FAST:

a proposal for a high precision muon lifetime (and G_F) measurement

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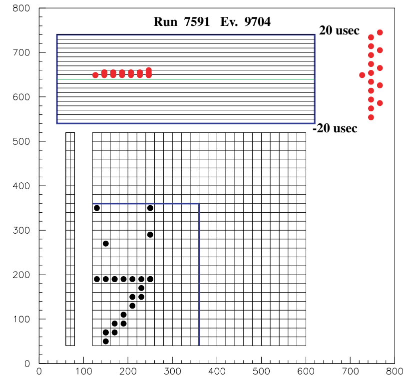


Outline:

....or what you are wondering as well
as I wondered some time ago....

Why do you want to do it?

What is it really?

How do you want do to it?

When do you plan to do it?

Why?

The best (→ most precise) physics theory so far is the Standard Model.

Anyhow it needs experimental inputs in order to be really predictive.

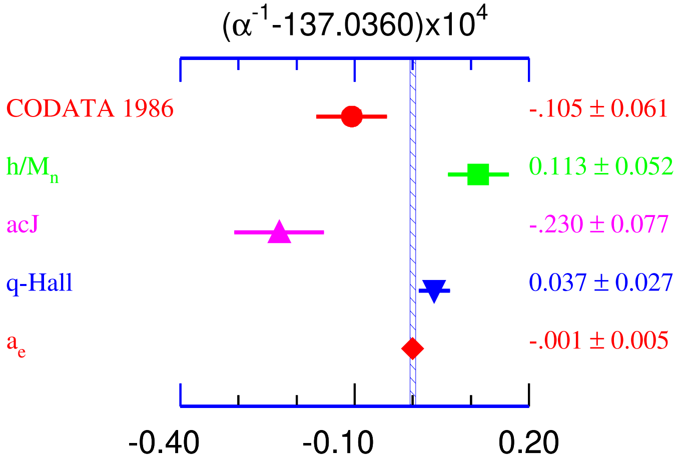
The three free parameters of its bosonic sector are constrained by:

$$\boxed{\begin{array}{rcll} \alpha(\mu^2=0) & = & 1/(137.035990 \pm 0.000006) & \longrightarrow (0.045\ ppm) \\ M_Z & = & 91.1867 \pm 0.0021 \text{ GeV} & \longrightarrow (23\ ppm) \\ G_F & = & 1.16639 \pm 0.00001 \times 10^{-5} \text{ GeV}^{-2} & \longrightarrow (9\ ppm) \end{array}}$$

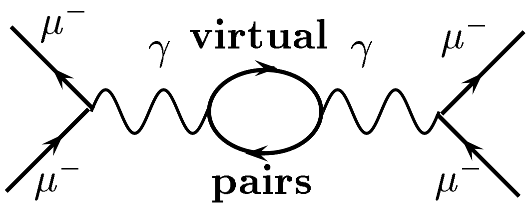
† Note: these three parameters fully describe the strength of the electroweak fields: γ, W and Z

Parameter n. 1: α

- Josephson effect
- Rydberg constant and de Broglie wavelength of neutrons
- Quantum hall effect
- Anomalous magnetic moment of the electron



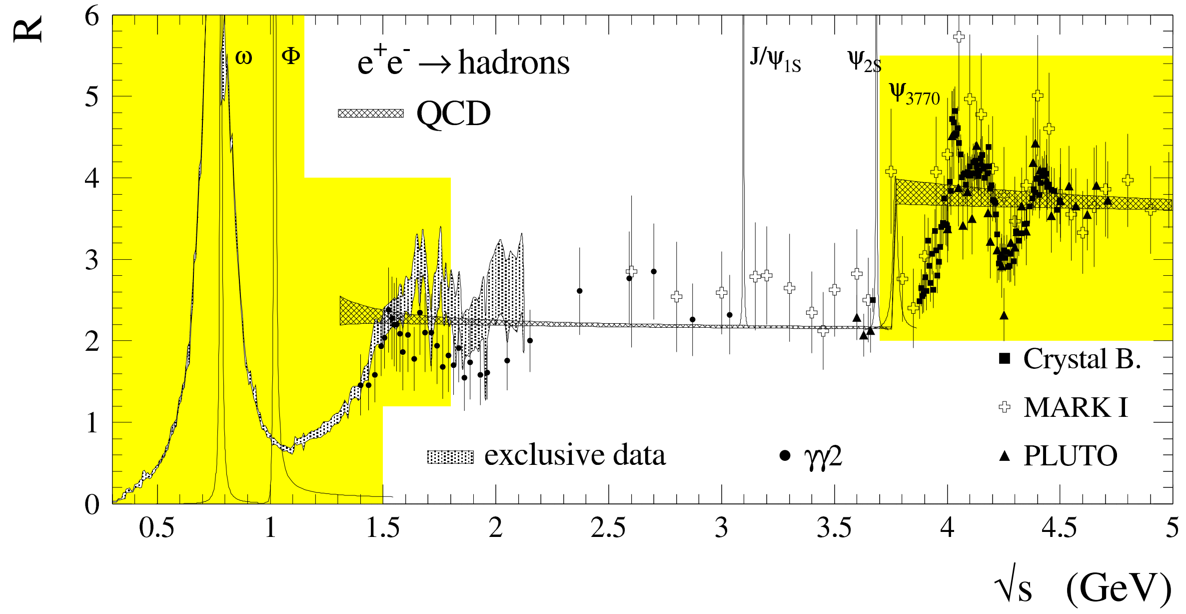
....but at nowadays energies the vacuum polarization effects degrade this accuracy:

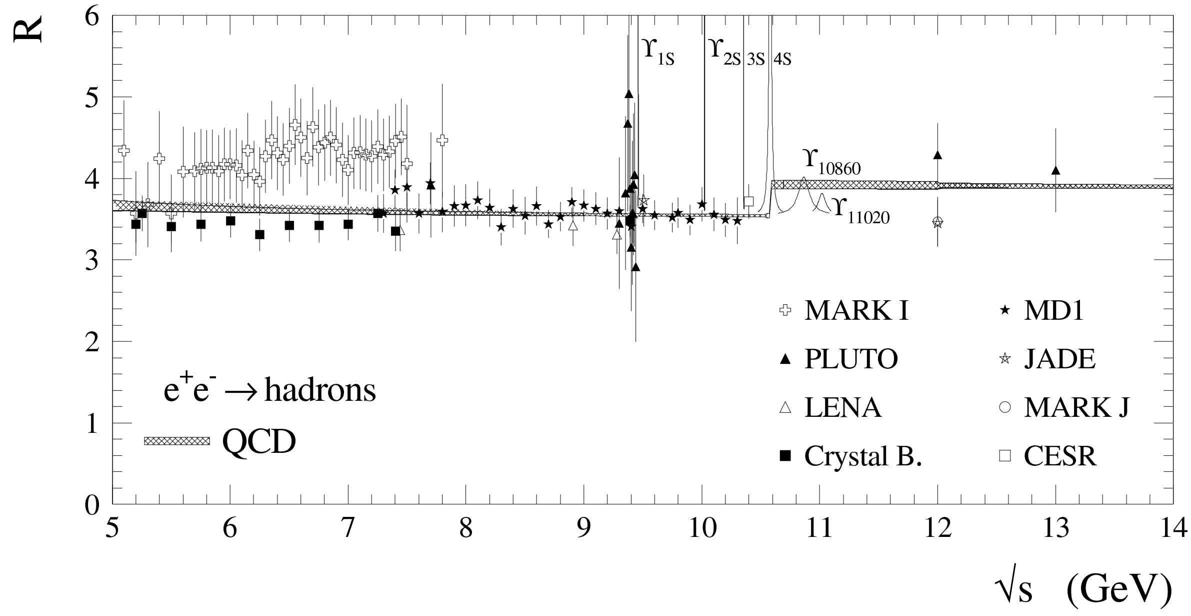


$\gamma^* \to e^+e^-, \mu^+\mu^-, \tau^+\tau^-, u\bar{u}, d\bar{d}, \cdots \to \gamma^*$

Parameter n. 1: α

Hadronic vacuum polarization measurements:



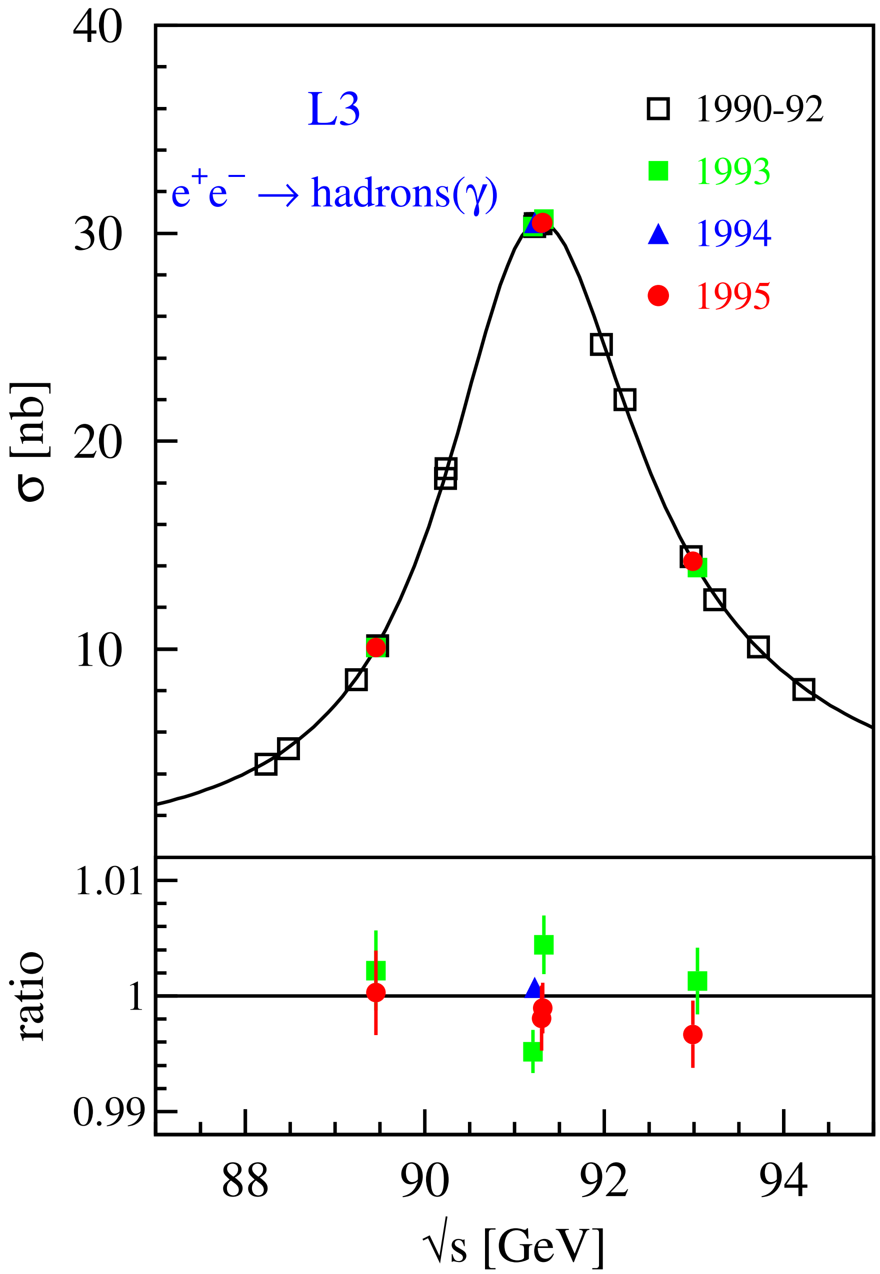


are used to extrapolate α at higher scales:

$$\alpha^{-1}(M_Z^2) = 128.978 \pm 0.027 \rightarrow (209\ ppm)$$

Parameter n. 2: M_Z

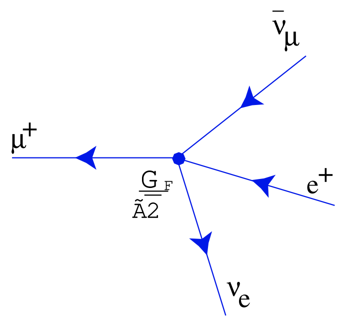
Needless to say:

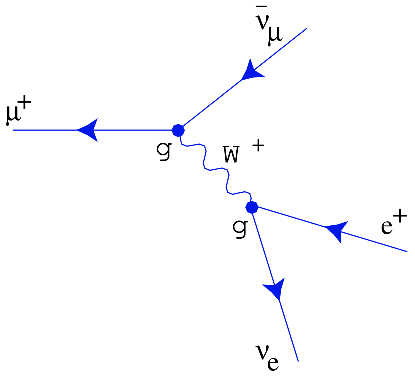


$$M_Z = 91.1867 \pm 0.0021 \text{ GeV} \quad \rightarrow (23\ ppm)$$

Parameter n. 3: G_F

G_F was introduced by Fermi in order to phenomenologically describe the strength of a "new" (weak) force.





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

Δq include the higher order QED and QCD correction known up to two-loop level (0.5 ppm)

→ *T. van Ritbergen and R.G. Stuart Phys. Lett. B 437 (1998) 201*

Unlike α, G_F doesn't suffer hadronic uncertainties which are suppressed by m_f^2/M_W^2:

measuring the muon lifetime is a sort of high energy physics experiment!

Parameter n. 3: G_F

Going from Fermi model (contact interaction) to Standard Model:

$$G_F = \frac{\sqrt{2}g^2}{8M_W^2}(1+\Delta r)$$

Δr are the Electro-Weak corrections:

$$\Delta r = f(\Delta\alpha, m_t, m_H) = \Delta\alpha - \cot^2\theta_W \Delta\rho + \ldots$$

W propagator effects ($\propto \mathcal{O}(m_\mu^2/m_W^2)$ ~ 0.52 ppm) are traditionally included in the definition of G_F
Other contributions ($\propto m_t^2$ and $\log m_H$) are used to derive indirect limits on unmeasured parameters.

The present value of $\delta G_F/G_F$ affect the prediction for M_H at the percent level .....not really impressive, but think about future linear colliders.

Parameter n. 3: G_F

Where the uncertainty on G_F comes from?

$$\frac{\delta G_F}{G_F} = -\frac{5}{2}\frac{\delta m_\mu}{m_\mu} - \frac{1}{2}\frac{\delta \tau_\mu}{\tau_\mu} + \text{th.} \left(+4\frac{m_\nu^2}{m_\mu^2} \right)$$

$$\frac{5}{2}\frac{\delta m_\mu}{m_\mu} = 0.38 \text{ ppm}$$ *PDG2000*

$$\text{theory} = 0.50 \text{ ppm}$$ *Ritbergen and Stuart*

$$4\frac{m_\nu^2}{m_\mu^2} = 10 \text{ ppm}$$ *PDG2000*

(if you assume neutrinos to be massive)

$$\frac{\delta \tau_\mu}{\tau_\mu} = 18 \text{ ppm}$$ *PDG2000*

Dominant contributions from:
Balandin et al. *(1974)*
Bardin et al. *(1984)*
Giovanetti et al. *(1984)*

Why do you want to do it?

- because G_F is a fundamental parameter of SM

- ....and, frankly, because it's FUN!

What is it really?

A proposal for an experiment aiming to measure the muon lifetime with an accuracy of 2 ps, i.e., G_F to 1 ppm including all errors.

Requirements:

Large data sample of 10^{12} events over at least 9 τ_μ periods

$\Downarrow$

$10^{12} \times 9\tau_\mu = 1.5$ years of data taking at 50 % efficiency if only one event per cycle is accepted: parallelization needed!

$\Downarrow$

Tracking capabilities in order to disentangle overlapping events

$\Downarrow$

In order to stay in a reasonable data taking period ($\sim$2 months), a high data rate is needed: 1 MHz.

What is it really?

Proposal for an Experiment at PSI

PSI Proposal R-99-06.1
May 27, 1999

Precision Measurement of the μ^+ Lifetime (G_F) with the FAST Detector

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Abstract

We propose to measure the μ^+ lifetime to a precision of 2 ps (1 ppm) with the fibre active scintillator target detector, FAST. After including all experimental and theoretical sources of error, this will measure the Fermi coupling constant, G_F, to a precision of 1 ppm, which is an order of magnitude improvement of the present world average. The detector is a small imaging target of dimensions about $20 \times 20 \times 20$ cm^3 made from scintillating plastic fibres and viewed by position-sensitive phototubes. A DC π^+ beam of momentum 170 MeV/c is stopped in the target and the subsequent decay time of each pion and muon is recorded. The detector and its readout are designed to operate at a high beam rate of 1 MHz. A data sample of 10^{12} stopped π^+ events is required, corresponding to a beam time of about two months.

