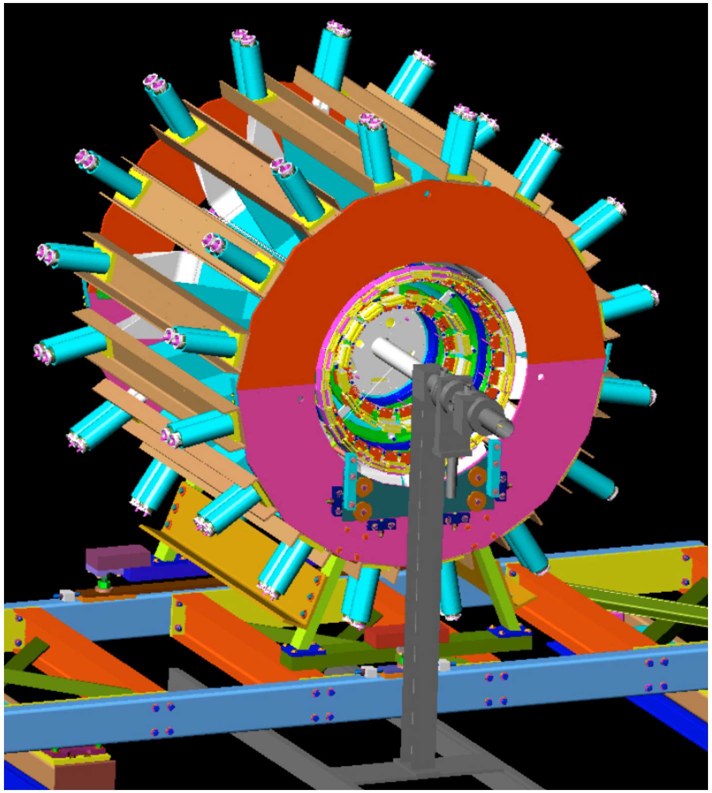
The MuCap experiment: A measurement of the rate of muon capture by the proton



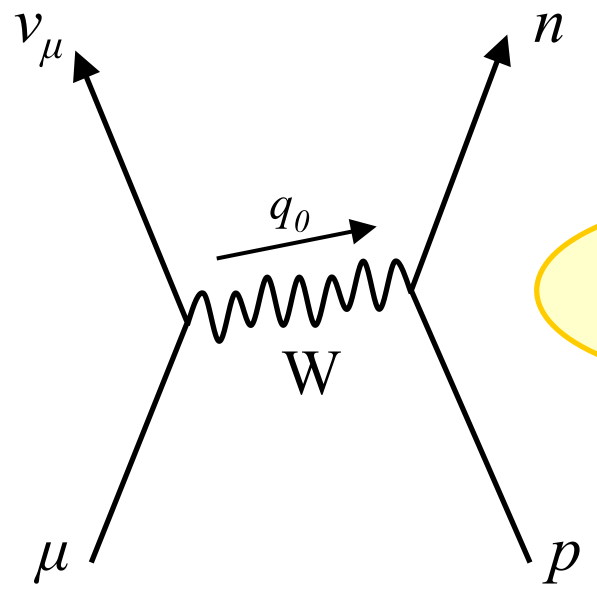
Tom Banks, on behalf of the MuCap Collaboration
University of California, Berkeley
KRL Seminar, Caltech
October 19, 2007

I. Introduction to muon capture

The reaction

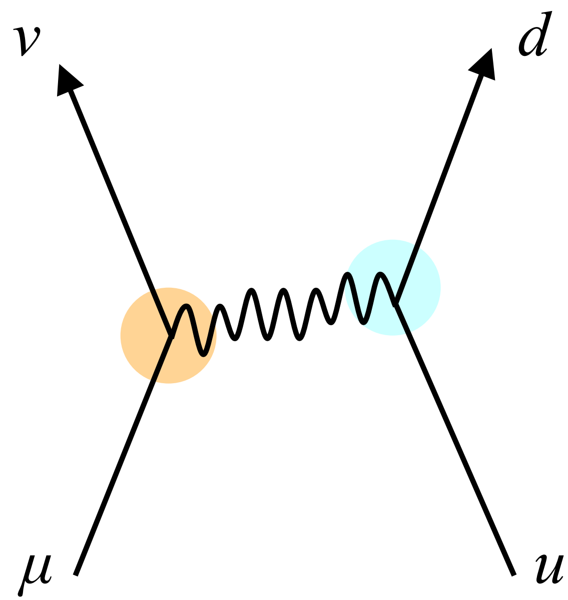
$$\mu^- + p \rightarrow n + \nu_\mu$$

- Semileptonic, weak interaction process
- Fixed momentum transfer



$$q_0^2 = -0.88 m_\mu^2$$

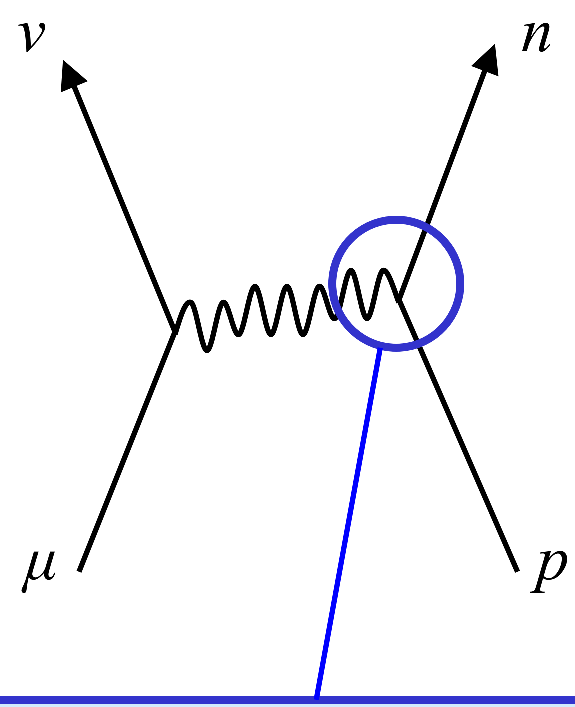
Current structure



$$L = \frac{G_F V_{ud}}{\sqrt{2}} \left[\nu \, \gamma_\alpha (1 - \gamma_5) \mu \right] \left[d \gamma_\alpha (1 - \gamma_5) u \right]$$

- The leptonic and quark currents in muon capture possess the simple *V-A* structure characteristic of the weak interaction

The hadronic current



$$\langle n | (\gamma_\alpha) g_V + (i\sigma_{\alpha\beta} q^\beta) g_M + (\gamma_\alpha \gamma_5) g_A + (q_\alpha \gamma_5)\, g_P \, | p \rangle$$

- But muon capture involves nucleons, not isolated quarks!
- The QCD substructure of the nucleon complicates the weak interaction physics
- QCD effects are encapsulated in the charged-current's four "induced form factors"

The pseudoscalar form factor

$$\langle n | (\gamma_\alpha) g_V + (i\sigma_{\alpha\beta} q^\beta) g_M + (\gamma_\alpha \gamma_5) g_A + (q_\alpha \gamma_5) g_P | p \rangle$$

- The pseudoscalar g_P is by far the least well known of the form factors

$g_V = 0.976(1)$

$g_M = 3.583(3)$

$g_A = 1.247(4)$

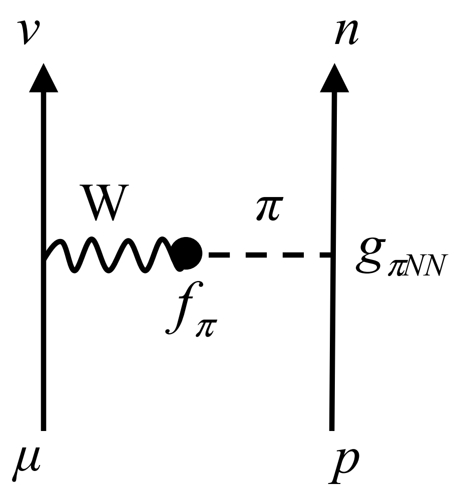
$g_P = 8.26, 8.7, 10.6, 12.2, \ldots ?$

values and q^2-dependence known from EM form factors via CVC (g_V, g_M)

value known from β–decay; q^2-dependence known from neutrino scattering (g_A)

- Modern theories make relatively precise (3%) predictions for g_P …
- … but experimental results for g_P are inconsistent with each other and theory.

Theoretical predictions for g_P



- Pion pole is dominant contributor to the pseudoscalar form factor
- PCAC yielded an expression for the pseudoscalar more than 30 years ago:

$$g_P(q^2) = \frac{2m_\mu f_\pi g_{\pi NN}(q^2)}{m_\pi^2 - q^2} - \frac{1}{3} g_A(0) m_\mu m_N \langle r_A^2 \rangle$$

- Modern chiral perturbation theories (ChPT), which are low-E effective QCD, reproduce the PCAC result in systematic expansions
- Present-day heavy baryon ChPT (HBChPT) predicts $\mathbf{g_P(q_0^2) = 8.26 \pm 0.23}$

Options for measuring g_P

- The pseudoscalar form factor participates in any process involving the nucleon's charged current:
  - beta decay
  - neutrino scattering
  - pion electroproduction
  - muon capture

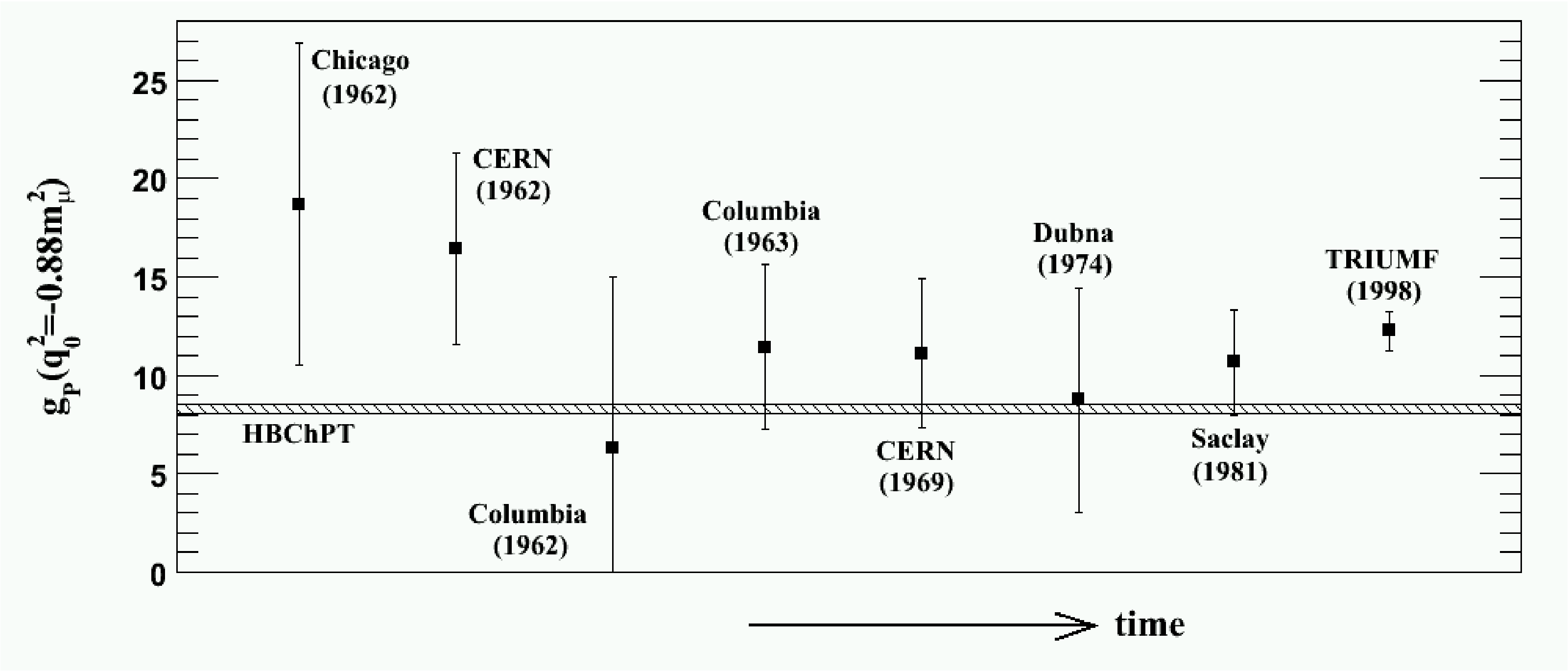
- Muon capture is the most attractive because of its
  - large momentum transfer
  - comparative ease of measurement
  - model-independent connection to g_P

- Muon capture offers a unique probe of the nucleon's electroweak axial structure

Muon capture experiments

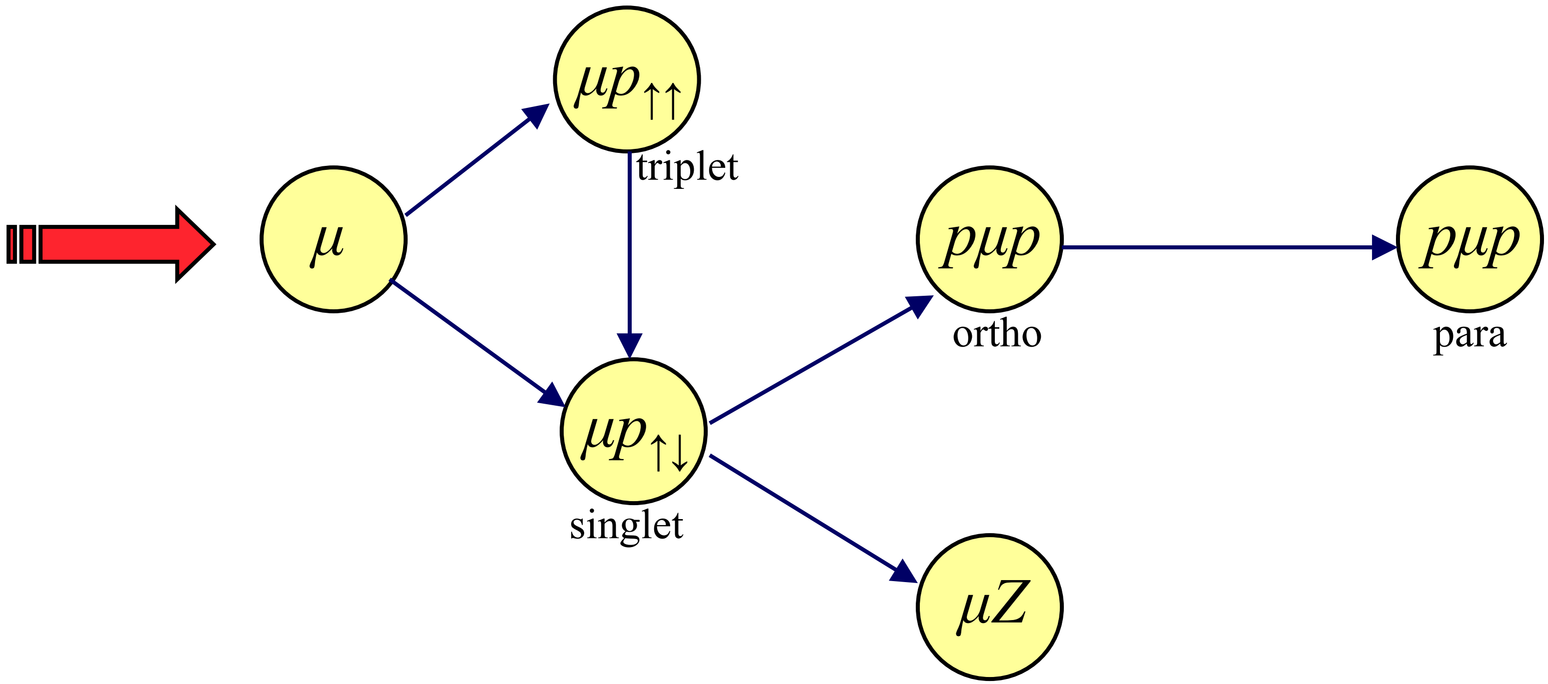
- Ordinary muon capture (OMC) in hydrogen: $\mu^- + p \rightarrow n + \nu_\mu$
  - branching ratio ~ 10^{-3}
  - > 5 neutron counting measurements
  - 1 muon lifetime measurement
- Radiative muon capture (RMC) in hydrogen: $\mu^- + p \rightarrow n + \nu_\mu + \gamma$
  - variable momentrum transfer → more sensitive to pion pole than OMC
  - branching ratio ~ 10^{-8}
  - only 1 measurement, counted photons > 60 MeV
- Muon capture in nuclei (helium, …)

Muon capture measurements in hydrogen



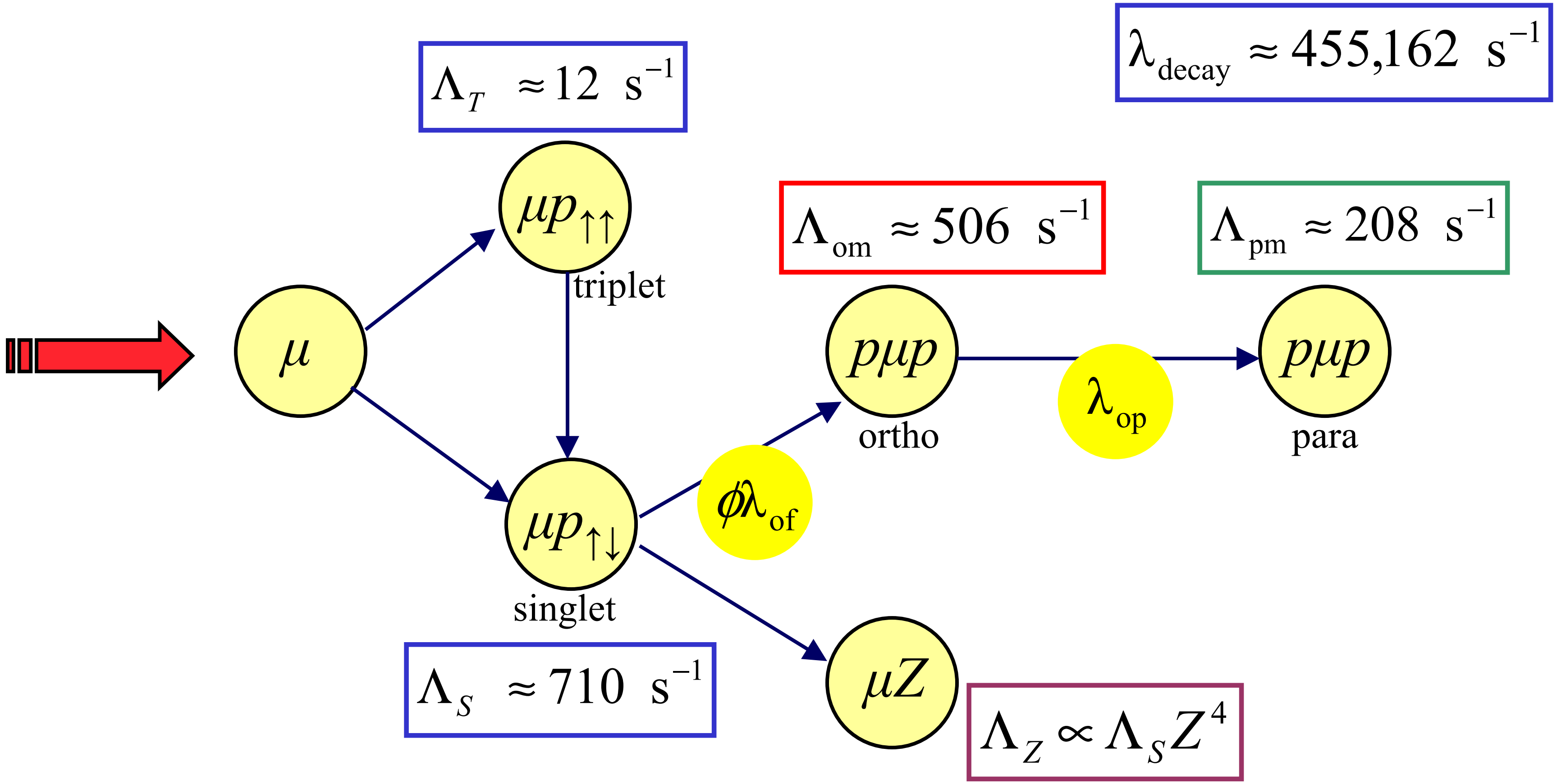
- Variety of experiments, using liquid and hydrogen targets
- Plotting the reported g_P values this way is somewhat misleading, as the extraction of g_P depends upon assumptions about hydrogen kinetics…

