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

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Low Energy Precision Electroweak Physics in the LHC Era
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The MEG collaboration

Tokyo U.
Waseda U.
KEK

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

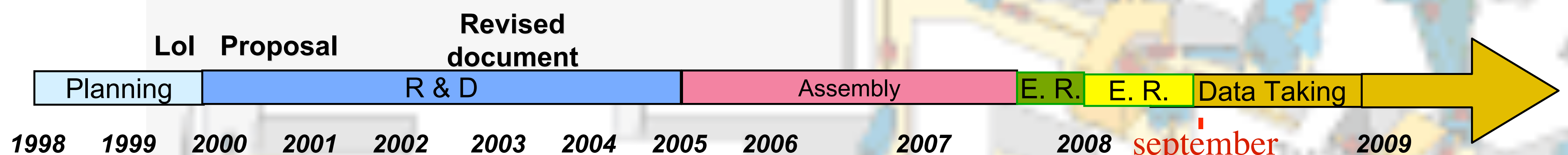
PSI

UCIrvine

JINR Dubna
BINP Novosibirsk

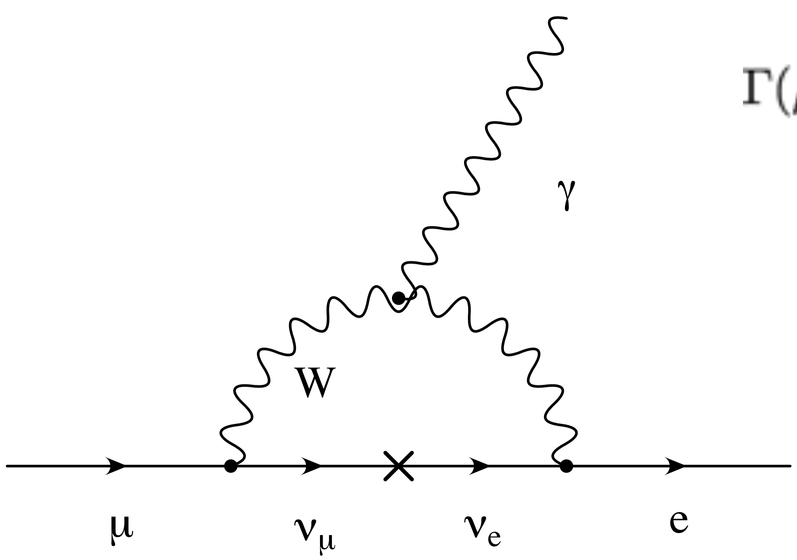
Outline

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



The μ→eγ decay

- The theoretical framework has been thoroughly covered by the previous speakers;
- The μ→eγ decay is forbidden in the Standard Model of elementary particles because of the (accidental) conservation of lepton family numbers;
- The introduction of neutrino masses and mixings induces μ→eγ radiatively, but at a negligible level



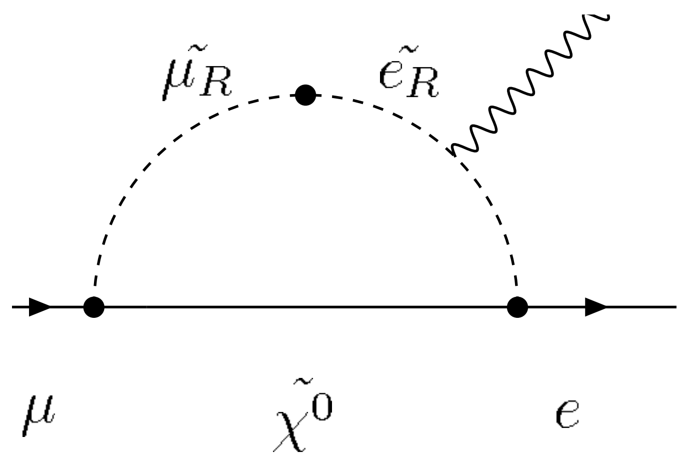
$$\Gamma(\mu\to e\gamma) \approx \underbrace{\frac{G_F^2 m_\mu^5}{192\pi^3}}_{\mu-\mathrm{decay}} \underbrace{\left(\frac{\alpha}{2\pi}\right)}_{\gamma-\mathrm{vertex}} \underbrace{\sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2}{M_W^2}\right)}_{\nu-\mathrm{oscillation}}$$

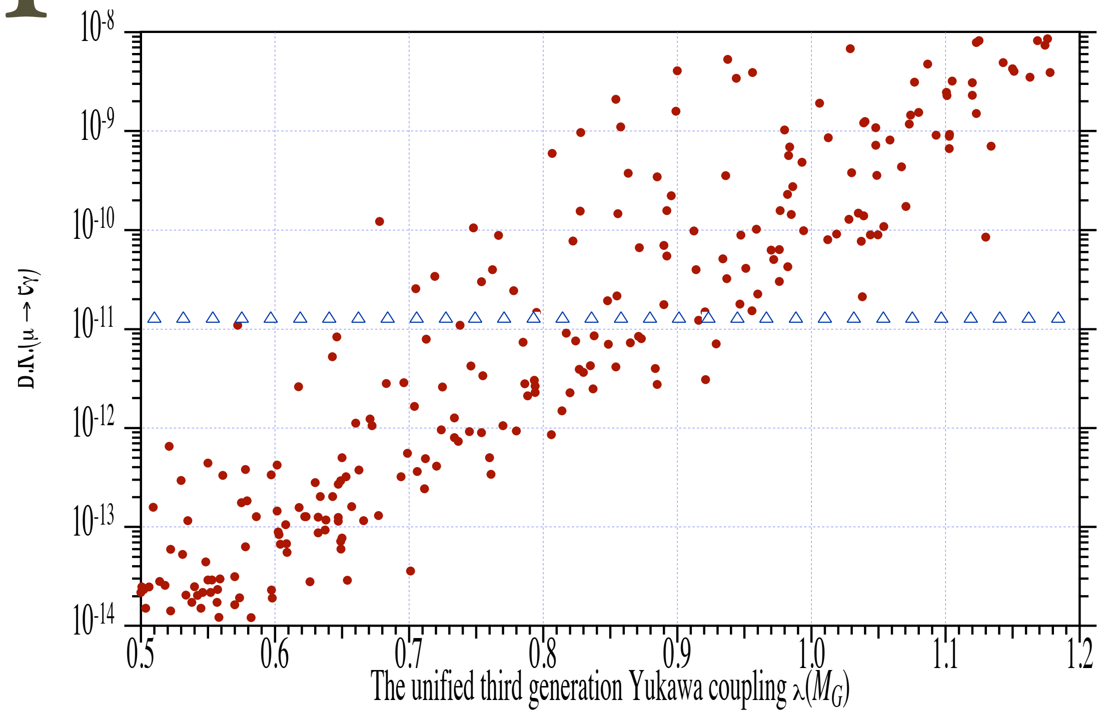
$$\approx \frac{G_F^2 m_\mu^5}{192\pi^3}\left(\frac{\alpha}{2\pi}\right)\sin^2 2\theta_\odot \left(\frac{\Delta m^2}{M_W^2}\right)^2,$$

Relative probability ~ 10^{-55}

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

For instance... predictions

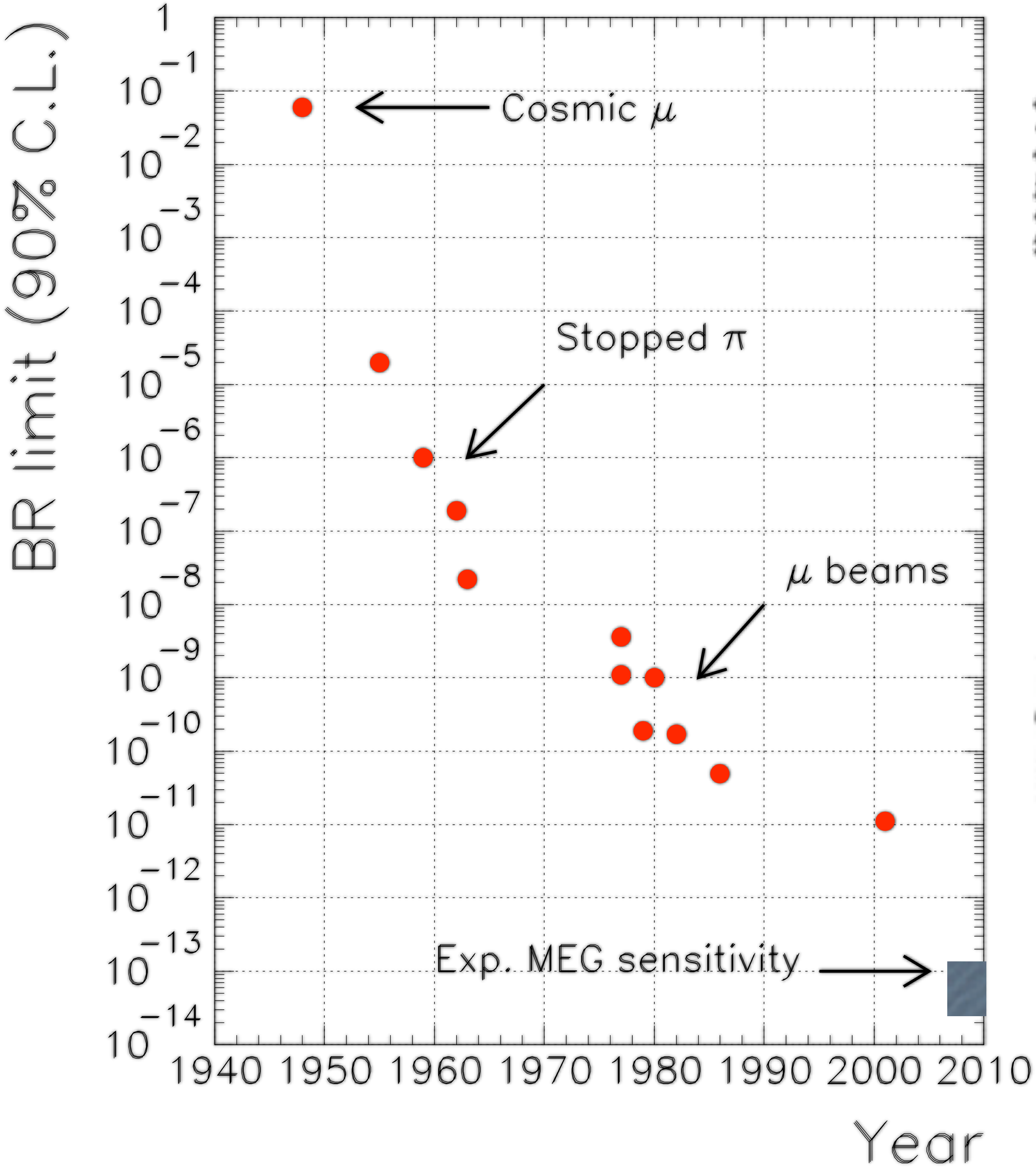


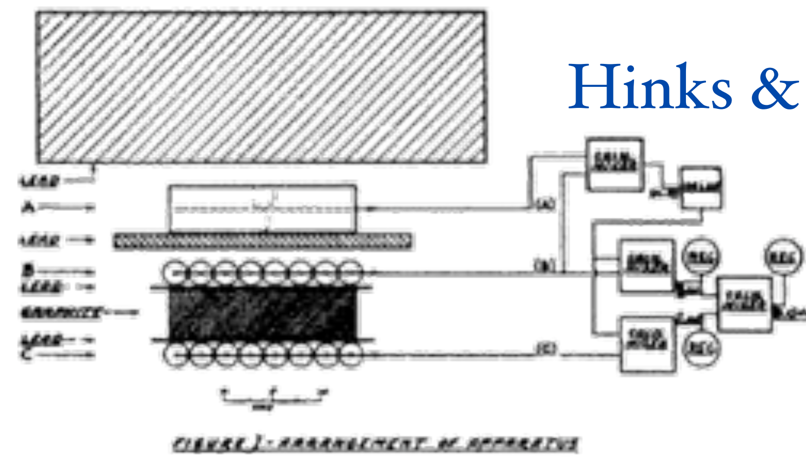


- SUSY SU(5) predictions: LFV induced by finite slepton mixing through radiative corrections. The mixing could be large due to the top-quark mass at a level of 10^{-12} - 10^{-15}
- SO(10) predicts even larger BR:
    - m(τ)/m(μ) enhancement
- Models with right-handed neutrinos also predict large BR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

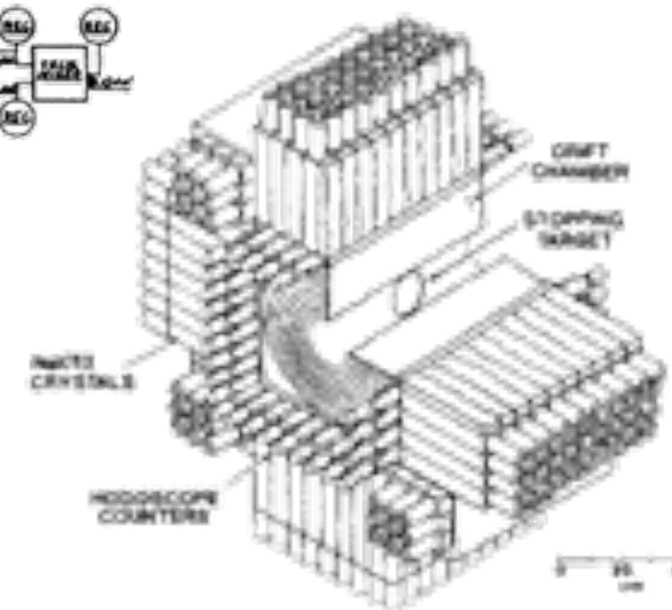
- In principle possibility to distinguish between various models e.g. angular distribution of the photon with respect to the muon spin

Historical perspective

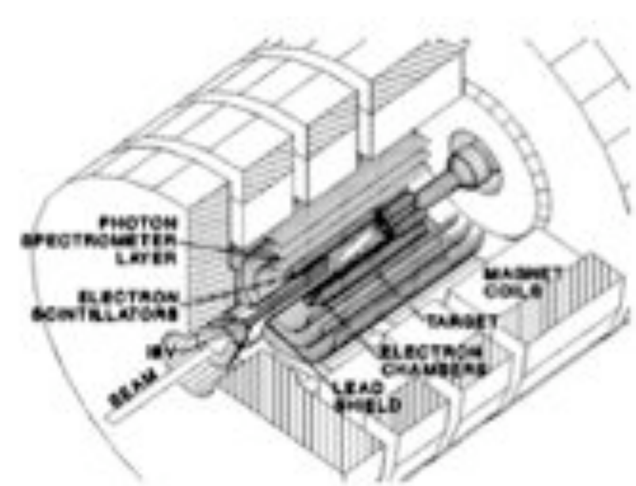




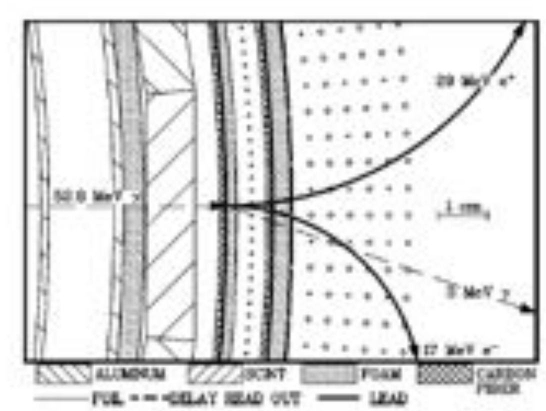
Hinks & Pontecorvo



Crystal Box



MEGA

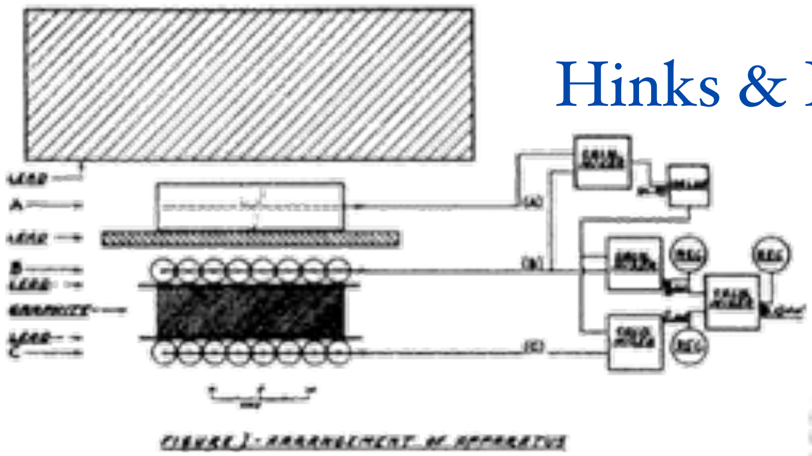


Each improvement linked to an improvement in the technology either in the beam or in the detector

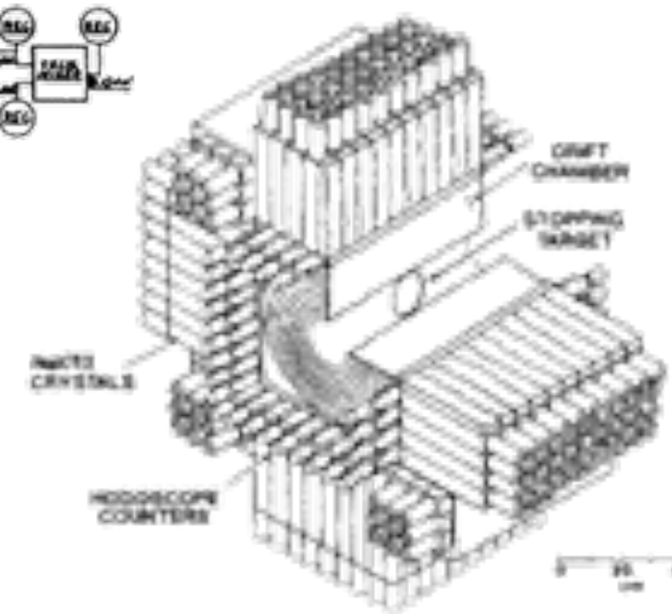
Historical perspective

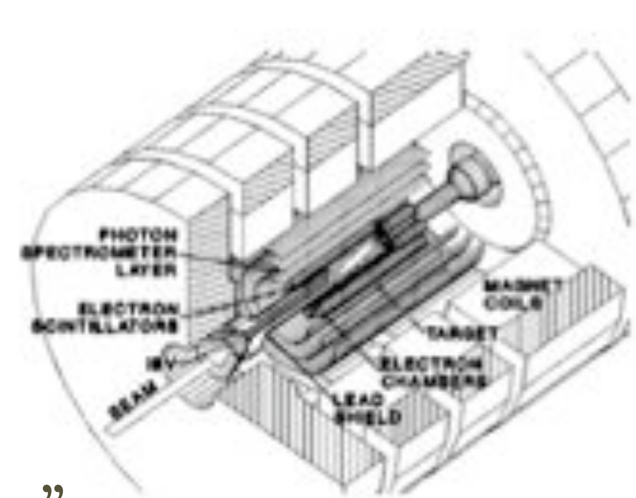
- All experiments stop the incoming muon
- H-P: Soon after the experiment of Conversi *et al.* ($\pi \neq \mu$)
- CB: Almost 4π coverage and calorimetric e.m. detector
- MEGA: Both electron and photon where detected by "charged particles" tracks

Hinks & Pontecorvo

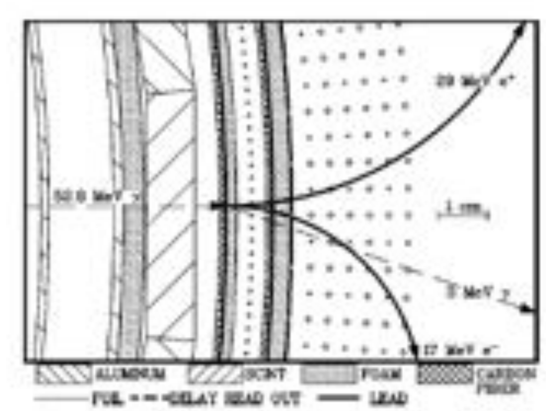


Crystal Box





MEGA



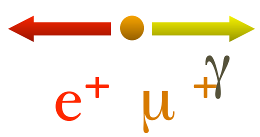
Always a trade-off between various elements of the detector to achieve the best "sensitivity"

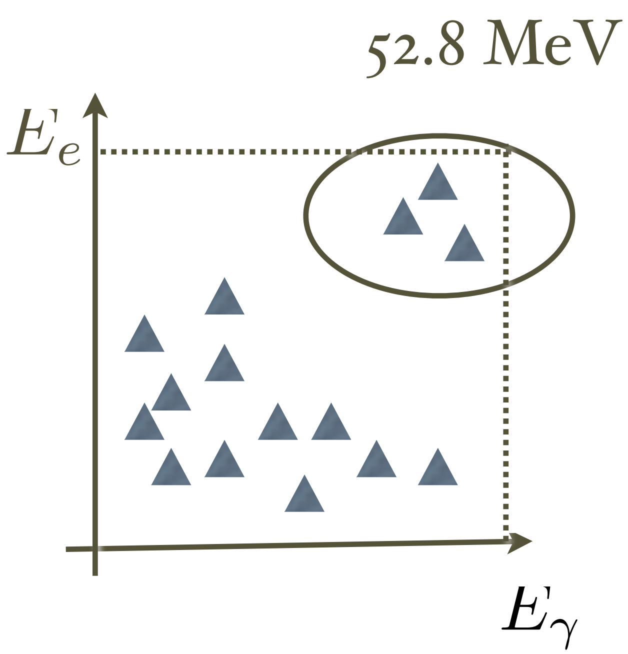
Signal and Background

- 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?

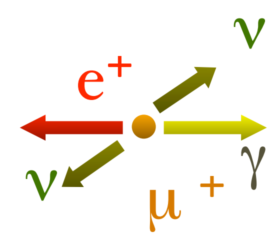
Signal and Background

"Signal"



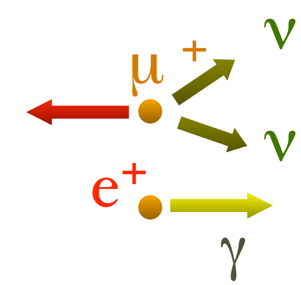


"Prompt"



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

"Accidental"



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

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

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

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

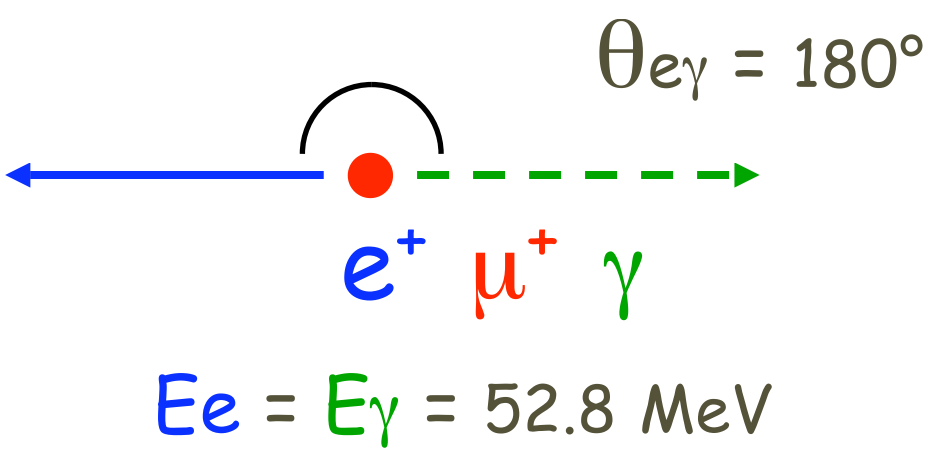
The accidental background is dominant and it is determined by the experimental resolutions

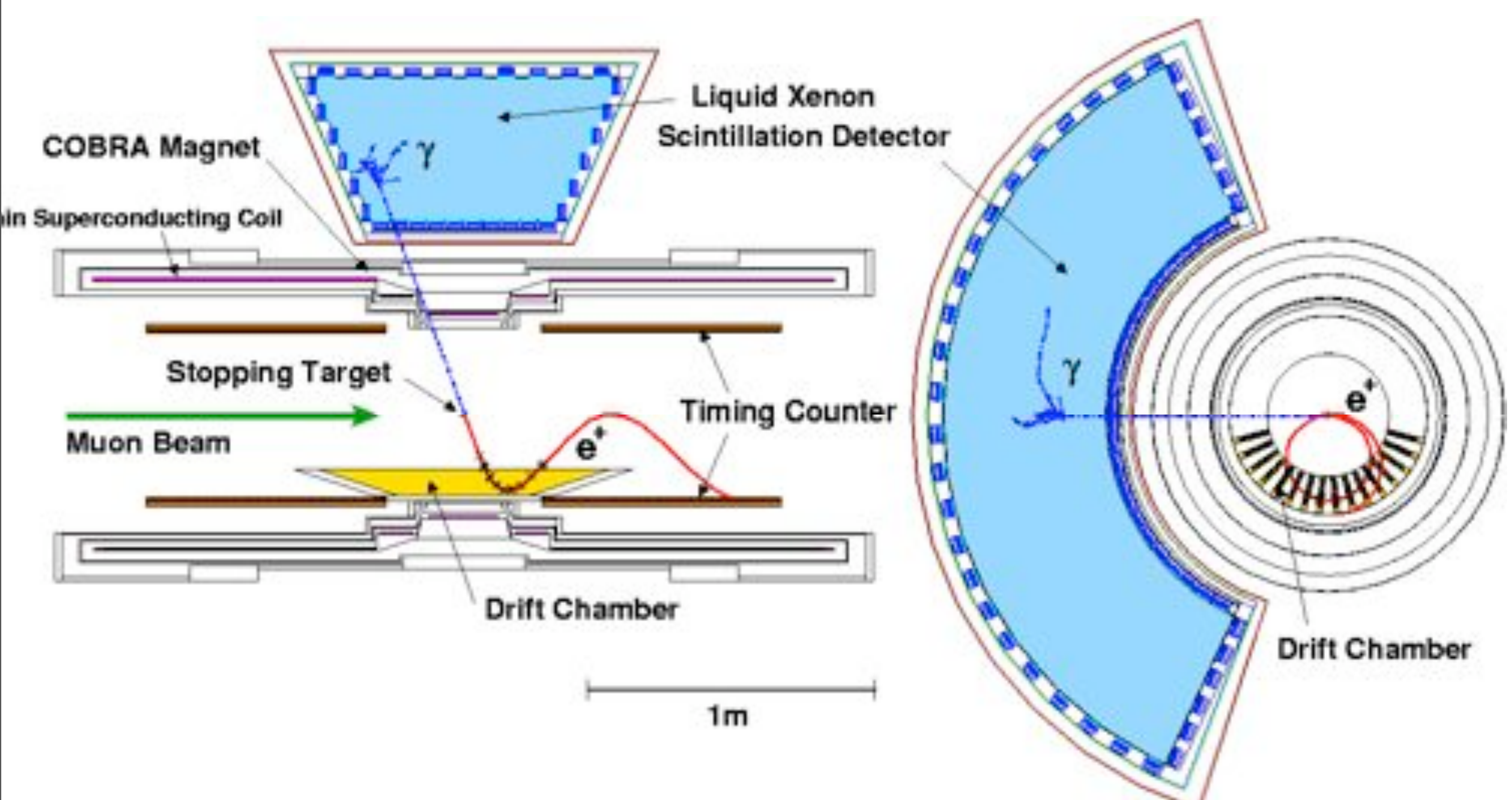
Exp./Lab	Year	ΔEe/Ee (%)	ΔEγ /Eγ (%)	Δteγ (ns)	Δθeγ (mrad)	Stop rate (s^{-1})	Duty cyc. (%)	BR (90% CL)
SIN	1977	8.7	9.3	1.4	-	5×10^{5}	100	3.6×10^{-9}
TRIUMF	1977	10	8.7	6.7	-	2×10^{5}	100	1×10^{-9}
LANL	1979	8.8	8	1.9	37	2.4×10^{5}	6.4	1.7×10^{-10}
Crystal Box	1986	8	8	1.3	87	4×10^{5}	(6..9)	4.9×10^{-11}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





- Stopped beam of >10^7 μ /sec in a 175 μm target
- γ detection

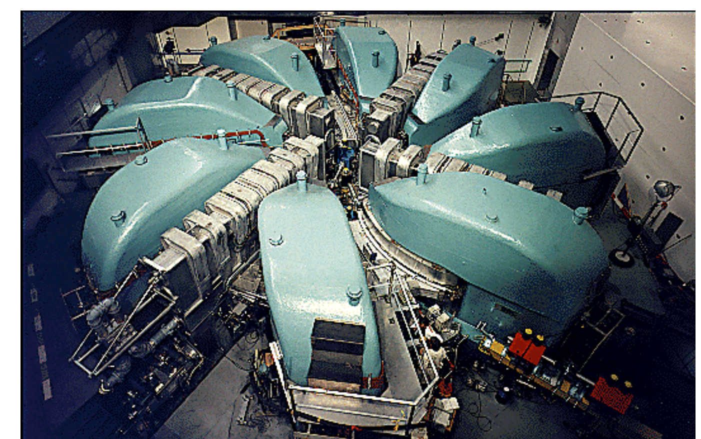
  Liquid Xenon calorimeter based on the scintillation light
  - fast: 4 / 22 / 45 ns
  - high LY: ~ 0.8 * NaI
  - short X_0: 2.77 cm
- e^+ detection

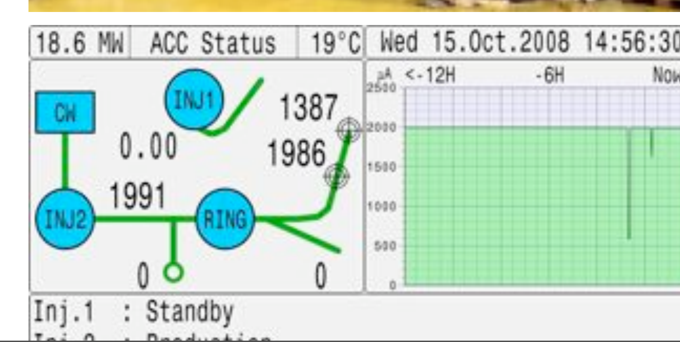
  magnetic spectrometer composed by solenoidal magnet and drift chambers for momentum

  scintillation counters for timing

Machine

- "Sensitivity" proportional to the number of muons observed
- Find a 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 x 10^8 muons/sec @ 2 mA



