Experiments on Muon Capture and Muon lifetime: Latest results and future goals.

Bernhard Lauss

Ultra-Cold Neutron Group
Paul Scherrer Institut

on behalf of the MuCAP / MuLAN / MuSUN collaborations

PNPI / UIUC / UCB / UB / JM / UCL / UKY / USC / RUD / PSI

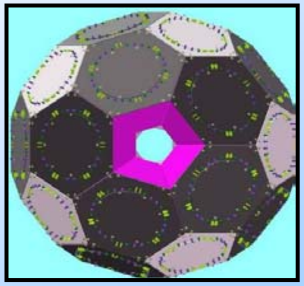
Overview of this talk

Introduction to the physics and the precision experiments of

1)

G_F

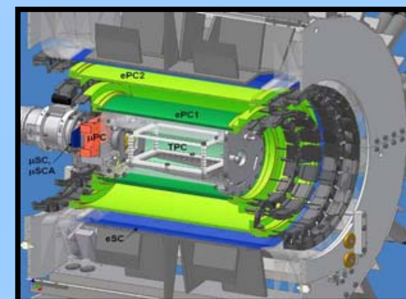
MuLan



2)

g_P

MuCap



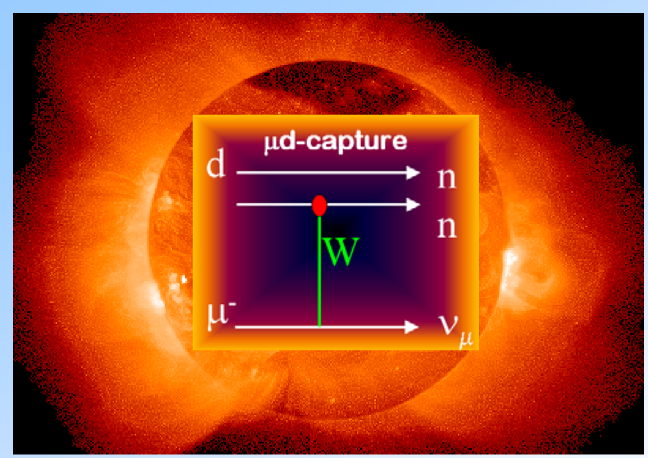
1st result published

3)

new project

L_{1A}

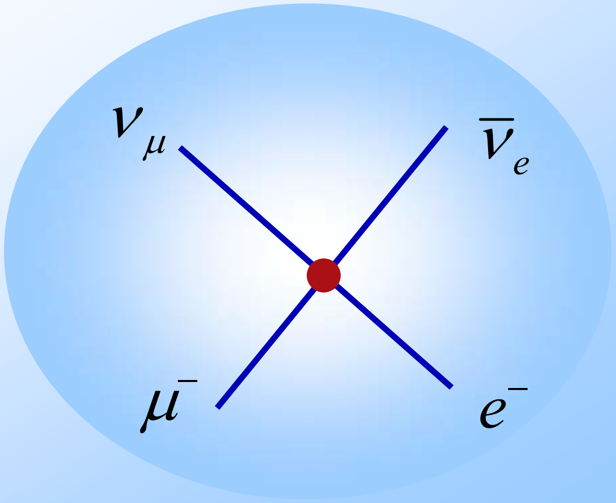
MuSun



V-A theory successfully describes all weak interaction processes
2 basic examples

muon decay

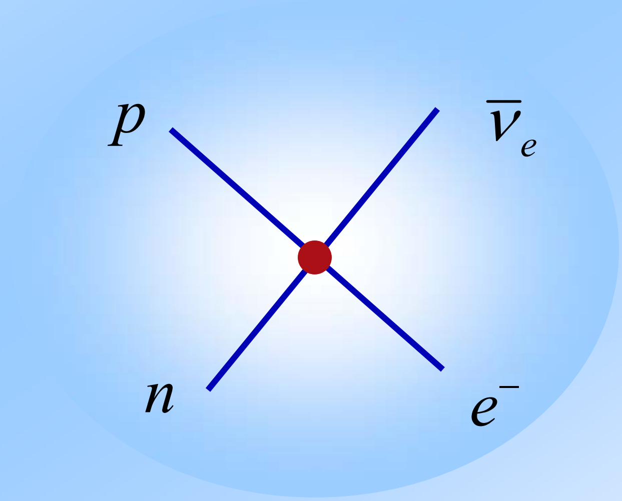
$$\mu^- \rightarrow \nu_\mu e^- \overline{\nu}_e$$



involves only leptons
(pointlike / elementary)

neutron beta decay

$$n \rightarrow p e^- \overline{\nu}_e$$



involves nucleons
(composite / with substructure)

The weak matrix element is defined by the currents and couplings.

muon decay

$$\mu^- \rightarrow \nu_\mu e^- \overline{\nu}_e$$

neutron beta decay

$$n \rightarrow p e^- \overline{\nu}_e$$

The current-current interaction successfully describes weak processes
weak current J
decay rate ≈ J^2
M ~ J

Fermi's Golden Rule

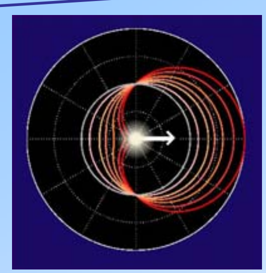
$$\lambda_{if} = \frac{2\pi}{\hbar} \left| M_{if} \right|^2 \rho_f$$

transition probability
interaction matrix element
final states density

elementary level

$$\mathbf{J}_\ell = \langle \nu_\mu | \gamma_\alpha (1 - \gamma_5) | \mu \rangle$$

maximum parity violation



elementary level (quarks)

$$\mathbf{J}_q = \langle \mathbf{d} | \gamma_\alpha (1 - \gamma_5) | \mathbf{u} \rangle$$

nucleon level

$$\mathbf{J}_N = \langle \mathbf{n} | \mathbf{V}_\alpha - \mathbf{A}_\alpha | \mathbf{p} \rangle$$

The G_F from V-A Theory is a common coupling constant.

muon decay

$$\mu^- \rightarrow \nu_\mu e^- \overline{\nu}_e$$

neutron beta decay

$$n \rightarrow p e^- \overline{\nu}_e$$

decay rate (life time) ≈ M²

$$M = \frac{G_F^\mu}{\sqrt{2}} \overline{\nu}_\mu \gamma^\lambda (1-\gamma_5) \mu \, \overline{e} \gamma^\lambda (1-\gamma_5) \nu_e$$

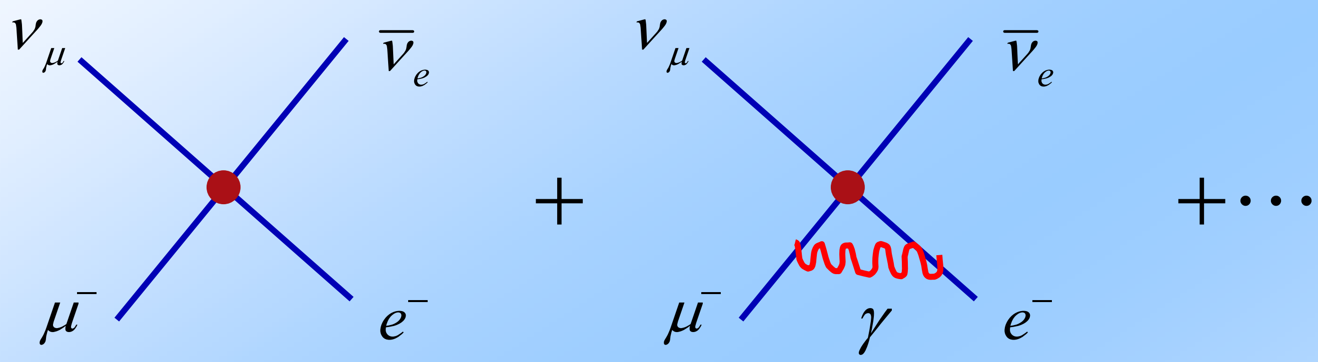
$$M = \frac{G_F^\beta}{\sqrt{2}} V_{ud} \overline{p} \gamma^\lambda \left(g_V + g_A \gamma_5 \right) n \, \overline{e} \gamma_\lambda (1-\gamma_5) \nu_e$$

Same coupling constant – Fermi's success

$$\frac{G_F^\beta}{G_F^\mu} = 1$$

PEN experiment at PSI wants to do a precision test of this μ-e (lepton) universality

Muon decay rate
standard QED calculation

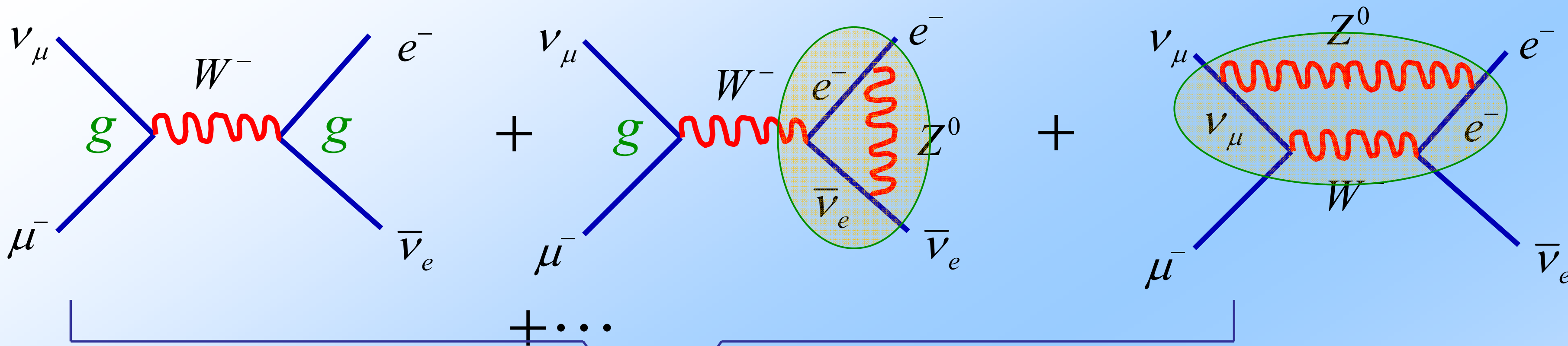


Schwinger Term

QED radiative corrections

$$\frac{1}{\tau_\mu} = \frac{G_F^2 m_\mu^5}{192\pi^3}\left[1 + \frac{\alpha}{2\pi}\left(\frac{25}{4} - \pi^2\right) + \cdots\right]$$

Weak radiative corrections from the Standard Model.



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

precision EW physics via quantum loops needs G_F.

