Precision Muon Lifetime Experiments

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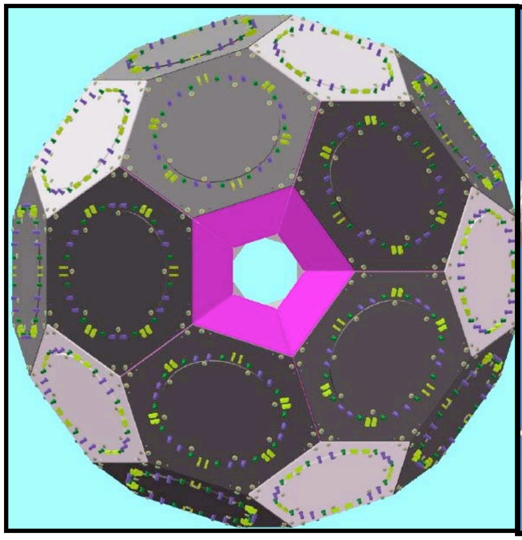
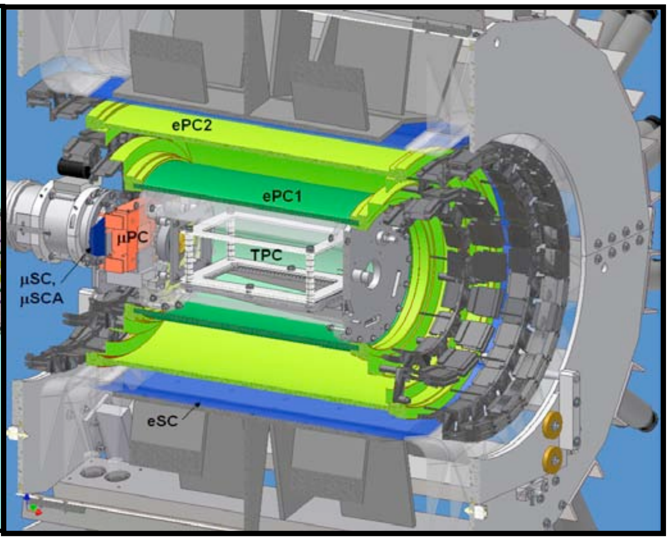
MuLan **MuCap**

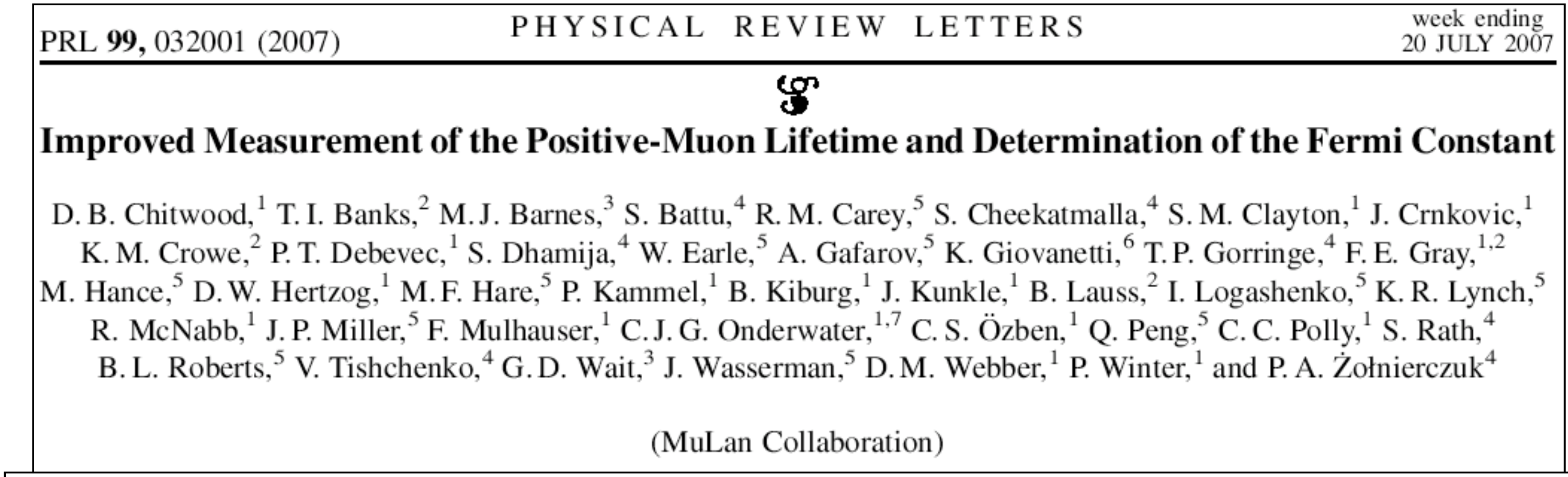
G_F





g_P

May 7, 2008, LANL Seminar



PRL **99,** 032001 (2007) PHYSICAL REVIEW LETTERS week ending 20 JULY 2007

Improved Measurement of the Positive-Muon Lifetime and Determination of the Fermi Constant

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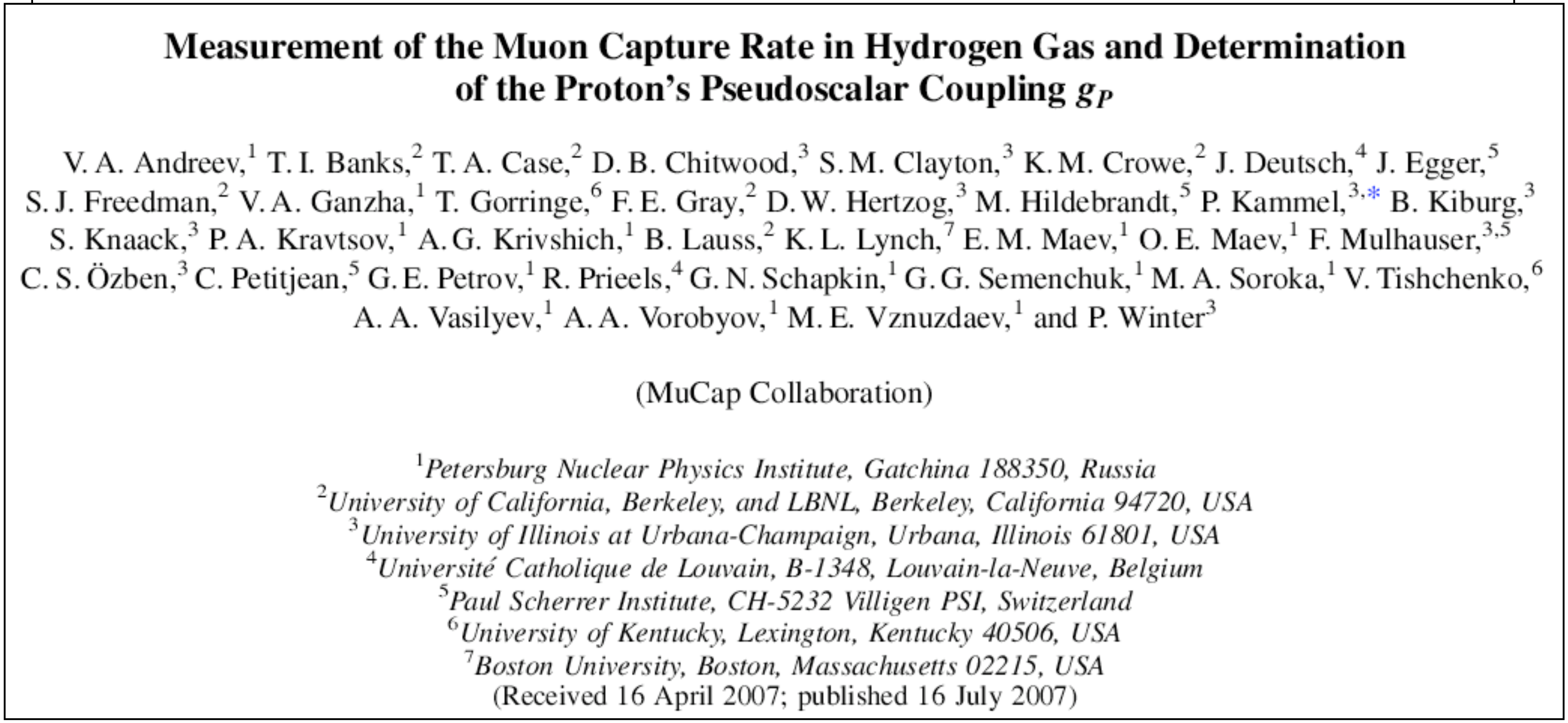
(MuLan Collaboration)



Measurement of the Muon Capture Rate in Hydrogen Gas and Determination of the Proton's Pseudoscalar Coupling g_P

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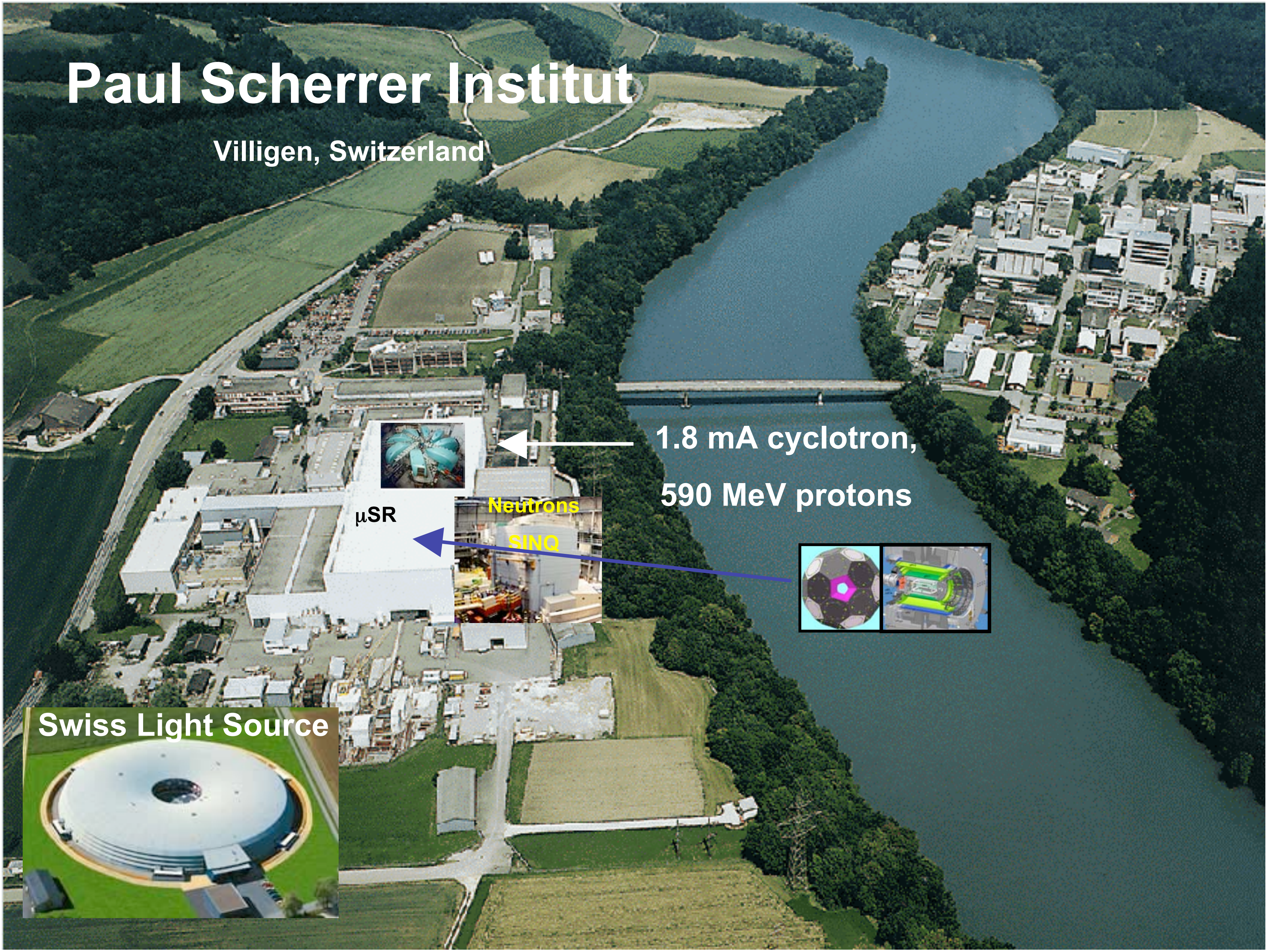
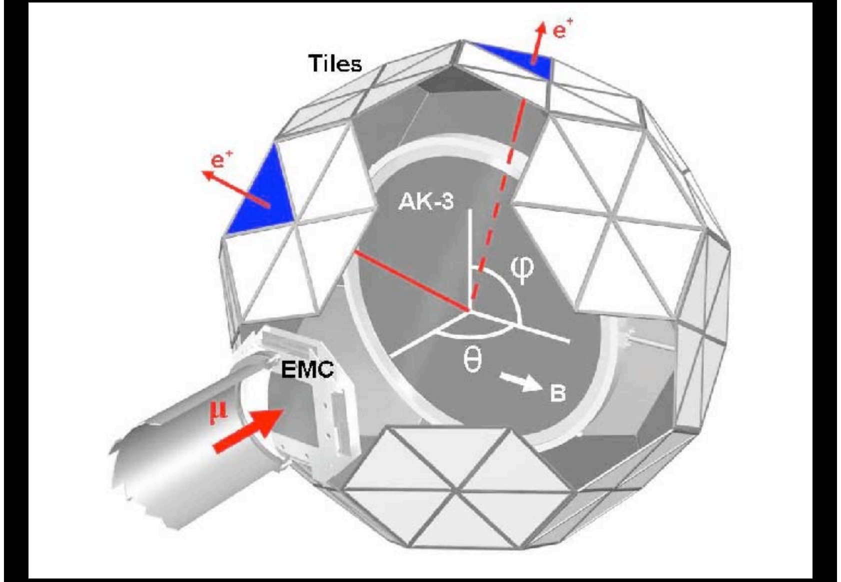


MuLan: Muon Lifetime Analysis

$$\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu}_\mu$$

Lifetime $\tau_{\mu+}$



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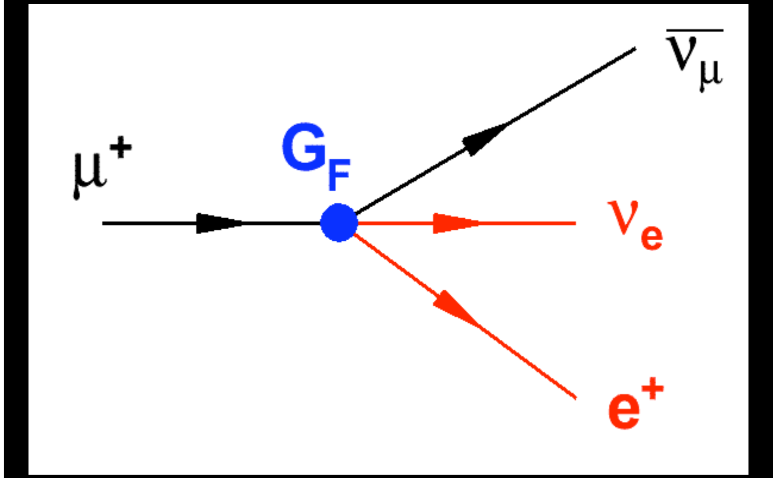
Fermi constant G_F



Muon Lifetime

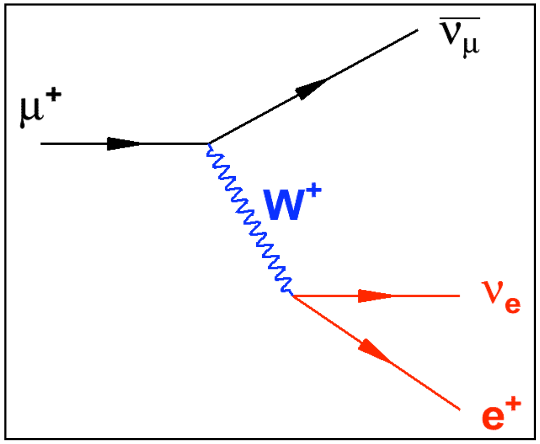
- Fundamental electro-weak couplings

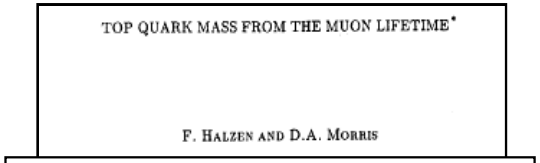
G_F	α	M_Z
9 ppm	**0.0007 ppm**	**23 ppm**

- G_F

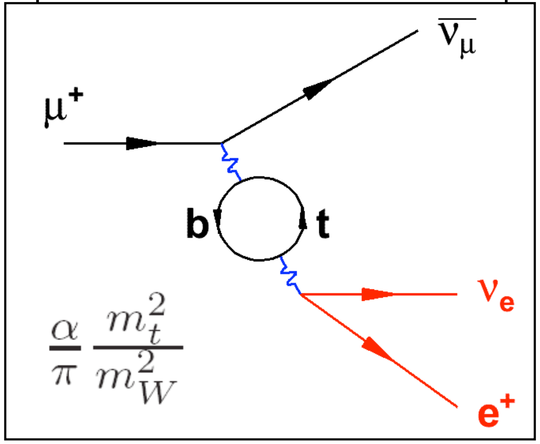
Implicit to all EW precision physics

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}\left(1+\Delta r(m_t, m_H, \ldots)\right)$$




TOP QUARK MASS FROM THE MUON LIFETIME*

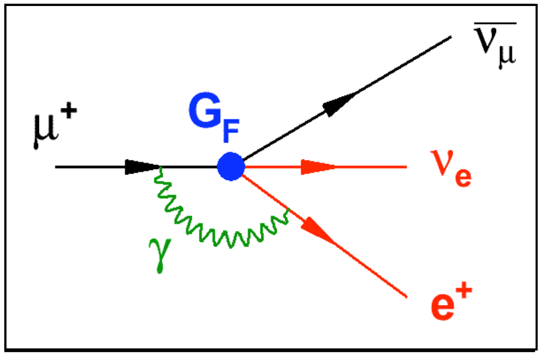
F. HALZEN AND D.A. MORRIS



Uniquely defined by muon decay

$$\frac{1}{\tau_{\mu^+}} = \frac{G_F{}^2 m_\mu^5}{192\pi^3}\left(1+q\right)$$

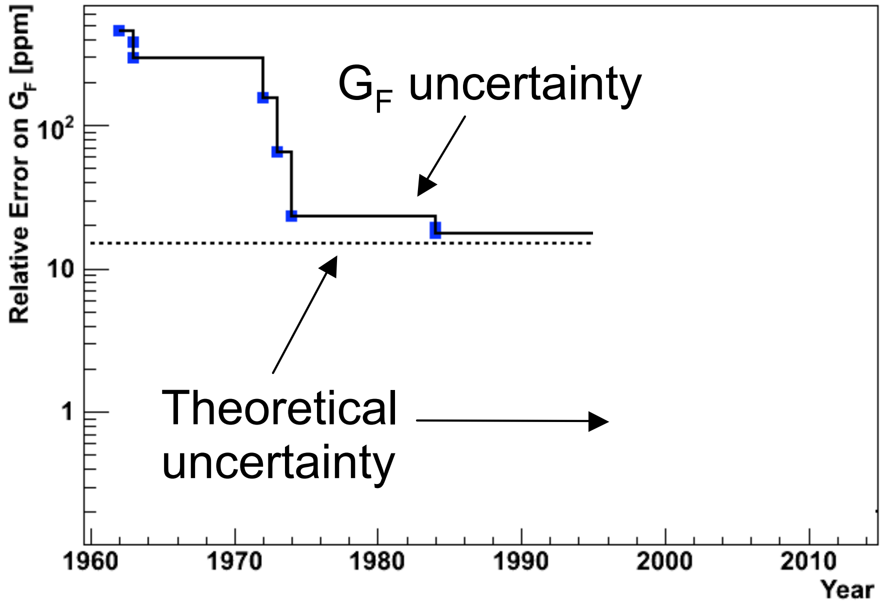
QED



The Standard Model Fermi extraction is no longer theory limited.

$$\frac{\delta G_F}{G_F} = \frac{1}{2}\sqrt{\left(\frac{\delta\tau}{\tau}\right)^2 + \left(5\frac{\delta m_\mu}{m_\mu}\right)^2 + \left(\frac{\delta\Delta q}{\Delta q}\right)^2}$$

Mid 90s:	17 ppm	18 ppm	0.09 ppm	30 ppm
1999:	9 ppm	18 ppm	0.09 ppm	< 0.3 ppm
2007:	5 ppm	9.6 ppm	0.09 ppm	< 0.3 ppm



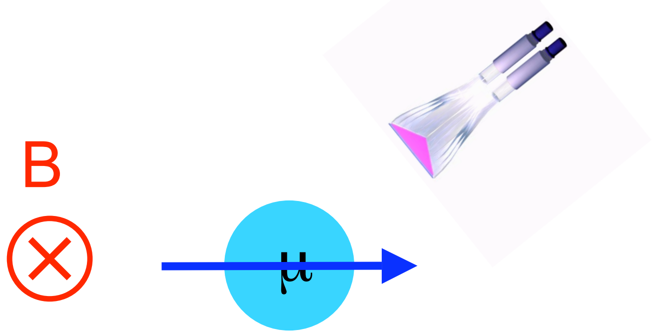
Uncertainty on the muon lifetime error now limits the uncertainty on G_F.

3 exp. efforts: MuLan, FAST, RIKEN-RAL

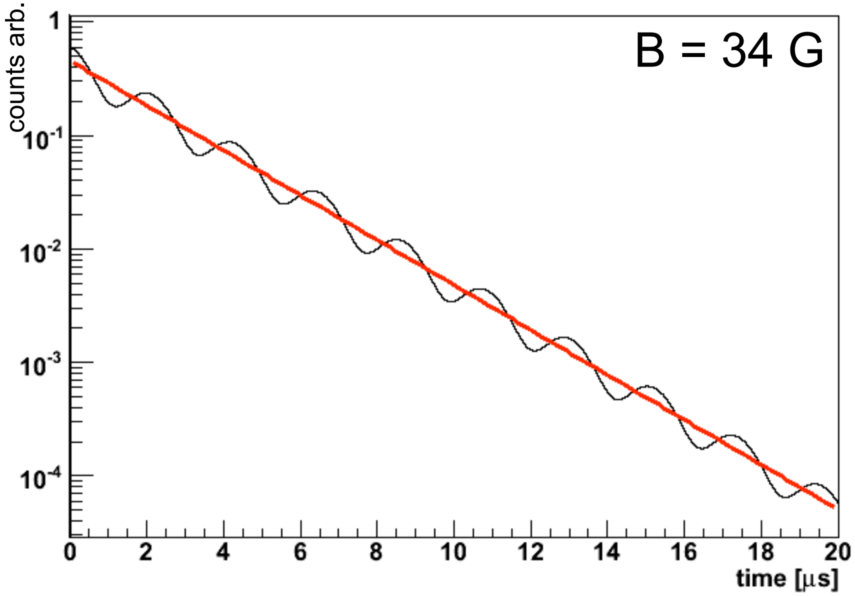
μSR rotation results in an oscillation of the measurement probability for a given detector.

