Muon lifetime experiments at PSI

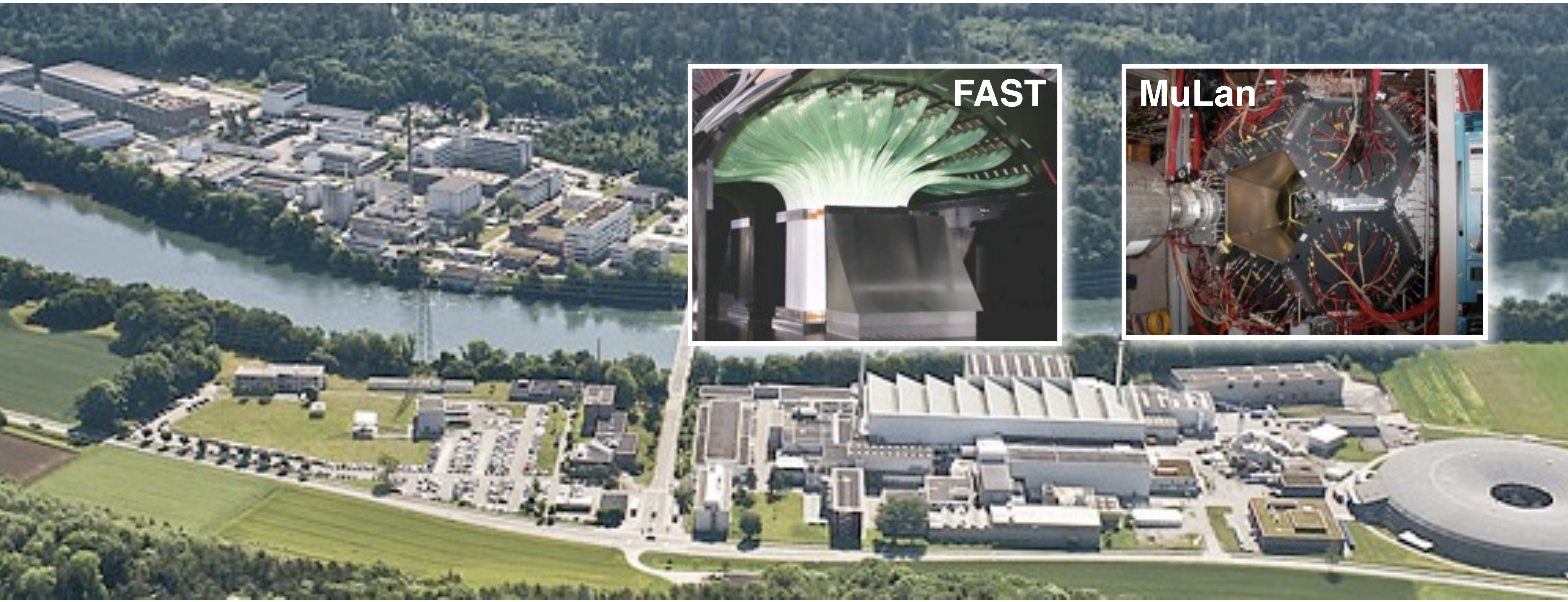
Chiara Casella - ETH Zurich

CHIPP Plenary Meeting, 23-24 August 2010

Muon lifetime experiments at PSI

Chiara Casella - ETH Zurich

CHIPP Plenary Meeting, 23-24 August 2010



OUTLINE :
- theoretical motivations
- precision measurement of the muon lifetime: **FAST** and **MuLan**
- experimental approach, status and <u>published</u> results

Precise muon lifetime measurement : Why?

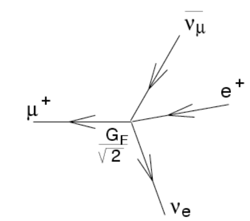
$$\tau_\mu \Rightarrow G_F$$

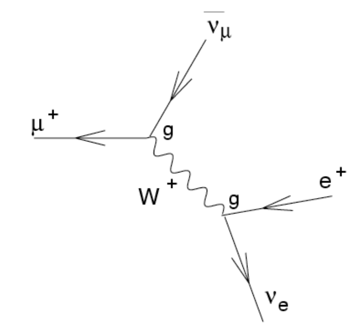
G_F is one of the input parameters of the SM
SM : Predictive only when supplied with sufficient number of exp. inputs
SM of EW interactions (bosonic sector) : 3 free parameters [α, M_Z, G_F]

$$\begin{aligned}
\alpha(\mu^2=0) &= 1/(137.03599911 \pm 0.00000046) && (\rightarrow 0.003ppm)\\
M_Z &= 91.1876 \pm 0.0021\mathrm{GeV} && (\rightarrow 23ppm)\\
G_F &= 1.16637 \pm 0.00001 \times 10^{-5}\mathrm{GeV}^{-2} && (\rightarrow 9ppm)
\end{aligned}$$

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

G_F was introduced in this context to describe phenomenologically the strength of a new force (weak)





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

=> Uncertainties in G_F: Theoretical (Δq) + Experimental (τ_μ , m_μ)

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]

Theoretical uncertainty on GF :

$\Delta q^{(0)}$, $\Delta q^{(1)}$ } 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 on GF :

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

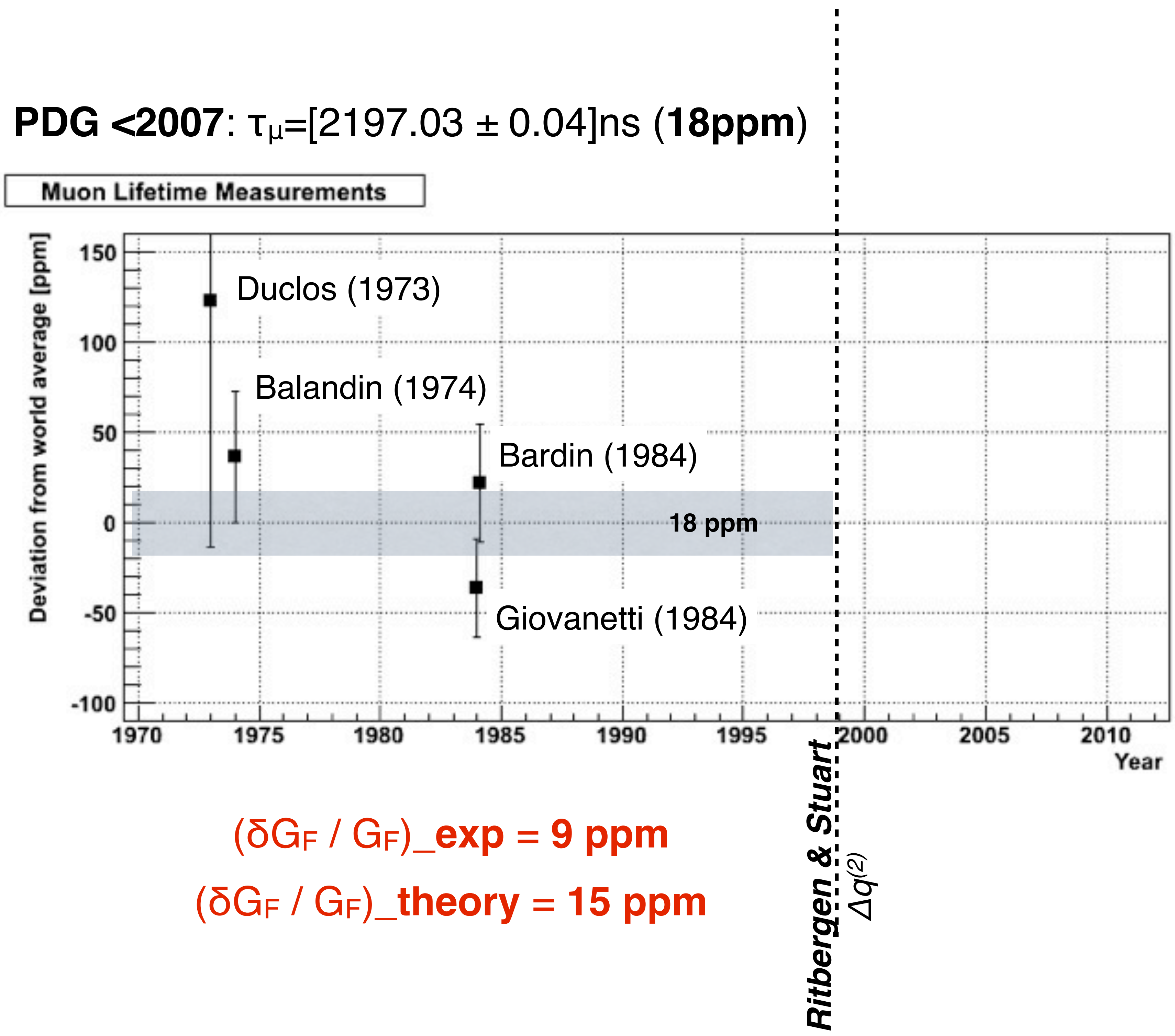
dominant contribution to the exp. uncertainty on G_F

0.2 ppm

negligible

Muon lifetime measurements : the history

PDG <2007: τ_{μ}=[2197.03 ± 0.04]ns (**18ppm**)

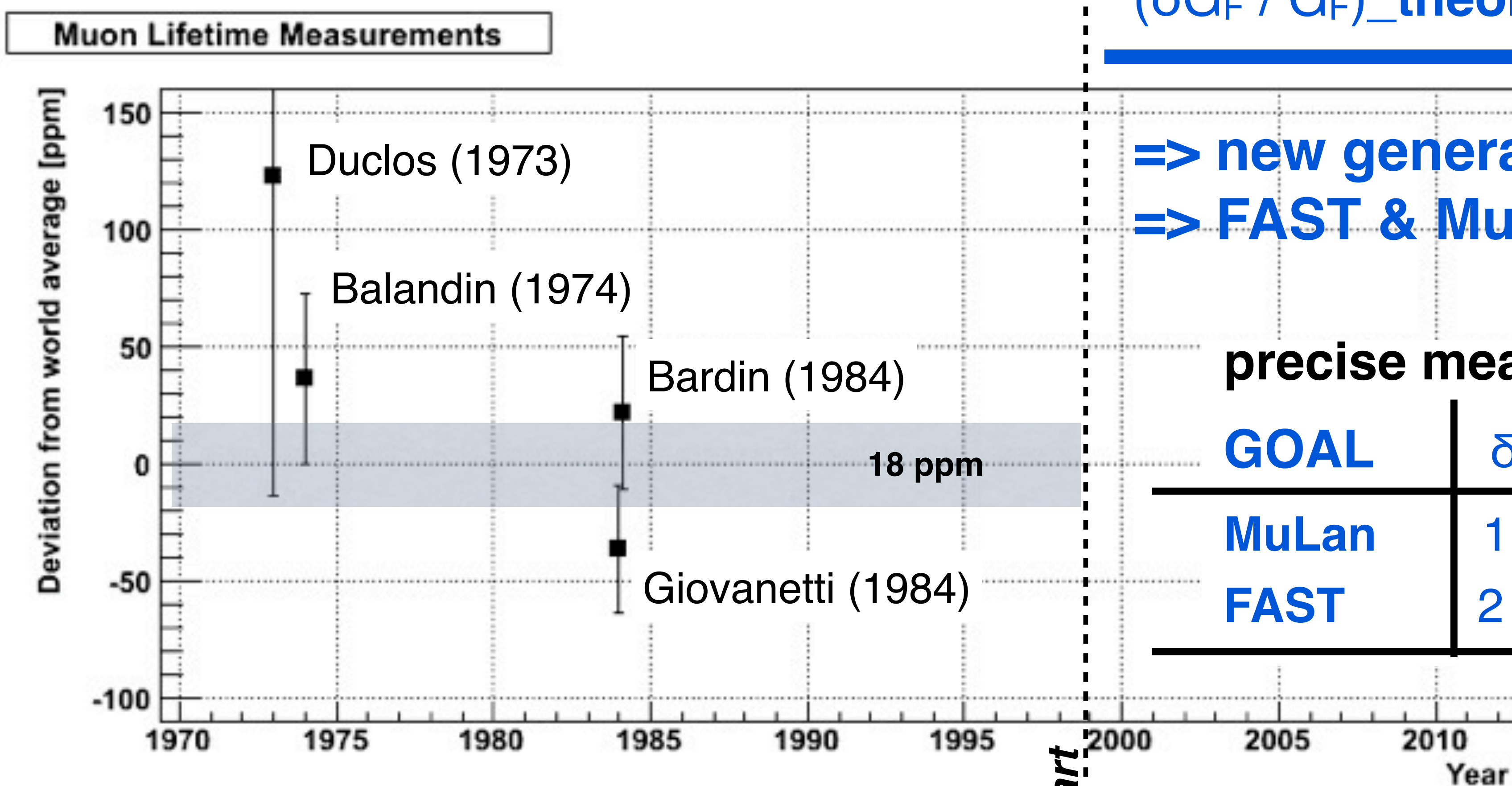


(δG_F / G_F)_**exp = 9 ppm**

(δG_F / G_F)_**theory = 15 ppm**

Muon lifetime measurements : the history

PDG <2007: τ_μ=[2197.03 ± 0.04]ns (**18ppm**)



(δG_F / G_F)_**exp = 9 ppm**

(δG_F / G_F)_**theory = 15 ppm**

Ritbergen & Stuart

$\Delta q^{(2)}$

(δG_F / G_F)_**theory = 0.3 ppm**

=> new generation of muon lifetime exps

=> FAST & MuLan experiments (at PSI)

precise measurement of muon lifetime

GOAL	$\delta\tau_\mu / \tau_\mu$	$\delta G_F / G_F$	N $\tau\mu$ evts
MuLan	1 ppm	0.5 ppm	10^{12}
FAST	2 ppm	1 ppm	2.5×10^{11}

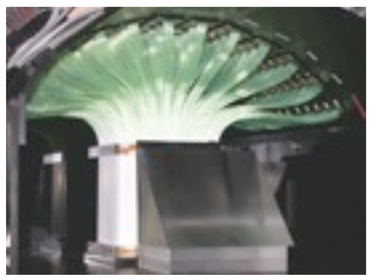
Huge statistical samples :

