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*Title:* ~~DNP Dissertation Prize Talk II~~: Data Analysis and Present Status of the MuCap Experiment

*Author(s):* Steven M. Clayton

*Intended for:* 2009 APS April meeting

Los Alamos NATIONAL LABORATORY EST. 1943

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Form 836 (7/06)

Abstract for an Invited Paper
for the APR09 Meeting of
The American Physical Society

**~~Dissertation Award in Nuclear Physics Talk~~: Data Analysis and Present Status of the MuCap Experiment**

STEVEN CLAYTON[1], University of Illinois

The MuCap experiment measures the rate of muon capture on the proton from a known initial state, providing an unambiguous determination of the pseudoscalar coupling $g_P$ of the proton's weak interaction. In 2007 the MuCap collaboration released their first physics results for $g_P$ with 20% precision, a statistics limited, unambiguous measurement of this coupling constant surpassing all previous efforts. Since that first data collection, several improvements to the experiment were made towards the final precision goal of $g_P$ to 7%. In this talk, the MuCap first physics measurement will be discussed, and the status of the subsequent experimental and analysis effort will be described.

[1]Present address: Los Alamos National Laboratory

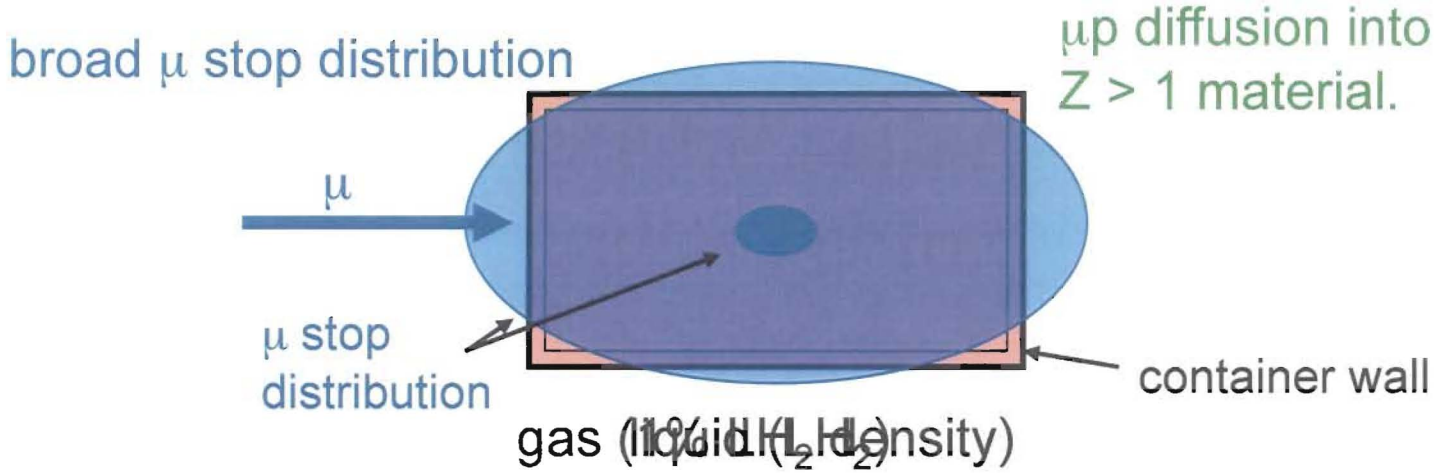
# Data Analysis and Present Status of the MuCap Experiment

Steven Clayton

University of Illinois

# Experimental Challenges

1) Unambiguous interpretation requires low-density hydrogen target to reduce μ-molecular formation.

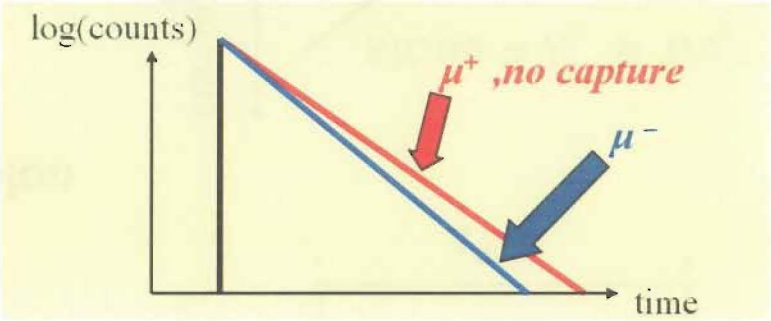



2) H2 must be pure chemically ($c_O, c_N$ < 10 ppb) and isotopically ($c_d$ < 1 ppm).

3) All neutral final state of muon capture
is difficult to detect (would require absolute calibration of neutron detectors, accurate subtraction of backgrounds).

# μCap Experimental Strategy

- Unambiguous interpretation
  - capture mostly from F=0 μp state at 1% $LH_2$ density
- Lifetime method
  - $10^{10}$ $\mu^- \rightarrow e\nu\nu$ decays
  - measure $\tau_{\mu^-}$ to 10ppm
  - $\rightarrow \Lambda_S = 1/\tau_{\mu^-} - 1/\tau_{\mu^+}$ to 1%



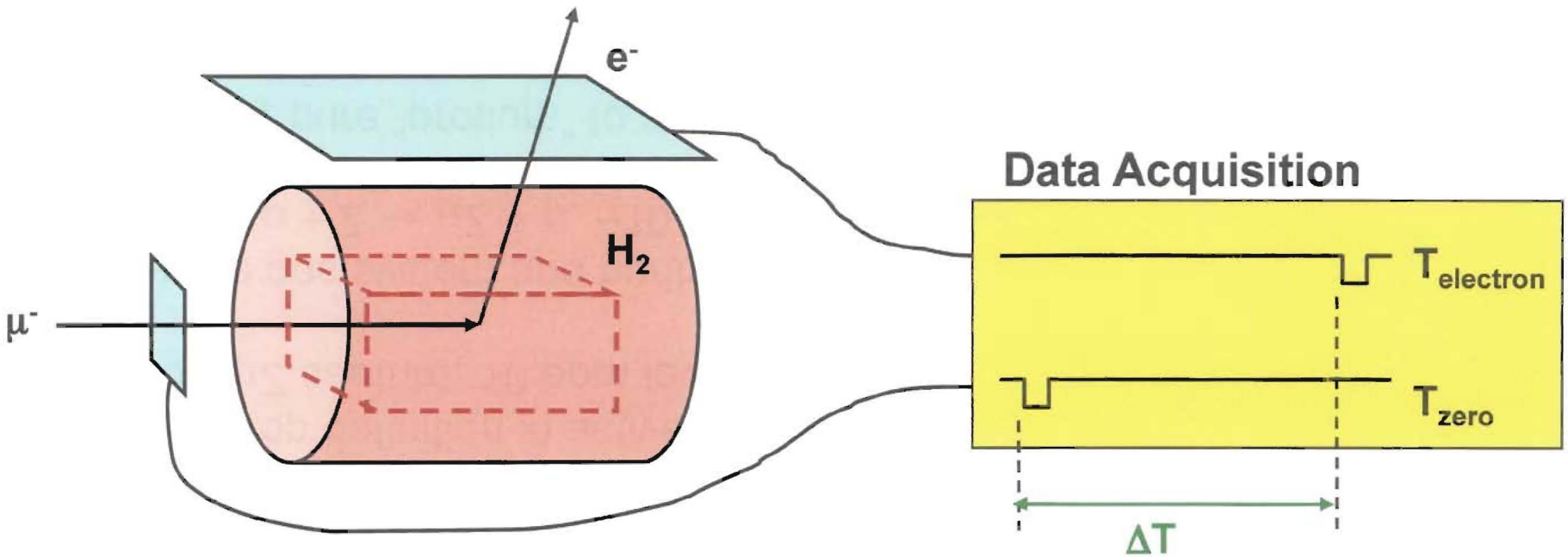

- Clean μ stop definition in active target (TPC) to avoid μZ capture, 10 ppm level
- Ultra-pure gas system and purity monitoring to avoid: $\mu p + Z \rightarrow \mu Z + p$, ~10 ppb impurities
- Isotopically pure "protium" to avoid $\mu p + d \rightarrow \mu d + p$, ~1 ppm deuterium

diffusion range ~cm

***fulfill all requirements simultaneously***
***unique μCap capabilities***

# μCap Method: Lifetime Technique

μCap measures the lifetime of $\mu^-$ in 10 bar Hydrogen.

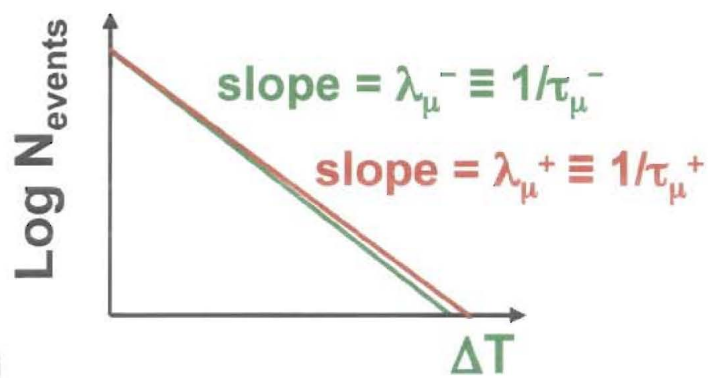



Repeat $10^{10}$ times for a 10 ppm precision lifetime measurement.

Compare to $\mu^+$ lifetime:

$$\lambda_{\mu^-} \approx \lambda_{\mu^+} + \Lambda_S$$

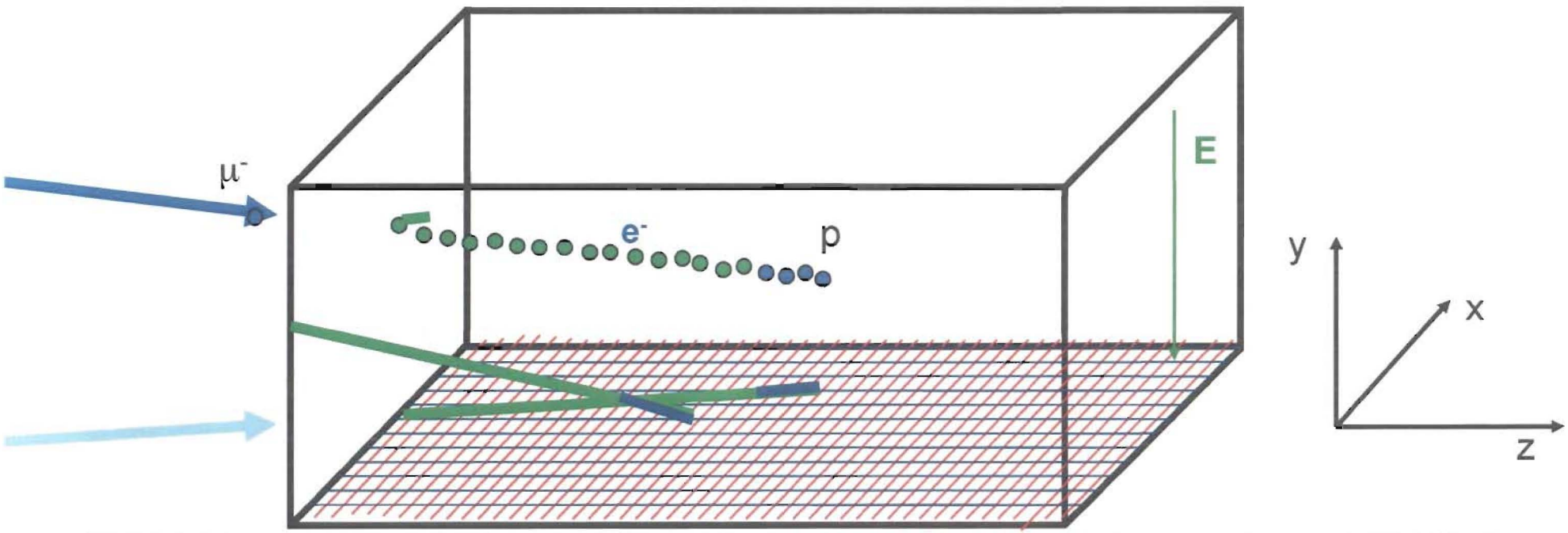
$$\Rightarrow \Lambda_S \text{ to 1\% precision}$$



# Tracking in the Time Projection Chamber

1) μ entrance, Bragg peak at stop.

2) ionization electrons drift to MWPC.



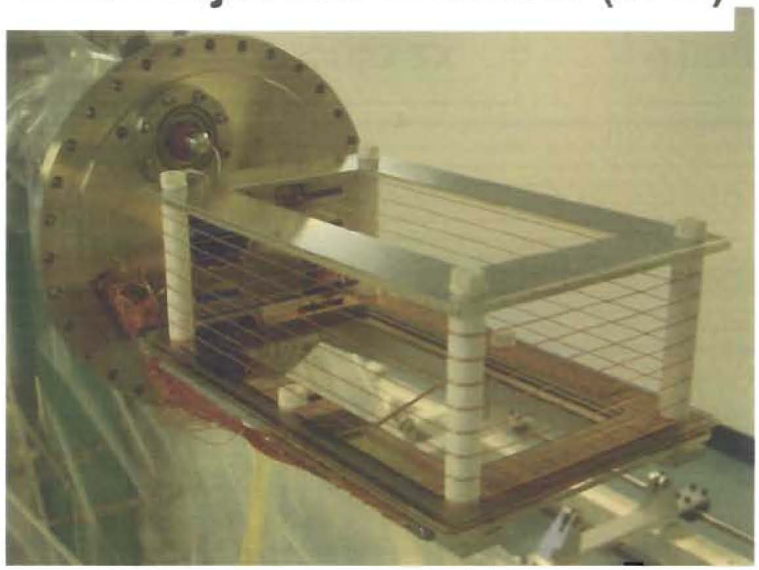

3) projection onto zx plane from anodes and strips.

4) projection onto zy plane from anodes and drift time.

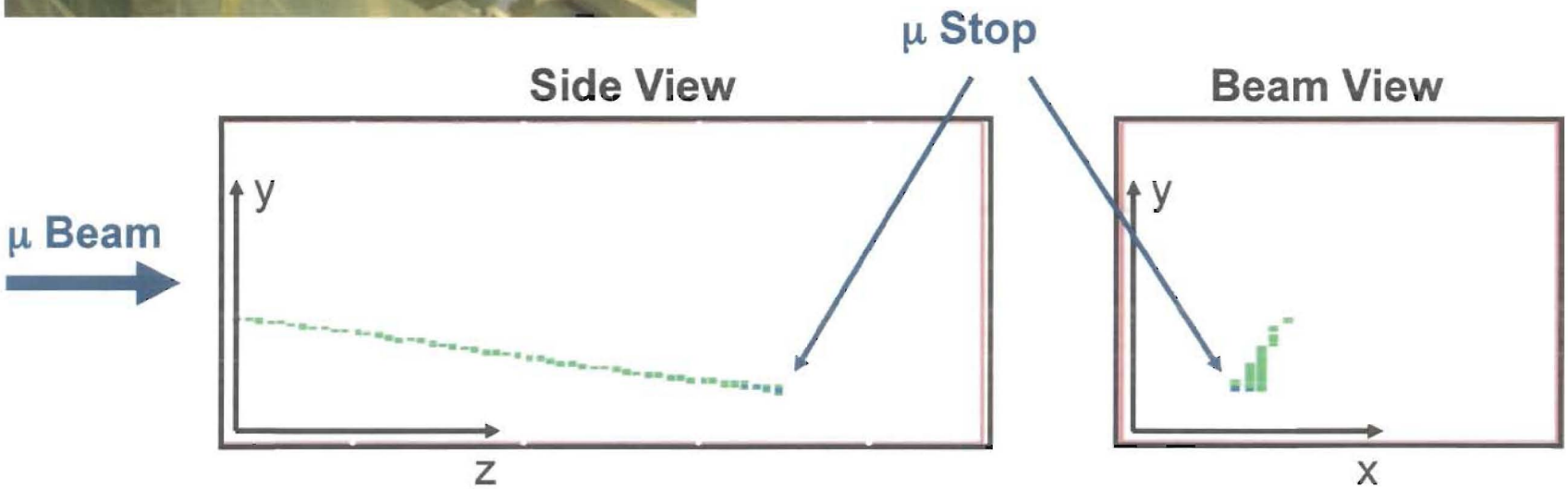
5) projection onto zy plane from strips and drift time.

