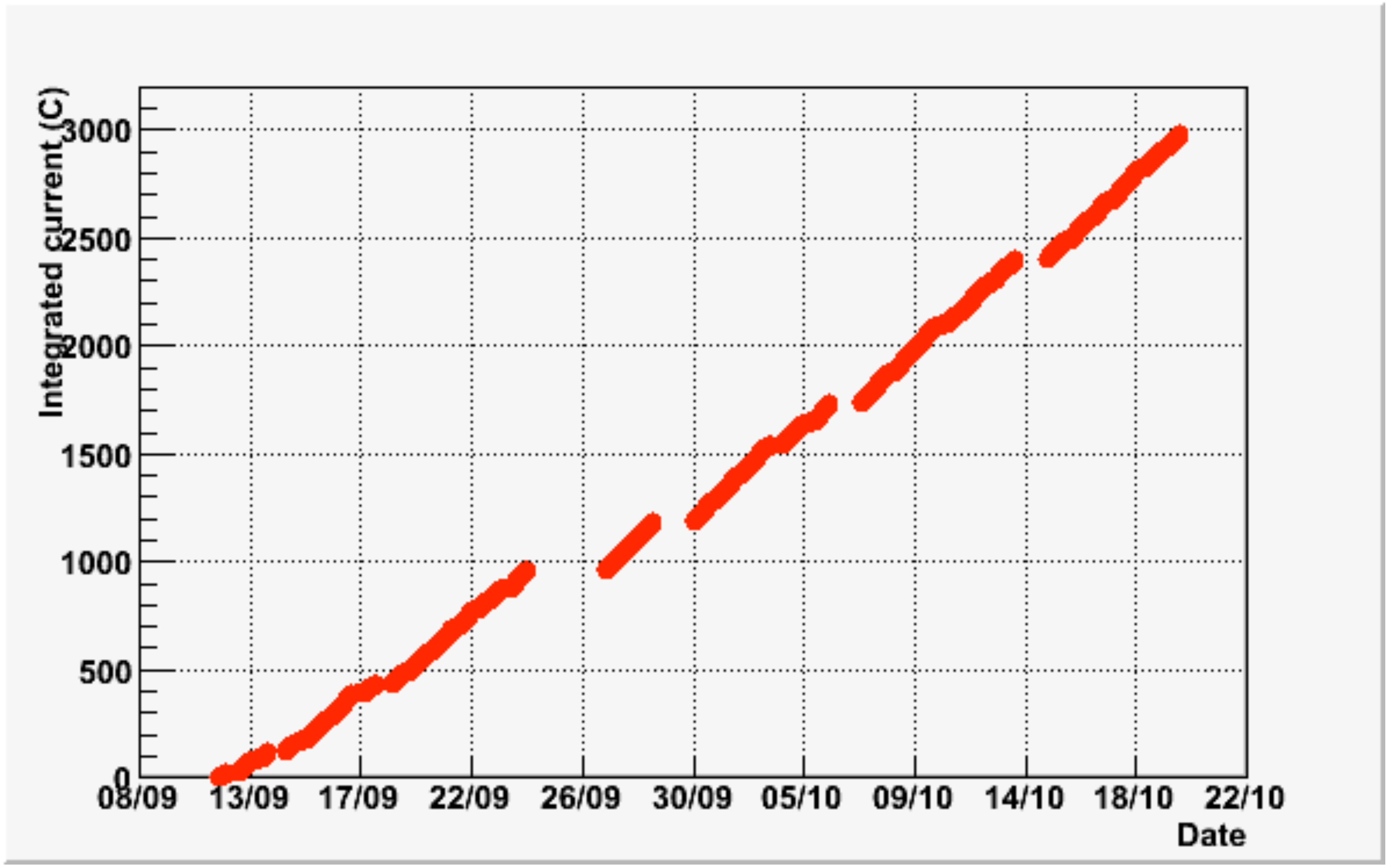






Selected results from 2007 engineering run

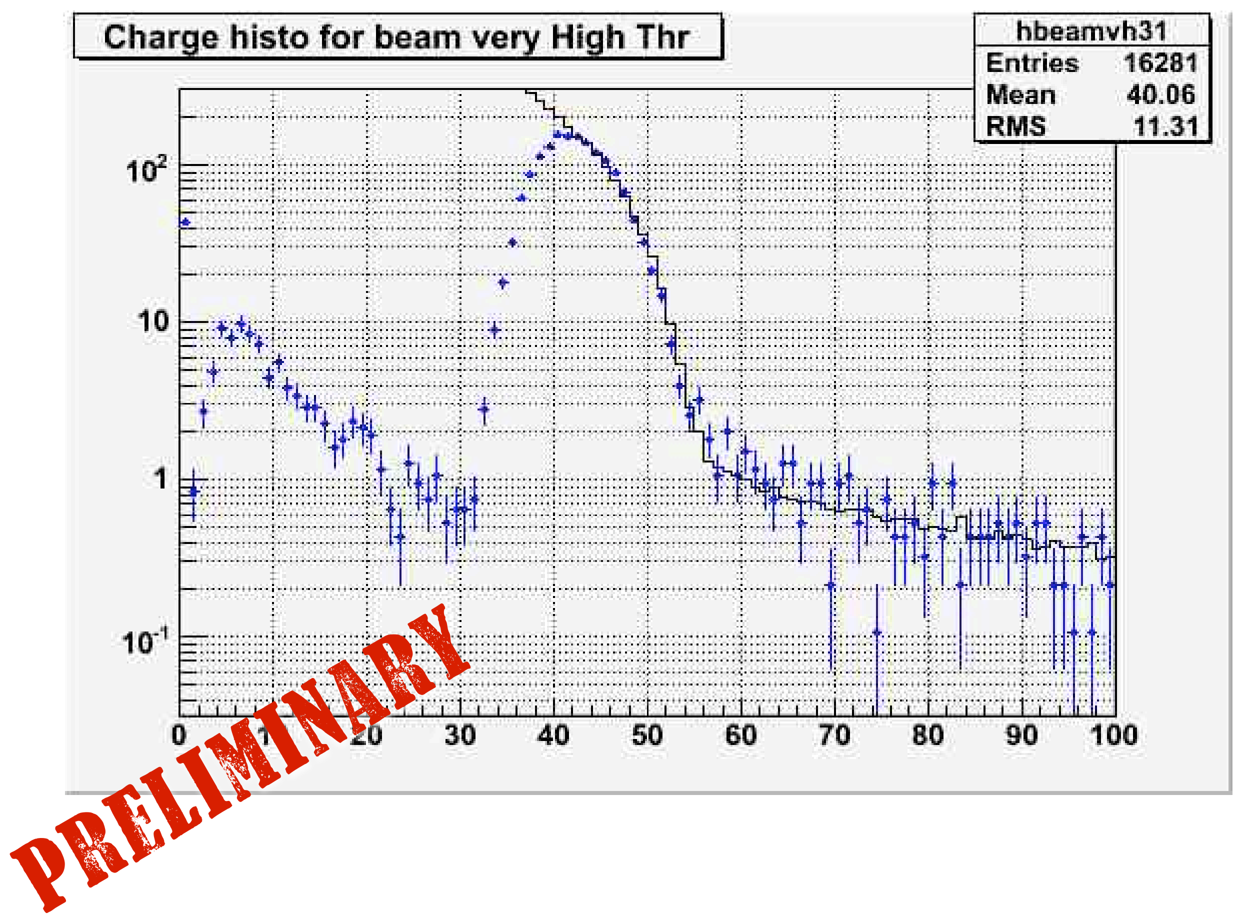
- We are presently taking data but I cannot show you any plot from this year “physics” data set
- Our strategy is masking some of the data
  - *blind* analysis