- **Parallelization** : i.e. more muon decays detected at the same time
- **Systematics control**

Data sets & Status of the experiments

- data taking completed for both experiments
- final stages of the (systematics) analysis

data collection	statistical accuracy on muon lifetime	muon lifetime events	publication / status	
2004 (AK-3 target)	11 ppm	1.8 x 10^10	published, 2007: D.B.Chitwood et al, Phys. Rev. Lett. 99 , 032001 (2007)	MuLan
2006 (AK-3 target)	1.2 ppm	~ 10^12	final systematics analysis results presented in Moriond (March 2010) by D.M. Webber	
2007 (quartz target)	1.7 ppm	~ 10^12		
2006	15 ppm	10^10	published, 2007: A.Barczcyk et al, Phys. Lett. B 663, 172-180 (2008)	FAST
2007 (TDC problem solving)	-	3 x 10^10	technical run : increase trigger rate / solve TDC-DAQ problems	
2008	2.4 ppm	4.2 x 10^11	ongoing analysis	
2009				



Data sets & Status of the experiments

- data taking completed for both experiments
- final stages of the (systematics) analysis

	data collection	statistical accuracy on muon lifetime	muon lifetime events	publication / status
MuLan	2004 (AK-3 target)	11 ppm	1.8 x 10^10	published, 2007: D.B.Chitwood et al, Phys. Rev. Lett. 99 , 032001 (2007)
MuLan	2006 (AK-3 target)	1.2 ppm	~ 10^12	final systematics analysis results presented in Moriond (March 2010) by D.M. Webber
MuLan	2007 (quartz target)	1.7 ppm	~ 10^12	
FAST	2006	15 ppm	10^10	published, 2007: A.Barczcyk et al, Phys. Lett. B 663, 172-180 (2008)
FAST	2007 (TDC problem solving)	-	3 x 10^10	te[illegible]al run : increase trigger rate / solve TDC-DAQ problems
FAST	2008 [illegible]	[illegible]	[illegible]	ongoing analysis

MuLan

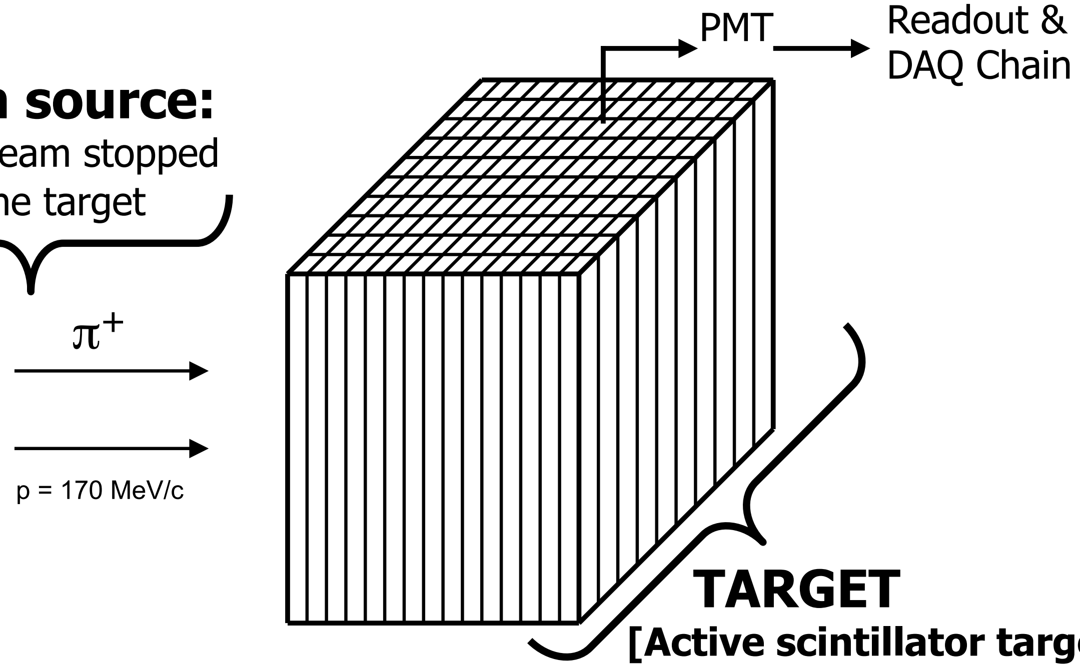
FAST

disclaimer :
my PhD thesis
- July 2007 -


Universite de Geneve - Switzerland
PSI - Switzerland
CERN - Switzerland
CIEMAT Madrid - Spain
FAST

FAST: Experimental concept

muon source:
DC π^+ beam stopped in the target



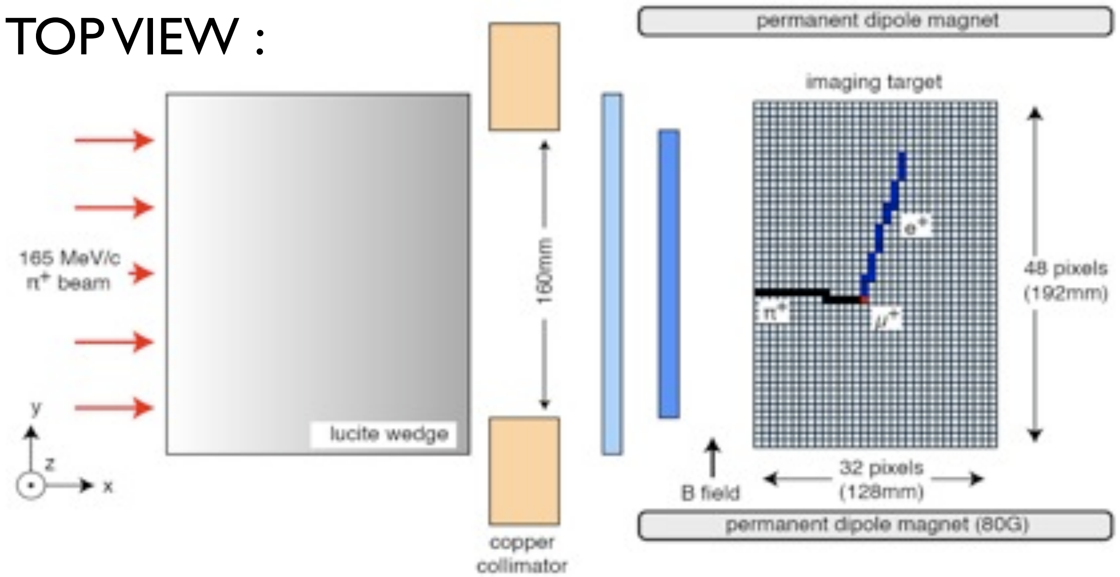
TARGET
[Active scintillator target]:
- stopping material for π^+ and μ^+
- detector for e^+

SIGNATURE FOR AN EVENT [$\pi \rightarrow \mu \rightarrow e$] :

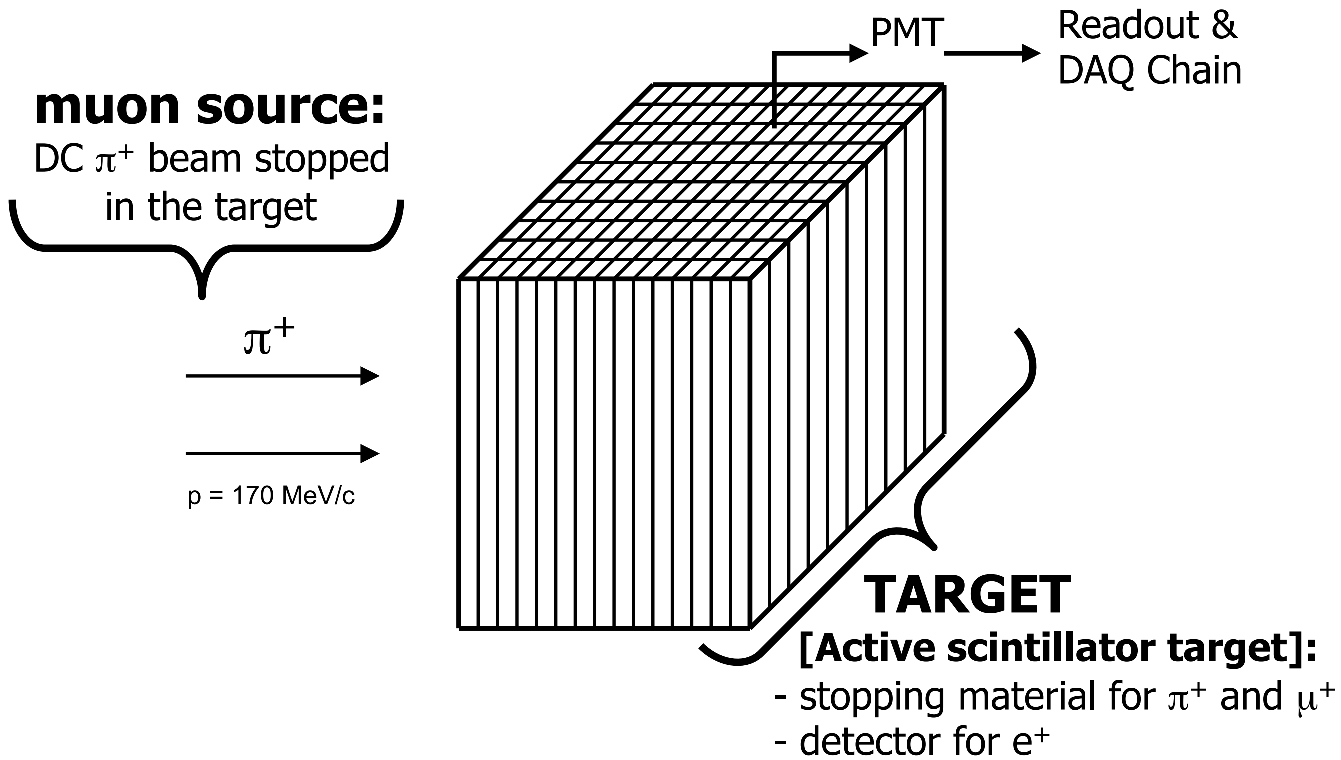
- $\pi^+ \rightarrow \mu^+ \; \nu_\mu \; (\tau_\pi \sim 26ns)$ $\quad E_\mu^{cin} \sim 4 \; MeV$, $\rho_\mu \sim 1.5 \; mm$
- $\mu^+ \rightarrow e^+ \; \nu_e \; \bar{\nu}_\mu \; (\tau_\mu \sim 2.2\mu s)$

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

TOP VIEW :



FAST: Experimental concept

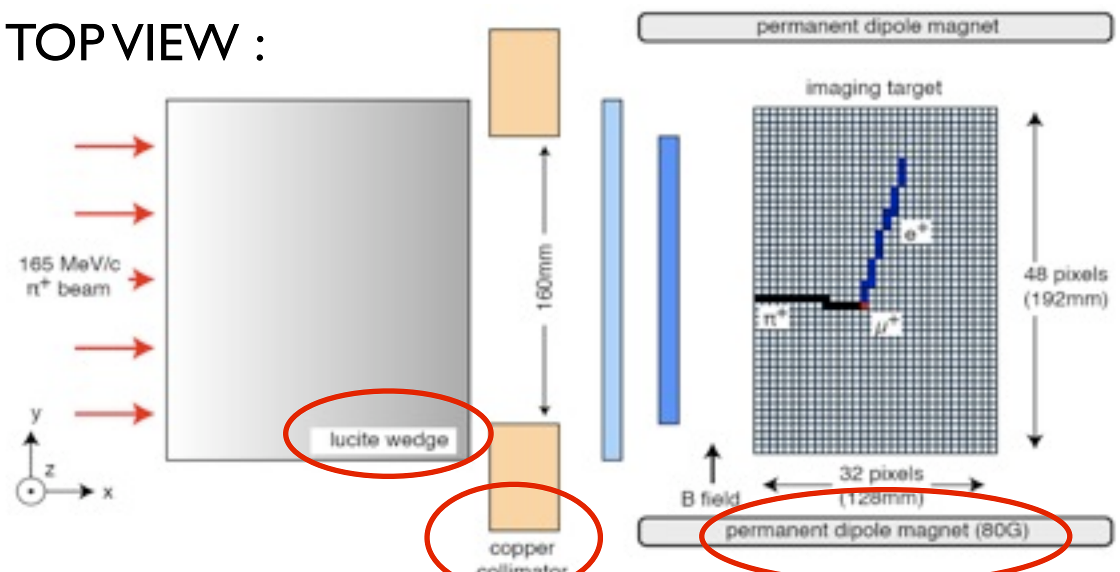


SIGNATURE FOR AN EVENT [$\pi \rightarrow \mu \rightarrow e$] :

