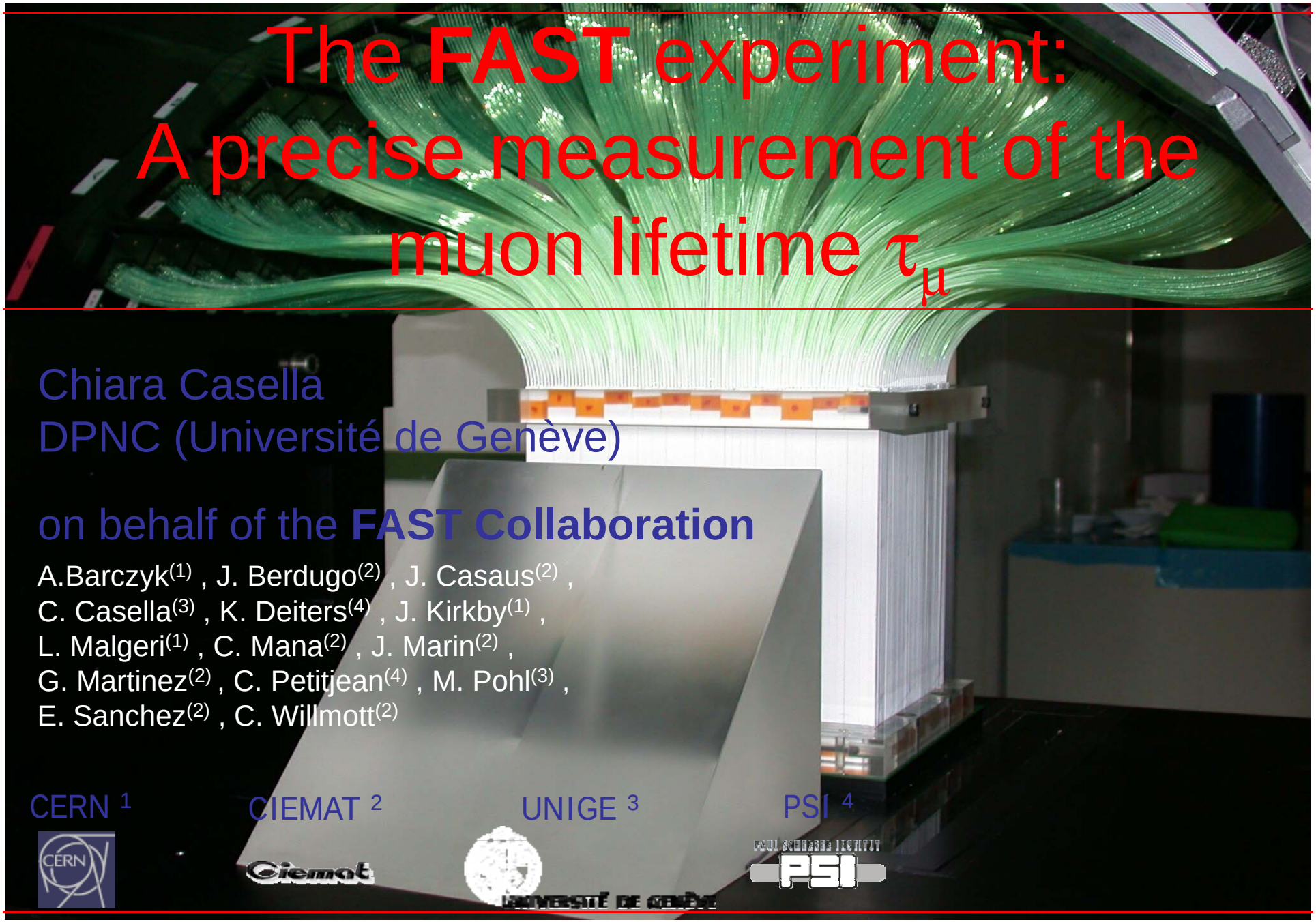
The **FAST** experiment: A precise measurement of the muon lifetime τ_μ



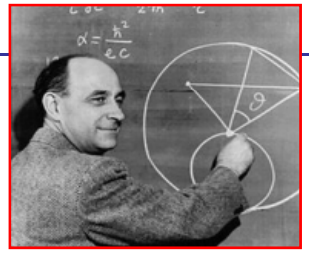
Chiara Casella
DPNC (Université de Genève)

on behalf of the **FAST Collaboration**

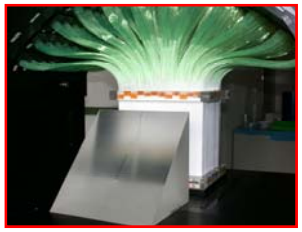
A.Barczyk[(1)] , J. Berdugo[(2)] , J. Casaus[(2)] ,
C. Casella[(3)] , K. Deiters[(4)] , J. Kirkby[(1)] ,
L. Malgeri[(1)] , C. Mana[(2)] , J. Marin[(2)] ,
G. Martinez[(2)] , C. Petitjean[(4)] , M. Pohl[(3)] ,
E. Sanchez[(2)] , C. Willmott[(2)]

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

OUTLINE



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



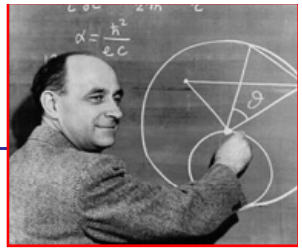
- **The FAST experiment**
  - general experimental concept
  - description of the setup elements

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

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

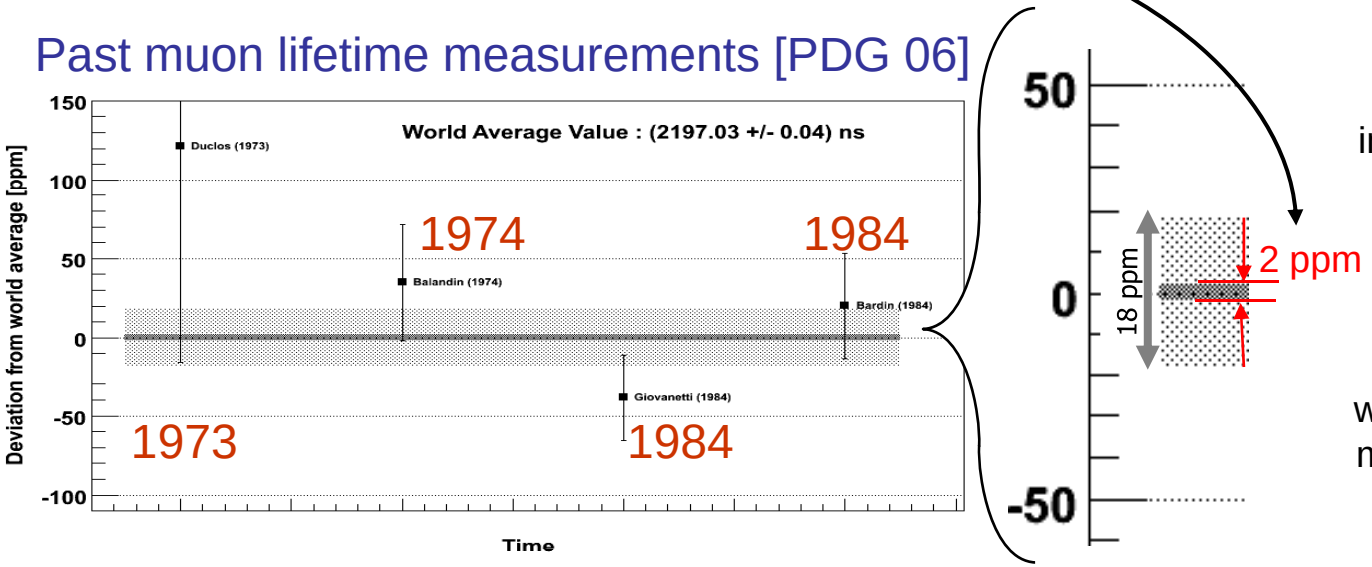
- **Conclusions & Future plans**

GOAL OF THE EXPERIMENT & MOTIVATIONS



FAST goal : precision measurement of the muon lifetime
$\delta\tau_\mu/\tau_\mu$ ~ 2 ppm [~ 4ps]

Past muon lifetime measurements [PDG 06]



ULTIMATE FAST GOAL
One order of magnitude improvement on the current world average

PRESENT ANALYSIS (2006 data sample):
world average competetitive muon lifetime measurement - as single experiment -

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

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

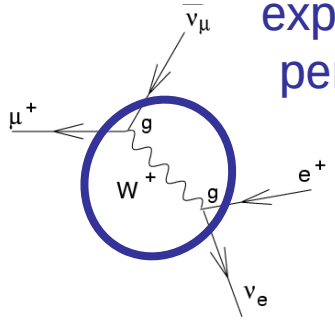
At present, the (exp) accuracy on τ_μ is the limiting factor for an improved precision on the Fermi Constant G_F

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

9 ppm; 0.2 ppm; < 13 ppm

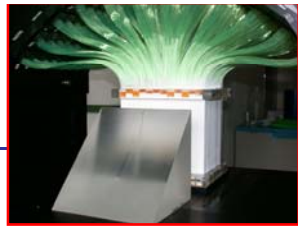
$$\left(\frac{\delta G_F}{G_F}\right)_{th.} = 0.3\ ppm$$

