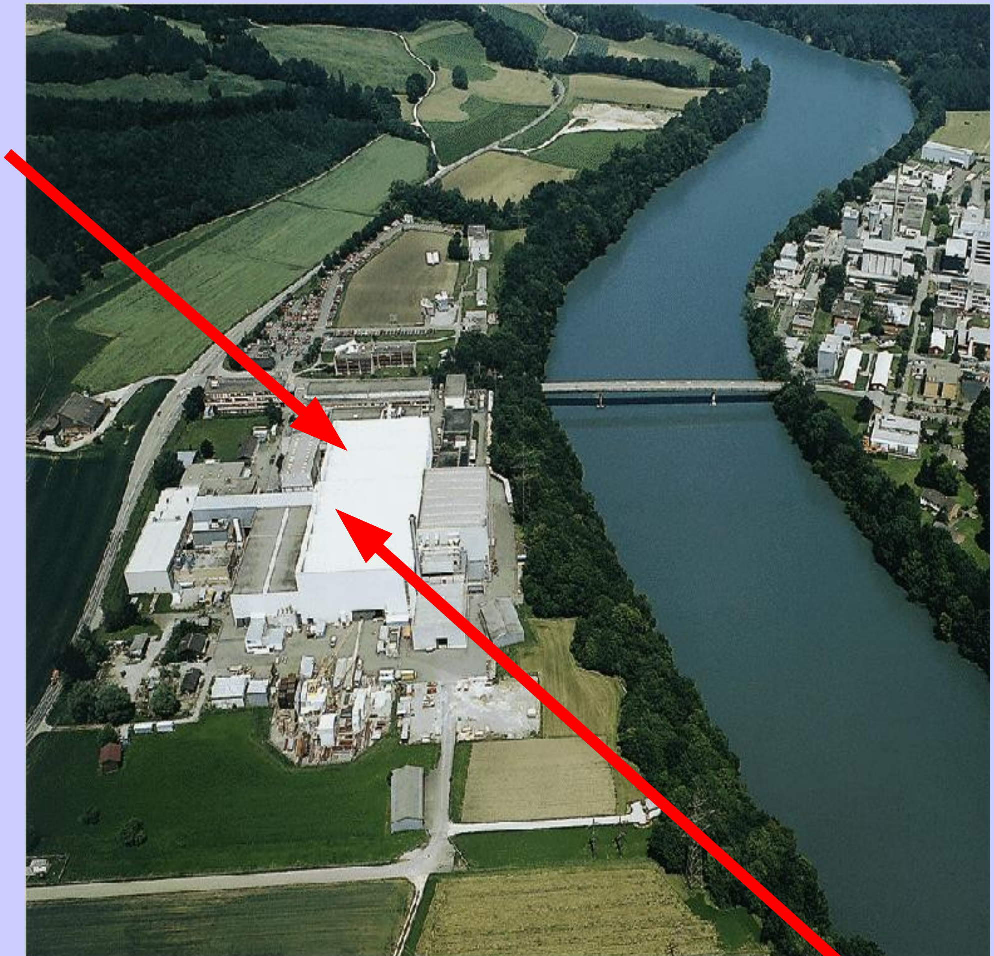
Precision measurements of μ^+, μ^-H, and μ^-D lifetimes.

Tim Gorringe, Univ. of Kentucky,
for the MuLan, MuCap, MuSun Collaborations

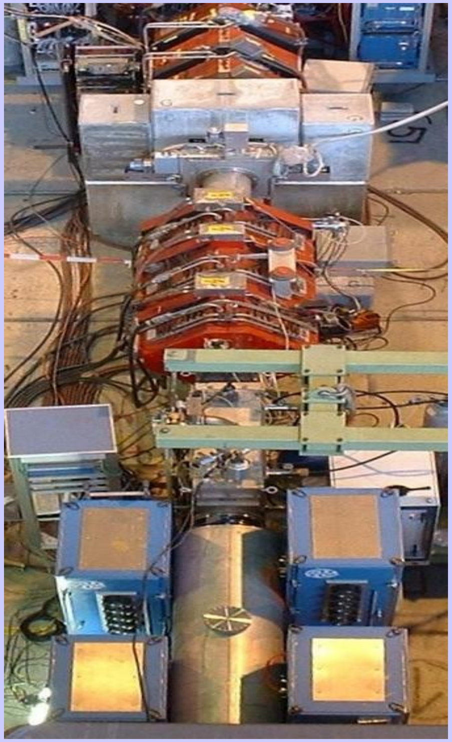
Elba XI, June 21-25

Paul Scherrer Institute.

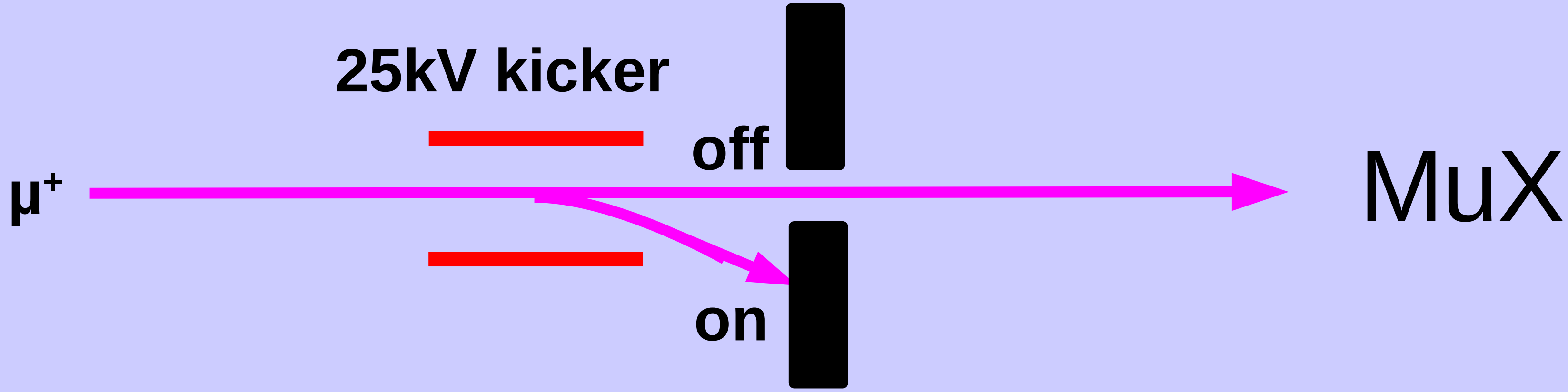
2.0mA, 590 MeV
proton cyclotron

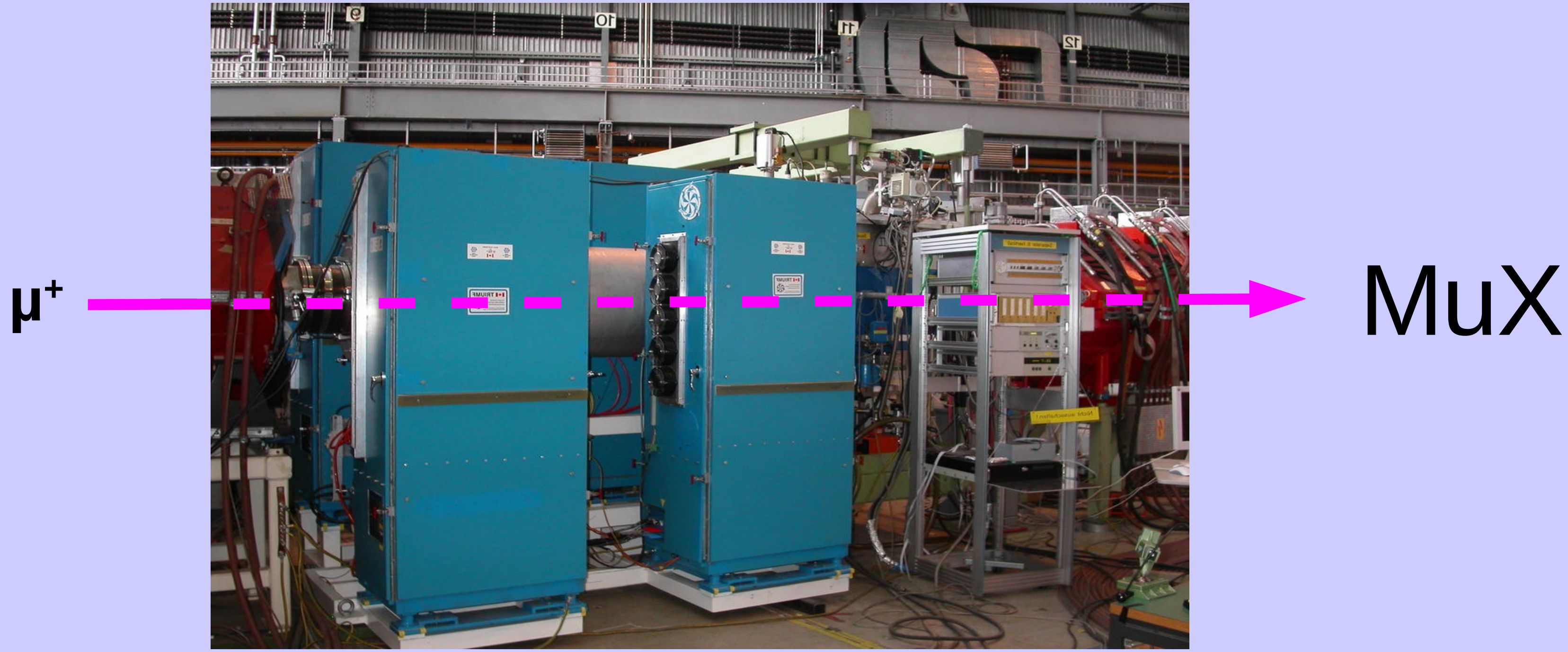


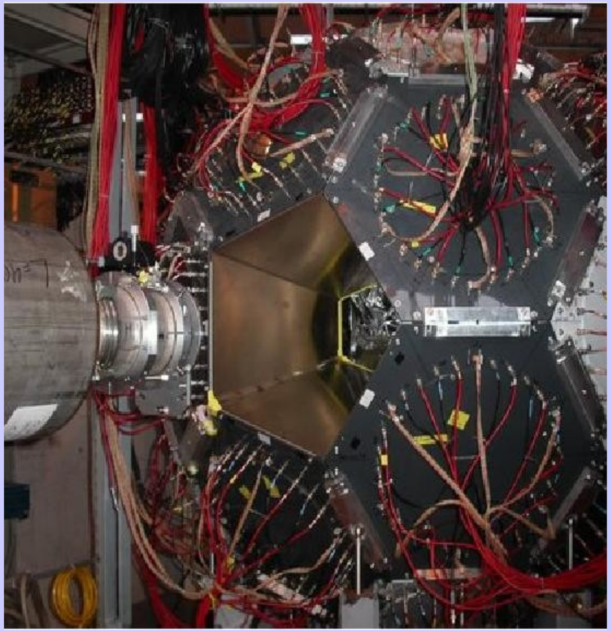
5 MeV, 30 MeV/c
pulsed muon beam

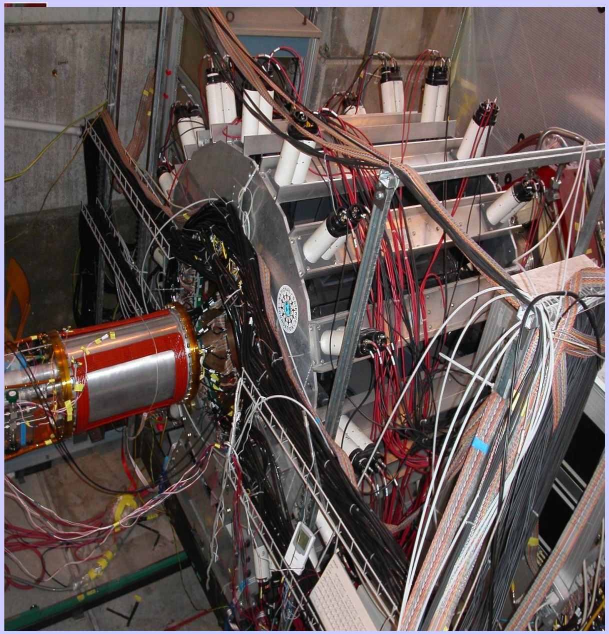


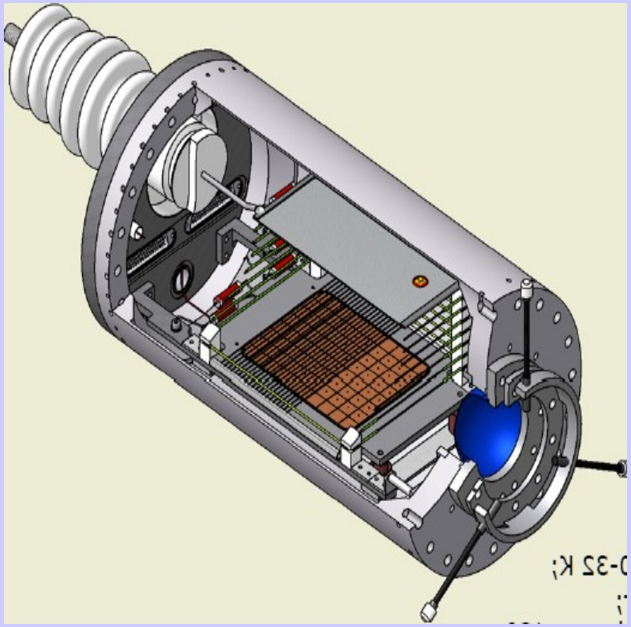
Pulsed Muons and Muon On Request.











MuLan MuCap MuSun

scientific goals, experimental setups, experimental challenges,and results and status

from the Fermi Constant...

to the proton's weak interaction...

and solar hydrogen burning

by part-per-million measurements of μ^+, μ^-H, and μ^-D lifetimes

MuLan – the muon lifetime and Fermi constant.

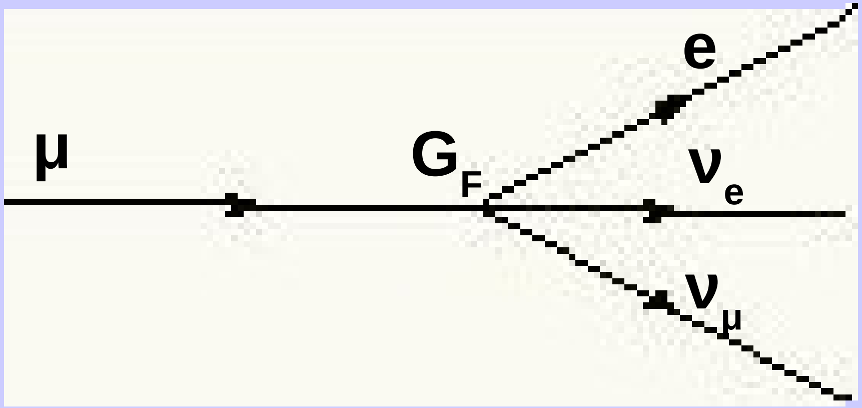
Why we measure $\tau_{\mu+}$?

knowledge of muon lifetime $\tau_{\mu+}$ allows precision measurements of weak nuclear interactions in muonic hydrogen, deuterium atoms.

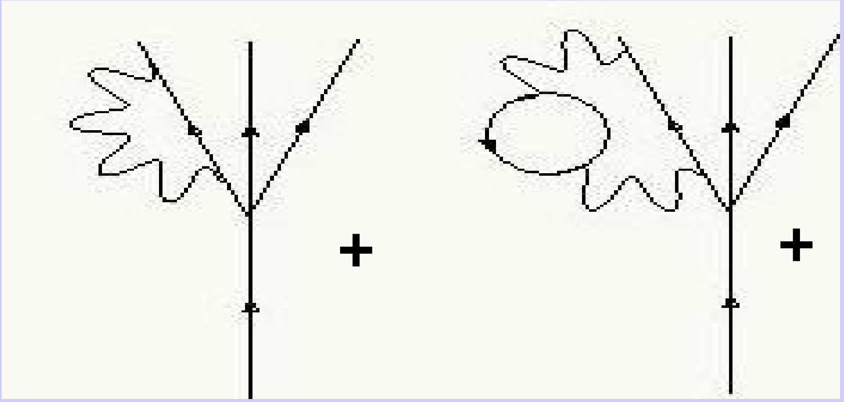
twenty-fold improvement in knowledge of fundamental constant G_F of weak interaction. [previously G_F (±10ppm)].

knowledge of α, G_F, M_Z allows precision tests of standard model via measurements of Weinberg angle Θ_W, W-boson mass M_W, ...