[1)]Permanent address: *DESY-Zeuthen, Germany*

Systematics - part 1: learn from the past

Saclay experiment (Bardin *et al.*):
A scintillator telescope surrounding a sulphur target in a pulsed pion beam.

- The polarized μ component of the beam introduced time dependent inefficiencies due to the limited coverage of the detector
- The low granularity of the detector, together with the beam time structure, produced time dependent effects
- Pile-up free background

TRIUMF experiment (Giovanetti *et al.*):
A water Čerenkov system coupled to two PM in a DC muon beam.

- Electronic pile-up suppression: low statistics.

...so we learned.

FAST experiment (near future):

- Capability to recognize the $\pi \rightarrow \mu$ signature avoiding the "polarization effect"
- Controlled pile-up thanks to a high granularity
- Full solid angle coverage
- High detection efficiency over the complete positron energy spectrum
- Cross checked time measurements and stability
- Something else ?????

Design characteristics

Beam:

- πM1 at PSI: DC current
- Momentum: 170 MeV/c ($\pm$ 3 %)
- Size: 10×16 cm^2
- Intensity: 10^6 s^{-1}
- Purity: 90 %

Target:

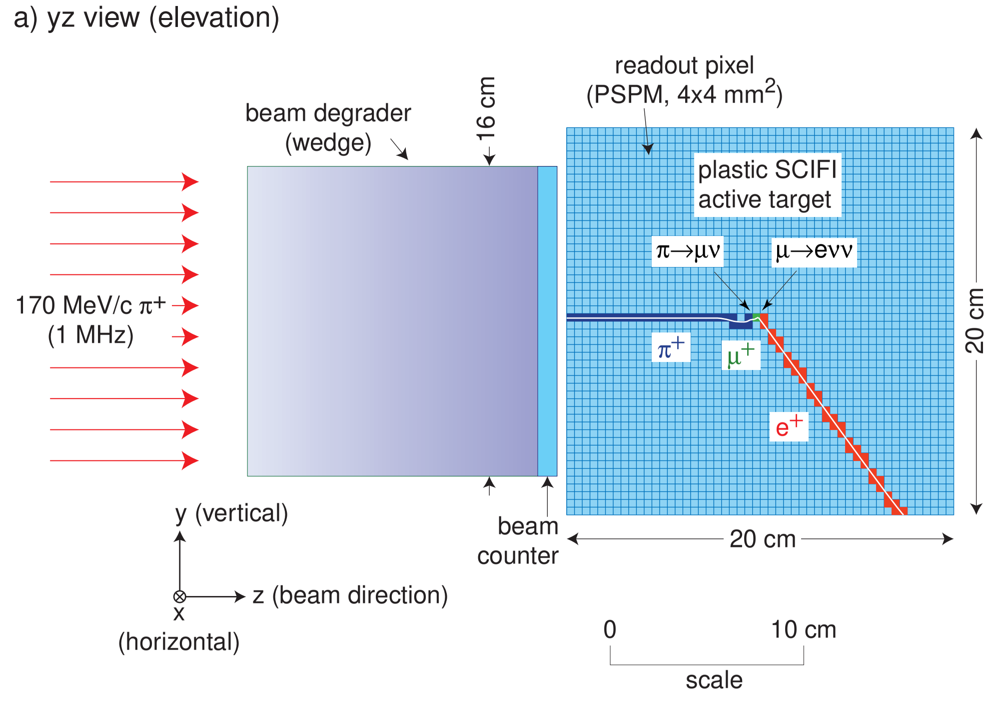
- 0.5 mm scintillating fibers
- 8×8 20 cm long fibers are bundled in one readout pixel
- 25 p.e./pixel for minimum ionising particle
- 48×48 pixel sensitive area
- 45 km of scint. fibers

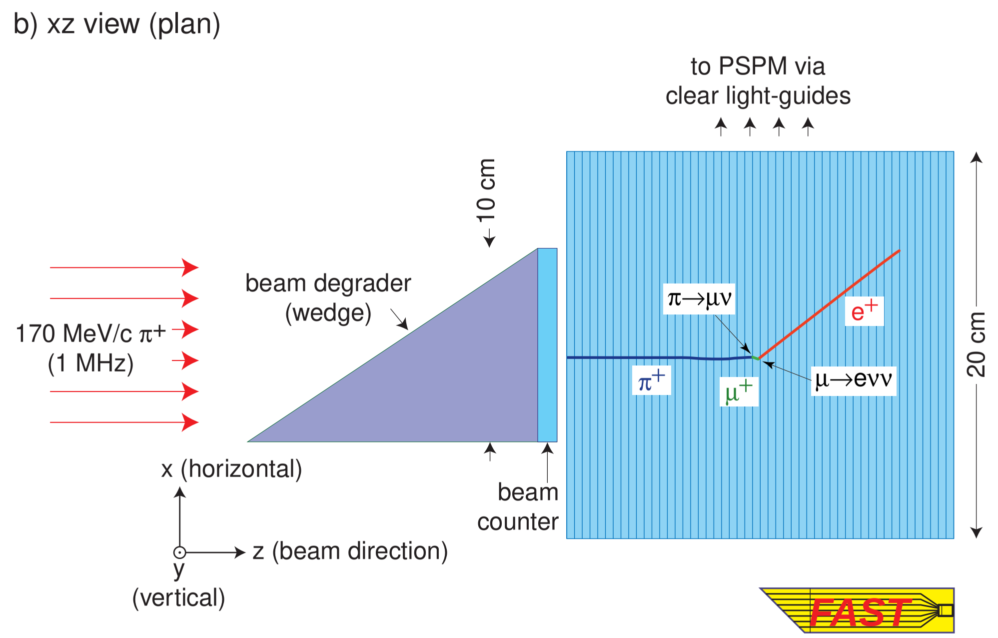
Readout system:

- 144 position sensitive PM with 4×4 photocatode pixels
- rise time < 2 ns
- $\sim$2.5 K deadtime-less TDC channels

Concept:

A scintillating fiber detector, on a DC pion beam, able to handle up to 30 $\pi \longrightarrow \mu \longrightarrow e$ decay chains in a 30 μs window:





Concept: from beam to decay time

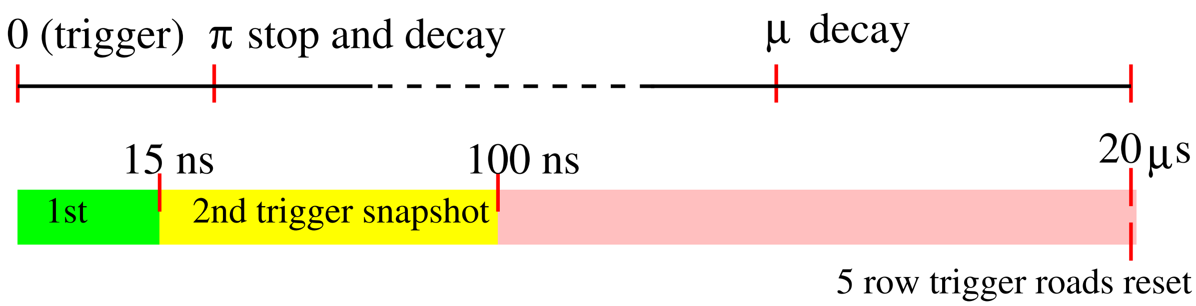
- The pion stopping point is modulated by the plastic degrader such that the occupancy is kept uniform
- The pulse height in the stopping pixel is ~ 5 times higher than a m.i.p. $\Rightarrow$ a double threshold discriminator (developed at PSI) is used for tagging purposes
- Every event is a good event and the readout system is almost dead-time free. So, why do we need a trigger?

