The MuCap Experiment

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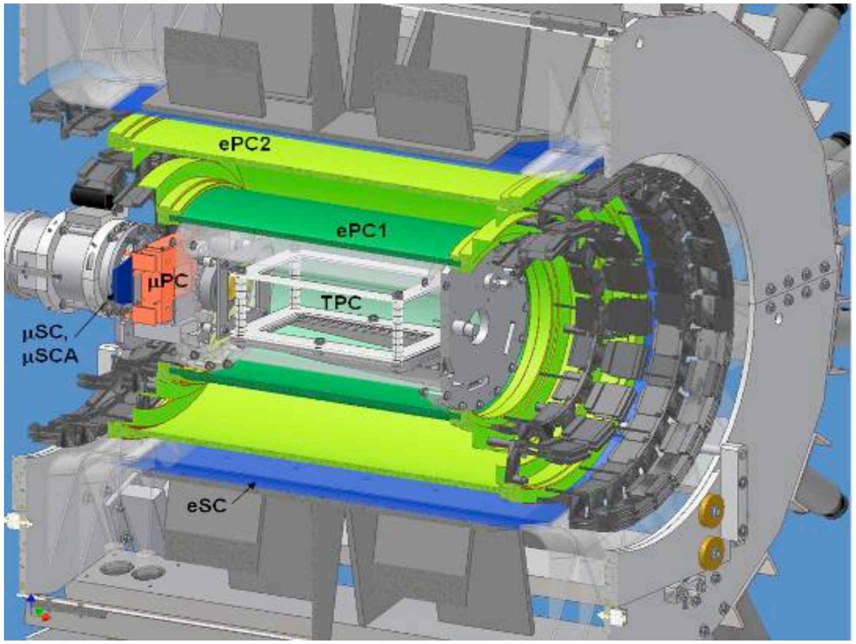
$\mu + p \rightarrow n + \nu_\mu$



Outline:

1) Nucleon form factors
2) Mu-molecular kinetics
3) Experimental challenges
4) MuCap strategy
5) First physics results
6) Improvements since first physics results

*Present address: LANL

MuCap Collaboration

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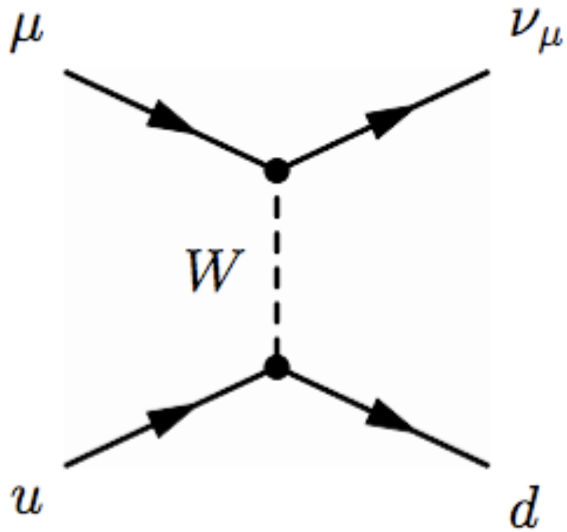
University of Illinois at Urbana-Champaign (UIUC), USA
Université Catholique de Louvain, Belgium
TU München, Garching, Germany
University of Kentucky, Lexington, USA
Boston University, USA

Nucleon Form Factors

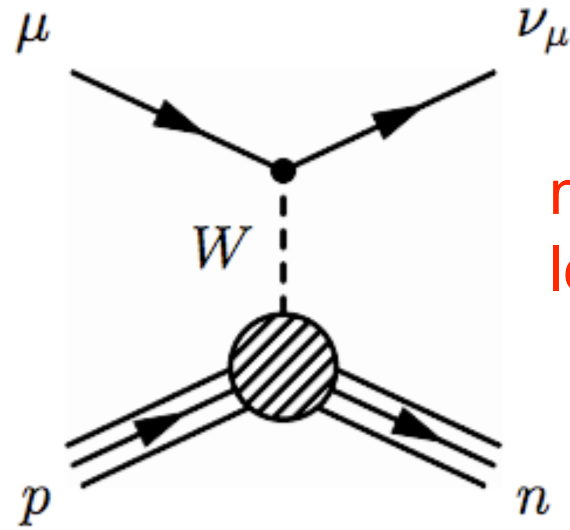
$$\mu^- + u \to \nu_\mu + d$$

quark level



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

nucleon level



$$\mathcal{M} = \frac{G_F}{\sqrt{2}} V_{ud} \langle \nu_\mu | \gamma^\alpha (1 - \gamma_5) | \mu \rangle \; \langle d | \gamma^\alpha (1 - \gamma_5) | u \rangle$$

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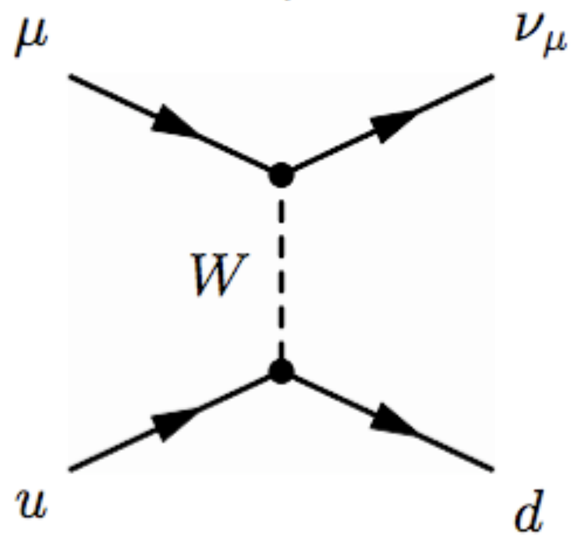

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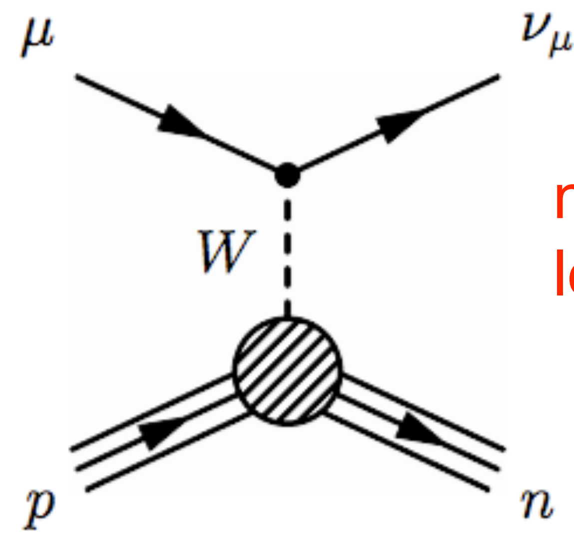
nucleon level



$$\mathcal{M} = \frac{G_F}{\sqrt{2}} V_{ud} \langle \nu_\mu | \gamma^\alpha (1-\gamma_5) | \mu \rangle \, \langle n | V^\alpha - A^\alpha | p \rangle$$

$$V^\alpha \;=\; \underline{g_v(q^2)}\gamma^\alpha + i\underline{g_m(q^2)}\sigma^{\alpha\beta}\frac{q_\beta}{2M_N} + \underbrace{\cancel{g_s(q^2)}}_{=\,0}\frac{q^\alpha}{m_\mu}$$

CVC ← EM FF's

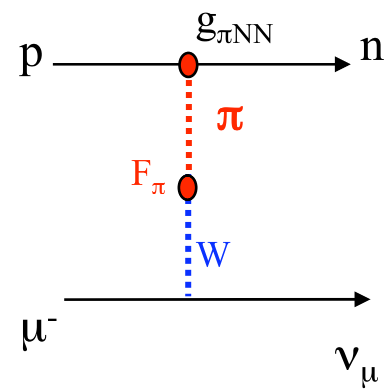
$$A^\alpha \;=\; g_a(q^2)\gamma^\alpha\gamma_5 + \cancel{i g_t(q^2)}\sigma^{\alpha\beta}\frac{q_\beta}{2M_N}\gamma_5 + g_p(q^2)\frac{q^\alpha}{m_\mu}\gamma_5$$

n-decay

G-parity

Pseudoscalar Form Factor g_p

g_P determined by chiral symmetry of QCD:



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

g_P= (8.74 ± 0.23) – (0.48 ± 0.02) = **8.26 ± 0.23**

PCAC pole term Adler, Dothan, Wolfenstein

ChPT leading order one loop two-loop <1%

N. Kaiser Phys. Rev. C67 (2003) 027002

- **solid QCD prediction via ChPT (2-3% level)**
- **basic test of QCD symmetries**

Recent reviews:
T. Gorringe, H. Fearing, Rev. Mod. Physics 76 (2004) 31
V. Bernard et al., Nucl. Part. Phys. 28 (2002), R1

Sensitivity of Λ_S to Form Factors

$$\frac{\delta\Lambda_S}{\Lambda_S} = \boxed{2\frac{\delta V_{ud}}{V_{ud}} + 0.466\frac{\delta g_v}{g_v} + 0.151\frac{\delta g_m}{g_m} + 1.567\frac{\delta g_a}{g_a}} - 0.179\frac{\delta g_p}{g_p}$$

Contributes 0.4% uncertainty to Λ_S(theory)

Uncertainty of extraction of g_p from Λ_S is dominated by uncertainty in g_a.

$\frac{\partial\Lambda_S}{\partial g_X}\frac{g_X}{\Lambda_S}$ from Govaerts, Lucio-Martinez, Nucl. Phys. A 678 (2000) 110-146

μ^- Stopping in Hydrogen

μ^- is a heavy electron:

- Quickly forms a μp atom, transitions to ground state, transitions to singlet hyperfine state.

  Bohr radius $a \approx a_0\, m_e/m_\mu \approx a_0/200$

- Most of the time, the μ decays:

  $\mu^- \rightarrow \nu_\mu + e^- + \nu_e$ rate $\lambda_0 \approx 1/\tau_{\mu+}$ BR≈0.999

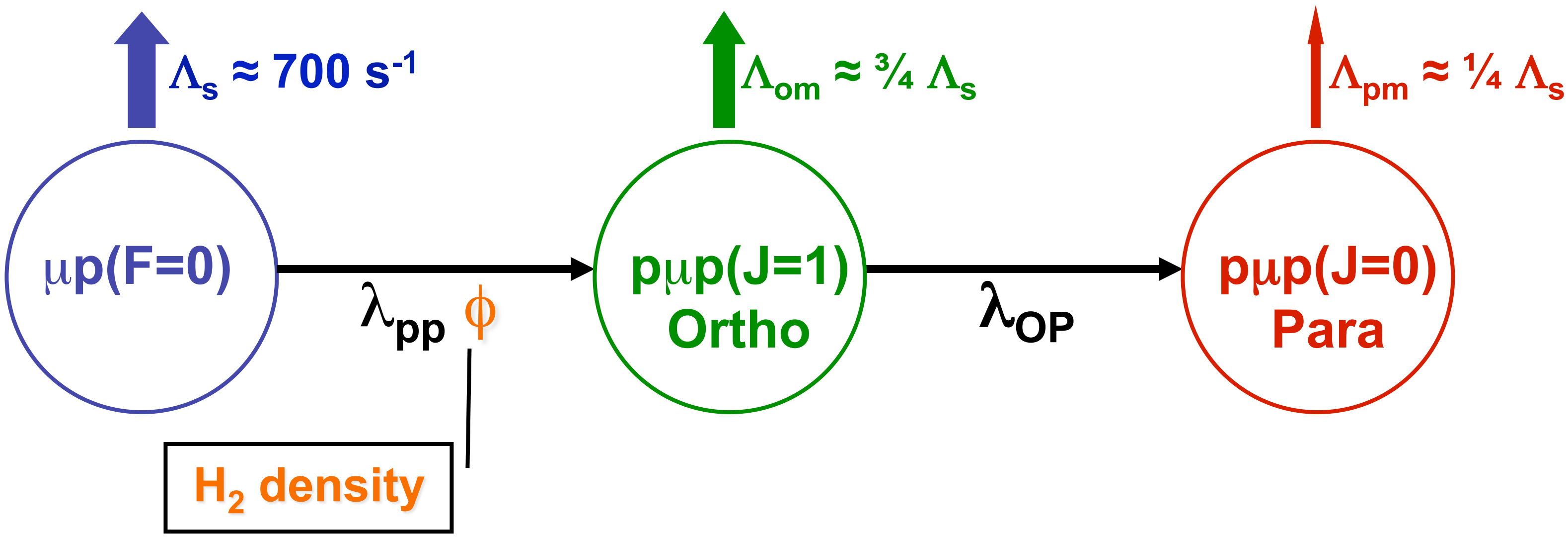
- Occasionally, it *nuclear* captures on the proton:

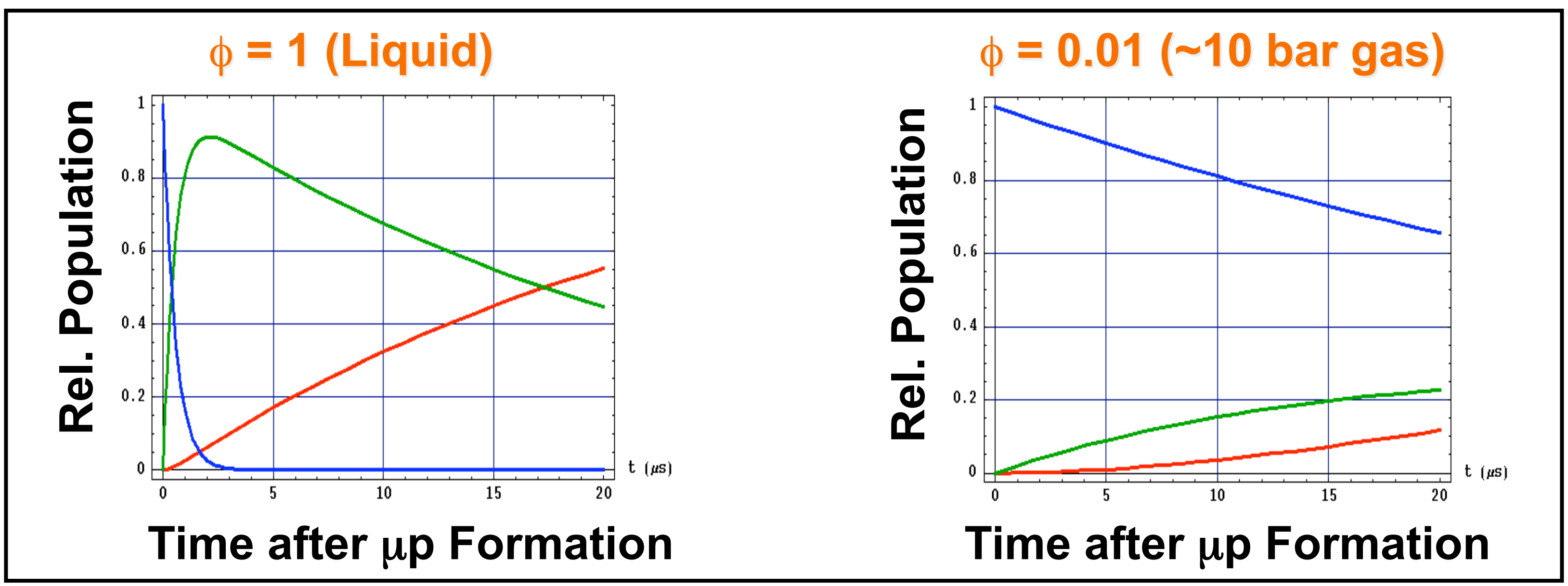
  $\mu^- + p \rightarrow \nu_\mu + n$ rate Λ_S BR~10^{-3}

  $\mu^- + p \rightarrow \nu_\mu + n + \gamma$ BR~10^{-8}, E>60 MeV

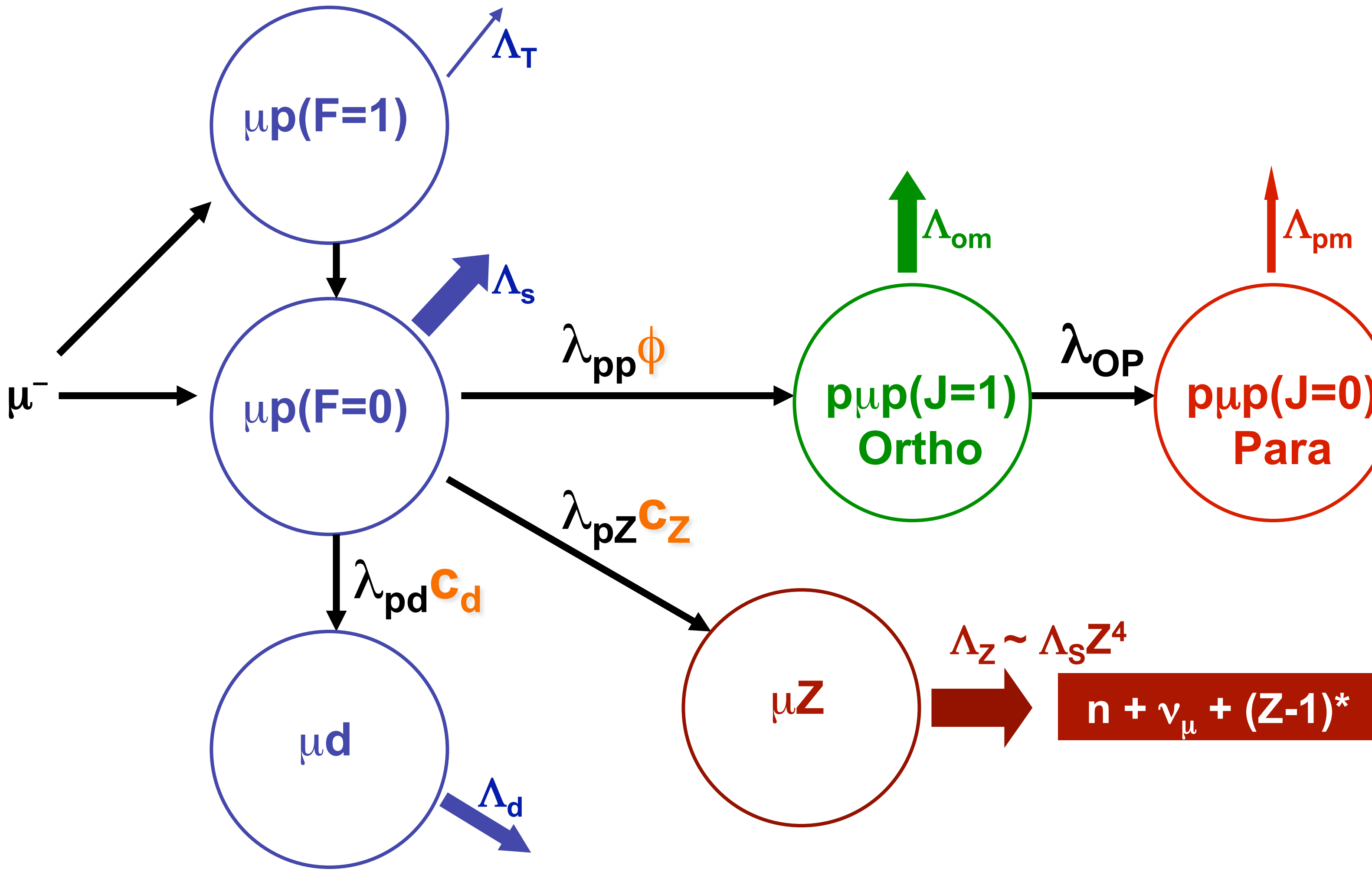
Complications: molecular formation/transitions, transfer to impurity atoms, …

Muon Atomic/Molecular State in Experiment must be known to connect with theory.





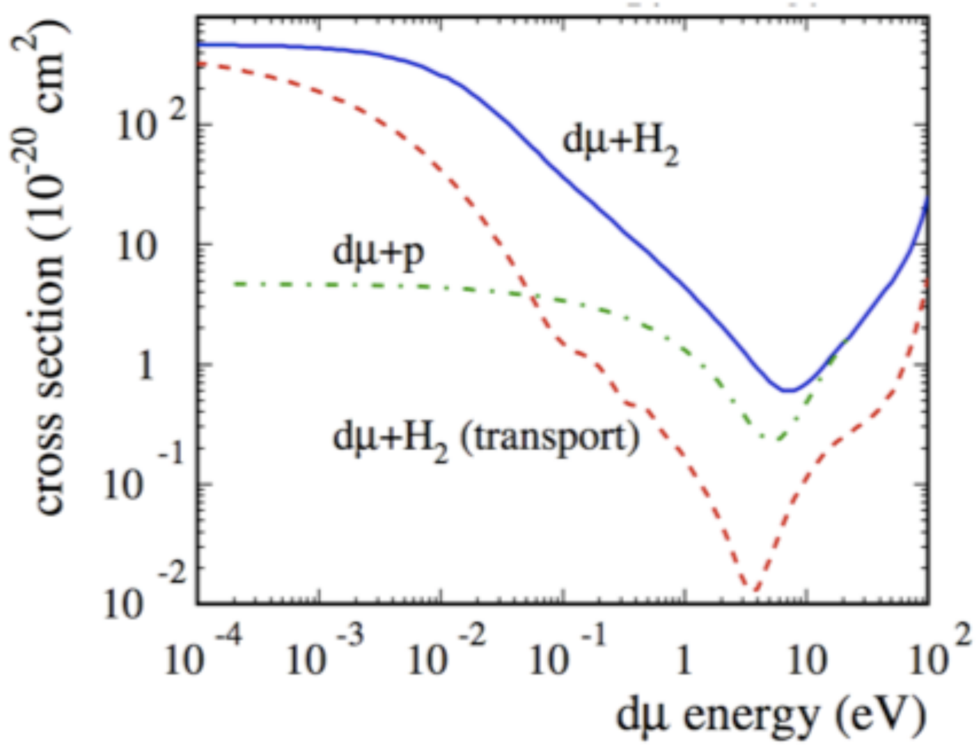
Muon atomic transitions set stringent purity requirements.