Muon kinetics in hydrogen



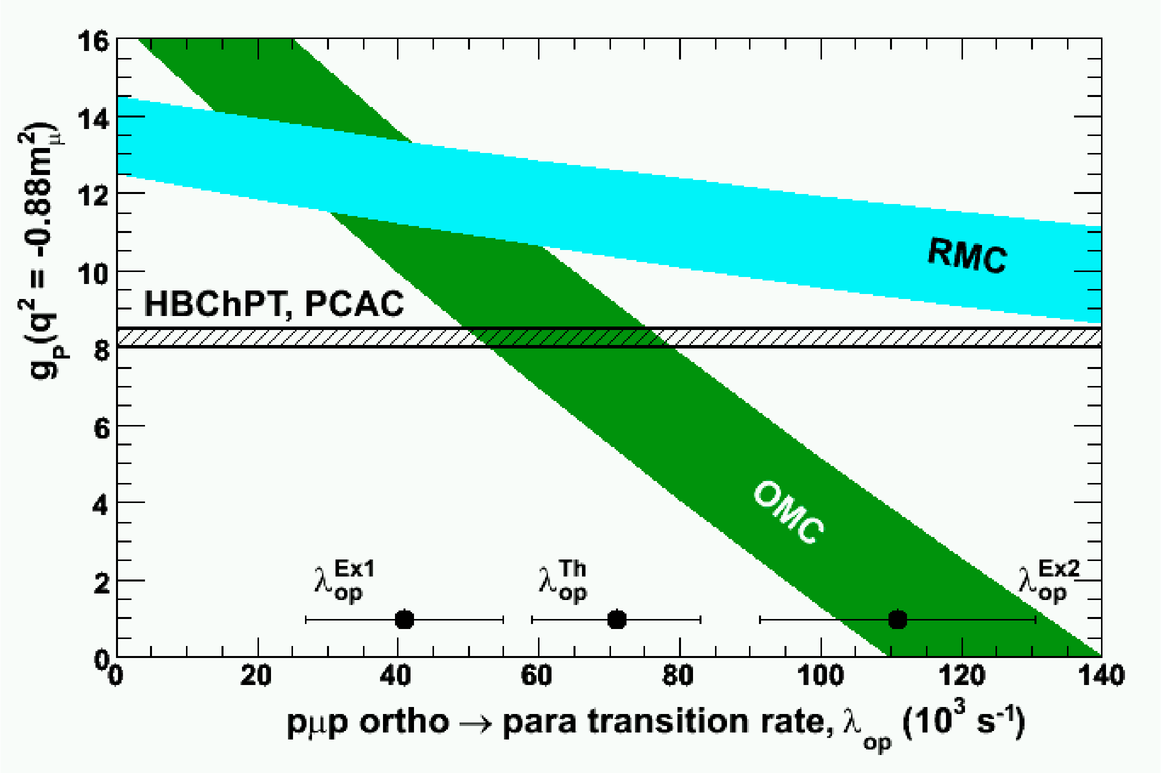
- Negative muons in pure hydrogen form a variety of atomic and molecular states
- Contamination from $Z>1$ elements introduces yet more pathways

Muon kinetics in hydrogen



- Each muonic state has a unique nuclear capture rate
- The measured capture rate is some combination of contributing rates
- Many of the important kinetics rates are poorly known

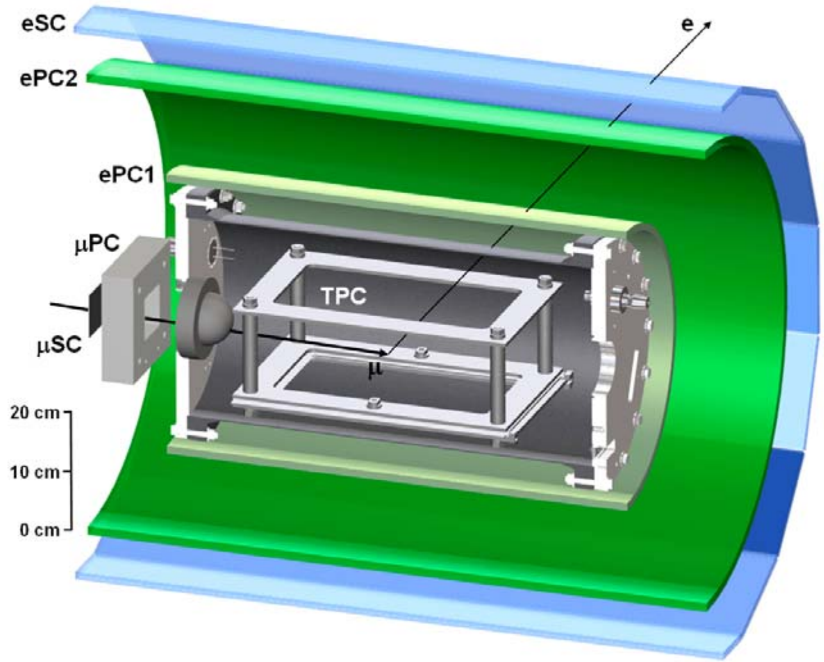
Knowledge of g_P prior to MuCap



- Interpretation of muon capture experiments depends upon poorly known molecular kinetics — namely, the transition rate λ_{op}.
- No way to reconcile theory with both RMC and OMC experiments!
- HBChPT makes precise prediction for $g_P \longrightarrow$ opportunity to test our understanding of role of chiral symmetries in QCD

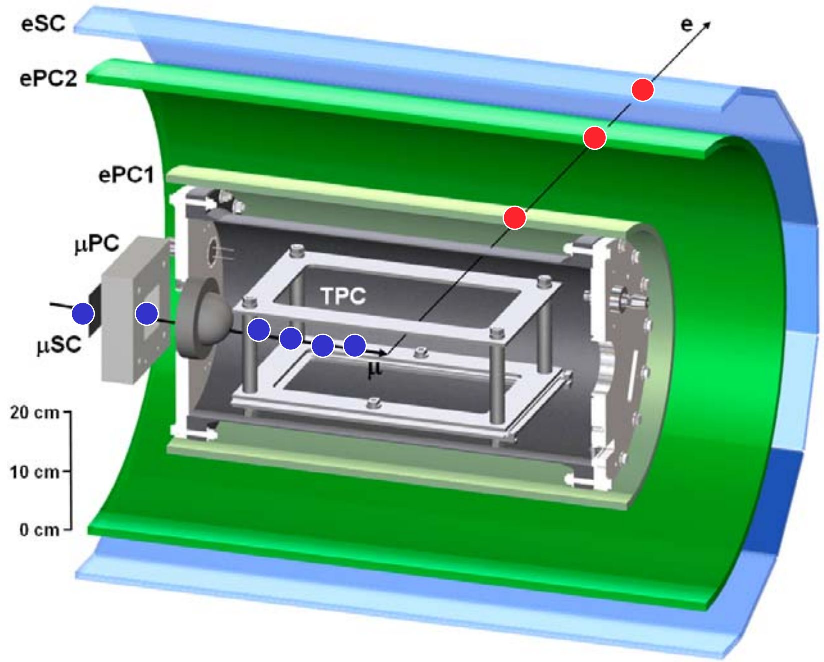
II. MuCap

Mission



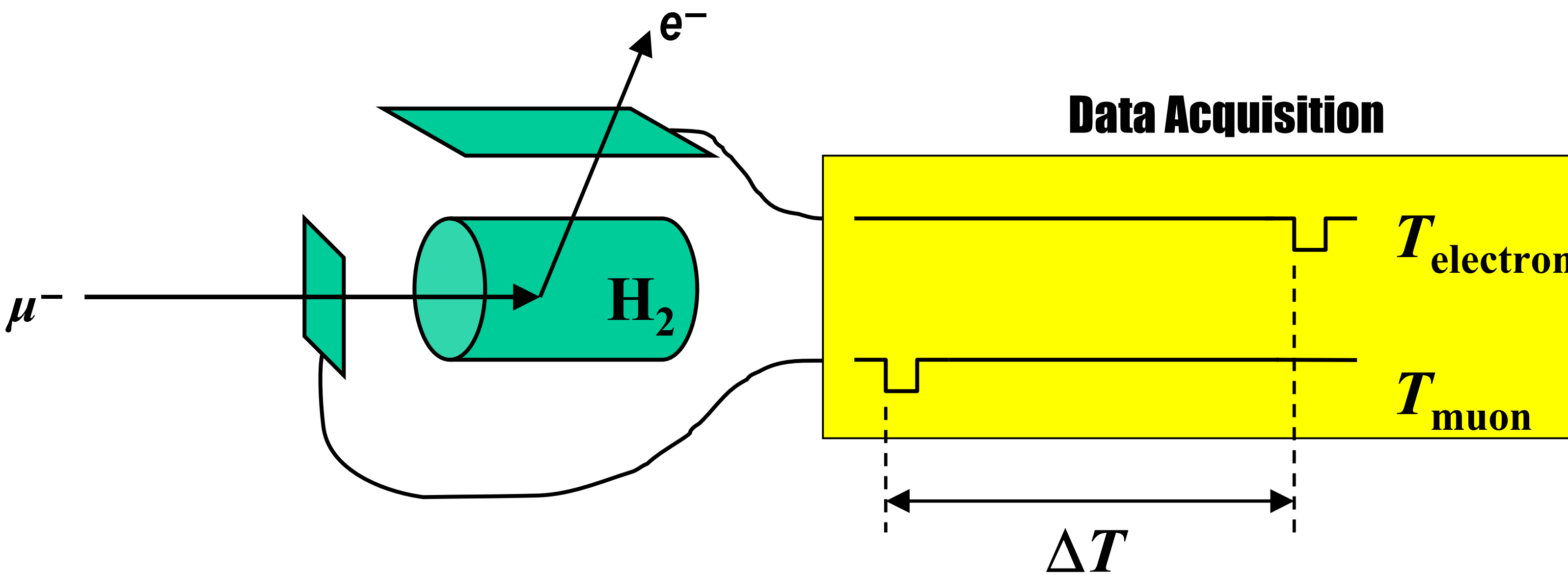
- We seek to measure the rate of nuclear muon capture by the proton, by stopping negative muons in hydrogen gas and observing the time spectrum of decay electrons.

Apparatus

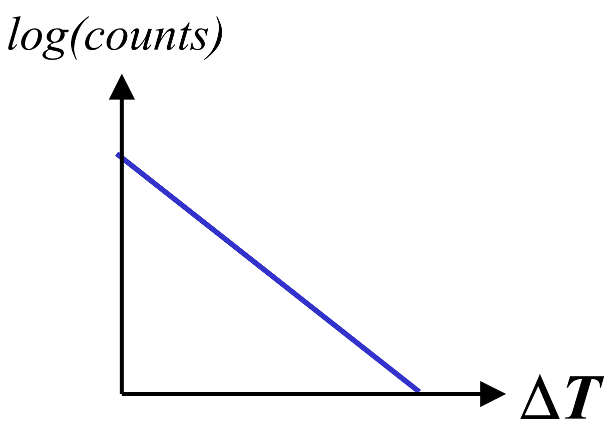


- **Muon detectors**
  - ***μ*SC**: fast timing of muon arrivals
  - ***μ*PC1,TPC**: 3D tracking of incoming muon trajectories
- **Electron detectors**
  - **ePC1, ePC2**: 3D tracking of outgoing electron trajectories
  - **eSC**: fast timing of outgoing decay electrons

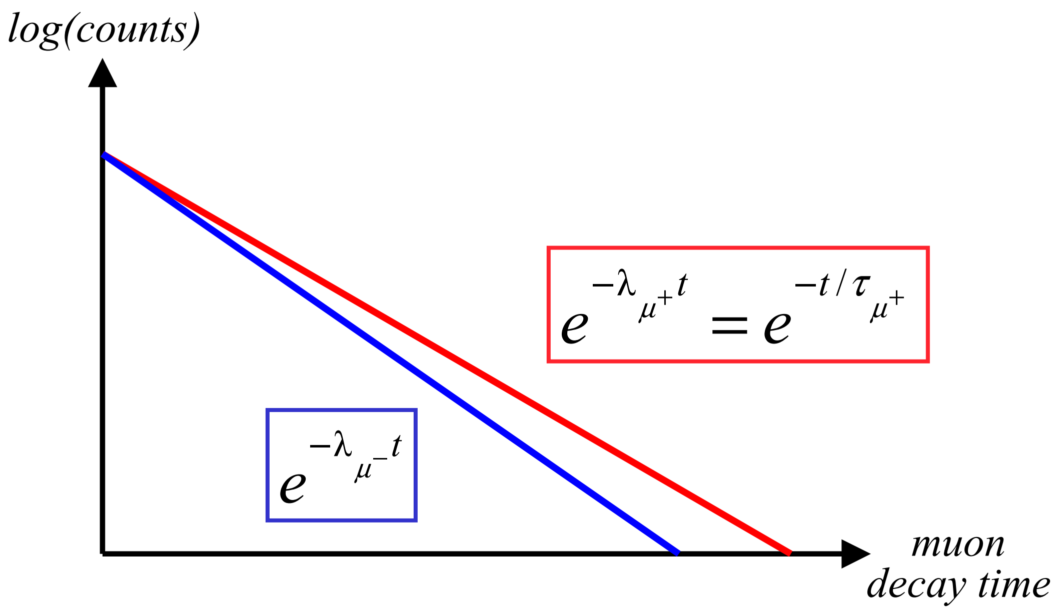
Method: “Lifetime technique”



- Fill histogram with muon’s lifetime ΔT
- Repeat N times for a $1/\sqrt{N}$ precision lifetime measurement:



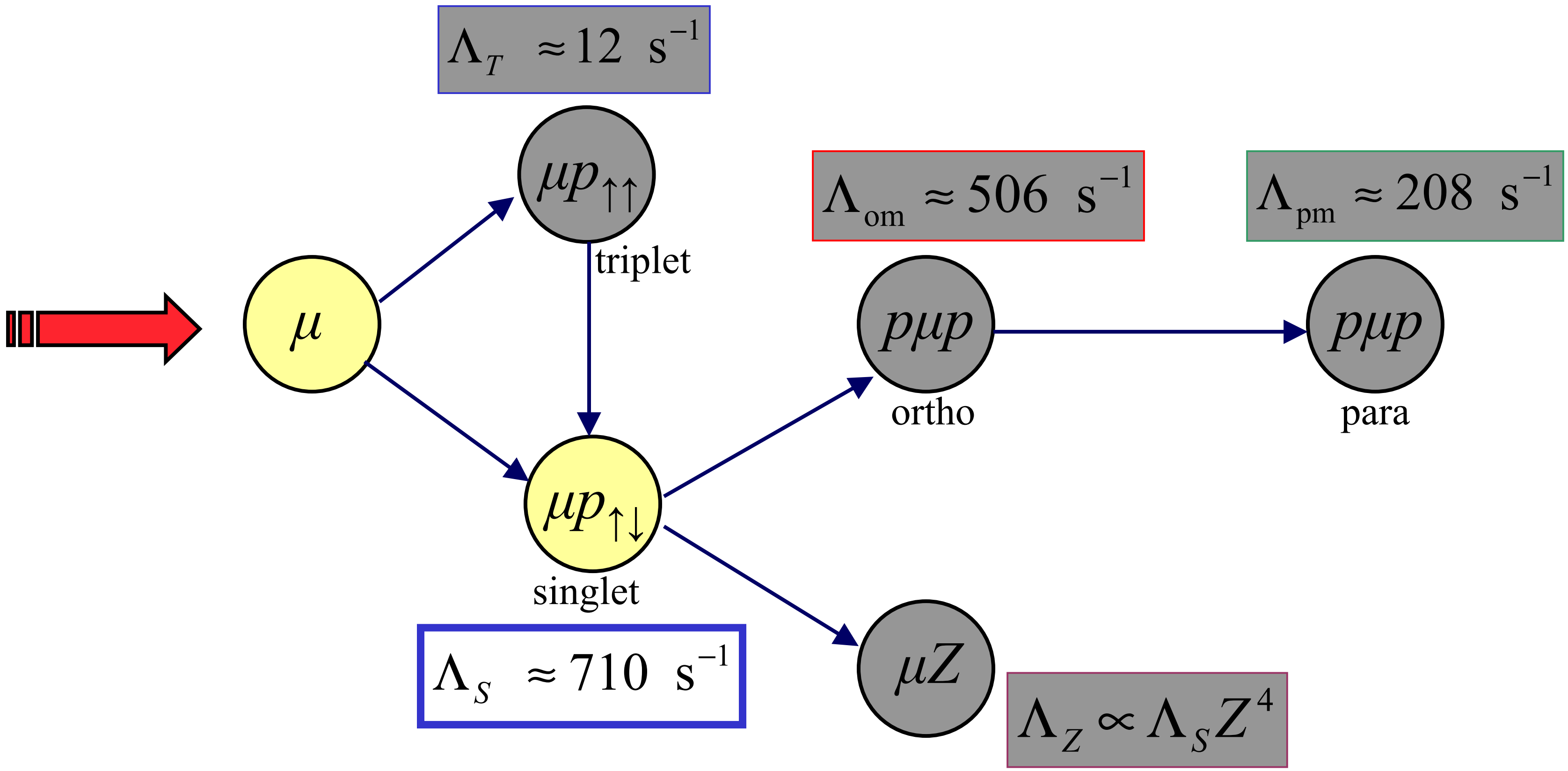
Method: "Lifetime technique"



- Negative muons can disappear via decay or nuclear capture
- Positive muons can only decay
- The muon capture rate can be obtained from the small (0.16%) difference between the disappearance rates (i.e. inverse lifetimes) of the two species:

$$\Lambda_{\text{capture}} = \lambda_{\mu^-} - \lambda_{\mu^+}$$

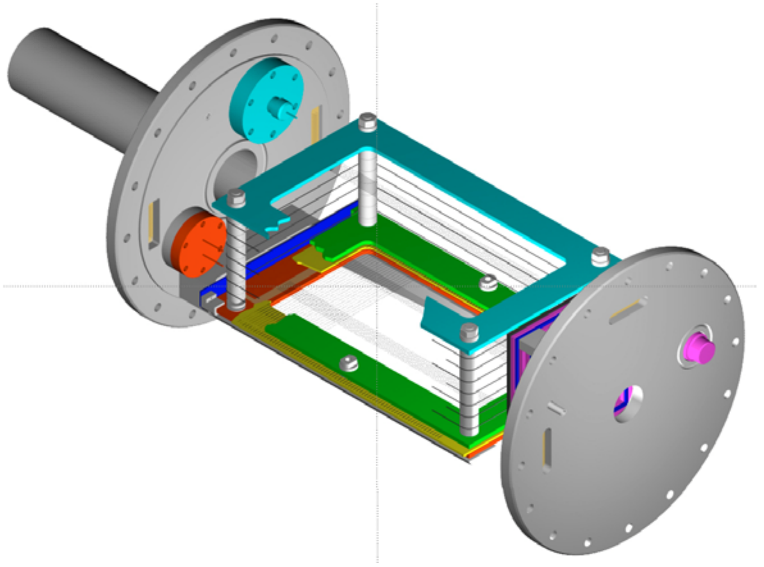
What about problematic kinetics?