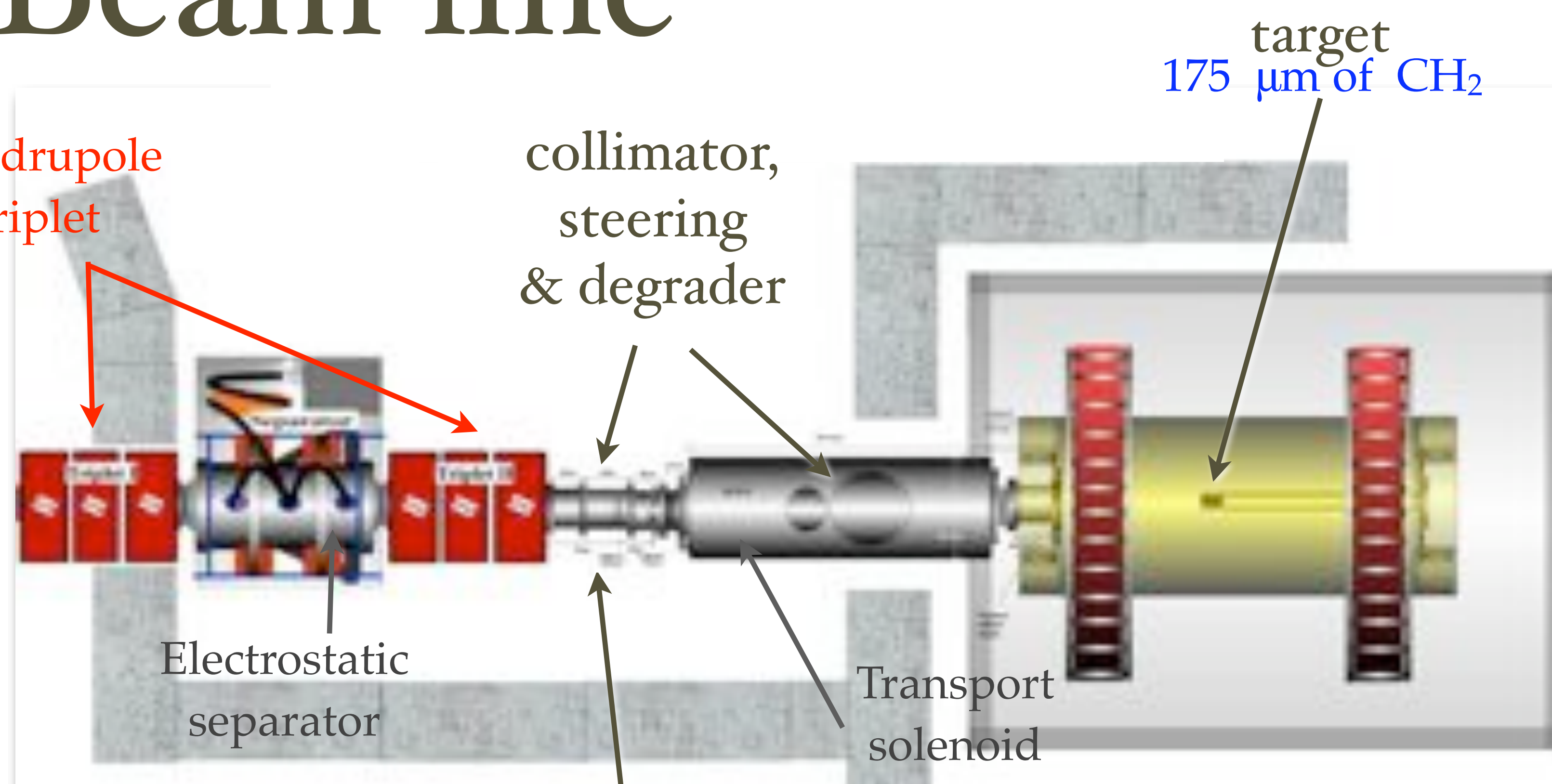


Beam line

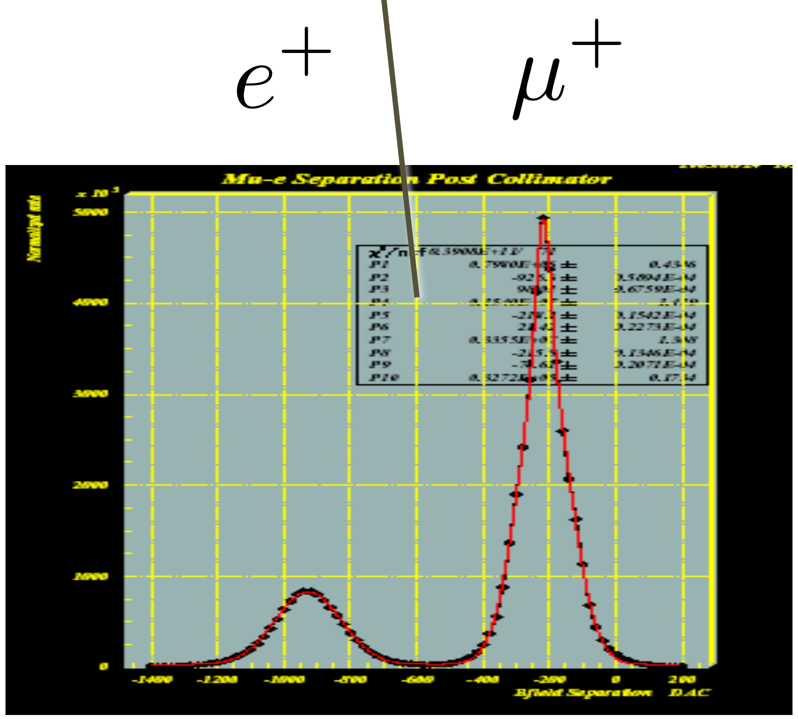
πE5 beam line at PSI

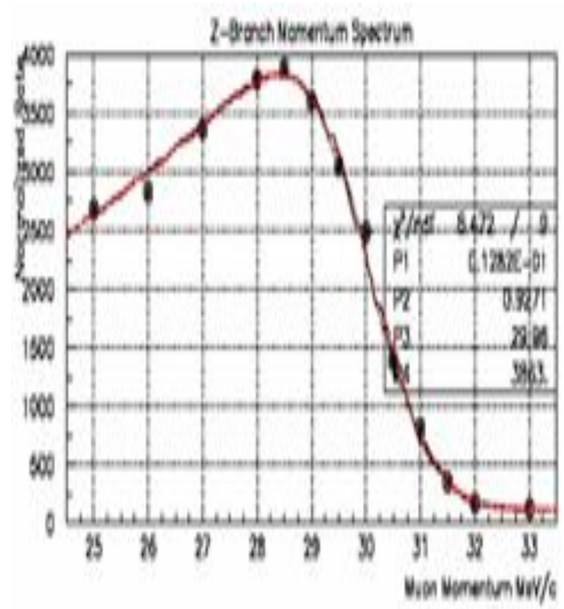
Optimization of the beam elements:

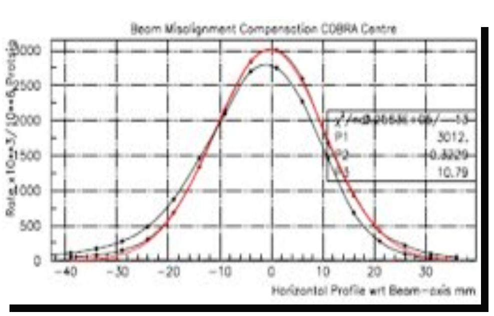
- Muon momentum ~ 29 MeV/c
- Wien filter for μ/e separation
- Solenoid to couple beam and spectrometer (BTS)
- Degrader to reduce the momentum for a 175 μm target



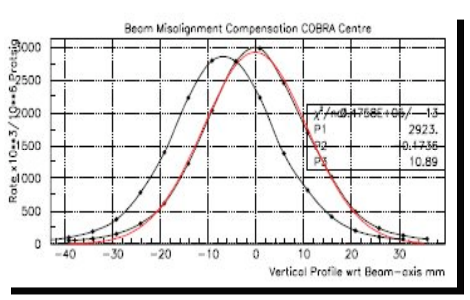
• μ/e separation	11.8 cm (7.2 σ)
• Rμ (exp. on target)	$6.4*10^7$ μ^+/s
• μ spot (exp. on target)	$\sigma_V \approx \sigma_H \approx$ 11 mm







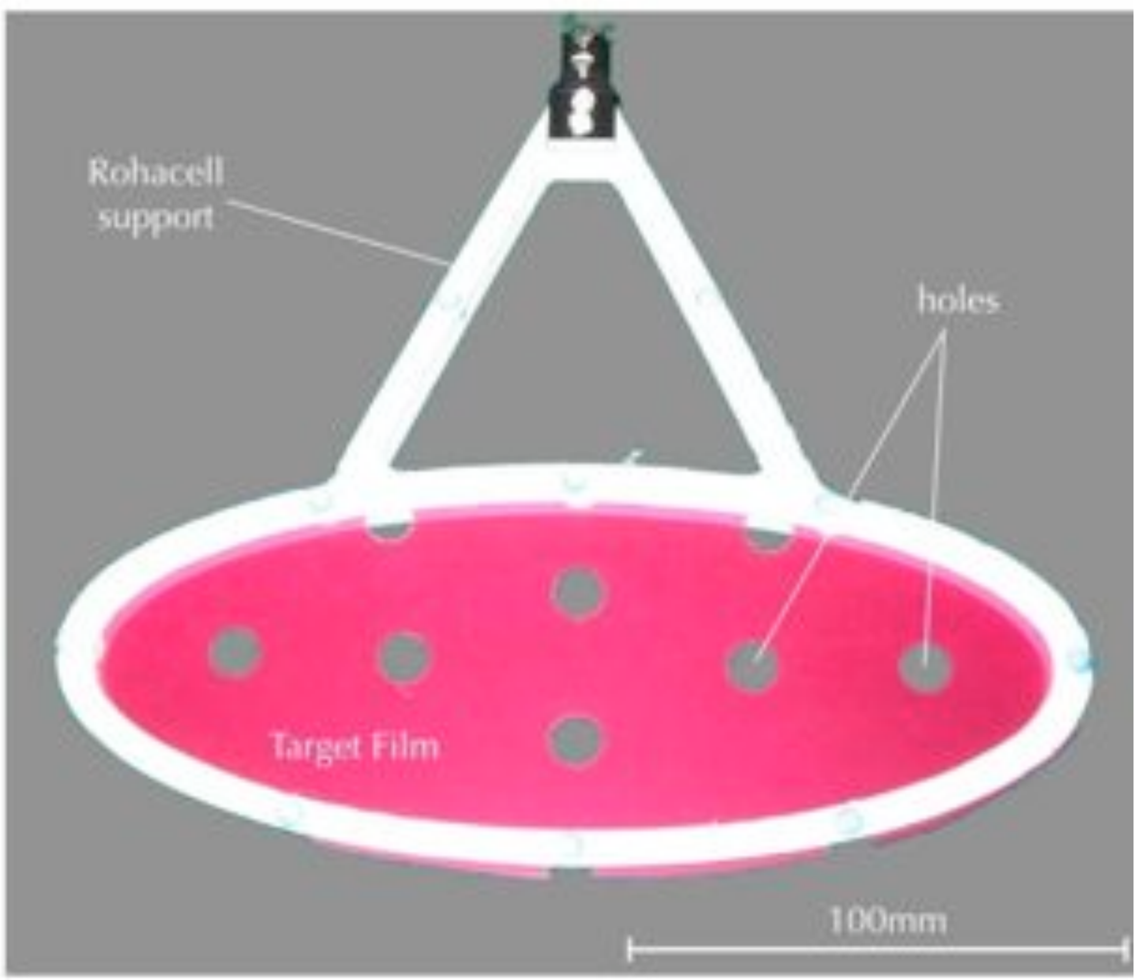
$\sigma_x = 11$ mm



$\sigma_y = 11$ mm

Target

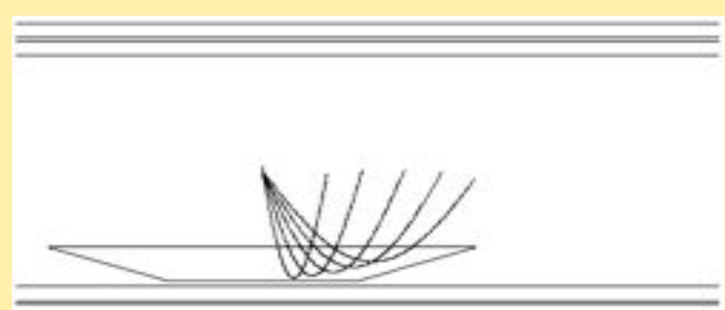
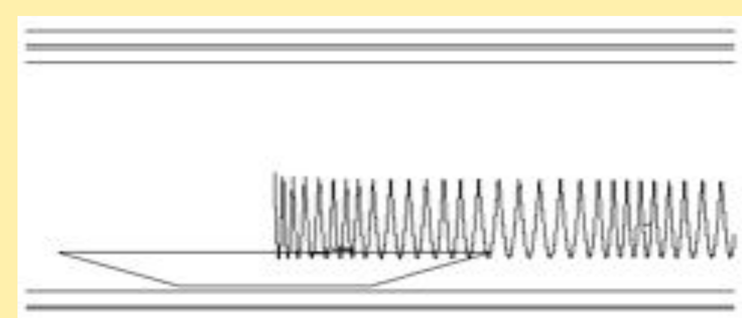
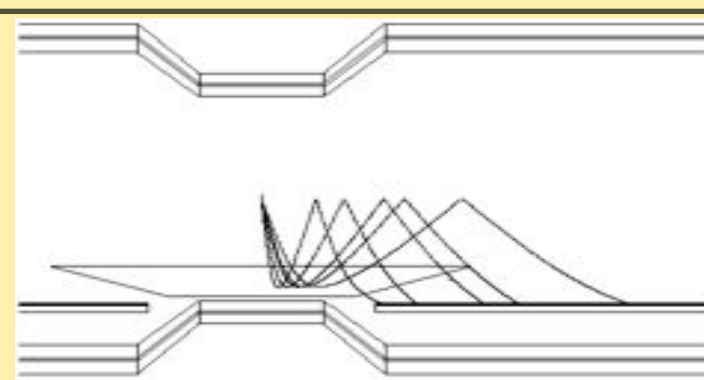
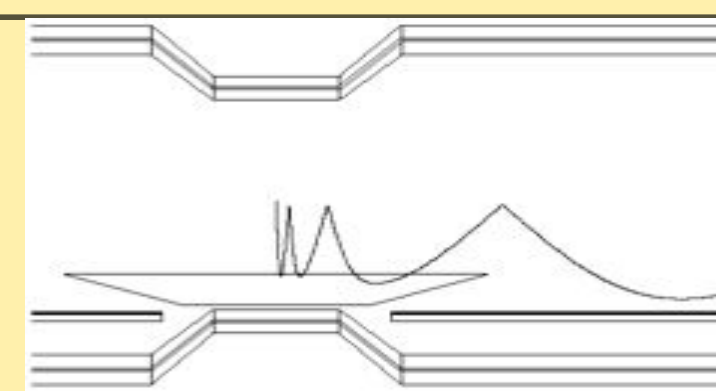
- Stop muons on the thinnest possible target 175 µm CH_2:
  - need low energy muons (lots of multiple scattering) but...
  - the MS of the decaying positron is minimized: precise direction/ timing
  - bremsstrahlung reduced
  - the conversion probability of the photon in the target is negligible



Holes to study position reconstruction resolution

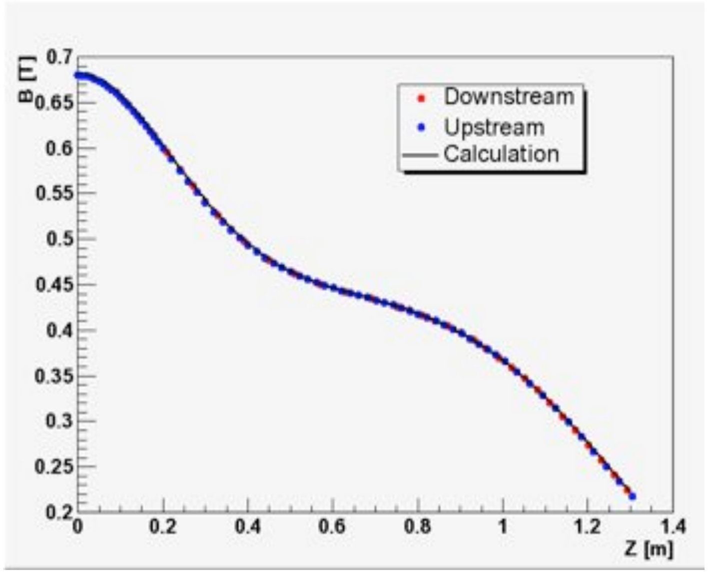
COBRA spectrometer

- 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		

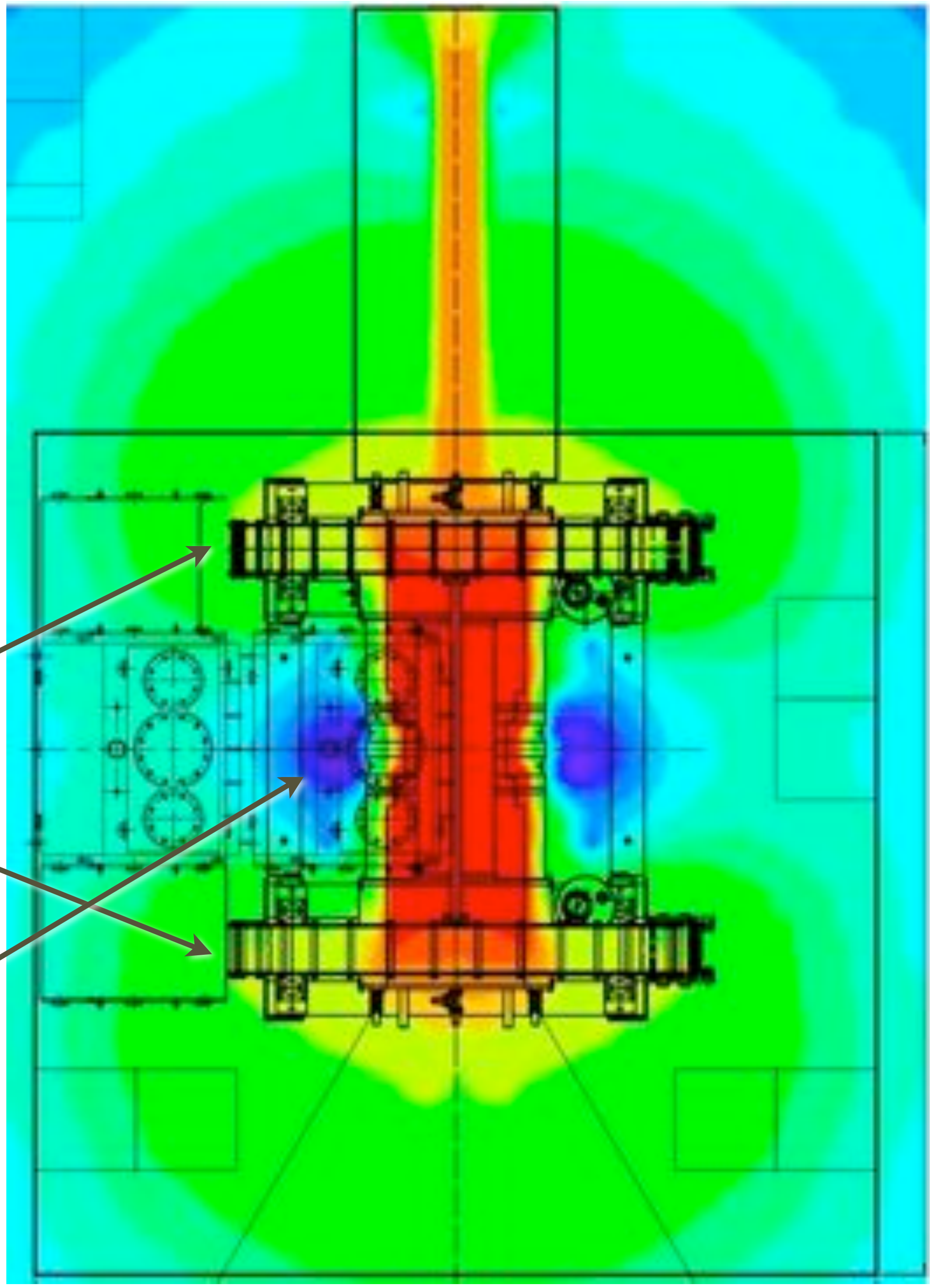
COBRA spectrometer

Non uniform magnetic field decreasing from the center to the periphery

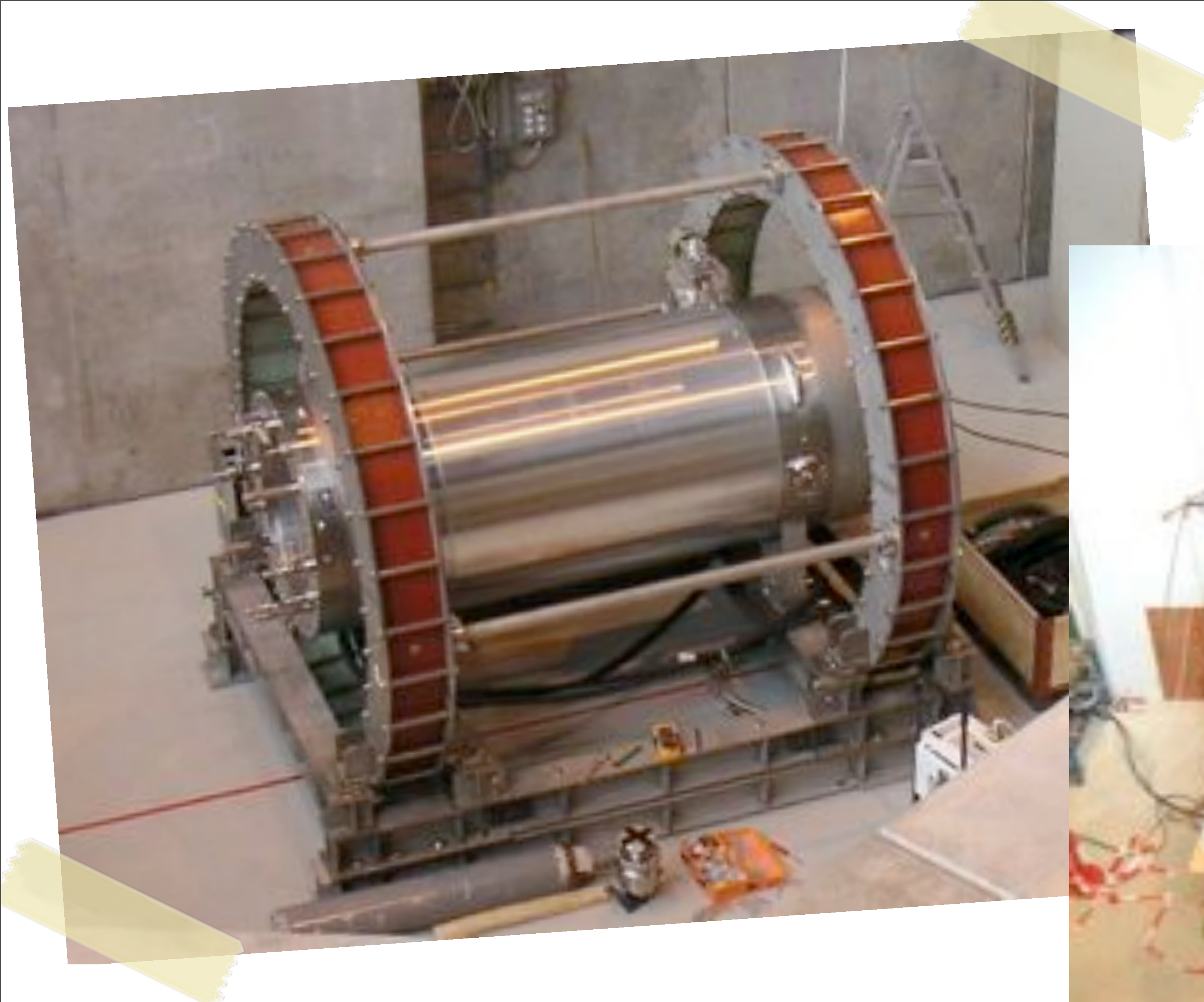


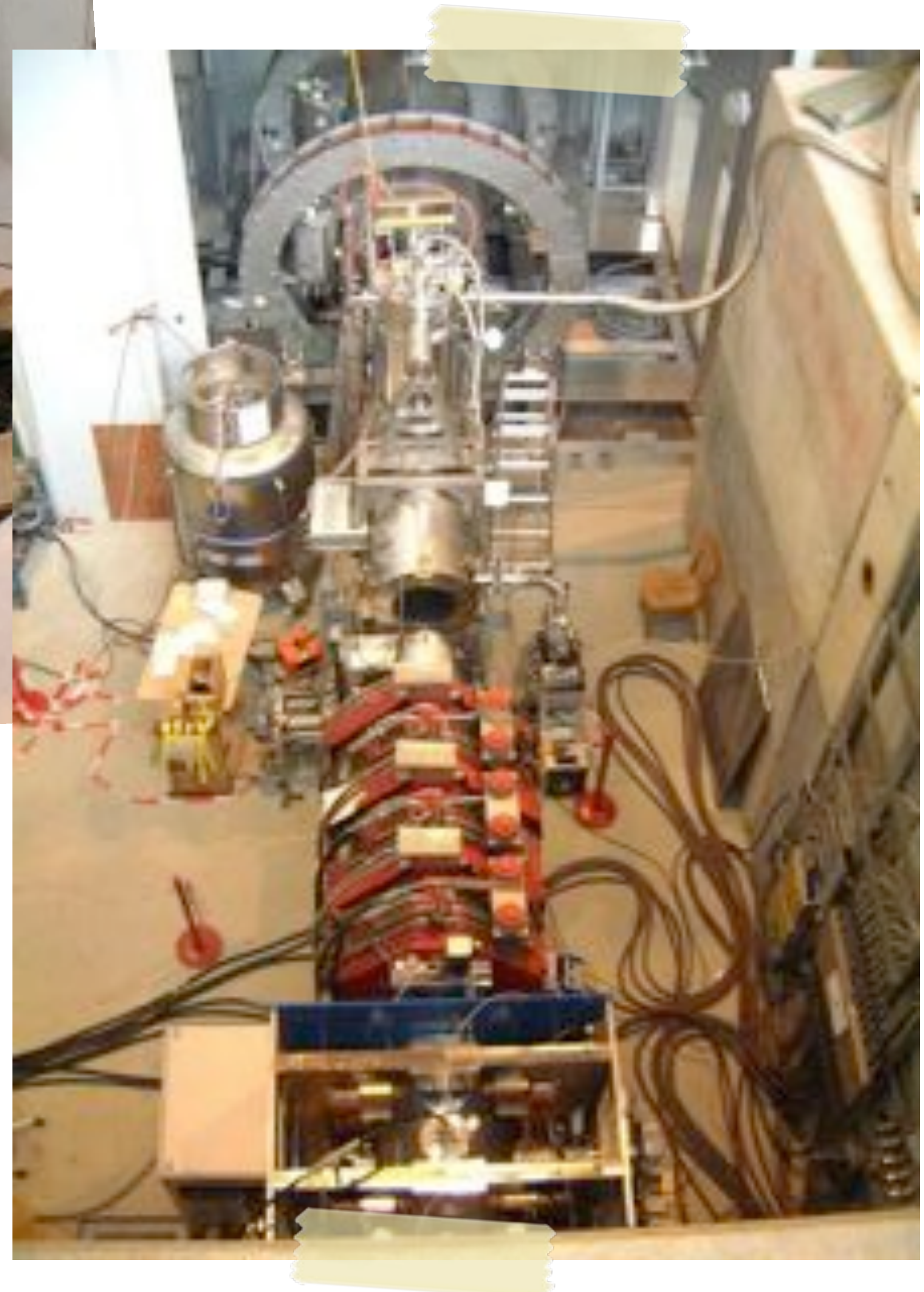
Compensation coil for LXe calorimeter

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



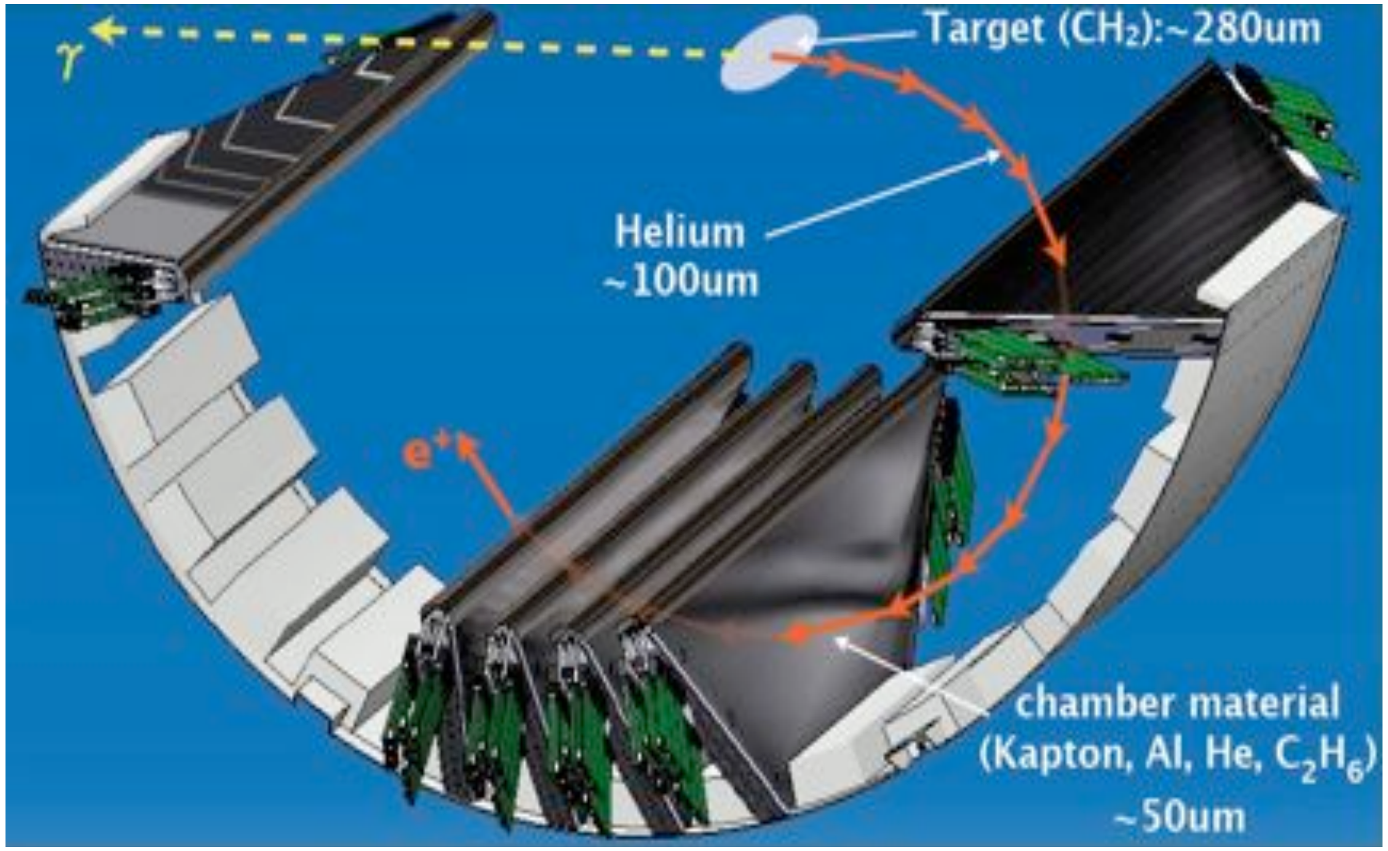
- The superconducting magnet is very thin ($0.2\ X_0$)
- Can be kept at 4 K with GM refrigerators (no usage of liquid helium)