$$\omega = g_\mu \frac{eB}{2m_\mu c}$$

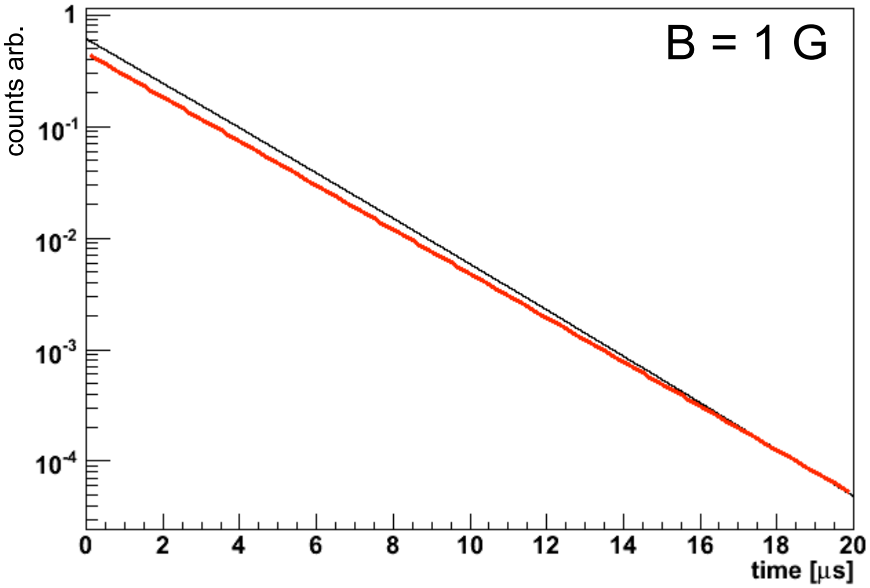
$$g_\mu \approx 2$$



$$N(t) = N_0 \exp(-t/\tau)\left[1 + aP\cos(\omega t + \phi)\right]$$



This oscillation is easily detected

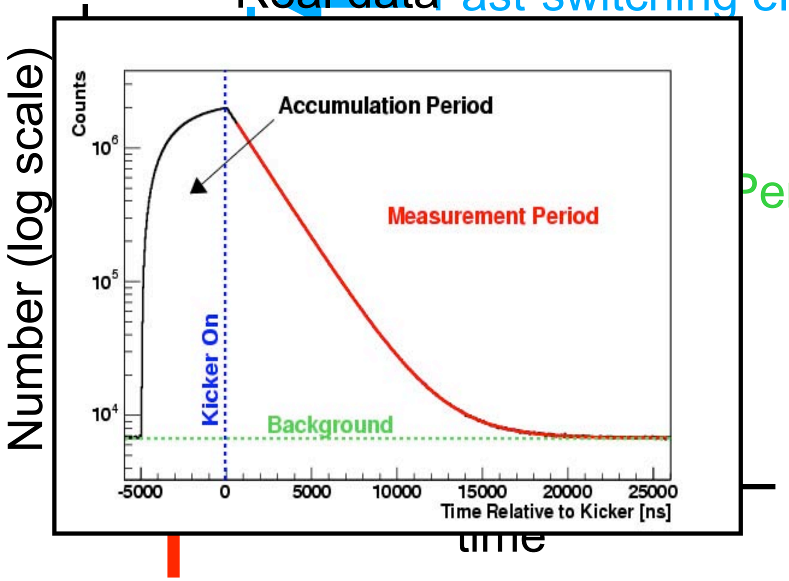


This oscillation is not easily detected and systematic errors may arise

The experimental concept in one animation …

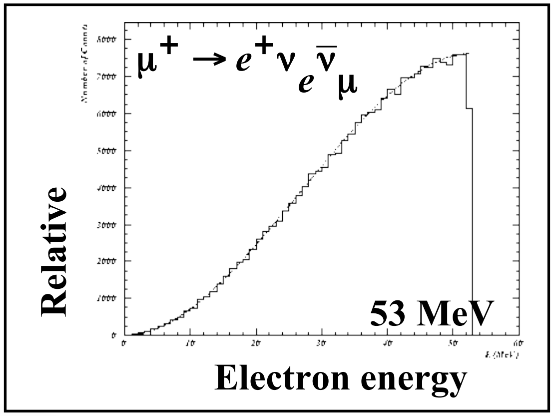
Real data

Fast-switching electric kicker on

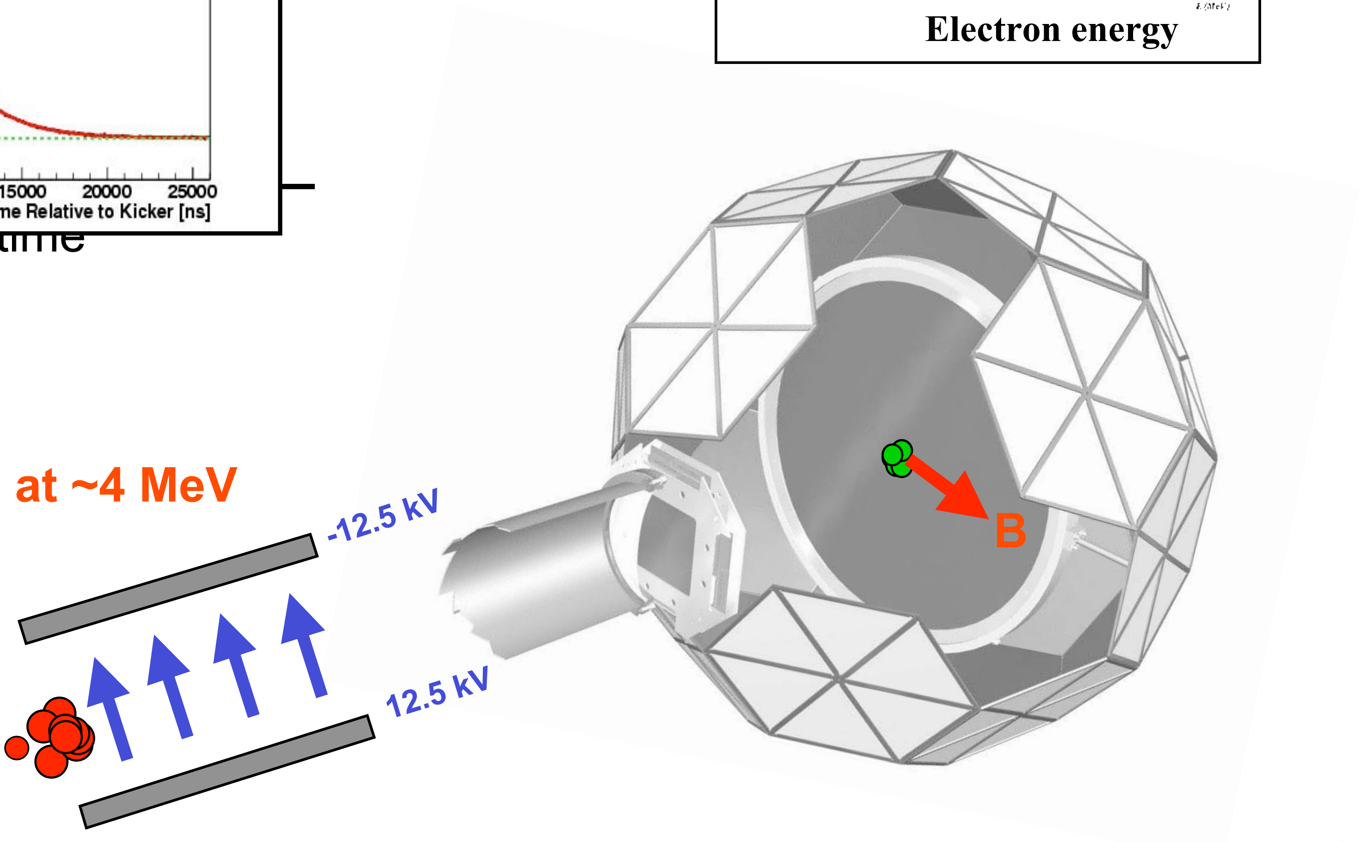


Period

Fill Period

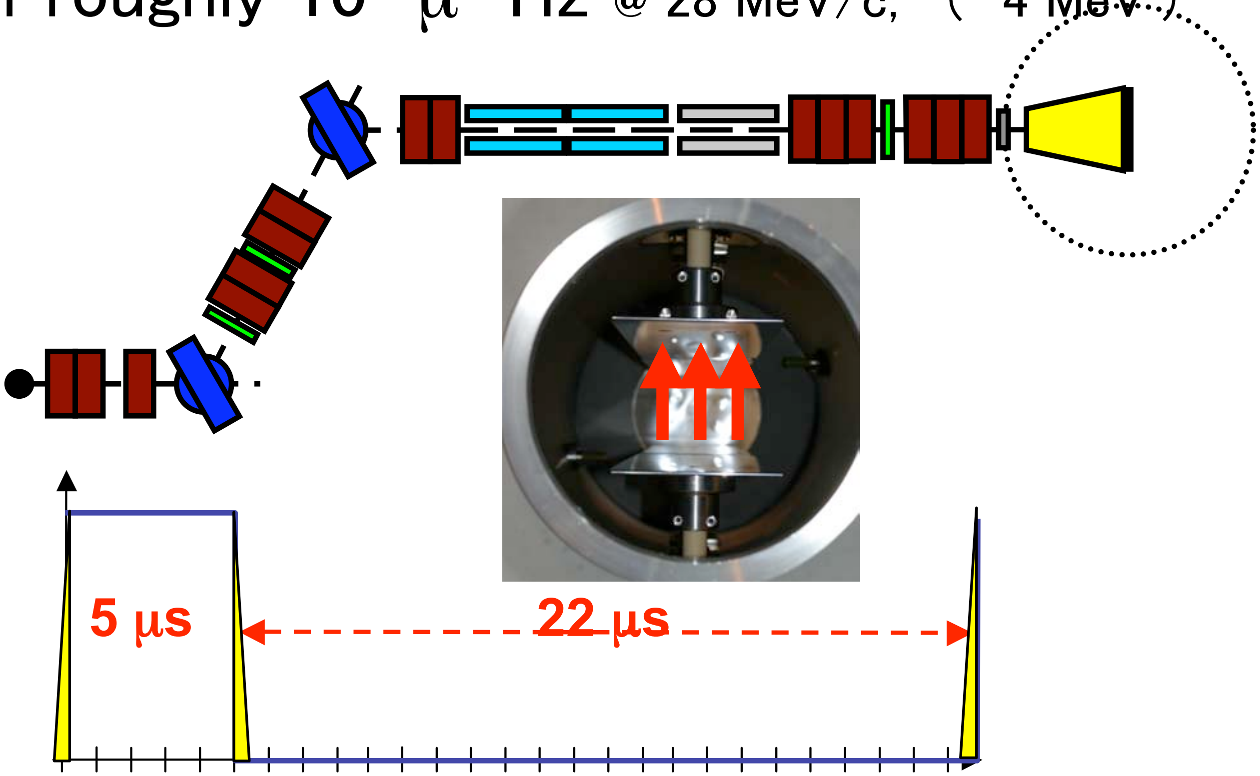


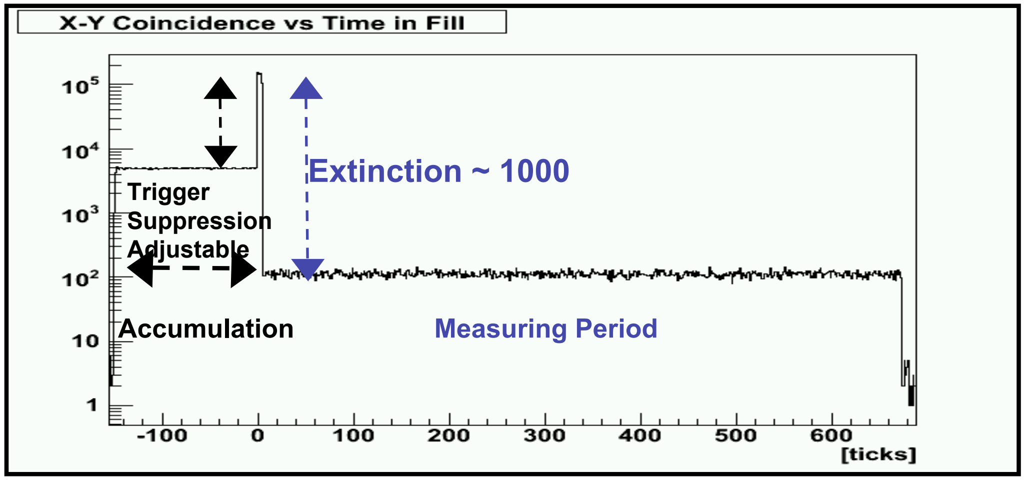
100% polarized muons at ~4 MeV

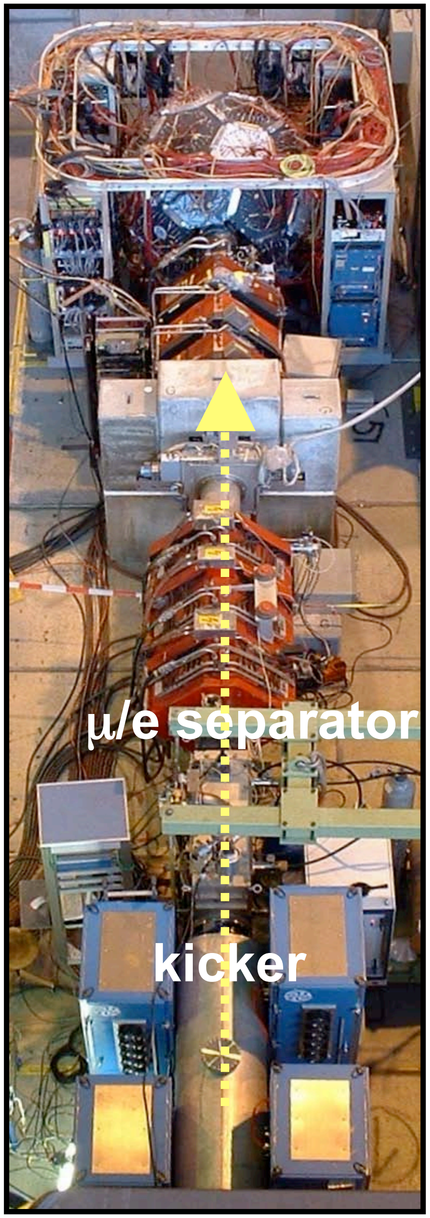


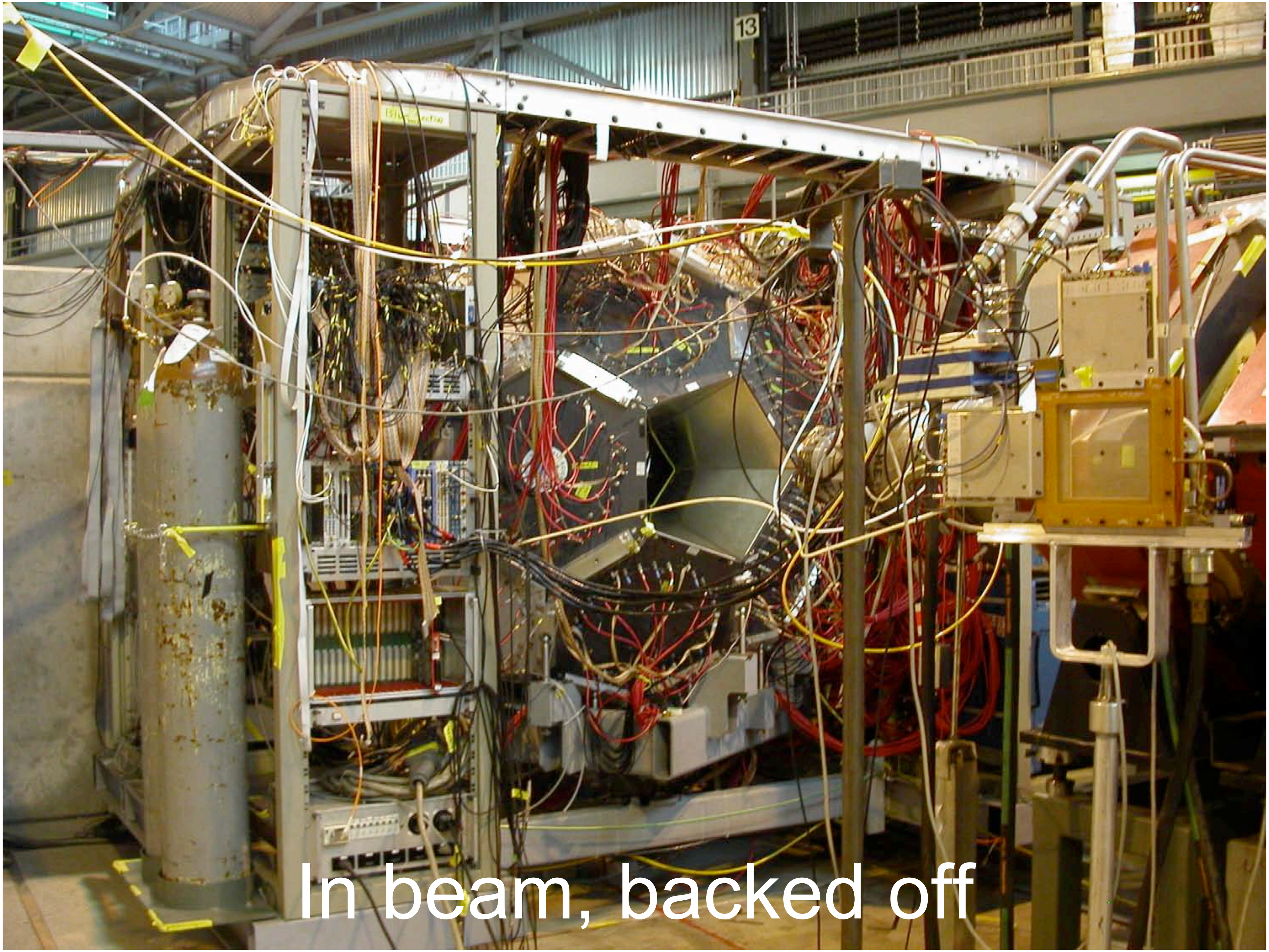
Rapidly precessed here

Create a time-structured “surface” muon beam with flux of roughly 10^7 μ^+ Hz @ 28 MeV/c, (~ 4 MeV)





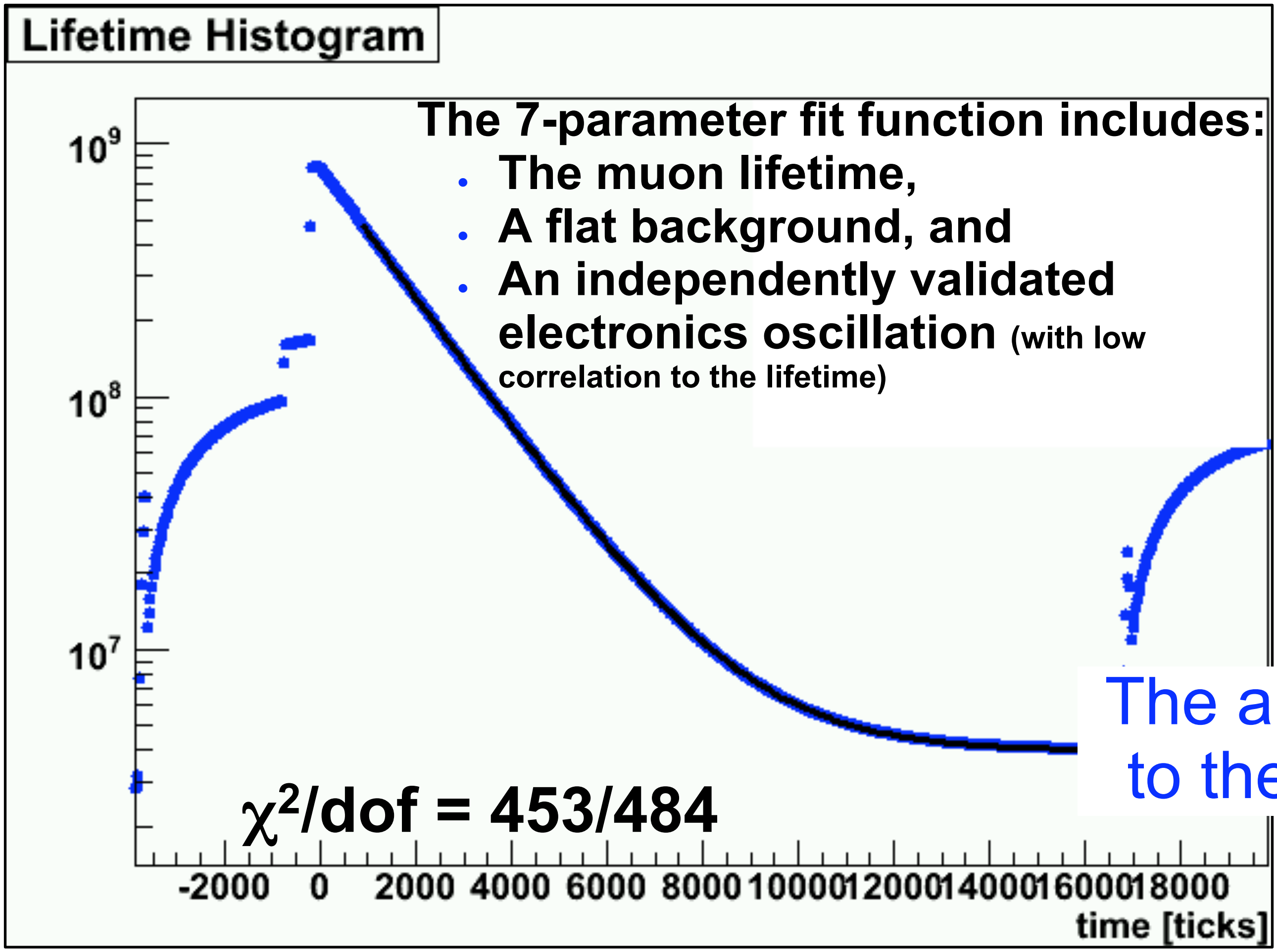




In beam, backed off

2004 Physics Results:

~10 ppm statistical uncertainty



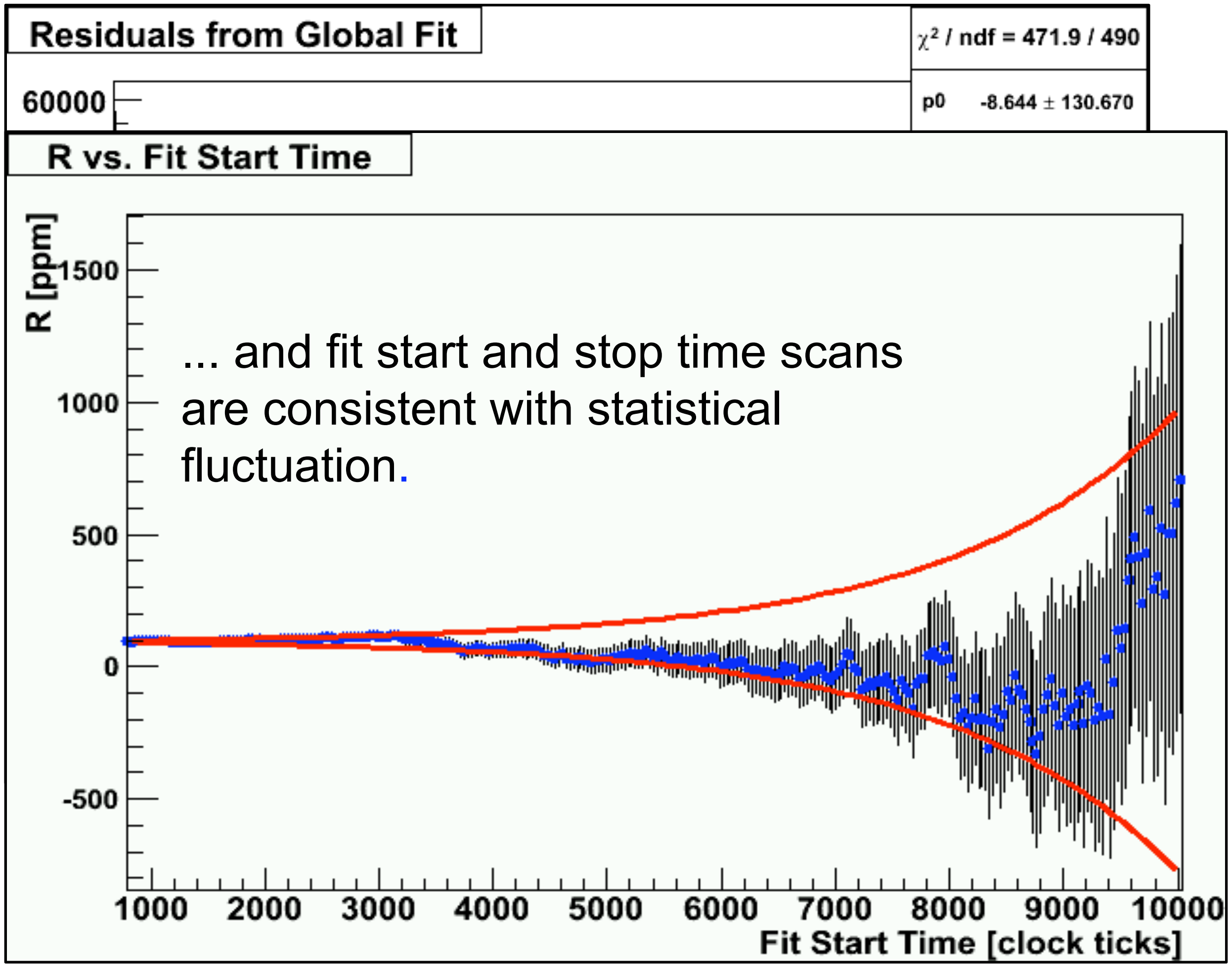
The 7-parameter fit function includes:

- **The muon lifetime,**
- **A flat background, and**
- **An independently validated electronics oscillation** (with low correlation to the lifetime)

χ^2**/dof = 453/484**

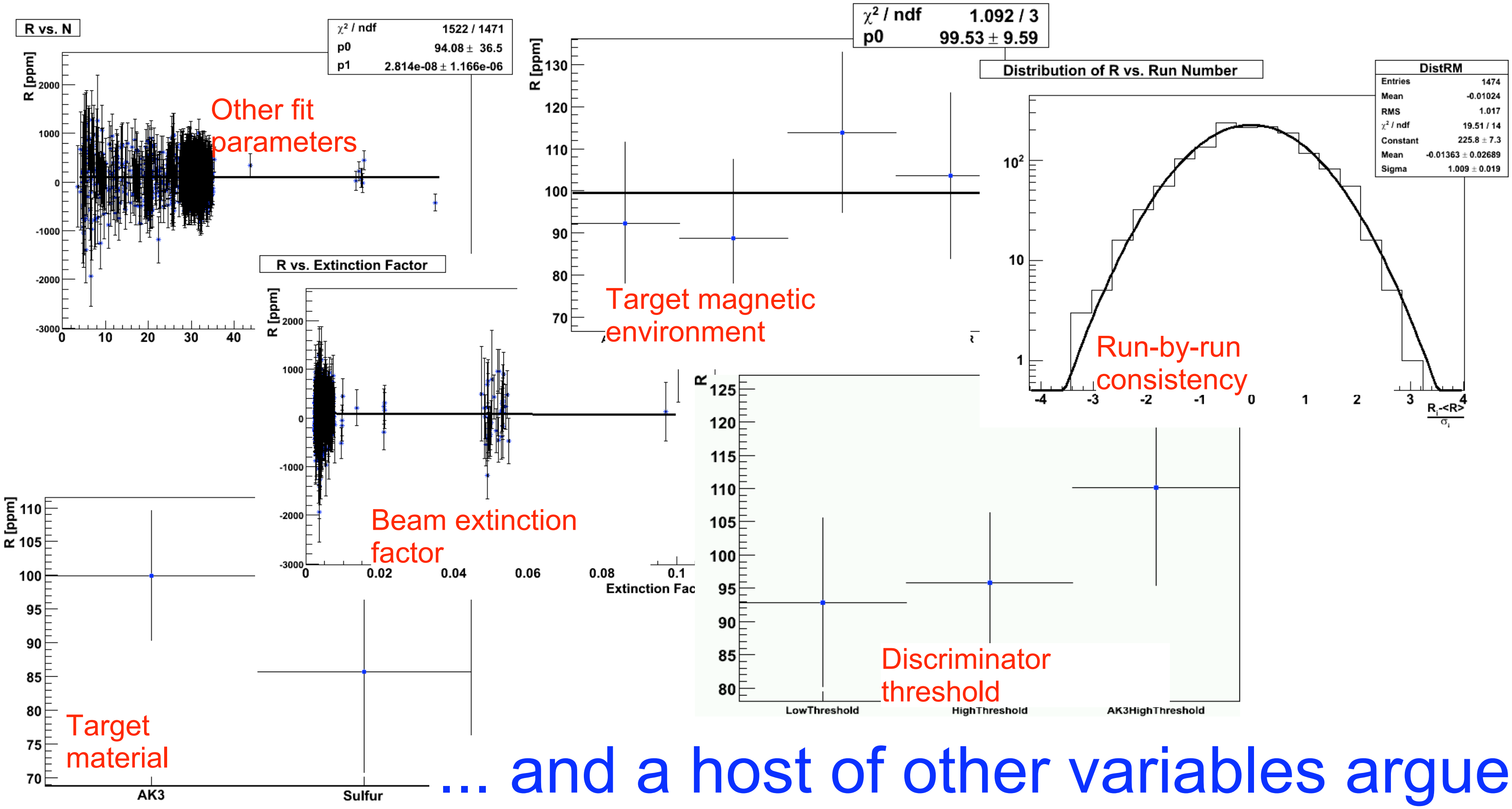
The analyzers are blind to the clock frequency

The fit residuals show no structure...



... and fit start and stop time scans are consistent with statistical fluctuation.

More fit consistency



Other fit parameters

Target magnetic environment

Run-by-run consistency

Beam extinction factor

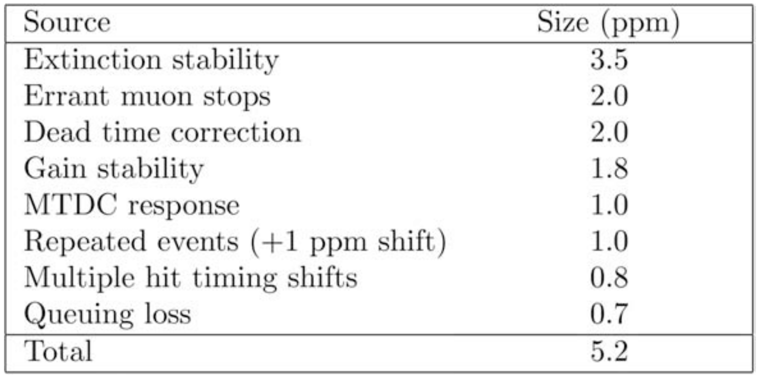
Target material

Discriminator threshold

... and a host of other variables argue for consistency of the global fit.

MuLan

Systematics

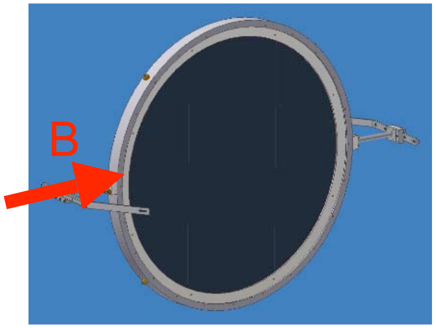


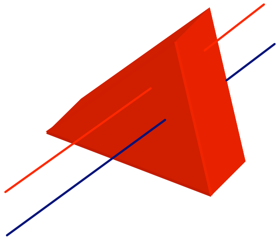
Source	Size (ppm)
Extinction stability	3.5
Errant muon stops	2.0
Dead time correction	2.0
Gain stability	1.8
MTDC response	1.0
Repeated events (+1 ppm shift)	1.0
Multiple hit timing shifts	0.8
Queuing loss	0.7
Total	5.2

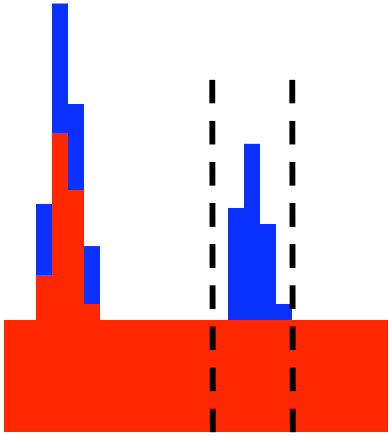
“Early-to-late” changes

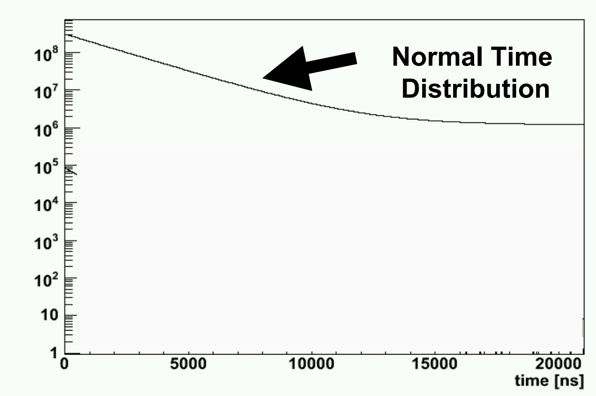
- Instrumental shifts
  - Gain or threshold
  - Time response
  - Kicker and accidentals
- Effective acceptance
  - Residual polarization or precession
  - target: Arnokrome III (AK-3) internal ~4000 G
  - symmetric detector
  - stray muons studied
- Pileup leads to missed events

500 MHz WFD

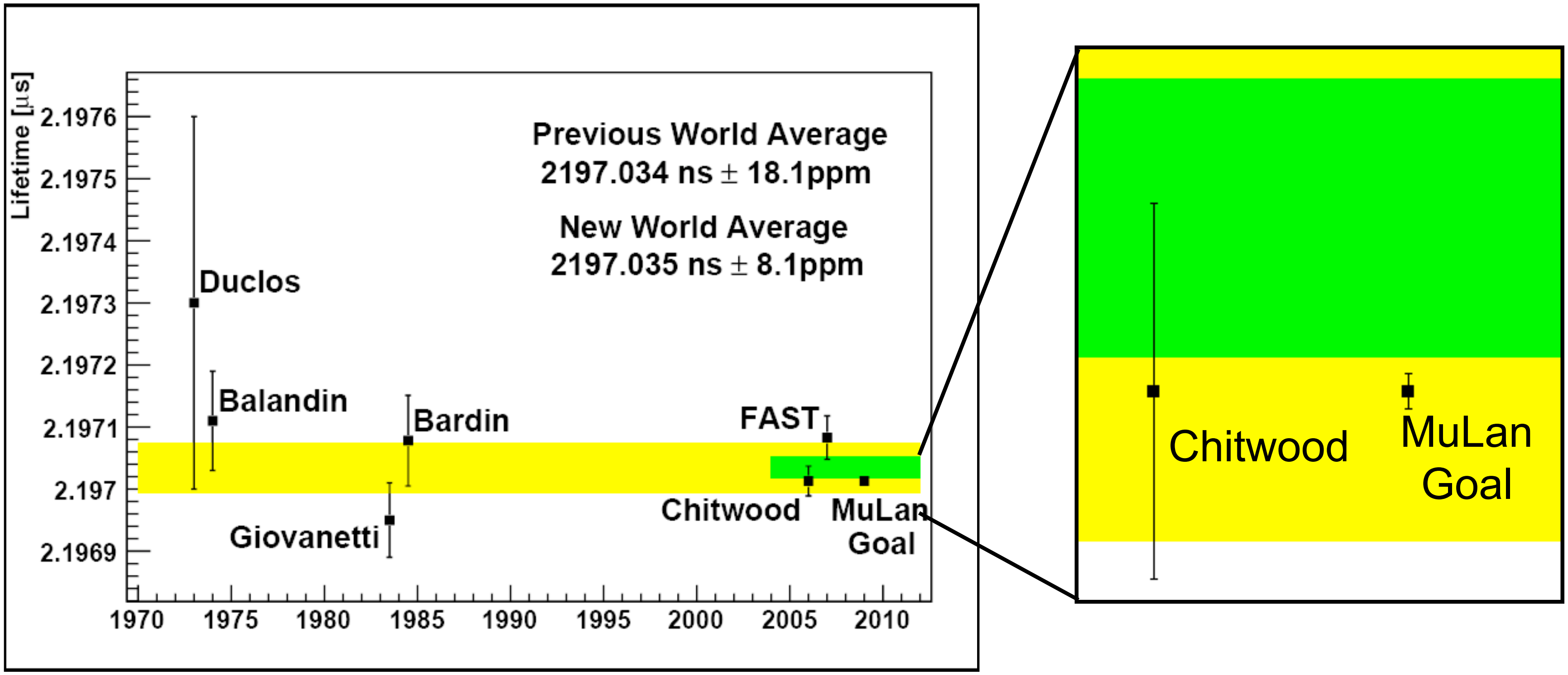








MuLan result from the 2004 Data is in excellent agreement with the world average



G_F = 1.166 371(5) x 10^{-5} GeV^{-2} (4.1 ppm)

MuLan result: τ_μ = 2197.013(21)(11) ns (11.0 ppm)

MuLan goal: 1 ppm uncertainty on τ_μ (0.5 ppm on G_F)

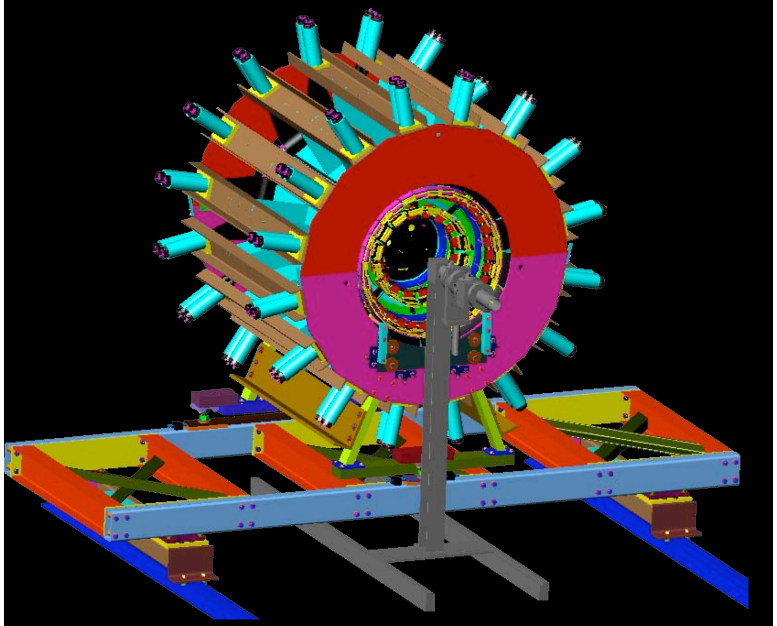
http://arxiv.org/abs/0704.1981

Chitwood *et al.*, Phys. Rev. Lett. 99, 032001 (2007)

First physics from MuCap

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

capture rate Λ_S



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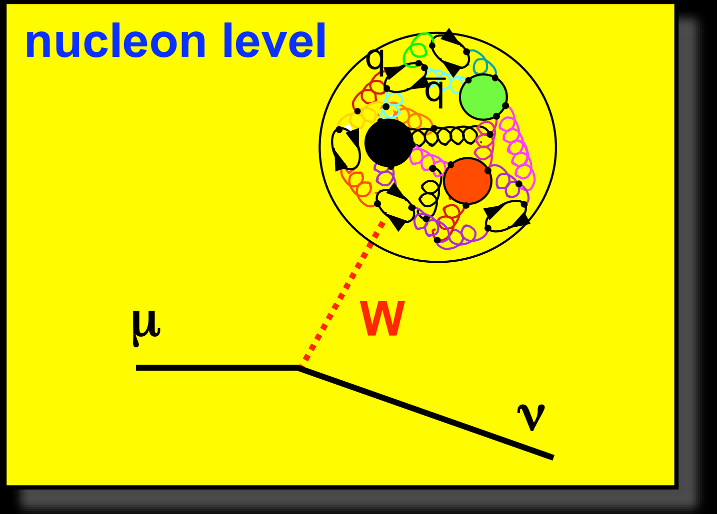
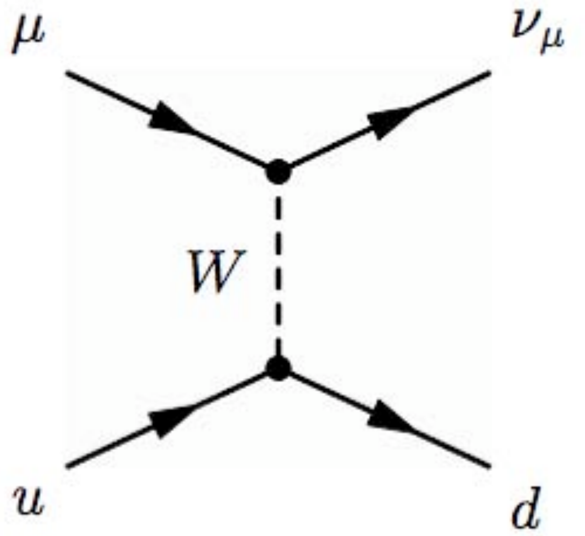
Proton's pseudoscalar form factor g_P