  - *likelihood* analysis



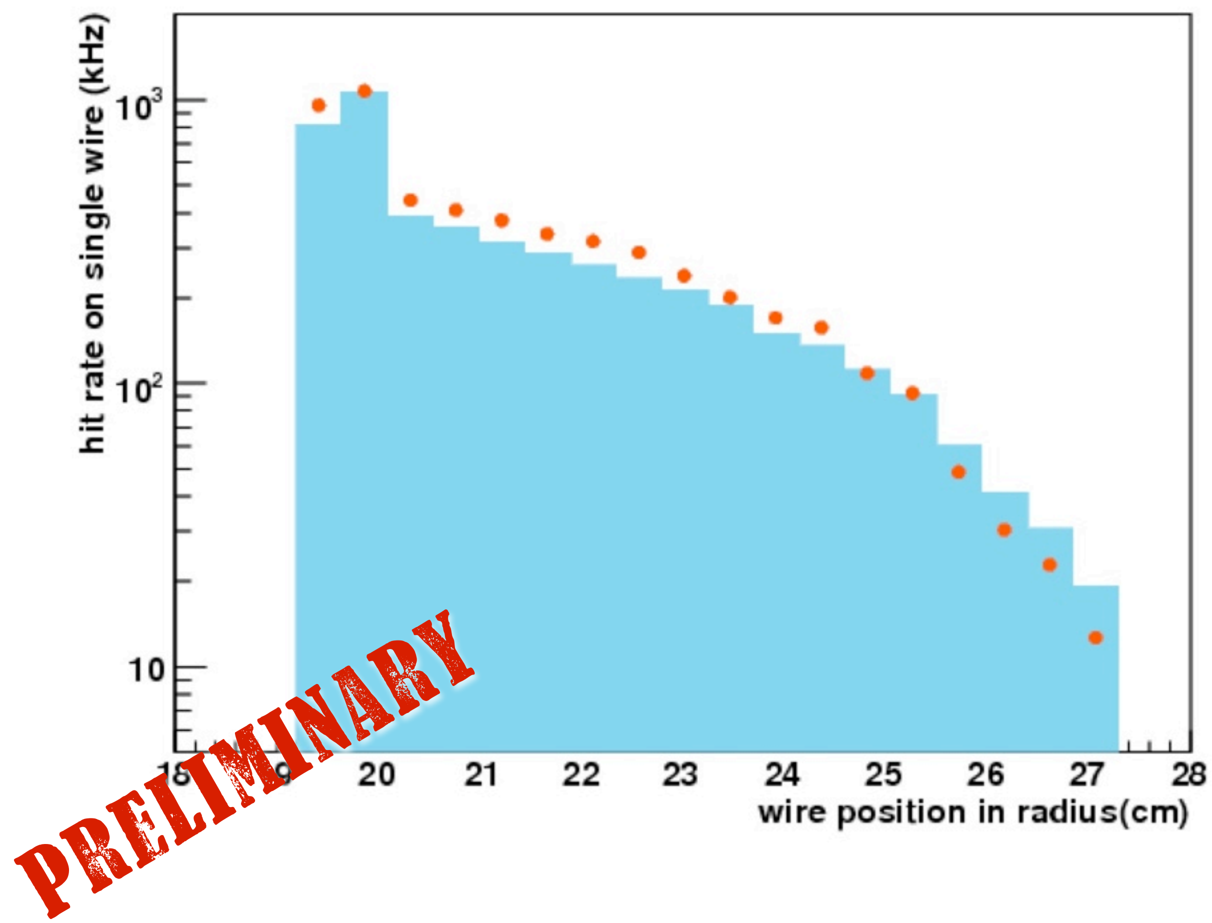
First: the rates

- Since our is a counting experiment we must be sure to have the background under control
- The *trigger* rate scales as expected
- Absolute wire rate in the chambers ok, details to be understood

