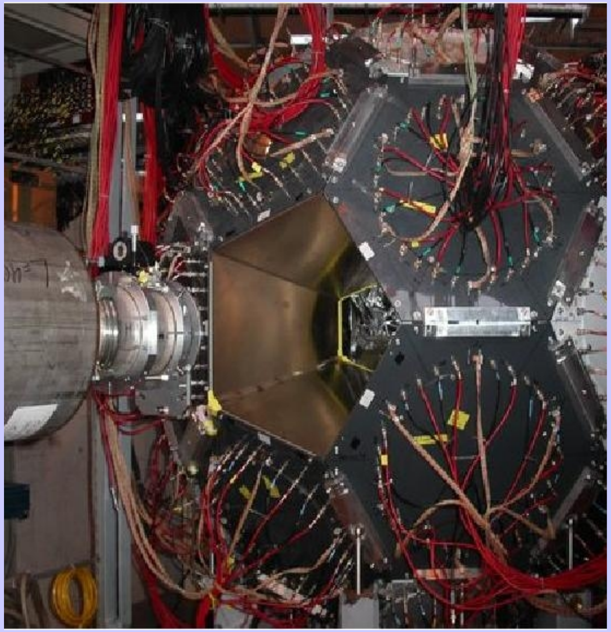
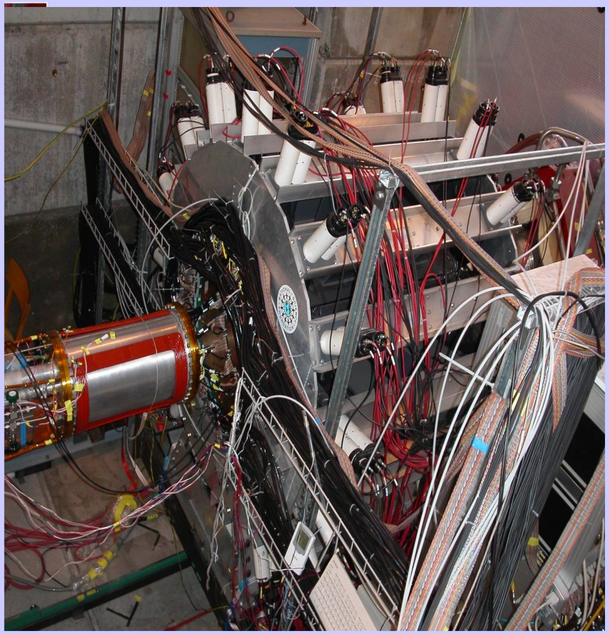
Precision measurements of μ^+, μ^-H, and μ^-D lifetimes.

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

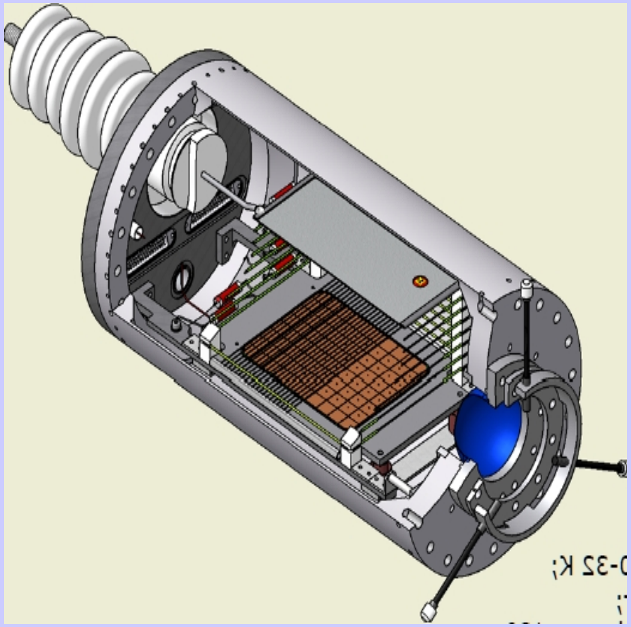
SLAC experimental seminars, May 10, 2011.



MuLan



MuCap



MuSun

pure leptonic weak interactions...

to nucleonic weak interaction...

and weak nuclear interaction

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

Outline

intense, pulsed µ's at PSI

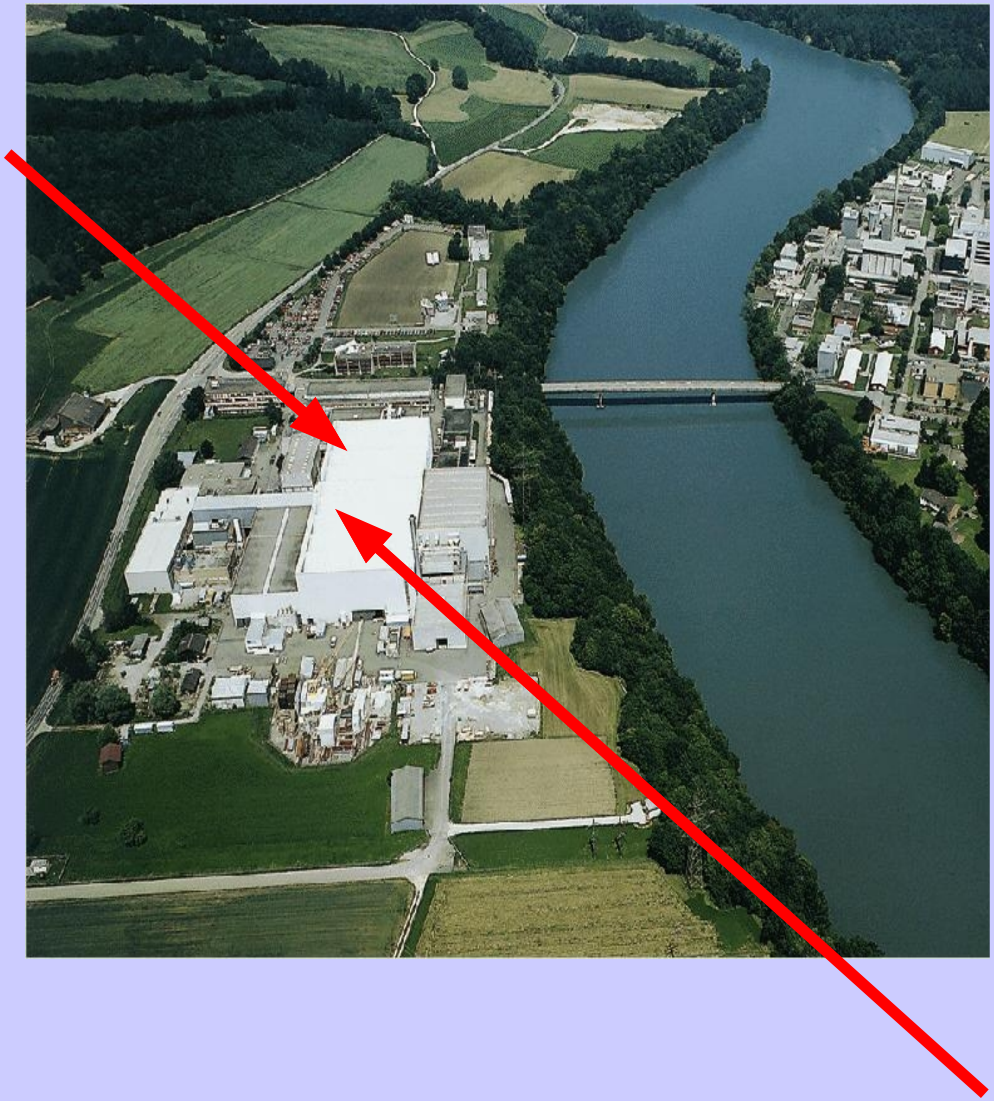
scientific goals

setups and challenges

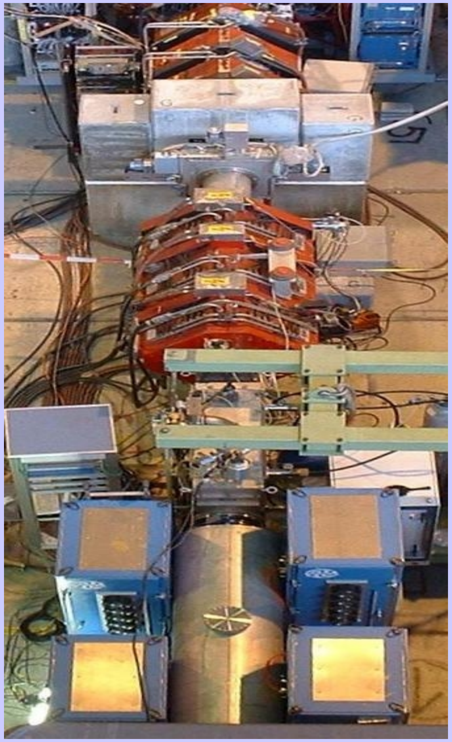
results and status

Paul Scherrer Institute.

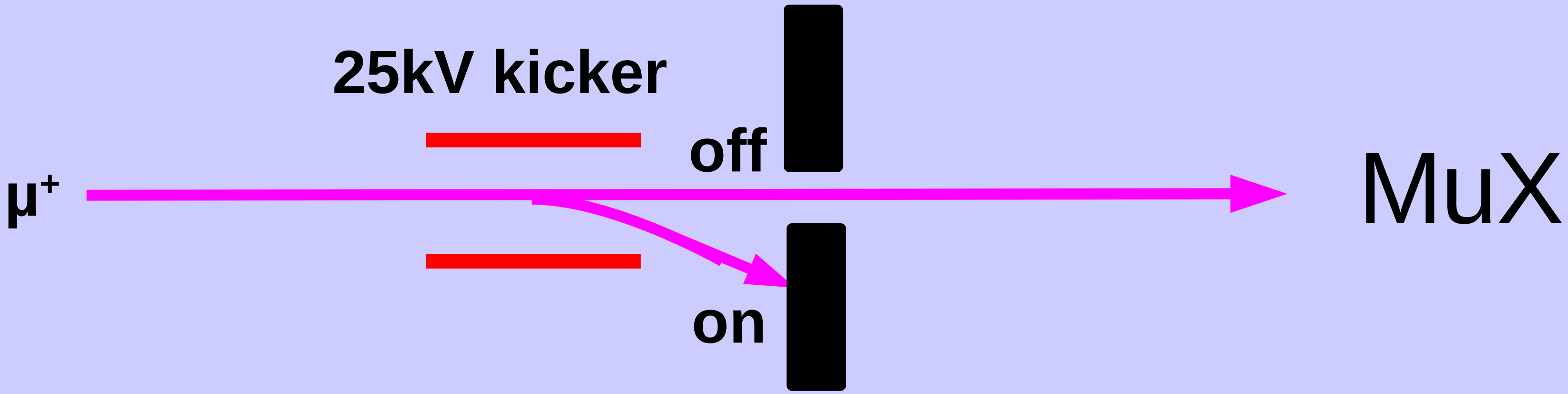
2.0 mA, 590 MeV,
1 MWatt, proton
cyclotron



time-structured,
5 MeV, 30 MeV/c
$\mu^{\pm}$ beams



Pulsed Muons and Muon On Request.