# 3D tracking w/o material in fiducial volume

**Time Projection Chamber (TPC)**

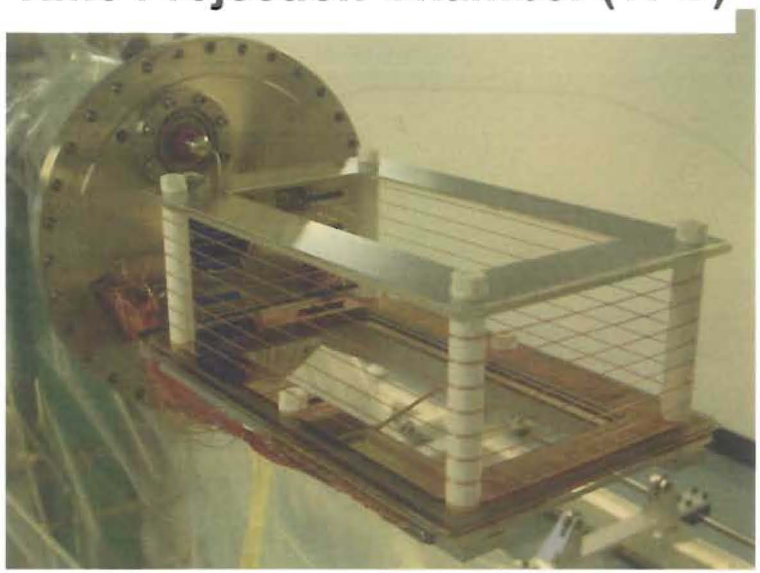


10 bar ultra-pure hydrogen, 1% $LH_2$
2.0 kV/cm drift field
>5 kV on 3.5 mm anode half gap
bakable glass/ceramic materials



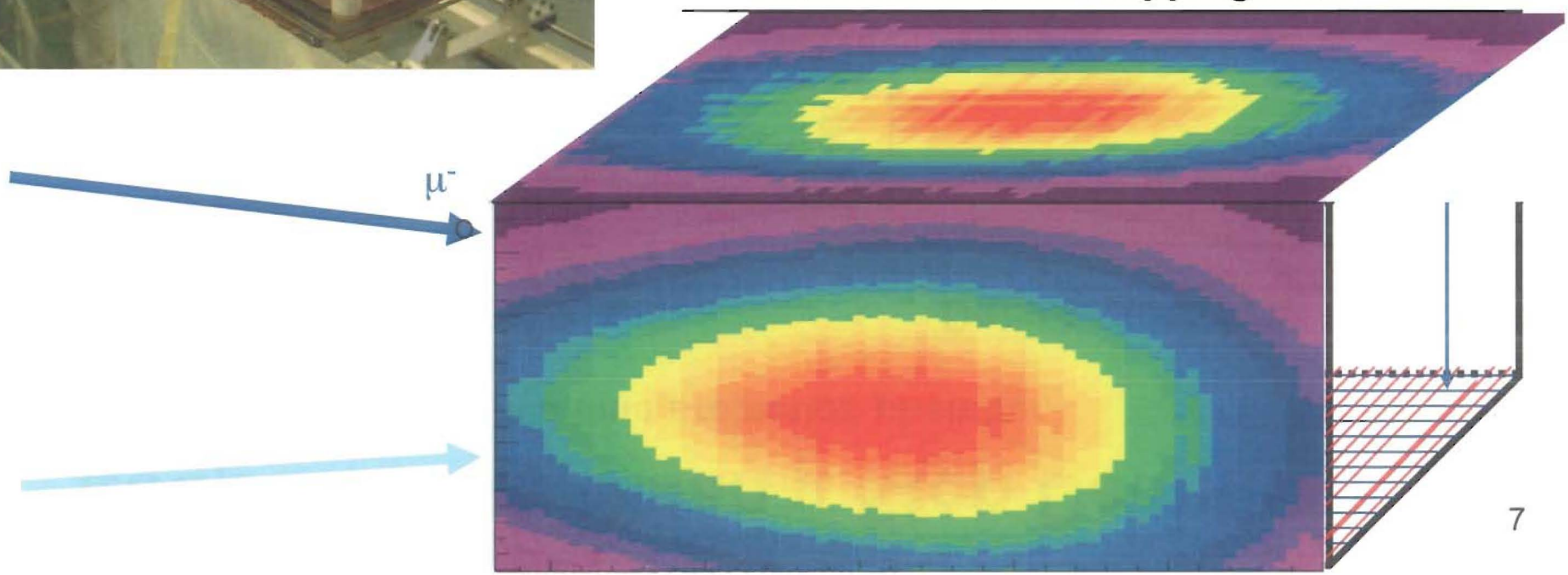
# 3D tracking w/o material in fiducial volume

**Time Projection Chamber (TPC)**



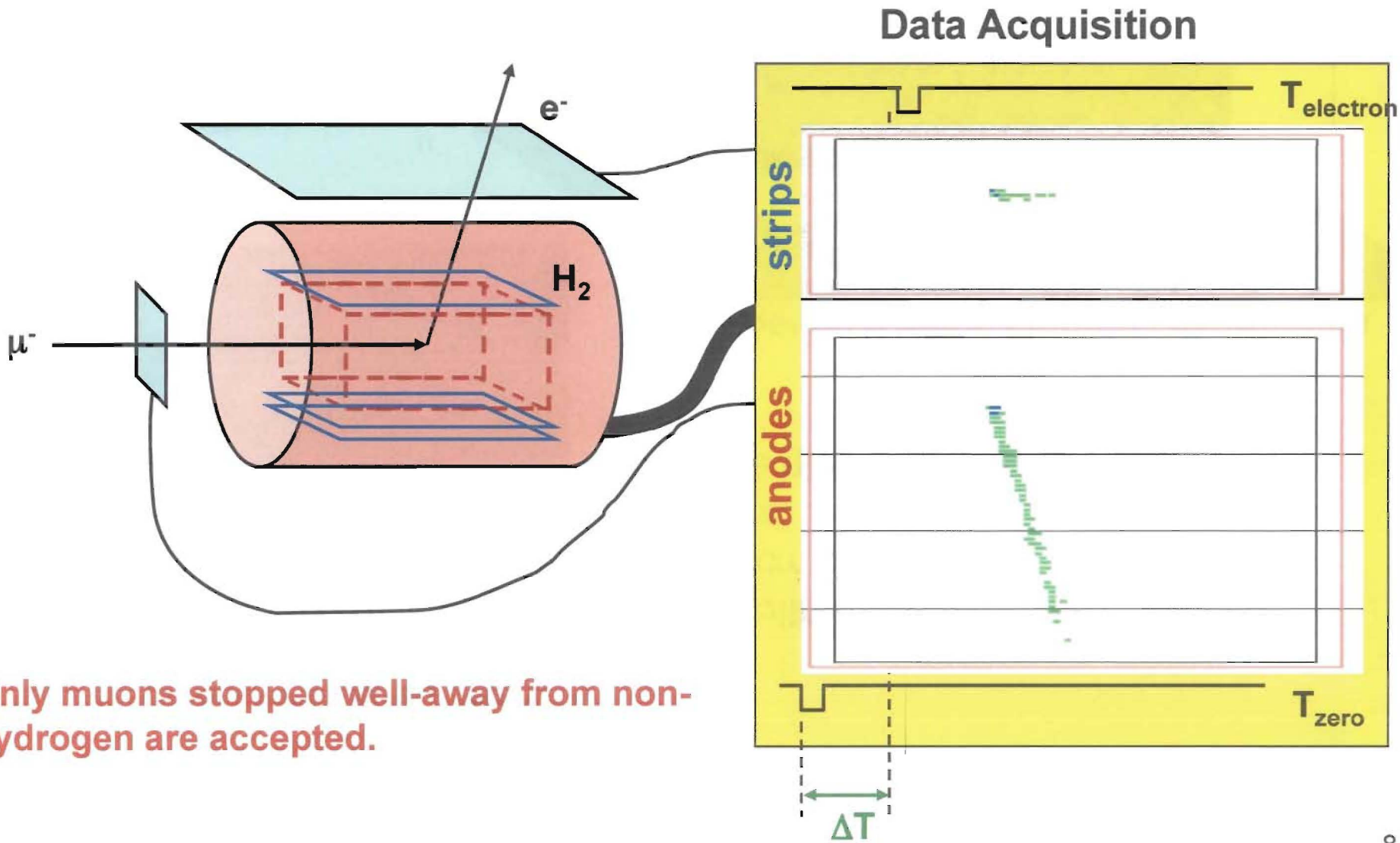
10 bar ultra-pure hydrogen, 1% $LH_2$
2.0 kV/cm drift field
>5 kV on 3.5 mm anode half gap
bakable glass/ceramic materials

**Observed muon stopping distribution**



# μCap Method: Clean μ Stop Definition

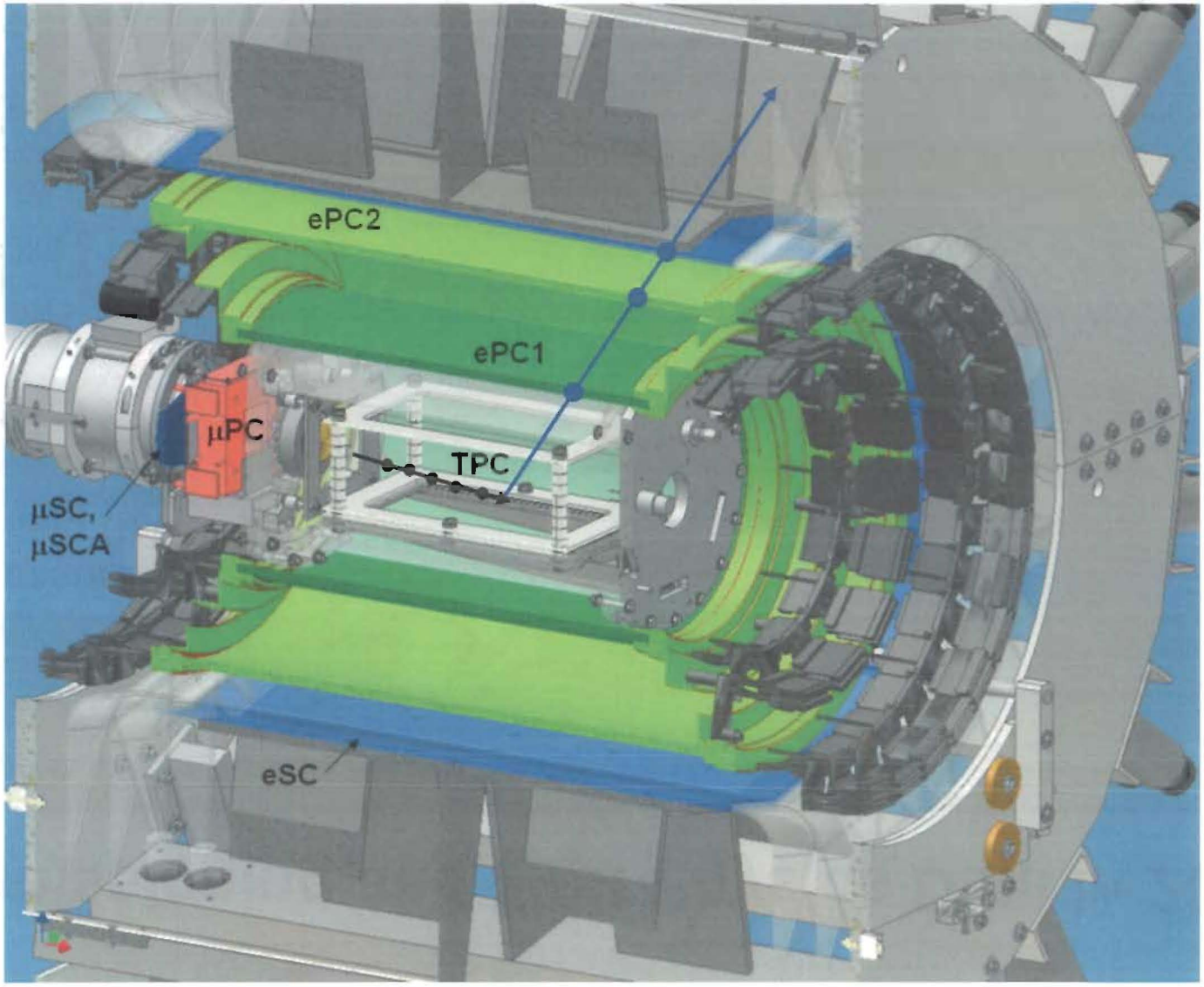
Each muon is tracked in a time projection chamber.