calorimeter energy spectrum

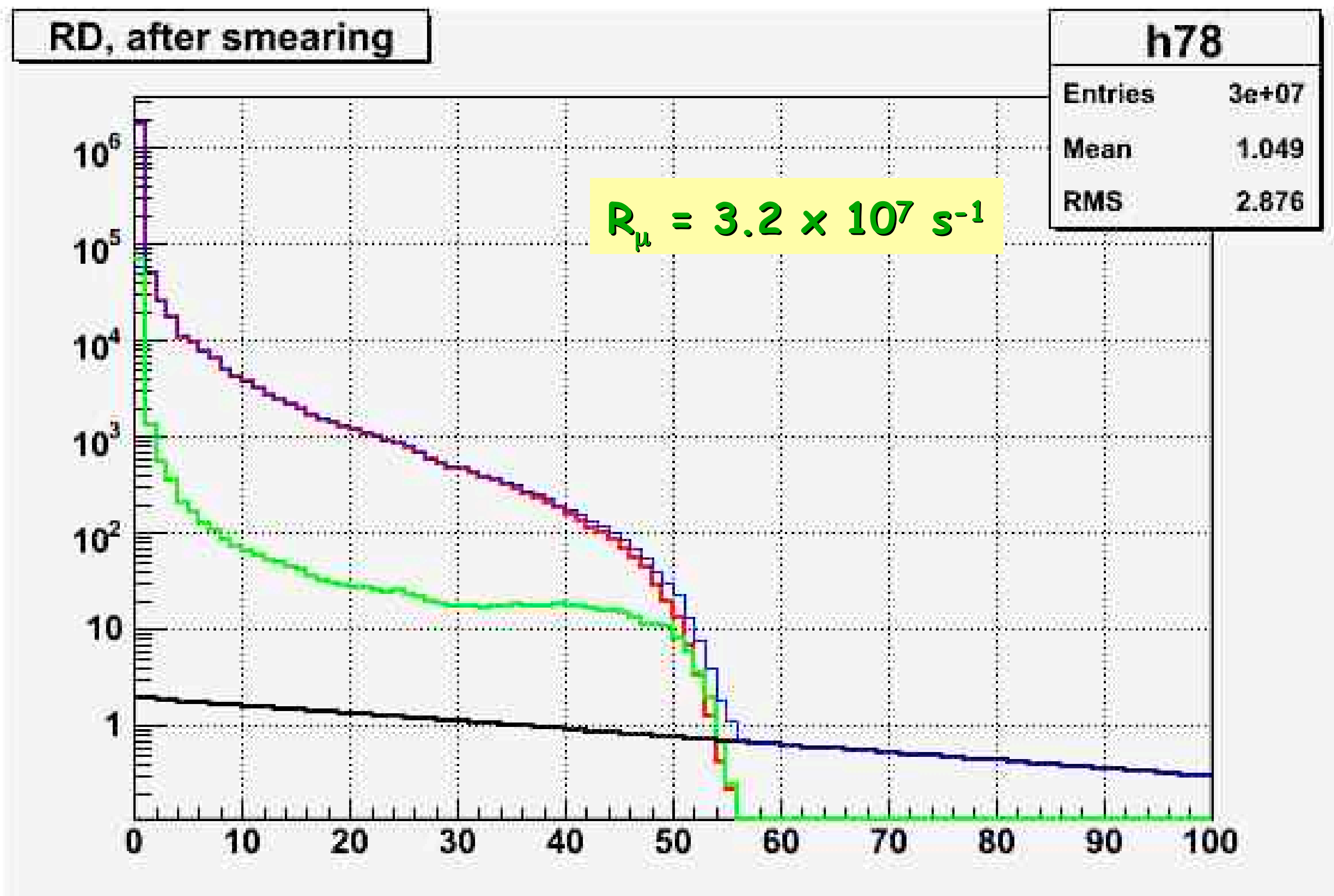


rate on DCH wires



The expected spectrum

- The simulated expected spectrum in the calorimeter contains several contributions