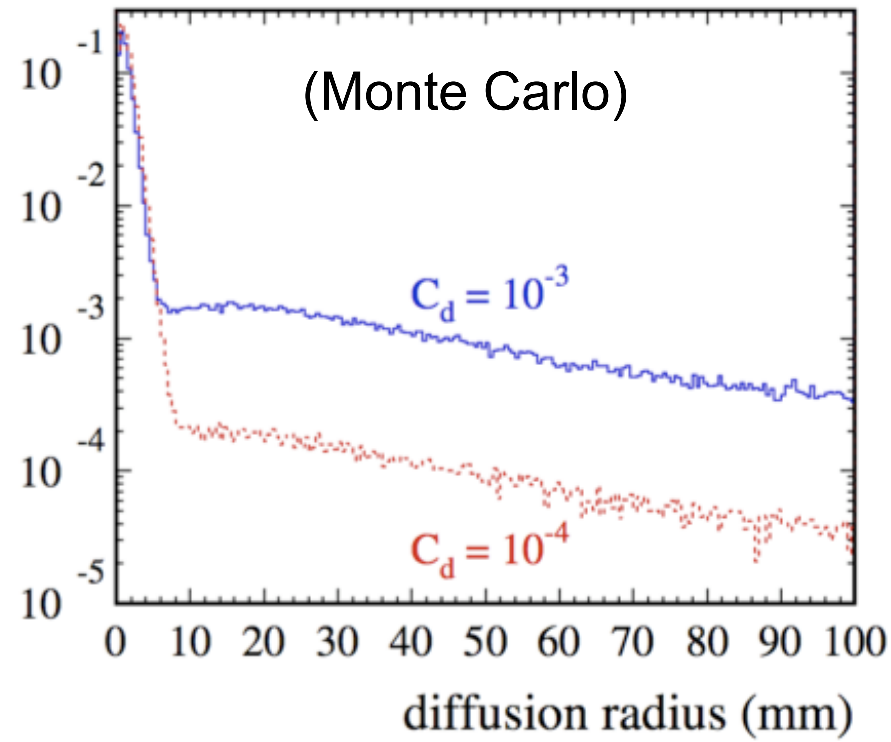
H_2 must be pure isotopically and chemically: $c_d < 1$ ppm, $c_Z < 10$ ppb

μd Diffusion into Z > 1 Materials

μd scattering in H_2



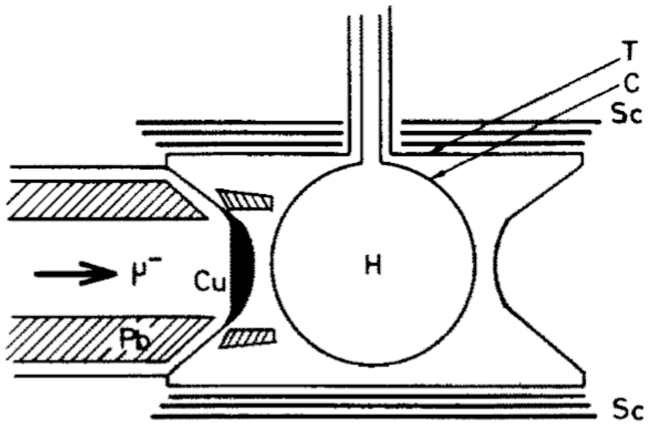
displacement (from μ^- stop position) at time of decay



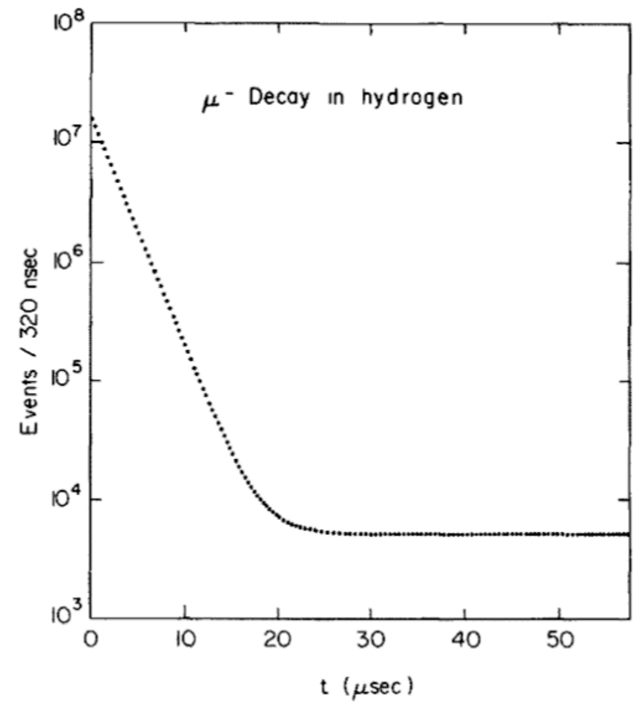
- Ramsauer-Townsend minimum in the scattering cross section
  - μd can diffuse ~10 cm before muon decay

Prev. expt: Ordinary muon capture in H_2

Bardin et al., Nuclear Physics A352 (1981) 365-378



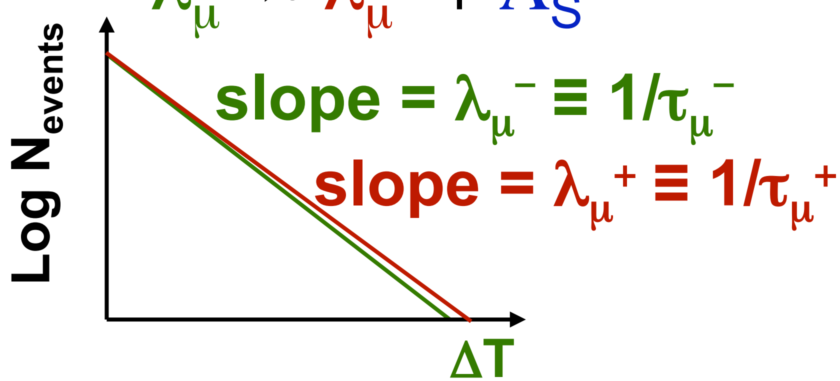
Purified, liquid protium target



Typical time distribution of the events from negative muons stopped in liquid protium.

Lifetime technique

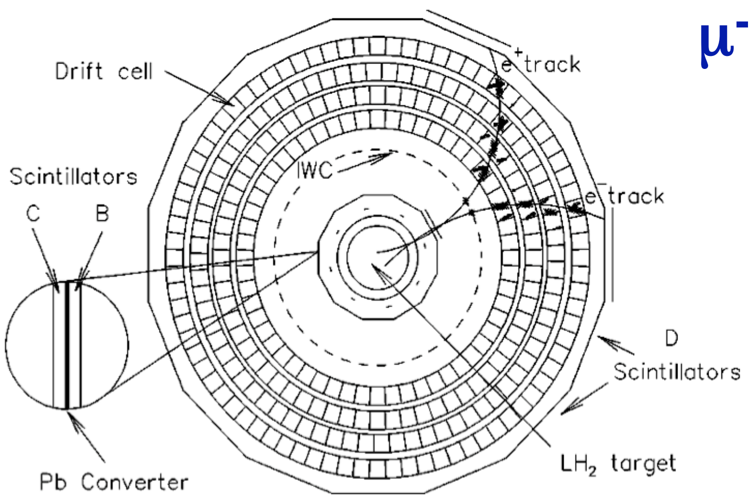
$$\lambda_{\mu^-} \approx \lambda_{\mu^+} + \Lambda_S$$

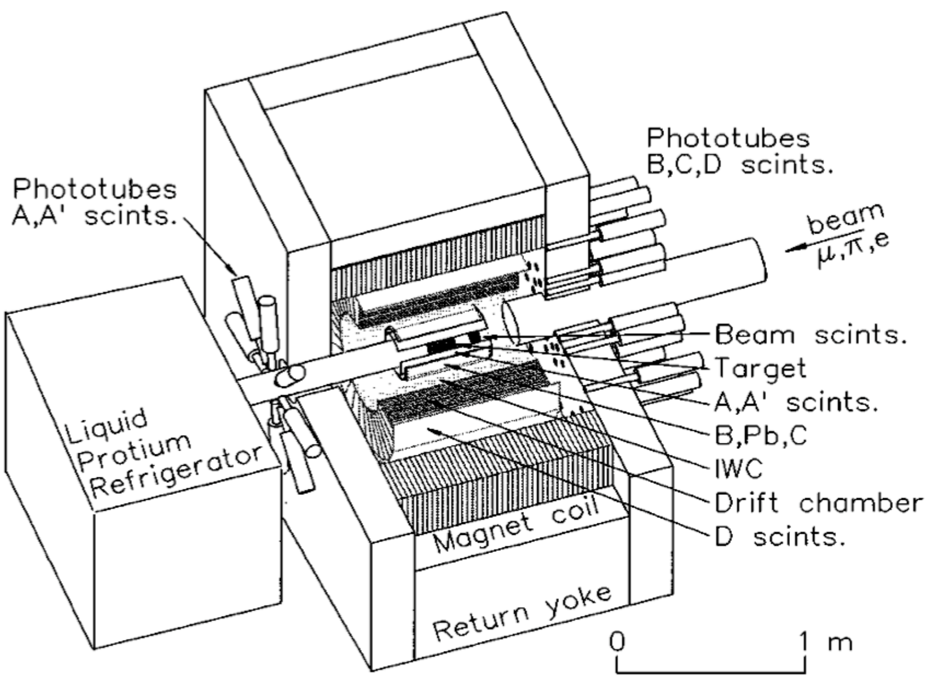


Prev. expt.: Radiative muon capture in H_2

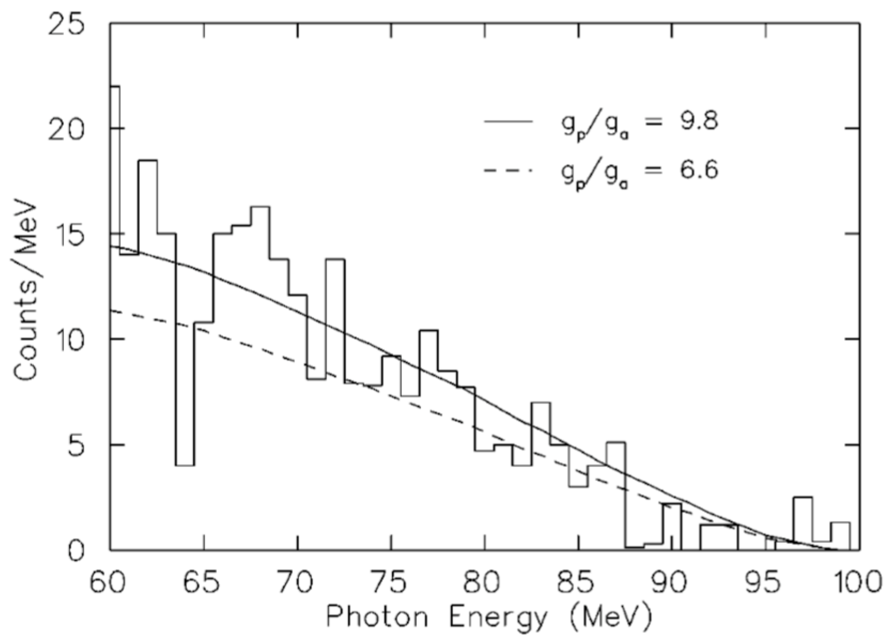
$\mu^- + p \rightarrow \nu_\mu + n + \gamma$ (BR~10^{-8}, E>60 MeV)

Only one measurement of RMC:
Wright et al., PRC v57 (Jan. 1998), p373.



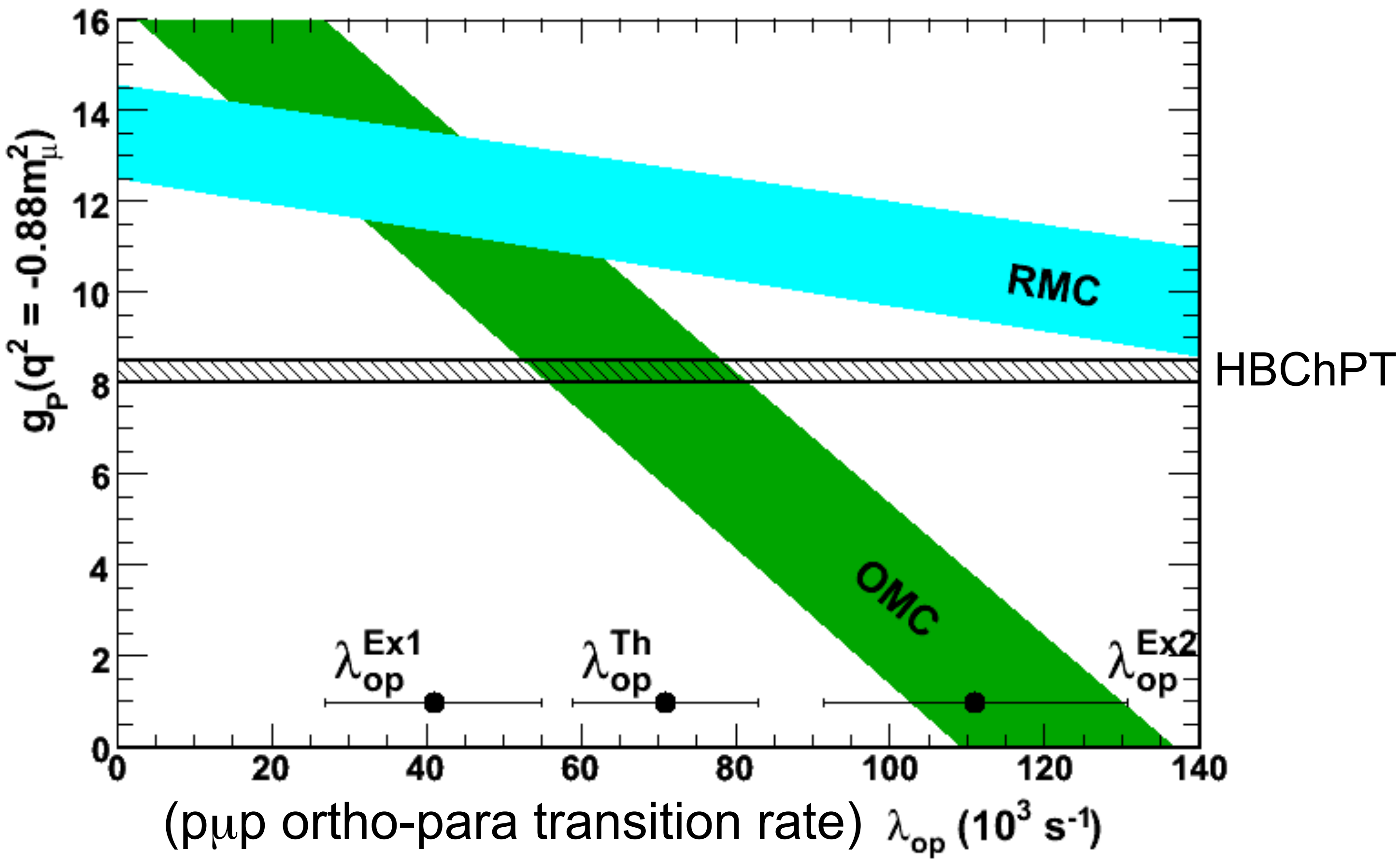


The RMC pair spectrometer at TRIUMF



Photon spectrum after all cuts and background subtraction, shown with theoretical fit.

Previous Data on g_p



No common region of overlap between both expts. and theory

g_P basic and experimentally least known weak nucleon form factor

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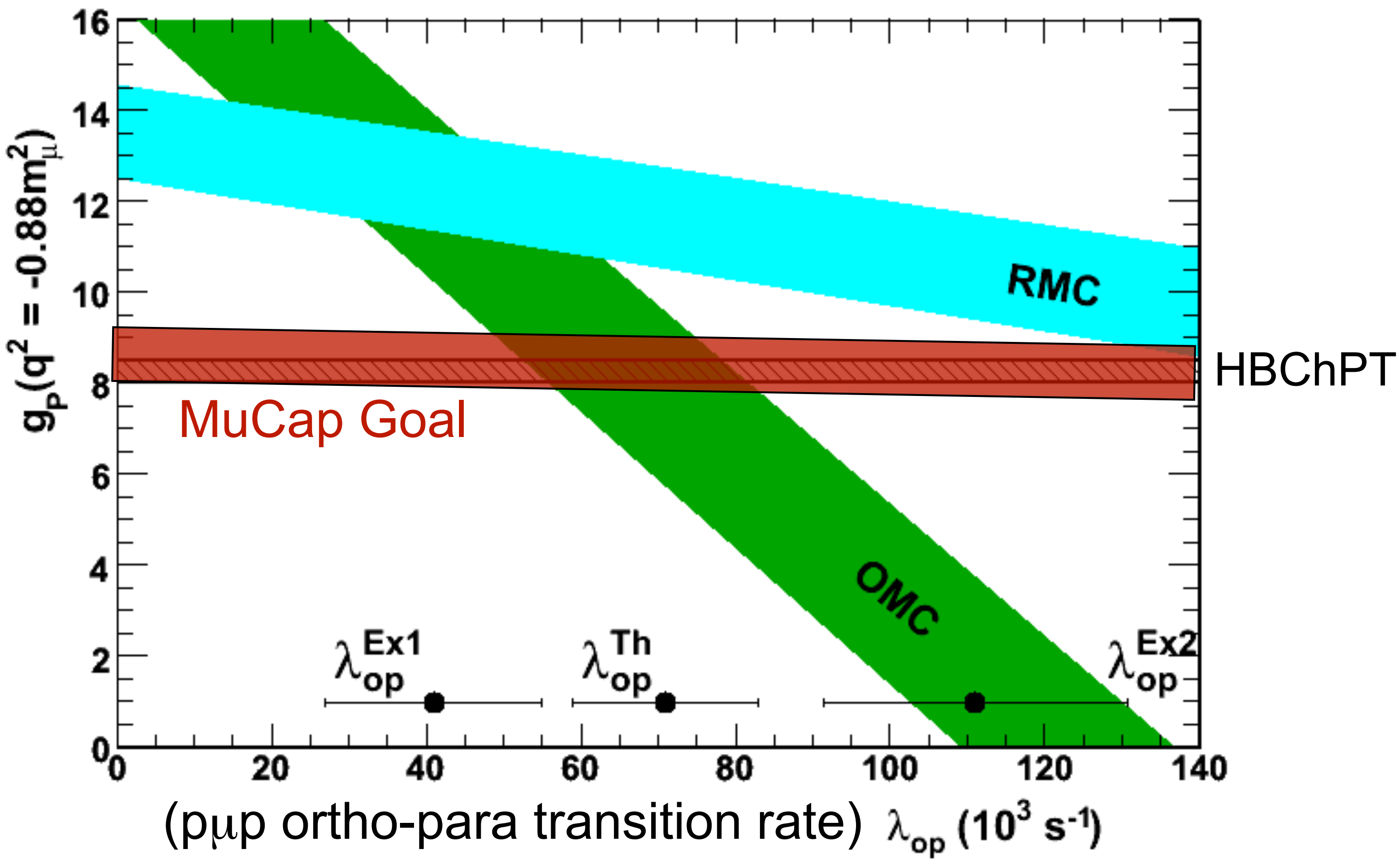

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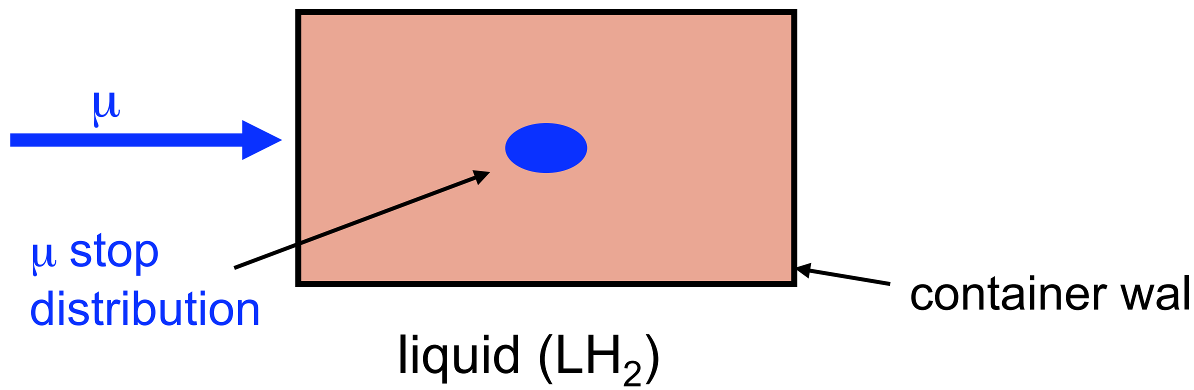
Experimental Challenges

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).

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is difficult to detect (would require absolute calibration of neutron detectors, accurate subtraction of backgrounds).