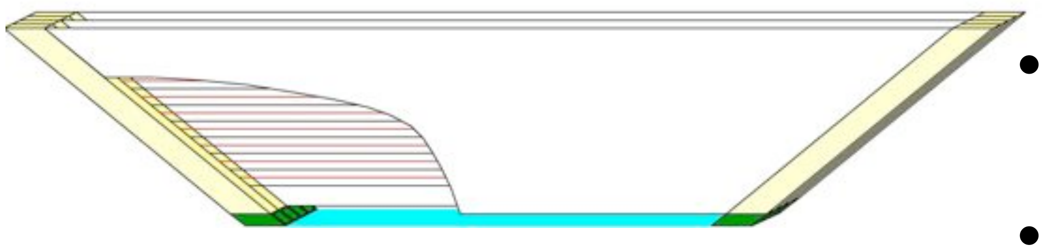


Positron tracker

- Excellent momentum resolution at ~50 MeV
- The energy is very low hence the multiple scattering is important
  - we tend to loose position/energy resolution
  - As little material as possible: balance the uncertainty on the track measurement with the expected multiple scattering
- The volumes of the chambers are independent
  - too much high-Z gas otherwise
  - find a clever way for a good z-reconstruction



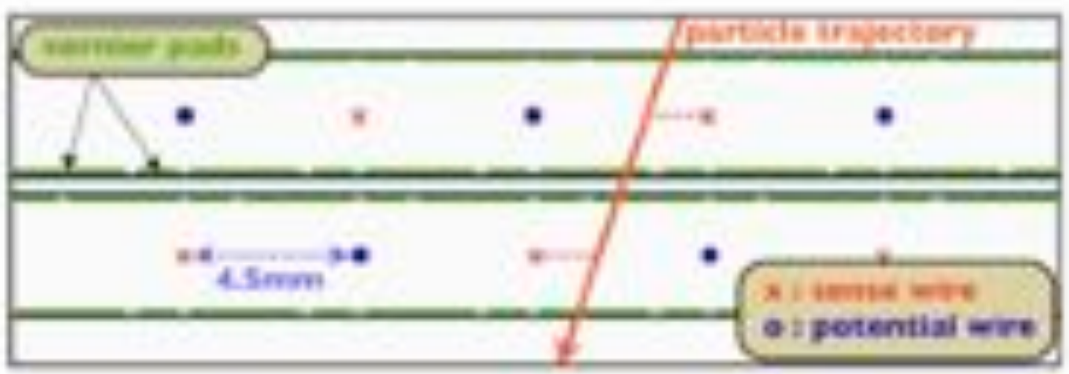
Positron Tracker

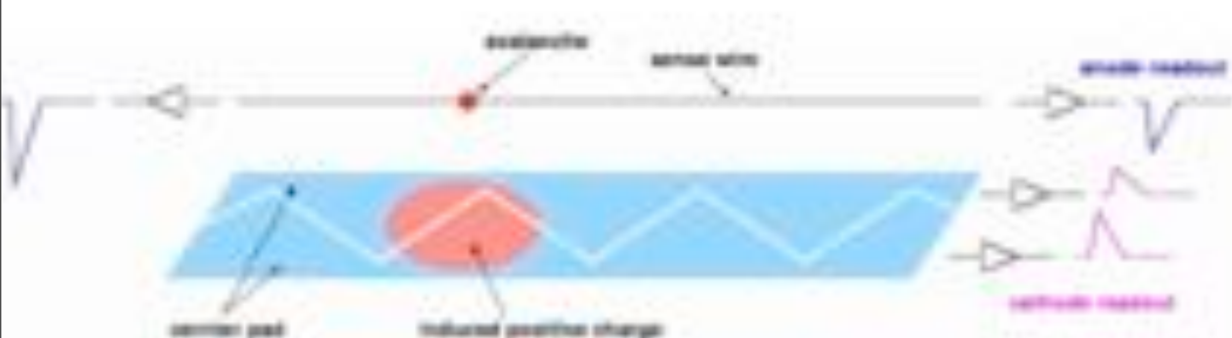


- 16 chambers radially aligned with 10°intervals
- 2 staggered arrays of drift cells
- 1 signal wire and 2 x 2 vernier cathode strips made of 15 µm kapton foils and 0.45 µm aluminum strips
- Chamber gas: $He\text{-}C_2H_6$ mixture

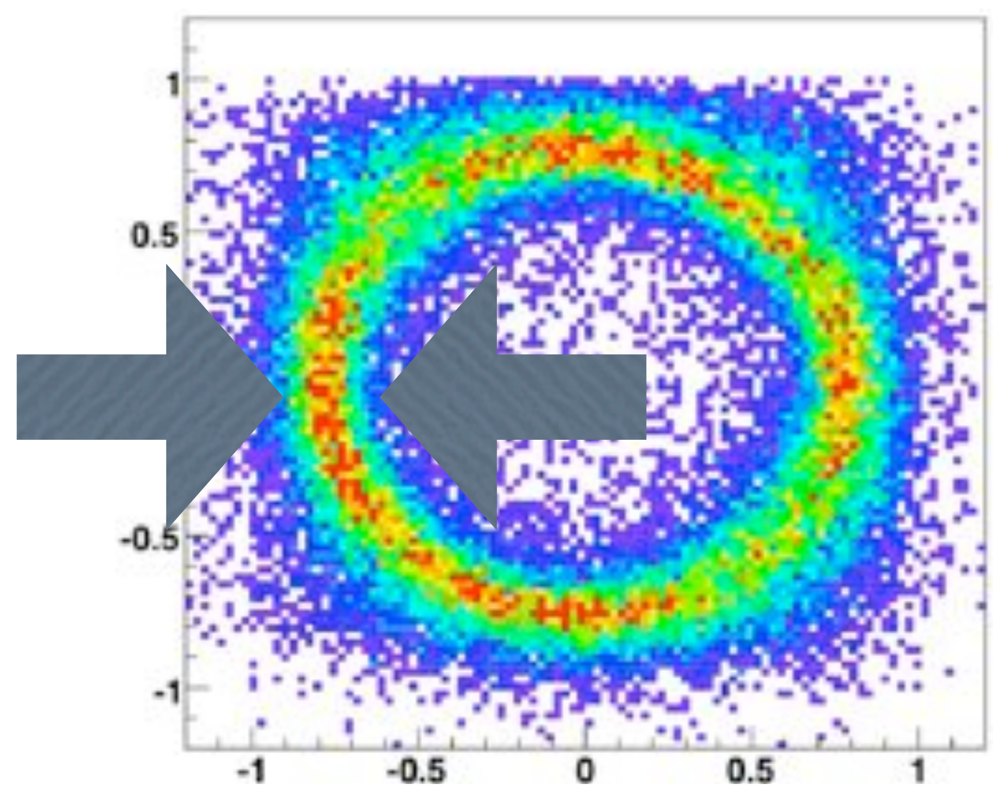
- Within one period, the *fine structure* is given by the Vernier circle

transverse coordinate (t drift)

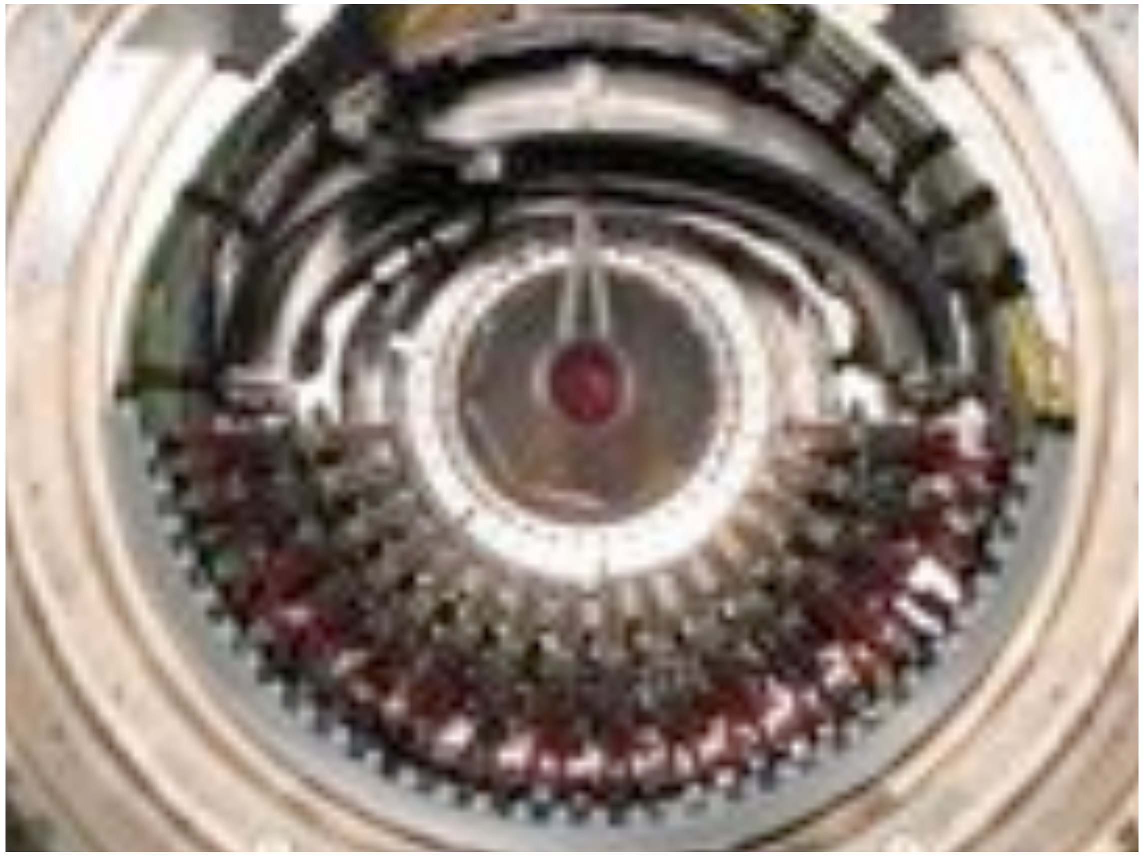


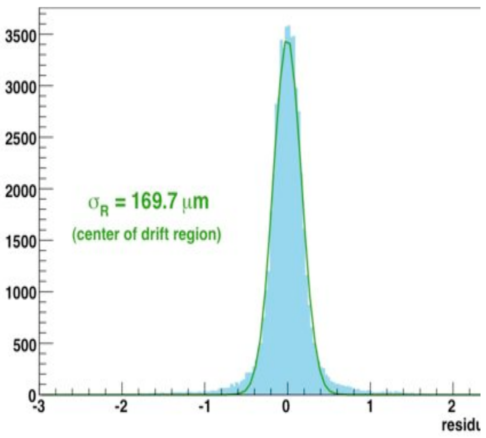


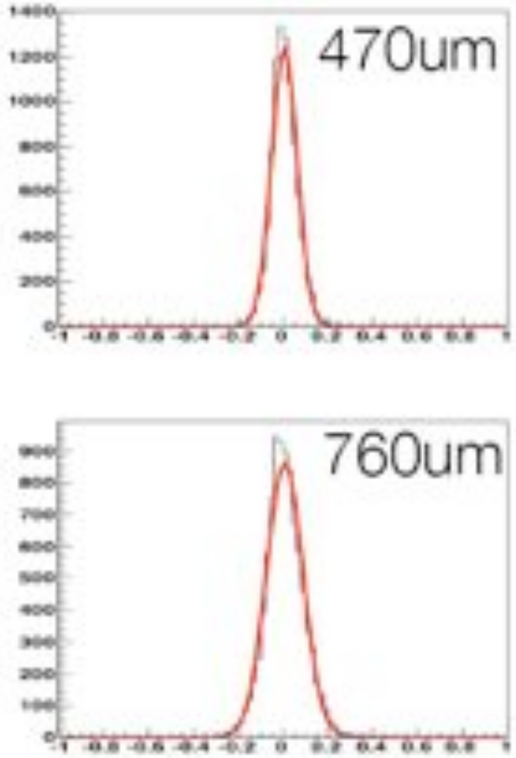
longitudinal coordinate (charge division + Vernier)

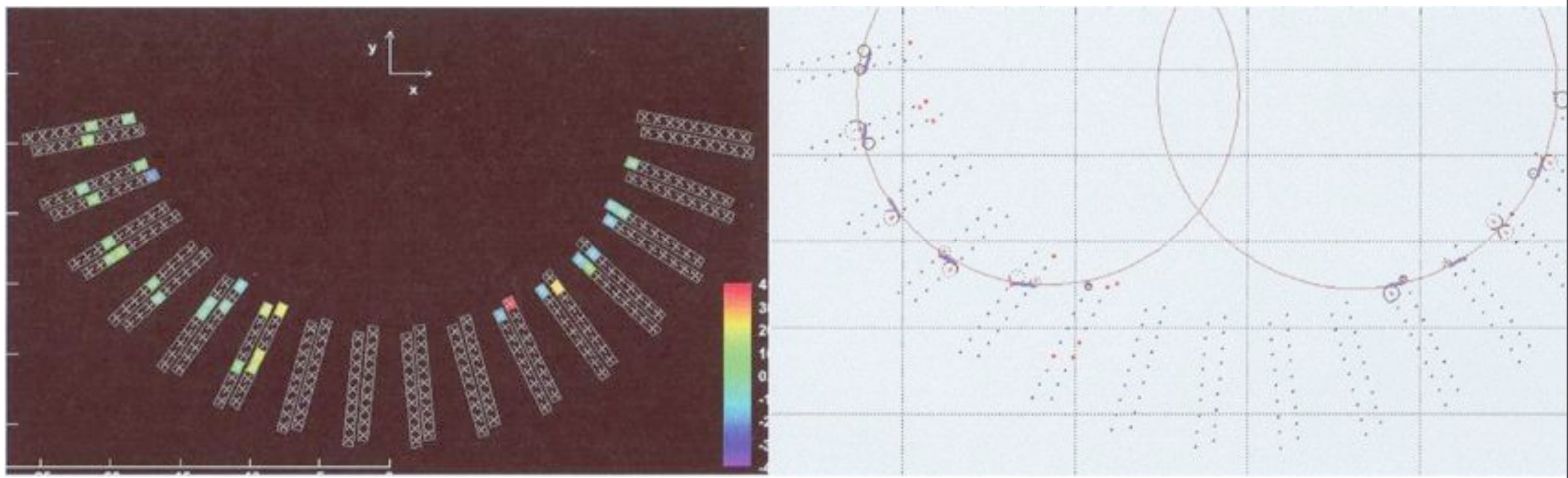


Drift chambers



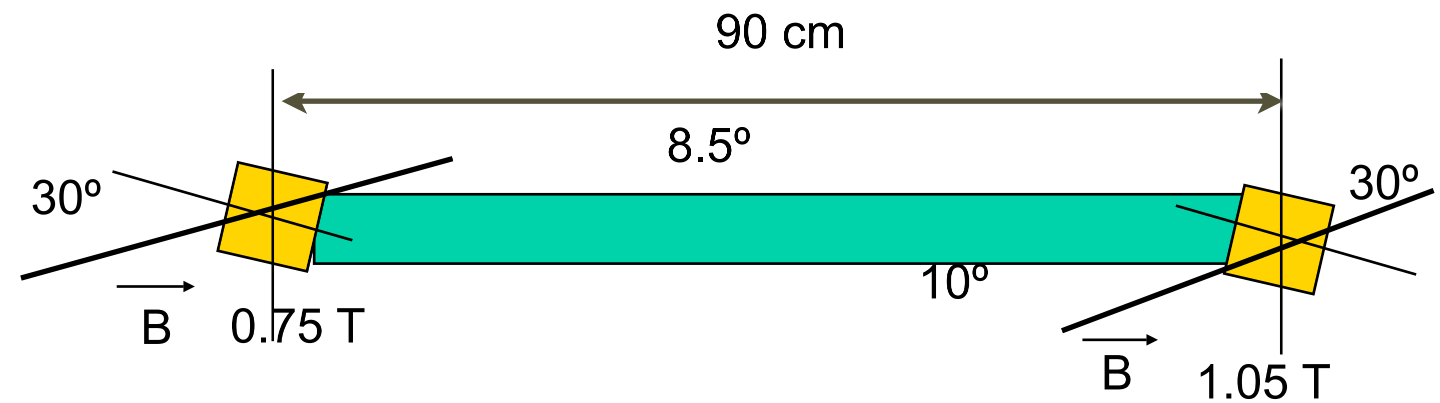


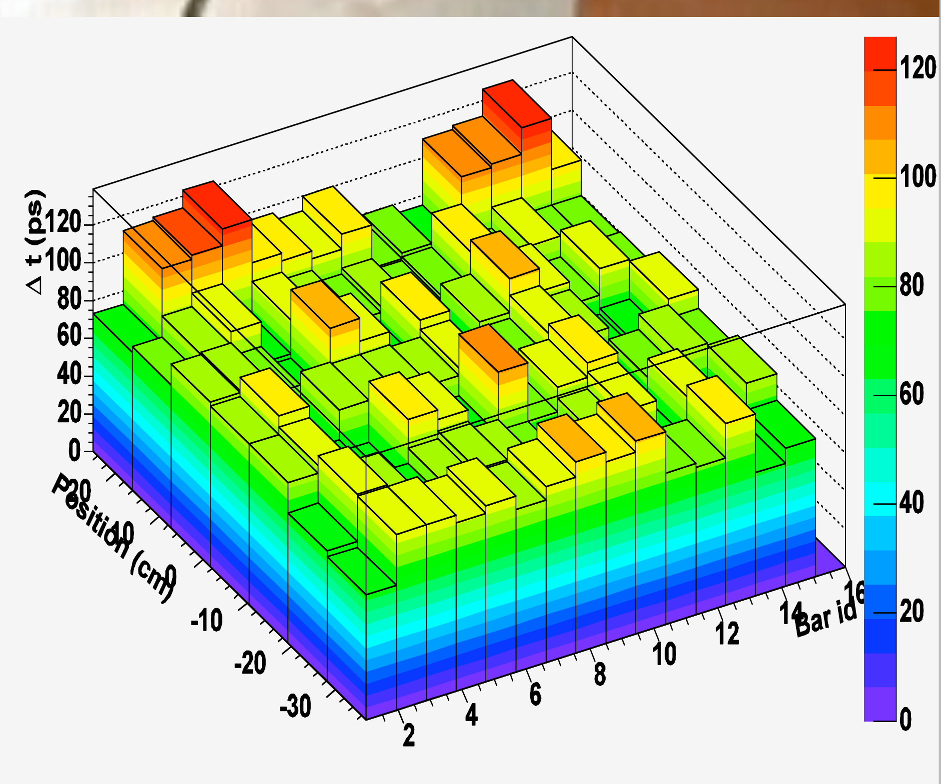




Timing Counter

- 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)



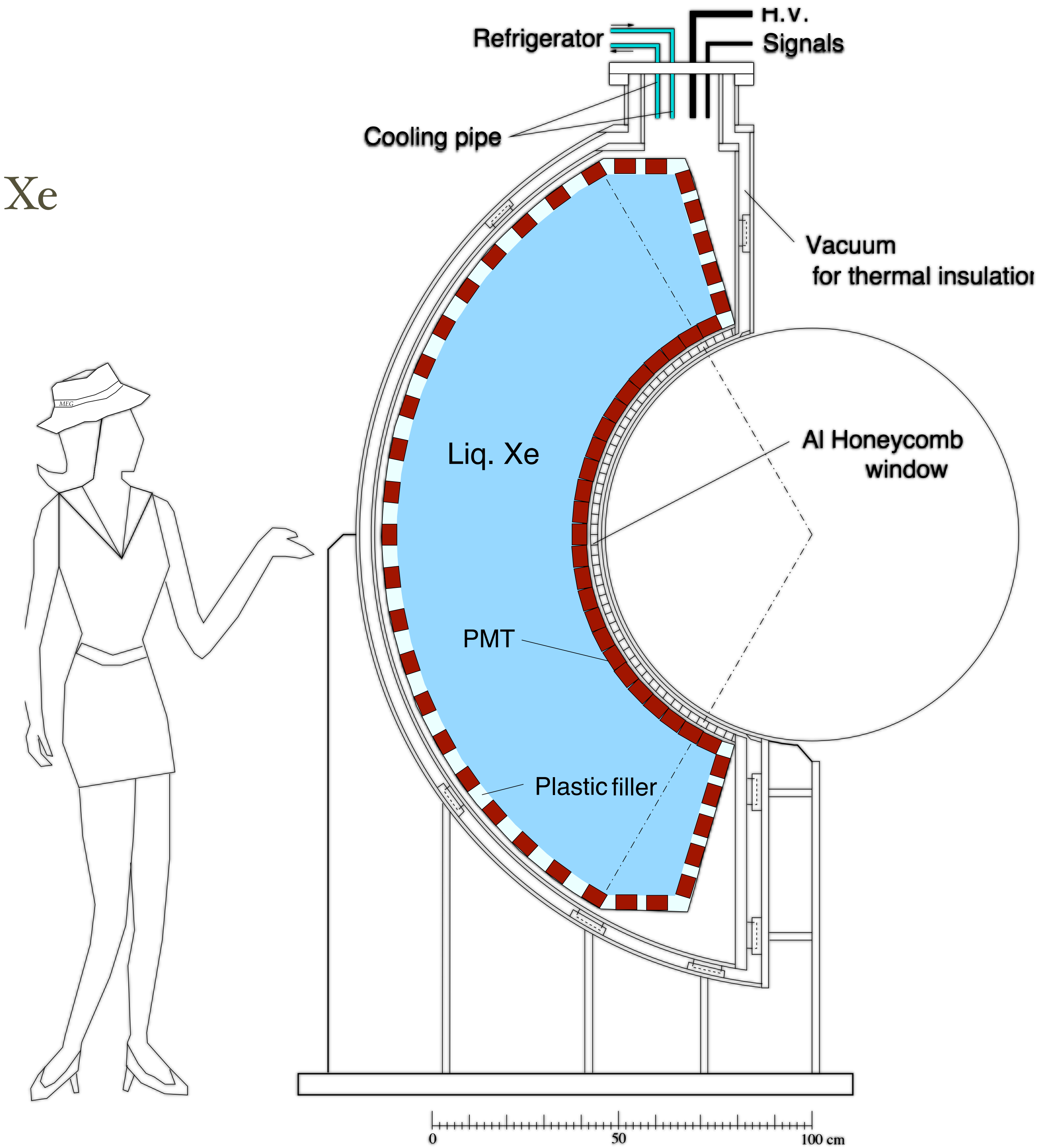


Exp. application (*)	Counter size (cm) (T x W x L)	Scintillator	PMT	λ_{att} (cm)	σ_t(meas)	σ_t(exp)
G.D.Agostini	3x 15 x 100	NE114	XP2020	200	120	60
T. Tanimori	3 x 20 x 150	SCSN38	R1332	180	140	110
T. Sugitate	4 x 3.5 x 100	SCSN23	R1828	200	50	53
R.T. Gile	5 x 10 x 280	BC408	XP2020	270	110	137
TOPAZ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

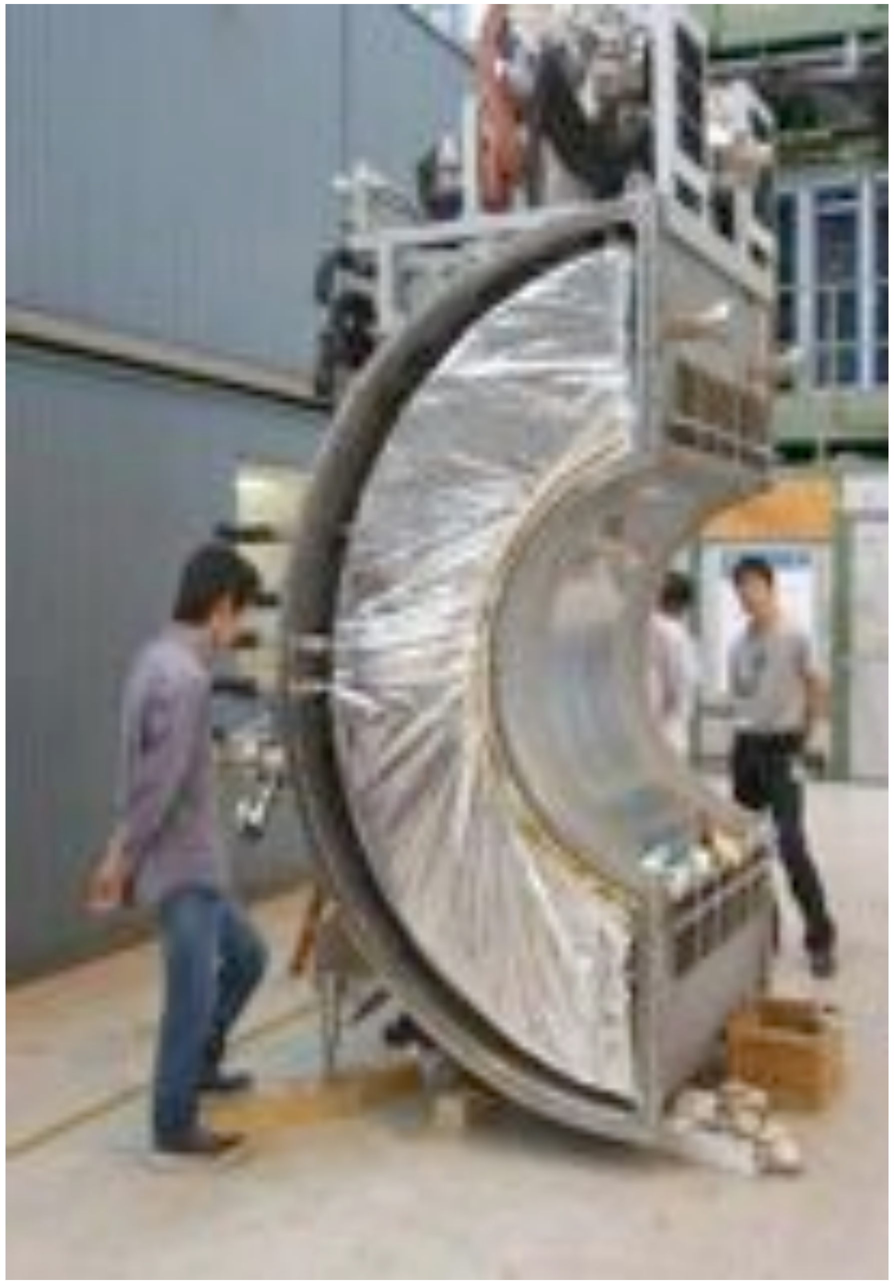
Best existing TC

The calorimeter

- γ Energy, position, timing
- Homogeneous 0.8 m^3 volume of liquid Xe
  - 10 % solid angle
  - $65 < r < 112$ cm
  - $|\cos\theta| < 0.35$ $|\varphi| < 60^o$
- 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