(probes particle spectrum by comparison of different processes / top mass prediction)

G_F is an integral part of the Standard Model

Dominant theoretical uncertainty in muon lifetime was reduced from 16 to 0.3 ppm ! (2-loop '99)

Experimental goal for MuLAN

τ_μ = 1 ppm precision

$\Rightarrow G_F$ = 0.5 ppm

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ra Cold Neutron Source

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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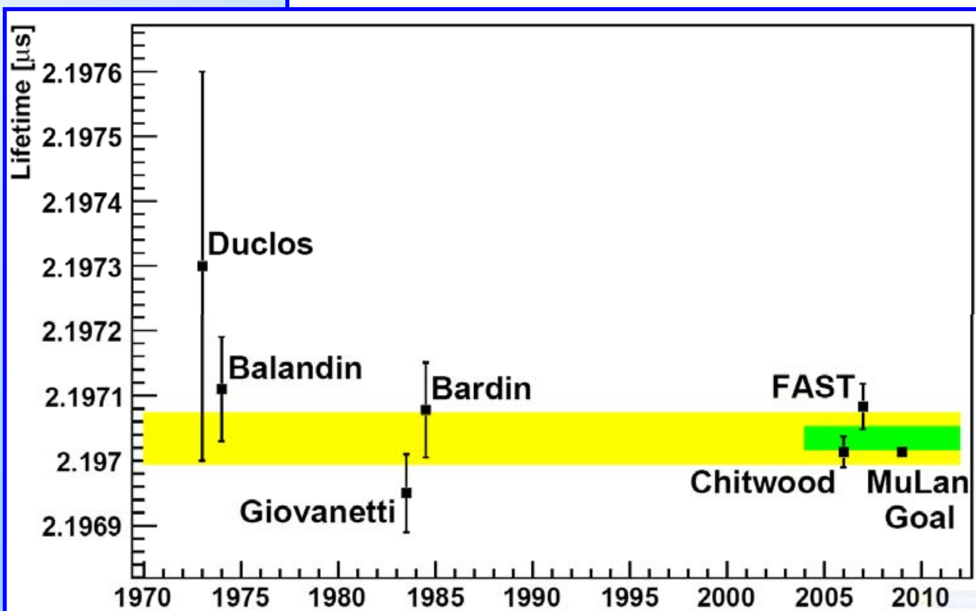

1st MuLAN result

τ_μ(MuLan) = 2.197 013(21)(11) µs (11ppm)

τ_μ(World) = 2.197 019(21) µs (9.6 ppm)

G_F = 1.166 371(6) x 10^{-5} GeV^{-2} (5 ppm)

FAST next presentation by C. Casella

e-Print: **arXiv:0707.3904** [hep-ex]

Neutron decay measures the axial coupling.

muon decay

$$\mu^- \to \nu_\mu e^- \bar{\nu}_e$$

$$M = \frac{G_F}{\sqrt{2}} \bar{\nu}_\mu \gamma^\lambda (1-\gamma_5) \mu \, \bar{e} \gamma^\lambda (1-\gamma_5) \nu_e$$

neutron beta decay

$$n \to p e^- \bar{\nu}_e$$

composite system

$V_{ud} \sim 0.97 \pm 0.01\%$
from CKM Matrix

modified axial coupling

$$M = \frac{G_F}{\sqrt{2}} V_{ud} \bar{p} \gamma^\lambda \left(g_V + g_A \gamma_5 \right) n \, \bar{e} \gamma_\lambda (1-\gamma_5) \nu_e$$

$g_A \approx 1.25$

Neutron decay measures the axial coupling.

modified axial coupling

$$M = \frac{G_F^\beta}{\sqrt{2}} V_{ud} \bar{p} \gamma^\lambda \left(g_V + g_A \gamma_5 \right) n \; \bar{e} \gamma_\lambda (1 - \gamma_5) \nu_e$$

$1/\tau_n \approx M^2$ determine $g_A \approx 1.25$

At this time the value of τ_n is heavily discussed.

Letter of Intent of TU Munich for a
" Precision measurement of the neutron lifetime confined in a magneto-gravitational trap "
at the PSI UCN source
(precision < 0.1 %)

Muon Capture

involves nucleons at higher momentum

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

muon capture is
the inverse of β - decay
(e.g. electron K-capture)

V-A current

$J_N = \langle n|\ V_\alpha - A_\alpha\ |p\rangle$

Not only g_V and g_A but more "induced" components in the current as a sign of the proton/neutron sub-structure (quarks) gain relevance at higher momentum transfer.

Muon capture process is at higher momentum transfer $q^2 = -0.88\ m_\mu^2$

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nucleon level

$$J_\alpha = \langle n|\ V_\alpha - A_\alpha\ |p\rangle$$

Lorentz invariance allows 6 terms and couplings in the nucleon charged current.

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

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

Muon capture involves one lepton and one hadron (semi-leptonic interaction).

Muon capture process is at higher momentum transfer $q^2 = -0.88\ m_\mu^2$

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nucleon level

$$J_\alpha = \langle n|\ V_\alpha - A_\alpha\ |p\rangle$$

G-symmetry

no second class currents

Lorentz invariance allows 6 terms and coupling ...e nucleon charged current.

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

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

G-Parity $G = C \times R = C \exp(i\pi I_2)$

R - 180 º Rotation in isospin space, C - charge conjugation

Strong Interaction is separately invariant under C and R = G-invariant ->

second class currents would conflict with standard quark model

$g_s = 0$ (CVC)

How well do we know these form factors ?

nucleon weak form factors g_V, g_M, g_A, g_P

(at the relevant q^2)

- determined by SM symmetries and data
- contribute < 0.4% uncertainty to Λ_S

$g_V = 0.9755(5)$

$g_M = -3.5821(25)$

$g_A = -1.245(3)$

remains induced pseudo-scalar

$g_P = ?$

known up to 2007 (before MuCAp experiment) at best only to 20% - 100% / value discussed

- Vector current in SM determined $g_V(0) = 1$
- $g_M(0) = \mu_p - \mu_n + 1 = -3.70589$
  q^2 dependence from e scattering

  g_V & g_M ep scattering / precision measurements at JLAB & MAMI
- Axial vector FF from neutron decay $g_A(0) = -1.2695(29)$
  q^2 dependence from ν-nucleon scattering or π electro-production
- 2nd class FF g_S, g_T forbidden by G symmetry e.g. $g_T/g_A = -0.15 \pm 0.15$ (exp), -0.0152 ± 0.0053 (QCD sum rule, up-down mass difference)
- error from $V_{ud} \sim 0.01$ %

Calculation of the pseudo-scalar form factor g_P

PCAC: Pion Pole Term & 1-loop

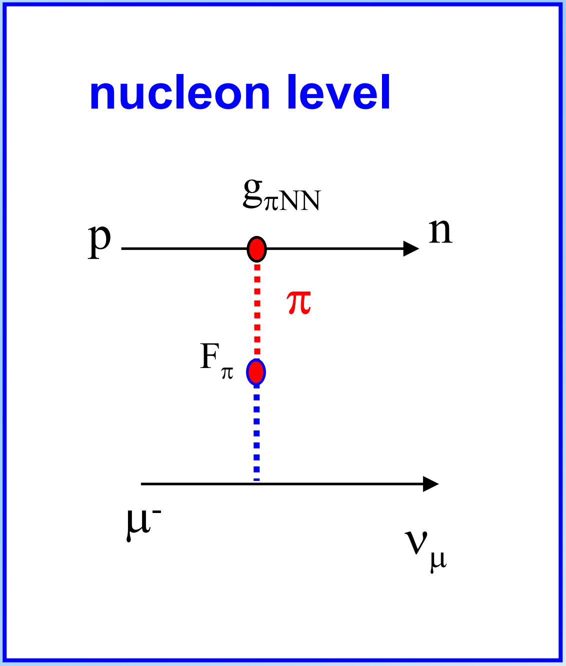
$$g_P(q^2) = \frac{2\, m_\mu\, g_{\pi NN}\, F_\pi}{m_\pi{}^2 - q^2} - \frac{1}{3}\, g_A(0) m_\mu M\, r_A{}^2$$

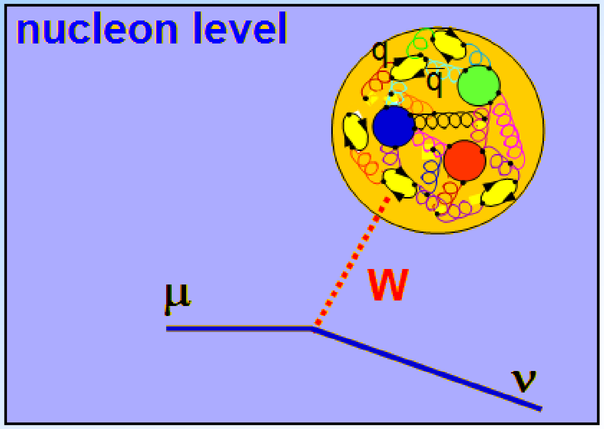
$g_P = (8.74 \pm 0.23) - (0.48 \pm 0.02) = 8.26 \pm 0.23$

U.Meißner et al.

Today: g_p can be calculated very successful via heavy baryon chiral perturbation theory from basic priciples, which gives a systematic expansion in the light quark masses and the coupling constant with reliable error estimate !

- solid QCD prediction via ChPT (2-3% level)
- NNLO < 1%: N. Kaiser, PRC67 (2003)
- basic test of QCD symmetries





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Experimental information on g_p comes from nuclear muon capture rate λ_s

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The best direct measurement is in hydrogen via 2 processes:

Ordinary Muon Capture

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

Yield = 10^{-3}

g_P contributes ~ 8% of to the OMC rate

Radiative Muon Capture

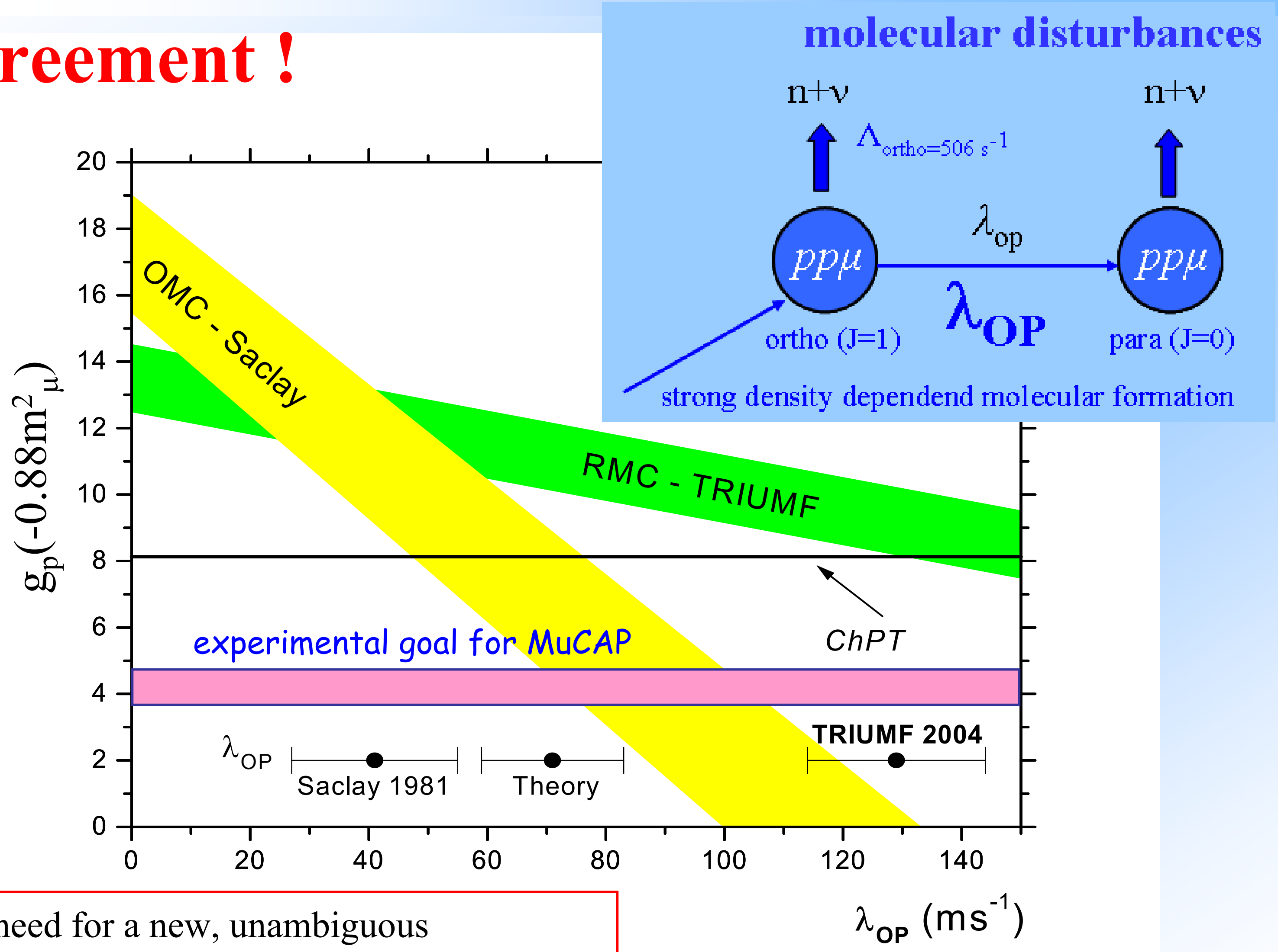
$$\mu^- + p \rightarrow \nu_\mu + n + \gamma$$

Yield = 10^{-8}
E_{PH}>60MeV

This is a hard experiment because there are only neutral particles as reaction products.

Experimental situation on g_P before MuCAP

Disagreement !



need for a new, unambiguous
precision determination without λ_{OP} dependence

Experimental situation on g_P with 1st MuCAP result

Disagreement solved !

PRL **99,** 032002 (2007) PHYSICAL REVIEW LETTERS week ending 20 JULY 2007

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

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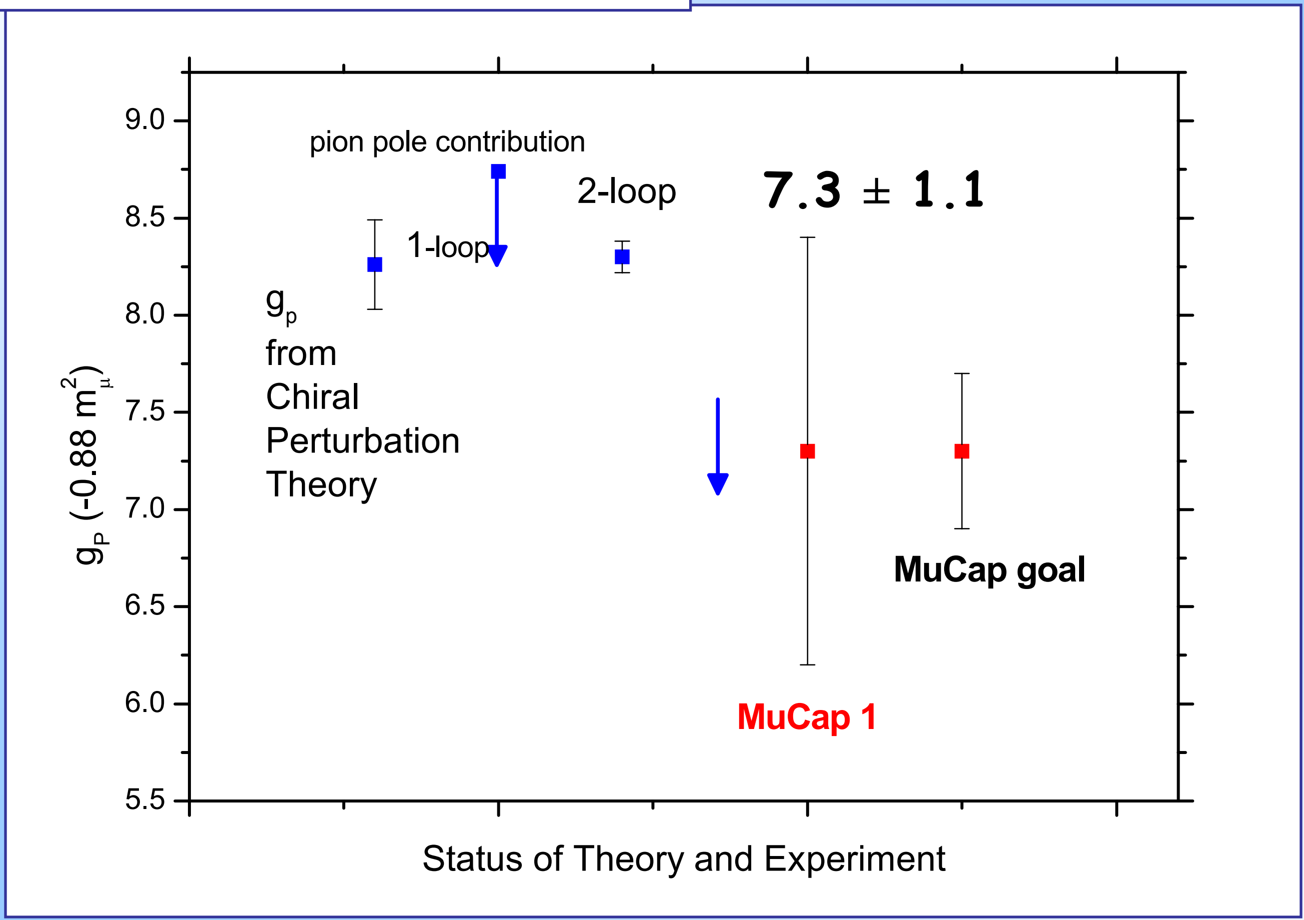
(Received 16 April 2007; published 16 July 2007)

New g_P world view and MuCAP Goal

$$g_P(q^2) = \frac{2\, m_\mu\, g_{\pi NN}\, F_\pi}{m_\pi^2 - q^2} - \frac{1}{3}\, g_A(0) m_\mu M\, r_A^2$$

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



How to do such experiments ?

How to measure the muon lifetime ?

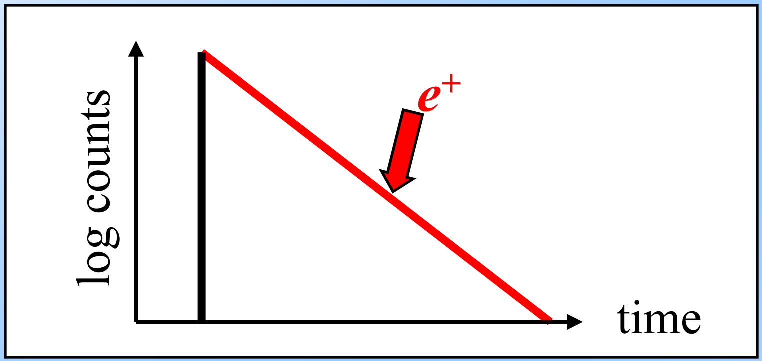
How to measure the muon capture rate ?

How to measure the muon lifetime ?

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

We measure the time difference between the muon stop signal and the decay electron signal.
The slope of the exponential time distribution ~ decay-rate λ !