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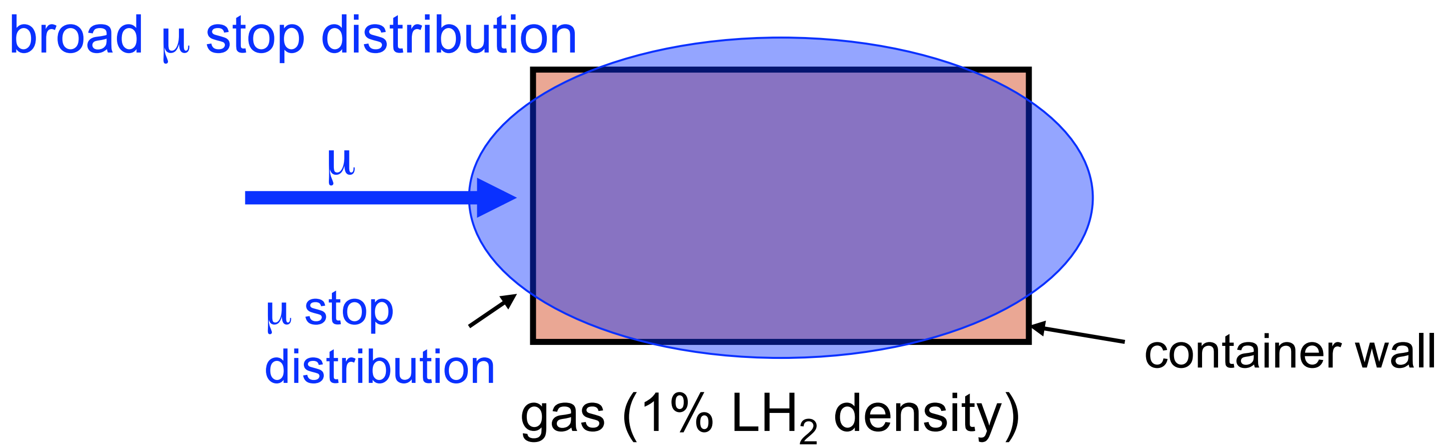

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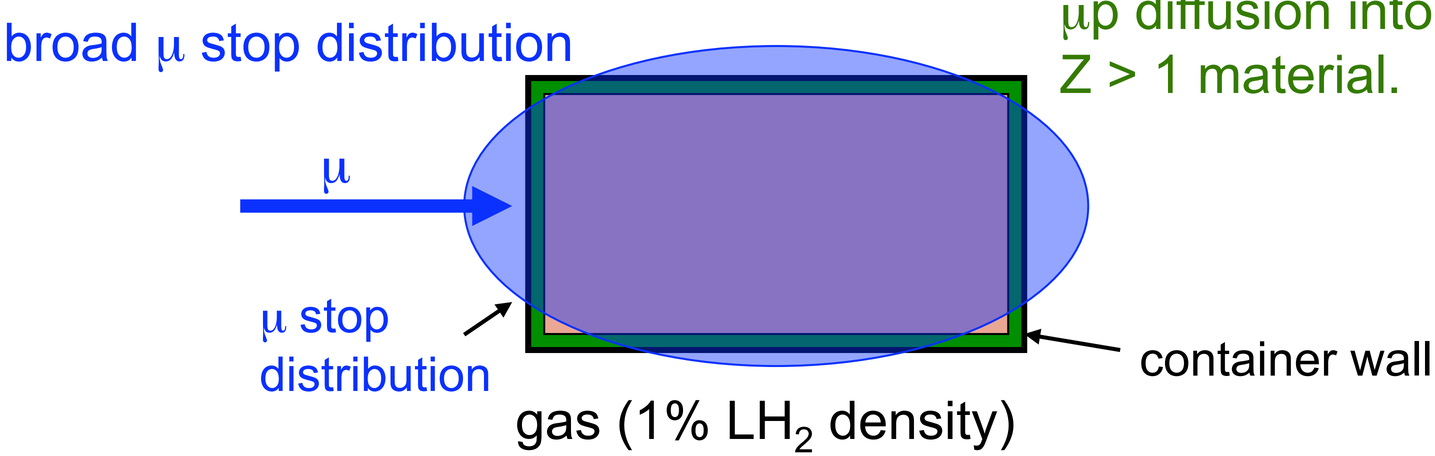

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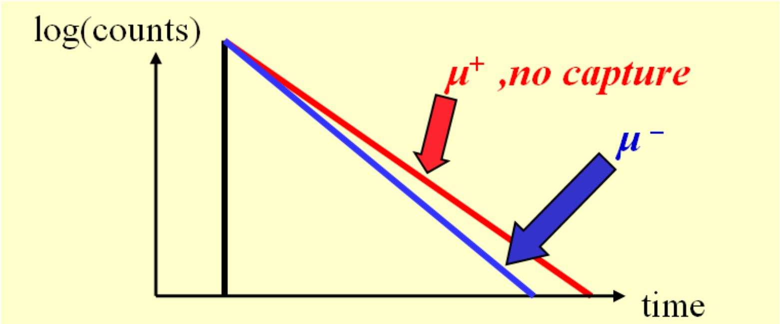
μCap Experimental Strategy

- 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%



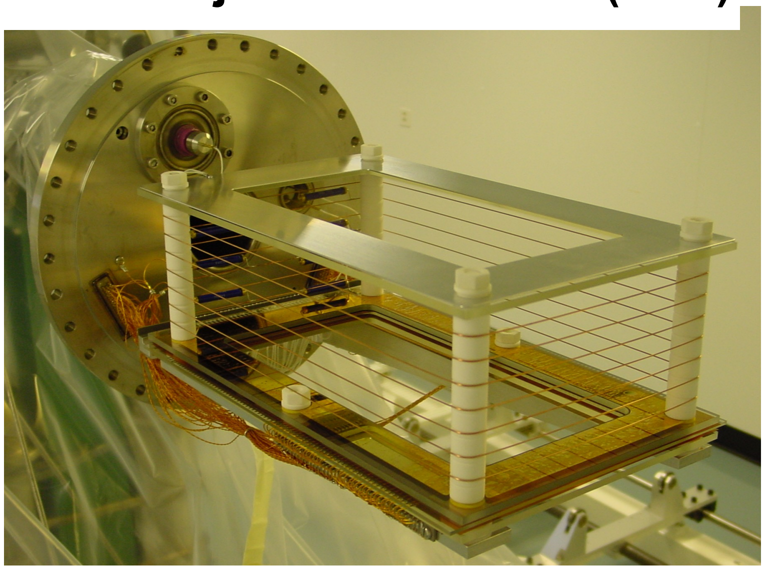
- Clean μ stop definition in active target (TPC) to avoid μZ capture, 10 ppm level
- Ultra-pure gas system and purity monitoring to avoid: $\mu p + Z \rightarrow \mu Z + p$, ~10 ppb impurities
- Isotopically pure "protium" to avoid $\mu p + d \rightarrow \mu d + p$, ~1 ppm deuterium

diffusion range ~cm

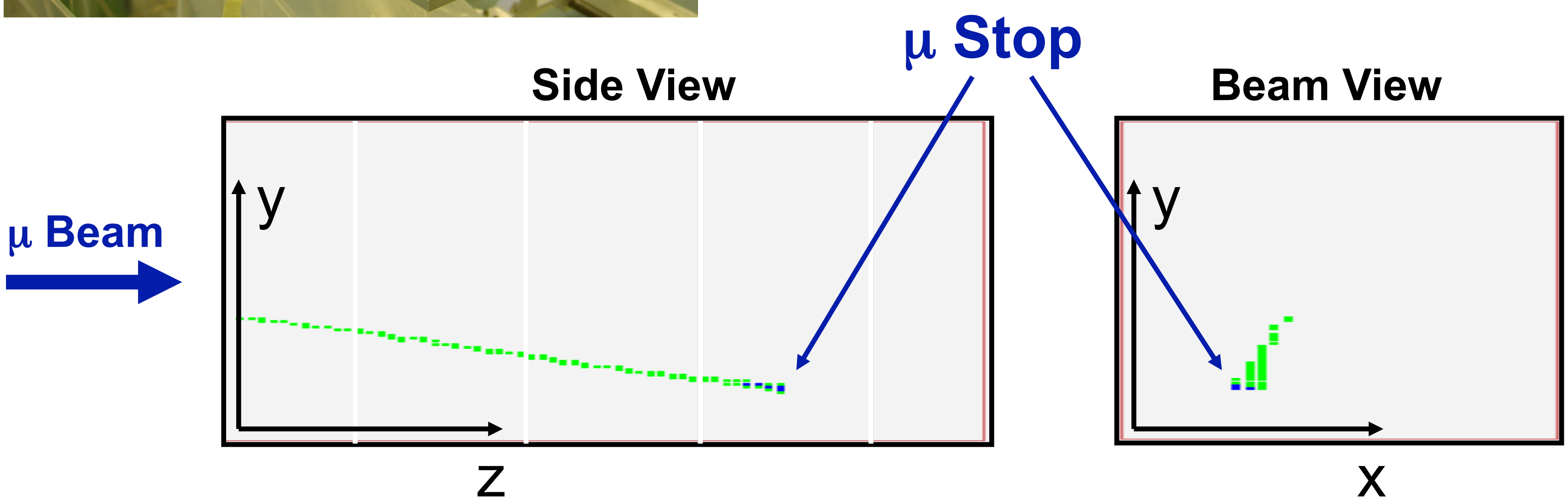
fulfill all requirements simultaneously
unique μCap capabilities

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



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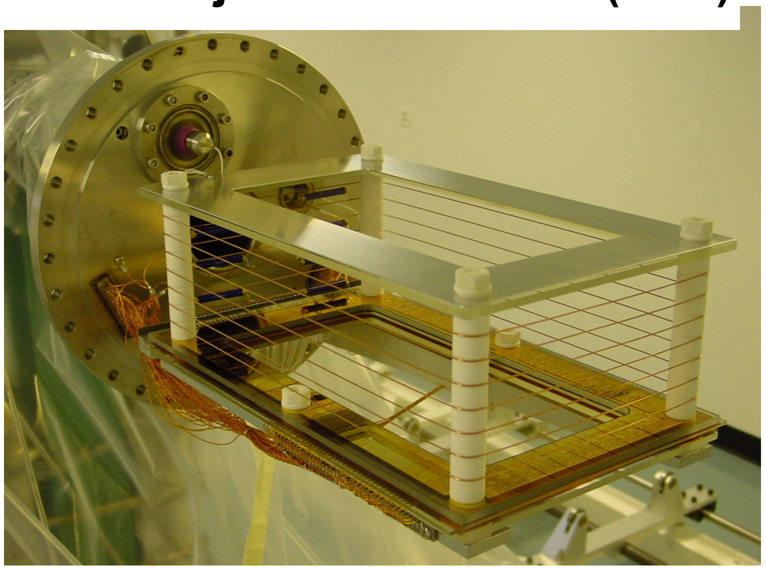

10 bar ultra-pure hydrogen, 1% LH_2
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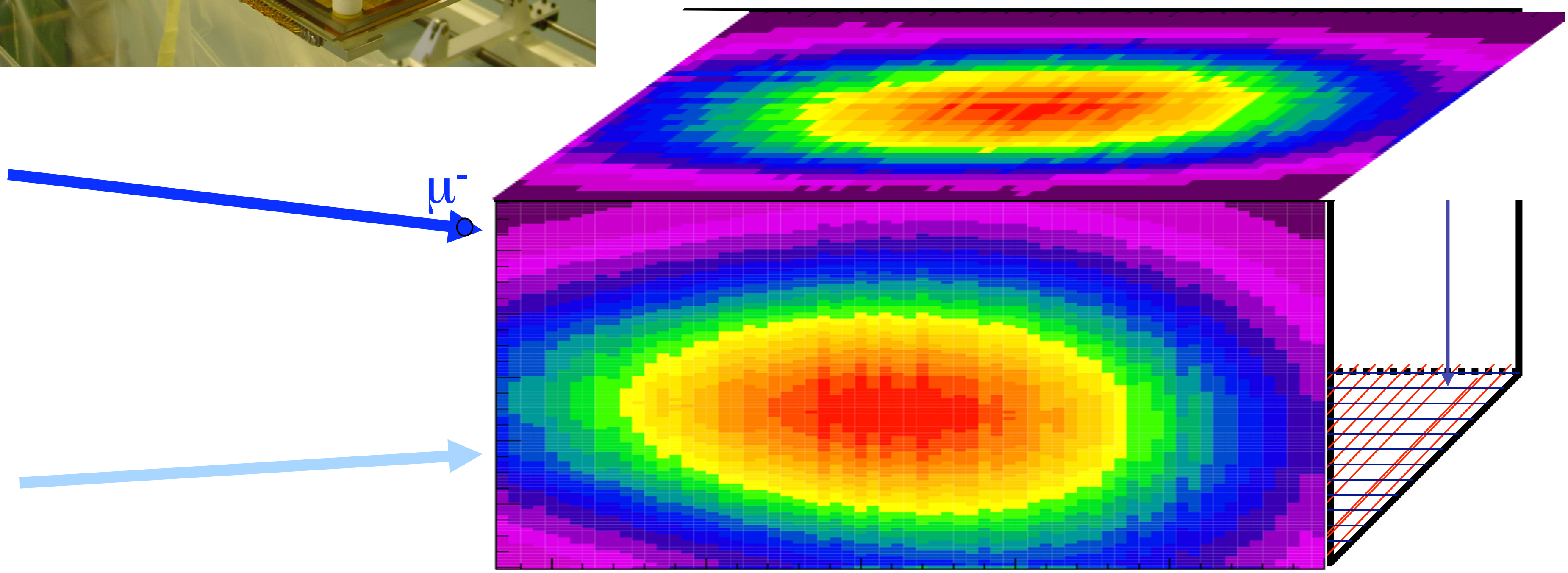
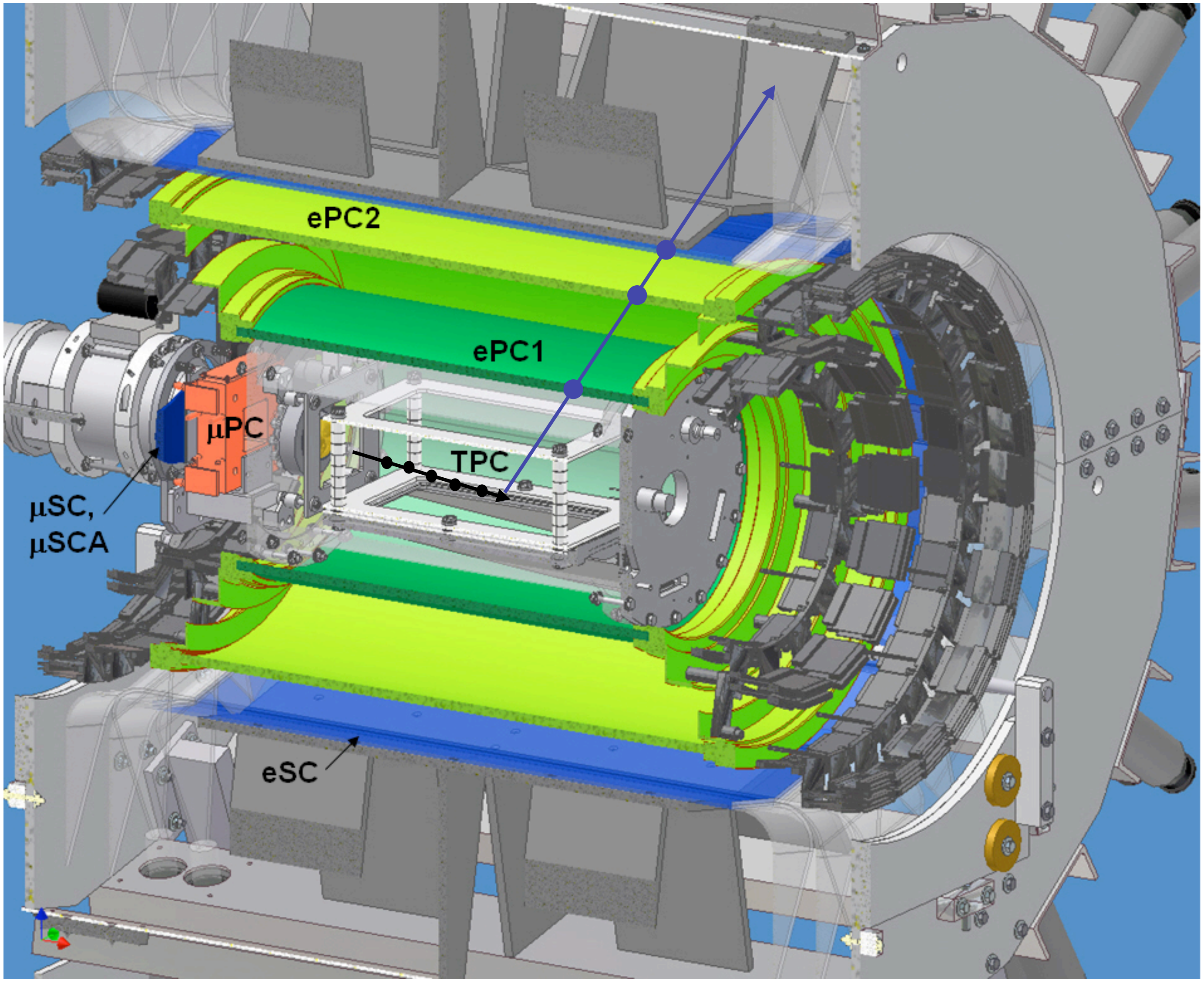
bakable glass/ceramic materials

Observed muon stopping distribution

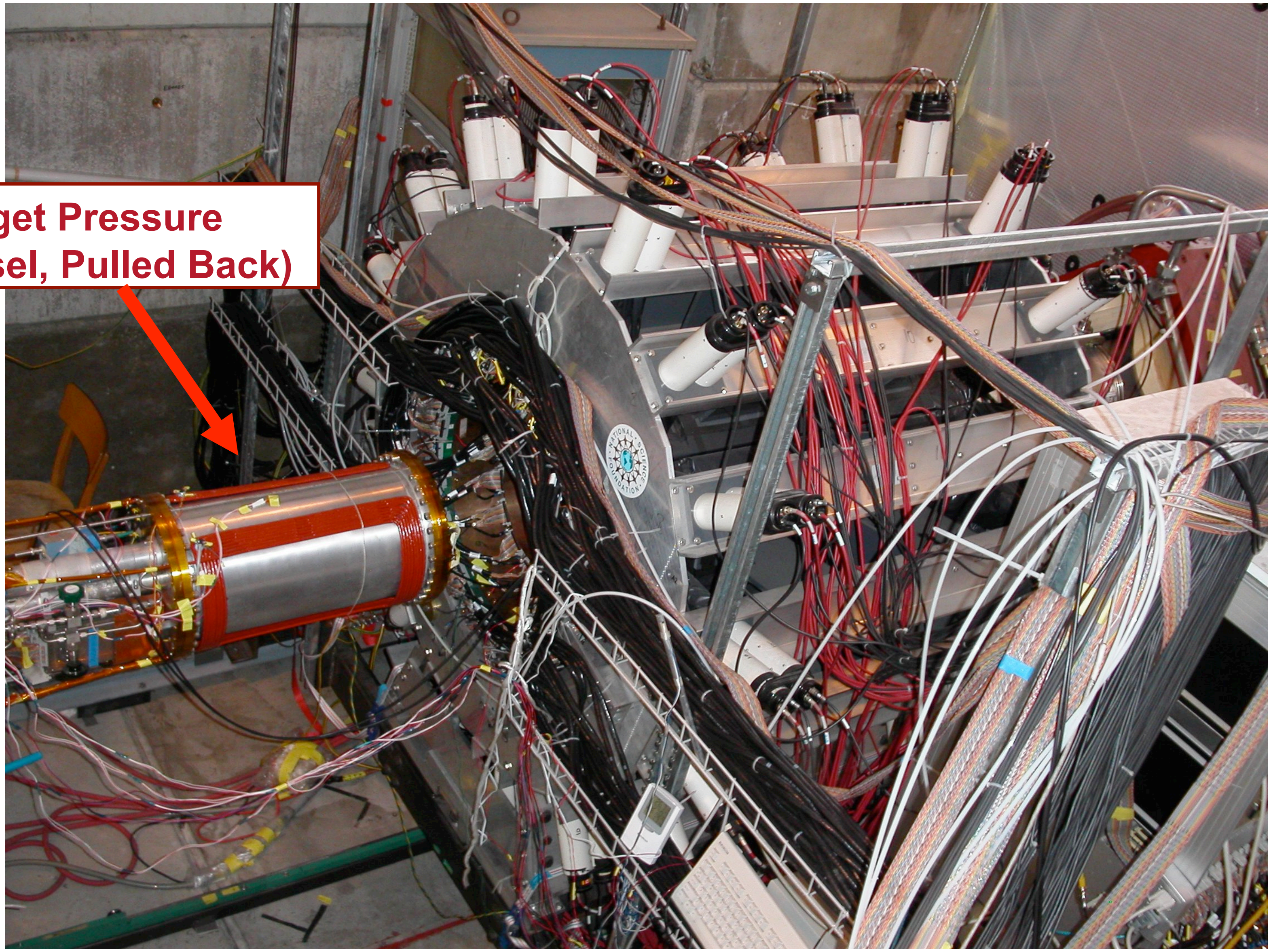


μCap Detailed Diagram

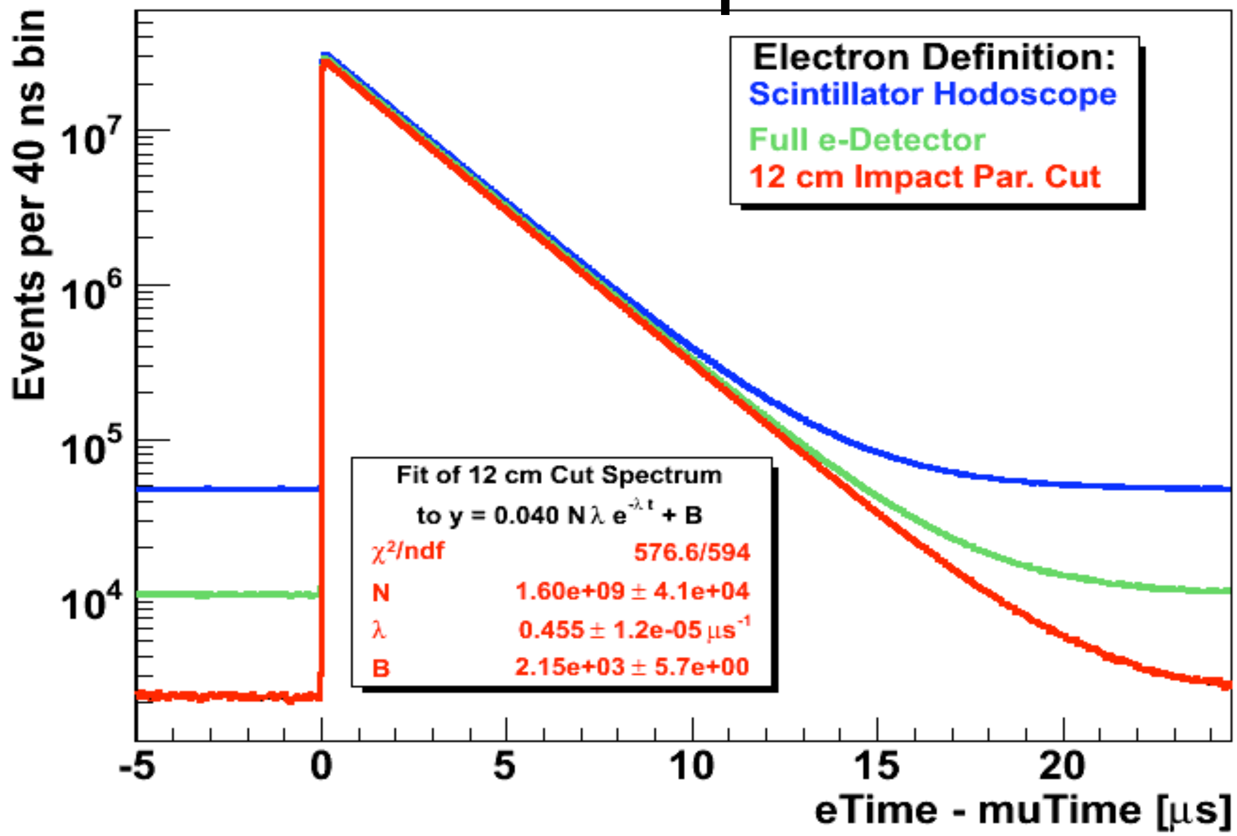
- Tracking of Muon to Stop Position in Ultrapure H_2 Gas
- Tracking of Decay Electron