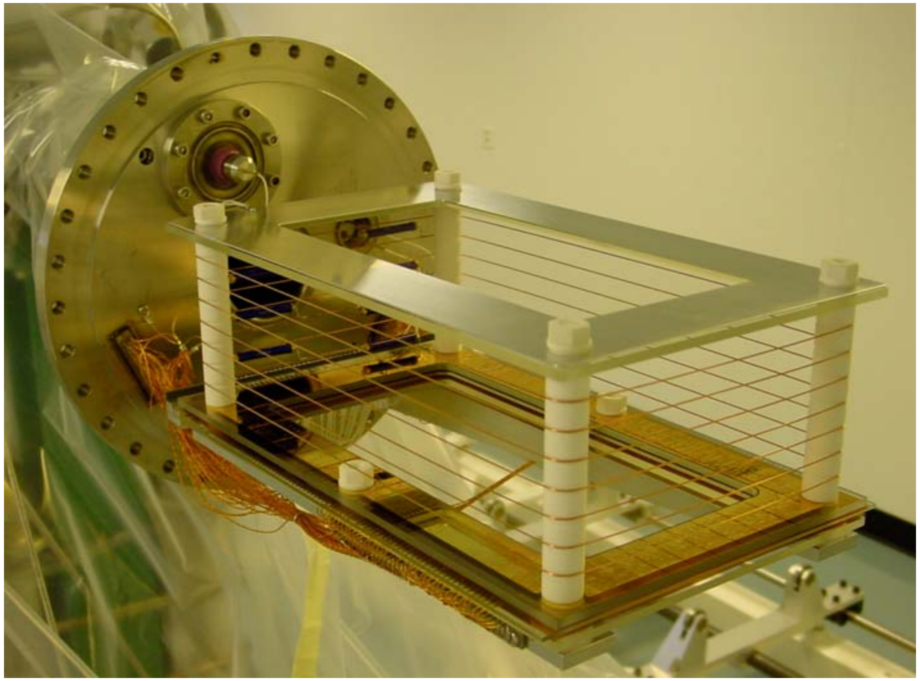
- We use an ultra-pure, low-density (1% of LH_2) hydrogen gas target, where muons primarily reside in the hyperfine singlet ground state of the μp atom
- Most nuclear captures (96%) proceed from the singlet state: $\Lambda_{\text{capture}} \approx \Lambda_S$.

Hydrogen target

- The gaseous hydrogen target is an optimal compromise among competing demands:
  - suppression of μp triplet and $p\mu p$ molecule formation
  - minimization of μp diffusion
  - preservation of substantive muon stopping power
- The TPC plays a critical role…



Active (& Novel!) hydrogen target



Time Projection Chamber (TPC)

- TPC sits in pressure vessel filled with 10-bar, ultra-pure hydrogen gas (protium)
- Protium gas is both muon stopping target and chamber gas
- TPC provides three-dimensional tracking of incoming muons, thus enabling identification of “clean” muon stops
- TPC is constructed of bakeable materials (quartz, ceramic)

Precision goals

10^{10} μ^- decay events in pure hydrogen gas
(c_Z < 10 ppb, c_d < 1 ppm)

↓

10 ppm measurement of μ^- disappearance rate

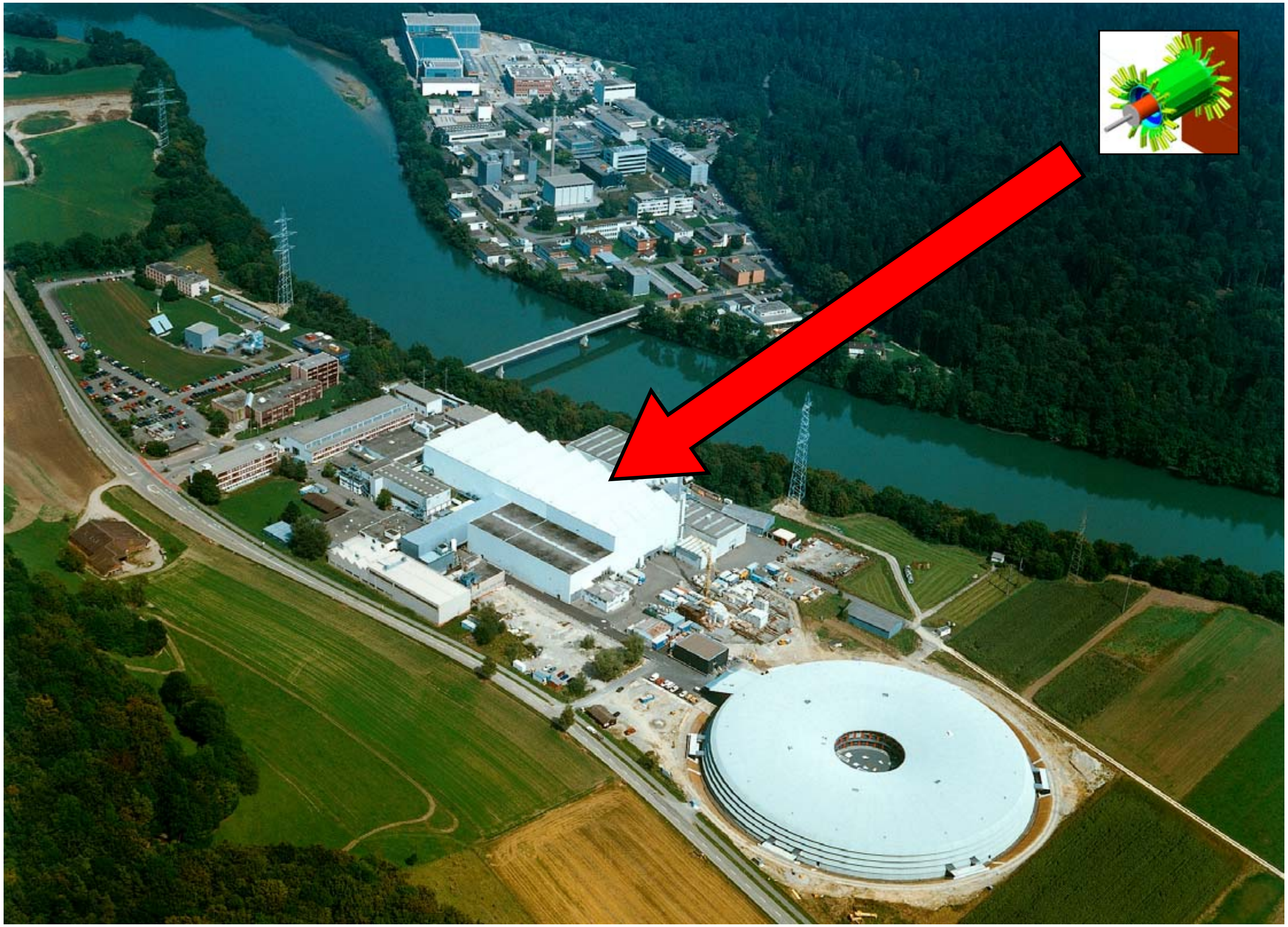
↓

1% determination of Λ_S

↓

7% determination of g_P

Experiment location



MuCap is conducted in the "ExperimentierHalle" at the Paul Scherrer Institut (PSI), in Villigen, Switzerland.

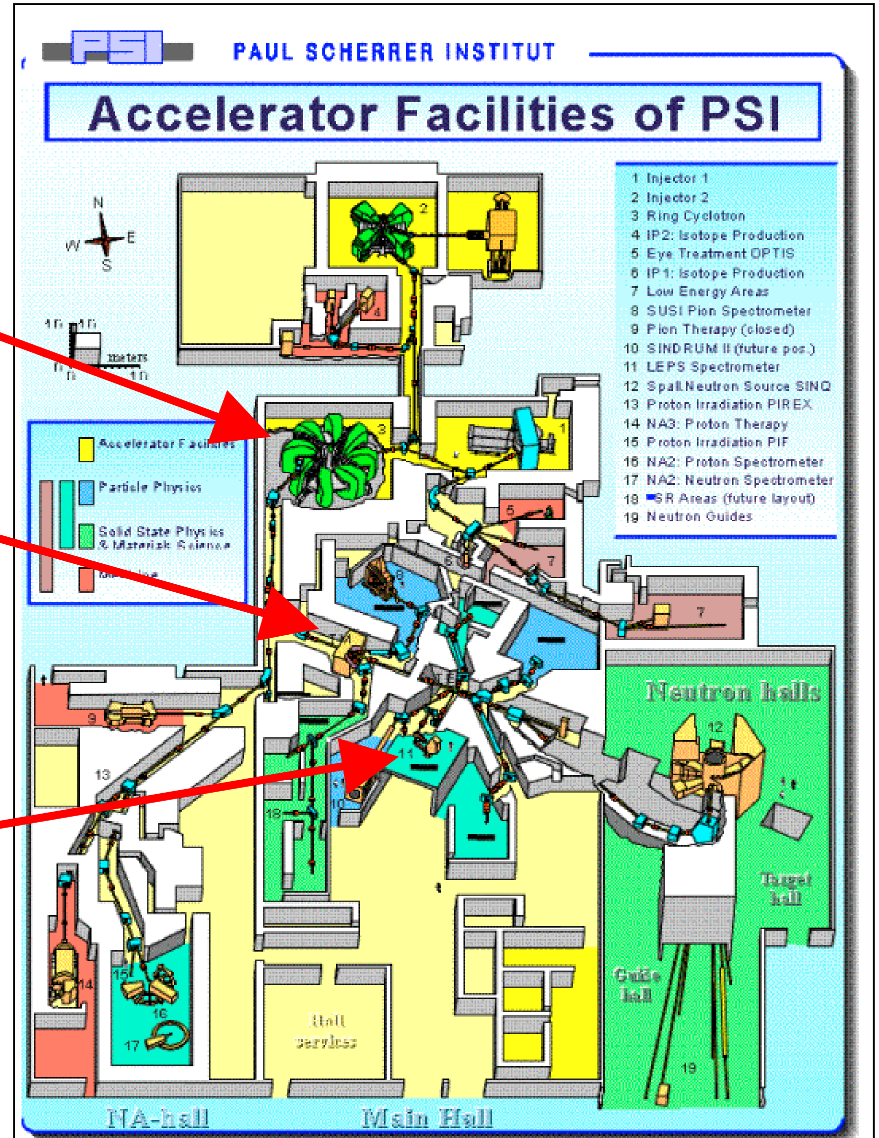
PSI experimental hall facilities

Muon Source

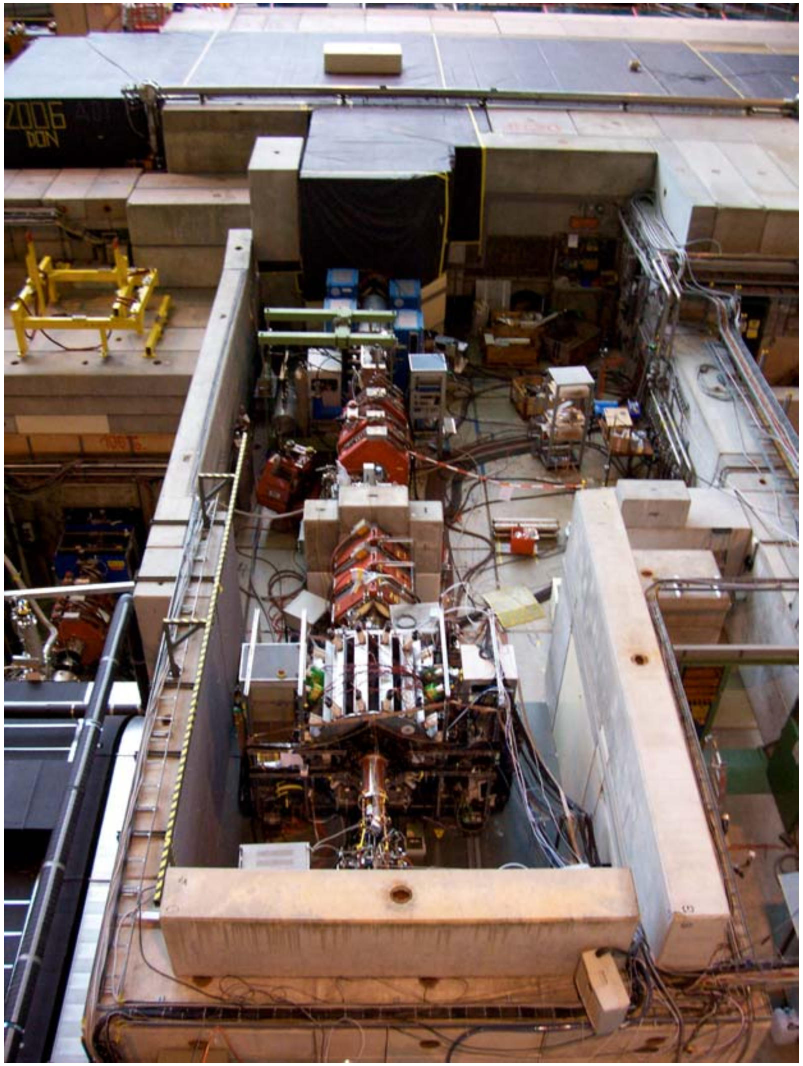
- PSI accelerator (ring cyclotron) generates 590 MeV proton beam ($v \sim 0.8c$)
- protons strike a spinning graphite target and produce pions
- pions decay to muons

Muon Beam Properties

- μ^{+} or μ^{-} selectable
- Momentum ~ 30-40 MeV/c
- Max intensity ~ 50 kHz



Beamline



Overhead view of the MuCap detector in the πE3 beamline at PSI.

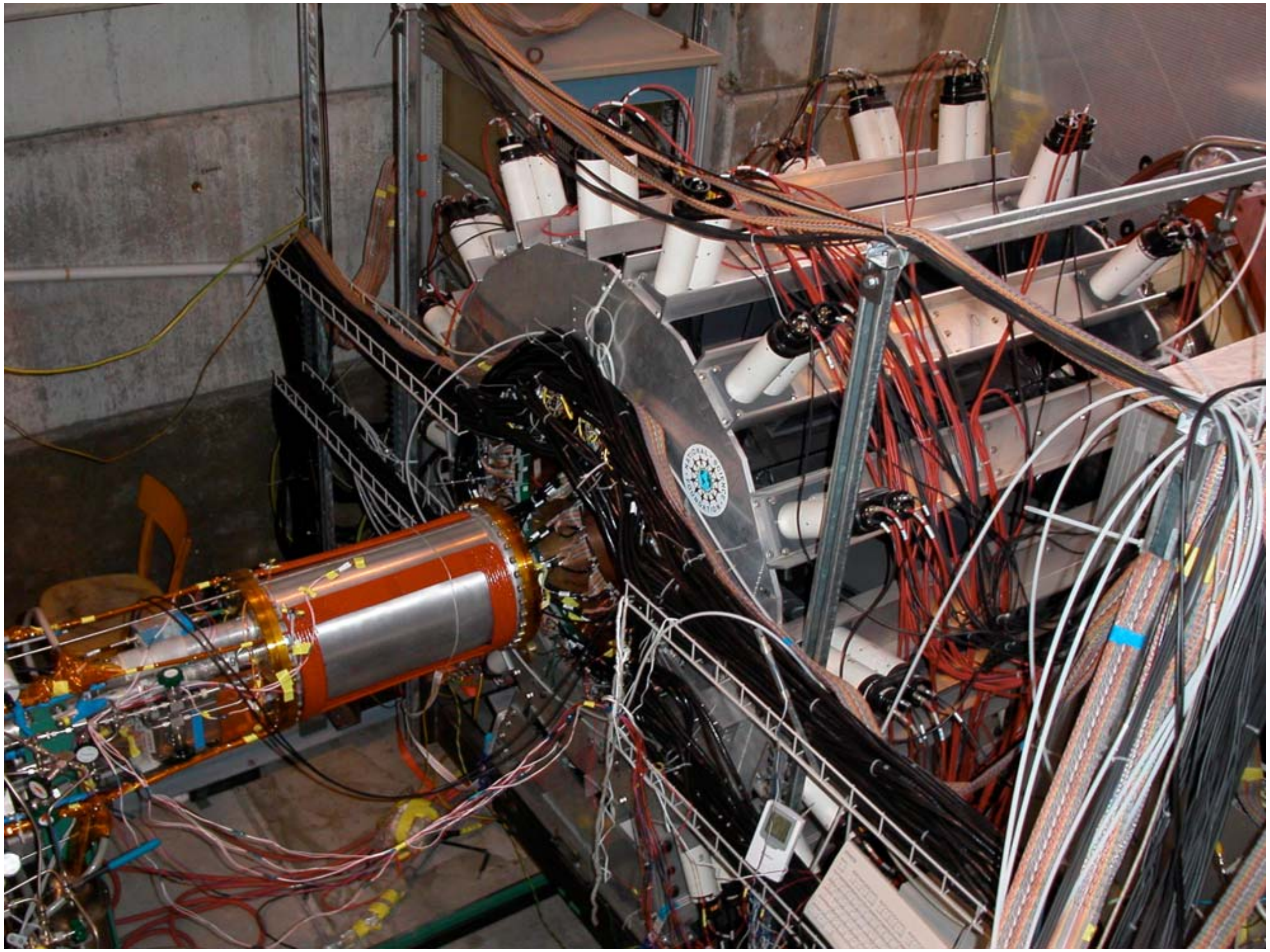
2004 data collection

- 2004 run was our first opportunity to collect good physics data:
  - All major detectors were installed (ePC2 was last to be added)
  - Material budget along muon path reduced $\longrightarrow$ scattering reduced $\longrightarrow$ muon stopping fraction in TPC doubled (30% $\longrightarrow$ 60%)
  - New CHUPS recirculation system continuously removed $Z>1$ impurities from the hydrogen gas
  - Reliable, fast DAQ