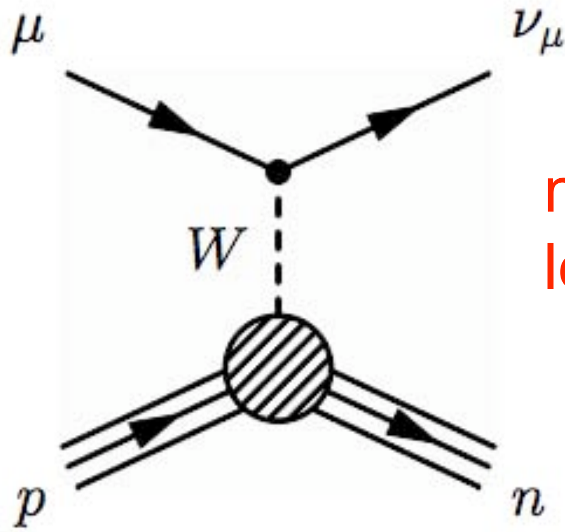
Nucleon Form Factors

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



quark
level

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



nucleon
level

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

$$V^\alpha = \underline{g_v(q^2)}\gamma^\alpha + i\underline{g_m(q^2)}\sigma^{\alpha\beta}\frac{q_\beta}{2M_N} + \underset{= 0}{\underline{\xcancel{g_s(q^2)}}}\frac{q^\alpha}{m_\mu}$$

CVC ← EM FF's

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

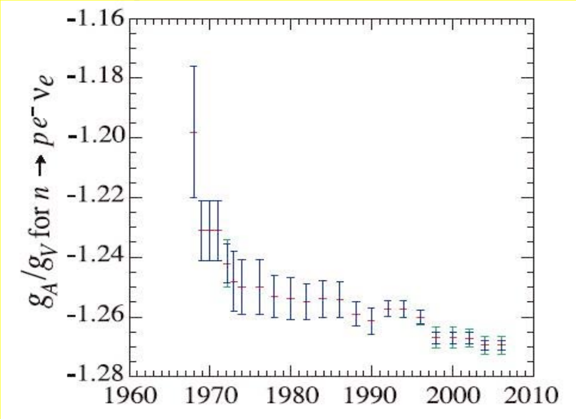
n-decay

G-parity

Axialvector Form Factor g_A

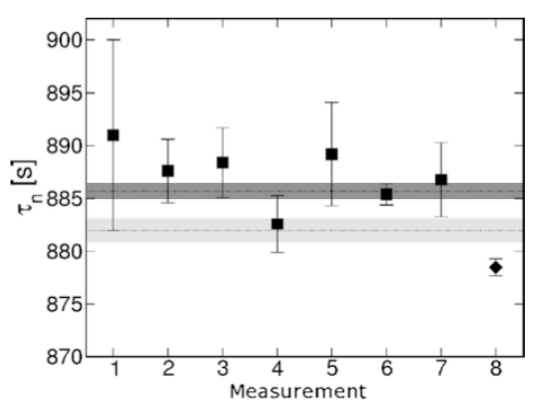
Neutron Decay Experiments

β Asymmetry



PDG 2006

Lifetime



Severijns et al. (2006) RMP

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)

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

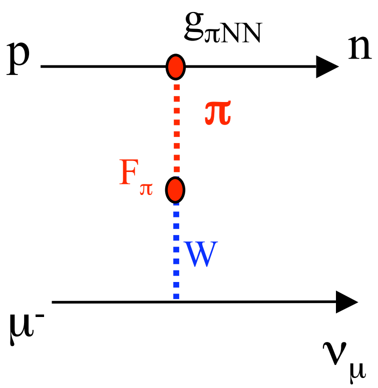
$$g_a(0) = 1.2695 \pm 0.0029$$

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

Introduces 0.45% uncertainty to Λ_S (theory)

Pseudoscalar Form Factor g_p

g_P determined by chiral symmetry of QCD:



$$g_p(q^2) = \frac{2 m_\mu g_{\pi NN}(q^2) F_\pi}{m_\pi^2 - q^2}$$

g_P= (8.74 ± 0.23)

PCAC pole term

ChPT leading order

- **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

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

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 0.45% uncertainty to Λ_S(theory)

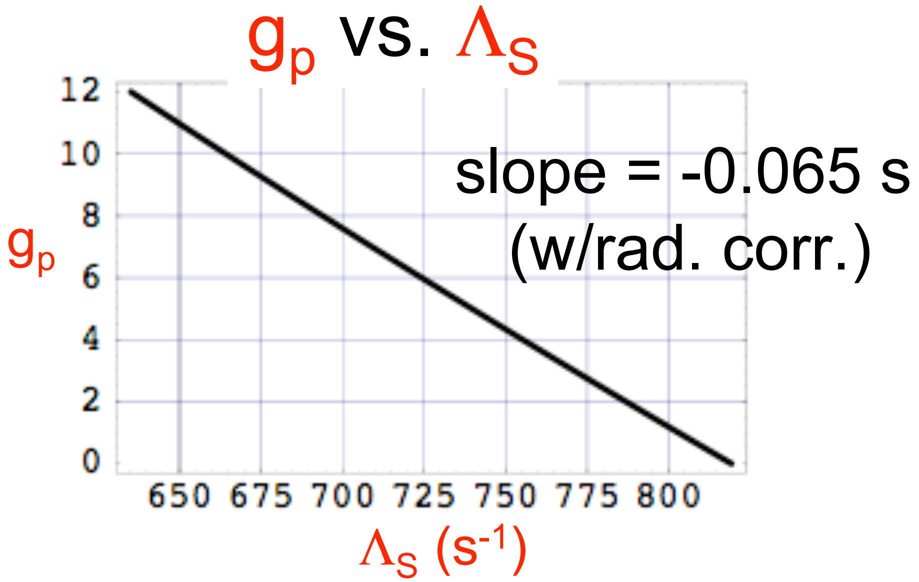
$$\frac{\delta\Lambda_S}{\Lambda_S} \leftrightarrow \frac{\delta g_p}{g_p}$$

Examples:

2.4% ↔ 13.6%

1.0% ↔ 6.1%

0.5% ↔ 3.8%



slope = -0.065 s
(w/rad. corr.)

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

μ^- Stopping in Hydrogen

- 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}

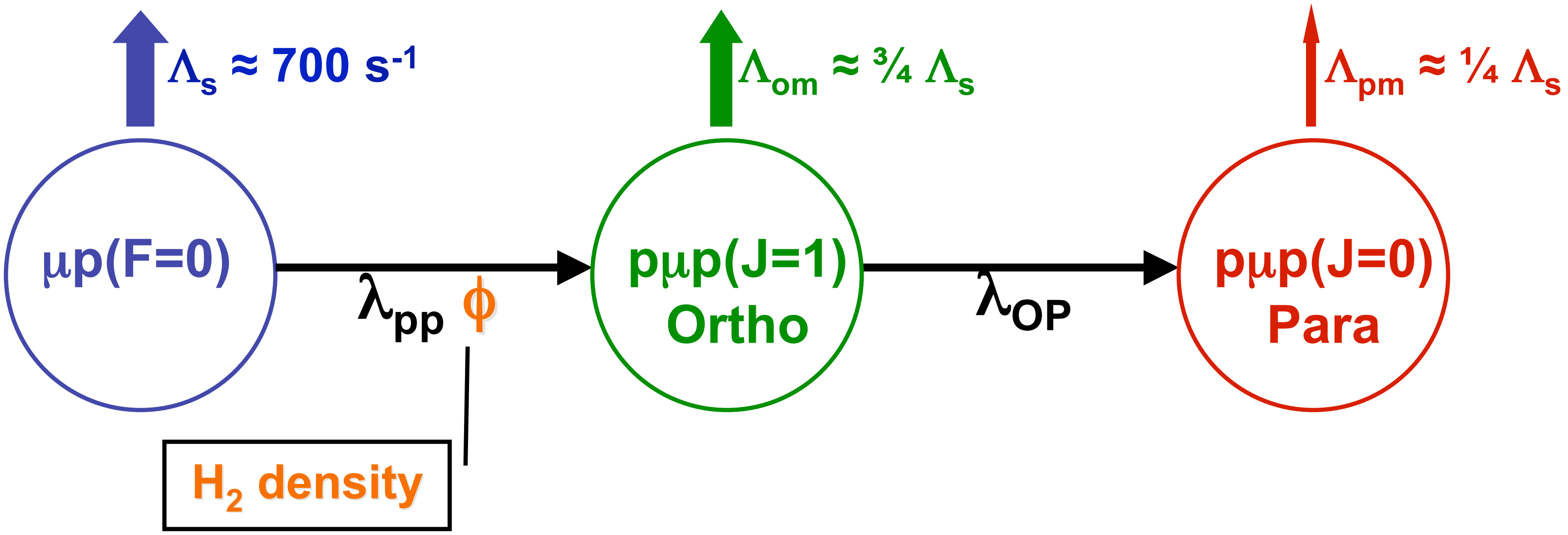
$\mu^- + p \rightarrow \nu_\mu + n + \gamma$ **BR~**10^{-8}**, E>60 MeV**

The goal of μCap is Λ_s to 1% precision:

$$\Lambda_s = \lambda - 1/\tau_{\mu+}$$

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

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



$\Lambda_s \approx 700\ \mathrm{s}^{-1}$

$\Lambda_{om} \approx \frac{3}{4}\ \Lambda_s$

$\Lambda_{pm} \approx \frac{1}{4}\ \Lambda_s$

μp(F=0)

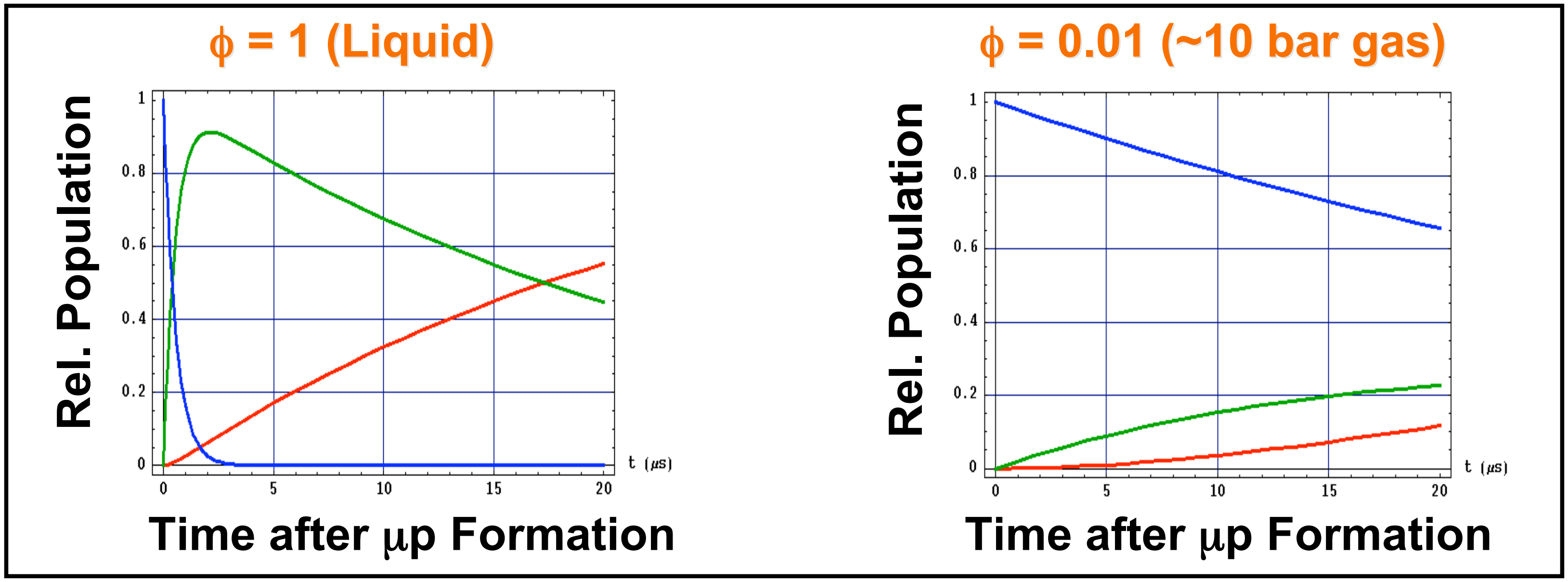
$\lambda_{pp}\ \phi$

pμp(J=1)
Ortho

λ_{OP}

pμp(J=0)
Para

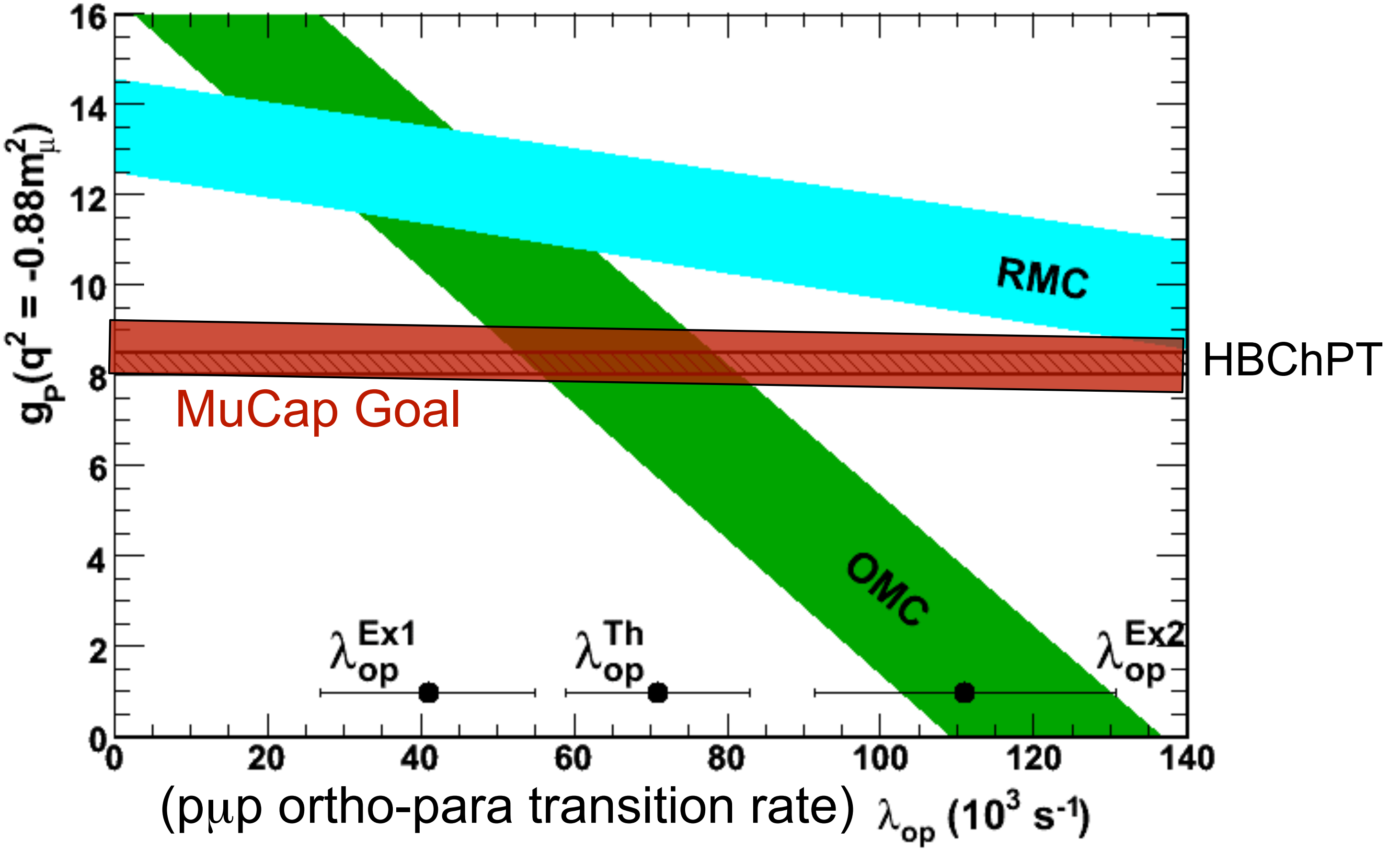
H_2 density



ϕ = 1 (Liquid)

ϕ = 0.01 (~10 bar gas)

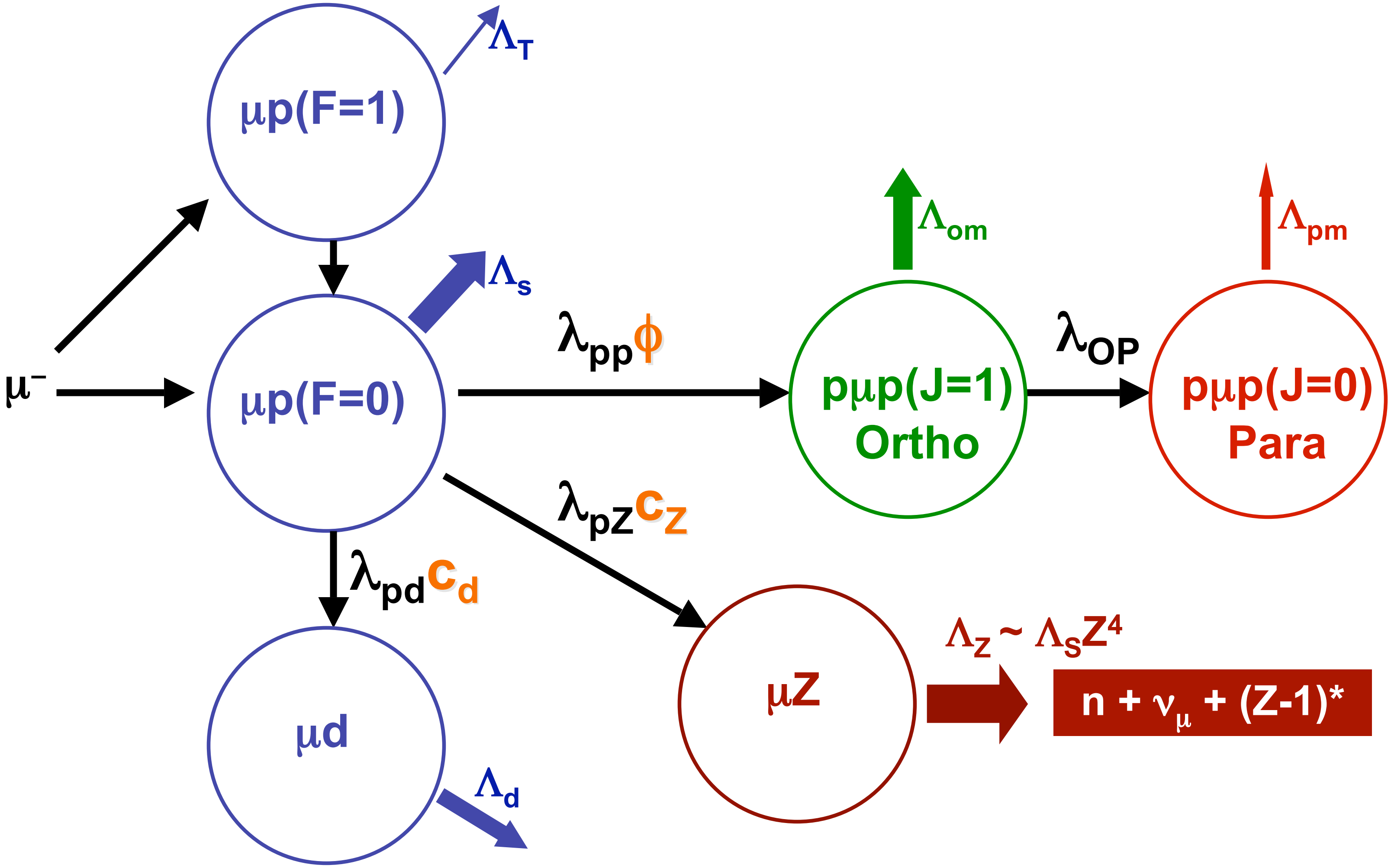
Previous Data on g_p



No common region of overlap between both expts. and theory

g_P basic and experimentally least known weak nucleon form factor

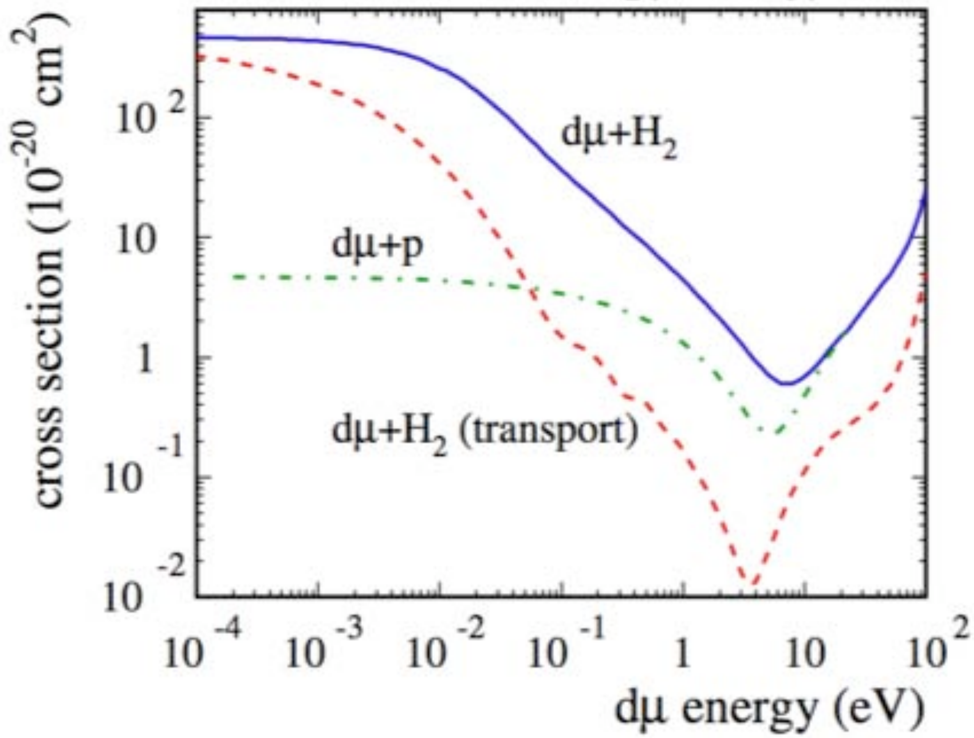
Muon atomic transitions set stringent purity requirements.



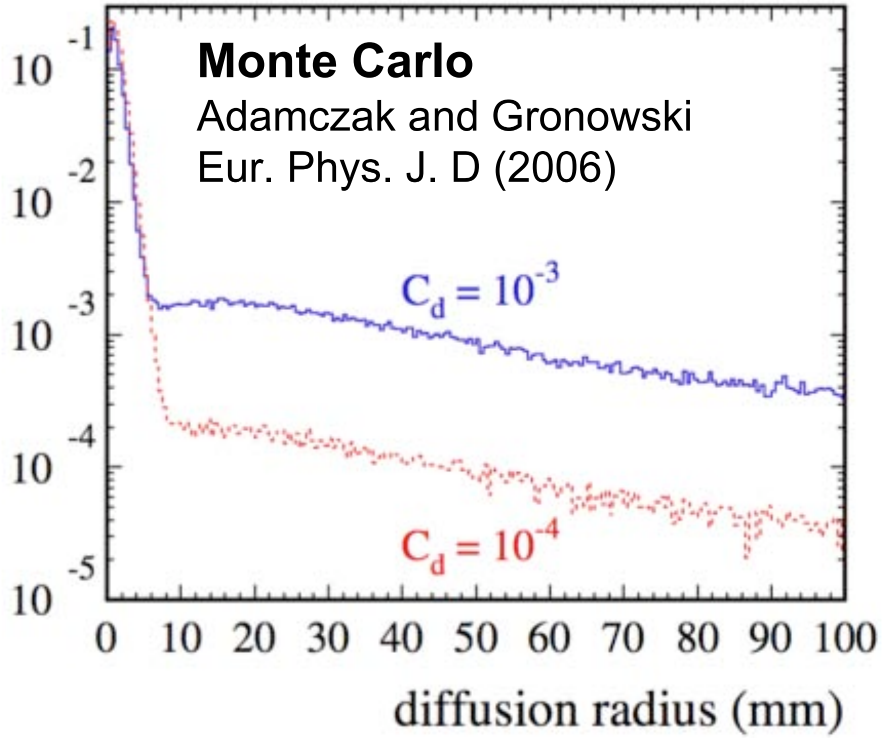
H_2 must be pure isotopically and chemically: c_d < 1 ppm, c_Z < 10 ppb

μd Diffusion into Z > 1 Materials

μd scattering in H_2



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


Monte Carlo

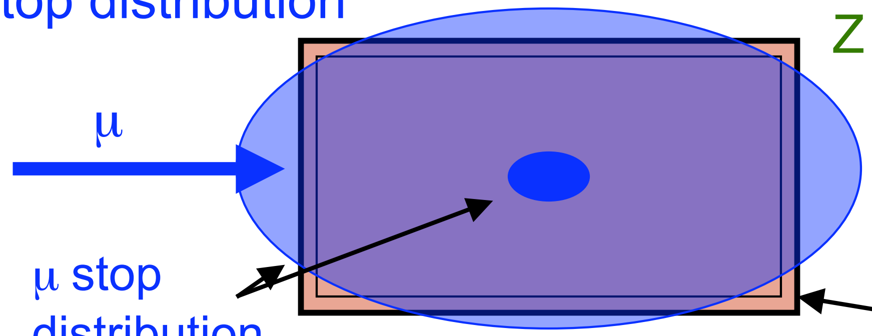
Adamczak and Gronowski
Eur. Phys. J. D (2006)

- Ramsauer-Townsend minimum in the scattering cross section

- μd can diffuse ~10 cm before muon decay, possibly into walls.

Experimental Challenges

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

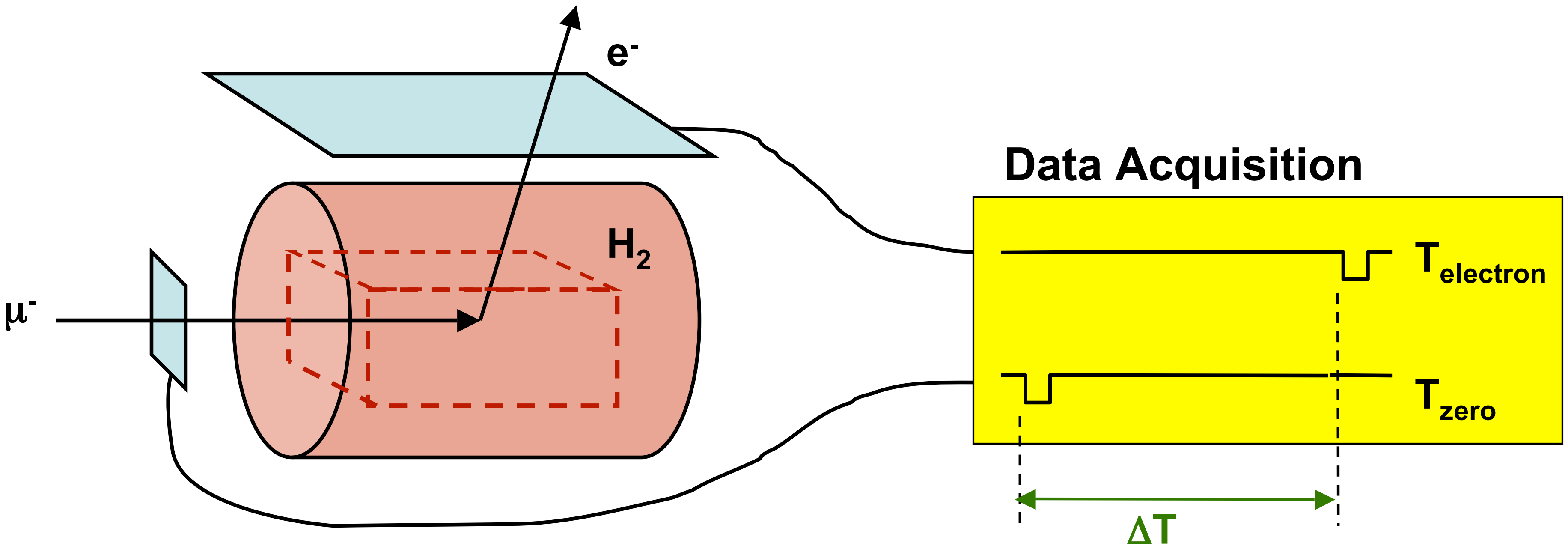


2) H2 must be pure chemically ($c_O, c_N < 10$ ppb) and isotopically ($c_d < 1$ ppm).

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

μCap Method: Lifetime Technique

μCap measures the lifetime of μ^- in 10 bar Hydrogen.

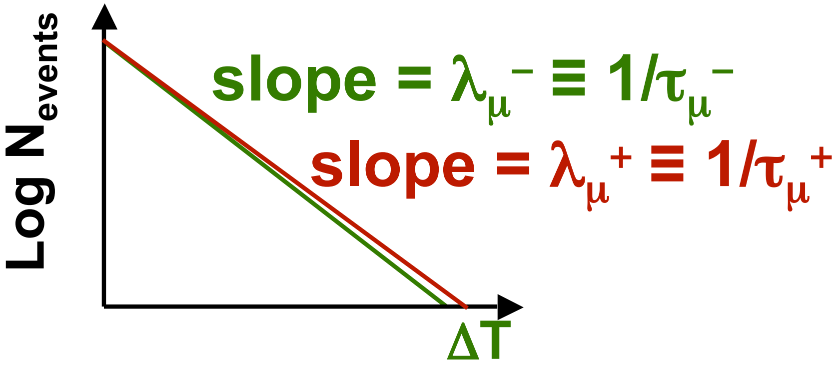


Repeat 10^{10} times for a 10 ppm precision lifetime measurement.

