Muon Capture and Muon Lifetime

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muon capture on proton

$m^- + \mathbf{p}$ ® $n_m + \mathbf{n}$

L **to 1 %**

Nucleon form factors, chiral symmetry of QCD

m Cap experiment

m**Cap I:** s(L$_S$) **1%,** s(**g$_P$**) **7 %**

μCap II: σ(Λ_S) 0.3 %, σ(g_P) 3%
with Muon-On-Request

muon decay

m^+ ® $\mathbf{e}^+ + n_{\mathbf{e}} + \bar{n}_m$

t_{m+} **to 1 ppm**

Fermi Coupling Constant

m Lan experiment

G_F to < 1ppm

muon capture on deuteron

$m^- + \mathbf{d}$ ® $n_m + \mathbf{n} + \mathbf{n}$

L **to 1 %**

Basic EW two nucleon reaction, calibrate v-d reactions

m*D project*

μD I: σ(Λ_D) few %

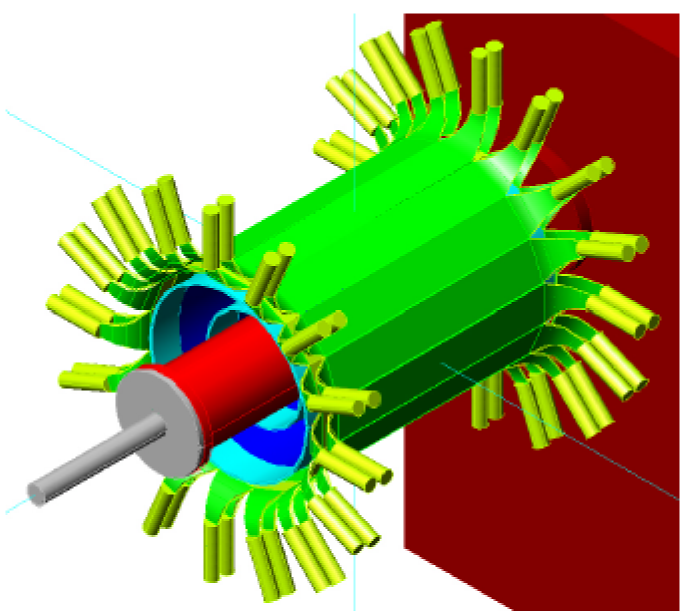
μD II: σ(Λ_D) 1 %
neutron coinc measurement
of n-n Dalitzplot

Precision Measurement of Muon Capture on the Proton “mCap experiment”

$$\mu^{-} + p \rightarrow \nu_{\mu} + n$$

www.npl.uiuc.edu/exp/mucapture/

Petersburg Nuclear Physics Institute (PNPI), Gatchina,Russia
Paul Scherrer Institut, PSI, Villigen, Switzerland
University of California, Berkeley, UCB and LBNL, USA
University of Illinois, Urbana-Champaign, USA
Universite Catholique de Louvain, Belgium
TU Munich,Garching, Germany
Boston University, USA
University of Kentucky, USA



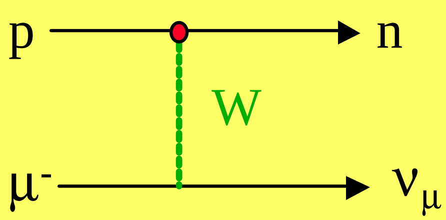
@ PSI

Scientific case: muon capture

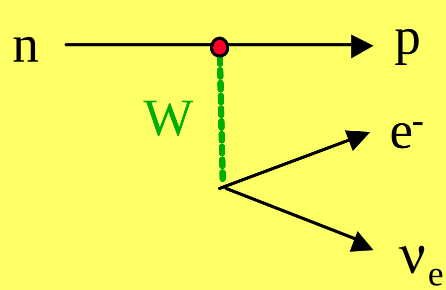
μ capture probes axial structure of nucleon

μ capture

$\mu^- + p \rightarrow \nu_\mu + n$



β decay



hadronic vertex dressed by strong int. Þ **q^2 dependent form-factors**

dual role of m

- μ acts as well defined probe of hadronic structure
  QCD tests, **pseudoscalar form-factor, chiral symmetry**
- Standard Model symmetries of lepton-quark interaction
  μ-e universality, second class currents, CVC

Main motivations for experiment

- g_P basic nucleon form-factor
- accurate QCD prediction via ChPT (1-3% level)
- RMC: 4.2 σ discrepancy between exp. and theory
  OMC: experiments ~50 % ambiguities

Nucleon charged current at $q^2 = -0.88\ m_m{}^2$

$J_a = V_a - A_a$

$V_\alpha = g_V(q^2)\,\gamma_\alpha \quad + \; i g_M(q^2)/2M\ \sigma_{\alpha\beta}\, q^\beta \; + \; g_S(q^2)/m\ q_\alpha$

$A_\alpha = g_A(q^2)\,\gamma_\alpha\,\gamma_5 + \; g_P(q^2)\, q_\alpha/m\ \gamma_5 \quad + i g_T(q^2)/2M\ \sigma_{\alpha\beta}\, q^\beta\, \gamma_5$

- Vector current in SM determined via CVC

  $g_V(0)=1$, $g(q^2)=1+q^2\, r^2/6$, $r_V{}^2=0.59\ \text{fm}^2$

  $g_M(0)=\mu_p-\mu_n-1=3.70589$, $r_M{}^2=0.80\ \text{fm}^2$ $\qquad$ q^2 dependence from e scatt.

- Axial vector FF from experiment

  $g_A(0)=1.2670(35)$, $r_A{}^2=0.42\pm0.04\ \text{fm}^2$
  q^2 dependence from quasi-elastic ν scattering, π e-production

- 2^{nd} class FF g_S, g_T forbidden by G symmetry, e.g.

  $g_T/g_A=-0.15\pm0.15$ (exp), -0.0152 ± 0.0053(QCD sum rule, up-down mass difference)

nucleon weak CC formfactors for mCap

$g_V = 0.9755(5)$ $\qquad$ $g_A = 1.245(3)$

$g_M = 3.5821(25)$ $\qquad$ **g_P = ?**

Sensitivity of capture rate:

$$\frac{\delta\Lambda}{\Lambda} = 0.466\,\frac{\delta g_V}{g_V} + 0.151\,\frac{\delta g_M}{g_M} + 1.567\,\frac{\delta g_A}{g_A} - 0.184\,\frac{\delta g_P}{g_P} + 0.0238\,\delta g_{S,T}$$

$\frac{\delta\Lambda}{\Lambda}$ [%] =	0.024	0.01	0.38	3.7	0.24

assuming optimistic 20% g_P error

assuming g_T<0.1

error from V_{ud} = 0.16 %

pseudoscalar form factor g_P

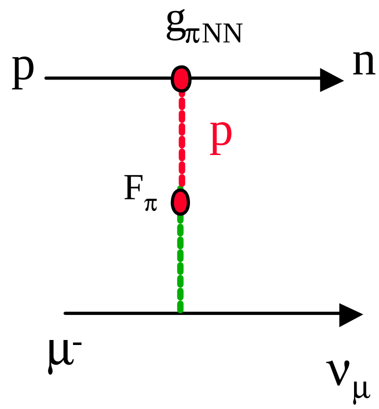
PCAC:

$q^2=0$ GT relation:

$g_{\pi NN}(0)\ F_\pi = M\ g_A(0)$

$q^2<0$ $g_p(q^2) = 2\ m\ M/(m_\pi^2 - q^2)\ g_A(0)$

$g_P = 8.7$



heavy baryon chiral perturbation theory:

$$g_p(q^2) = \frac{2m_\mu g_{\pi NN} F_\pi}{m_\pi^2 \;\; q^2} - \frac{1}{3} g_a(0) m_\mu M r_a^2$$

agrees with Wolfenstein estimate

$g_P = (8.74 \pm 0.23) - (0.48 \pm 0.02) = 8.26 \pm 0.23$

g_{pNN}
13.31(34)
13.0(1)
13.05(8)

Λ calculations $O(p^3)$ show good convergence: 100 % 25 % 3 %

delta effect small LO NLO NNLO

BHM, AMK

author	year	g_P	Λ_S	Λ_T	comment
Primakoff	1959		664(20)	11.9(7)	smaller g_A
Opat	1964		634	13.3	smaller g_A
Bernard et al	1994	8.44(23)			
Fearing et al	1997	8.21(9)			
Govaerts et al	2000	8.475(76)	688.4(38)	12.01(12)	
Bernard et al	2000/1		687.4 (711*)	12.9	NNLO, small scale
Ando et al	2001		695 (722*)	11.9	NNLO

*NLO result

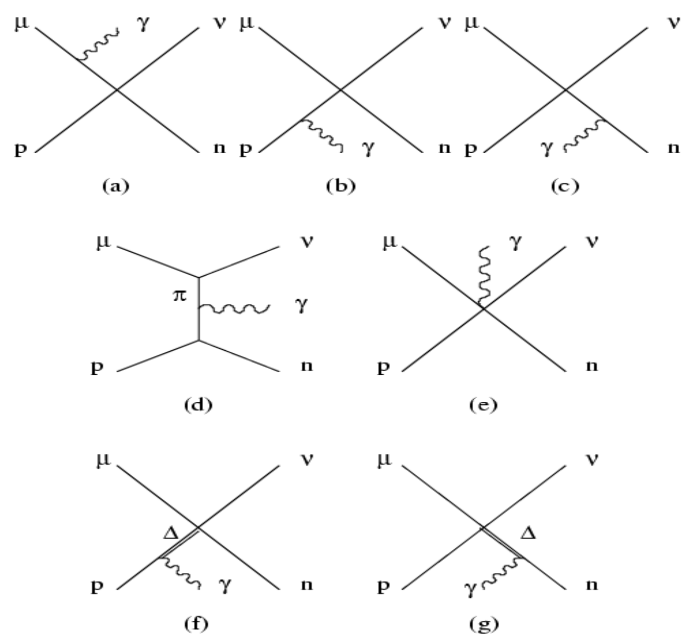
Experimental information on g_P

Ordinary **M**uon **C**apture $m^- + \mathbf{p}$ ® $n_m + \mathbf{n}$

BR~10^{-3}, 8 experiments 1962-82, BC, neutron, electron detection
"in principle" most direct g_P measurement

Radiative **M**uon **C**apture $m^- + \mathbf{p}$ ® $n_m + \mathbf{n} + g$

BR~10^{-8}, TRIUMF (1998),
E_γ>60 MeV, 297 ± 26 events
closer to pion pole →
3x sensitivity of OMC
theory more involved
(min substitution, ChPT)



other

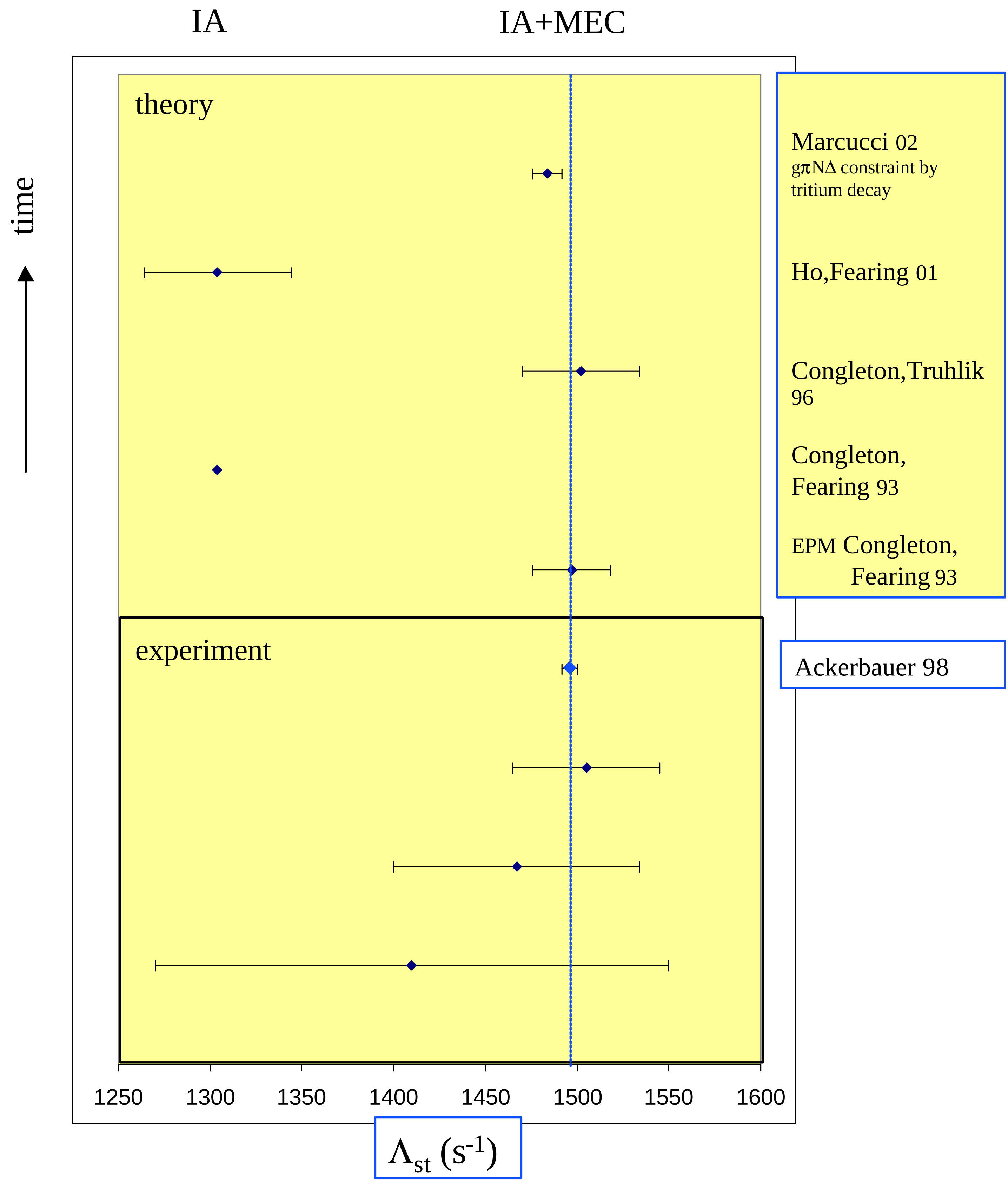
• Muon capture in nuclei

$m + {}^3\mathbf{He}$ ® $\mathbf{n} + {}^3\mathbf{H}$ Λ_{st}=1496 ±4 s^{-1} PSI (1998)
$g_p = g_p^{th}$ (1.08 ±0.19) error dominated by 3-N theory