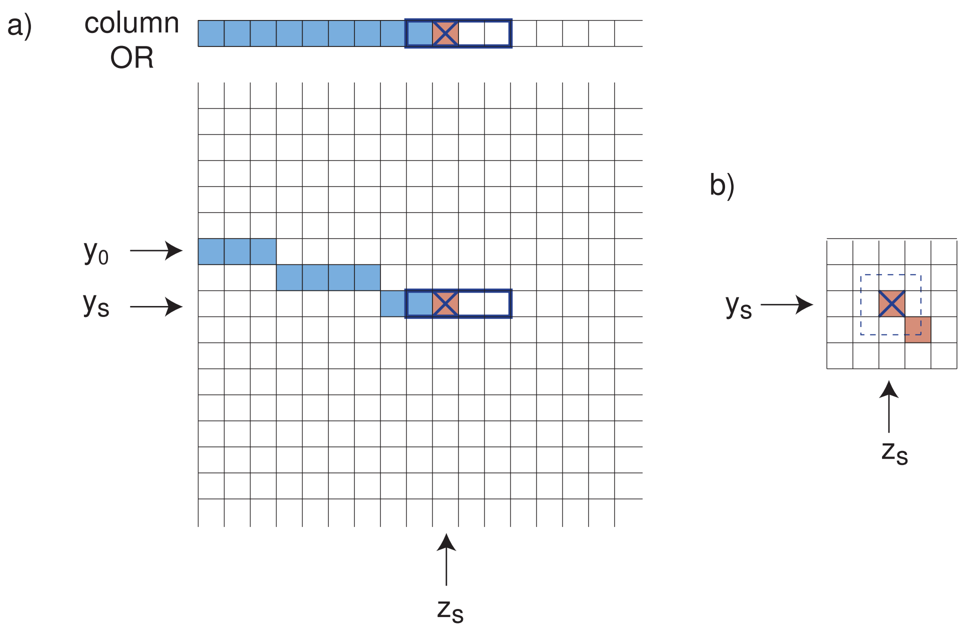
> - t0 for the whole system;
> - <u>definition of a "region of interest" where to look for decaying muons and decrease the data rate.</u>

Trigger system

1^{st} level: three-fold coincidence defining the t0

2^{nd} level: two snapshots of the event (15 ns and 100 ns) are used to find, respectively, the stopping point of the pion and muon. Only the 5×5 superpixel around the stopping point will be analysed. For each row a 100 MHz controller search for "stopping patterns":





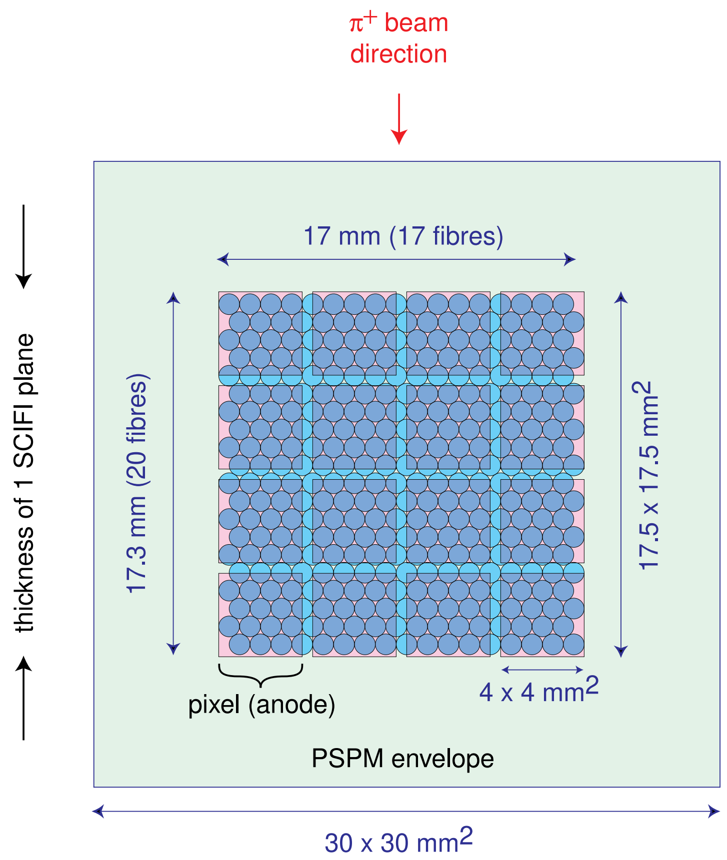
Readout system: PSPM

The double cladded scintillating fibers are winded using an established technique developed at DESY-Zeuthen

$\rightarrow$ *R. Nahnhauer et al.*

The signal is transported, via clear fiber light guides, to the 144 Hamamatsu Position Sensitive PM's.

Each PM, packaged with HV divider and plastic cover, provides $4 \times 4 = 16$ anodes (channels), 4×4 mm^2 each:



Readout system: TDC

The stopping point coordinates are used to mask the hits digitization in the heart of the system:

- ✔ 80 TDC chips developed by CERN/ECP-MIC group and engineered by CAEN on 20 128-channel boards (v767)
- ✔ "0" conversion time
- ✔ up to 520 ps of time resolution
- ✔ up to 1 MHz rate capability

The TDC system is driven by an external Rubidium clock with a base output frequency of 30 MHz and a stability of $\Delta f/f = 2.2 \times 10^{-10}$, much beyond the requirements.

A second Rubidium clock is used as an external time reference and calibration system.

DAQ system: a challenge

The Data AcQuisition system must sustain a continuous event rate of 1 MHz.

From physics to tape:

- ☞ 60 hits/event + control words → 420 Mbytes/s
- ☞ using LV2 info (+ tricks) → 80 Mbytes/s

Note: only a 5×5 superpixel region is used. We are forced to drop the rest.

An unfair comparison:

	LHC detector	FAST
n. channels	100,000,000	2304
event size	1 MByte	500 Bytes
Physics data throughput	100 MBytes/s	420 MBytes/s

The data are sent, via a fast ethernet switch, to a PC farm which analyses them and stores histograms. Only a fraction of the event is recorded for systematics checks.

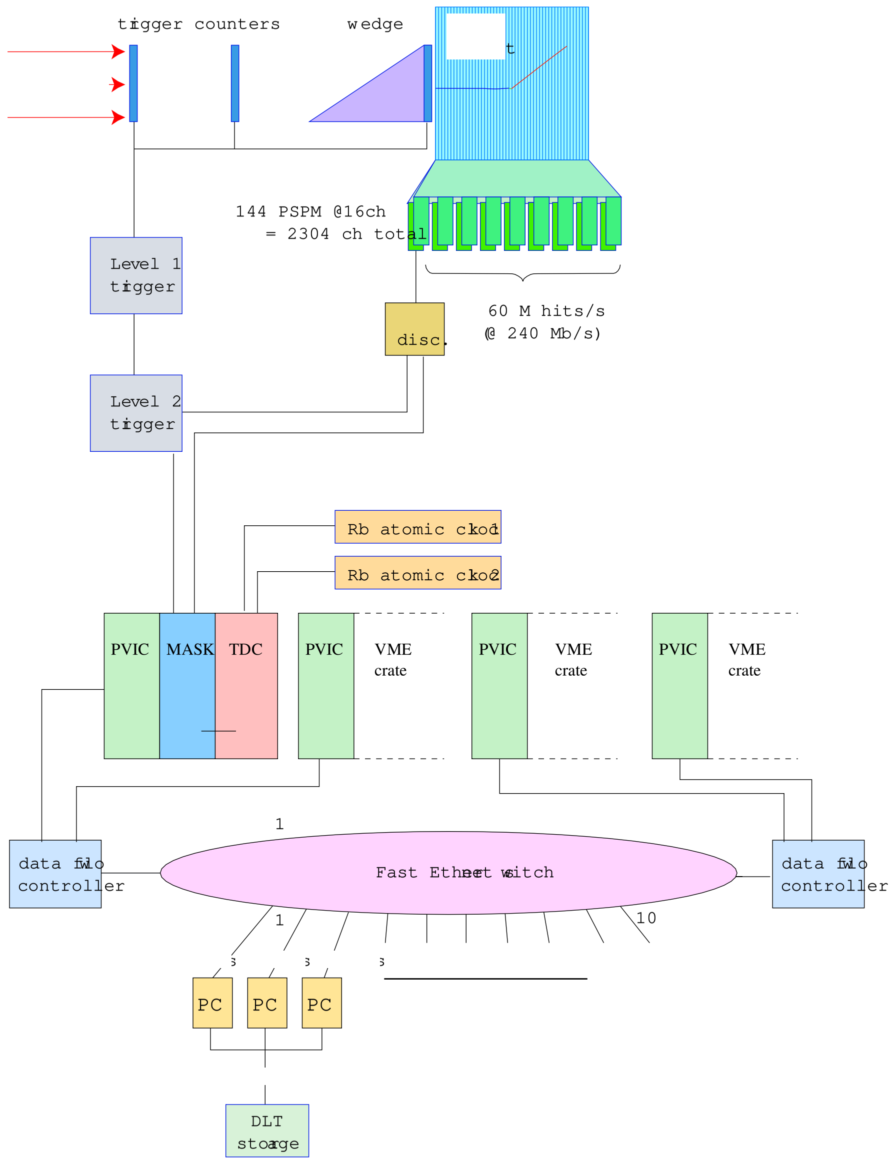
The full (LV2 info) saving would require a huge amount of mass storage ($\sim$ 80 Tbytes equivalent to a 3 months period of a LHC detector) filled with W.O.R.N.'s†. The reading+processing time would require much longer than a new data taking period.