Compare to μ^+ lifetime:

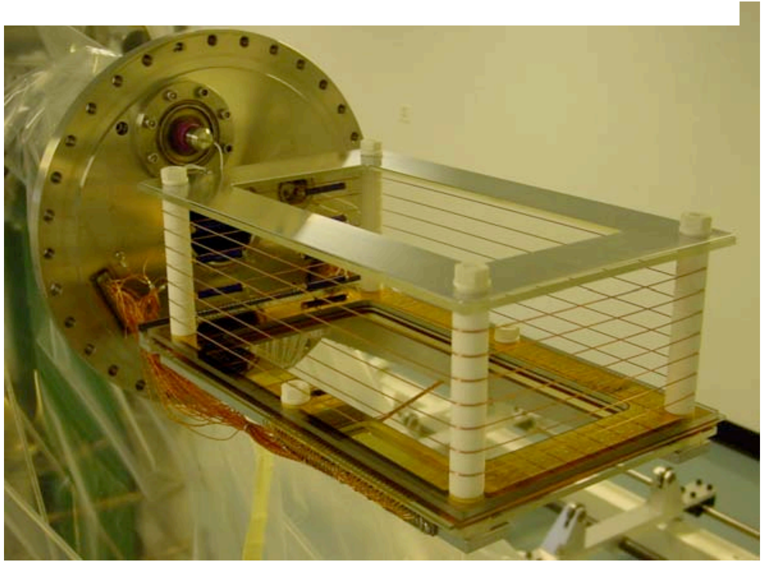
$$\lambda_{\mu^-} \approx \lambda_{\mu^+} + \Lambda_S$$

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

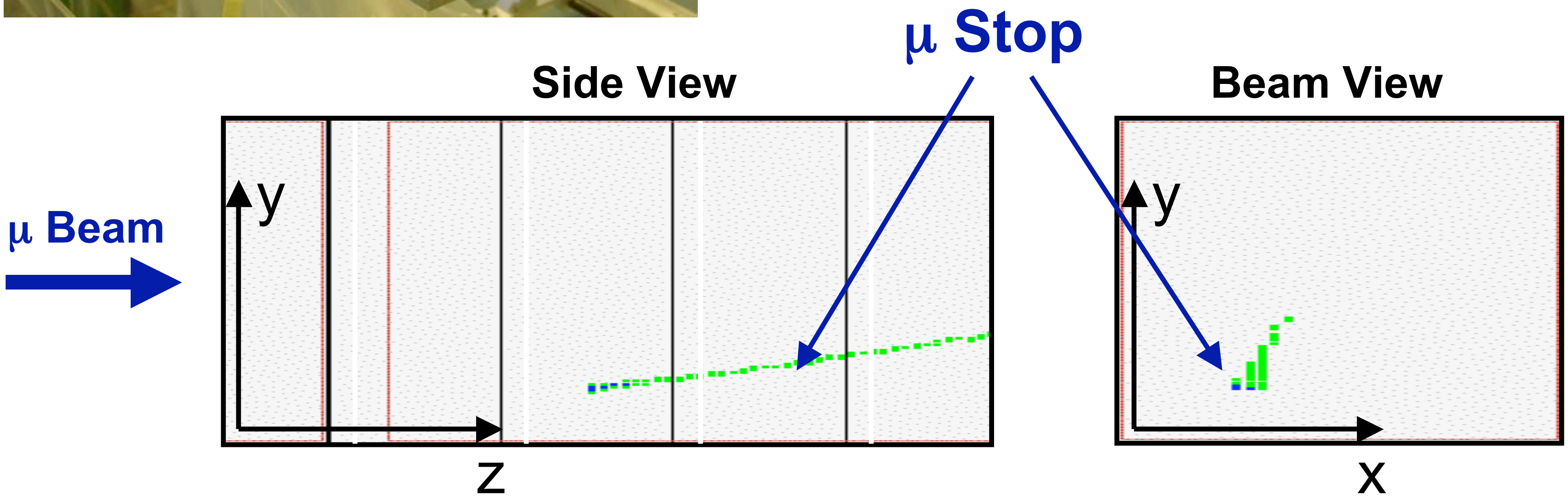


3D tracking w/o material in fiducial volume

Time Projection Chamber (TPC)

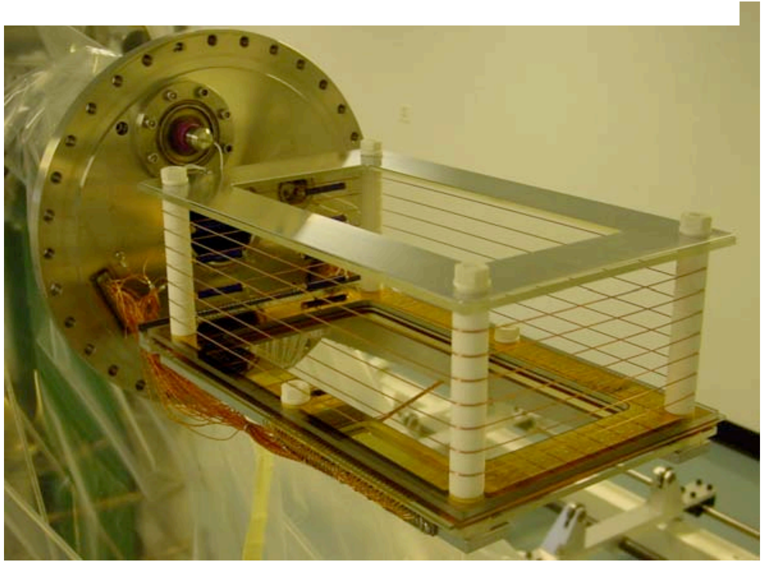


10 bar ultra-pure hydrogen, 1% LH_2
2.0 kV/cm drift field
>5 kV on 3.5 mm anode half gap
bakable glass/ceramic materials



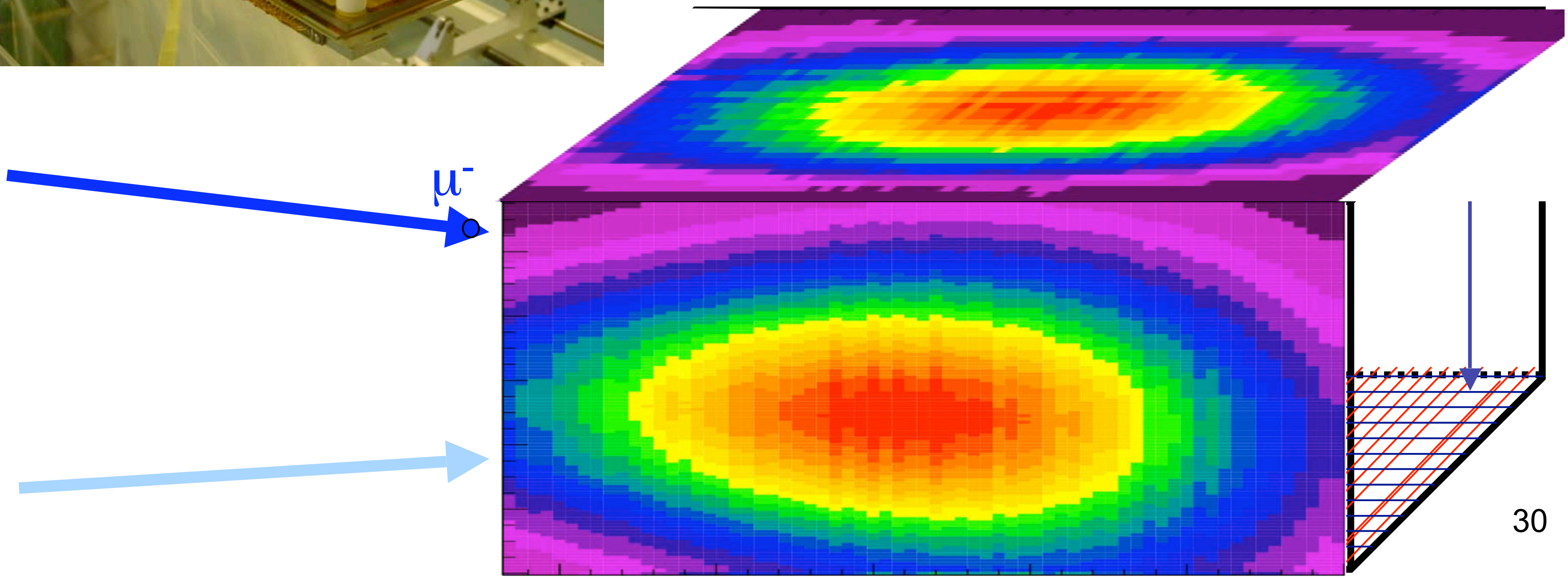
3D tracking w/o material in fiducial volume

Time Projection Chamber (TPC)



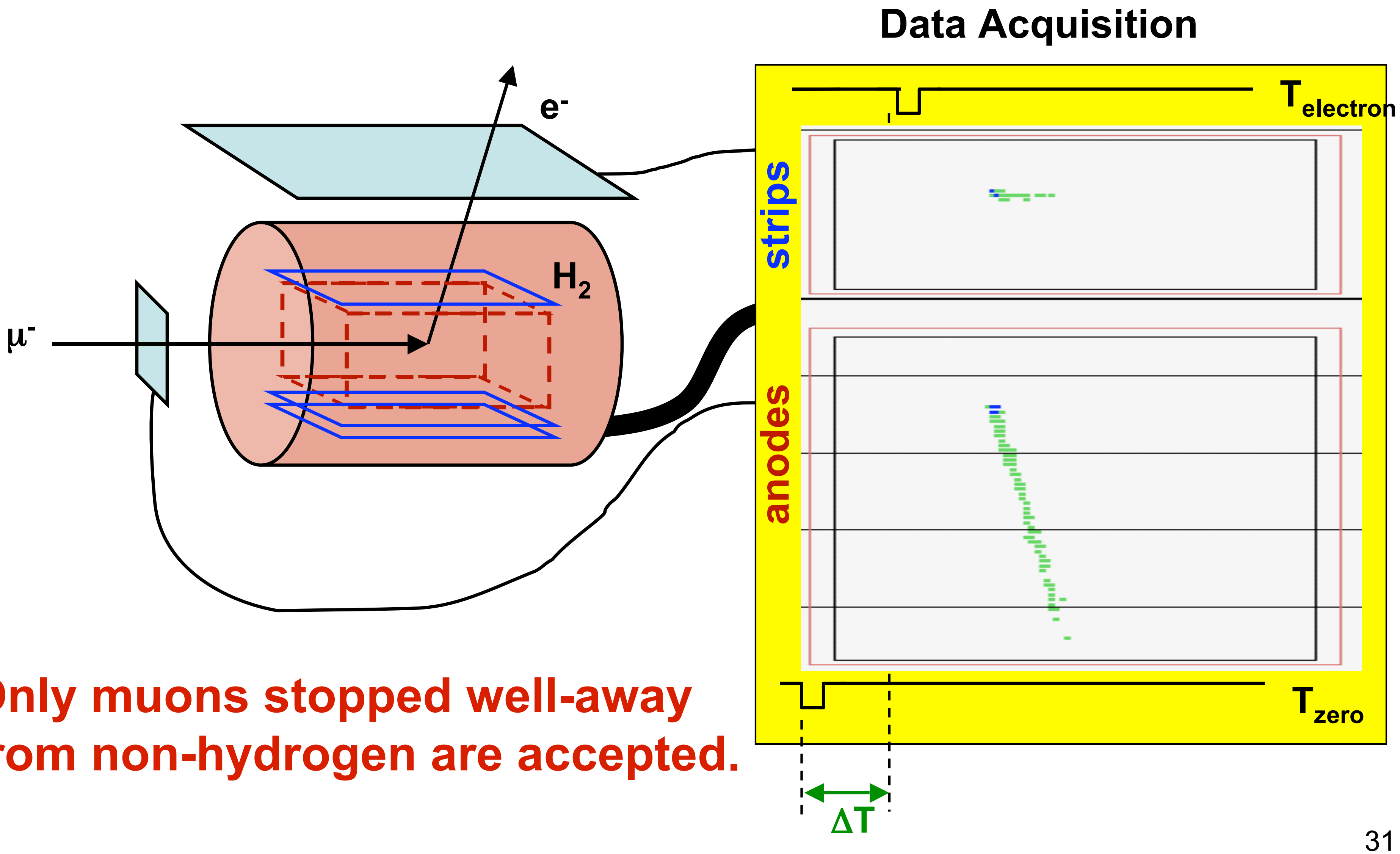
10 bar ultra-pure hydrogen, 1% LH_2
2.0 kV/cm drift field
>5 kV on 3.5 mm anode half gap
bakable glass/ceramic materials

Observed muon stopping distribution



μCap Method: Clean μ Stop Definition

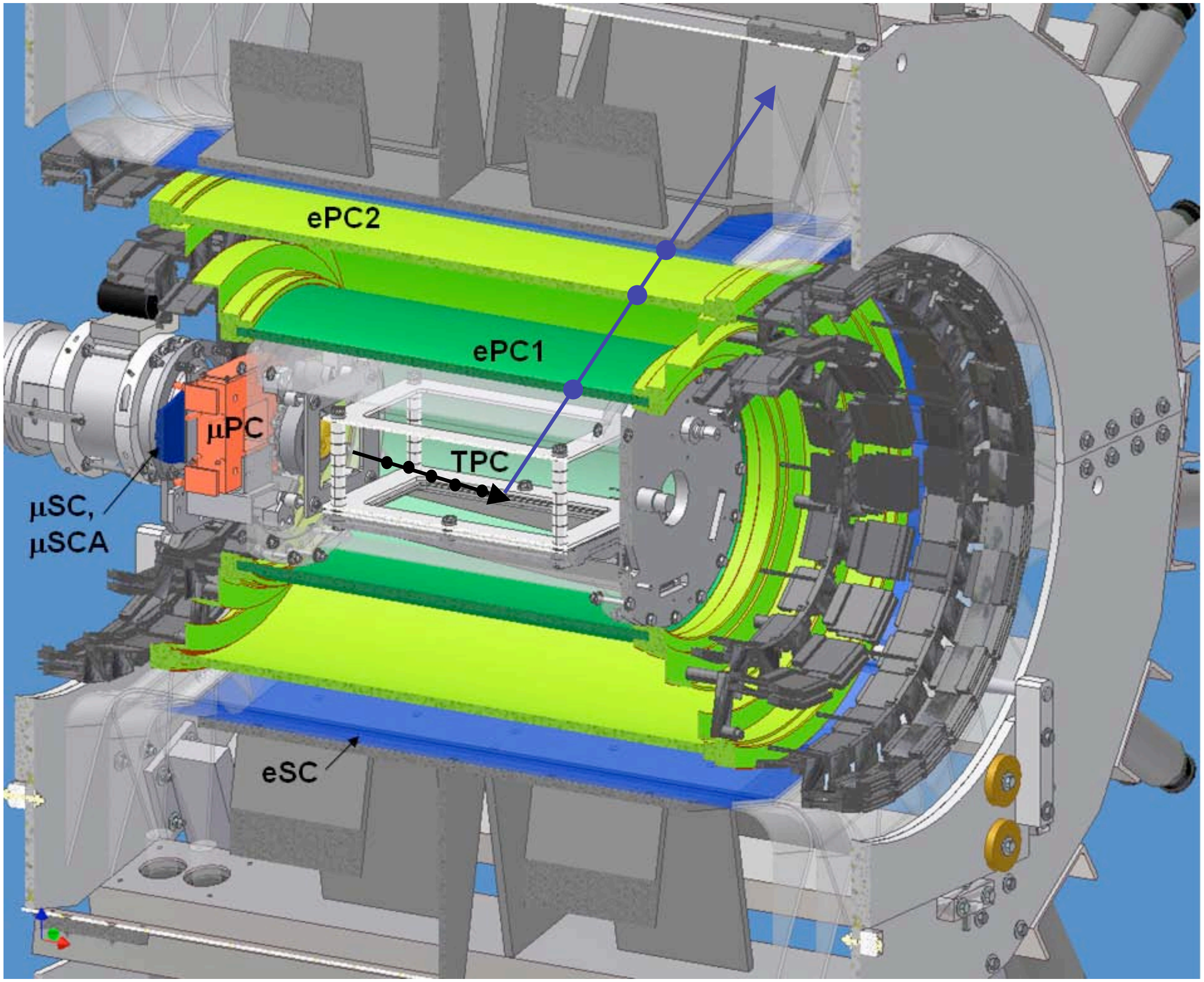
Each muon is tracked in a time projection chamber.



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

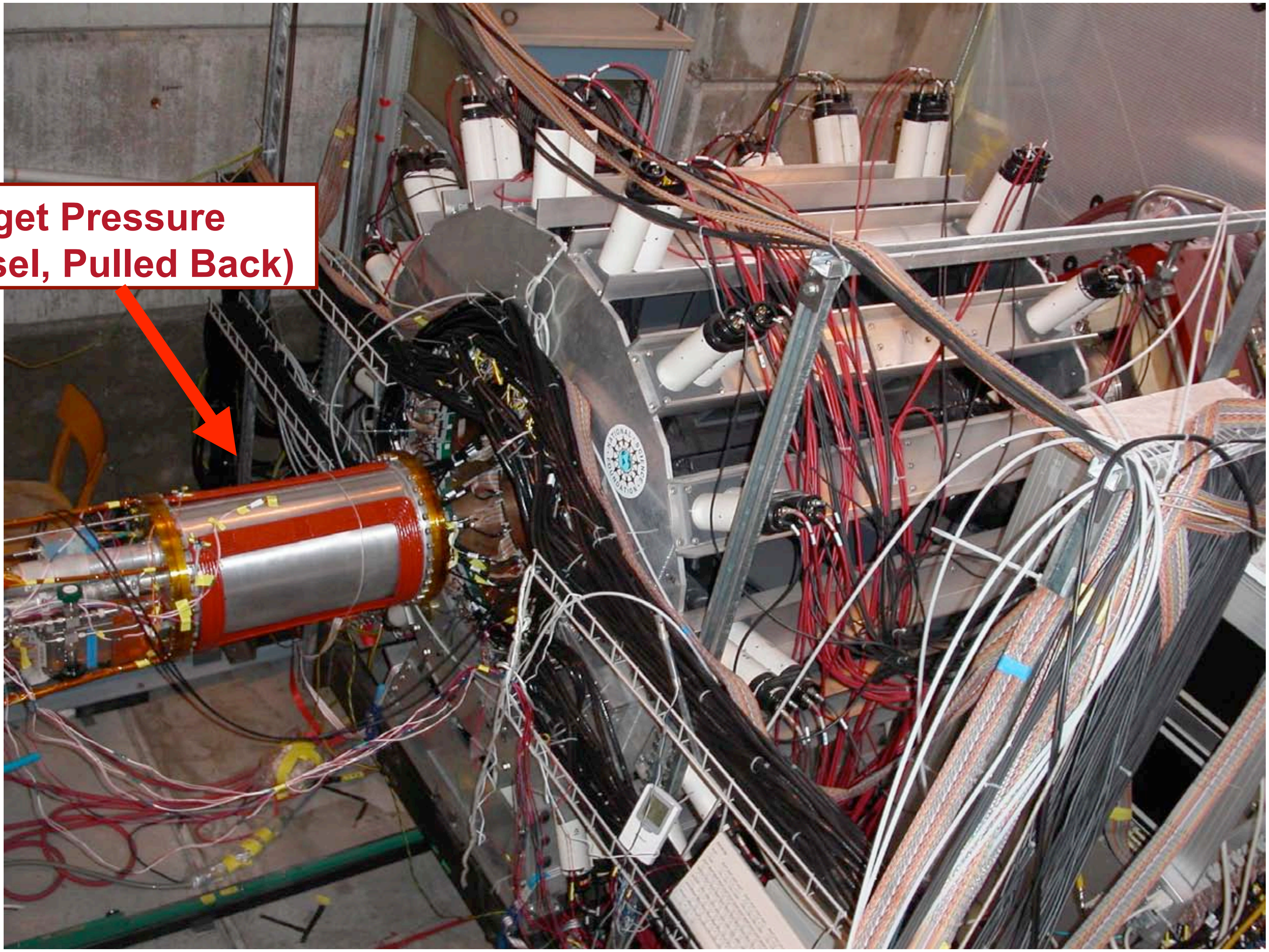
μCap Detailed Diagram

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

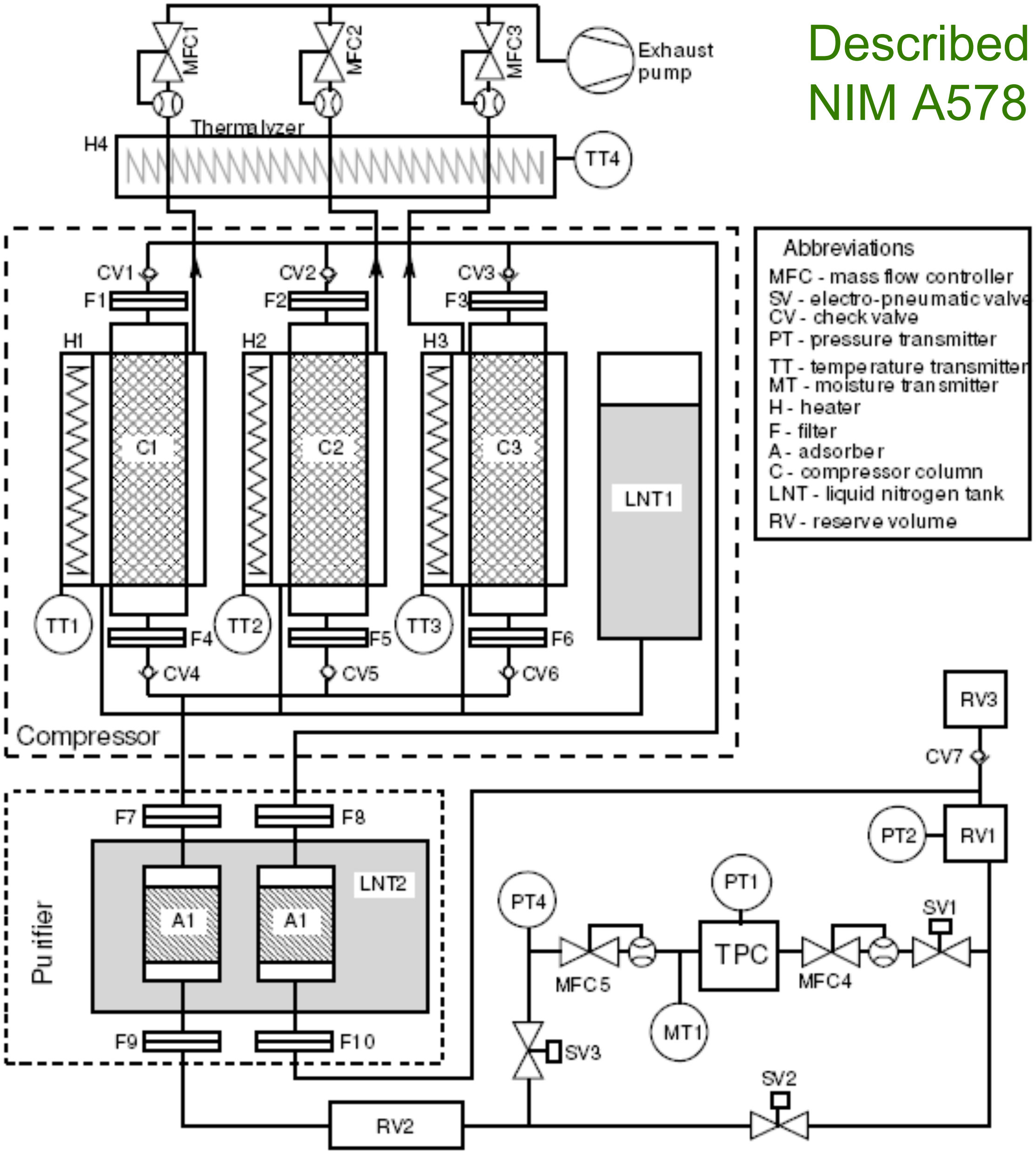


Commissioning and First Physics Data in 2004

(Target Pressure Vessel, Pulled Back)



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

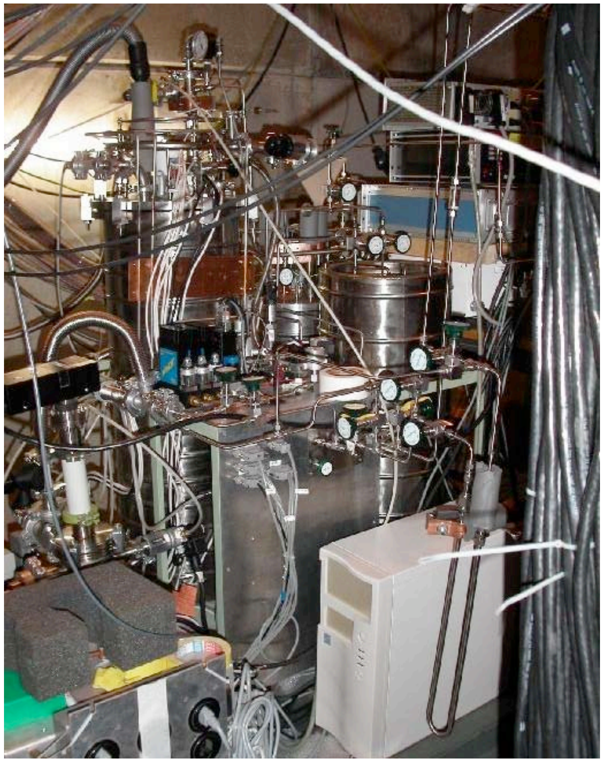


Abbreviations

MFC - mass flow controller
SV - electro-pneumatic valve
CV - check valve
PT - pressure transmitter
TT - temperature transmitter
MT - moisture transmitter
H - heater
F - filter
A - adsorber
C - compressor column
LNT - liquid nitrogen tank
RV - reserve volume

Described in
NIM A578 (2007) 485-497.

Commissioned 2004

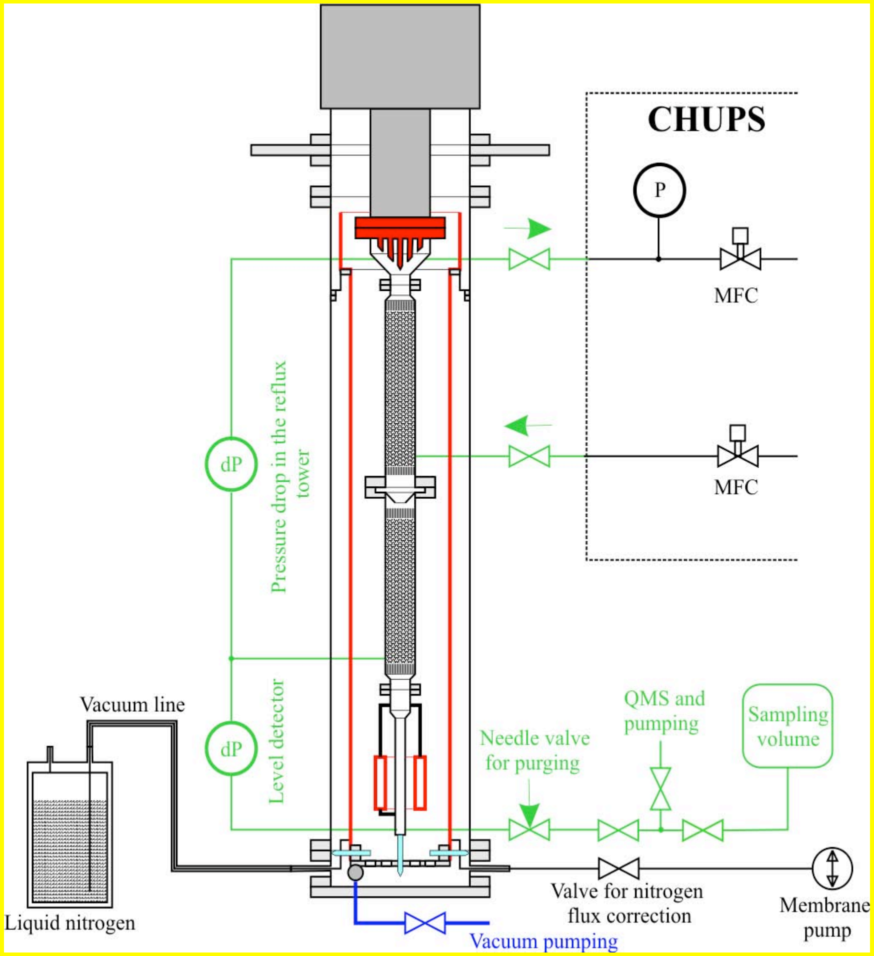


c_{N2}, c_{O2} < 0.01 ppm

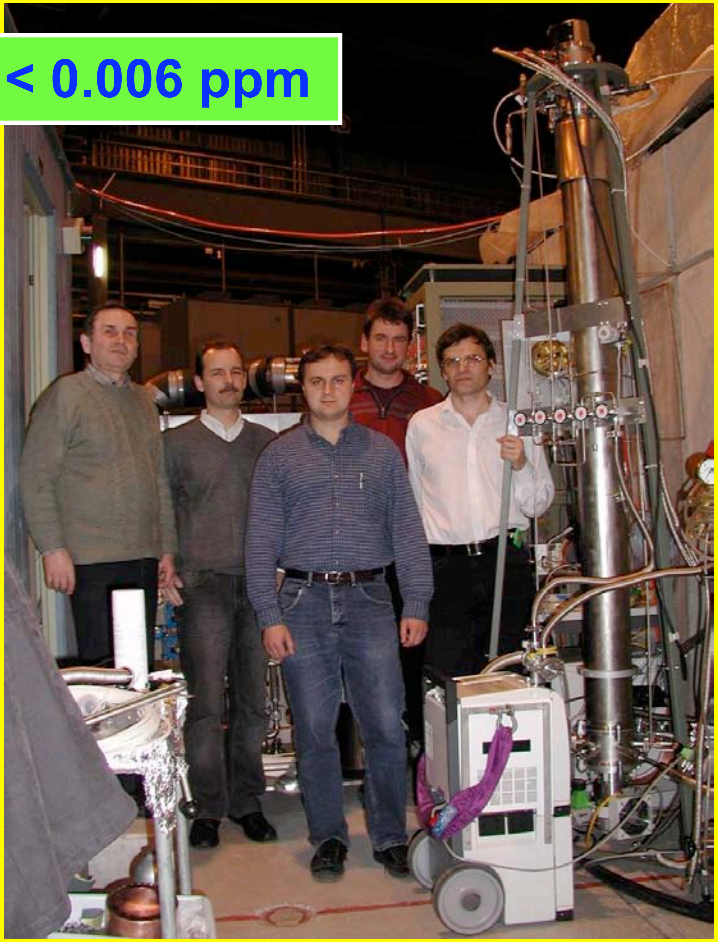
Isotopically Pure “Protium” Target

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

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



c_d < 0.006 ppm

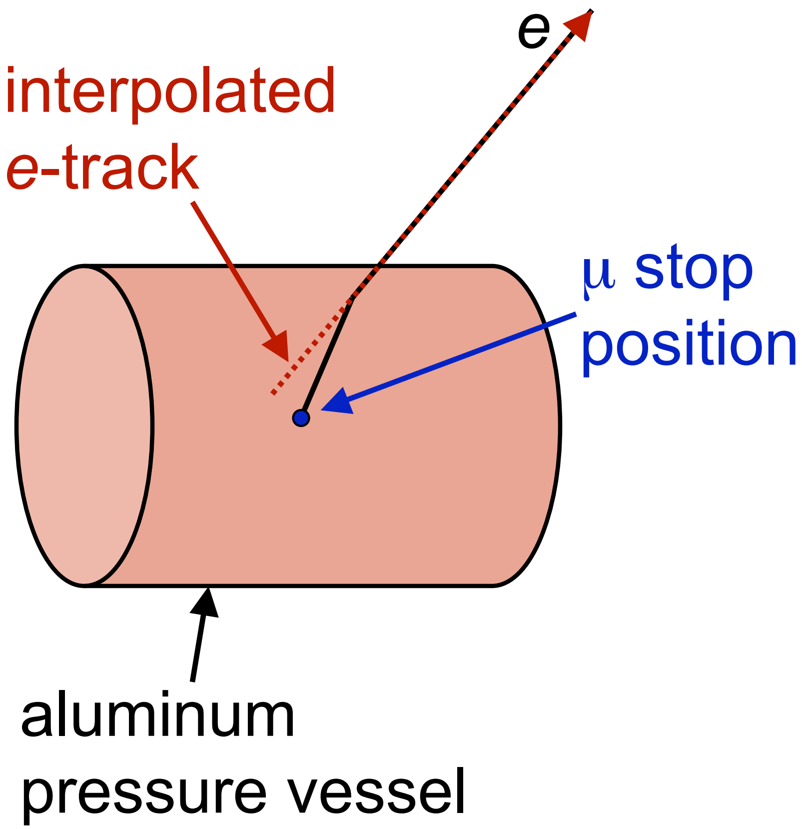


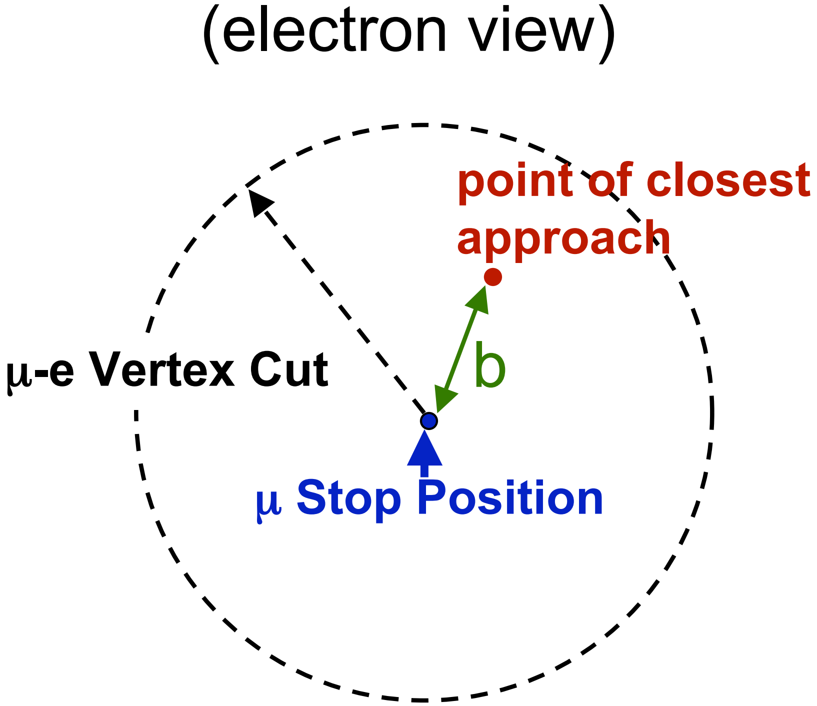
Analysis of MuCap data collected in 2004