$$\lambda = \tau^{-1} \qquad N(t) = N(0)\,e^{-t/\tau}$$

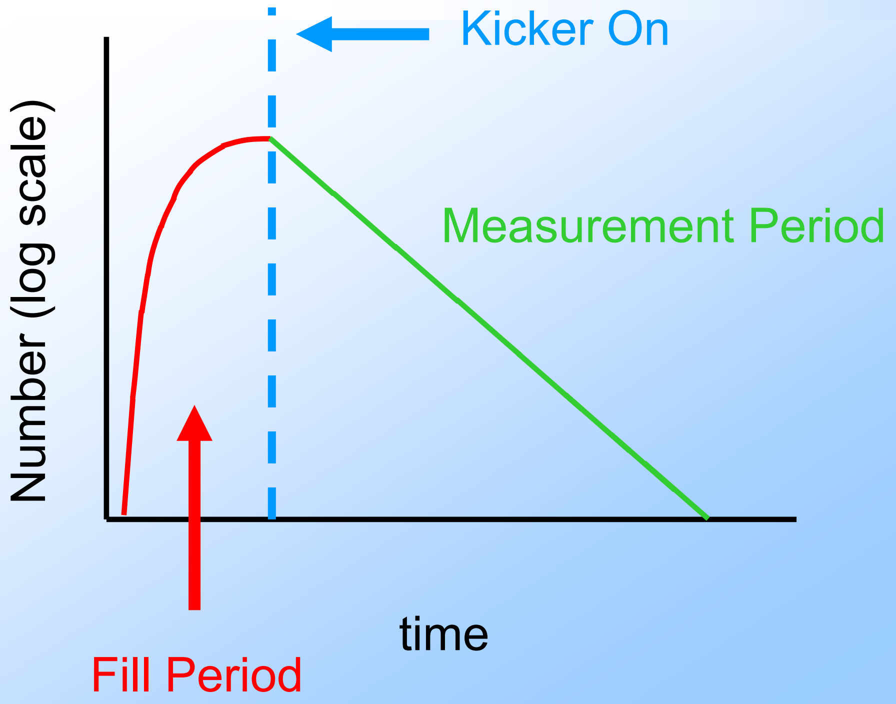


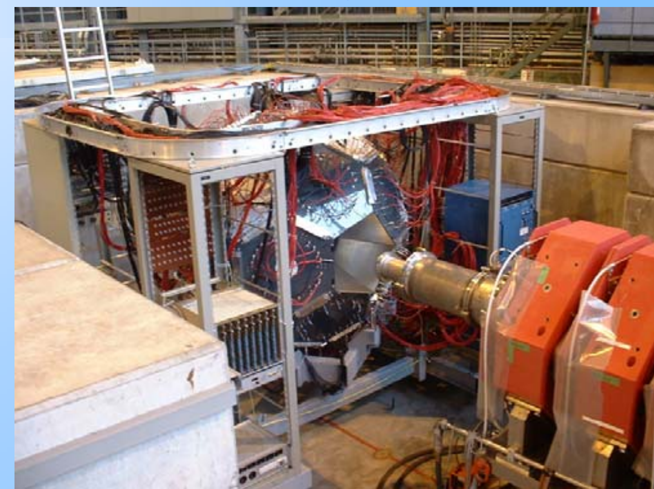
MuLAN result

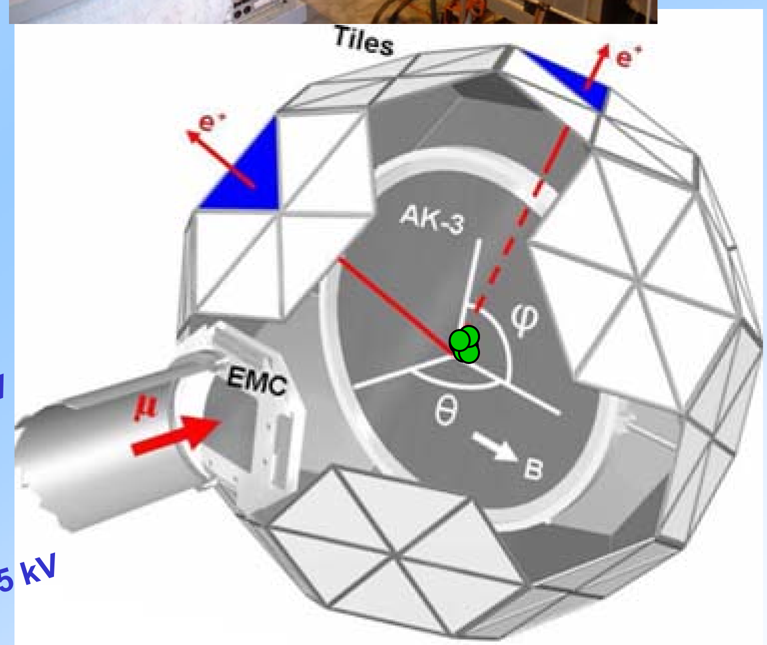
$G_F(\mu+)$

new beamline
Kicker operation for MuLan experiment

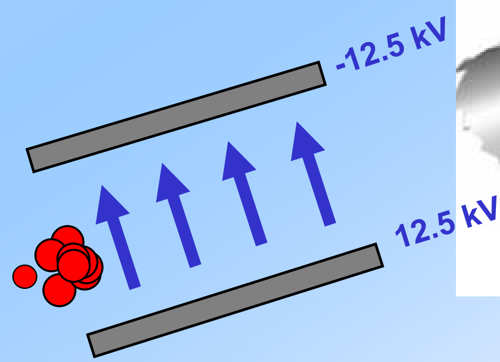
Ultra Cold Neutron Source







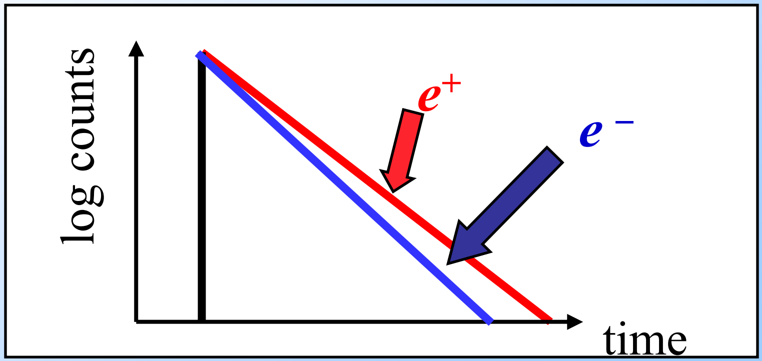
μ^+ lifetime
-> G_F



MuCAP experimental principle:

Measurement of the muon capture rate via comparison of μ+ and μ- lifetimes in hydrogen.

Lifetime method



$$\Lambda_S = \Lambda_{(\mu^-)'} - \Lambda_{\mu^+} = \left(\tau_{(\mu^-)'}\right)^{-1} - \left(\tau_{\mu^+}\right)^{-1}$$

MuCAP measures decay electrons and avoids absolute neutron counting but the small difference of two large numbers is also hard to measure. ⇒ need for high precision.

μ^- capture competes with muon decay:

$$\mu^- \to e^- \nu_\mu \bar{\nu}_e \qquad (99.85\%)$$

$$(p\mu^-)_{\uparrow\downarrow} \to n + \nu_\mu \qquad (0.15\%)$$

Experimental goal: measure $\tau_{\mu+}$ and $\tau_{\mu-}$ to 10^{-5} ⇒ g_p to ~ 5%

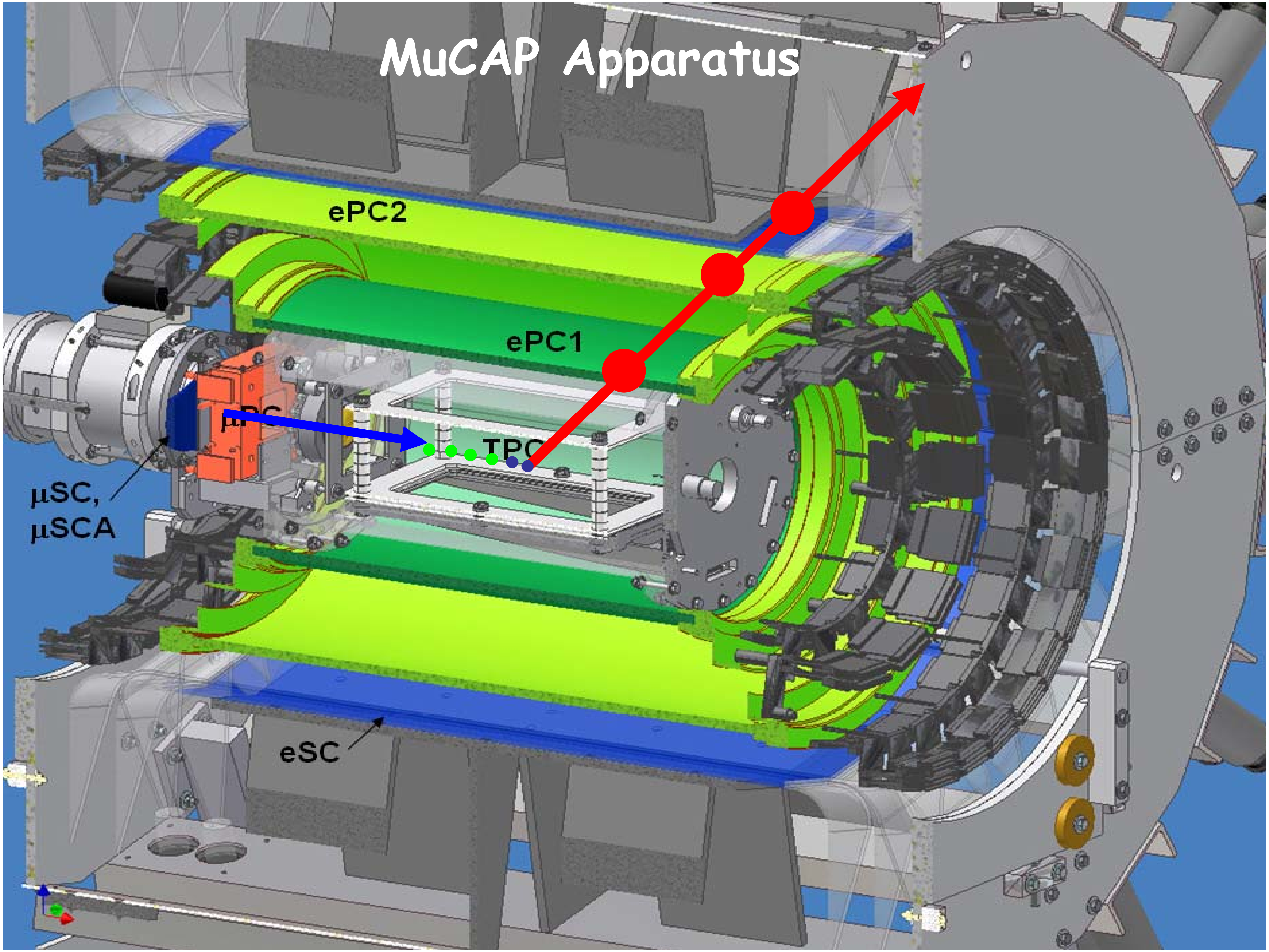
How to do such a measurement ?

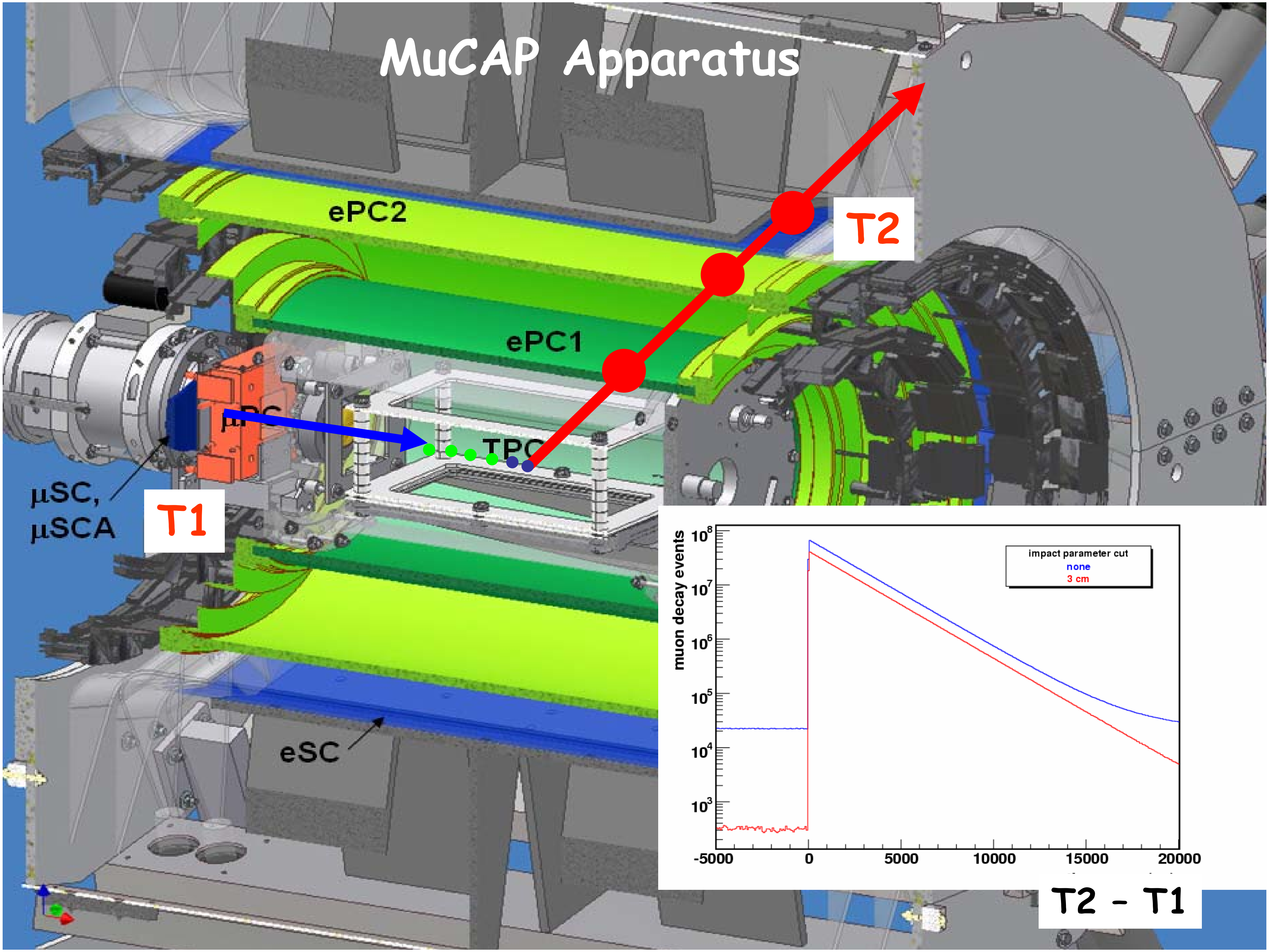
With the requirement of high precision a simple slope measurement is not so simple anymore.