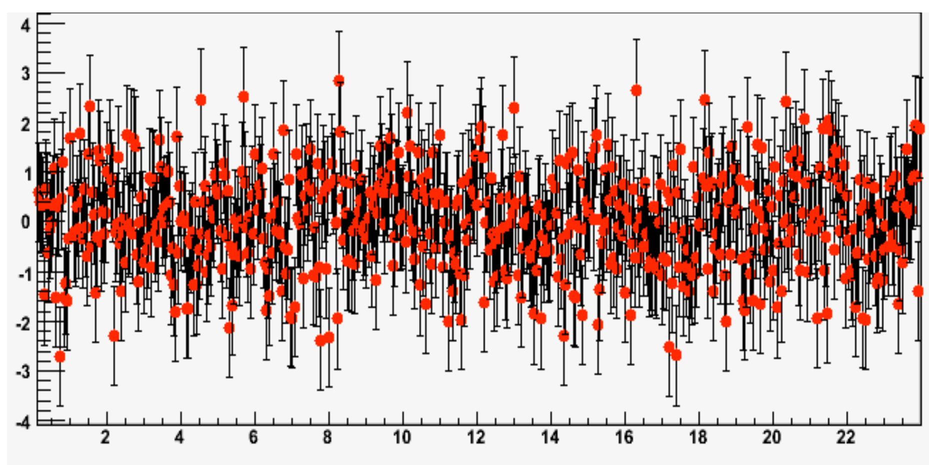
Commissioning and First Physics Data in 2004



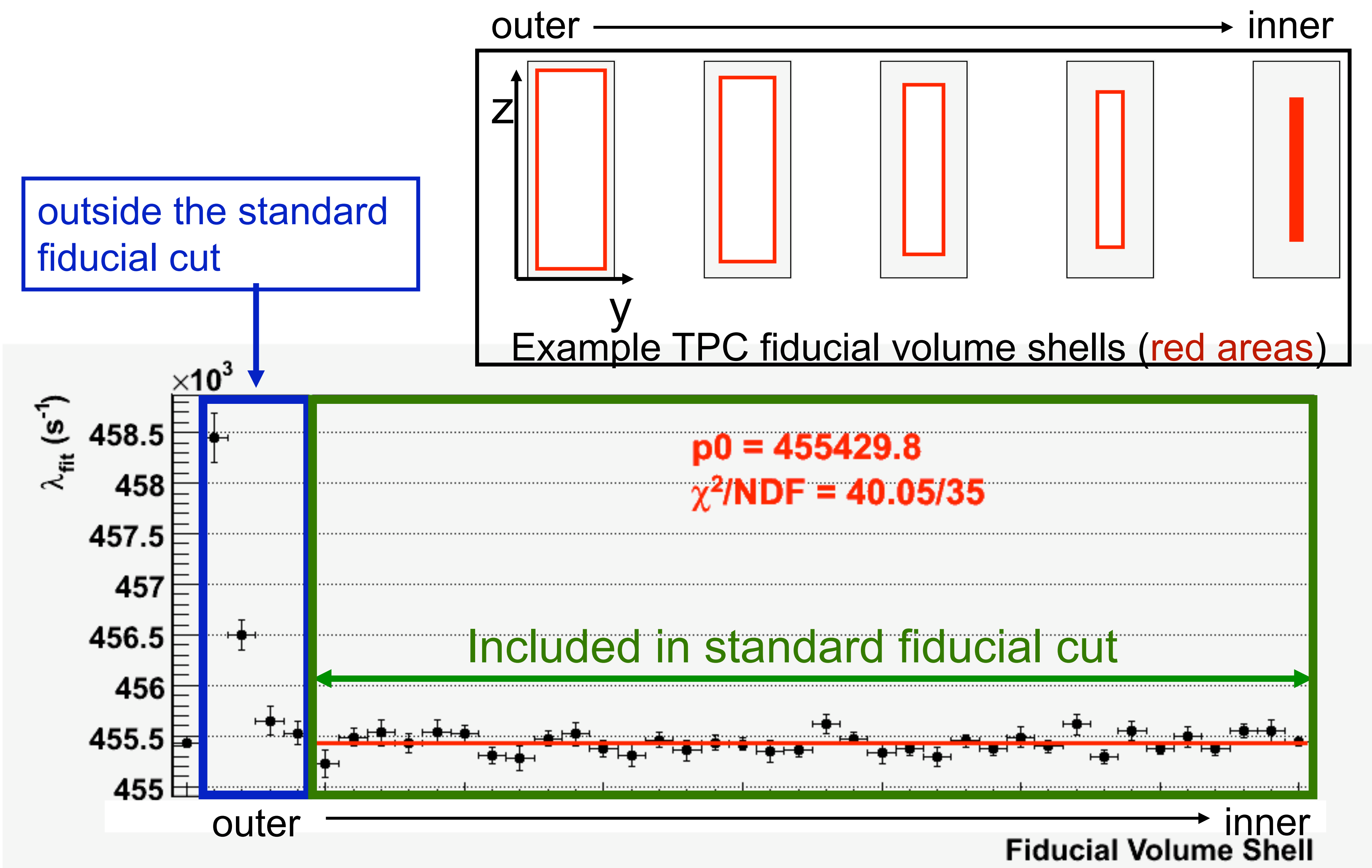
Lifetime Spectra



Normalized residuals ("pull")



Lifetime vs. Non-Overlapping Fiducial Volume Shell

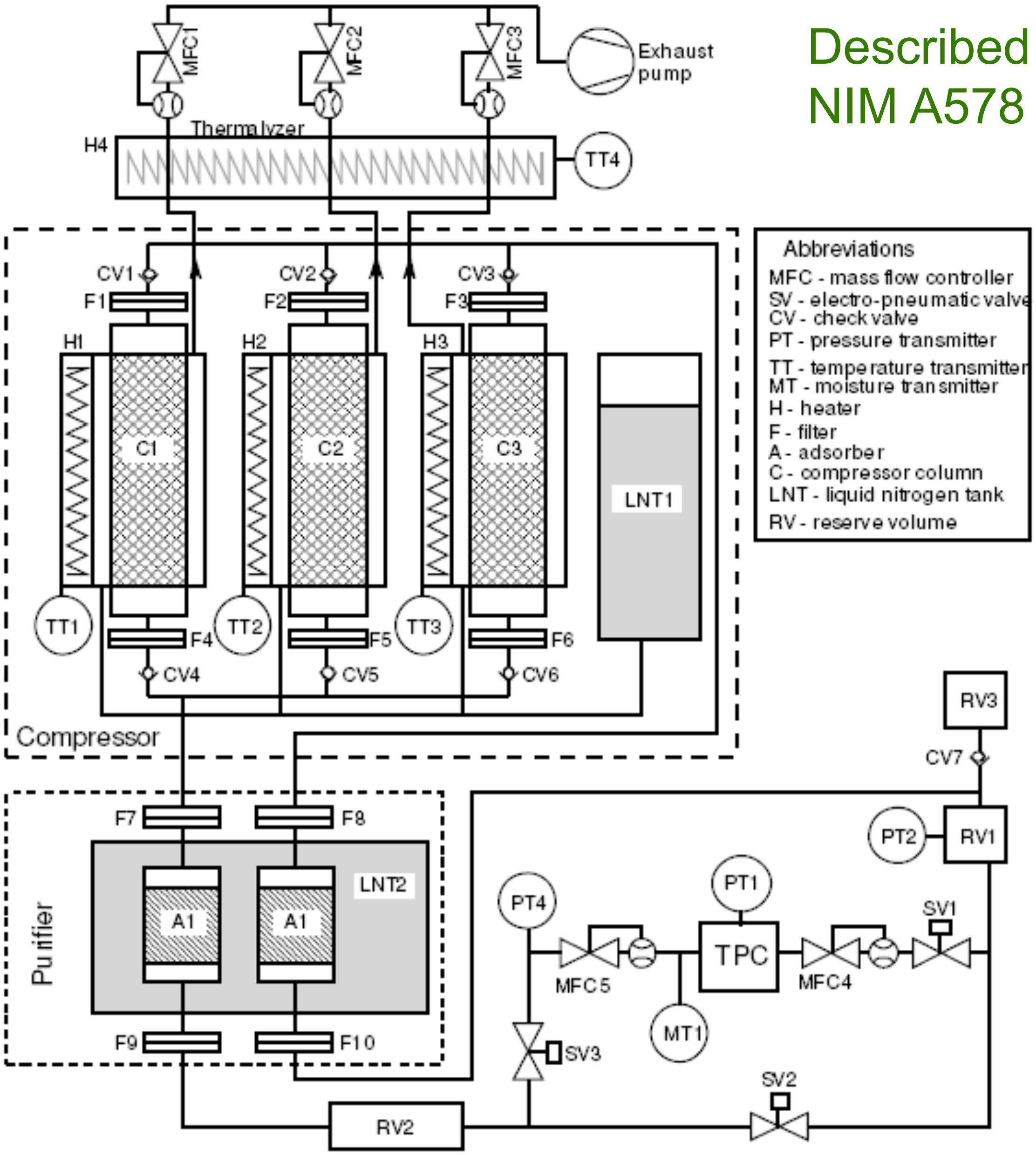


Internal corrections to λ_{μ}^{-}

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
μp Diffusion ($\Delta\lambda_k$)	-3.1	0.1
Unseen $\mu + p$ scatters ($\Delta\lambda_{\mathrm{sc}}$)	0.0	3.0
μ stop definition ($\Delta\lambda_{\mathrm{tr}}$)	0.0	2.0
μ pileup veto inefficiency ($\Delta\lambda_{\kappa}$)	0.0	3.0
Analysis methods ($\Delta\lambda_{\mathrm{Ana}}$)	0.0	5.0
Total	-32.6	± 8.4

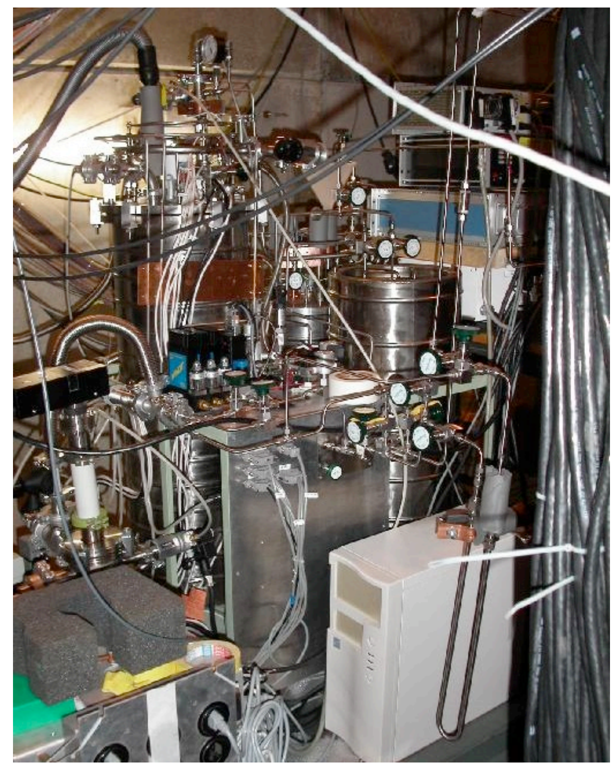
(statistical uncertainty of λ_{μ}^{-}: 12 s^{-1})

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



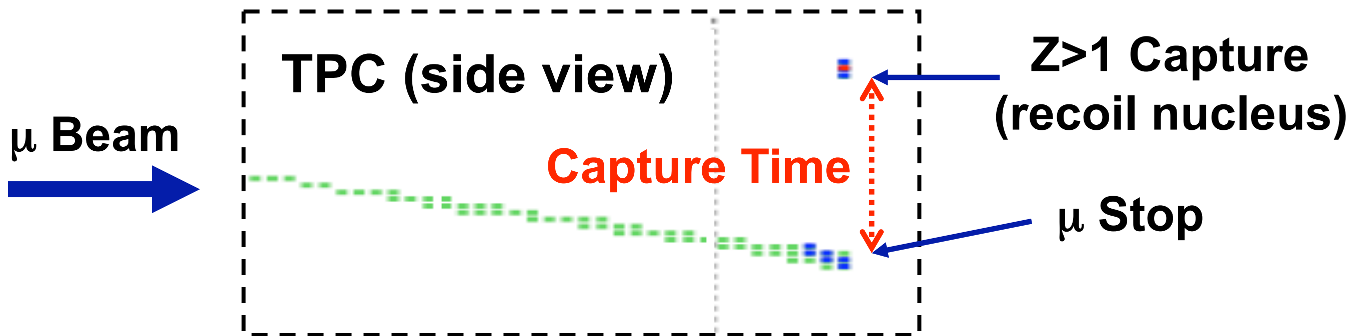
Described in
NIM A578 (2007) 485-497.

Commissioned 2004



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

In situ detection of Z > 1 captures



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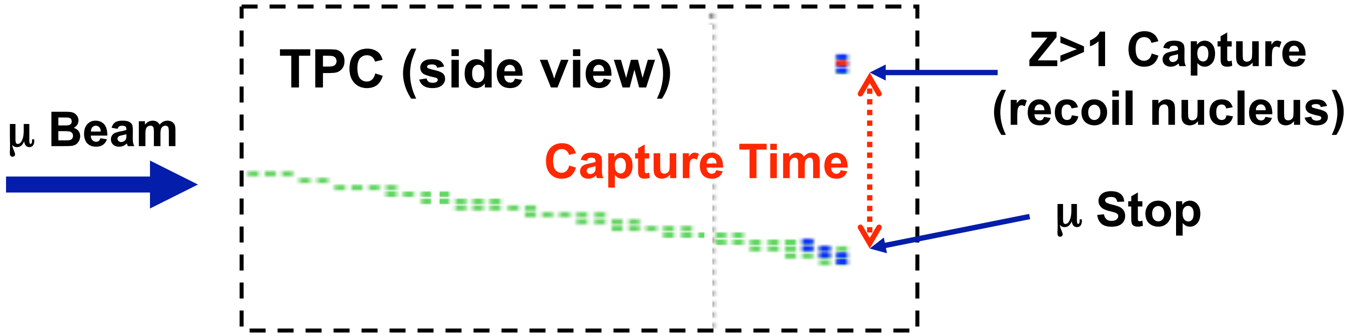

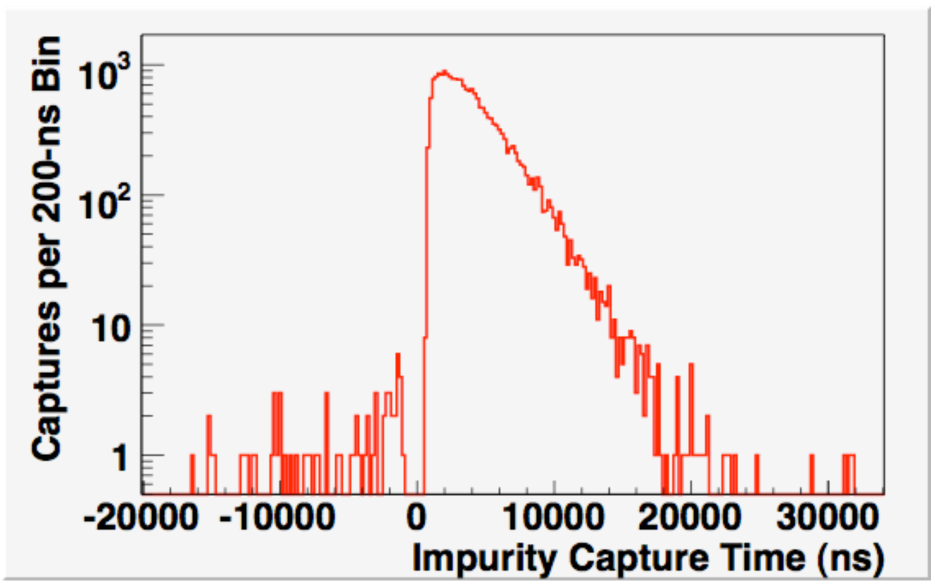

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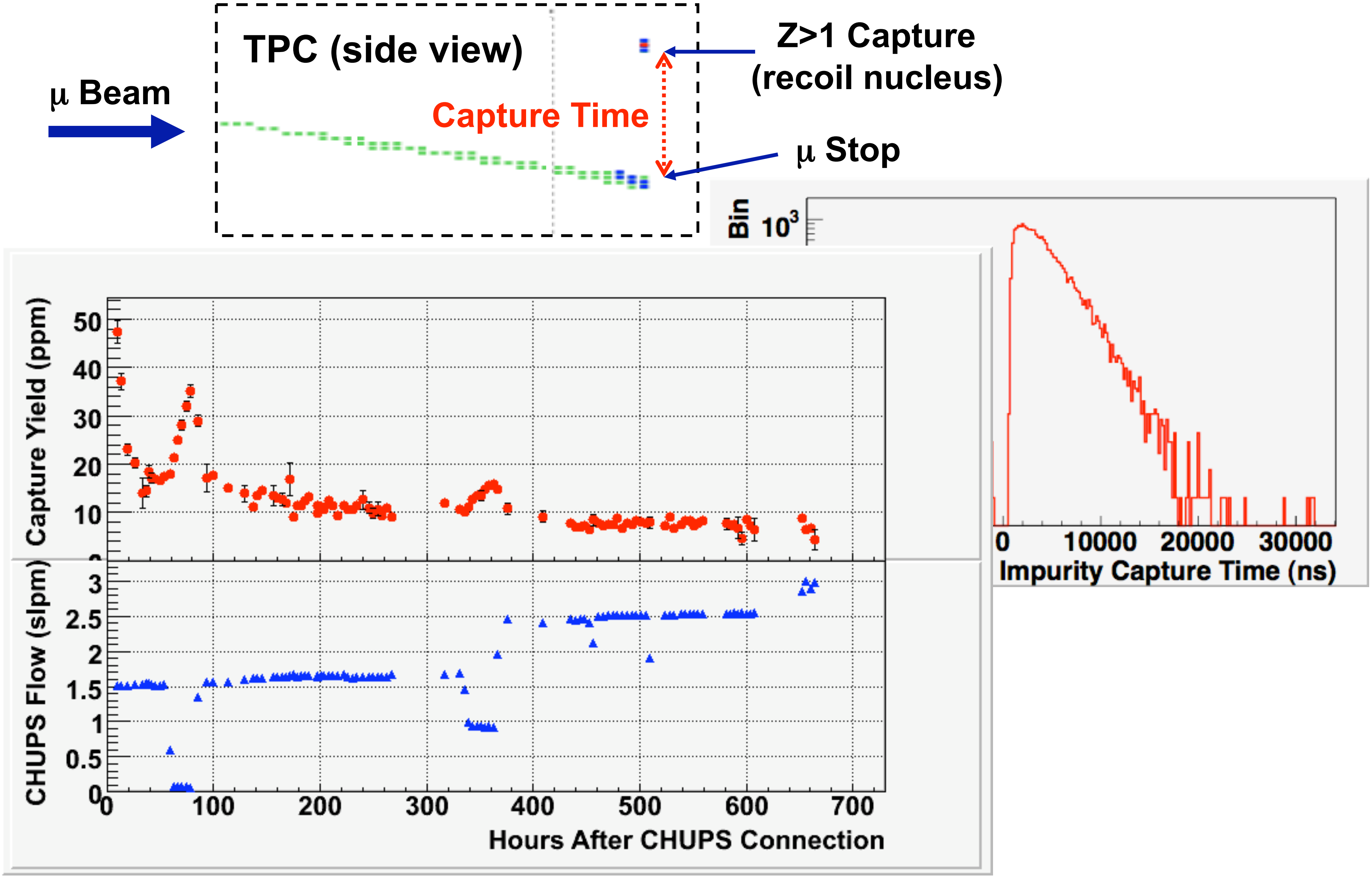
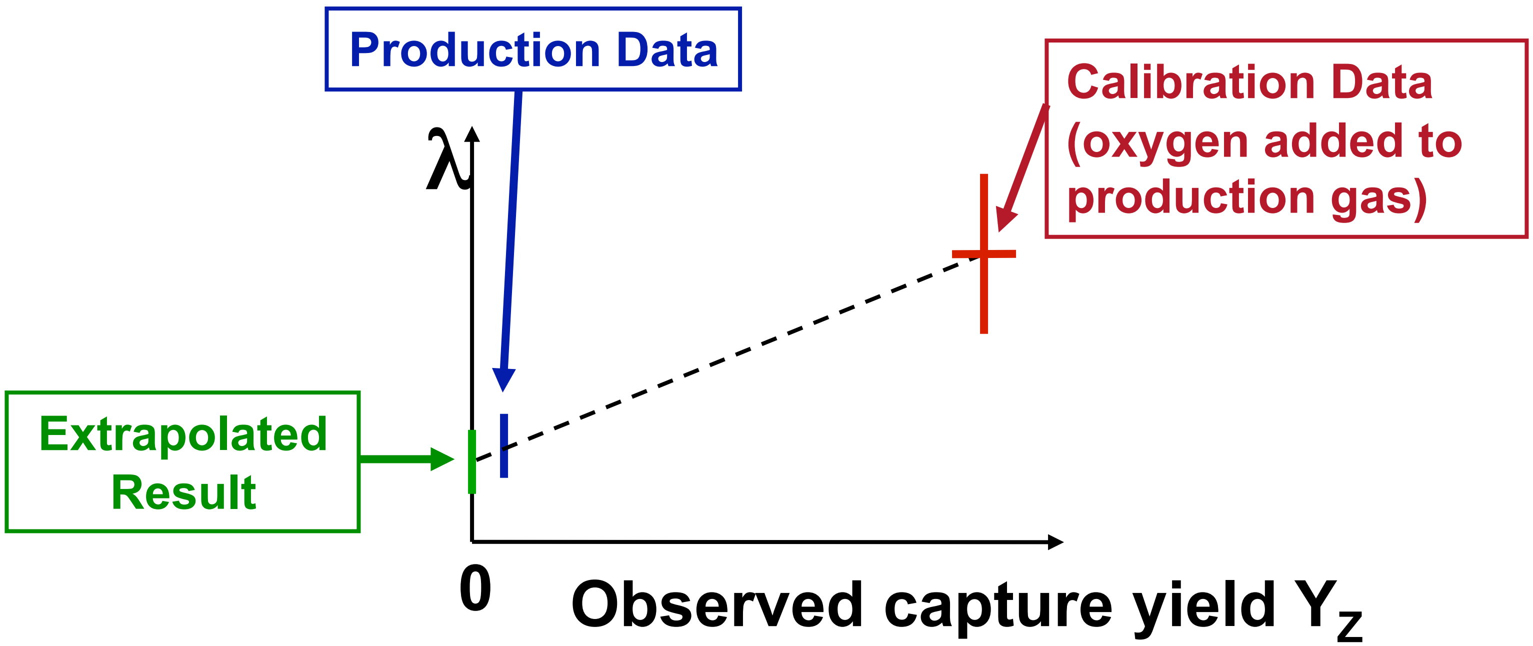