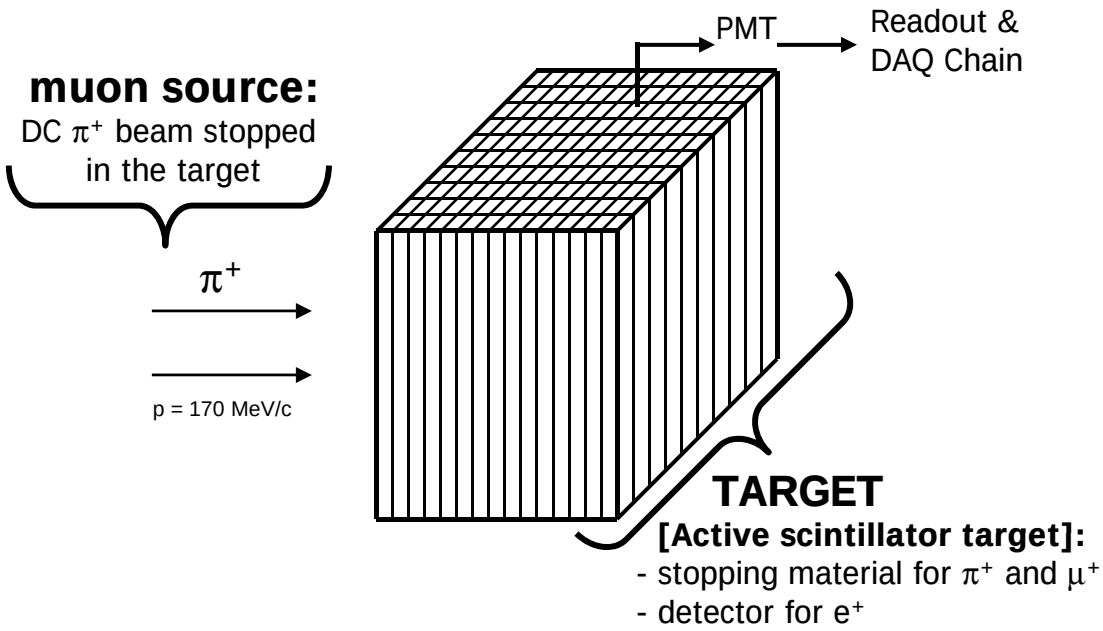
Ritbergen & Stuart, Phys.Rev.Lett. 82, 488 ***1999***



FAST: high energy experiment performed at low energy scale

THE FAST EXPERIMENT





SIGNATURE FOR AN EVENT [π→μ→e] :

- $\pi^+ \rightarrow \mu^+ \ \nu_\mu \ (\tau_\pi \sim 26ns)$ $E_\mu^{cin} \sim 4 \ MeV$ $\rho_\mu \sim 1.5 \ mm$
- $\mu^+ \rightarrow e^+ \ \nu_e \ \bar{\nu}_\mu \ (\tau_\mu \sim 2.2\mu s)$

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

Size of the statistical sample → max achievable precision

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

$$\frac{\delta\tau_\mu}{\tau_\mu} \sim 2 \text{ ppm} \Rightarrow N_{evts} \geq 2.5 \times 10^{11}$$

PARALLELISATION needed
i.e. treat more π→μ→e events at the same time inside the target:

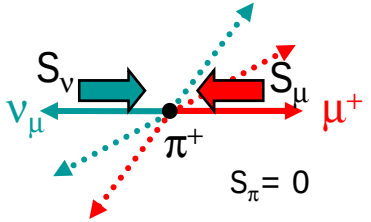
- High granularity of the target
- Tracking capabilities
- Ability to disantangle overlapping events

- High beam rate
- Huge data rate throughput

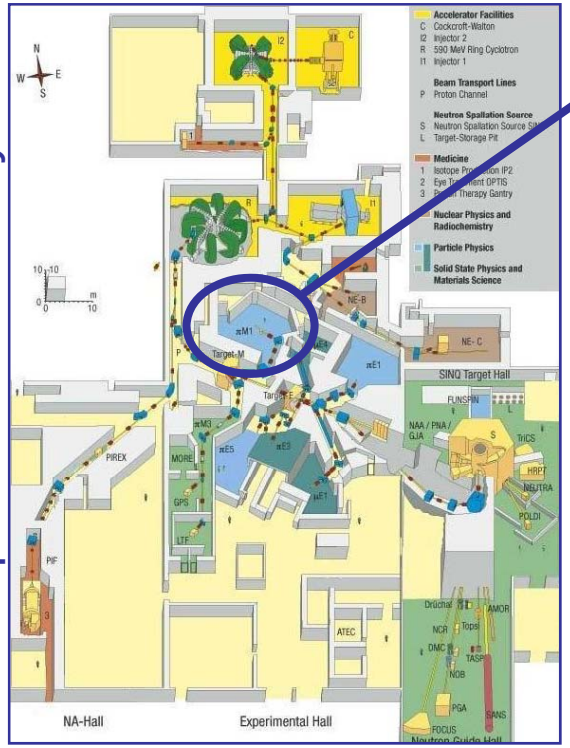
- Systematics under control

MUON SOURCE (i.e. DC π^+ BEAM)

μ source = π decay at rest in the target
➔ isotropic & unpolarized μ source

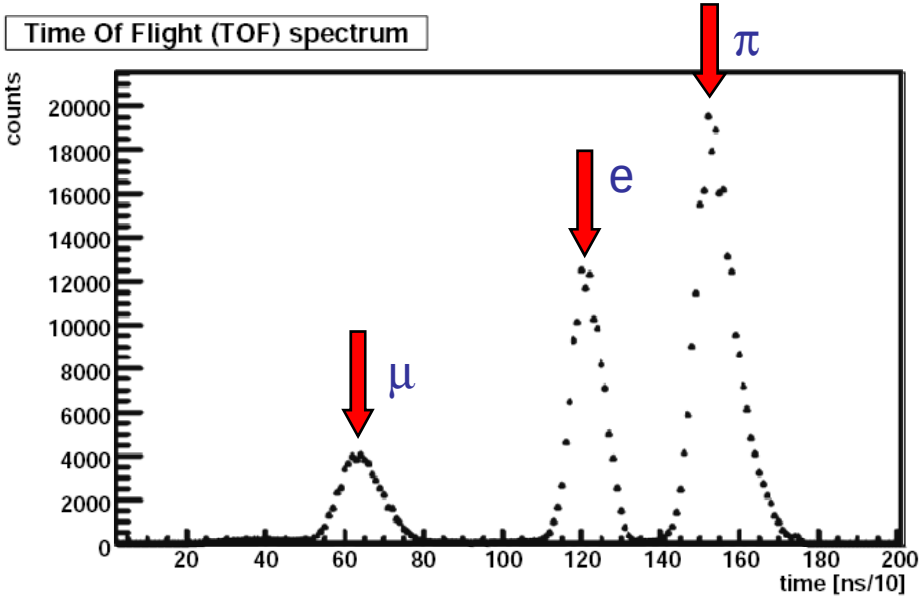


PSI Experimental Hall - layout



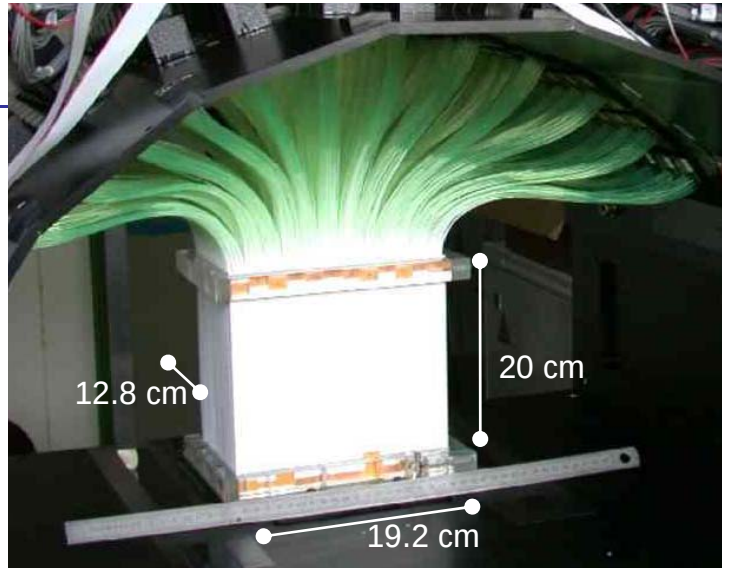
πM1 area at PSI :

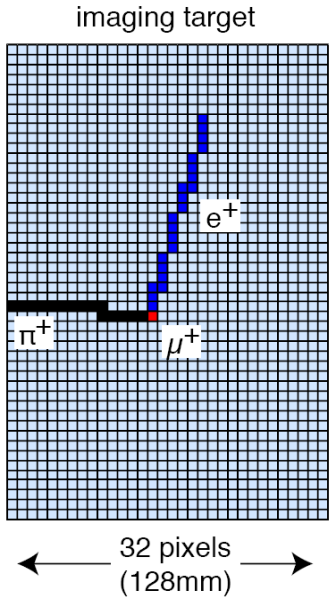
- πM1	: **π^+ DC beam**
- momentum	: **170 MeV/c** (±3%)
- RF frequency	: 50.633 MHz (T=19.75 ns)
- beam size	: variable **(~ 10 x 10 cm^2)**
- intensity	: variable **(~ 500 kHz)**
- purity	: ~ 50%



TARGET

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

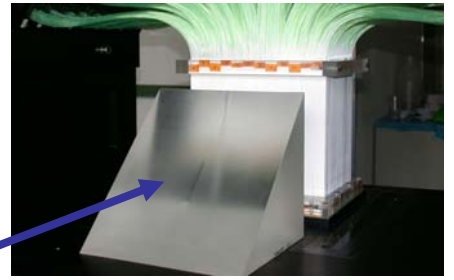




- **high granularity**
- **tracking capabilities**
- **fast imaging detector**
- **identical replicated mini-detectors (pixels)**
- **vertical arrangement 32 x 48**