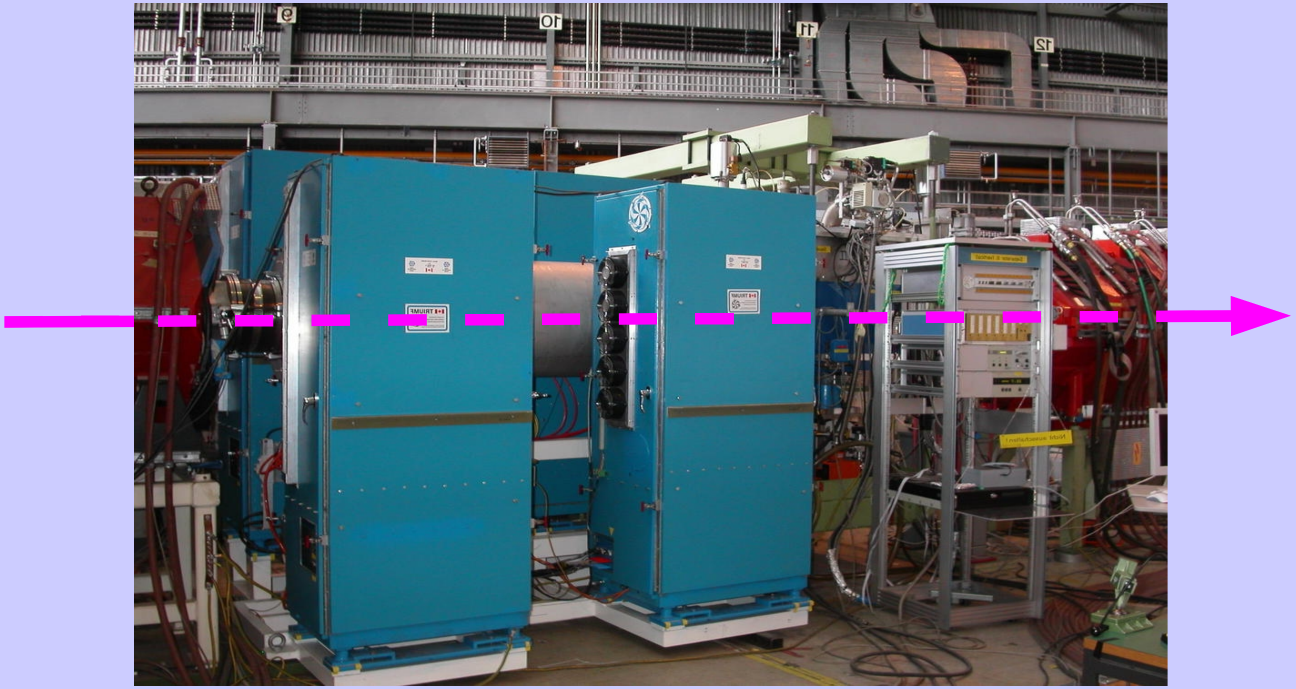

25kV kicker

off

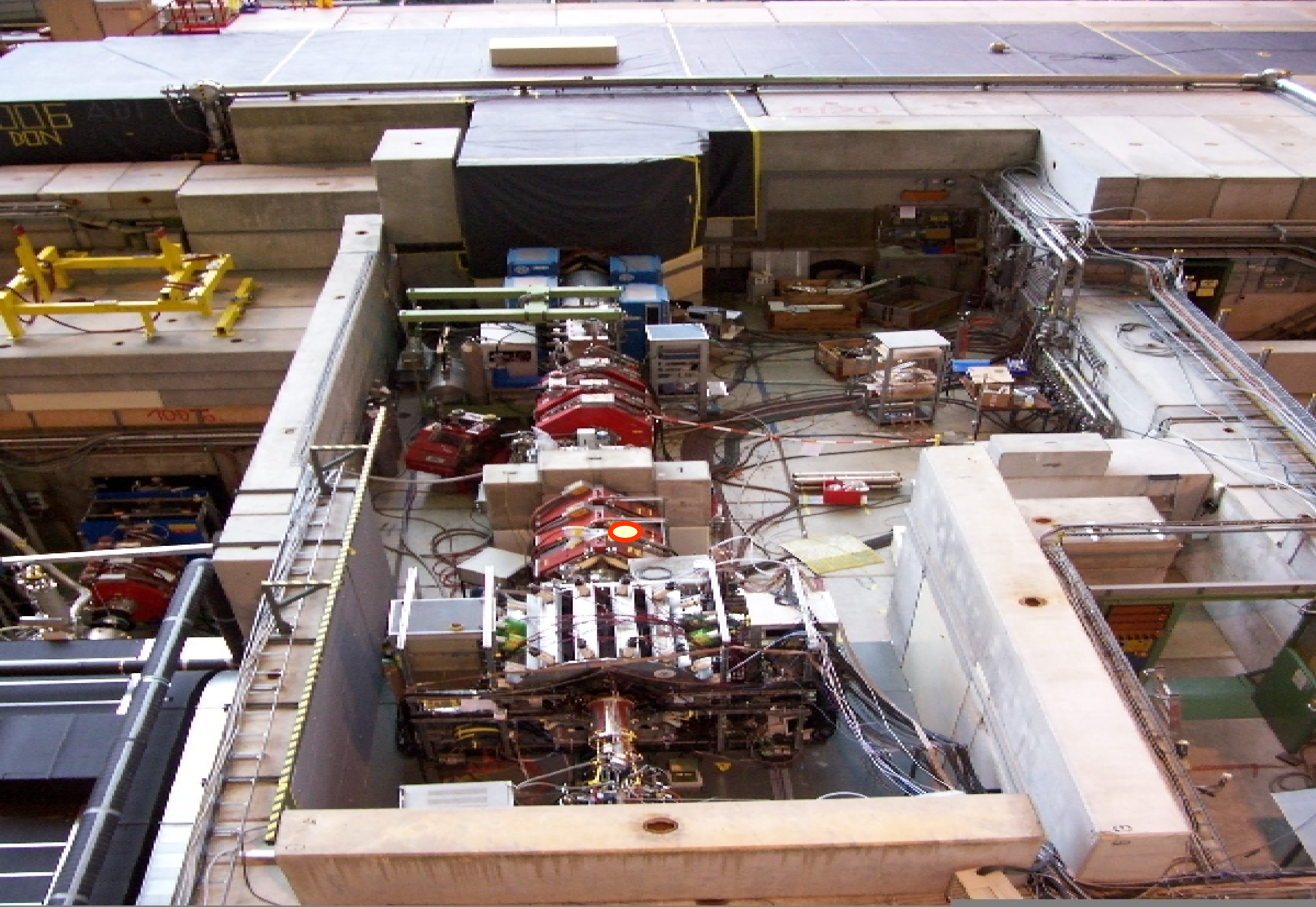
on

μ^+

MuX


μ^+

MuX



πE3 beamline

MuLan – the muon lifetime and Fermi constant.

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

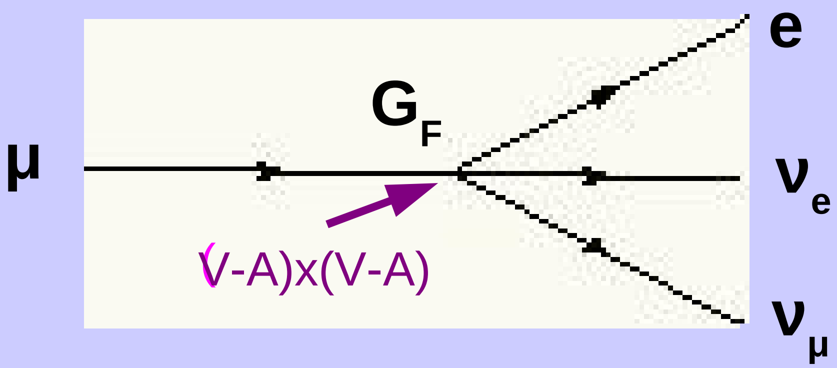
knowledge of muon lifetime $\tau_{\mu+}$ allows precision measurements of weak nuclear interactions in muonic hydrogen, deuterium atoms.

twenty-fold improvement in knowledge of fundamental constant G_F of electroweak sector of standard model [presently α (±0.7ppb), G_F (±10ppm) M_Z (±23ppm)].

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

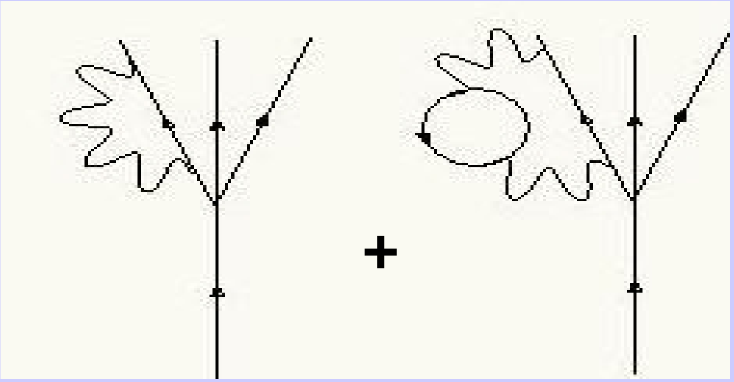
Relation between muon lifetime and Fermi constant.

(muon decay is pure leptonic weak decay with lifetime that's straightforward to measure)



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

Δq contains electron mass and QED, QCD radiative corrections

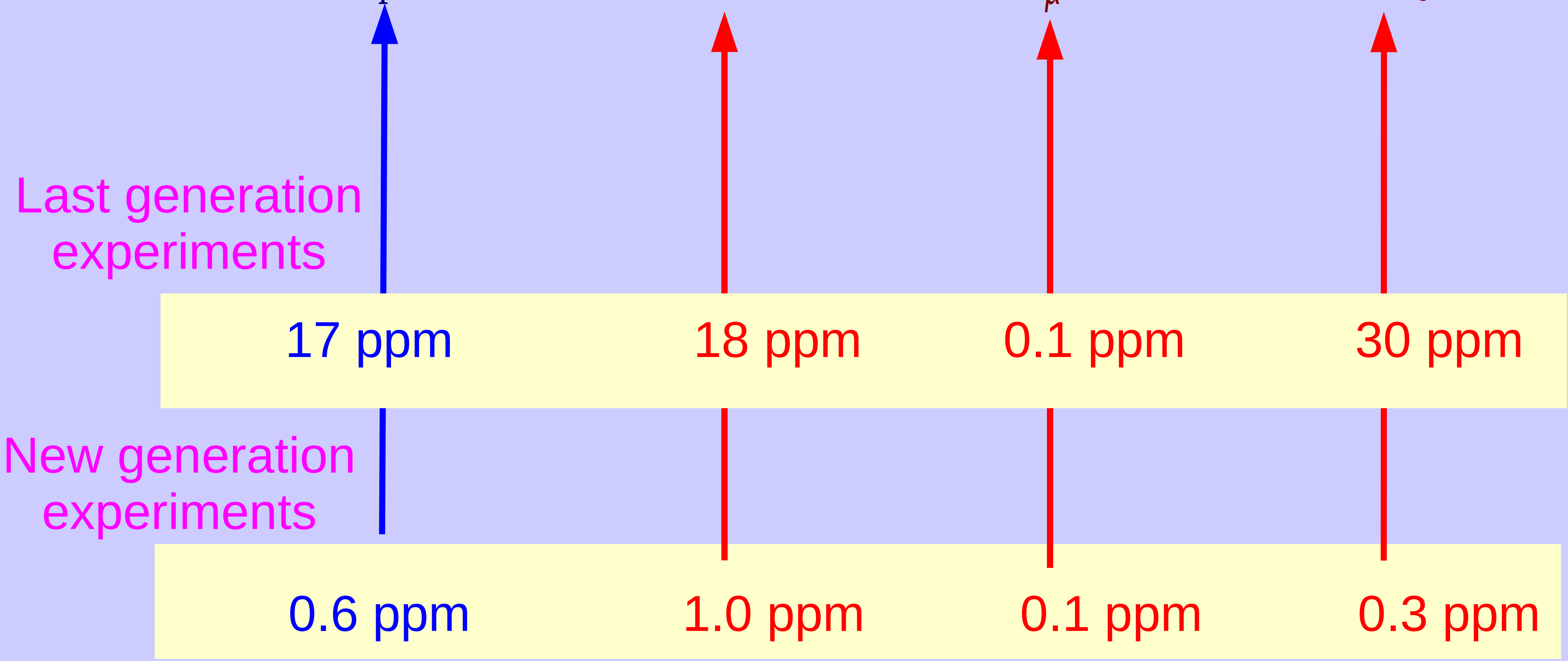


1999, von Rittbergen and Stuart, 2-loop QED corrections

2008, Pak and Czarnecki, higher-order electron mass corrections

Relation between muon lifetime and Fermi Constant.

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



Last generation experiments

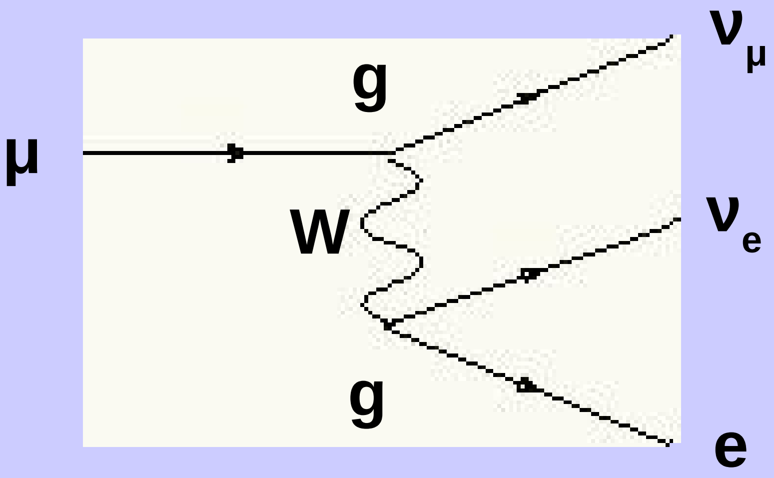
17 ppm 18 ppm 0.1 ppm 30 ppm

New generation experiments

0.6 ppm 1.0 ppm 0.1 ppm 0.3 ppm

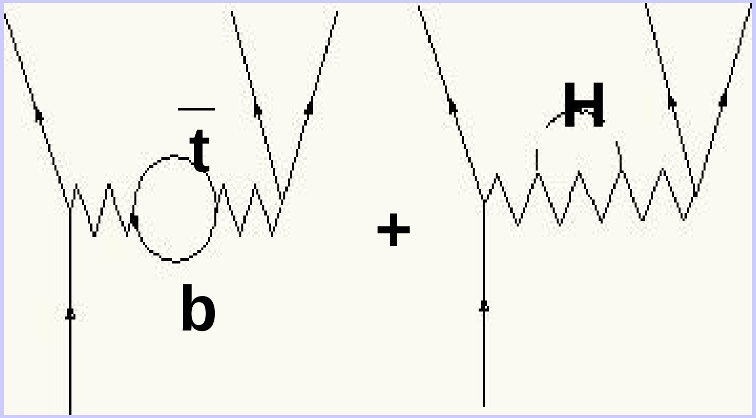
(negligible effect from finite ν-mass)