How we determine G_F?



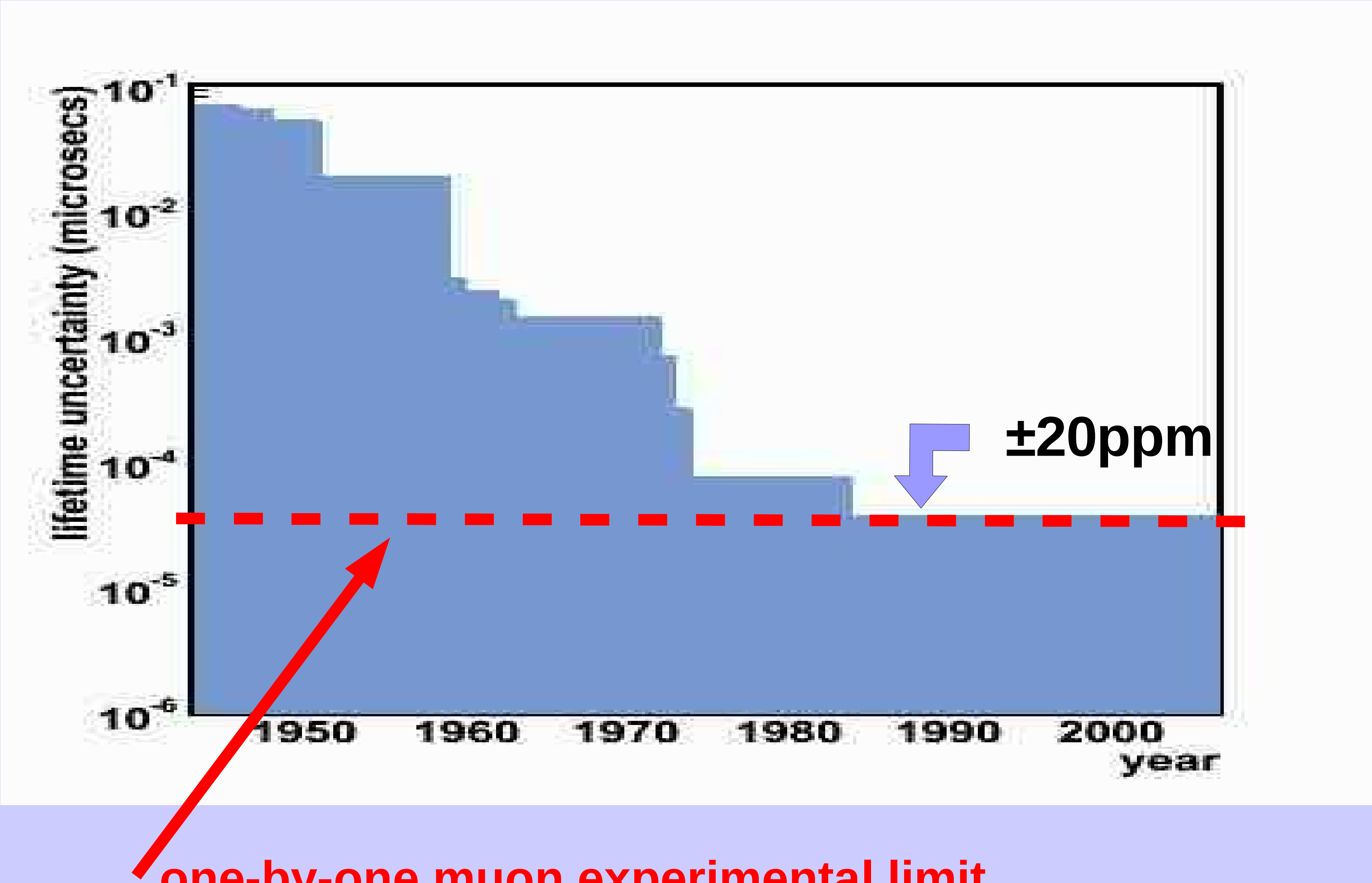
$$\frac{1}{\tau_\mu} = \frac{G_F^2 m_\mu^5}{192\pi^2}(1+\Delta q)$$



Δq contains QED, QCD radiative corrections

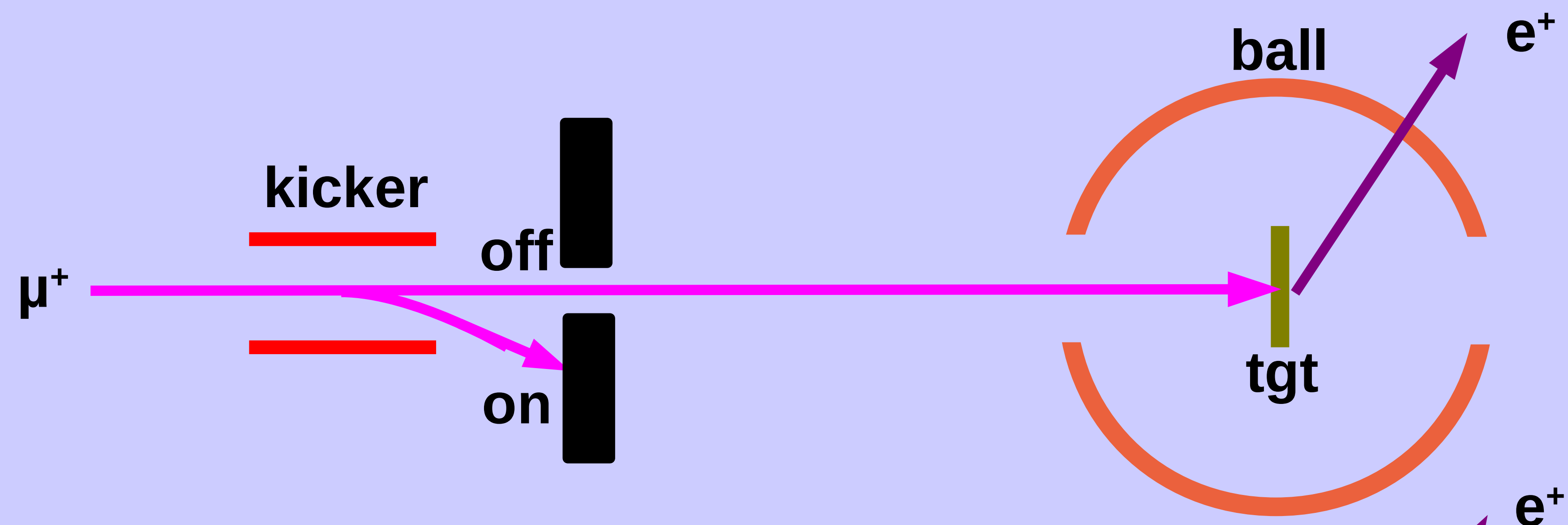
~ **0.1 ppm** uncertainty in $\mathbf{T_\mu}$**-**$\mathbf{G_F}$ relationship from **Δq,** $\mathbf{m_\mu}$

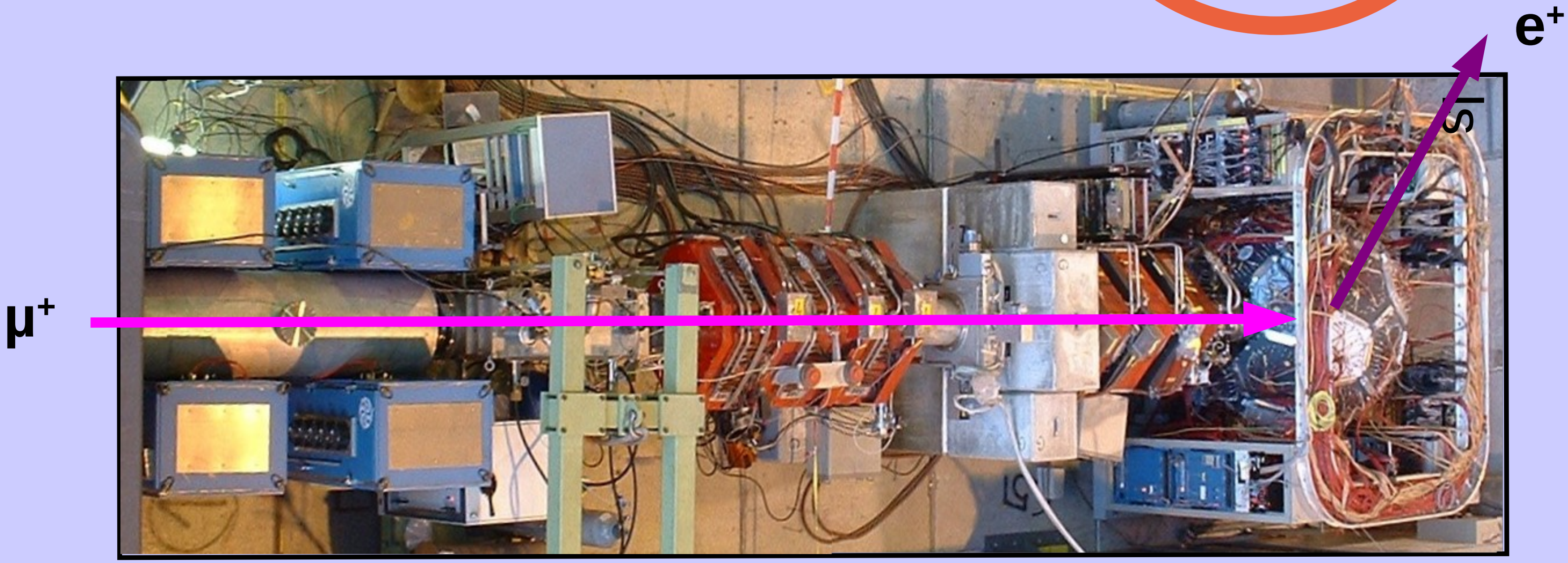
pre-MuLan history of τ_μ = 2.19703(4) μs