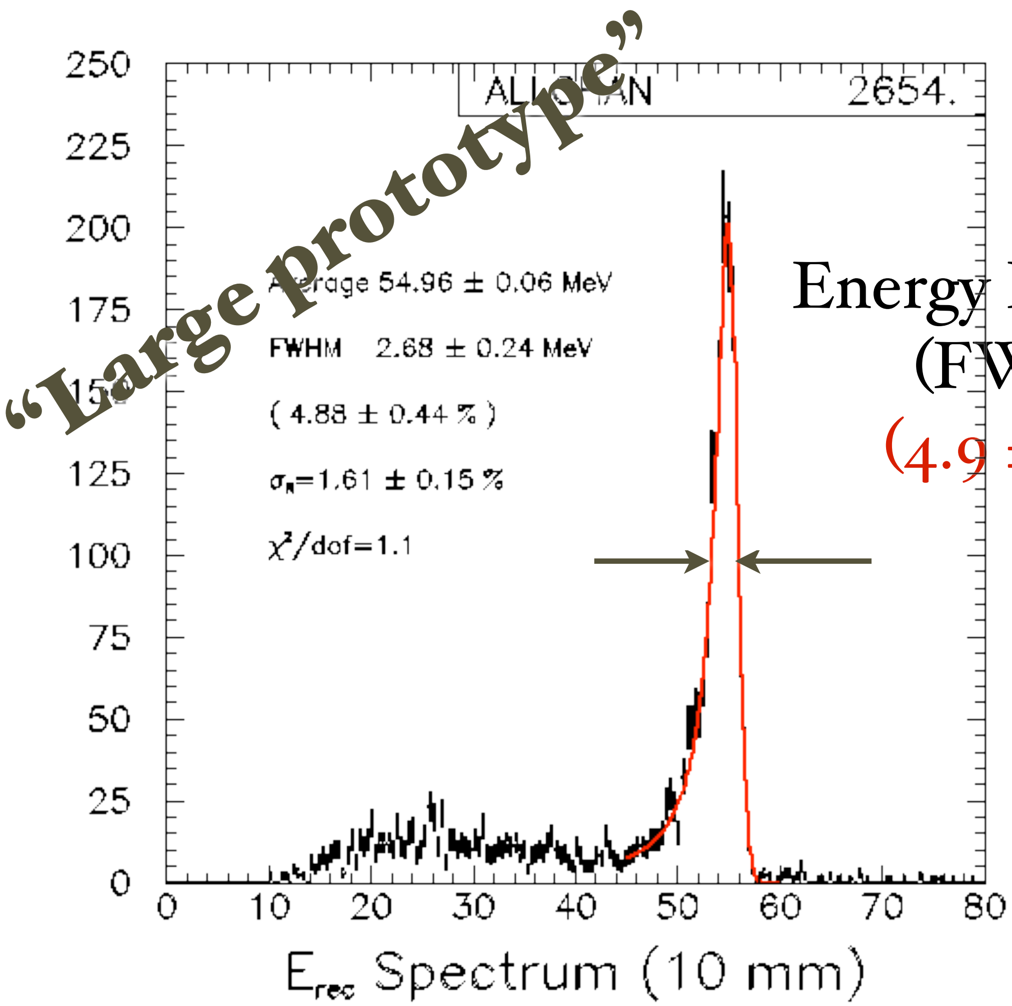


Red: Radiative decay
Green: Annihilation In Flight
Black: Cosmics (approximated)
Blue: Total (including pile-up)

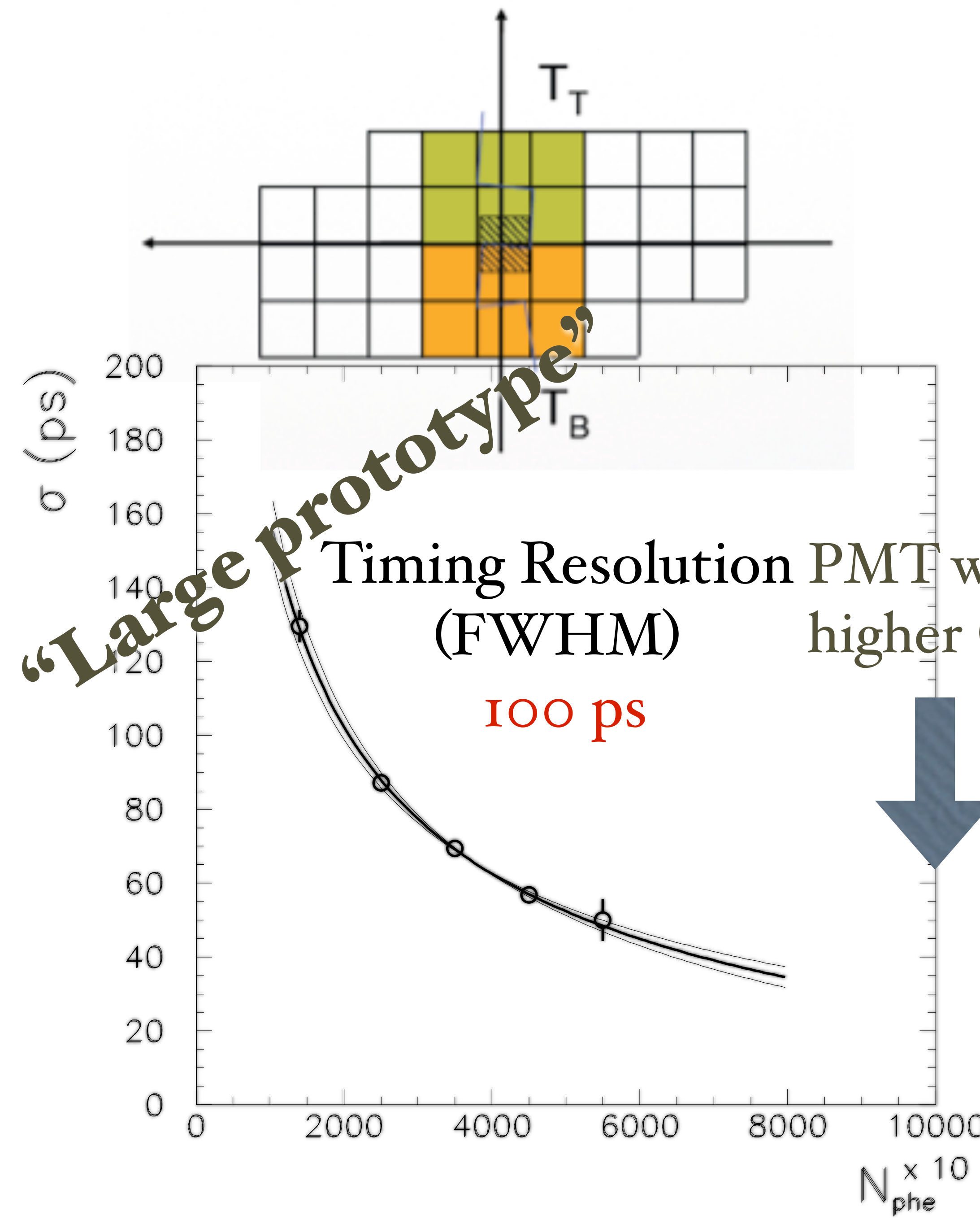
LXe energy and timing

- Determined during CEX run
- Energy resolutions contains still a large contribution from pedestal
  - solved this year
- XEC intrinsic timing resolution