Interpretation of Fermi constant in Standard Model



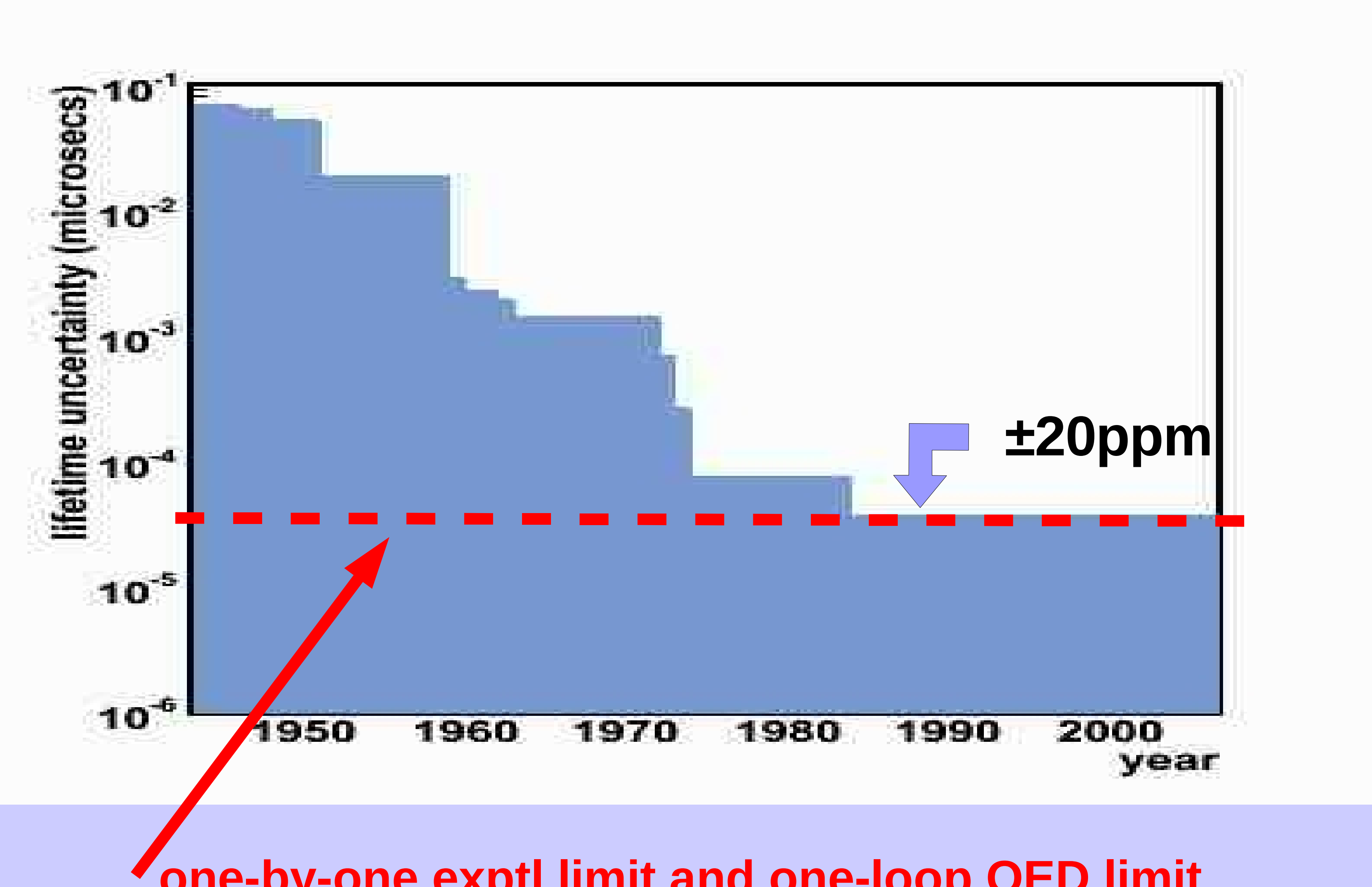
$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8 M_W^2}(1 + \Delta r)$$

Δr contains electroweak radiative corrections



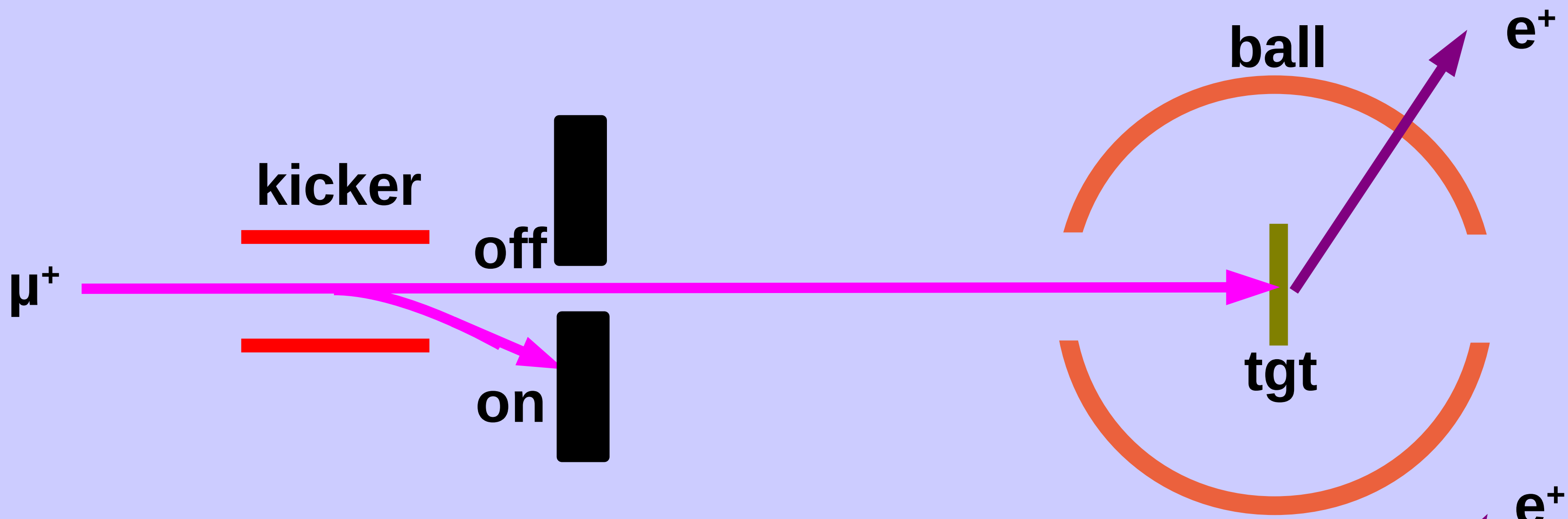
e.g. Contributions from top quark, Higg's particle

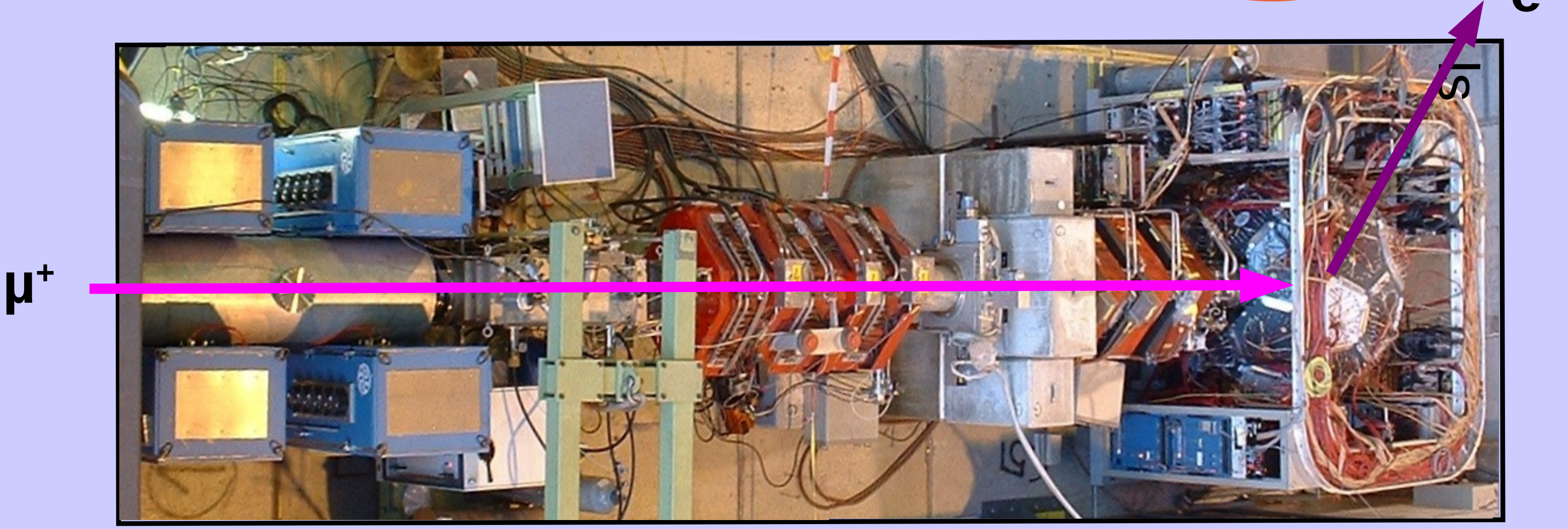
muon lifetime history, $\tau_\mu = 2.19703(4)\ \mu s$