- **1536 pixels**

1 pixel = 1 scintillator bar
(4 x 4 x 200 mm^3) with 2 WLSF



- **wedge beam degrader**

to achieve a uniform distribution of the stopping pion points

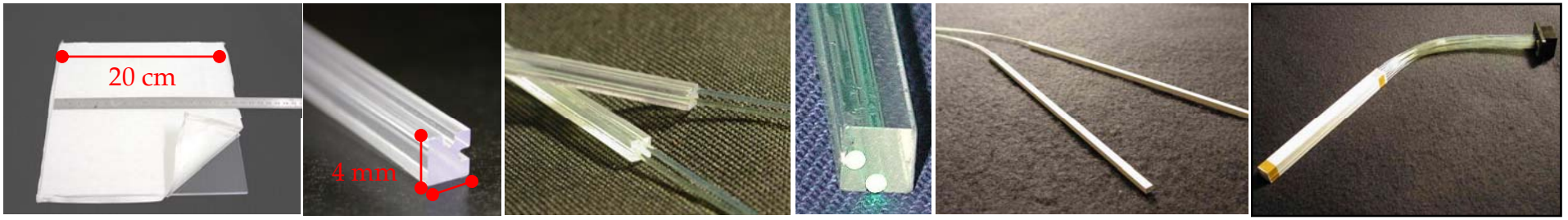
BC400 solid plastic scintillator plates

- 4x4x200mm3 bars
- two grooves machined

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

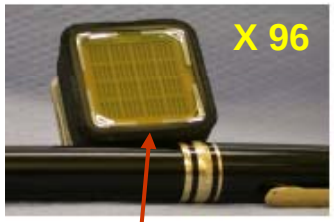
diffusive reflective paint (BC-620)

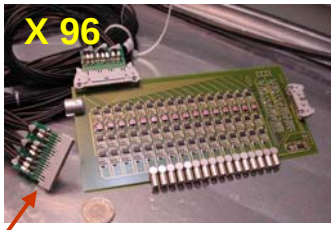
- bundle of 4x4 pixels [96 bundles]
- fibers housed in a special mask



FAST READOUT & DAQ CHAIN

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

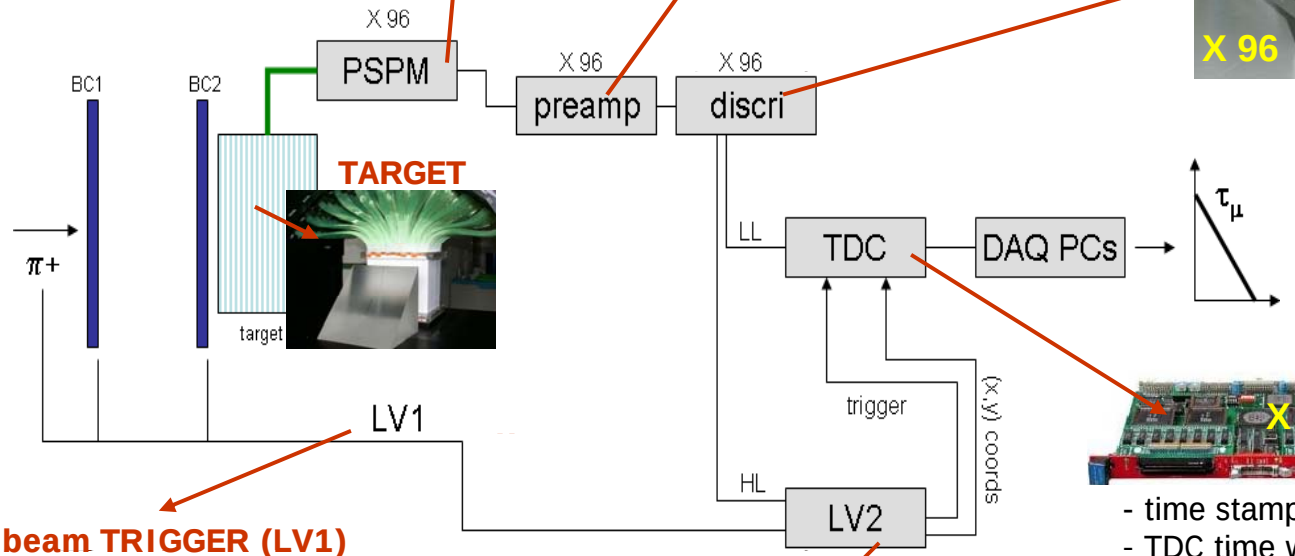




- **Preamplifiers**
- shaper & preamp (x5)
- custom made units (PSI)

- **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)

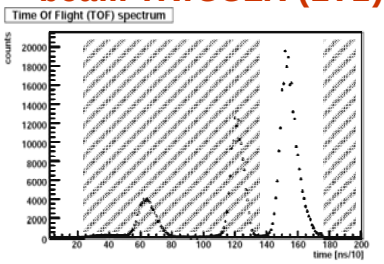


- CAEN v767 128-channs **TDCs**

- time stamping of the raw pulses from discri
- TDC time window: [-10,+20]μs w.r.t. Trigger
- trigger : π in the target (entry/π stop time)

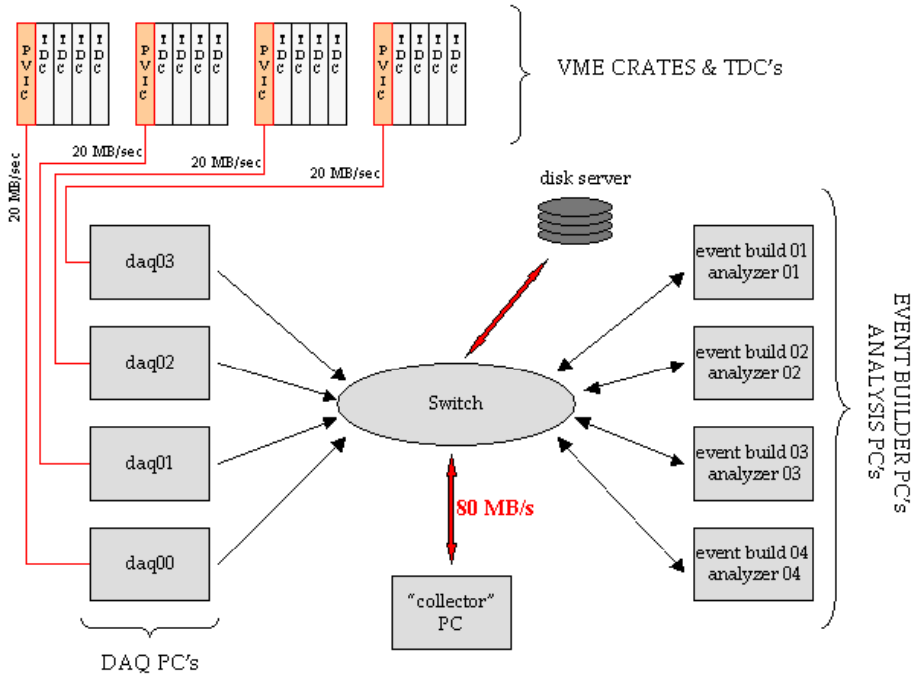
- output of the TDCs: into the DAQ PC's

beam TRIGGER (LV1)



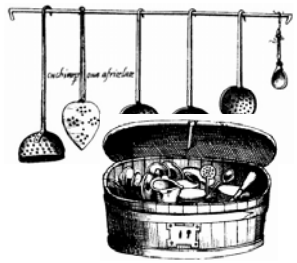
Second Level TRIGGER (LV2)
- Hardware trigger for the TDCs
- Selective trigger (definition of ROI, around the pion stopping point)
- Event quality selection
- DATA REDUCTION SYSTEM
- Custom made FPGA based electronics (CIEMAT)

DAQ ARCHITECTURE



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

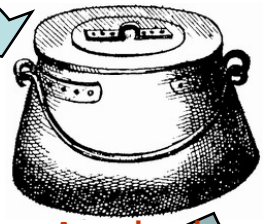
80 MB/sec (~ 7 TB/day):
max allowed data rate



RAW DATA

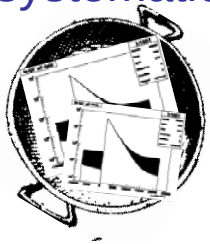
EVENTS

Ev.Builder



Analysis

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



- **This has to be ONLINE**
- The full set of data cannot be stored on disk
- Only histograms are saved as the output of the analysis process
- Histo: control, lifetime, syst