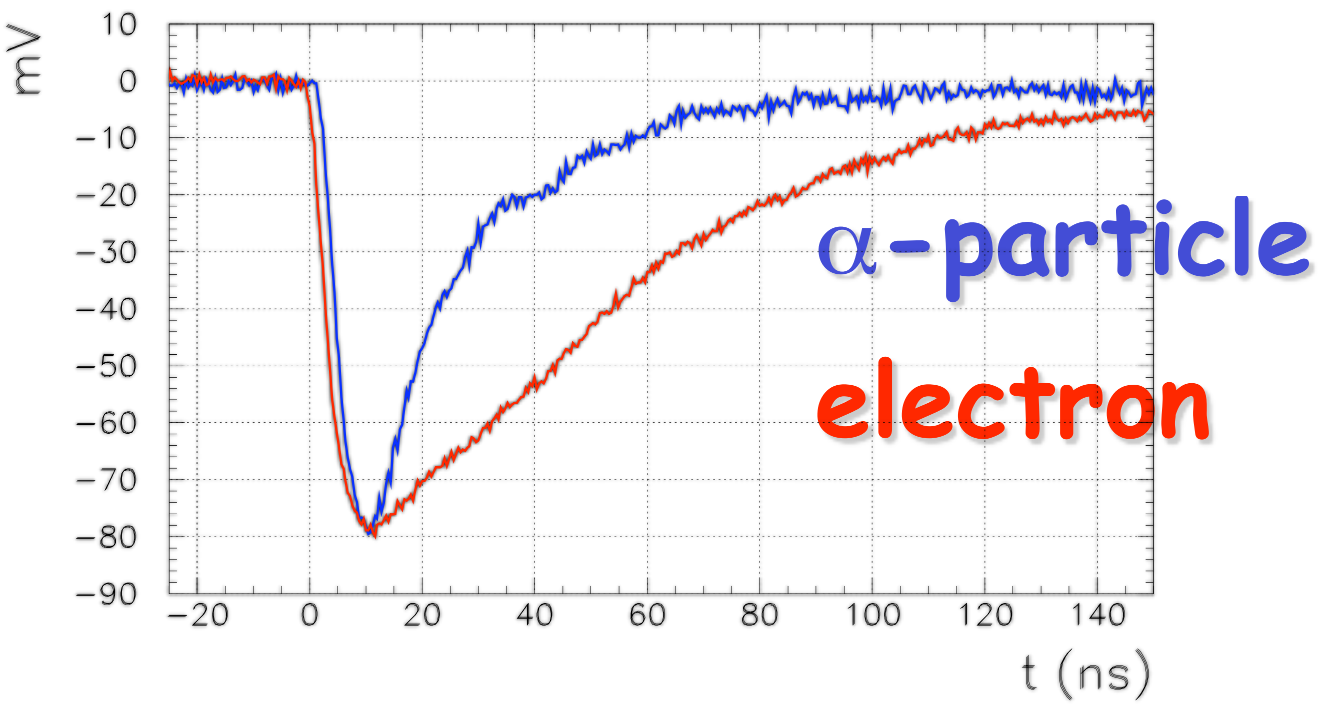


Calorimeter construction

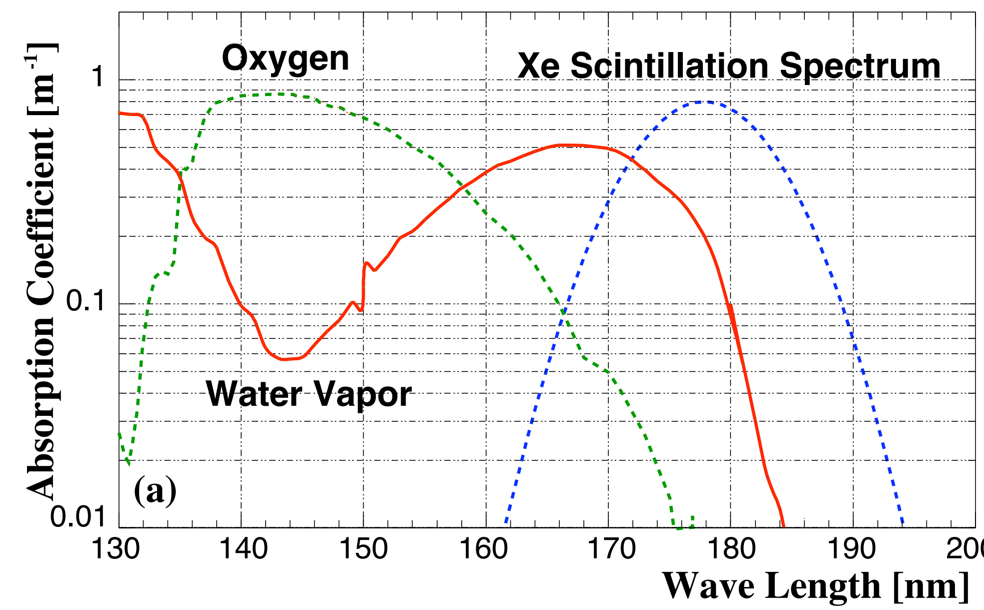

Xe properties

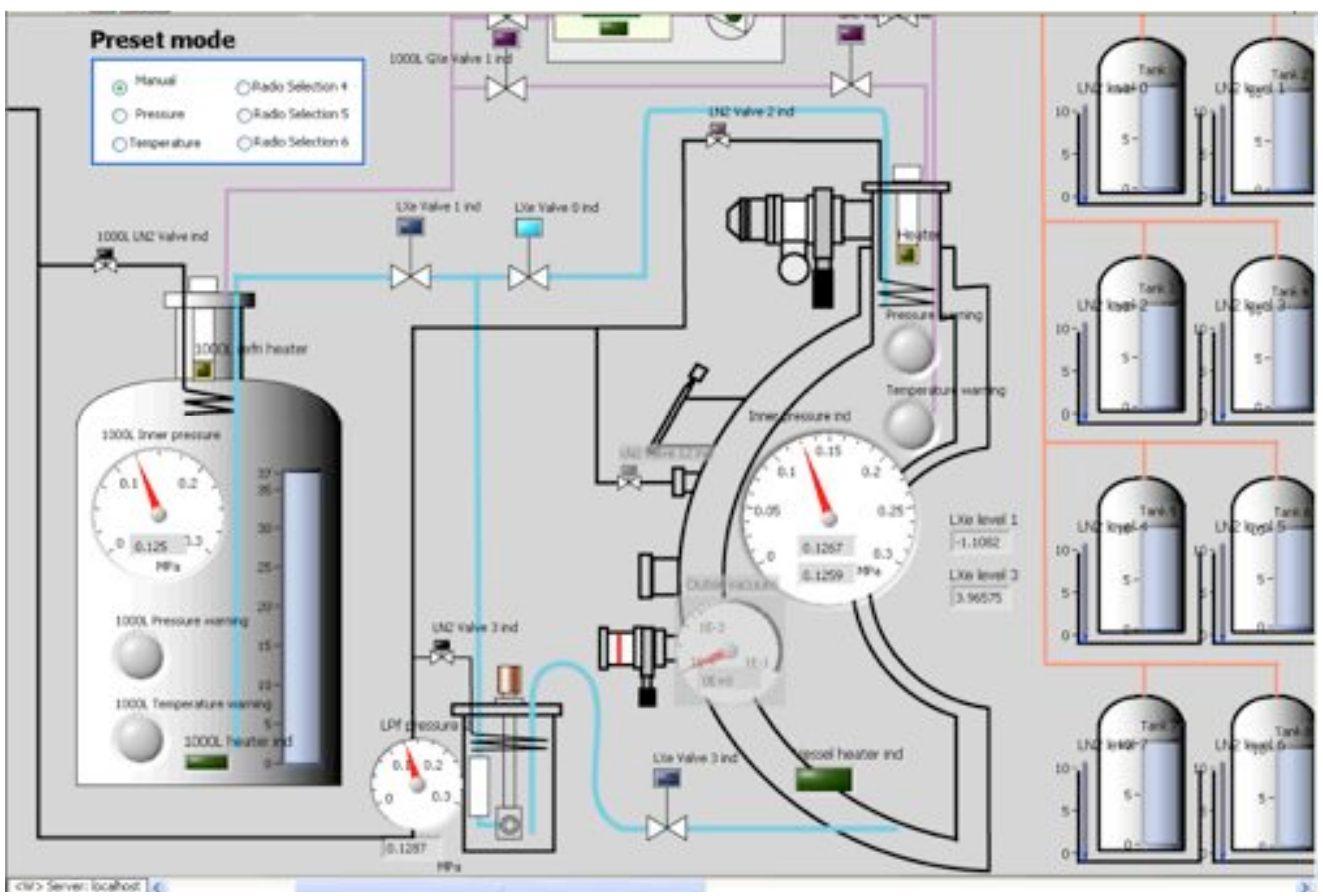
- Fast
  - $\tau_{singlet}$= 4.2 ns
  - $\tau_{triplet}$= 22 ns
  - τ_{recomb}= 45 ns
- Particle ID
  - LY alpha = 1.2 x LY gamma/e
- High LY (≈ NaI)
  - 40000 phe/MeV
- n = 1.65
- Z=54, ρ=2.95 g/cm^3 (X_o=2.7 cm), R_M=4.1 cm
- No self-absorption ($\lambda_{Abs}=\infty$)

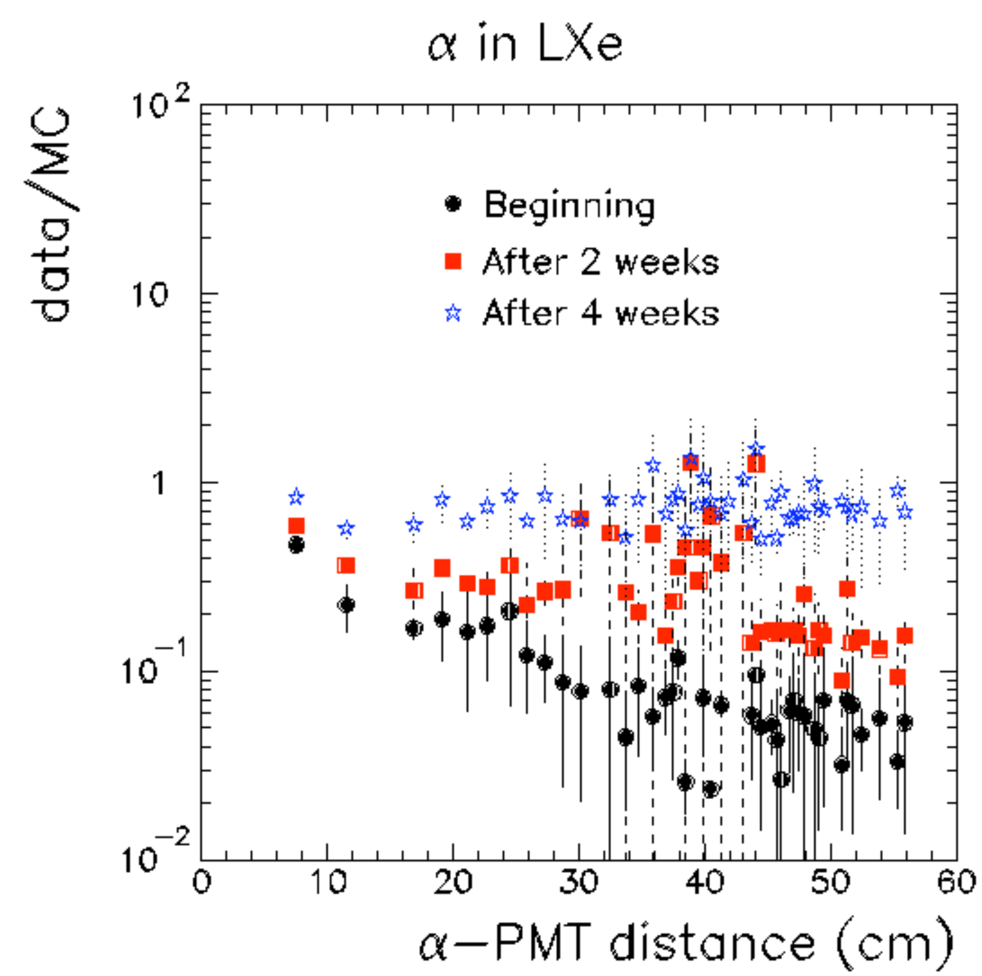


Xenon purity

- 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
  - $e^+ - \gamma$ time coincidence
  - $e^+ - \gamma$ collinearity
- Built on a FADC-FPGA architecture
- More performing algorithms could be implemented

❖ Beam rate ~ $2.5\ 10^7\ s^{-1}$

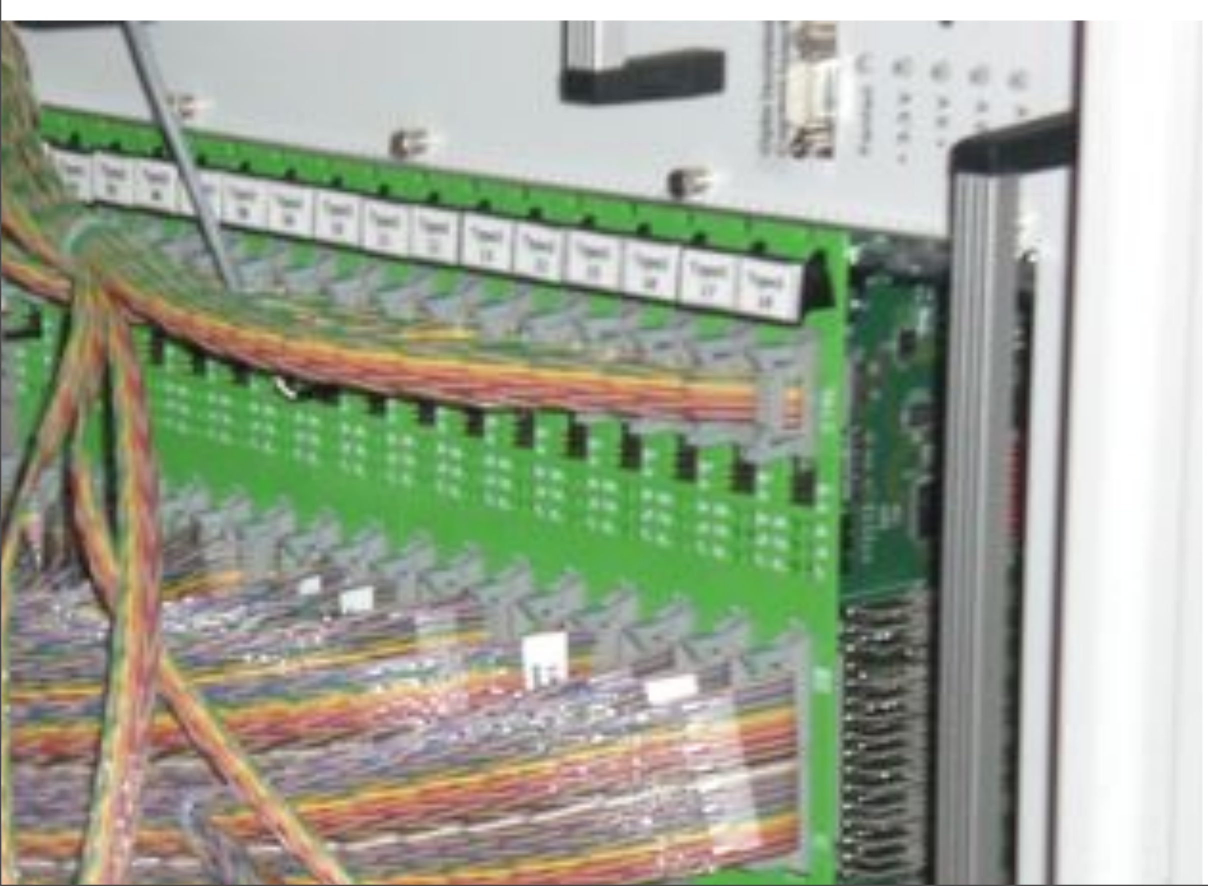
❖ Fast LXe energy sum > 45MeV
$2\times10^3\ s^{-1}$

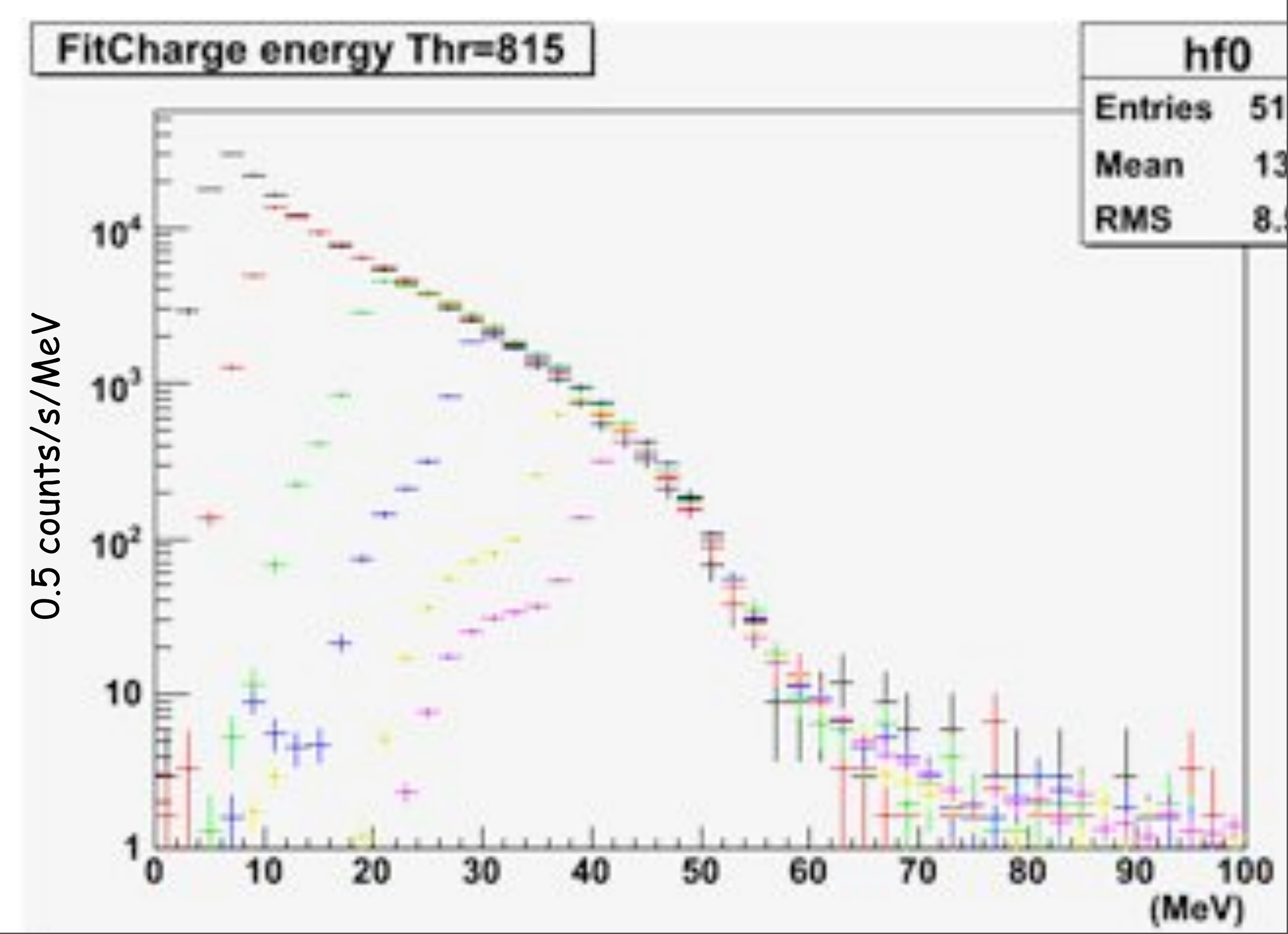
gamma interaction point (PMT of max charge)

e^+ hit point in timing counter

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

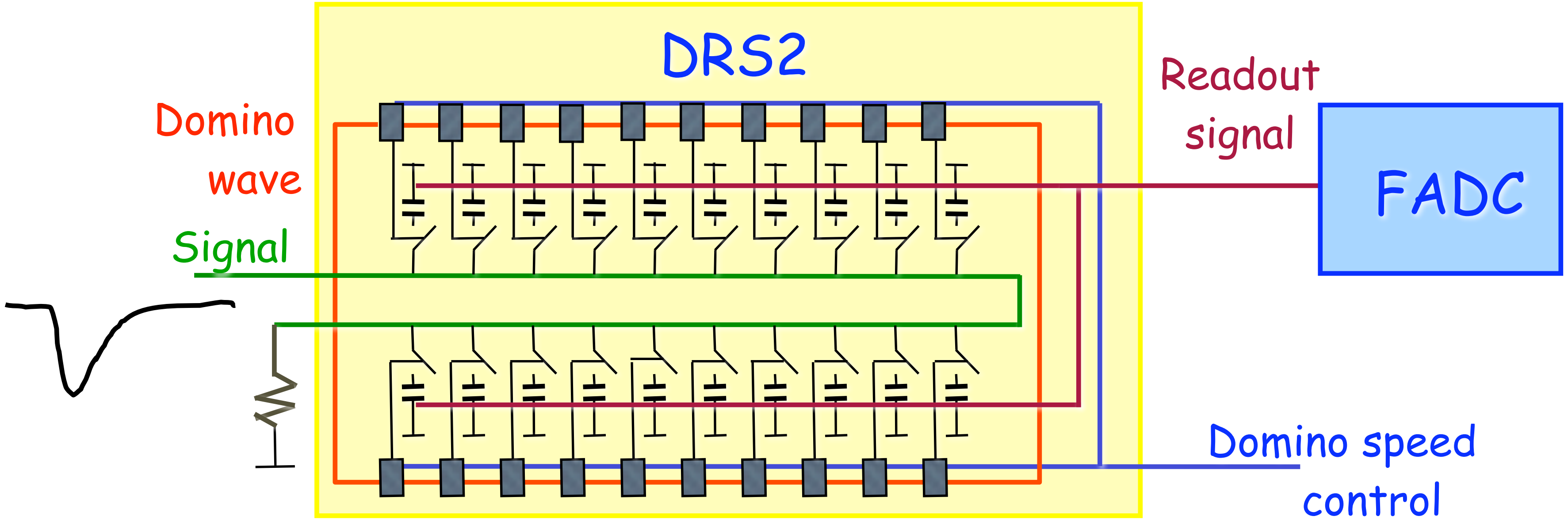
❖ angular correlation $\gamma - e^+$ $10\ s^{-1}$





Readout electronics

2 GHz Waveform digitization for all channels

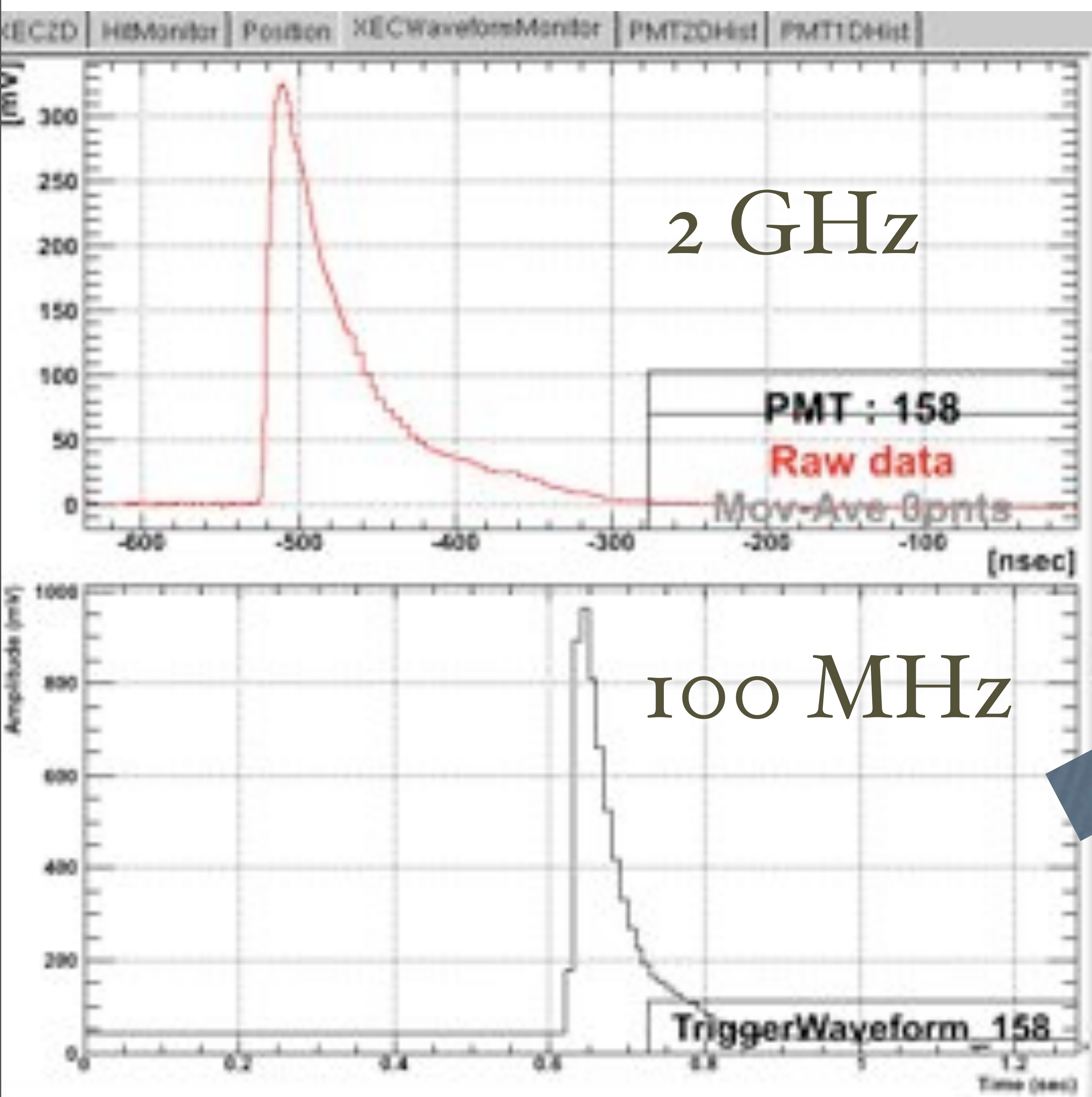


DRS chip (Domino Ring Sampler)

- 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

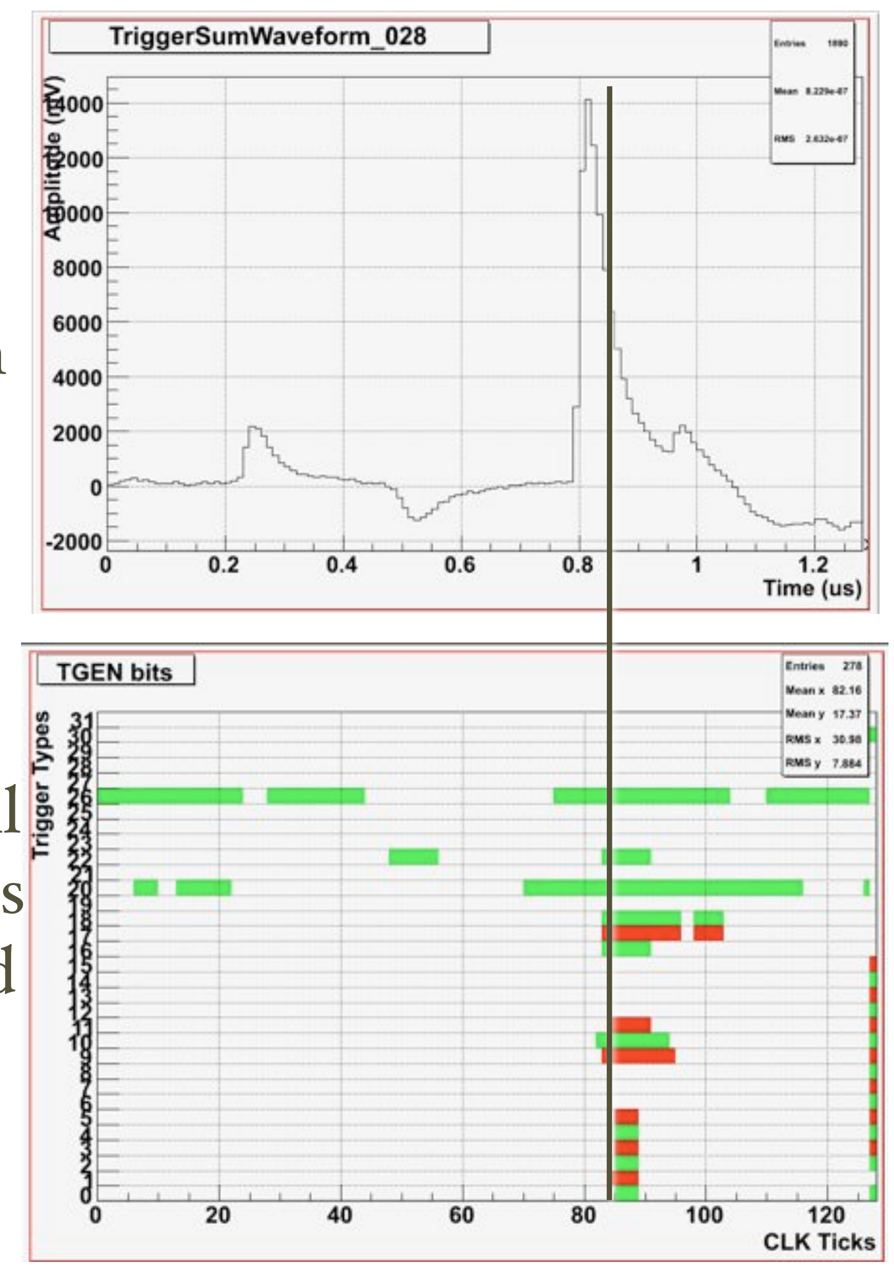
- For (almost) all channels, for each subdetector we have two waveform digitizers with complementary characteristics



online pedestal subtraction for LXe

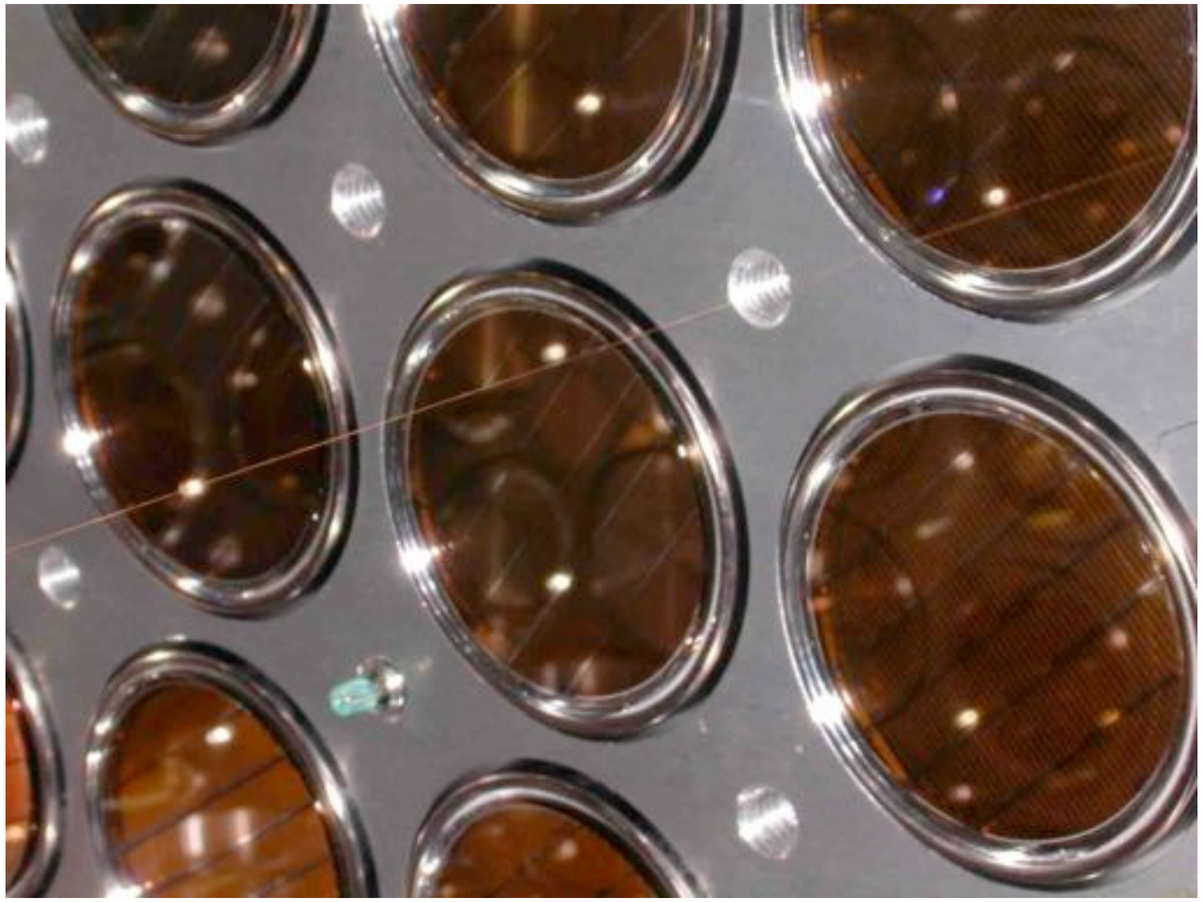
info from all subdetectors is combined

Trigger!