π^o Run



Energy Resolution (FWHM)
(4.9 ± 0.4) %



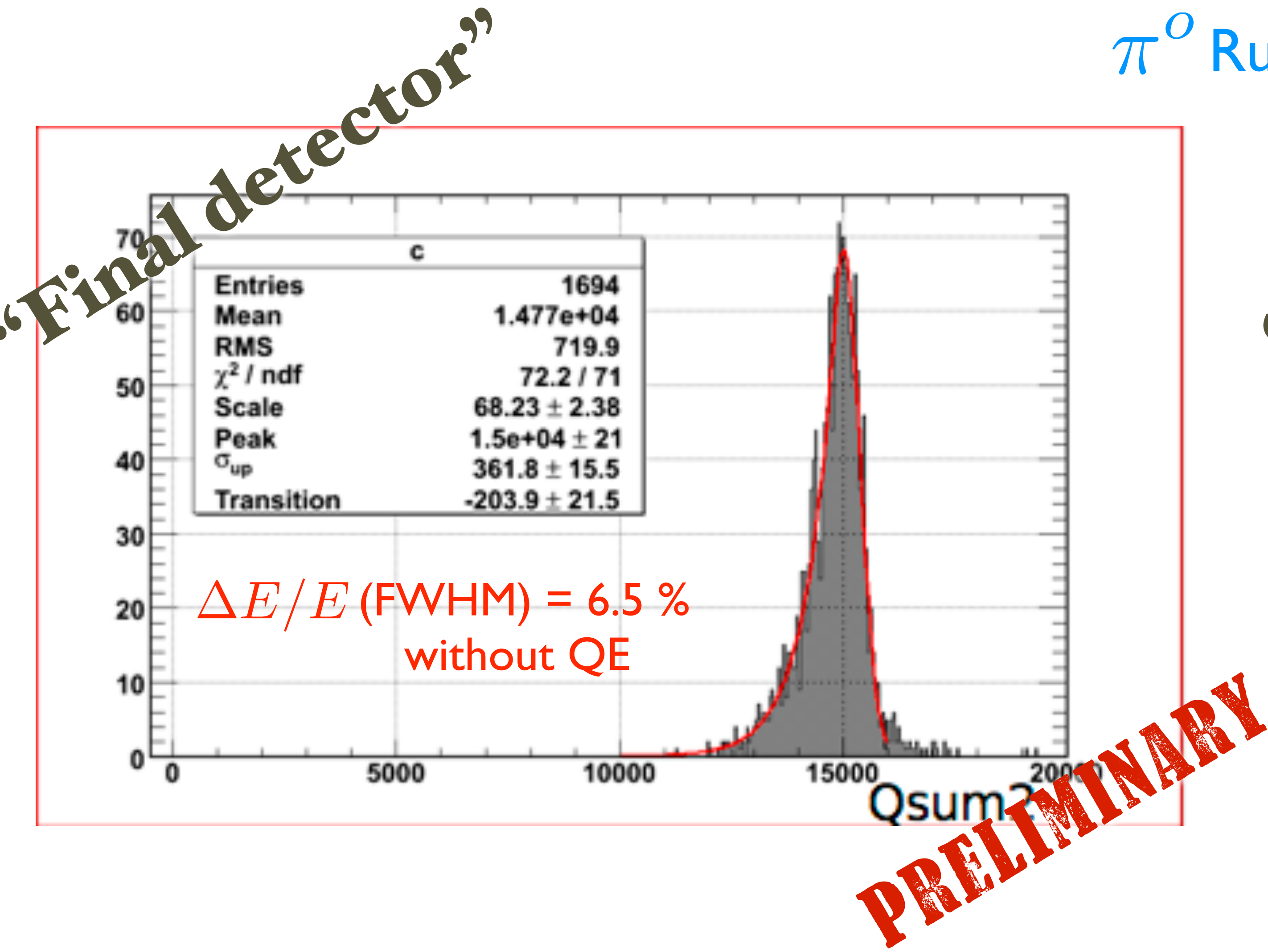
Timing Resolution (FWHM)
100 ps

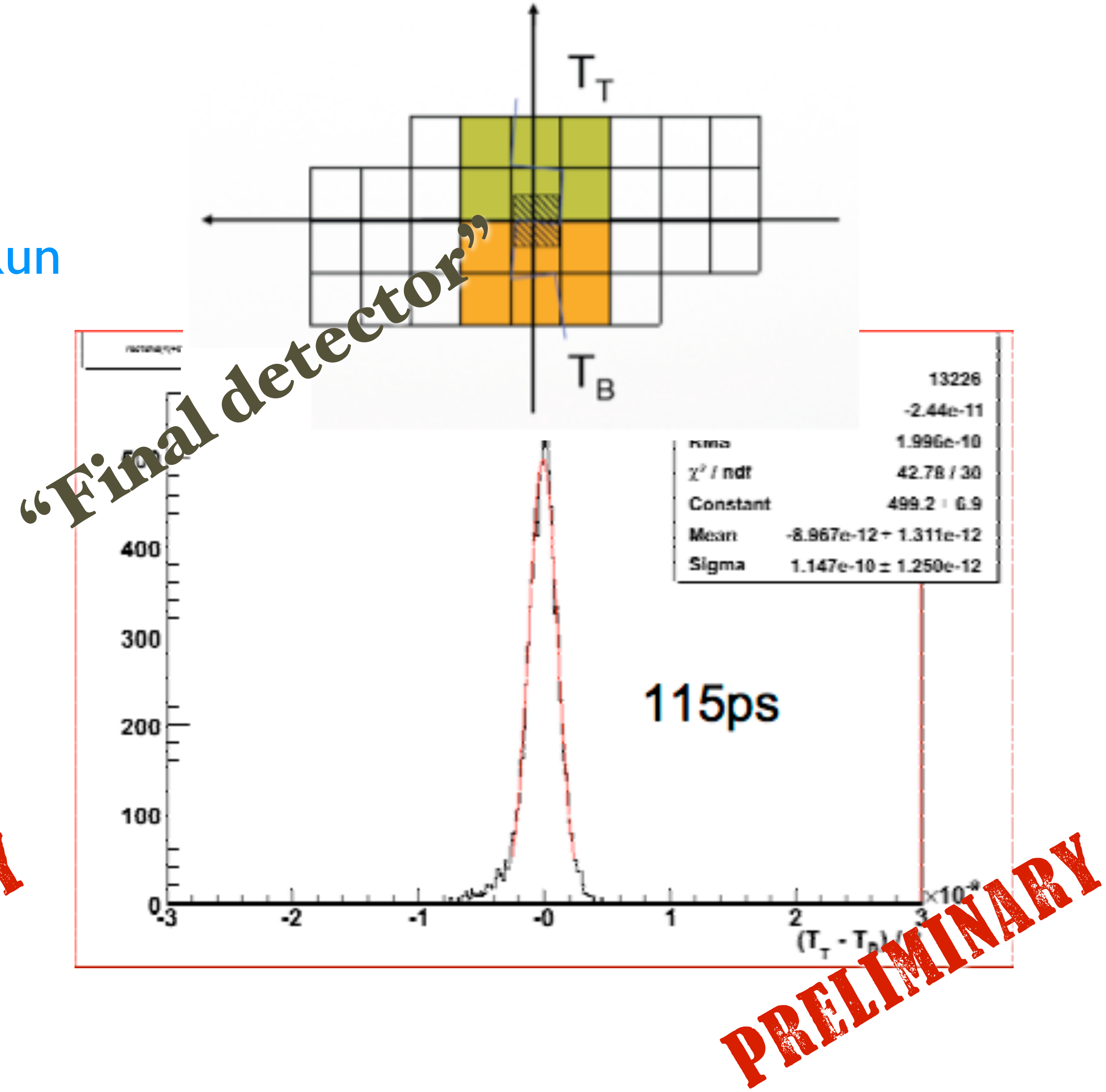
PMT with higher QE

LXe energy and timing

- Determined during CEX run
- Energy resolutions contains still a large contribution from pedestal
  - solved this year
- XEC intrinsic timing resolution