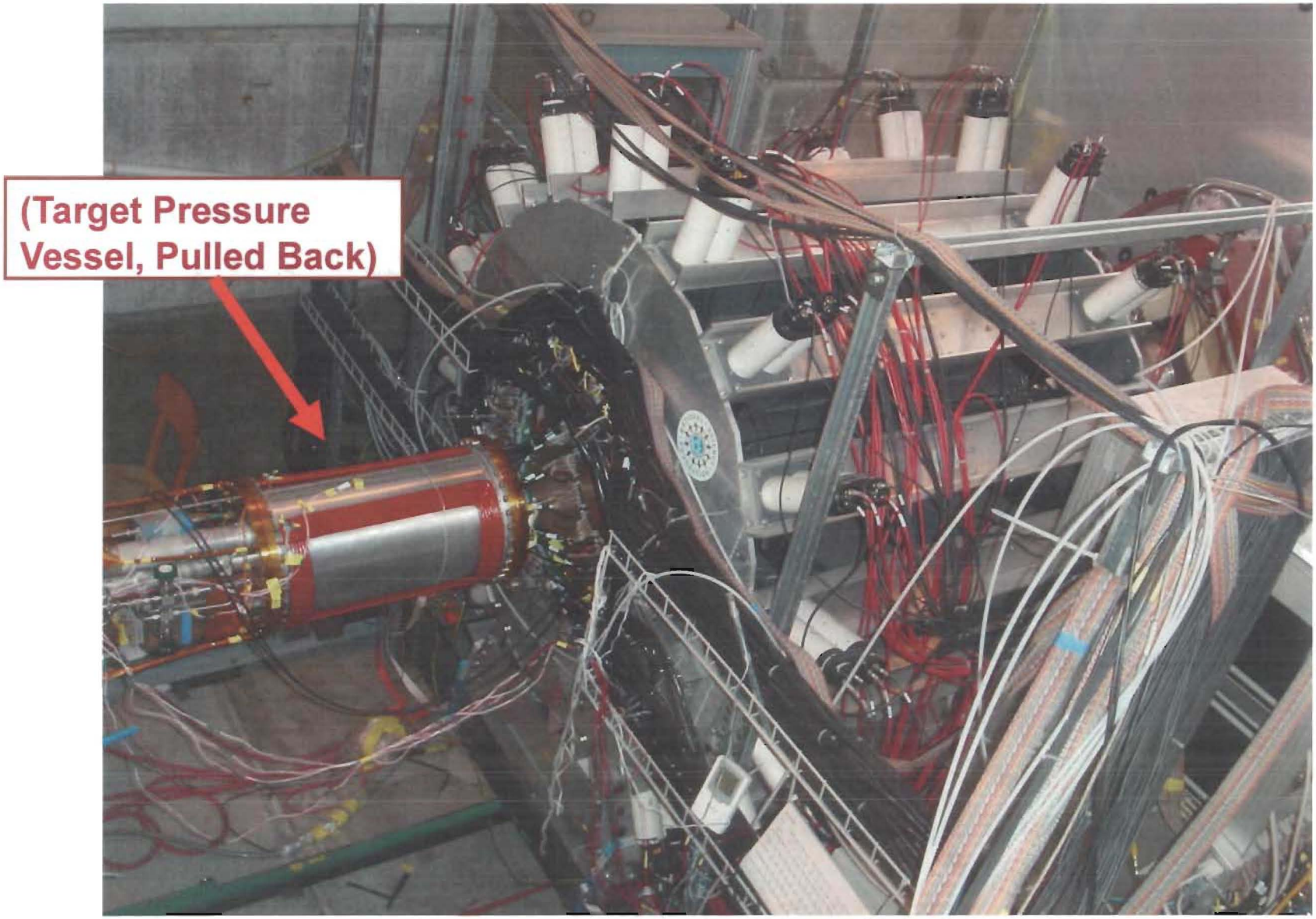

Only muons stopped well-away from non-hydrogen are accepted.

# μCap Detailed Diagram

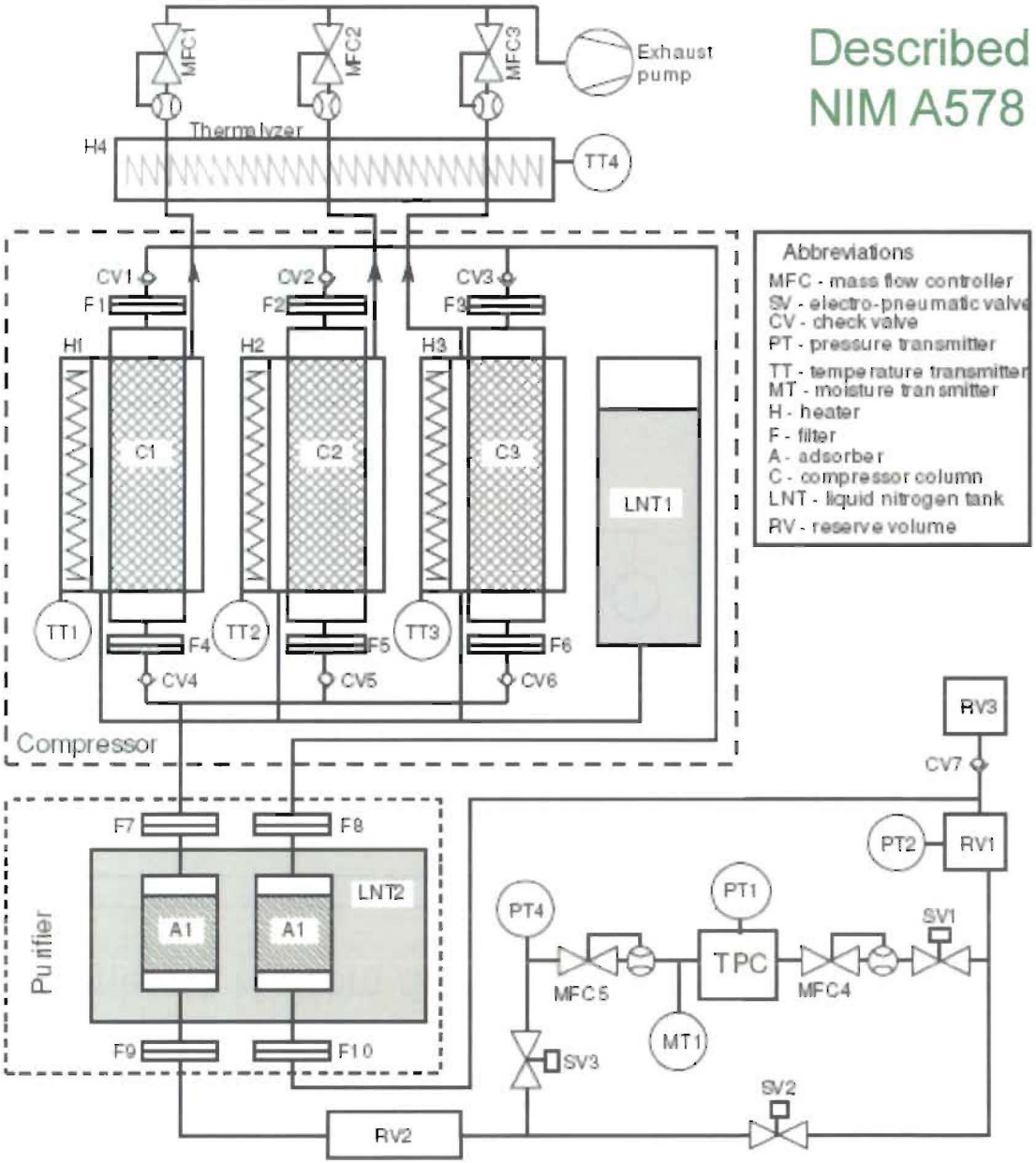
- Tracking of Muon to Stop Position in Ultrapure $H_2$ Gas
- Tracking of Decay Electron



# Commissioning and First Physics Data in 2004

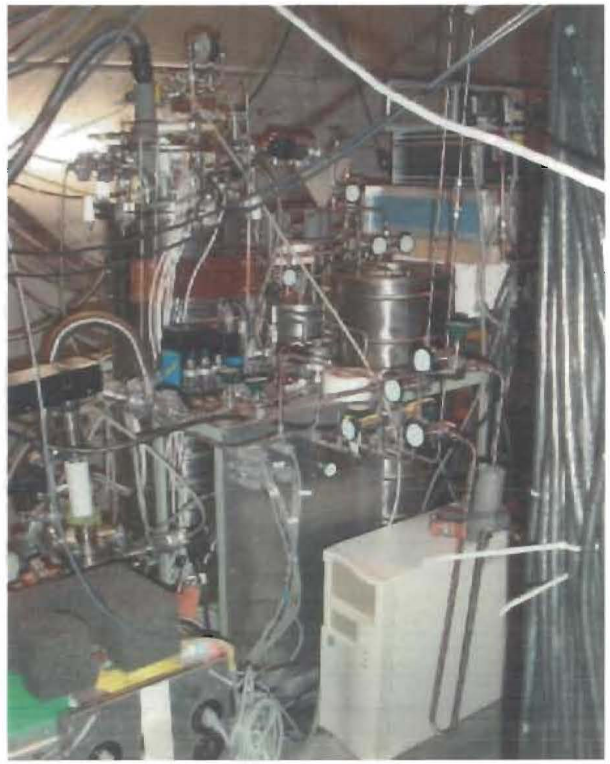


# Gas impurities (Z > 1) are removed by a continuous $H_2$ ultra-purification system (CHUPS).




Described in
NIM A578 (2007) 485-497.

Commissioned 2004

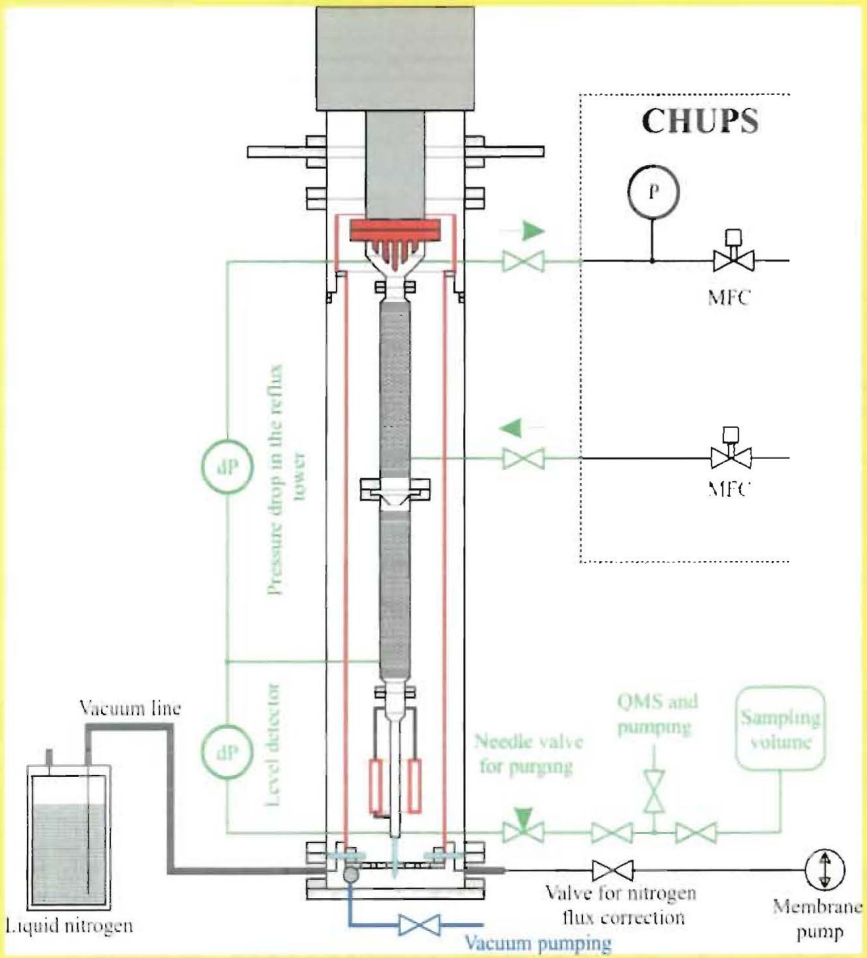


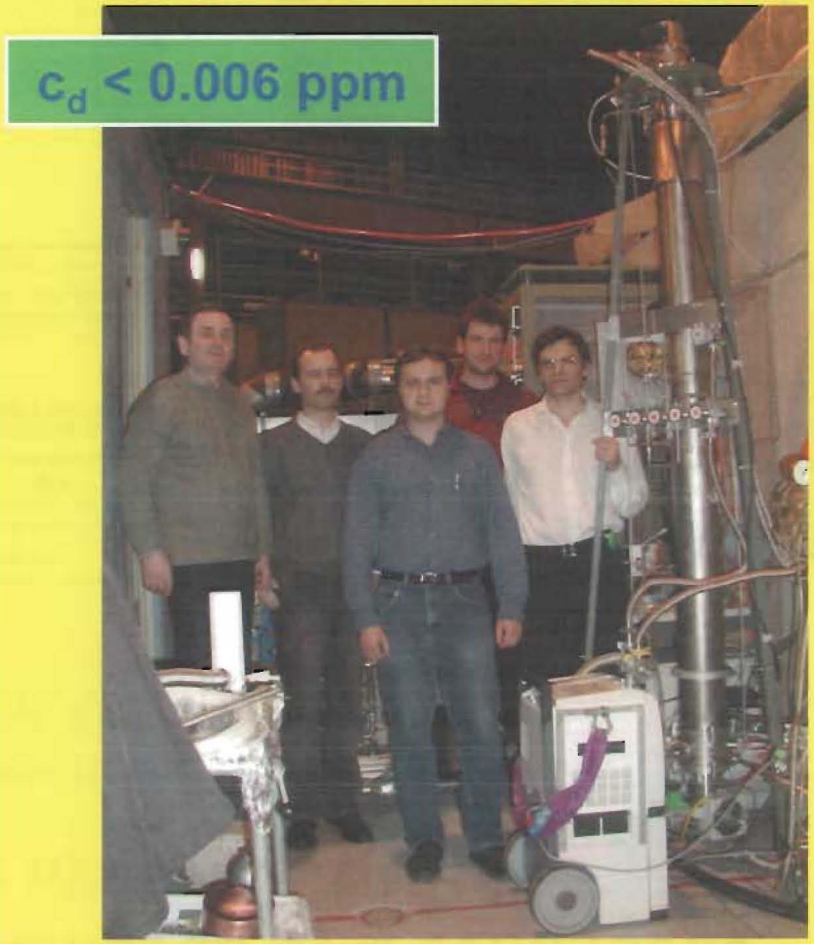
$c_{N2}$, $c_{O2}$ < 0.01 ppm

# Isotopically Pure "Protium" Target

1) Generate $H_2$ from deuterium-depleted water ($c_d$ ~1 ppm)

2) On-site isotopic purifier 2006 (PNPI, CRDF)



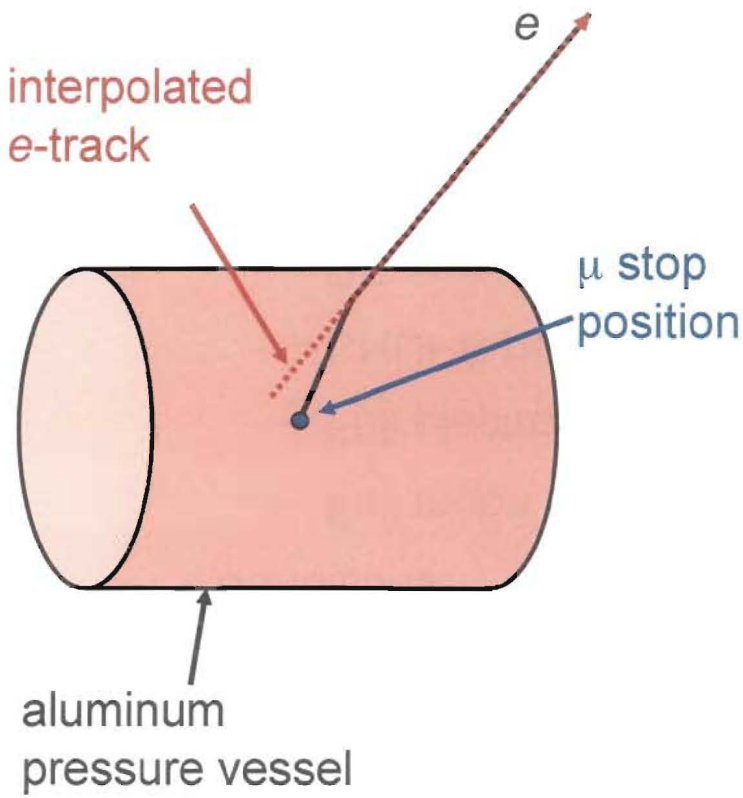



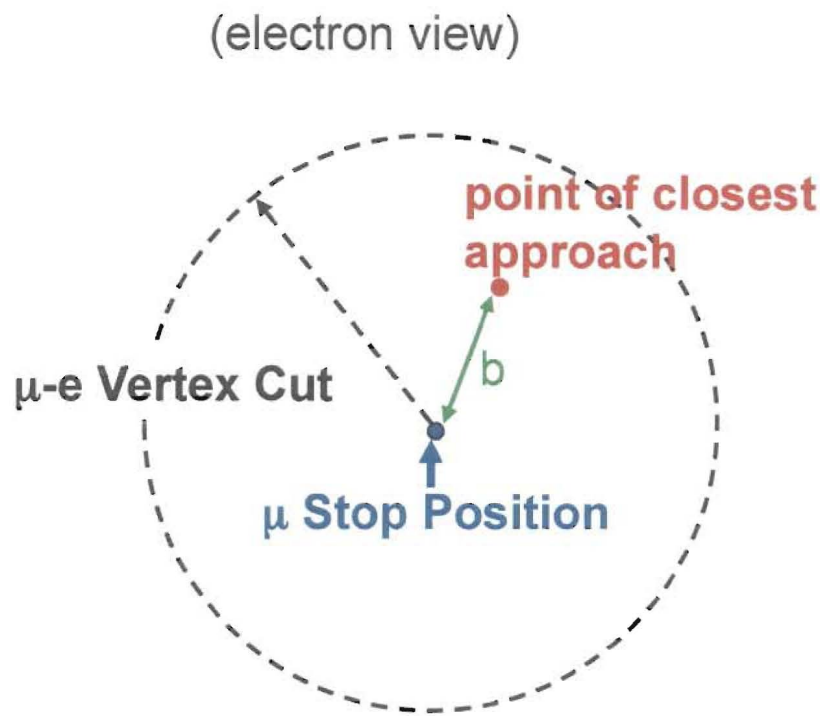
# Analysis of MuCap data collected in 2004