- 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
  - -- No isotopic purification column (c_d ~ 1 ppm)

Impact Parameter Cuts

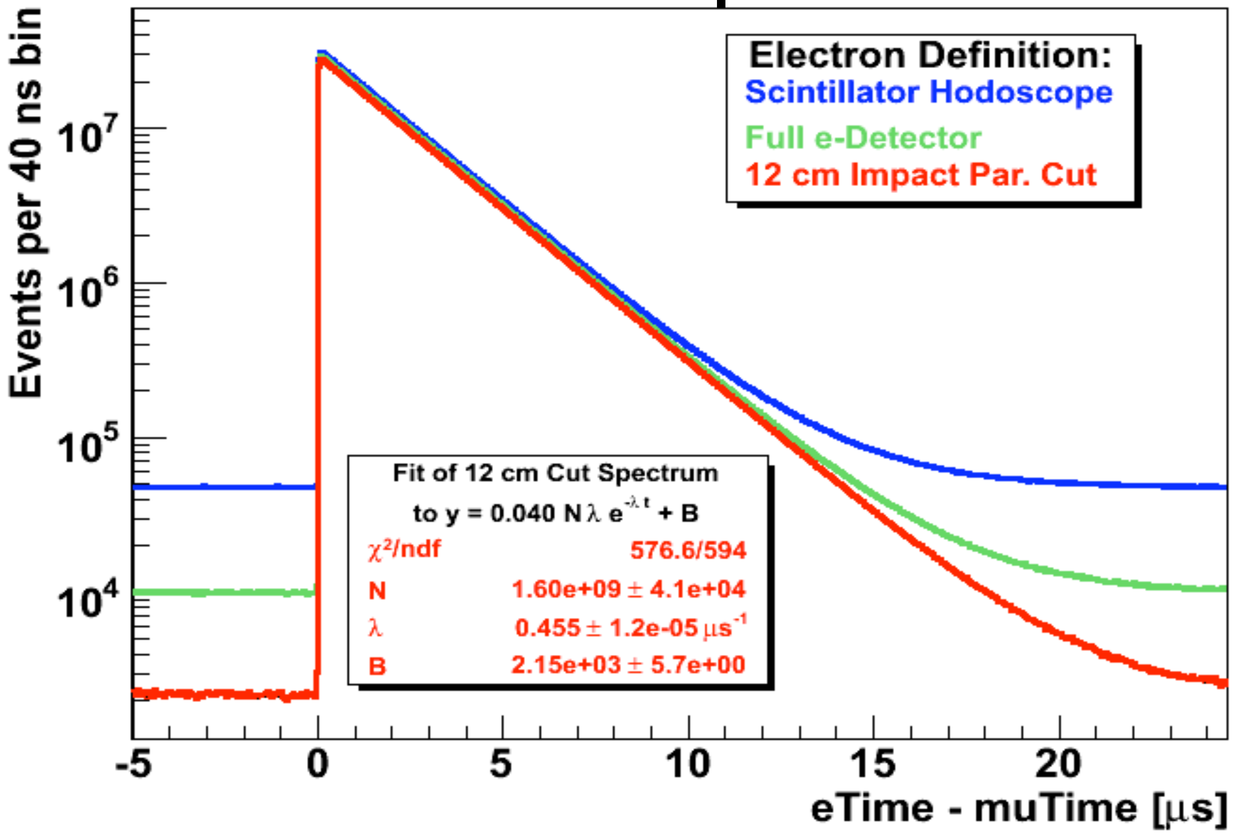
(also known as μ-e vertex cuts)



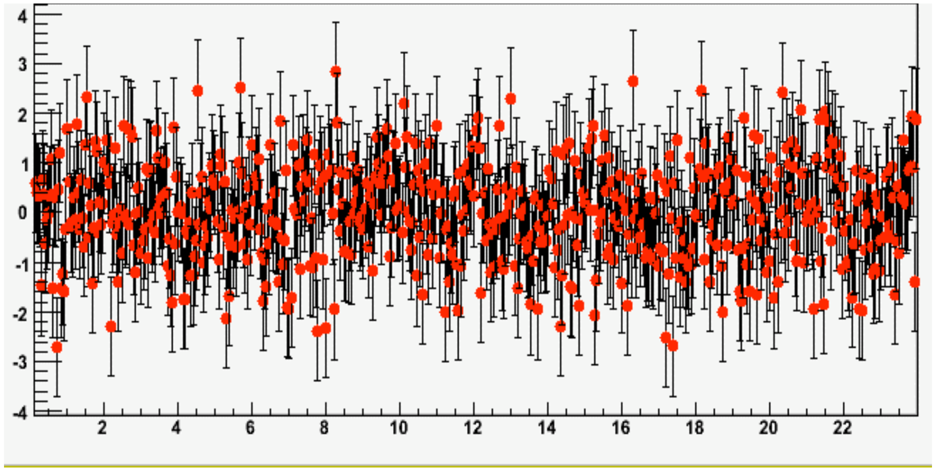


The impact parameter b is the distance of closest approach of the e-track to the μ stop position.

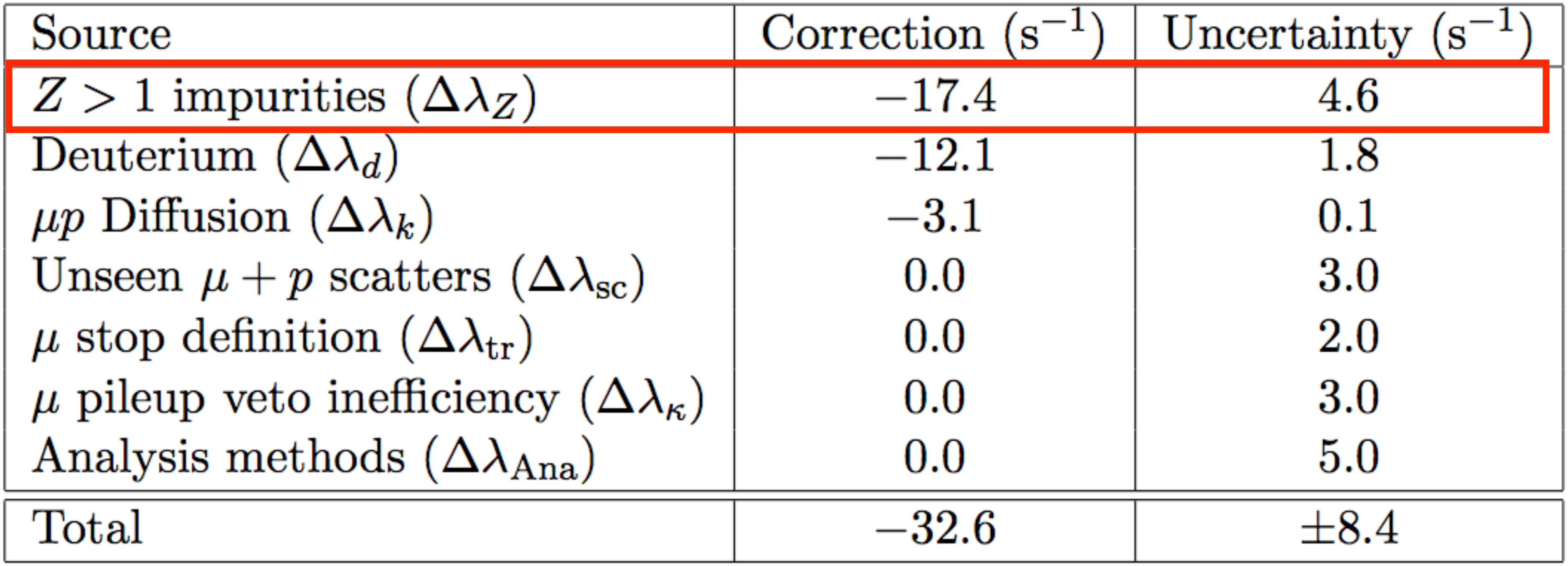
Lifetime Spectra



Normalized residuals (“pull”)



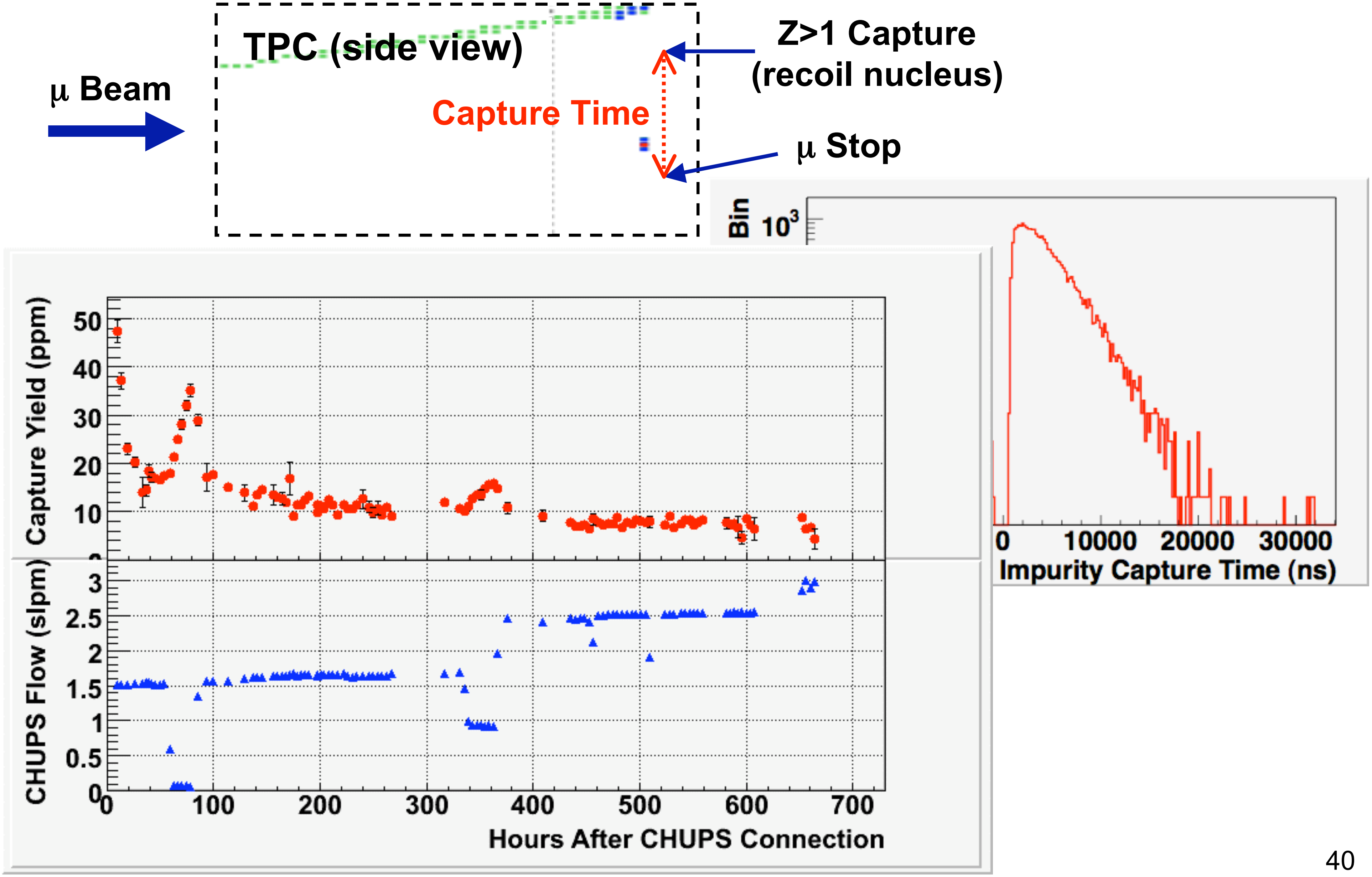
Internal corrections to λ_{μ}^{-}



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 ($\Delta\lambda_{\text{sc}}$)	0.0	3.0
μ stop definition ($\Delta\lambda_{\text{tr}}$)	0.0	2.0
μ pileup veto inefficiency ($\Delta\lambda_{\kappa}$)	0.0	3.0
Analysis methods ($\Delta\lambda_{\text{Ana}}$)	0.0	5.0
Total	-32.6	± 8.4

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

In situ detection of Z > 1 captures



μ Beam

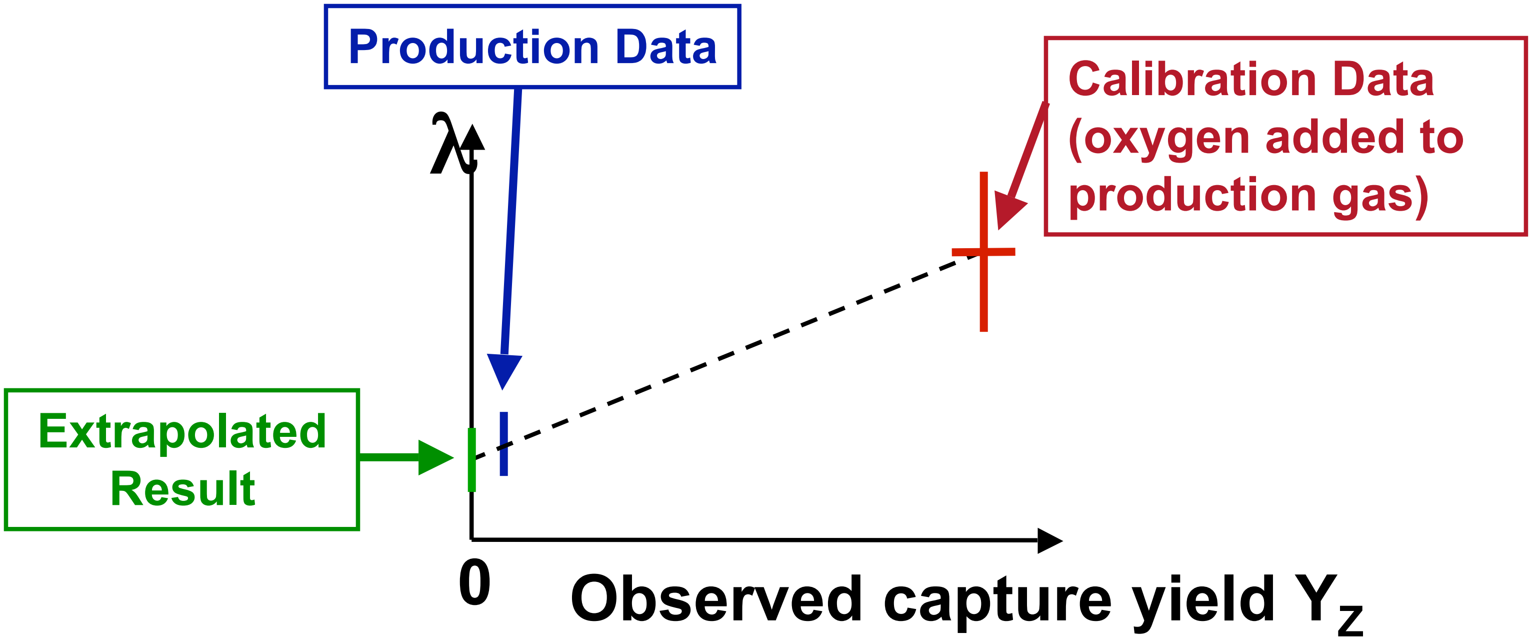
TPC (side view)

Capture Time

Z>1 Capture (recoil nucleus)

μ Stop

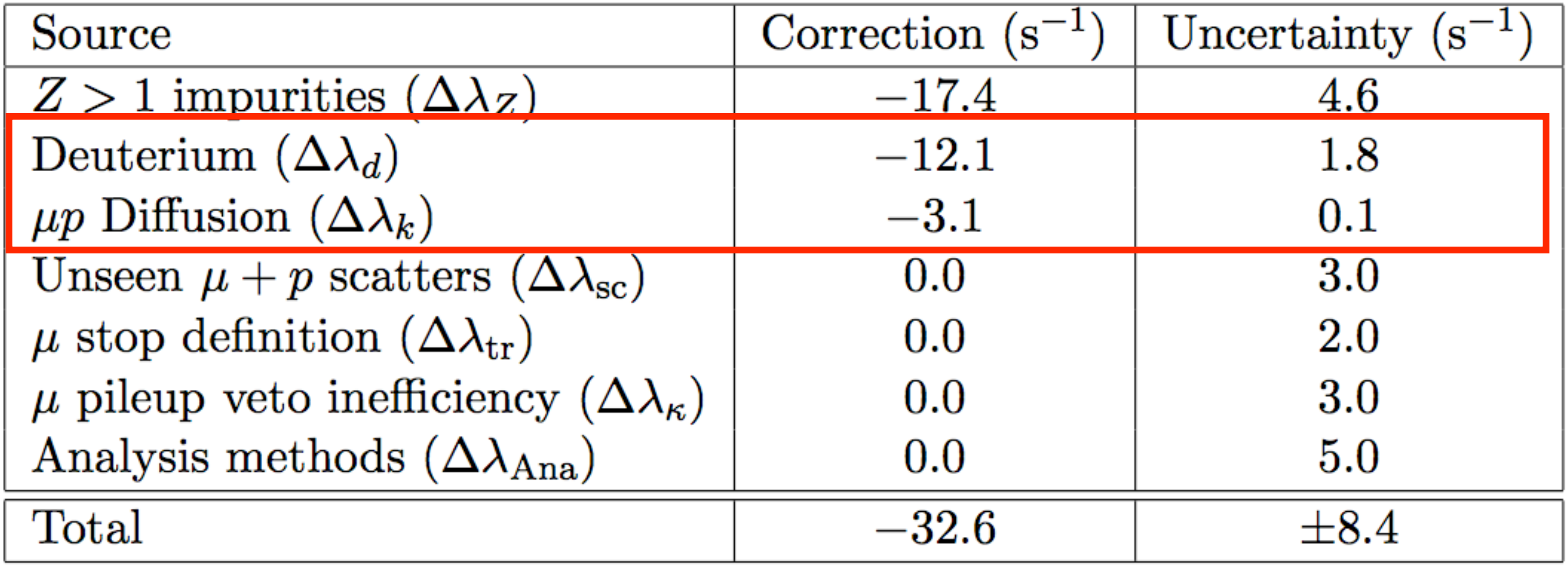
The final Z > 1 correction $\Delta\lambda_Z$ is based on impurity-doped calibration data.



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 λ_μ^-



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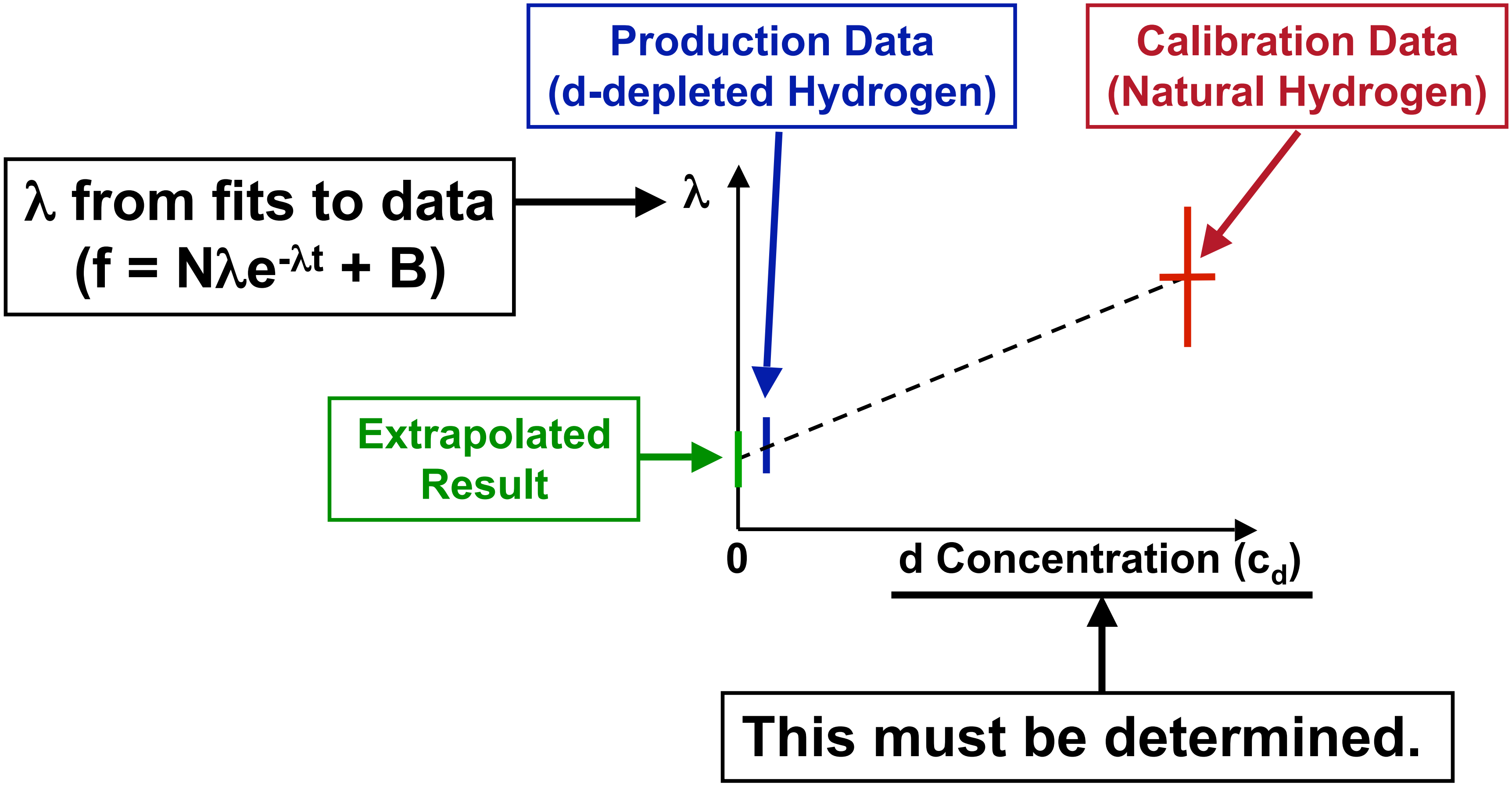
Analysis methods ($\Delta\lambda_{\text{Ana}}$)	0.0	5.0
Total	-32.6	± 8.4

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

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



Production Data (d-depleted Hydrogen)

Calibration Data (Natural Hydrogen)

λ from fits to data ($f = N\lambda e^{-\lambda t} + B$)

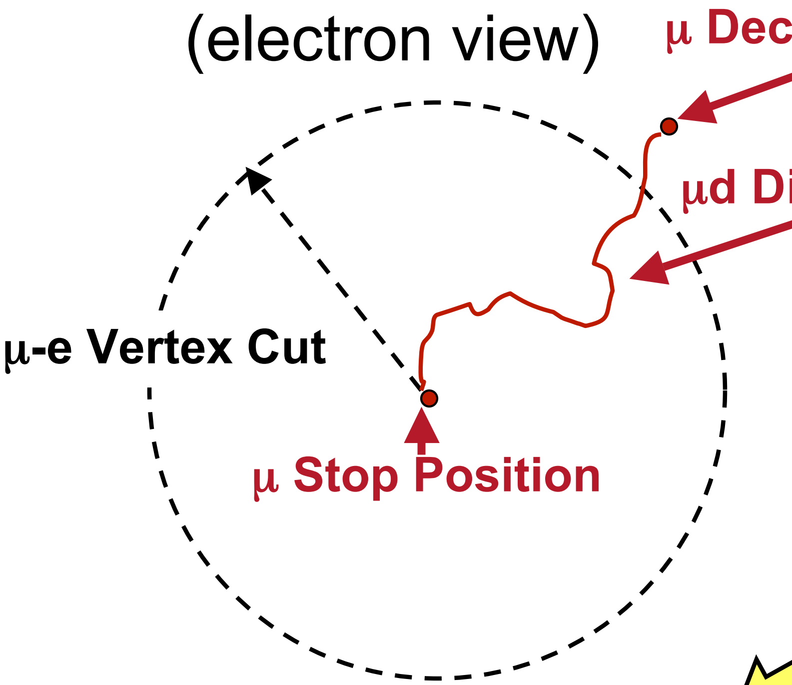
Extrapolated Result

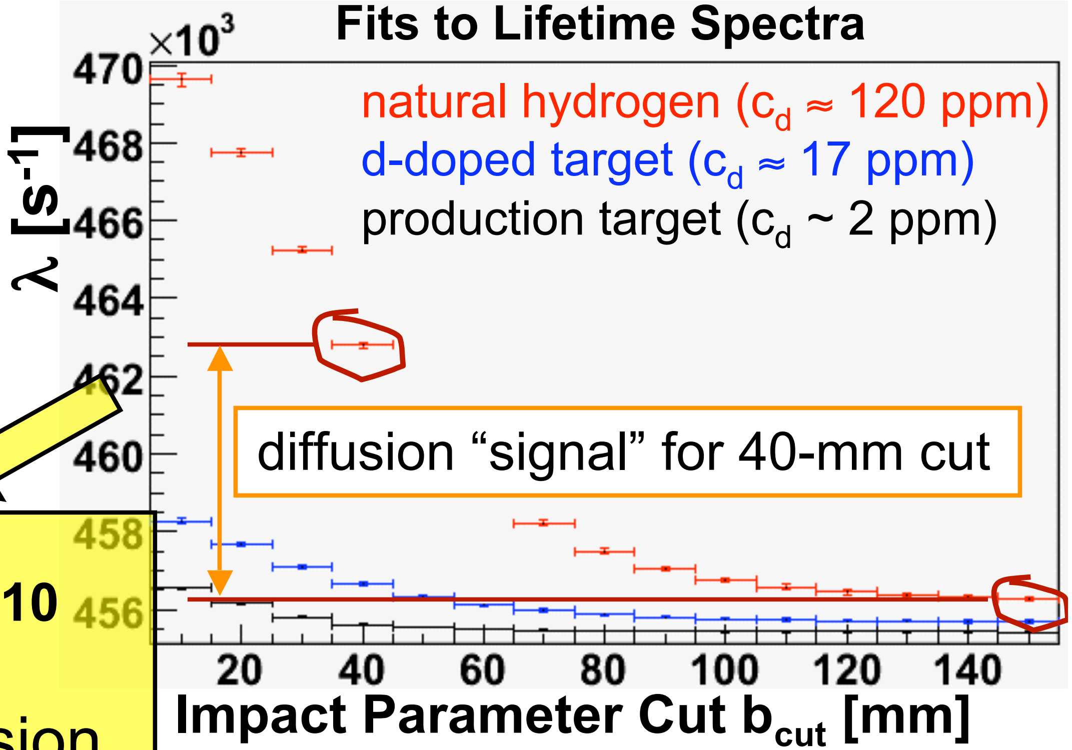
This must be determined.

c_d Determination: Data Analysis Approach

μd can diffuse out of acceptance region:

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





natural hydrogen ($c_d \approx 120$ ppm)

d-doped target ($c_d \approx 17$ ppm)

production target ($c_d \sim 2$ ppm)

diffusion “signal” for 40-mm cut

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

*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,

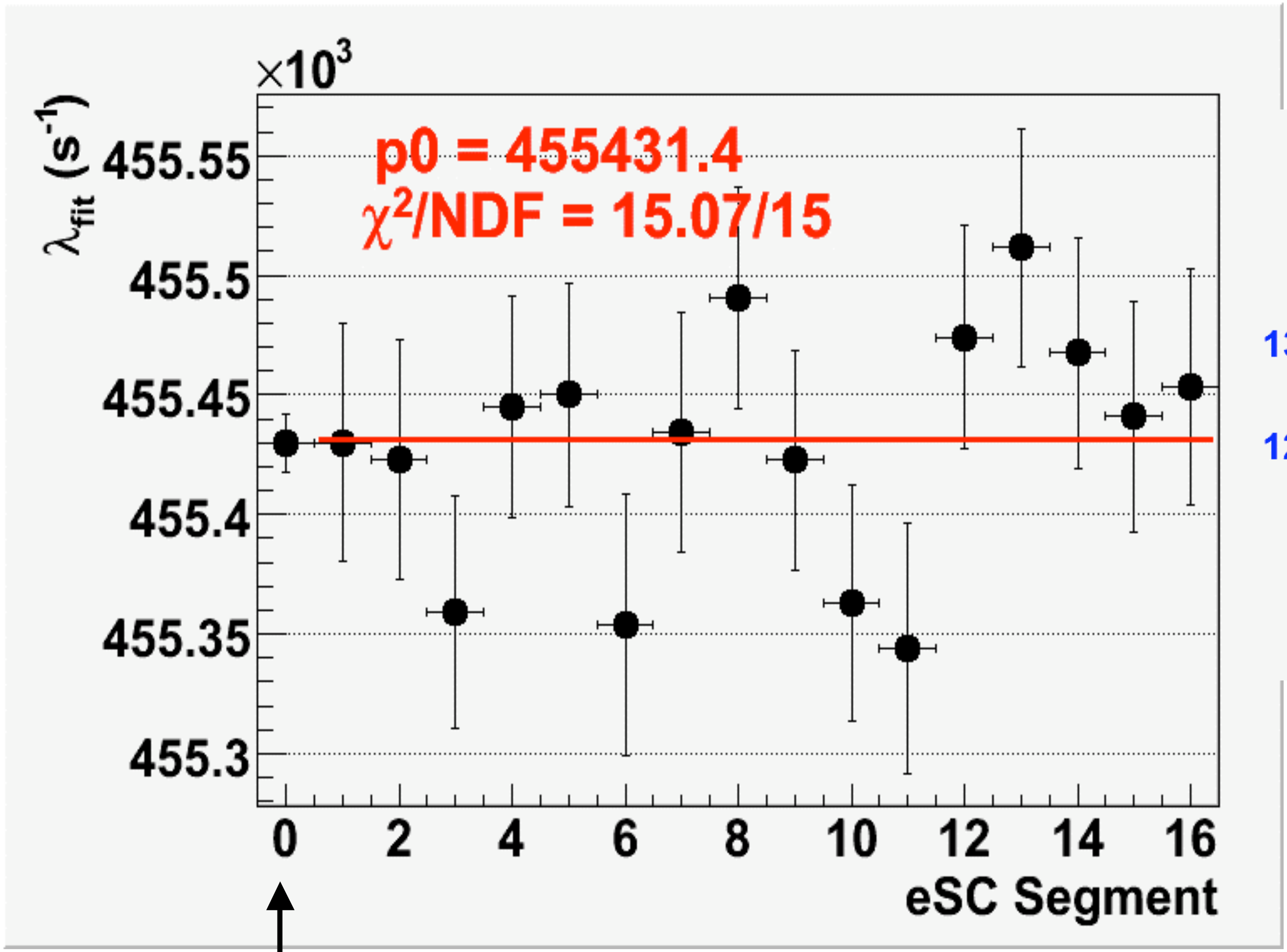
  $c_D = (0.0125 \pm 0.0010) \times (122 \text{ ppm D})$