- We recorded approximately 1.6×10^9 good μ^- decay events in purified hydrogen

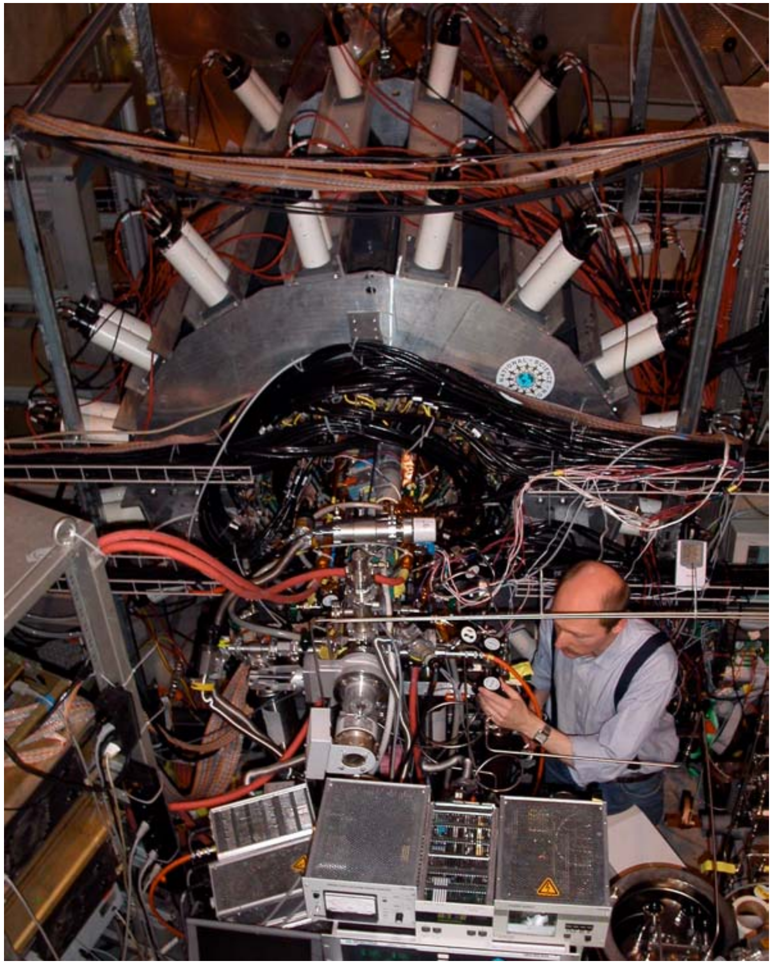
- We also performed several impurity-doped calibration measurements

2004 data collection



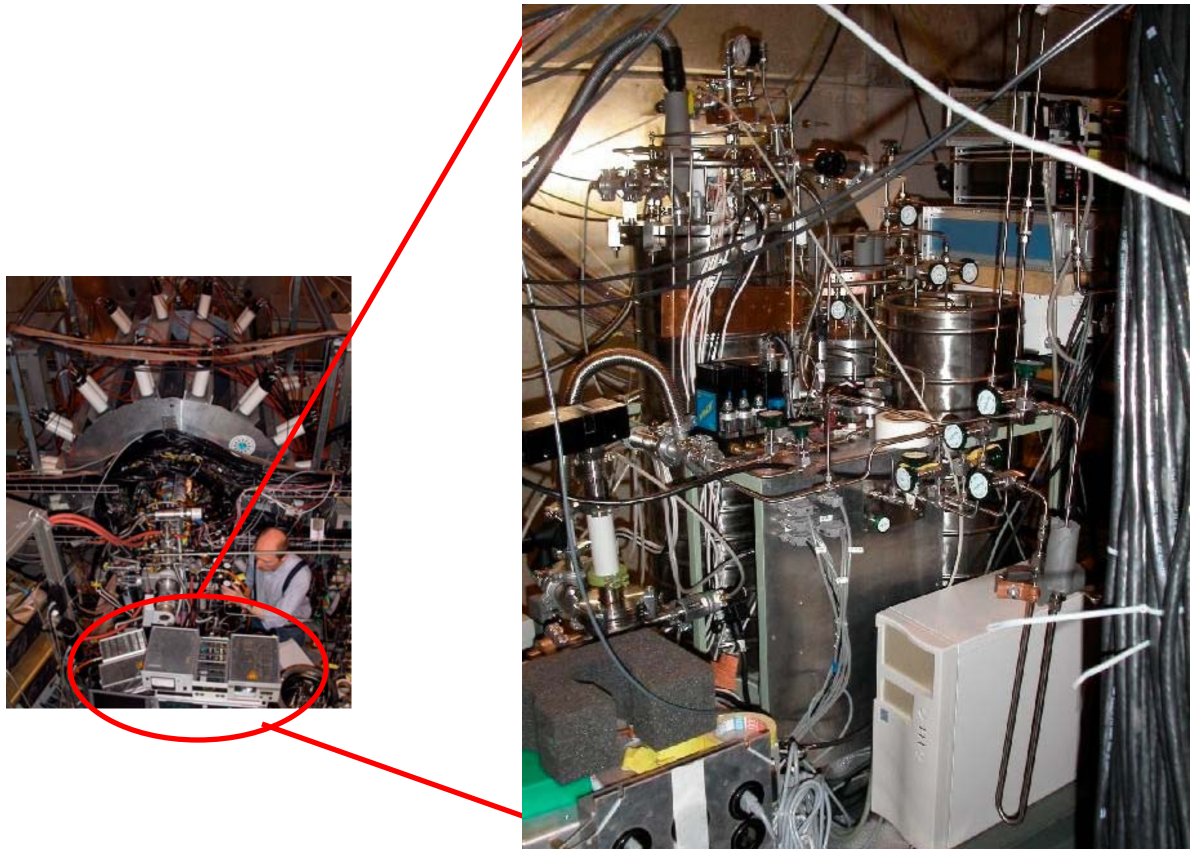
MuCap detectors assembled at PSI,
October – November 2004.

2004 data collection



MuCap detectors assembled at PSI,
October – November 2004.

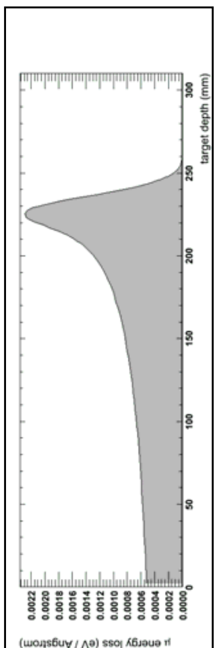
2004 data collection — CHUPS gas cleaning system

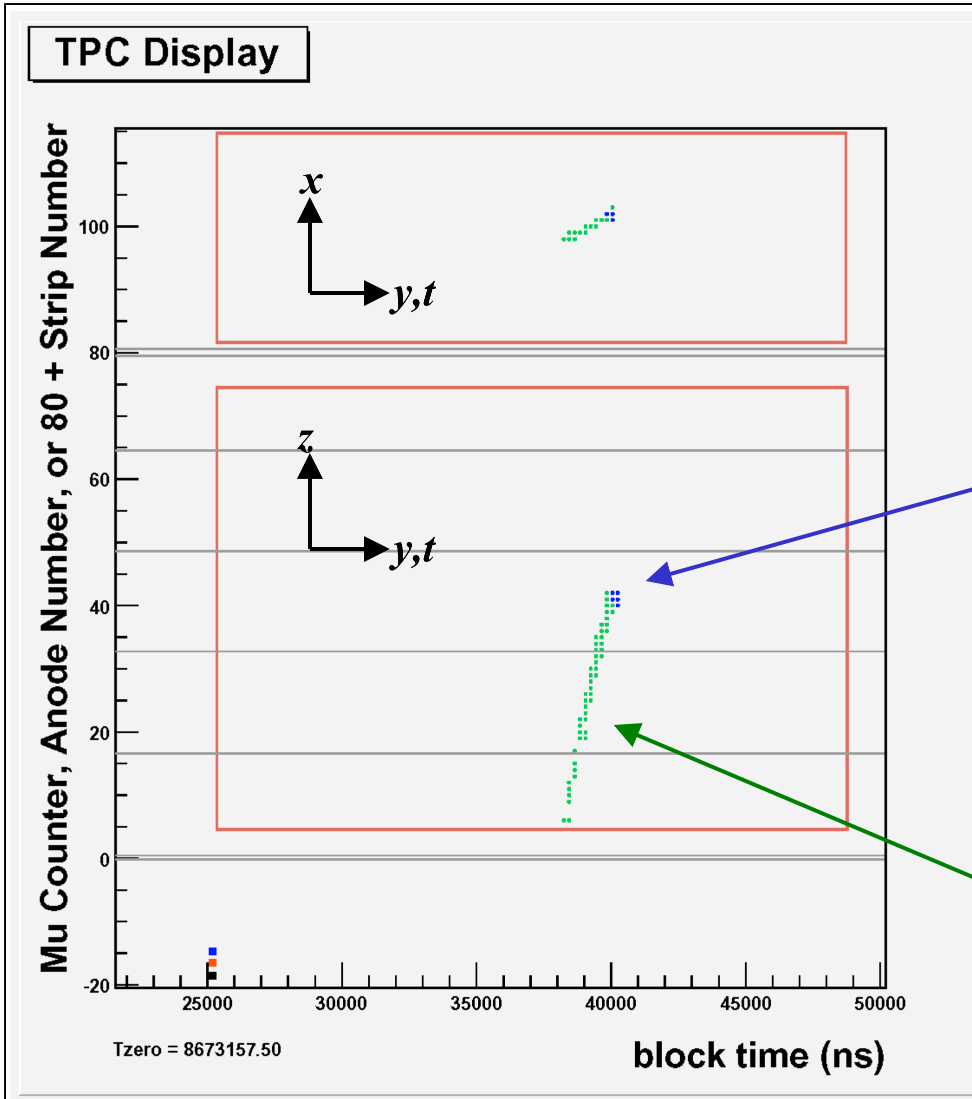


- **CHUPS: C**ontinuous **H**ydrogen **U**ltra-**P**urification **S**ystem
- Developed by colleagues at PNPI, Gatchina, Russia
- Suppressed Z>1 impurities orders of magnitude below previous levels
- Recently published in **V. A. Ganzha et al., NIM A578 (2007) 485**

III. Analysis of 2004 data

Identifying muon stops in the TPC

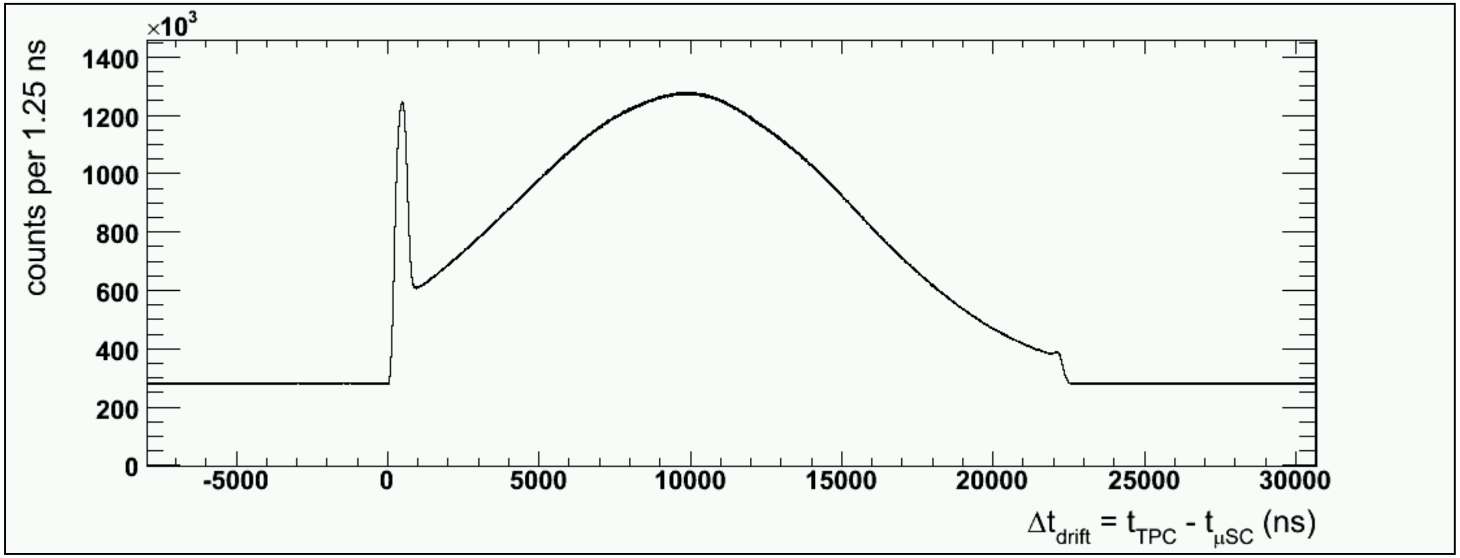




muon stop
(Bragg peak)

muon entrance
(low energy loss)

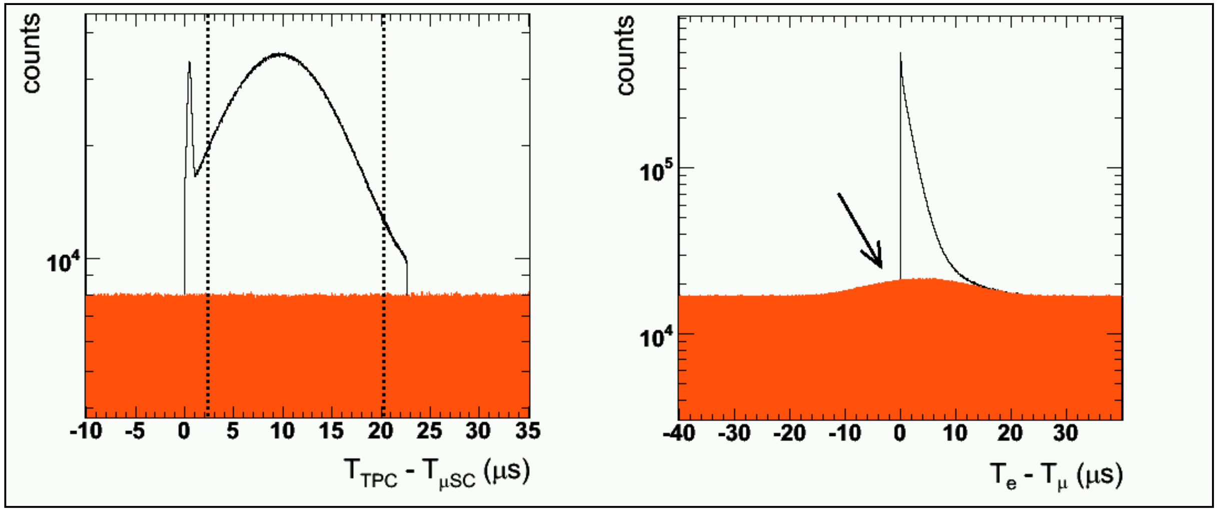
Identifying muon stops in the TPC



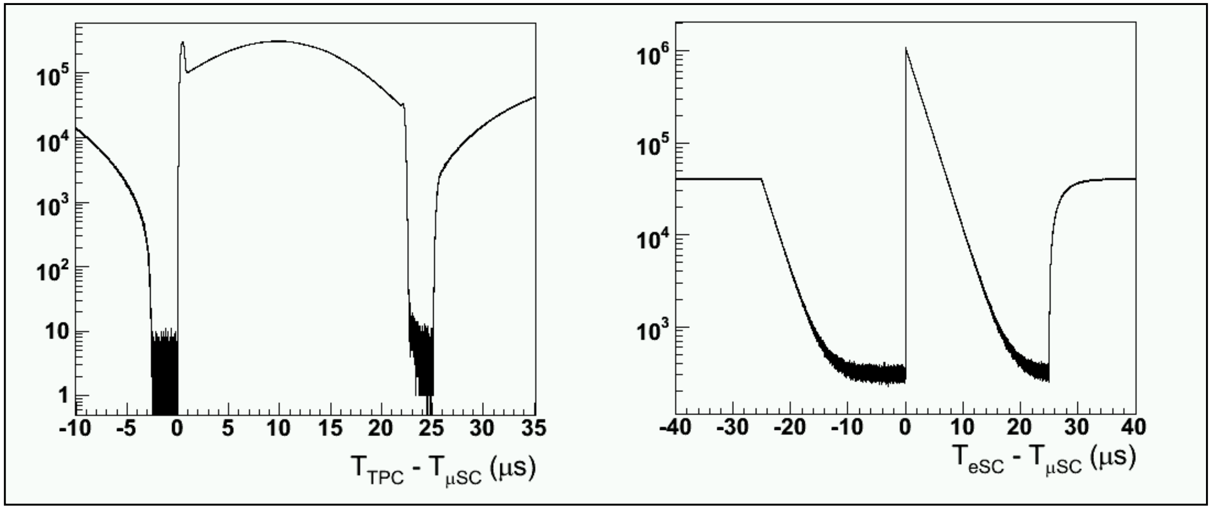
- Drift time of a muon track in the TPC is given by $T_{TPC} - T_{\mu SC}$
- Drift time ↔ muon stopping position in the TPC
- Gaussian shape of drift distribution comes from muon beam profile