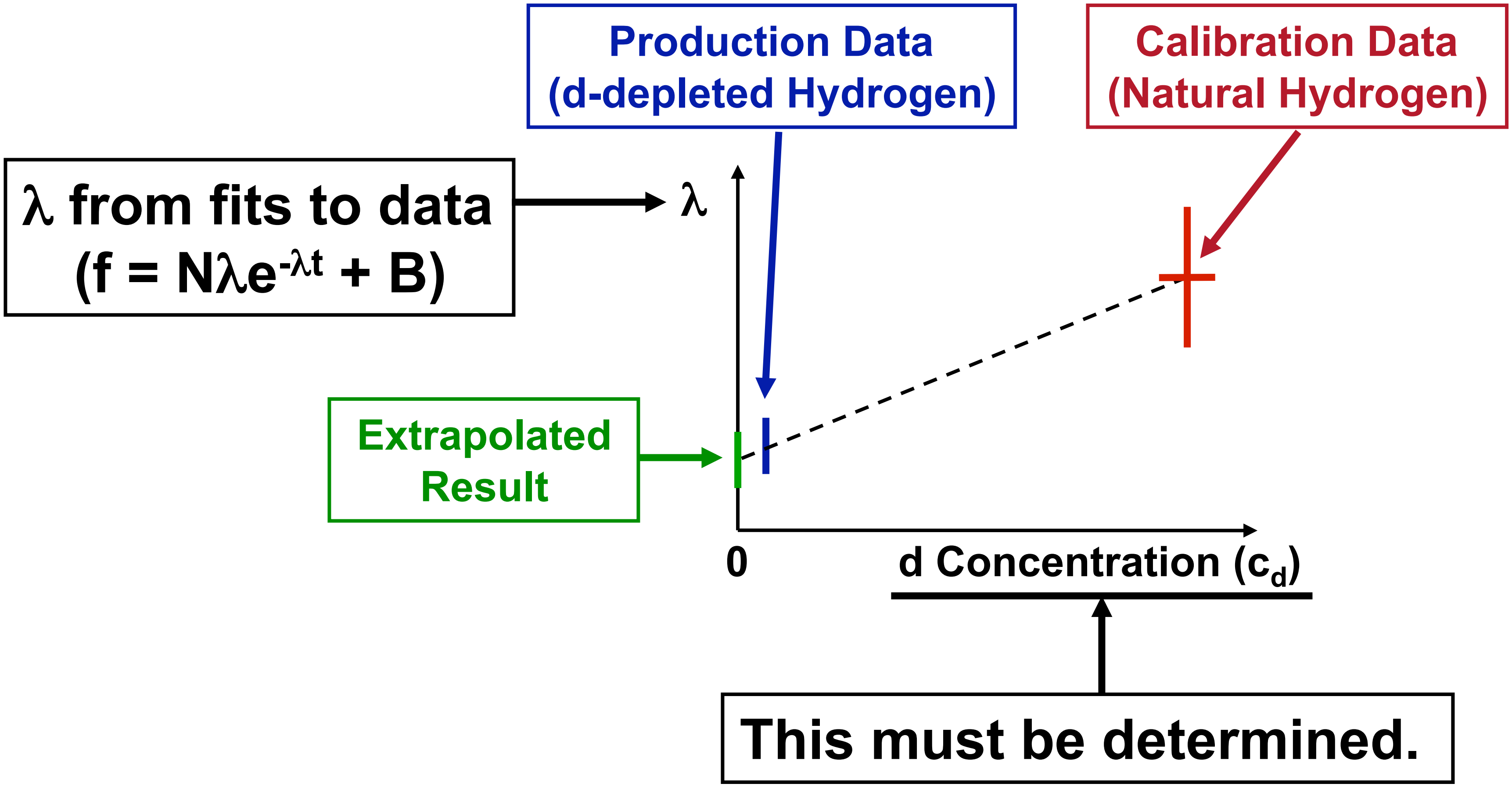
The final Z > 1 correction $\Delta\lambda_Z$ is based on impurity-doped calibration data.



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).

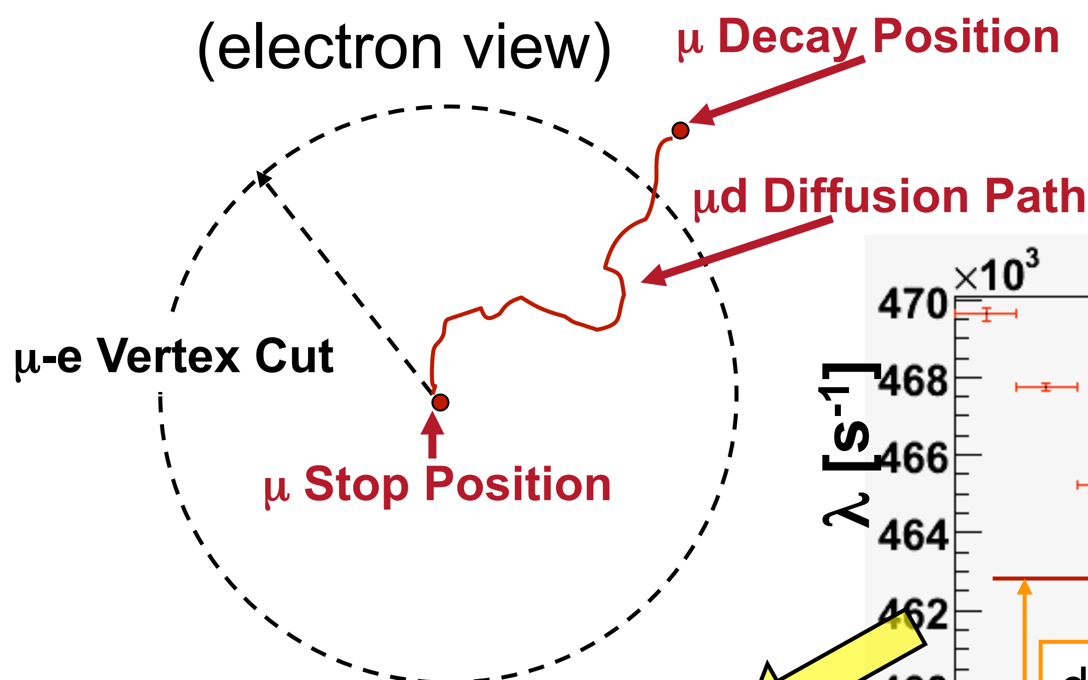
Residual deuterium content is accounted for by a zero-extrapolation procedure.

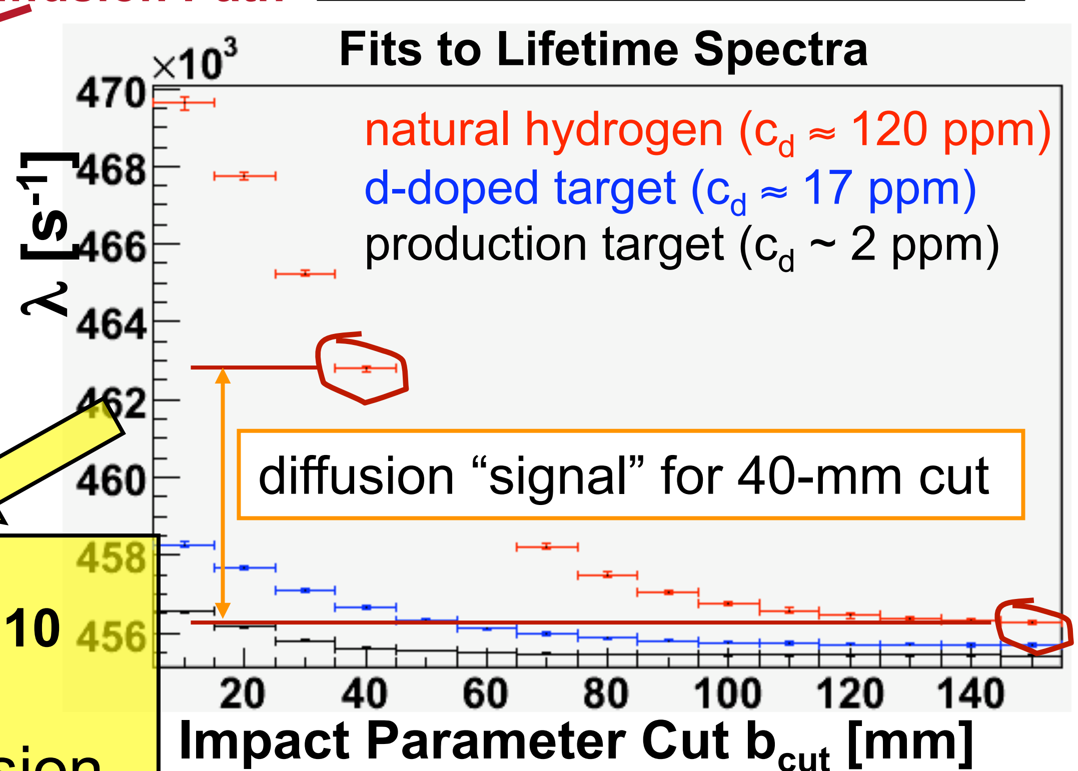


c_d Determination: Data Analysis Approach

μd can diffuse out of acceptance region:

> ➢ **signal proportional to number of μd, and therefore to c_d.**





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

*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

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

MuCap Λ_S from the μ^- lifetime λ_{μ}^-

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

molecular formation

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

μ^+ decay rate

bound-state effect

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

Averaged with UCB result gives

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

Λ_s and g_P Results 07

- MuCap Result 07

with $\tau_{\mu}+$ from PDG and MuLan

PRL 99, 032001 (2007)

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

- Theory 07

Average of HBChPT calculations of Λ_S:

$(687.4\ s^{-1} + 695\ s^{-1})/2 = 691.2\ s^{-1}$

Apply new rad. correction (2.8%):

$(1 + 0.028)691.2\ s^{-1} = 710.6\ s^{-1}$

Czarnecki, Marciano,Sirlin , PRL 99 (2007)

$\Lambda_S^{Theory} = 710.6\ s^{-1}$

further sub percent theory required

- Pseudoscalar coupling from MuCap 07

$g_P = 7.3 \pm 1.1$

Λ_s and g_P Results 07

- MuCap Result 07

with $\tau_{\mu}+$ from PDG and MuLan

PRL 99, 032001 (2007)

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

- Theory 07

Average of HBChPT ca

$(687.4\ s^{-1} + 695\ s^{-}$

Apply new rad. correct

$(1 + 0.028)691.2\ s$

Czarnecki, Marciano,Sirlin

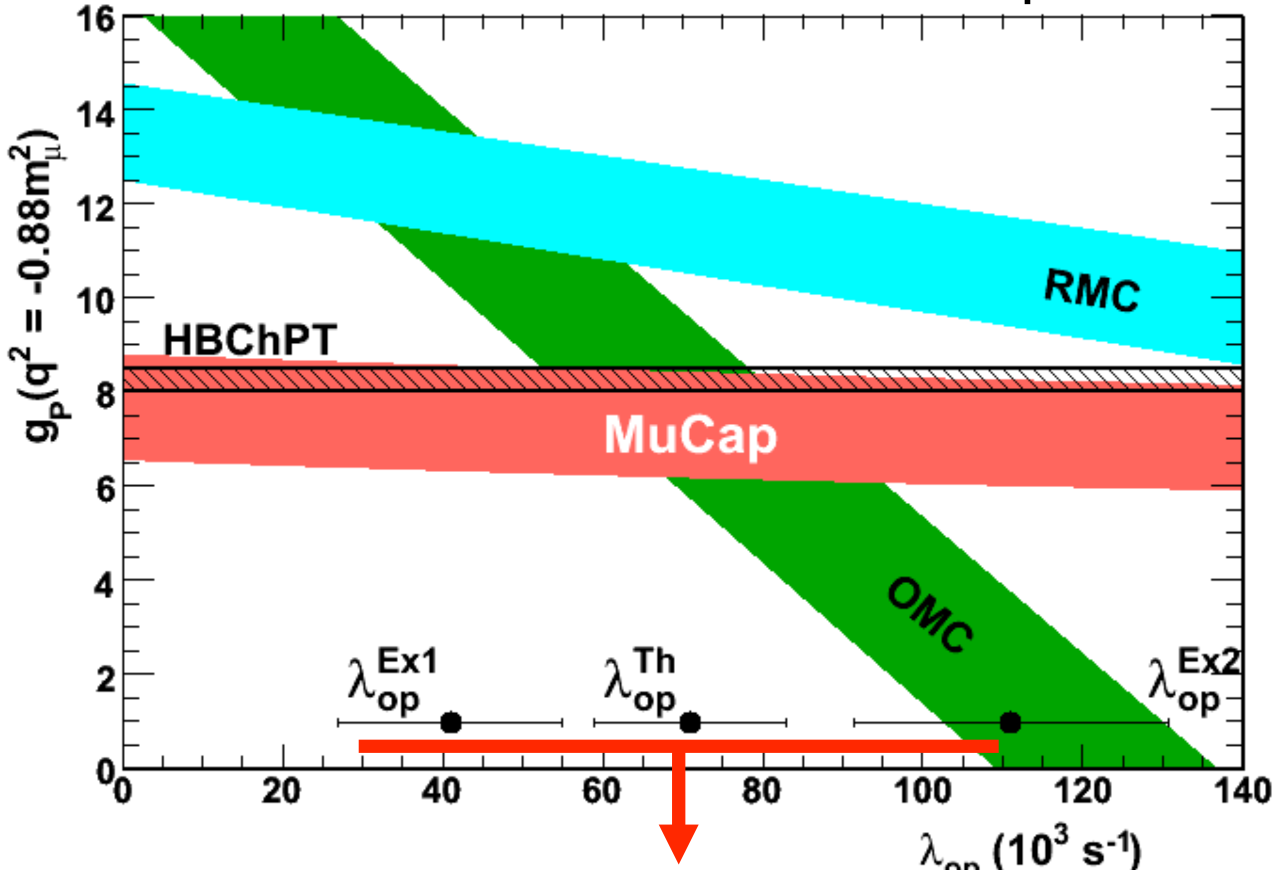
- Pseudosc

☐ **Improved Measurement of the Positive-Muon Lifetime and Determination of the Fermi Constant**
D. B. Chitwood *et al.* (MuLan Collaboration)
Published 16 July 2007
032001 Abstract Full Text: [PDF (241 kB) GZipped PS Buy Article]

☐ **Measurement of the Muon Capture Rate in Hydrogen Gas and Determination of the Proton's Pseudoscalar Coupling *gp***
V. A. Andreev *et al.* (MuCap Collaboration)
Published 16 July 2007
032002 Abstract Full Text: [PDF (270 kB) GZipped PS Buy Article]

☐ **Electroweak Radiative Corrections to Muon Capture**
Andrzej Czarnecki, William J. Marciano, and Alberto Sirlin
Published 16 July 2007
032003 Abstract Full Text: [PDF (101 kB) GZipped PS Buy Article]

Updated g_P vs. λ_{op}

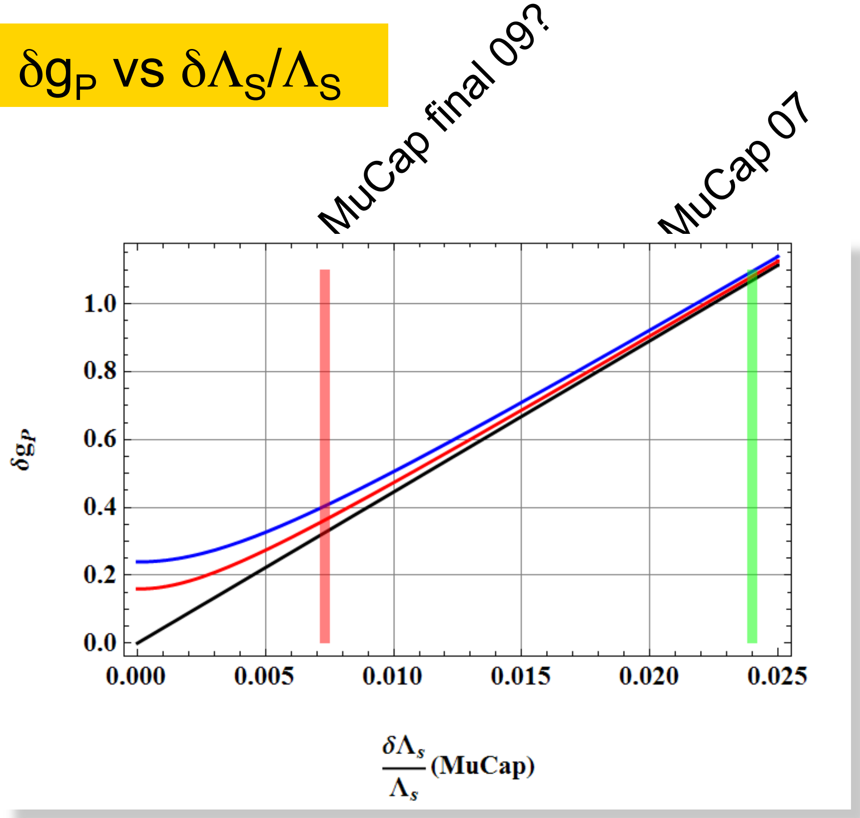


(contributes 3% uncertainty to g_p^{MuCap})

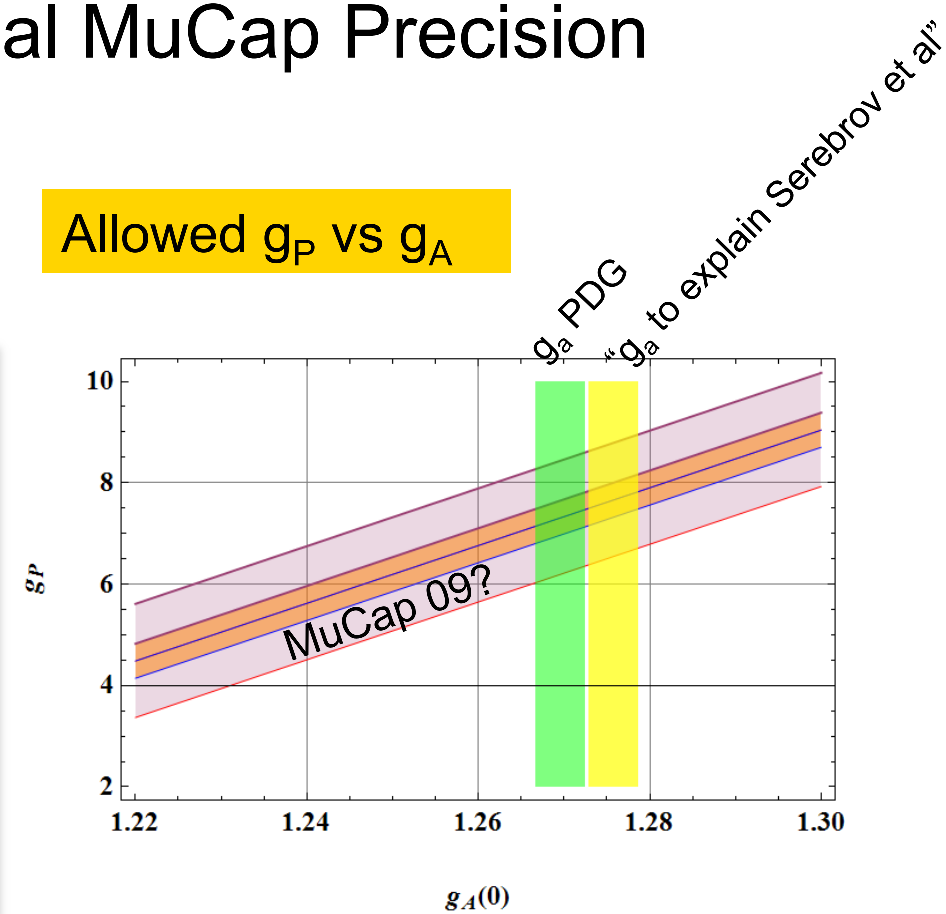
- MuCap 2007 result (with g_P to 15%) is consistent with theory.
- This is the first precise, unambiguous experimental determination of g_P