• Neutrino scattering

• π electro production at threshold

update μ^3He capture rate



experimental methods

$\mu^- p\,(\uparrow\downarrow) \rightarrow \nu_\mu + n$

p

m[-] ® **e+$\bar{\text{n}}_{\mathbf{e}}$+n$_{\text{m}}$**

measure neutrons
BR≈10^{-3}

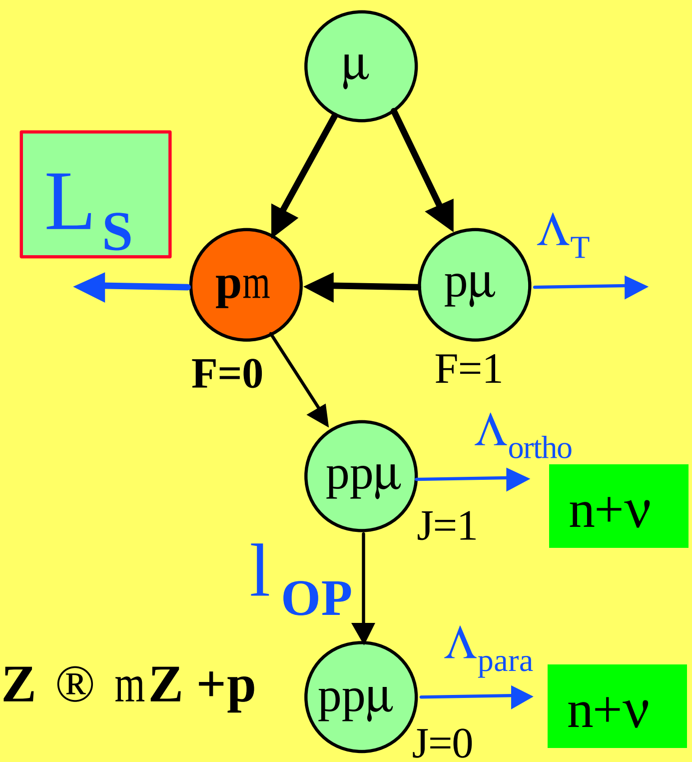
measure t_{m+} **and** t_{m-}
Þ $L_S = 1/t_{m-} - 1/t_{m+}$

challenges

(Rich) physics effects

- **Interpretation:**
  where does capture occur **?**

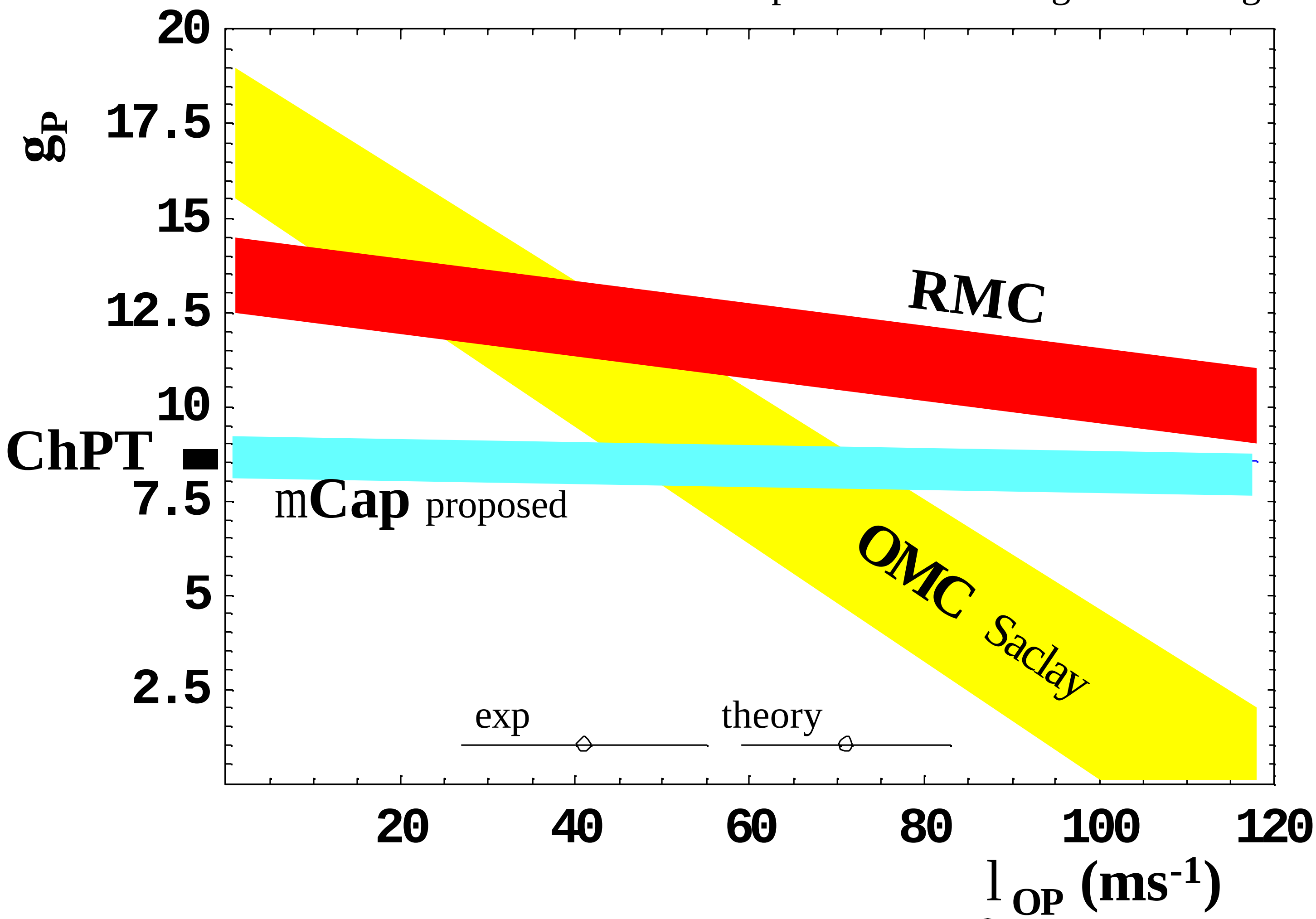
  Critical because of strong spin dependence of V-A interaction



- **Background:**
  Wall stops and diffusion
  Transfer to impurities m**p+Z** ® m**Z +p**
- **Rate and statistics**
- m**SR effect for** m^+

Muon Capture and g_P

update from Gorringe & Fearing



Interpretation of observed rate sensitive to ppμ state, where capture occurs, atomic physics

Summary of confusing exp situation

- **OMC not precise, ambiguous interpretation**
- **RMC 4 s discrepancy exp/th**
- **no overlap theory & OMC & RMC**

theory summary and questions

g_P

1. **fundamental and least known weak nucleon FF**
2. **solid theoretical prediction at 2-3% level**
3. **basic test of QCD symmetries**

Numerous papers to solve the puzzle, see refs in

T. Gorringe, H. Fearing, nucl-th/0206039, Jun 2002

V. Bernard et al., Nucl. Part. Phys. 28 (2002), R1

Conc. 2

- **critical assessment of assumptions**

  atomic physics issues

  $g_{\pi NN}(q^2)$ issues, future improvements

  ChPT issues

- **potential deficiencies in RMC calc?**
- **radiative corrections**

Conc. 3

- **What if g_P really 50% larger than PCAC,ChPT predict?**
- **Which experimental efforts/stages are justified?**