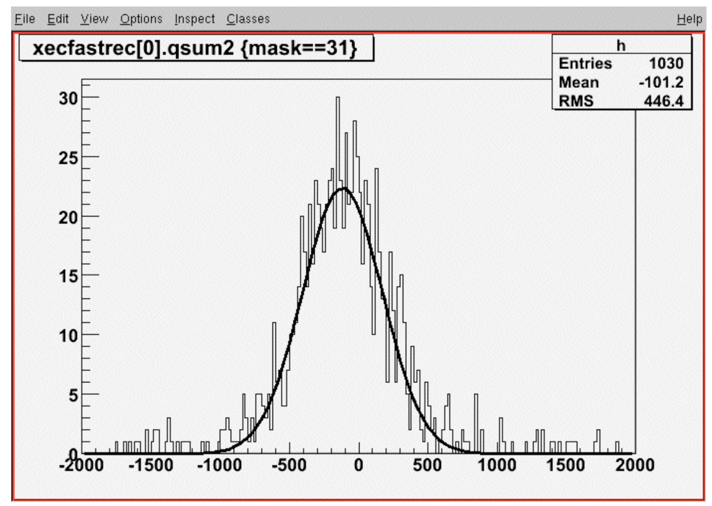
π^o Run



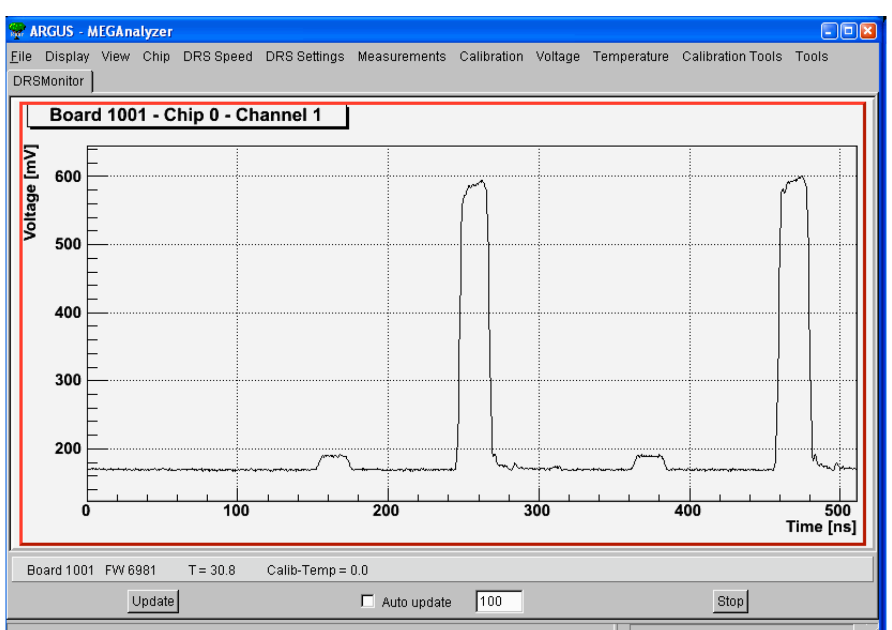


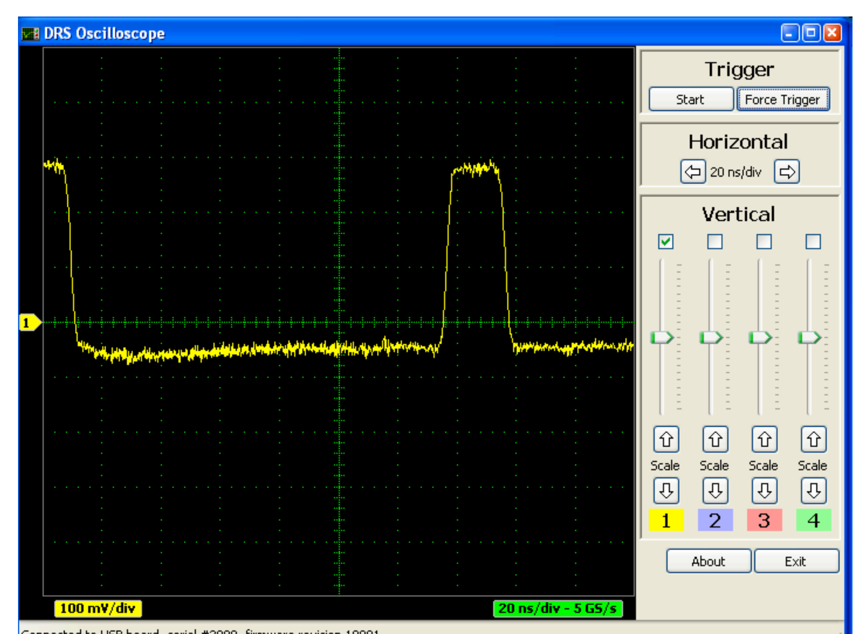
Pedestal

- Residual large (2%) contribution of pedestal due to ghost pulses in DRS2



- Should be solved with new version of chip (to be insalled end 2008)