Calibrations

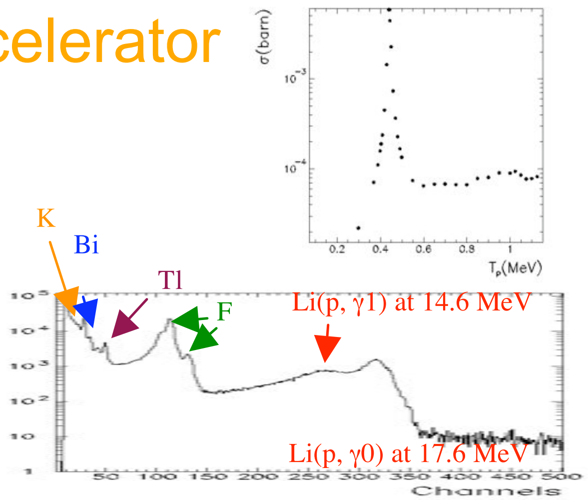
- It is understood that in such a complex detector a lot of parameters must be constantly checked
- We are prepared for redundant calibration and monitoring
- Single detector
  - PMT equalization for LXe and TIC
  - Interbar timing (TIC)
  - Energy scale
- Multiple detectors
  - relative timing



Calibrations

Xenon Calibration

Proton Accelerator



Li(p,γ)Be

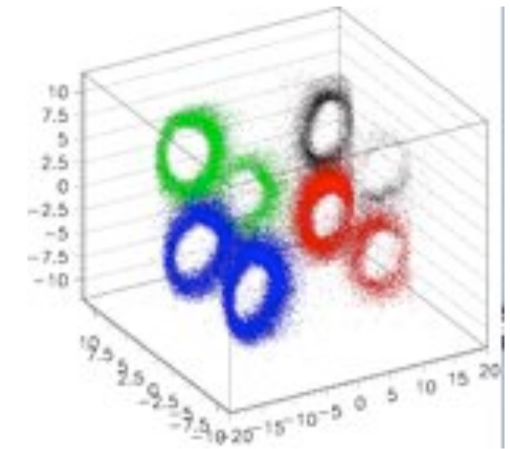
LiF target at COBRA center

17.6MeV γ

~daily calib.

also for initial setup

Alpha on wires

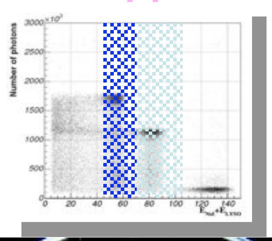


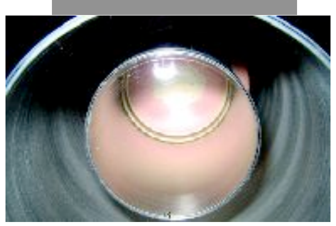
PMT QE & Att. L

Cold GXe

LXe

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



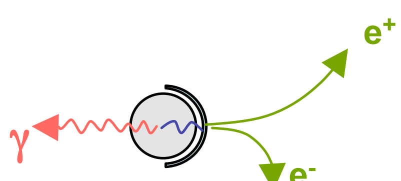


$\pi^- + p \rightarrow \pi^0 + n$

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

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

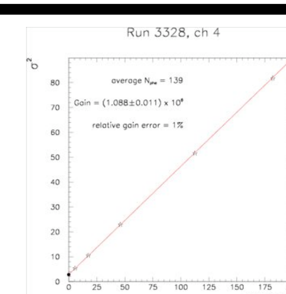
LH_2 target



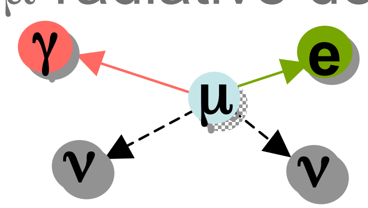
LED

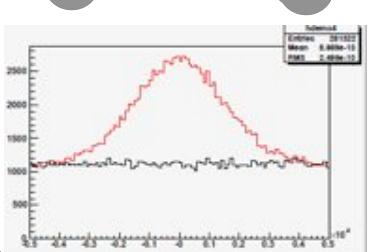
PMT Gain

Higher V with light att.



μ radiative decay





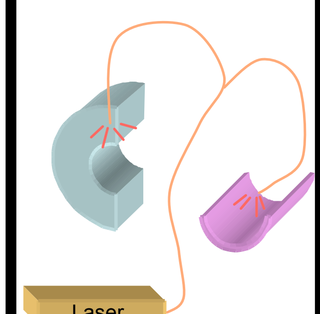
Lower beam intensity < 10^7

Is necessary to reduce pile-ups

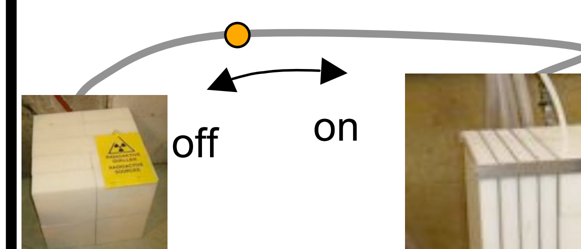
A few days ~ 1 week to get enough statistics

Laser

relative timing calib.

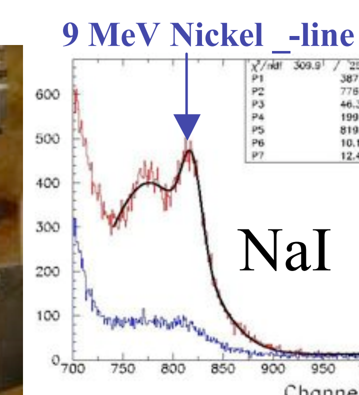


Nickel γ Generator



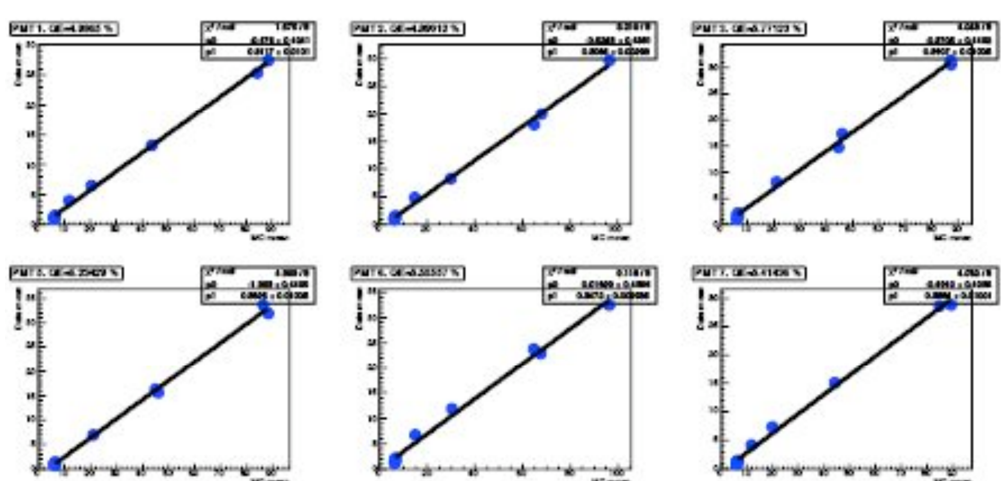
Illuminate Xe from the back

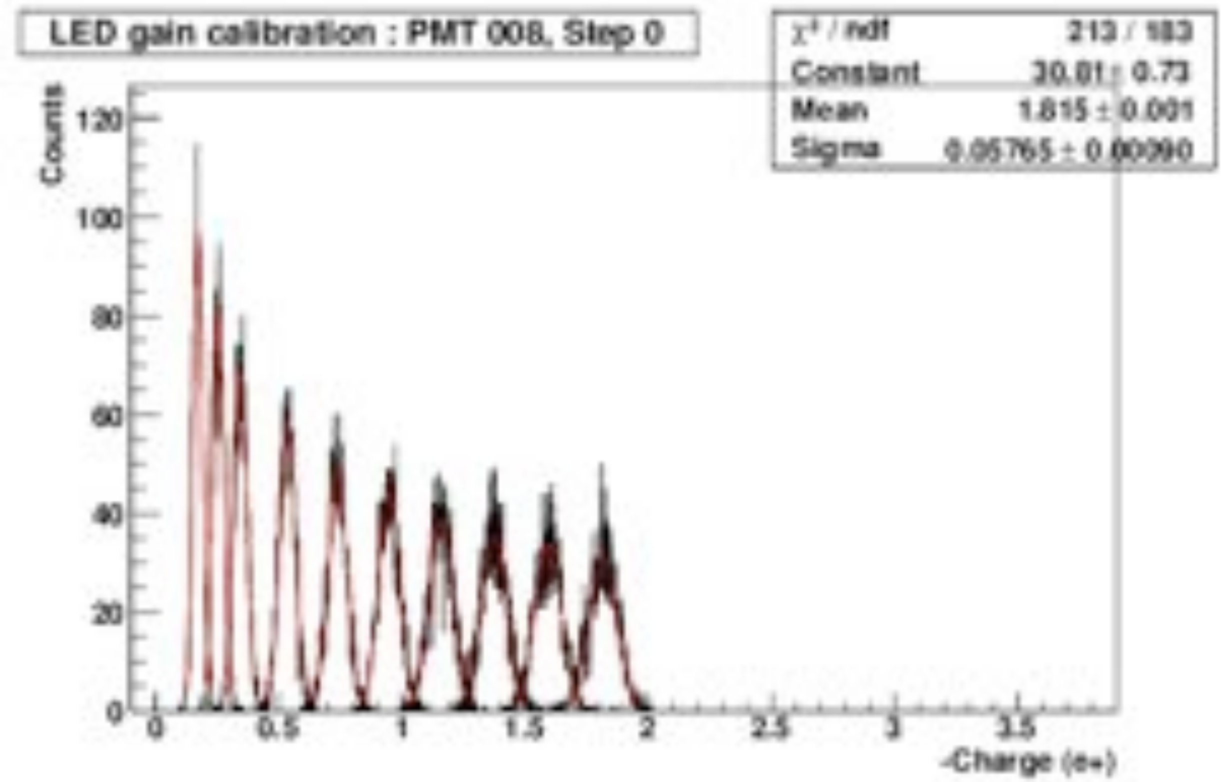
Source (Cf) transferred by comp air → on/off

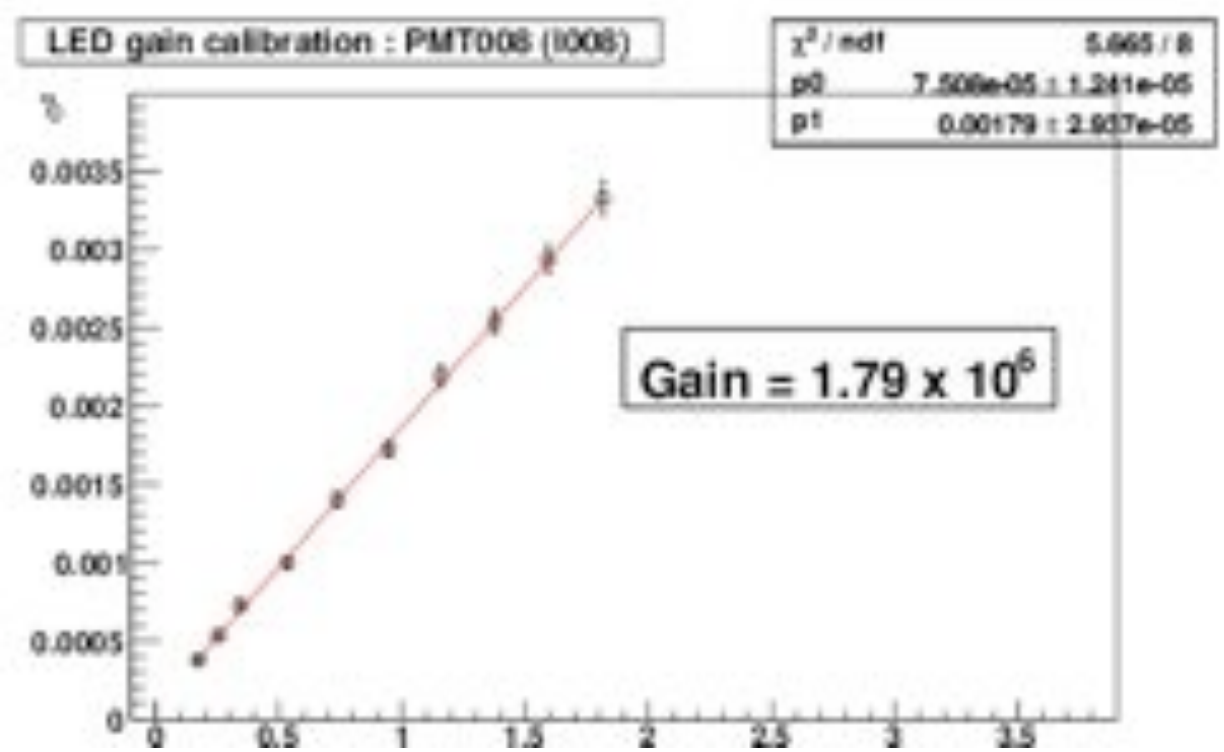


LXe: *g* and QE

- The calorimeter is equipped with blue LEDs and alpha sources
- Masurements 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

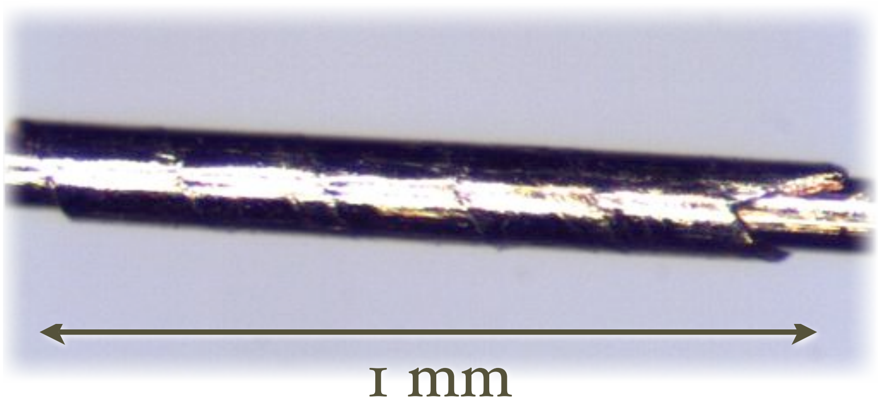


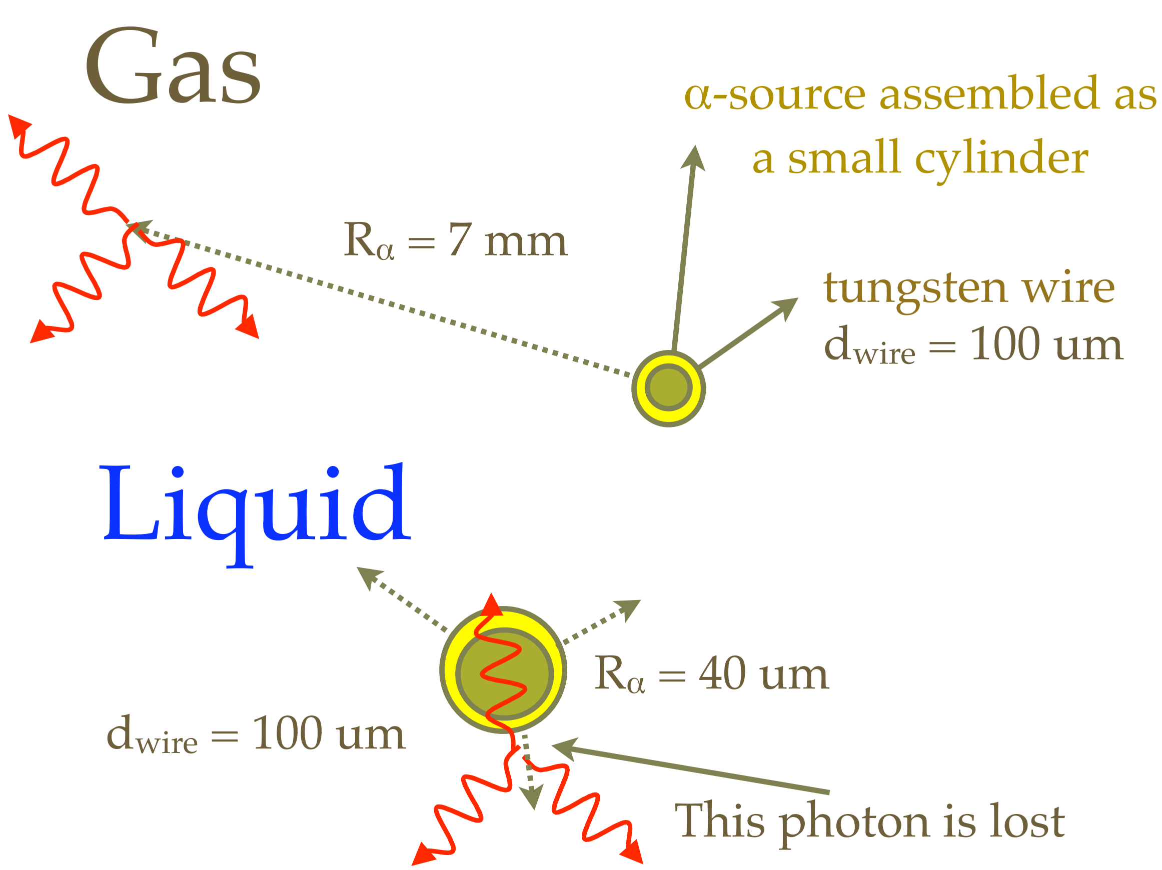


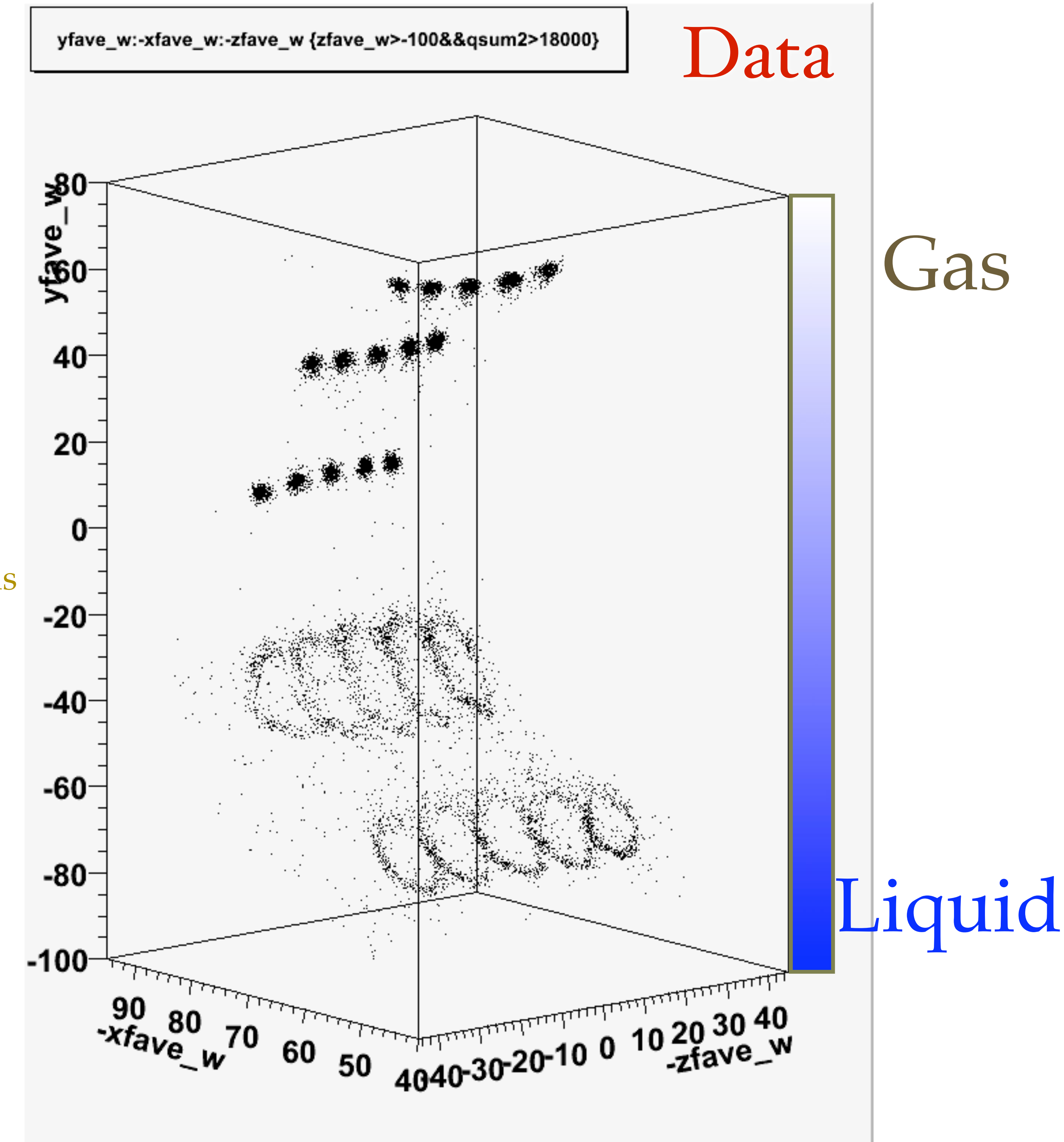


α-sources in Xe

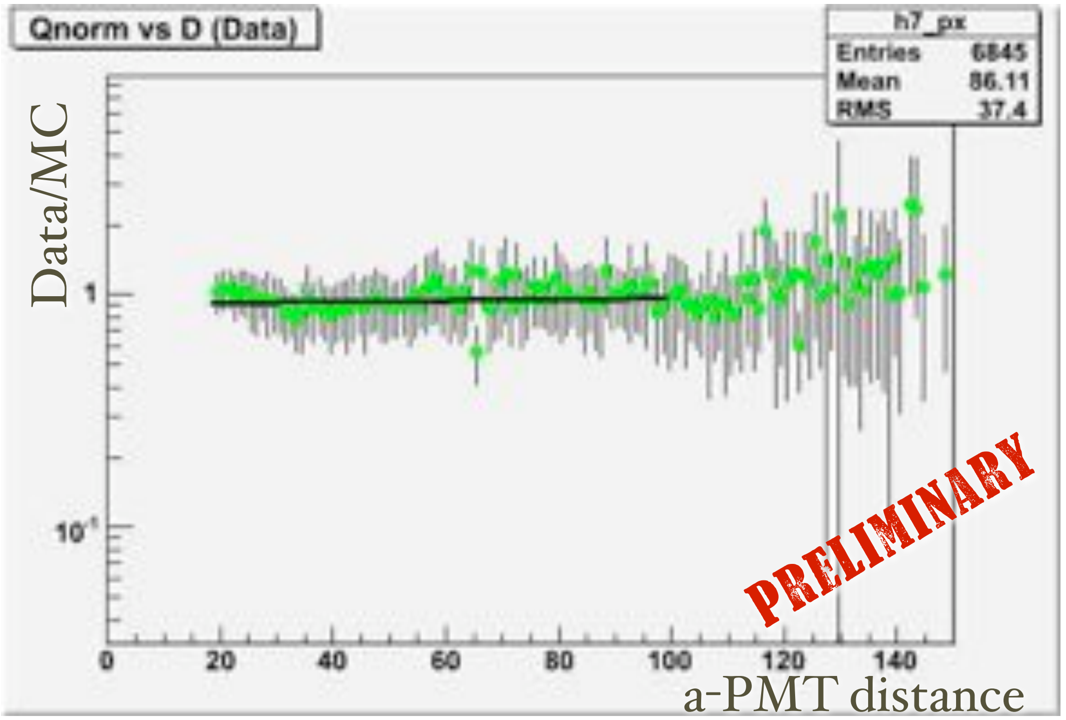
- Specially developed Am sources:
  - 5 dot-sources on thin (100 um) tungsten wires







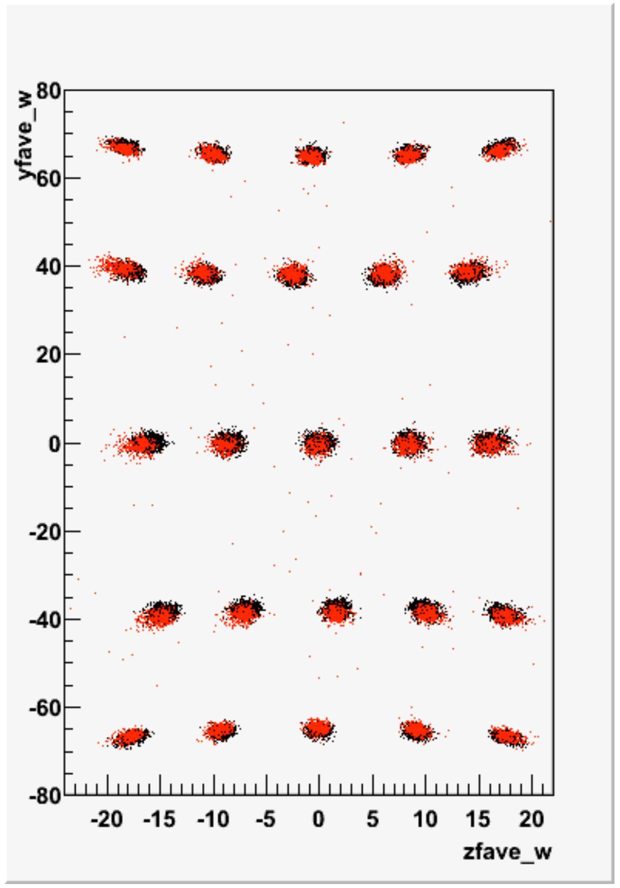
α-sources in Xe



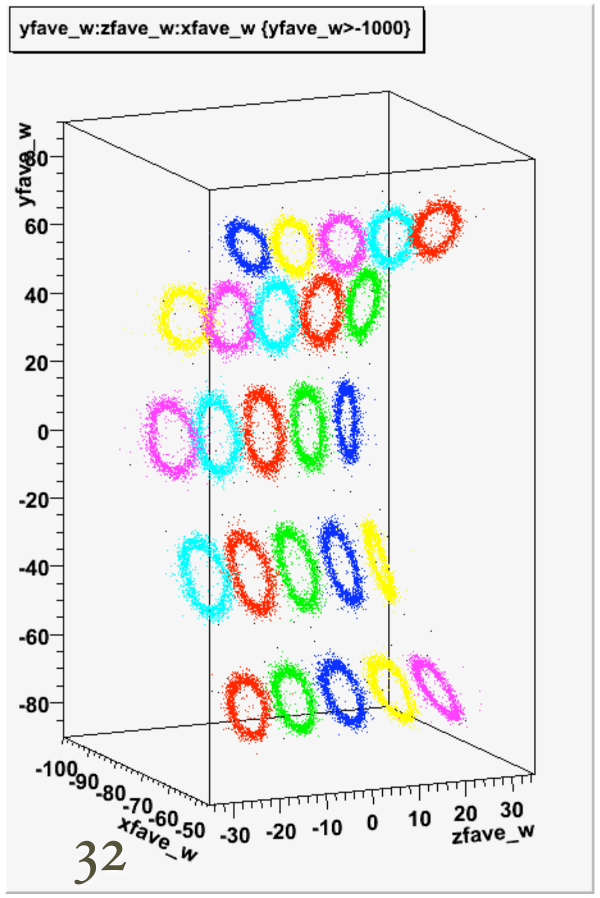
- Used to
  - QE determination
  - Monitor Xe stability
  - Measure absorption
  - Measure Raileigh scattering

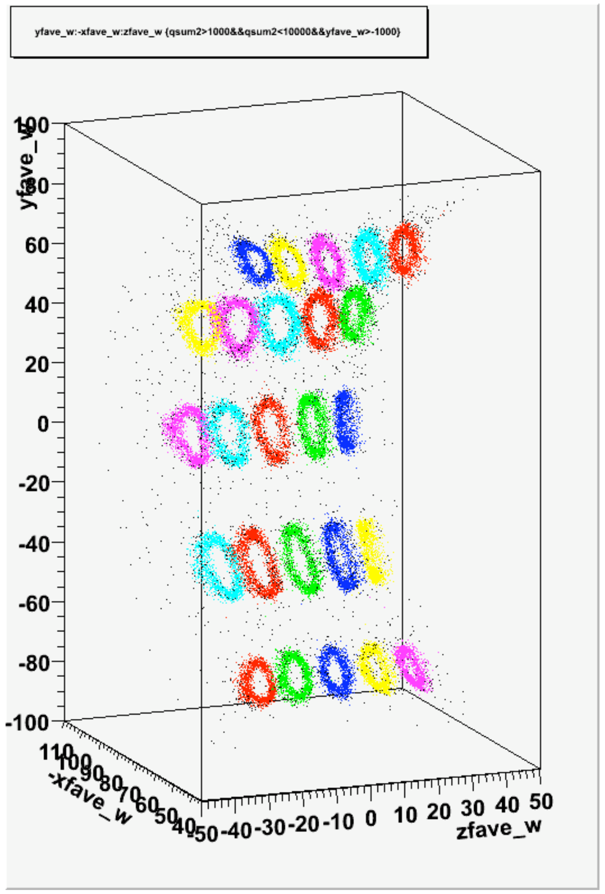
l_{Abs} > 300 cm

GXe: MC & data



LXe: MC & data





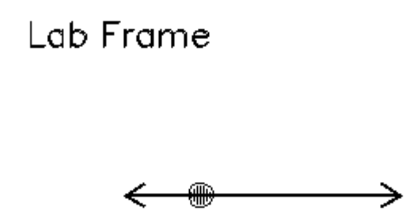
Energy scale calibrations

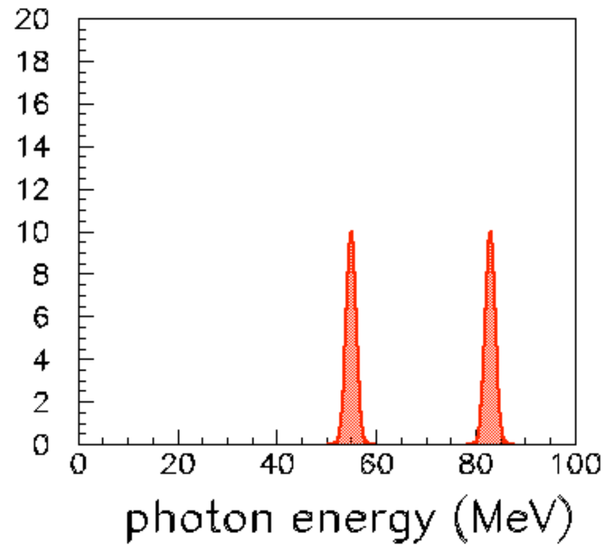
- A reliable result depend on a constant calibration and monitoring of the apparatus
- We are prepared for continuous and redundant checks
  - different energies
  - different frequency

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	$^{60}\mathrm{Co}$, AmBe	1.1 -4.4 MeV	daily

