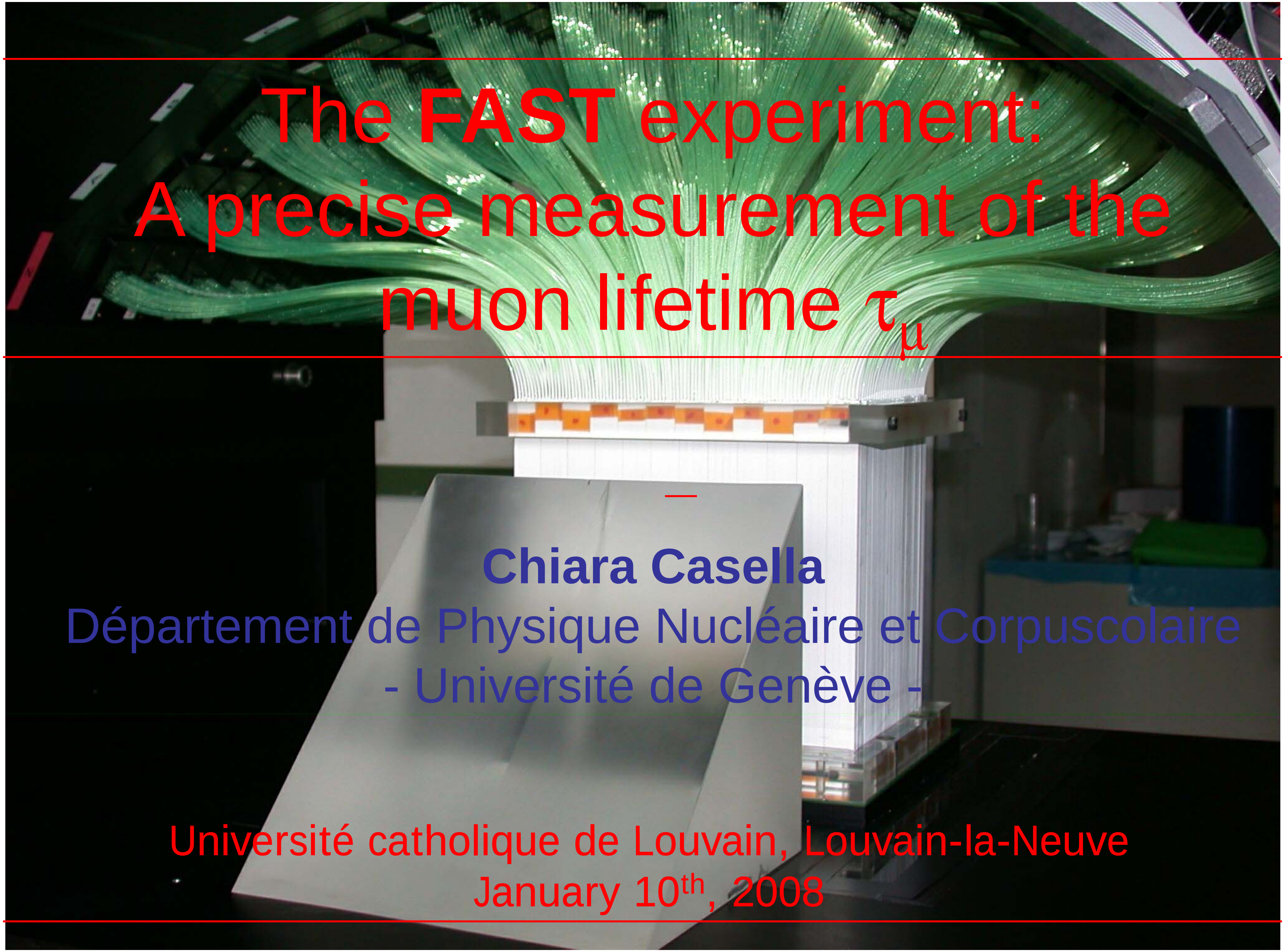
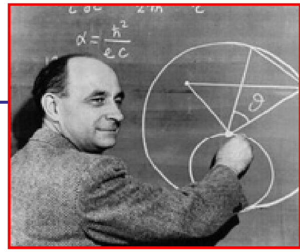


The **FAST** experiment: A precise measurement of the muon lifetime τ_μ

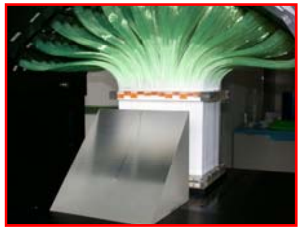
Chiara Casella
Département de Physique Nucléaire et Corpusculaire
- Université de Genève -

Université catholique de Louvain, Louvain-la-Neuve
January 10th, 2008

OUTLINE



- **Theoretical motivations & Goal of the experiment**

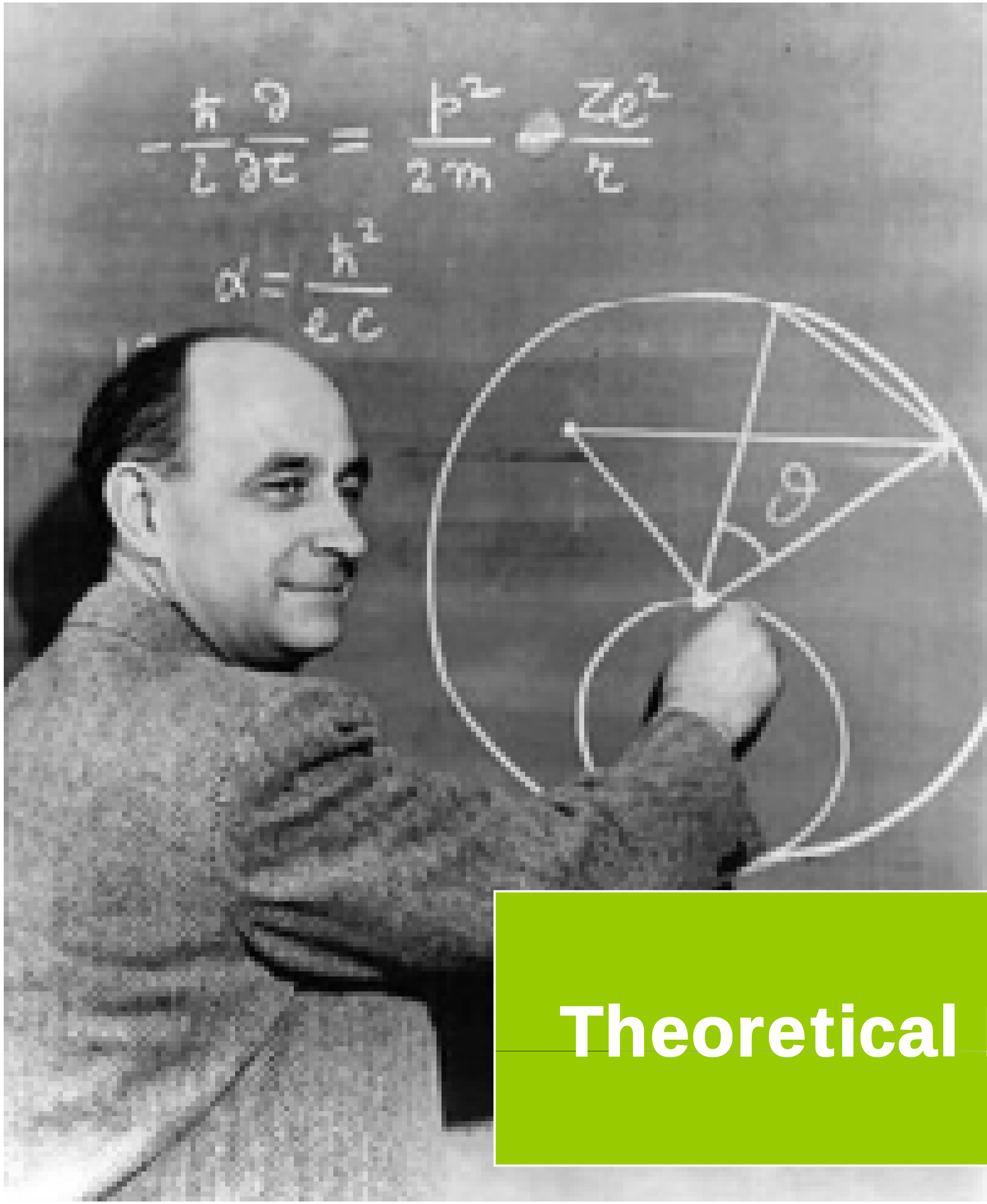


- **The FAST experiment**
    - general experimental concept
    - description of the setup elements

      (beam; target; readout; DAQ; LV2 trigger)

- **Muon Lifetime Measurement (2006 data sample)**
    - run 2006 data sample
    - analysis procedure (from raw data to histograms)
    - fit procedure (i.e. muon lifetime measurement)

- **Study of the Systematic Uncertainties**
- **Present Status of the Experiment (2007 beam time)**
- **Conclusions**

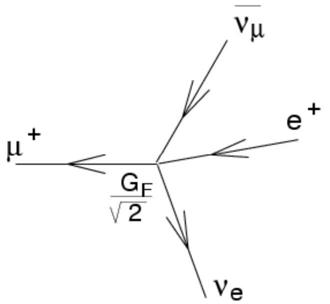


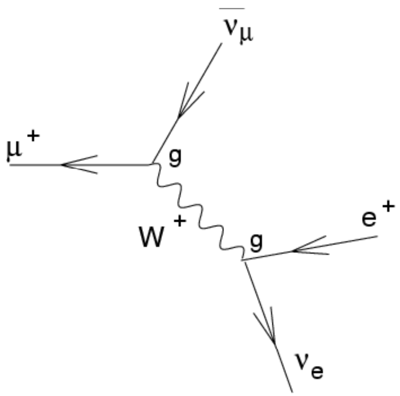
Theoretical Motivations

A PRECISE MEASUREMENT OF τ_μ : WHY ?

$$\tau_\mu \Rightarrow G_F$$

$$\mu^+ \rightarrow e^+ \; \nu_e \; \bar{\nu}_\mu$$





- **G_F: one of the input parameter of the SM**
  - SM is predictive only when supplied with a sufficient number of experimental inputs
  - SM of ElectroWeak interaction (BOSONIC SECTOR) : 3 input parameters needed **[α, M_Z, G_F]**

- **G_F** : introduced by Fermi in a **contact interaction theory** for the **muon decay** to describe the strenght of a new force (the weak force)

- The muon decay proceeds via **W boson exchange**.
The contact interaction is a valid approximation in the limit of small momenta [q^2 << MW]

- **G_F** is **extracted directly by $\tau\mu$** (in the Fermi model + all orders in α)

$$\tau_\mu{}^{-1} = \frac{G_F^2 m_\mu^5}{192\pi^3}(1 + \Delta q)$$

electron mass term +
all higher orders QED and QCD corrections

$$\Delta q = \sum_{i=0}^{\infty} \Delta q^{(i)} \qquad \Delta q^{(i)} = \mathcal{O}(\alpha_r^i)$$

[Calculated up to 2nd order]

PDG 2006

$$\tau_\mu = (2197.03 \pm 0.04) \text{ ns}$$

$$\frac{\delta\tau_\mu}{\tau_\mu} = 18 \; ppm$$

PDG 2006

$$G_F = (1.16637 \pm 0.00001) \times 10^{-5} \text{ GeV}^{-2}$$

$$\frac{\delta G_F}{G_F} = 9 \; ppm$$

UNCERTAINY ON G_F

$$\tau_\mu{}^{-1} = \frac{G_F^2 m_\mu^5}{192\pi^3}(1+\Delta q)$$

- theoretical uncertainty (i.e. knowledge of Δq)

$\Delta q^{(0)}$, $\Delta q^{(1)}$ } 1970's → $\left(\frac{\delta G_F}{G_F}\right)_{th.} = 15\ ppm$ from predictions of (uncalculated) $\Delta q^{(2)}$

$\Delta q^{(2)}$ 1999: ***Ritbergen & Stuart*** *Phys.Rev.Lett. 82, 488* ***(1999)***

$$\left(\frac{\delta G_F}{G_F}\right)_{th.} = 0.3\ ppm$$

- experimental uncertainty (i.e. experimental accuracy of the quantities in the τ_μ/G_F formula)

$$\left(\frac{\delta G_F}{G_F}\right)_{exp} = \frac{1}{2}\frac{\delta\tau_\mu}{\tau_\mu} - \frac{5}{2}\frac{\delta m_\mu}{m_\mu} + \left(4\frac{m_{\nu_\mu}^2}{m_\mu^2}\right)$$

9 ppm 0.2 ppm < 13 ppm (direct meas.)
0 (CMB & neutrino oscill.)

$$\left(\frac{\delta G_F}{G_F}\right)_{exp} = 9\ ppm$$

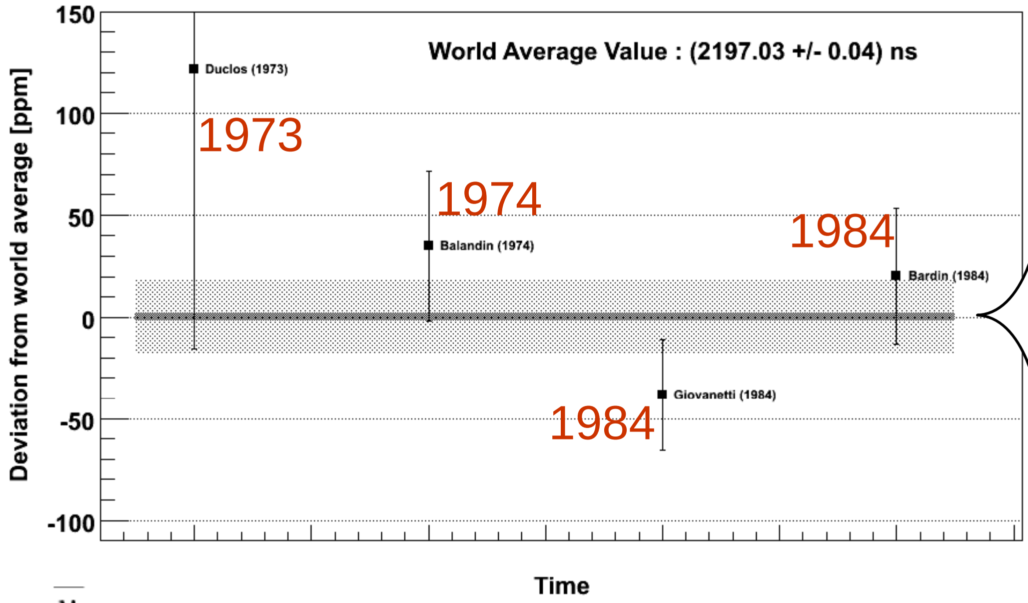
	relative precision	contribution to $\delta G_F/G_F$		
τ_μ	18 ppm	9 ppm		
m_μ	0.09 ppm	0.2 ppm		
m_{ν_μ}	-	$<$ 13 ppm	m_{ν_μ}	$<$ 0.19 MeV (90% C.L.)
	-	0		$< 2-3$ eV (95% C.L.)

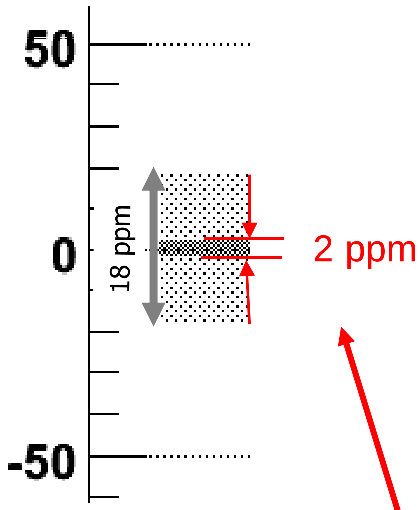
At present, the (exp) accuracy on τ_μ is the limiting factor for an improved precision on the Fermi Constant G_F

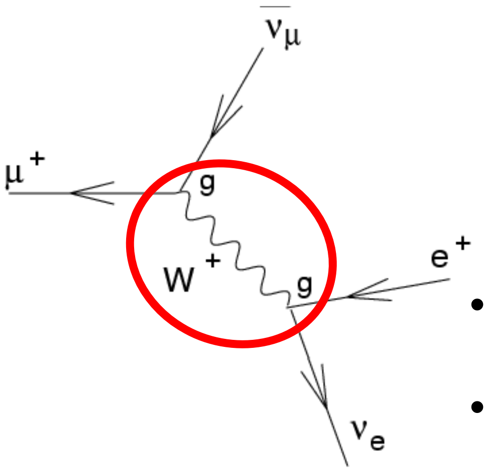
Experimental knowledge of τμ & GOAL of the FAST EXPERIMENT

present experimental knowledge of τμ

PDG 2006 : $\frac{\delta\tau_\mu}{\tau_\mu} = 18\ ppm \Rightarrow \frac{\delta G_F}{G_F} = 9\ ppm$







FAST GOAL : $\frac{\delta\tau_\mu}{\tau_\mu} = 2\ ppm \Rightarrow \frac{\delta G_F}{G_F} = 1\ ppm$

- precise enough to show the effects of the W propagator in G_F calculation
- **FAST: high energy experiment performed at a low energy scale**

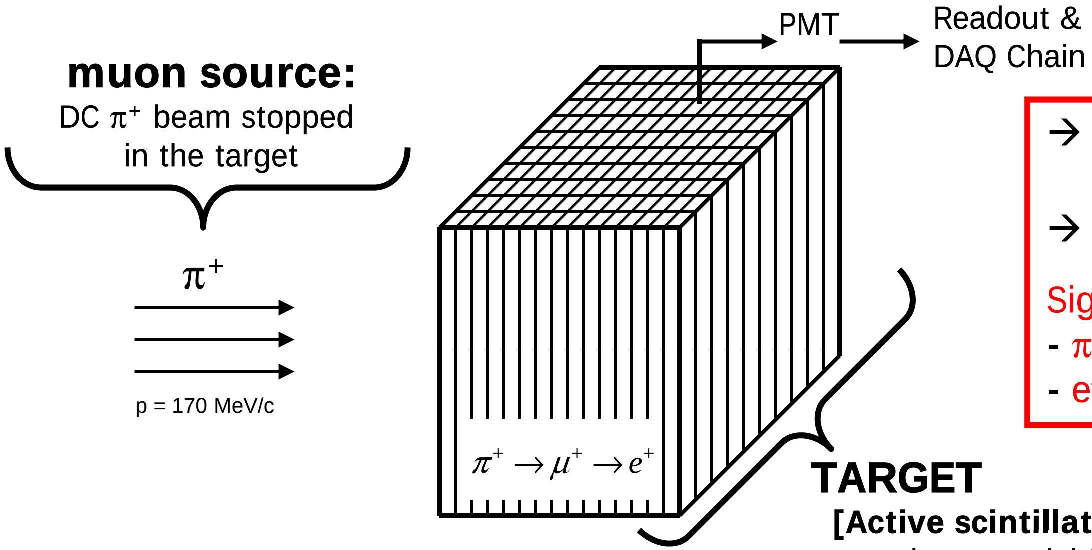
The FAST Experiment

THE FAST COLLABORATION

A.Barczyk [1], J.Berdugo [2], J.Casaus [2], C.Casella [3], K.Deiters [4], J.Kirkby [1], L.Malgeri [1], C.Mana [2], J.Marin [2], G.Martinez [2], C.Petitjean [4], M.Pohl [3], E.Sanchez [2], C.Willmott [2]