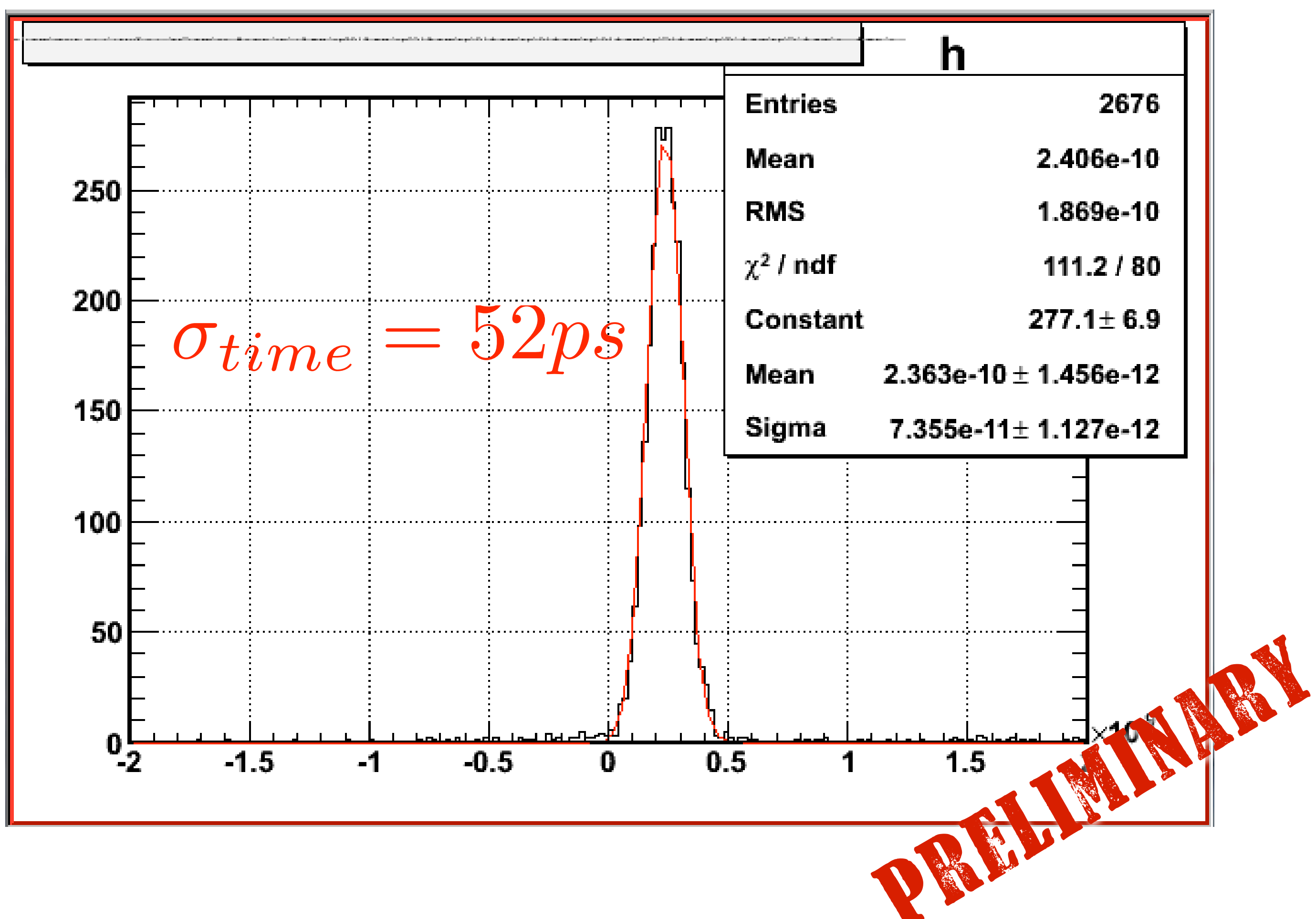




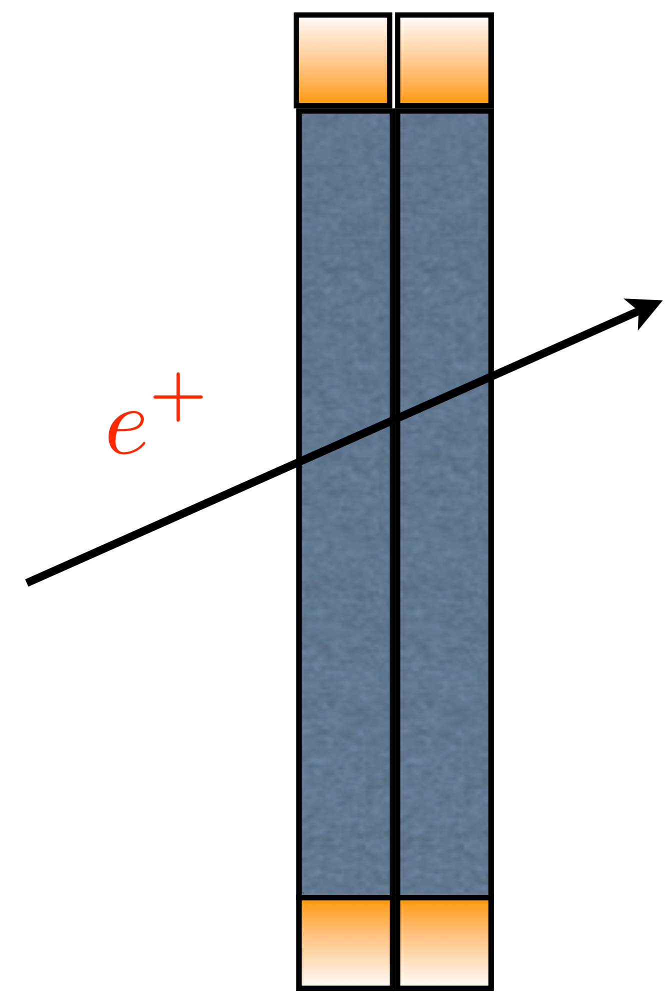
TIC timing resolution

- Michel positrons crossing two adjacent TC bars
- Difference of the two bar timings
  - Time walk
  - DRS timing calibration

Michel e+ Run



Adjacent bar



...a comment

- In 2007 we had an engineering run with (almost) all the apparatus running for ~1 month
  - no fiber TC detector, no laser, no QEs
  - Xe light yield < than expected
  - DCH failures, noisy electronics

→ partly solved

- In 2008 run
  - intensive study of detector stability (LXe) l.y. almost recovered
  - all detector & calibrations operational
  - "new" electronics available only at the end of the run
  - DCH system: some sparking chambers
  - but... more months of data taking to get a physics result!

Background and Sensitivity

	" Goal "		Perspectives for 2008	
	Measured	Simulated	Measured 2007	Applied to 2008
Gamma energy %	4.5 – 5.0		6.5	<
Gamma Timing (ns)	0.15		0.27*	<
Gamma Position (mm)	4.5 – 9.0		15	<
Gamma Efficiency (%)	>40		>40	>
e^+ Timing (ns)	0.1		0.12*	=
e^+ Momentum (%)		0.8	2.1	<
e^+ Angle (mrad)		10.5	17.**	=
e^+ Efficiency (%)		65	65	<?
Muon decay Point (mm)		2.1	3.**	=
Muon Rate (10^8/s)	0.3		0.3***	0.26***
Running Time (weeks)	100			12
Single Event Sens (10^{-13})	0.5			20-40
Accidental Rate (10^{-13})	0.1 – 0.3			10
# Accidental Events	0.2 - 0.5			O(1)
90% CL Limit	2 10^{-13}			< 10^{-11}

1 week = 4 x 10^5 s   * Added 250 ps due to present estimate of DRS systematics

** Very pessimistic

*** The muon rate is optimized to improve the limit

Perspective

- We had an engineering run in 2007 and a second engineering and calibration run between April and August 2008;
- We started the physics data taking on 9/12;
  - the detector is getting more and more in its optimal shape
- We expect first results in 2009
  - use the beginning of 2009 to deal with few upgrades
- We are confident to reach a sensitivity of few $\times 10^{-13}$ in $\mu \rightarrow e\gamma$ BR in 3 years of acquisition time.

Back-up slides