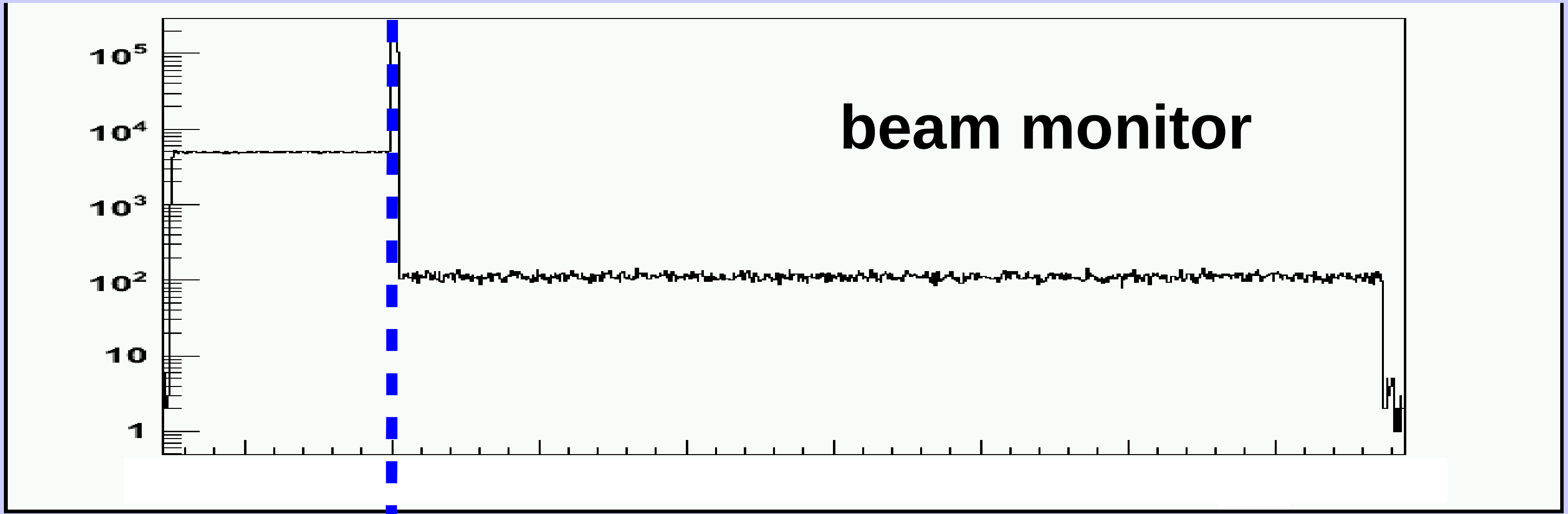
one-by-one muon experimental limit

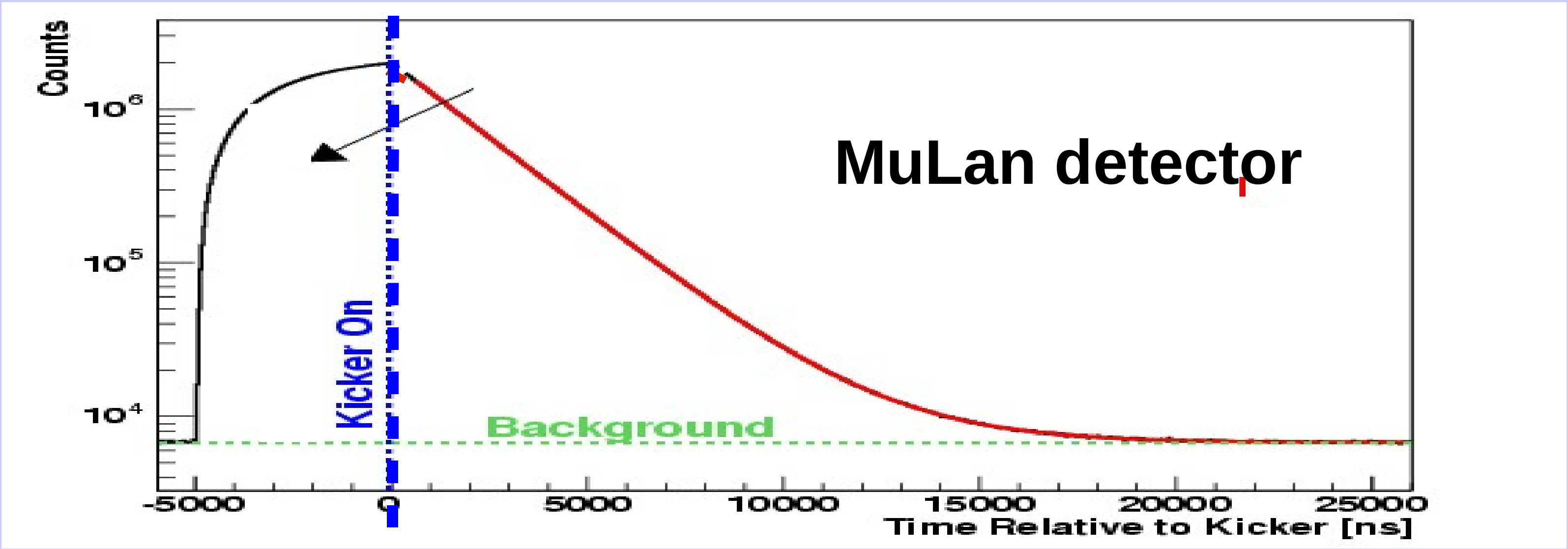
accumulating μ^+'s and measuring e^+'s





accumulating μ^+'s and measuring e^+'s

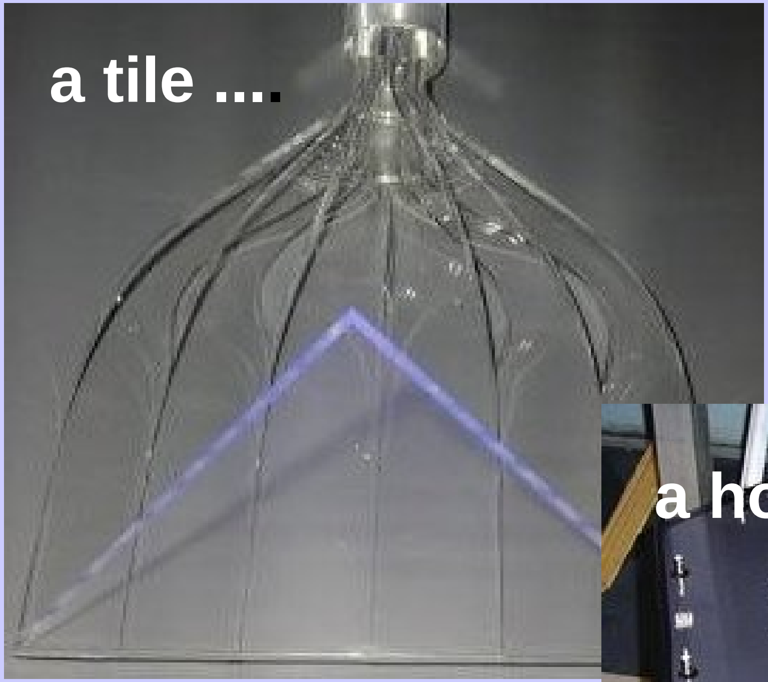


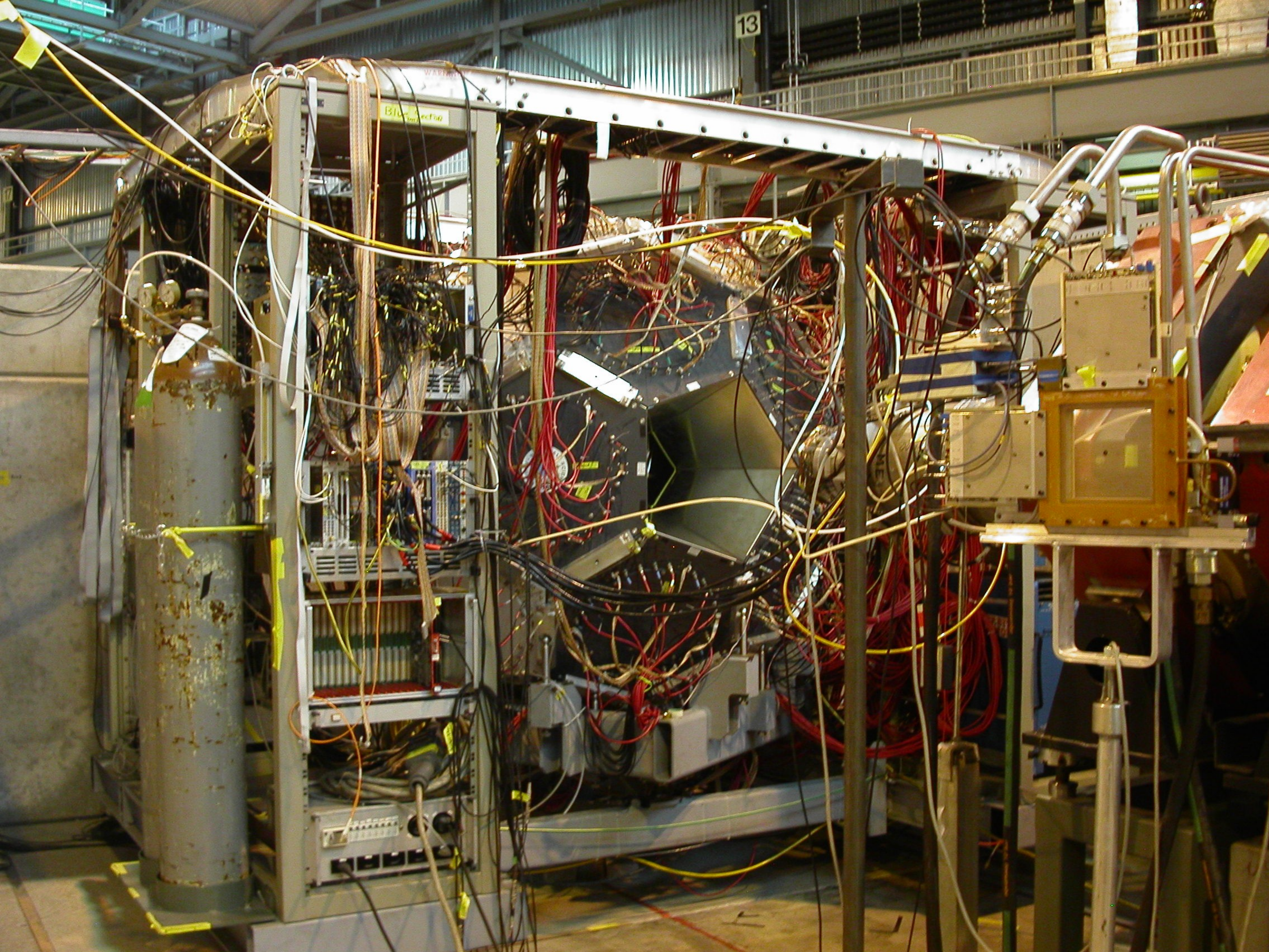


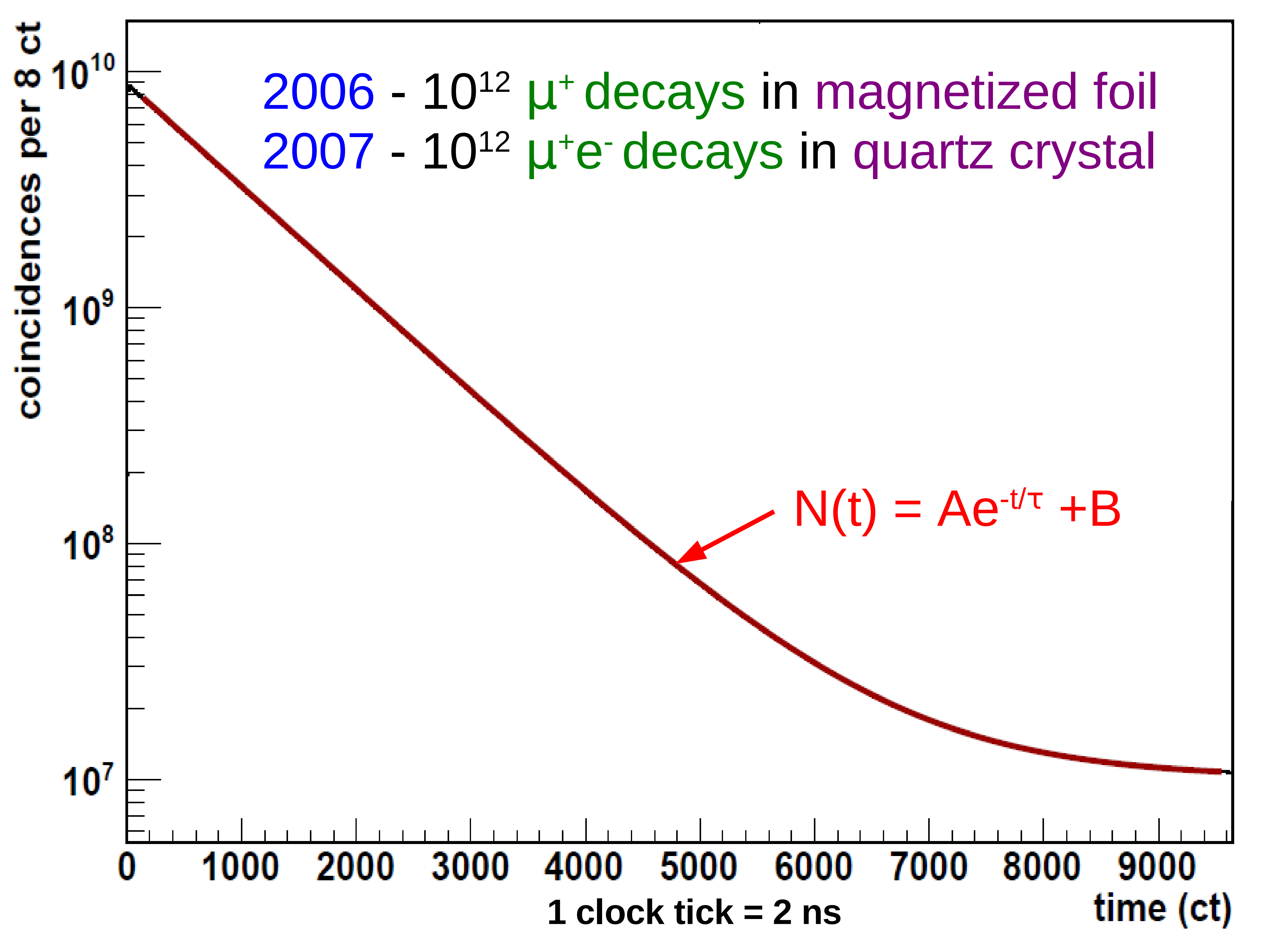
beam on

beam off

MuLan detector

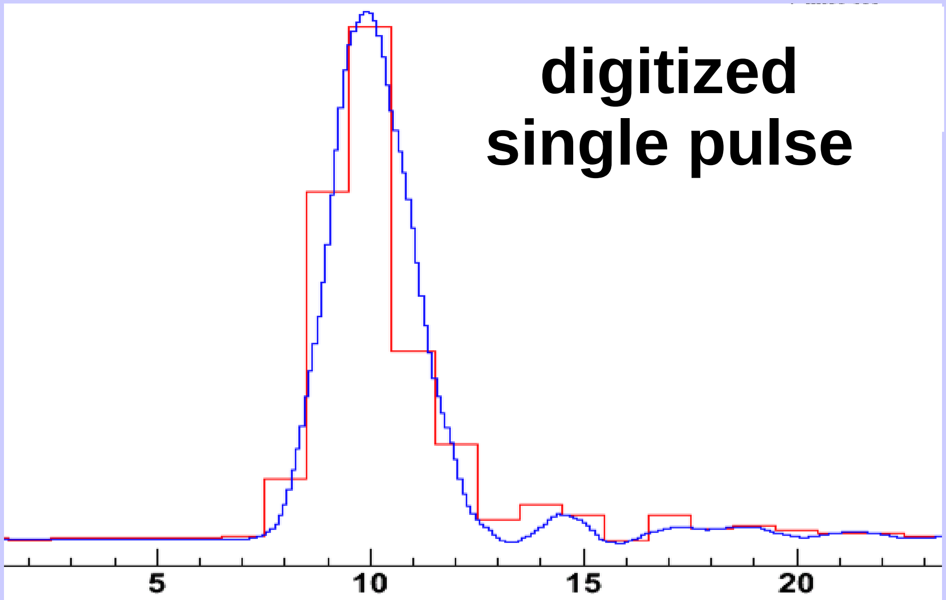


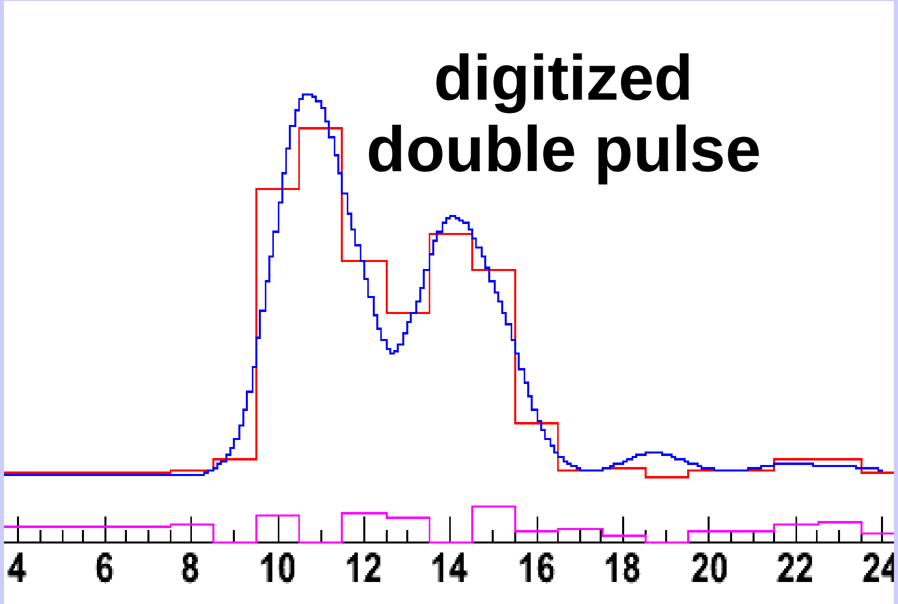

13

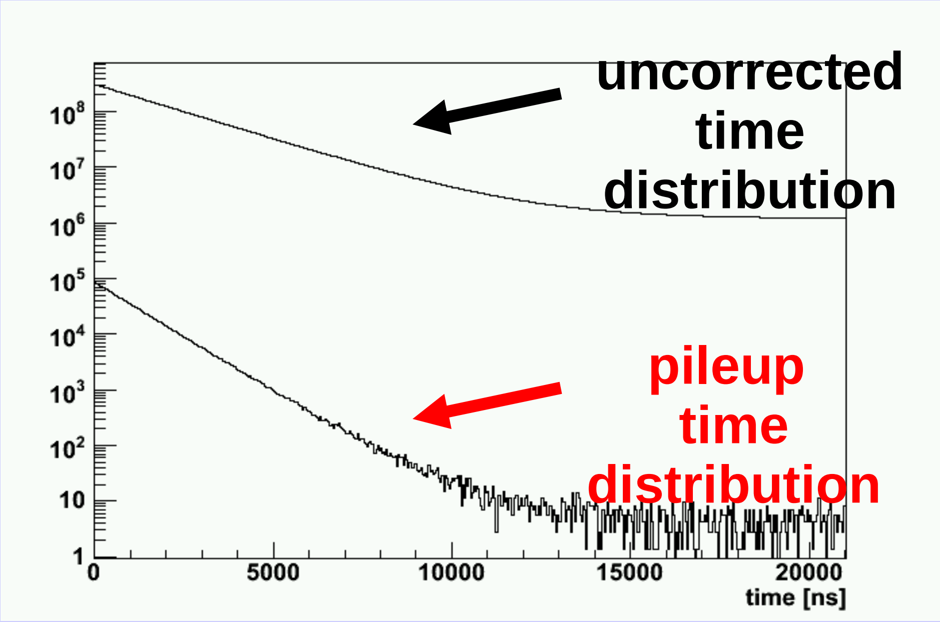


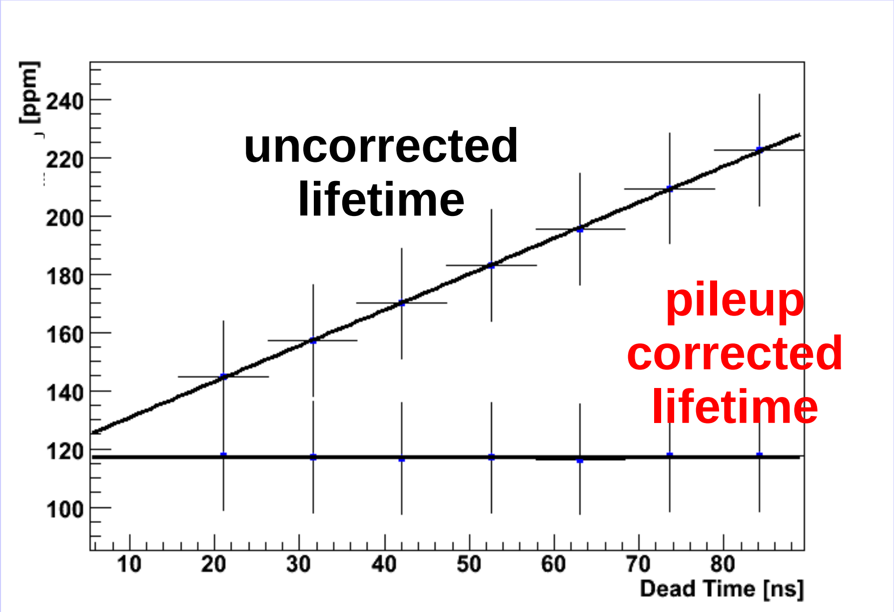
2006 - 10^12 μ+ decays in magnetized foil
2007 - 10^12 μ+e- decays in quartz crystal
N(t) = Ae^-t/τ +B
coincidences per 8 ct
10^10
10^9
10^8
10^7
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
time (ct)
1 clock tick = 2 ns