Muon pileup effects

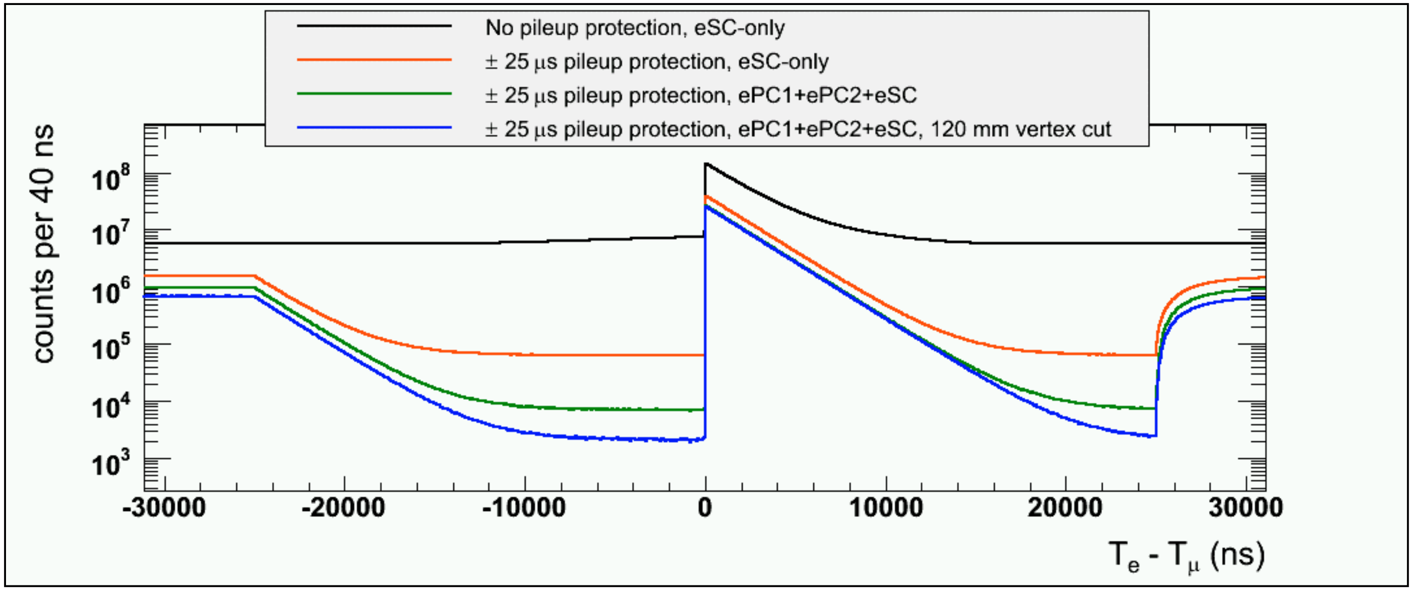
Problem: accidentals in TPC drift distribution lead to nonuniform accidentals in lifetime histogram



Solution: impose a 25 μs veto on muon arrivals ("pileup protection")

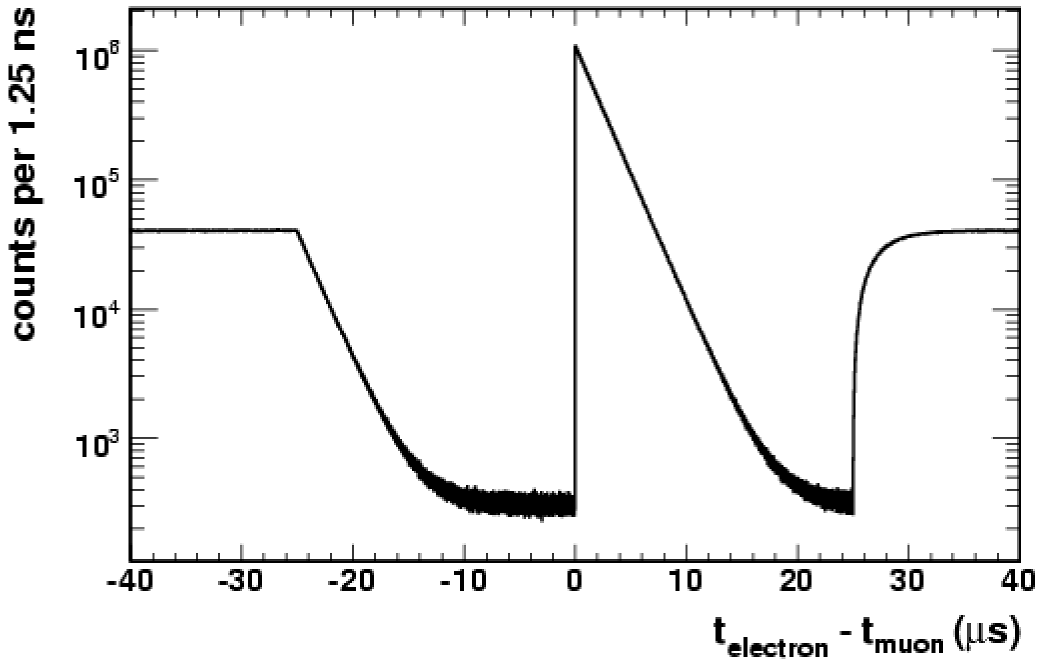


The lifetime histogram



- The signal-to-background ratio of the lifetime histogram is enhanced by
  - imposing a ± 25 μs veto on muon pileup
  - requiring coincident hits in all 3 electron detectors
  - imposing an “impact” cut on the muon/electron vertex

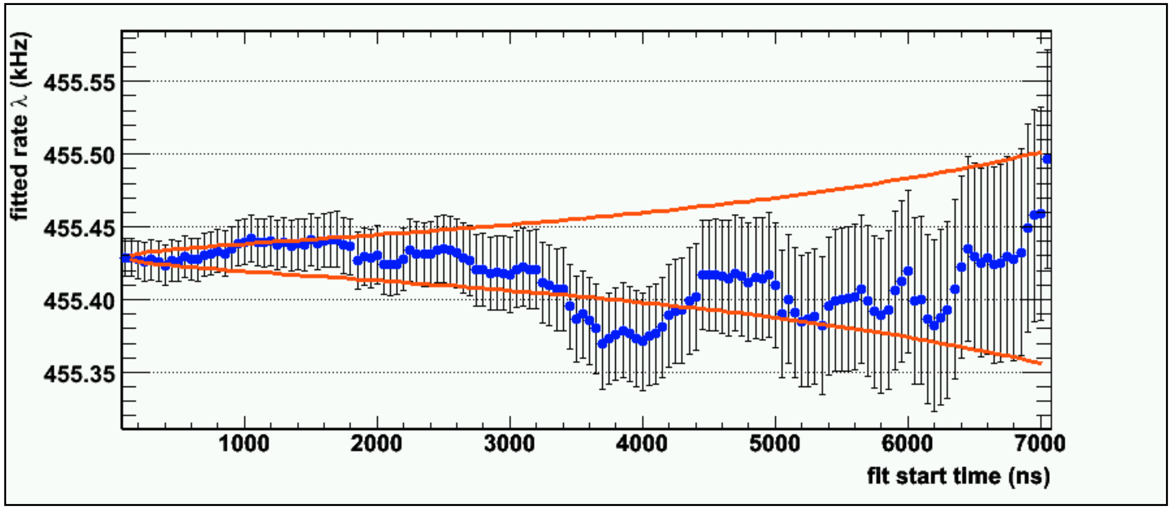
Fit function

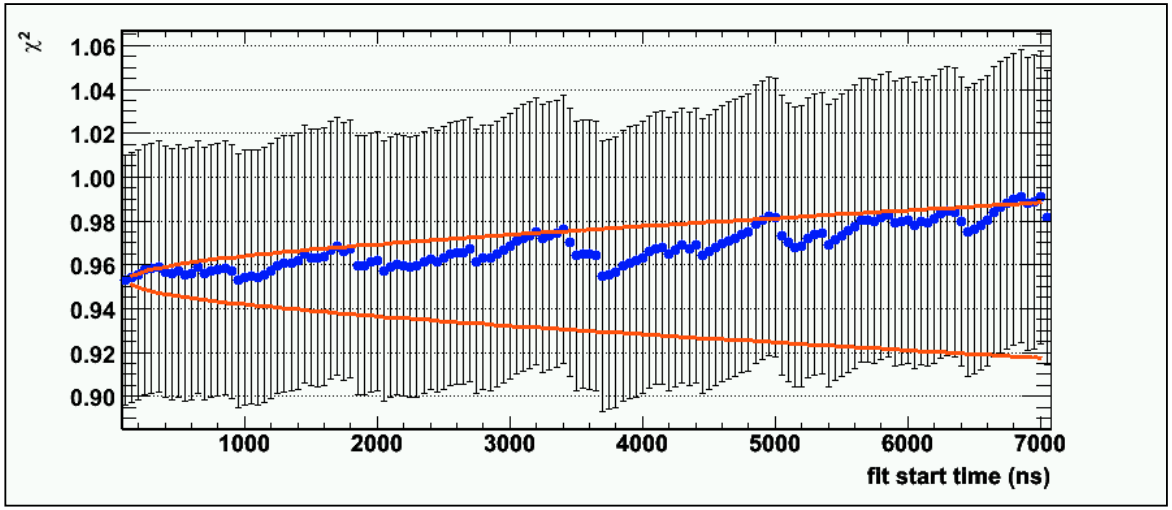


- The muon disappearance rate is obtained by fitting the measured decay spectrum with an exponential function,

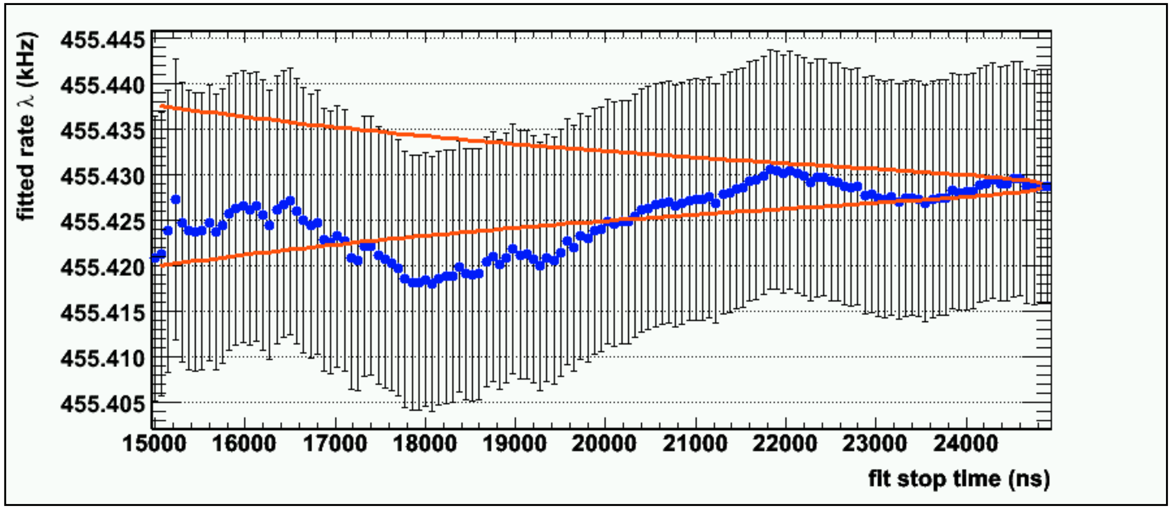
$$f(t) = Ne^{-\lambda t} + B \, .$$

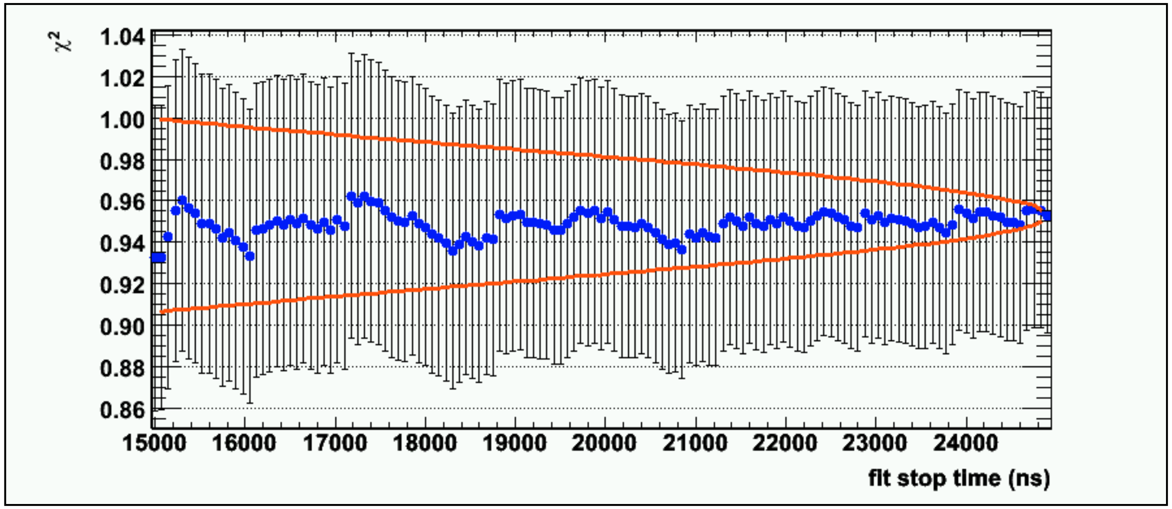
Consistency check: fit start time scans



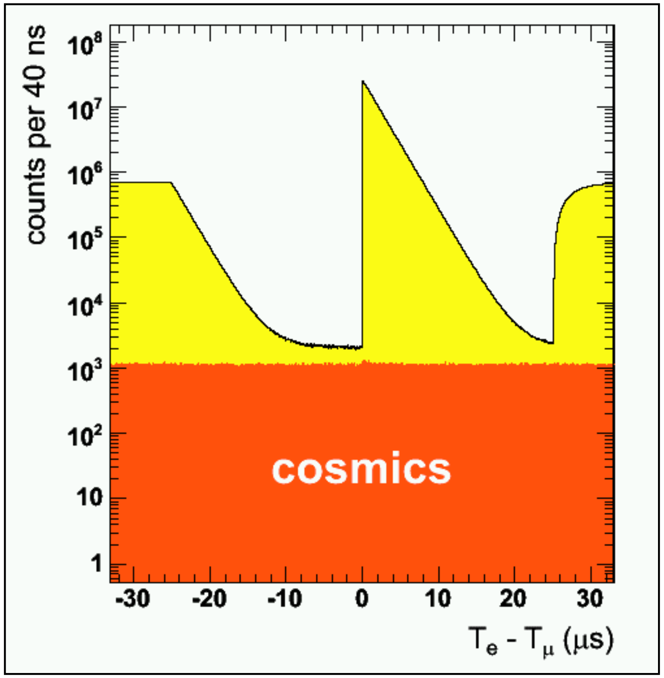


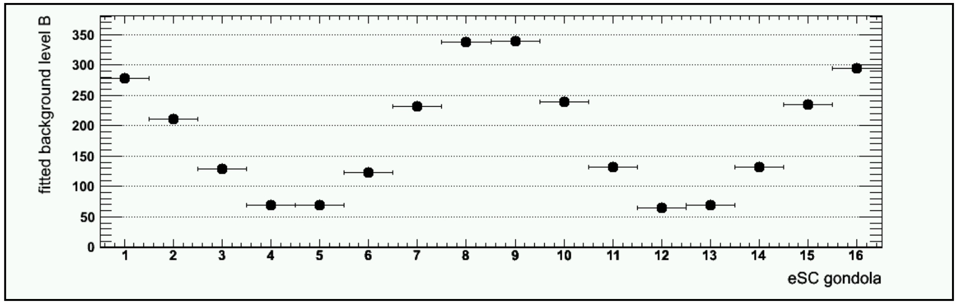
Consistency check: fit stop time scans





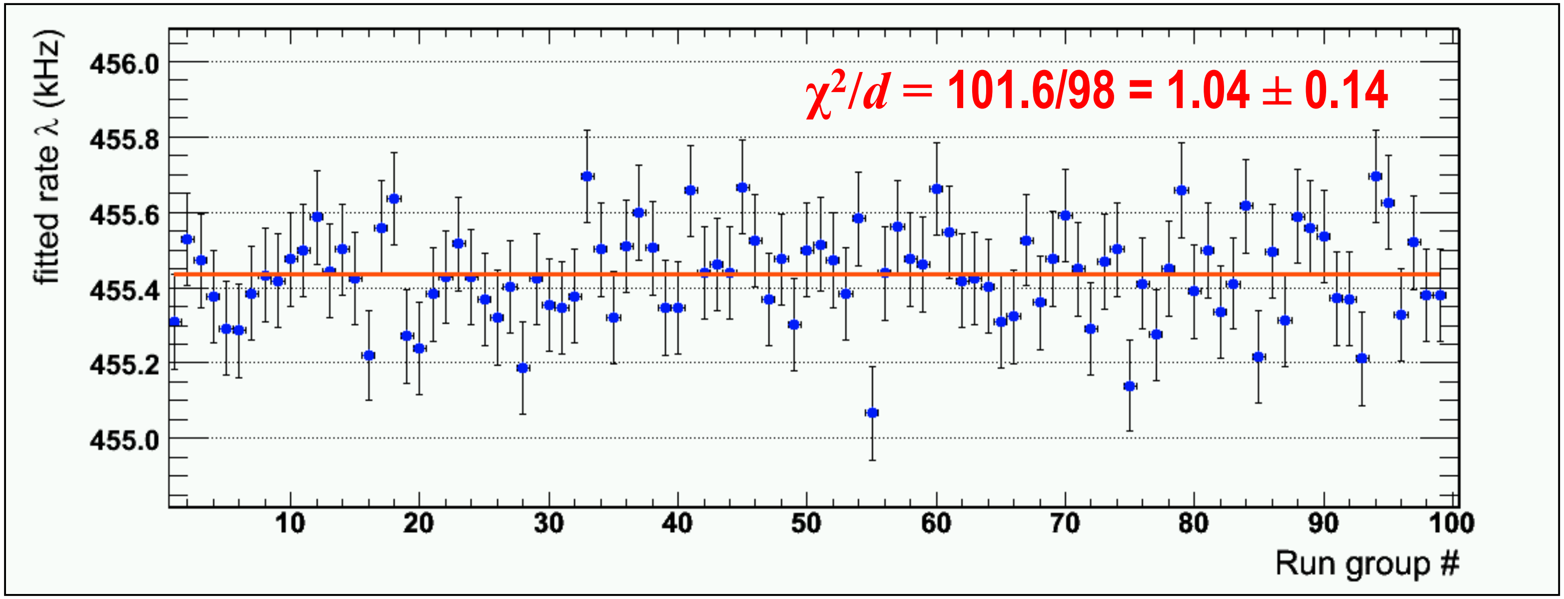
Cosmics



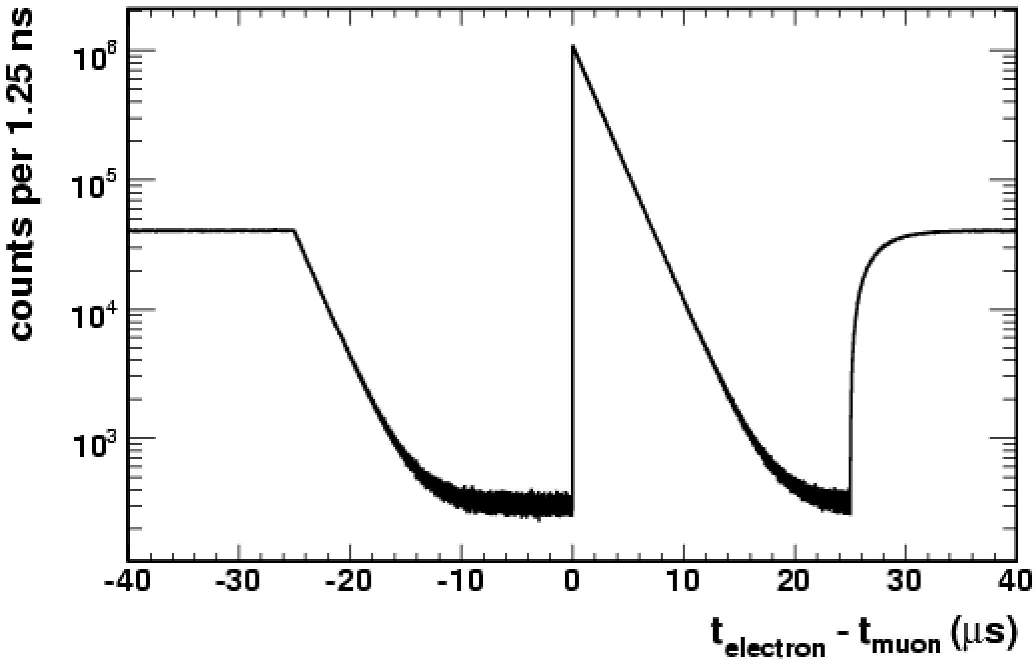


- Cosmics contribute to the lifetime spectrum's uniform background
- Fit background varies sinusoidally around eSC, as expected from cosmics
- We simply adjust the lifetime histogram's bin errors to correct for cosmics double-counting, thereby improving the fits' χ^2