CEX measurement

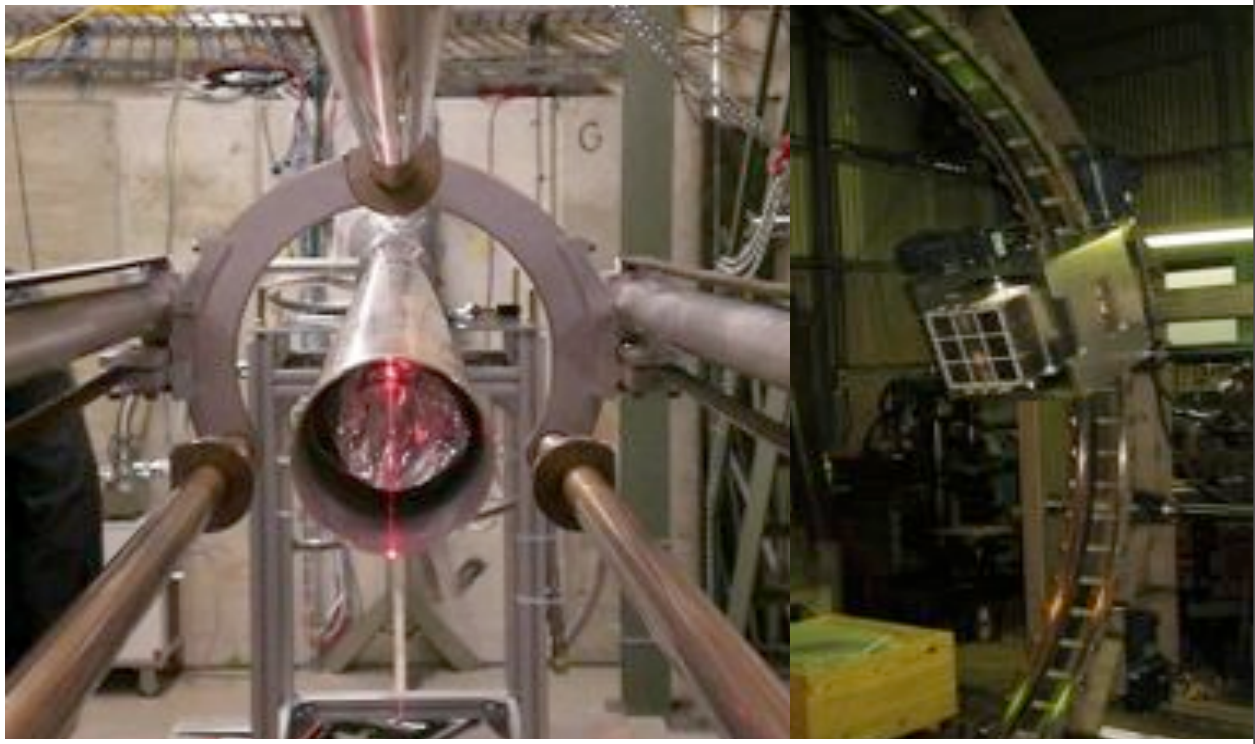
$$\pi^- p \to \pi^0 n$$
$$\pi^0 \to \gamma\gamma$$



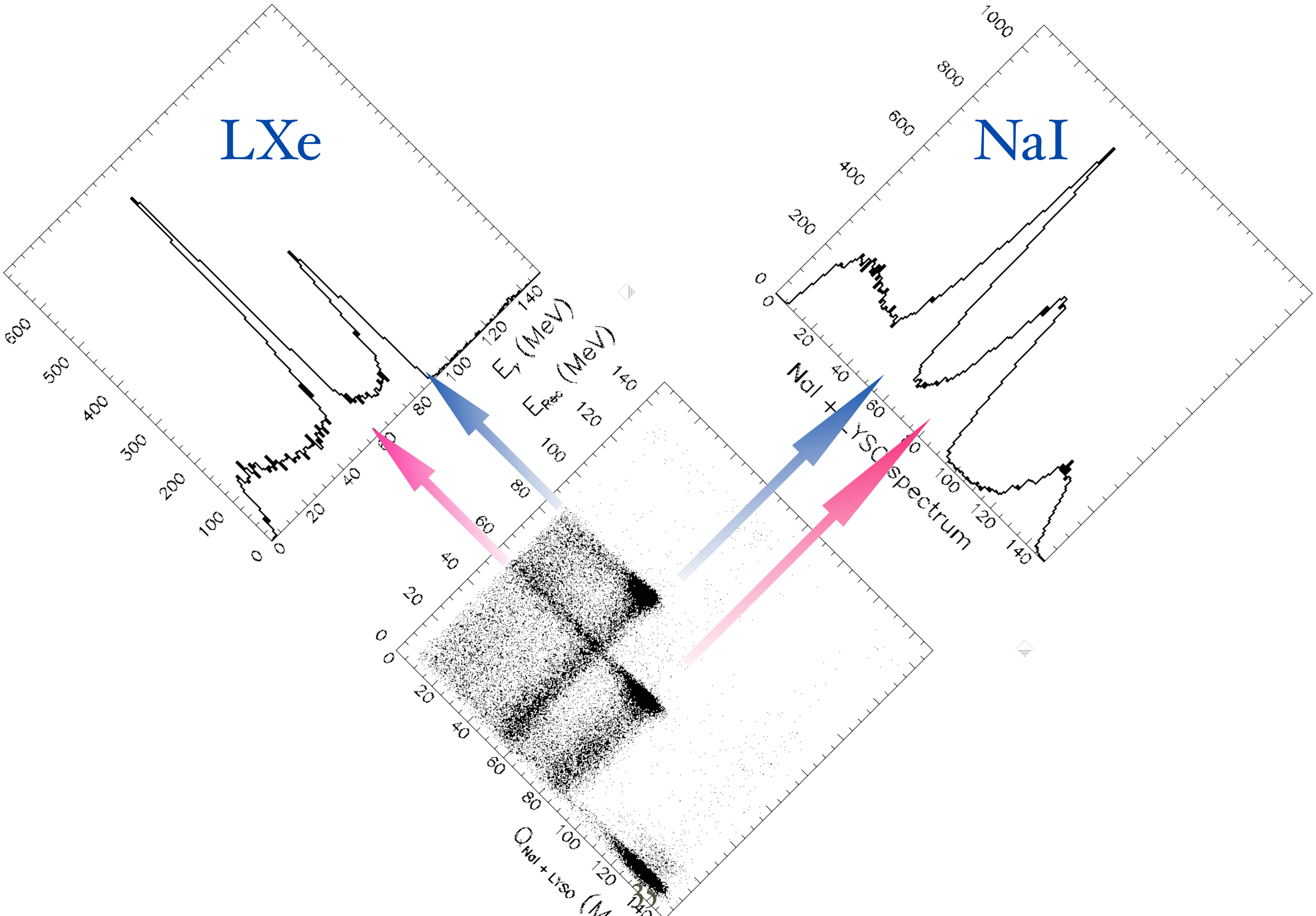


- The monochromatic spectrum in the pi-zero rest frame becomes flat in the Lab
- In the back-to-back configuration the energies are 55 MeV and 83 MeV

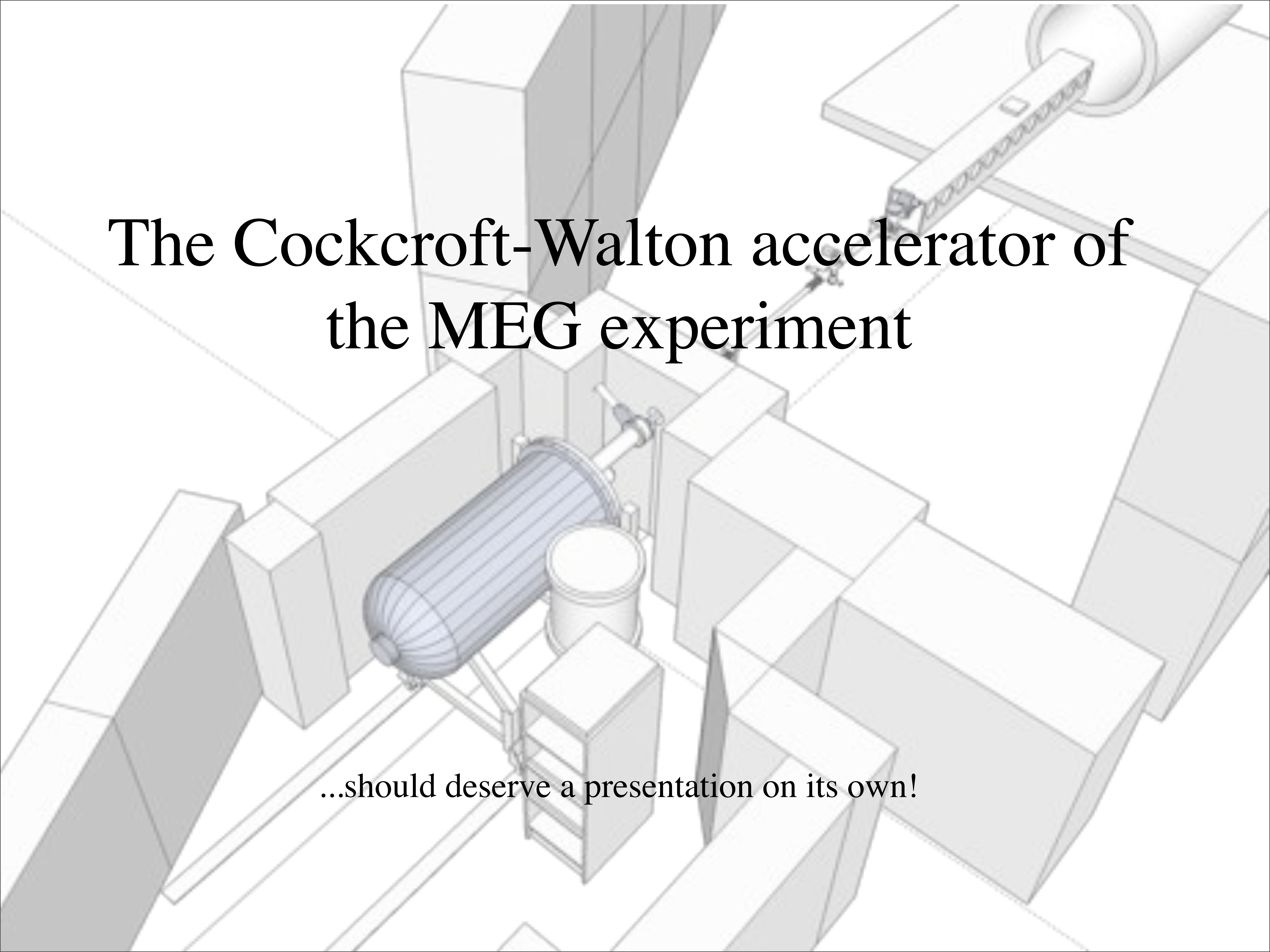
- Even a modest collimation guarantees a sufficient monochromaticity
- Liquid hydrogen target to maximize photon flux
- An "opposite side detector" is needed (NaI array)



- 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)



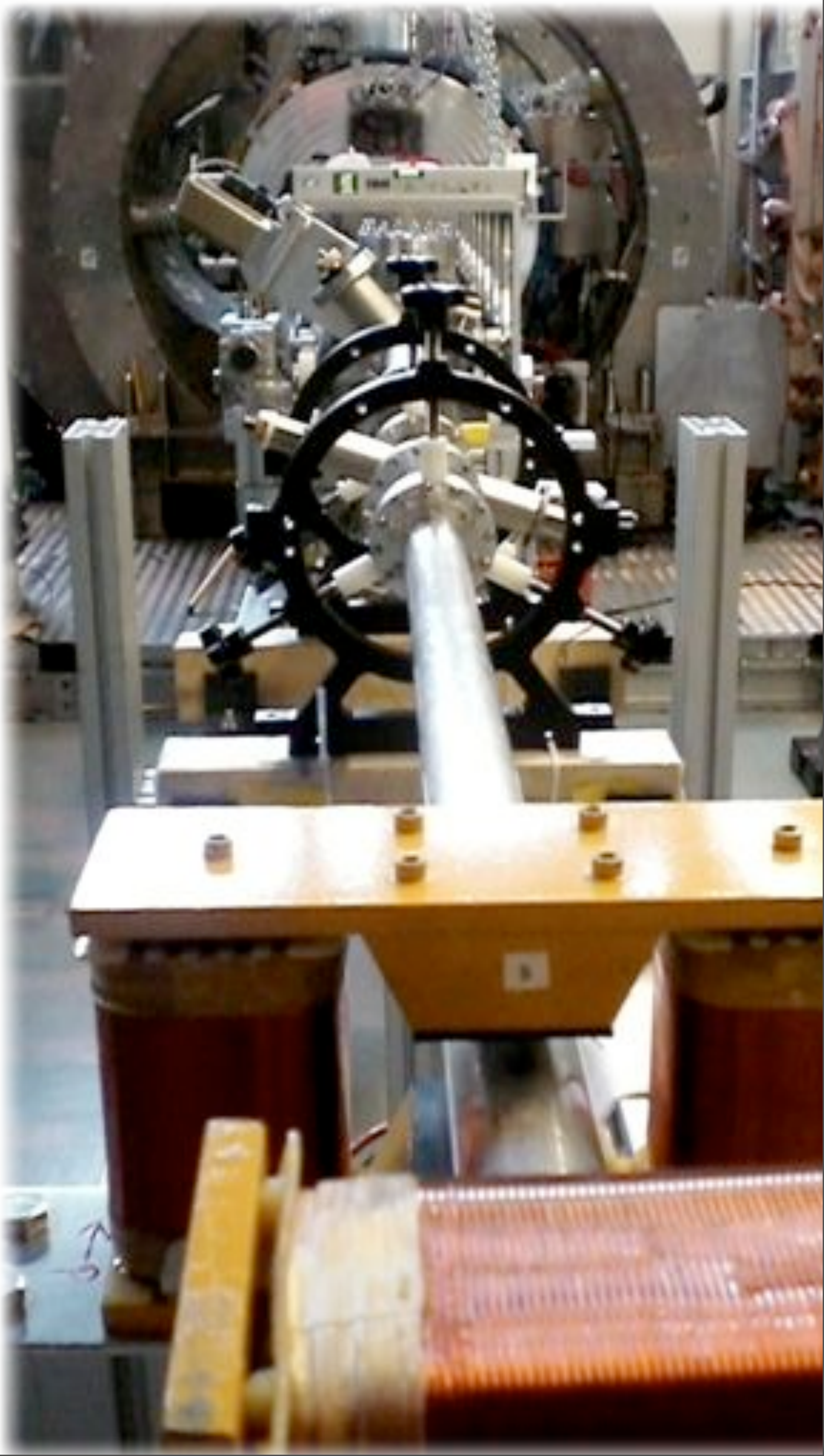
The Cockcroft-Walton accelerator of the MEG experiment



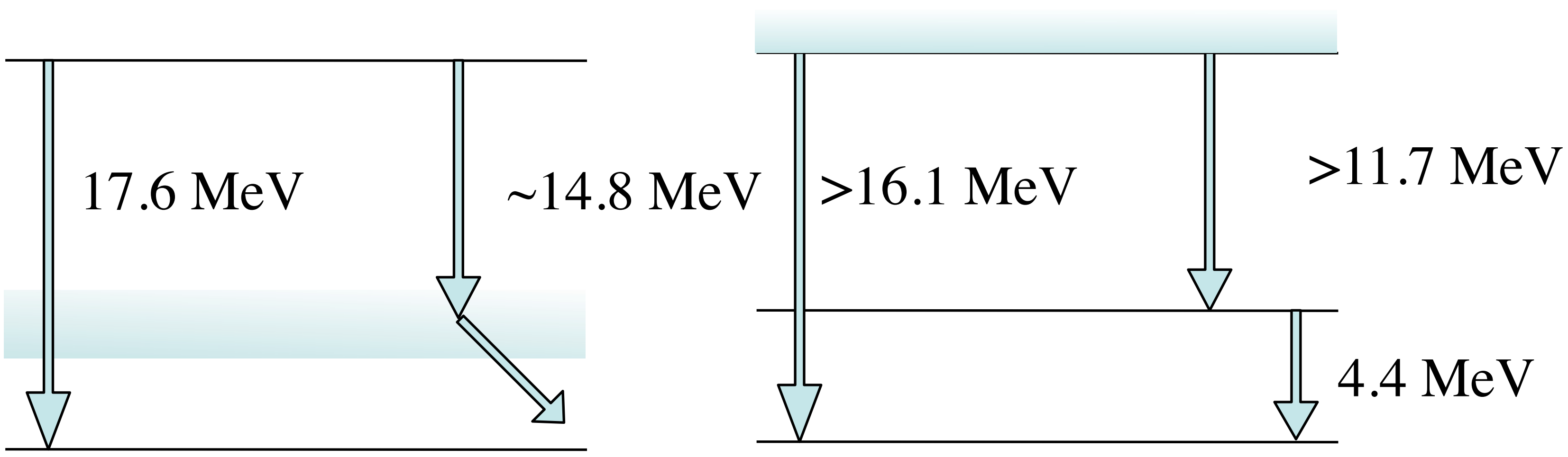
...should deserve a presentation on its own!

Intro & reactions

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

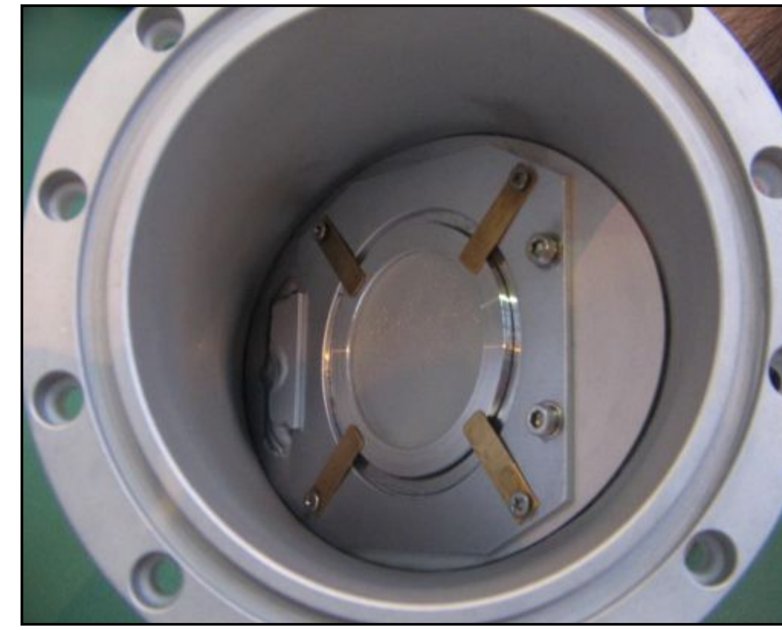


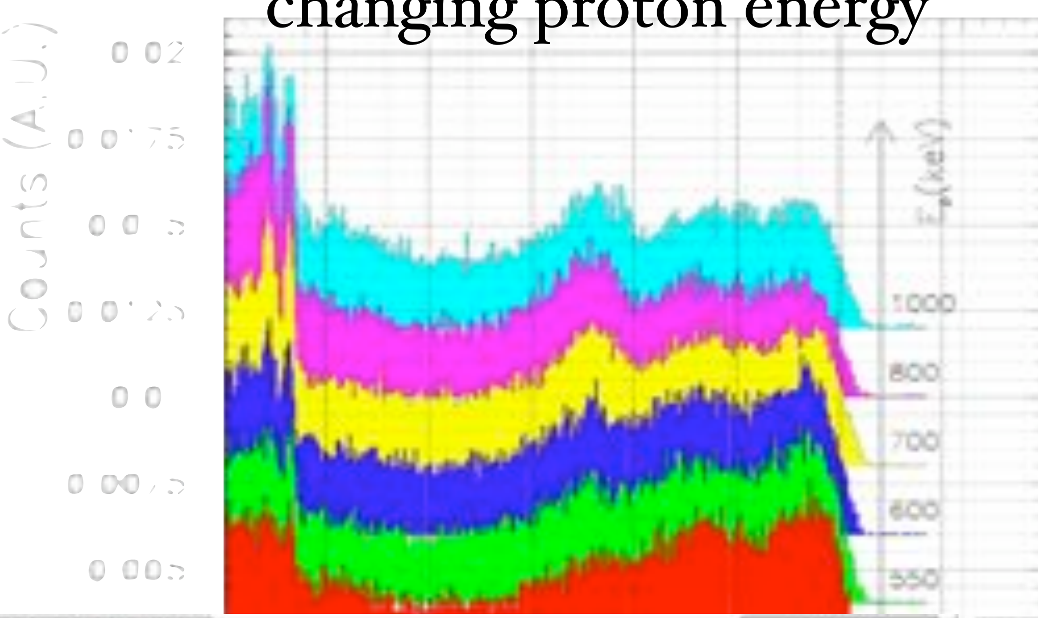
Reaction	***Peak energy***	**σ peak**	**γ-lines**
Li(p,γ)Be	*440 keV*	5 mb	(17.6, 14.6) MeV
B(p,γ)C	*163 keV*	$2\ 10^{-1}$ mb	(4.4, 11.7, 16.1) MeV