- most worrisome systematics - positron pulse pile-up

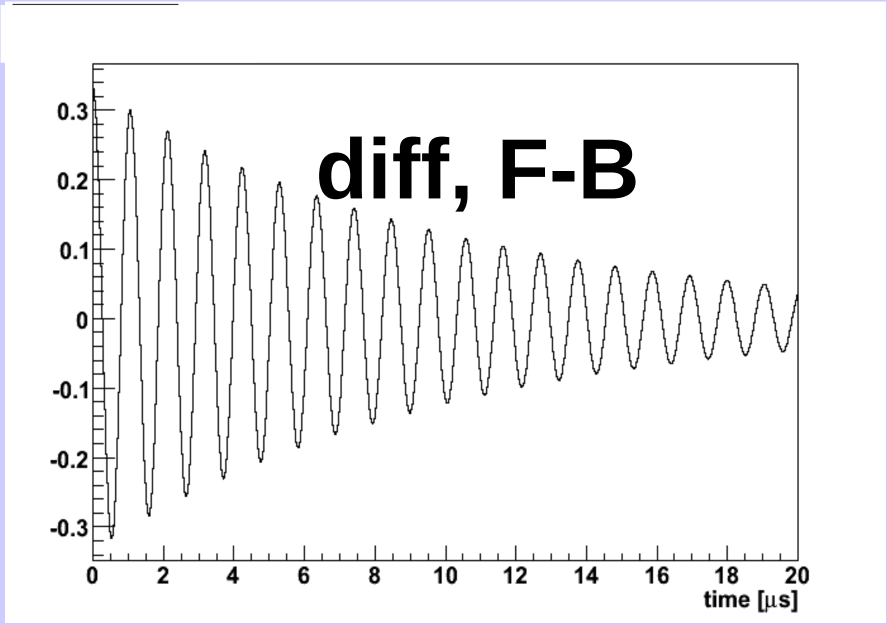


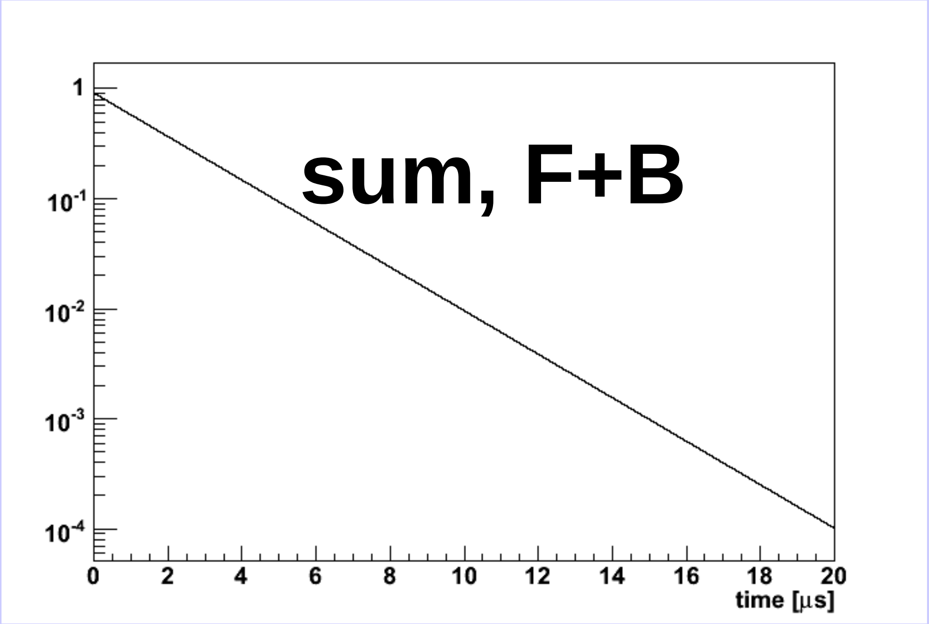


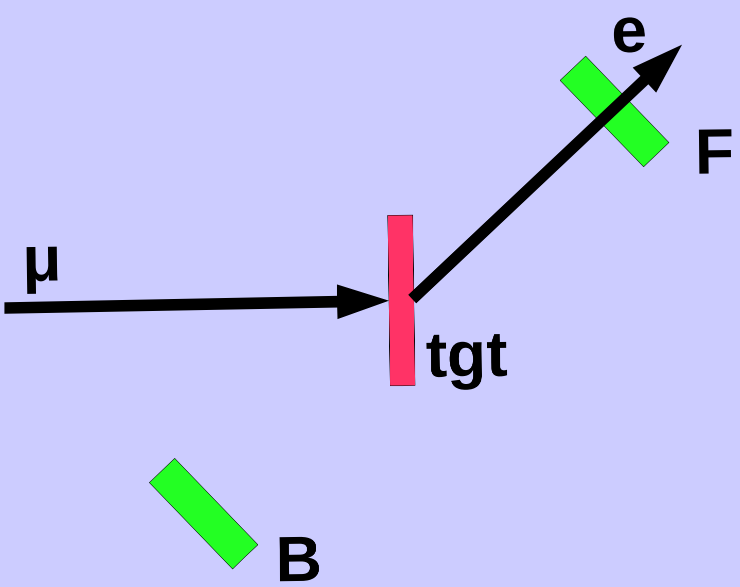




- most worrisome systematics -
muon spin rotation







TARGETS

magnetized ferromagnetic foil
(high internal B-field, fast μ^+ precession)

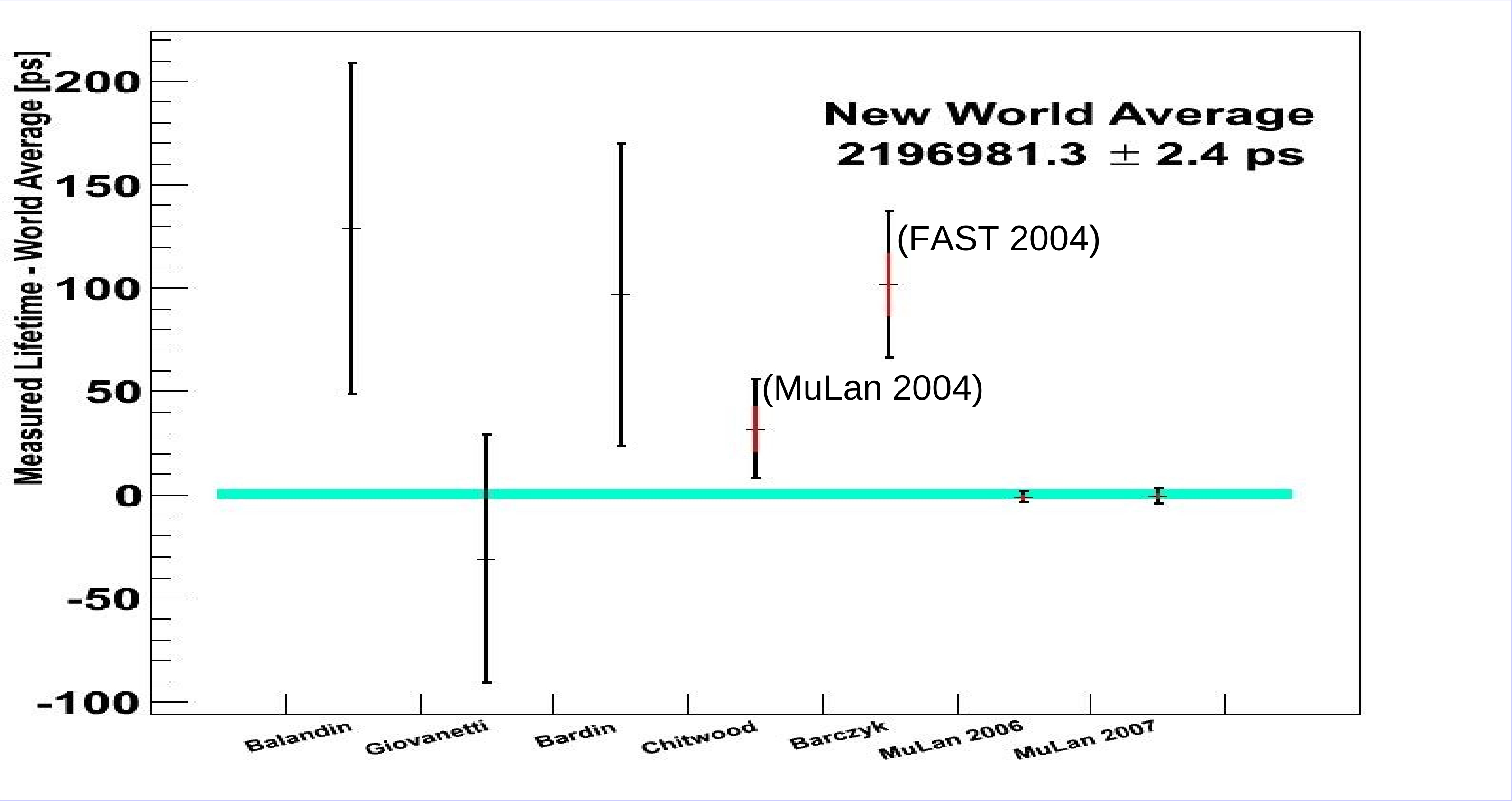
single quartz crystal
(moderate external B-field, fast μ^+e^- precession)

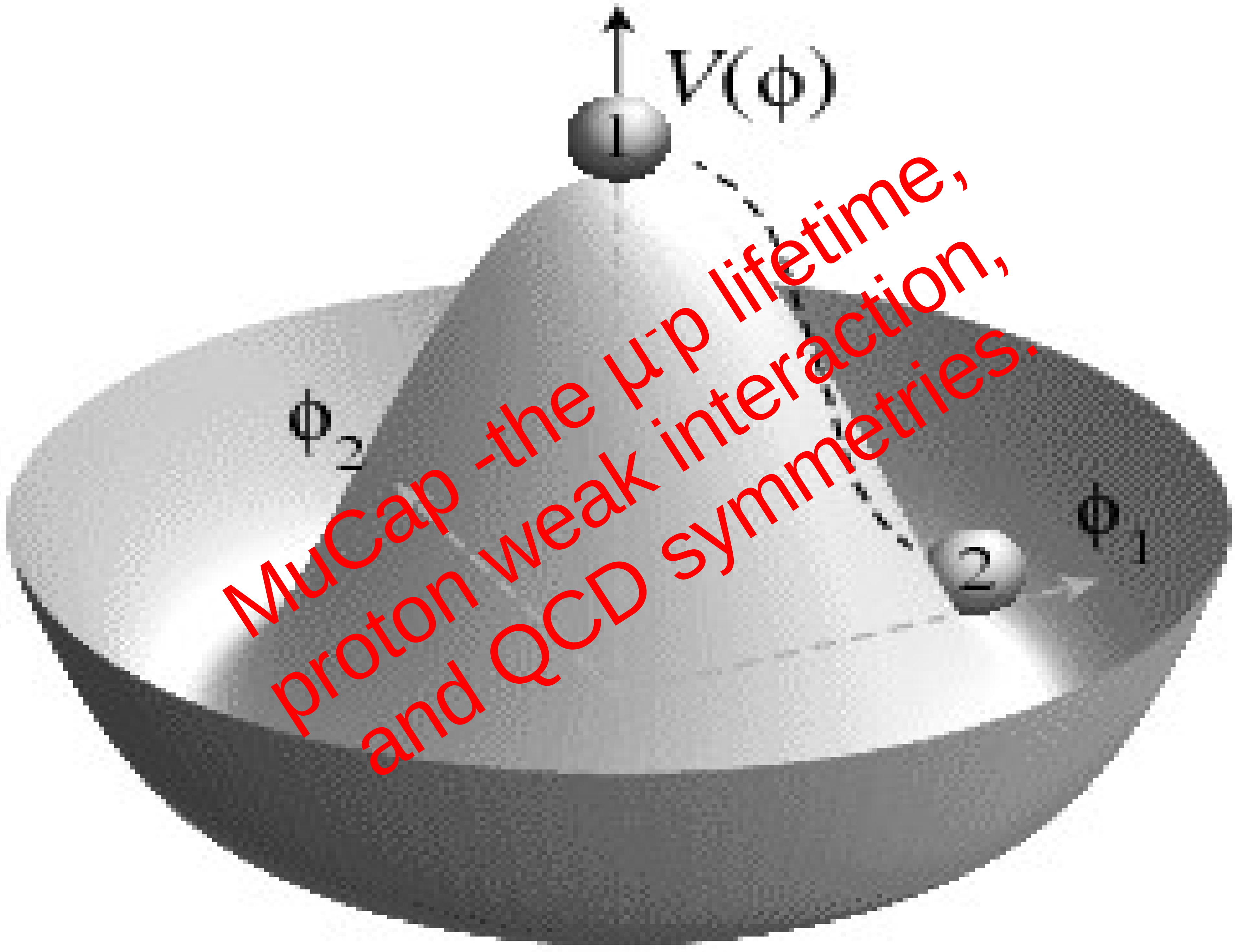
MuLan Results

2006: τ_μ = 2196980.1 ± 2.5(stat) ± 1.2(sys) ps

2007: τ_μ = 2196980.7 ± 3.7(stat) ± 1.2(sys) ps

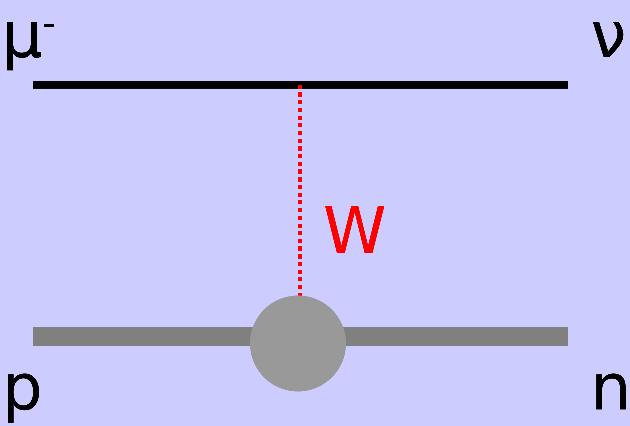
G_F = 1.166 381 8 (7) x 10-5 GeV^{-2} (0.6 ppm)*




$V(\phi)$
1
ϕ_2
ϕ_1
2
MuCap -the μ^-p lifetime,
proton weak interaction,
and QCD symmetries.

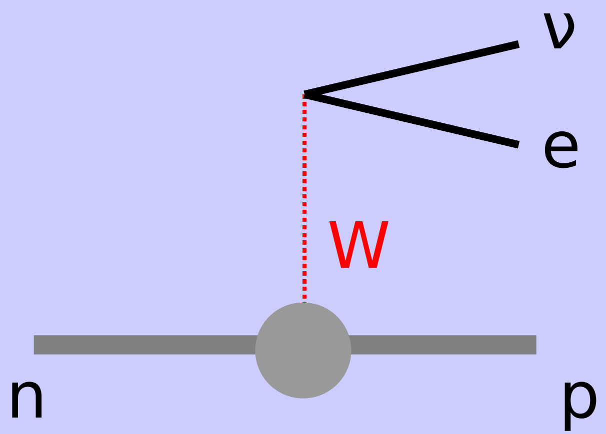
Why we measure $\tau_{\mu p}$?

muon capture,
$\mu^- p \rightarrow \nu n$



proton's weak couplings
g_v, g_a, g_m, g_p

beta decay,
$p \rightarrow n e^+ \nu$



proton's weak couplings
g_v, g_a

knowing g_v, g_a, g_m determine g_p,
the poorly known proton induced pseudoscalar coupling

Why we determine g_p?

fundamental quantity describing the proton's weak interaction

the approximate conservation of axial current enforces a rigorous relation between the weak couplings g_p, g_a