Expectations for Final MuCap Precision

δg_P vs $\delta\Lambda_S/\Lambda_S$



Allowed g_P vs g_A



	$\boxed{\frac{\delta\Lambda_s}{\Lambda_s}}$
• big exp. improvement	0.7 %
• sub-percent theory needed	?
• PDG g_a contributes	0.36 %
• Rad. corr.	0.4 %

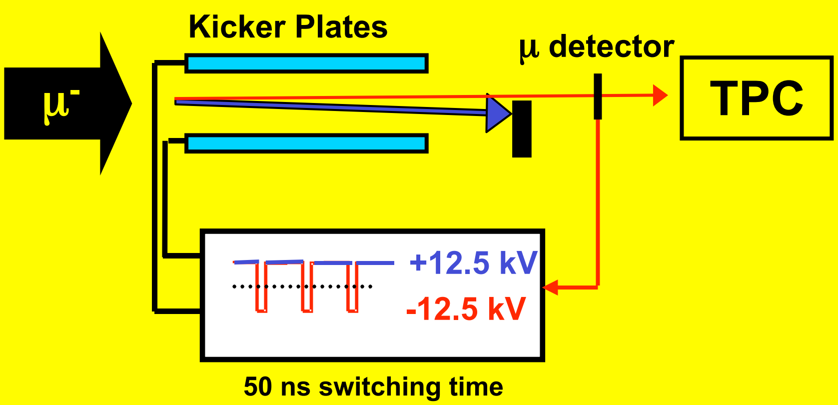
Several upgrades should lead to a 3-fold improved precision in 2006-2007 runs

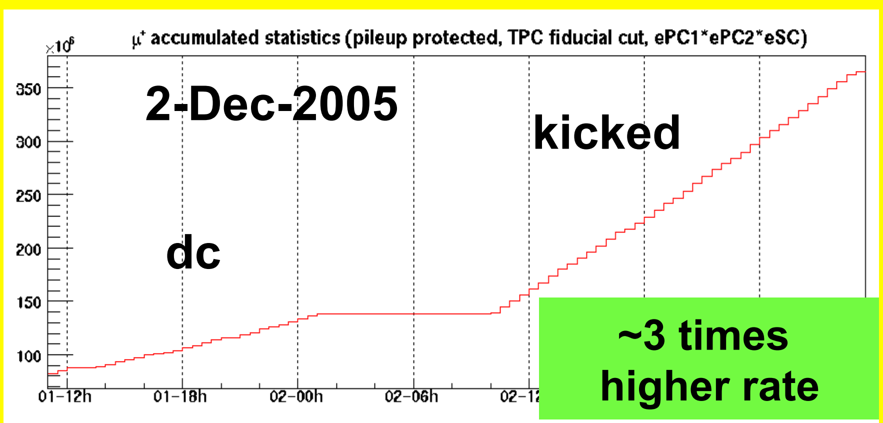
Source	2007 Uncertainty (s^{-1})	Projected Final Uncertainty (s^{-1})
Statistical	13.7	3.7
Z > 1 impurities	5.0	2
μd diffusion	1.6	0.5
μp diffusion	0.5	0.5
μ + p scattering	3	1
μ pileup veto eff.	3	1
Analysis Methods	5	2
Muon kinetics	5.8	2
Systematic	10.7	3.8
Total	17.4	5.3

Muon-On-Demand

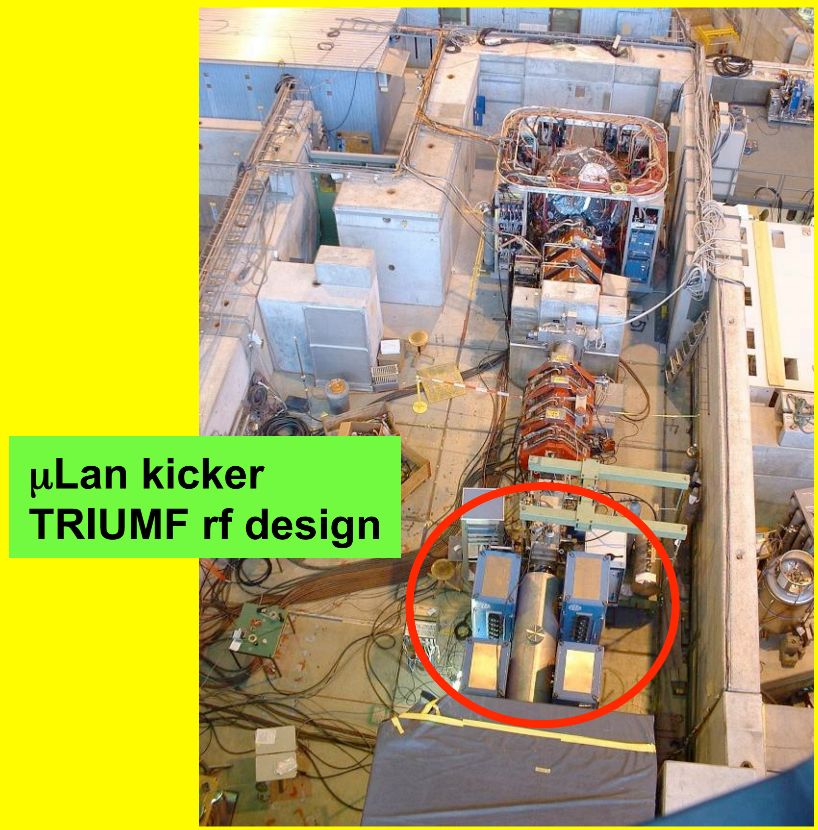
- Single muon requirement (to prevent systematics from pile-up)
- limits accepted μ rate to ~ 7 kHz,
- while PSI beam can provide ~ 70 kHz

- Muon-On-Demand concept





- Beamline



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μ pileup veto eff.	3	1
Analysis Methods	5	2
Muon kinetics	5.8	2
Systematic	10.7	3.8

Z>1 Impurities Reduced and Measured

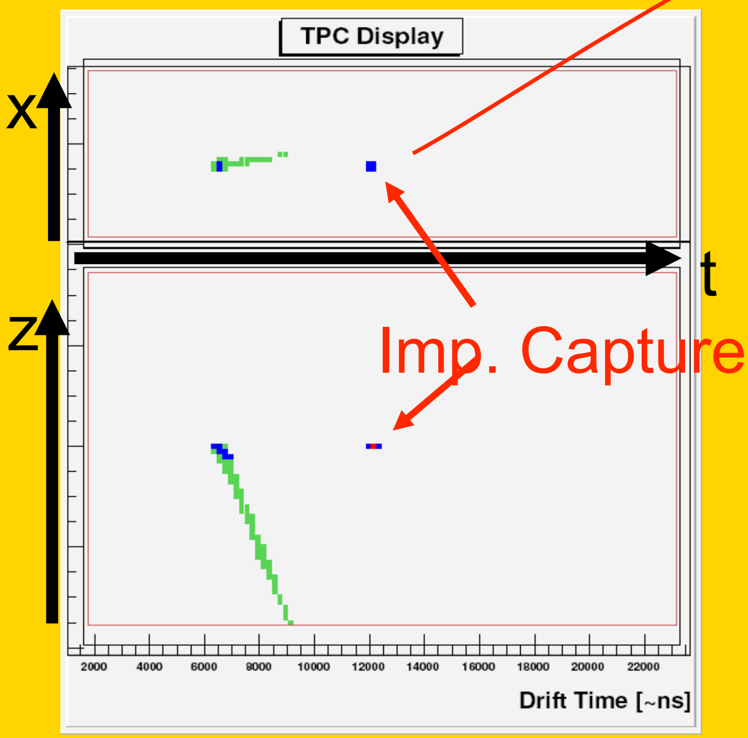
Circulating Hydrogen Ultrahigh
Purification System (CHUPS)

Gas chromatography

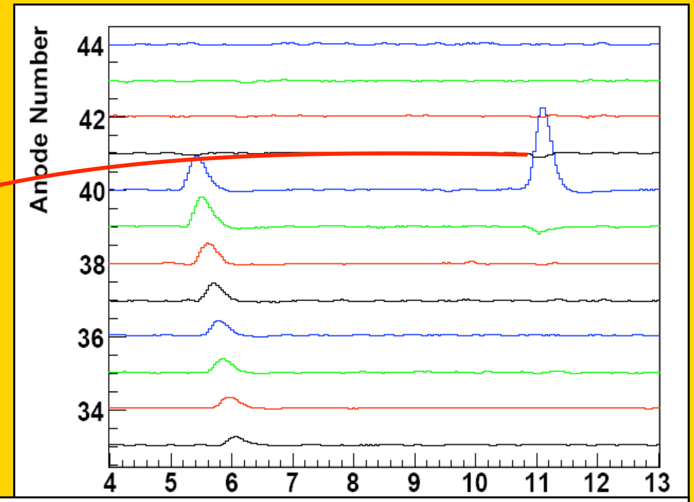
c_N, c_O < 5 ppb, c_{H2O} <10 ppb

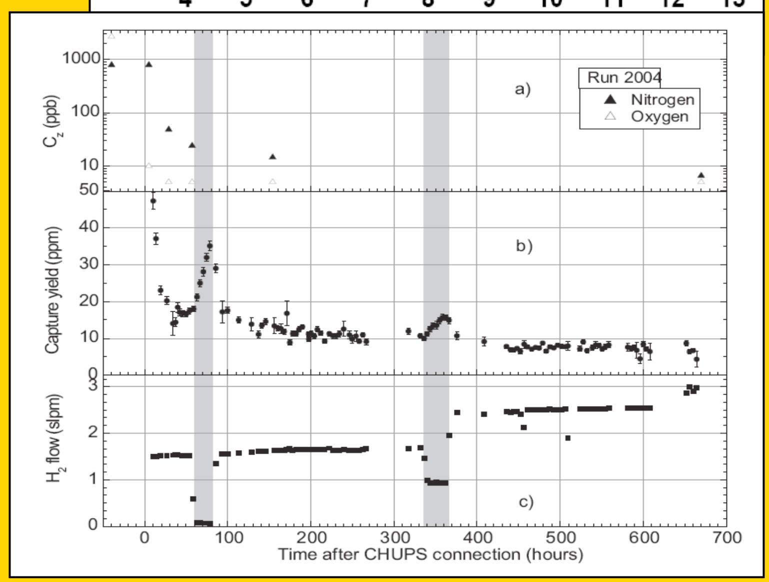
CRDF support

Diagnostic in TPC



- FADC upgrade on all TPC channels





Several upgrades should lead to a 3-fold improved precision in 2006-2007 runs

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Muon kinetics	5.8	2
Systematic	10.7	3.8

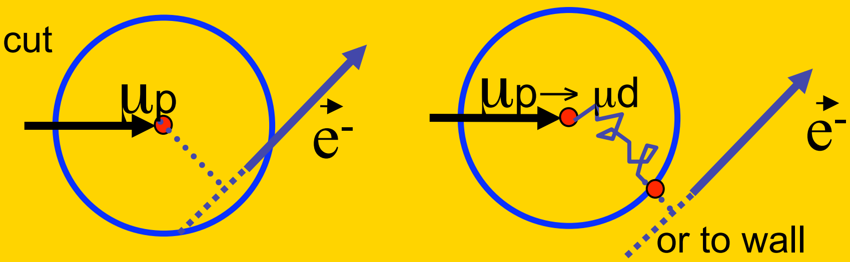
Record Isotopic Purity Achieved

$\mu p + d \rightarrow \mu d + p$ (134 eV)

large diffusion range of μd

< 1 ppm isotopic purity required

μ-e impact par cut



Diagnostic:

2007 Result

Data (λ vs. μ-e vertex cut):

c_d= 1.49 ± 0.12 ppm

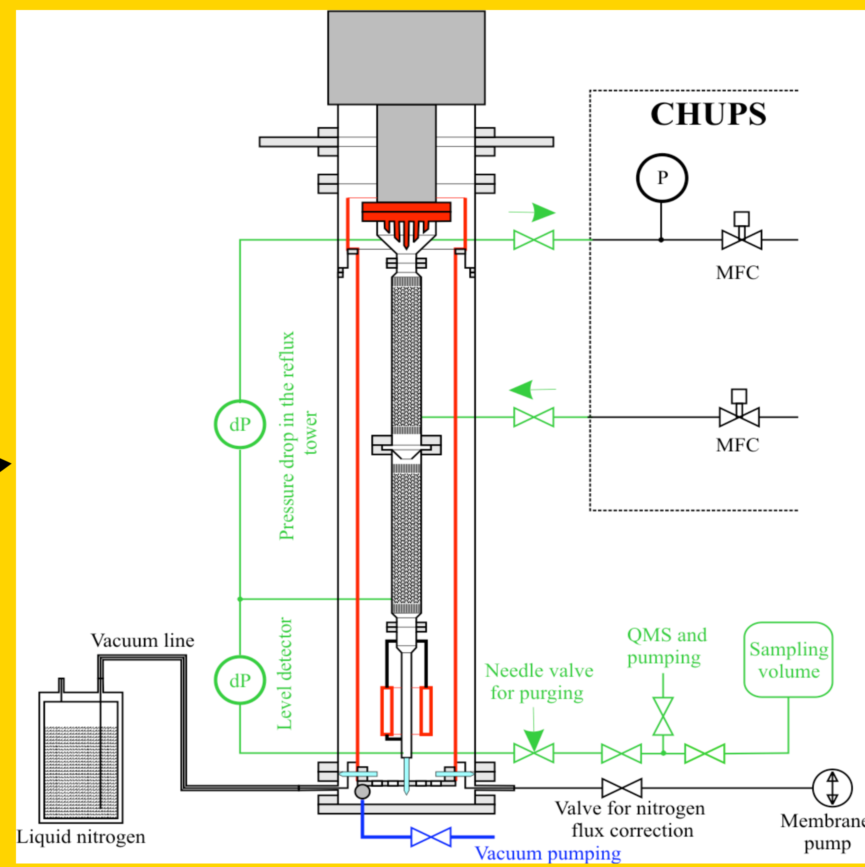
AMS (ETH Zurich):

c_d= 1.44 ± 0.15 ppm

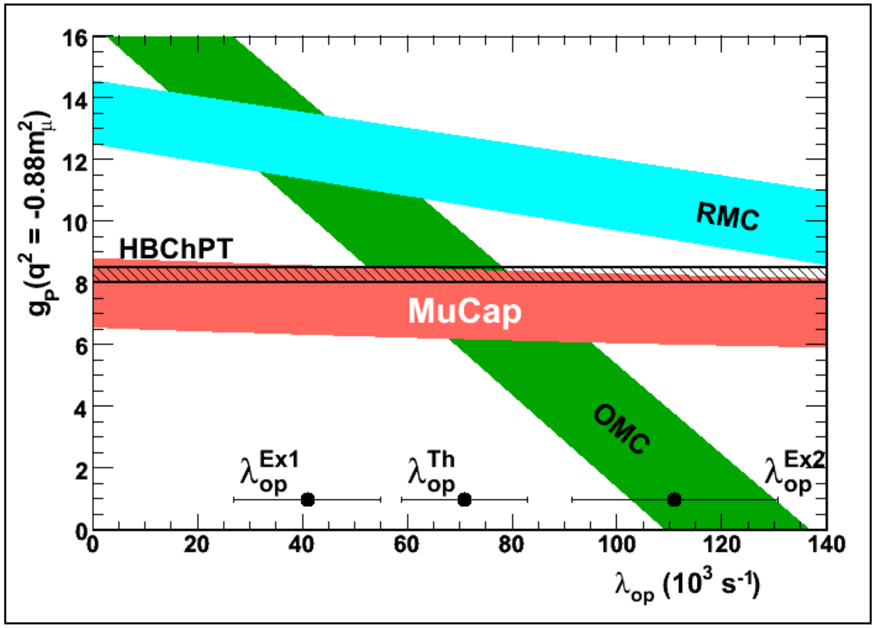
On-site isotopic separator:

c_d < 0.010 ppm !

World record



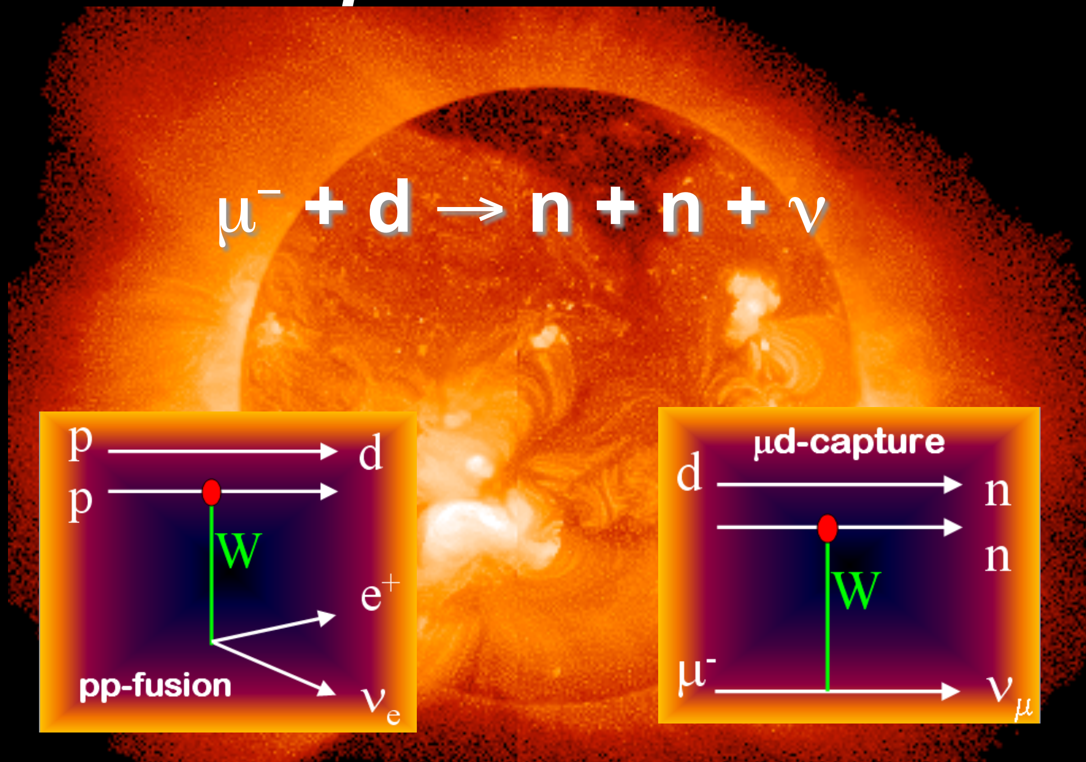
Summary



– First g_P with non-controversial interpretation
– Agrees with χPT expectation
– Factor 2.5 additional improvement on the way
  - kicker → >10^{10} good events on tape
  - higher purity target + more impurity-doped calibration runs → smaller Z>1 correction
  - deuterium removal → negligible deuterium correction

"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 (ν's in SNO, pp fusion)
- Comparison to modern high-precision calculations

Extra Slides

Phenomenological Calculation

- Gives an expression in terms of form factors g_V, g_M, g_A, g_P.
- W.F.s are solutions to the Dirac equation.
- μ in bound state:

$$e^{-iE_\mu t}\psi_\mu(\vec{x}) = e^{-iE_\mu t}\phi_\mu(\vec{x})\begin{pmatrix}\chi_\mu \\ 0\end{pmatrix}, \quad \phi_\mu(\vec{x}) = \frac{1}{\sqrt{\pi a_0^3}}e^{-r/a_0}$$

- Non-relativisitic expansion to order $v_{nucleon}/c$:
  - effective Hamiltonian in terms of “Primikoff factors” and Pauli matrices.
  - particle states in terms of 2-spinors (χ).
  - results in an explicit expression for the transition rate W:

$$W = \frac{C_p^2}{2\pi^2 a_0^3}\frac{E_\nu^2}{1+E_\nu/\sqrt{m_n^2+E_\nu^2}}G_V^2(1+3\eta)\left(1-\frac{\langle\vec{\sigma}\cdot\vec{\sigma}_A\rangle\xi}{1+3\eta}\right)$$

total μp spin dependence

$$\boxed{\Lambda_S = W_{F=0} = 690.0\ \mathrm{s}^{-1}},$$

μp(↑↓) singlet

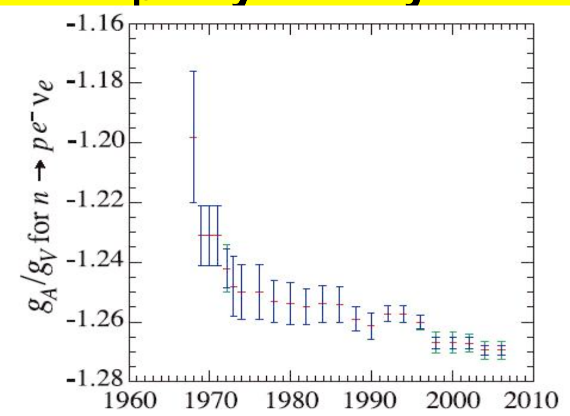
$$\boxed{\Lambda_T = W_{F=1} = 11.3\ \mathrm{s}^{-1}}$$

μp(↑↑) triplet

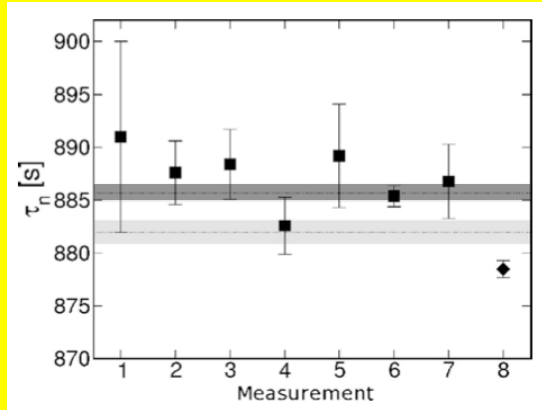
Axialvector Form Factor g_A

Neutron Decay Experiments

β Asymmetry



Lifetime



Axial radius

ν+N scattering

$$M_A = (1.026 \pm 0.021)\ GeV$$

$$\sqrt{< r_A^2 >} = (0.666 \pm 0.014)\ fm$$

consistent with π electroproduction (with ChPT correction)