CERN [1] CIEMAT [2] UNIGE [3] PSI [4]

DESIGN of the FAST EXPERIMENT



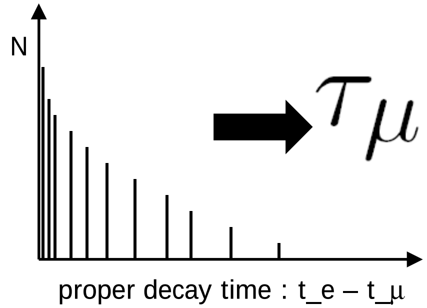
TARGET
[Active scintillator target]:
- stopping material for π^+ and μ^+
- detector for e^+

SIGNATURE FOR AN EVENT:

→ $\pi^+ \to \mu^+ \nu_\mu \; (\tau_\pi \sim 26ns)$ $\quad E_\mu^{cin} \sim 4\ MeV$, $\rho_\mu \sim 1.5\ mm$

→ $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu \; (\tau_\mu \sim 2.2\mu s)$

Signature:
- π^+ & μ^+ close in time & space [high pulses]
- e^+ track [mip's]



Size of the statistical sample => achievable precision in the measurement

$$\frac{(\delta\tau)_{stat}}{\tau} = \frac{1}{\sqrt{N_{events}}}$$

New generation muon lifetime experiments ($\delta\tau_\mu/\tau_\mu$ ~ ppm) → 2 main requirements:
1. Achieve a large statistical sample (N_events ~ 10^{11} - 10^{12})
2. Control the systematic effects

DESIGN of the FAST EXPERIMENT

1. Large statistical sample:

$$\left.\begin{array}{l}\dfrac{\delta\tau_\mu}{\tau_\mu} \sim 2\ \mathrm{ppm} \Rightarrow N_{evts} \geq 2.5 \times 10^{11} \\ \text{observation period per event: } 10\ \tau\mu \rightarrow\ 20\mu s\end{array}\right\} 10^{11} \times 20\mu s/\ \mathrm{eff}(0.5) \sim O(year)$$

Only for data taking

PARALLELISATION IS NEEDED

in the same observation window (20 μs) several events should be handled

CONSTRAINTS IN THE DESIGN :

Target
- high granularity
- tracking capabilities
- imaging detector

Beam
- high beam rate (~ 500 kHz)

Analysis
- huge data rate → online analysis

2. Suppress systematic effects:

pile-up effects
- high granularity, imaging detector, uniform occupancy

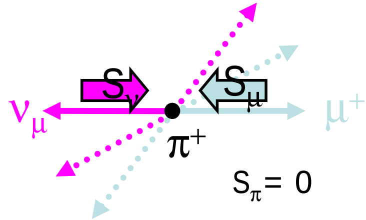
Gain shifts / event losses
- DC beam

μSR effects
- unpolarized & isotropic muon source (from π decay at rest)
- range cuts for beam muon suppression
- large angular acceptance and isotropic detection efficiency
- local magnetic field to assess residual systematics

MUON SOURCE (i.e. DC π^+ BEAM)

μ source = π decay at rest in the target

➔ isotropic & unpolarized μ source

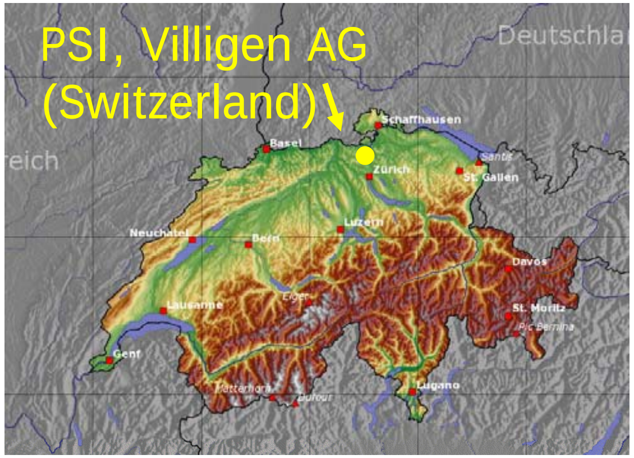


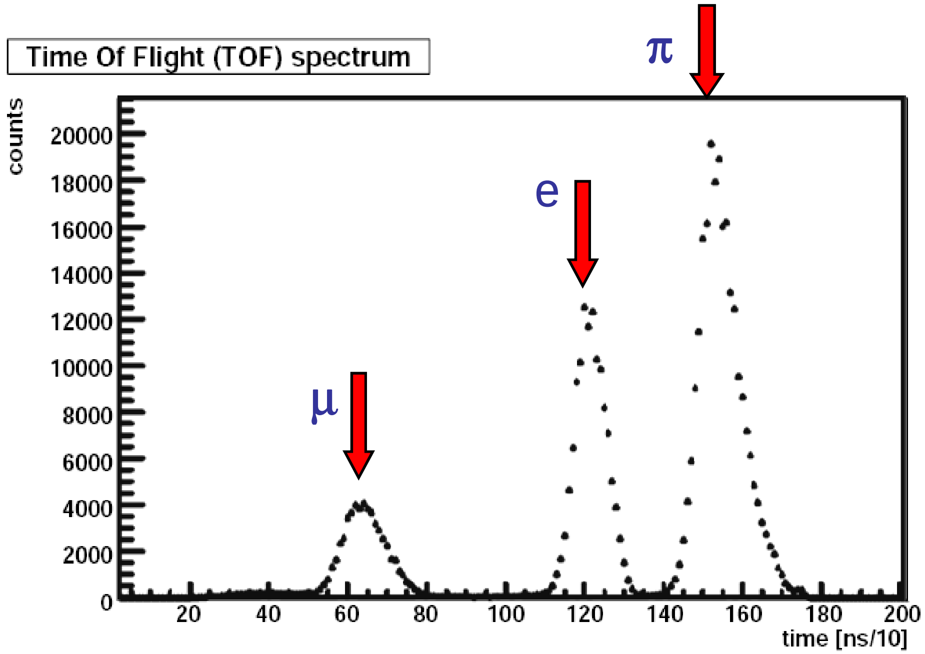
DC π^+ BEAM @ Paul Scherrer Institute (PSI)

PSI :

proton cyclotron (590 MeV) (2mA p curr)

several secondary beamlines

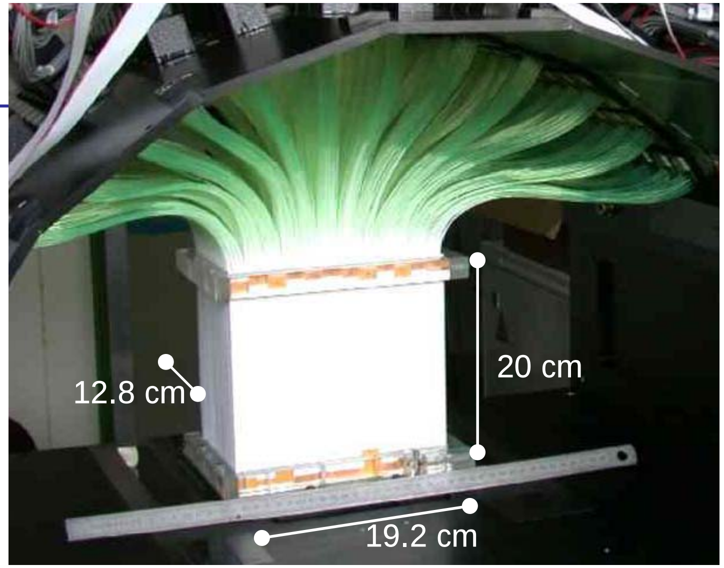


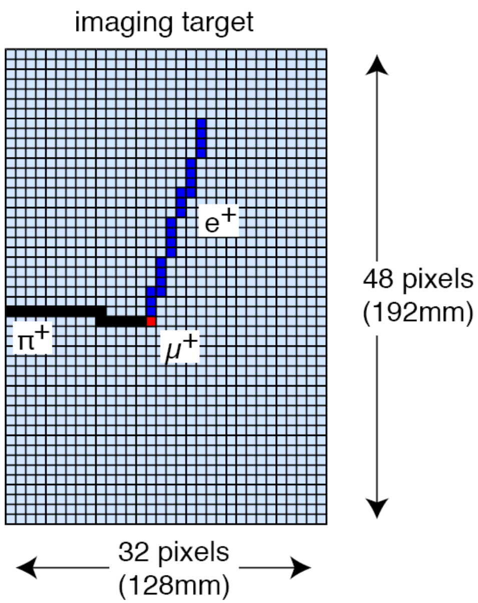


- **πM1 area**	: **π^+ DC beam**
- momentum	: **170 MeV/c** (±3%)
- RF frequency	: 50.633 MHz (T=19.75 ns)
- size	: variable **(~ 10 x 10 cm^2)**
- intensity	: variable **(~ 500 kHz)**
- purity	: ~ 50%

TARGET

- Active target :
  - stopping material for π^+/μ^+
  - detector for the particles
- Solid plastic scintillator (Bicron BC400)

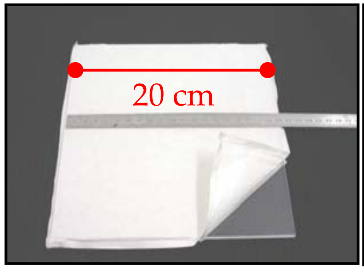




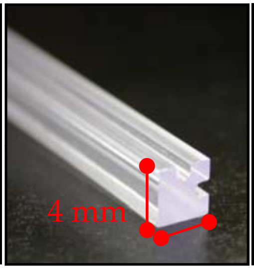
- requirements imposed by the design:
  - **high granularity**
  - **tracking capabilities**
  - **fast imaging detector**
  - **identical replicated mini-detectors**
  - **vertical arrangement 32 x 48**

- **1536 pixels** (8 x 12 [4x4]-bundles)
  1 pixel = scintillator bar (4 x 4 x 200 mm^3) with 2 WLSF

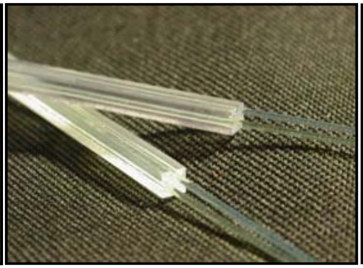
BC400 solid plastic scintillator plates



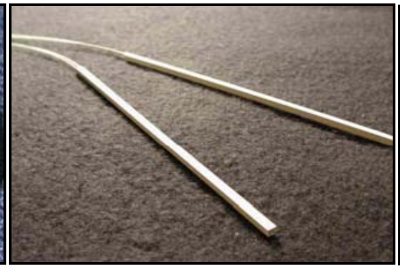
- 4x4x200mm3 bars
- two grooves machined



2 WLSF (BCF-92) inserted and glued into the grooves

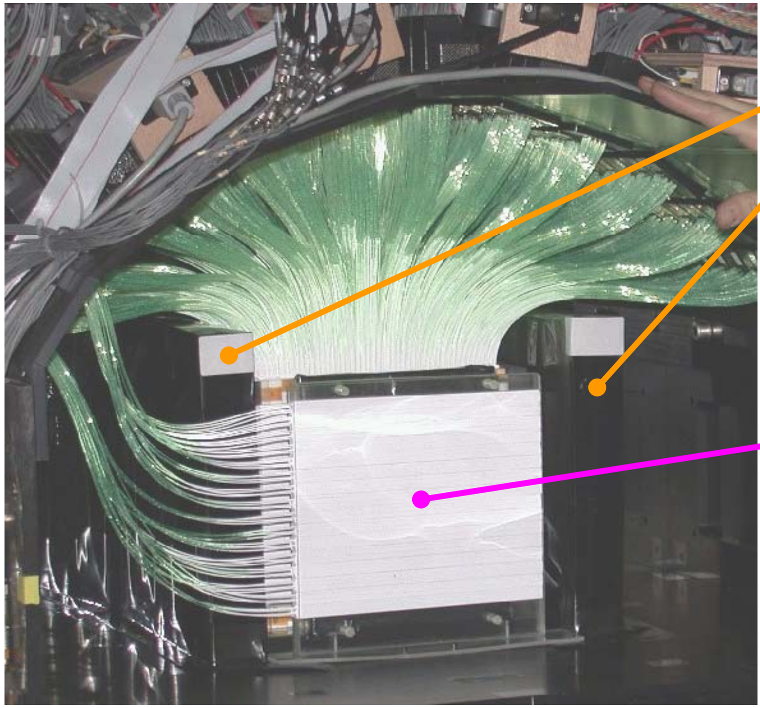


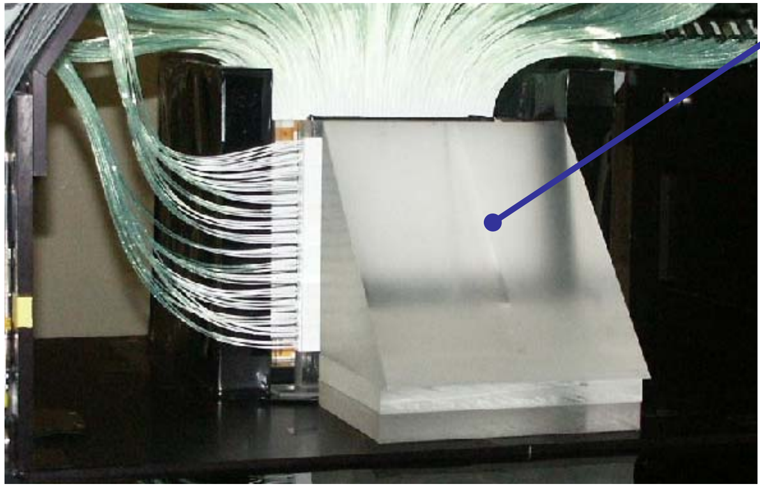
diffusive reflective paint (BC-620)



- bundle of 4x4 pixels [96 bundles]
- fibers housed in a special mask

TARGET: FINAL CONFIGURATION





dipolar magnetic field:

- permanent magnet
  (2 planes of magnetized ferrite blocks)
- B = 80 G
- homogeneous & transverse magnetic field
- assess systematics related to μSR effects

z-counter hodoscope:

-16 horizontal counters (10x10x200mm3)
- register vertical entry position of the beam pcls
- range requirements on beam pions

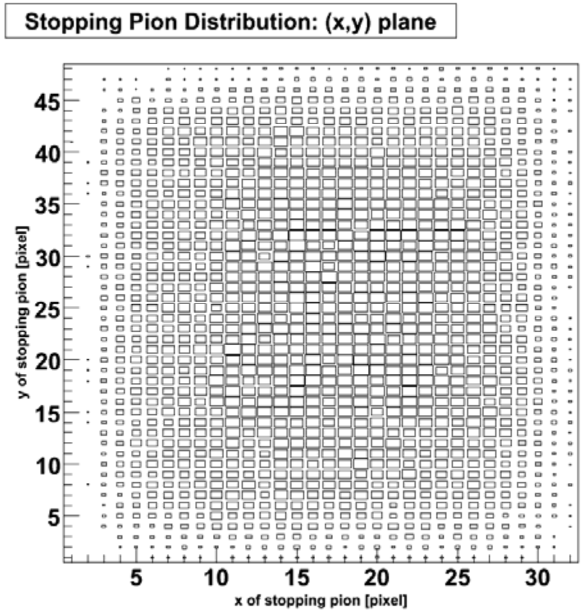
wedge shaped beam degrader

- vertical gradient in the thickness of the absorber
- achieve a uniform distribution of the stopping pions points
  (combined with large beam profiles)

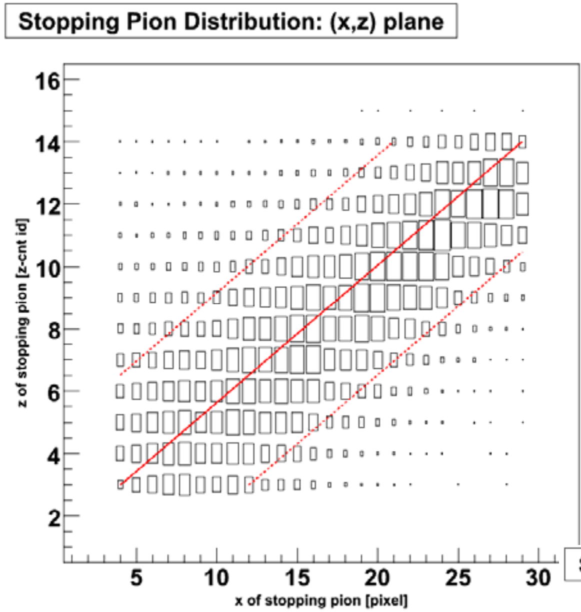
TARGET: OCCUPANCY & RANGE REQUIREMENTS

PION BEAM (nominal running conditions)

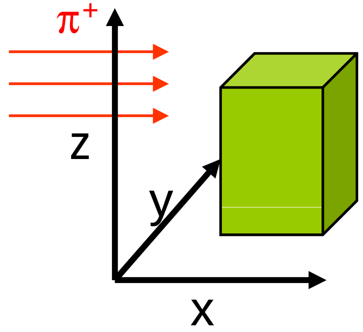
achieved uniform occupancy of pion stopping point



transverse plane (x,y)