one-by-one exptl limit and one-loop QED limit

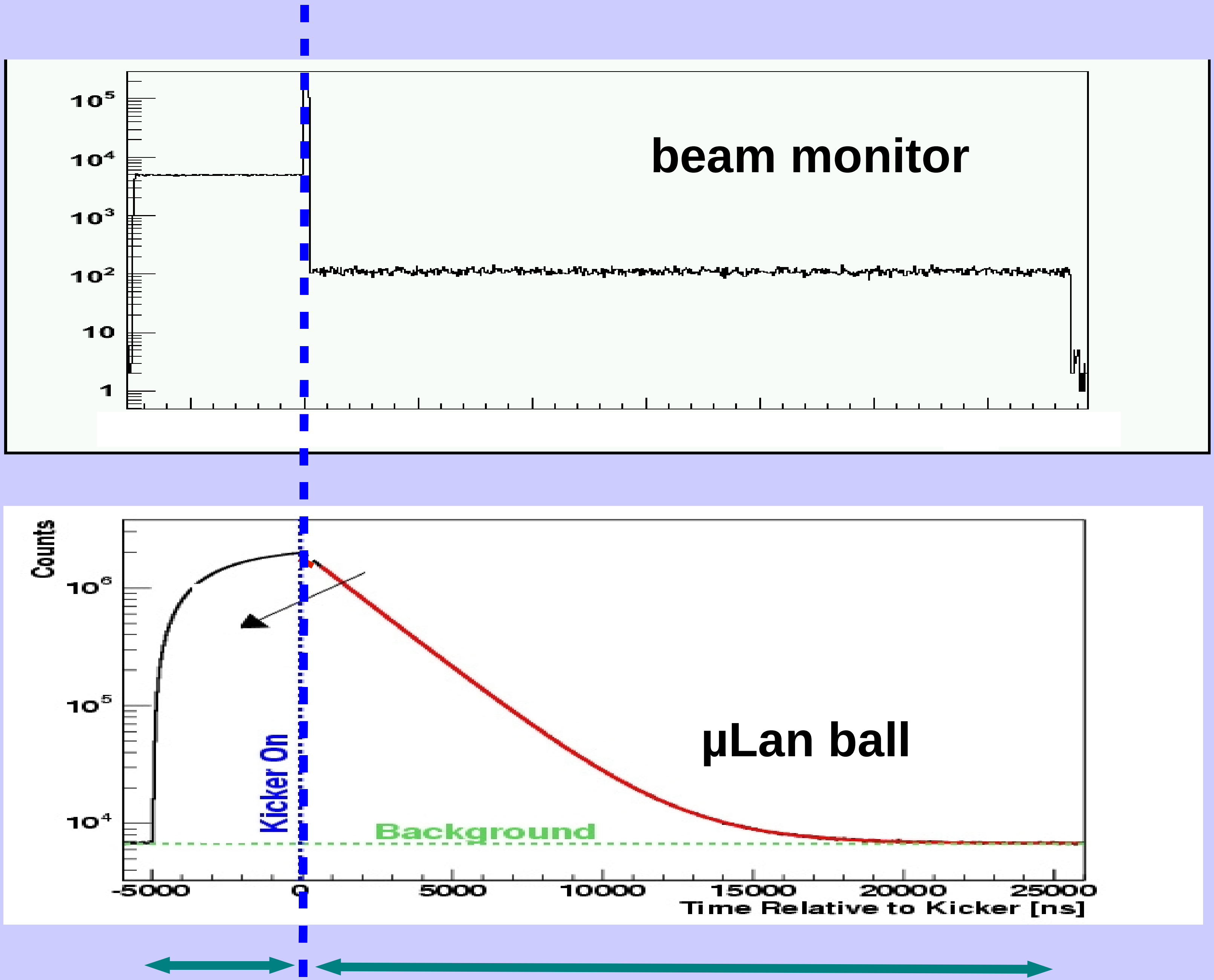
accumulating μ^+'s and measuring e^+'s





roughly 30 μ stops, 20 e detected per cycle

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



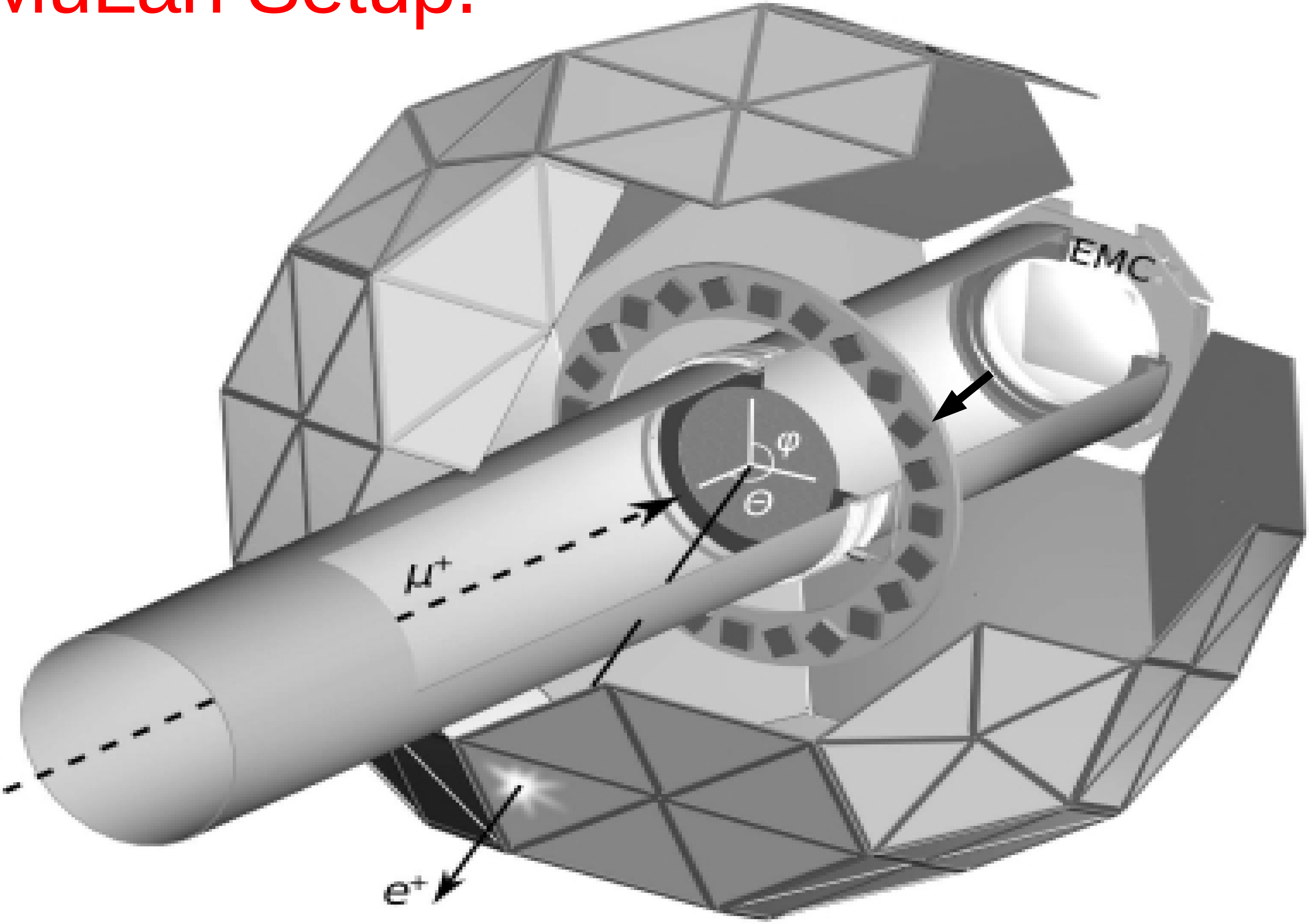
beam monitor

μLan ball

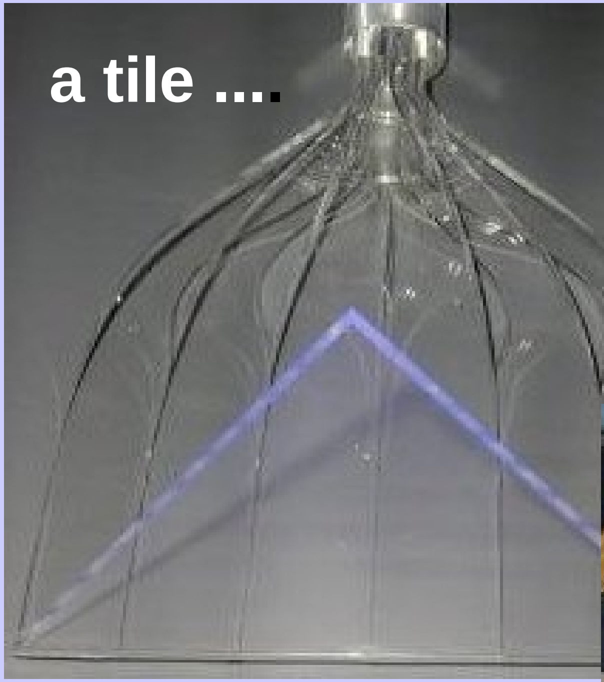
beam on

beam off

MuLan Setup.