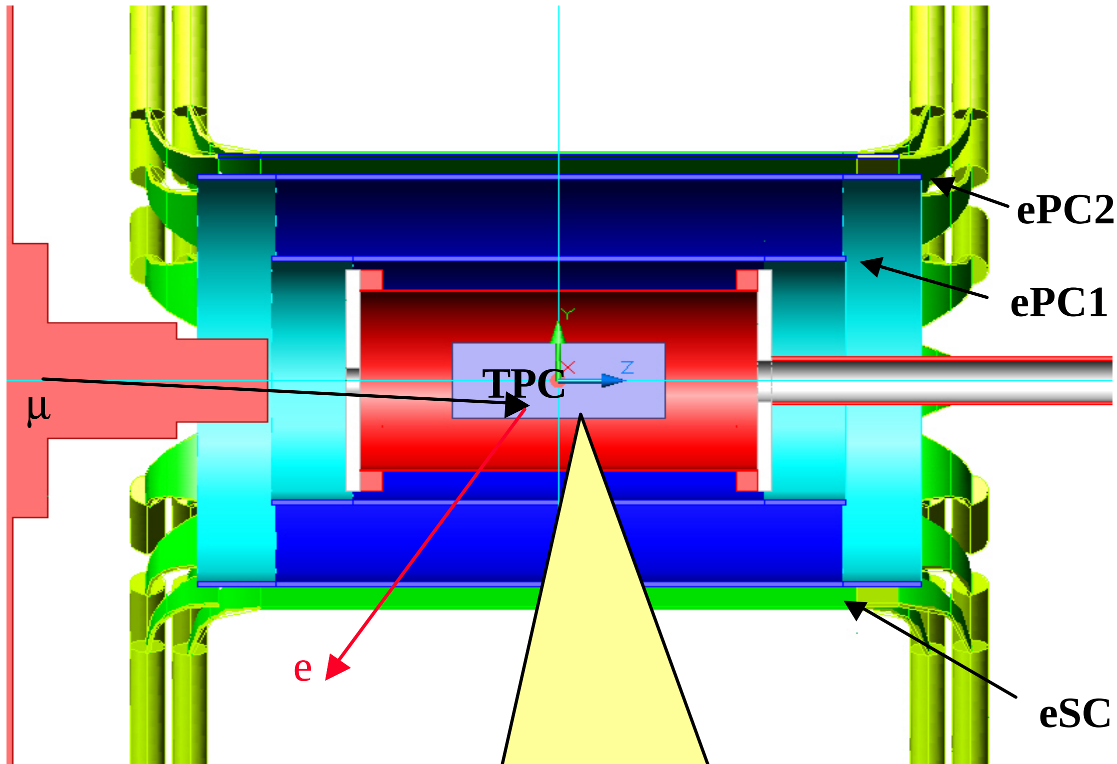
  Clarify 50% effect

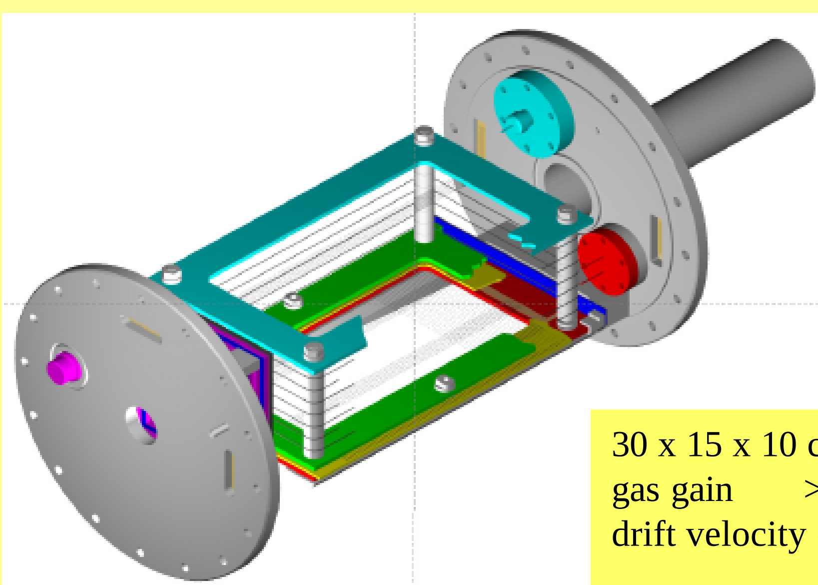
  determine g_P to 2-3%

  try to improve second class current limits…

mCap overview

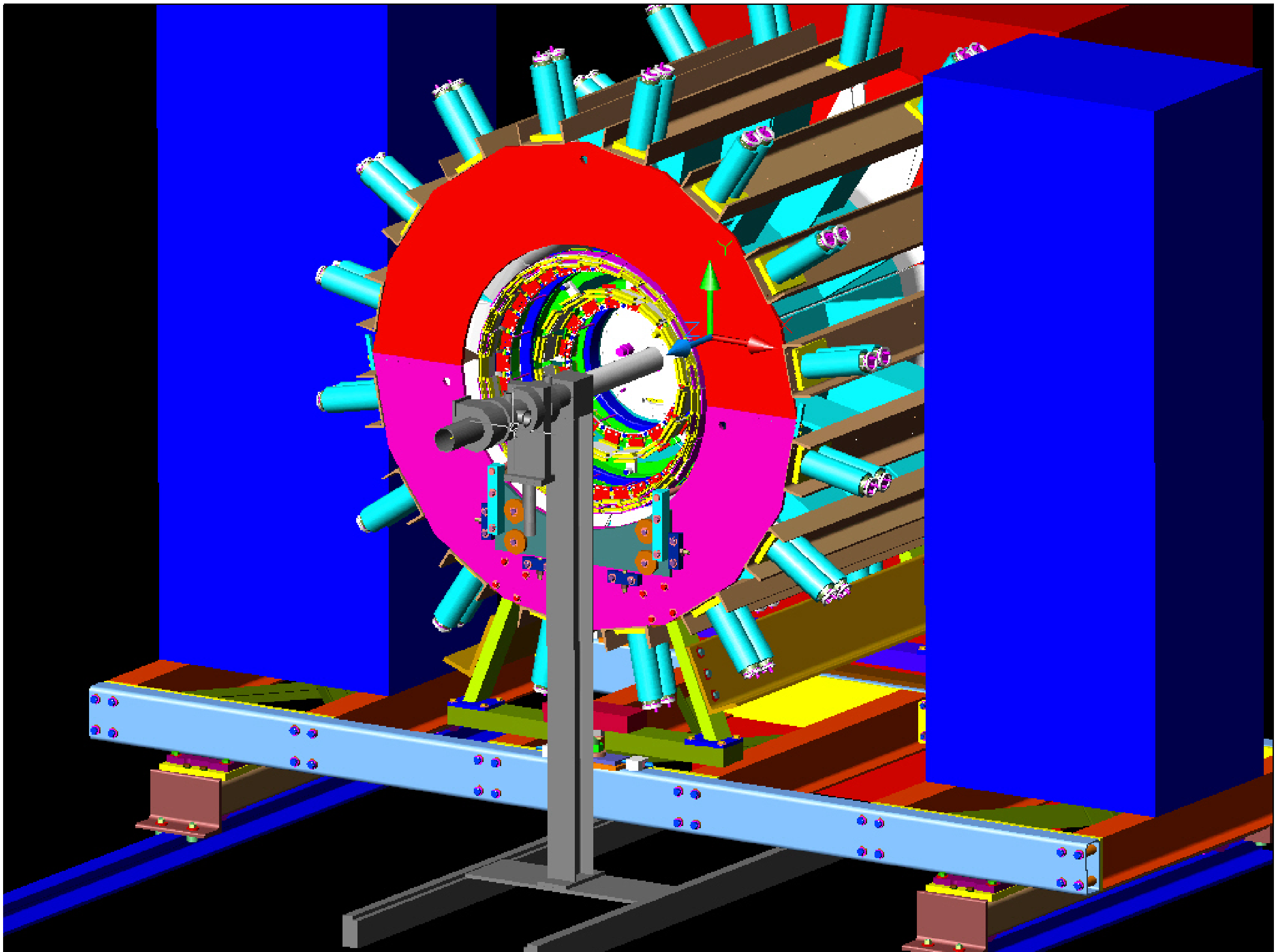
New idea: **time projection chamber with**
ultra-pure H_2 gas 10 bar as active target
lifetime method, t_m to 10^{-5}