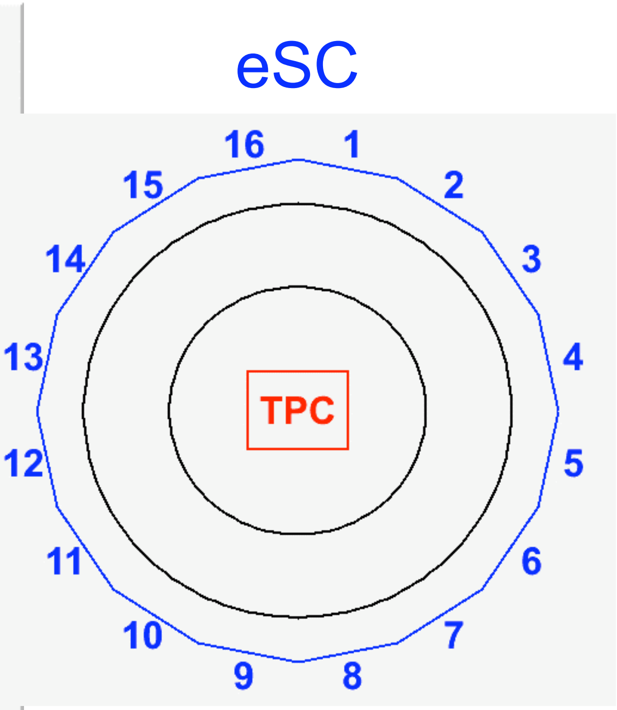
  $= 1.53 \pm 0.12$ ppm

Consistency Checks

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

Lifetime vs eSC segment

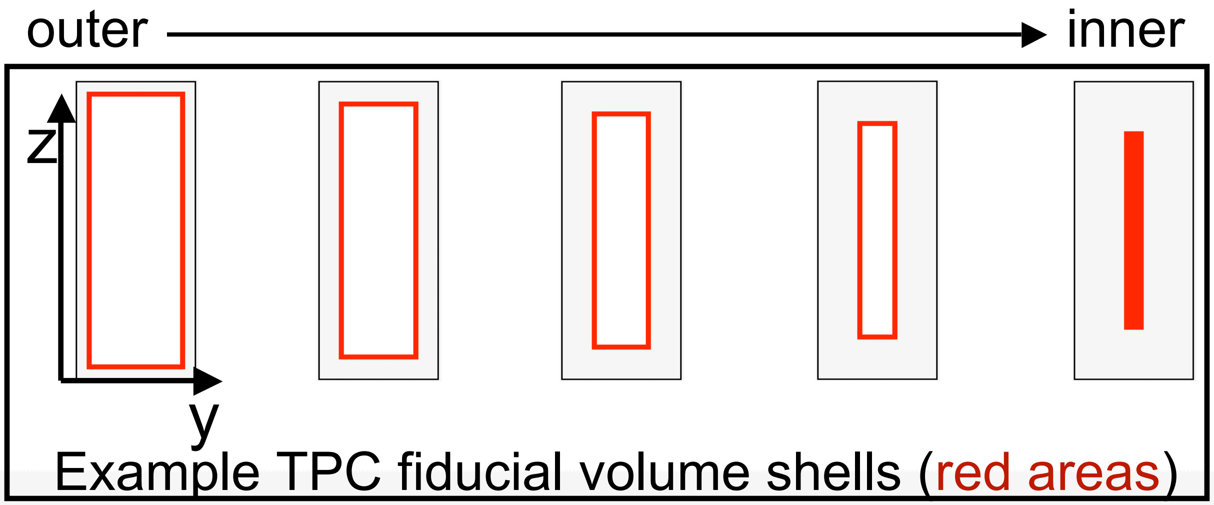




Beam view of MuCap detector

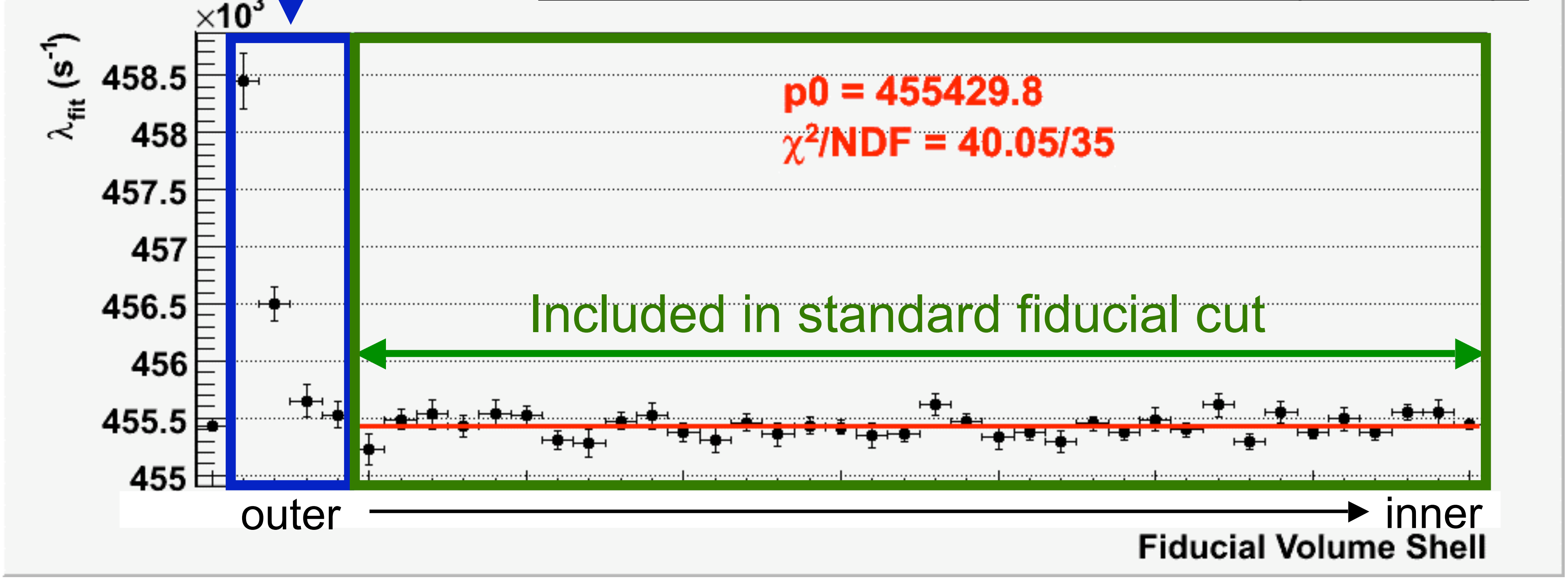
Sum over all segments

Lifetime vs. Non-Overlapping Fiducial Volume Shell



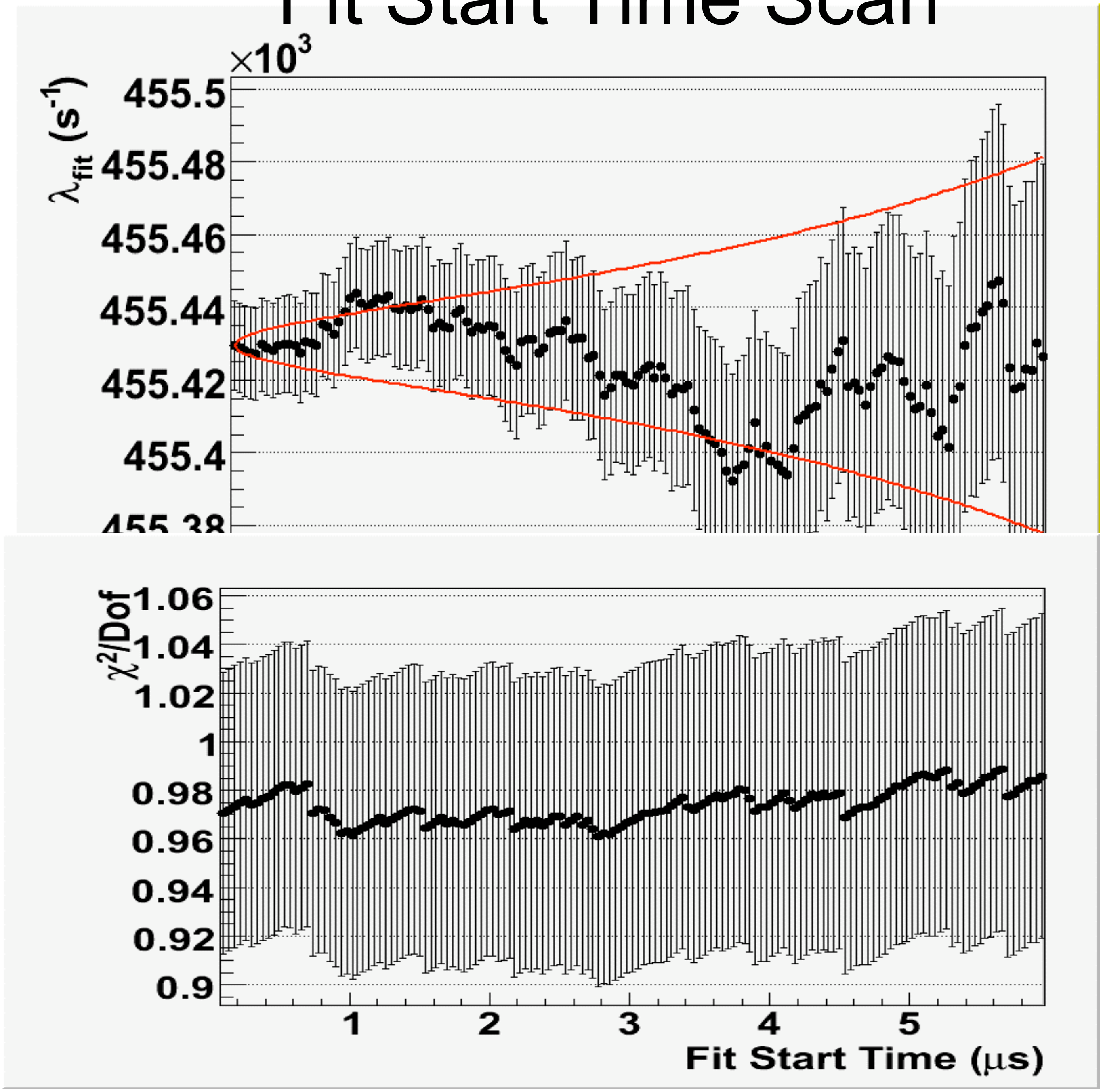
Example TPC fiducial volume shells (red areas)

outside the standard fiducial cut

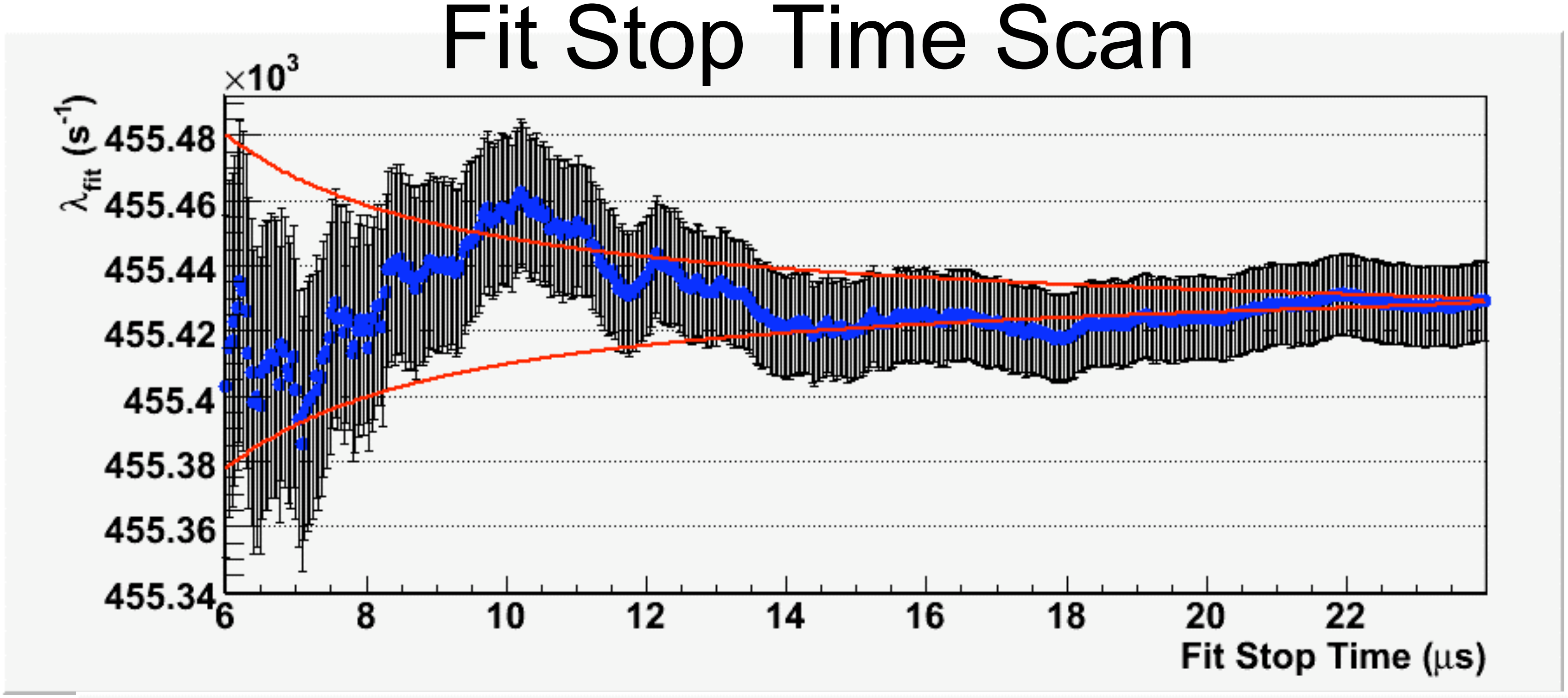


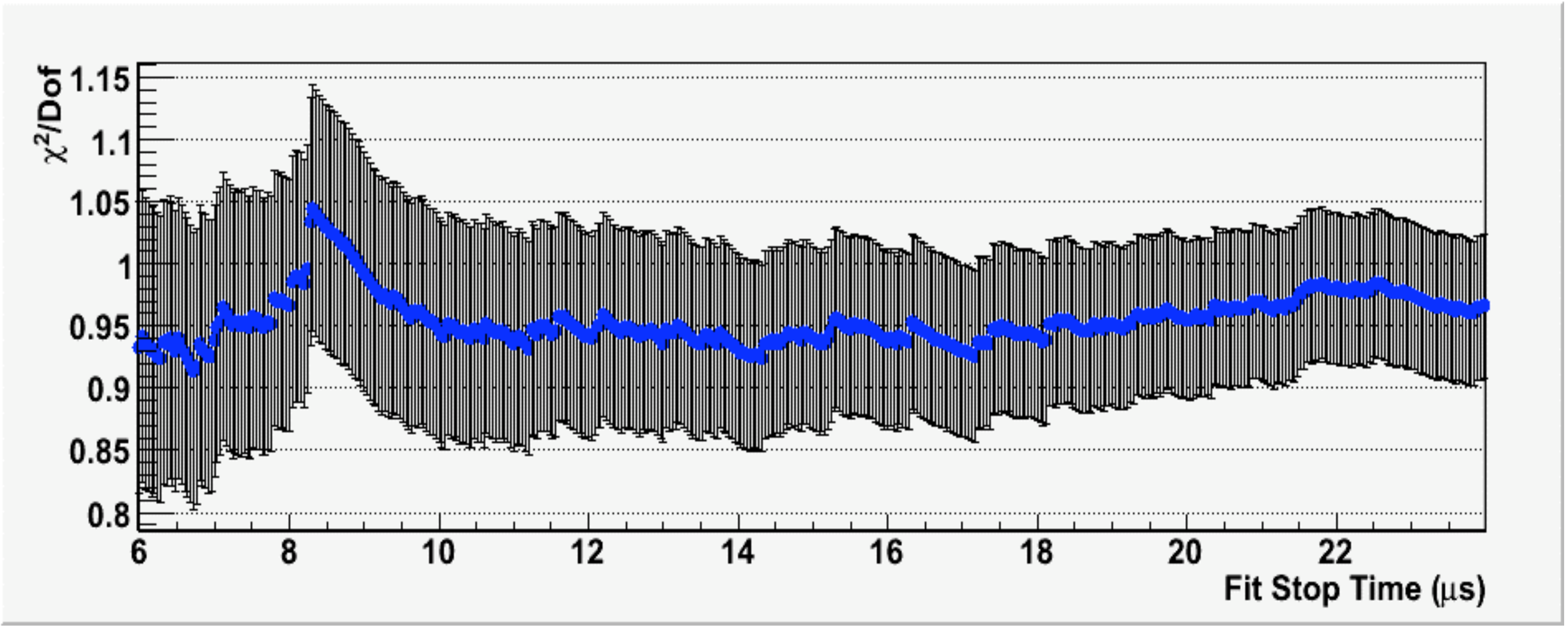
Included in standard fiducial cut

Fit Start Time Scan

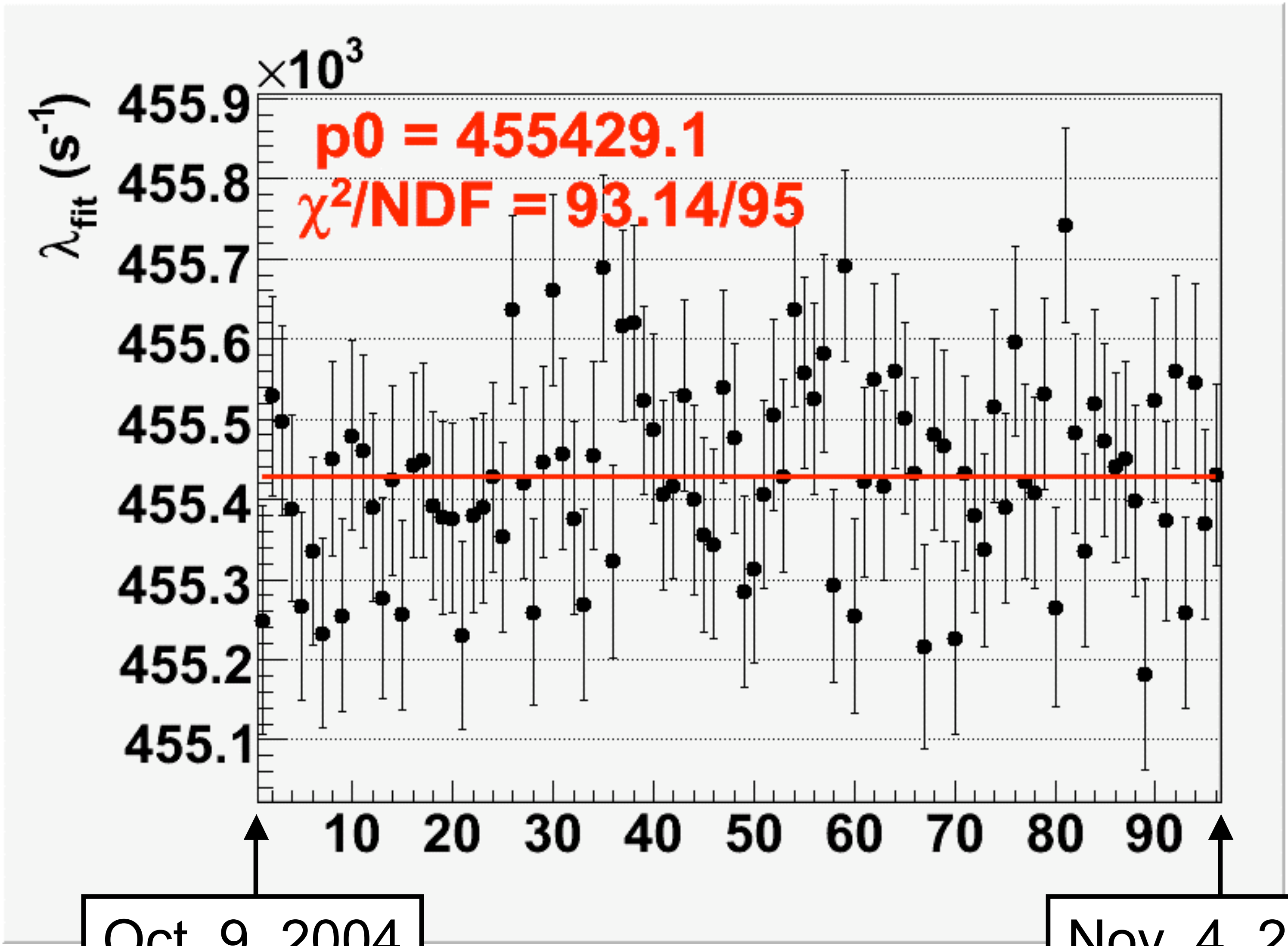


Fit Stop Time Scan





Lifetime vs. Chronological Subdivisions



Oct. 9, 2004

Nov. 4, 2004

MuCap Λ_S from the μ^- lifetime λ_μ^-

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

molecular formation

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

μ^+ decay rate

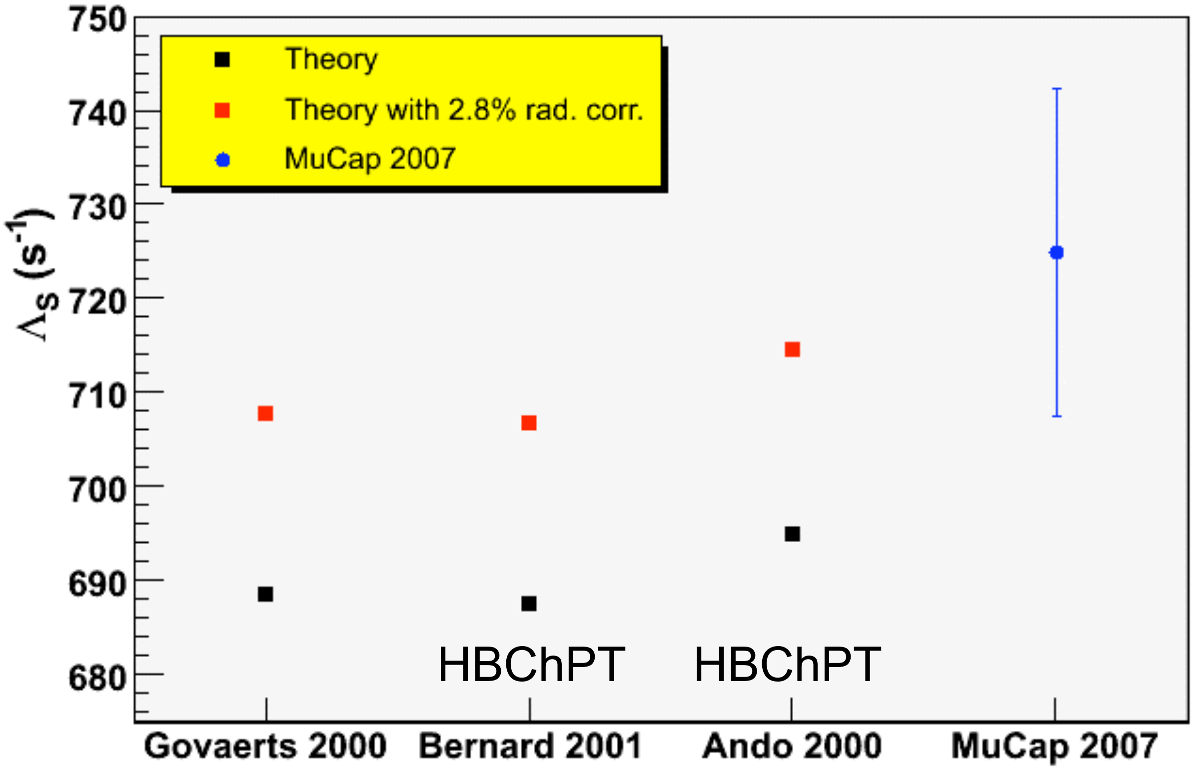
bound-state effect

	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 $\Lambda_S{}^a$	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 Calculations and MuCap (2007) Result

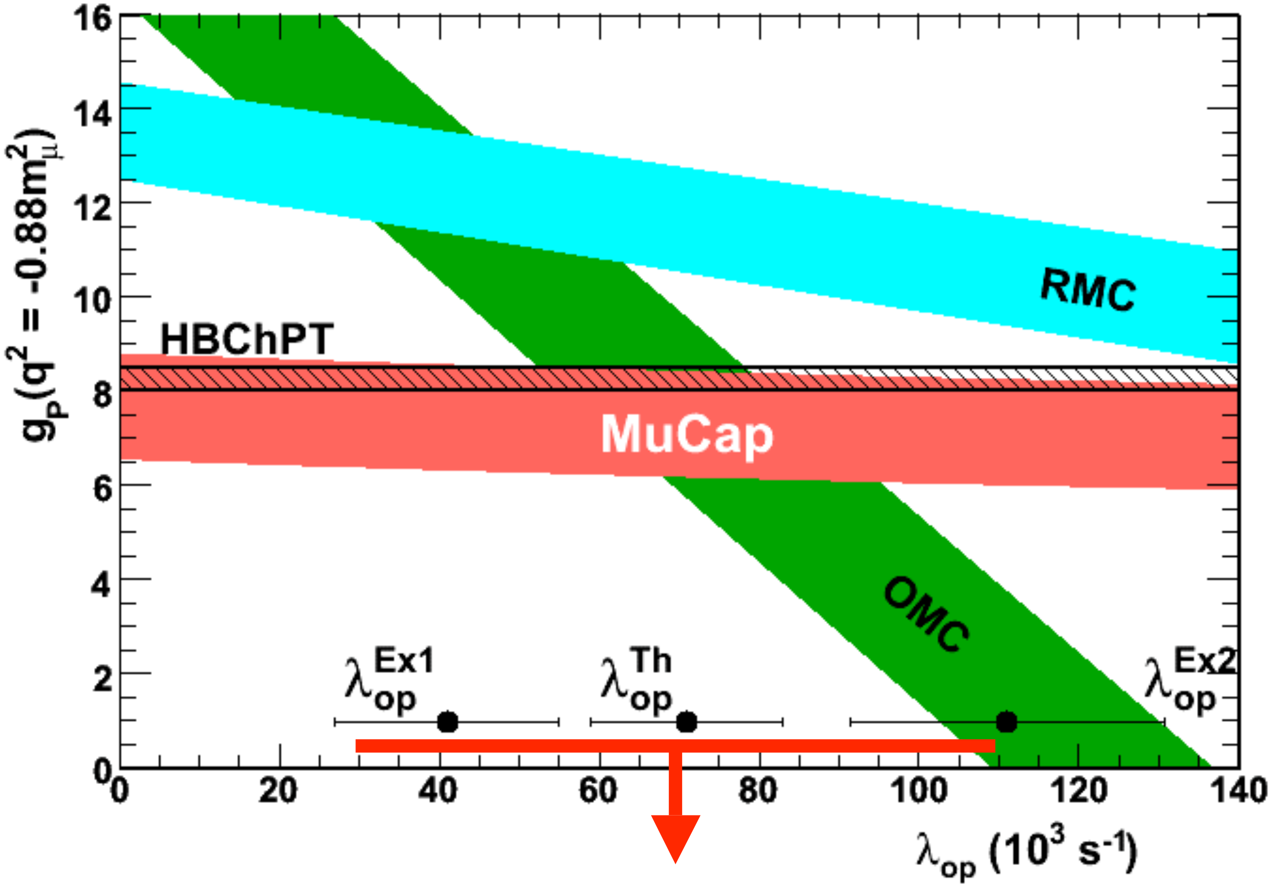


rad. corrections

- ***Czarnecki Marciano Sirlin (2006)***
  Δ_R = 2.8%

MuCap agrees within ~1σ with Λ_S theory

Updated g_P vs. λ_{op}

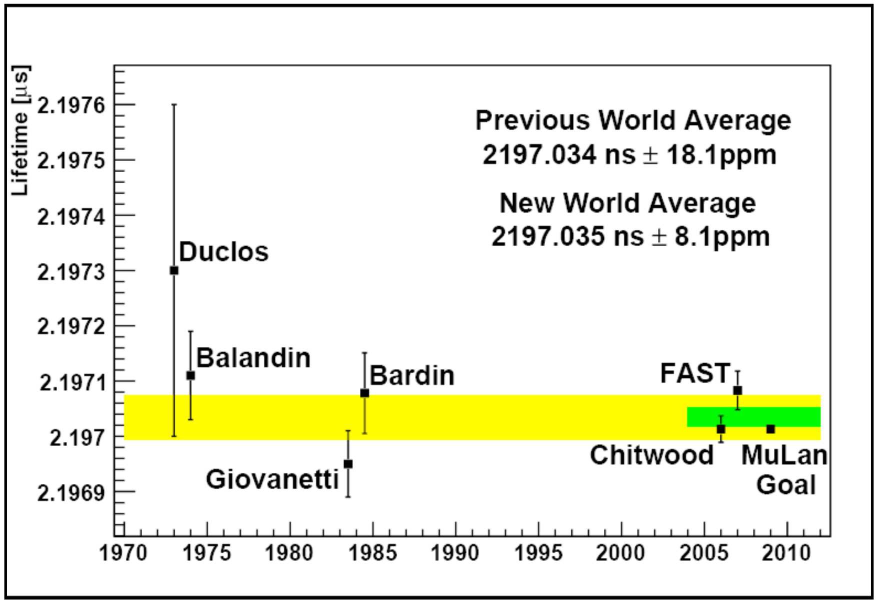


(contributes 3% uncertainty to g_p^{MuCap})

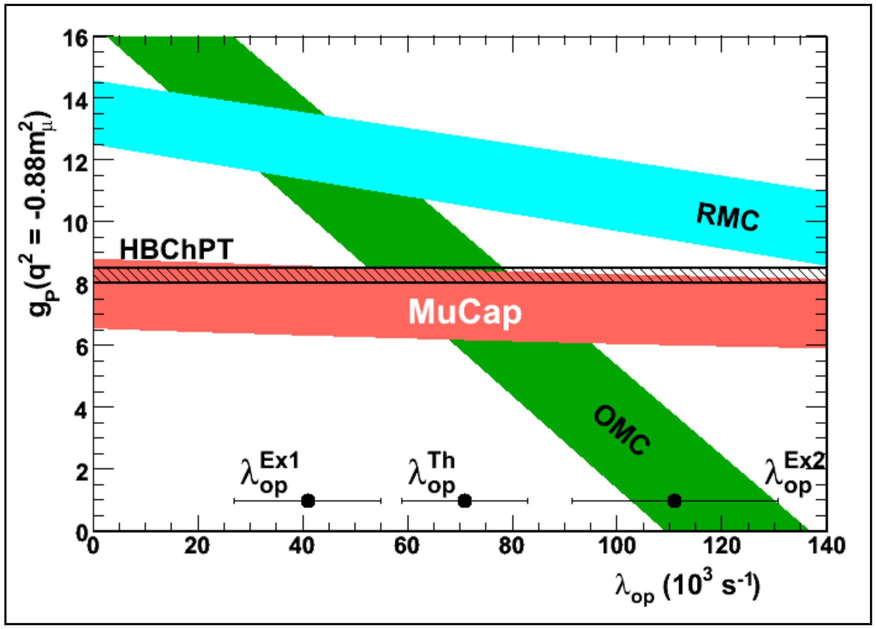
- MuCap 2007 result (with g_P to 15%) is consistent with theory.
- This is the first precise, unambiguous experimental determination of g_P

Summary

- MuLan:
  - First G_F update in > 23 years - no surprise
  - Factor 10 additional improvement on the way (more events; WFDs)

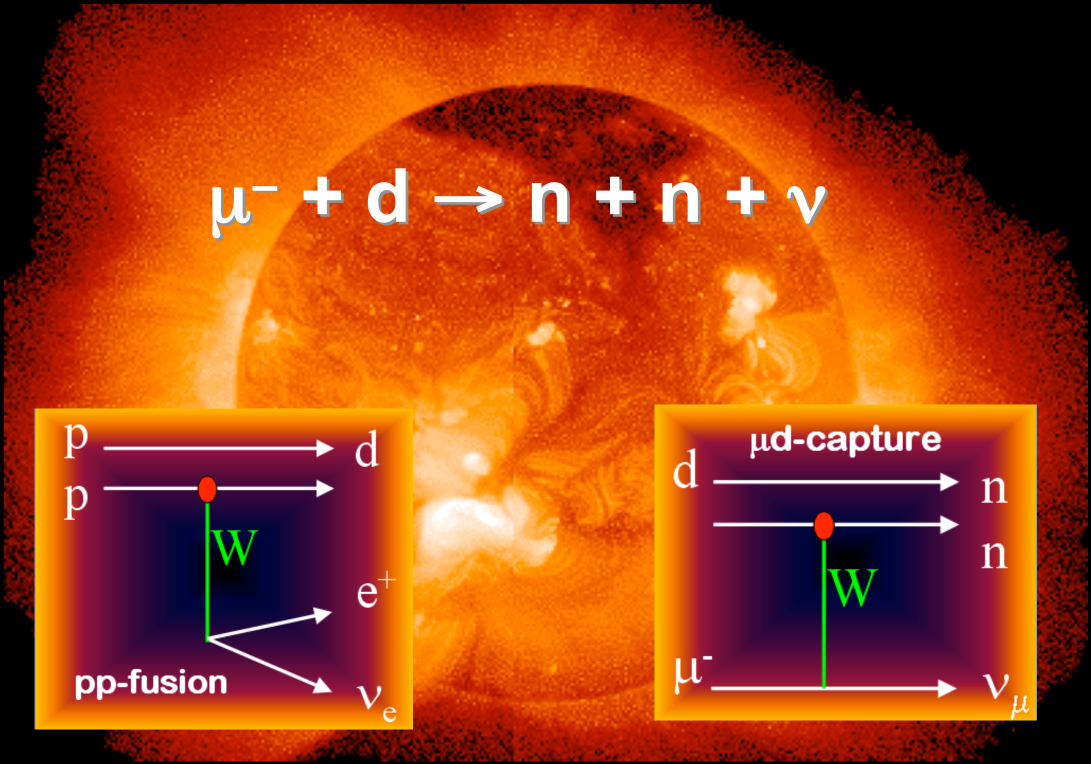


- MuCap:
  - First g_P with non-controversial interpretation
  - Agrees with χPT expectation
  - Factor 2.5 additional improvement on the way (more events; systematics studies)