- Led to first physics result published July 2007
- Based on 1.6 $10^9$ observed muon decay events
- Conditions:
  - -- Full muon tracking
  - -- Full electron tracking
  - -- CHUPS running ($c_Z$ ~ 10 ppb)
  - -- DC muon beam ~20 kHz
  - -- <u>No</u> isotopic purification column ($c_d$ ~ 1 ppm)

# Impact Parameter Cuts

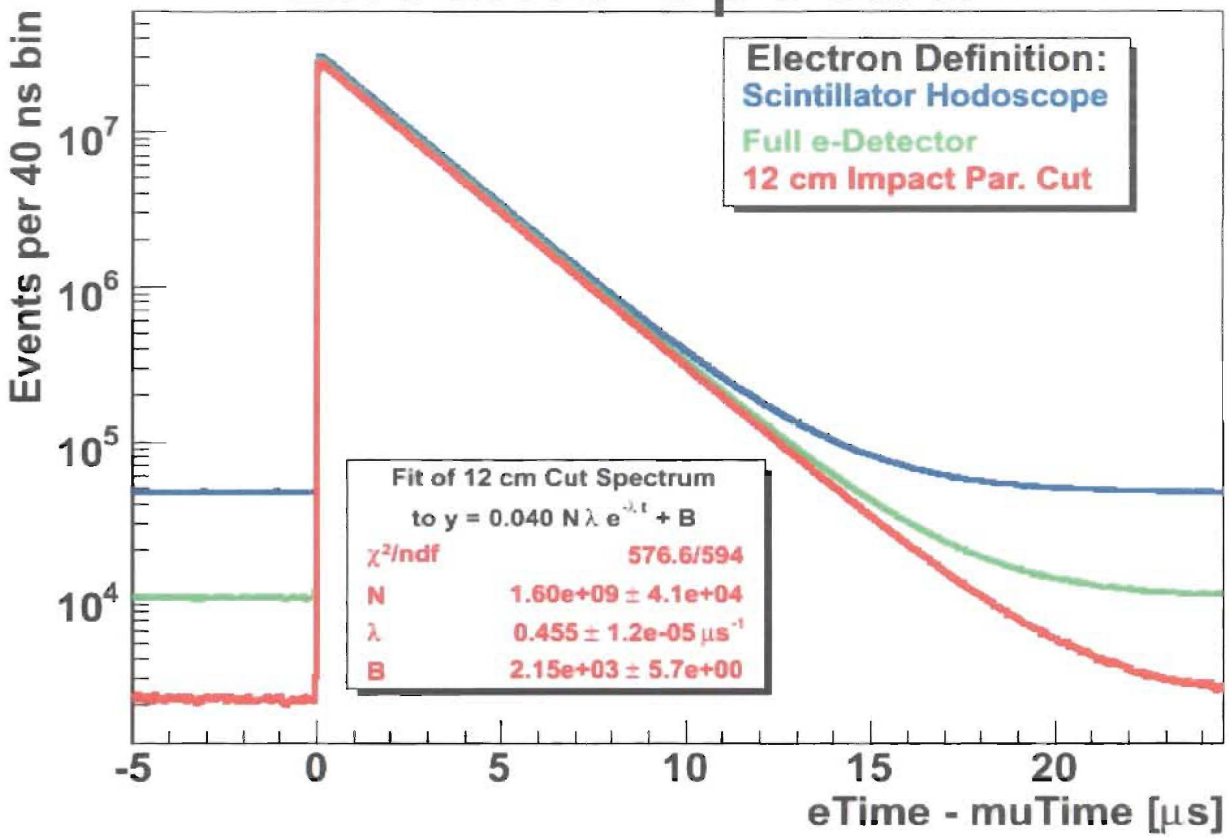
(also known as μ-e vertex cuts)



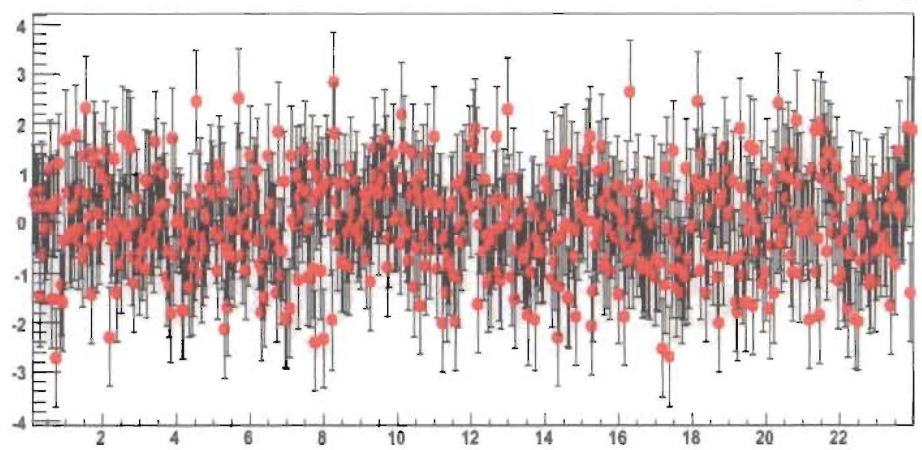




The impact parameter b is the distance of closest approach of the e-track to the μ stop position.

# Lifetime Spectra




Normalized residuals ("pull")

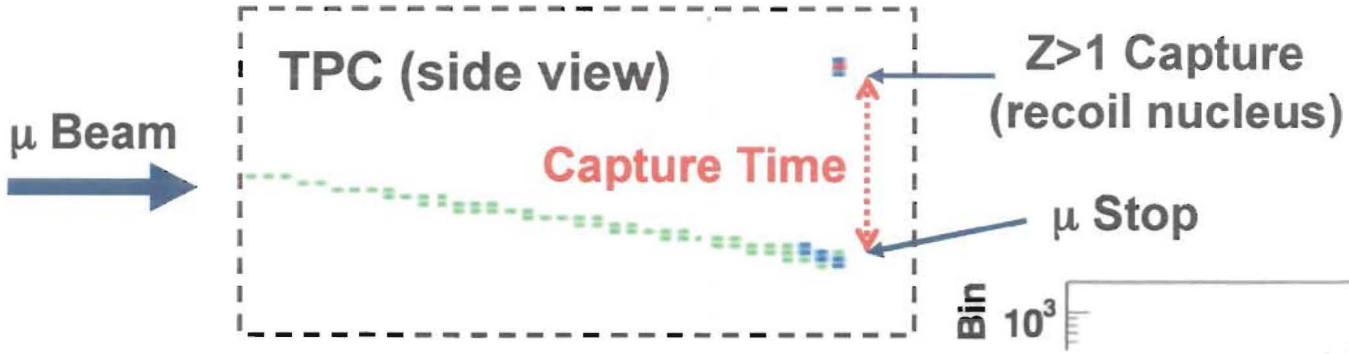


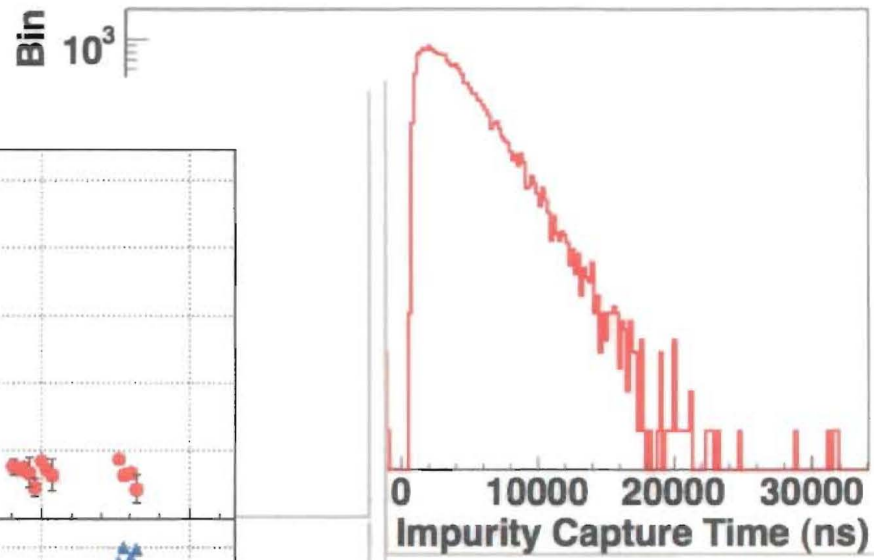
# Internal corrections to $\lambda_{\mu^-}$

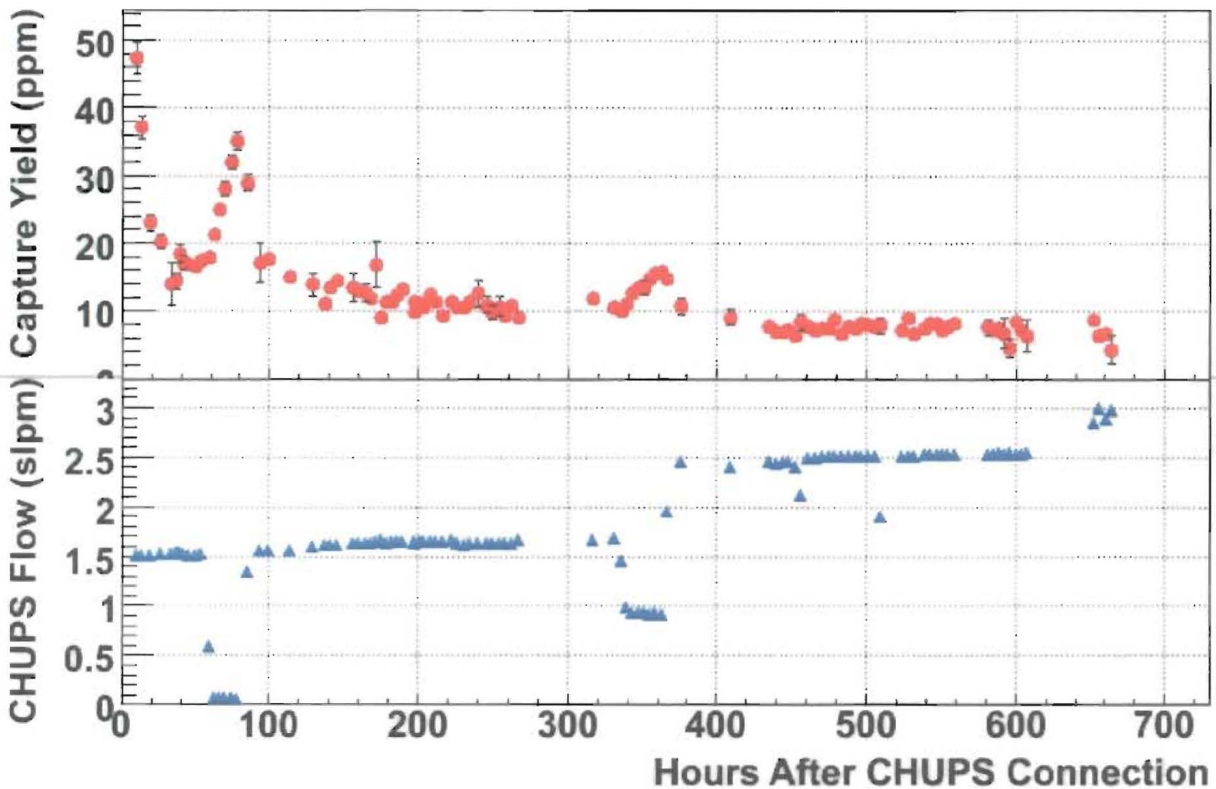
| Source | Correction ($s^{-1}$) | Uncertainty ($s^{-1}$) |
|---|---|---|
| $Z > 1$ impurities ($\Delta\lambda_Z$) | $-17.4$ | 4.6 |
| Deuterium ($\Delta\lambda_d$) | $-12.1$ | 1.8 |
| $\mu p$ Diffusion ($\Delta\lambda_k$) | $-3.1$ | 0.1 |
| Unseen $\mu + p$ scatters ($\Delta\lambda_{\rm sc}$) | 0.0 | 3.0 |
| $\mu$ stop definition ($\Delta\lambda_{\rm tr}$) | 0.0 | 2.0 |
| $\mu$ pileup veto inefficiency ($\Delta\lambda_\kappa$) | 0.0 | 3.0 |
| Analysis methods ($\Delta\lambda_{\rm Ana}$) | 0.0 | 5.0 |
| Total | $-32.6$ | $\pm 8.4$ |

(statistical uncertainty of $\lambda_{\mu^-}$: 12 $s^{-1}$)

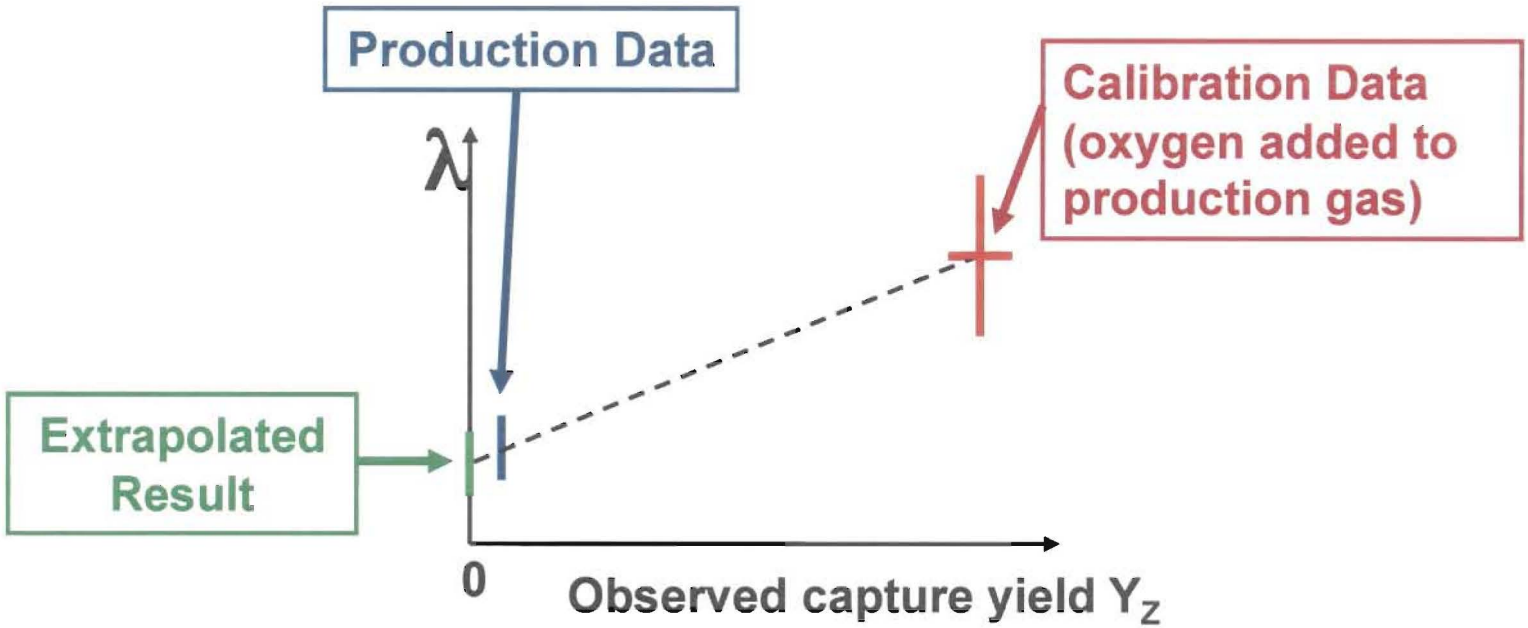
# In situ detection of Z > 1 captures



# The final Z > 1 correction $\Delta\lambda_Z$ is based on impurity-doped calibration data.




Lifetime deviation is linear with the Z>1 capture yield.