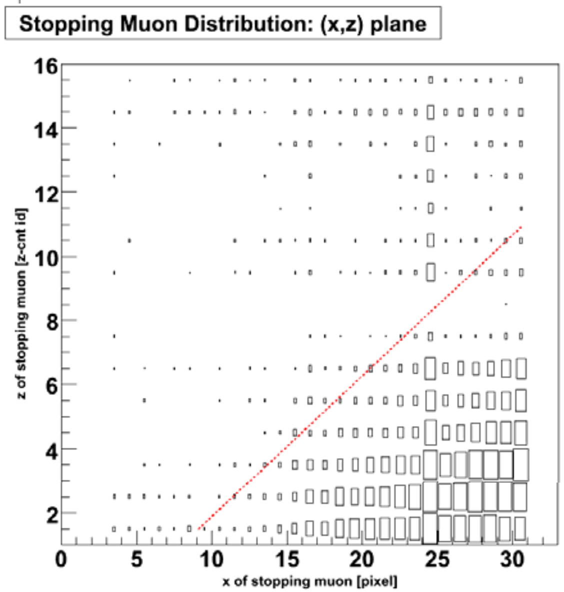


vertical plane (x,z)



MUON BEAM

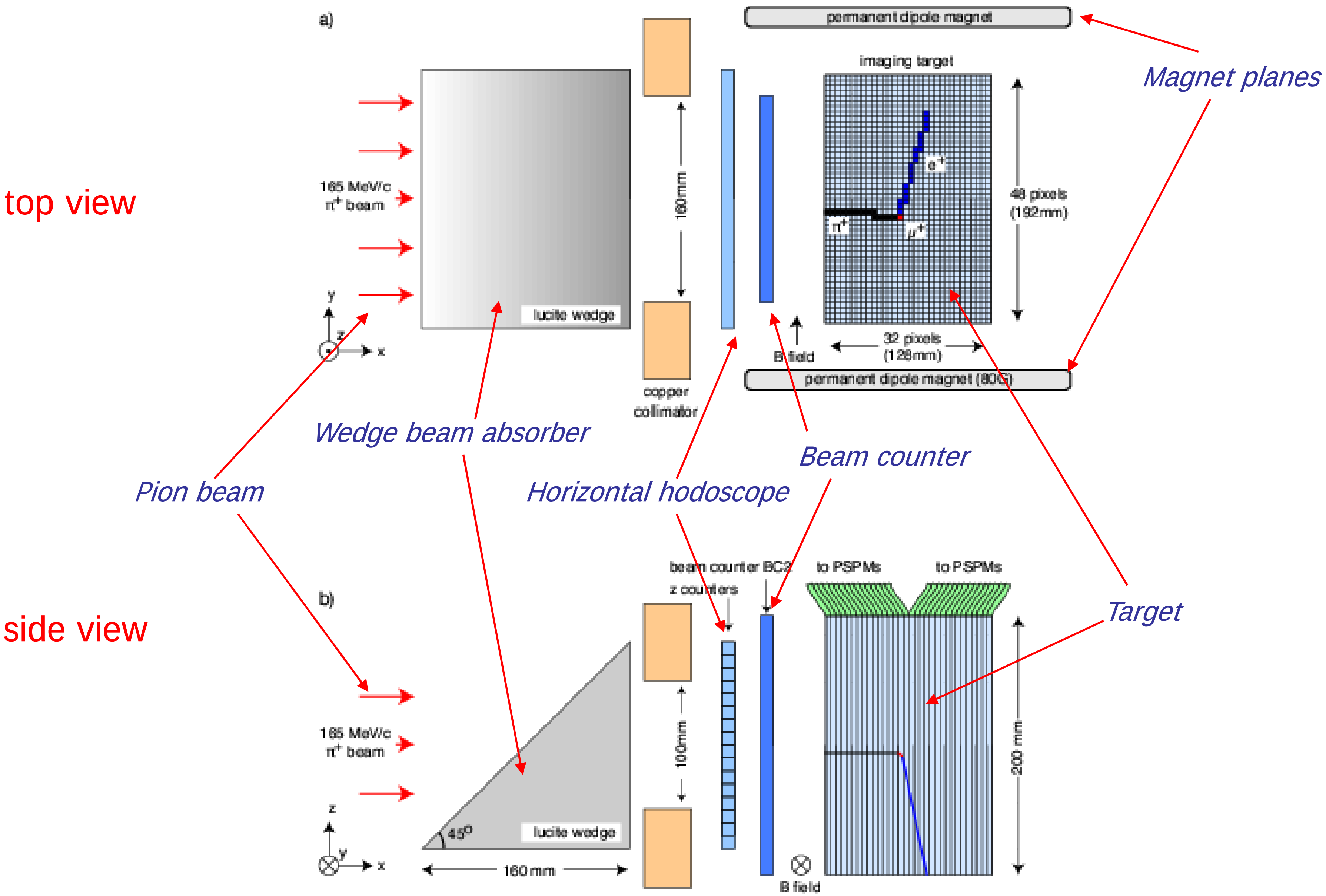
vertical plane (x,z)



Strong range separation (20 pixel ~ 8 cm)
between beam π's and μ's :

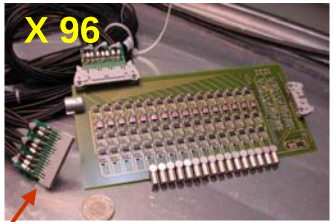
Wedge + hodoscope z-cnt tags
efficient suppression of residual beam muons

FAST: GLOBAL SETUP OVERVIEW



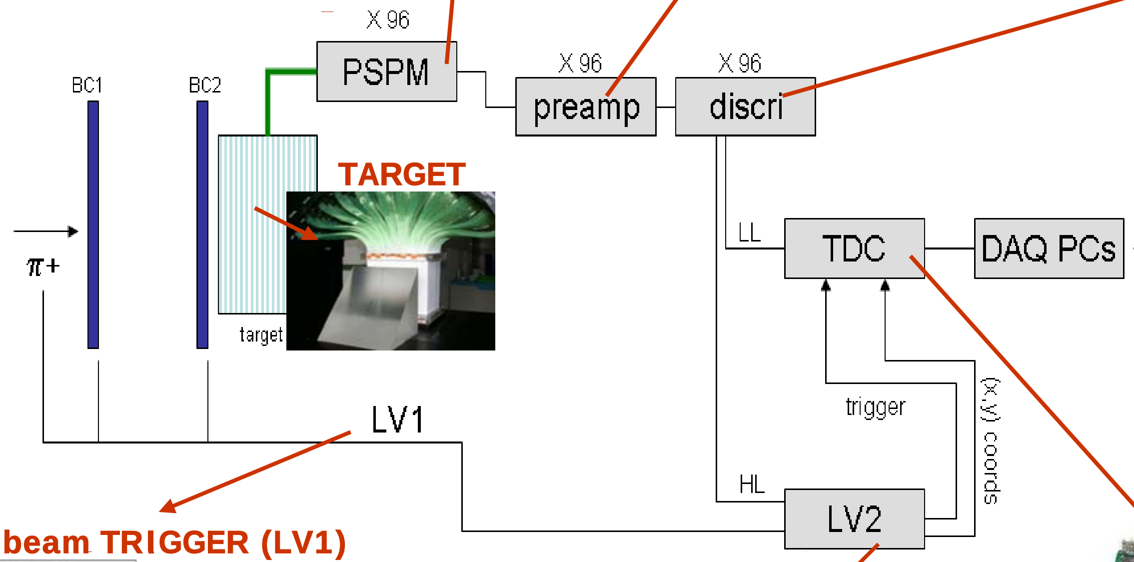
FAST: READOUT & DAQ CHAIN

- Position Sensitive **PhotoMultipliers (PSPM's)**
- Hamamatsu H6568-10
- multianode (4x4)



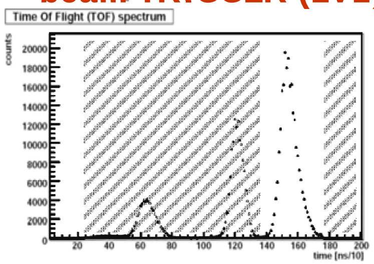
- **Preamplifiers**
- shaper & preamp (x5)
- custom made units (PSI)

- **Double THR discriminators**
  LOW (LL) & HIGH (HL)
  LL → mip's (e^+ tracks)
  HL → π^+/μ^+ (stop points)
- remotely adjustable thr (50 mV – 2 V)
- custom made units (PSI)



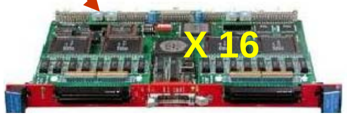
Particle Type	Light Yield [pe]
electrons (i.e. mip's)	9
pions with 20 mm range	25
stopping pions	35
$\pi \to \mu$ decay	35
LL V_{thr} = 100 mV	~ 3
HL V_{thr} = 400 mV	~ 18

beam TRIGGER (LV1)



-Narrow BC1.BC2.RF coinc
-Selective trigger on pions

Second Level TRIGGER (LV2)
- Hardware trigger for the TDCs
- DATA REDUCTION SYSTEM
- Custom made FPGA based electronics (CIEMAT)

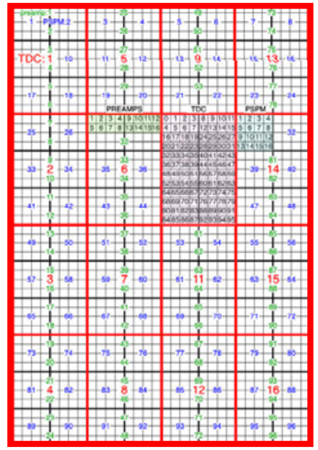


- CAEN v767 128-channs **TDCs**
- time stamping of the raw pulses from discri
- output to the DAQ chain

TIME MEASUREMENT: TDCs & DAQ

TDC task → time stamping of the raw pulses (LL discri outputs)

- precise time measurement
- high rate capabilities



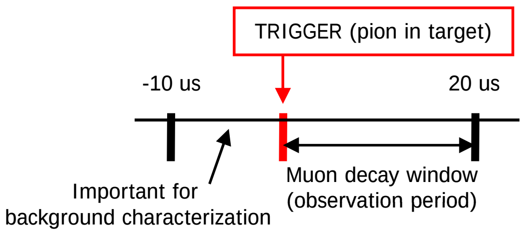
- **CAEN v767** 128-channels **TDC's** [x 16]
- **External Rb clock** [30 MHz]: **stability : $\Delta t/t \sim 10^{-10}$**

- **1 TDC tickmark = 1.041667 ns** [1 TDC tick = 1 clock period/32 bits]

- for every hit in the target : **(x,y,time)**

16 TDC units needed to read out the target **2048 channels (1536 data hits + control words)**

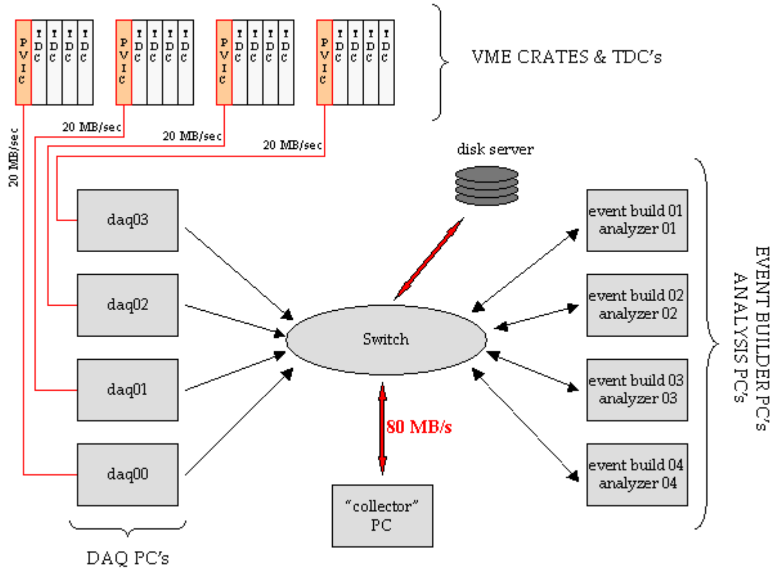
- internal circular buffer:
[-10,+20] μs w.r.t trigger
trigger = π in target



DAQ ARCHITECTURE

-16 TDC's accomodated in 4 VME crates
- VME-PCI interface:
PVIC link **(20 MB/s/node)**

80 MB/s : MAX ALLOWED BANDWIDTH



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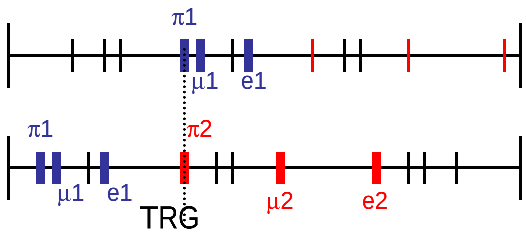
DATA THROUGHPUT & BANDWIDTH

20 MB/sec per DAQ PVIC node; 4 nodes ➡ **max achievable bandwidth: 80 MB/sec**
(Dec 2007: upgrade to 8 nodes) **(160 MB/sec)**

- parallelisation → high beam rate
- high granularity → 1536 data channels + control words
- 30 usec time window



events repeated several times
if overlapping triggers

➡ huge event size
huge data bandwidth

from simulations: full target read for each event → **bandwidth ~ 2000 MB/sec**

➡ NEED of a DATA REDUCTION SYSTEM

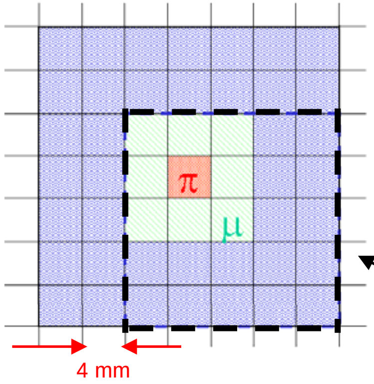
➡ LV2 TRIGGER SYSTEM :

- Hardware trigger to the TDCs
- <u>Selective trigger</u> for the TDCs
- Event <u>data quality</u> selection

→ Reduce the data thoughput at an early stage for the DAQ

2nd LEVEL TRIGGER (LV2)

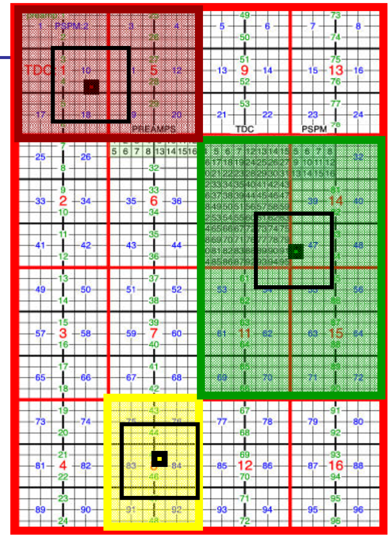
<u>LV2 trigger idea / SUPERPIXEL logic:</u>



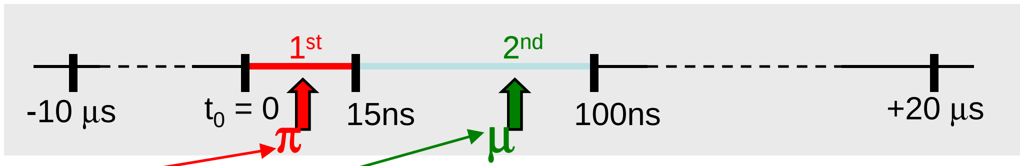
all the relevant time informations are contained in the "superpixel" (7x7 pixels) centered on the stopping π

5x5 pixels around μ region for **e⁺ detection**

- no need to read out the full target for every event
- **RoI** : only 1, 2, or 4 TDCs (depending on the pion position)



[LV2 input : HL discri output]

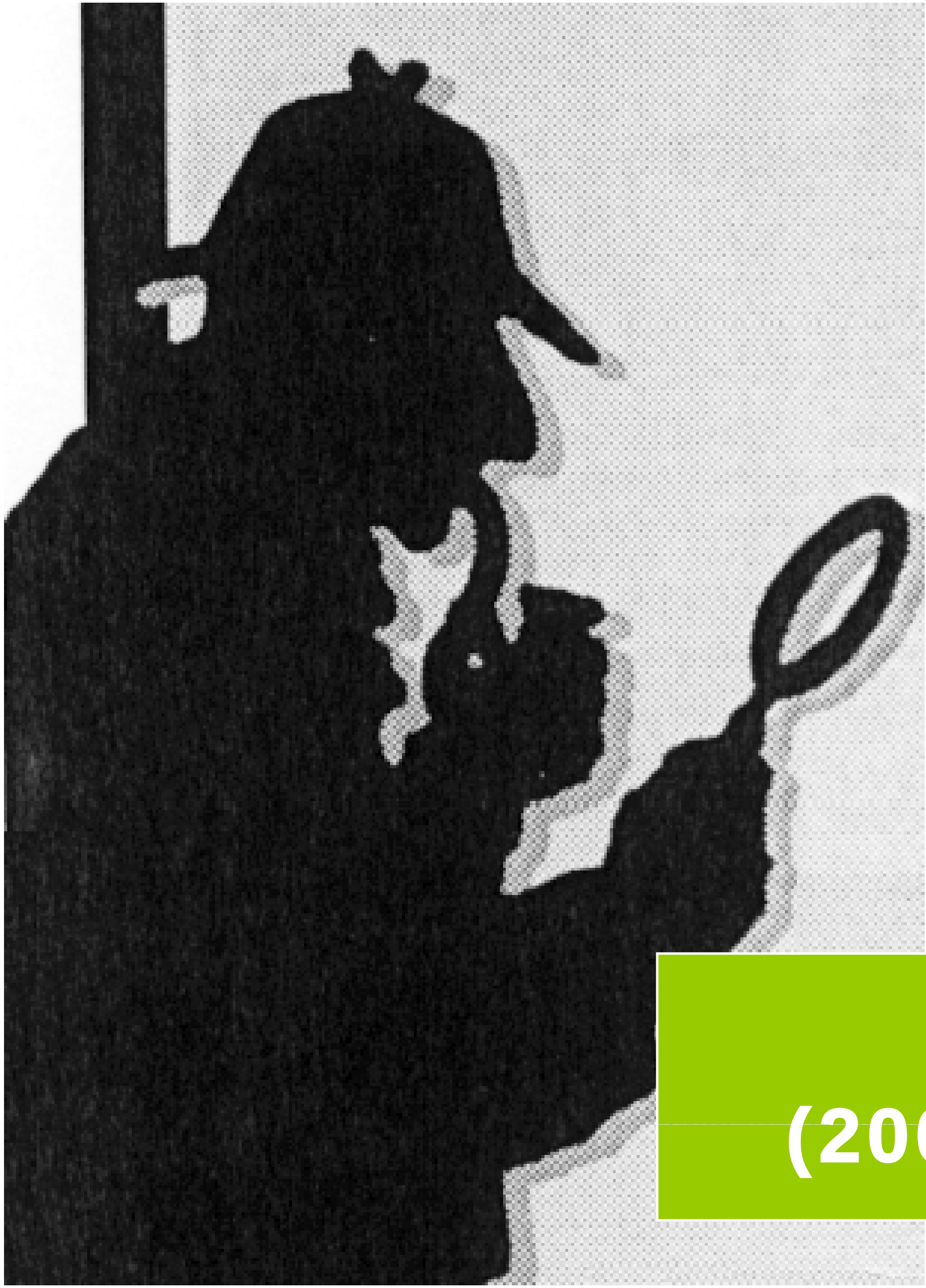


LV2 operations :