Fitted rate vs. time during run



Fitted rate



- Result for the fitted μ^- disappearance rate:

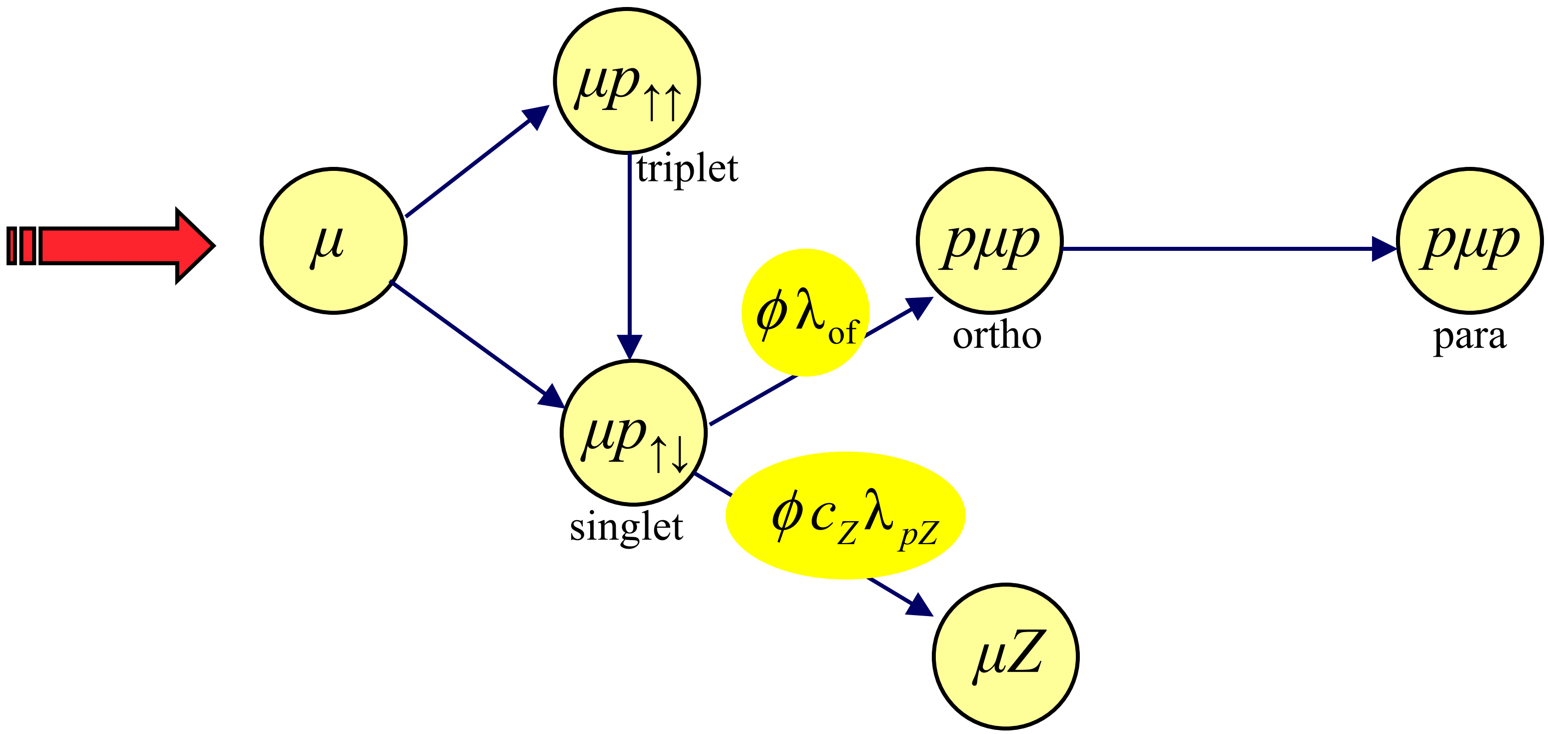
$$\lambda = 455\,886.6 \pm 12.6 \;\; s^{-1}$$

- However, in reality the lifetime spectrum is not a pure exponential, and

$$\lambda \neq \lambda_{\mu^+} + \Lambda_S \;!$$

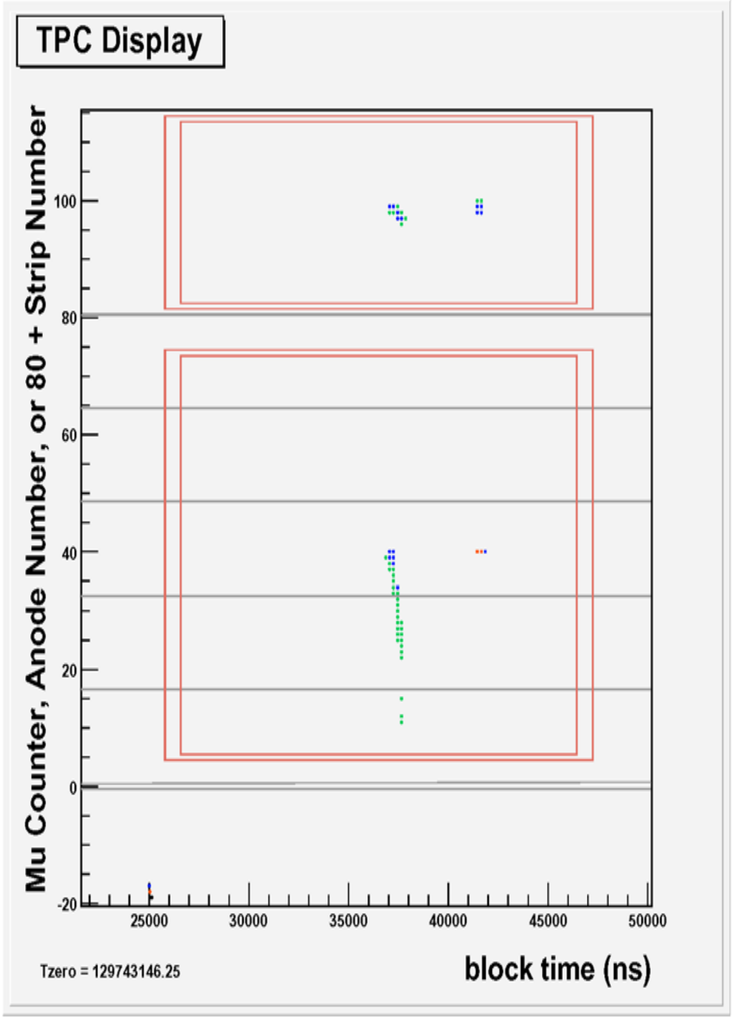
IV. Corrections

Corrections: Captures by *Z*>1 gas impurities



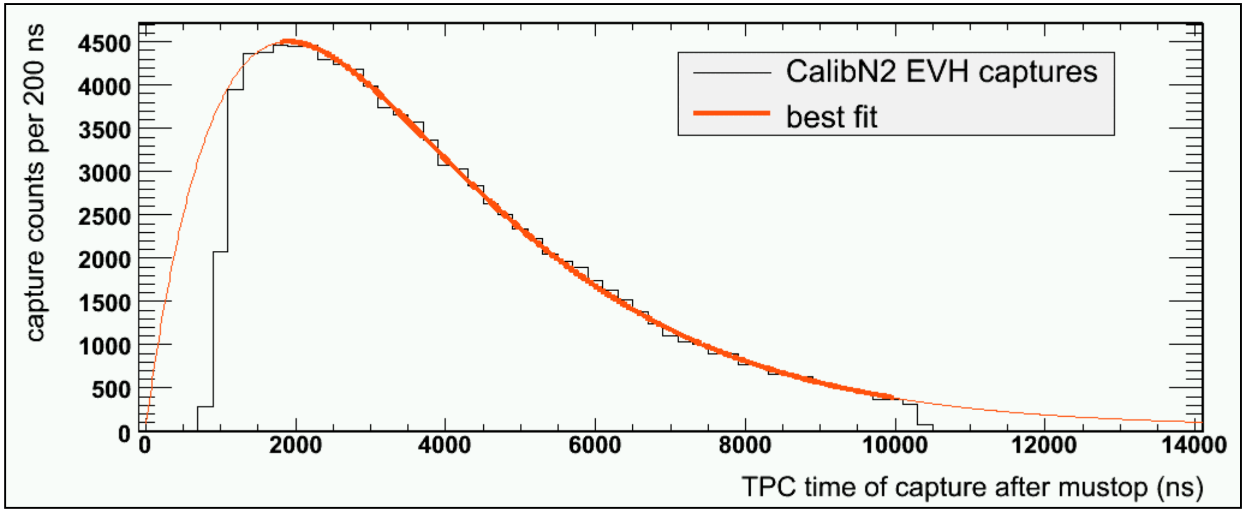
- Muons preferentially transfer to *Z*>1 impurities in the hydrogen gas (transfer rates λ_{pZ} ~ 10^{10} – 10^{11} Hz; λ_{of} ~ 10^{6} Hz)
- Ensuing nuclear captures distort the lifetime measurement (for C,N,O, Λ_Z ~ 40 – 100 kHz, whereas Λ_S ~ 0.7 kHz)
- Circulation system did a great job of suppressing impurity levels in 2004, but there was still nonnegligible level of contamination (~ 50 ppb O from humidity)

Corrections: Captures by Z>1 gas impurities



- The TPC can detect a fraction of Z>1 nuclear captures!

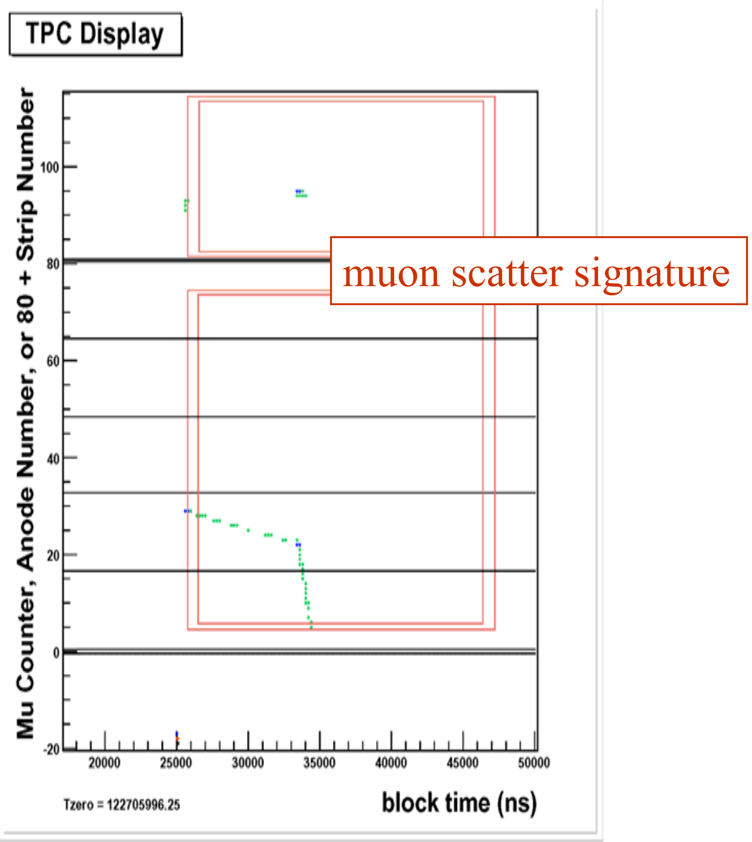
Corrections: Captures by *Z*>1 gas impurities



- Effect of impurities on the lifetime is proportional to the capture yield *Y*, the number of observed TPC captures per good muon stop
- Proportionality for contaminants N,O is established by calibration measurements
- Capture-yield-based correction is:

$$\Delta\lambda_Z = -19.2 \pm 5.0\ \mathrm{s}^{-1}$$

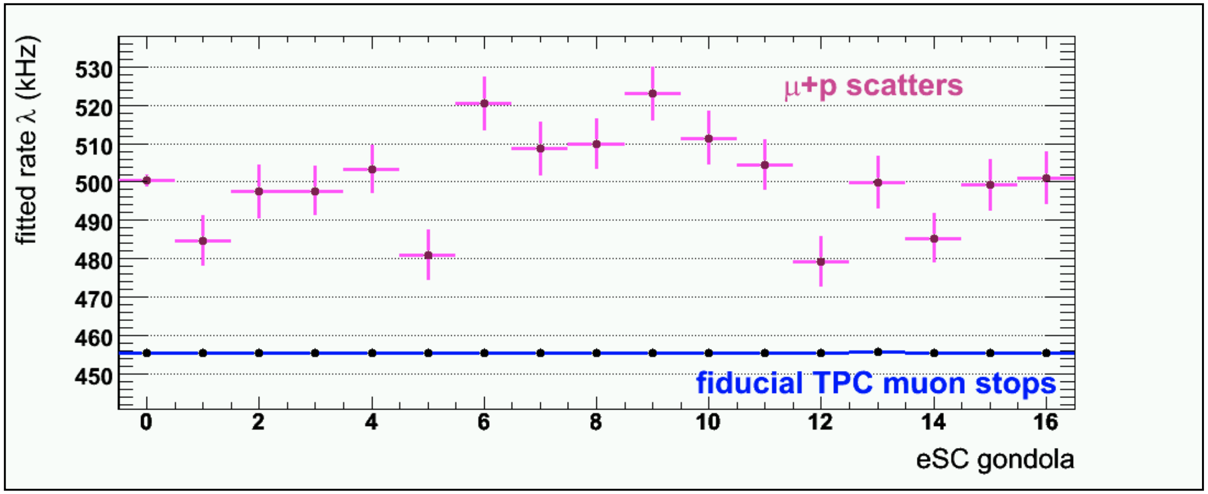
Corrections: Muon scatters into *Z*>1 materials



- Sometimes a muon scatters off a proton, mimicking a stop in the TPC
- Scatter events are dangerous because the scattered muons can stop in surrounding *Z*>1 detector materials
- We can catch some of these events, but the signature is not always robust

Corrections: Muon scatters into Z>1 materials

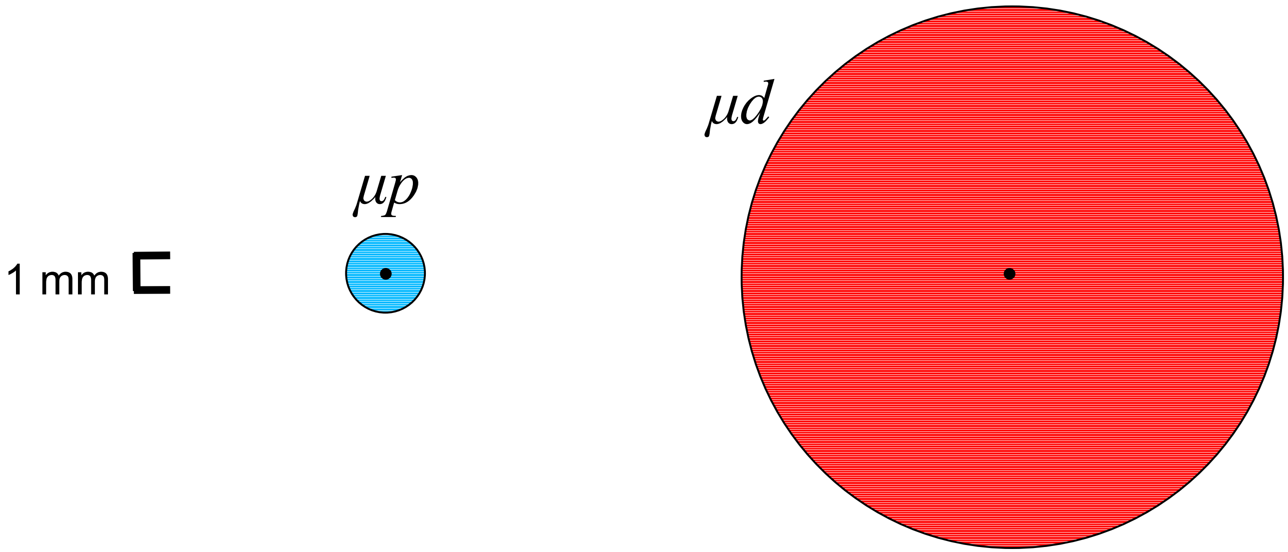
- Differential study of scatter events indeed exhibits a higher disappearance rate:



- Unfortunately, we must rely on simulations to estimate our identification efficiency
- We remove the scatters we find, and conservatively assume ~ 50% inefficiency:

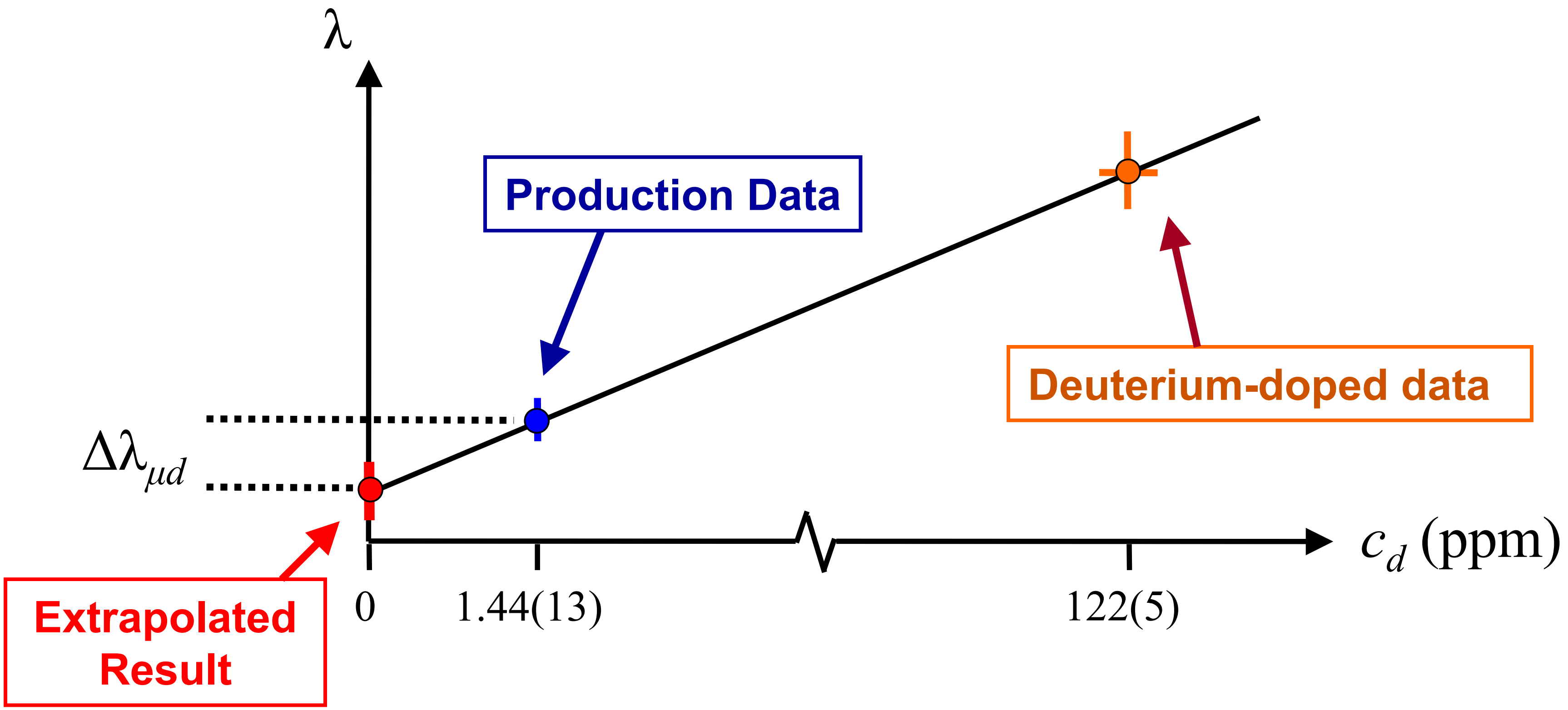
$$\Delta\lambda_{\text{scatter}} = -3.1 \pm 3.0\ \text{s}^{-1}$$

Corrections: Deuterium (μd diffusion)



- Muons preferentially transfer from $\mu p \rightarrow \mu d$
- H_2 gas is more "transparent" to μd atoms, so they diffuse faster = farther
- The rapid diffusion can raise the observed muon disappearance rate in two ways:
  - muons can diffuse out of the decay vertex reconstruction radius
  - muons can diffuse into surrounding detector materials and capture there

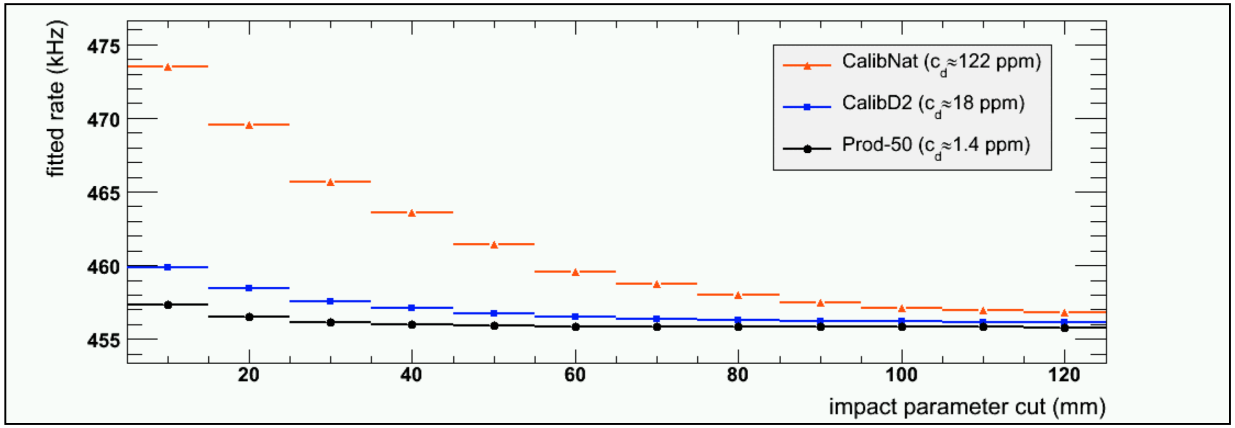
Corrections: Deuterium (μd diffusion)



► We perform a zero-extrapolation to correct for the effects of μd diffusion

Corrections: Deuterium (μd diffusion)

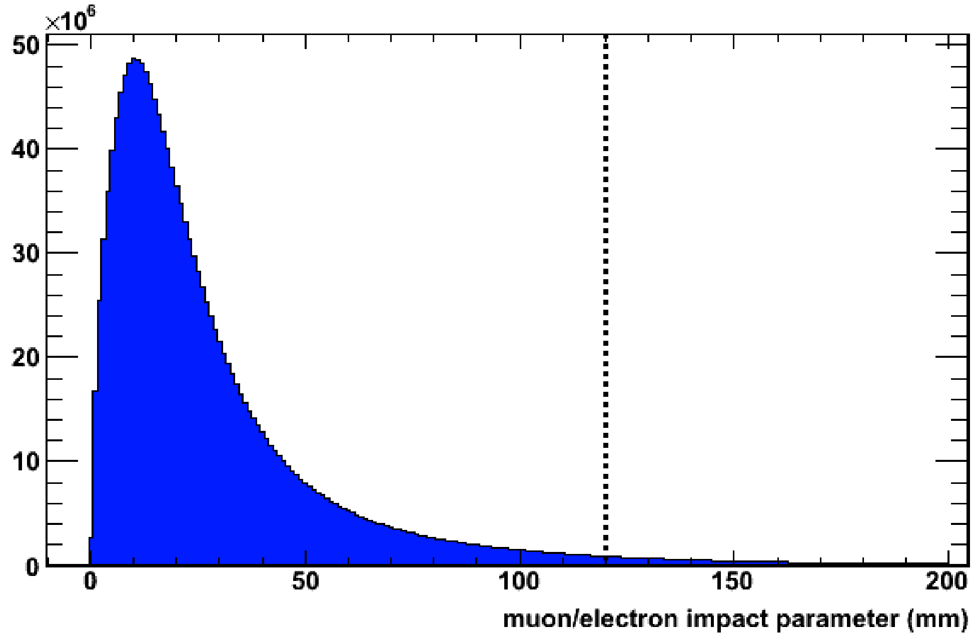
- The deuterium concentrations were determined using two complementary methods:
  - External measurements of gas samples
  - From data analysis of the λ vs. impact parameter dependence:



- The results from the two approaches were consistent
- The zero-extrapolation yields:

$$\Delta\lambda_{\mu d} = -10.2 \pm 1.6 \text{ s}^{-1}$$

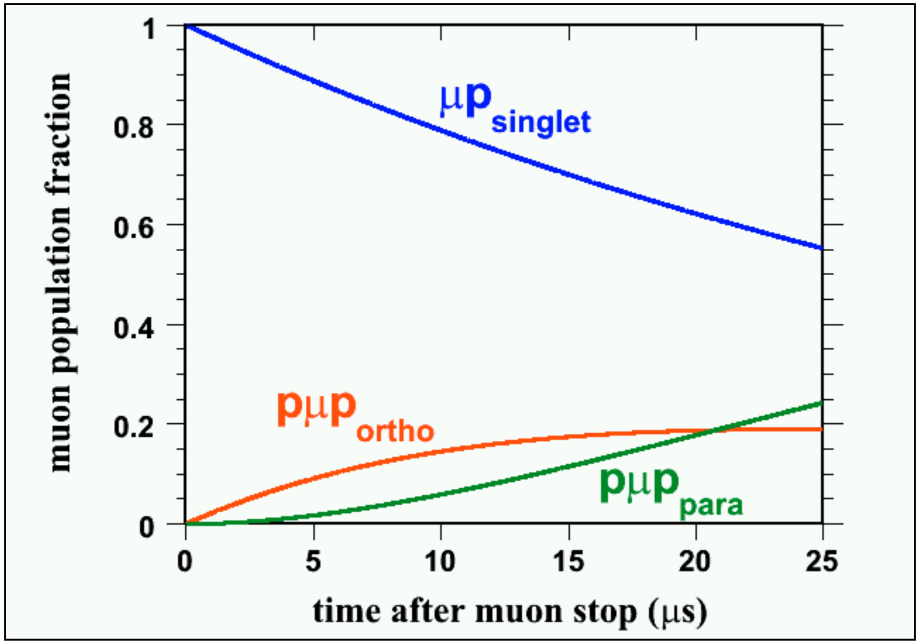
Corrections: μp diffusion



- Although μp diffusion distances are small (~ 1 mm), the scattering of outgoing decay electrons by the aluminum pressure vessel magnifies the behavior
- By combining the electron scattering distribution (i.e. the impact parameter distribution) with a simple model of isotropic μp diffusion, we calculate:

$$\Delta\lambda_{\mu p} = -2.7 \pm 0.5 \text{ s}^{-1}$$

Corrections: $p\mu p$ molecule formation



(exponential decay has been divided out)

$\Lambda_S \approx 710\ \text{s}^{-1}$

$\Lambda_{\text{om}} \approx 506\ \text{s}^{-1}$

$\Lambda_{\text{pm}} \approx 208\ \text{s}^{-1}$

- Even in perfectly clean, pure hydrogen gas, muons will slowly form $p\mu p$ molecules
- The nuclear capture rates in $p\mu p$ molecules are lower than in the μp atom

Corrections: $p\mu p$ molecule formation

- In order to extract the μp singlet capture rate, we must make some assumptions about $p\mu p$ kinetics
- We use conservative averages of the published $p\mu p$ formation and transition rates to obtain:

$$\Delta\lambda_{p\mu p} = 23.5 \pm 7.3\ \mathrm{s}^{-1}$$

Summary of corrections

Source	$\lambda\ (s^{-1})$		$\sigma_\lambda\ (s^{-1})$
Uncorrected rate	**455 886.6**	**±**	**12.6**
Z>1 gas impurities	–19.2	±	5.0
Muon scatter events	–3.1	±	3.0
μd diffusion	–10.2	±	1.6
μp diffusion	–2.7	±	0.5
$p\mu p$ molecule formation	23.5	±	7.3
Muon detector inefficiencies		±	3.0
Analysis consistency		±	5.0
μp bound state decay rate	12.3		
Adjusted disappearance rate	**455 887.2**	**±**	**16.8**

V. Conclusions

The positive muon lifetime

	$\tau_{\mu^+}\,(\mu\mathrm{s})$	$\lambda_{\mu^+}\,(\mathrm{s}^{-1})$
Previous world average	2.197 030(40)	455 160 (8)
MuLan (2007)	2.197 013(24)	455 163.4 (4.9)
Updated world average	2.197 019(21)	455 162.2 (4.4)
MuCap (2007)		455 164 (28)
FAST (2007)	2.197 083(35)	455 149 (7)

- It only remains to subtract off the μ^+ decay rate…
- The MuLan experiment collected 1.8 x 10^{10} μ^+ decay events in 2004, yielding the most precise lifetime measurement to date (D. Chitwood et al., PRL **99**, 032001 (2007)).
- We elected to use the MuLan+PDG updated world average, highlighted above

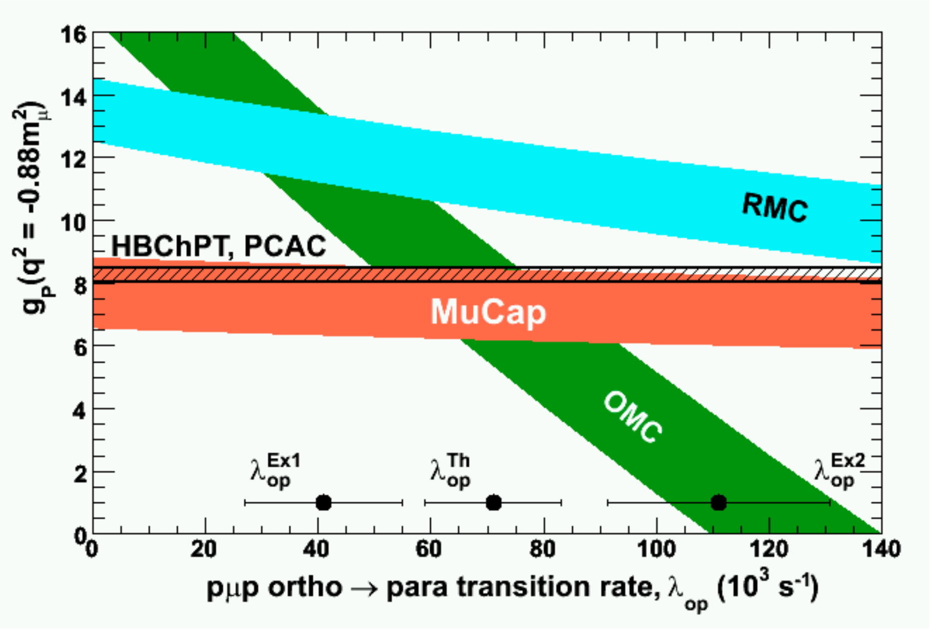
Result for the capture rate

- **Finally,** subtracting the positive muon's decay rate yields

$$\Lambda_S = 725.0 \pm 17.4\ \ \mathrm{s}^{-1}$$

- Roughly 13.7 Hz of the uncertainty is statistical, and 10.7 Hz is systematic
- This 2.4% result is consistent within 1σ with the latest theoretical calculations which predict **711.5 ± 4.5 Hz**
- MuCap result appeared in the July 20, 2007 issue of Physical Review Letters as V.A. Andreev et al., PRL **99**, 032002 and 032003 (2007).

Implications for g_P



- From the capture rate we can extract the value

$$g_P = 7.3 \pm 1.1$$

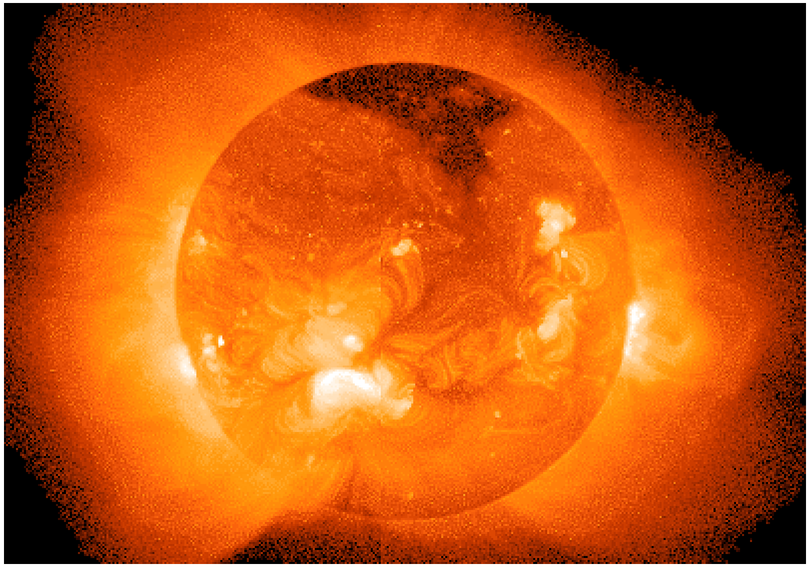
- This 15% result is the first precise, unambiguous determination of g_P
- Consistent with the HBChPT prediction of **8.26 ± 0.23**, corroborating the modern understanding of the role of chiral symmetries in QCD

Outlook for MuCap

- During 2005 — 2007 we have continued to collect data of superior quality:
  - Higher statistics (~ 1.5×10^{10} decay events)
  - Muon "kicker" installed in the beamline, increasing good muon stop rate by 3x
  - Cleaner, better-monitored hydrogen gas:
    - Z>1 impurity content was reduced by a factor of 2
    - deuterium content was reduced by a factor of 10 (c_d < 100 ppb!) by introducing an isotopic separation column
    - humidity sensors installed
  - The TPC operated at a higher voltage, with increased sensitivity
  - Neutron detectors were added to the apparatus in hopes of measuring molecular kinetics parameters
  - Analog TPC and eSC information is now being recorded
- Primary challenge now is systematics
- We expect to reduce the statistical and systematic errors by at least a factor of 2, reaching the design goal of a 1% capture measurement.