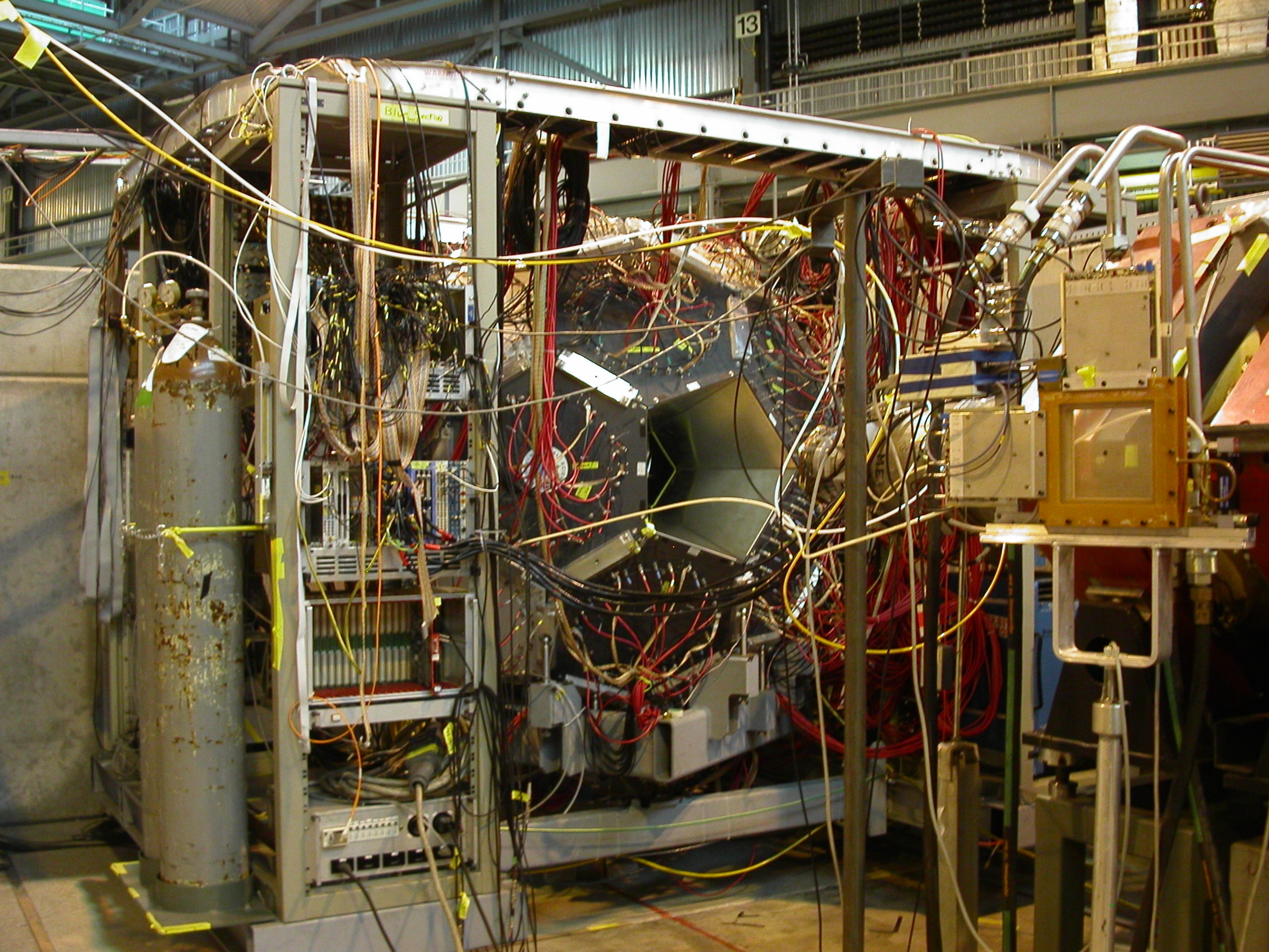
MuLan

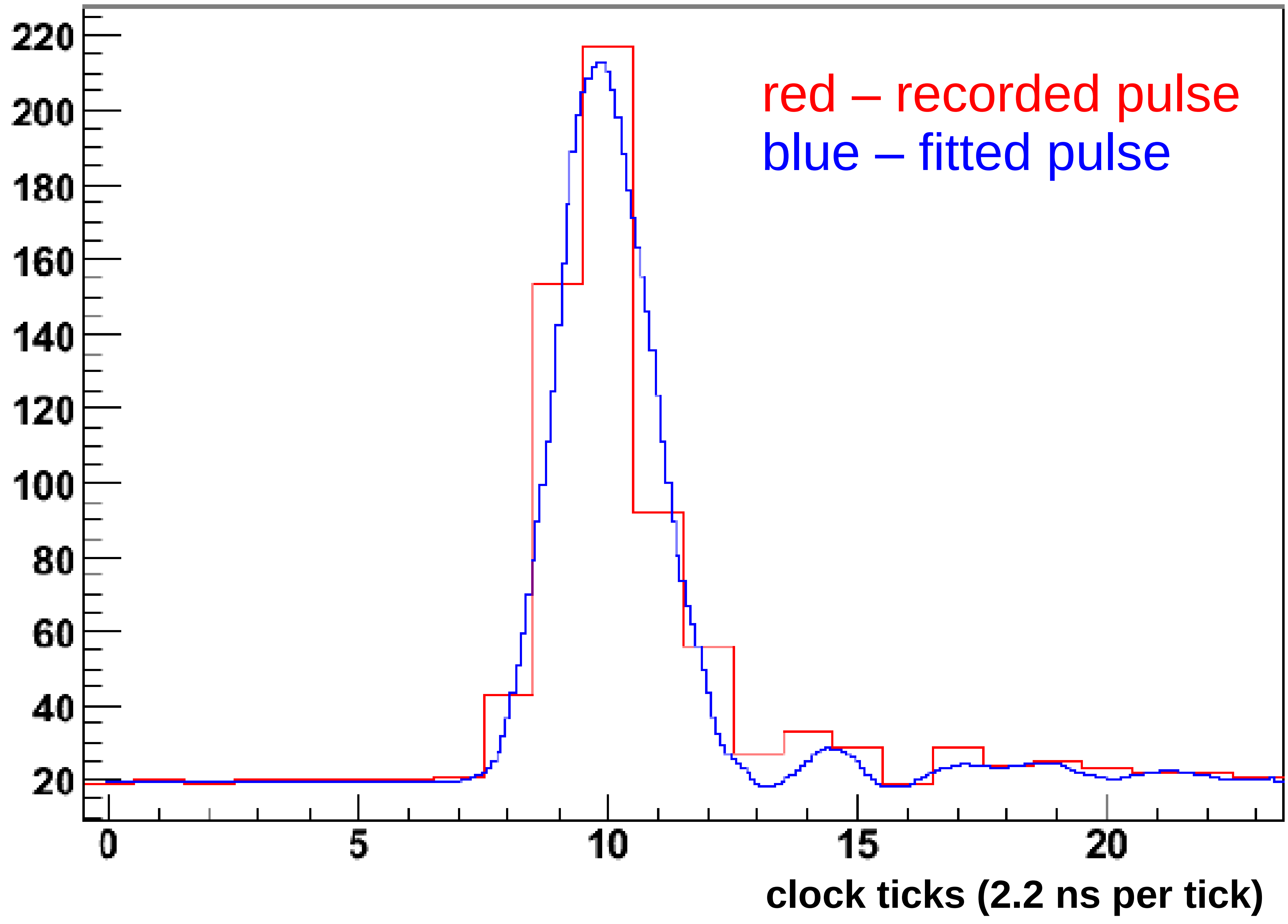


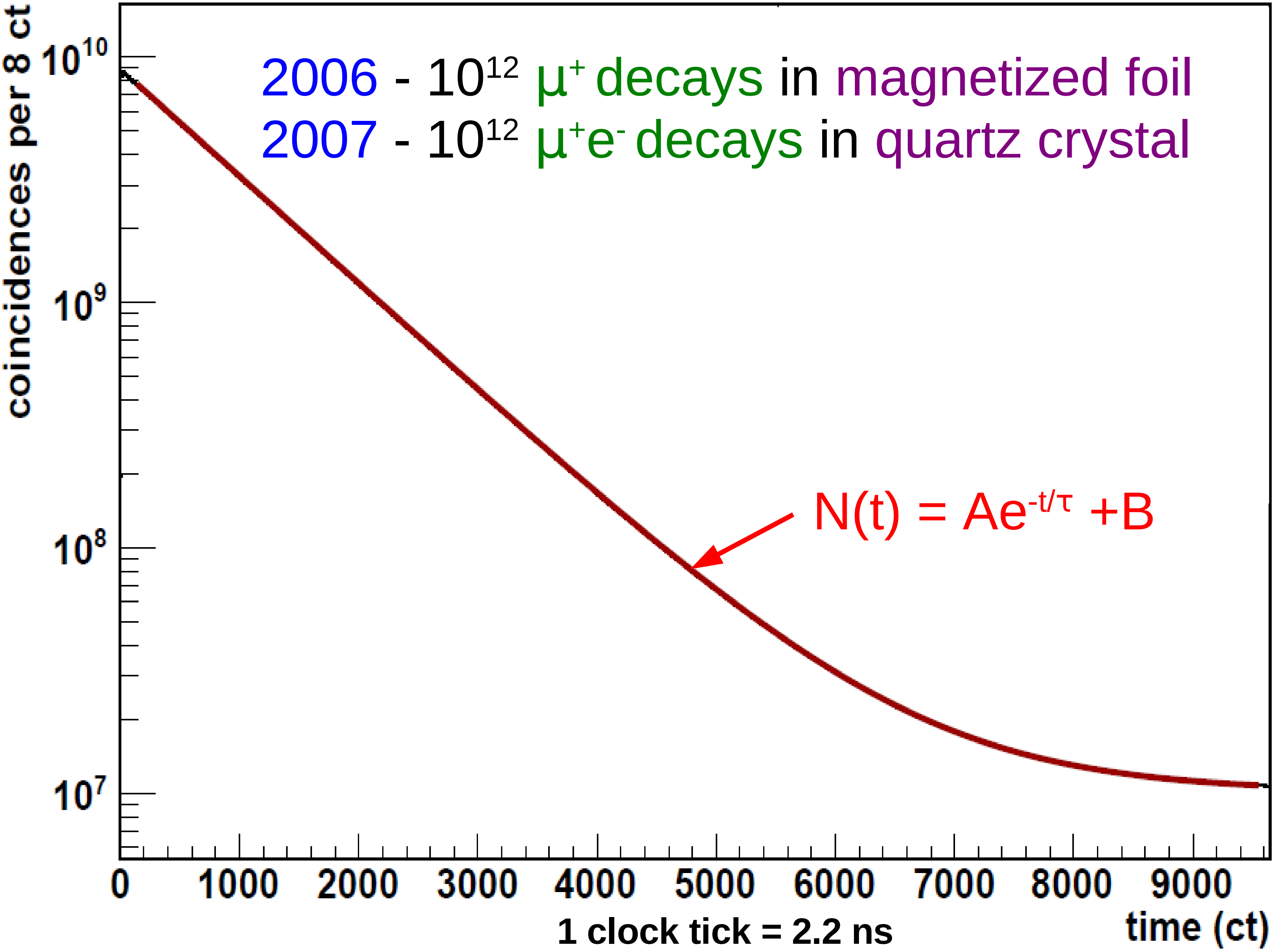
a tile ....

a house ..

the ball.


13


red – recorded pulse
blue – fitted pulse
220
200
180
160
140
120
100
80
60
40
20
0
5
10
15
20
clock ticks (2.2 ns per tick)

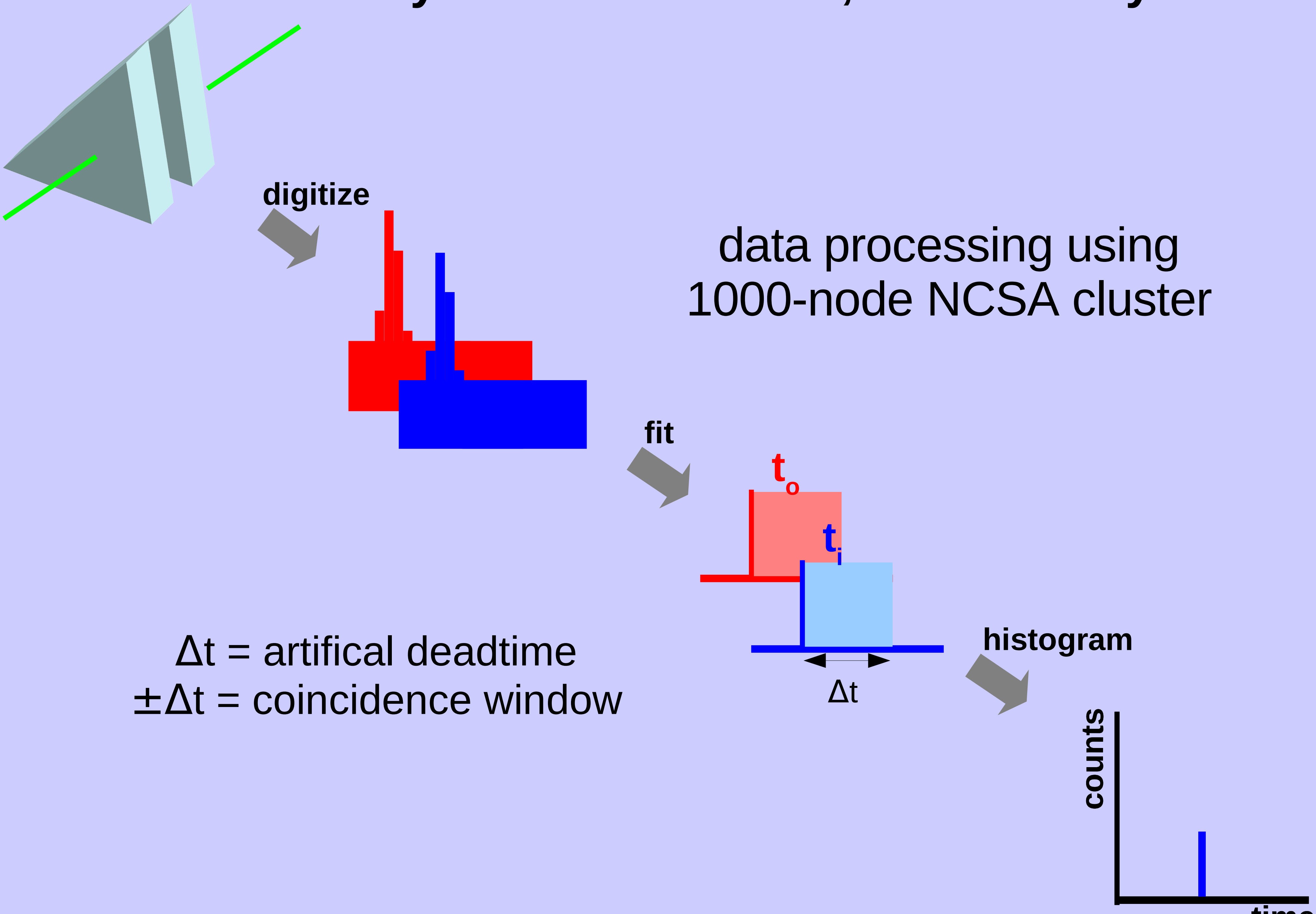


2006 - 10^{12} μ^+ decays in magnetized foil

2007 - 10^{12} μ^+e^- decays in quartz crystal

$N(t) = Ae^{-t/\tau} + B$

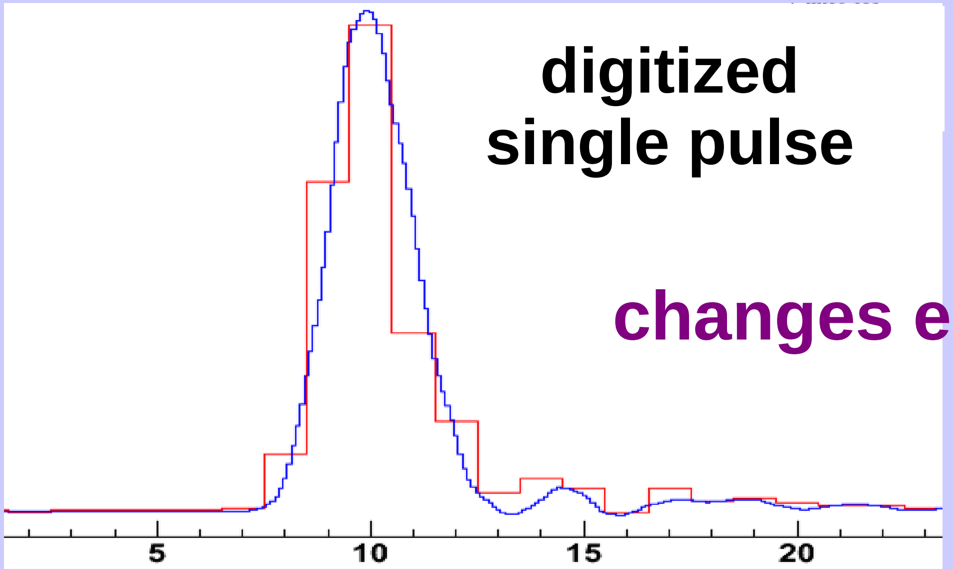
blind analyses of 130TB data, 2x10^{12} decays



data processing using
1000-node NCSA cluster

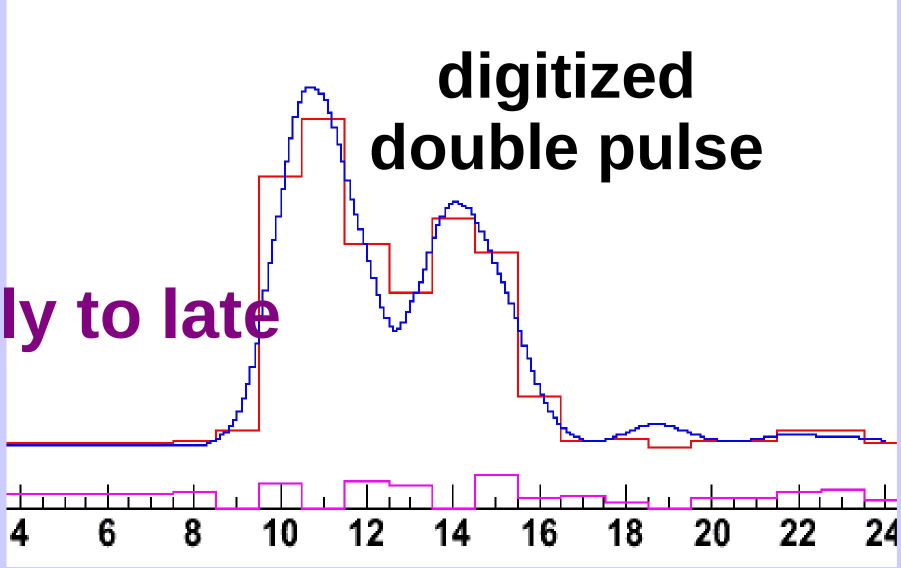
Δt = artifical deadtime
±Δt = coincidence window