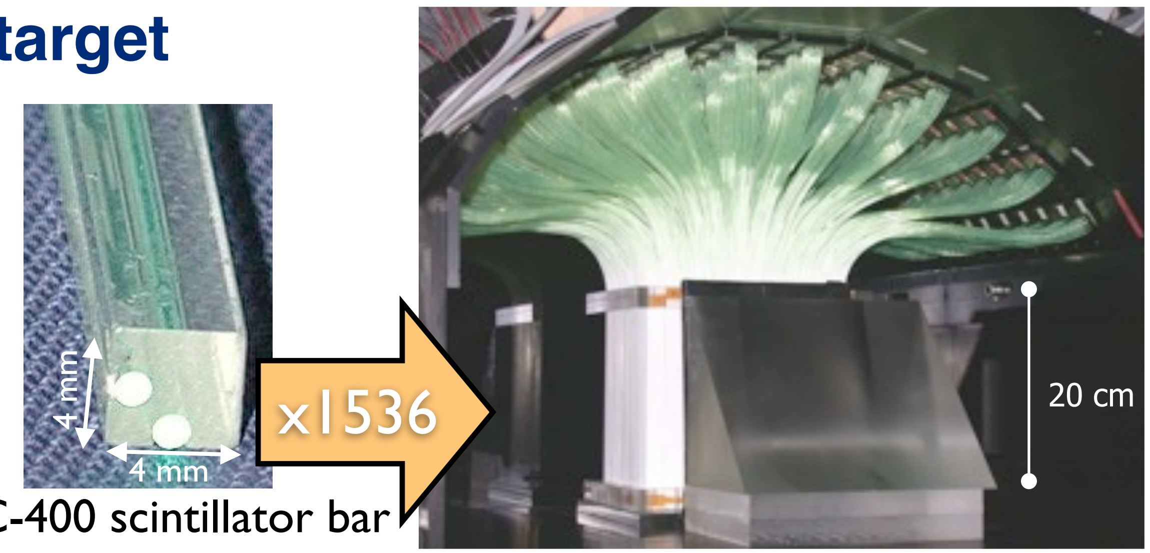
- $\pi^+ \rightarrow \mu^+ \, \nu_\mu \; (\tau_\pi \sim 26ns)$ $\quad E_\mu^{cin} \sim 4 \; MeV$, $\rho_\mu \sim 1.5 \; mm$
- $\mu^+ \rightarrow e^+ \, \nu_e \, \bar{\nu}_\mu \; (\tau_\mu \sim 2.2\mu s)$

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

TOP VIEW :



- **target**

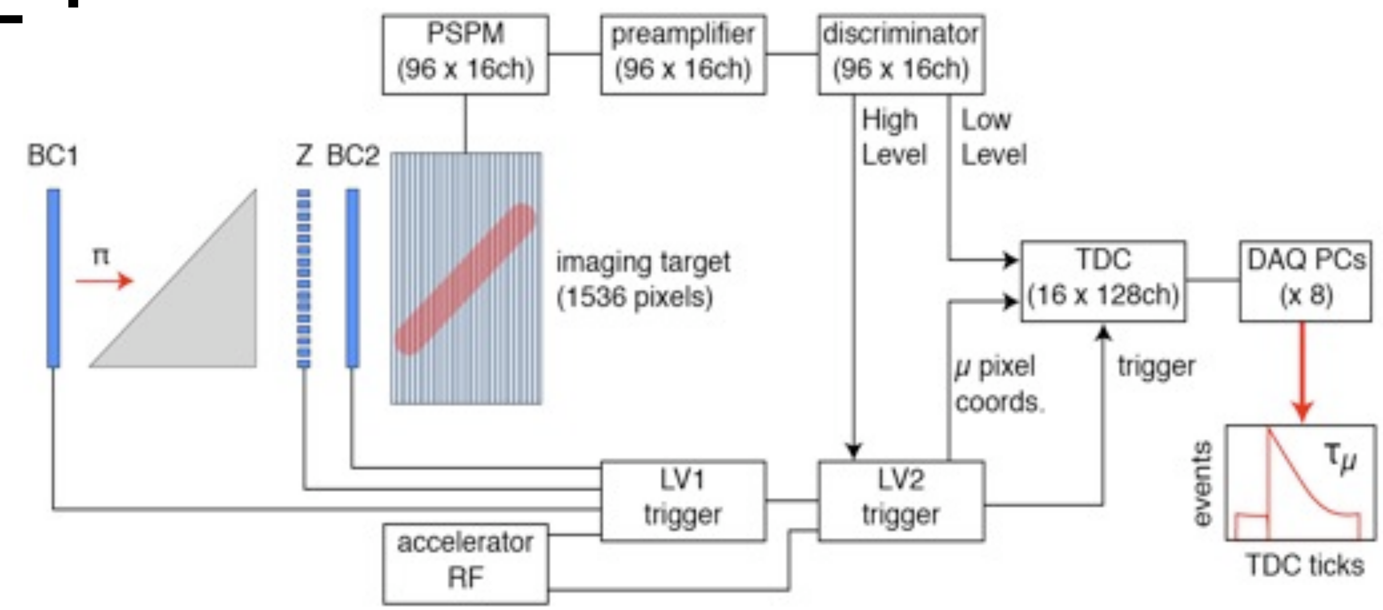


BC-400 scintillator bar

- lucite **wedge** + **collimator** => uniform distribution of stopping π's in the target
- π->μ => unpolarized muons <Sμ>=0
- to visibly enhance **residual μSR effects: B = 80 G** (with a permanent magnet)
- highly segmented target, **tracking capabilities**
- register **several decays at the same time** in different regions of the target
- **beam :**
DC π^+ beam (piM1); 165 MeV/c; 56% purity

FAST: Experimental concept

readout / trigger / DAQ scheme



- target readout :
  - **PMTs (x96)** [Hamamatsu]
  - **Preamps (x96)** [custom]
  - **Dual thr. discr.(x96)** [custom]

- DAQ core :
  TDC's (x16) [CAEN V767]
  - time stamp of all LL channels (i.e. **time and position information**)
  - external trigger (t=0)
  - circular hit buffer => measurement time window ~ **[-8 , 22] μs wrt trigger**

- 2-levels trigger :
  - **LV1** : selects beam pions => t=0 ref.
  - **LV2** : identifies π -> μ ; identify the region required to measure the decay
  - **LV2 trigger rate ~ 100 kHz**

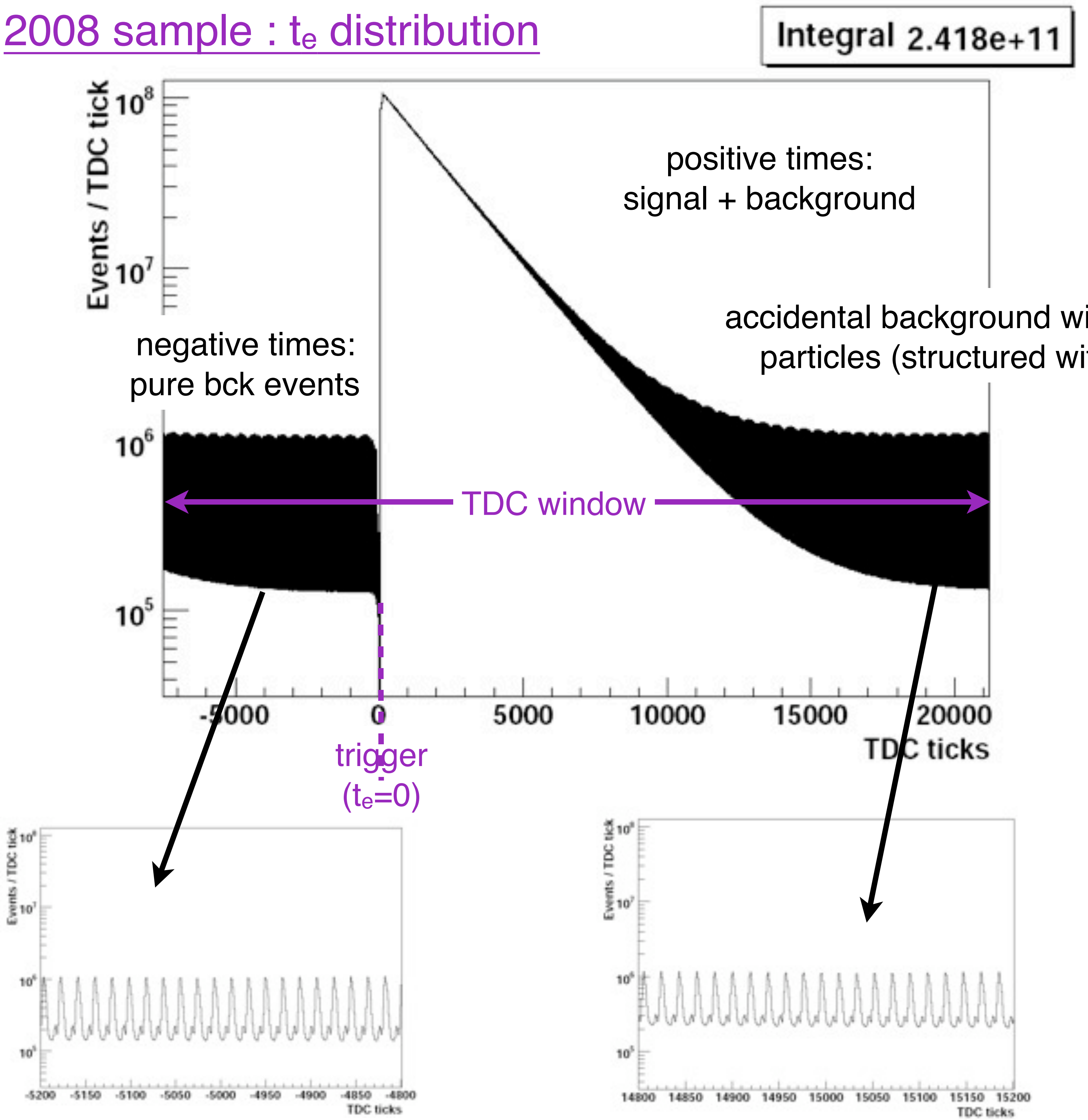
DAQ & analysis:
from raw data to histograms

- huge data bandwidth ~ **160 MB/s** [~ 14 TB/day]
  => **all data fully analyzed online in real time** (PC farm)
- information stored on disk :
  (a) **histograms [O(3000)]**
  with fine time granularity [few mins]
  (b) **~ 1% of raw data** [for offline checks]

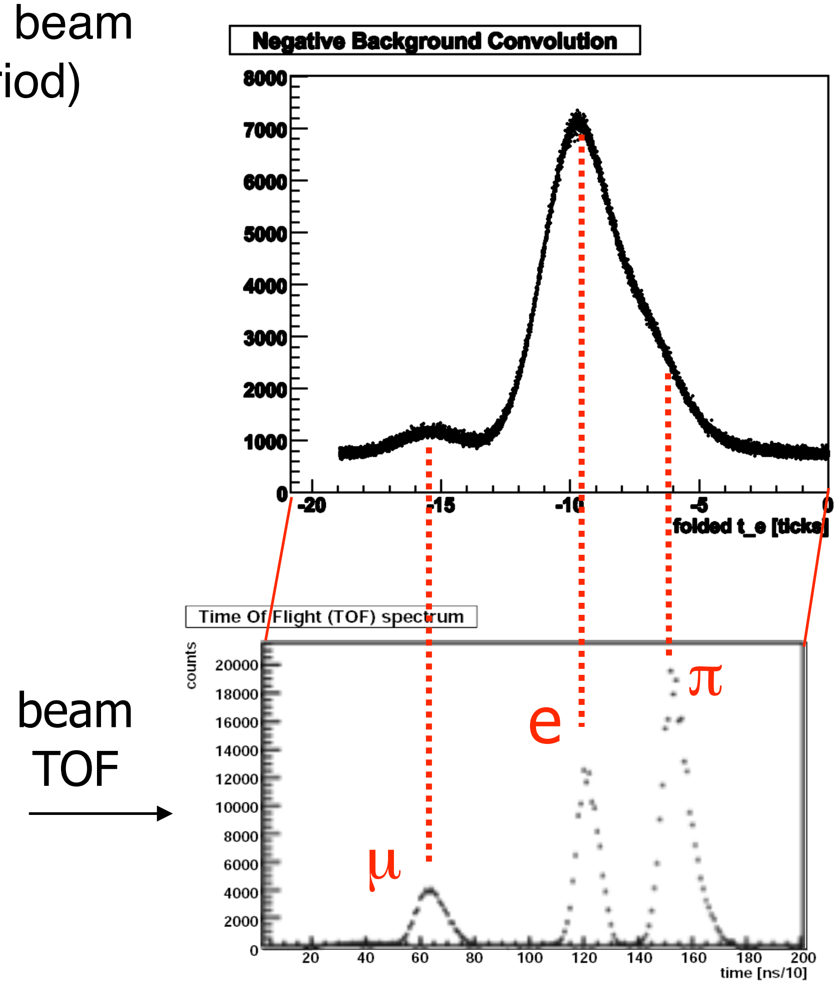
- **the bulk of RAW DATA is NOT STORED ON DISK**

FAST: muon lifetime histogram

2008 sample : t_e distribution



BACKGROUND CONVOLUTION (T_RF)