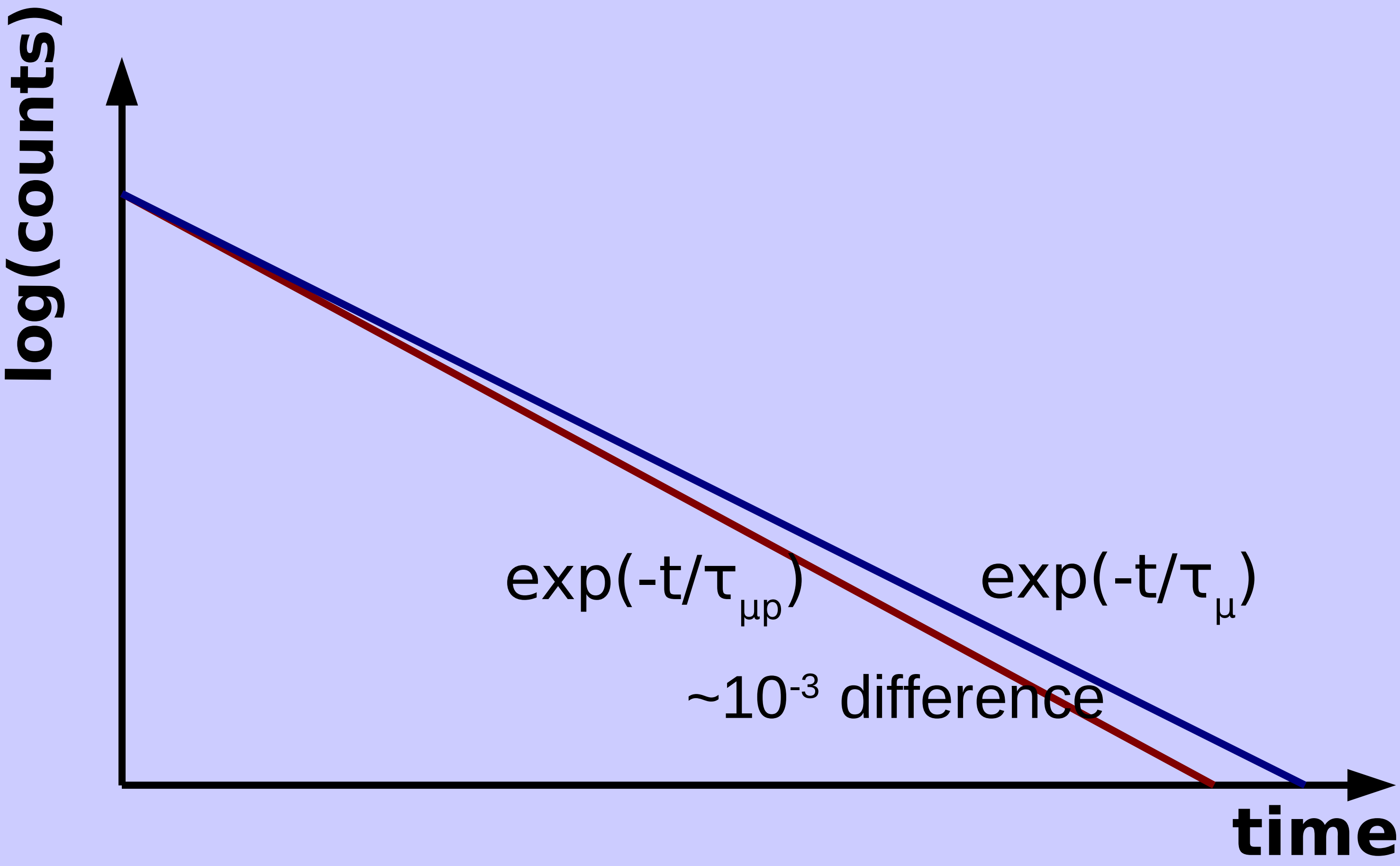
$$g_p(q^2 = -0.9m^2_\mu) = (6.47 \pm 0.18)\, g_a(0) = 8.26 \pm 0.23$$

Verification represents an important test of QCD symmetries

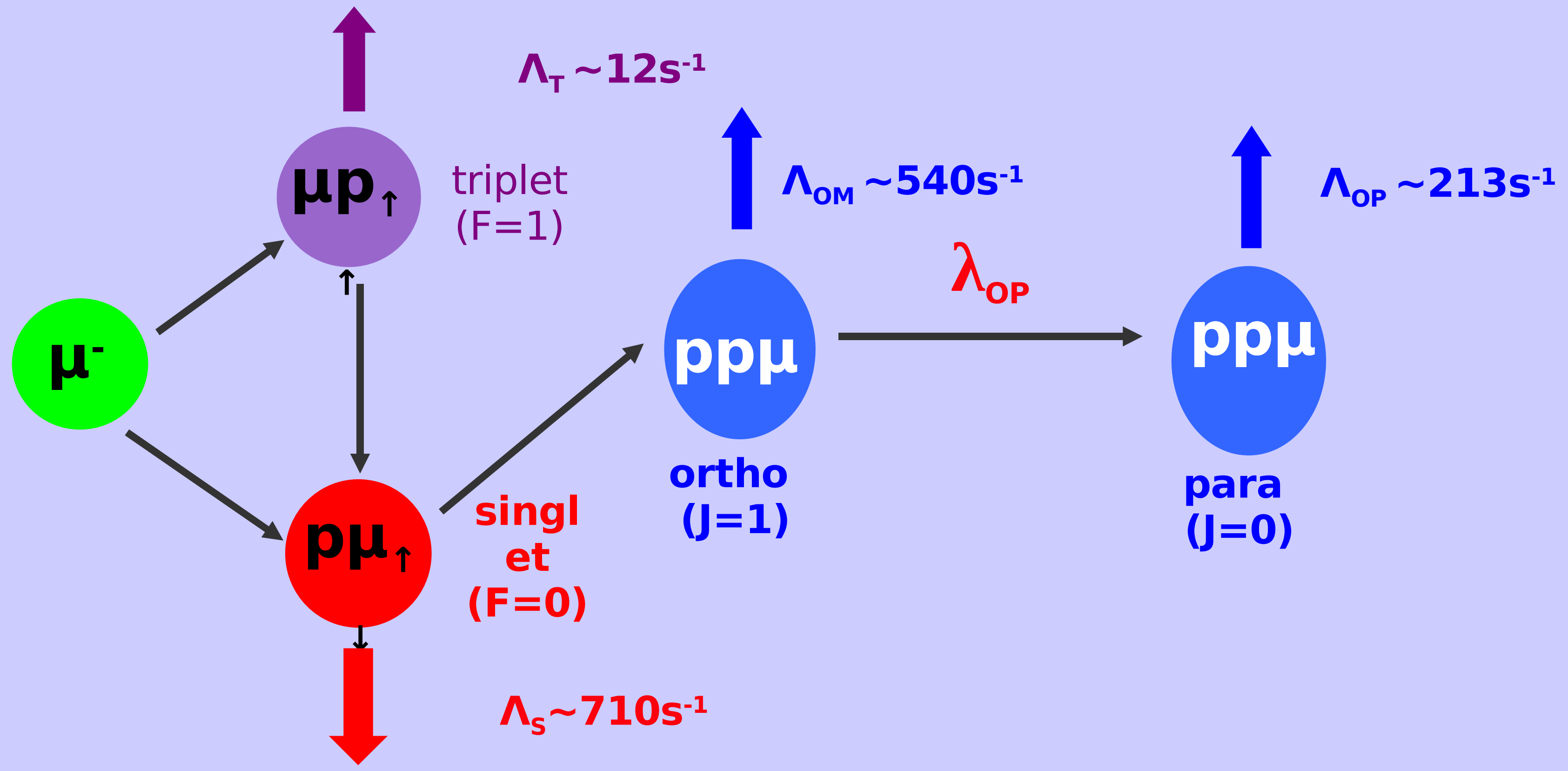
knowledge of g_p (with g_v, g_a, g_m) allows precision studies of weak nuclear interactions through nuclear muon capture (e.g. μ^-D experiment).

How we determine g_p?

determine the $\mu^- p \rightarrow \nu n$ rate
by $\Lambda = 1/\tau_\mu - 1/\tau_{\mu p}$



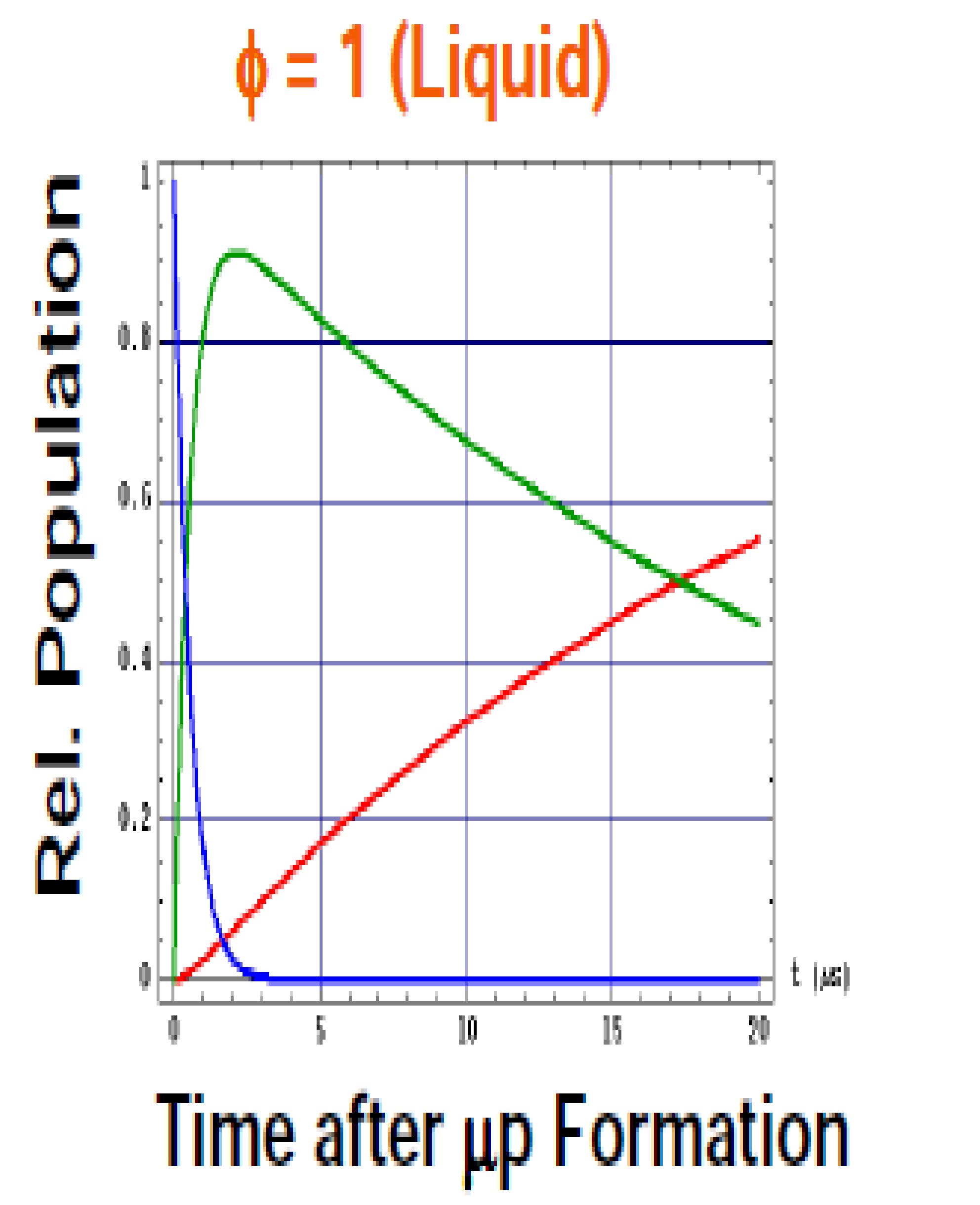
μ chemistry, a complication

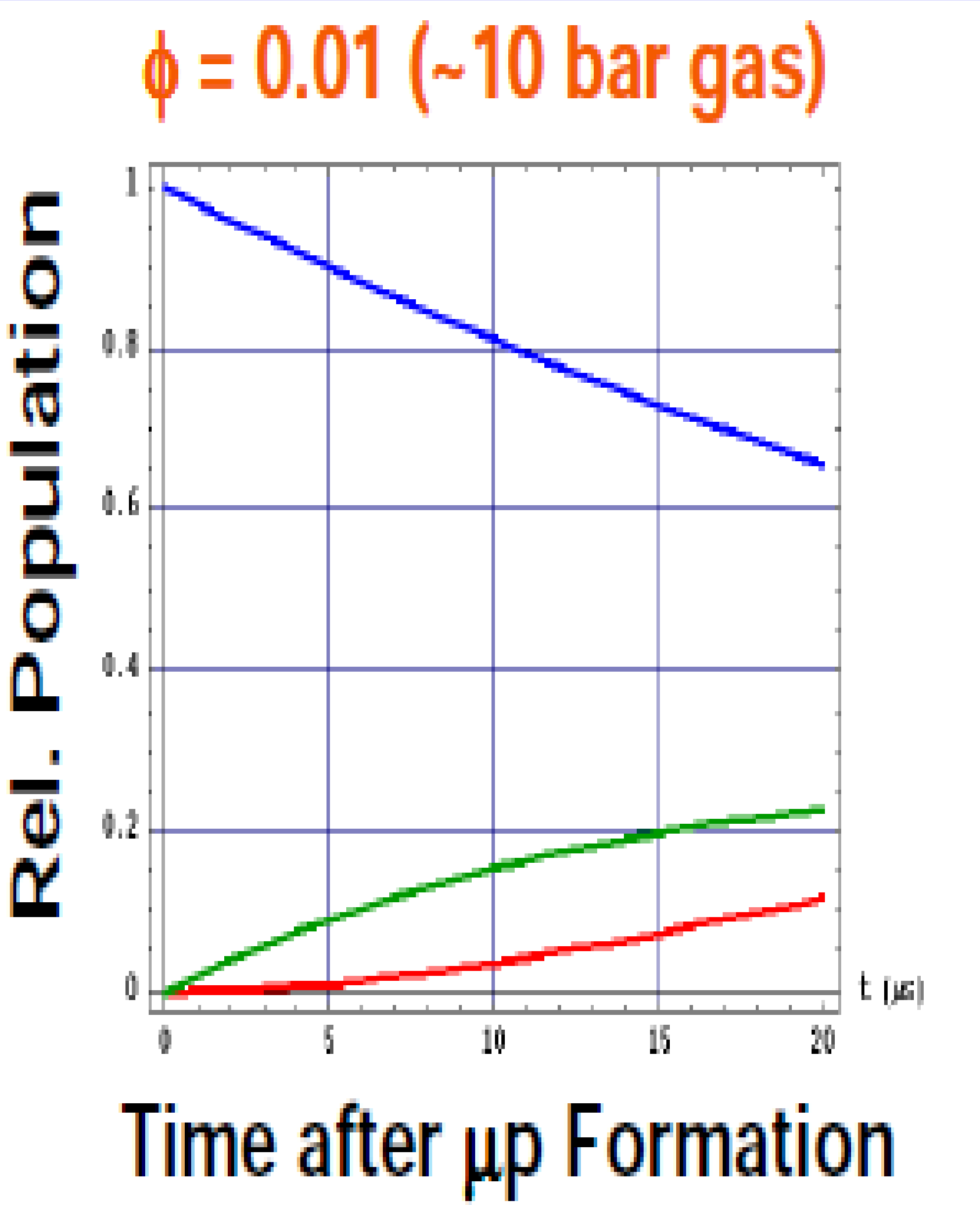


use ulltra-pure (chemically, isotopically

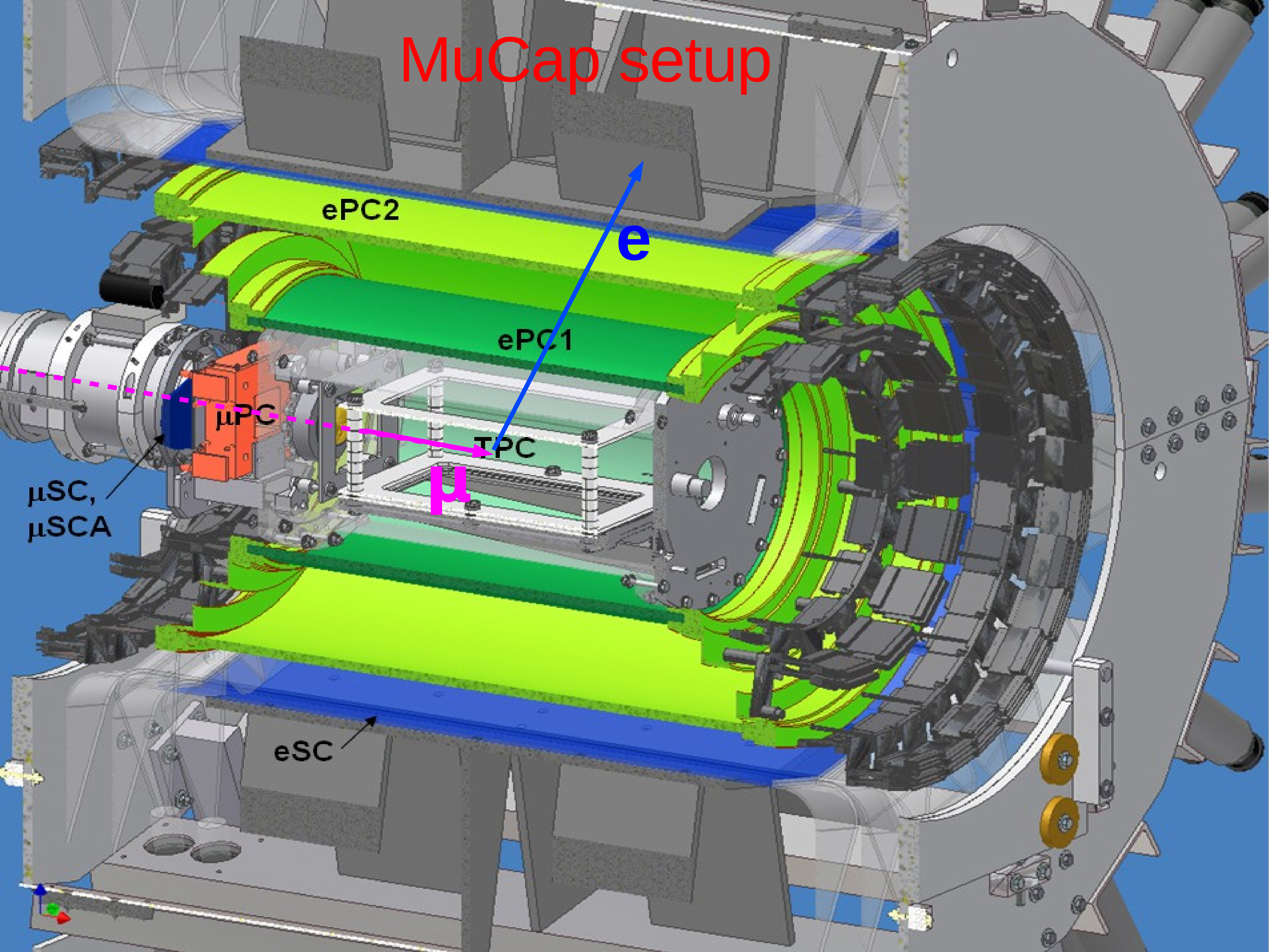
10 bar H_2 (1% liquid hydrogen density)