RUN 2006

&

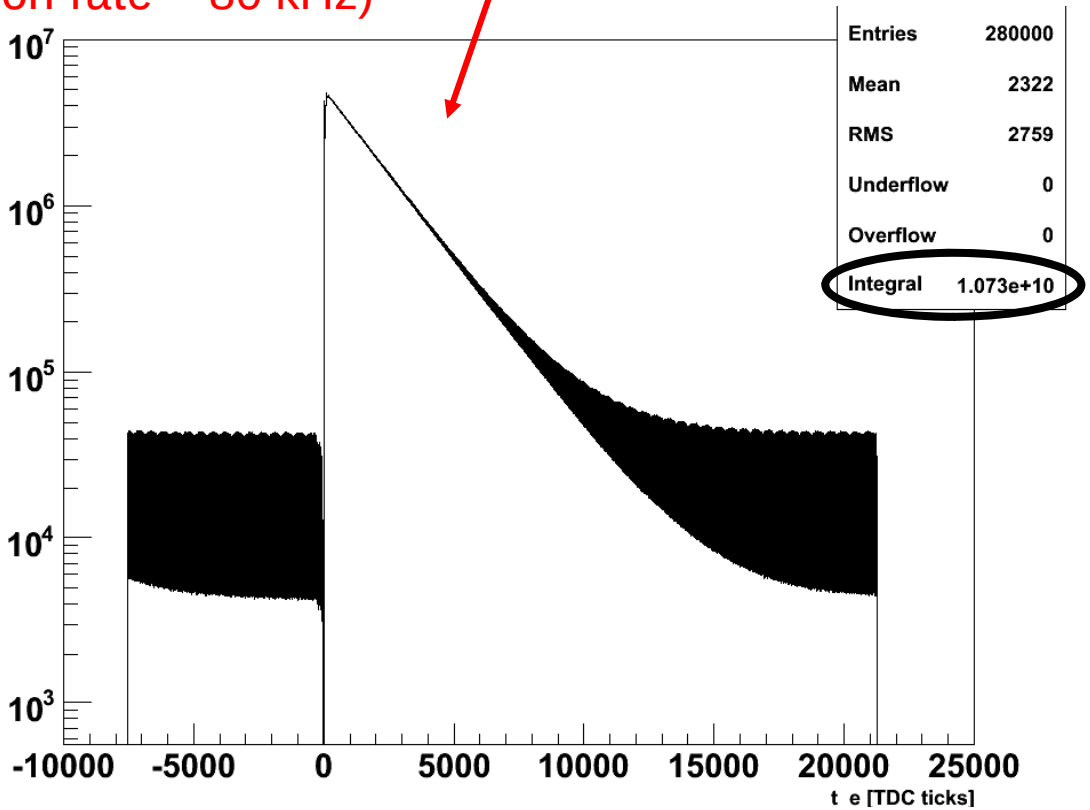
MUON LIFETIME ANALYSIS

RUN 2006: DATA SAMPLE

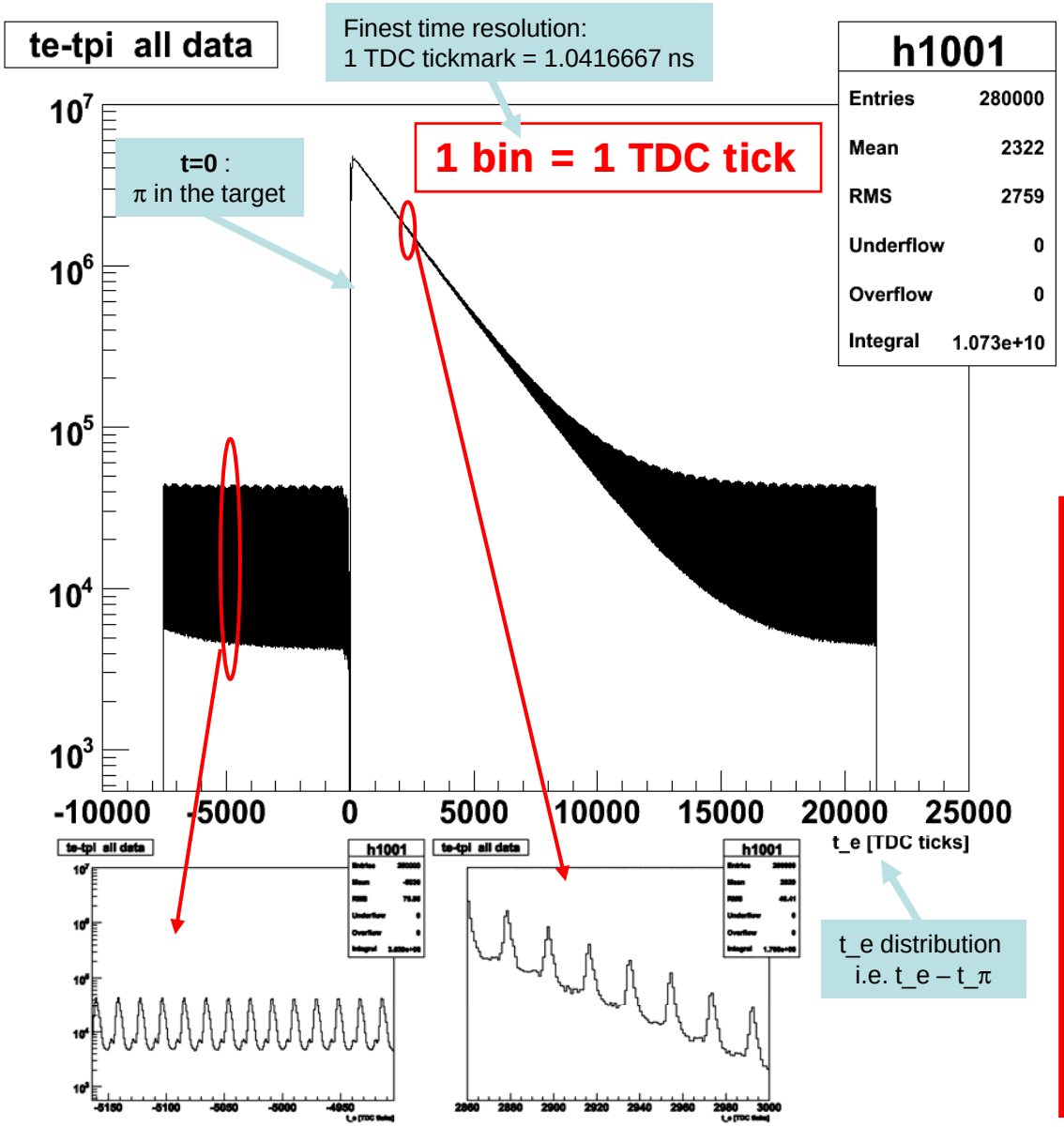
- **3 weeks data taking** (Nov – Dec 2006)
- first physics data taking run for FAST
- running conditions very close to the final one except for the reduced adopted rate :
  LV2 trigger rate ~ 30 kHz (pion rate ~ 80 kHz)
- **total statistics :**
  1.073 x 10^{10} events
  → precision comparable with world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

« THE » PLOT
Muon lifetime histogram

t_e distribution i.e. t_e-t_π
[in TDC tickmarks]



MUON LIFETIME HISTOGRAM



- 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

measure τ_μ = fit distribution

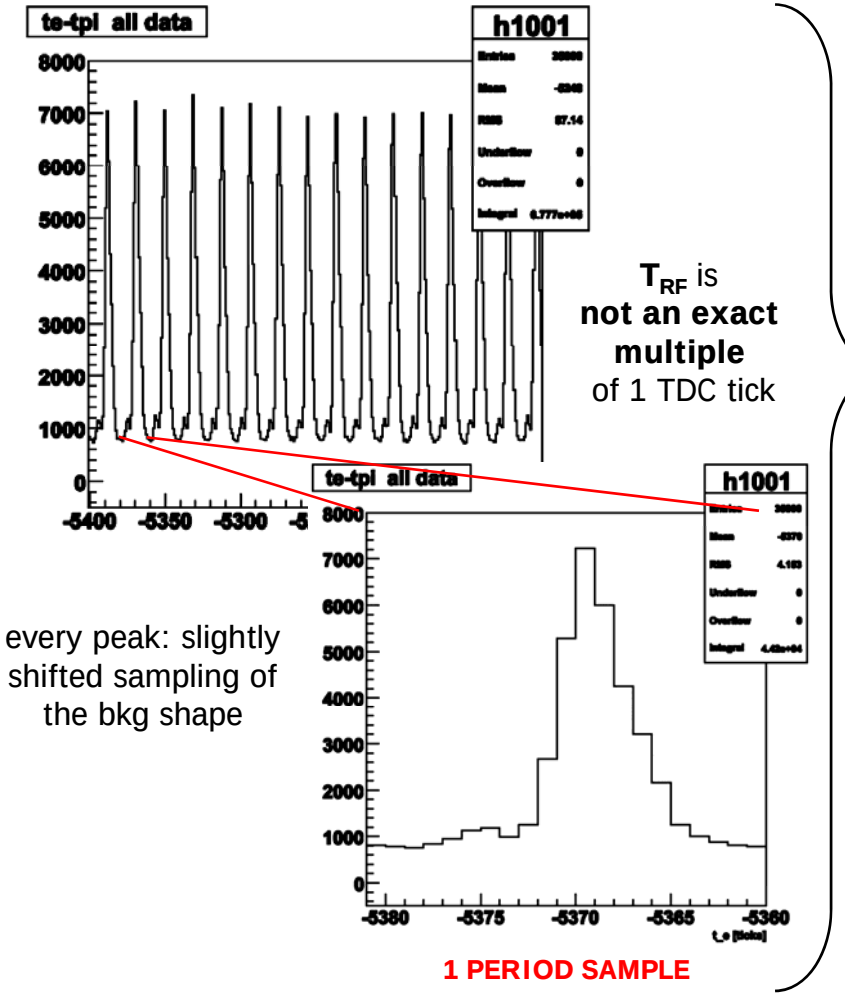
- Fine binning distribution → study and understand all the structures of the data
  → RF structure
  → TDC non linearity