- most worrisome systematics (1) - positron pulse pile-up

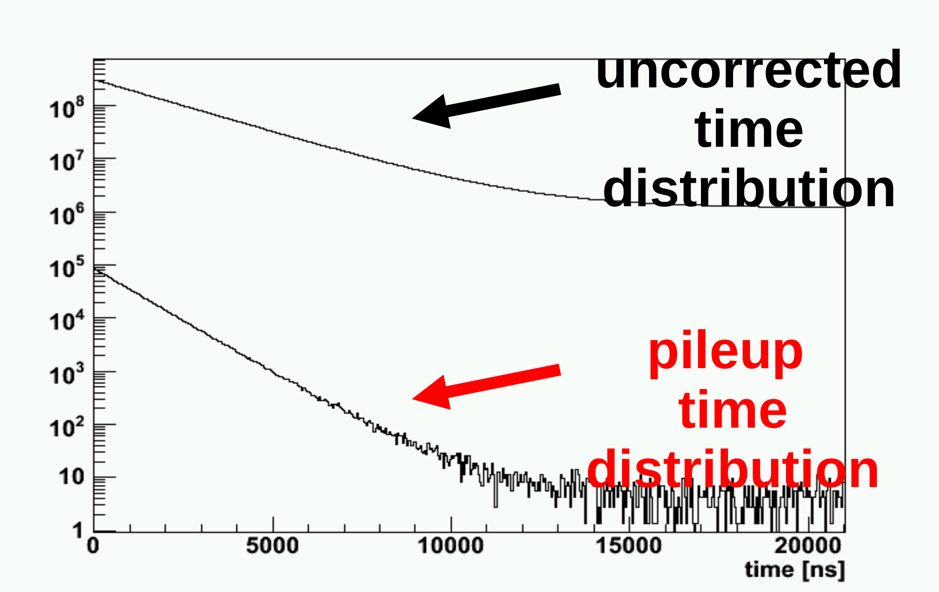


digitized single pulse

changes early to late

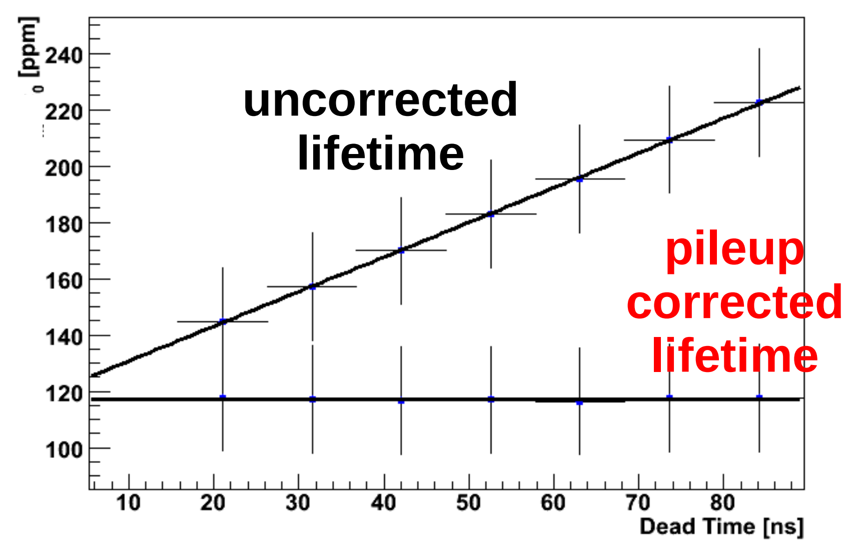


digitized double pulse



uncorrected time distribution

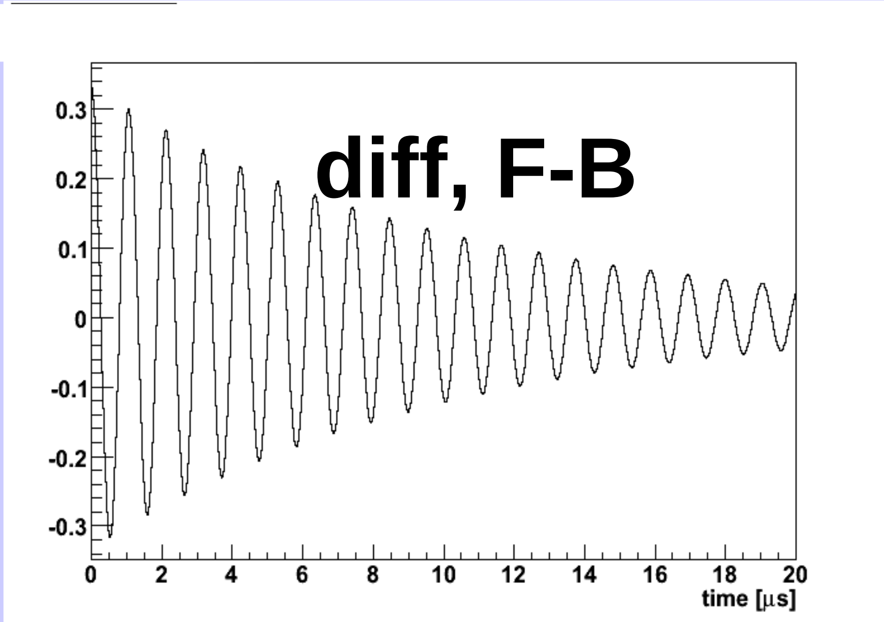
pileup time distribution

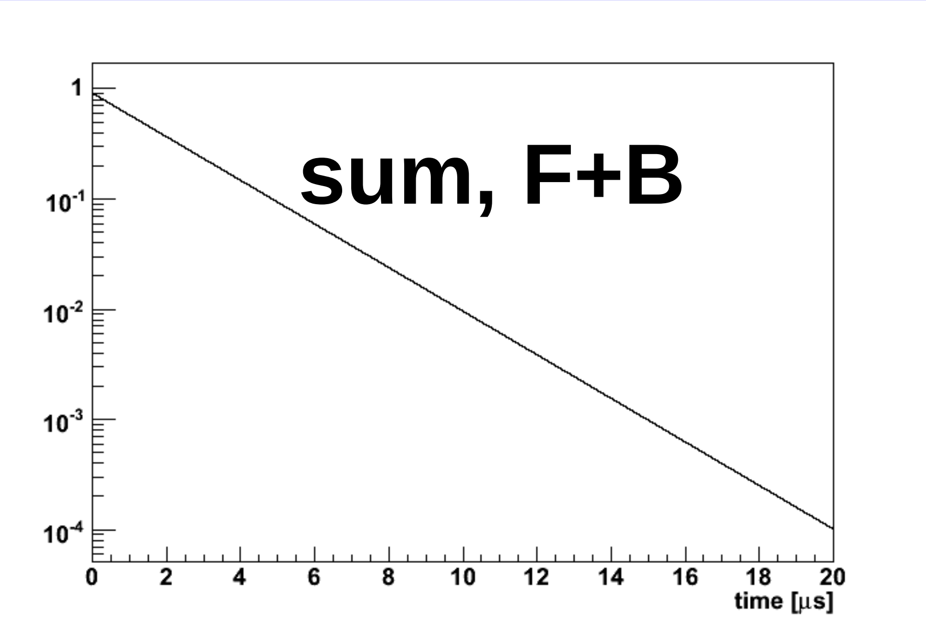


uncorrected lifetime

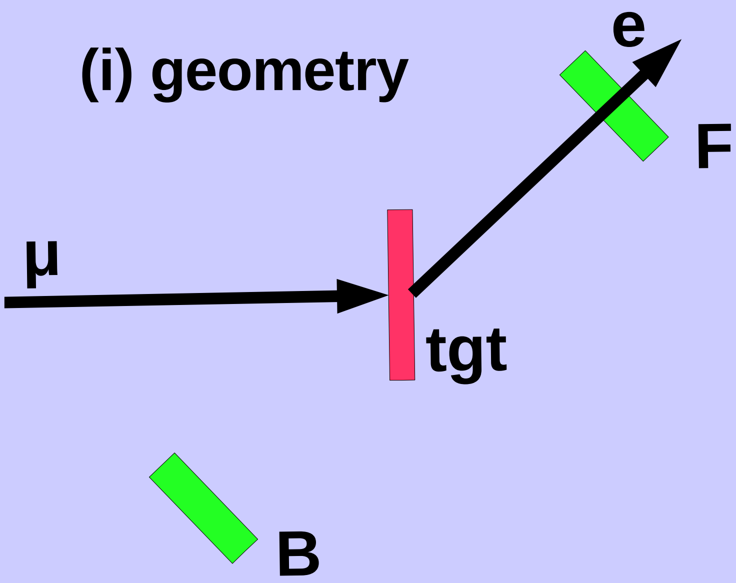
pileup corrected lifetime

- most worrisome systematics (2) - muon spin rotation





(i) geometry

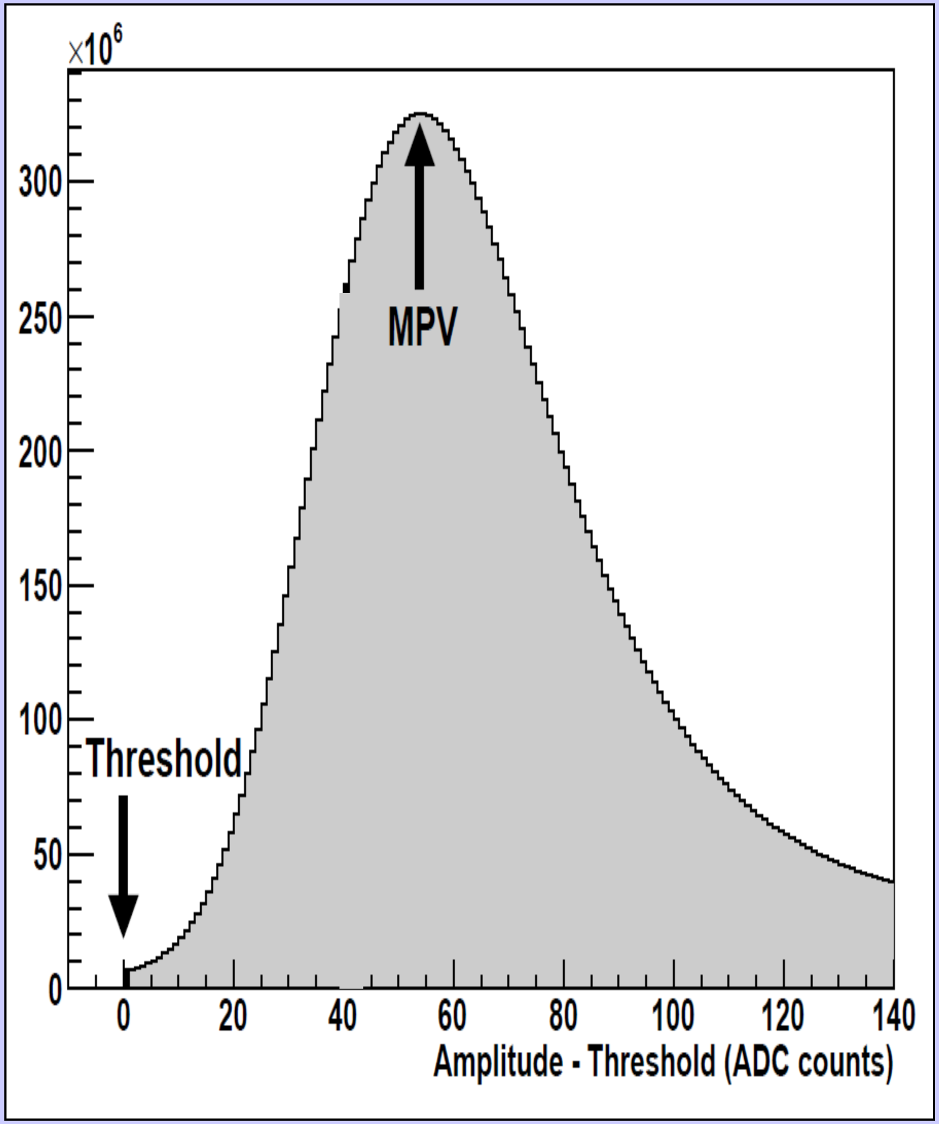


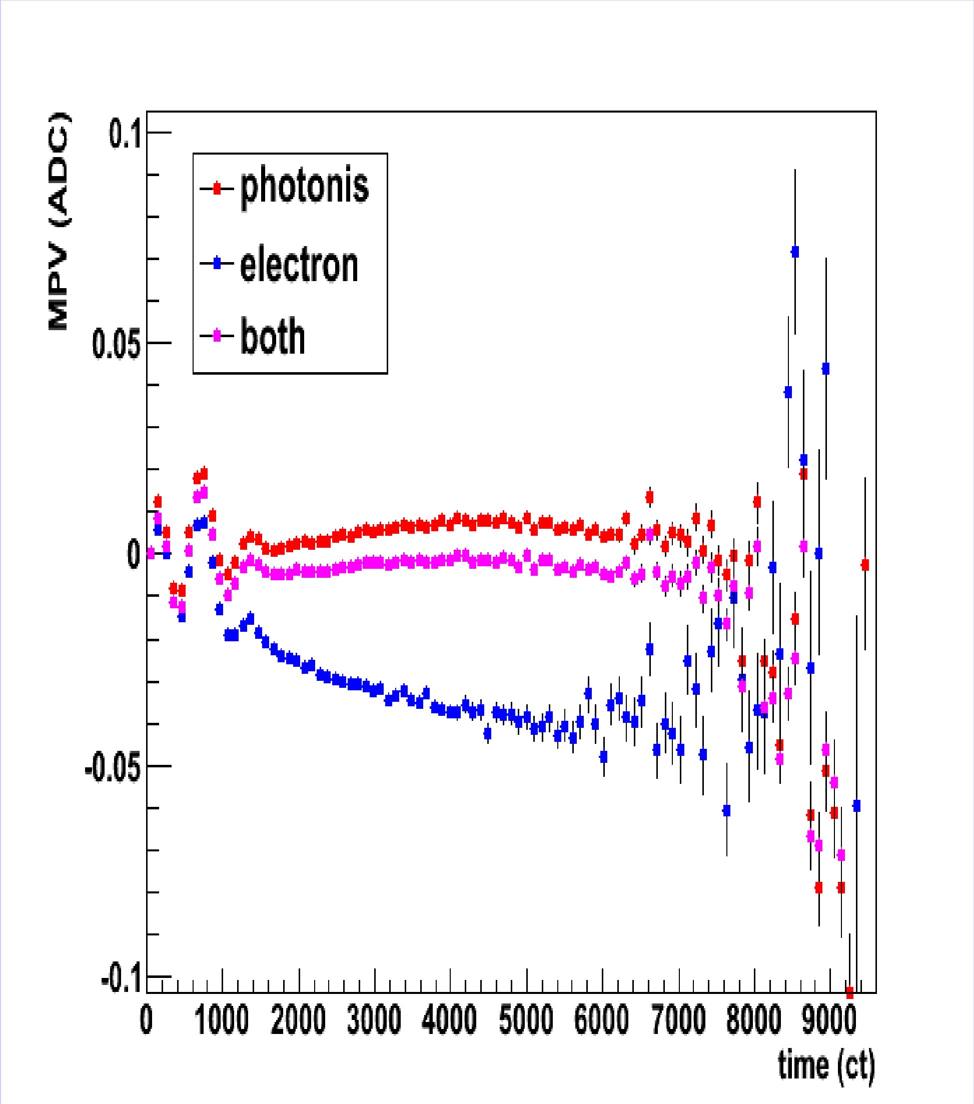
(ii) dephasing

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

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

- most worrisome systematics (3) - gain variations



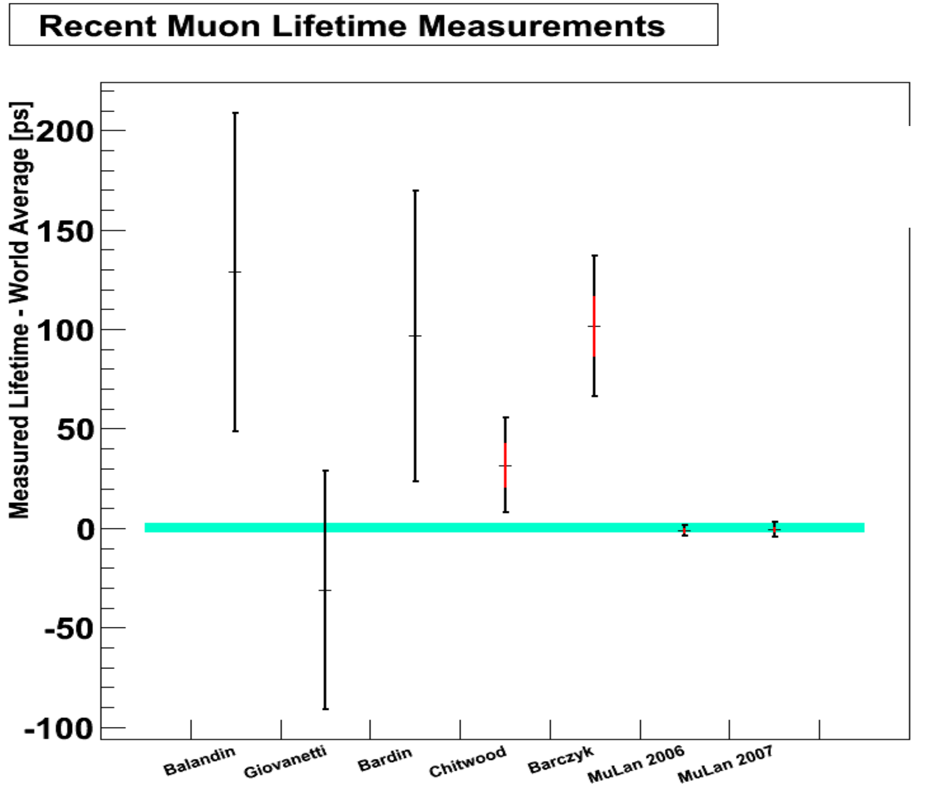


MuLan Results

2006: τ_μ = 2196979.9 ± 2.5(stat) ± 0.9(sys) ps

2007: τ_μ = 2196981.2 ± 3.7(stat) ± 0.9(sys) ps

G_F = 1.166 378 8(7) x 10-5 GeV^{-2} (0.6 ppm)