-Look for pion stop point (1st snapshot)
-Look for muon decay (2nd snapshot)
-Decide which TDCs should be triggered (RoI, i.e. TDCs containing superpixel)
-Send the trigger to the TDCs
-Send muon coordinates as additional information

LV2 as DATA REDUCTION SYSTEM :

1. Selective trigger (RoI)
2. Event selection tool (only evts with π stop & π→μ decay retained)



Analysis
(2006 data sample)

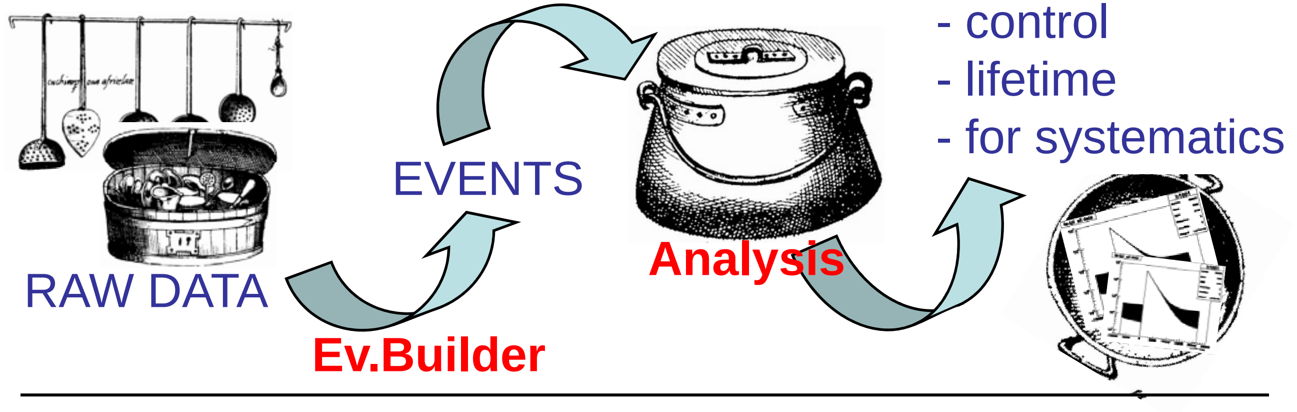
RUN 2006: DATA SAMPLE

- **3 weeks data taking** (Nov – Dec 2006)
- first physics data taking run for FAST
- running conditions very close to the final ones except for the reduced adopted rate : **LV2 trigger rate ~ 30 kHz** (pion rate ~ 80 kHz)
- **total statistics :** **1.073 x 10^{10} events** → precision comparable with world average

Run 2006: Data Samples

Sample ID	Sample Name	N. events
1	01a	2.068 10^9
2	01b	1.070 10^9
3	02	0.266 10^9
4	03	0.886 10^9
5	04	0.974 10^9
6	05	0.562 10^9
7	06	2.022 10^9
8	07	1.565 10^9
9	08a	0.928 10^9
10	08b	0.390 10^9
Full Statistics (Run 2006)		1.073 10^{10}

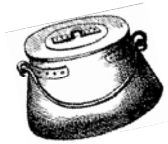
ANALYSIS TASKS



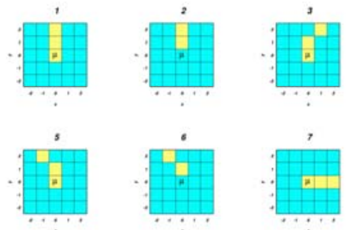
HISTOGRAMS:
(~ 1200 histos)
- control
- lifetime
- for systematics

80 MB/sec

- Main role of the analysis:
  1. in every event recognize the correct $\pi \rightarrow \mu \rightarrow e$ chain
     - -Pion ID
     - -Muon ID
       (From LV2 hardware)
     - -Positron ID
  2. measure the time of the particles
  3. fill the histograms



- 512 predefined pattern topologies



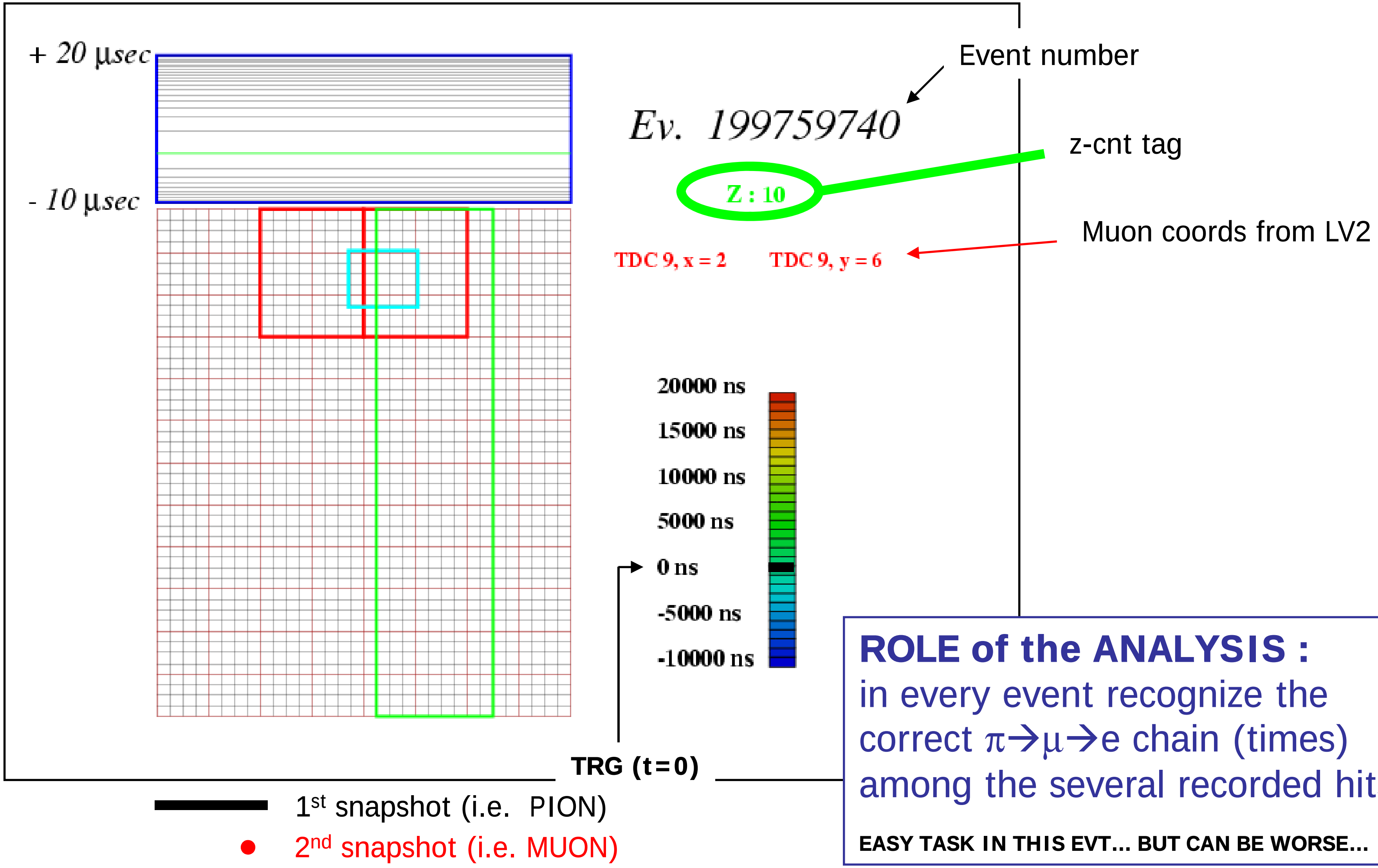
- any time in the TDC window is allowed
- electron time = average track time
- only 1 positron candidate allowed

- **ONLINE ANALYSIS :**

- 80 MB/sec **~ 7 TB/day**
- Impossible (& unpractical) to store data
- **Only histograms are** (periodically) **saved** (together with a prescaled fraction of data)
- **ORIGINAL BULK OF RAW DATA IS LOST !!!!**

EVENT DISPLAY

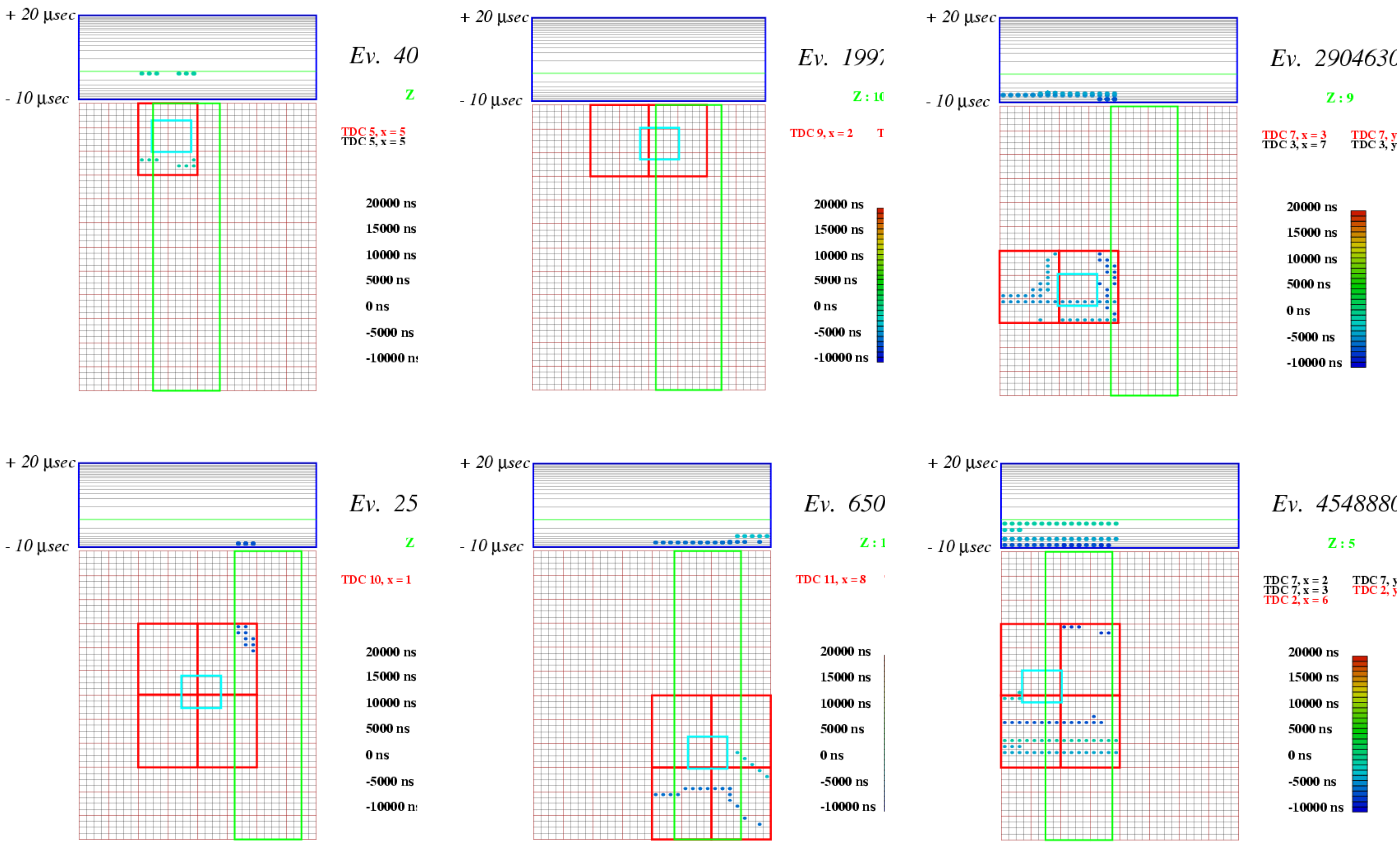
Example of a **REAL EVENT** (from online monitoring tool)



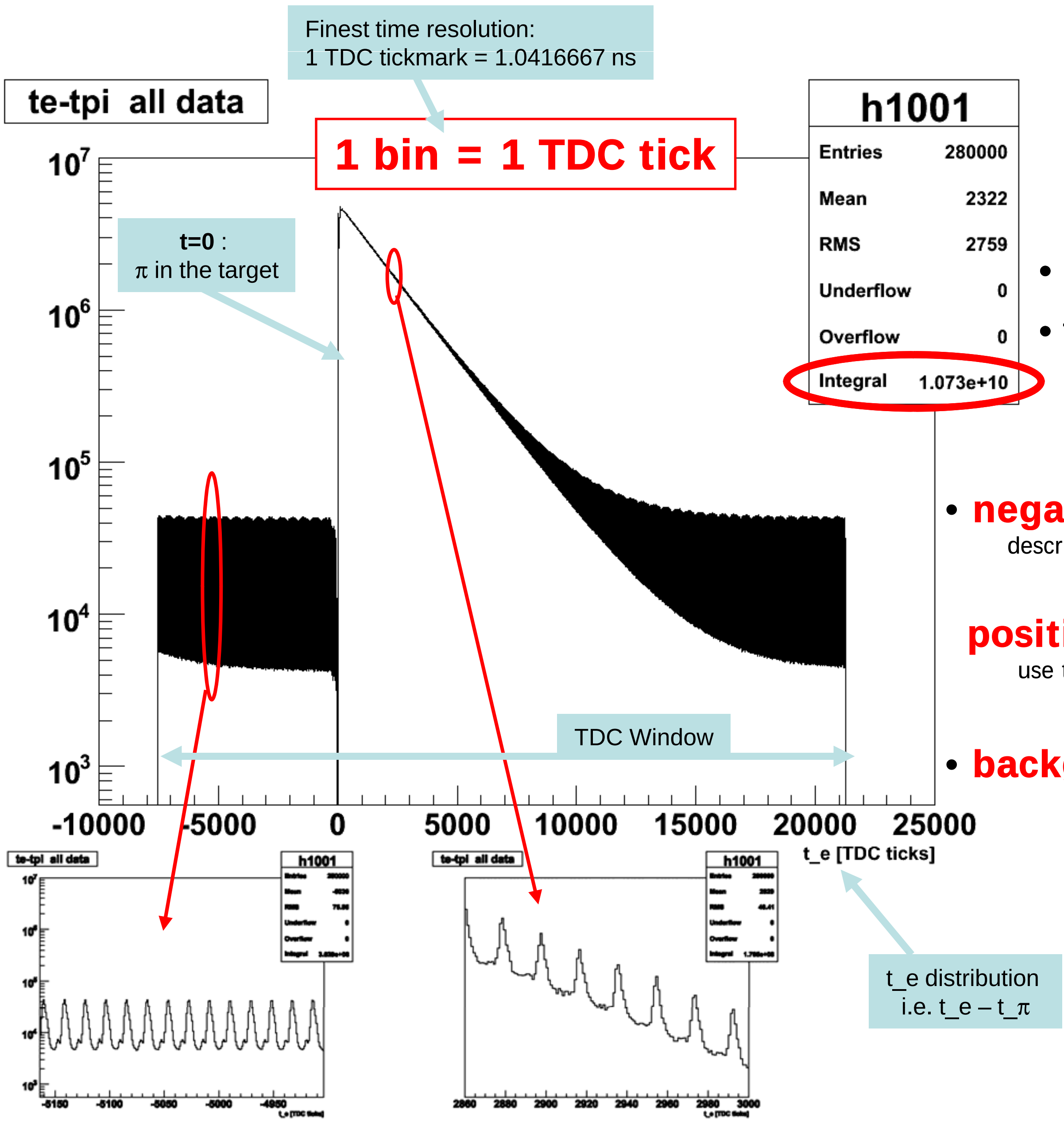
ROLE of the ANALYSIS :
in every event recognize the correct $\pi \rightarrow \mu \rightarrow e$ chain (times) among the several recorded hits

EASY TASK IN THIS EVT… BUT CAN BE WORSE…

~10^{10} EVENTS LIKE THESE HAVE BEEN COLLECTED !!!



ANALYSIS OUTPUT: LIFETIME DISTRIBUTION



"THE" PLOT !!!