$\Rightarrow$ systematic issues are dominant

- One needs high statistics of ~ 10^{10} events
  -> built new beamline
- Need for a clean muon stop identification / wall effects.
- Need for a clean decay electron identification.
  -> built new detectors

- Control of atomic and molecular effects.
- Control of muon spin rotation.
  -> optimize measurement conditions

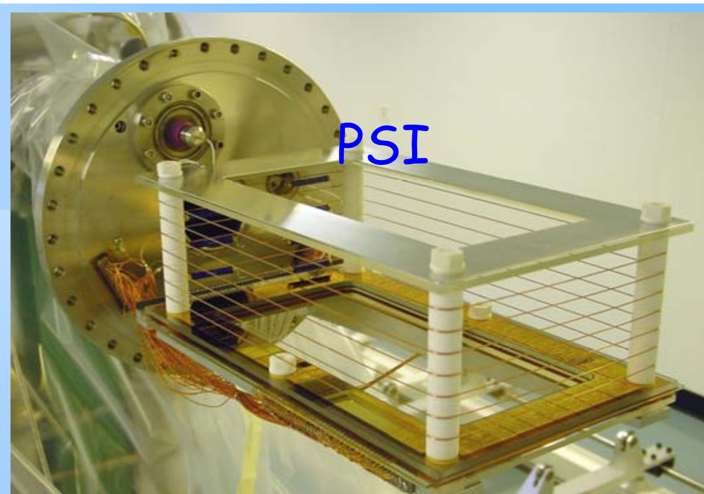

MuCAP Apparatus
ePC2
ePC1
μPC
TPC
μSC,
μSCA
eSC



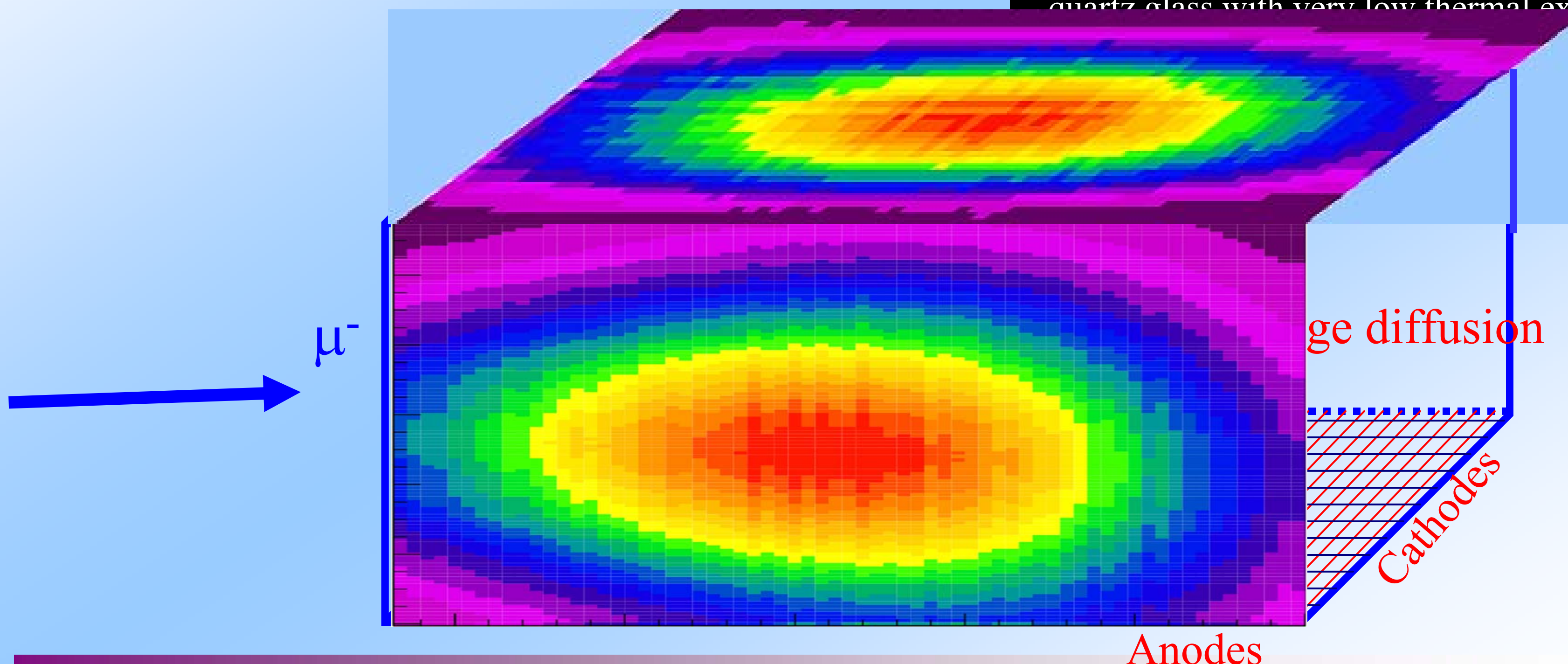
MuCAP Apparatus
ePC2
T2
ePC1
μPC
TPC
μSC,
μSCA
T1
eSC
muon decay events
impact parameter cut
none
3 cm
10^8
10^7
10^6
10^5
10^4
10^3
-5000
0
5000
10000
15000
20000
T2 – T1

TPC
= active hydrogen Target
-> systematics control

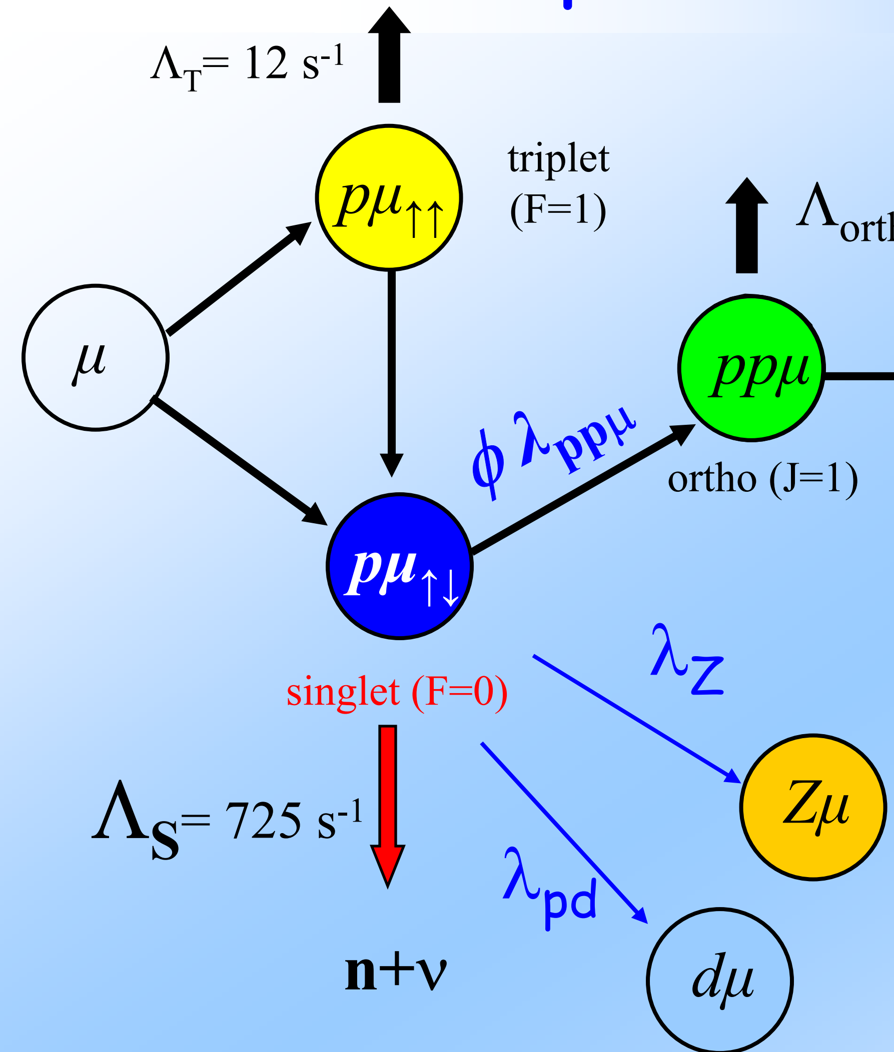
The Time Projection Chamber tracks muon stops in 3D
- eliminates wall stops
- observe high Z captures



- operates in *proportional mode* (gain ~10^4)
- 5 - 6 kV
- bakeable
- quartz glass with very low thermal expansion