Some adjustments were made because calibration data with the main contaminant, oxygen ($H_2O$), were taken in a later running period (2006).

# Internal corrections to $\lambda_{\mu^-}$

| Source | Correction ($s^{-1}$) | Uncertainty ($s^{-1}$) |
|---|---|---|
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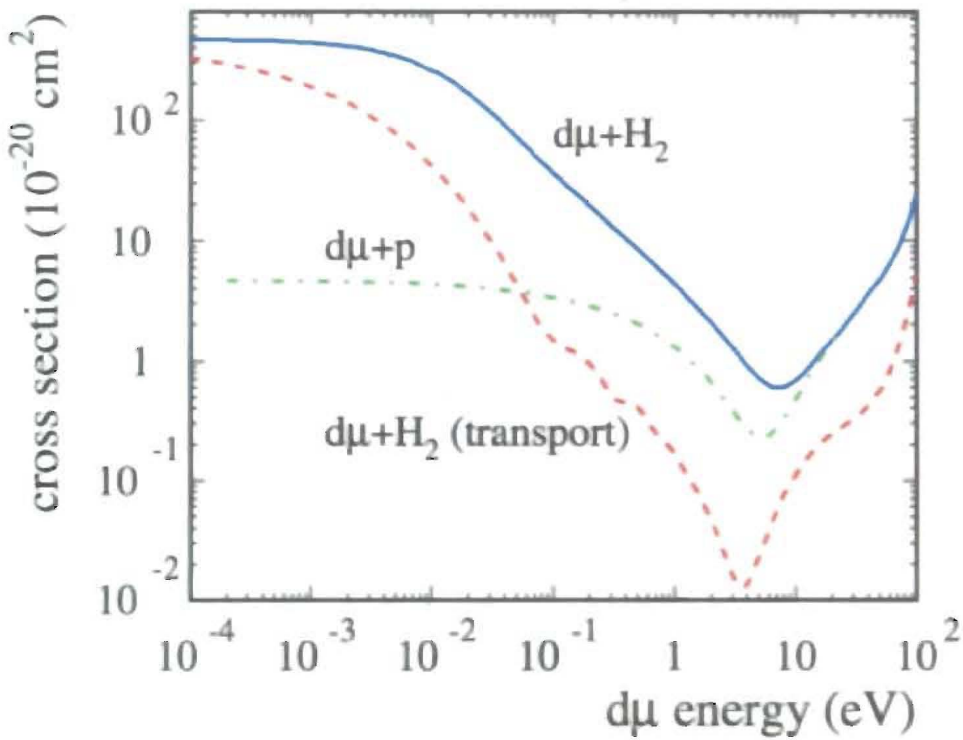
| Analysis methods ($\Delta\lambda_{\rm Ana}$) | 0.0 | 5.0 |
| Total | $-32.6$ | $\pm 8.4$ |

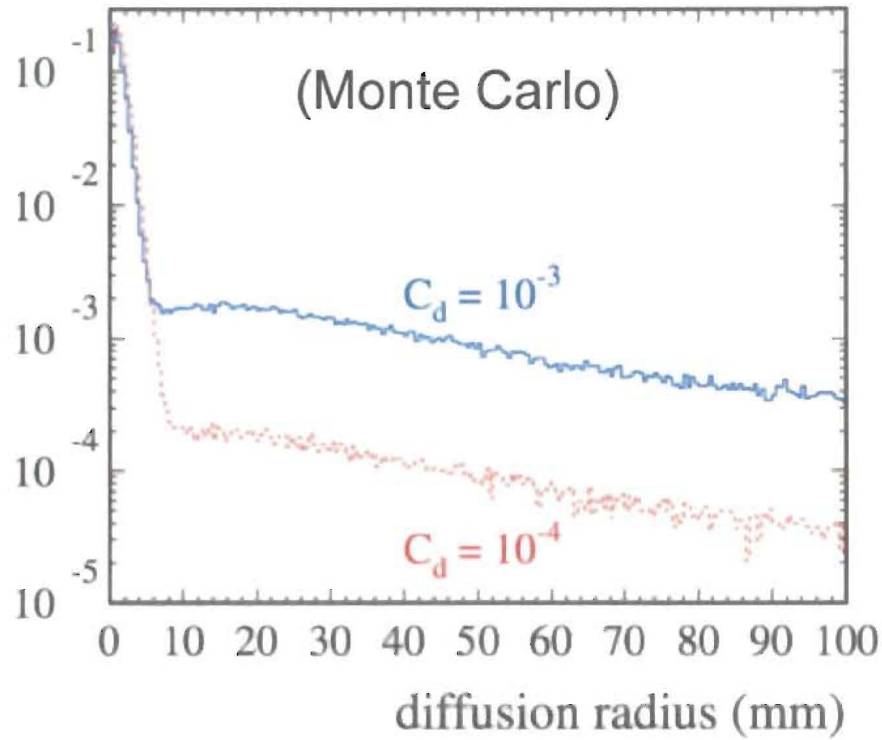
(statistical uncertainty of $\lambda_{\mu^-}$: 12 $s^{-1}$)

# μd Diffusion into Z > 1 Materials

μd scattering in $H_2$

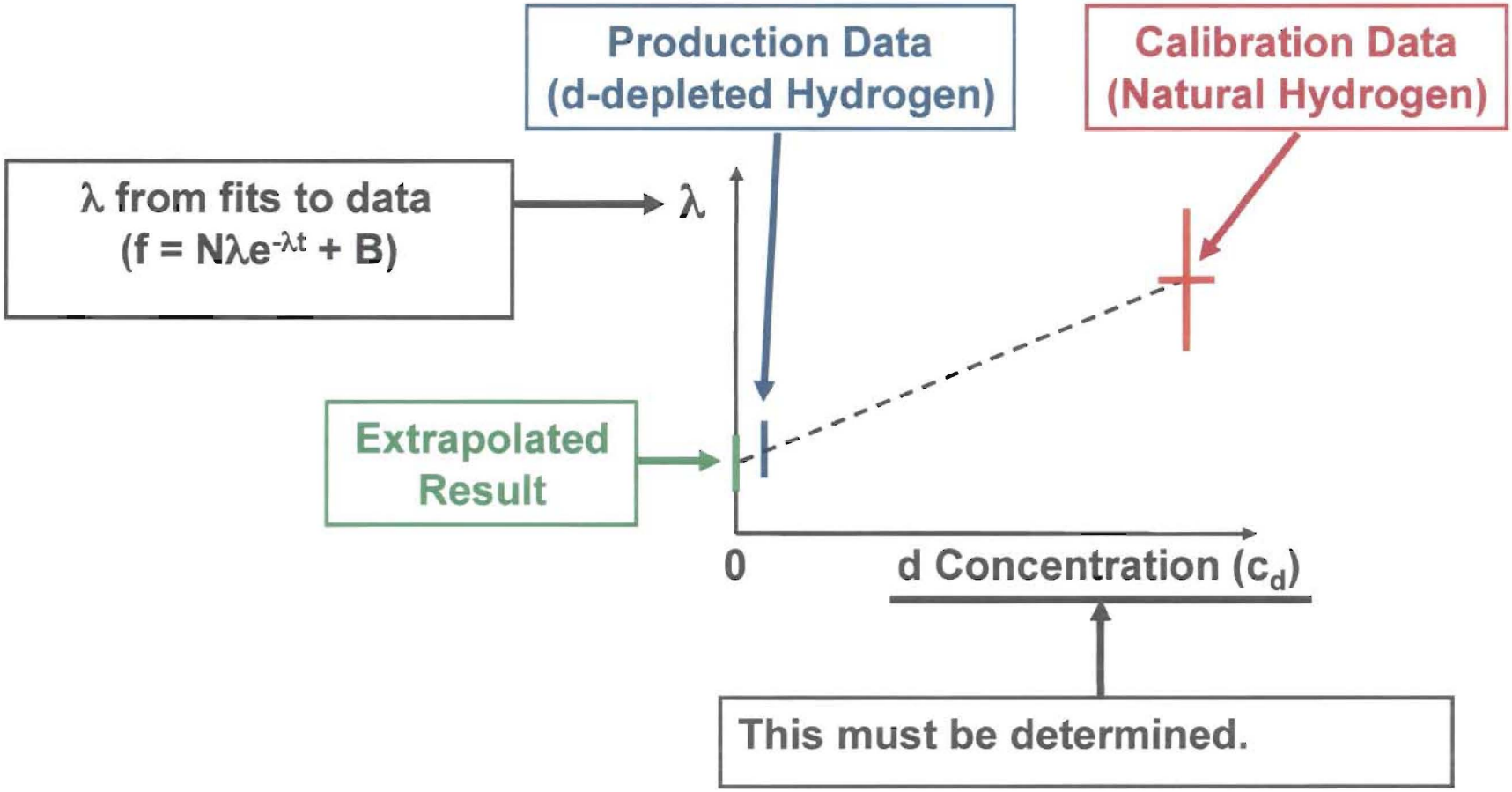



displacement (from $\mu^-$ stop position) at time of decay

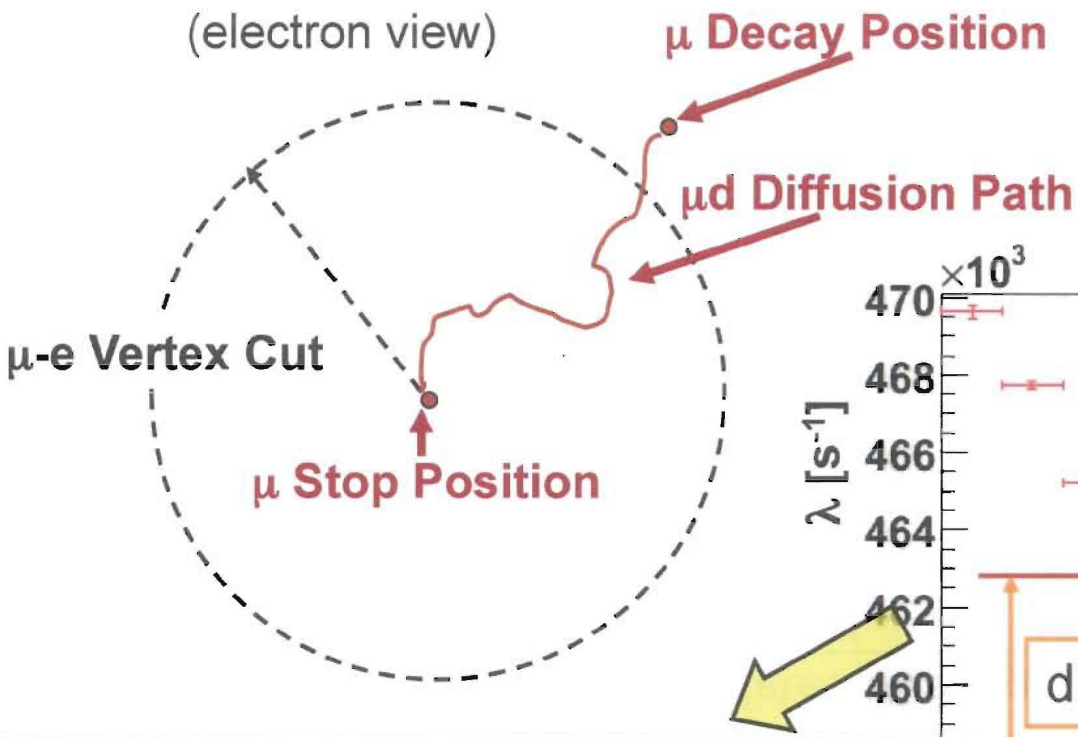



- Ramsauer-Townsend minimum in the scattering cross section
- μd can diffuse ~10 cm before muon decay, possibly into walls.
- MuCap uses deuterium-depleted hydrogen ($c_d \approx 1.5$ ppm).
- Residual effects are accounted for by a zero-extrapolation.