- t_e distribution i.e. t_e-t_π
- total stat : 10^{10} μ decay events

- **negative times** (pure bkg events) &
  description of the background (totally decoupled from the signal) from the negative times region

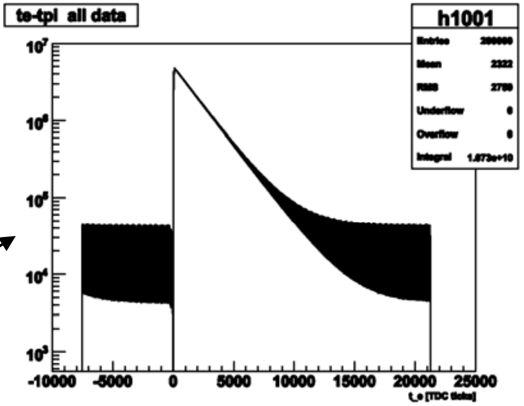
  positive times (signal+bkg)
  use the background description also for the positive times region

- **background**: flat component
  no time dependent

  \+ RF periodicity structure (T_{RF})
  beam induced background

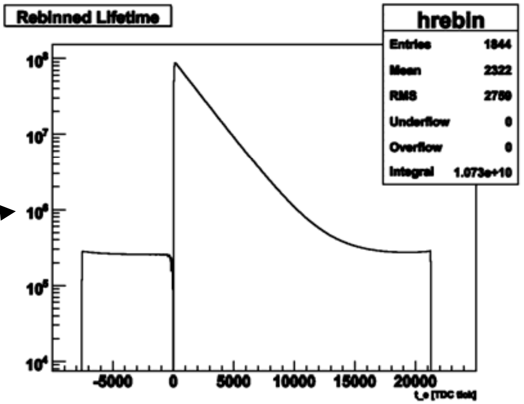
STRATEGY for MUON LIFETIME MEASUREMENT

τ_μ measurement = fit of the distribution



STEPS FOR THE FIT :

1. Study of the fine binning distribution
i.e. Study and understand all the structures in the data
→ RF structure
→ TDC non linearity (t>0)

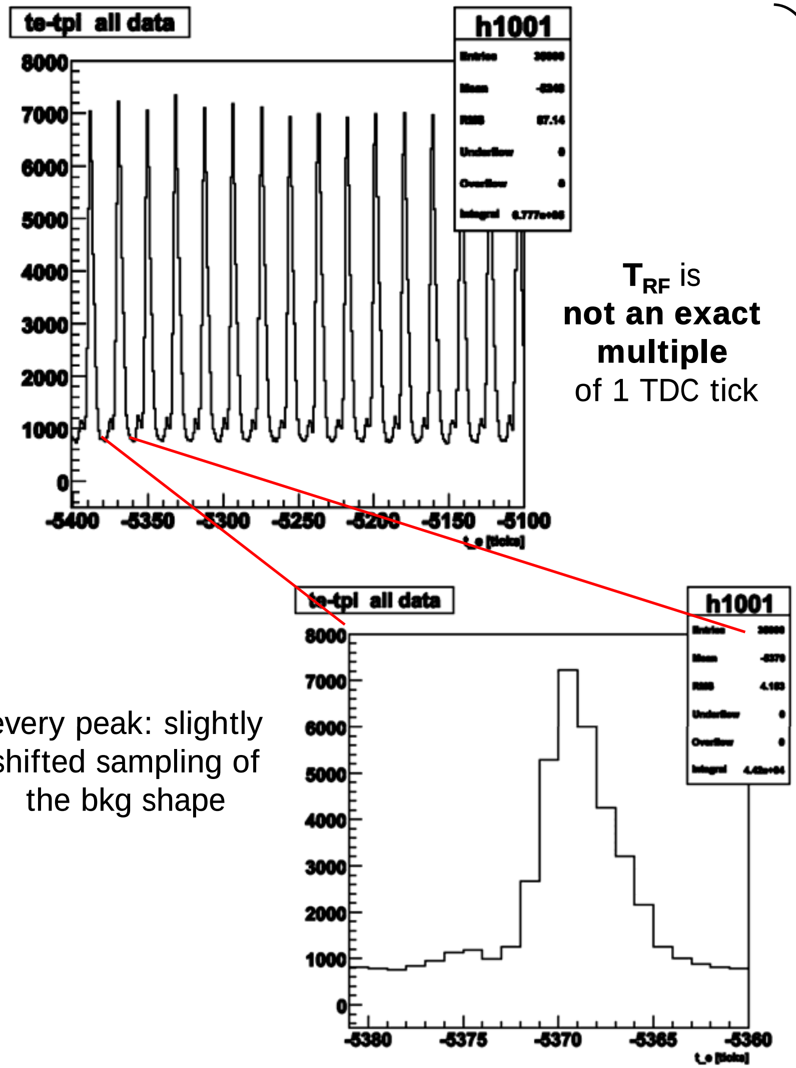


2. Rebin the histogram
(new bin size = T_{RF})
to minimize the effects of the periodic background on the lifetime measurement

3. Define a **proper fitting function**

4. Binned maximum likelihood fit (TMinuit - ROOT) on the rebinned distribution, with τ_μ as free parameter

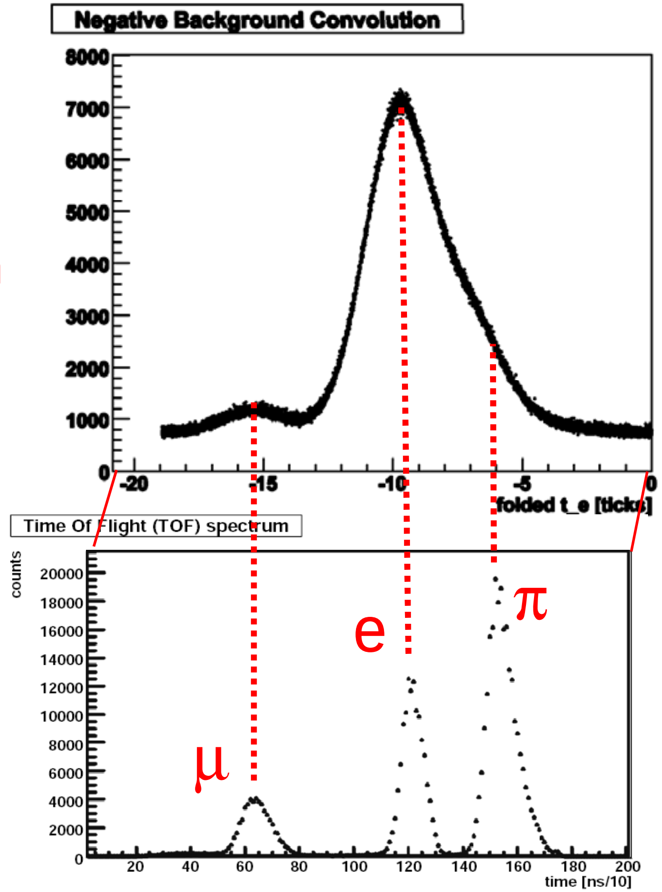
STEPS FOR THE FIT: understand the background (t<0)



T_{RF} is
not an exact multiple
of 1 TDC tick

every peak: slightly shifted sampling of the bkg shape

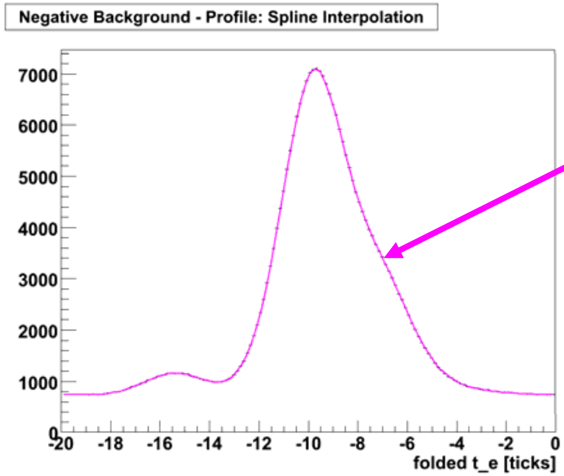
convolution (T_{RF})



beam TOF

Periodic background shape:
- exactly reproduces the beam content
- dominated by e
- accurate description of the shape is possible
(through a polynomial smooth interpolation)

STEPS FOR THE FIT: understand the background (t<0)



Polynomial (cubic) function defined on consecutive intervals limited by knots

Spline interpolation (150 knots) of the bkg shape:

➔ $B(t)$

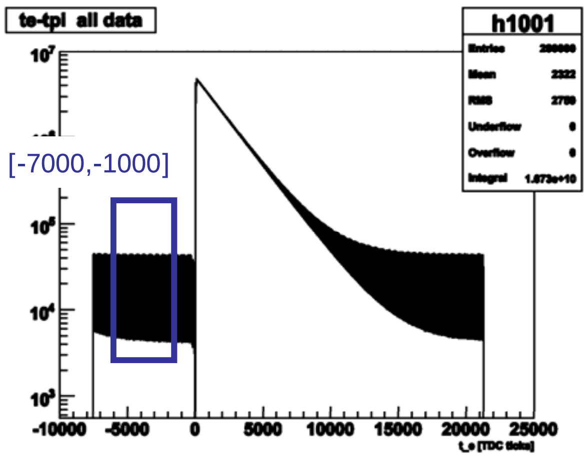
Periodic background description:

Initial phase

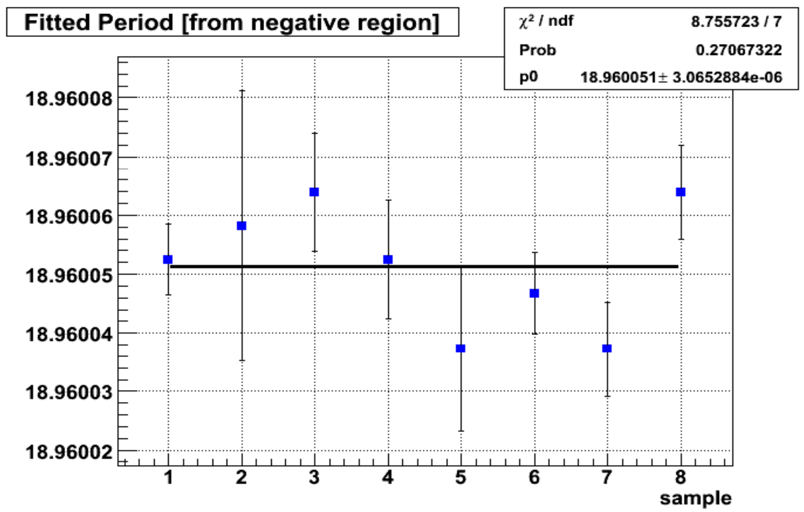
period

➔ $B(t_{rel}) \qquad t_{rel} = \mathrm{mod}(t - t_0, T_{RF})$

Negative times region fit
(with fixed shape of the background)



T_{RF} free param in the fit



$$N_{neg}(t) = B(t_{rel}) + P_{neg} + \frac{N_{neg}}{\tau} e^{-t/\tau}$$

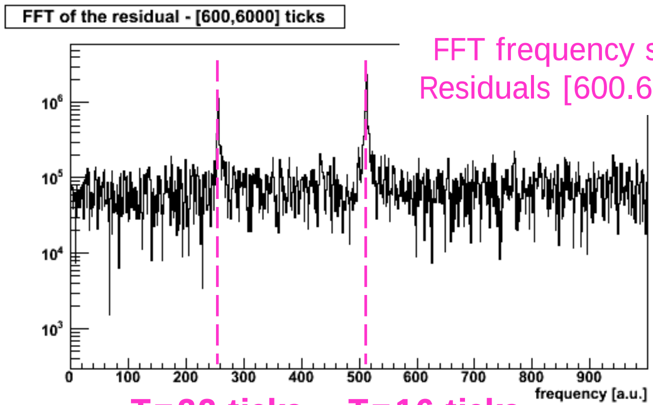
➔ T_{RF} = [18.960051 +/- 0.000003] ticks

~ 0.2 ppm

STEPS FOR THE FIT: periodic structures in the data (t>0)

- Positive times region fit
- Fast Fourier Transform of its residual

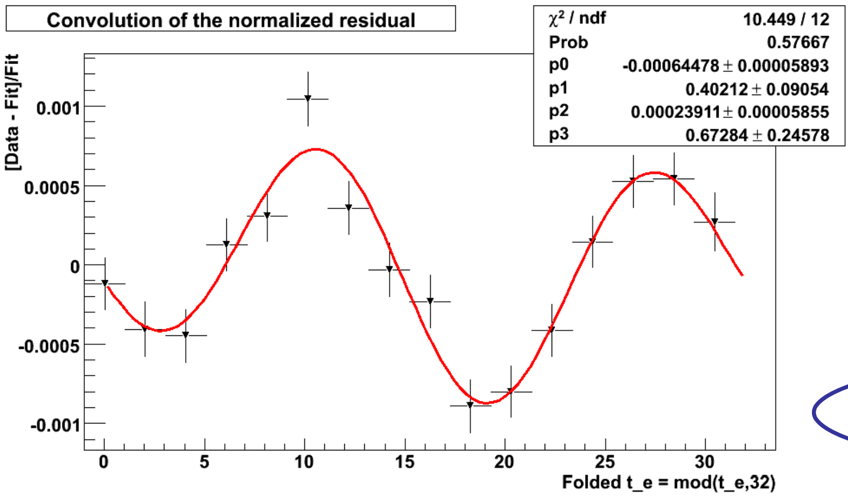
FFT frequency spectrum
Residuals [600.6000] ticks



T=32 ticks T=16 ticks

- Convolution applied on the residual (T = 32)

mod(t,32)



$$F_{tdc}(t) = p_1 \sin\left(\frac{2\pi t}{16} + p_2\right) + p_3 \sin\left(\frac{2\pi t}{32} + p_4\right)$$

Fitting function: $N(t) \longrightarrow [1 + F_{tdc}(t)] \times N(t)$

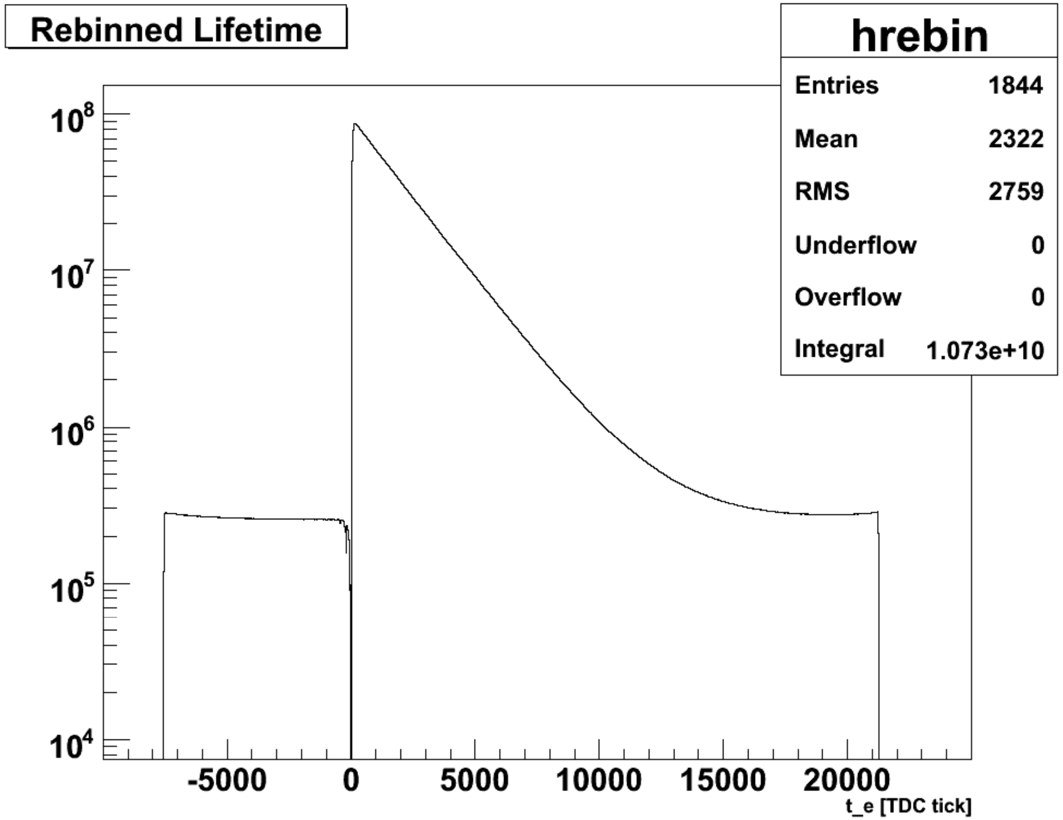
- TDC non linearity effects
- per mille level effect
- confirmed also in lab tests

[TDC CLK = 32 ticks]

STEPS FOR THE FIT: rebin the histogram

Rebin the histogram using the measured beam period T_{RF}

- to minimize the influence of the periodic background on τ_μ measurement
- information loss – but only on the details of the background, not the lifetime

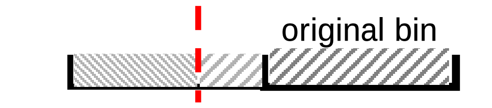


T_{RF}

1 new bin = 18.960051 original bins

"SMART REBIN"

i. e. rebin + bin sharing procedure :

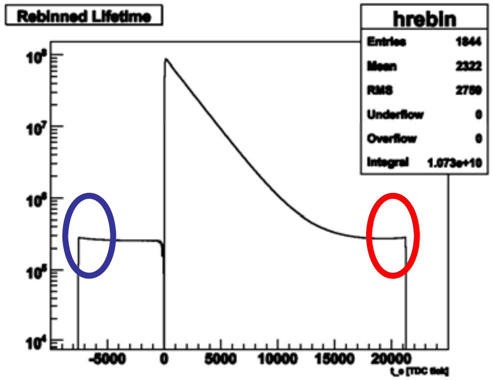


→ different algorithms tried (uniform, linear, quadratic, exp) for the sharing of evts inside the original bin

→ no appreciable differences found (see systematics)

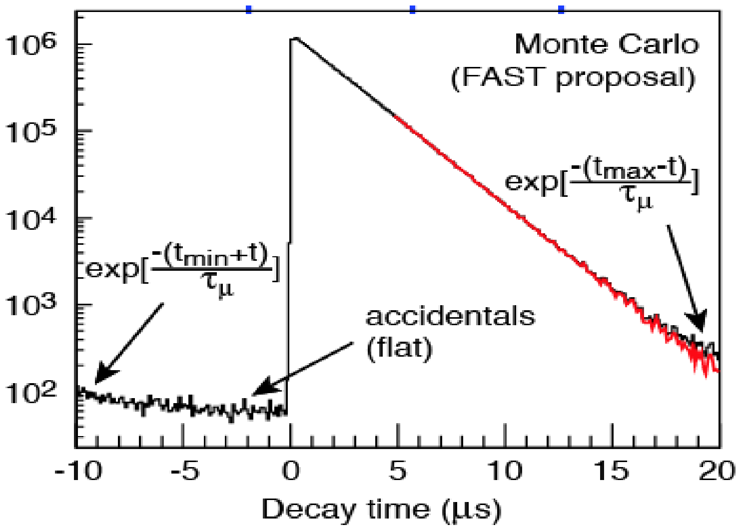
→ default: uniform distribution inside the bin

STEPS FOR THE FIT: boundary effects in the lifetime distr.