†W.O.R.N.: Write Once Read Never

DAQ system: a challenge

A commercially available CPU-less solution has been adopted for the VME system:

- PVIC= PCI to VME Intercrate Connection: you can use your desktop PC as a remote CPU for accessing VME addresses
- High PCI data rate → 80 MBytes/s
- High VME data rate (tested in lab.) → 18MBytes/s
- 4 VME crates + 2 controller PC's are sufficient



How do you want do to it?

Several simulations have been performed to assess different topics:

1) Trigger configuration and efficiency
51 % of the incoming pions are triggered within the two snapshot structure. The losses are mainly due to early decaying pions, before the second snapshot takes place. Muons are identified by means of the pulse height signal.

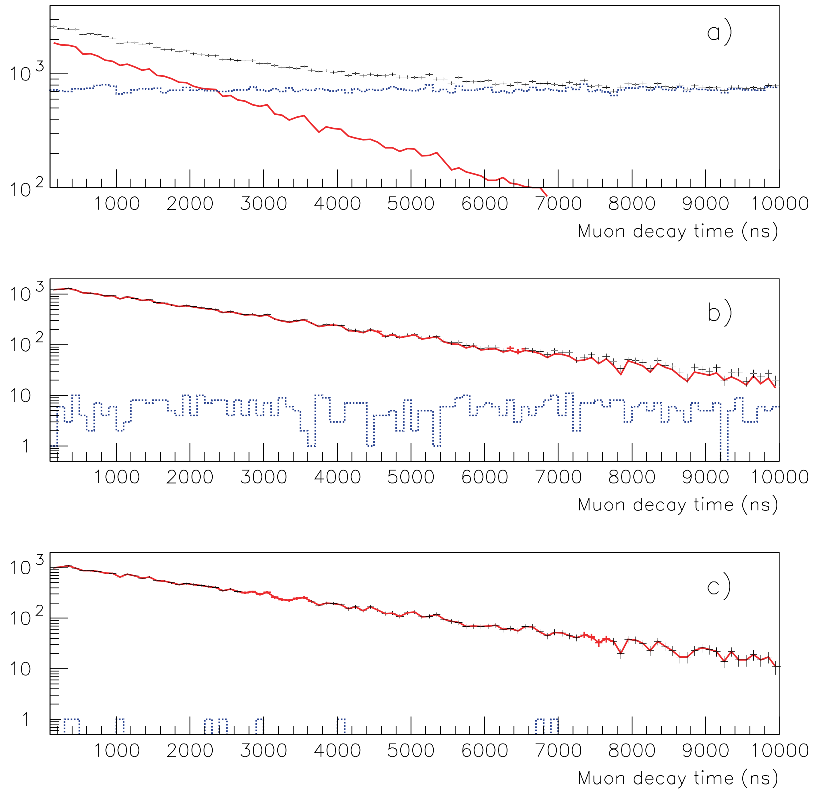
2) Selection algorithm
85 % of the events have one or more particles originating from other decay chains and traversing the same 5×5 pixels region. In order to reduce this accidental background component, positron topology cuts have to be applied

$\Longrightarrow$

How do you want do to it?

- Hits in the 5×5 pixels region are clustered in time
- A positron track is defined as a track with hits in both the inner (3×3) and outer (5×5) region
- Only one cluster of less than 4 pixels is required in the outer layer
- Events with more than one positron track are rejected

Total efficiency: 25 %
Accidentals: 3×10^{-4}



– Total
– Muons
– Accidentals

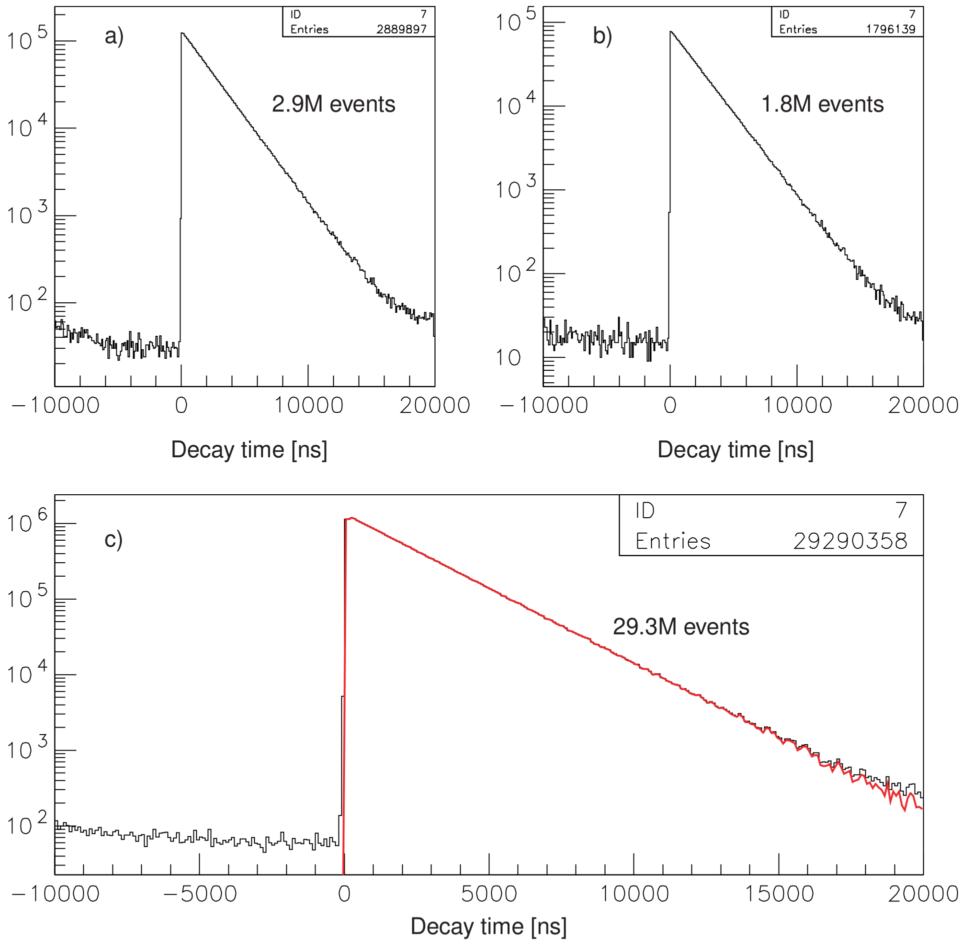
a) all events
b) positrons tracks
c) only one positron track

How: systematics - simulation

The control of systematics effects is a crucial point for an experiment based on huge statistics.

A detailed simulation study is mandatory, but you would need at least four times the expected statistics: 4×10^{12} events!

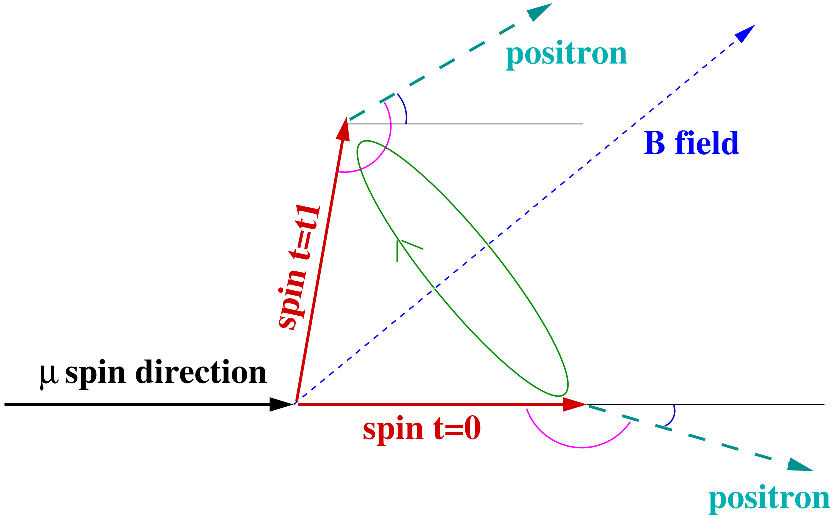
An overlapping/mixing technique based on a large set of fully simulated events has been tested and shown to be working