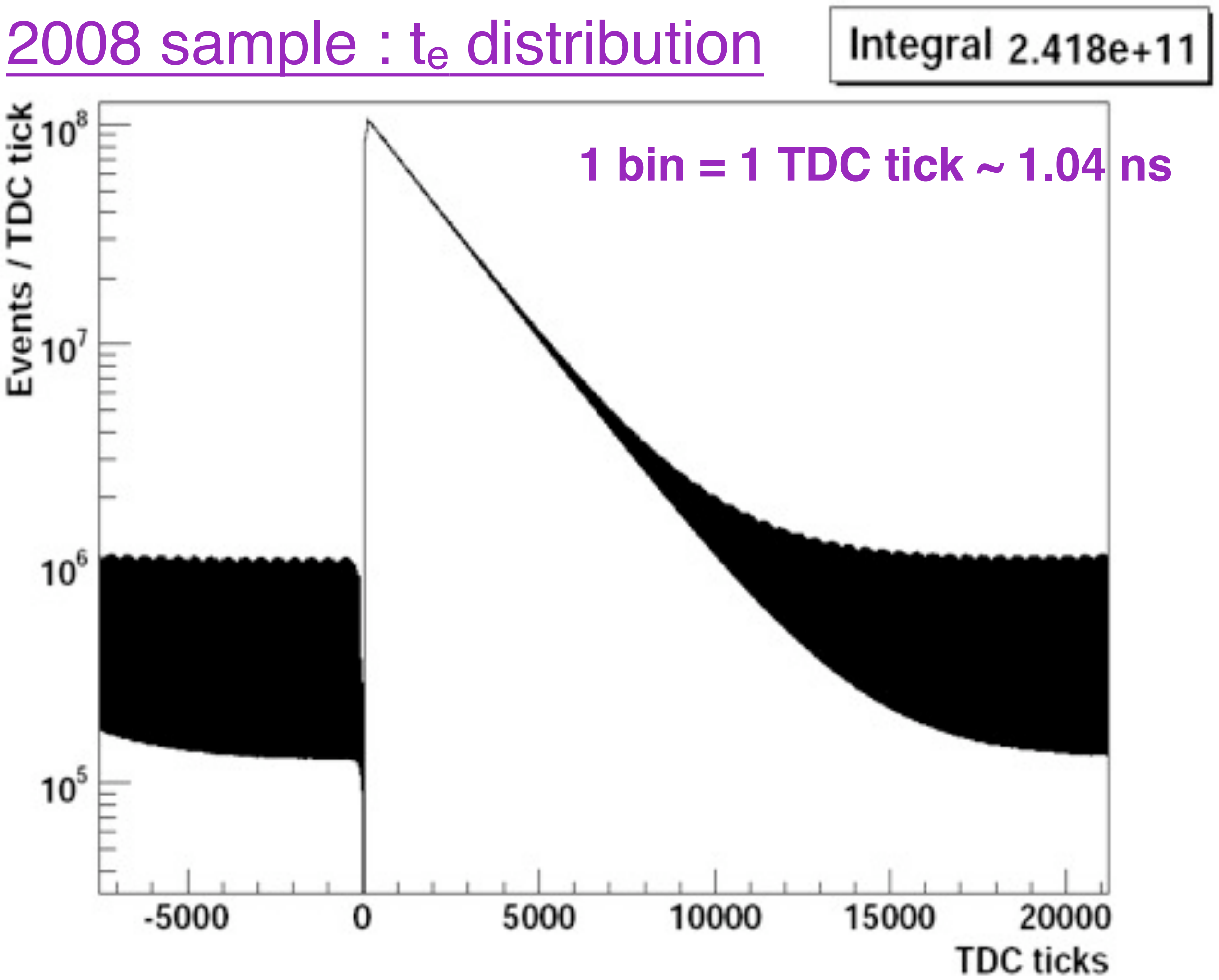


Periodic background shape:
- exactly reproduces the beam content
- dominated by positrons (e)

1 TDC tick ~ 1.04 ns (30 MHz TDC clock / 32 DLL divisions)

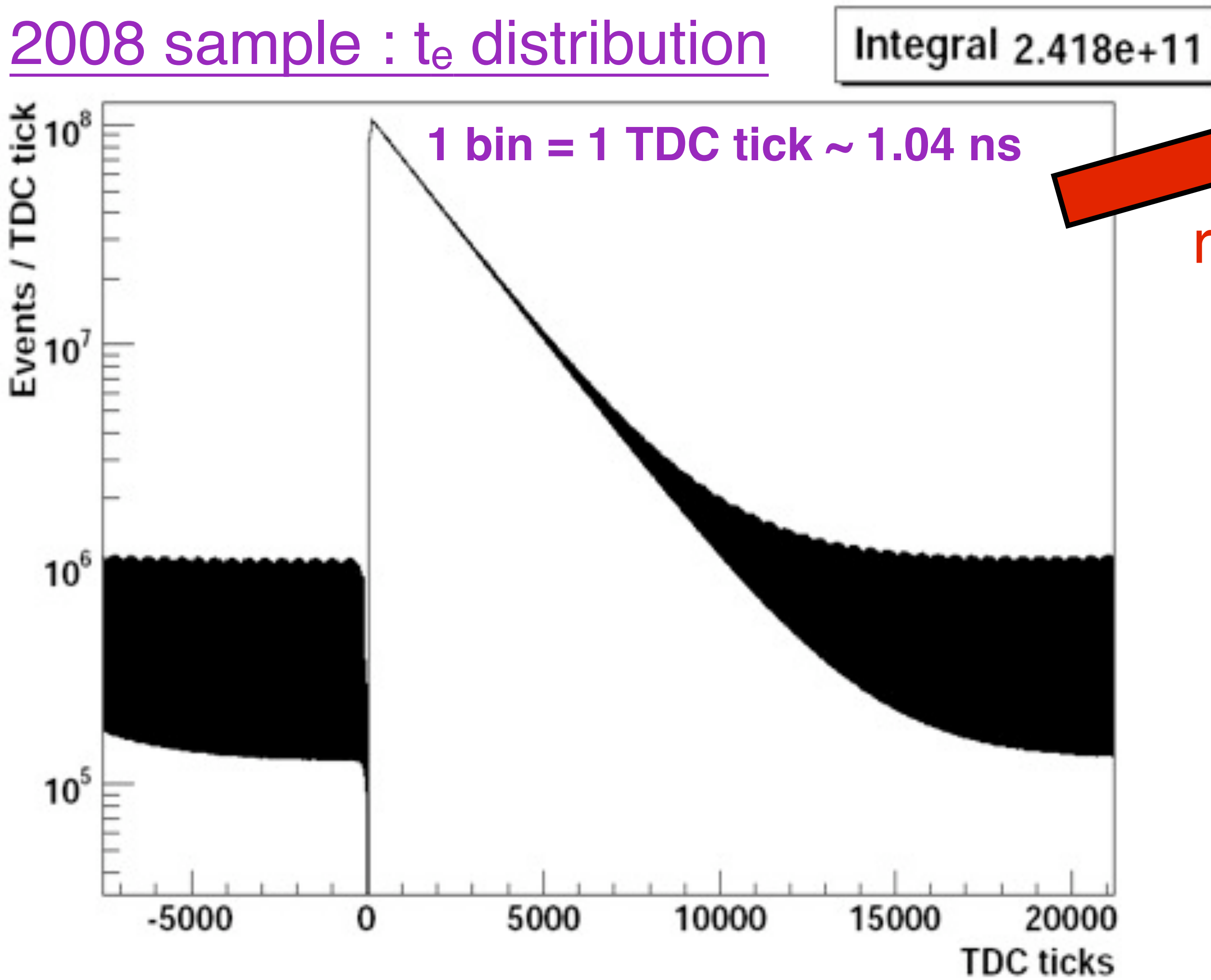
FAST: Fit strategy

2008 sample : t_e distribution

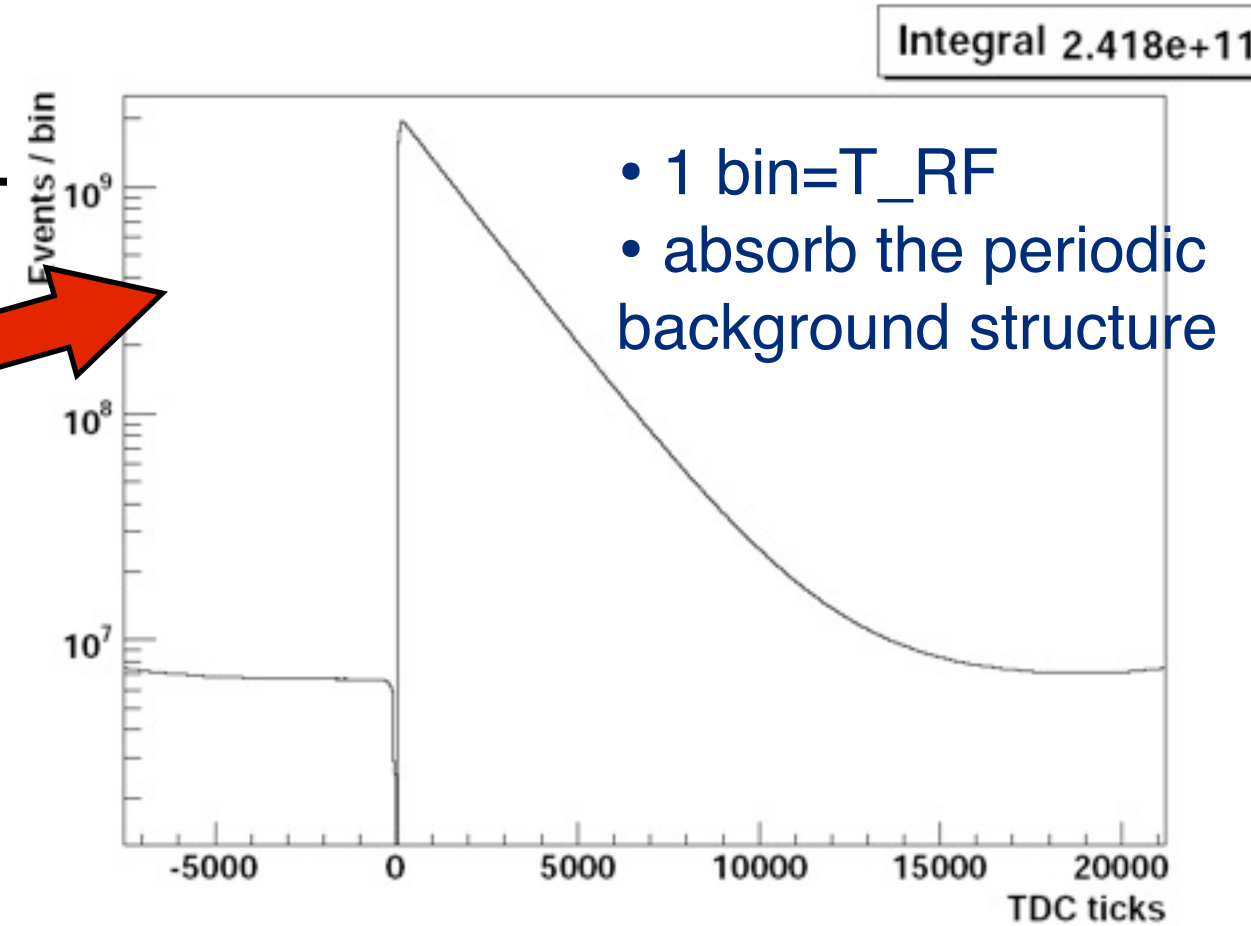


FAST: Fit strategy

2008 sample : t_e distribution



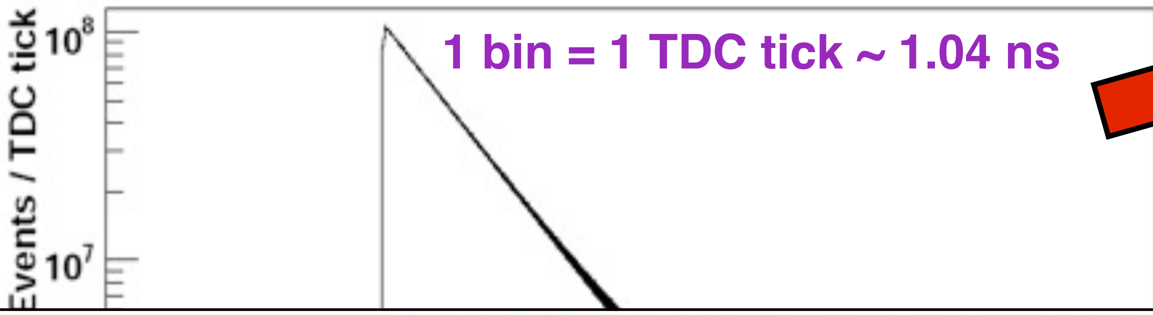
rebin



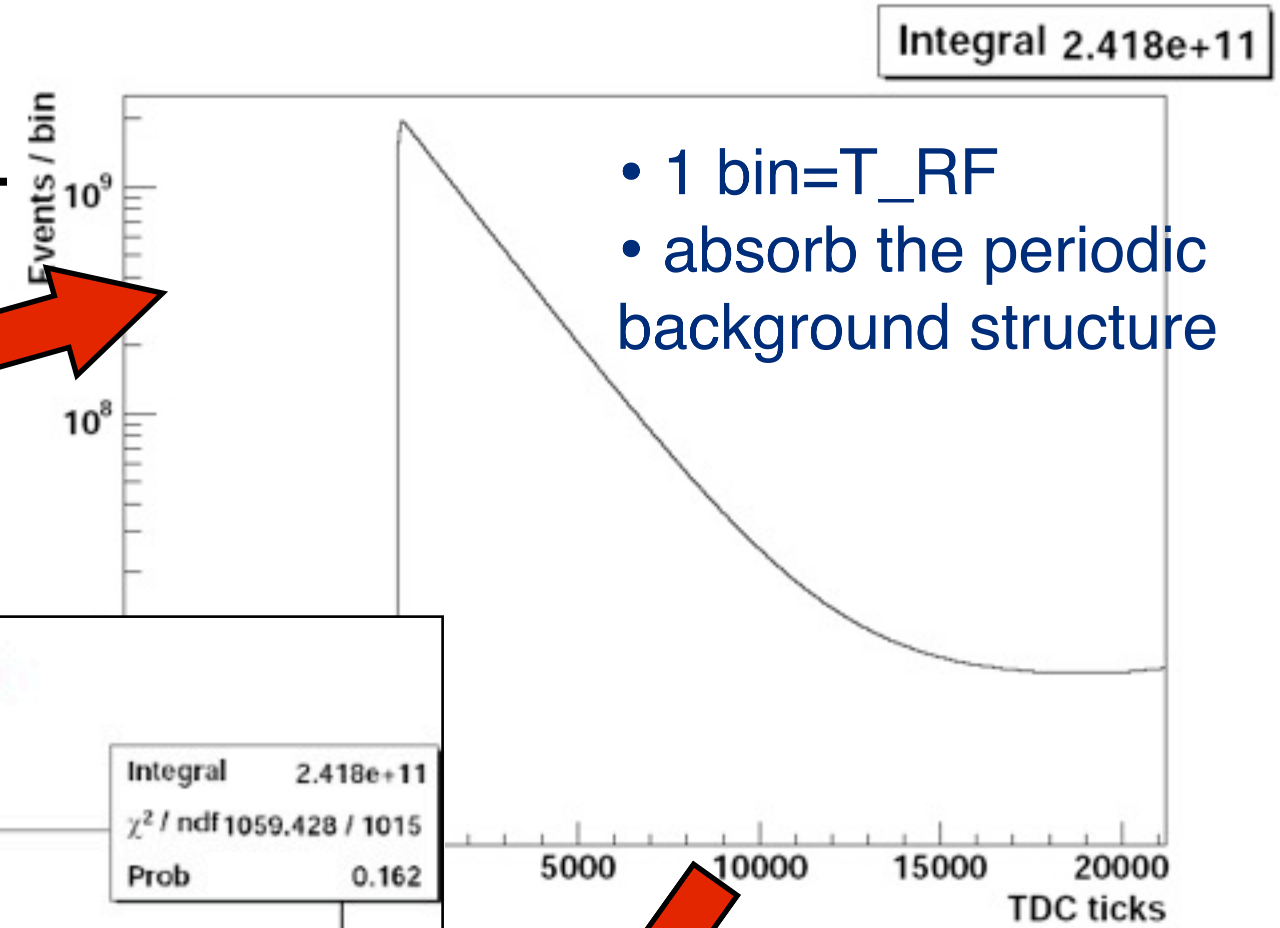
- 1 bin=T_RF
- absorb the periodic background structure