“Calibrating the Sun” via
Muon Capture on the Deuteron

NEW
PROJECT



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

Motivation for the MuSun Experiment:

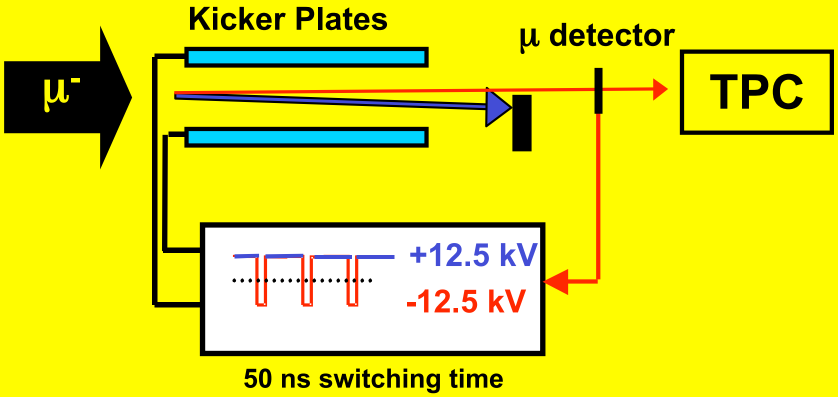
- First precise measurement of basic Electroweak reaction in 2N system,
- Impact on fundamental astrophysics reactions (ν’ s in SNO, pp fusion)
- Comparison to modern high-precision calculations

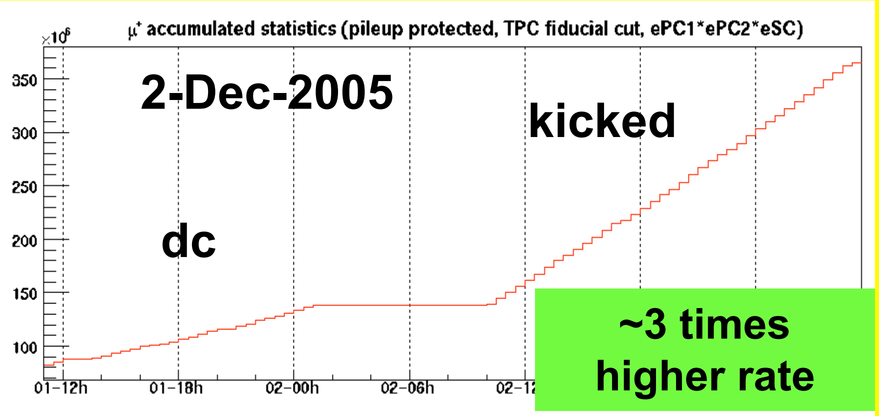
Extra Slides

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

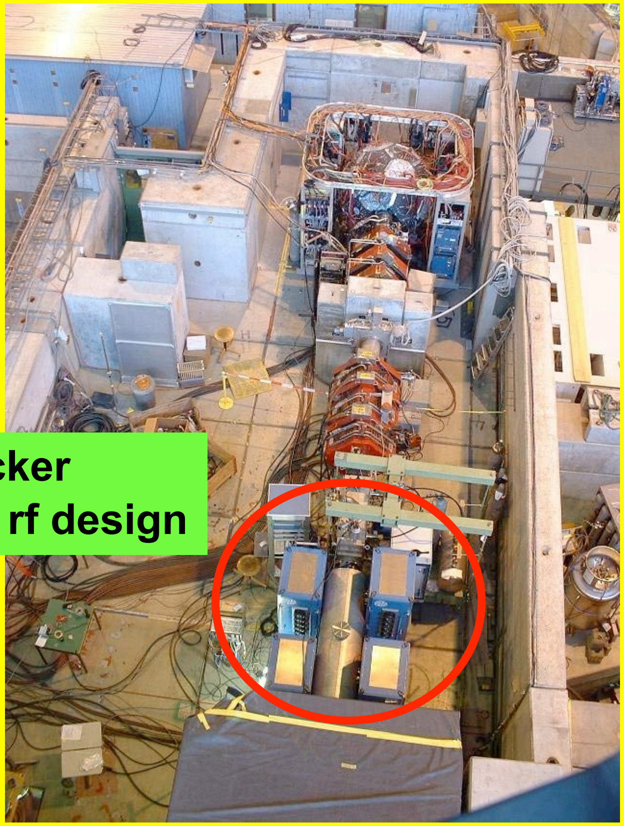
- Muon-On-Demand concept





~3 times higher rate

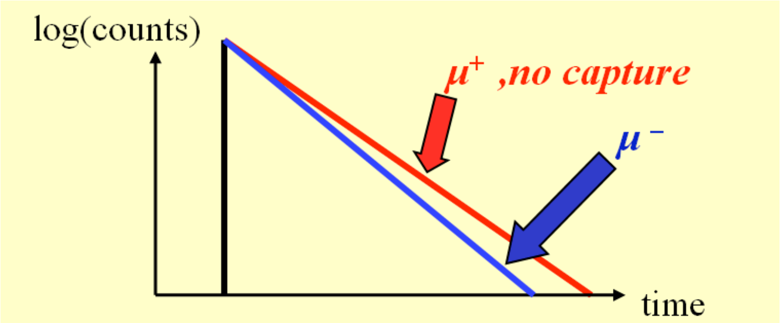
- Beamline



μLan kicker TRIUMF rf design

μCap Experimental Strategy

- Unambiguous interpretation
  - capture mostly from F=0 μp state at 1% LH_2 density



- Lifetime method
  - 10^{10} $\mu^- \to e\nu\nu$ decays
  - measure $\tau_{\mu-}$ to 10ppm

  → $\Lambda_S = 1/\tau_{\mu-} - 1/\tau_{\mu+}$ 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: μp + Z → μZ + p, ~10 ppb impurities

- Isotopically pure “protium” to avoid μp + d → μd + p, ~1 ppm deuterium

diffusion range ~cm

fulfill all requirements simultaneously
unique μCap capabilities

MuCap Collaboration

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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 0.45% uncertainty to Λ_S(theory)

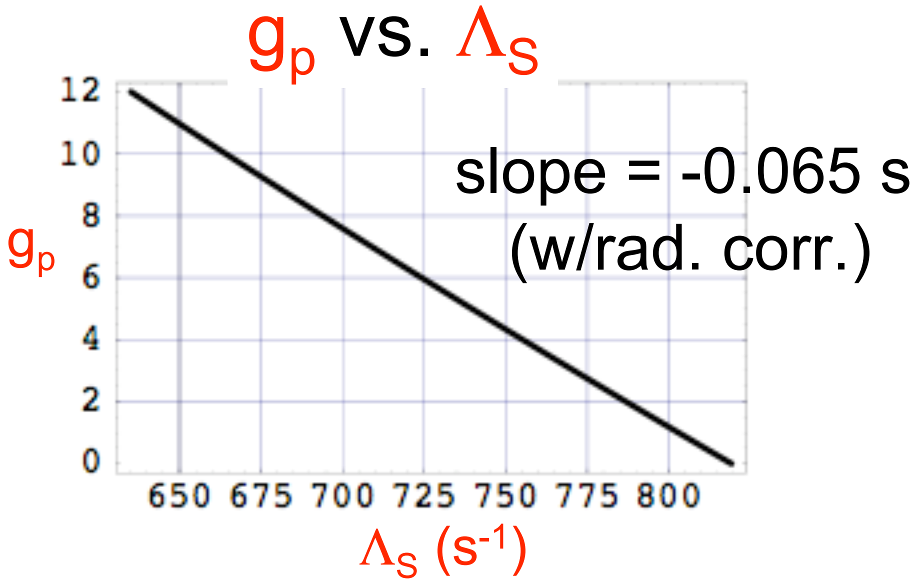
$$\frac{\delta\Lambda_S}{\Lambda_S} \longleftrightarrow \frac{\delta g_p}{g_p}$$

Examples:

2.4% ↔ 13.6%

1.0% ↔ 6.1%

0.5% ↔ 3.8%



slope = -0.065 s
(w/rad. corr.)

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

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

$$g_p^{MuCap} = g_p^{theory} + \frac{\partial g_p}{\partial \Lambda_S}(\Lambda_S^{MuCap} - \Lambda_S^{theory})$$

Average HBChPT calculations of Λ_S:

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

Apply new rad. correction (2.8%):

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

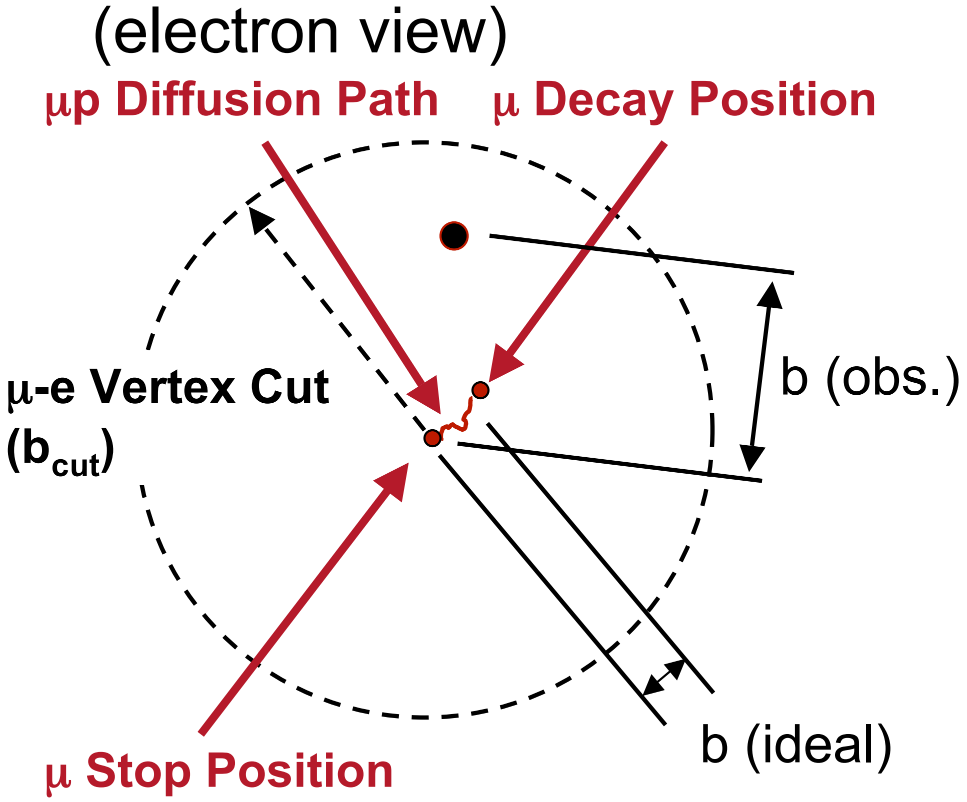
$$\rightarrow \Lambda_S^{theory} = 710.6\ \mathrm{s}^{-1}$$

$$g_p^{MuCap} = 8.26 + (-0.065\ \mathrm{s})\left((725.0 \pm 17.4\ \mathrm{s}^{-1}) - (710.6\ \mathrm{s}^{-1})\right)$$

$$= \boxed{7.3 \pm 1.1\ \ \text{(MuCap 2007, Final)}}$$

Note: uncertainty in theory (~0.5%) not propagated.

μp Diffusion Effect


(electron view)

μp Diffusion Path

μ Decay Position

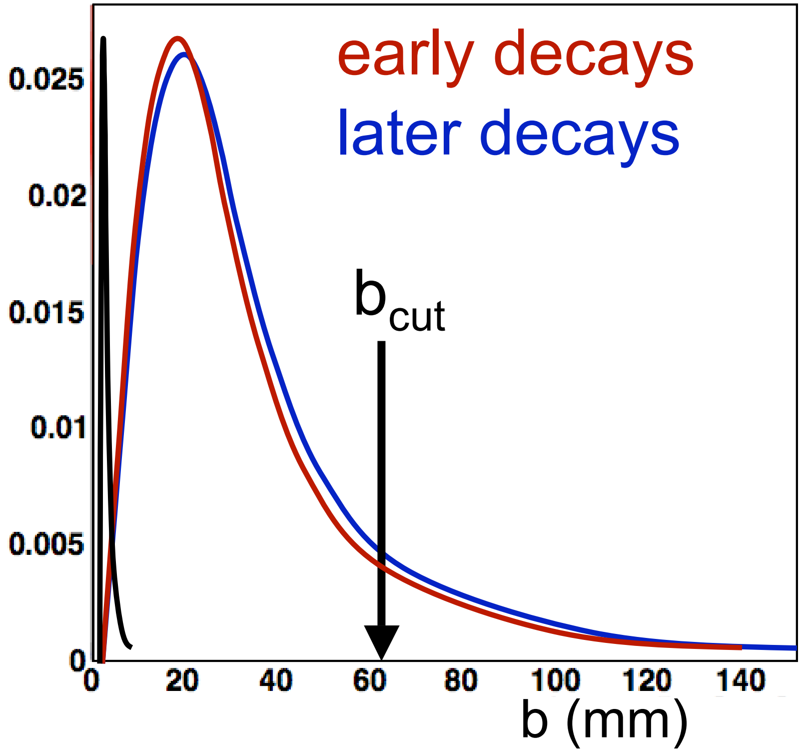
μ-e Vertex Cut (b_{cut})

b (obs.)

b (ideal)

μ Stop Position

Impact Parameter Distribution F(b)

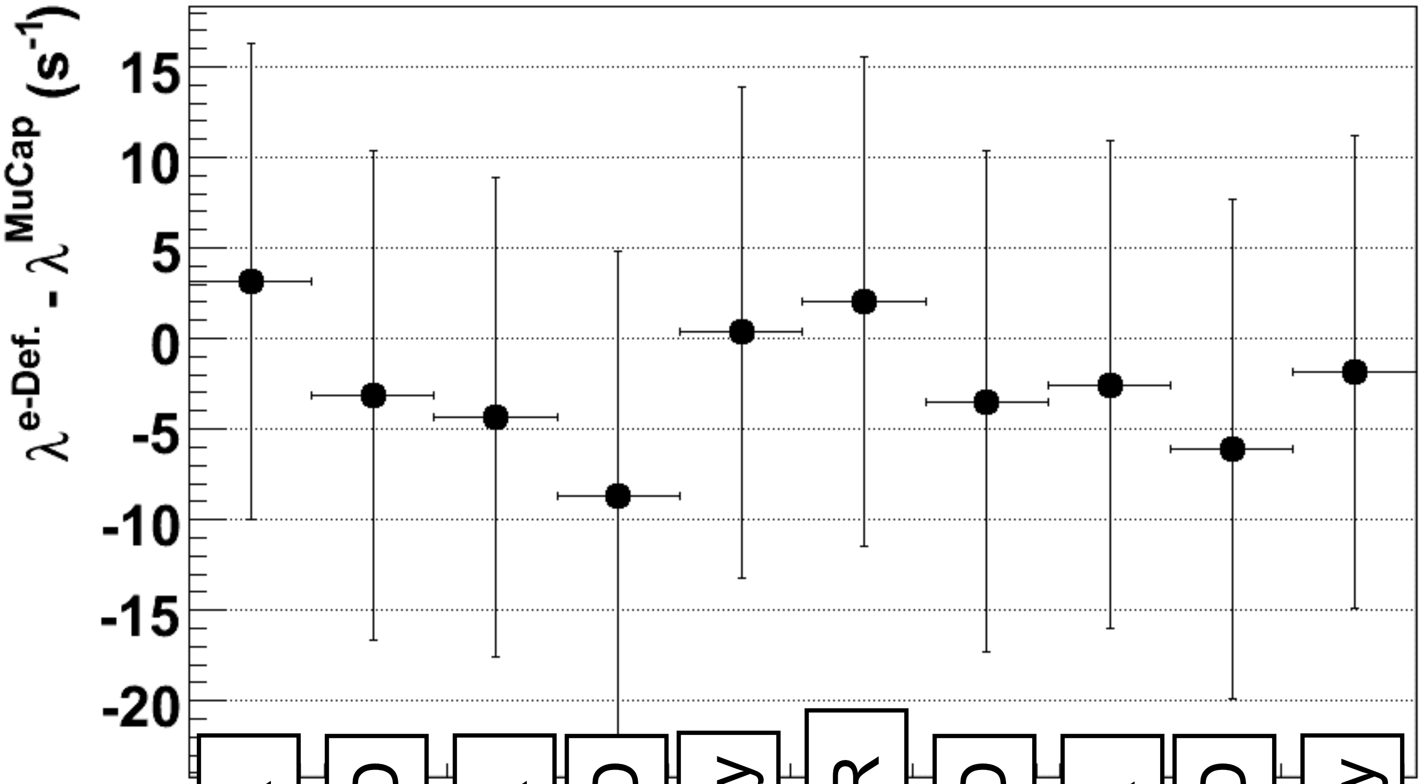


Later decays are less likely than early decays to pass the impact parameter cut.

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).

Lifetime vs. *e*-definition

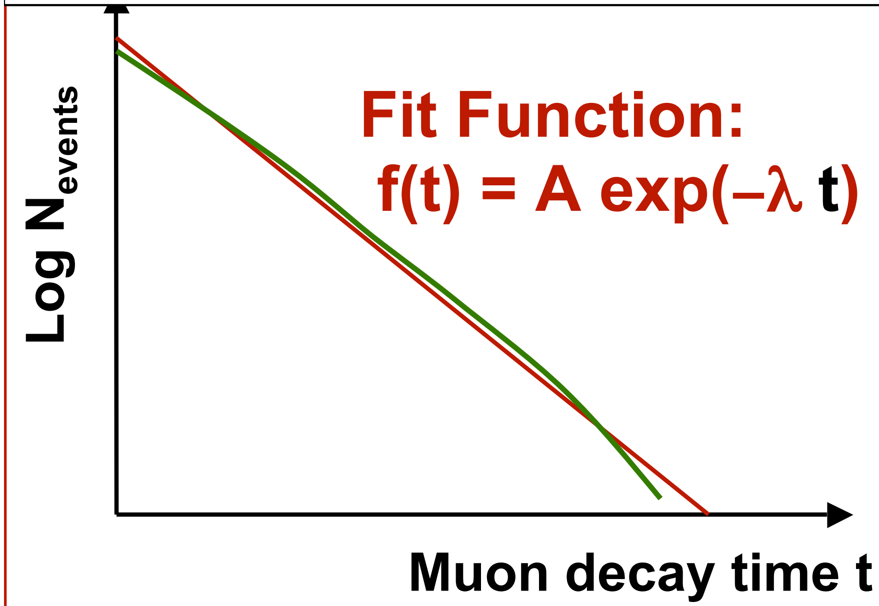


CathOR	CathAND	CathOR	CathAND	eSC Only	CathOR	CathAND	CathOR	CathAND	eSC Only	(treatment of detector planes)
b<12cm		no b-cut			b<12cm		no b-cut			(impact par. cut)
All e accepted					One e gated					(*e*-multiplicity)

Lifetime deviations $\Delta\lambda_Z$ due to Z > 1 impurities can be calculated.

Based on full kinetics solution: $y_e(t)$

Fit $y_e(t)$ to a single exponential or calculate first moment.



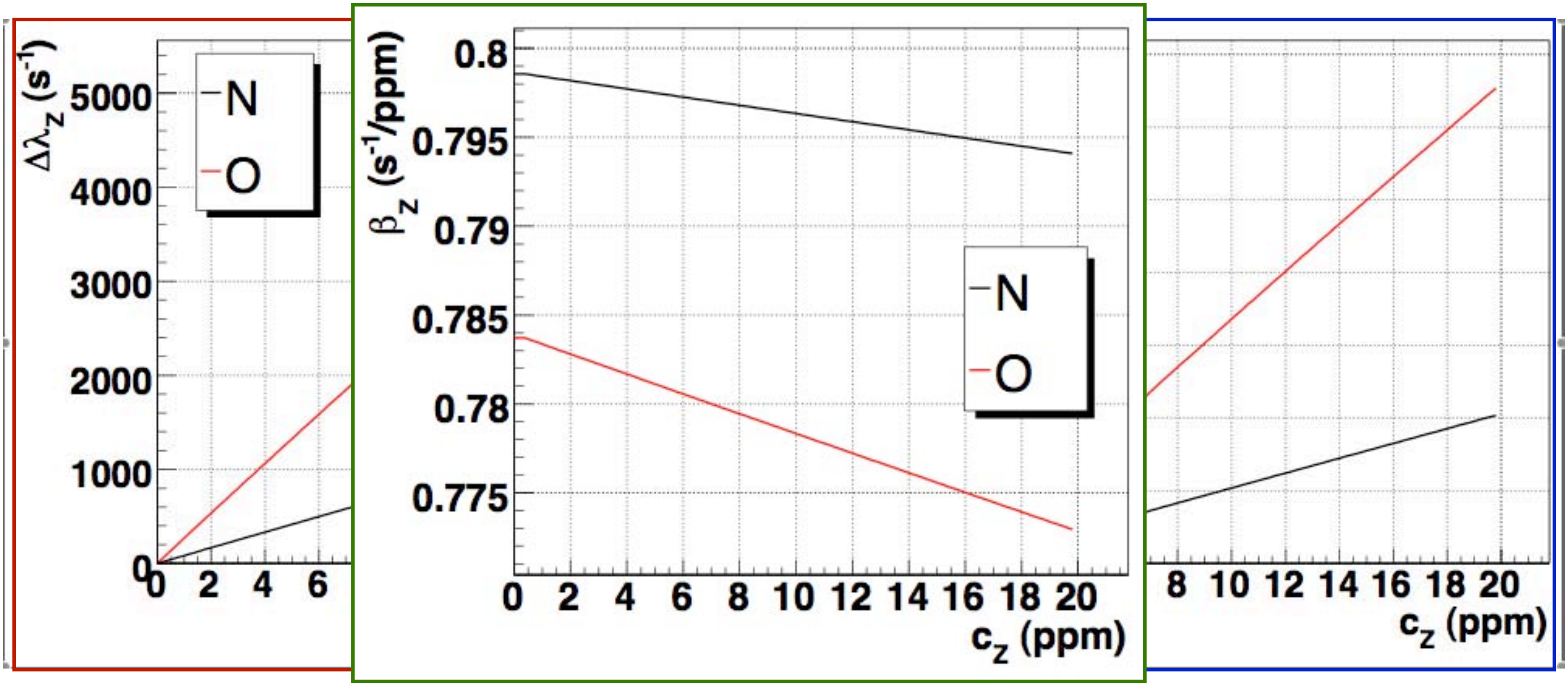
Fit Function:

$f(t) = A \exp(-\lambda t)$

$$\lambda^{-1} = \lambda_{1\text{st}}^{-1} \equiv \frac{\int_0^\infty t y_e(t) dt}{\int_0^\infty y_e(t) dt}$$

$$\Delta\lambda_Z = \lambda_{1\text{st}}(c_Z = 0) - \lambda_{1\text{st}}(c_Z)$$

Impurity correction scales with Z > 1 capture yield.

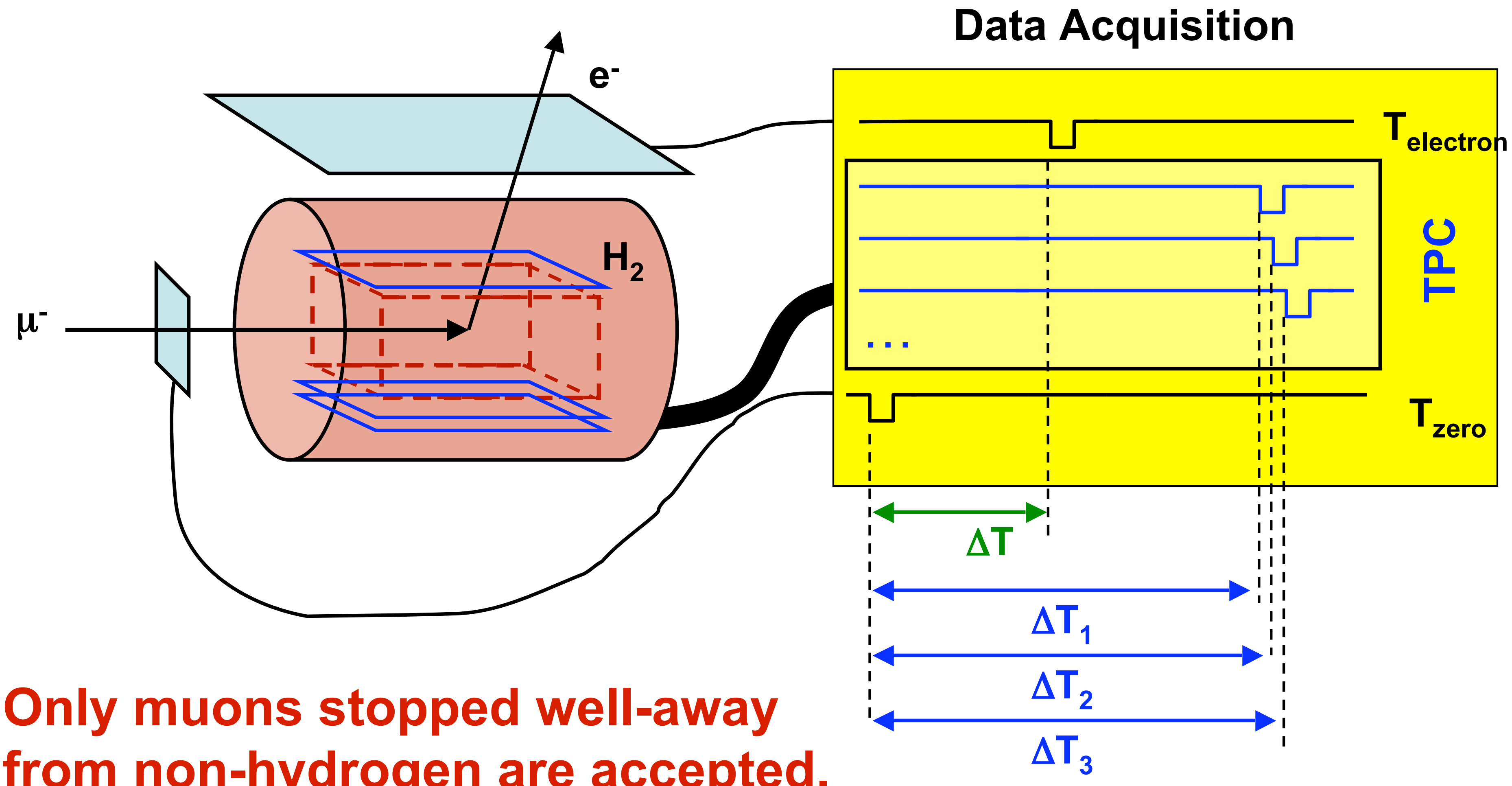


$\beta_Z = \Delta\lambda_Z / Y_Z$ is similar for C, N, and O.

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

μCap Method: Clean μ Stop Definition

Each muon is tracked in a time projection chamber.



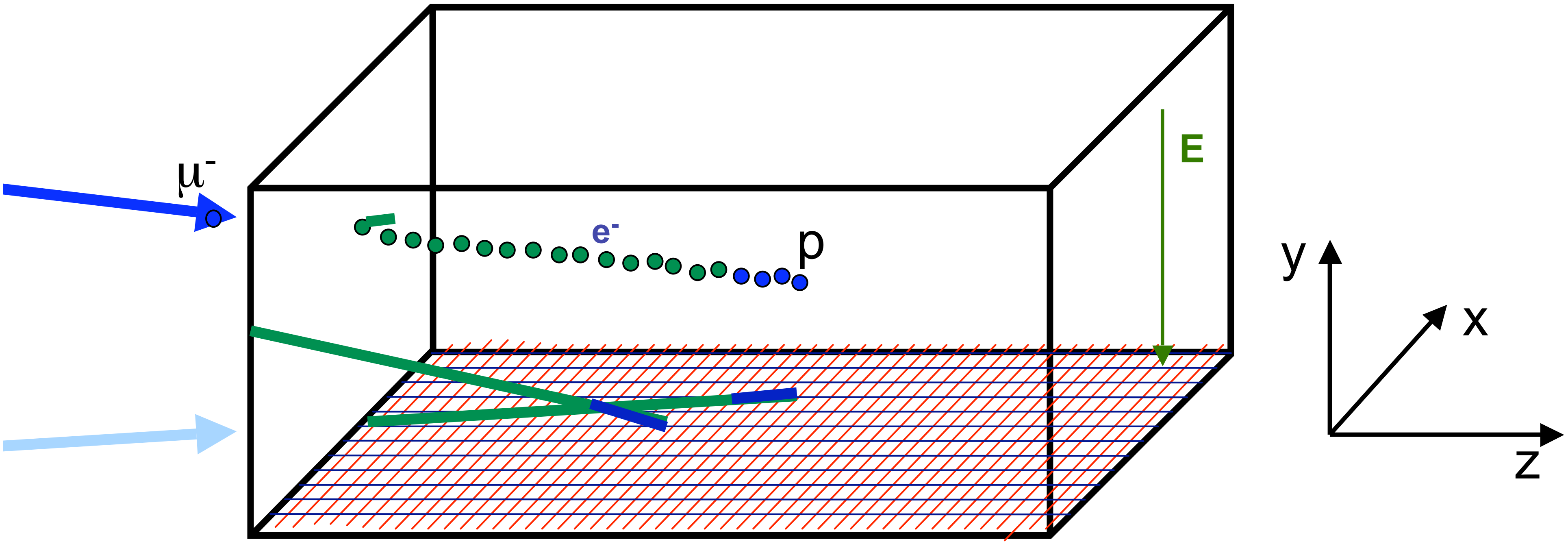
Only muons stopped well-away from non-hydrogen are accepted.

$0 < \Delta T_i < 22\ \mu s$

Tracking in the Time Projection Chamber

1) μ entrance, Bragg peak at stop.

2) ionization electrons drift to MWPC.

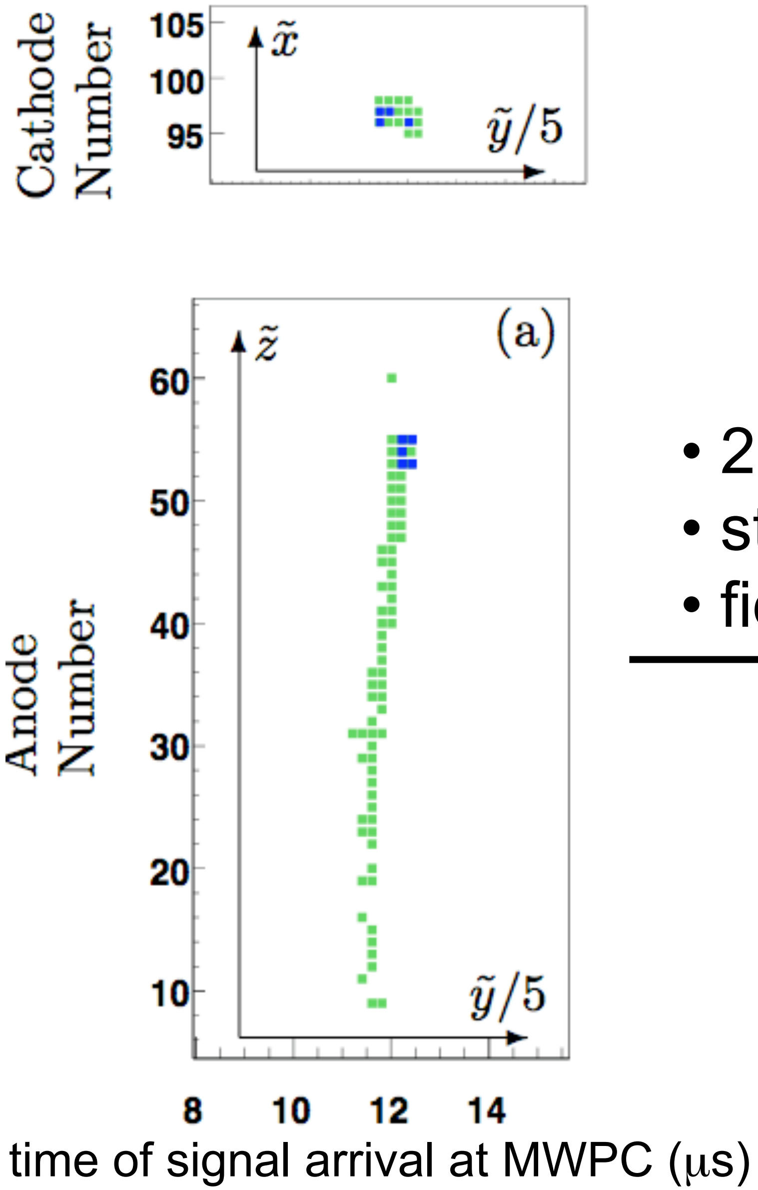


3) projection onto zx plane from anodes and strips.