Relative populations of singlet atoms, ortho molecules, para molecules in liquid and gas

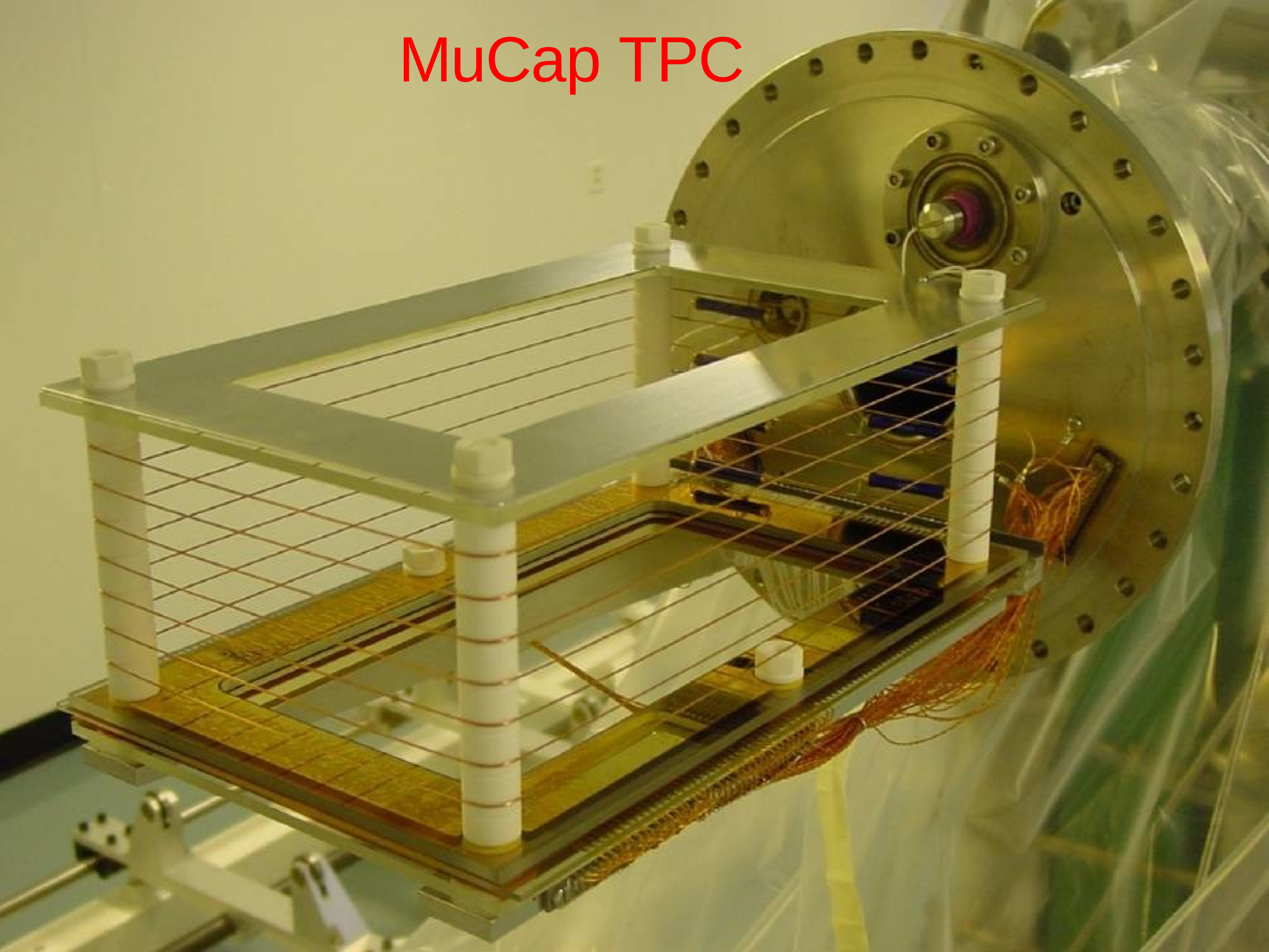




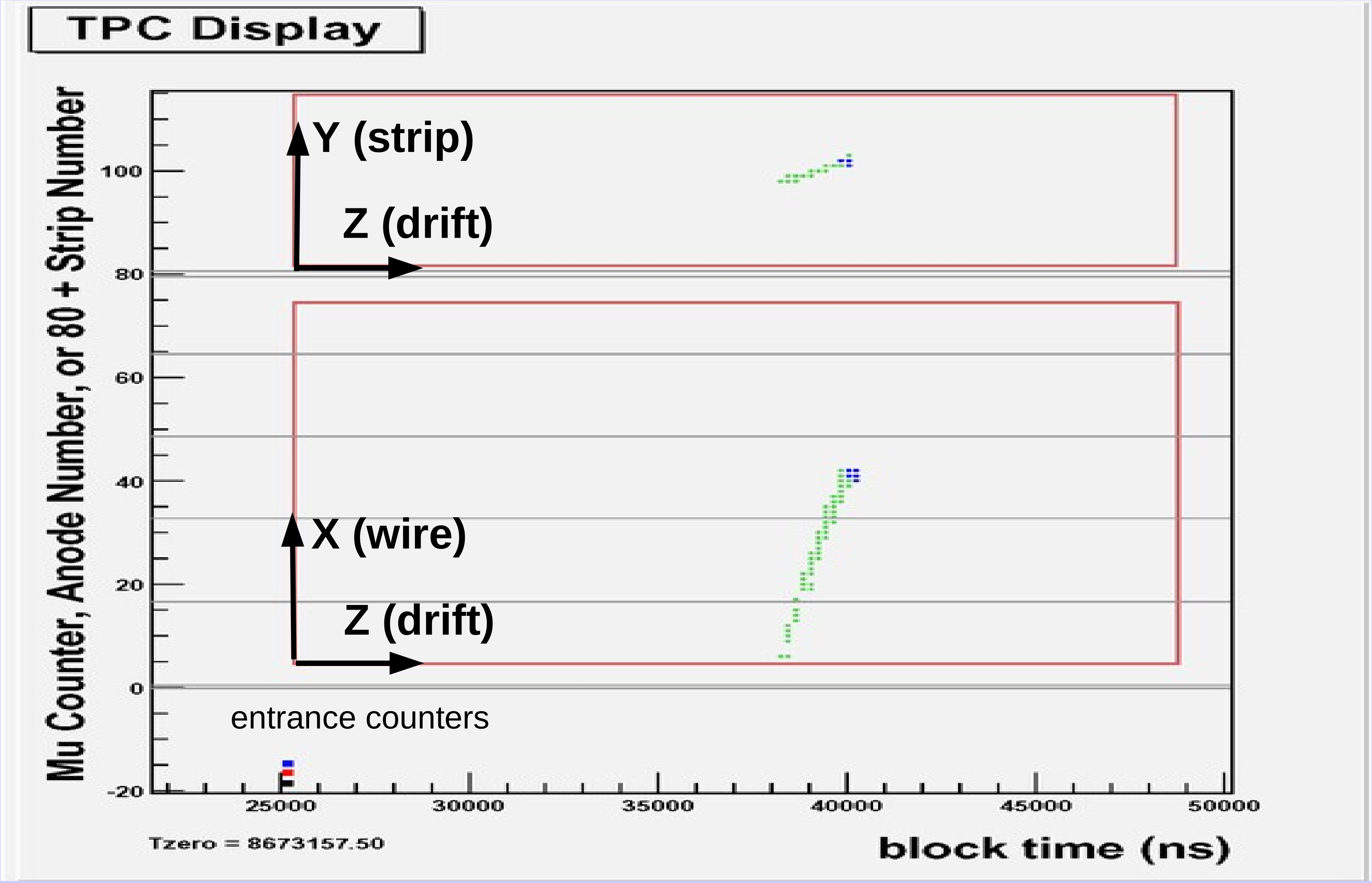
MuCap setup

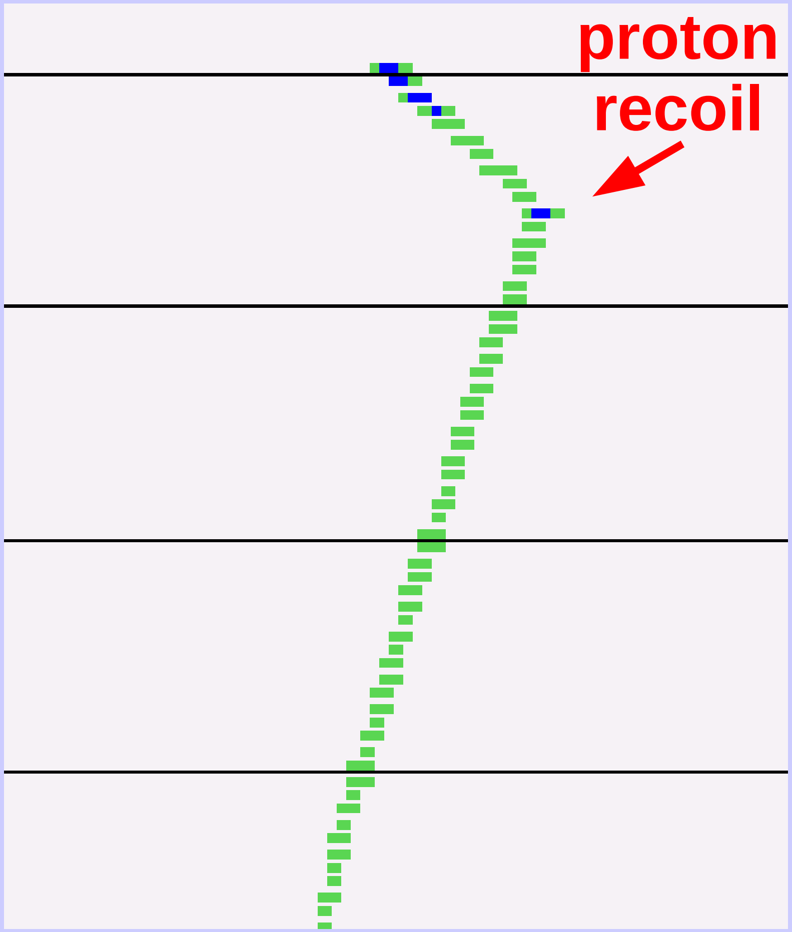


MuCap TPC

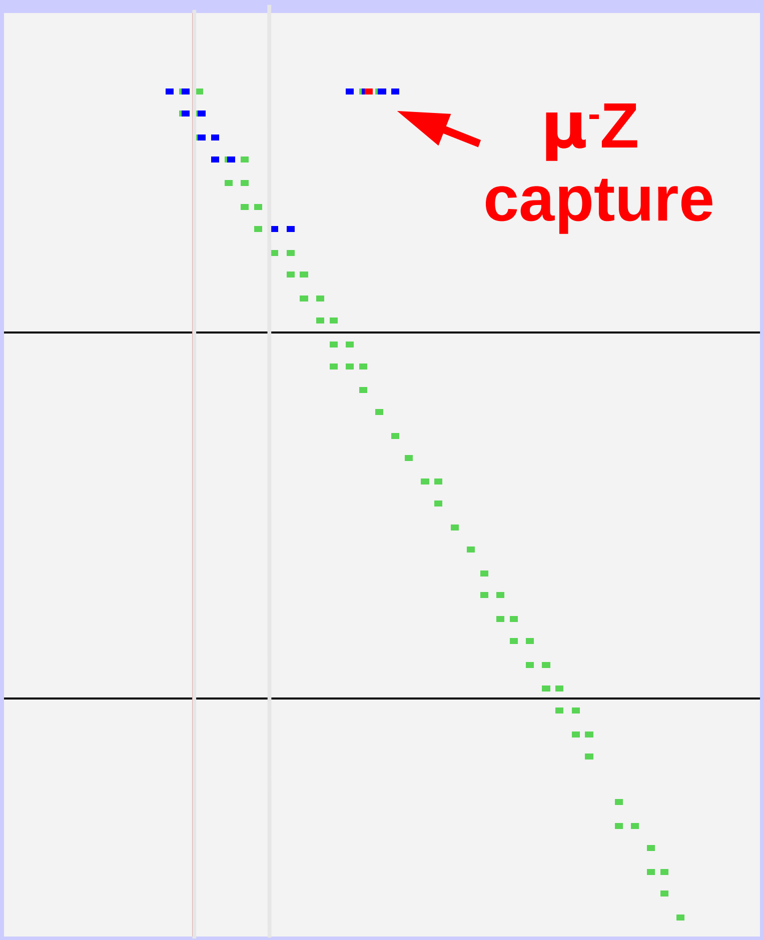


Event display of μ stop in H_2 gas

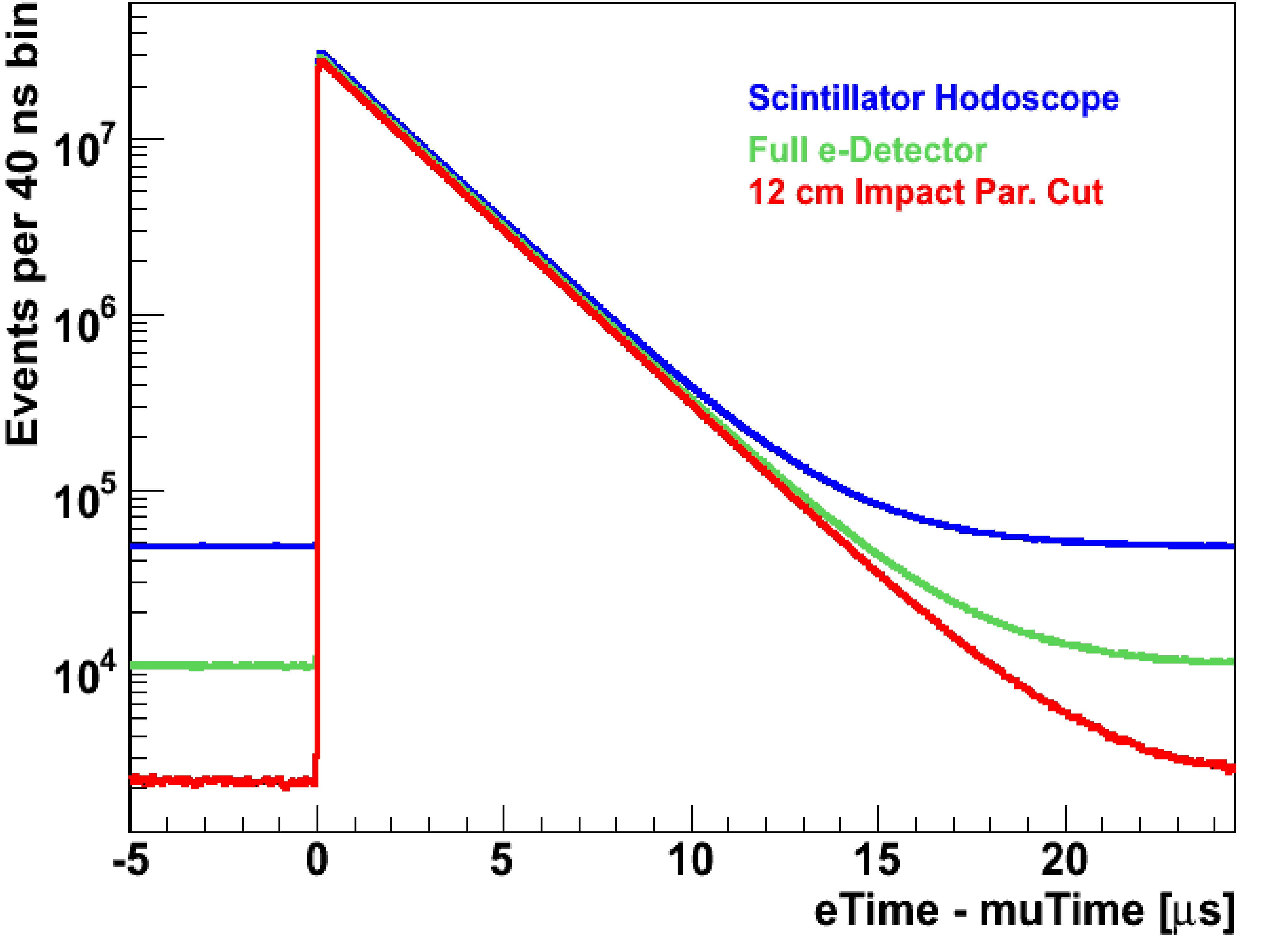




Rare μ scatter



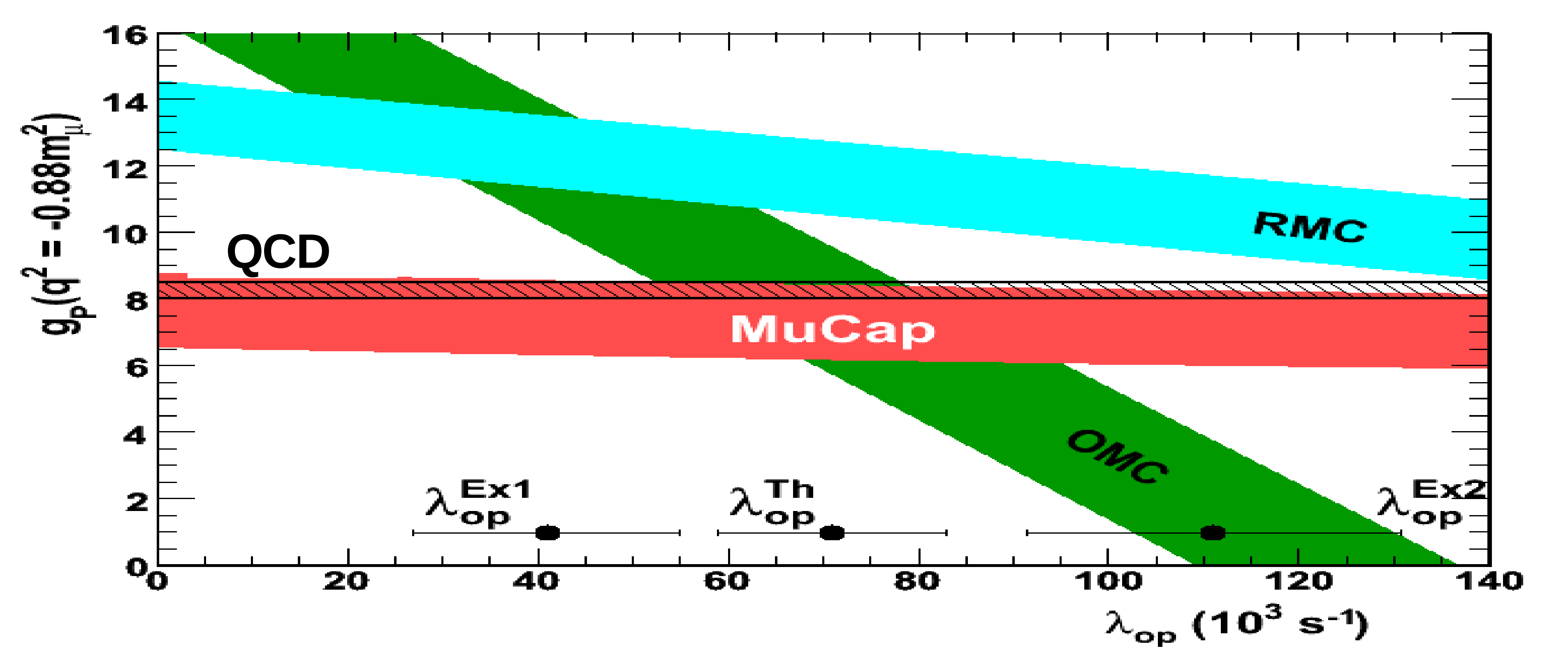
Rare μ transfer


Scintillator Hodoscope
Full e-Detector
12 cm Impact Par. Cut
Events per 40 ns bin
10^7
10^6
10^5
10^4
-5
0
5
10
15
20
eTime - muTime [μs]

MuCap Results

2005: Λ_S = 725.0 ± 13.7(stat) ±10.7(syst) s^{-1}

g_p (q^2 = $-0.88m^2_\mu$) = 7.3±1.1

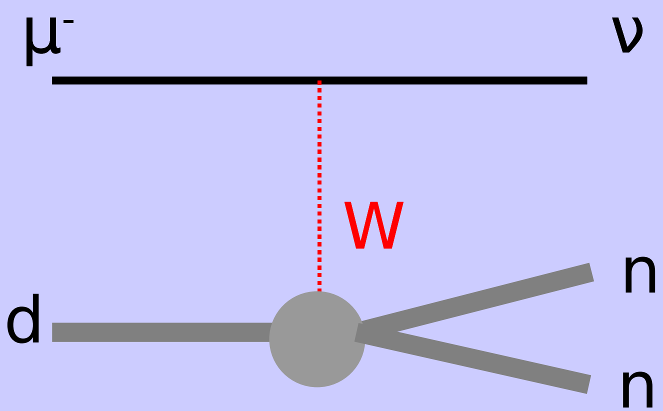


goal for 2006/2007 dataset is Λ_s to $\pm 5s^{-1}$

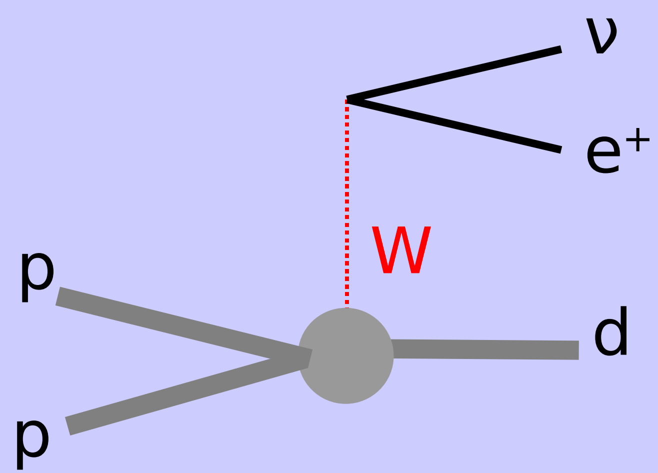
MuSun -the $\mu^- d$ lifetime,
elementary weak nuclear interaction,
and solar hydrogen burning.