Increase of muon decay events at the boundary of the TDC window

Already forseen in the systematic study with MC simulations



trend
$e^{+t/\tau}$

Due to overlapping events in the TDC window *[t_min,t_max]*

(π1,μ1,e1)

(π2,μ2,e2)

→ (π1,μ1,X)

X=beam pcl → beam induced bkg

X=π2 → (π1,μ1,π2) → peaked at *t_max*

X=e2 → (π1,μ1,e2) → peaked at *t_min*

(π1,μ1,~~e1~~) (π2,μ2,e2)

TDC time window — next window

(π2,μ2,e2) (π1,μ1,~~e1~~)

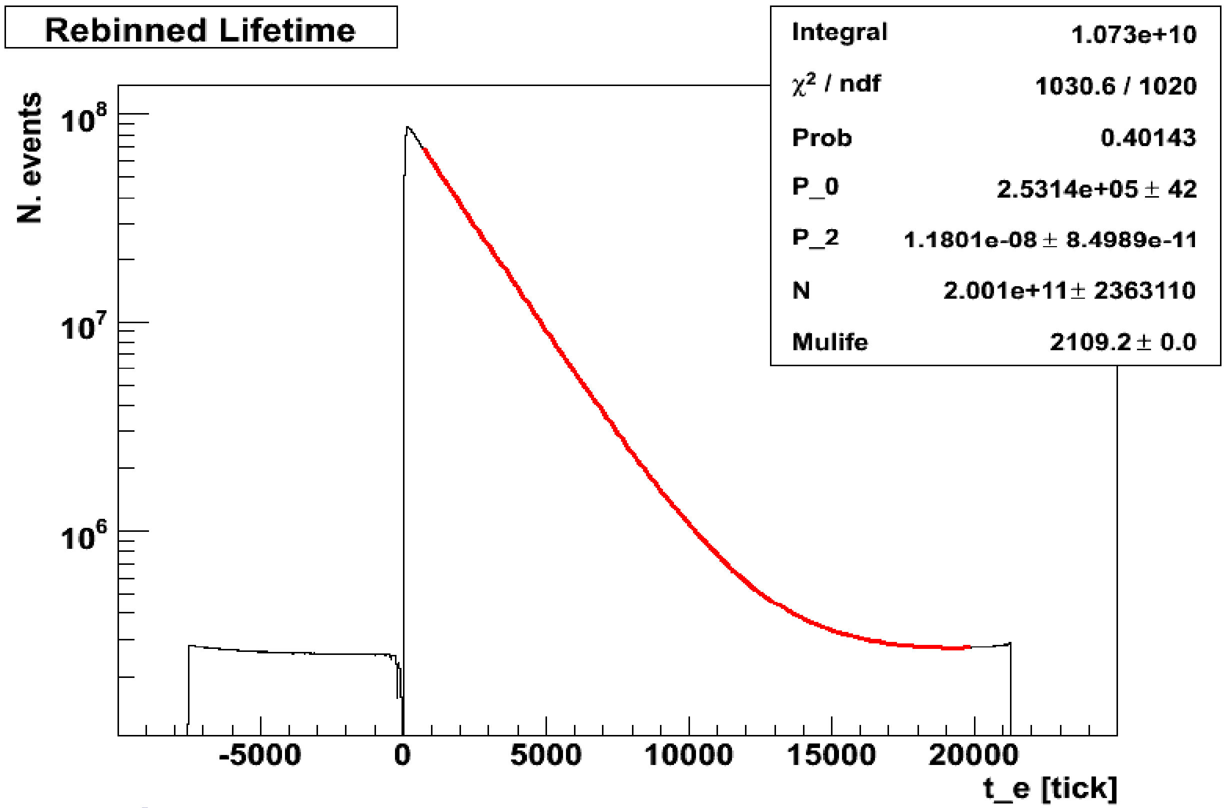
previous window — TDC time window

THE FIT

TDC non linearity — Accidental bkg — Signal — Time dependent background

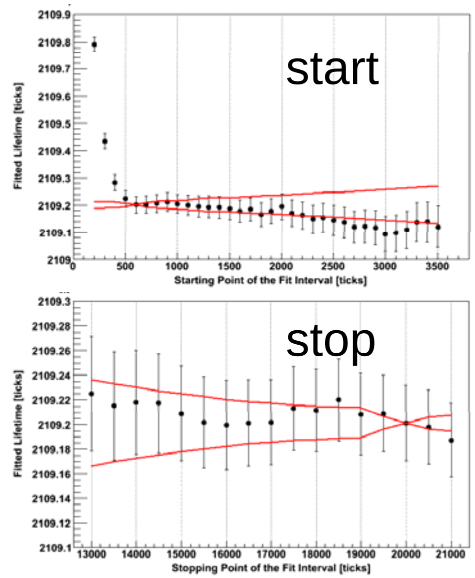
$$N(t) = [1 + F_{tdc}(t)] \times \left[P_0 + \frac{N_0}{\tau}(e^{-t/\tau} + P_2 e^{t/\tau}) \right]$$

no precise description of the periodic beam induced background is required



- Fit interval: [600,20000] ticks

Largest region of stable lifetime

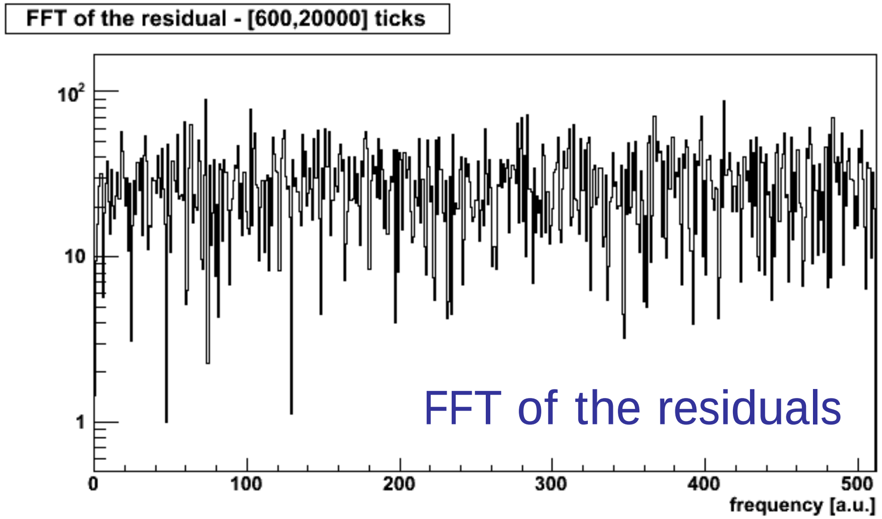


→ VERY HIGH QUALITY FIT

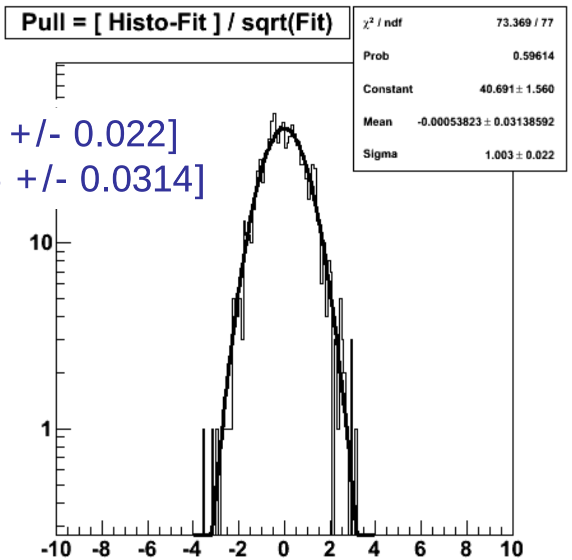
FIT QUALITY

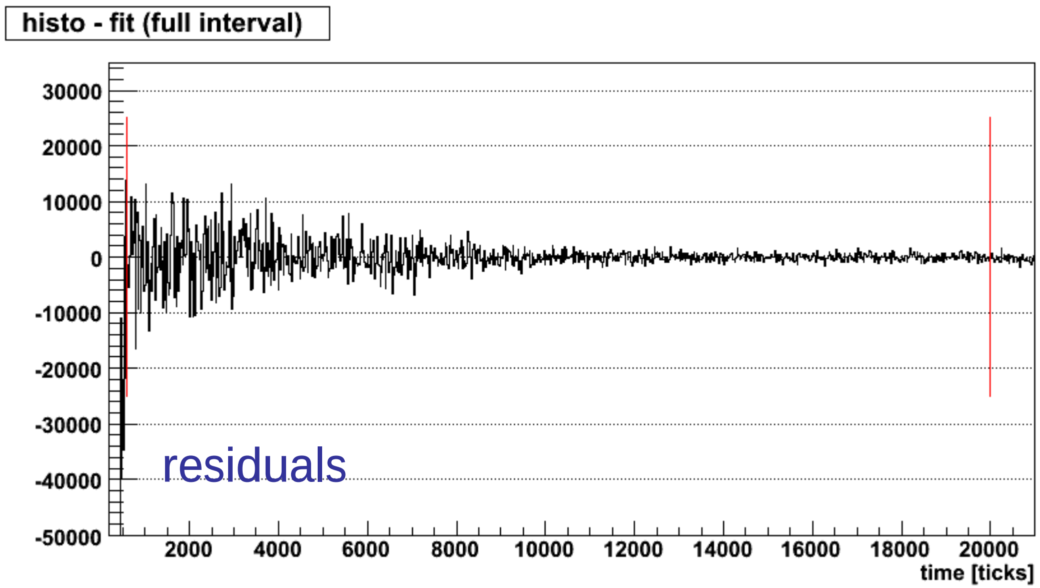
Full Statistics Sample (Run2006) *Smart Rebin Method*		*Fit:* [600, 20000] *ticks*
χ^2/ndf		1030.65/1020 = 1.0104
Prob(χ^2,ndf)		0.4014
Fitted Parameters		
Offset	P_0	253135 ± 39
Exp. Tail Norm.	P_2	$(1.180 \pm 0.008) \times 10^{-8}$
Normalization	N_0	$(2.00104 \pm 0.00002) \times 10^{11}$
Lifetime [ticks]	τ	2109.200 ± 0.031

	P_0	P_2	N_0	τ
P_0	1.000	-0.714	-0.104	-0.498
P_2	-0.714	1.000	0.084	0.335
N_0	-0.104	0.084	1.000	-0.157
τ	-0.498	0.335	-0.157	1.000



σ=[1.003 +/- 0.022]
X=[-0.0005 +/- 0.0314]





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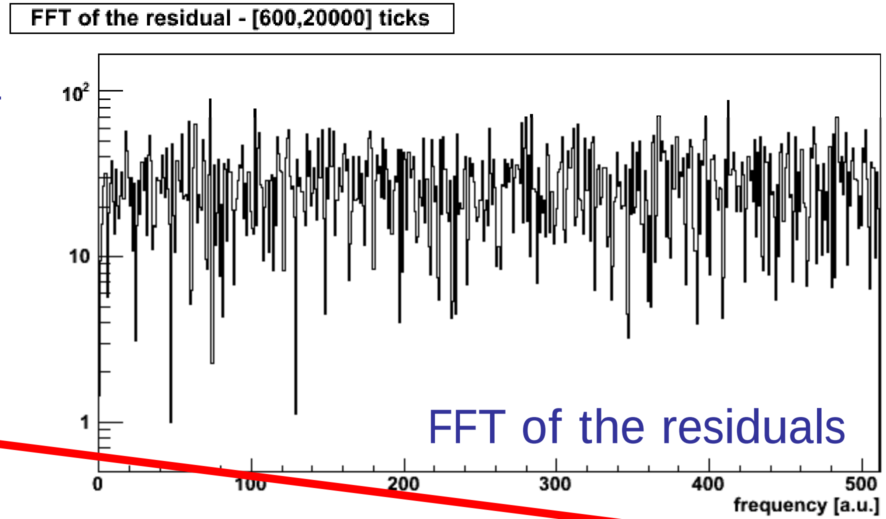
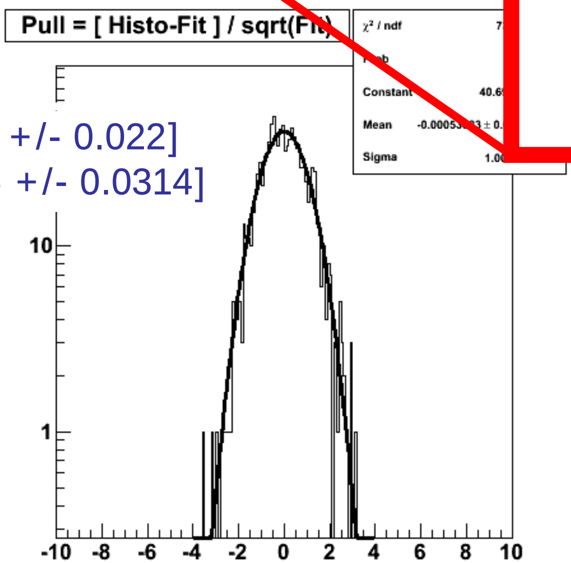
N_0	-0.104	0.084	1.000	-0.157
τ	-0.498	0.335	-0.157	1.000

$$\tau_\mu = [2197.083 \pm 0.032]\ \text{ns}$$

$$\left(\frac{\delta\tau_\mu}{\tau_\mu}\right)_{stat} = 15\ \ \text{ppm}$$





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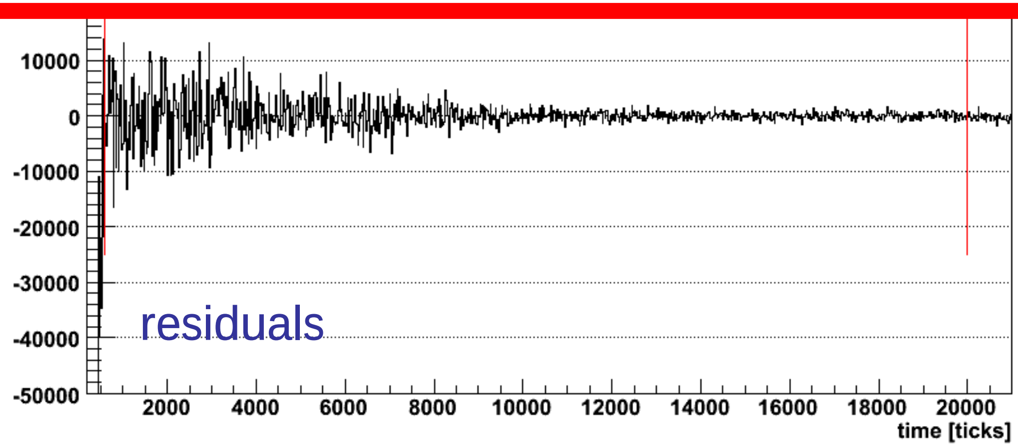


Systematic Uncertainty

SYSTEMATIC UNCERTAINTIES

- Different classes of systematic errors identified:
    - DETECTOR UNIFORMITY ($\tau\mu$ VS: x_π; y_π; position inside PSPM; PSPM; chip; TDC)
    - FIT METHOD
    - τ_μ ESTIMATOR ($t_e - t_\pi$ VS $t_e - t_\mu$)
    - μSR EFFECTS
    - STABILITY OF THE MEASUREMENT (time stability, clock, rate dependence)

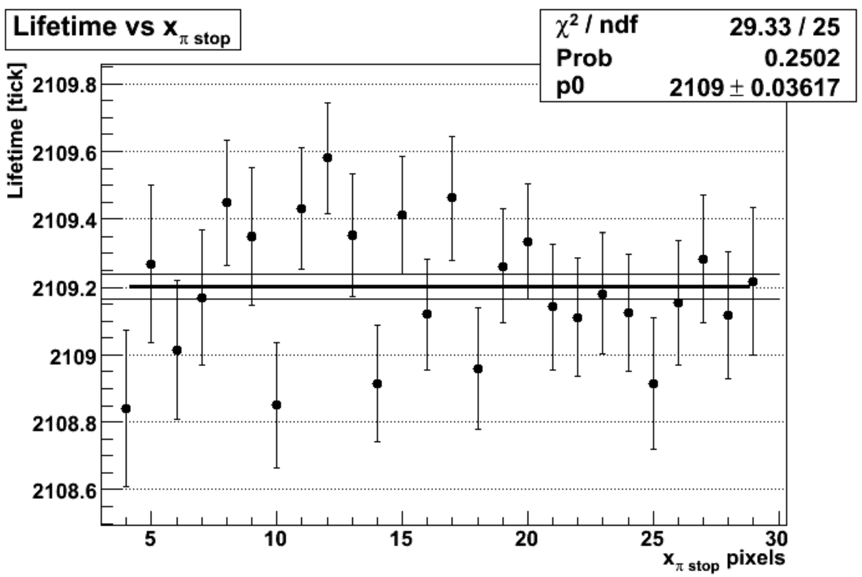
- Evaluated using several dedicated histograms (produced online)
- General recipe (when several lifetime measurements are available)

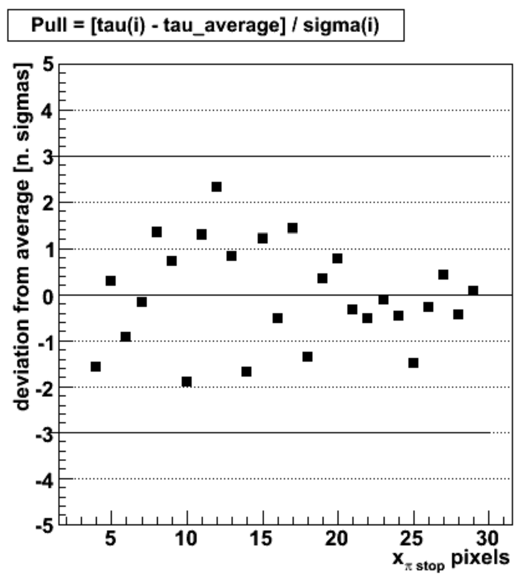
  - Any deviation inconsistent with the statistical fluctuations is considered to be of systematic origin
  - **A PRIORI consistency criteria = 3 sigma's**

1. Fit histograms corresponding to the subsamples & compute the average
2. Look if there are statistically incompatible points (i.e. deviation from the average $\Delta\tau_\mu > 3\sigma$)
3. How much the average changes when those points are excluded
4. Quote this variation as (signed) systematic shift

SYSTEMATICS: UNIFORMITY

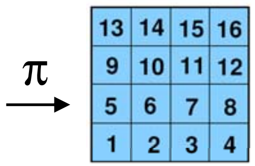
2 examples for no evidence of a systematic effect beyond the expected statistical fluctuations