# Residual deuterium content is accounted for by a zero-extrapolation procedure.



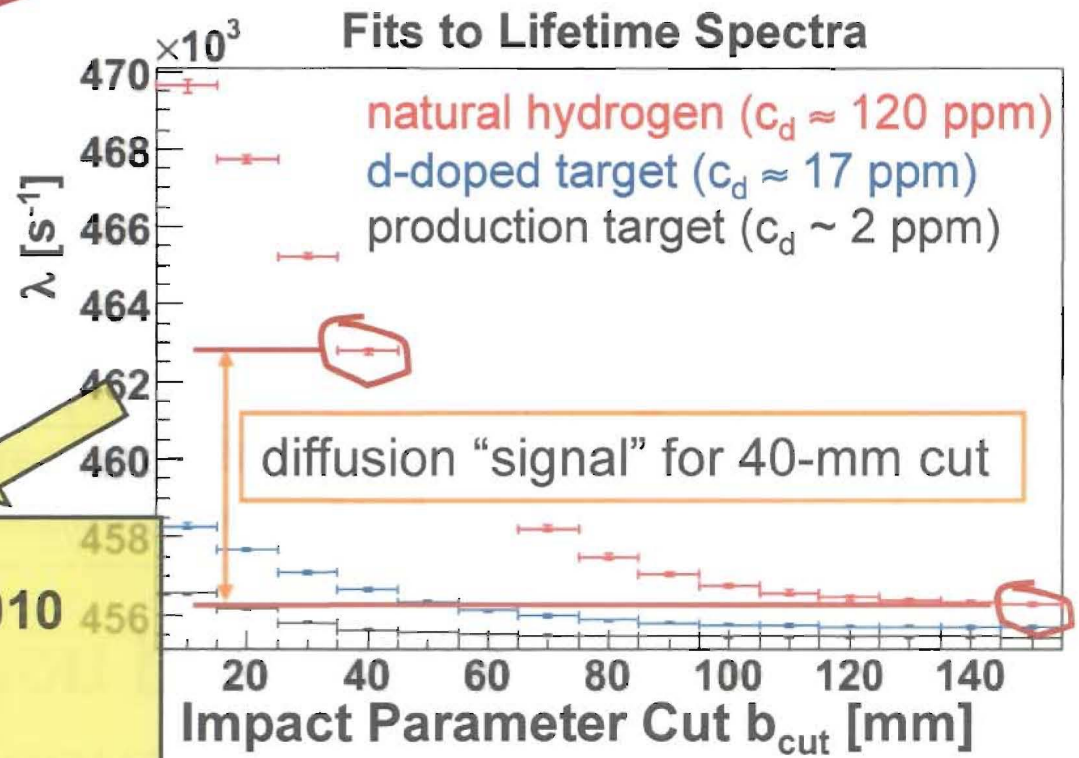
# $c_d$ Determination: Data Analysis Approach




**μd can diffuse out of acceptance region:**

- **signal proportional to number of μd, and therefore to $c_d$.**

**Fits to Lifetime Spectra**




$$\frac{c_d(\text{Production})}{c_d(\text{Natural H2})} = 0.0125 \pm 0.0010$$

*after accounting for μp diffusion

## $c_D$ Monitoring: External Measurement

**Measurements with New ETH Zürich Tandem Accelerator:**

- **2004 Production Gas,**

  $c_D = 1.44 \pm 0.13$ ppm D

- **2005 Production Gas,**

  $c_D = 1.45 \pm 0.14$ ppm D

- **2006 Production Gas (isotope separation column),**

  $c_D < 0.06$ ppm D

**The "Data Analysis Approach" gives a consistent result:**

- **2004 Production Gas,**

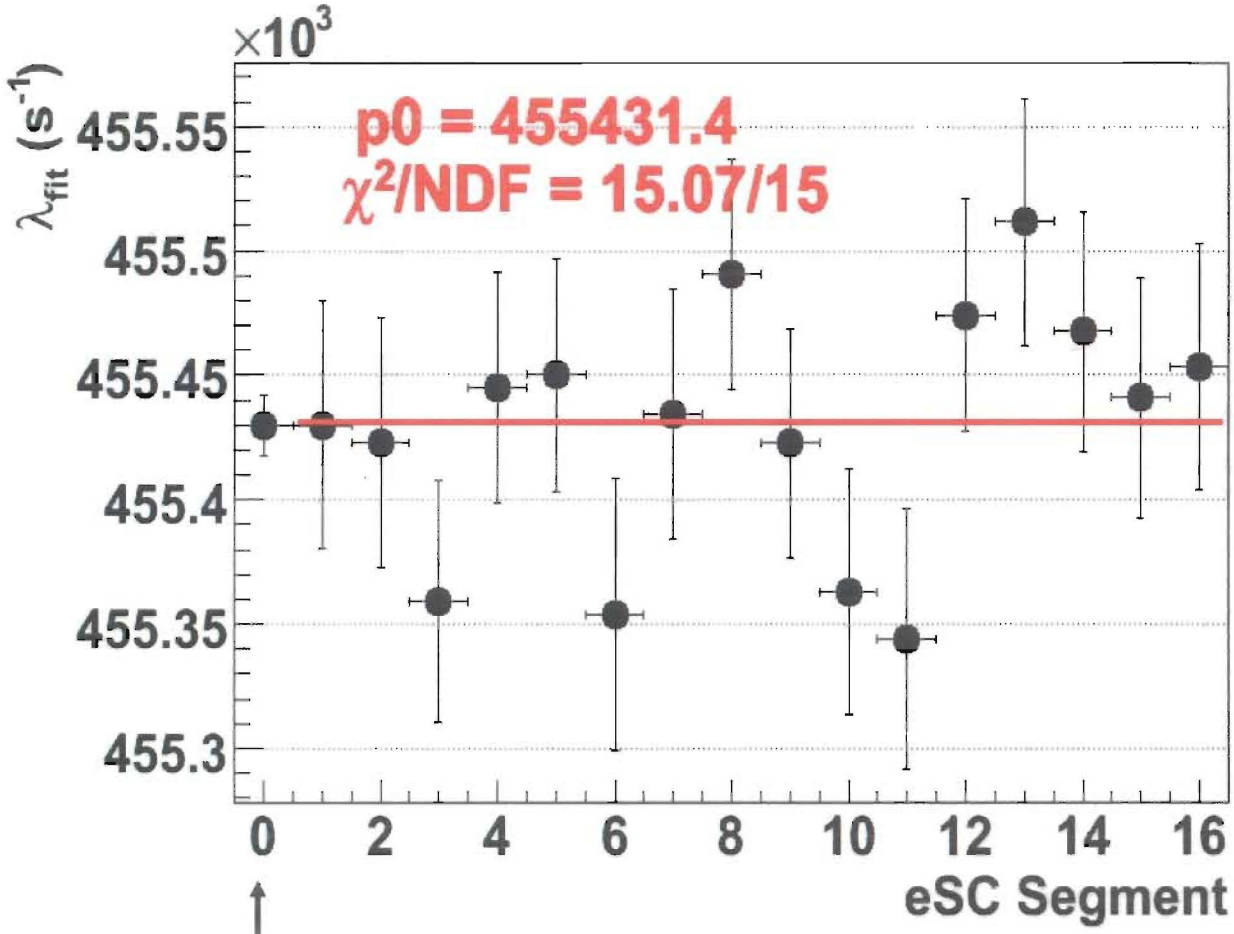
  $c_D = (0.0125 \pm 0.0010) \times (122 \text{ ppm D})$