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

- Define a proper fitting function

- Binned maximum likelihood fit (TMinuit-ROOT) with τ_μ as free parameter

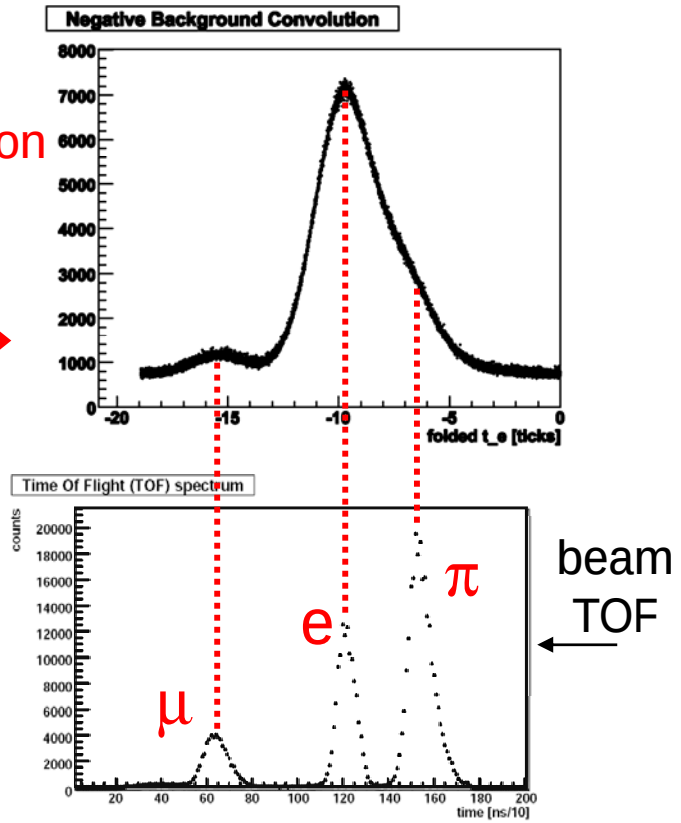
STEPS FOR THE FIT: 1. understand the background (t<0)



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

every peak: slightly shifted sampling of the bkg shape

convolution (T_{RF})

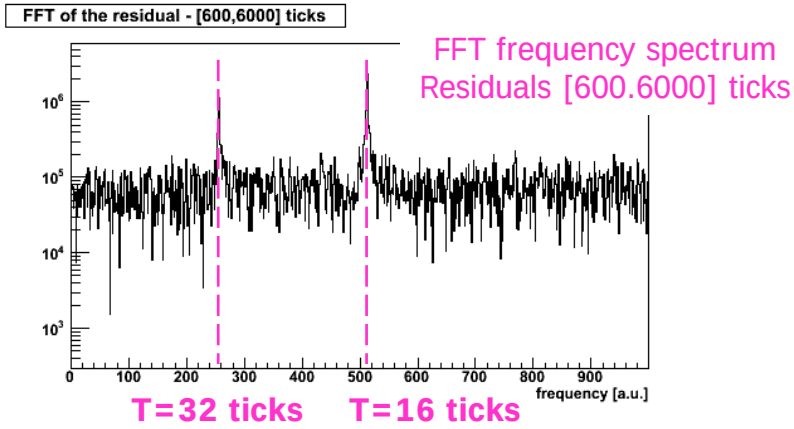


1. Periodic background shape:
- exactly reproduces the beam content
- dominated by electrons (e)

2. Extraction of the exact RF period from the fit of the negative background:
- T_RF = (18.960051 +/- 0.000003) ticks → 0.2 ppm

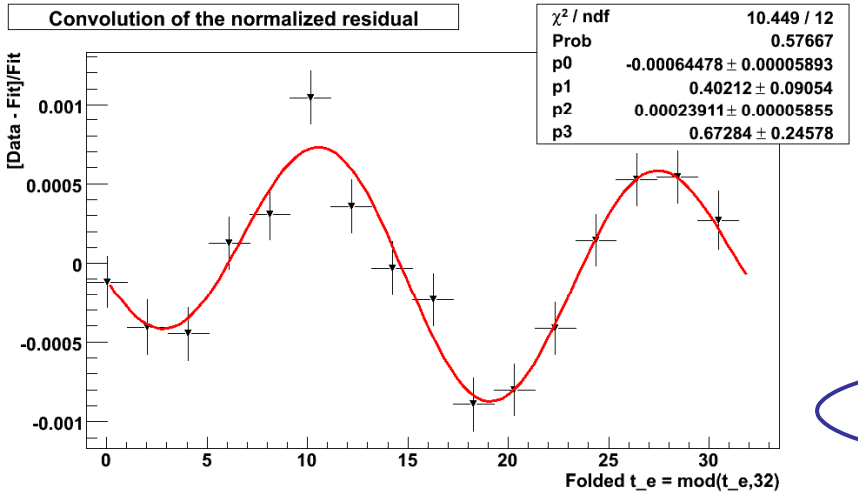
STEPS FOR THE FIT: 2. periodic structures in the data (t>0)

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



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

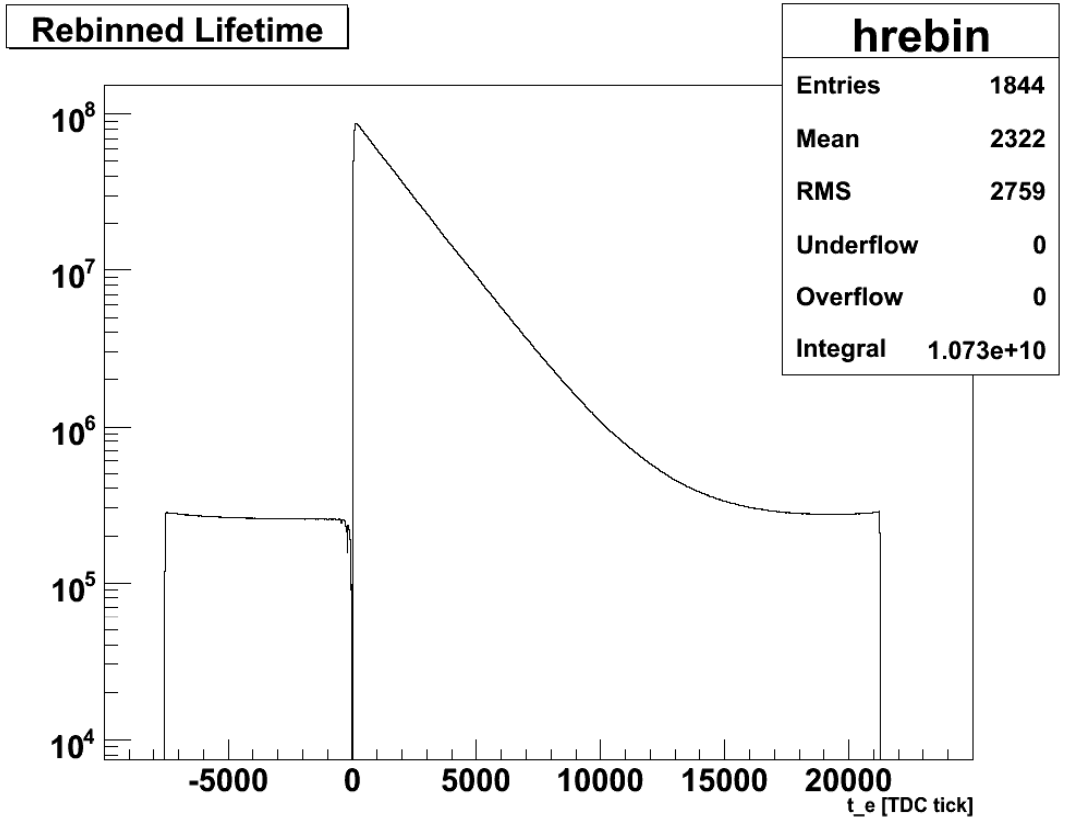
- TDC non linearity effects
- per mille level effect
- confirmed also in lab tests

[TDC CLK = 32 ticks]

STEPS FOR THE FIT: 3. 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

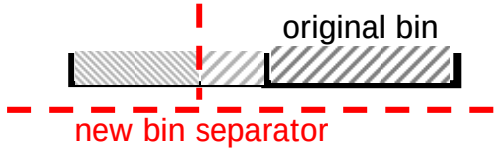


T_{RF}

1 new bin = 18.960051 original bins

"SMART REBIN"

i. e. rebin + bin sharing procedure :

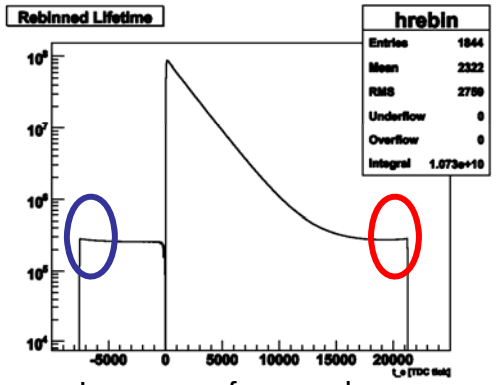


→ different algorithms tried (uniform, linear, quadratic, exp) for the sharing of evts inside the original bin

→ no appreciable differences found (see systematics)