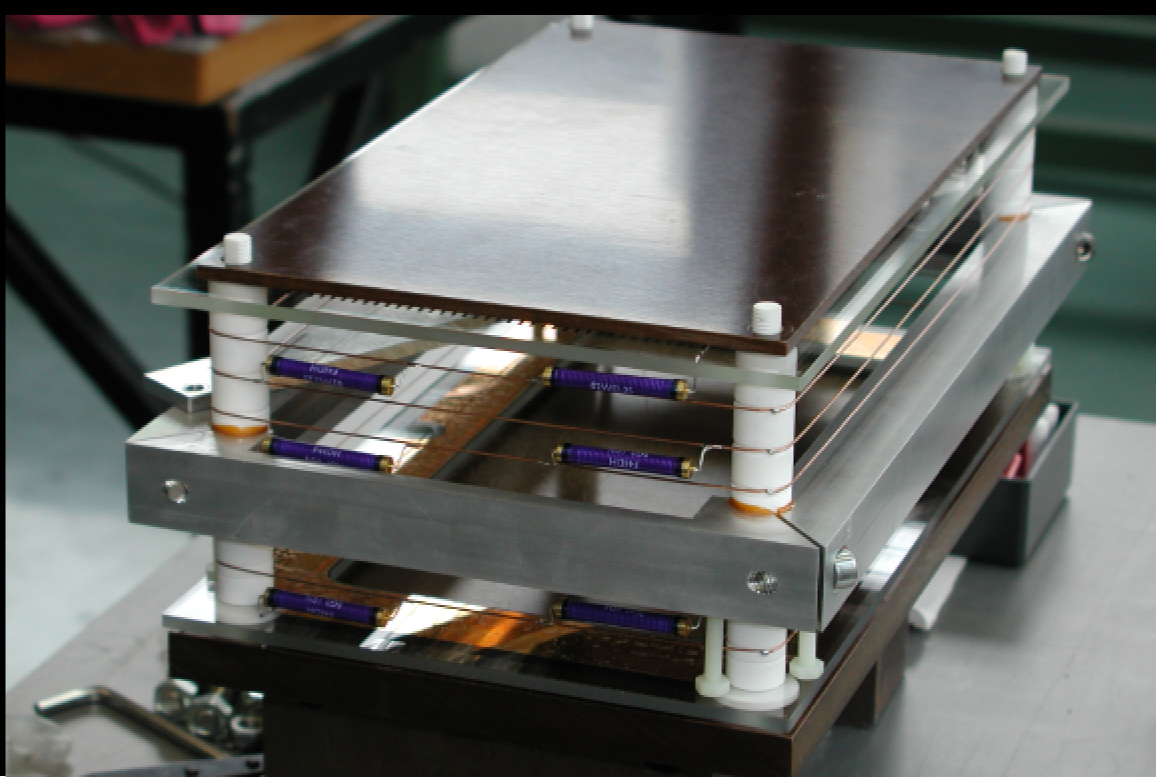




30 x 15 x 10 cm^3 , HiVacuum construction
gas gain > 5000 (e)
drift velocity (cm/μs) 0.7 @ 2 kV/cm

voltage (kV)	cathode	-30
	cathodes strip	- 7
	anodes	0





experimental strategy

Physics effects

- **Interpretation**
  At low density (1% LH_2) mostly
  capture from m**p(F=0)** atomic state.

- **Wall stops and diffusion**
  muon stop fiducial volume determined by 3-D tracking

- **Transfer to impurities** ($c_Z<10^{-8}$, $c_d<10^{-6}$)

  - purification
    hydrogen chambers bakeable to 150 C
    continuous purification, CRDF
    protium: monitoring, isotope separation ISTC?

  - monitoring system
    TPC monitors m**+Z** ® **Z'+n+**n and transfer to d
    10^{-8} sensitivity with gas chromatograph

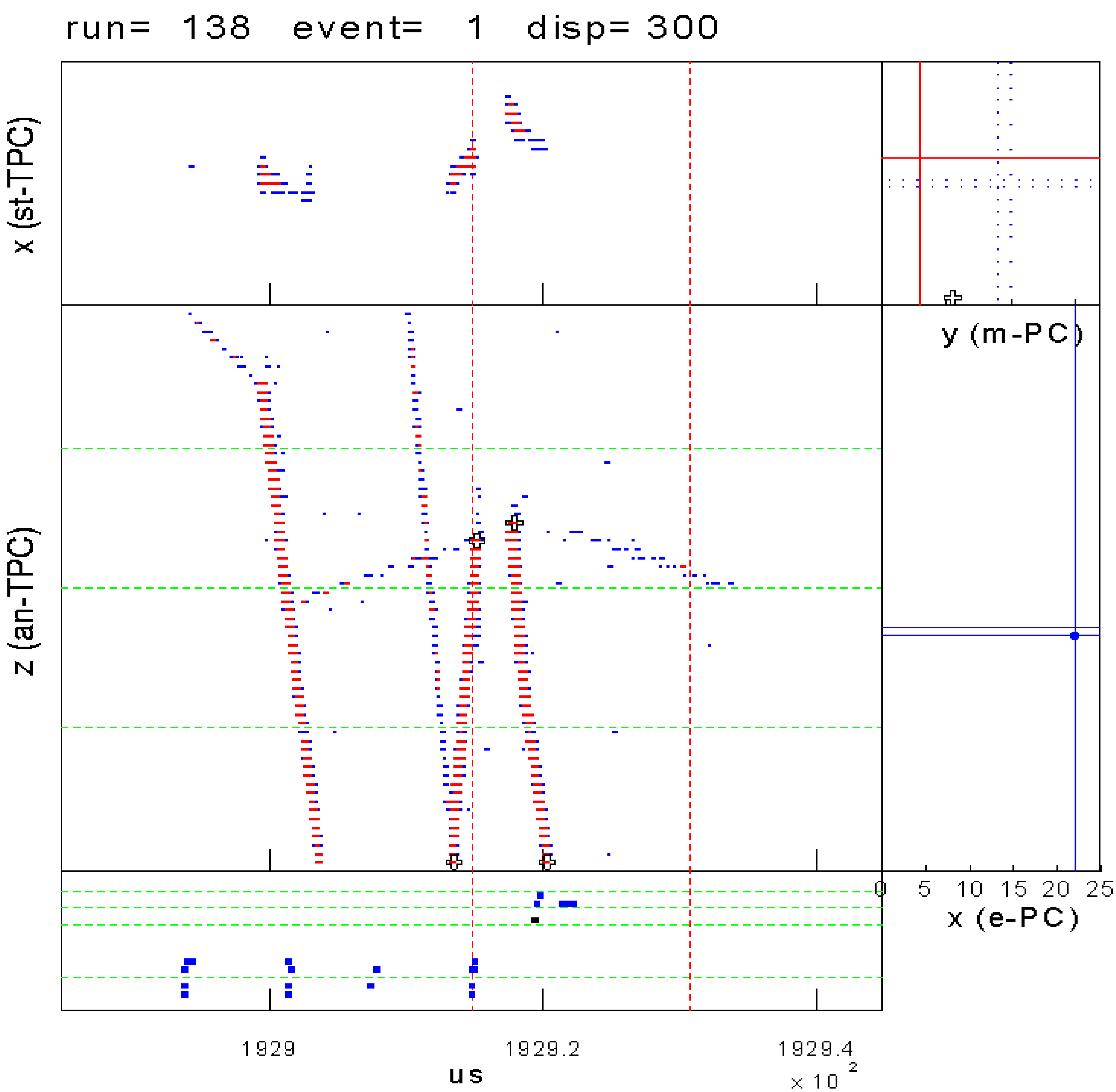
- **m^+SR**: calibrated with tranverse field 70 G