FAST: Fit strategy

2008 sample : t_e distribution



rebin

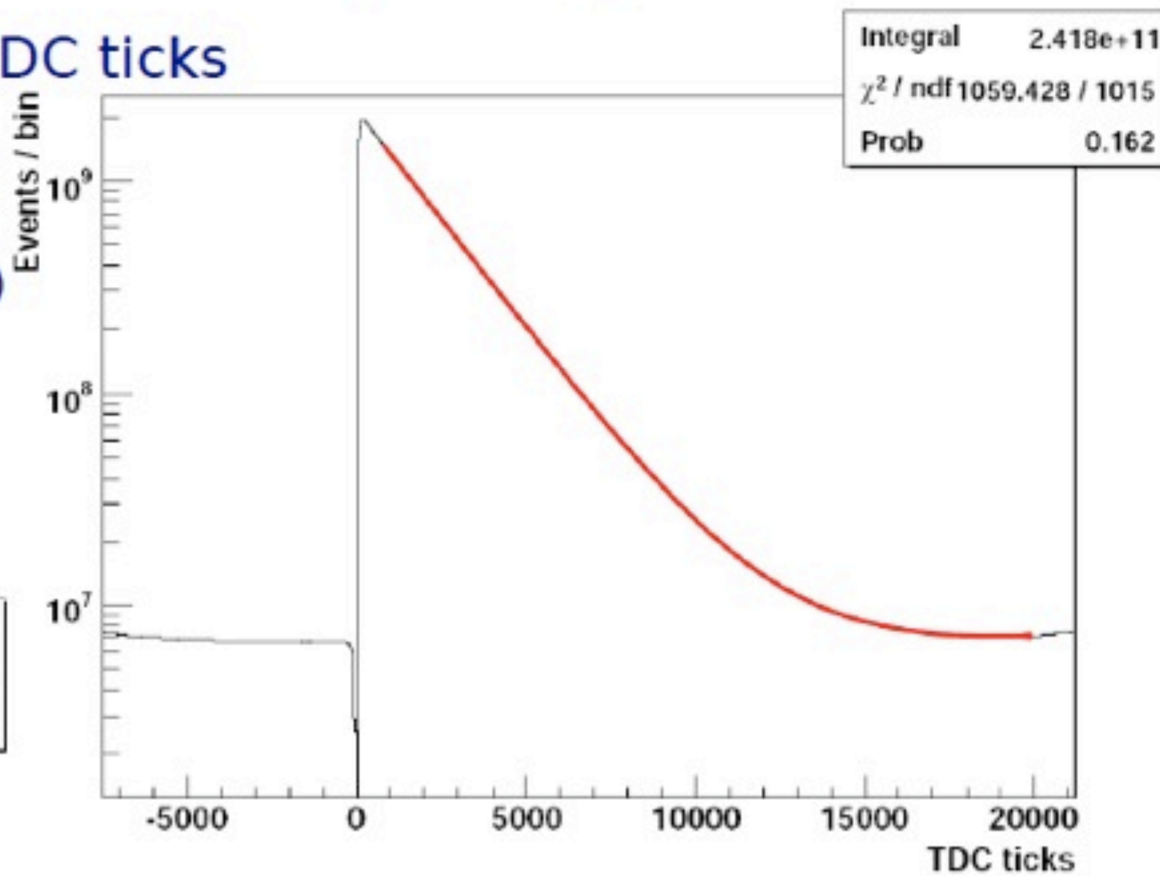


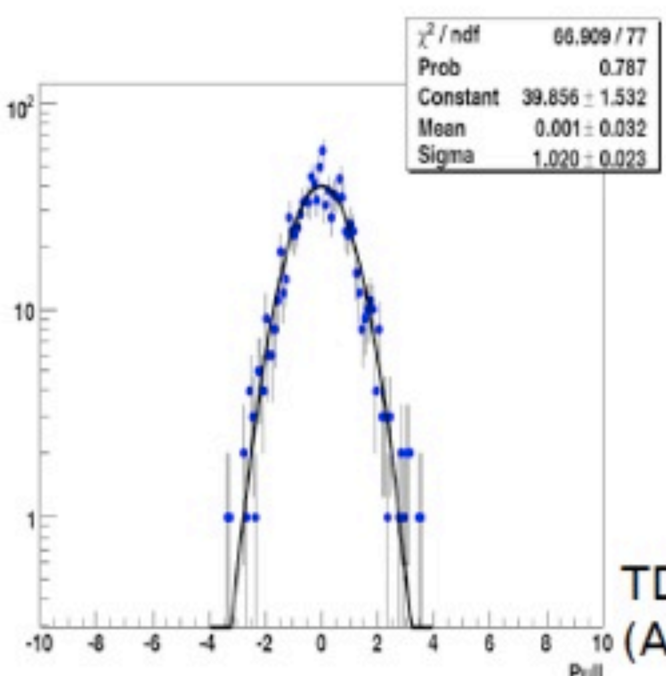
- 1 bin=T_RF
- absorb the periodic background structure

fit

2008 Preliminary Analysis

- Fit range 680-20000 TDC ticks
- $\sigma(\tau_\mu)$ = 3.2 ppm (stat.)
- χ^2/dof=1.04 (Prob=0.16)
- Pulls follow Gaussian distribution of width 1





$$Data(t_e) = f_{TDC}(t_e)\,(\,A\,e^{-t_e/\tau_\mu} + B\,e^{t_e/\tau_\mu} + C\,)$$

- TDC small tick non-linearity (Amplitude ~0.1%)
- μ-decay signal
- edge effect @ t↑
- flat background (~4% in fit region)

J.Casaus - presented at the PSI USER MEETING **BV40 (Feb 2009)**

FAST: Systematics

from 2006 data sample (10^{10} evts)

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

- statistics limited measurement
- now obsolete

Detailed table of the systematic uncertainties on 2008/2009 sample (4 x 10^{11}) : **coming soon**

Main checks / systematics addressed:
- residual frequencies (Fourier transform of the residuals)
- μSR
- stability vs calendar time (τ_μ / T_{RF})
- electron candidate definition
- event selection
- trigger conditions
- fit method
- fit stability vs starting/stopping point of the fit interval
  i.e. max allowed fit region => highest possible statistical yield
- target uniformity (high segmentation of the target) : τ_μ vs PSPM's / τ_μ vs TDC / τ_μ vs X_π / τ_μ vs Y_π...

FAST: Systematics

Detailed table of the systematic uncertainties on 2008/2009 sample (4 x 10^{11}) : **coming soon**

from 2006 data sample (10^{10} evts)

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

- statistics limited measurement
- now obsolete

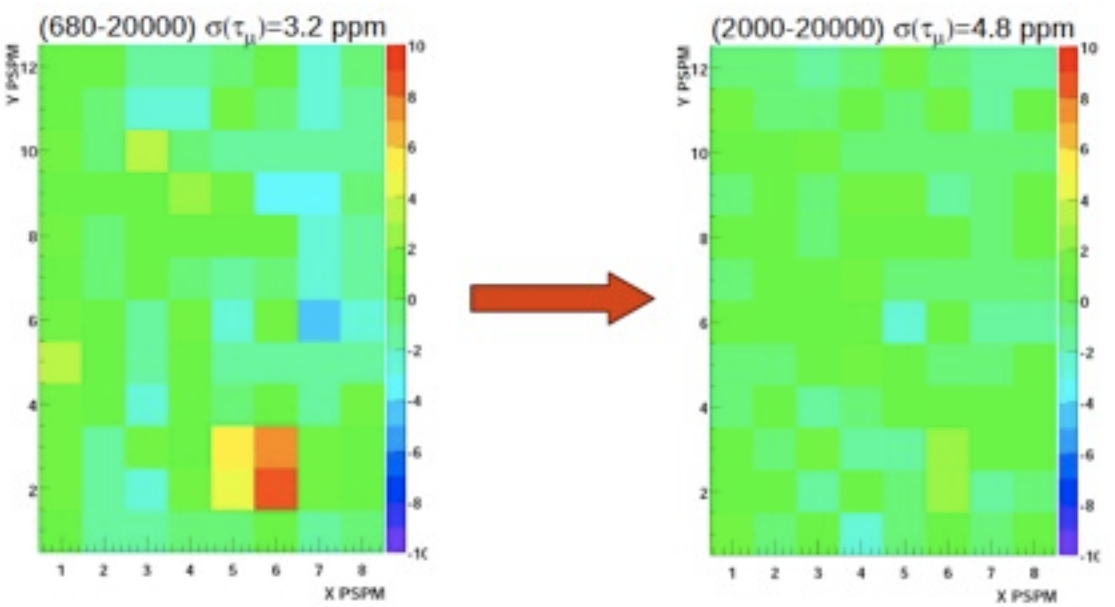
Main systematics topics addressed:

- residual frequencies (Fourier transform of the residuals)
- μSR
- stability vs calendar time (τ_μ / T_{RF})
- electron candidate definition
- event selection
- trigger conditions
- fit method
- fit stability vs starting/stopping point of the fit interval
  i.e. max allowed fit region => highest possible statistical yield
- target uniformity (high segmentation of the target) : τ_μ vs PSPM's / τ_μ vs TDC / τ_μ vs X_π / τ_μ vs Y_π...

Dominant contribution to systematics
(starting from ~ 3ppm stat. accuracy)

- **due to PSPM AFTERPULSES** (from 2008 data sample)
- AP : can spoil the electron candidate => **time dependent loss of efficiency in el_ID** (more pronounced at early times)
- Each PSPM has its own characteristics AP curve (HV dep.)

- WORKS IN PROGRESS : Effect of the AP on τμ (PSPM basis)



J.Casaus - presented at the PSI USER MEETING
BV40 (Feb 2009)

FAST Status : Summary

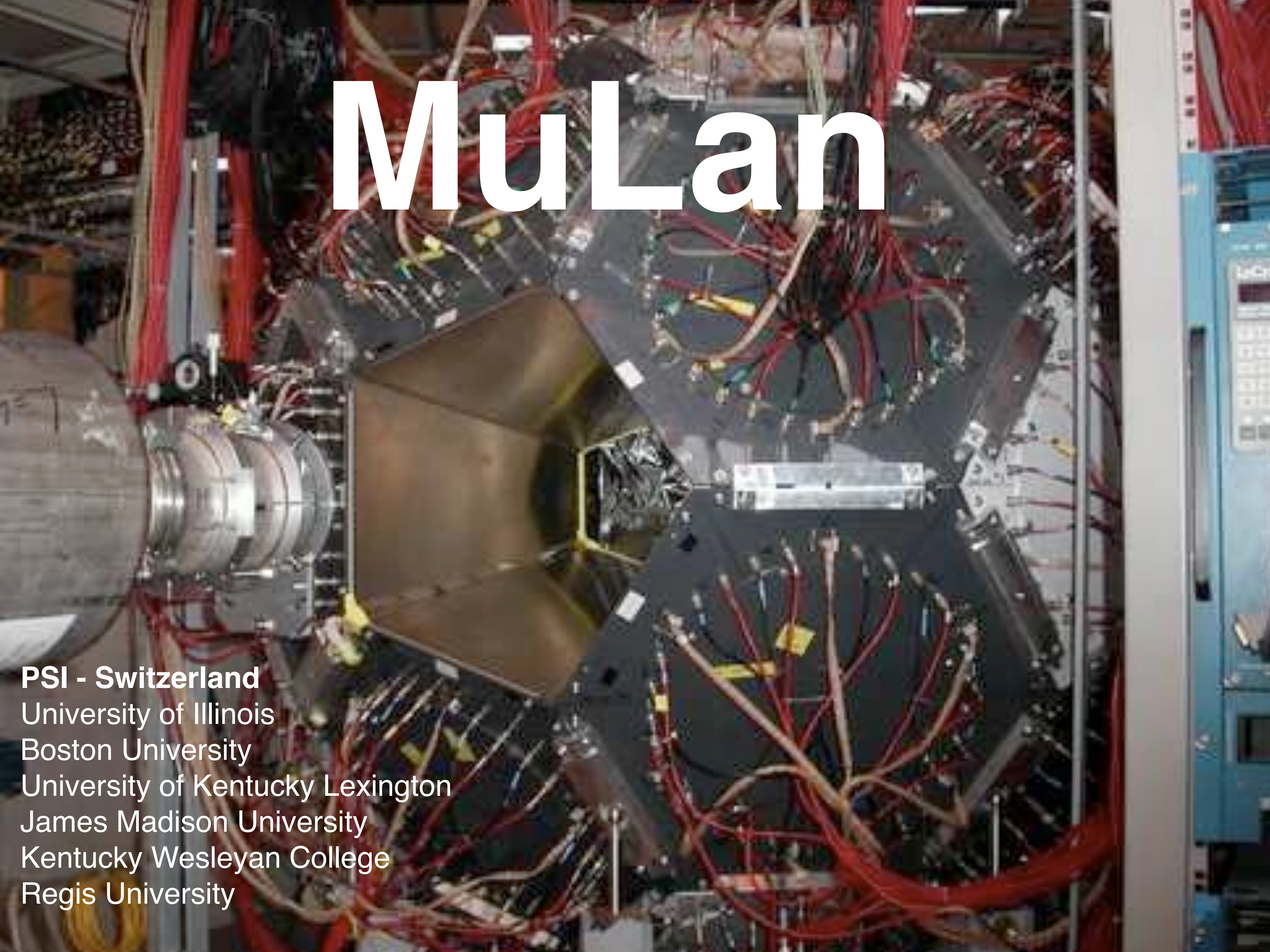
- **Data taking: completed [2008/2009]**
  => 4.2 x 10^{11} muon decay evts
  => ~ 2.4 ppm measuerement on $\tau\mu$