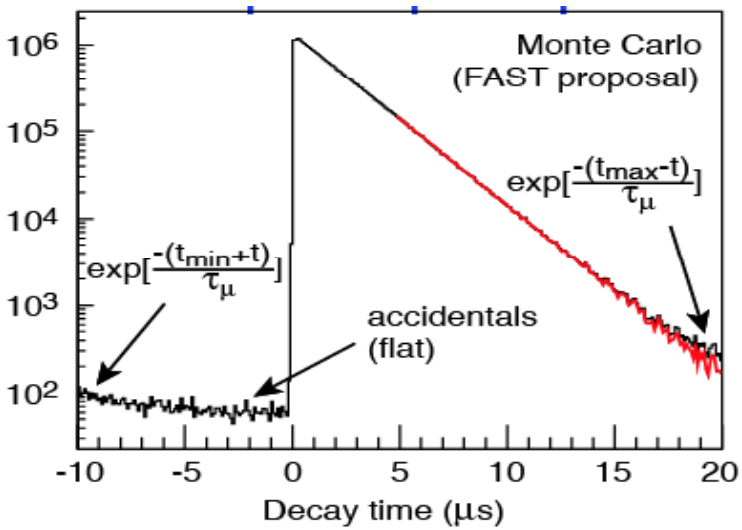
→ default: uniform distribution inside the bin

STEPS FOR THE FIT: 4. 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) ↘

(π1,μ1,X)

(π2,μ2,e2) ↗

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

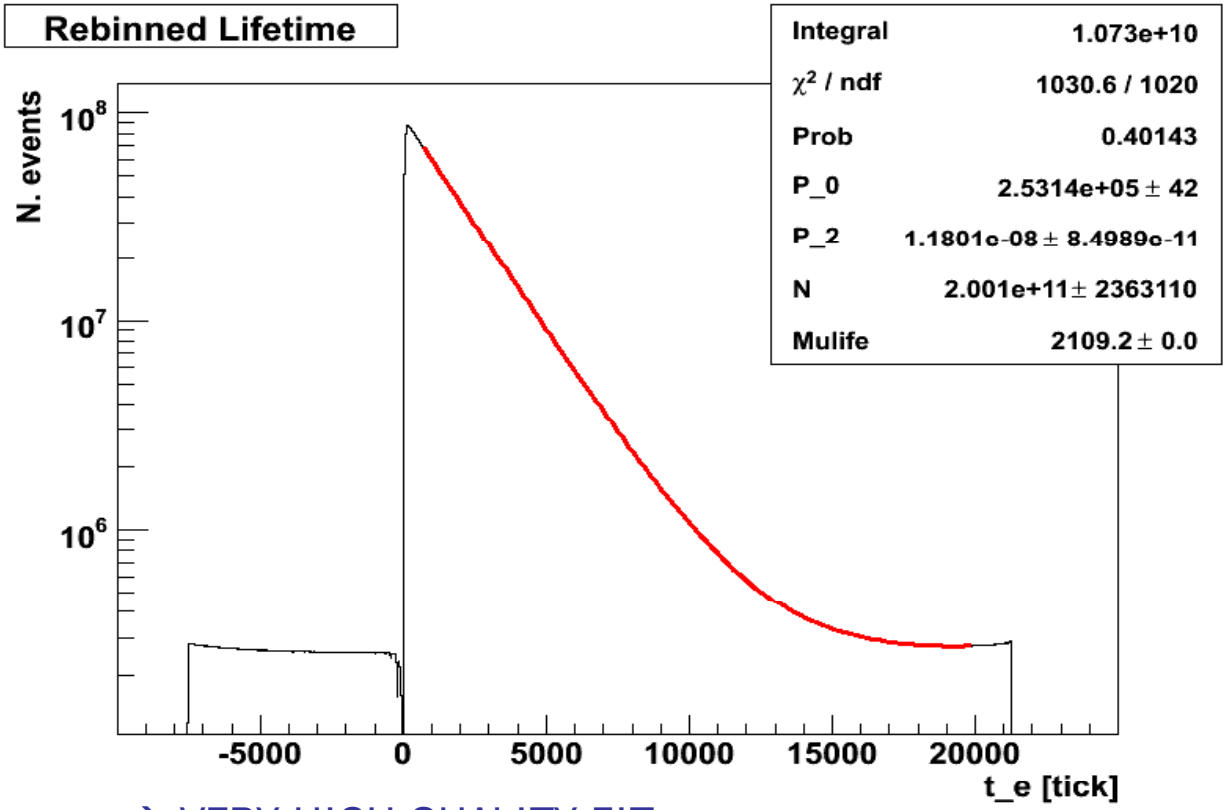
Accidental bkg

Signal

Time dependent background

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

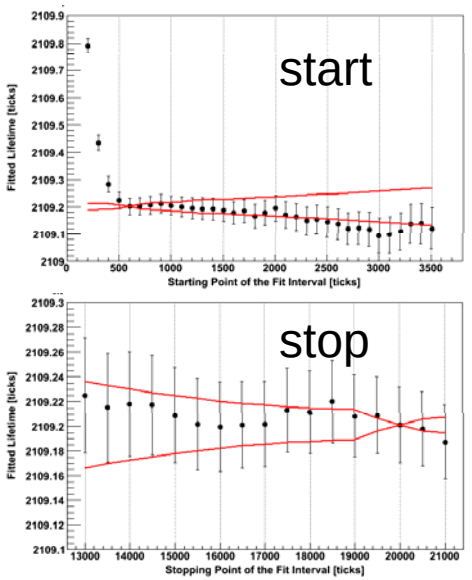
no precise description of the periodic beam induced background is required



→ VERY HIGH QUALITY FIT

- Fit interval: [600,20000] ticks

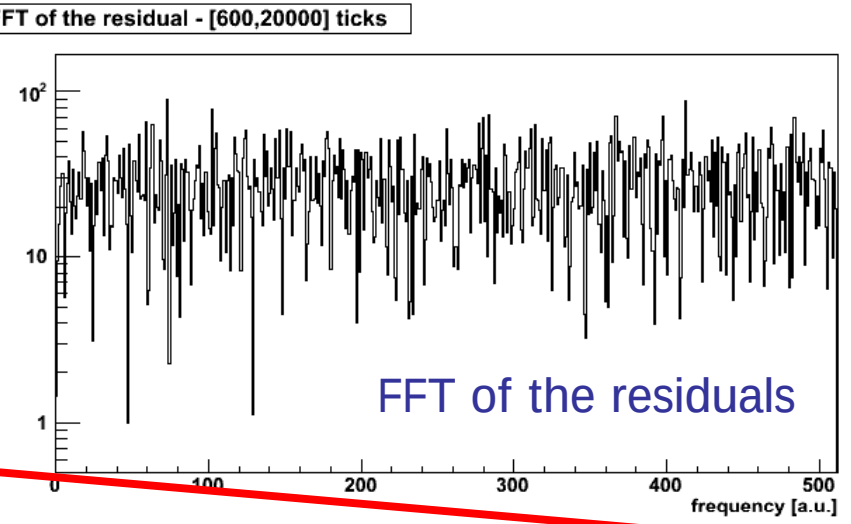
Largest region of stable lifetime



FIT QUALITY

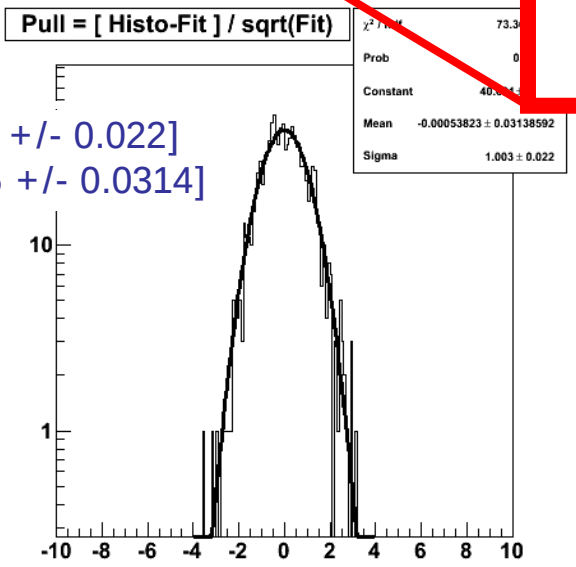
Full Statistics Sample (Run2006)		*Fit: [600, 20000] ticks*
Smart Rebin Method		
χ^2/ndf		1030.65/1020 = 1.0104
Prob(χ^2,ndf)		0.4014
Fitted Parameters		
Offset	P_0	253135 ± 39
Exp. Tail Norm.	P_2	(1.180 ± 0.008) × 10^{-8}
Normalization	N_0	(2.00104 ± 0.00002) × 10^{11}
Lifetime [ticks]	τ	2109.200 ±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

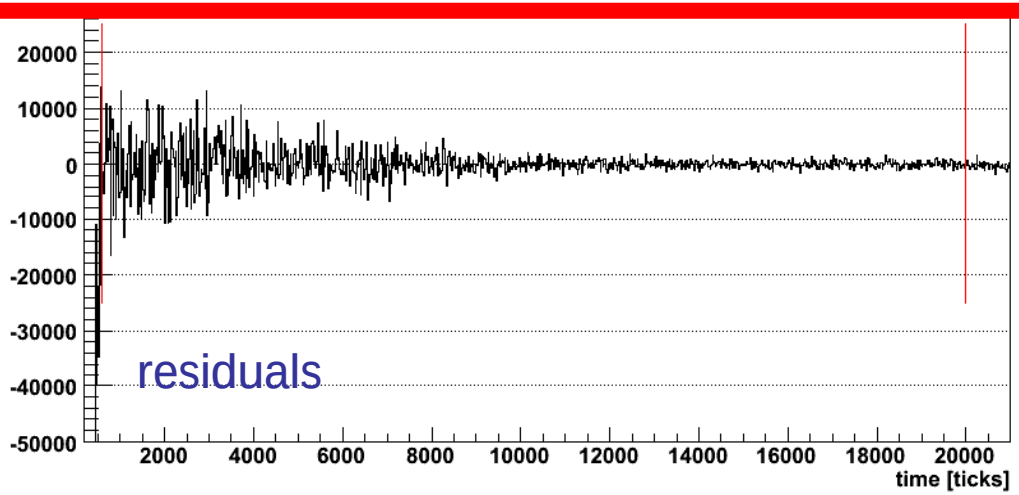
	P_0	P_2	N_0	τ
P_0	1.000	-0.714	-0.104	-0.498
P_2	0.714	1.000	0.084	0.335
N_0	-0.104	0.084	1.000	-0.157
τ	-0.498	0.335	-0.157	1.000