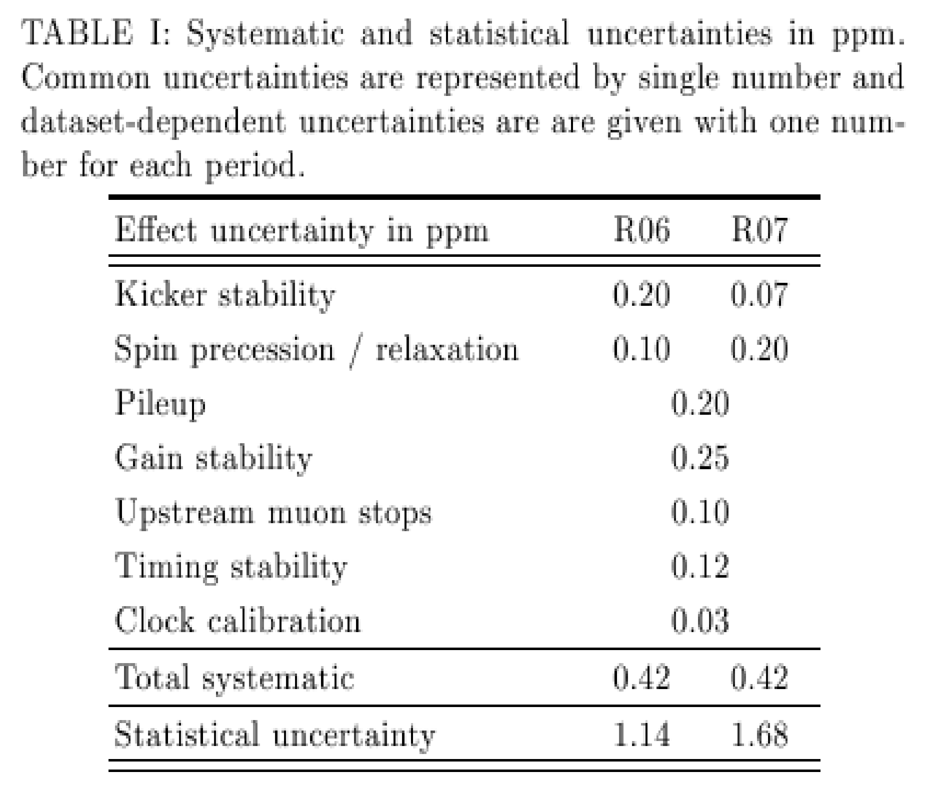
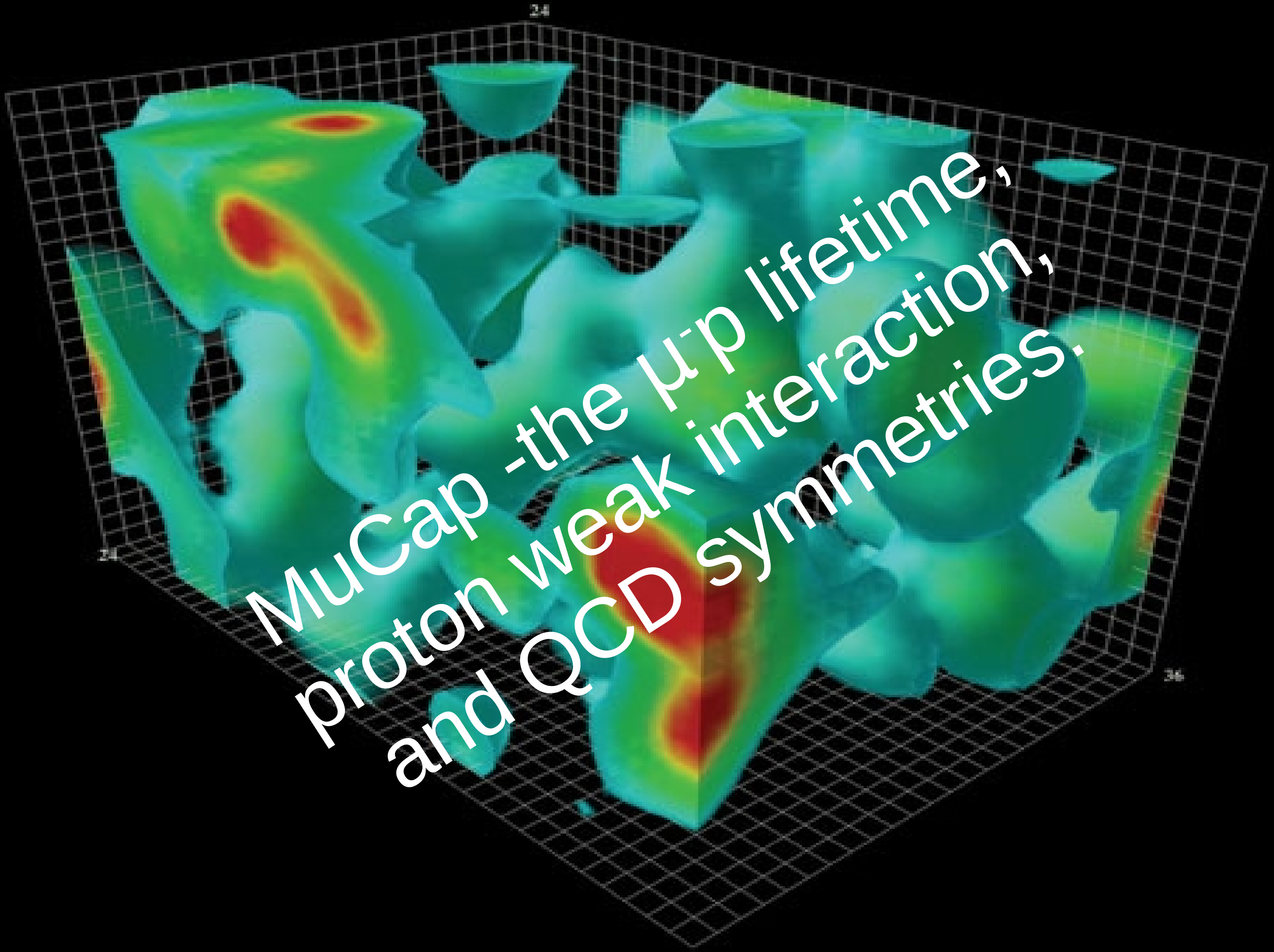


TABLE I: Systematic and statistical uncertainties in ppm. Common uncertainties are represented by single number and dataset-dependent uncertainties are are given with one number for each period.

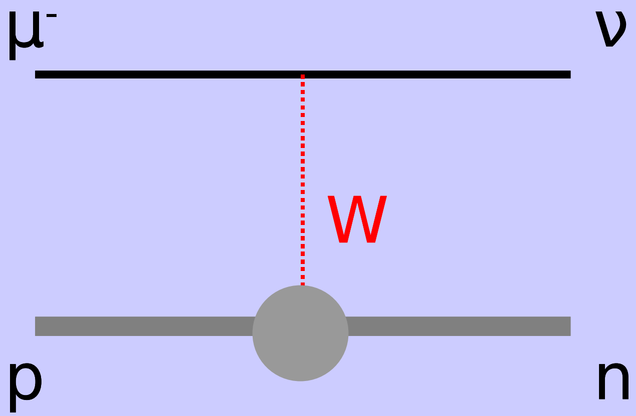
Effect uncertainty in ppm	R06	R07
Kicker stability	0.20	0.07
Spin precession / relaxation	0.10	0.20
Pileup	0.20	
Gain stability	0.25	
Upstream muon stops	0.10	
Timing stability	0.12	
Clock calibration	0.03	
Total systematic	0.42	0.42
Statistical uncertainty	1.14	1.68

MuCap -the μ^-p lifetime, proton weak interaction, and QCD symmetries.



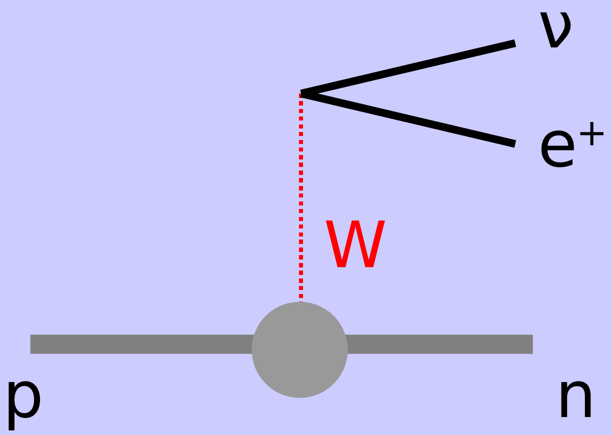
Why we measure $\tau_{\mu p}$?

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

$$g_p(q^2 = -0.88m^2_\mu) = (6.47\pm0.18)\, g_a(0) = 8.26\pm0.23$$

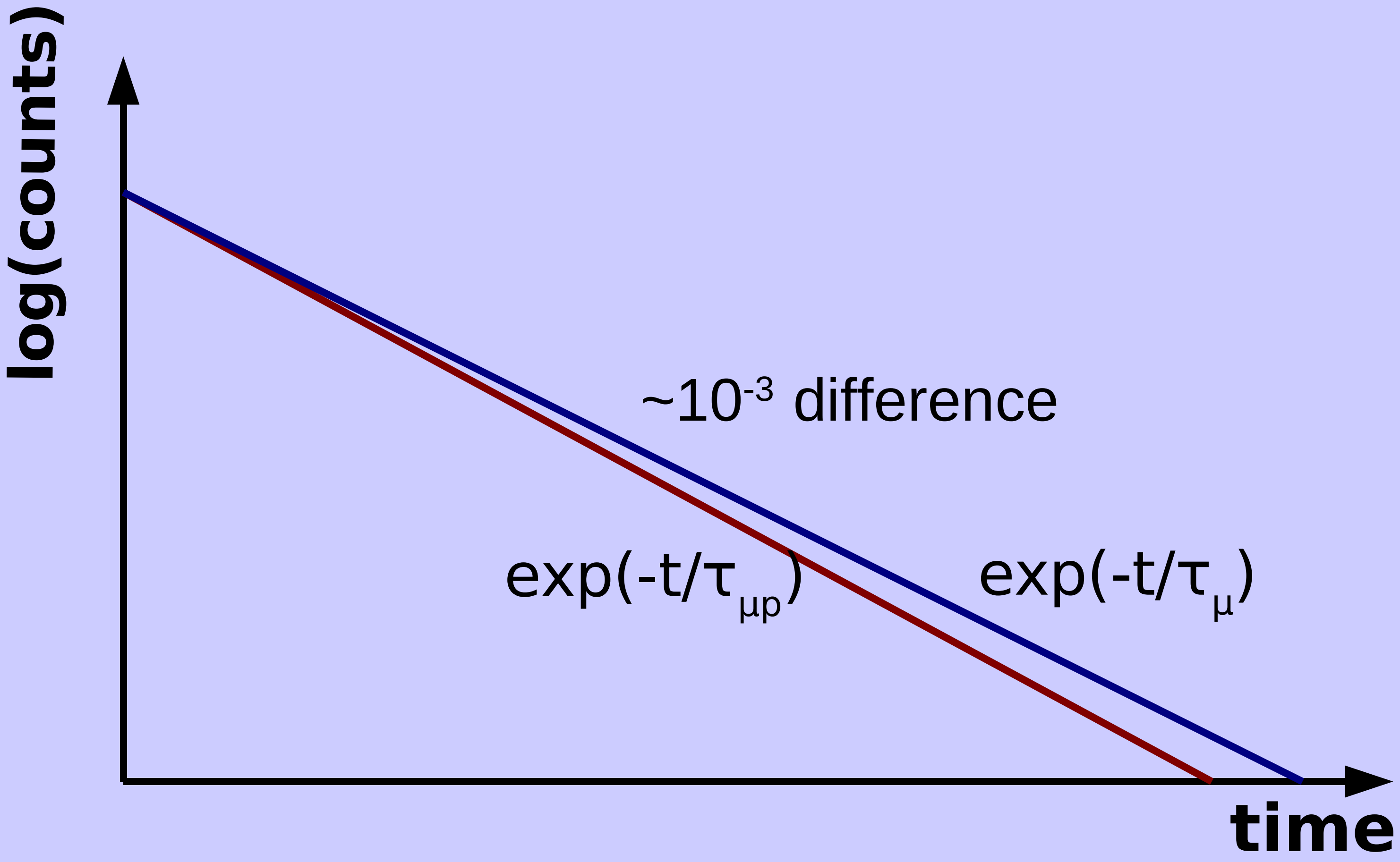
Its verification represents an important test of QCD symmetries

and spontaneous, explicit symmetry breaking.