Future evolution

MuSun



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

- Goal: measurement of the μd capture rate to 1%
- "Calibrating the sun"
- Determines L_{1A}
- Of relevance to astrophysical studies

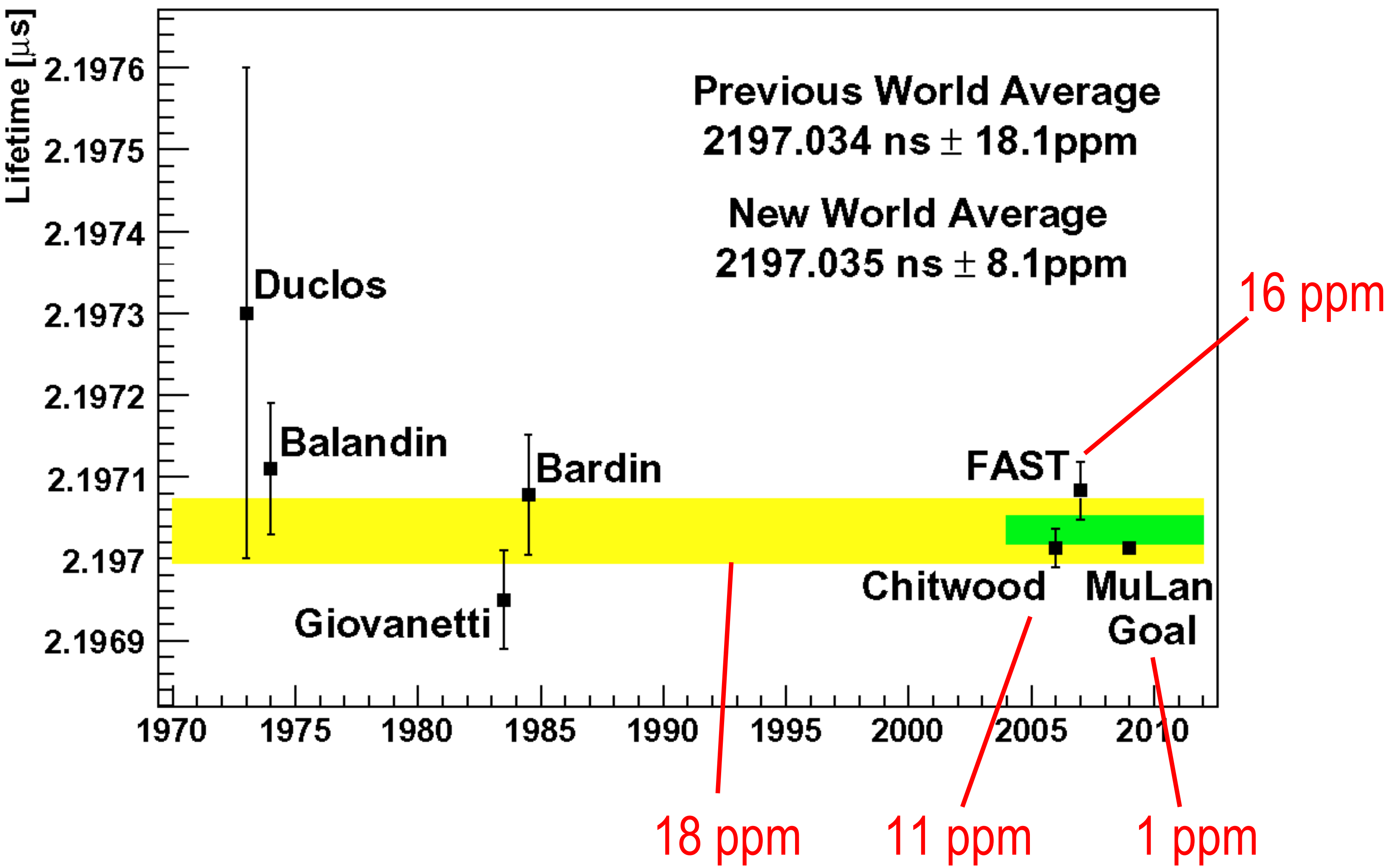
Collaborating Institutions

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

The MuCap experiment is supported in part by the United States Department of Energy and the National Science Foundation.

www.npl.uiuc.edu/exp/mucapture

Graphical summary of τ_{μ^+} experiments



μ^+ lifetime measurements and the extracted g_P

$$g_P^{\mathrm{MuCap}}(q_0^2) = g_P^{\mathrm{Th}} + \frac{\partial g_P}{\partial \Lambda_S}\left[\left(\lambda_{\mu^-}^{\exp} - \lambda_{\mu^+}^{\exp}\right) - \Lambda_S^{\mathrm{th}}\right]$$

$$= 8.26 + (-0.065)\left[\left(455{,}887.2 - \lambda_{\mu^+}^{\exp}\right) - 710.6\right]$$

	$\lambda_{\mu^+}\ (\mathrm{s}^{-1})$	g_P^{MuCap}
2006 world average (W.A.)	455 160	7.1
MuLan (2007)	455 163.4	7.4
2006 W.A. + MuLan	455 162.2	7.3
FAST (2007)	455 149	6.4
2006 W.A. + MuLan + FAST	455 159	7.1

Muon capture measurements in hydrogen

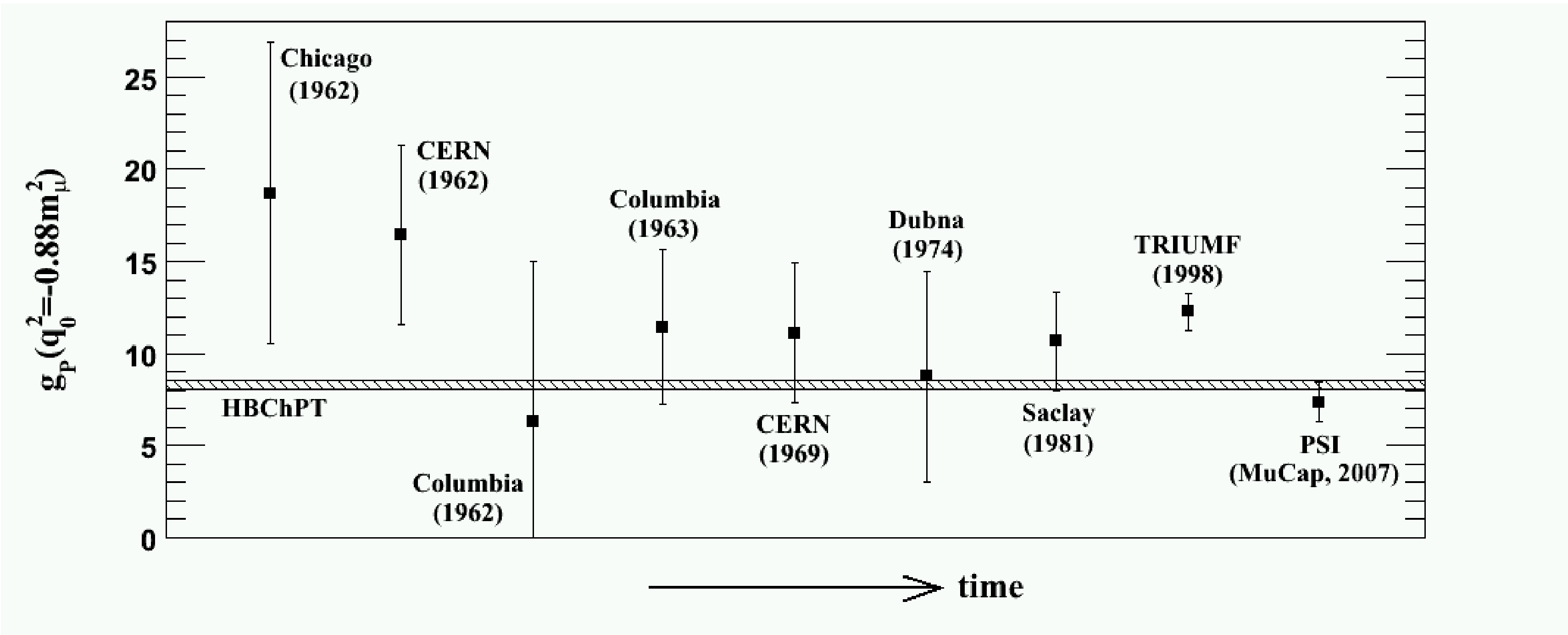
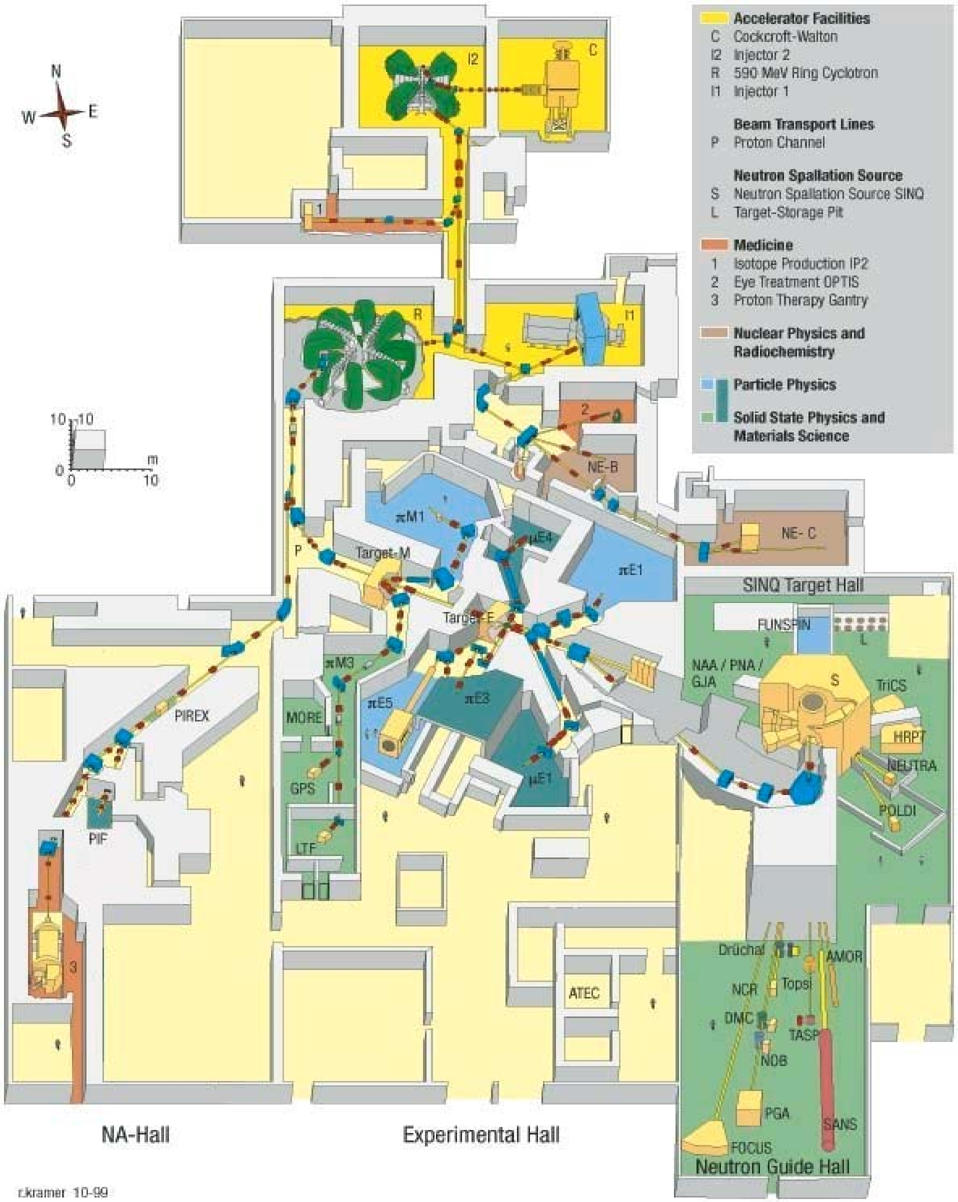


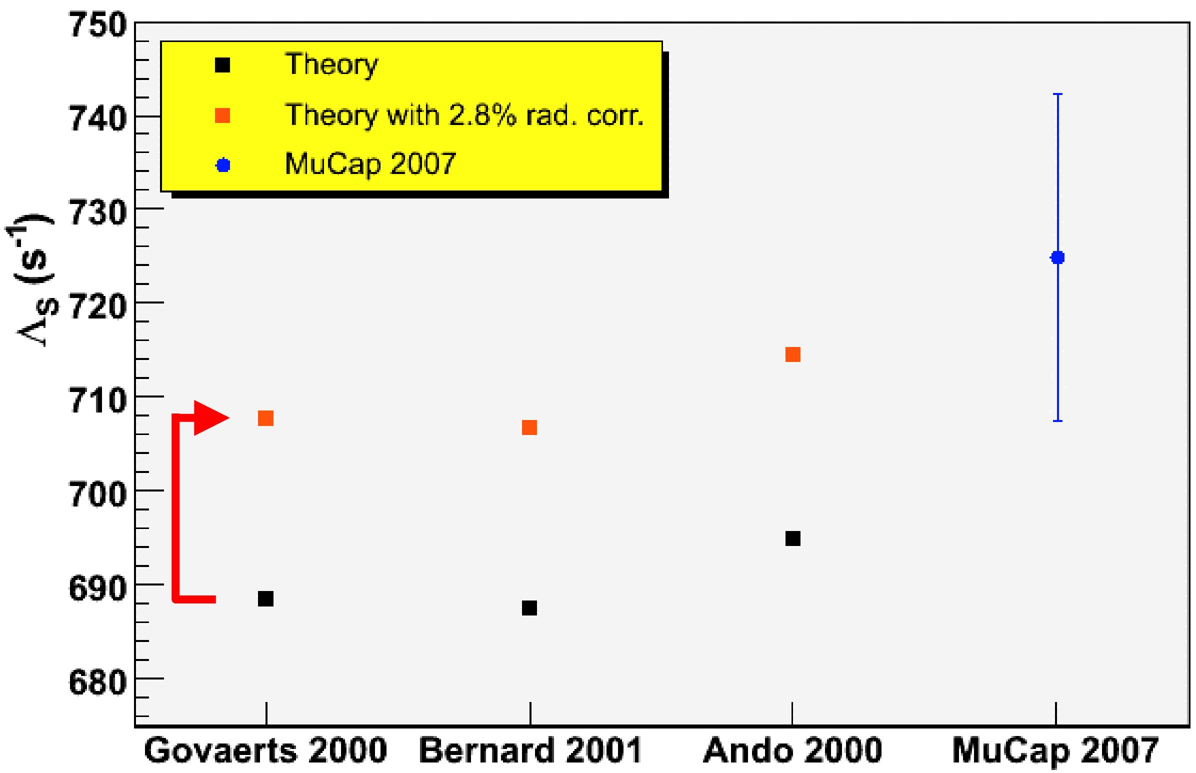
TABLE I. Numerical values of the parameters and derived quantities used in the text and in our evaluations of rates for comparison with experiment.

Symbol	Description	Value	Reference
F_π	pion decay constant	92.4 ± 0.3 MeV	Particle Data Group (2000)
$g_{\pi NN}(m_\pi^2)$	pion nucleon coupling	13.05 ± 0.08	de Swart *et al.* (1997)
$G_F V_{ud}$	Fermi constant for β decay	$1.135\,48 \times 10^{-5}$ GeV^{-2}	Particle Data Group (2000)
$g_a(0)$	axial coupling from β decay	1.2670 ± 0.0035	Particle Data Group (2000)
r_A^2	rms radius squared for g_a	0.44 ± 0.02 fm^2	Liesenfeld *et al.* (1999)
g_p^{PCAC}	PCAC value, $g_p(-0.88 m_\mu^2)$	$6.87\, g_a(0) = 8.70$	Eq. (5), leading term only
	PCAC value, NLO constant term included	$6.50\, g_a(0) = 8.23$	Eq. (5), including NLO correction
$\Lambda_{p\mu p}$	$p\mu p$ molecular formation rate	2.5×10^6 s^{-1}	average, Wright *et al.* (1998)
$\Lambda_{p\mu p}^{ortho}/\Lambda_{p\mu p}^{para}$	ratio of ortho to para molecular formation	240:1	Faifman and Men'shikov (1999)
Λ_{op}	ortho to para transition rate	$4.1 \pm 1.4 \times 10^4$ s^{-1}	Bardin *et al.* (1981a)
$2\gamma^{ortho}$	ortho-molecular overlap factor	1.009 ± 0.001	Bakalov *et al.* (1982)
$2\gamma^{para}$	para-molecular overlap factor	1.143 ± 0.001	Bakalov *et al.* (1982)
$g_m(0)$	weak magnetism coupling, $\kappa_p - \kappa_n$	$3.705\,89$	Particle Data Group (2000)
r_m^2	rms radius squared for g_m	0.80 fm^2	Mergell *et al.* (1996)
r_v^2	rms radius squared for g_v	0.59 fm^2	Mergell *et al.* (1996)

PSI experimental hall facilities



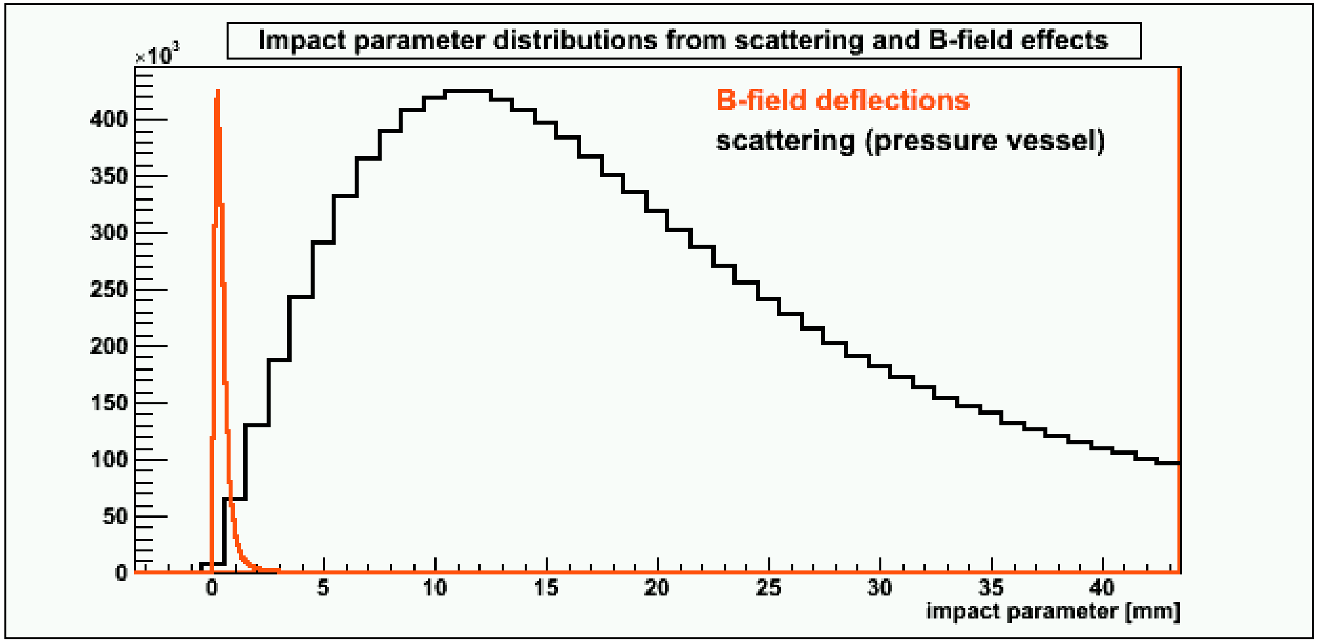
Updates to capture rate calculations



- Radiative corrections: Δ_R **= 2.8%**

  A. Czarnecki, W.J. Marciano, A. Sirlin, PRL99, 032003 (2007)

Magnetic field effects



Z>1 impurity captures vs. time during Run8