Statistics

- **10^{10} statistics**: Complementary analysis methods
  global pile-up free: only one μ in chamber
  local pile-up free: only one μ in acc. cylinder around e track

Digital Readout

- two thresholds for TPC (electrons, muons)
- custom made deadtime less TDCs
- high bandwidth DAQ to processor farm, VME-64, VX works
- readout of contiguous (ms) time regions to provide complete history information



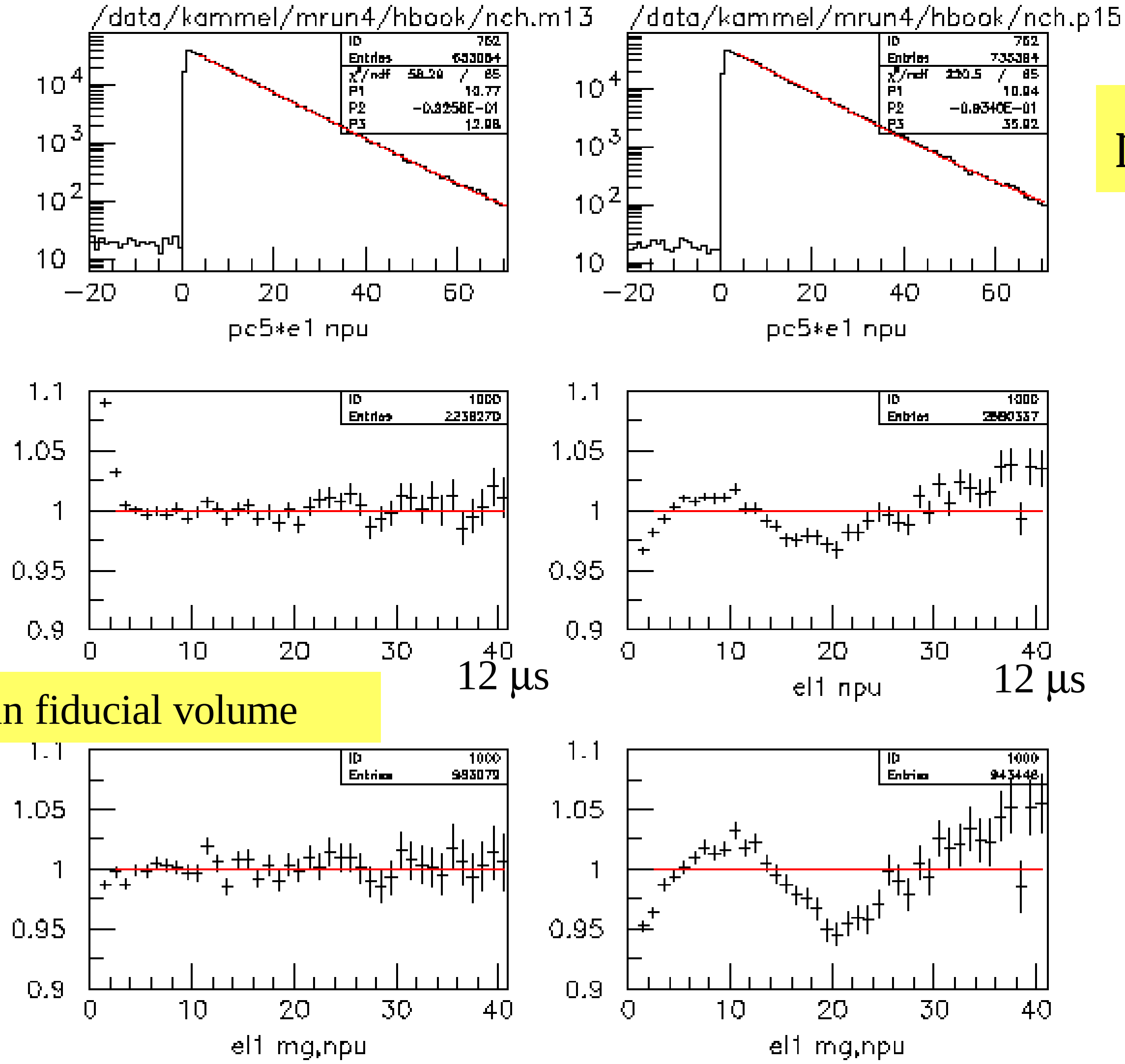
time spectra

el scintillator only

2000/05/09 16.48

m -

m +



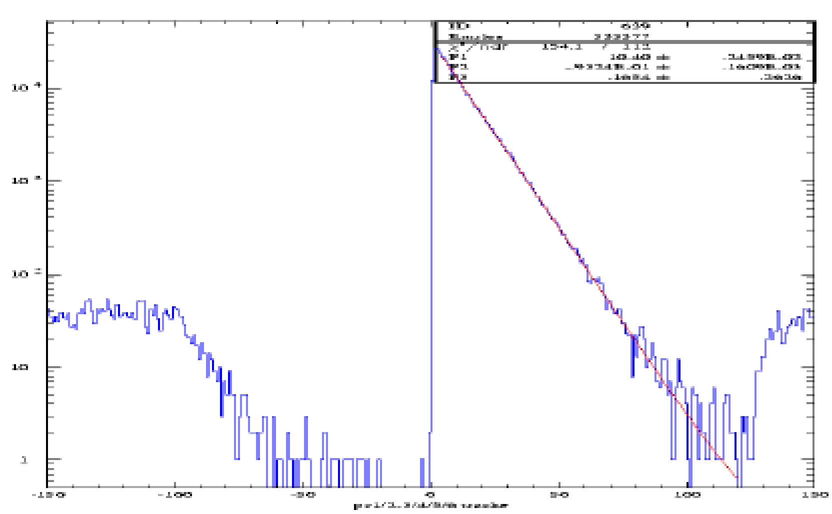
12 µs

12 µs

µ stop in fiducial volume

e after µ time (bin width 200ns)