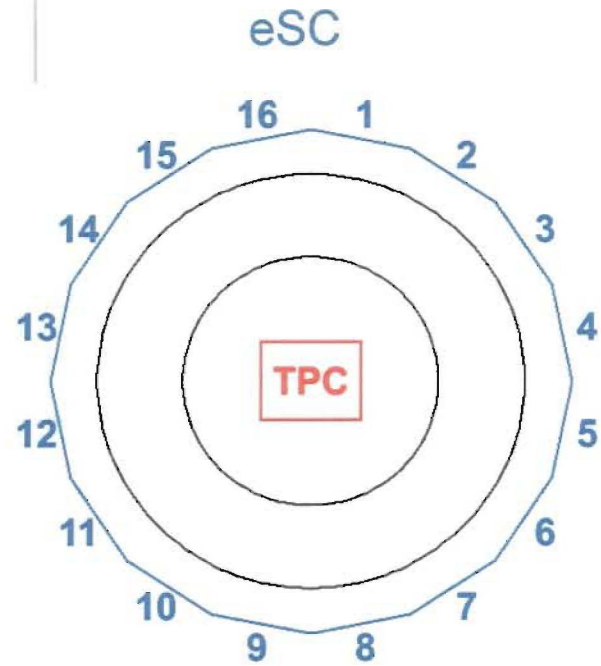
  $= 1.53 \pm 0.12$ ppm

# Consistency Checks

- lifetime vs. variations in parameters not expected to change the results

# Lifetime vs eSC segment

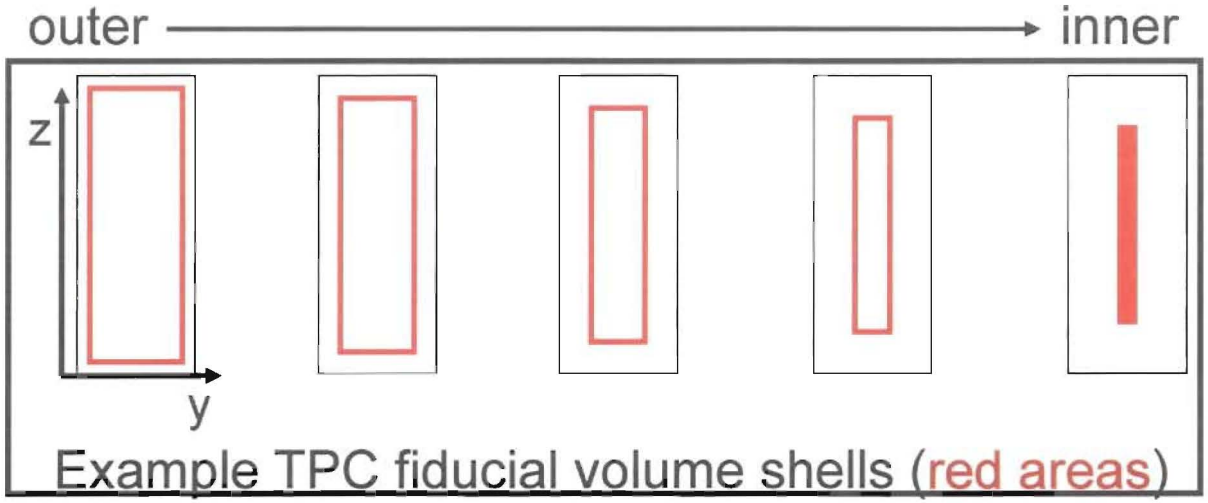


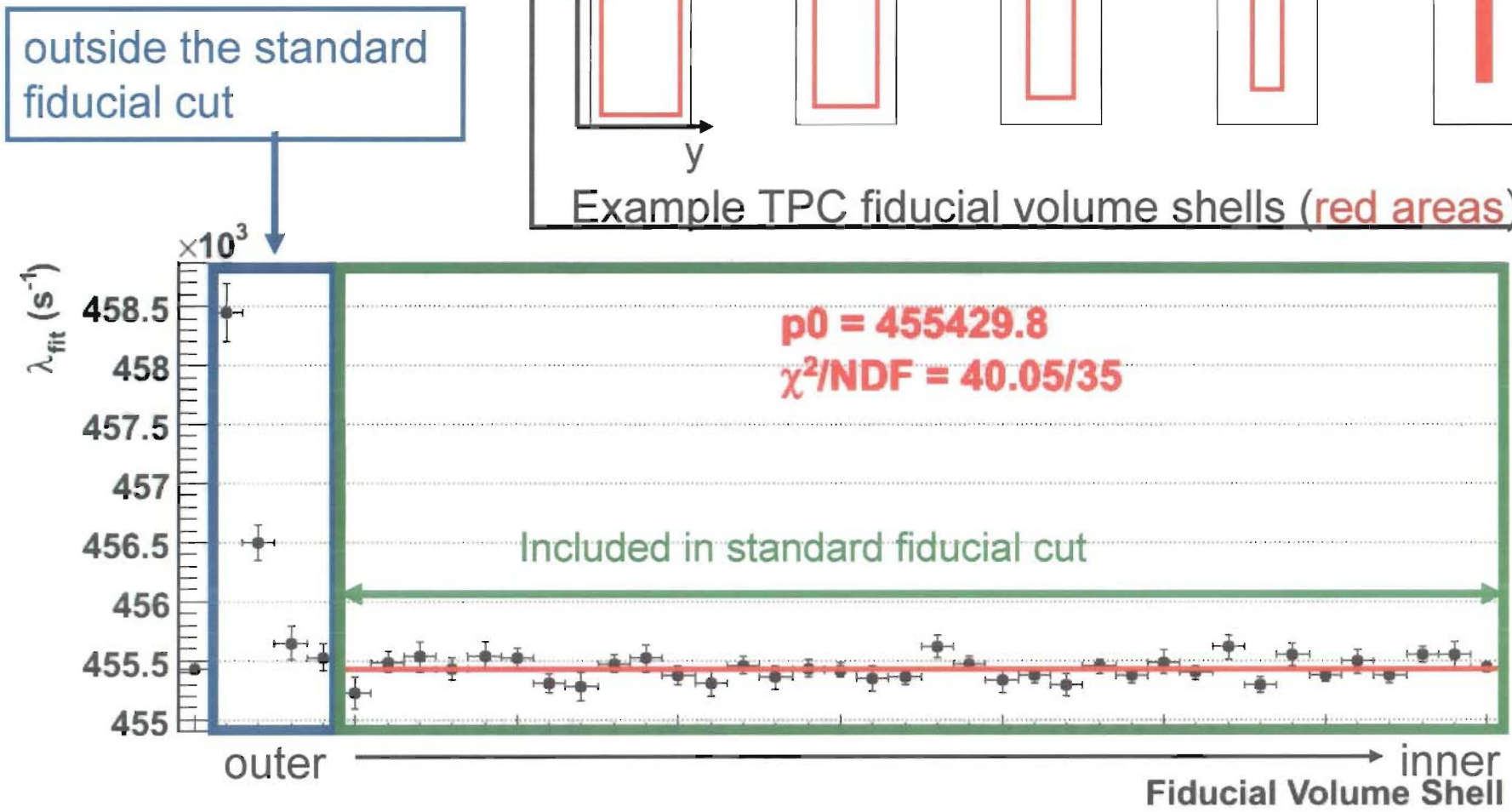




Beam view of MuCap detector

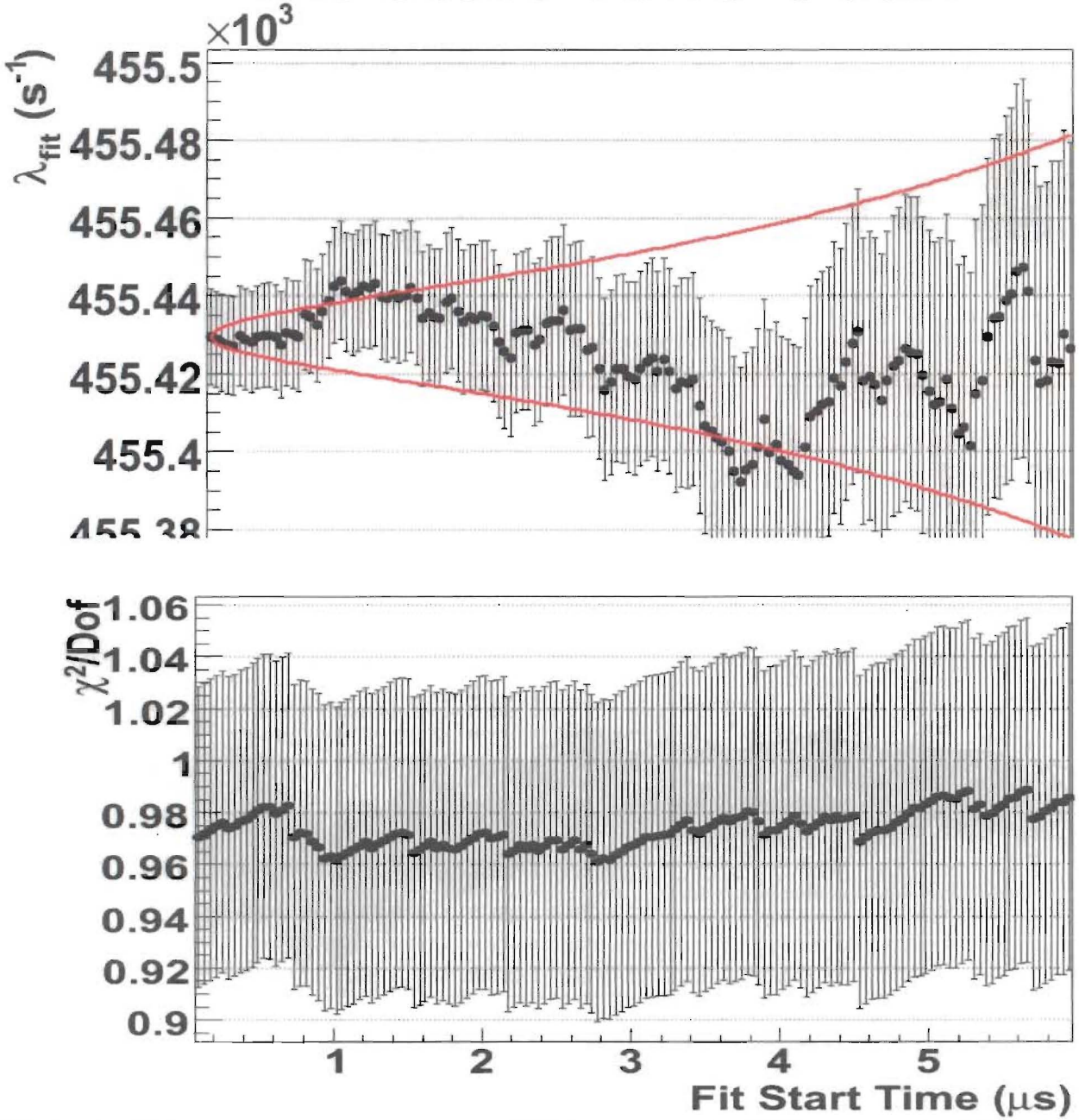
Sum over all segments

# Lifetime vs. Non-Overlapping Fiducial Volume Shell

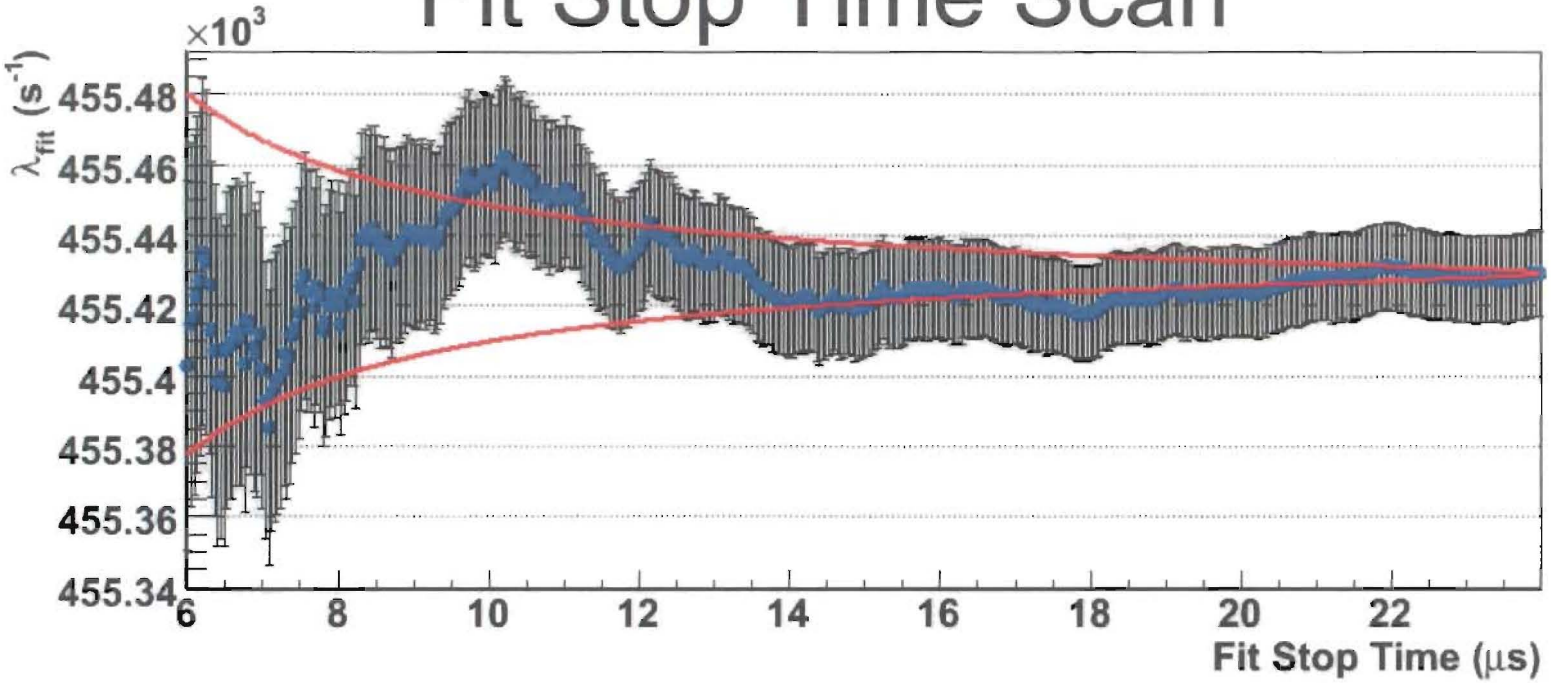


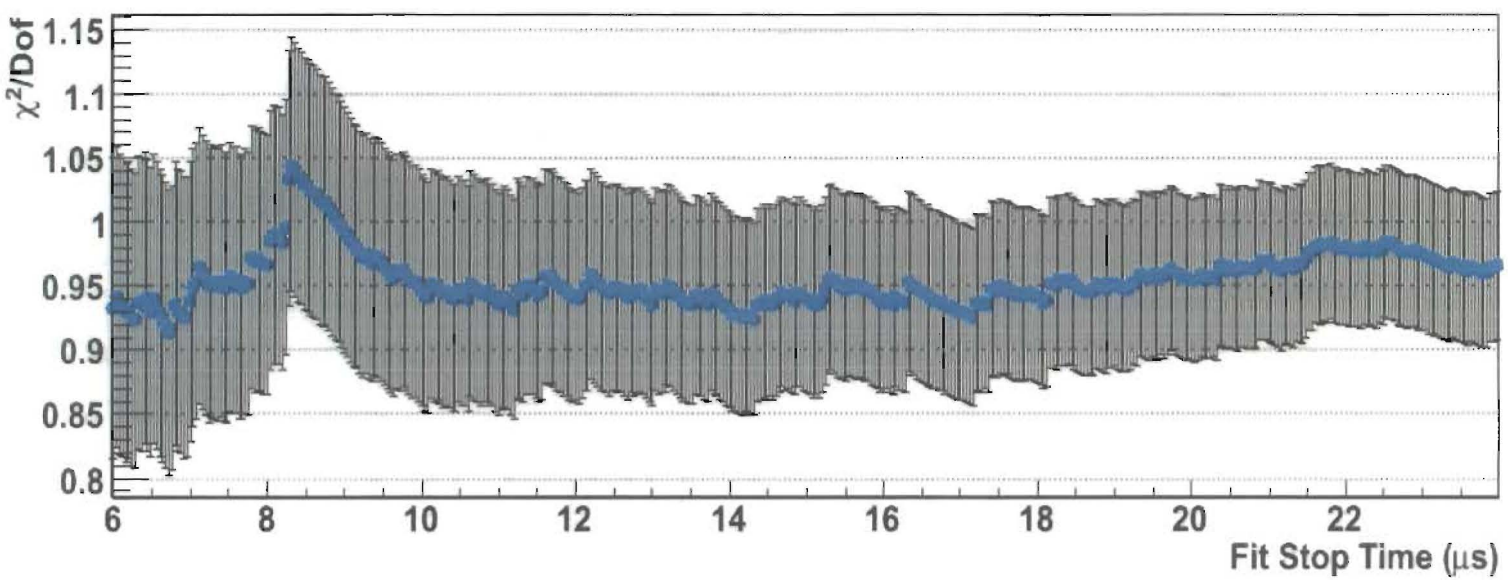



# Fit Start Time Scan

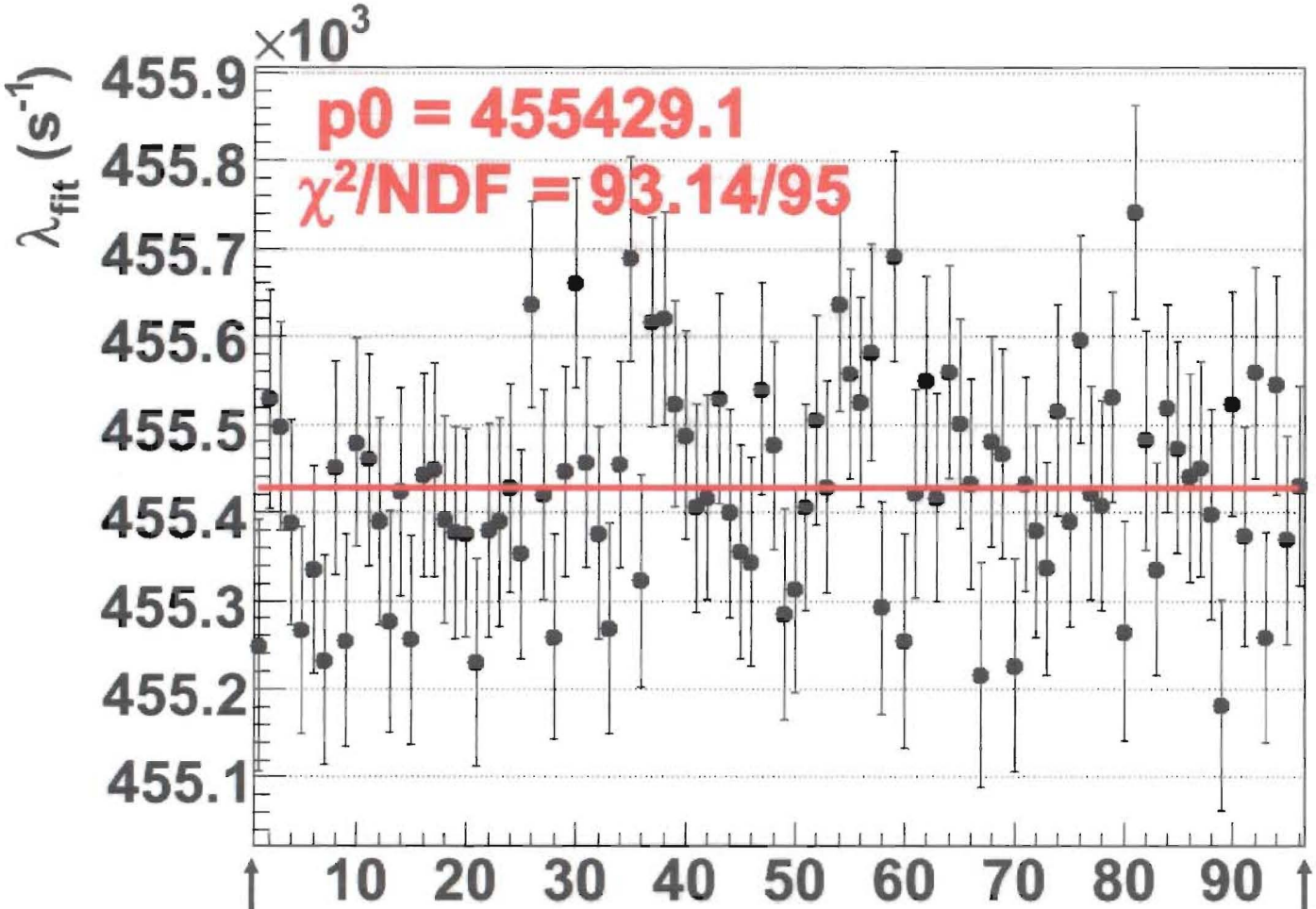


# Fit Stop Time Scan



# Lifetime vs. Chronological Subdivisions




Oct. 9, 2004

Nov. 4, 2004

# MuCap $\Lambda_S$ from the $\mu^-$ lifetime $\lambda_{\mu^-}$

$$\lambda_\mu^- = \lambda_0 + \Lambda_S + \Delta\lambda_{p\mu p}$$

molecular formation

$$\lambda_\mu^+ + \Delta\lambda_{\mu p}$$

$\mu^+$ decay rate

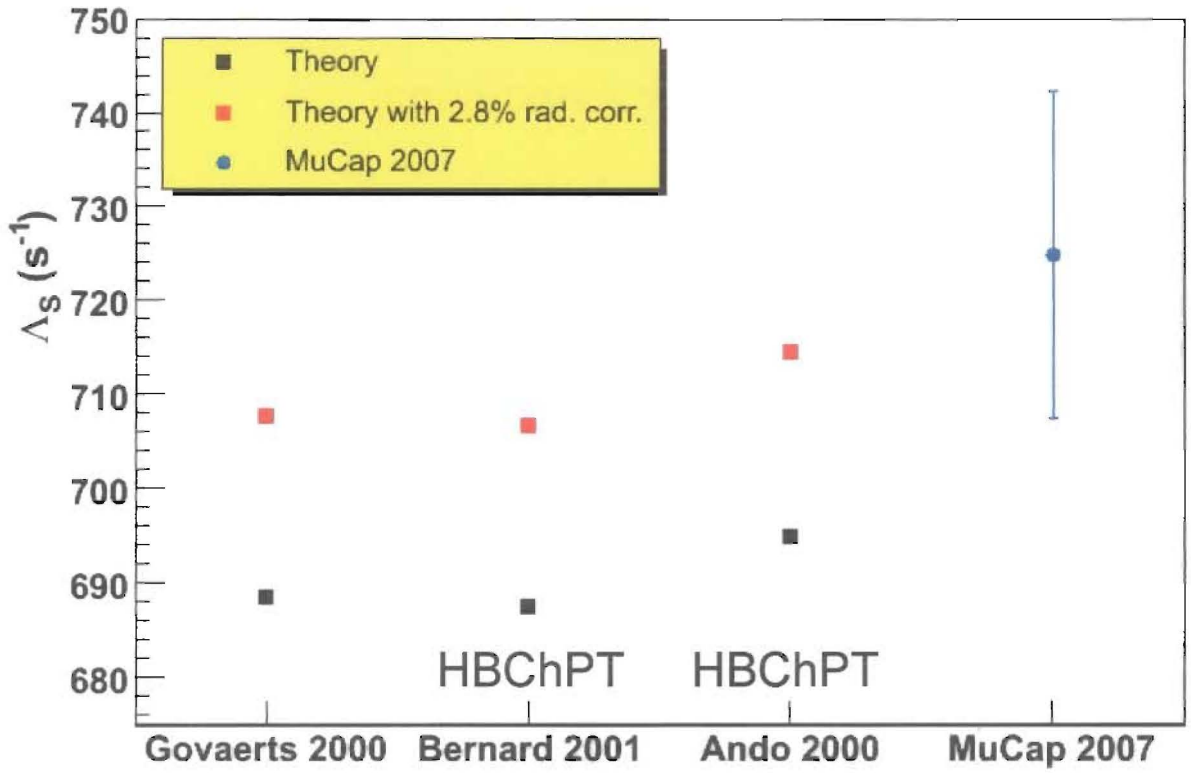
bound-state effect

| | Value ($s^{-1}$) | Uncertainty ($s^{-1}$) Stat. | Syst. |
|---|---|---|---|
| MuCap $\lambda_\mu^-$ | 455849.1 | 12.4 | 8.4 |
| Molecular Formation ($\lambda_{OF}$) Correction | 17.3 | | 4.7 |
| Molecular Transitions ($\lambda_{OP}$) Correction | 5.7 | | 3.4 |
| Bound State Correction ($\Delta\lambda_{\mu p}$) | 12.3 | | |
| World Average $\lambda_\mu^+$ | 455162.2 | 4.4 | |
| MuCap $\Lambda_S$ [a] | 722.2 | 13.6 | 10.6 |