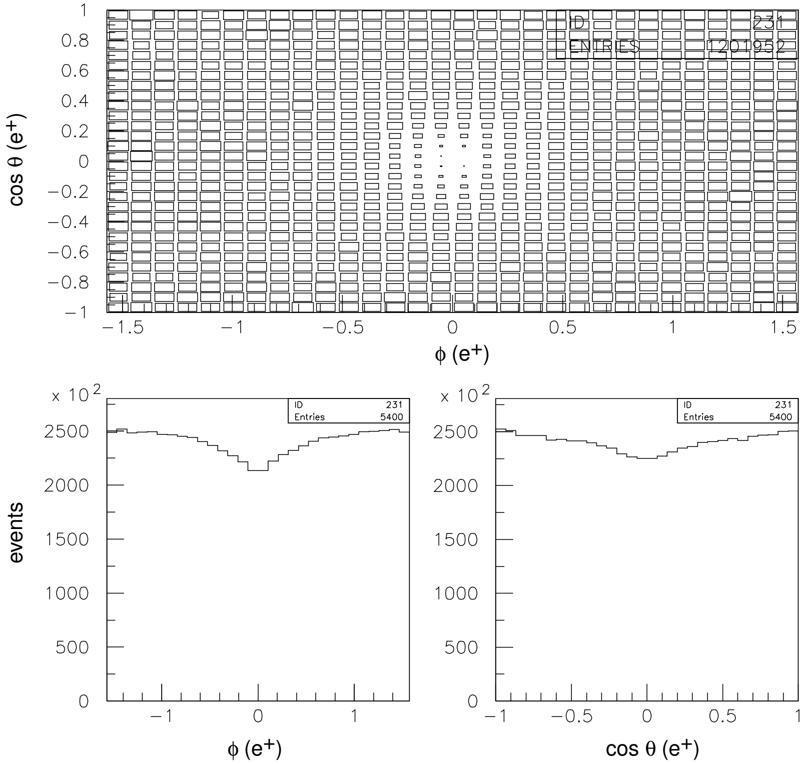


a) b) fully simulated events
c) mixed events

How: systematics - muon spin rotation

A polarized muon source (from beam or from asymmetric muon detection efficiency) precesses around a magnetic field (Earth). If ALSO the positron detection efficiency is asymmetric this can cause a time dependent effect:





How: systematics - muon spin rotation

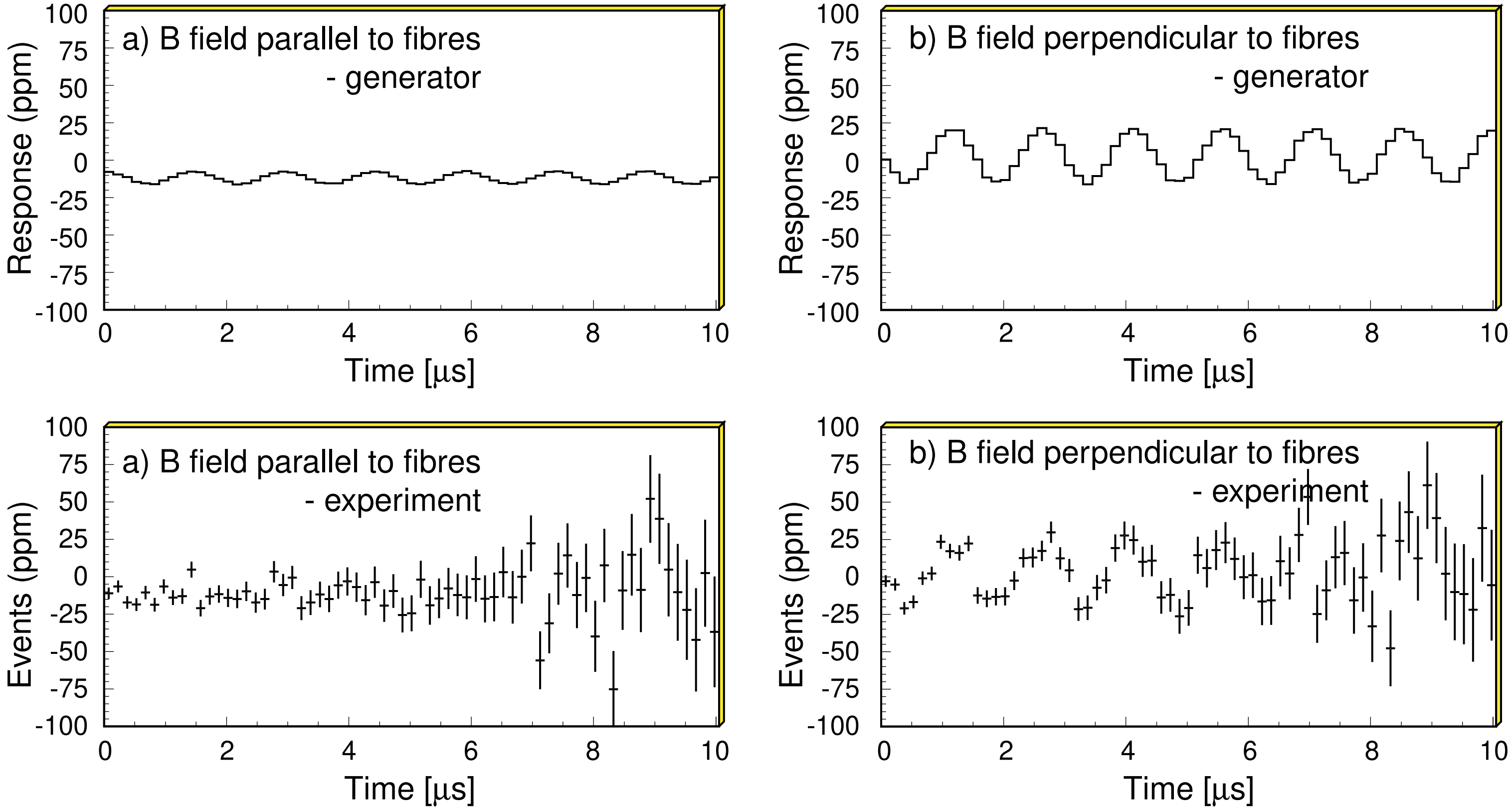
- ✔ Avoid polarized beam muons requiring a detectable $\pi \rightarrow \mu$ transition.
- ✔ Make the detector as uniform as possible:
  - residual muon detection anisotropy along the beam direction from double hit time resolution and high threshold discriminator (10 %)
  - positron detection inefficiency from local effects (unstable thresholds/gain $\rightarrow$ 1 %)

Precession frequencies:

$$\nu^{\mu} = 13.55 \frac{\mathrm{KHz}}{G} \times B \quad \nu^{\mathrm{muonium}} = 1355 \frac{\mathrm{KHz}}{G} \times B$$

How: systematics - muon spin rotation

Residual of time distributions after applying a weak magnetic field (50 G):



With a suitable choice of the magnetic field and a proper fit procedure this effect can be kept at the level of (0.2 ppm).

How: systematics - time dependent detection efficiencies

- After-pulses, in a 10 ns scale, could fake a muon pulse and affect the requirement of a fully detected $\pi \to \mu \to$ e chain.

  Prob. $\to 10^{-4}$ with double threshold discriminator

- On a longer time scale (0.5 μs), after-pulses, gain changes and baseline shifts may affect the electron detection efficiency in pixels already visited by a pion or muon.

Low Threshold	probability
≥ 1 pe	10 %
≥ 2 pe	1 %
≥ 3 pe	0.1 %

The decay time distribution gets two additional terms:

1) $\propto \exp\left(-t\frac{2}{\tau_\mu}\right)$: prob. for an electron to be just under threshold

2) $\propto \exp\left[-t\left(\frac{1}{\tau_\mu}+\frac{1}{\tau_\beta}\right)\right]$: τ_β is the slow after-pulse time component

Simulations based on lab. tests give a total effect of less than 0.3 ppm.

How: systematics - tracks overlap and pile-up

Given the high occupancy of the detector, event and single track overlap have to be taken into account.

Two separate decay chains (independent on each other):

$$(\pi_1, \mu_1, e_1) \Longleftrightarrow (\pi_2, \mu_2, e_2)$$

may "interact" and give rise to *fake* decay chains:

$$(\pi_1, \mu_1, \pi_2),\ (\pi_2, \mu_1, e_1),\ (\pi_1, \mu_2, \pi_1), \ldots$$

Most of these backgrounds have either flat or well behaved $\propto \exp\left(-\frac{t}{\tau_\mu}\right)$ time distributions.