PDG 2006

Severijns et al. (2006) RMP

Bernard et al. (2002)

$$g_a(q^2) = g_a(0)(1 + \tfrac{1}{6}\langle r_a^2 \rangle q^2)$$

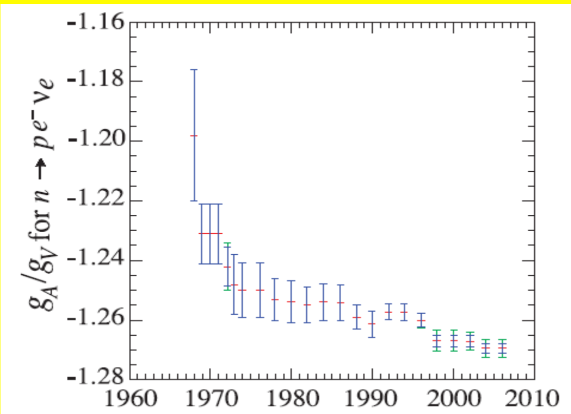
$$g_a(0) = 1.2695 \pm 0.0029$$

$$g_a(-0.88 m_\mu^2) = 1.247 \pm 0.004$$

Introduces 0.45% uncertainty to Λ_S (theory)

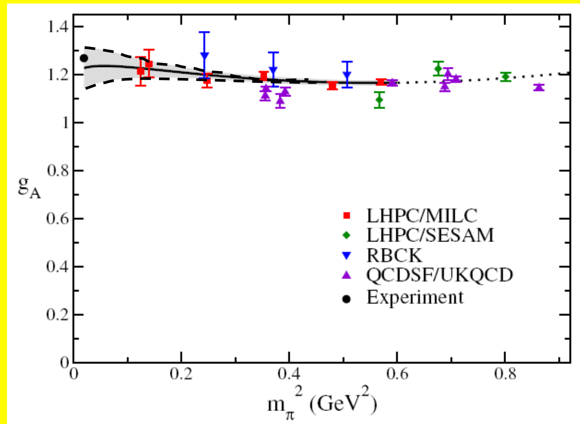
Axialvector Form Factor g_A

Exp. History



PDG 2006

Lattice QCD



Edwards et al. LHPC Coll (2006)

Axial radius

ν+N scattering

$$M_A = (1.026 \pm 0.021)\ GeV$$

$$\sqrt{< r_A^2 >} = (0.666 \pm 0.014)\ fm$$

consistent with π electroproduction (with ChPT correction)

Bernard et al. (2002)

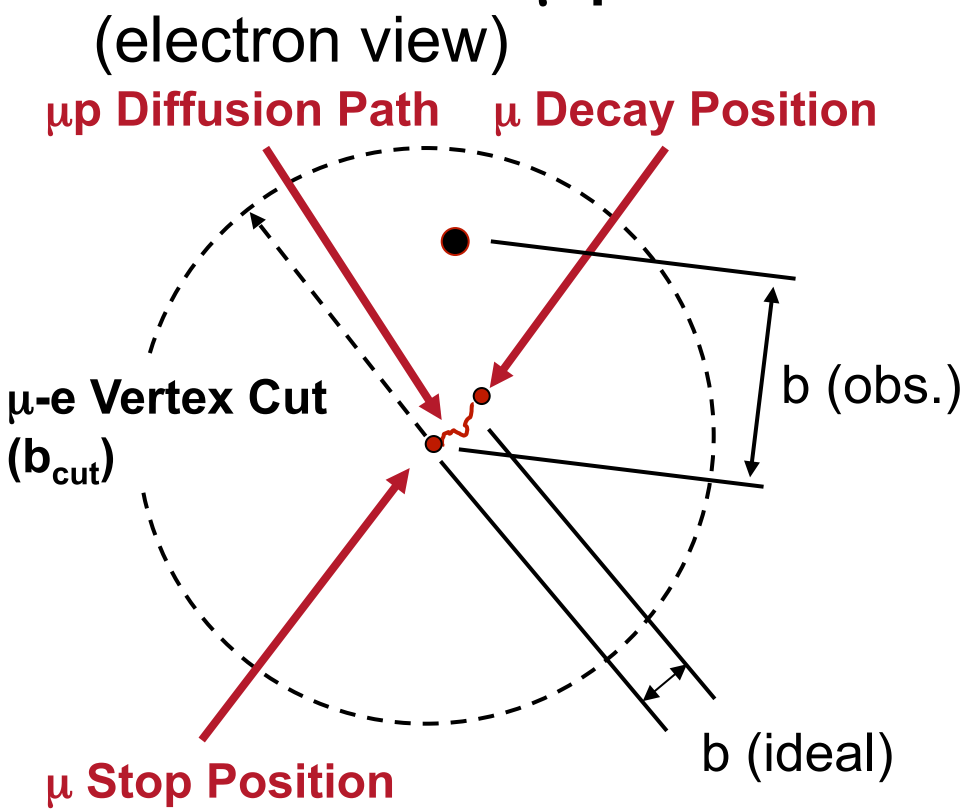
$$g_A(q^2) = g_A(0)(1 + \tfrac{1}{6} < r_A^2 > q^2)$$

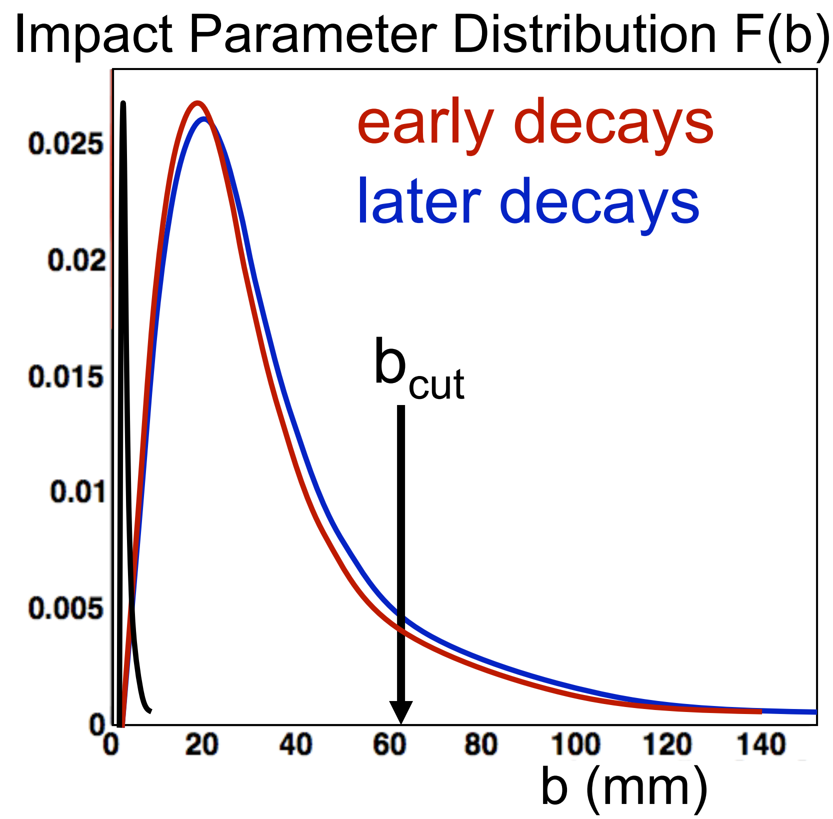
$$g_A(0) = -1.2695 \pm 0.0029$$

$$g_A(-0.88 m_\mu^2) = -1.245 \pm 0.003$$

introduces 0.4% uncertainty to Λ_S (theory)

μp Diffusion Effect

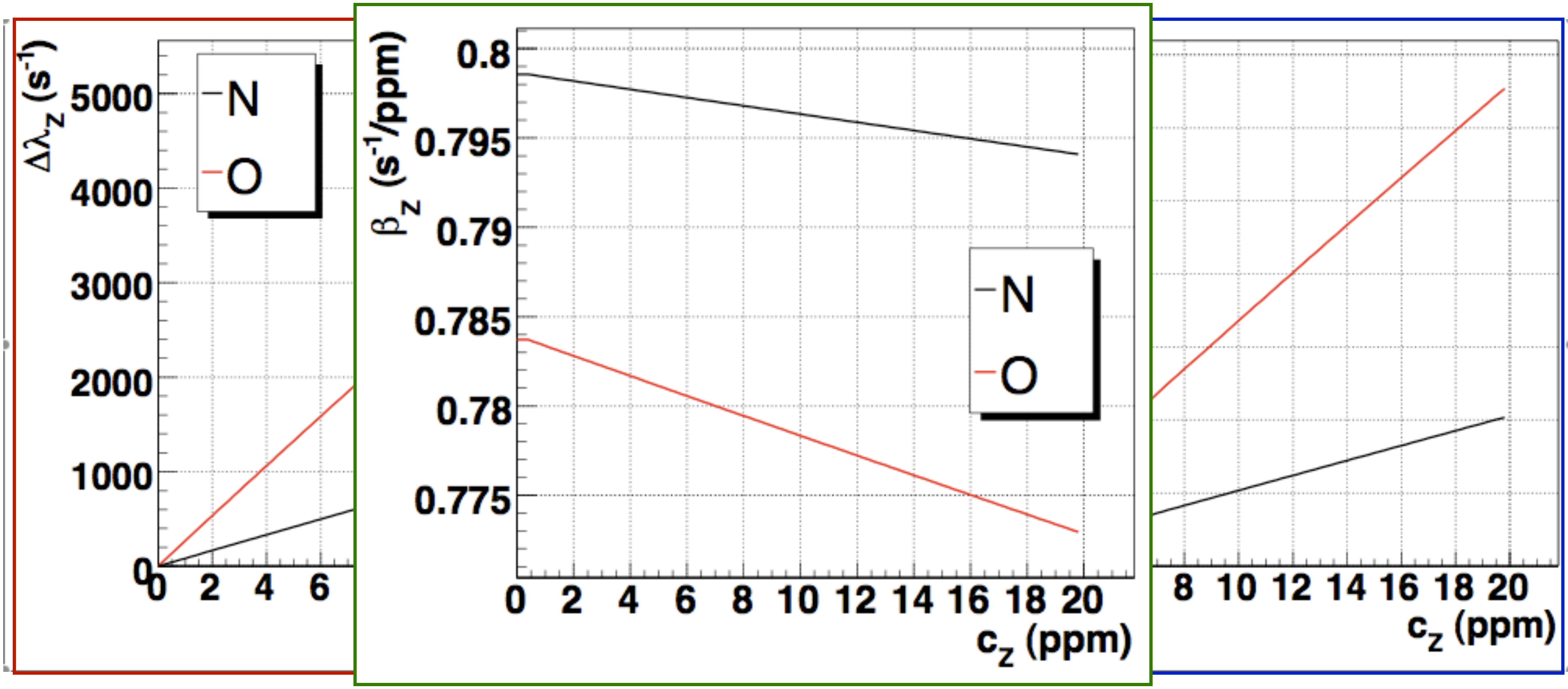




Later decays are less likely than early decays to pass the impact parameter cut.

The effect is calculated based on:
1) the observed F(b),
2) a thermal diffusion model,
3) the requirement of consistency of the c_d ratio vs. b_{cut} (prev. slide).

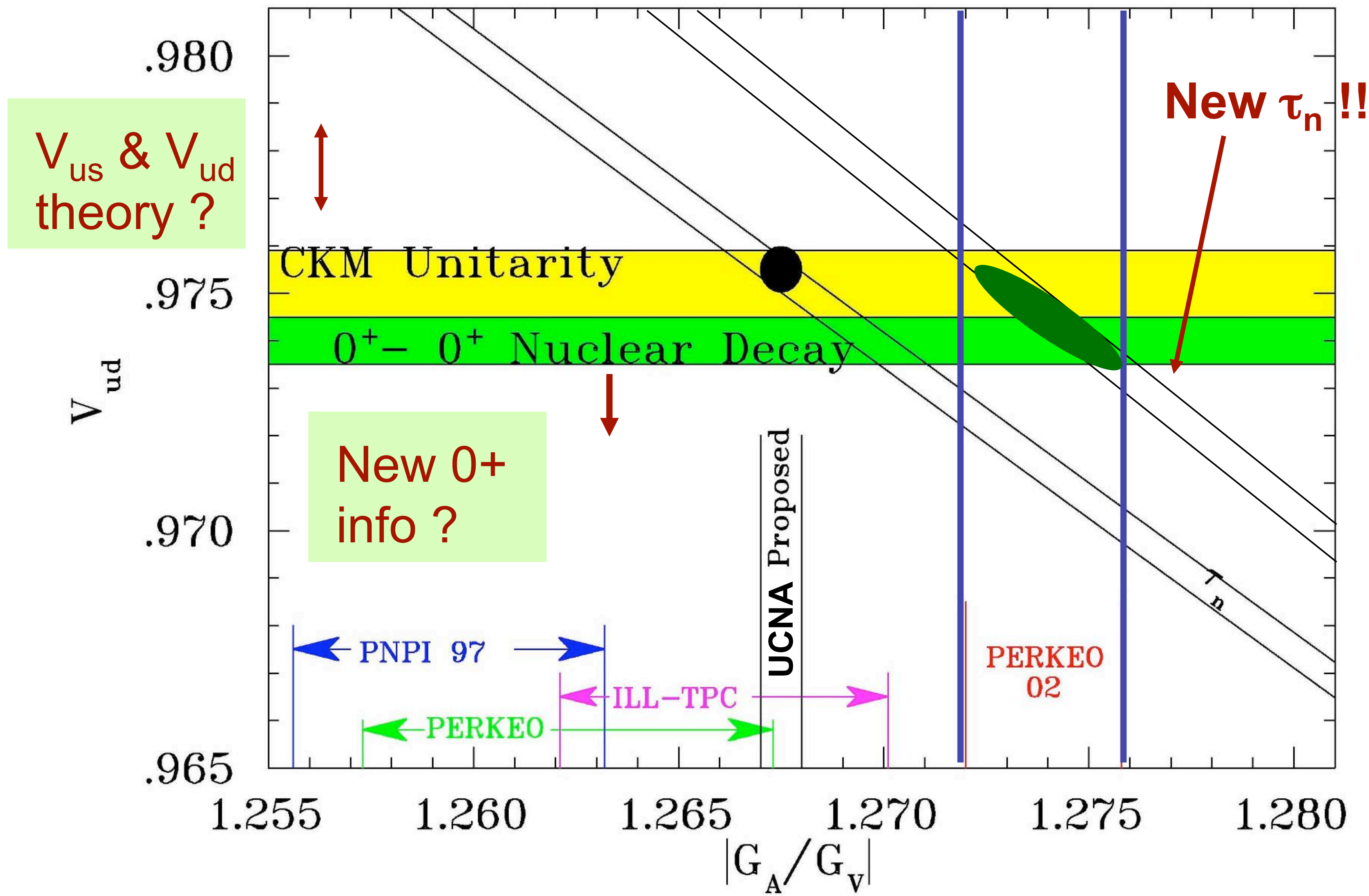
Impurity correction scales with Z > 1 capture yield.



$\beta_Z = \Delta\lambda_Z / Y_Z$ is similar for C, N, and O.

We can correct for impurities based on the observed Z > 1 capture yield, <u>if we know the detection efficiency</u> ε_Z.

CKM Summary: New V_{us} & τ_n ?



neutron (J. Nico, CIPANP 06)

$$dW \propto (g_V^2 + 3g_A^2)F(E_e)[1 + a\frac{\vec{p_e}\cdot\vec{p_\nu}}{E_eE_\nu} + \vec{\sigma_n}\cdot(A\frac{\vec{p_e}}{E_e} + B\frac{\vec{p_\nu}}{E_\nu} + D\frac{\vec{p_e}\times\vec{p_\nu}}{E_eE_\nu})]$$

Jackson, Treiman, Wyld, *Nucl. Phys.* **4**, 206 (1957)

Lifetime

$$\tau = \frac{1}{f(1+\delta_R)}\frac{K/ln2}{(1+\Delta_R^V)(g_V^2+3g_A^2)} = (885.7 \pm 0.8)\,\mathrm{s}$$

Coupling ratio

$$\lambda = \frac{|g_A|}{|g_V|}e^{i\phi} = (-1.2695 \pm 0.0029)$$

Electron-antineutrino asymmetry

$$a = \frac{1-|\lambda|^2}{1+3|\lambda|^2} = (-0.103 \pm 0.004)$$

Spin-antineutrino asymmetry

$$B = 2\frac{|\lambda|^2 - |\lambda|cos\phi}{1+3|\lambda|^2} = (0.983 \pm 0.004)$$

Spin-electron asymmetry

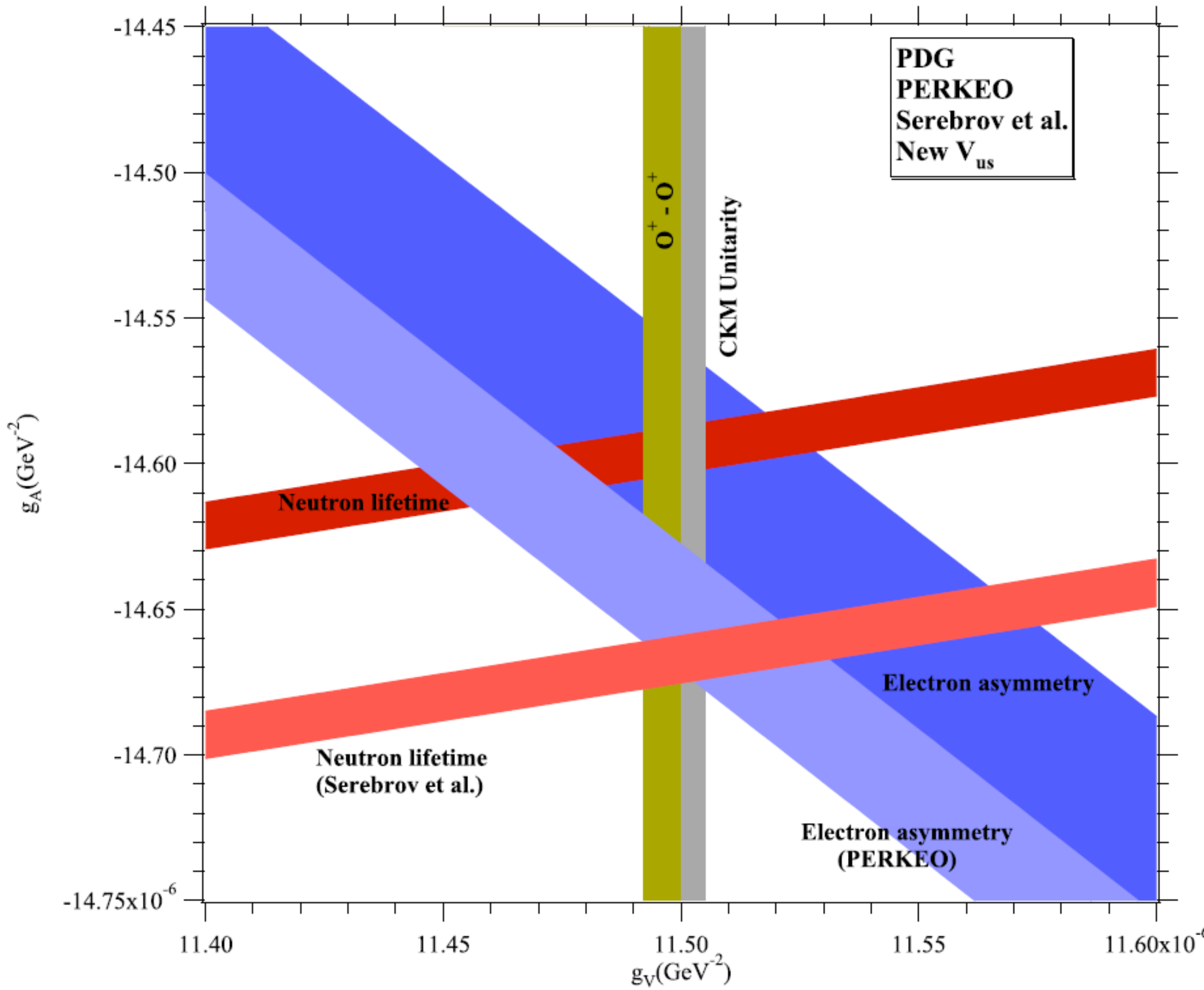
$$A = -2\frac{|\lambda|^2 + |\lambda|cos\phi}{1+3|\lambda|^2} = (-0.1173 \pm 0.0013)$$