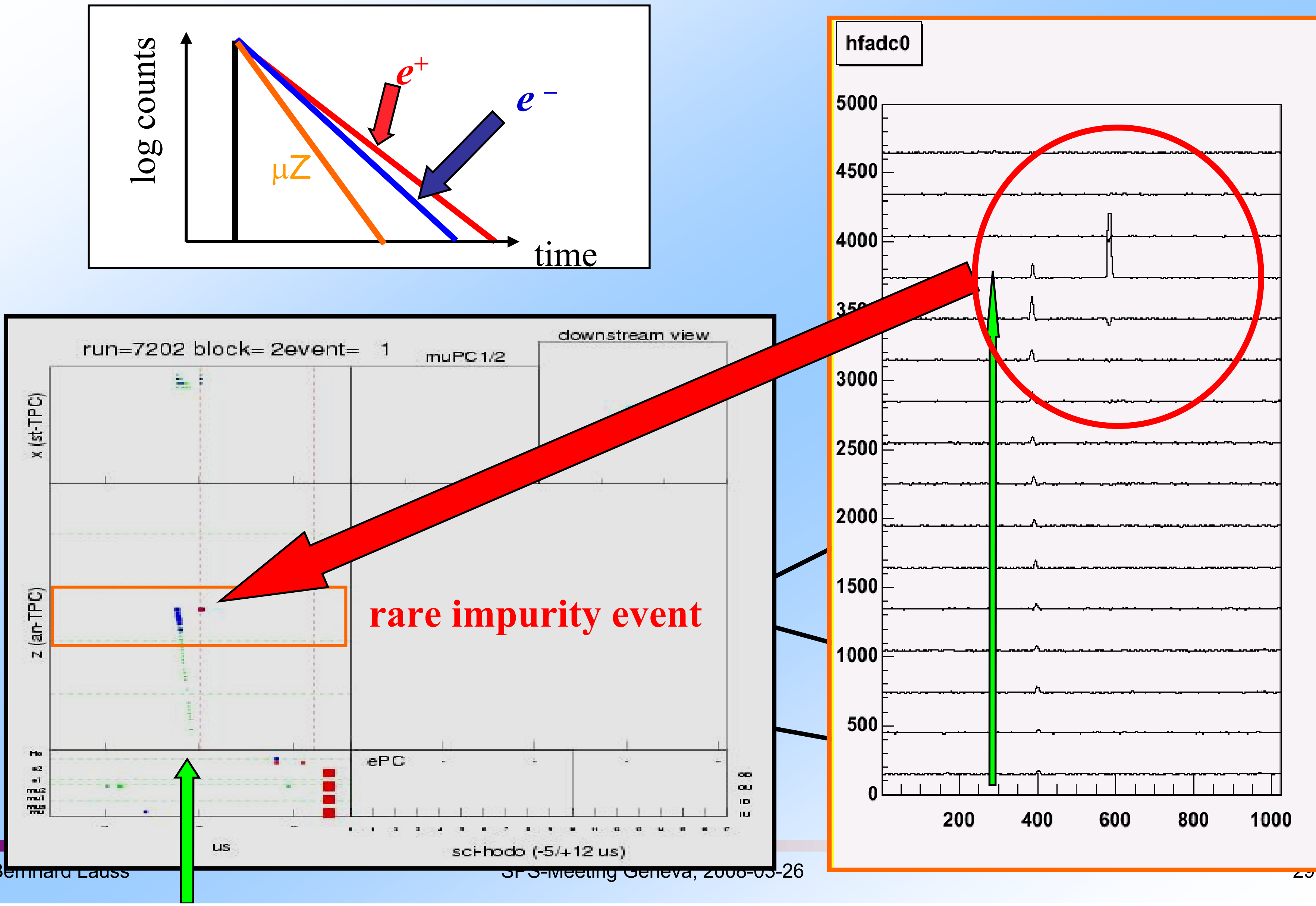
Optimize target conditionsfor a clean interpretation of Experiments ?



- **Interpretation requires knowledge of ppm population**
- **Strong dependence on hydrogen density φ**
- **Wall stops and diffusion**
- **Transfer to impurities**

μp+Z → μZ +p with subsequent nuclear capture

Continuous high Z purity monitoring via “very high” signals in the TPC.



1st MuCAP result after long systematic discussion

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

Unblinding

Average of HBChPT calculations of Λ_S:

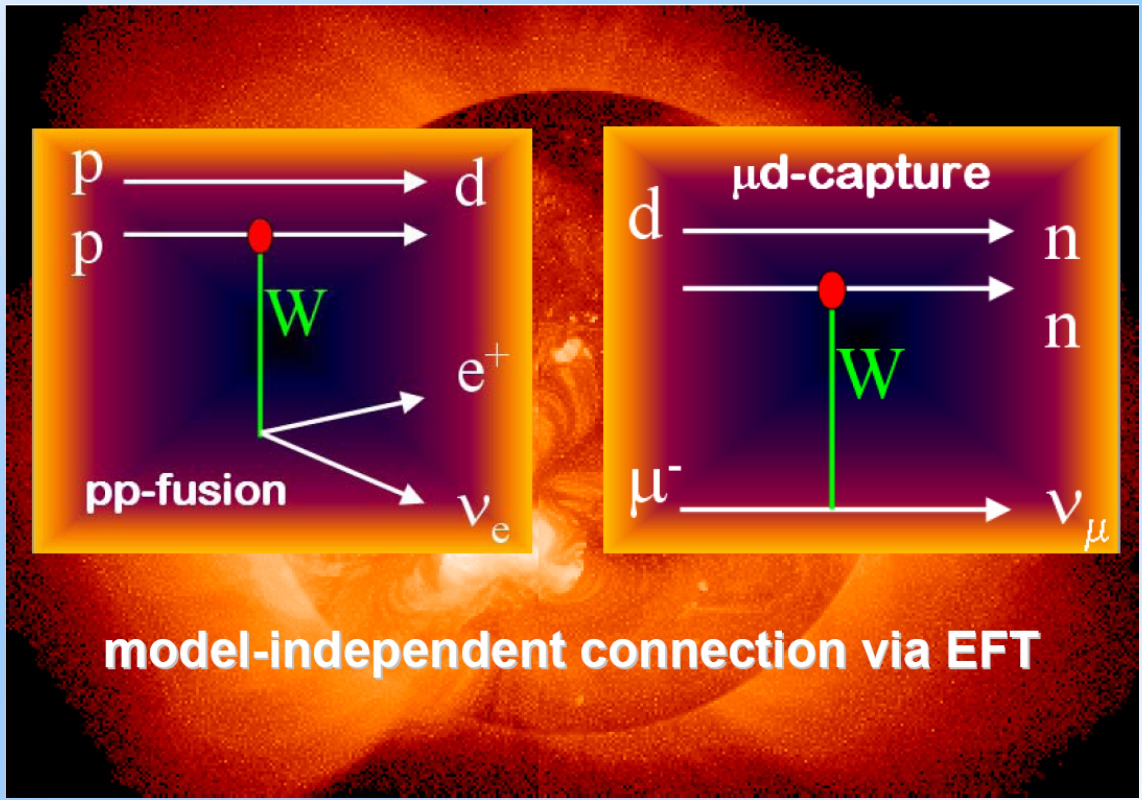
$$(687.4\ \mathrm{s}^{-1} + 695\ \mathrm{s}^{-1})/2 = 691.2\ \mathrm{s}^{-1}$$

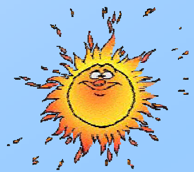
Muon Capture on the Deuteron

new proposal accepted at PSI Feb 2008

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

The MuSun Experiment

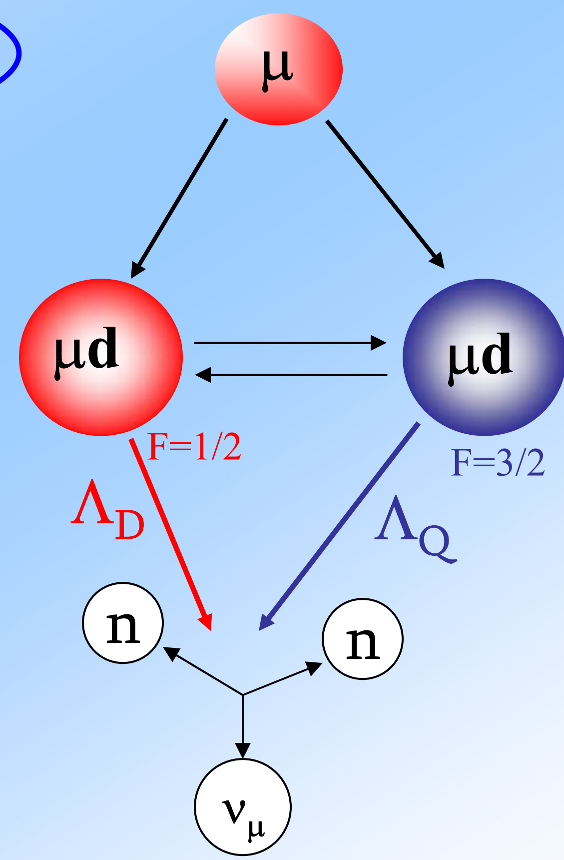




The Basic Process to be investigated is muon capture on the deuterium doublet state

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

strong spin dependence !



2 hyperfine states: (1/2) μd ↑↓
(3/2) μd ↑↑

doublet capture rate: $\Lambda_{d\ 1/2} \sim 400 s^{-1}$
quartet capture rate: $\Lambda_{d\ 3/2} \sim 10 s^{-1}$

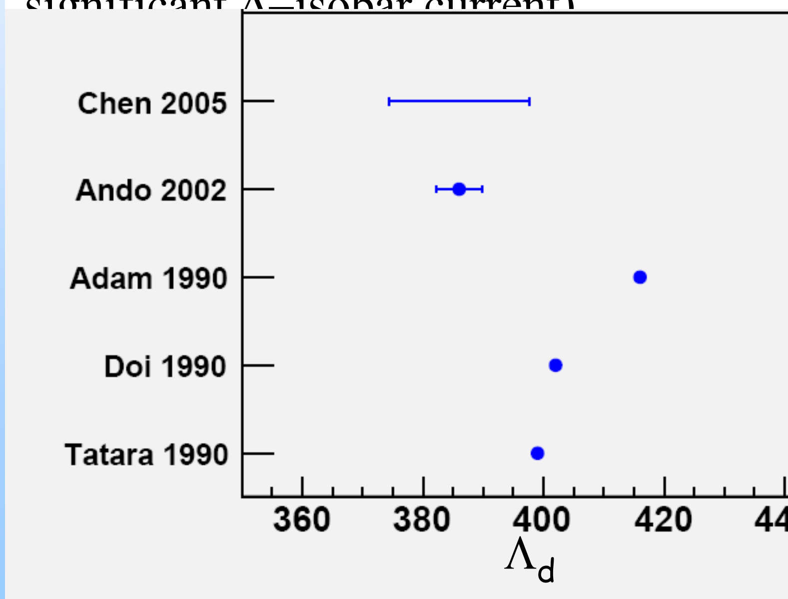
Λ_D Calculation

SNPA

2-body nuclear system is well known

➔ test of our description of nuclear response to weak probes at intermediate energies; two nucleon interaction.