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

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





SYSTEMATICS STUDY

- Evaluated with several dedicated histograms (produced online)
- Different classes of systematic errors studied, with different sets of specific lifetime histograms
- General recipe:
  - 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 sub-samples & 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

SUMMARY TABLE OF SYSTEMATICS

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

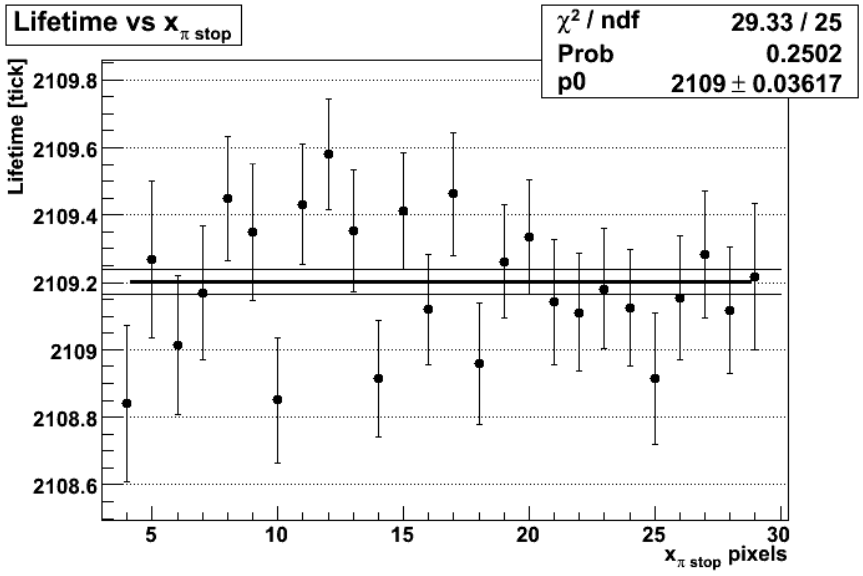
* Examples described here

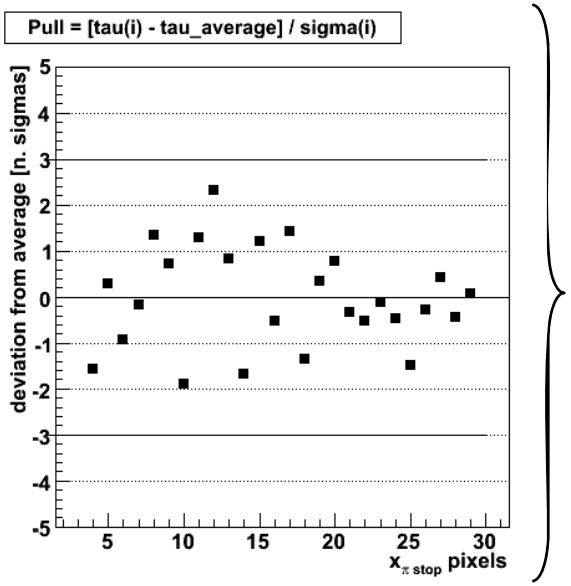
→ At present, the determination of the systematic uncertainty is limited by the statistics

→ There is no evidence of large systematic effects

SYSTEMATICS: HOMOGENEITY OF THE TARGET

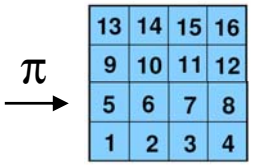
2 examples for no evidence of a systematic effect beyond the expected statistical fluctuations

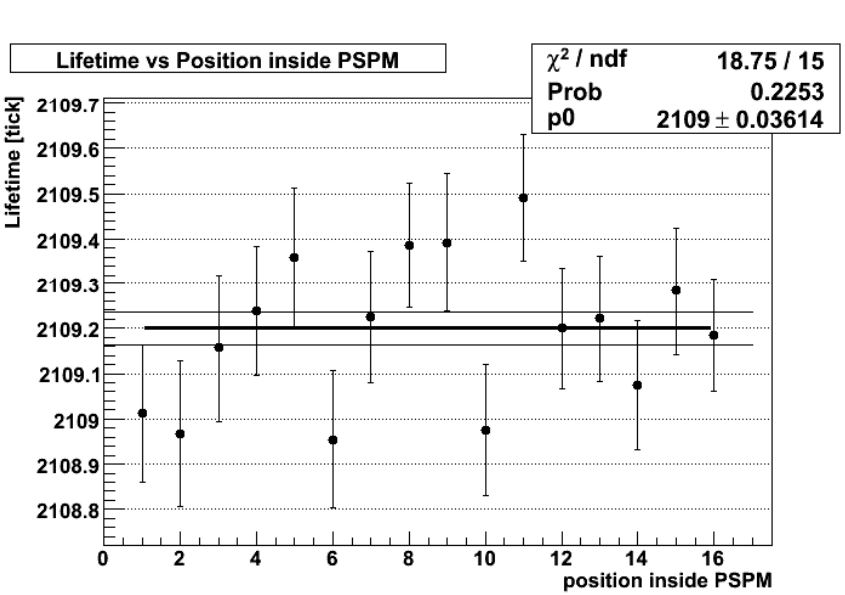


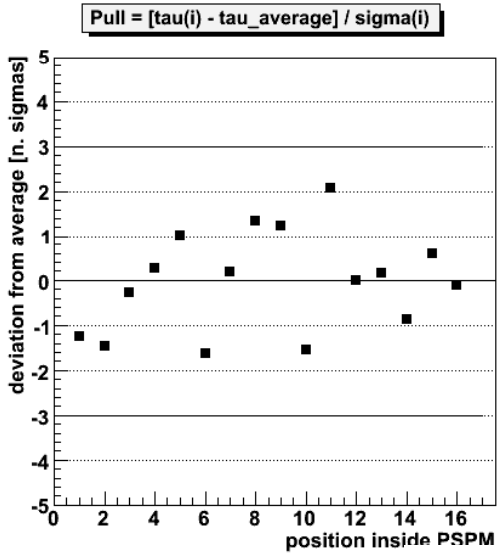


lifetime vs position of the pion in the target (x coord)