- **Analysis in a mature state**
  - fitting procedure and method well established
  - systematics under study, mainly concerning the afterpulsing effect on the PSPMs
    - 2008 sample => dominant systematic comes from AP
    - 2009 data taking:
      - few tubes strongly affected by AP: replaced
      - new HV tuning
      - 2009A : HV2009
      - 2009B : HV2008 (to check consistency with 2008 data set)

      - New added online histograms (>2700 $\tau\mu$ histos!!!) to extract precision characterization of the AP on PSPM basis

      - The effect of AP can be directly calibrated from the data
        (e.g. $\tau\mu$ vs PSPM : nominal electron time window , x2 , x3 , x4)
      - 2009B sample can be used for 2008 sample

- **First final results expected in a few months from now !**

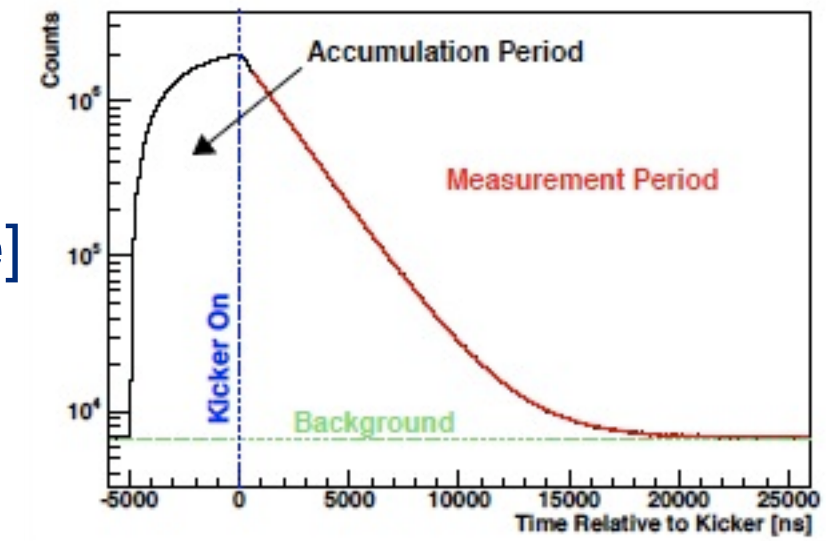


MuLan

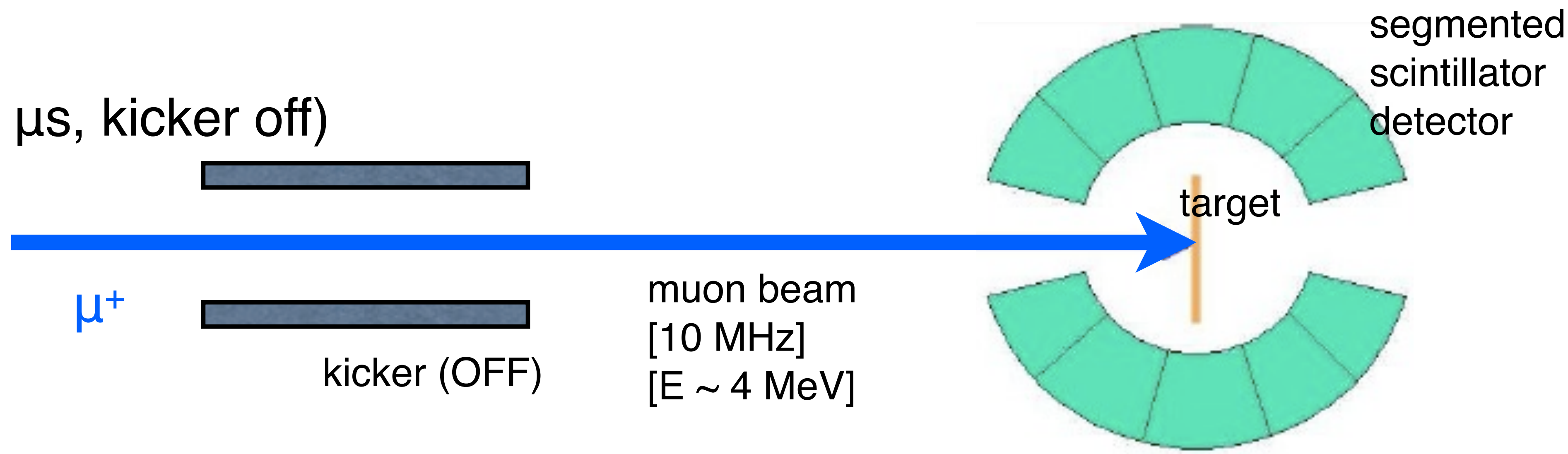
PSI - Switzerland
University of Illinois
Boston University
University of Kentucky Lexington
James Madison University
Kentucky Wesleyan College
Regis University

MuLan: Experimental concept

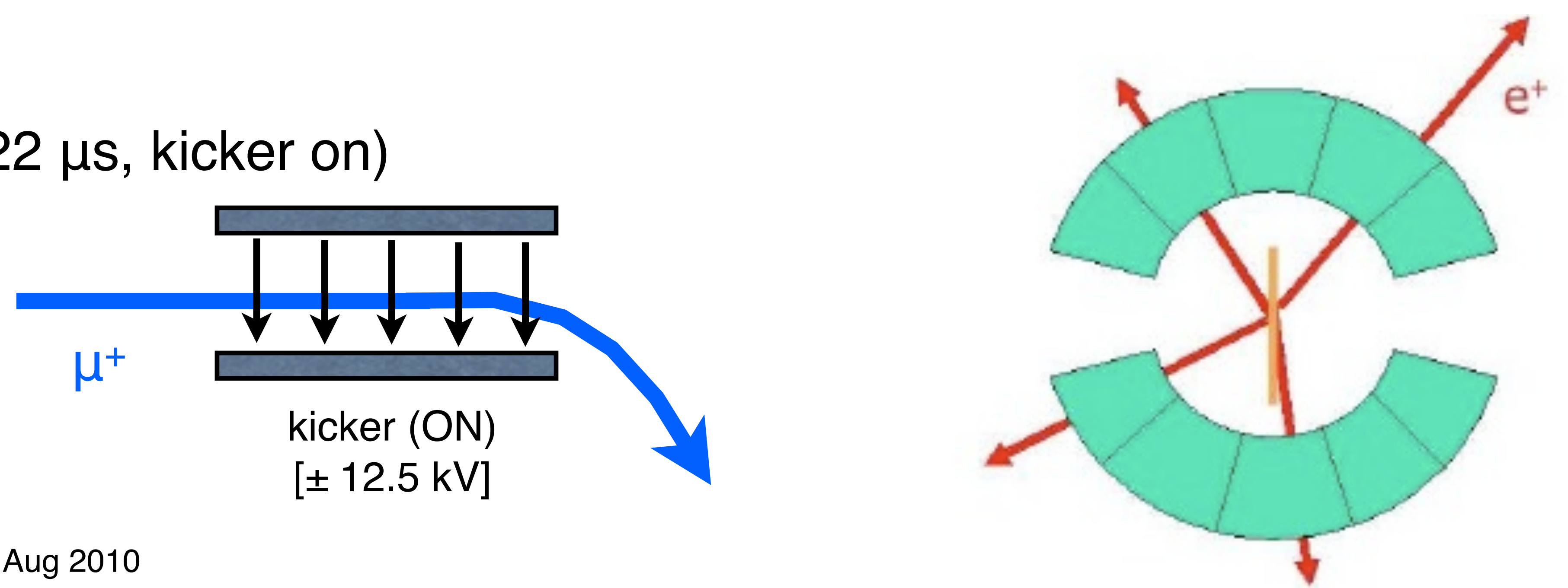
- low energy muon beam - 100% polarized muons [piE3 beamline]
- time-structured beam (with electrostatic kicker)
- muon stopping target
  including magnetic field B (e.g. ferromagnetic target)
- symmetric, segmented scintillator detector



- Accumulation period (~ 5 μs, kicker off)



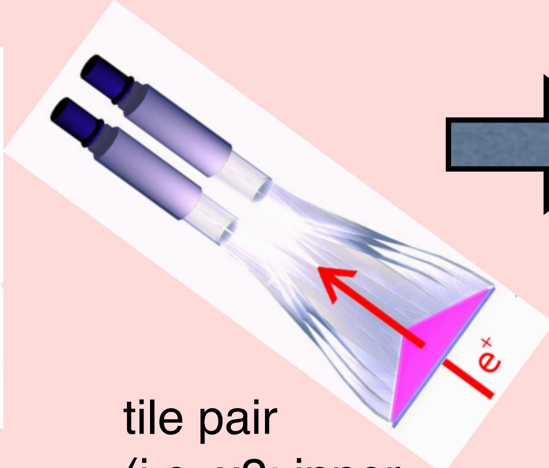
- Measurement period (~ 22 μs, kicker on)



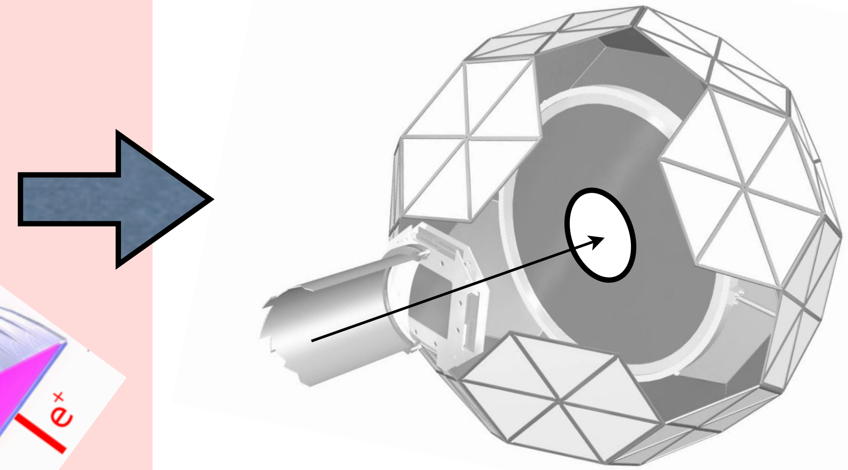
MuLan: Detector elements

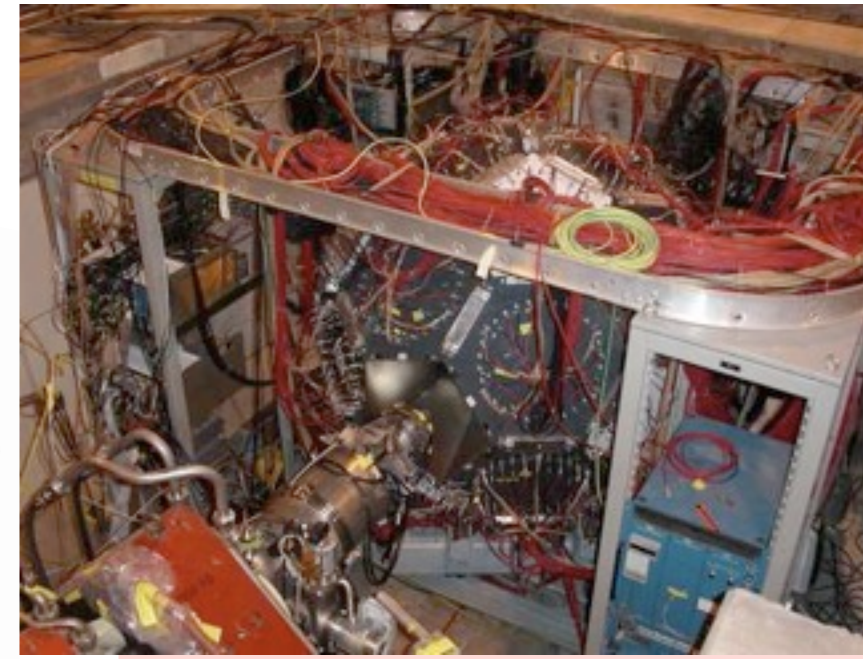
e+ DETECTOR UNIT :

triangular scintillator
+ PMT



tile pair
(i.e. x2: inner
and outer tile)





- **170 tile pairs**
- **340 channels**

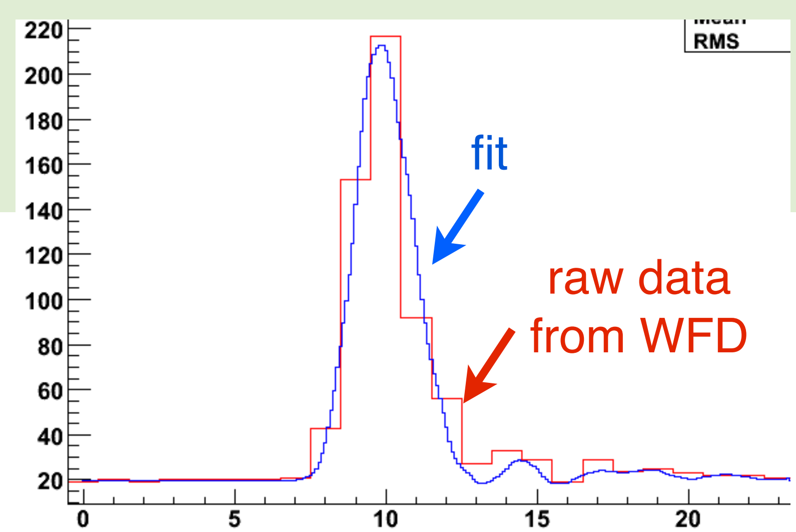
TARGET :