➔ test of MECs (π,ρ exchange / significant Δ–isobar current)



Effective field theories (EFT)

- pion less EFT (q/m_π)
- ChPT(q/Λ_χ)
- hybrid EFT **(EFT operators, Pot.Model wavefunctions)**

New Calculation

Ando et al. PLB 533 (2002)

EFT* (HBCPT+EFT)

reduces MECs effect

error estimation for the first time

|1B| = 370 s-1

|1+2B| = 386 s-1

Connection to Neutrino/Astrophysics

- **EFT connection to μ+d capture**
  via a single LowEnergyConstant L_{1A}, d^R in the relevant two-nucleon current term in the systematic expansion

- **Basic solar fusion reaction**

$$p + p \rightarrow d + e^{+} + \nu$$

- **Key reactions for Sudbury Neutrino Observatory**

$$\nu_e + d \rightarrow p + p + e^{-} \quad \text{(CC)}$$

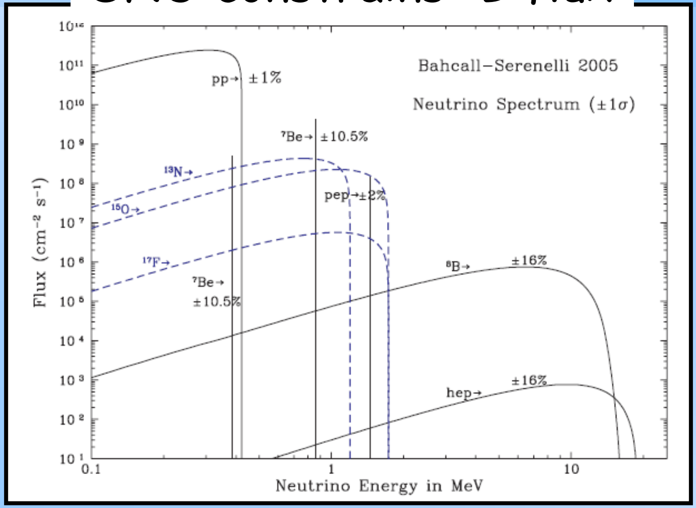
$$\nu_x + d \rightarrow p + n + \nu_x \quad \text{(NC)}$$

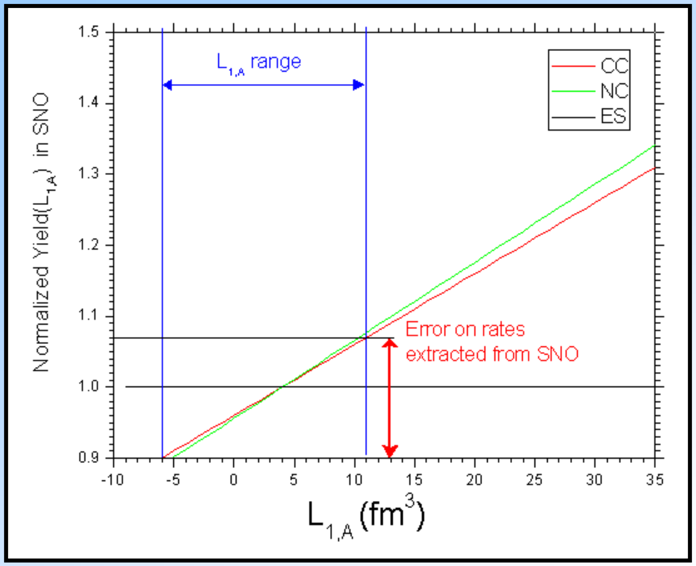
$$\sigma \approx \sigma_0 (1 + 0.013 \frac{L_{1A}}{fm^3})$$

L_{1A} parametrization

Intense theoretical studies, scarce direct data

SNO constrains ^{8}B flux





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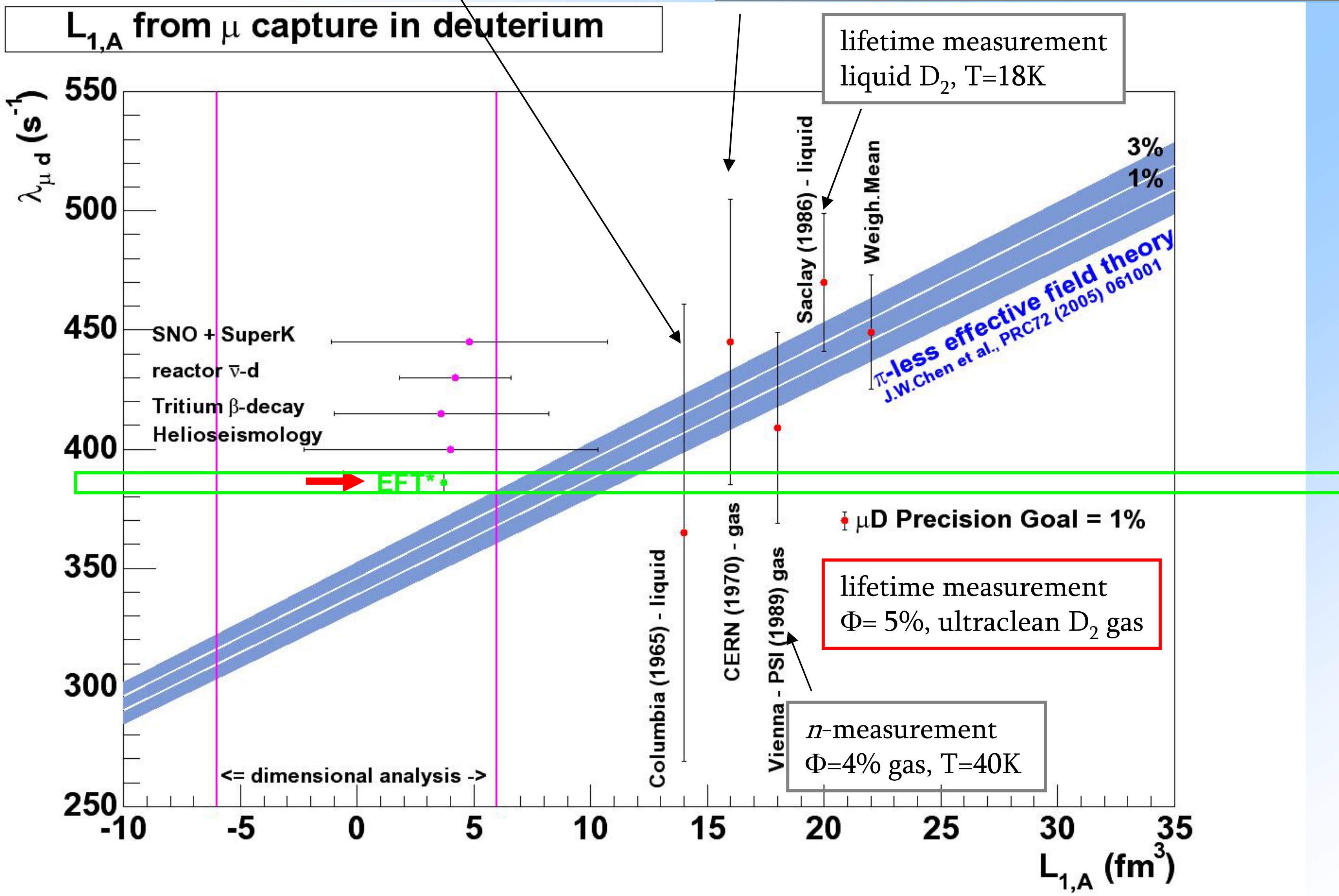
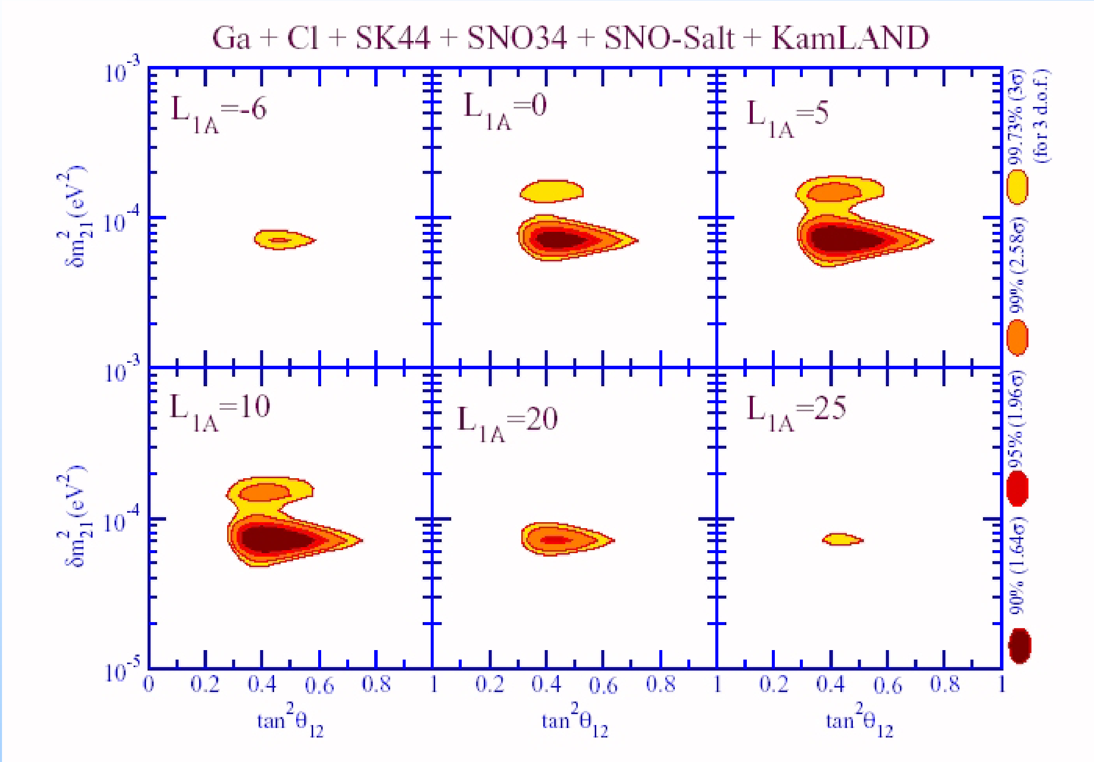
n-measurement
liquid H_2-D_2(0.32%) mixture
T=18K

n-measurement
H_2-D_2(5%) gas mixture, T=293K
but only if pure hf=1/2 population is
assumed / statistical mix -> result × 3



Influence of L_{1A} on ν mixing



precision ν physics -> L_{1A} important

Allowed region of neutrino mixing parameter space using combined solar neutrino and KamLAND data as a function of $L_{1,A}$ assuming $\Theta_{13} = 0$.
(areas correspond to 90, 95, 99, 99.73% confidence level)
A.B.Balantekin, H.Yüksel, Int.Journ.Mod.Phys. E14 (2005) 39.

Experimental Strategy

Two main experimental requirements

- Unambiguous physics interpretation
  Muon kinetics → **optimization of D_2 conditions**