electrons fully tracked

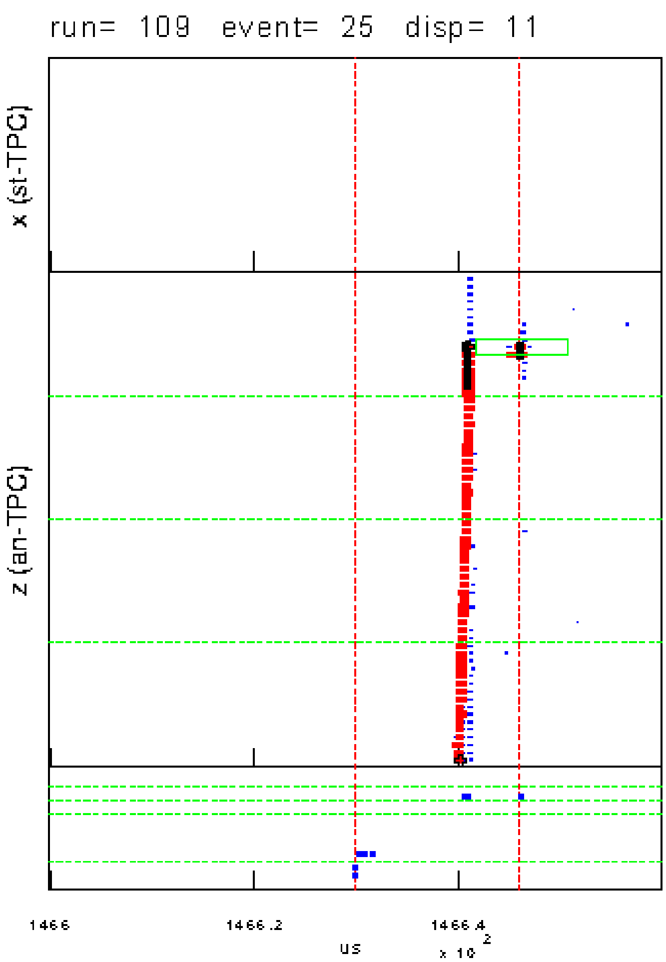


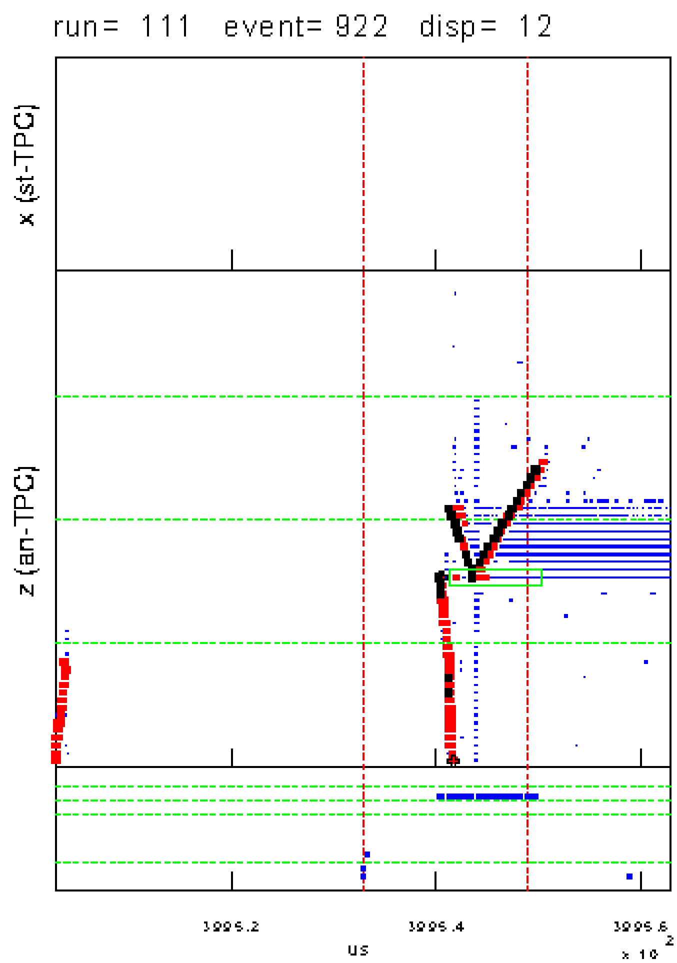
impurity capture

$\mu + Z \rightarrow Z' + n + \nu$

purity requirements	0.01 ppm Z>1
	1. ppm D
or 0.1 ppm if measured & corrected	

FADC and TDC analysis
3 threshold trigger



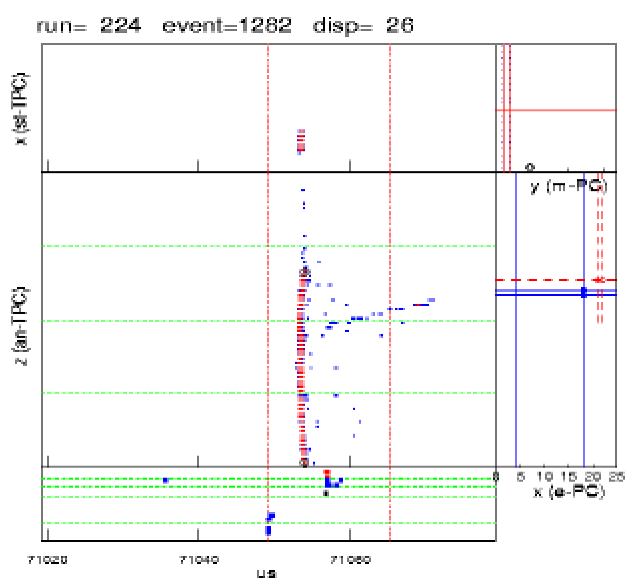


m transfer to deuterium, diffusion

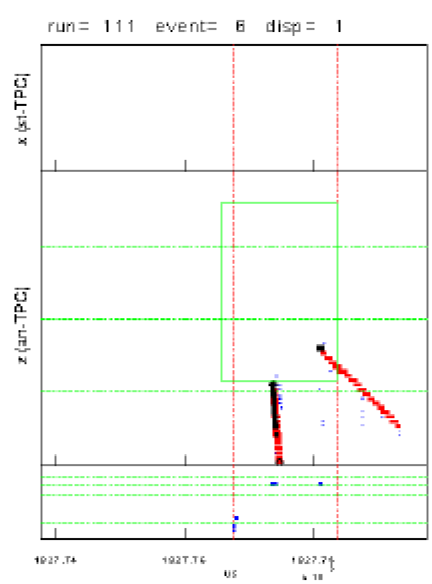
$$\mu p + d \rightarrow \mu d + p \rightarrow p\mu d \rightarrow \mu(5.3\text{MeV}) + {}^{3}\text{He}(0.2\text{KeV})$$