Triple correlation

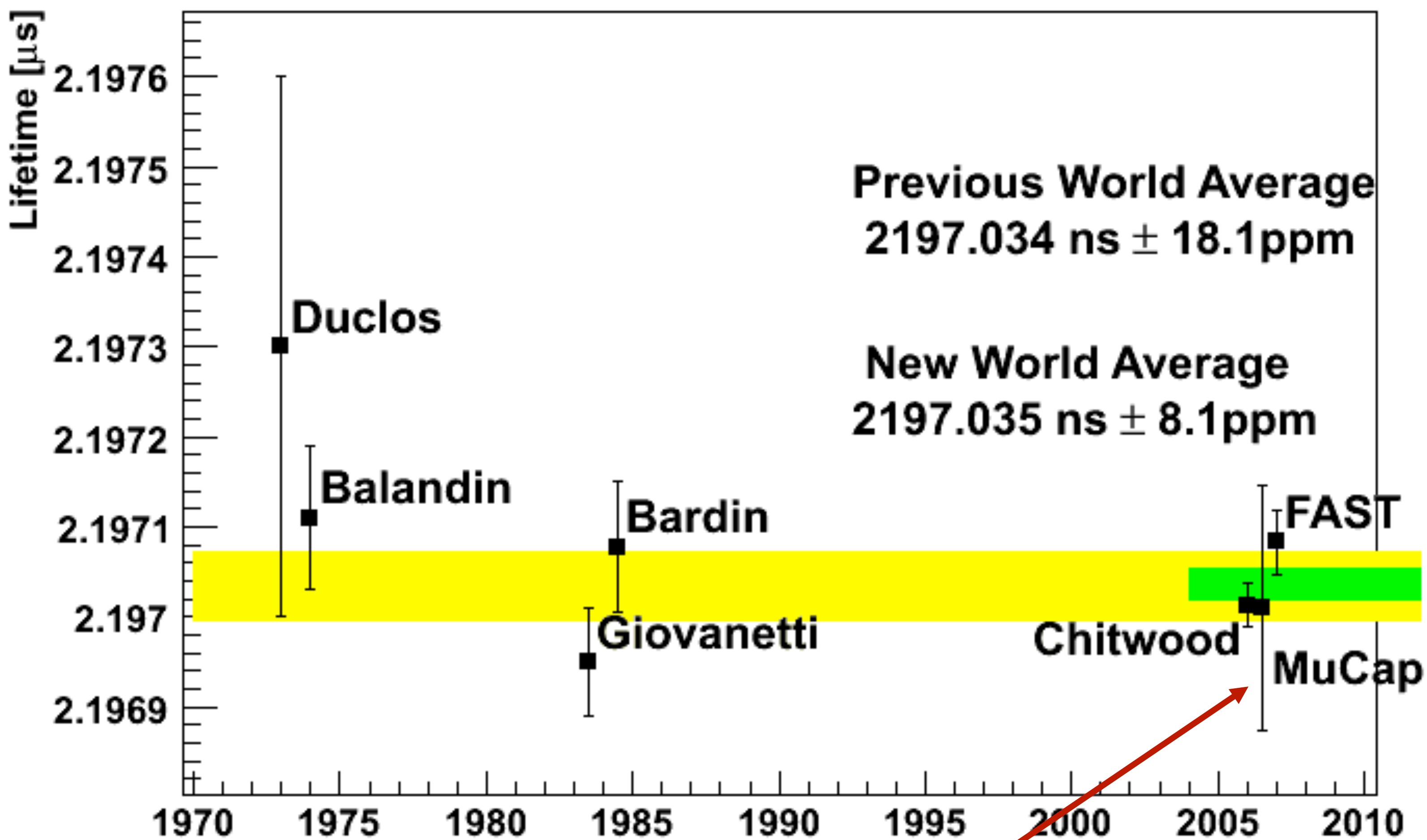
$$D = 2\frac{|\lambda|sin\phi}{1+3|\lambda|^2} = (-4 \pm 6)\times 10^{-4}$$

PDG, 2005 update

neutron



PDG
PERKEO
Serebrov et al.
New V_{us}
$0^+ - 0^+$
CKM Unitarity
Neutron lifetime
Electron asymmetry
Neutron lifetime
(Serebrov et al.)
Electron asymmetry
(PERKEO)
-14.45
-14.50
-14.55
-14.60
-14.65
-14.70
-14.75×10^{-6}
$g_A(\text{GeV}^{-2})$
11.40
11.45
11.50
11.55
11.60×10^{-6}
$g_V(\text{GeV}^{-2})$



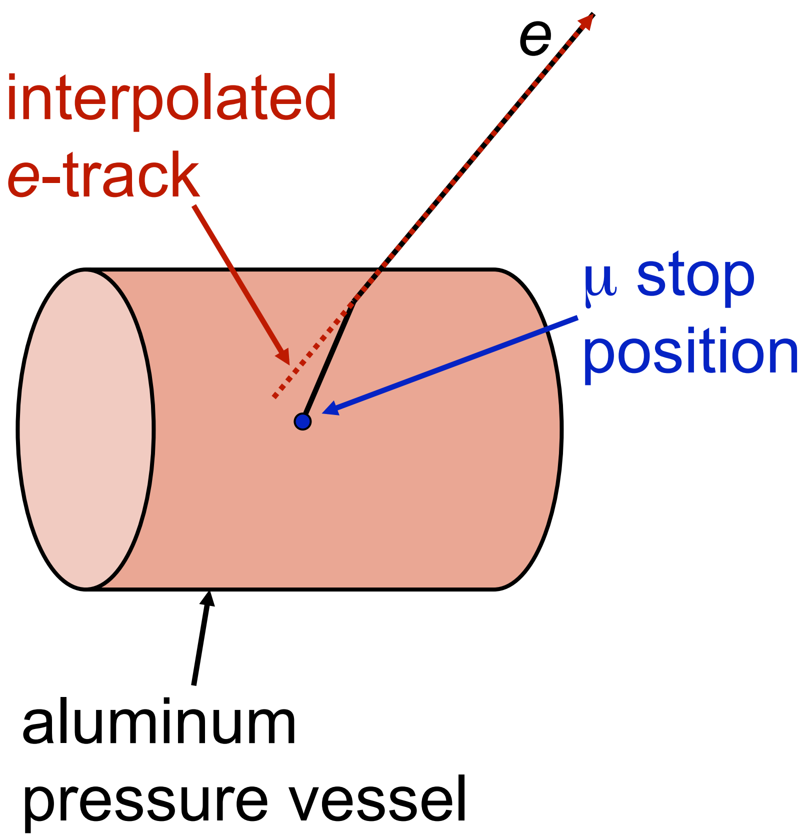
Unpublished analysis of MuCap μ^+ data taken in 2004

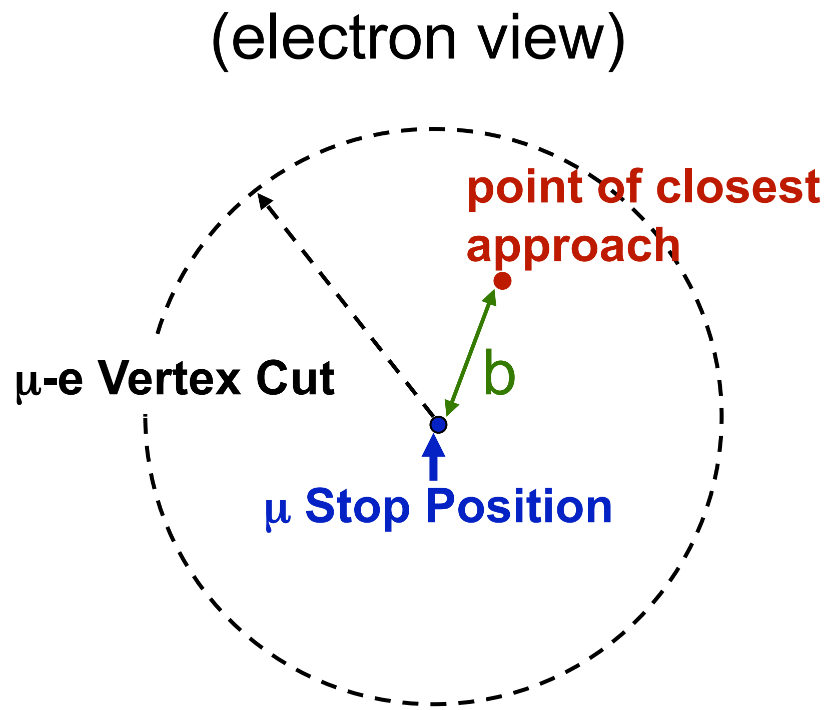
Analysis of MuCap data collected in 2004

- 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

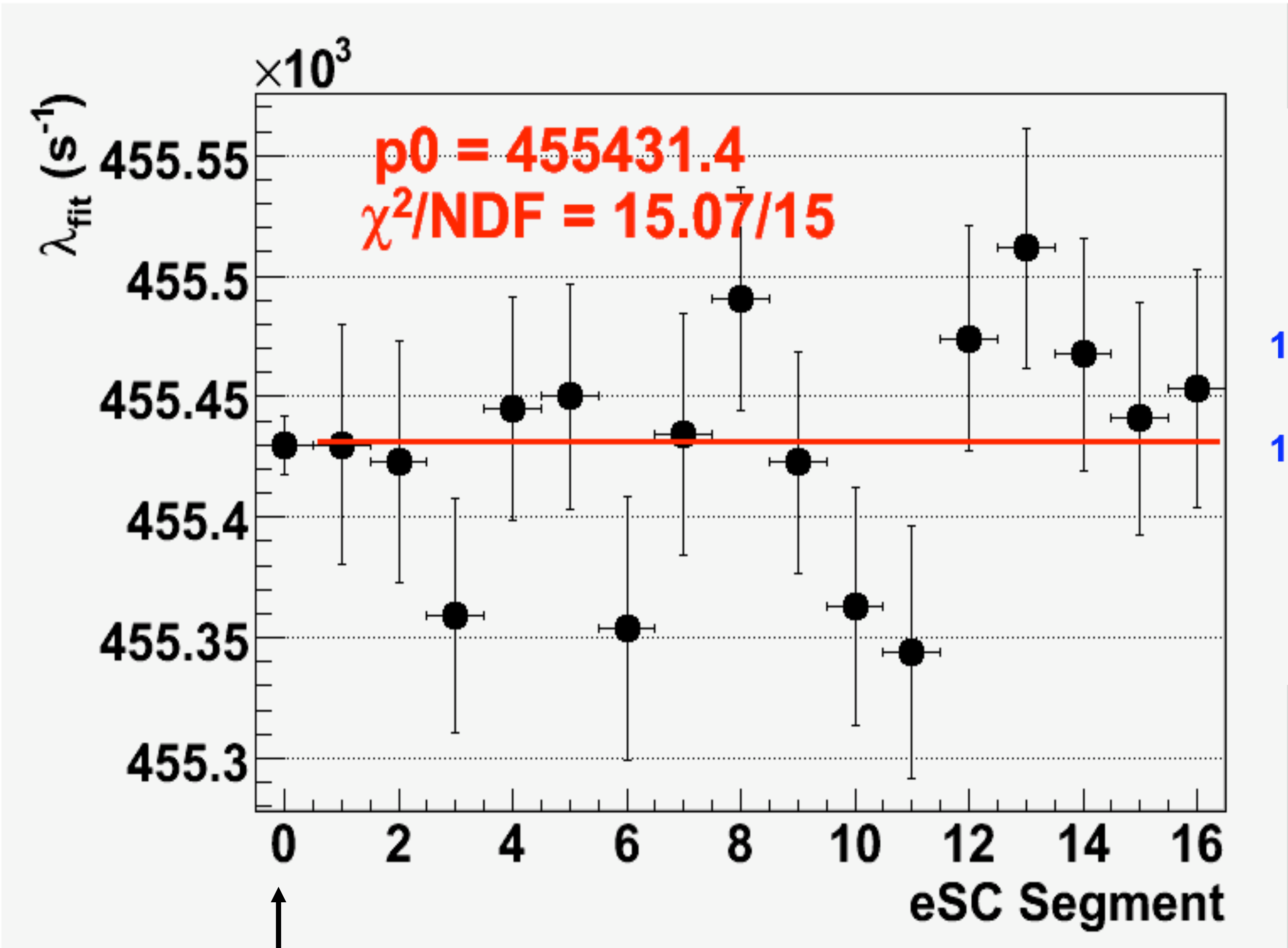
(also known as μ-e vertex cuts)

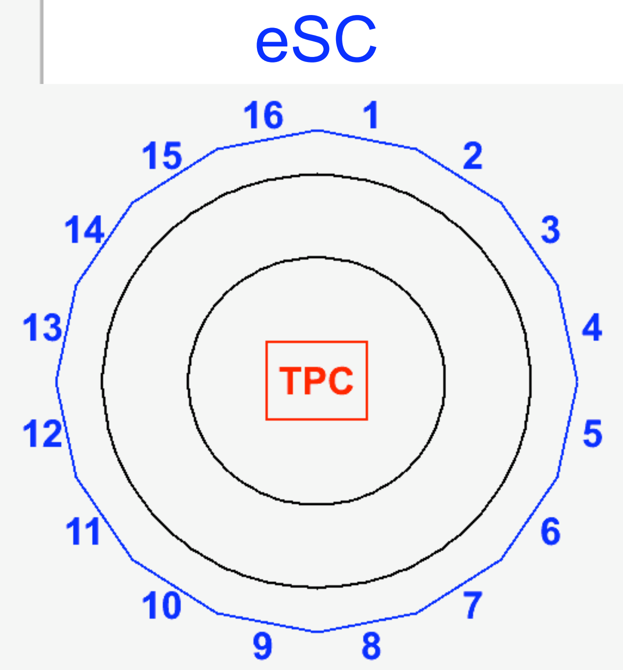




The impact parameter b is the distance of closest approach of the e-track to the μ stop position.

Lifetime vs eSC segment

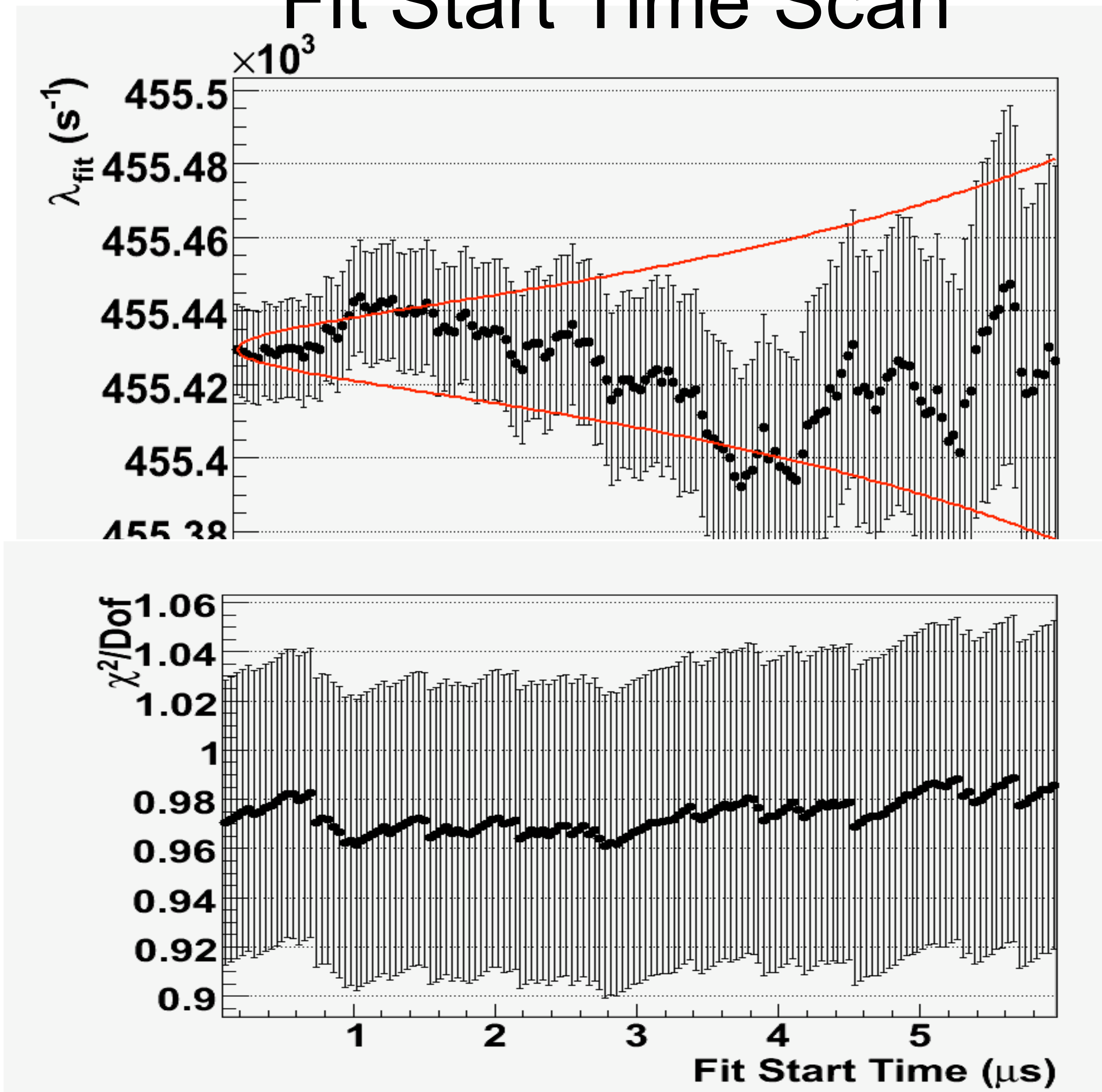




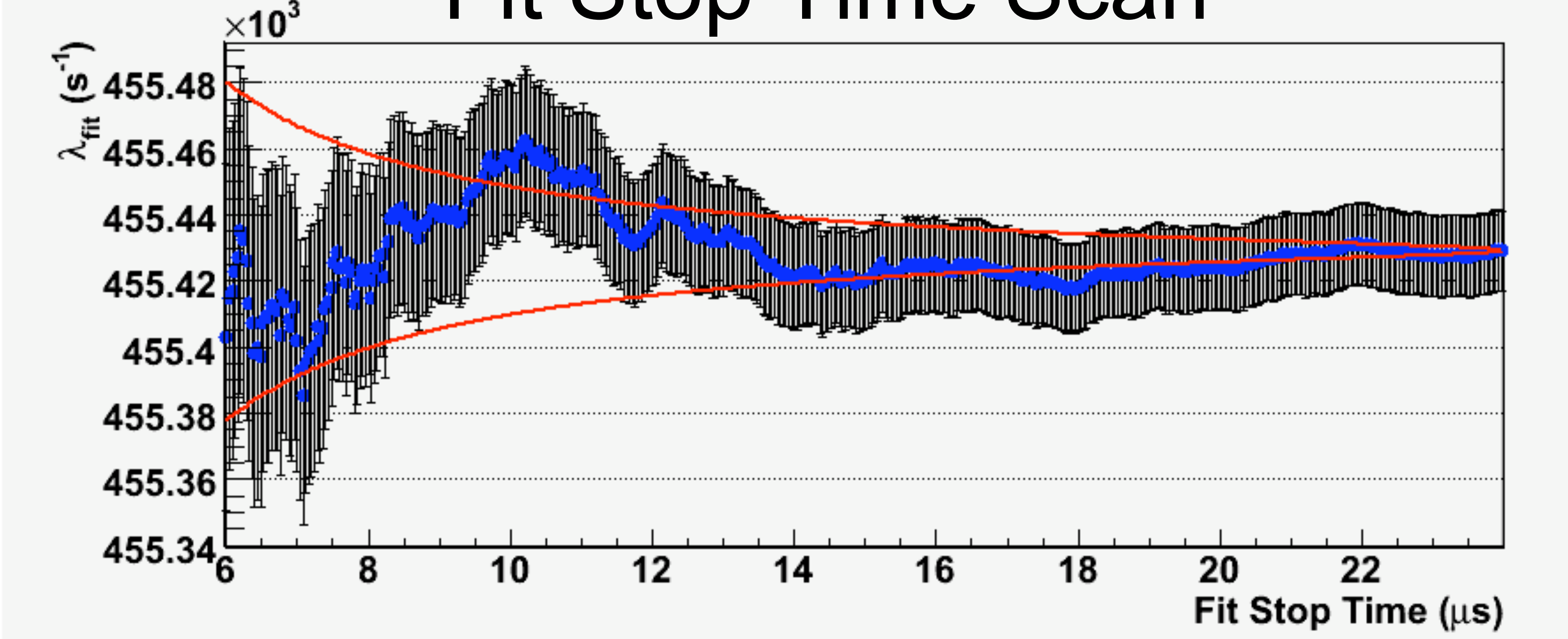
Beam view of MuCap detector

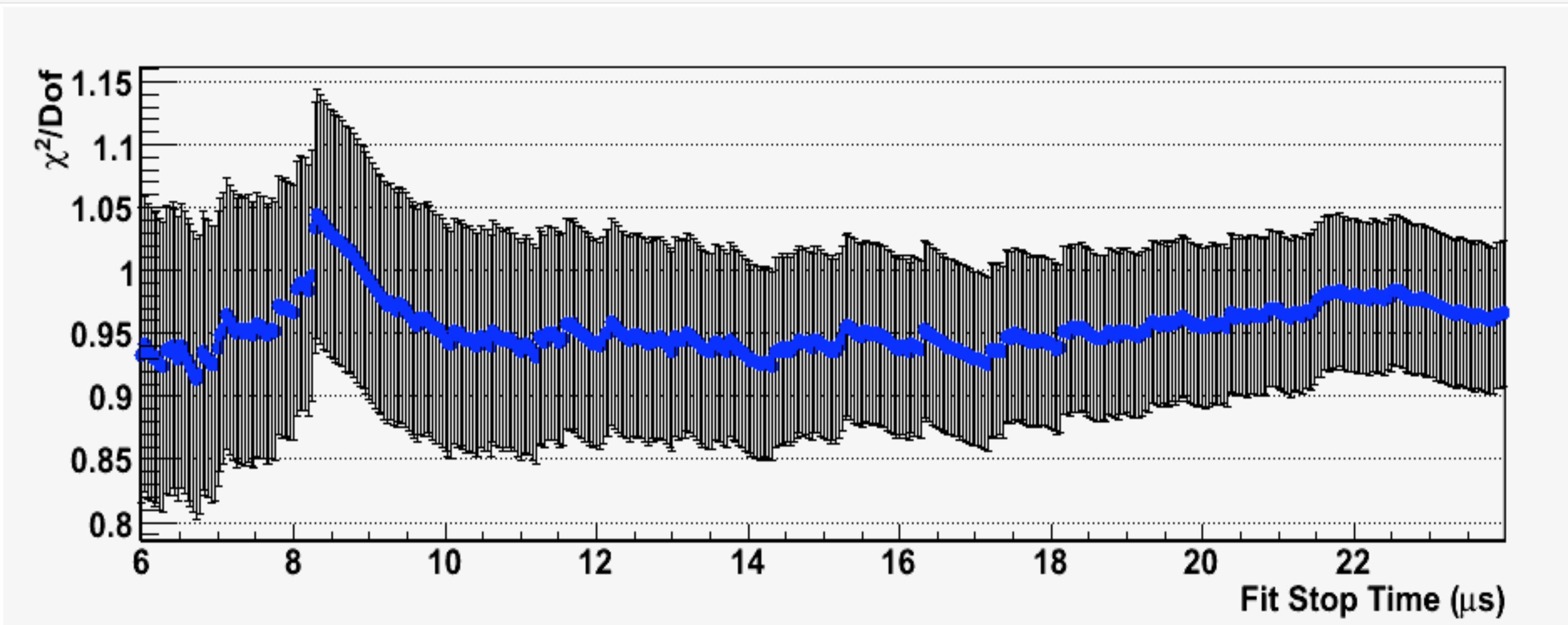
Sum over all segments

Fit Start Time Scan



Fit Stop Time Scan





Lifetime vs. Chronological Subdivisions