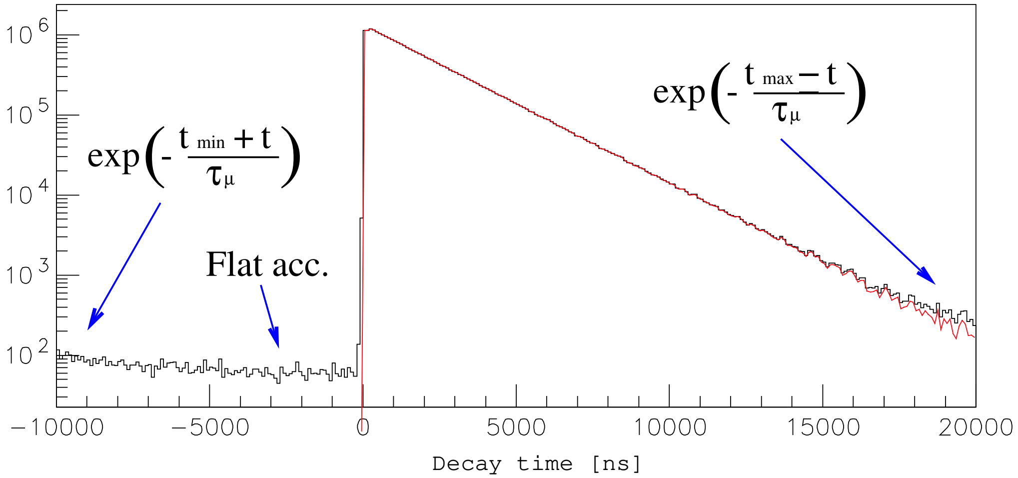
$\rightarrow$ *no or little effect on final measurement*

but for some of them ....

How: systematics - tracks overlap and pile-up

(π_1, μ_1, π_2): the positron e_1 is lost and an incoming π_2 fakes it. If the following decay appear in the predefined time window $[-10\ \mu s; 20\ \mu s]$ the event is not accepted ($\rightarrow$ multiple-track): late pions have better chance to be accepted

(π_1, μ_1, e_2): mirror component, with the positron coming from a (previous) very late decay in the same super-pixel



Using $t_{min} = -10\ \mu s$, $t_{max} = 20\ \mu s$, and the probability for the pion track to be reconstructed as a positron track (Montecarlo), this effect is found to be negligible and under control studying the negative time distribution region.

How: systematics - tracks overlap and pile-up

A little bit more complicated case: double kill

The presence of two events with same (or somehow related) space and time structure may give rise to time dependent inefficiencies:

$$\mathrm{prob}(\mathrm{e}_{\mathrm{kill}}) \propto 1 + af(t_{\mathrm{e}_2} - t_{\mathrm{e}_1}) \qquad \mathrm{prob}(\pi_{\mathrm{kill}}) \propto 1 + a'f'(t_{\pi_2} - t_{\pi_1})$$

$$\mathrm{eff.} = 1 - af(t_{\mathrm{e}_2} - t_{\mathrm{e}_1}) - a'f'(t_{\pi_2} - t_{\pi_1}) + aa'f(t_{\mathrm{e}_2} - t_{\mathrm{e}_1})f'(t_{\pi_2} - t_{\pi_1})$$

The first two "single kill" terms are NOT dependent on $(t_{\mathrm{e}_1} - t_{\pi_1})$, while the third gives an additional contribution $\propto \exp(-t/\tau_\mu)$.

$\pi_2 \leftrightarrow \pi_1$ correlations:

- π_2 enter the detector just after π_1 during the trigger dead-time
- π_2 enter the detector just after π_1 and TDC cannot resolve the two hits
- π_2 enter much before π_1 when pile-up rejection doesn't apply ($< -10\ \mu$s)

$\mathrm{e}_2 \leftrightarrow \mathrm{e}_1$ correlations:

- e_2 overlaps in time and space e_1

under control using the beam rate → 0.2 ppm

How: systematics - physics effects

Muonium formation in scintillator is highly probable (66 %). Is the muon lifetime bound in Muonium state different?

- ✔ Early studies claimed YES
- ✔ A more recent paper from *Czarneki, Lepage and Marciano (hep/ph-9908439)* show that the correction is at the level of 10^{-9}, in agreement with phase space arguments
- ✔ Negligible effect on FAST measurement

Rare decays:

- ✔ Radiative decays may alter the topology of the event and hence the detection efficiency
- ✔ Full GEANT simulation show negligible effects
- ✔ Additional electrons from γ conversions increase the number of positron tracks in the detector by 0.25 % $\rightarrow$ negligible effect
- ✔ Internal conversions $\mu^+ \rightarrow \mathrm{e}^+ \bar{\nu}_\mu \nu_\mathrm{e} \mathrm{e}^+ \mathrm{e}^-$ produce an efficiency loss of $< 3.4 \times 10^{-5}$ but same time structure as the signal

How: fit and summary

Including all considered systematic effects the final fit function will look like:

$$N(t) = \frac{N_0}{\tau_\mu}\delta t \left[P_0 + \exp\left(-\frac{t}{\tau_\mu}\right) + P_1 \exp\left(-\frac{2t}{\tau_\mu}\right) + P_2 \exp\left(+\frac{t}{\tau_\mu}\right)\right] \otimes \mu\mathrm{SR}$$

P_0 =flat accidental
P_1 =double kill
P_2 =late pions

P_0 and P_2 can be left free in the fit but P_1 would increase the systematic error by 2-3 ppm.
Need to get it from data: dedicated runs for efficiency studies, beam rate, off-line extrapolation.

Systematics summary tables

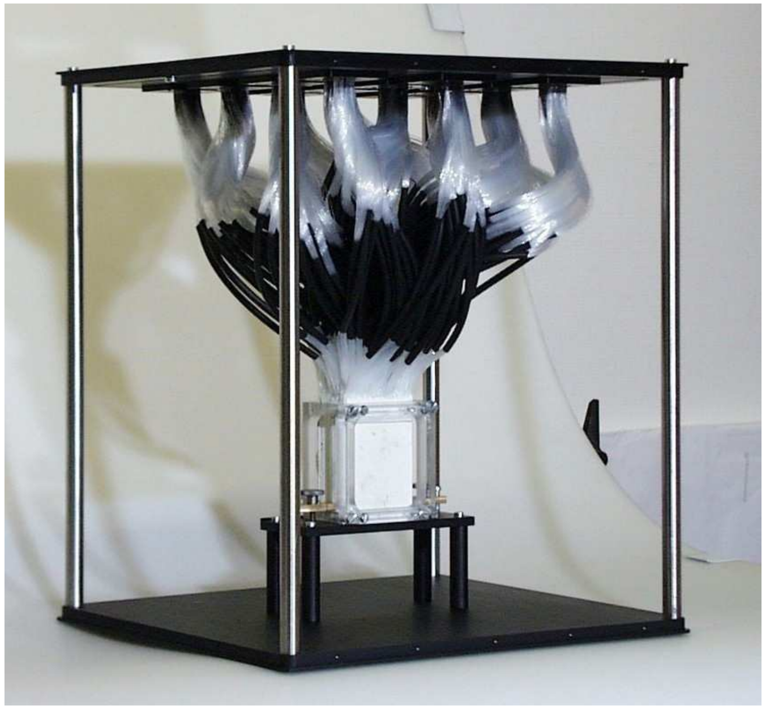
Source	Syst. error (ppm) Before	After corr.
Muon spin rotation	1.7	0.2
Time dep. efficien.	0.9	0.3
Track overlap	1.1	0.2
Physics effects	-	0.001
Total systematics		0.41