Ramsauer Townsend minimum in μd + p scattering at 1.6 eV

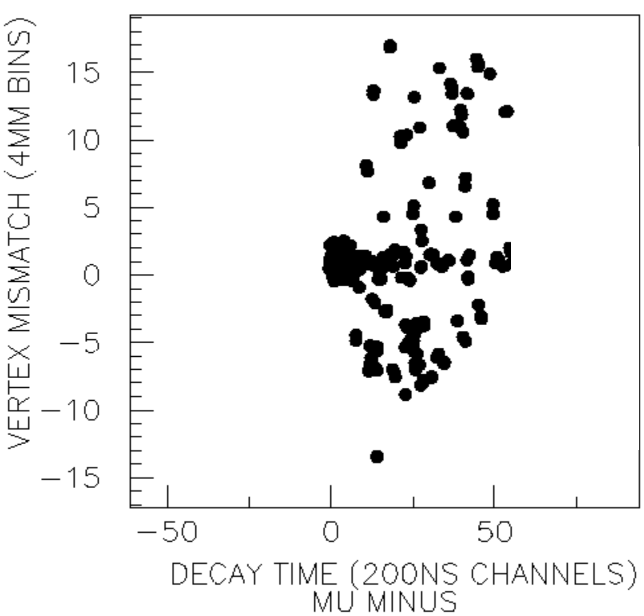
diffusion



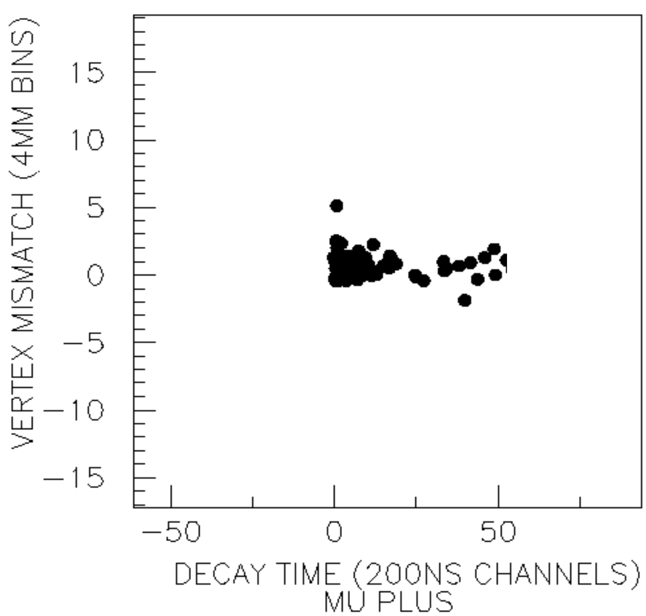
μ catalyzed pd fusion



μ^- diffusion



μ^+ diffusion



mCap summary

	correction(error) to λ(ppm)					
	global PU free data			local PU free data		
	μ^-	μ^+	comment	μ^-	μ^+	comment
statistics	(10)	(10)	10^{10}events	(7)	(7)	$2\text{x}10^{10}$events
wall stops	(2)	-		(2)	-	
impurities	2(3)	-	$c_Z=10^{-8}$assumed	2(3)	-	$c_Z=10^{-8}$assumed
flat accidentals	(2)	(2)	level 10^{-4}	(3)	(3)	level $5\text{x}10^{-4}$
μSR	-	(2)		-	(2)	
diffusion	1(1)	-	no vertex cut	100(5)	-	5 cm radial cut
μ effect on electronics	-	-		-	-	
two event correlation	-	-		(2)	(2)	accidental structure
total systematic error	**4.2**	**2.8**		**7.1**	**4.1**	
$\delta\lambda$ **total error**	**10.9**	**10.4**		**10.**	**8.1**	

Table 11: Summary of statistical and systematical errors for 2 complementary analysis methods

Planned schedule μCap I

- technical proposal spring 2001,
  received "high priority status"
- development final detector components and
  high purity chambers, 2001-2002
- commissioning and first test data 2002
- data run 2003, 2004

μCap II with **muon-on-request** beam (2004, 2005)
chopper development and μ^+ result from μLan,

- goal Λ_S from 1% to 0.3 %, g_P 7 % to 2-3%

  20-30x exp improvement
  Λ_S similar precision as τ_n
  exp challenges: statistics, purity, atomic physics

MORE concept

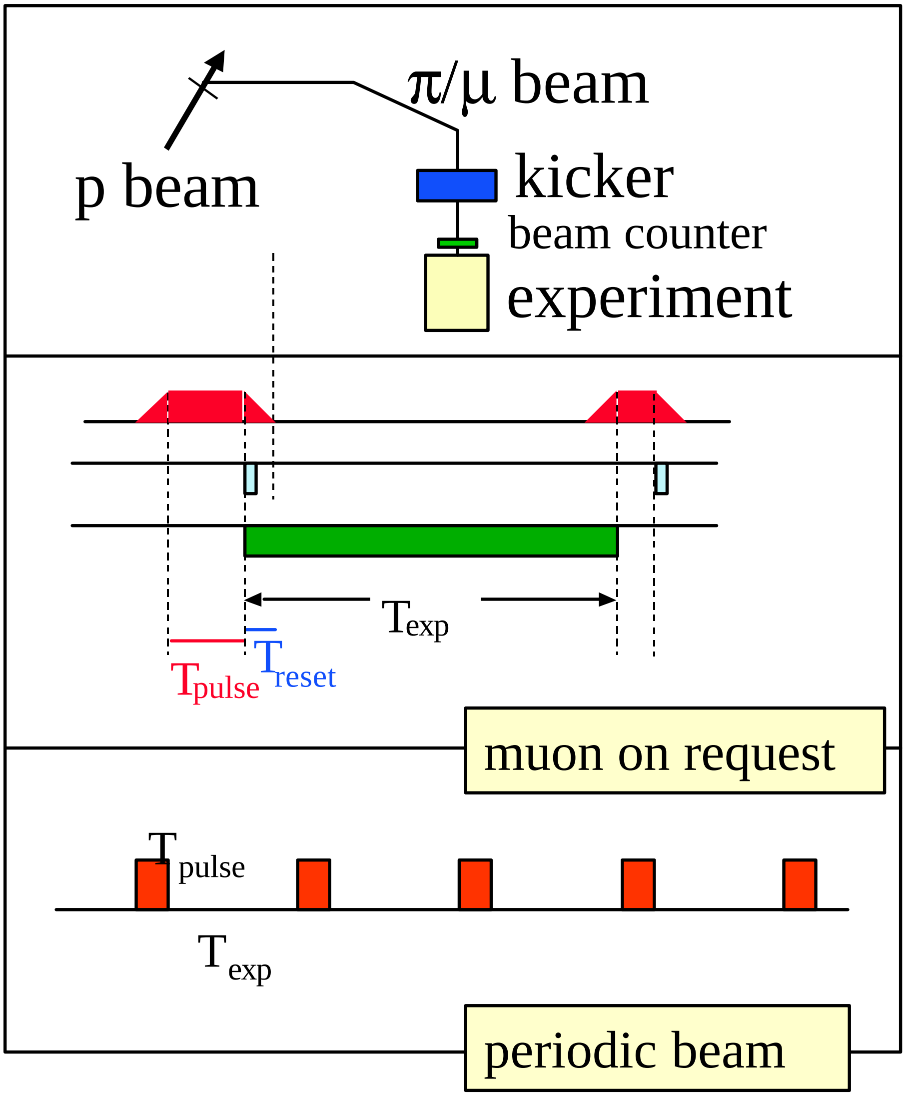


Table 8: Statistics estimates for the two main analysis methods and the potential future MORE beam

	local PU free	global PU free	MORE	source for estimate
incident μ flux(kHz)	30	30	70	measured
efficiencies				
e acceptance	0.7	0.7	0.7	Monte Carlo
e efficiency, reconstruction	0.95	0.95	0.95	measured, MC
μ stopping	0.8	0.8	0.8	measured
fit time window	0.9	0.9	0.9	measured
reconstruction				
pile-up free	0.70	0.40	1.0	estimate / equ. in sect 5.3
total acceptance	0.33	0.20	0.48	
event rate (kHz)	10.	5.8	33.	
days for 10^{10} **reconst. events**	11.5	20.0	3.5	