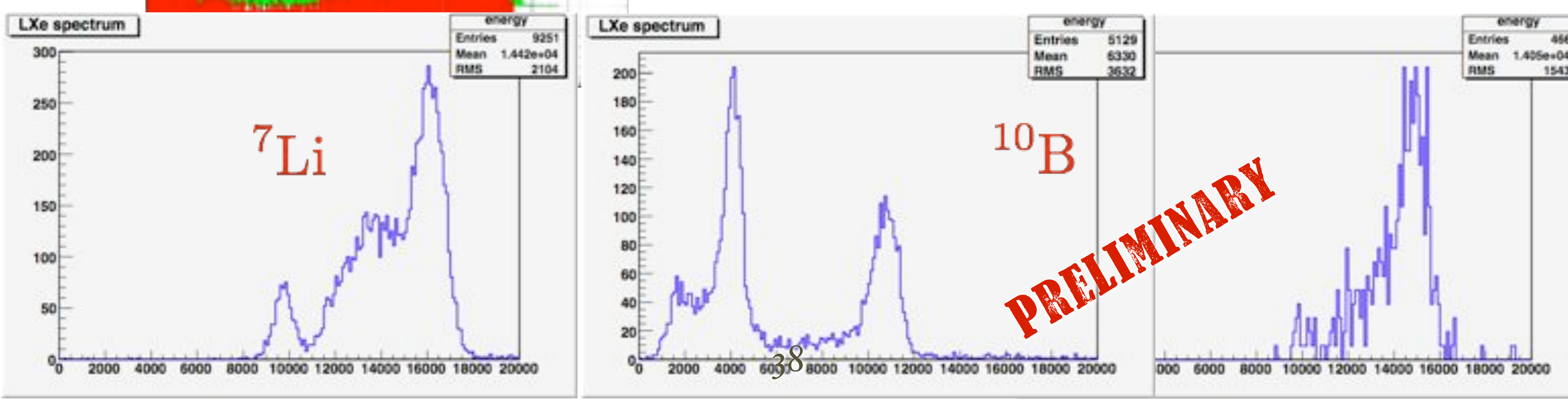
CW - daily calibration

- 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





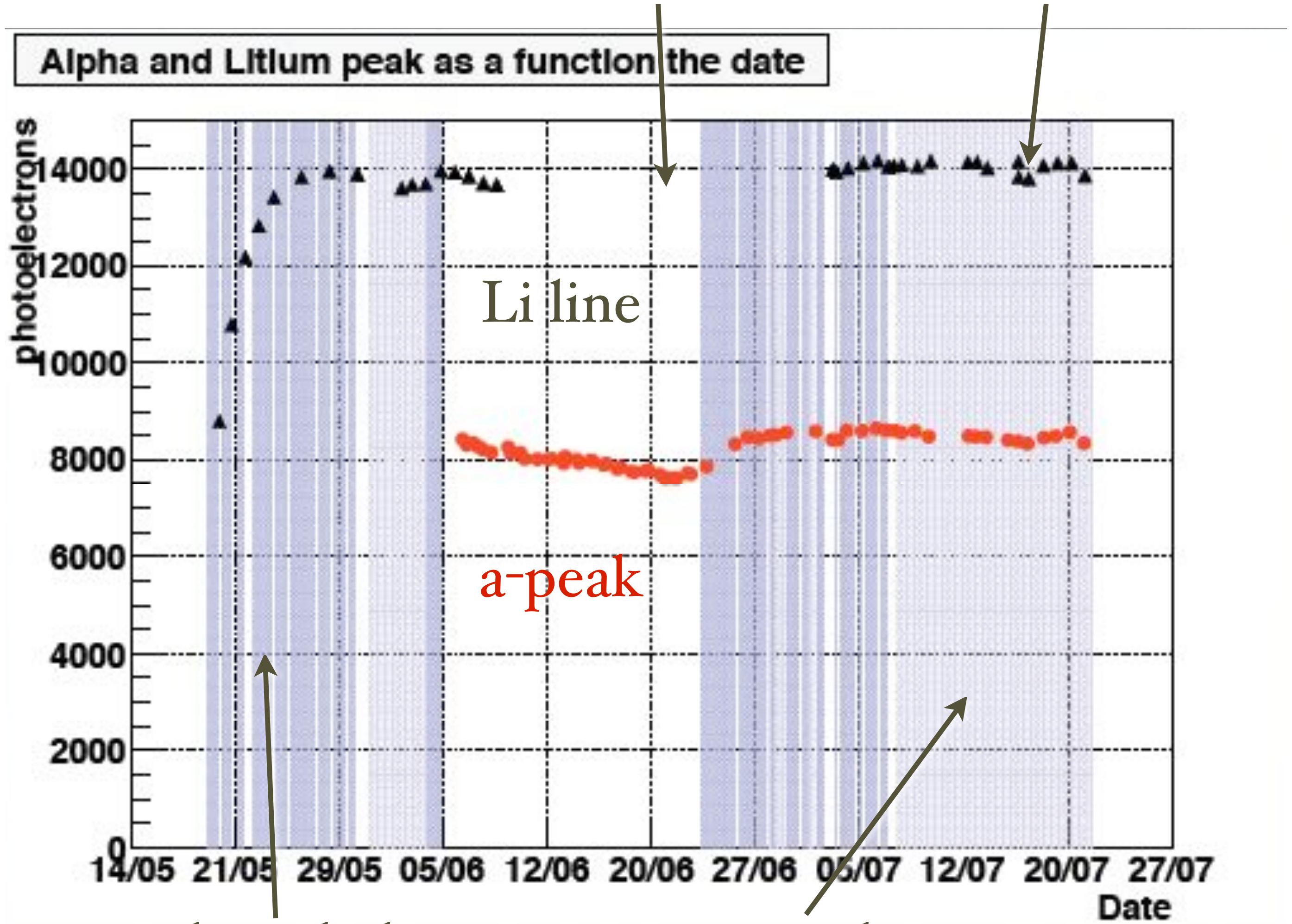
When p energy increases B lines appear

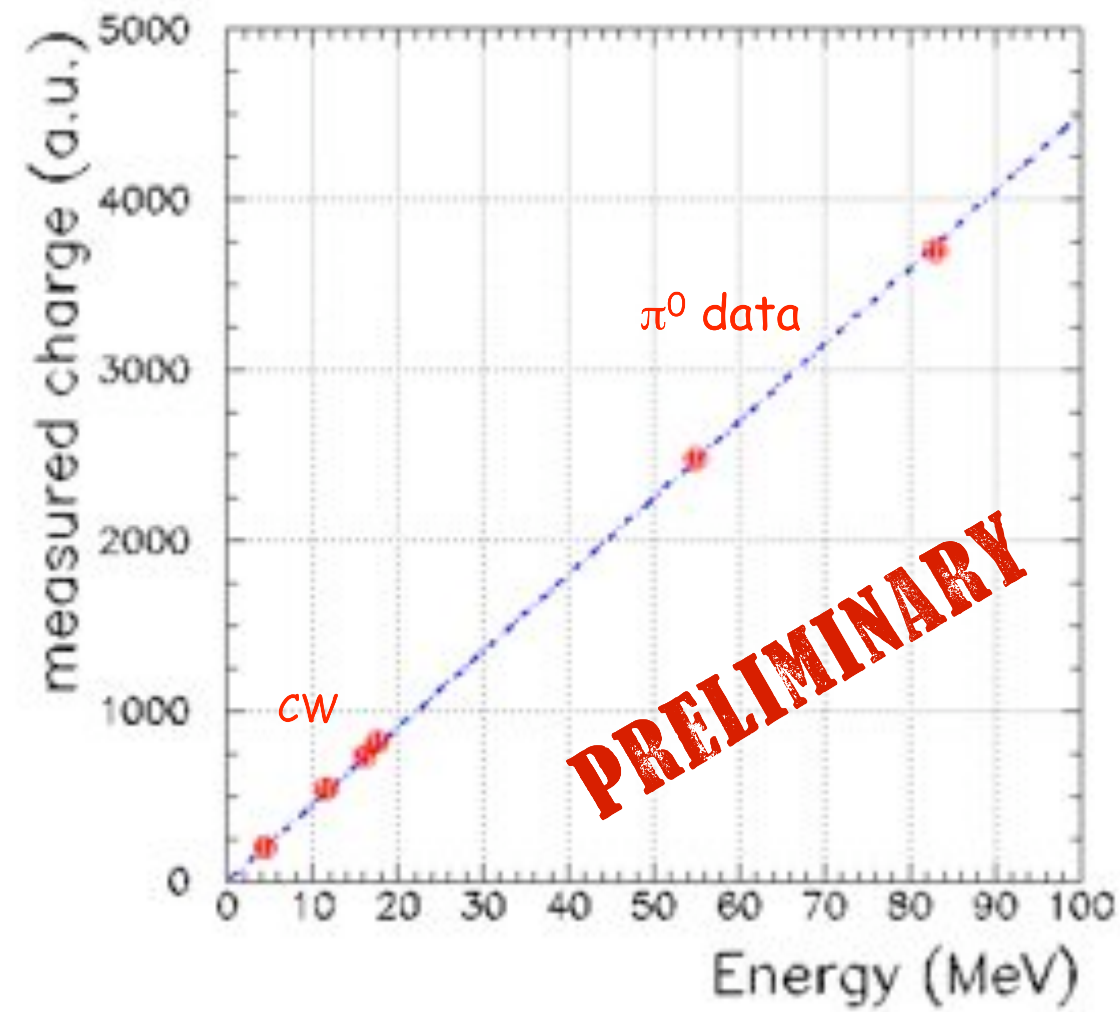


Daily monitoring

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

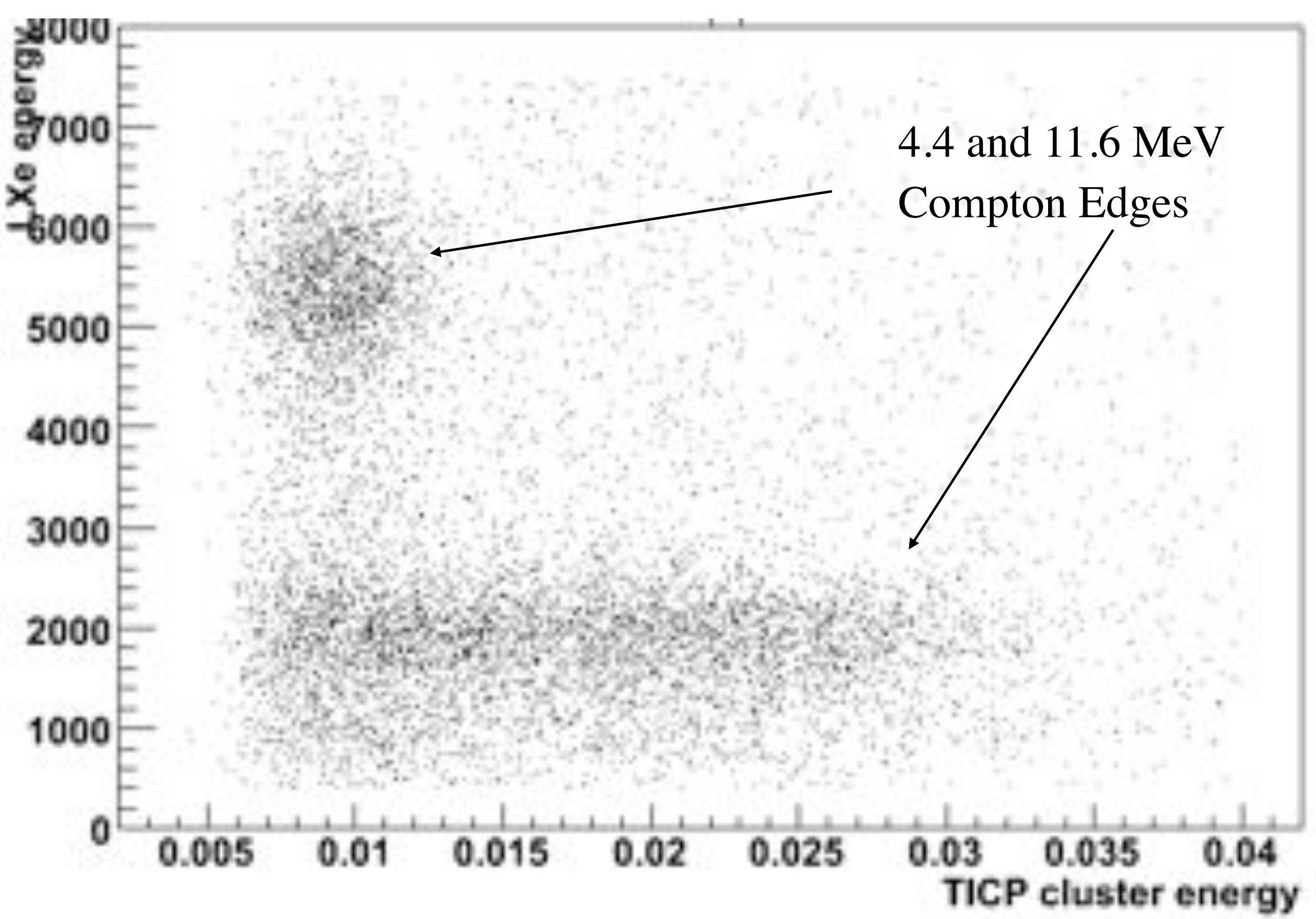
< 1% knowledge of l.y. and energy scale

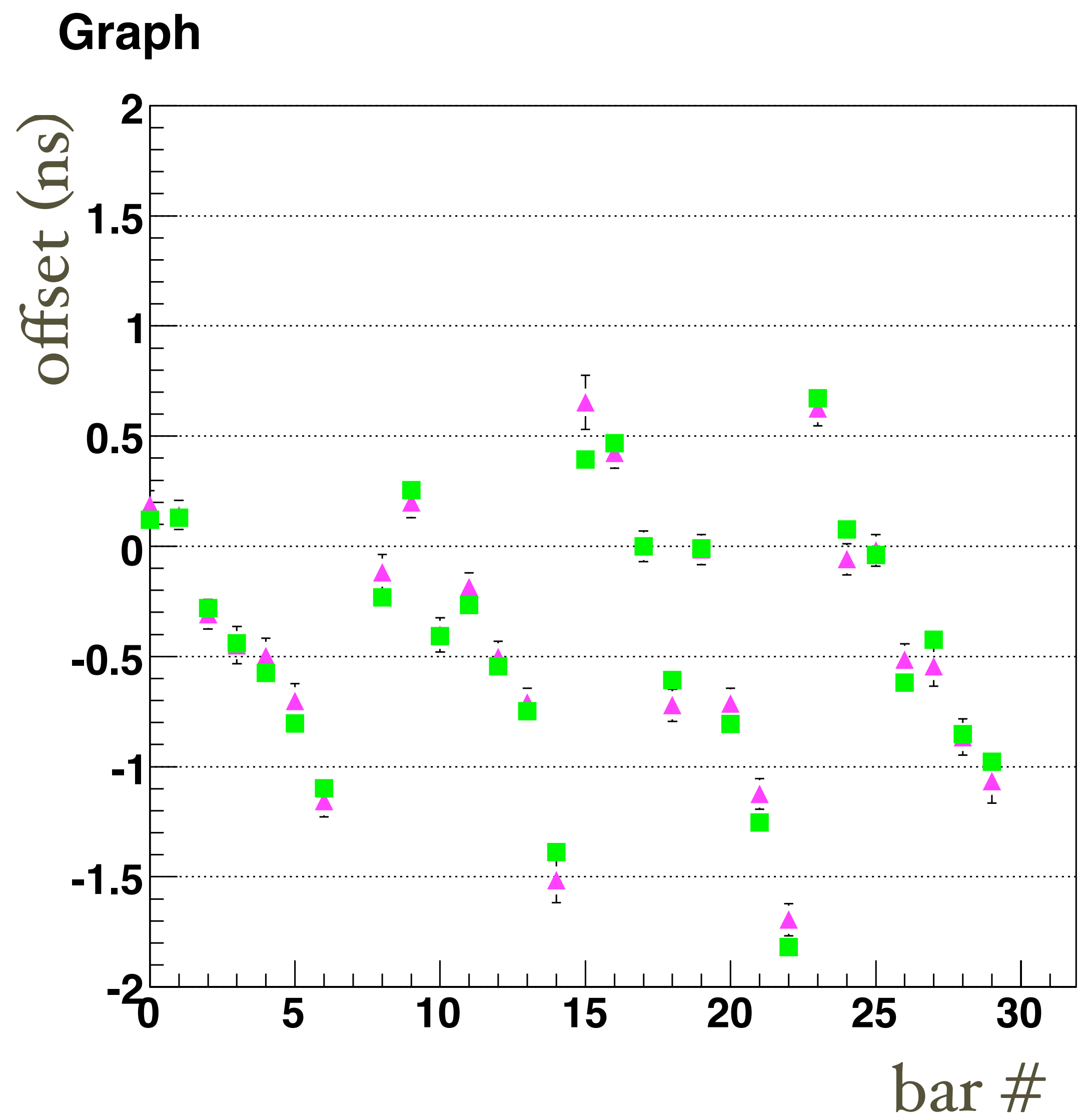




CW and timing counter

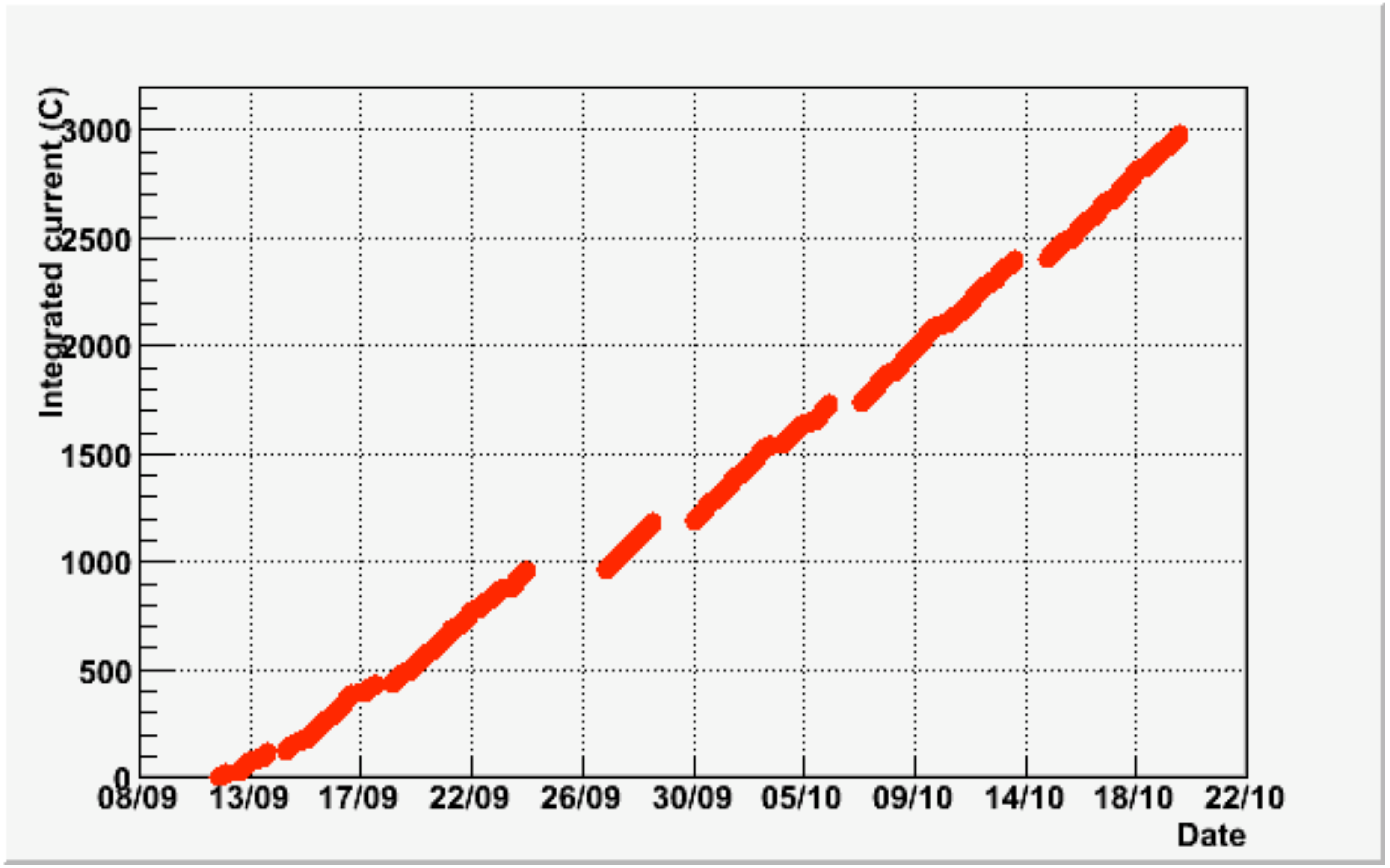
- The simultaneous emission of two photons in the Boron reaction is used to
  - determine relative timing between Xe and TIC
  - Inter-calibrate TIC bar (LASER)





Selected results from 2007 engineering run

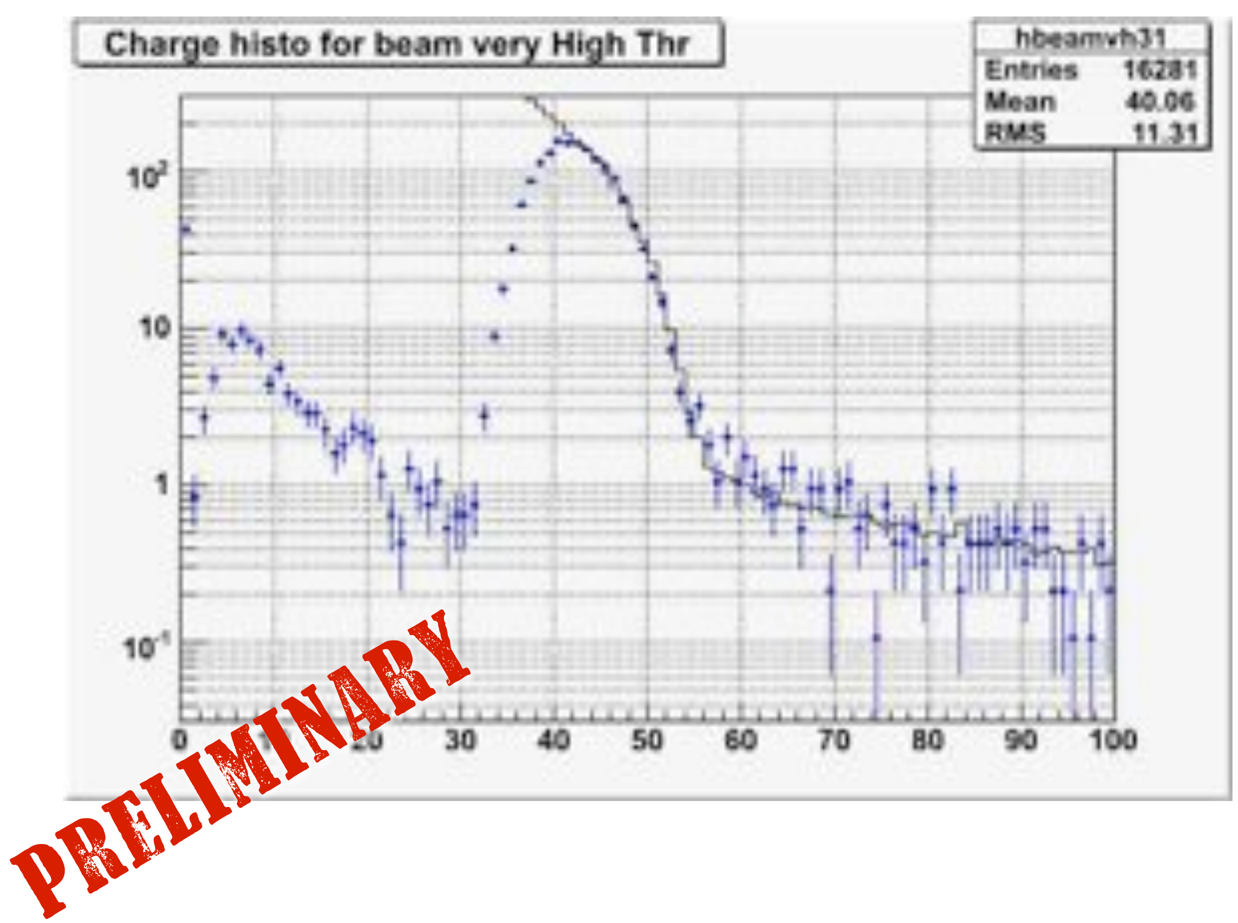
- We are presently taking data but I cannot show you any plot from this year "physics" data set
- Our strategy is masking some of the data
  - *blind* analysis
  - *likelihood* analysis



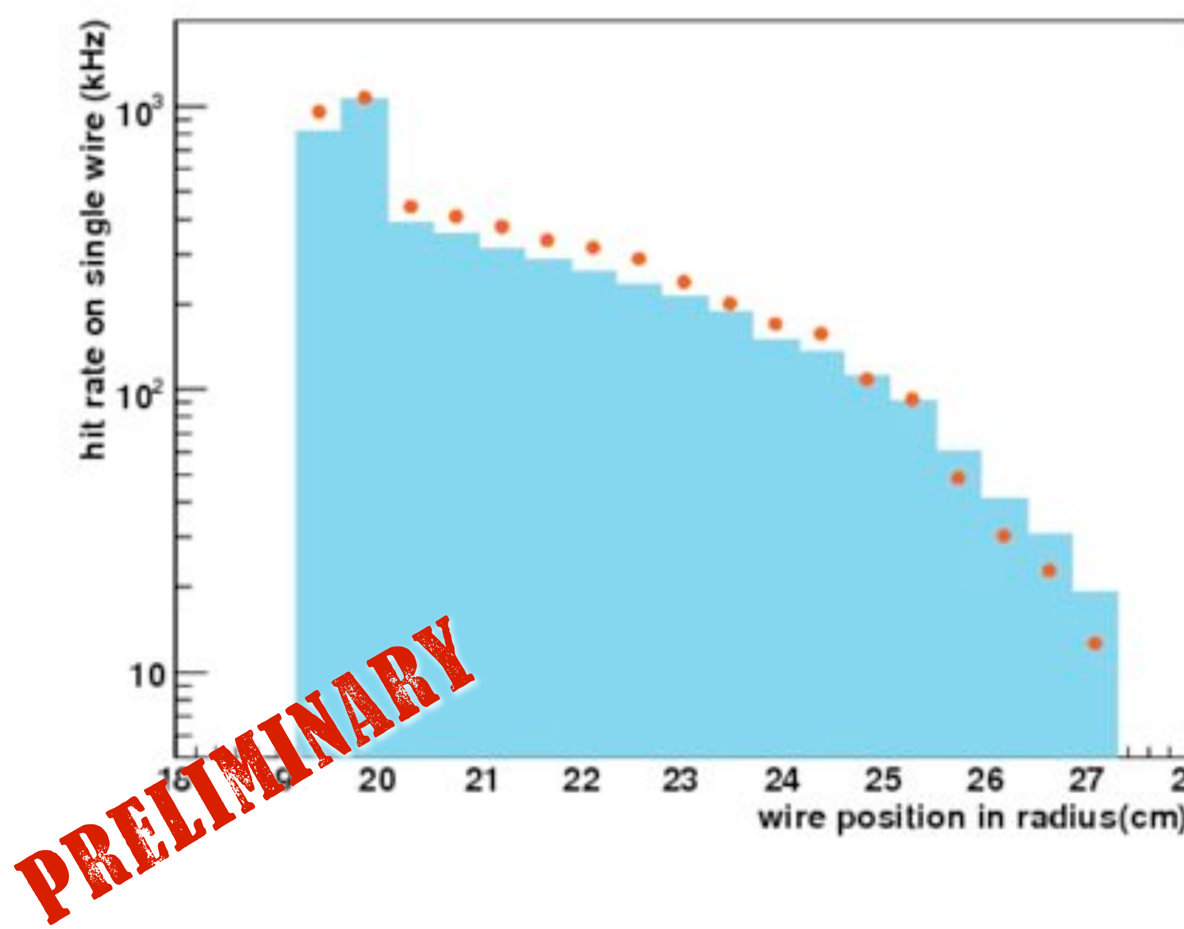
First: the rates

- 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

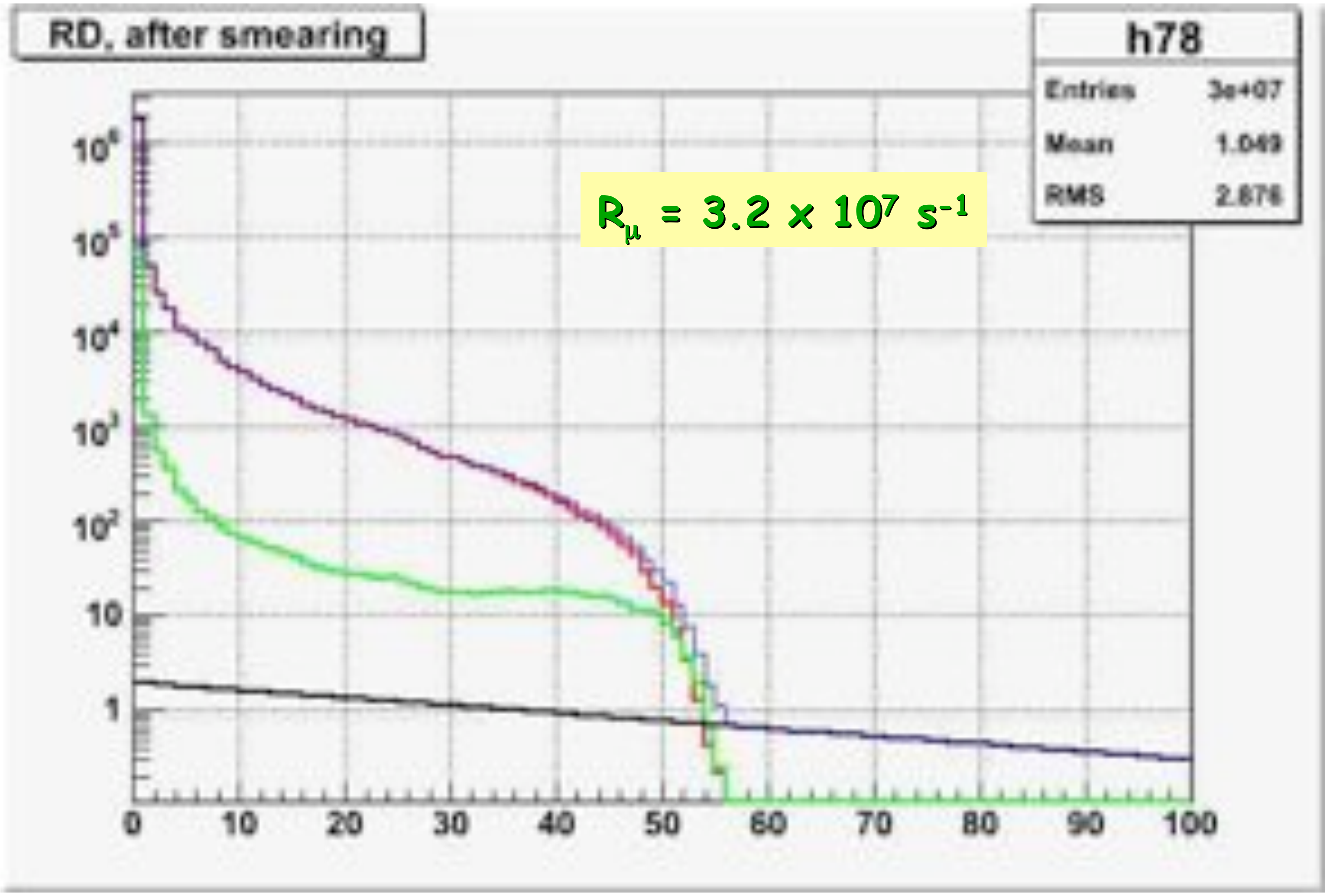


rate on DCH wires



The expected spectrum

- The simulated expected spectrum in the calorimeter contains several contributions

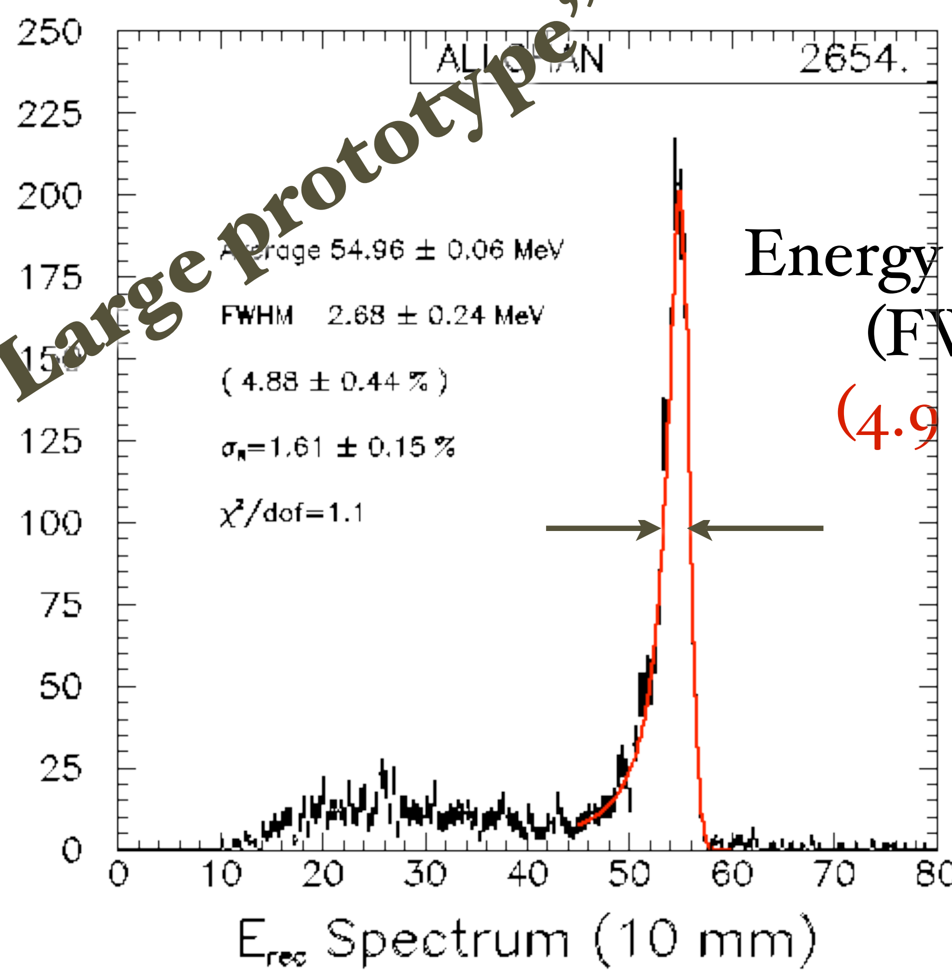


Red: Radiative decay
Green: Annihilation In Flight
Black: Cosmics (approximated)
Blue: Total (including pile-up)

LXe energy and timing

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

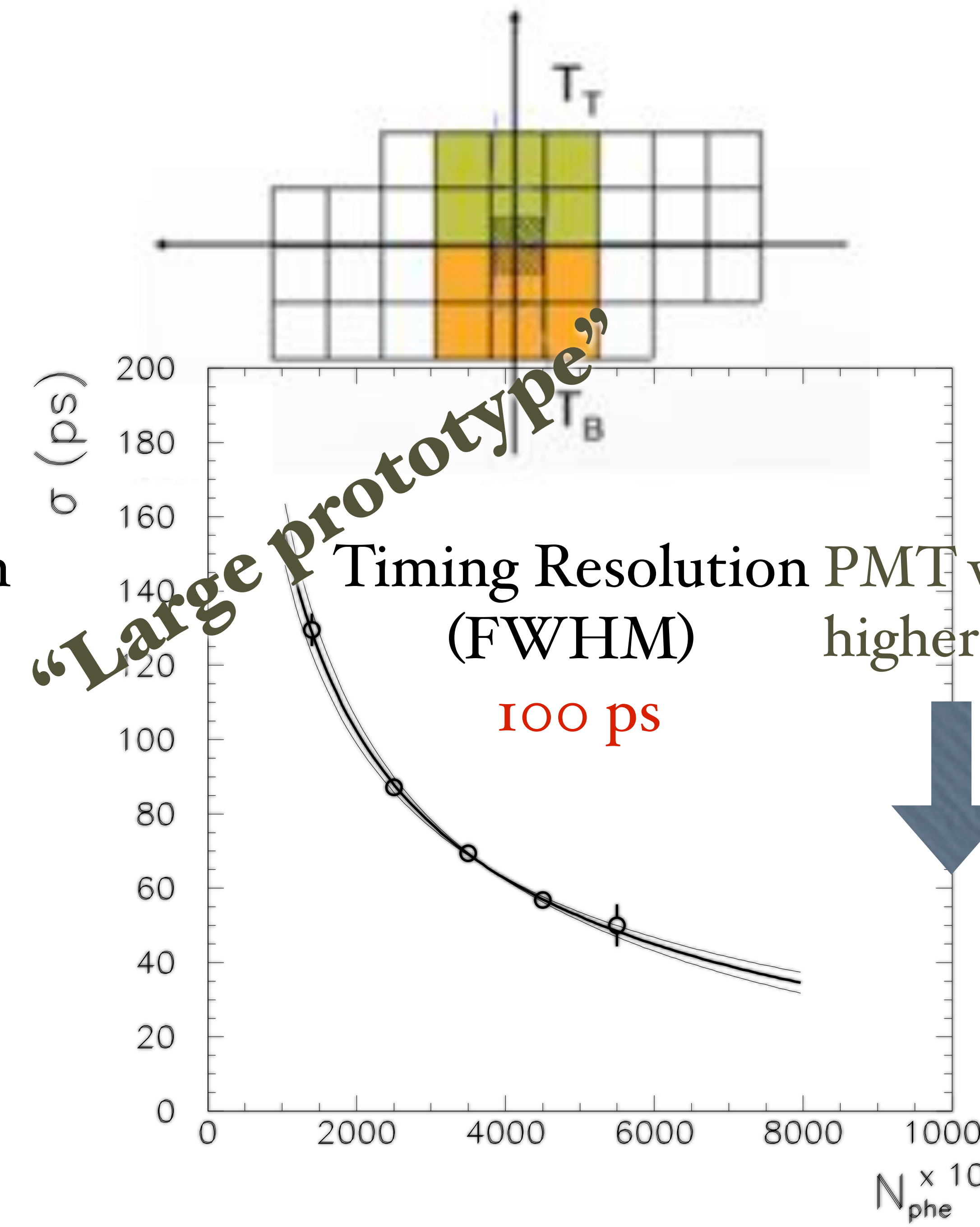
π^0 Run



"Large prototype"

Energy Resolution (FWHM)

(4.9 ± 0.4) %



"Large prototype"

Timing Resolution (FWHM)