Why we measure $\tau_{\mu d}$?

muon capture,
$\mu^- d \rightarrow \nu n n$



pp fusion,
$pp \rightarrow d e^+ \nu$



knowing g_v, g_a, g_m and g_p,
the deuteron wavefunction and NN interaction,
measure the poorly known $\mu^- d$ capture rate and
determine the poorly known two-nucleon weak axial current.

Why we determine Λ_d?

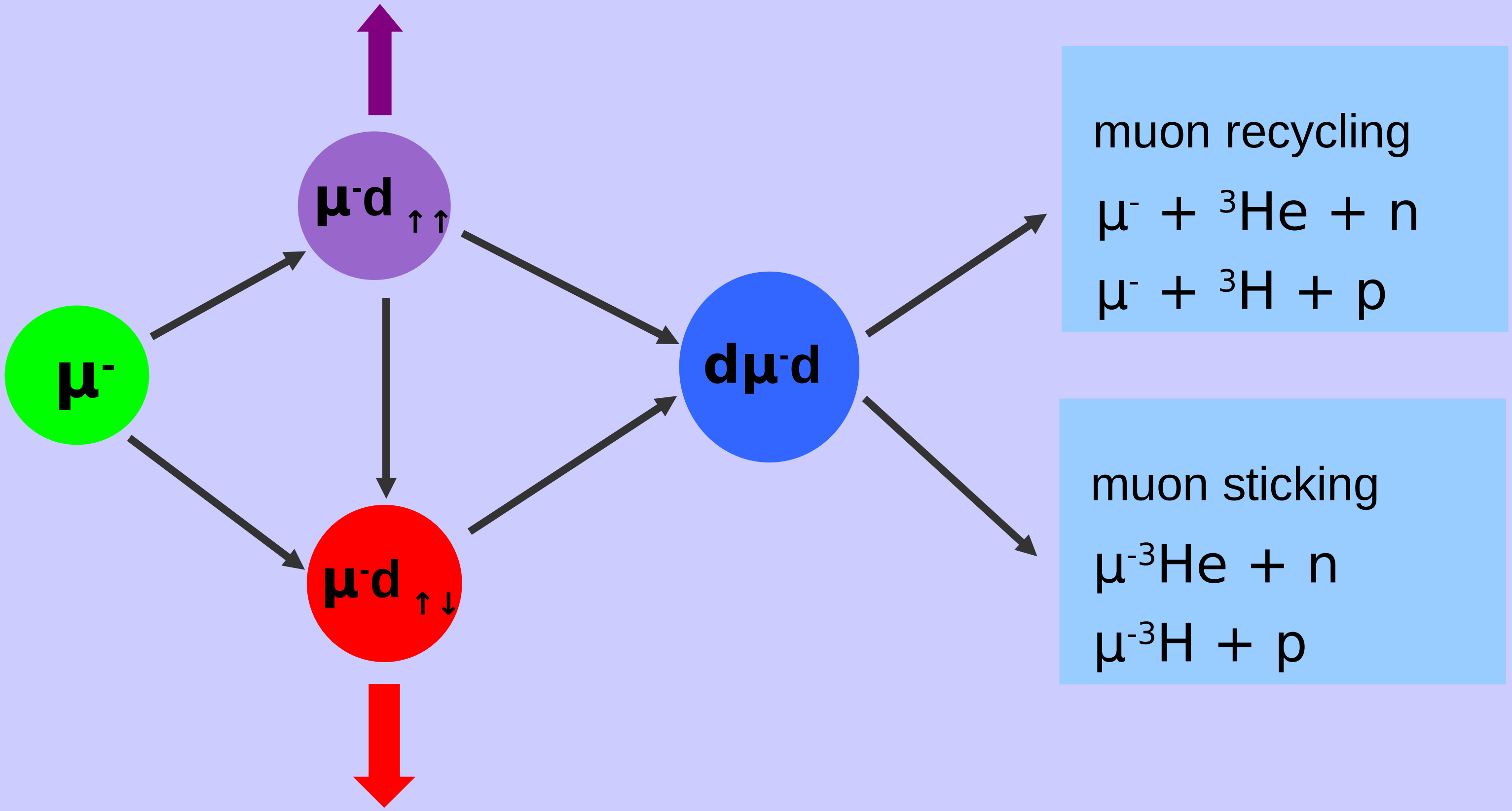
two-nucleon weak nuclear interaction where precision measurement and precision calculation are both possible.

determine the contribution of two-nucleon axial current.

relation of μ^-d capture to other weak processes of intense interest in solar physics (pp fusion) and neutrino physics (νd interactions).

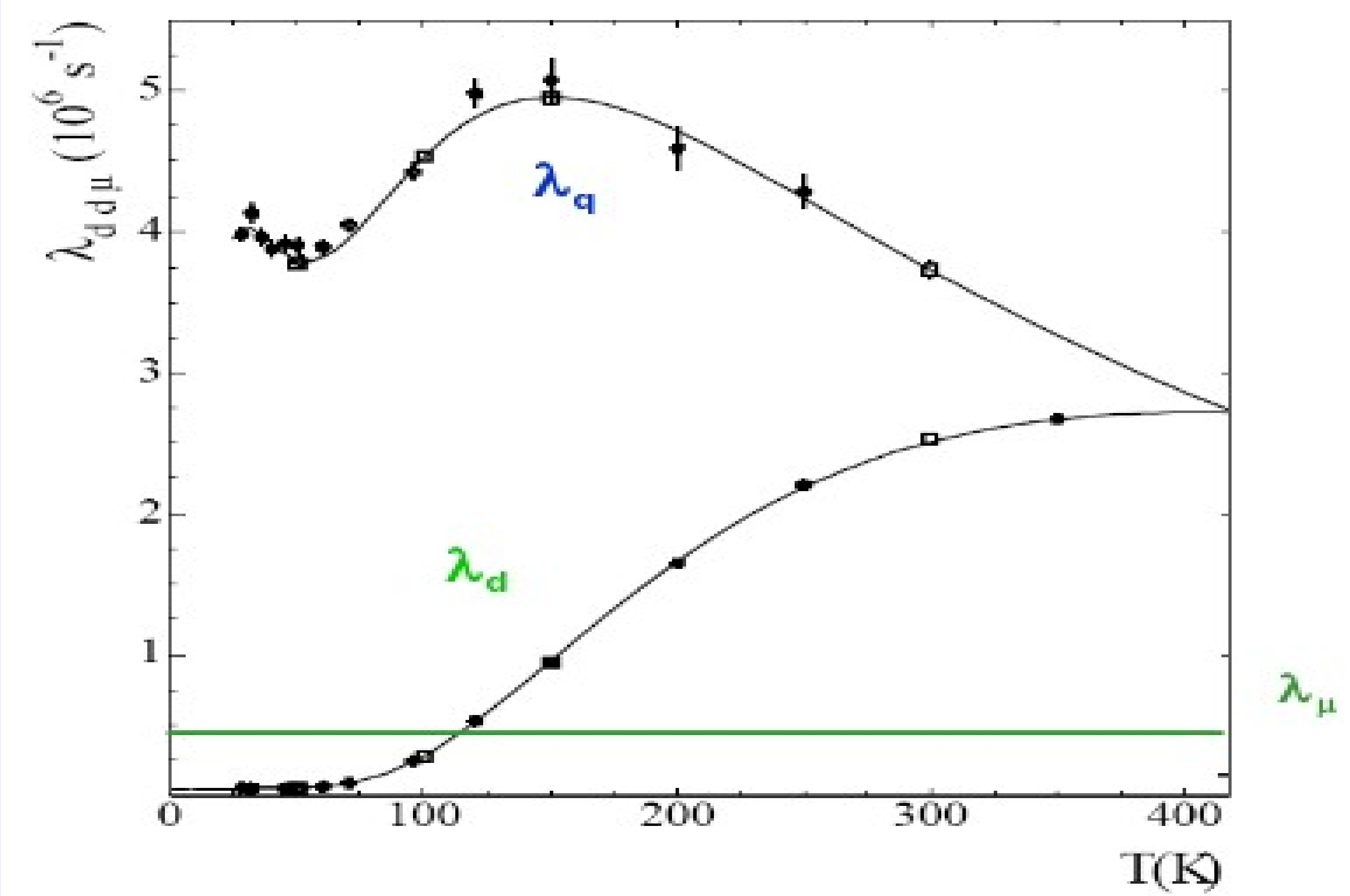
goal of ±1.5% measurement of capture rate Λ_d is five-fold improvement over existing measurements of 470±29 s^{-1} (Bardin et al.) and 409±40 s^{-1} (Cargnelli et al.).