- **Arnokrome III (AK-3) :**
  - ferromagnetic alloy
  - Binternal ~ 0.5 T => fast Sμ precession (f ~ 100 MHz)
  - dephase the μ spin during the accumulation period
  - AK-3 : known "polarization-destroying" material
  - 2004 / **2006** data taking

- **Quartz crystal disk :**
  - with an array of permanent magnets (~130 G)
  - 90% of muons form muonium (μ^+e^-)
    very high precession frequency ~ 180 MHz
    => no contribution to μSR
  - 10% free muons
    precession frequency ~ 1.8 MHz
    => magnetic field to visibly precess their spins
  - **2007** data taking

READOUT :

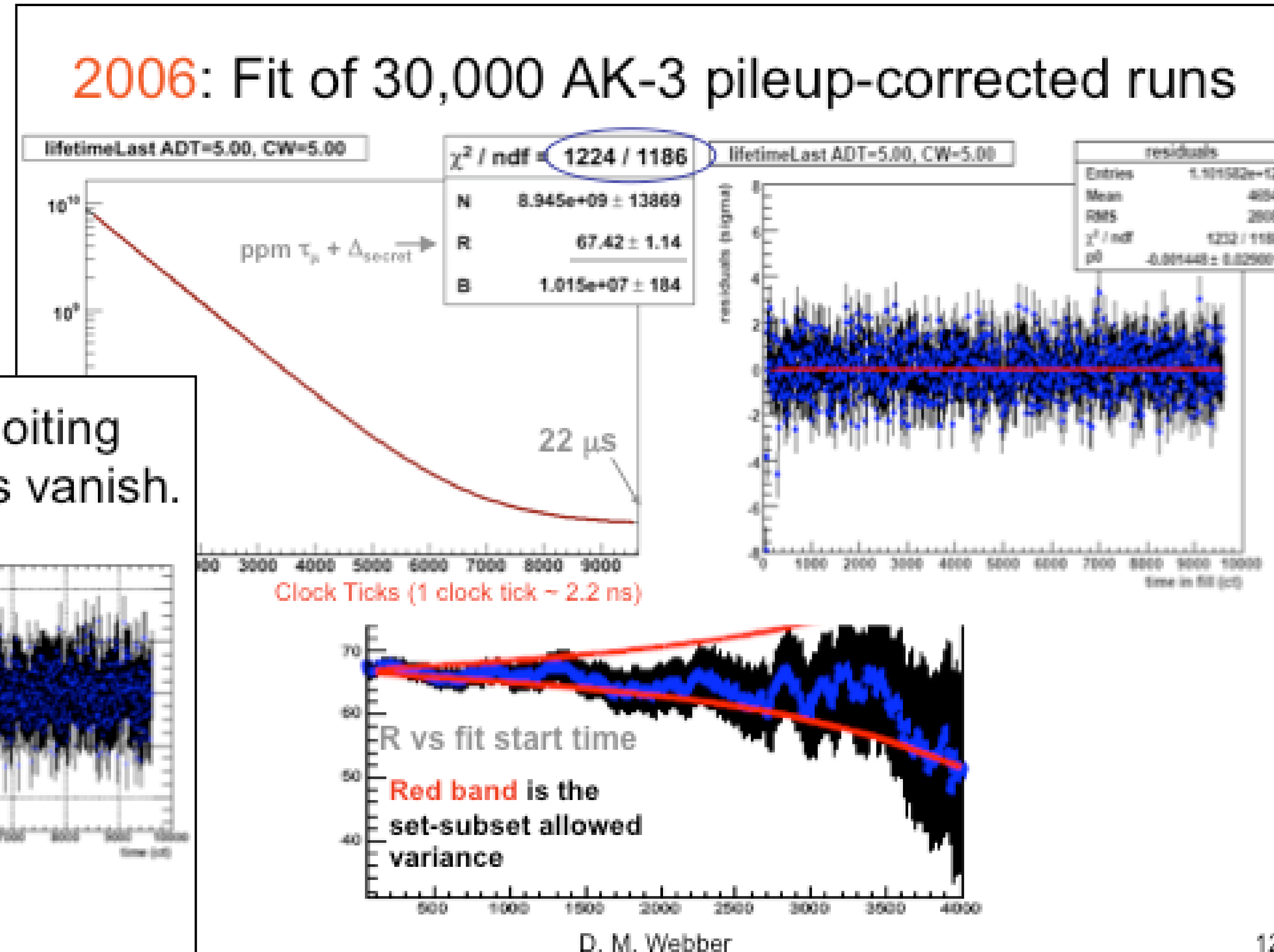
- **wave form digitizer (WFD)** [> 2004]
- 450 MHz - 8bit - 24 samples (~ 53 ns)
- each channel is digitized
  => pulse **time and energy information**
- pulse -finding and fitting algorithm
- coincidence formed for the 2 scintillators of the same tile

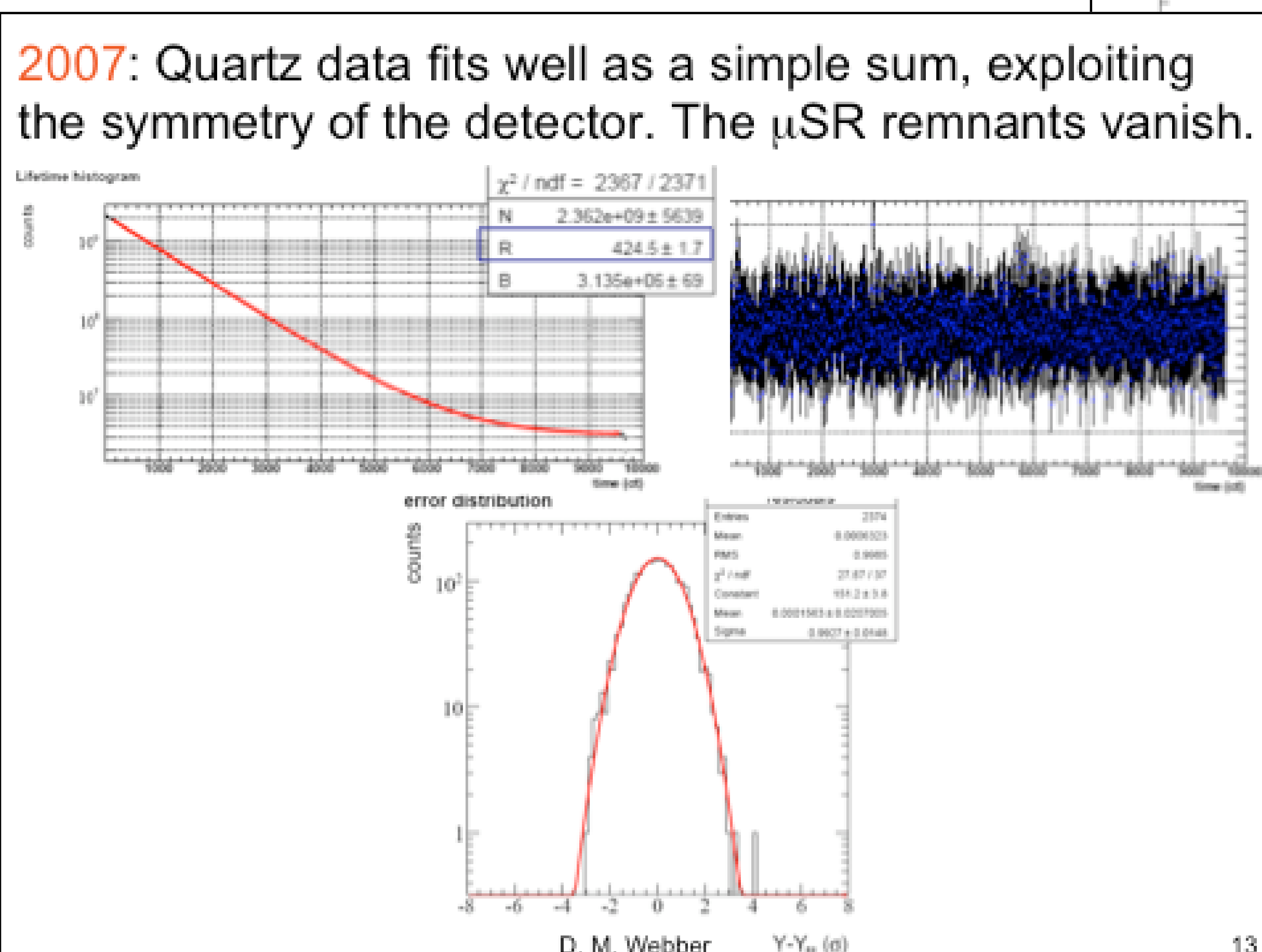


MuLan: Analysis strategy

- all channels digitized
- coincidence formed between inner and outer tiles of each pair
- coincidence times histogrammed
- histograms corrected for pileup
  [see next slide]

- fitting (exponential + const bkg)





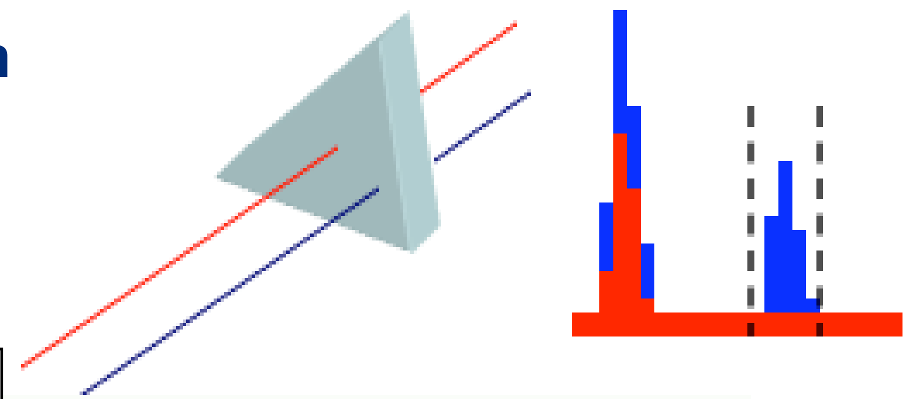
from **D.M. Webber - Rencontres de Moriond (March 2010)**

MuLan: pileup correction

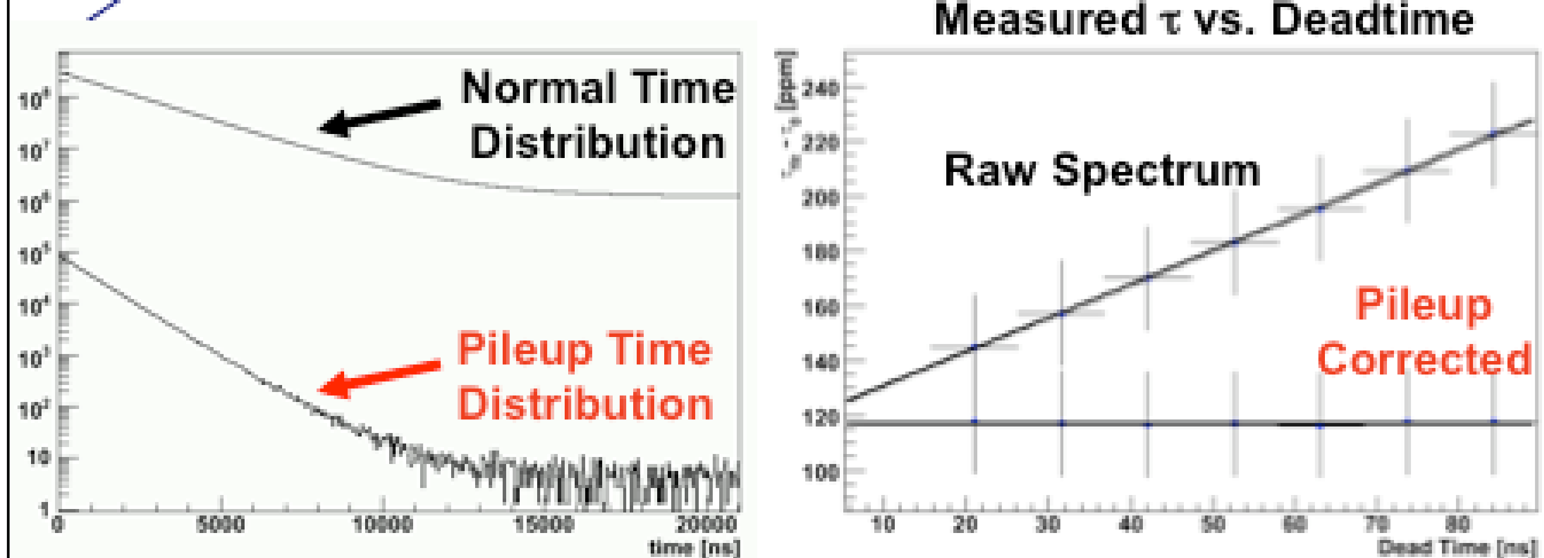
- most significant **pileup effect : PMT deadtime** (~ 12 ns) [probability ~ 5 x 10^{-4}]
- time structured **loss of events** => potential syst.
- left uncorrected, it would result in a shift in lifetime ~ 100 ppm
- should be included in the fit:
  - 1st order : $N_2\ e^{-2t/\tau}$
  - 2nd order : $N_3\ e^{-3t/\tau}$ ...

  "expensive" fit option-
  significant reduction in τ precision
- strategy : **Apply a statistical correction for pileup (added to lifetime hist.)**
- works in progress ...