lifetime vs position of the pion inside the PSPM

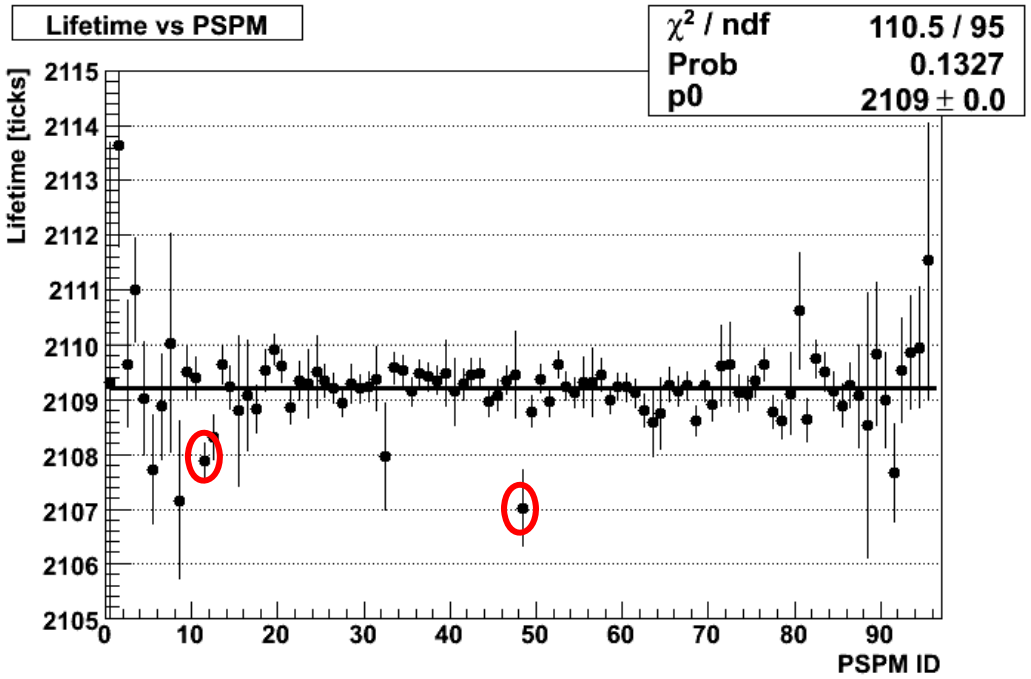


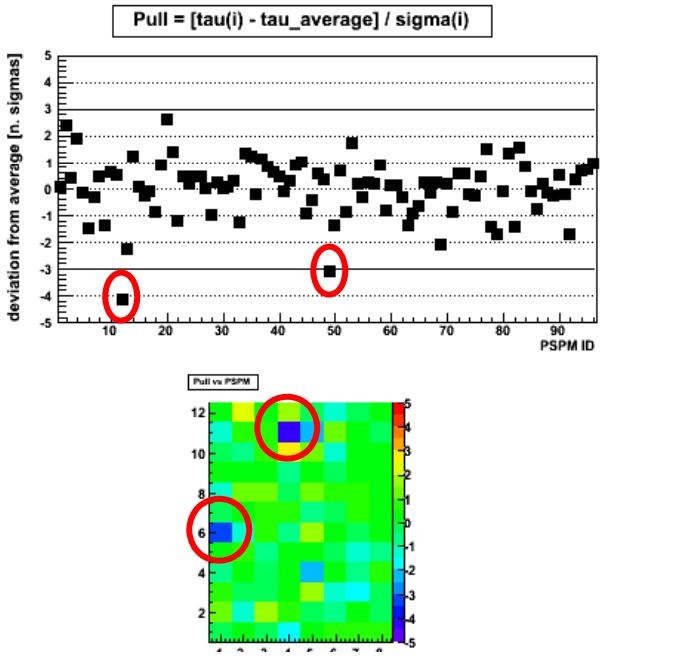




SYSTEMATICS: HOMOGENEITY OF THE TARGET

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

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

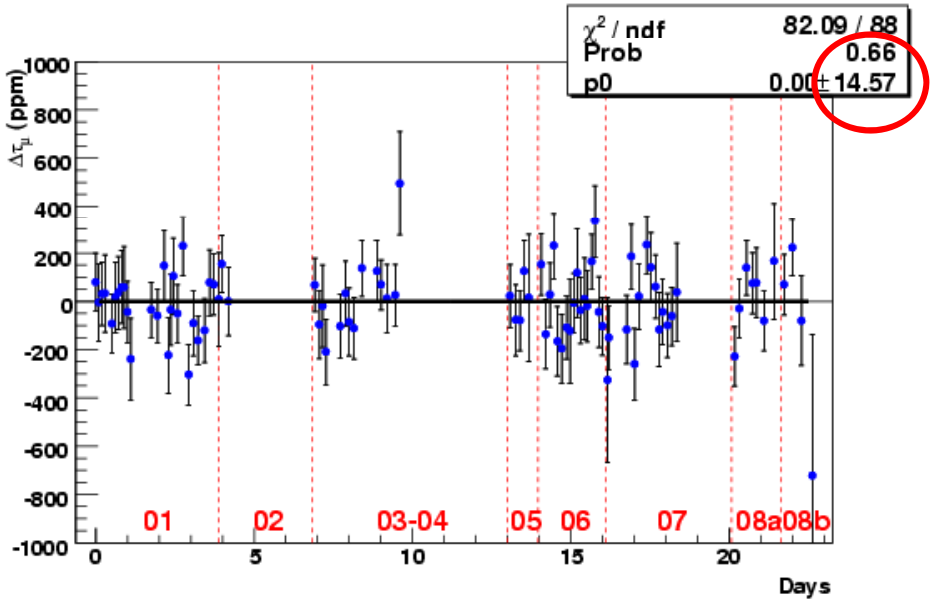
SYSTEMATICS : TIME STABILITY & RATE DEPENDENCE

TIME STABILITY

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

Nominal fit applied to every subset:

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

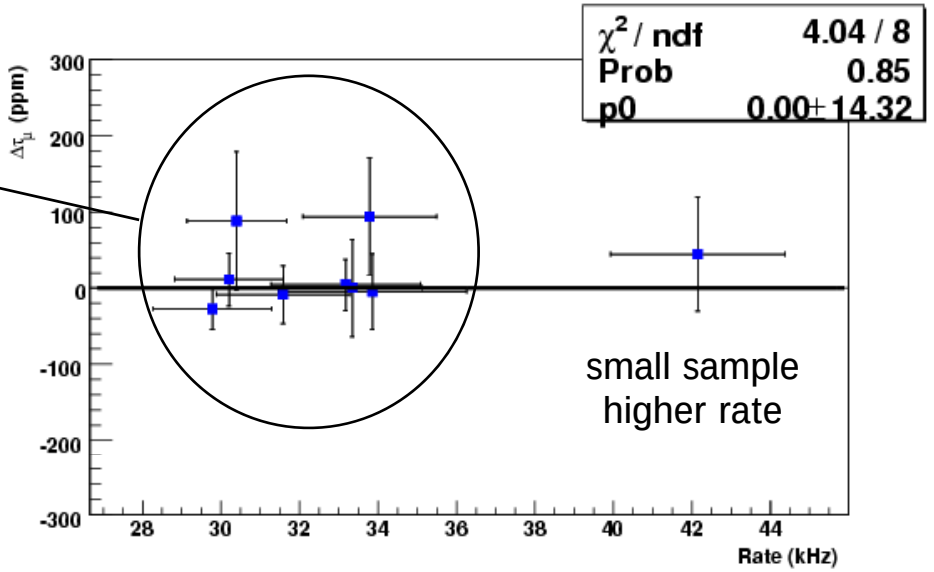


RATE DEPENDENCE

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

NO EFFECT OF SYSTEMATICS RELATED TO THE TRIGGER RATE

Limited rate interval available



RESULTS & CONCLUSIONS

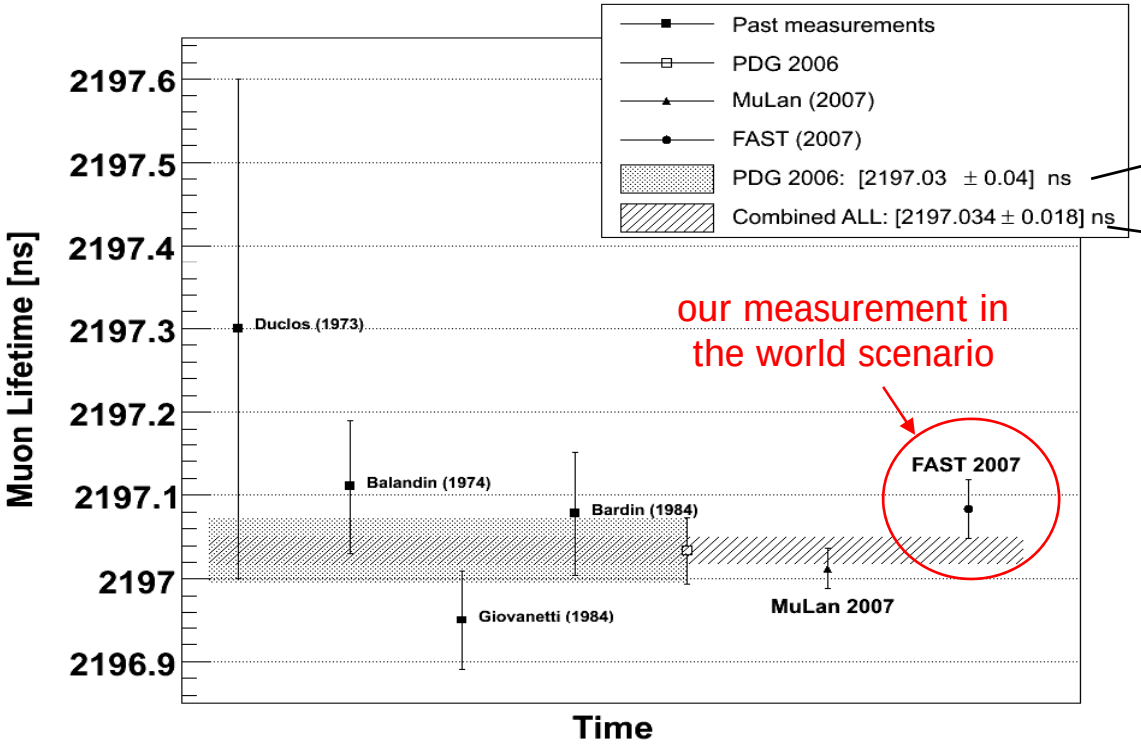
first FAST precise measurement of the positive muon lifetime and Fermi Constant GF :

→Run 2006, 3 weeks data taking / 1.073 10^{10} μ^+ decay events / precision compatible with PDG
→Good agreement with the PDG / The uncertainty is totally dominated by the statistics

$$\tau_\mu = [2197.083 \pm 0.032\ (\text{stat}) \pm 0.015\ (\text{syst})]\ \text{ns} \qquad \frac{\delta\tau_\mu}{\tau_\mu} = 16\ \text{ppm}$$

$$G_F = [1.166353 \pm 0.000009] \times 10^{-5}\ \text{GeV}^{-2} \qquad \frac{\delta G_F}{G_F} = 8\ \text{ppm}$$

arXiv: 0707.3904 [hep-ex] & submitted to PLB



18 ppm → **8.2 ppm**

G_F accuracy: 9 ppm → 4 ppm

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

… ppm accuracy on G_F is expected soon!

FUTURE PLANS FOR FAST

• RUN 2006 largely proved the reliability and feasibility of the measurement, but **a few more steps are needed to achieve the final FAST goal**

• **increase the working rate :**
30 kHz (LV2) → 100 – 120 kHz (LV2)

1. Solve some malfunctioning in the TDCs
   (considering CAEN V767→V1190A replacement)
2. Double the DAQ hardware (number PVIC nodes)
   (max bandwidth: 80 MB/s → 160 MB/s)
3. New mode of reading the TDCs
   (continuous mode VS trigger matching mode)

• **analysis:**

1. Higher statistics: new/different systematics
2. Extended LV1 tagging (all pcls) i.e.
pulsed structure is expected to be reduced

• 2007 beam time (from now to Dec) :
final upgrade of the DAQ performance

• 2008 beam time :
data collection (at max rate) for the final measurement