μ chemistry, a complication

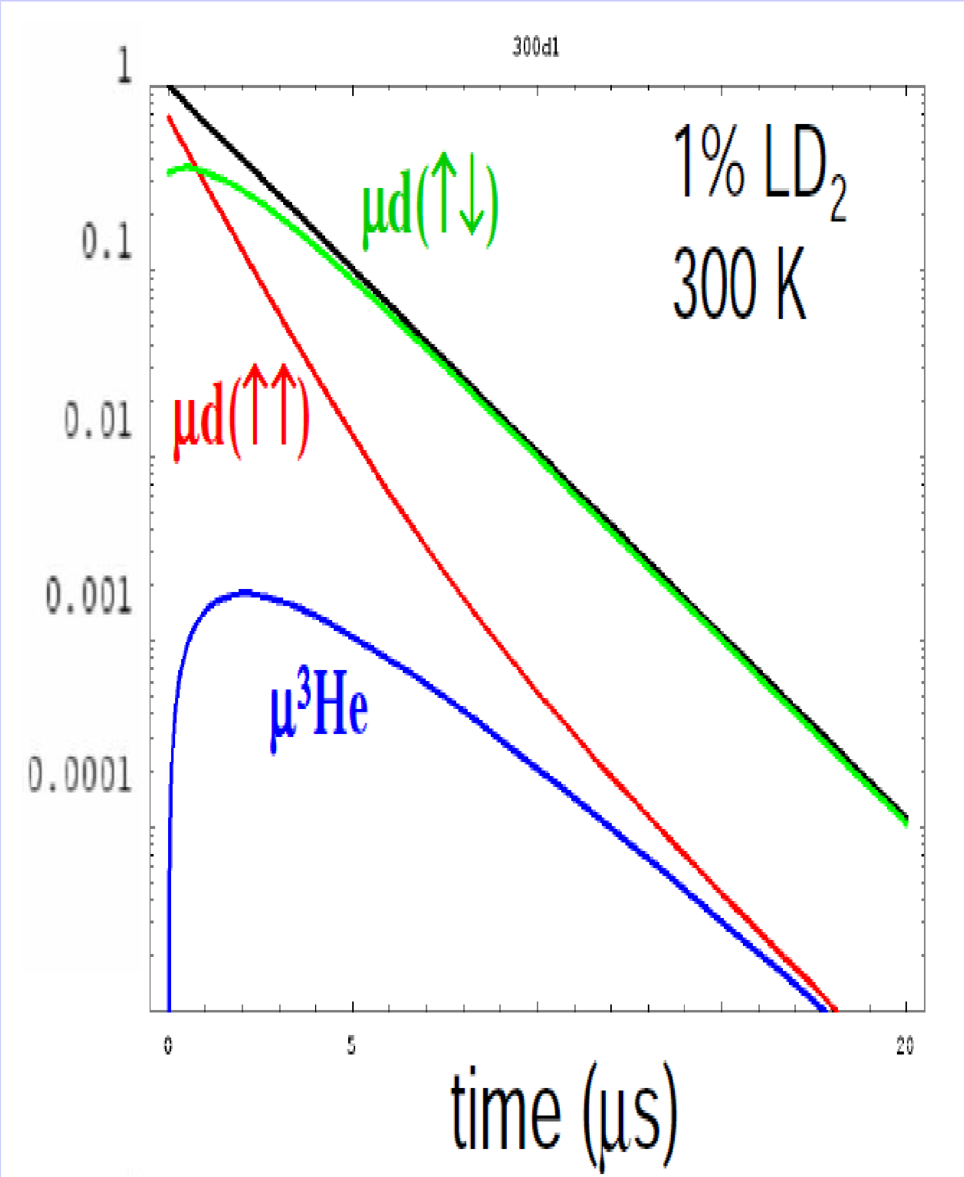


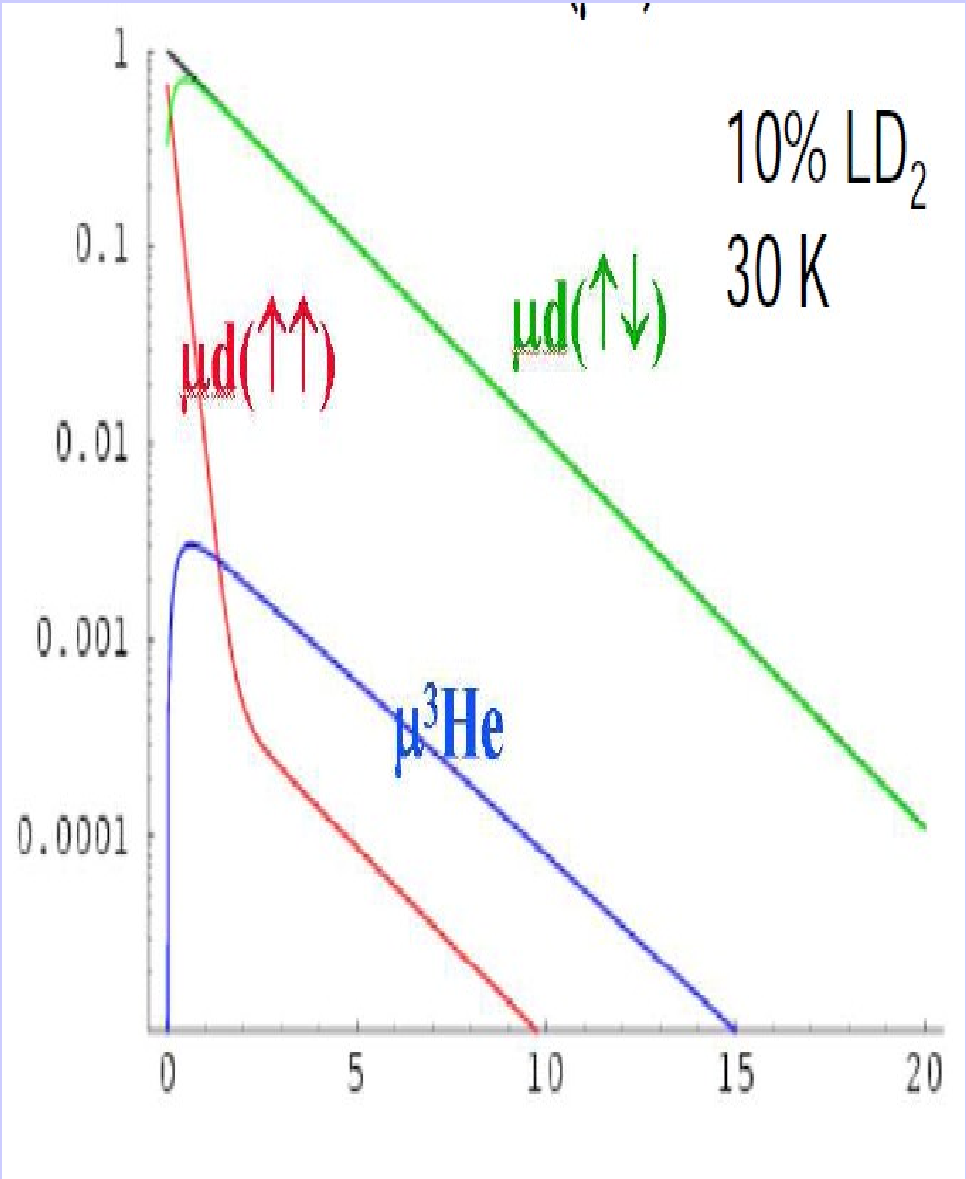
use ulltra-pure (chemically, isotopically)
30 Kelvin, 5% liquid density D_2 gas

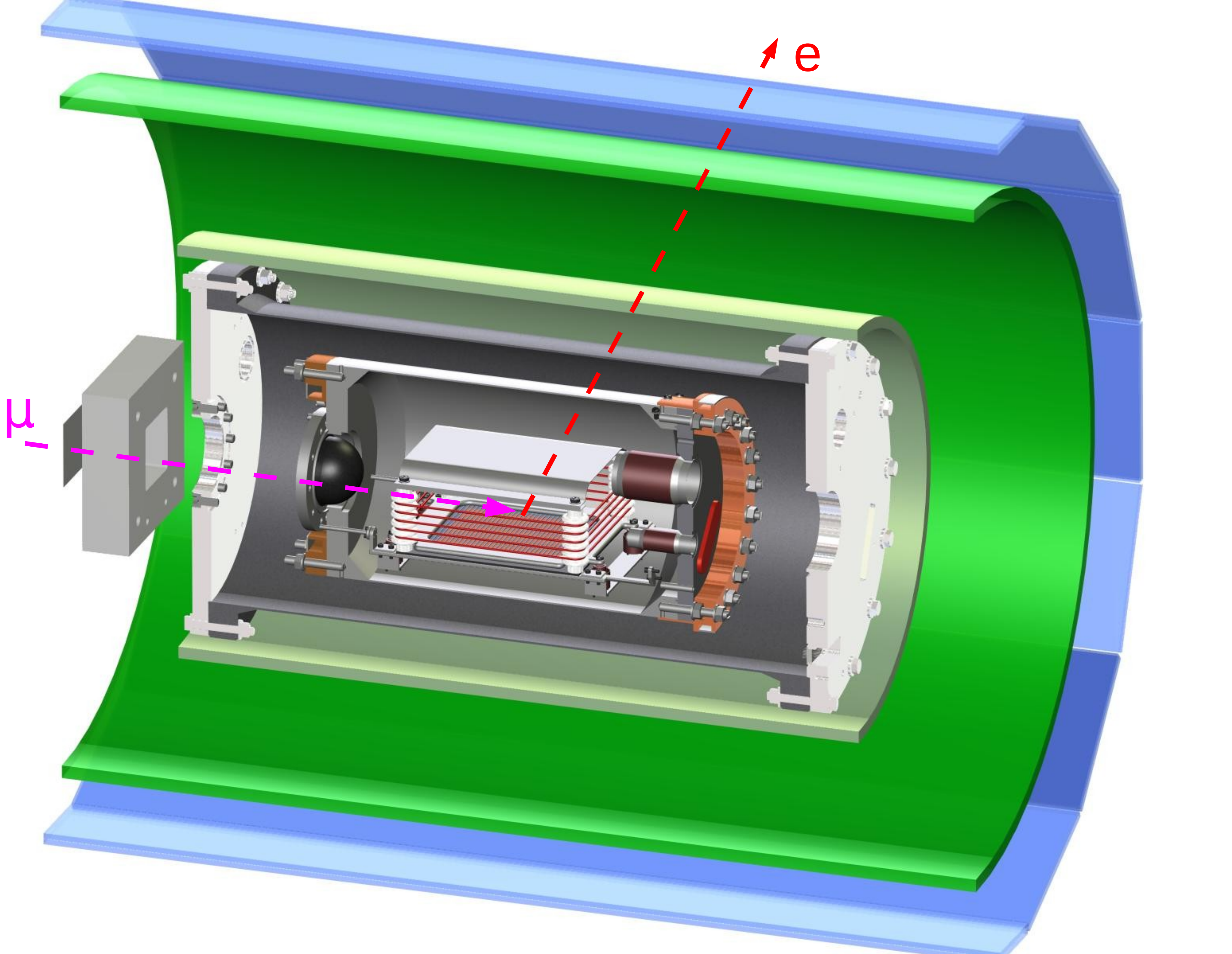
temperature dependence of dμd formation.



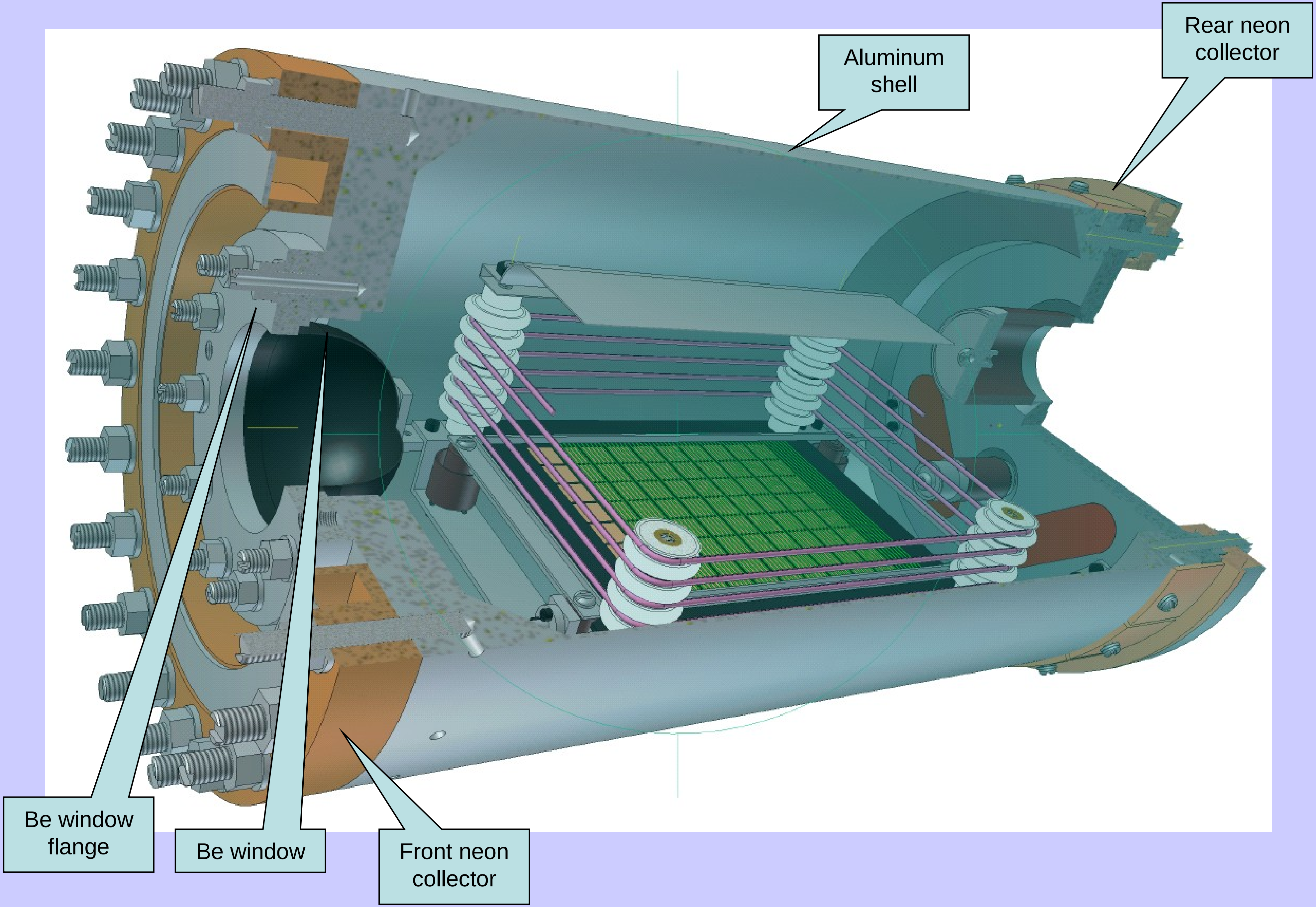
Relative populations of doublet atoms, quadruplet atoms, $\mu^{-3}He$ atoms in warm/cold gas






e
μ

Cryogenic TPC



Conclusions

MuX experiments - precision measurements of positive muon, muonic hydrogen, muonic deuterium lifetimes addressing fundamental leptonic, nucleonic and nuclear weak interactions.

MuLan experiment - **τ_μ= 2196980.1 ± 2.5(stat) ± 1.2(sys) ps [2006], τ_μ= 2196980.7 ± 3.7(stat) ± 1.2(sys) ps [2007], G_F= 1.166 381 8 (7) x 10^{-5} GeV^{-2}** - a twenty-fold improvement over earlier experiments.

MuCap experiment - **Λ_S = 725.0 ± 13.7(stat) ±10.7(syst) s^{-1}, $g_p(q^2 = -0.88 m^2_\mu)$ = 7.3±1.1** – with goal of reaching ±5s^{-1}.

MuSun experiment – **goal of Λ_S to ±1.5% -** recent milestone of operation of 3K, 5% LD_2 cryo-TPC

Extras

Relation to Standard Model

$$\sqrt{4\pi\alpha} = g g' / \sqrt{g^2 + g'^2}$$

$$G_F = \sqrt{2}/v^2$$

$$M_Z = \sqrt{g^2 + g'^2}\, v$$

→ **exacting tests of standard model by precision measurements of θ_W, M_W, ...**

Detection of μ stops in H_2 gas