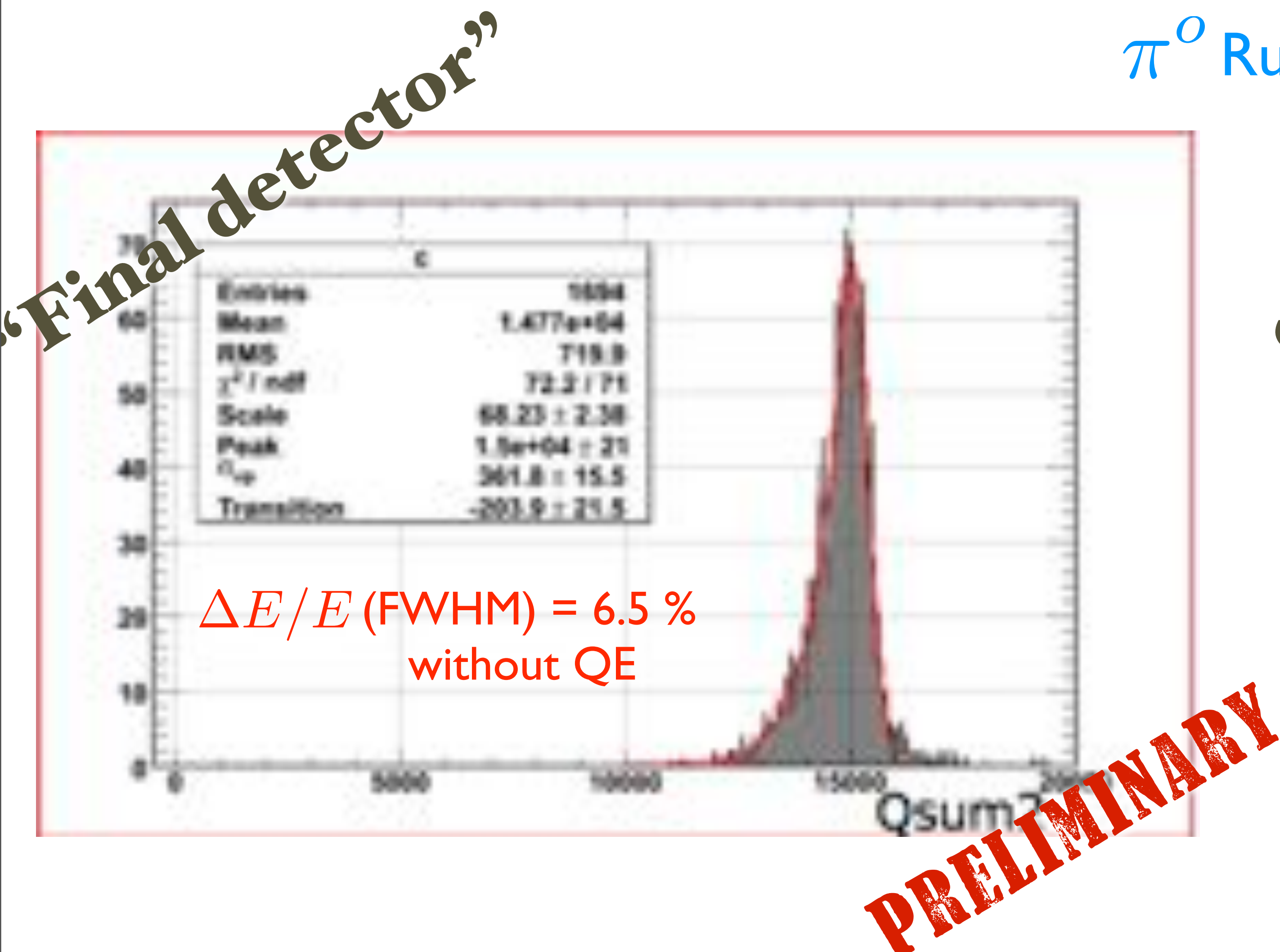
100 ps

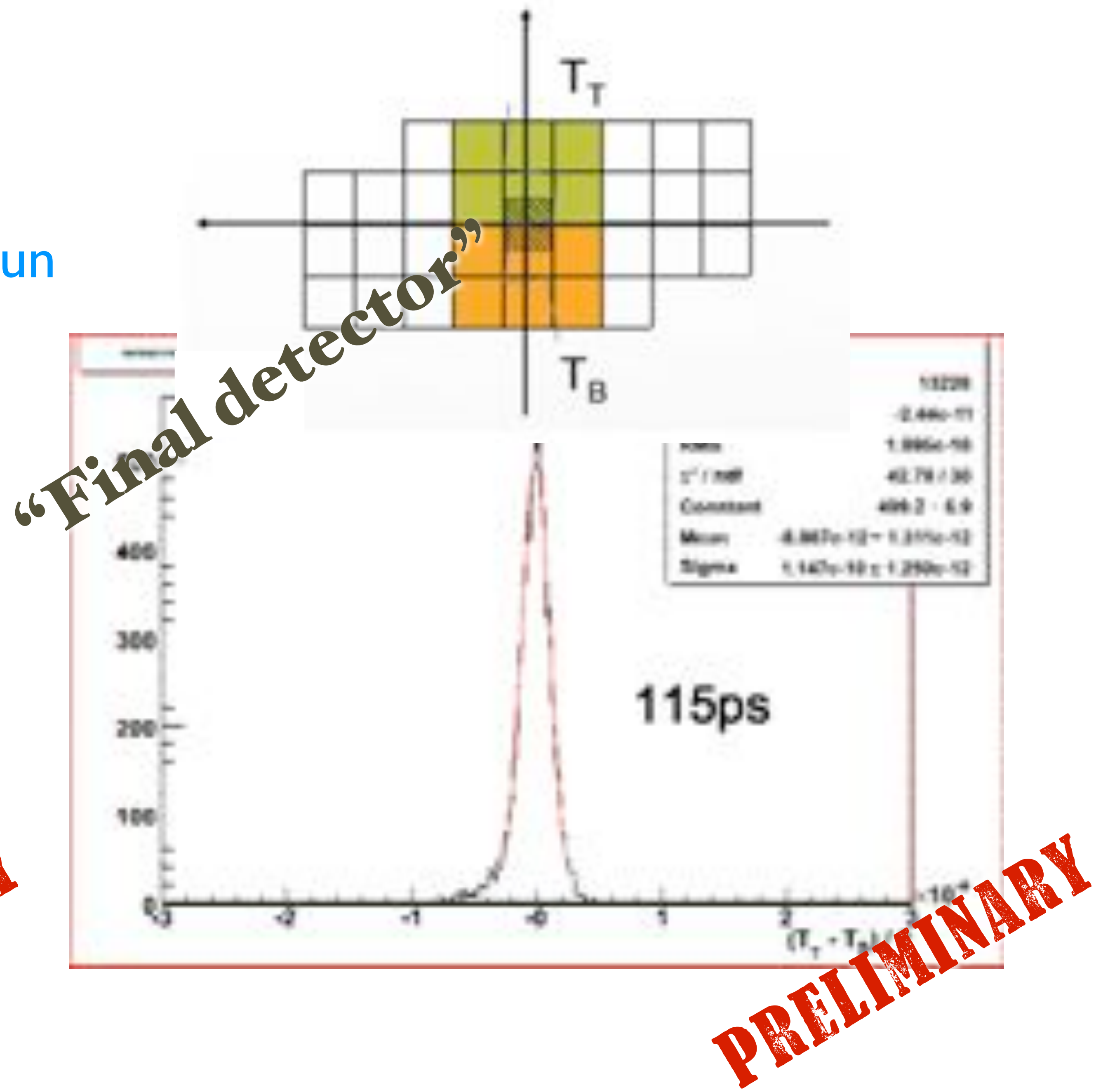
PMT with higher QE

LXe energy and timing

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

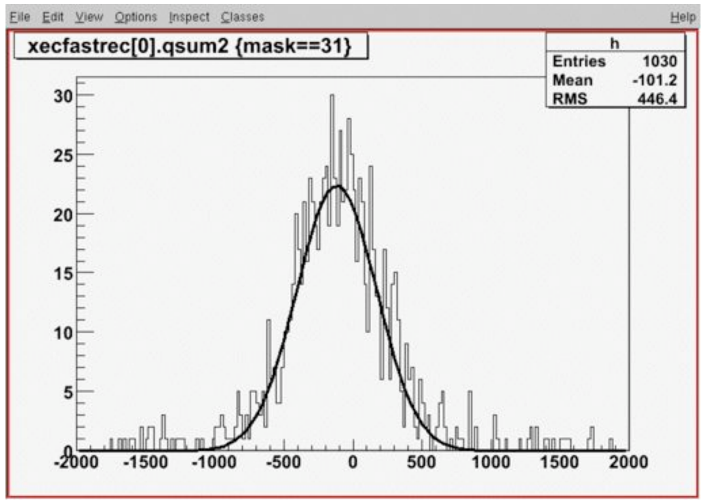
π^o Run



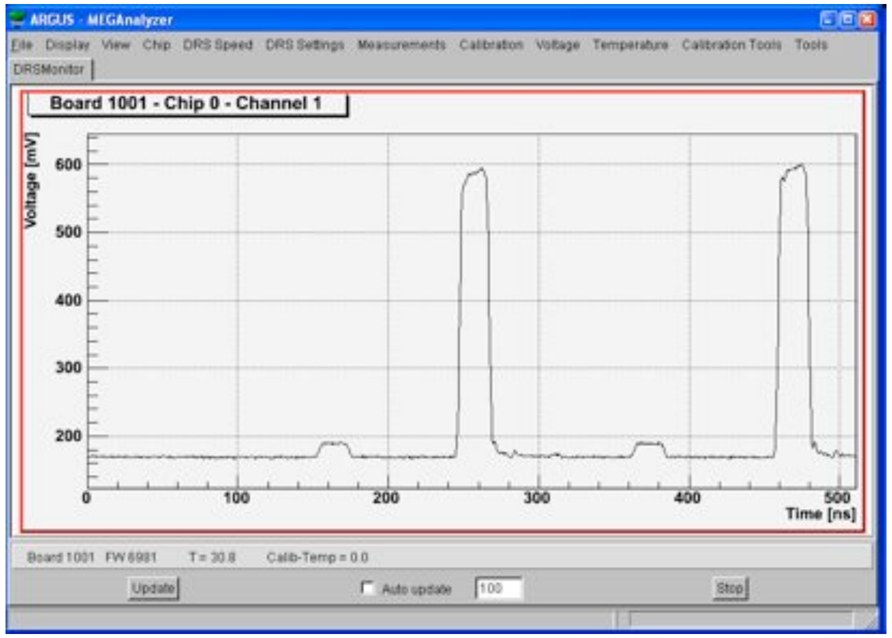


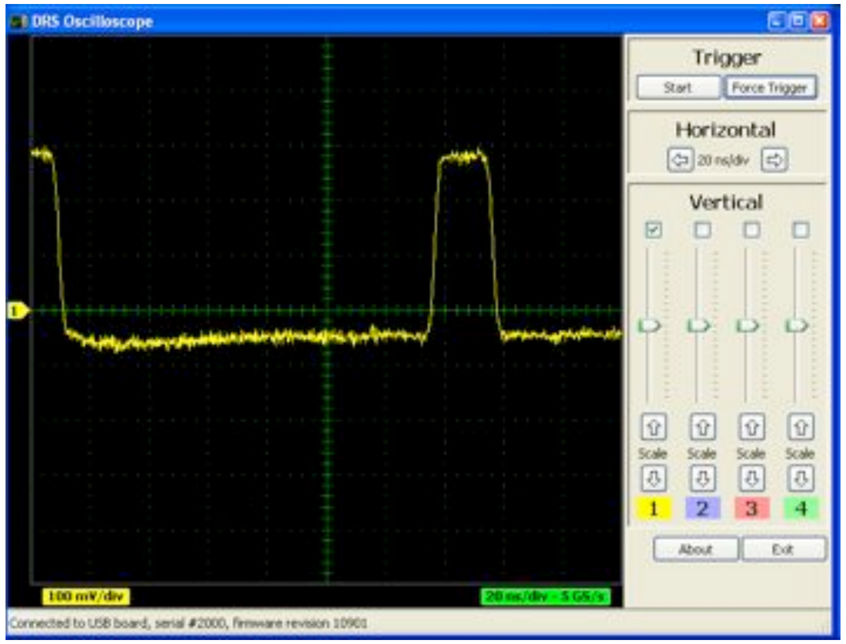
Pedestal

- 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)

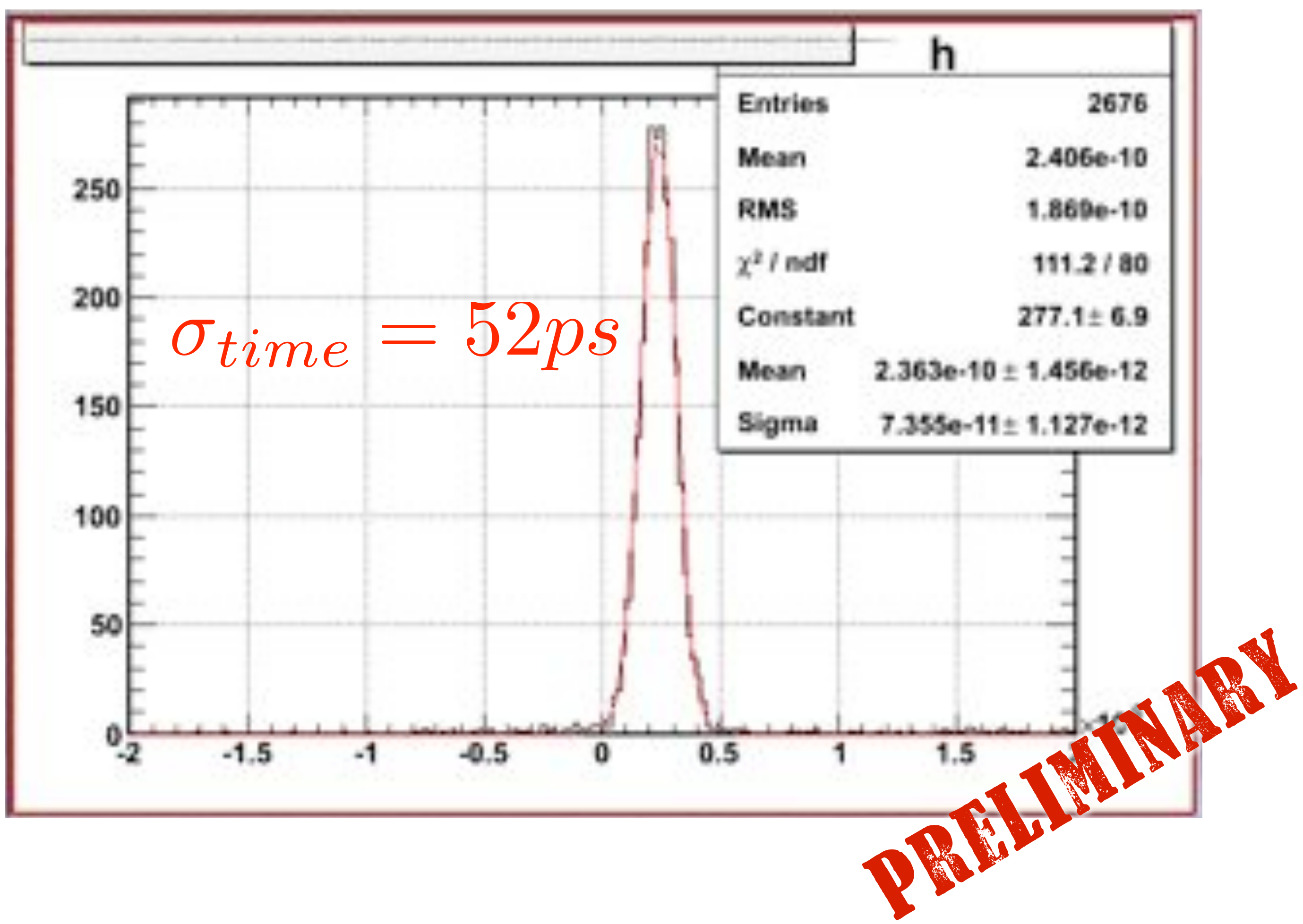


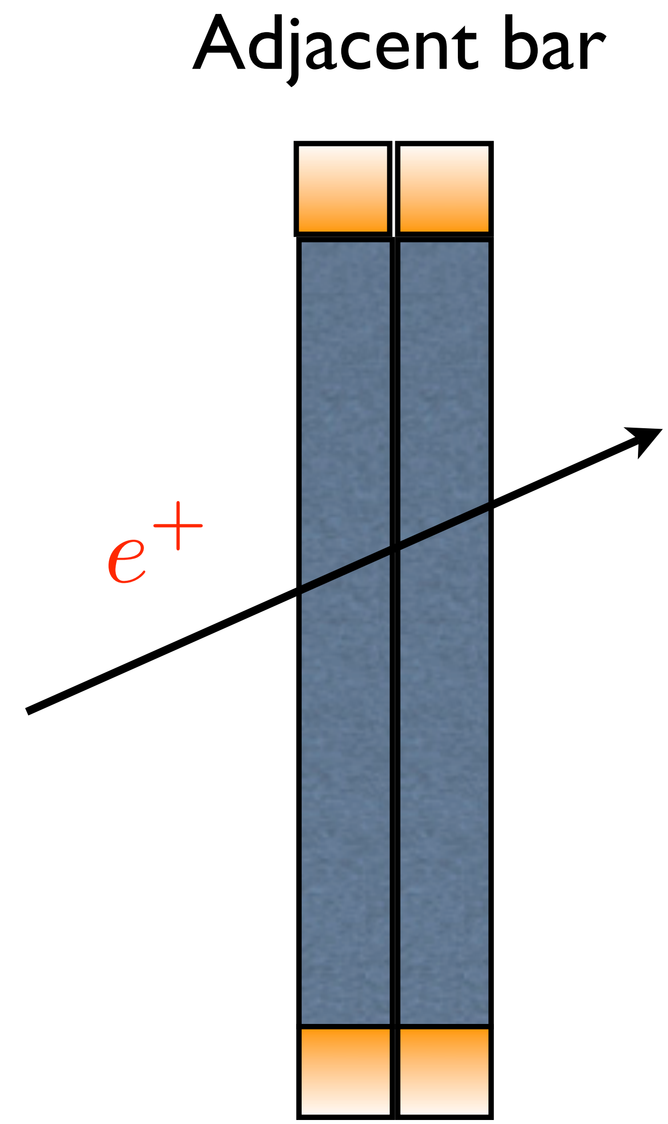


TIC timing resolution

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

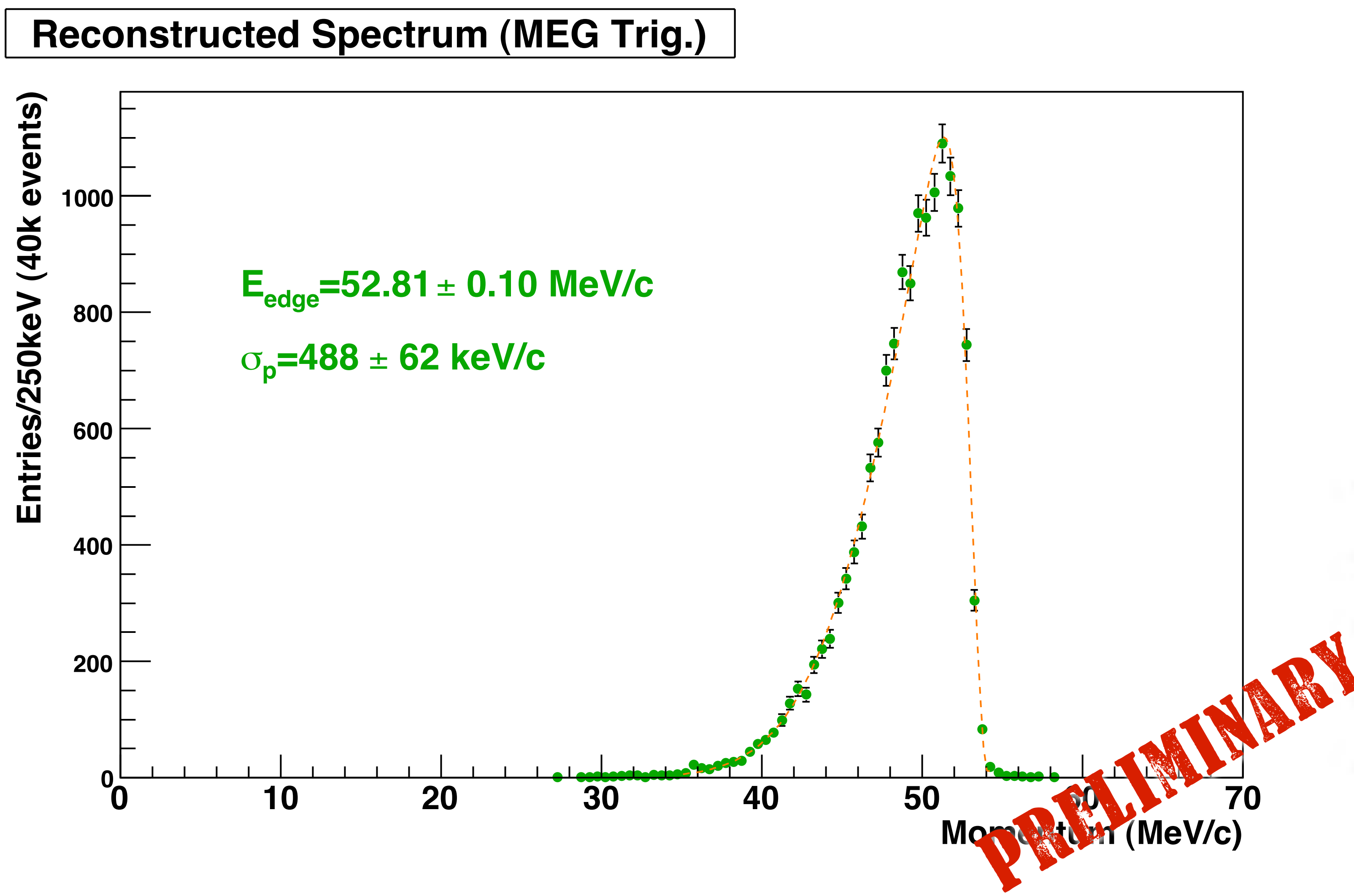
Michel e⁺ Run

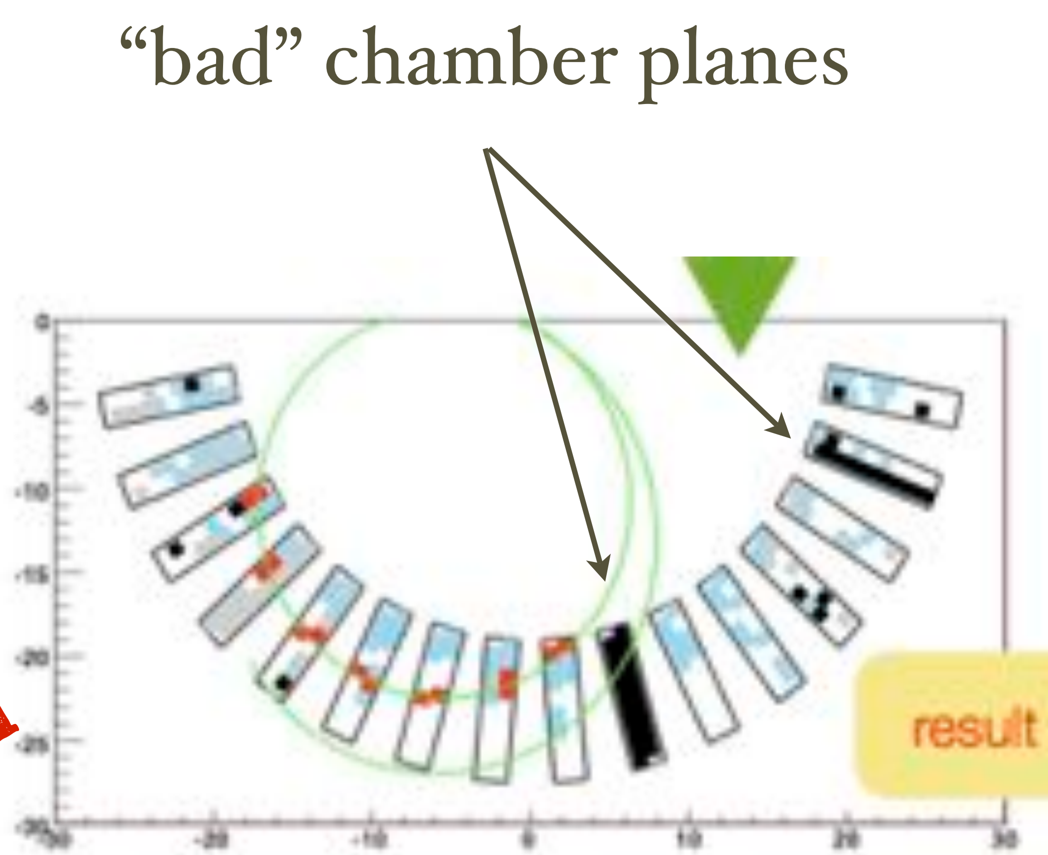




DCH performance

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





...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

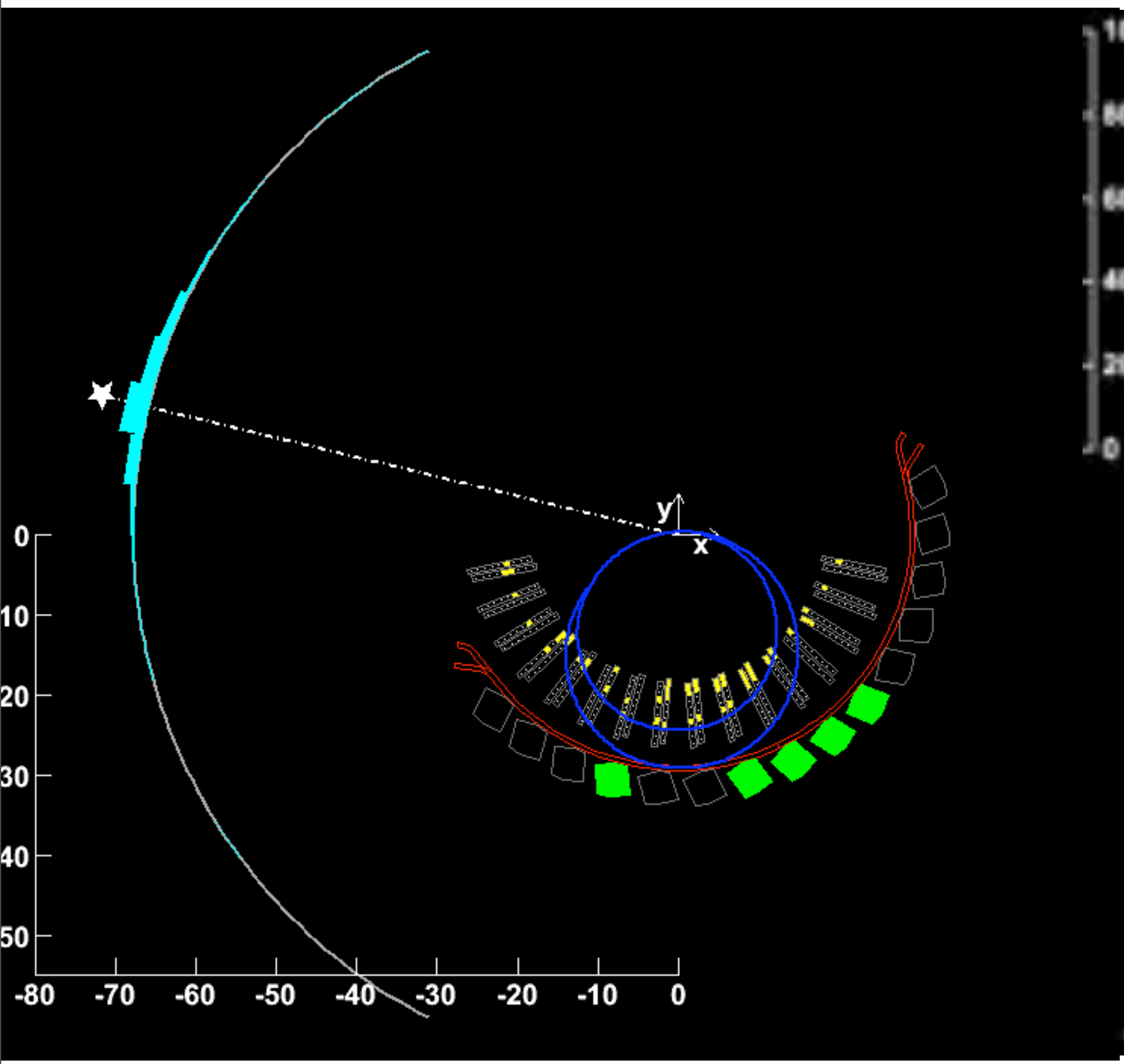
*** The muon rate is optimized to improve the limit

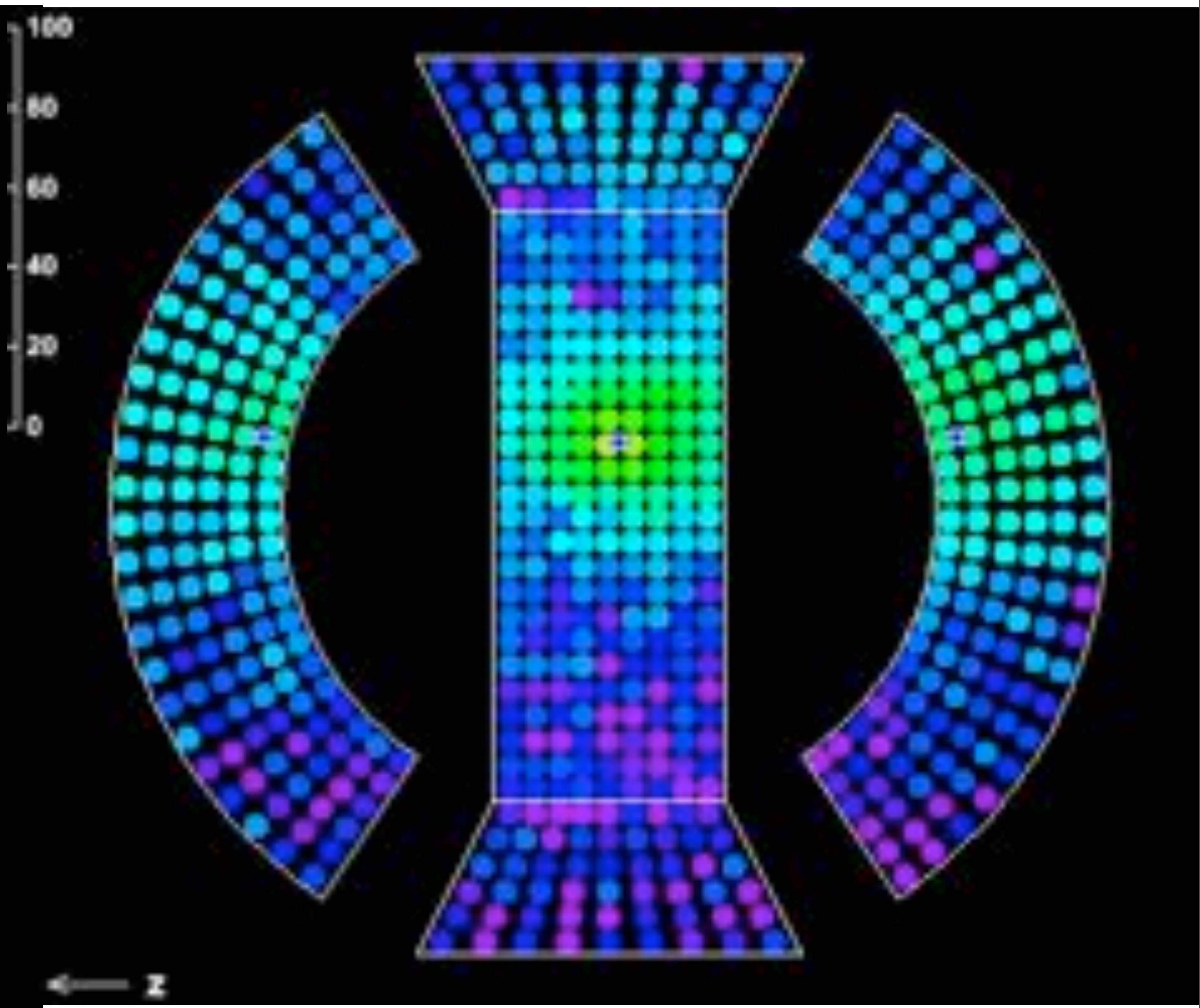
Perspective

- 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.

A 2008 candidate event

- A good hint for this year!





Thanks

Back-up slides