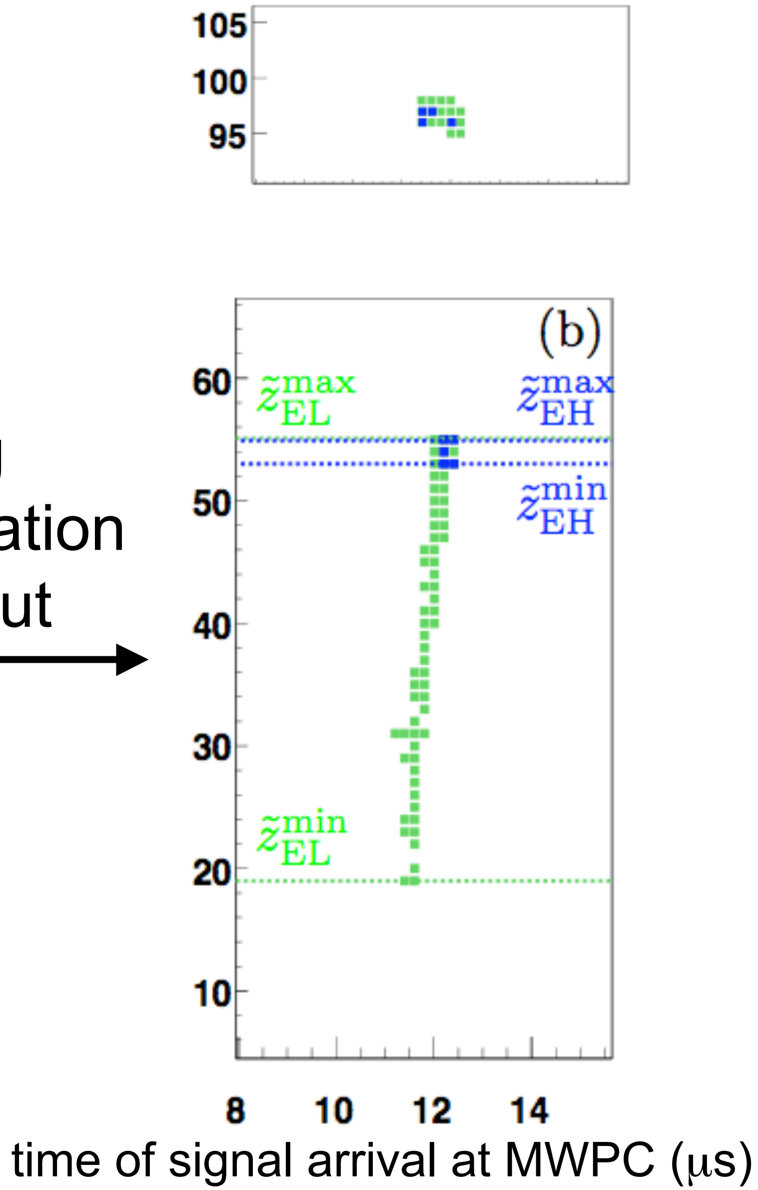
4) projection onto zy plane from anodes and drift time.

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

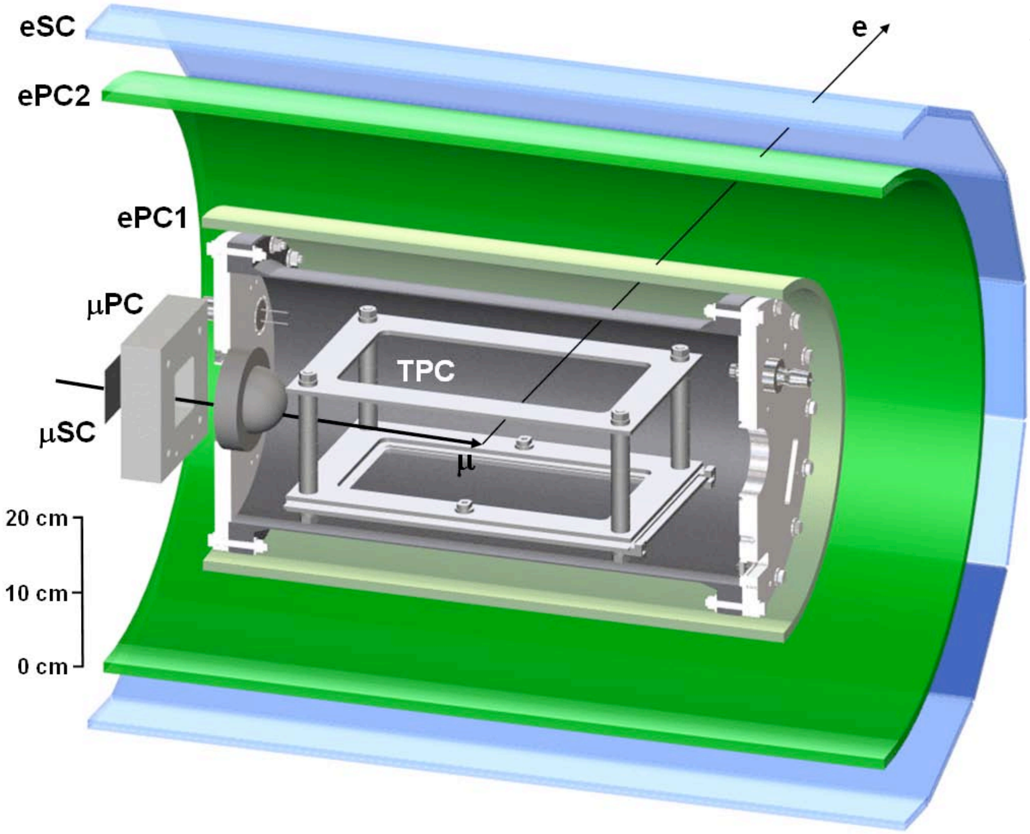
Muon Definition



- 2D clustering
- stop identification
- fiducial vol. cut

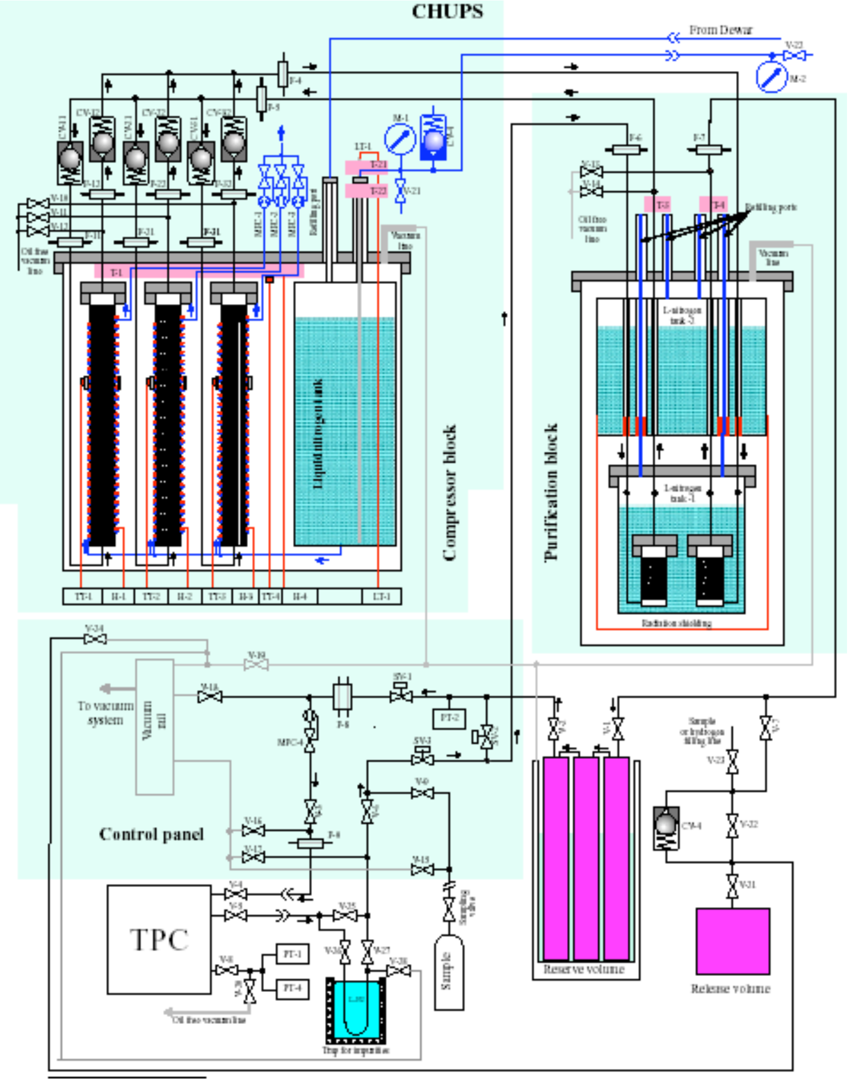


Electron Definition

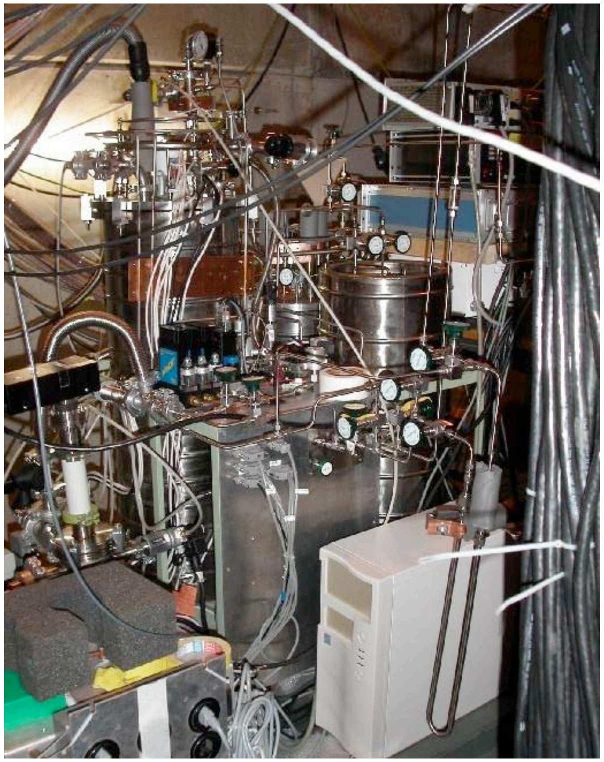


- timing from scintillator (eSC)
- temporal and spatial coincidences with wire chamber planes: full 3D tracking

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



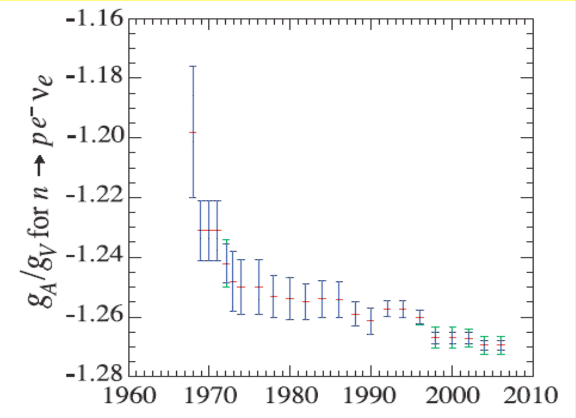
Commissioned 2004



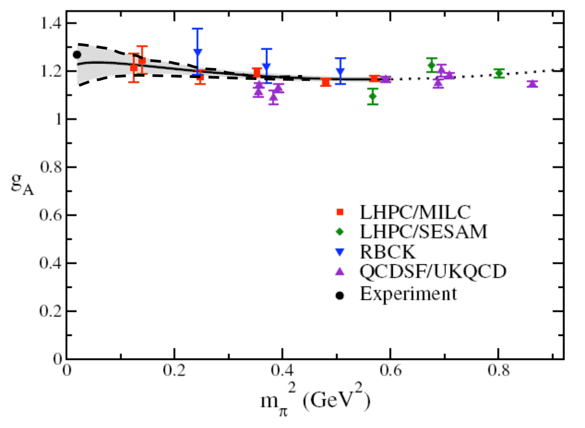
$c_{N2}, c_{O2} < 0.01$ ppm

Axialvector Form Factor g_A

Exp. History



Lattice QCD



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

Edwards et al. LHPC Coll (2006)

Bernard et al. (2002)

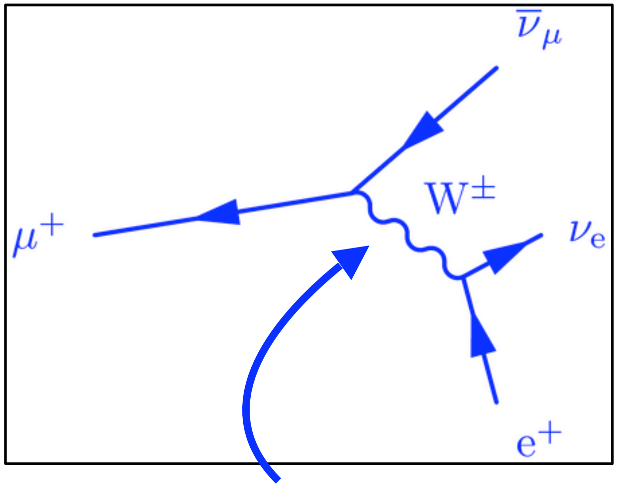
$$g_A(q^2) = g_A(0)(1 + \tfrac{1}{6} < r_A^2 > q^2)$$

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

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

introduces 0.4% uncertainty to Λ_S (theory)

Muon decay gives us unique access to the electroweak scale

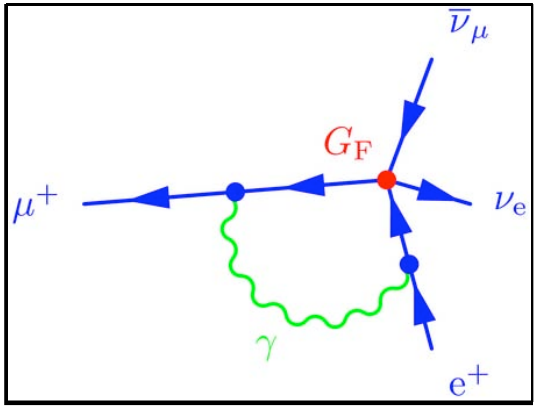


The muon decays only via the weak interaction

The V-A theory factorizes into a pure weak contribution,

and non-weak corrections, essentially uncontaminated by hadronic uncertainties.

$$\frac{1}{\tau_{\mu^+}} = \frac{G_F{}^2 m_\mu^5}{192\pi^3}$$

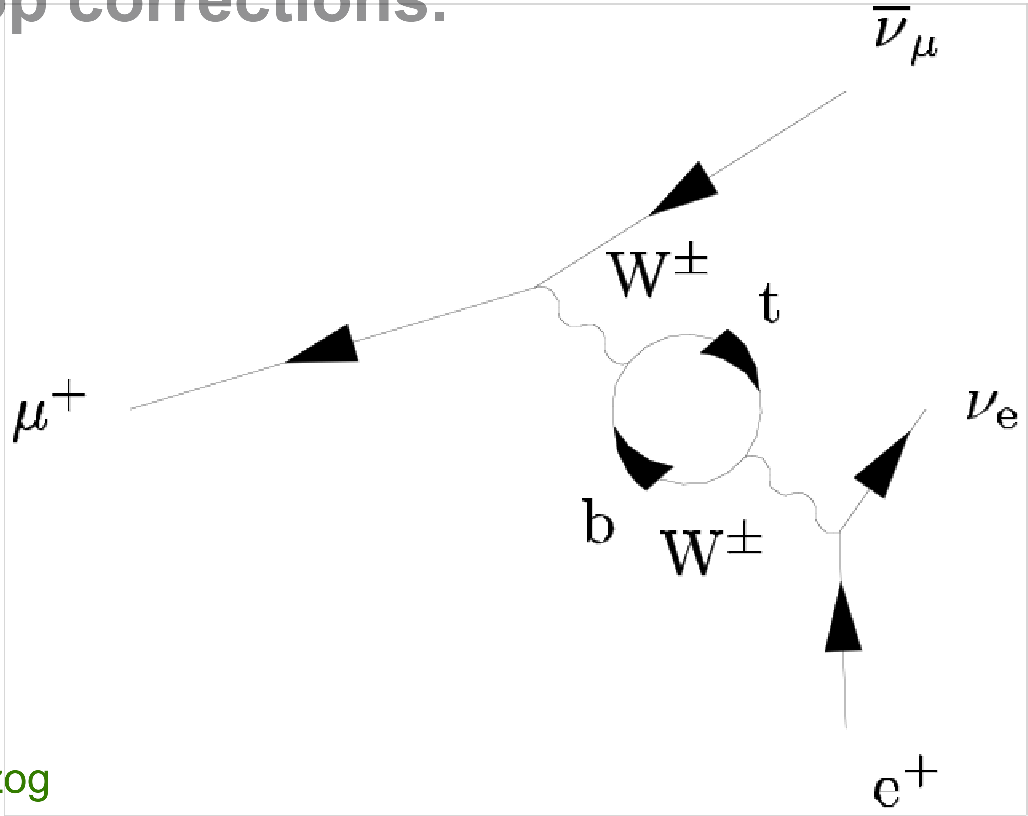


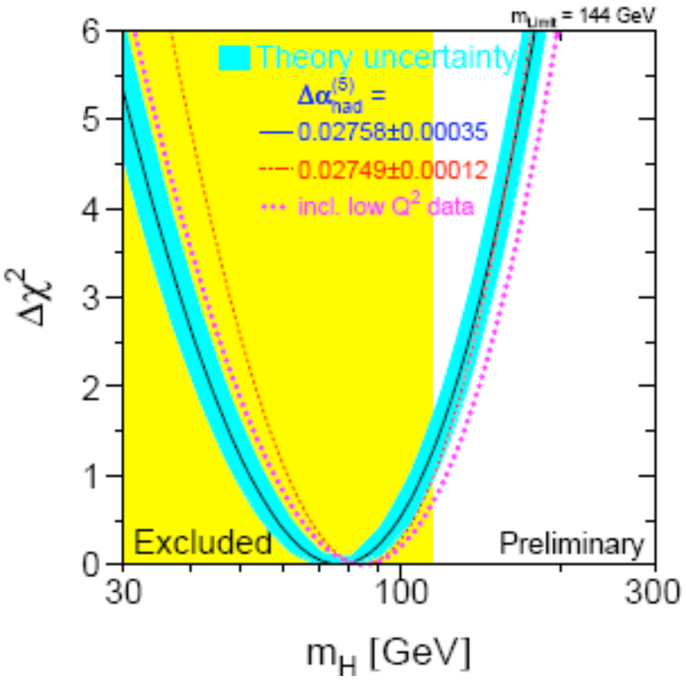
D. Hertzog

The Fermi constant is an implicit input to all precision electroweak studies

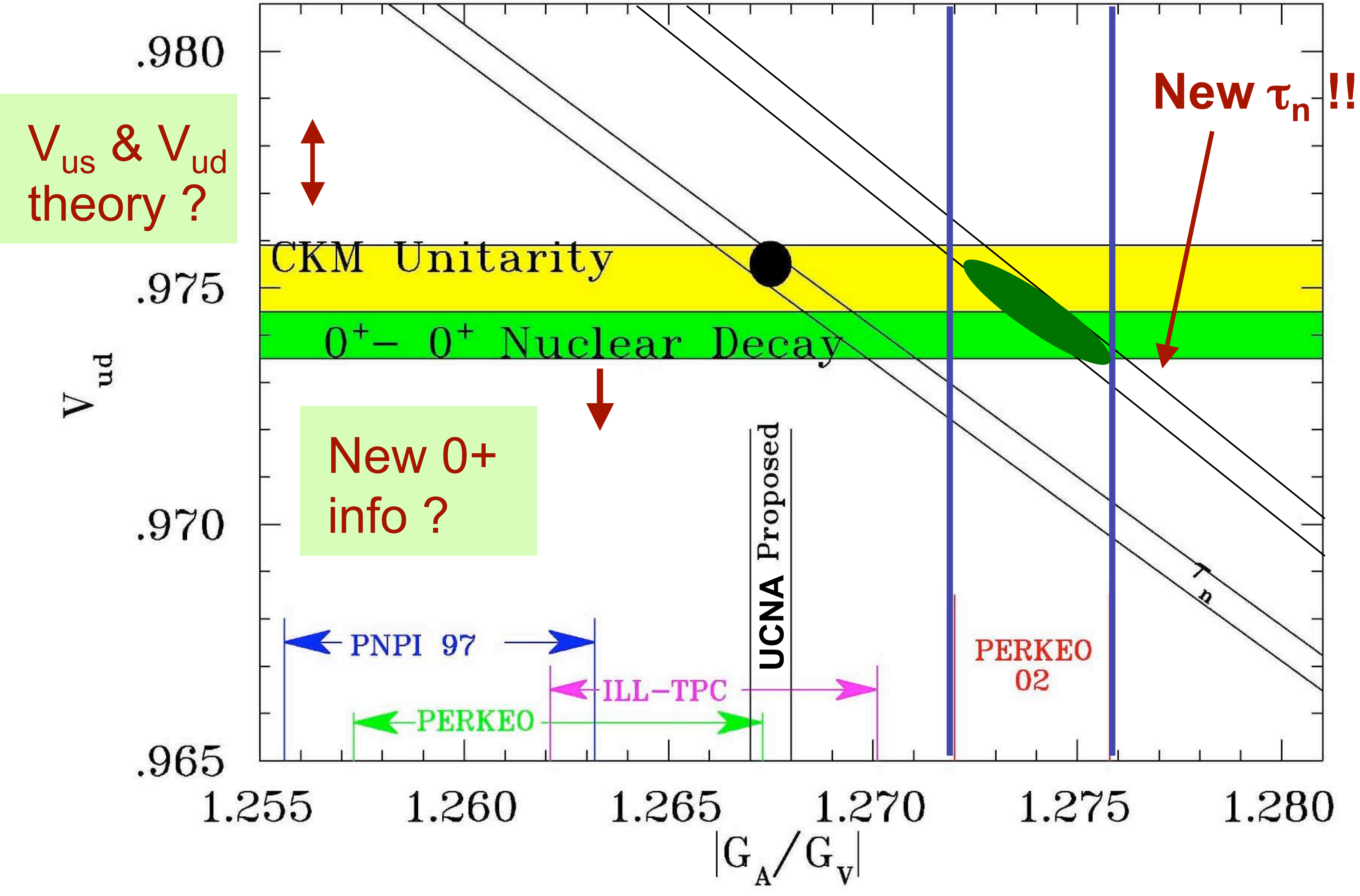
$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}\left(1 + \Delta r(m_t, m_H, \ldots)\right)$$

Contains all weak interaction loop corrections.





CKM Summary: New V_{us} & τ_n ?



V_{us} & V_{ud} theory ?

New 0+ info ?

New 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

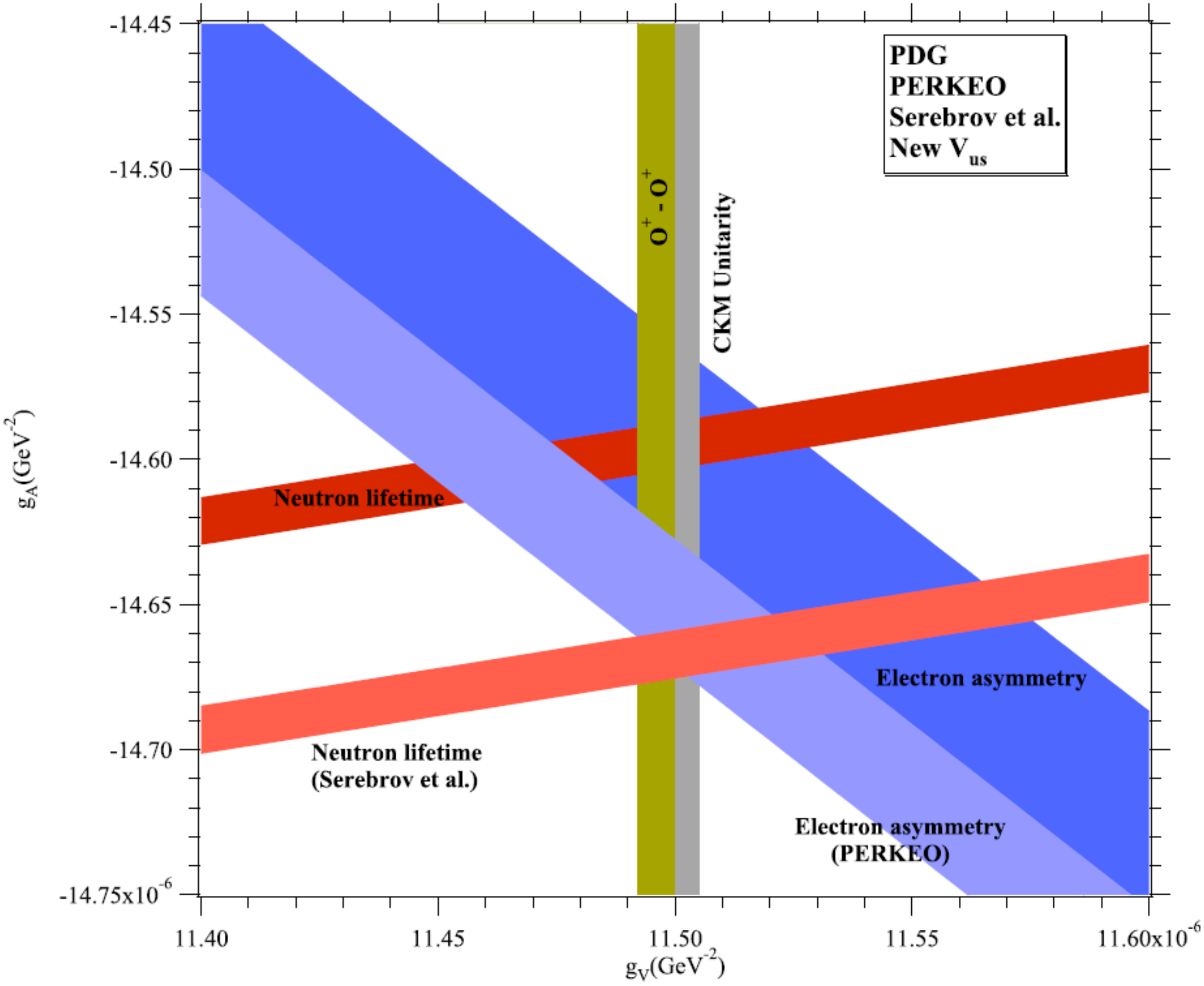
$$A = -2\frac{|\lambda|^2 + |\lambda|cos\phi}{1+3|\lambda|^2} = (-0.1173 \pm 0.0013)$$

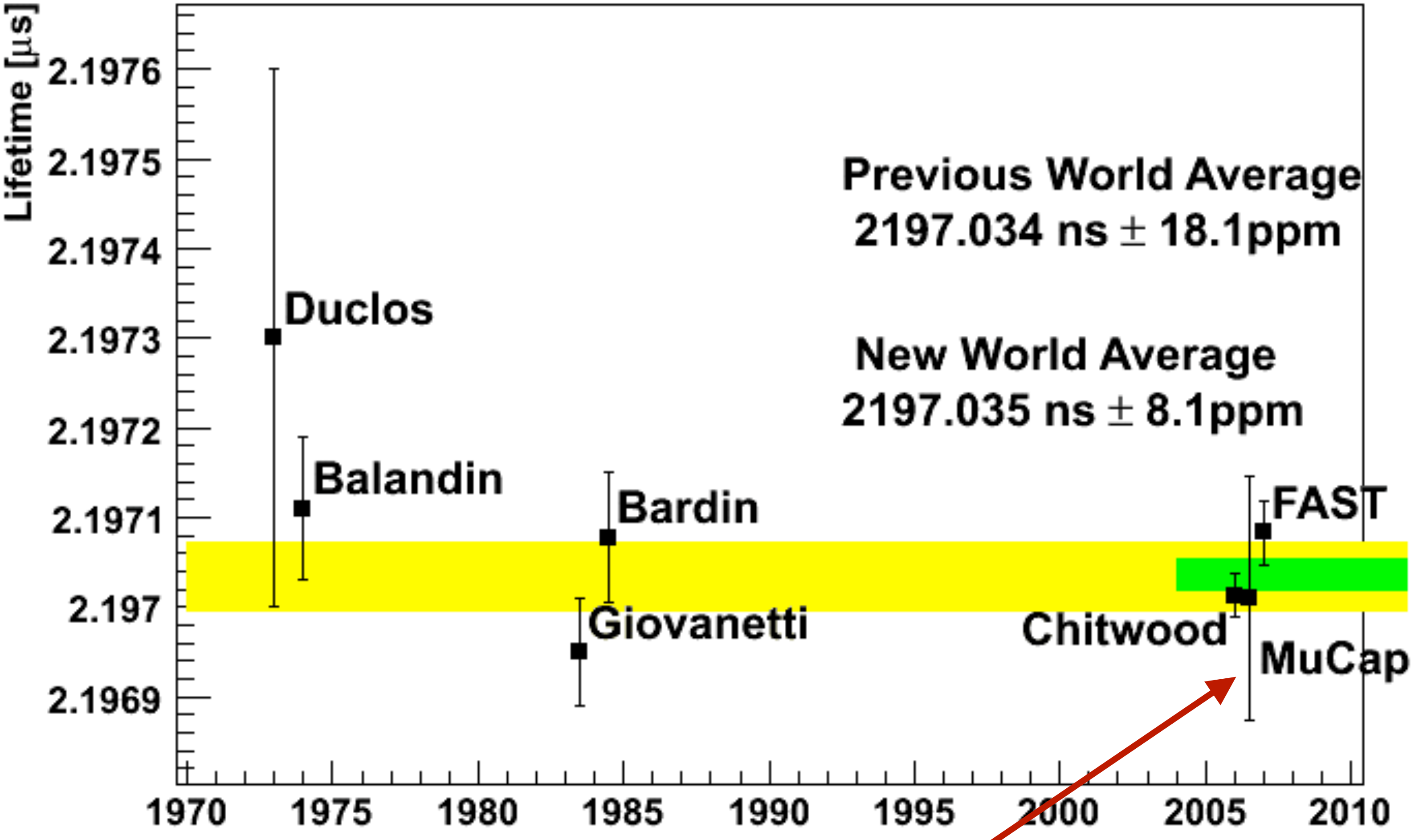
Triple correlation

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

PDG, 2005 update

neutron


PDG
PERKEO
Serebrov et al.
New V_{us}
$0^+ - 0^+$
CKM Unitarity
Neutron lifetime
Neutron lifetime
(Serebrov et al.)
Electron asymmetry
Electron asymmetry
(PERKEO)
-14.45
-14.50
-14.55
-14.60
-14.65
-14.70
-14.75x10^{-6}
$g_A(GeV^{-2})$
11.40
11.45
11.50
11.55
11.60x10^{-6}
$g_V(GeV^{-2})$



Unpublished analysis of MuCap μ^+ data taken in 2004