Averaged with UCB result gives

$$\Lambda_S^{\text{MuCap}} = 725.0 \pm 13.7_{\text{stat}} \pm 10.7_{\text{syst}}\ \text{s}^{-1}$$

# $\Lambda_S$ Calculations and MuCap (2007) Result

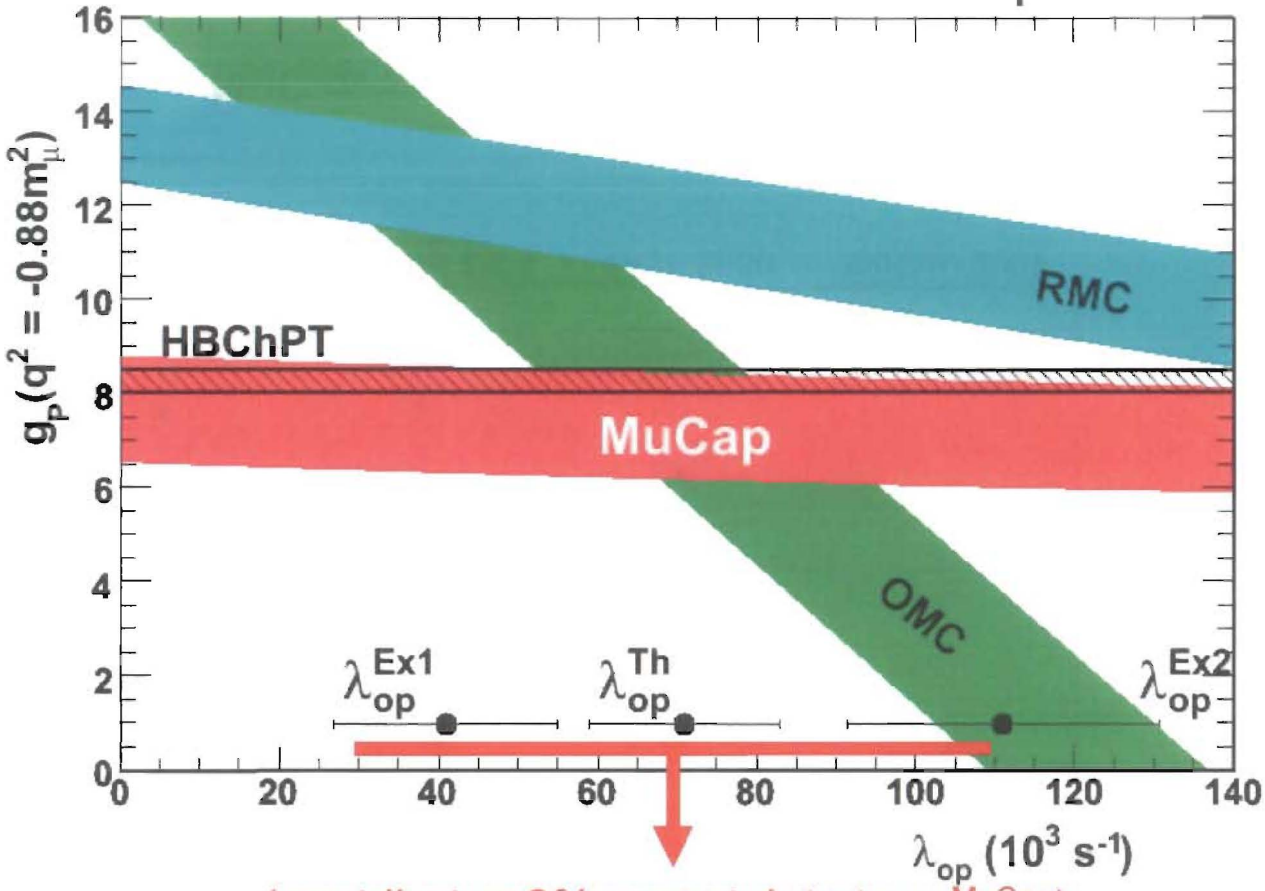



**rad. corrections**

- ***Czarnecki Marciano Sirlin (2006)***
  **$\Delta_R$ = 2.8%**

**MuCap agrees within ~1$\sigma$ with $\Lambda_S$ theory**

# Updated $g_P$ vs. $\lambda_{op}$



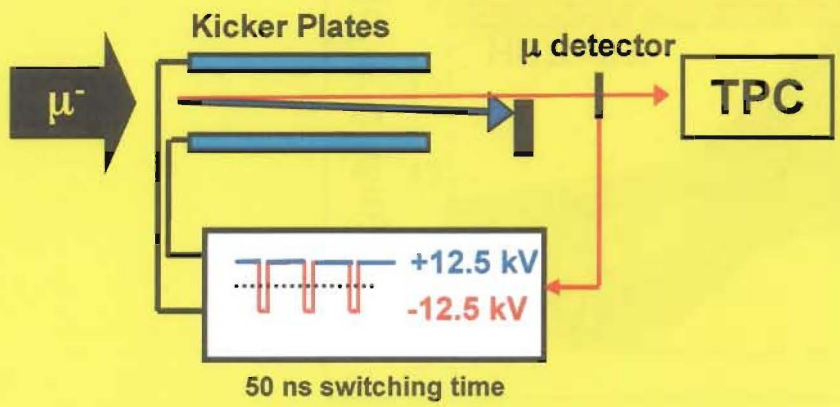

(contributes 3% uncertainty to $g_p^{MuCap}$)

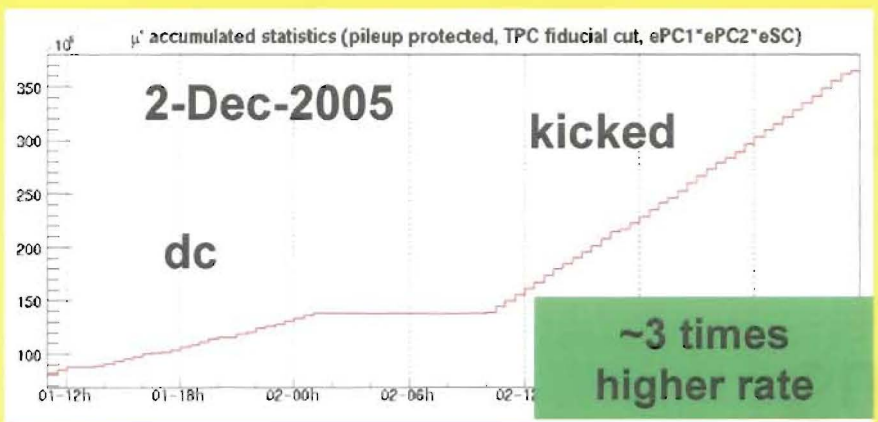
- MuCap 2007 result (with $g_P$ to 15%) is consistent with theory.
- This is the first precise, unambiguous experimental determination of $g_P$

# Muon-On-Demand

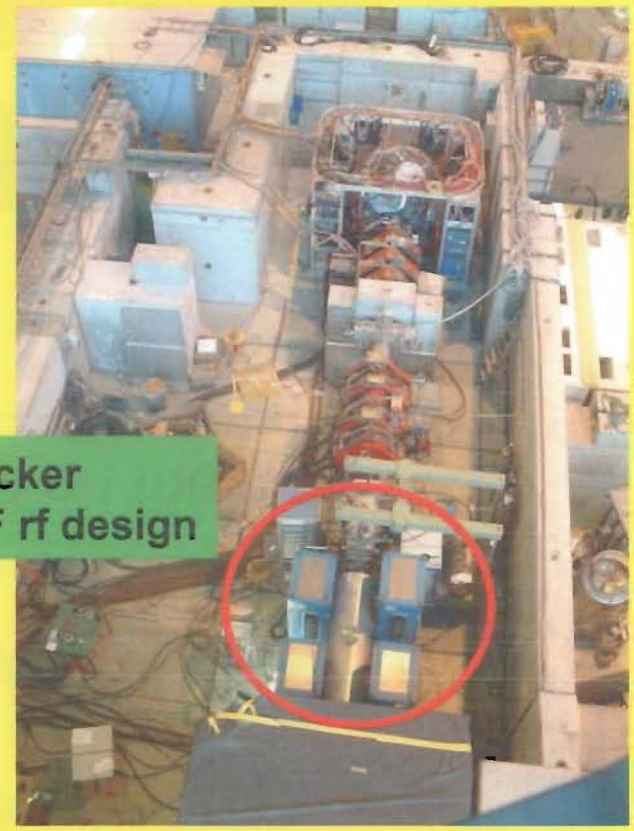
- Single muon requirement (to prevent systematics from pile-up)
- limits accepted $\mu$ rate to ~ 7 kHz,
- while PSI beam can provide ~ 70 kHz

- Muon-On-Demand concept



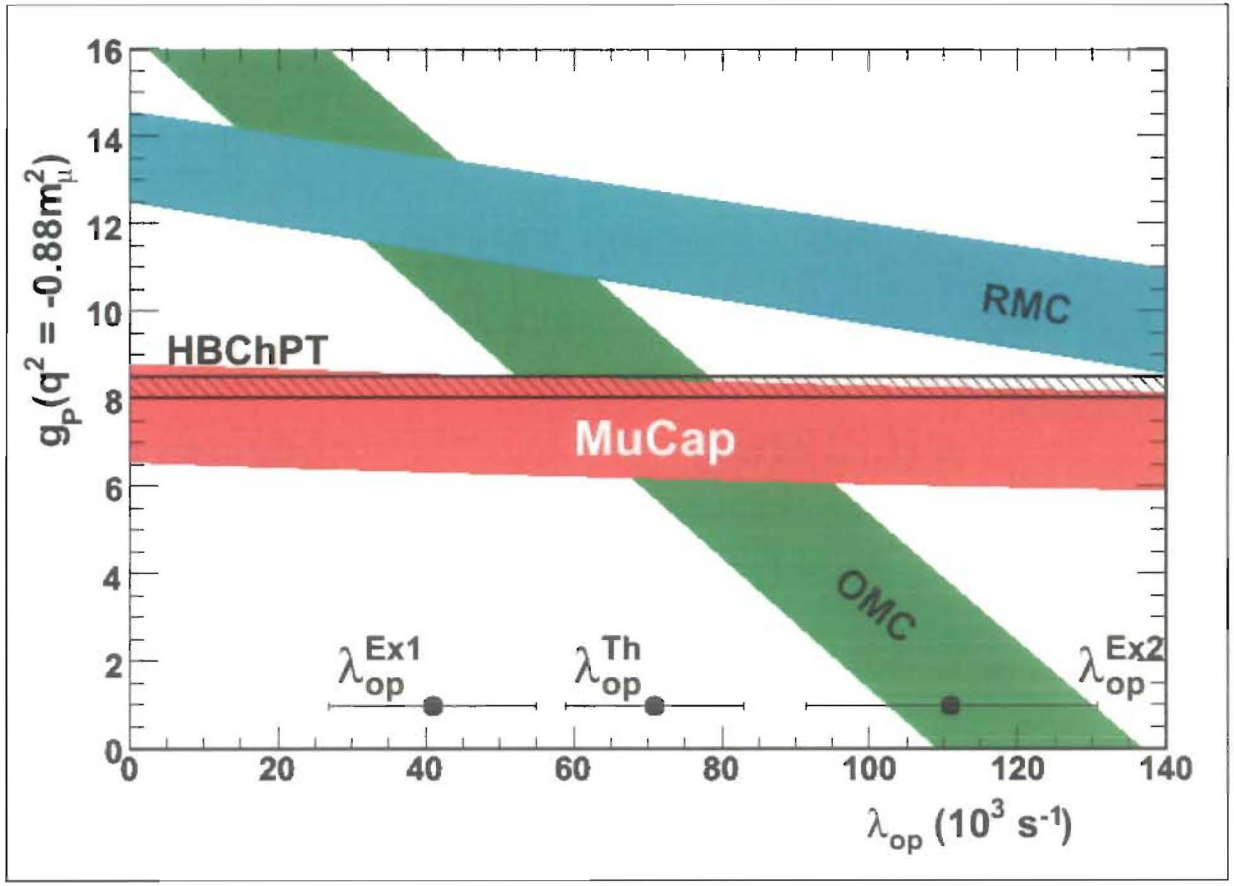




- Beamline



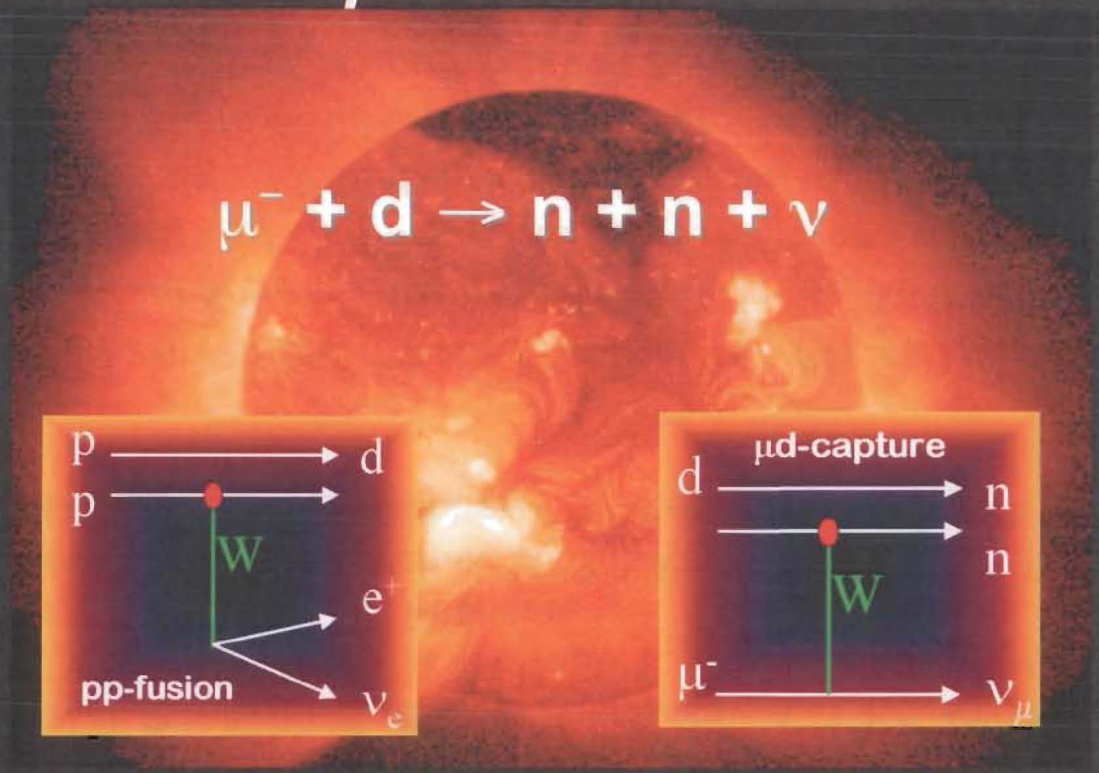
# Summary

- First $g_P$ with non-controversial interpretation
- Agrees with $\chi$PT expectation
- Factor 2.5 additional improvement on the way



# *"Calibrating the Sun" via Muon Capture on the Deuteron*

NEW PROJECT




## Motivation for the MuSun Experiment:

- First precise measurement of basic Electroweak reaction in 2N system,
- Impact on fundamental astrophysics reactions ($\nu$'s in SNO, pp fusion)
- Comparison to modern high-precision calculations

# MuCap Collaboration

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