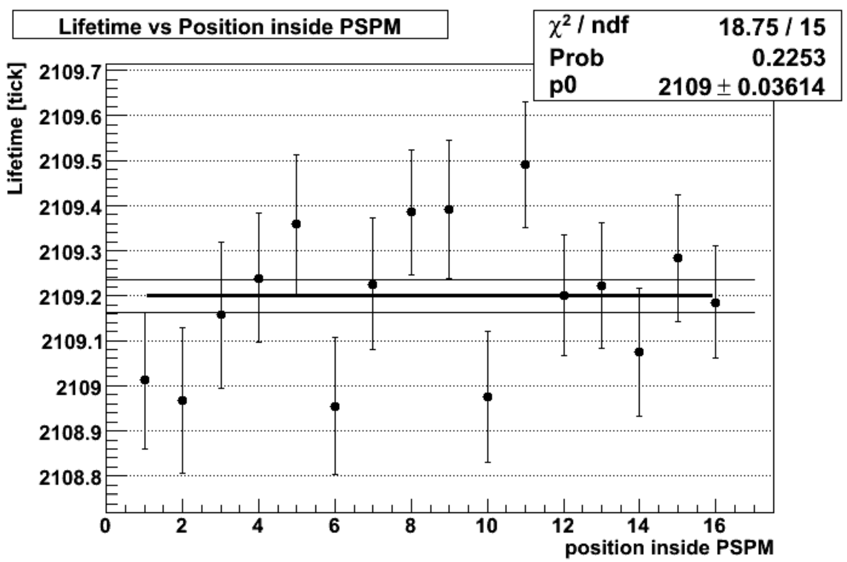


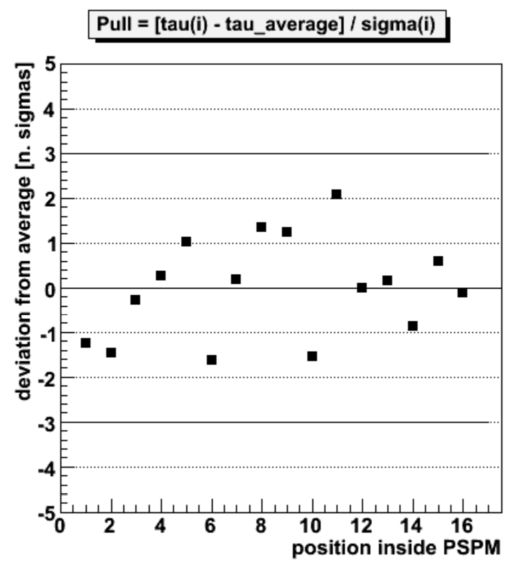


lifetime vs position of the pion in the target (x coord)

lifetime vs position of the pion inside the PSPM

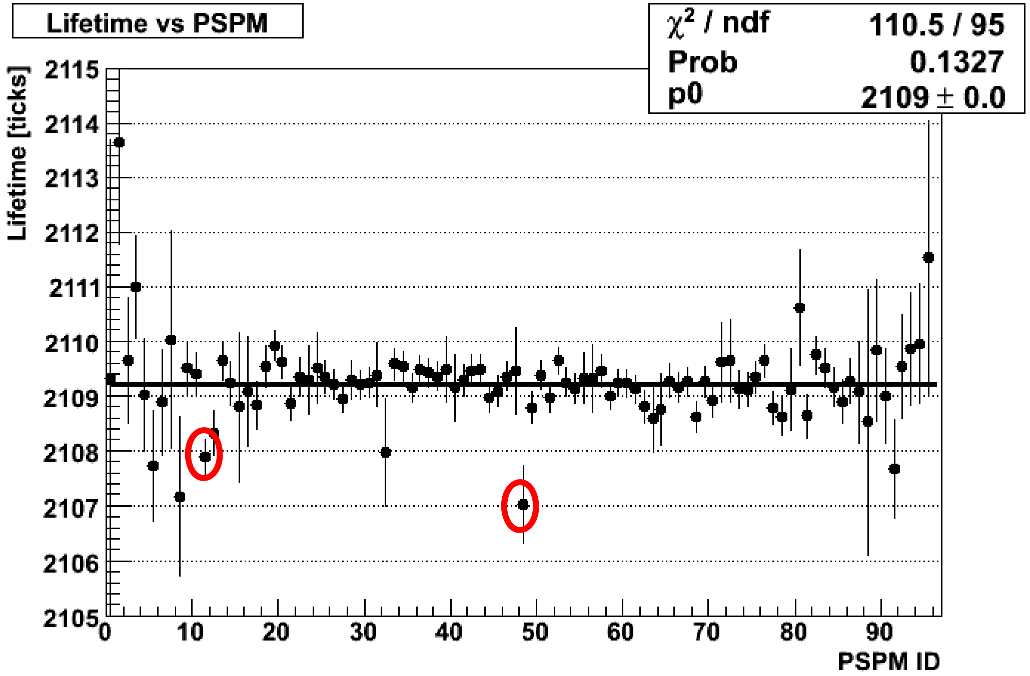


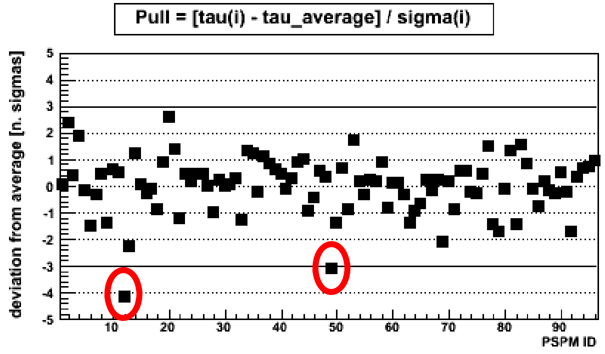


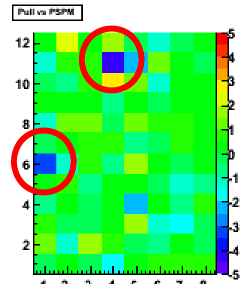


SYSTEMATICS: UNIFORMITY

Lifetime VS position of the tube in the target:







- evidence for a systematic effect – due to 2 tubes

$$\Delta\tau_\mu = +0.016 \text{ ticks} = +7.6 \text{ ppm}$$

SYSTEMATICS -- GEOMETRY :

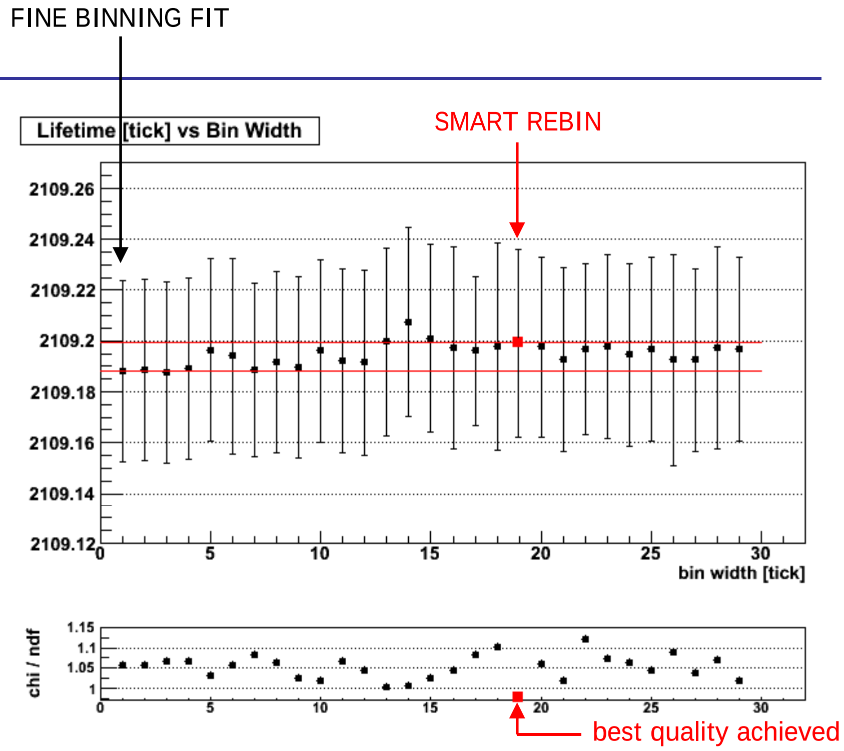
- lifetime vs pion position (x,y) ✓
- lifetime vs position inside the PSPM ✓
- lifetime vs detection efficiency ✓
- lifetime vs position of PSMP in the target ✗
- lifetime vs position of TDC chip in the target ✓
- lifetime vs position of TDC in the target ✓

Systematics associated to the target (dis)homogeneity

$$\Delta\tau_\mu = +0.016 \text{ ticks} = +7.6 \text{ ppm}$$

SYSTEMATICS: FIT METHOD

- smart rebin method VS fine binning fit
  - lifetime VS bin width
  - larger bin size = less required precision on the background description



Systematics associated to the fit method

$$\Delta\tau_\mu = -0.011 \text{ ticks} = -5.2 \text{ ppm}$$

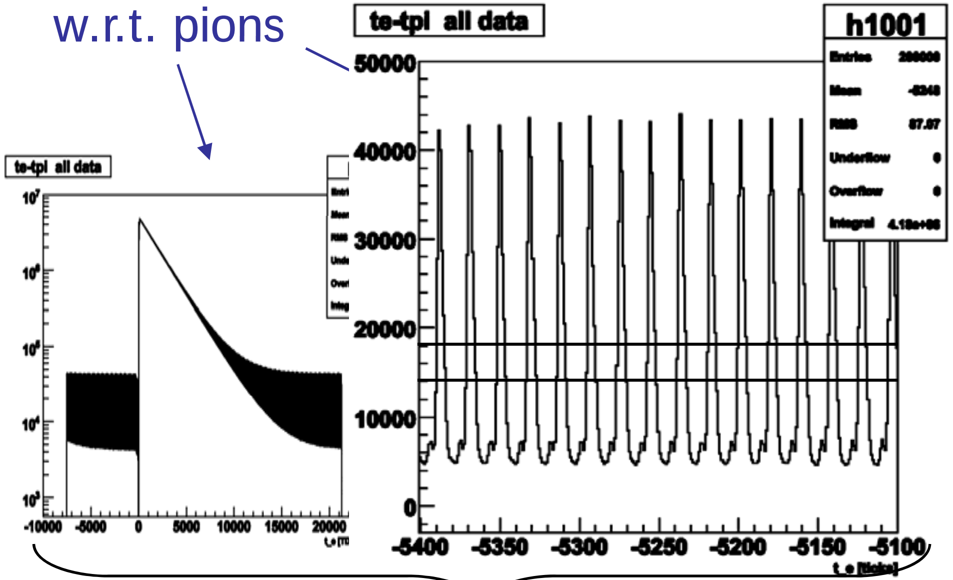
Dominated by not satisfactory description of the background in the fine binning fit method

CROSS CHECKS & VALIDATION OF THE REBIN METHOD

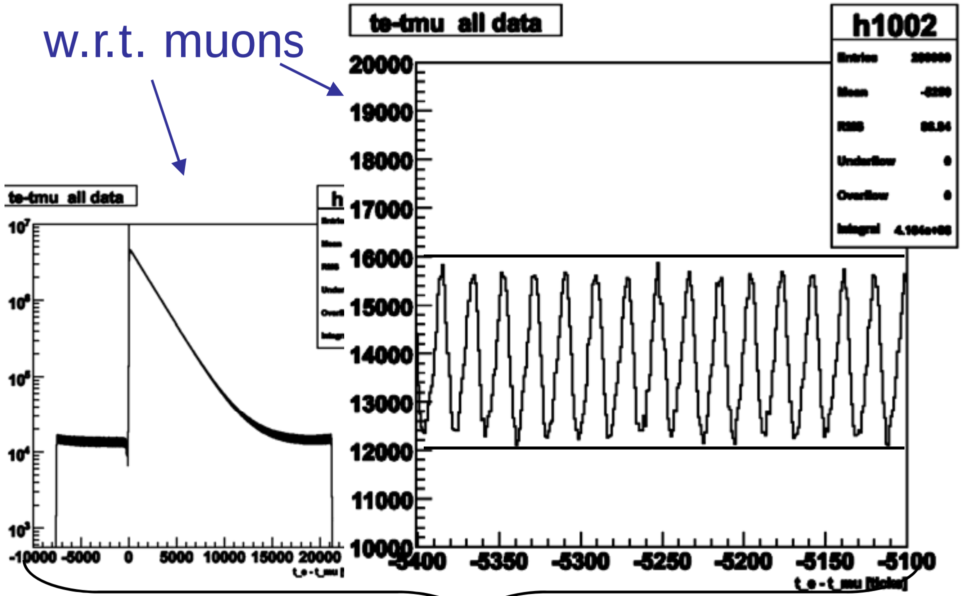
- exact value of T_{RF} T_{RF} +/- 20 σ's => $\Delta\tau_\mu < 0.1$ ppm
- phase of the periodic beam background t_0 in $[0,T_{RF}]$ => $\Delta\tau_\mu < 0.1$ ppm
- different bin event migration algorithms (uniform, linear, quadratic) => $\Delta\tau_\mu < 0.1$ ppm
- τ_μ vs number of integration steps => $\Delta\tau_\mu < 0.1$ ppm

SYSTEMATICS: τ_μ ESTIMATOR

w.r.t. pions



w.r.t. muons



Nominal lifetime analysis: t_e-t_π

- independent on t_μ
- the analysis is focused on this

Alternative distribution: t_e-t_μ

- less sensitive to the background shape
- larger uncertainty in the bkg description

- Estimator different from the one adopted for any other systematic study

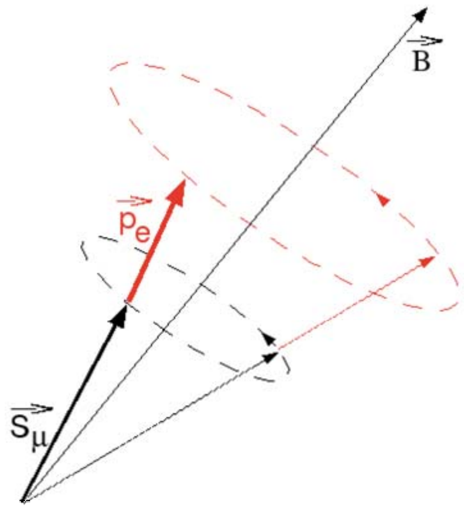
➔ Independent lifetime measurement

Systematics associated with the choice of the estimator

$$\Delta\tau_\mu = +0.0037 \text{ ticks} = +1.8 \text{ ppm.}$$

SYSTEMATICS: μSR EFFECTS

μSR effects = effects on the lifetime of the $\vec{S}_\mu$ precession movement in a magnetic field



$$f_\mu = 13.55 \frac{kHz}{G} \times B \quad \Rightarrow T_{\mu SR}$$ precession period

Why can this affect τ_μ?

S_μ direction ~ e^+ direction (V-A structure of muon decay)

- *IF* polarized muons (i.e. preferential direction for S_μ)
  ➔ time dependent angular distribution of e^+
- *IF* (in addition) anisotropies in the target
  ➔ ***time dependent detection efficiency*** [time scale $T_{\mu SR}$]

2 remarks:

- 2nd order effect, which requires both { Polarized μ's / Anisotropies in the target }
  - unpolarized μ source: π→μ
  - beam μ's suppression by range req.
  - uniformity ; large solid angle

  Both already strongly suppressed in the FAST design

  but... ppm level precision!!

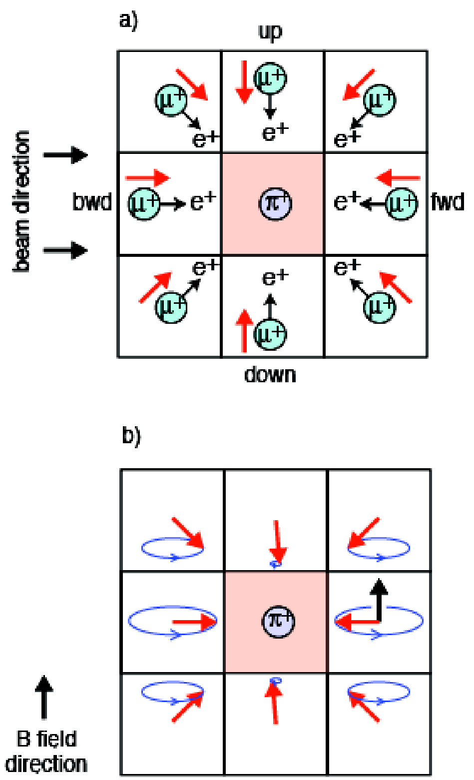
- magnetic field & precession period (τ_μ observation period ~ 20 μs)
  - B ~ 0.5 G (Hearth) ➔ $T_{\mu SR}$ ~ 150 μs
  - B ~ 80 G (FAST magnet) ➔ $T_{\mu SR}$ ~ 0.9 μs ← **magnetic field to enhance the effects of μSR on a known and measurable scale (RUNNING CONDITIONS 2006)**

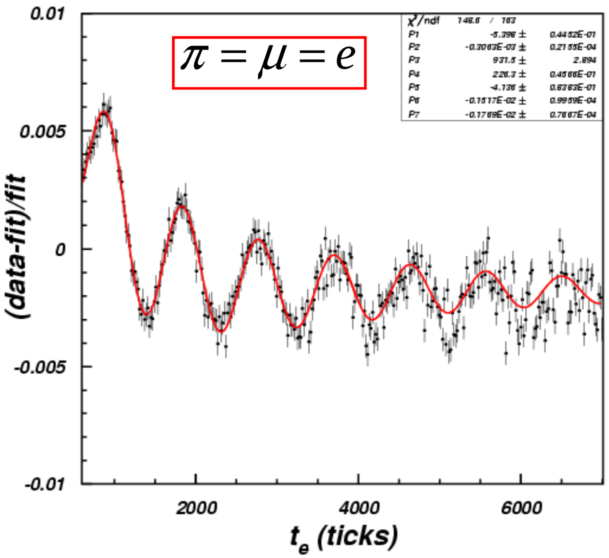
SYSTEMATICS: μSR EFFECTS on lifetime measurement