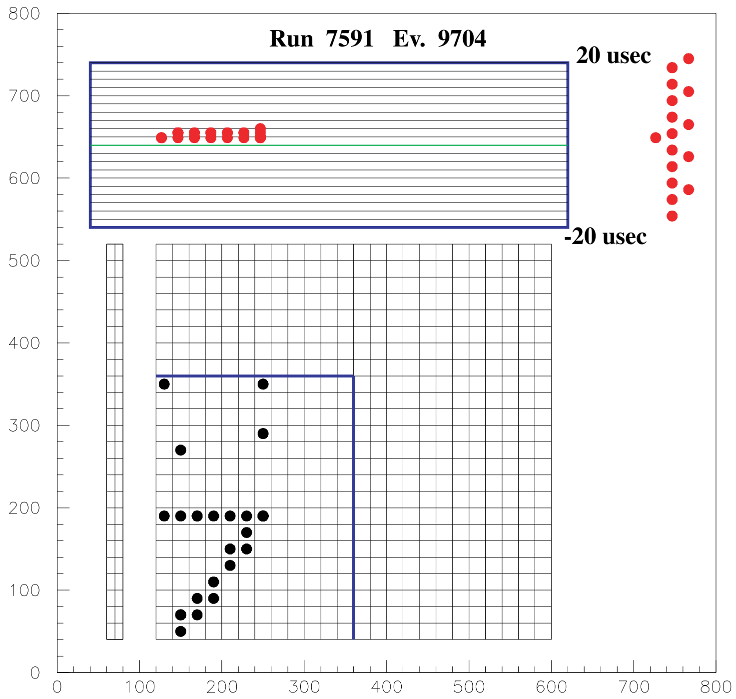
Source	Error (ppm)
Statist. + acc.	1.2
Systematics	0.4
Error on τ_μ	1.3
Radiative corr.	0.2
Error on G_F	0.66

When do you plan to do it

First milestone met at the end of year 1998: test-beam at PSI

- Check feasibility studies
- 1/10 of the detector with several configurations
- Low intensity
- Check fibers, PSPM and TDC's behaviors

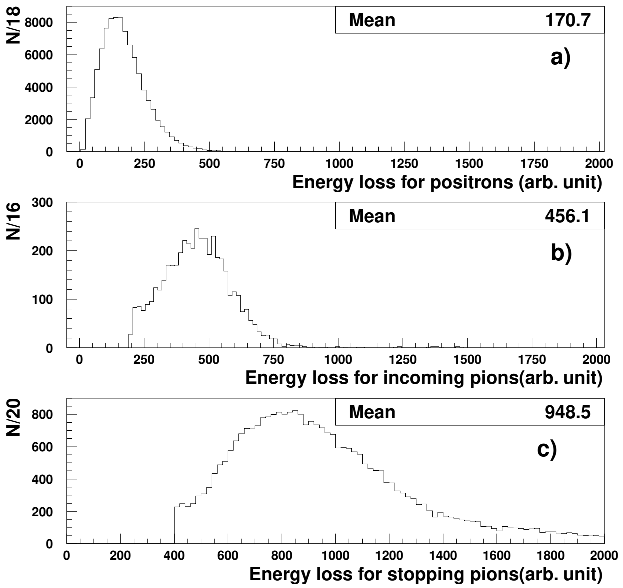


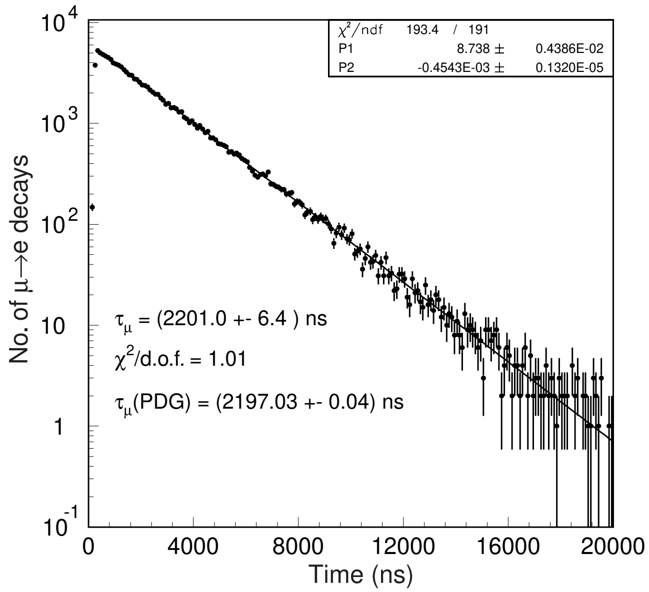


Test beam

The dynamic range has been studied, together with double hit resolution, discriminator requirements, TDC performances, etc.

The TDC boards were carefully debugged (beta version) and a first measurement of the muon lifetime has been obtained in a glorious data-taking night (50k events) after some problems were solved....





B.T.W. we also learned that Villigen can be quite uncomfortable during winter time (-20°) when you can only eat "hirschen"

When do you plan to do it: cont'd

	Date	Activity
✔	2000 (1^{st})	Experiment approved at PSI
✔	2001 (1^{st})	Prototype tests, re-design of DAQ
	2001 (4^{th})	System integration tests at PSI
	2002 (2^{nd})	Installation
	2002 (4^{th})	Check-out
	2003	Data taking

Last paper signed by:

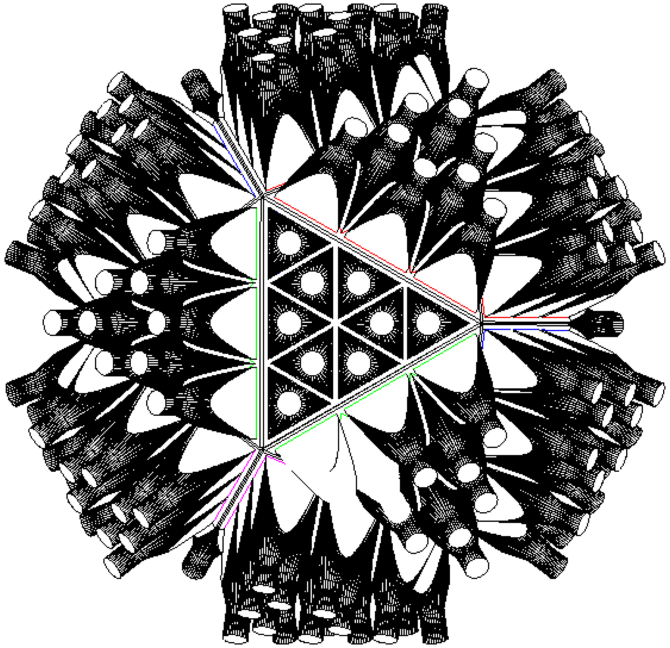
6 collaborations: Geneva, PSI, CERN, (UCB, Bologna, NIKHEF)
18 collaborators: do you want do join us?
`http://www.cern.ch/fast/`

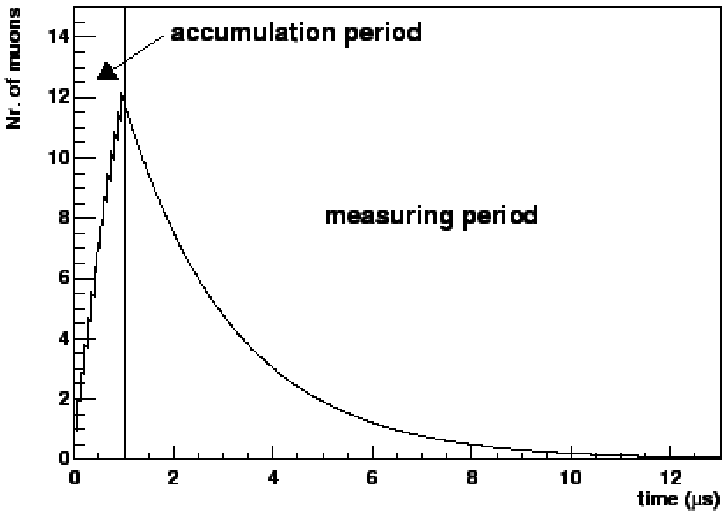
Competitors

μLAN: http://www.npl.uiuc.edu/exp/mulan/muLanMain.html

A structured muon beam (pulsed approach) is used to generate a radioactive muon source in a depolarazing sulfur target.

180 triangular timing tiles are distributed uniformly within the 20 SuperTriangles of an icosahedral geometry centered on the target.





Given the different approaches (pion DC vs pulsed muon beam) FAST and μLAN will have complementary systematics sources: good cross-check!

Conclusions

- FAST is a small experiment in dimension, time, people and even costs but it will measure with 10 times better accuracy than the present world average the Fermi coupling constant G_F
- Its feasibility has been established in simulation and test beams
- Major challenges:
  - stability and data rate: from a 0.008 m^3 detector, an LHC detector equivalent throughput has to be handled $\longrightarrow$ a test bench for new generation experiments
  - very subtle systematic effects have to be sorted out
- In a world of BIG experiments... a SMALL one can be really fun.

Credits for the material:

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