Leading order pileup



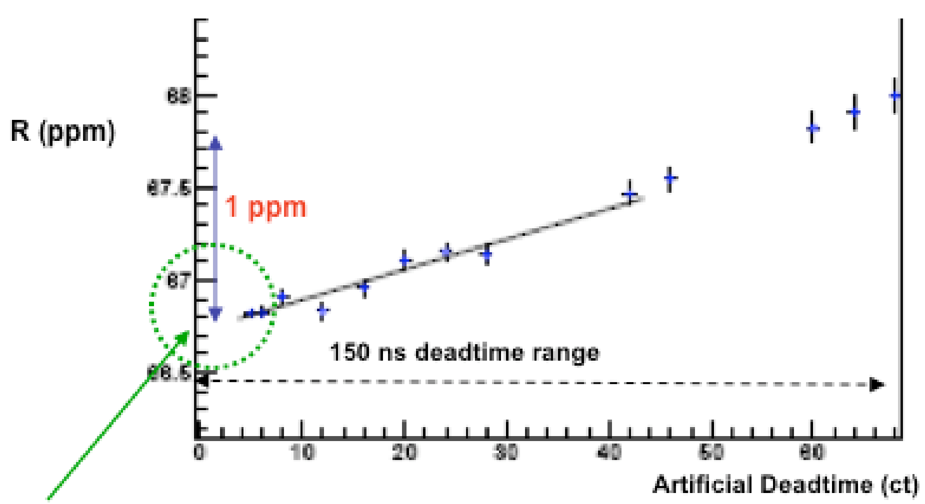
- Same probability
- Statistically reconstruct pileup time distribution
- Fit corrected distribution



D. M. Webber 9

Lifetime vs artificially imposed deadtime window is an important diagnostic

- A slight slope exists, which we continue to investigate



Extrapolation to 0 deadtime should be correct answer and our indications are that this extrapolation is right

(Work in progress) Pileup Correction Uncertainty: 0.15—0.3 ppm

from **D.M. Webber - Rencontres de Moriond (March 2010)**

MuLan: Summary of systematics

Preliminary upper bounds on systematic uncertainties (arXiv:1006.3982v1 - Jun2010)

Effect	Size (ppm) 2006	2007
Kicker stability	0.22	0.07
Spin precession	n/a	0.20
Clock calibration	0.03	
Errant muon stops	0.10	
Gain stability vs. time	0.70	
Gain stability vs. Δt	0.27	
Timing stability vs. time	0.09	
Timing stability vs. Δt	0.08	
Electronics stability vs. time	0.26	
Pileup correction	0.20	
Total systematic	0.85	
Statistical uncertainty	1.18	1.7
Total uncertainty	1.3	

time = time in measurement period
Δt = time after a prior pulse

from **D.M. Webber - Rencontres de Moriond (March 2010)**

MuLan Status : Summary

- **Data taking: completed [2006 / 2007]**
  => O(2 x 10^{12}) muon decay evts
  => ~ 1 ppm measuerement on $\tau\mu$

- two different targets [different behavior of μSR]

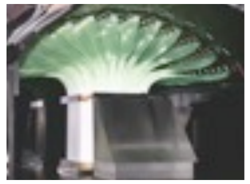
- **Analysis in a very mature state**
  finalizing the systematics study

- **Preliminary results presented at "Recontres de Moriond" (D.Webber) - March 2010**

- **First final results expected very soon.**

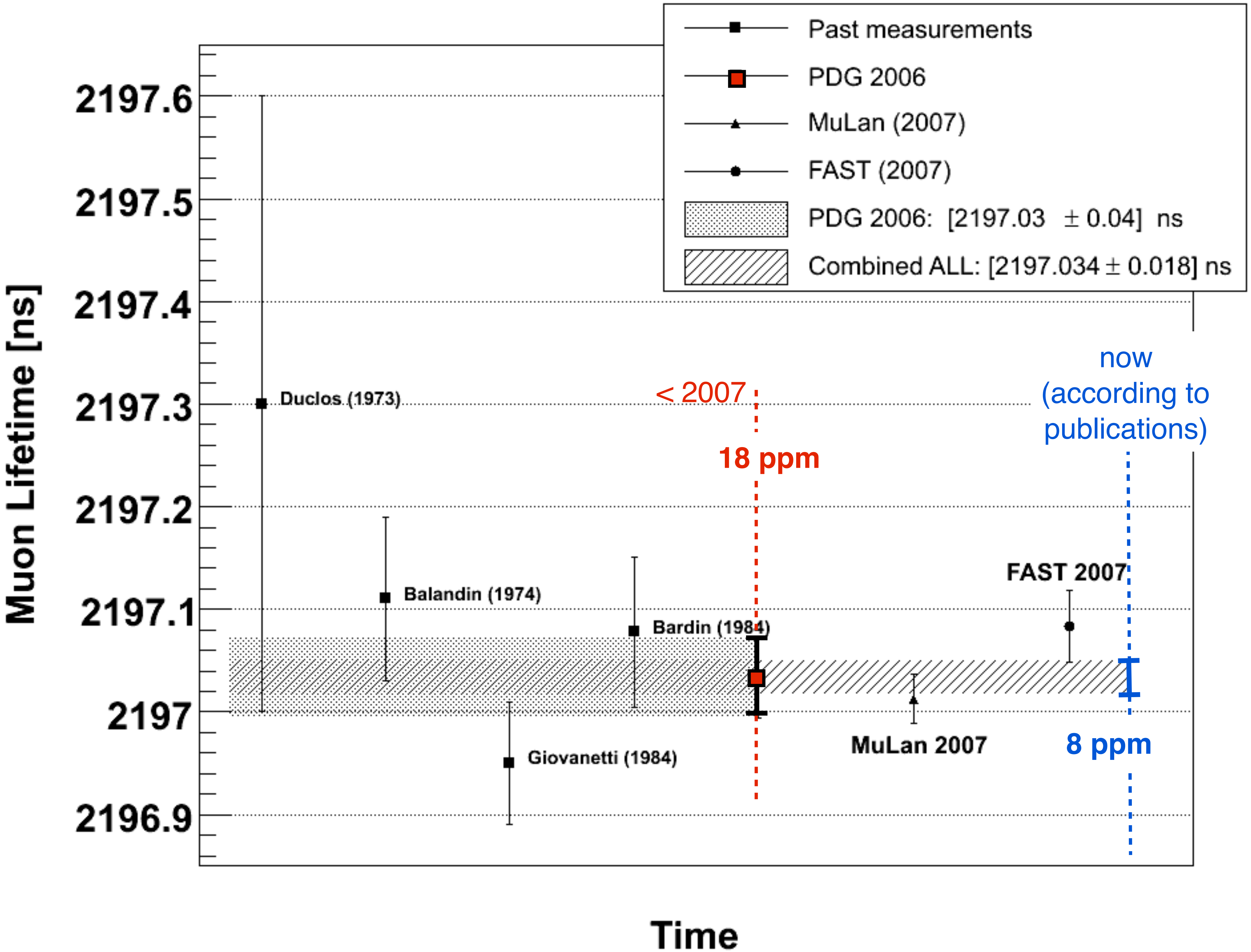
FAST & MuLan : Two different experiments...

Some of the most striking differences (far from being a complete list) :

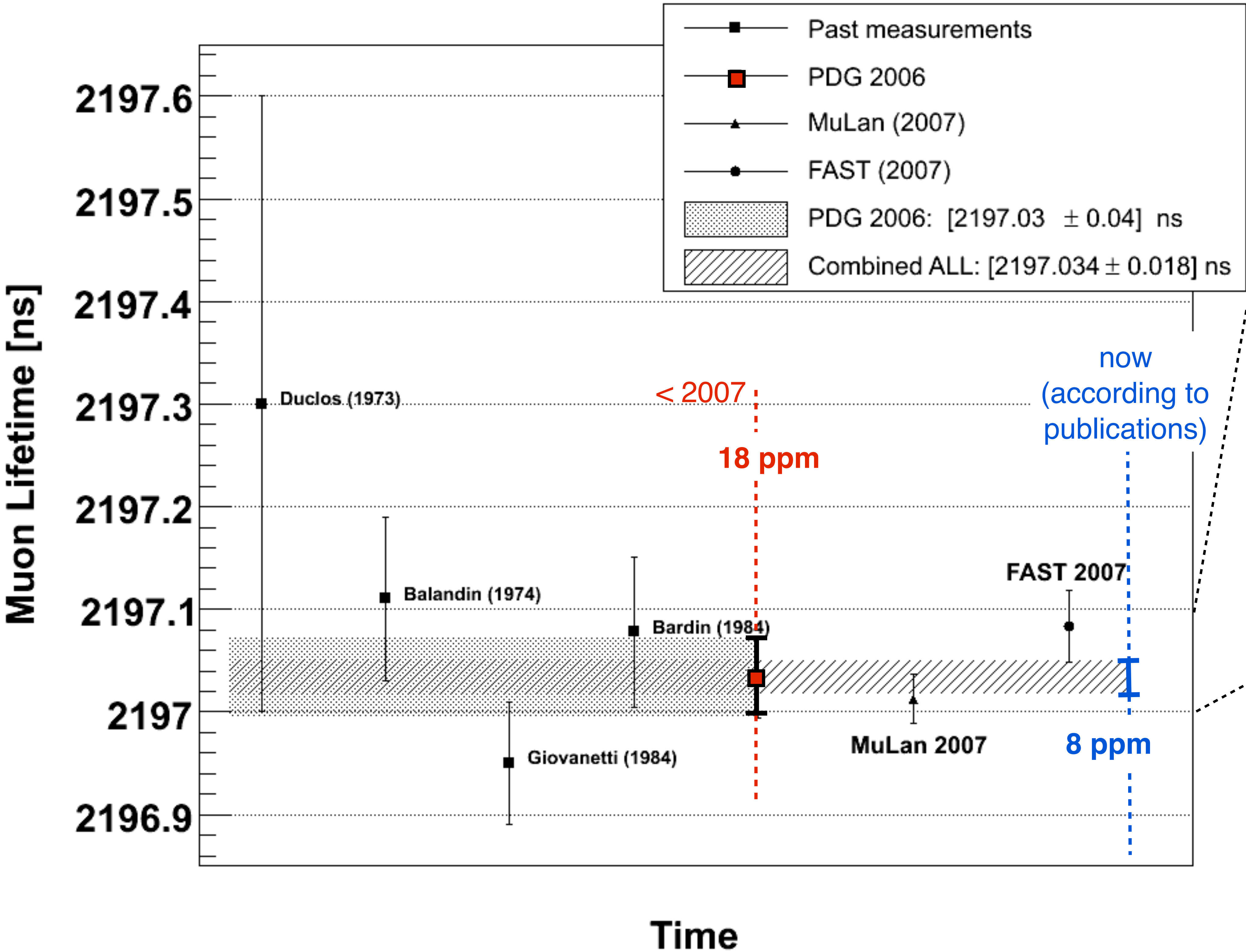


	FAST	MuLan
μ source	π stopped in a target (i.e. unpolarized μ's)	beam μ (i.e. fully polarized)
beam	DC π beam (~ 0.5 MHz)	pulsed μ beam (~ 10 MHz)
beam optics	simple - large π beam (defocused configuration) + wedge	more delicate beam development (beamline, kicker, vacuum beampipe...)
parallelization	in SPACE : more μ decay at the same time in the target (different regions of the target) - repeated modular structure of the detector	in TIME: bunches of several μ's all at once in the target - repeted at high frequency
target	target = detector imaging target / tracking	target and detector are different
magnetic field	external, permanent magnet B ~ 80 G for residual muSR effects	2 targets: μSR dephasing / visibly precessing
readout	TDC + dual thr discr. (i.e. No Analogue information)	WFD => Timing & Pulse Information
Nchannels	~ 2000 (1536 scintillator chann + control words)	340 scintillator chann
data bandwidth	~ 160 MB/sec	~ 25 MB/sec [total storage ~ 220 TB : raw + processed histos]
analysis strategy	fully online O(3000) histograms periodically stored on disk only ~1% of raw data stored on disk	raw data stored on disk
	DIFFERENT SYSTEMATICS !!!	

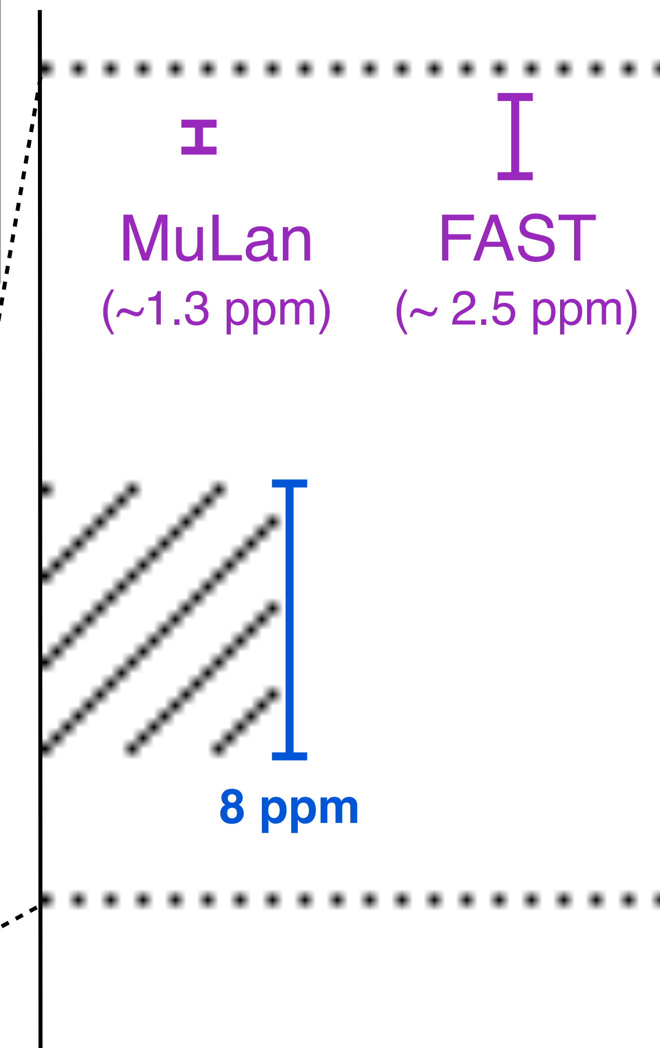
... with a common goal



... with a common goal



near future :



O(ppm) measurement of τ_μ [G_F] is behind the corner...