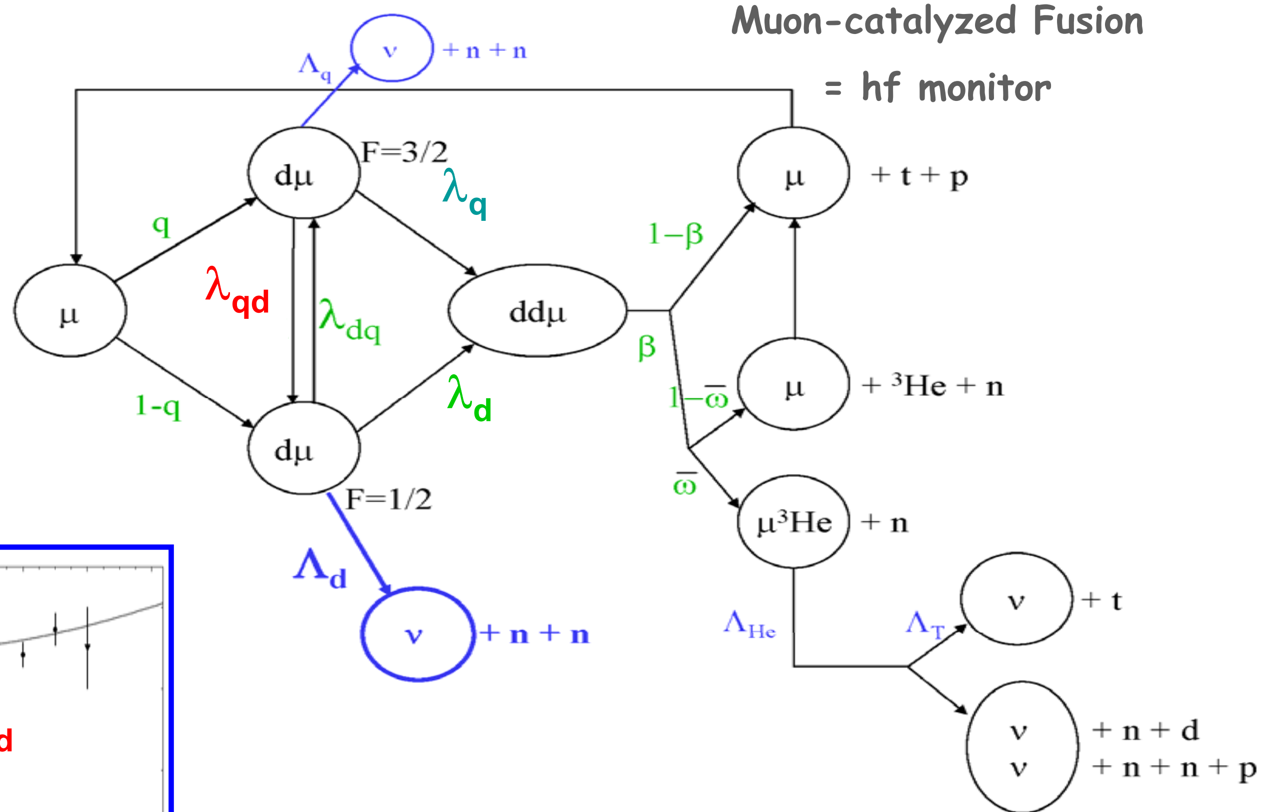
- Very high precision Λ_d to 1.2% ($5\ s^{-1}$)
  Statistics: several 10^{10} events

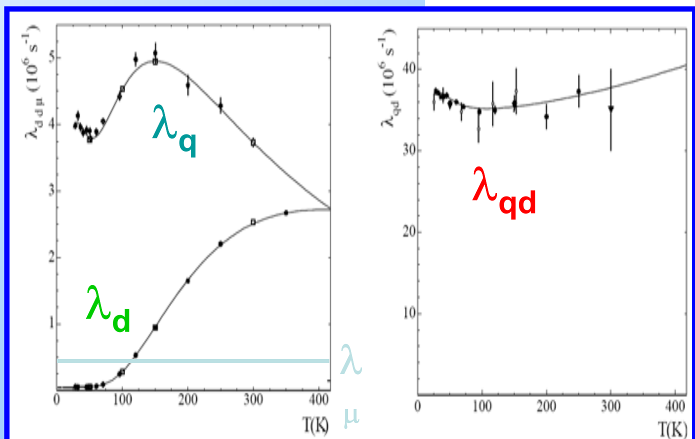
- **Similar method to MuCAP**
  Lifetime method 10^{10} $\mu \rightarrow e\nu\nu$ decays
  measure $\tau_{\mu-}$ to 10ppm, $\Lambda_d = 1/\tau_{\mu-} - 1/\tau_{\mu+}$

Muon Kinetics in Deuterium

Optimization of process interplay

Muon-catalyzed Fusion = hf monitor





molecular formation

hyperfine transition

Collisional processes density ϕ dependent, e.g.
hfs transition rate from q to d state = $\phi\ \lambda_{qd}$
density ϕ normalized to LH_2 density

Optimize Muon Kinetics

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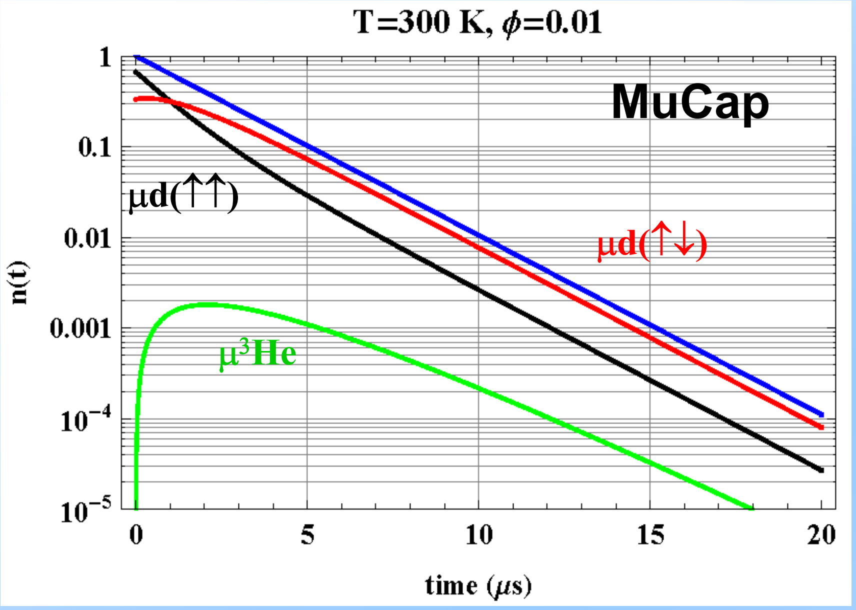
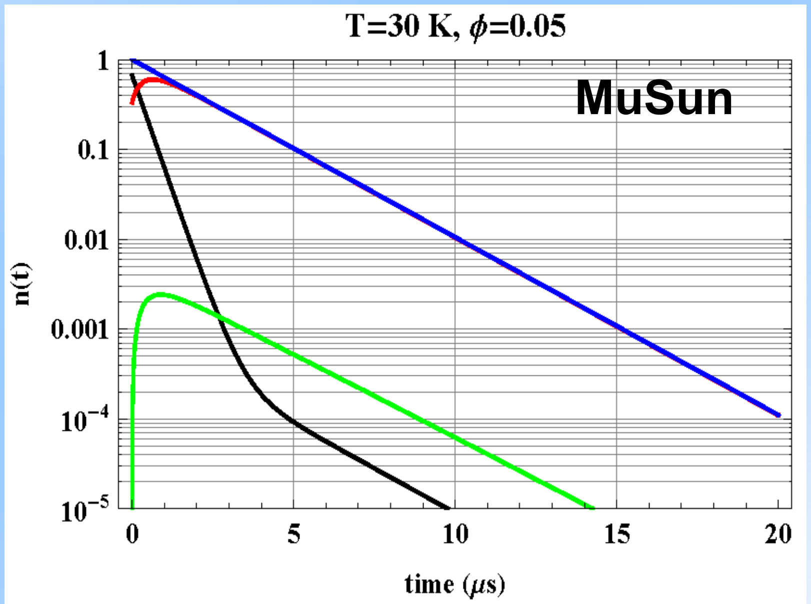
Ultra Cold Neutron Source

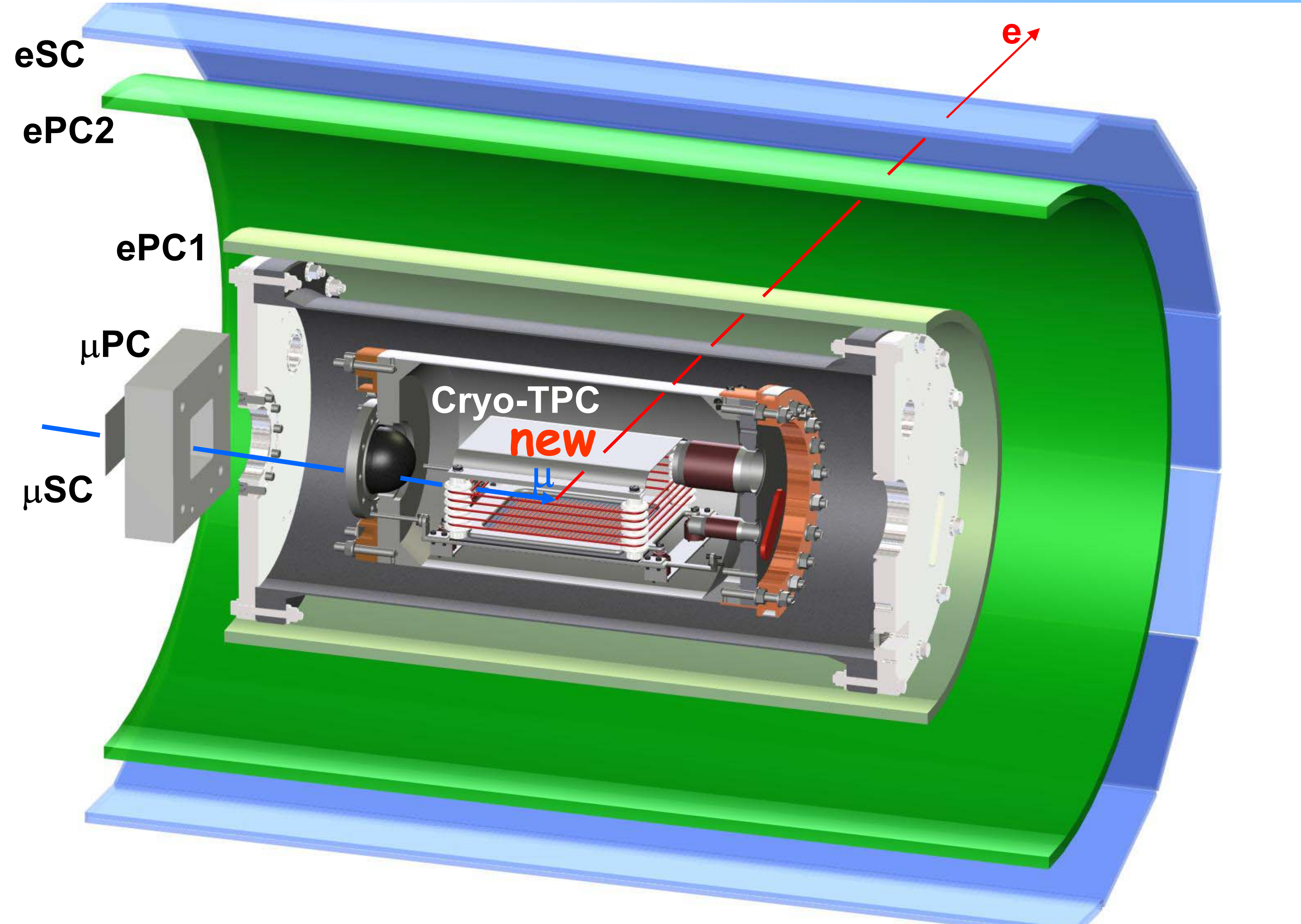
new target conditions : 30 Kelvin / 10 bar = 5% LHD (30K)





ultra clean deuterium necessary

Experiment Overview



MuSUN Road Map

- Stage 1 – 300 K D_2
  - **test measurements to optimize setup**
  - **measure contributing physics**
    d → μZ transfer rate

start fall 08

- Stage 2 – Cryo-TPC
- measure μd capture rate with high statistics
- study systematics of the measurement

start fall 09

Collaboration

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New collaborators are very welcome !


THE END
thank's for
your attention