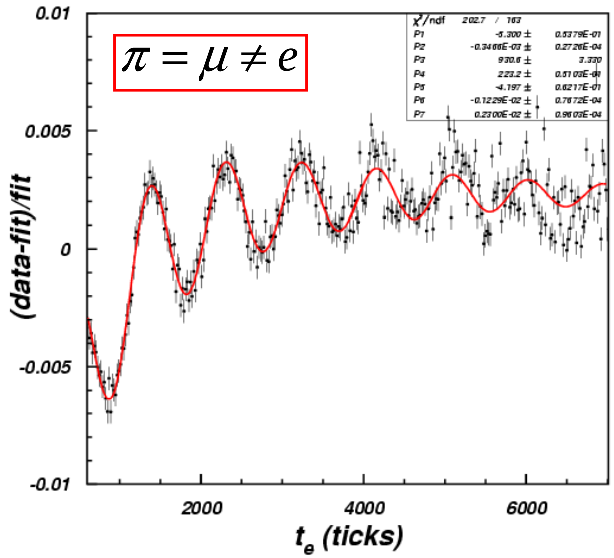
- **FFT Study => no μSR effects on the global τ_μ distribution**

Systematics associated with μSR: negligible (< 1ppm)

- special subsamples of data → μSR effects can be "explicitly forced to appear"







- continuous migration of events from one topology to the other
- μSR periodicity → fitted **T = 931 ticks → B ~ 76 G**

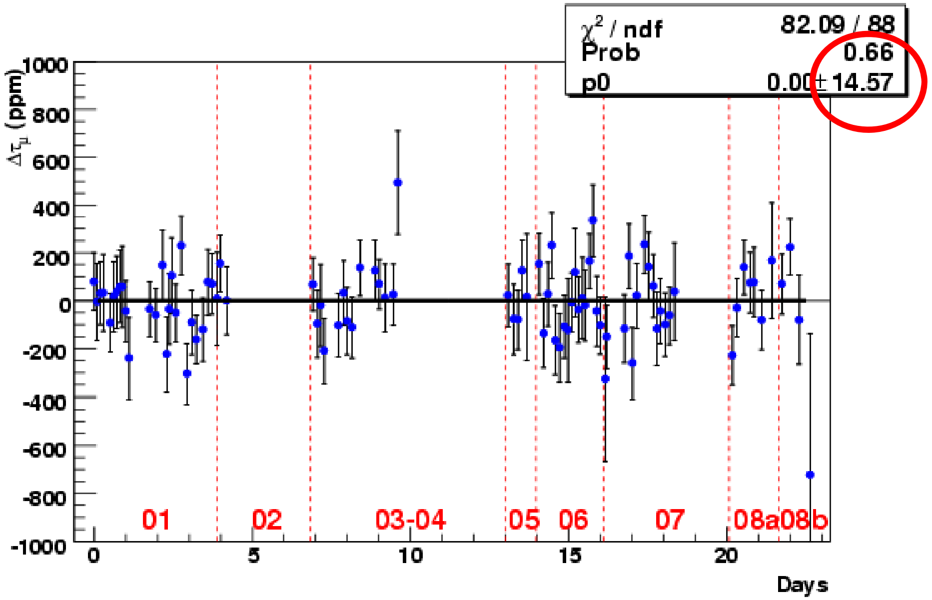
- T included in the fitting function for the full statistics → amplitudes = 0
- **μSR effects visible on dedicated subsamples**
  but **GOOD COMPENSATION** occurs when the full statistic is considered

TIME STABILITY

Data set divided in 89 subsets of
 similar size (~ 1.2 10^8 evts)
 similar duration (~ 4 hours)

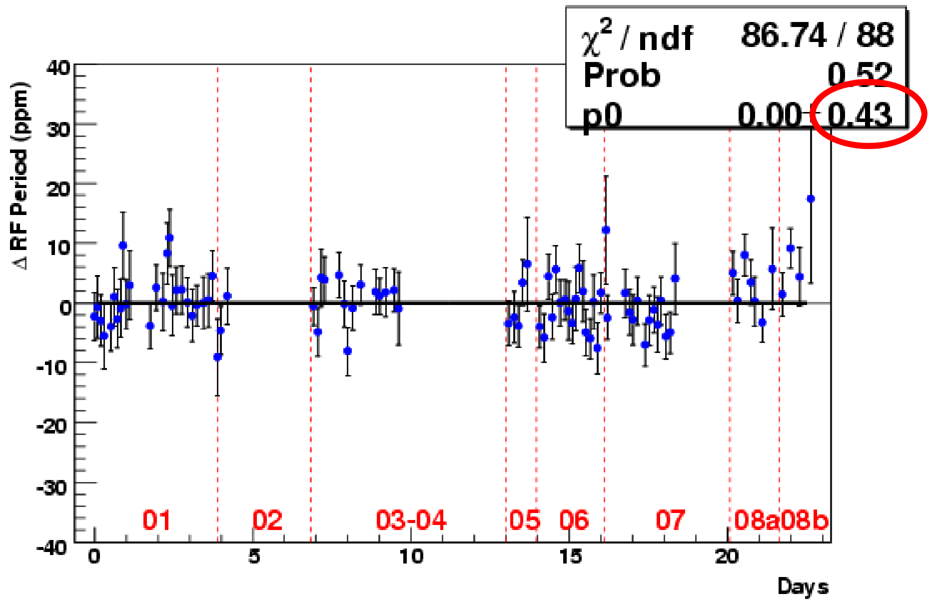
LIFETIME STABILITY

Nominal fit applied to every subset:



GOOD TIME STABILITY WITHIN STATISTICAL UNCERTAINTY of **15 ppm**

CLOCK STABILITY



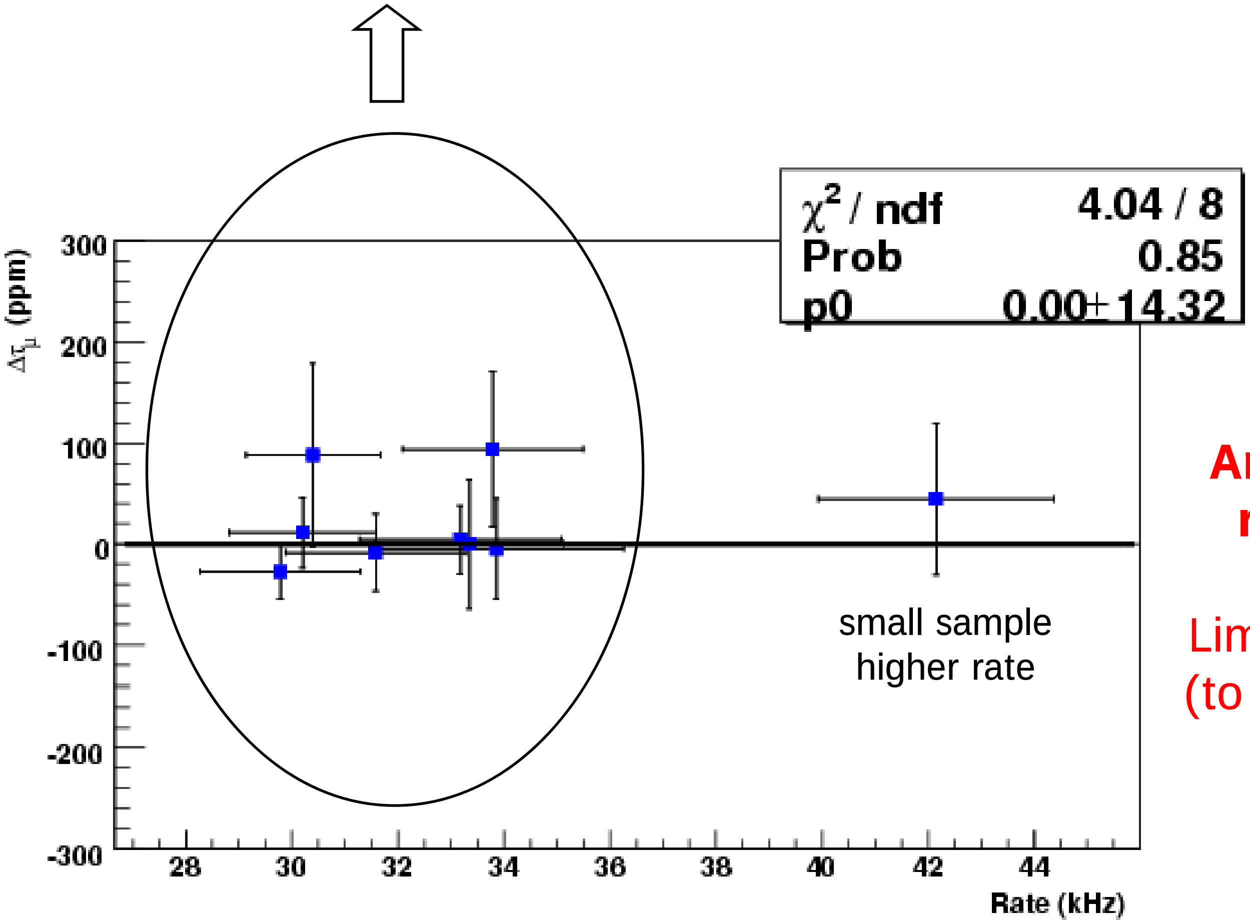
Tested before & after data taking with equivalent clock

Tested during data taking:full Fourier transform of negative times regions for every subset:

CLOCK IS STABLE WITHIN **0.5 ppm**

RATE DEPENDENCE

- Analyzed data sample
- Trigger rate (LV2) ~ 30 kHz
- Profit of the small spread in range to study lifetime VS rate



Any effect of systematic related to trigger rate

Limited rate interval available (to be extended in the future)

SYSTEMATIC UNCERTAINTIES: SUMMARY

SIGNED difference btw the 'alternative procedure' and the nominal fit
(i.e. Maximum bias allowed by our analysis method and our data sample)

Source of systematic	$\Delta\tau_\mu$[ticks]	$\Delta\tau_\mu$[ppm]
Homogeneity of the Target	$+0.016$	$+7.6$
Fit Method	-0.011	-5.2
Lifetime Estimator (i.e. $t_e - t_\mu$ vs $t_e - t_\pi$)	$+0.004$	$+1.8$
μSR and Isotropy of the Target	-	< 1
Time Stability (i.e. clock)	-	< 1
Beam Rate	-	< 1
TDC performance (i.e. time smearing)	-	< 1
TOTAL	± 0.0137	± 6.5

- **no evidence for large systematic uncertainty in our data**
(within the statistical precision of the sample)

- **the determination of systematics is limited (and dominated) by the present statistics**

- **no correction to the central value from the nominal fit is applied**
  SIGNED uncertainty quoted!
  Conservative estimate of the systematics

Conclusions:
Results (run 2006)
Present Status & Future Plans

RESULTS (run2006)

- first precise measurement of the positive muon lifetime with the FAST experiment:

$$\tau_\mu = [2197.083 \pm 0.032\ (\text{stat}) \pm 0.015\ (\text{syst})]\ \text{ns}$$

$$\frac{\delta\tau_\mu}{\tau_\mu} = 16\ \text{ppm}$$

  - run 2006 [3 weeks data taking, Nov-Dec06]
  - data sample : 1.073 10^{10} μ^+ decay events
  - precision comparable to PDG, value compatible with PDG
  - uncertainty dominated by the statistics

- FAST measurement of the Fermi coupling constant G_F

$$G_F = [1.166353 \pm 0.000009] \times 10^{-5}\ \text{GeV}^{-2}$$

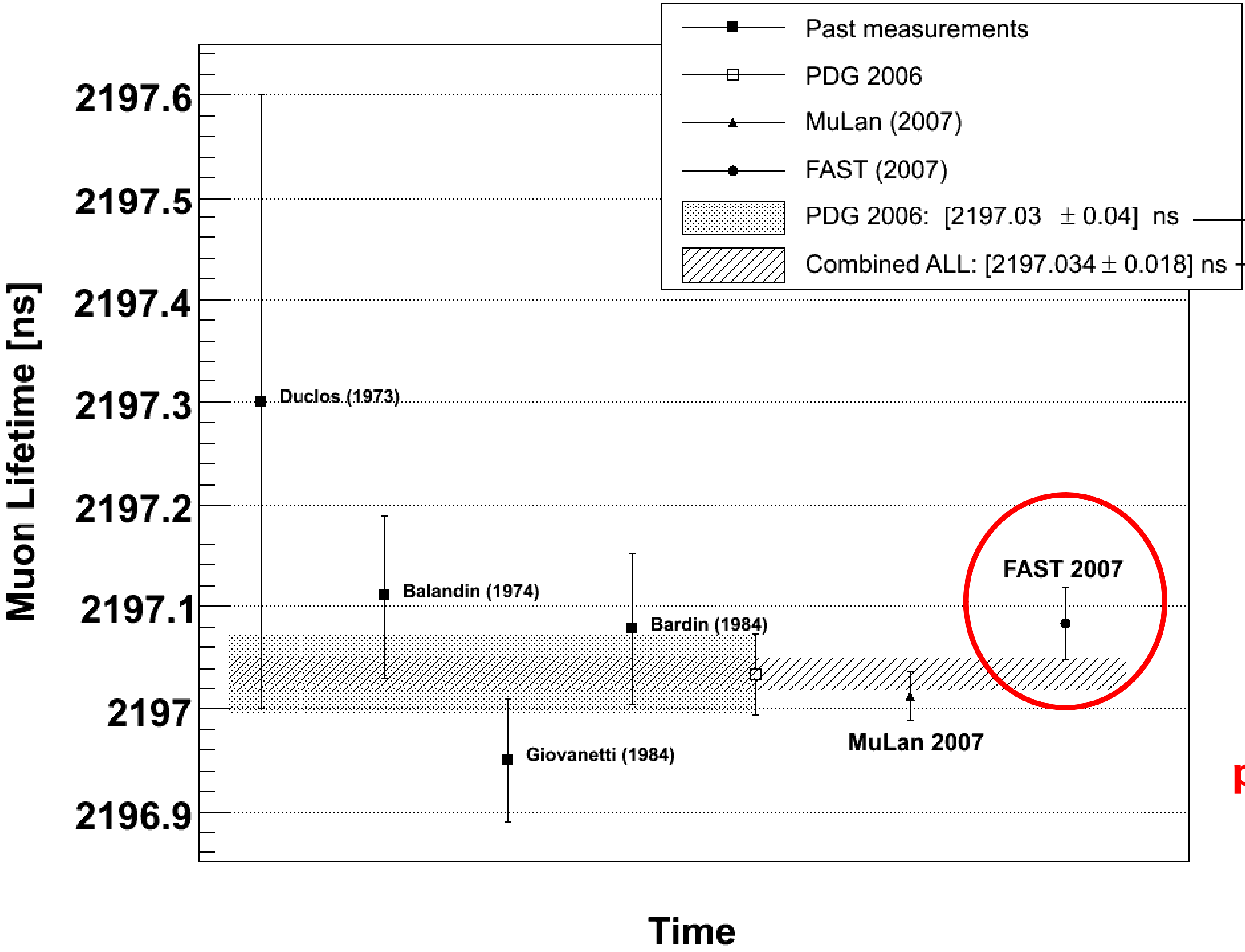
$$\frac{\delta G_F}{G_F} = 8\ \text{ppm}$$

arXiv: 0707.3904 [hep-ex]
(July 2007)
&
submitted to PLB

RESULTS

OUR MEASUREMENT IN THE WORLD SCENARIO OF MUON LIFETIME EXPERIMENTS

→ after more than 20 years two new experiments (MuLan & FAST) are taking the lead



18 ppm

8.2 ppm

G_F accuracy:
9 ppm → 4 ppm

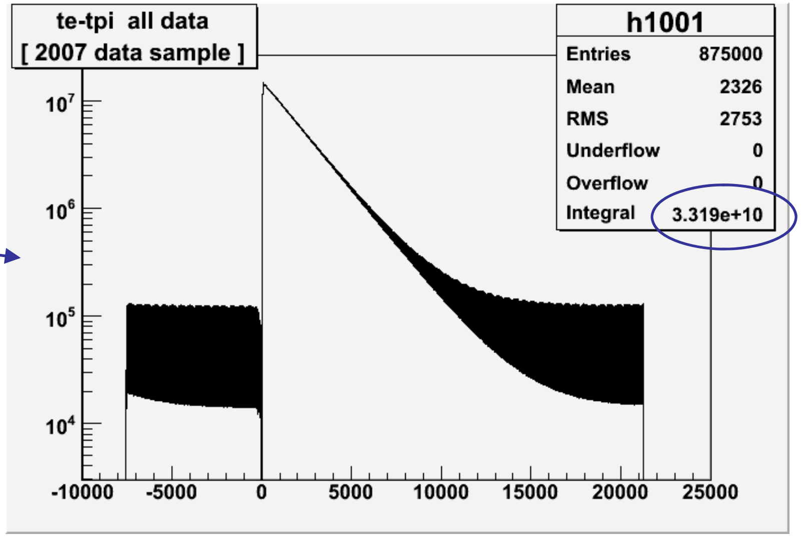
ppm accuracy on G_F expected soon!

FAST: PRESENT STATUS

Run 2006 largely proved the feasibility of the experiment and the validity of the method for the measurement.
One main issue is still required to achieve the final goal [1ppm GF]

- **increase the working rate: 30 kHz LV2 (2006) → ~ 100 kHz LV2 (2007-2008)**

- **2007 beam time at PSI: Sept 2007 – Dec 2007**
  - not foreseen for physics data taking but **mainly devoted to DAQ / rate improvement**
  - ~ 3 x 10^{10} muon decay events collected [STILL **PRELIMINARY** ANALYSIS]



- **DAQ progresses**:

- Hardware : 4 PVIC nodes → 8 PVIC nodes i.e. **80 MB/sec → 160 MB/sec**

- 'malfunctioning' of the TDC induced by an anomaly in LV2 **[noise problem]**
  [loss of syncronization among the 4 chips of the same TDC board]
  → partly solved => 60 kHz (stable running) accessible

- new mode of reading the TDCs: **continuous mode VS trigger matching mode**
- **100 kHz LV2 rate will be accessible using the TDCs in continuous mode**

FAST: FUTURE PLANS

- **2008 beam time** (to be defined, > May)

  final data taking foreseen ; rate ~ 100 kHz (TDCs used in cont mode)

- to-do list :
  - complete the analysis for the sample collected in 2007 (~ 8ppm τ_μ)
  - develop new code for the event building with TDCs used in continuous mode
  - attempts to solve definitevely the noise problem
  - higher statistical sample ➔ new/unknown/unforeseen systematics

does not require beam time

requires beam time

FINAL DATA COLLECTION FOR FAST IS FORESEEN IN 2008

WORKS ARE STILL IN PROGRESS... ... ...


Stay
Tuned!