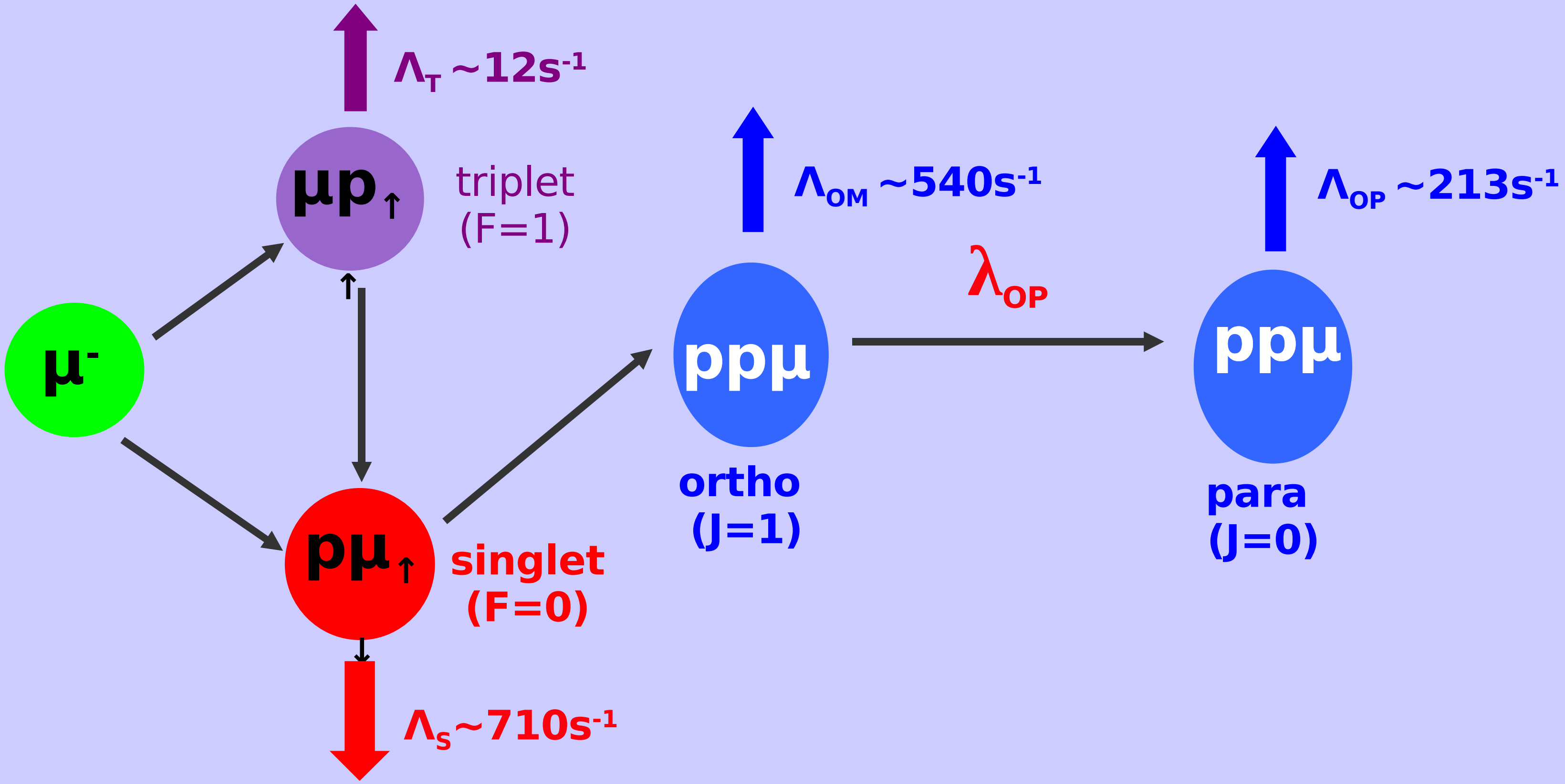
knowledge of g_p (and g_v, g_a, g_m) allows precision studies of weak nuclear interactions through nuclear muon capture (for example our μ^-D experiment)

How we determine g_p?

$$\Lambda_S \cong 1/\tau_{\mu\text{-}p} - 1/\tau_{\mu+}$$



μ chemistry, a complication



Λ_T ~12s^{-1}

$\mu p_{\uparrow}$ triplet (F=1)

μ^-

$p\mu_{\uparrow}$ singlet (F=0)

Λ_S~710s^{-1}

Λ_{OM} ~540s^{-1}

ppμ ortho (J=1)

λ_{OP}

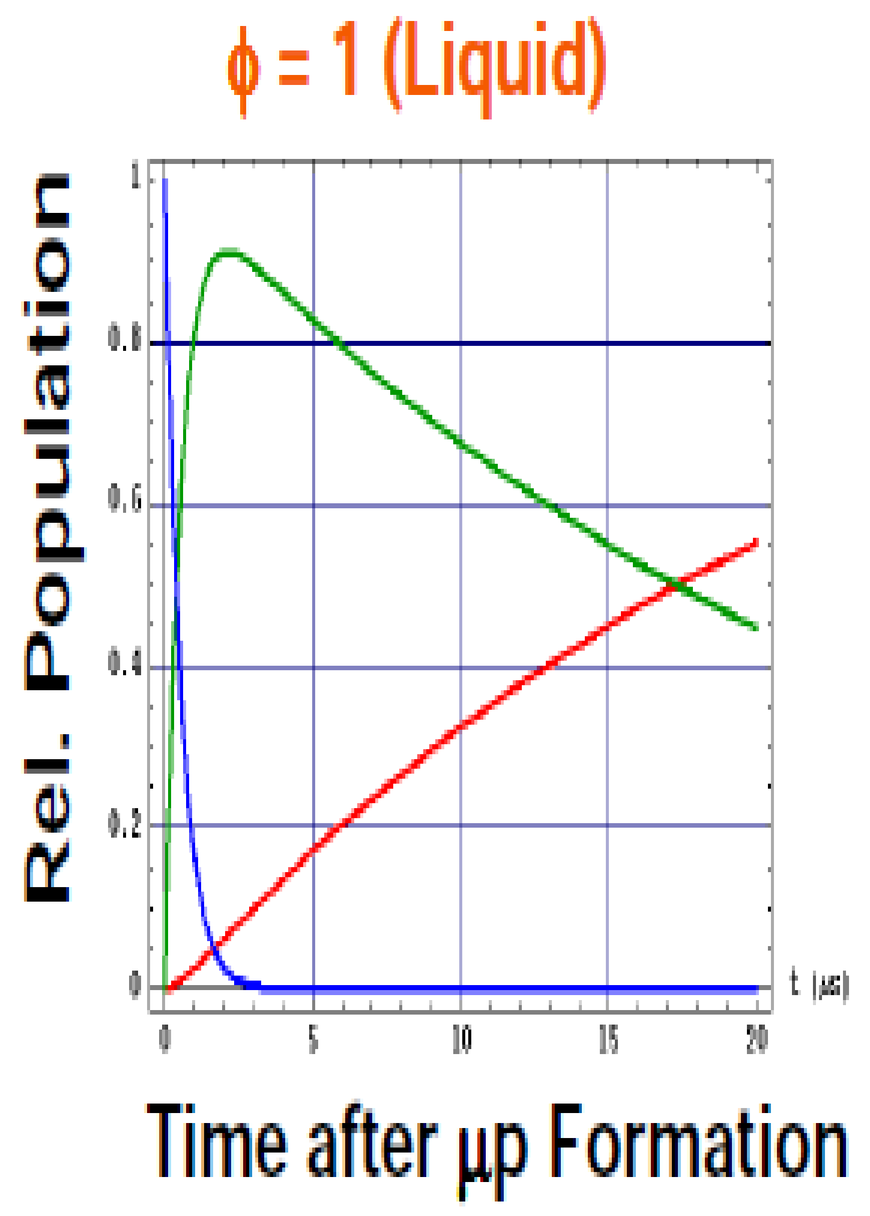
Λ_{OP} ~213s^{-1}

ppμ para (J=0)

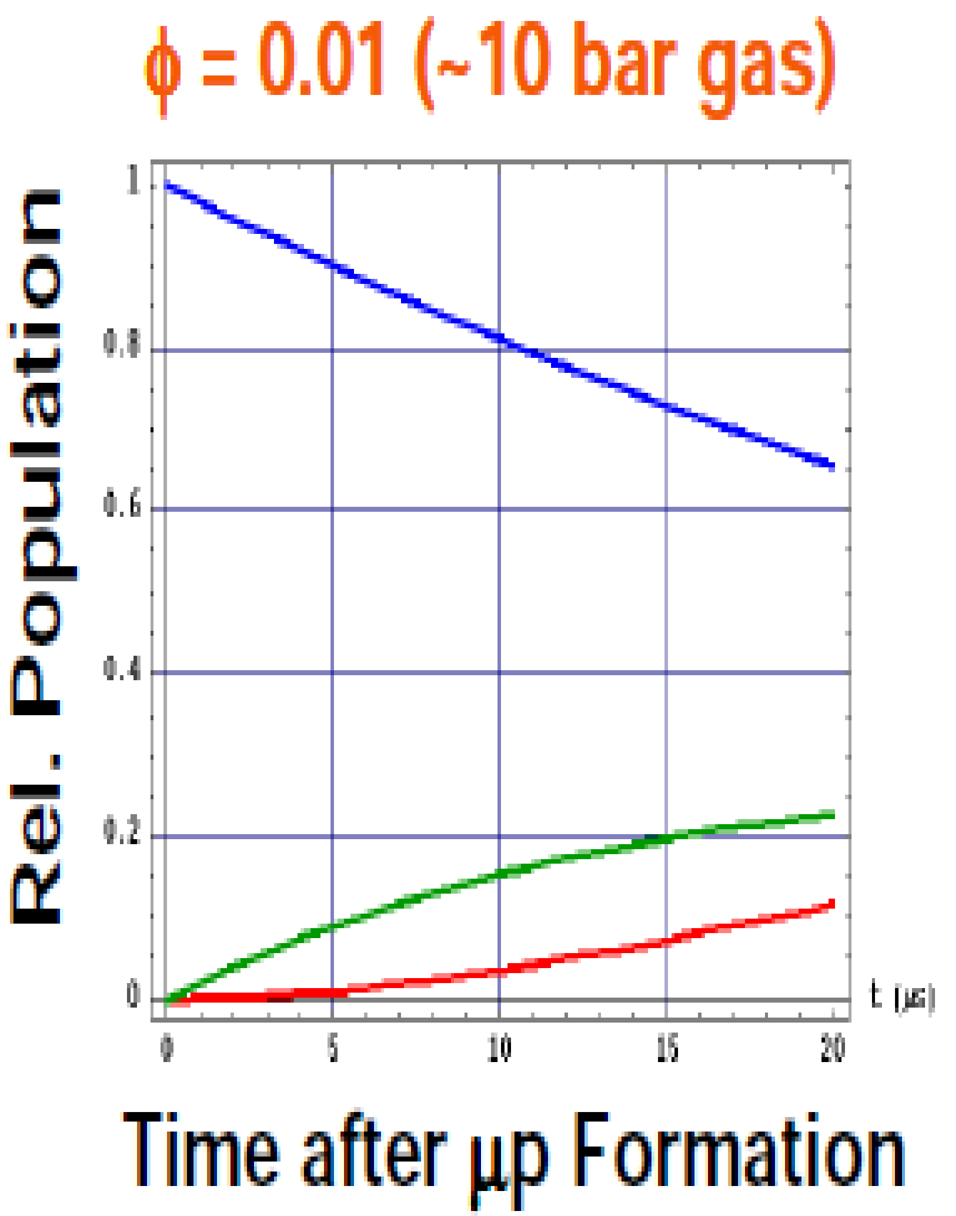
use ultra-pure (chemically, isotopically)
10 bar H_2 (1% liquid hydrogen density)

→ 96% singlet capture

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

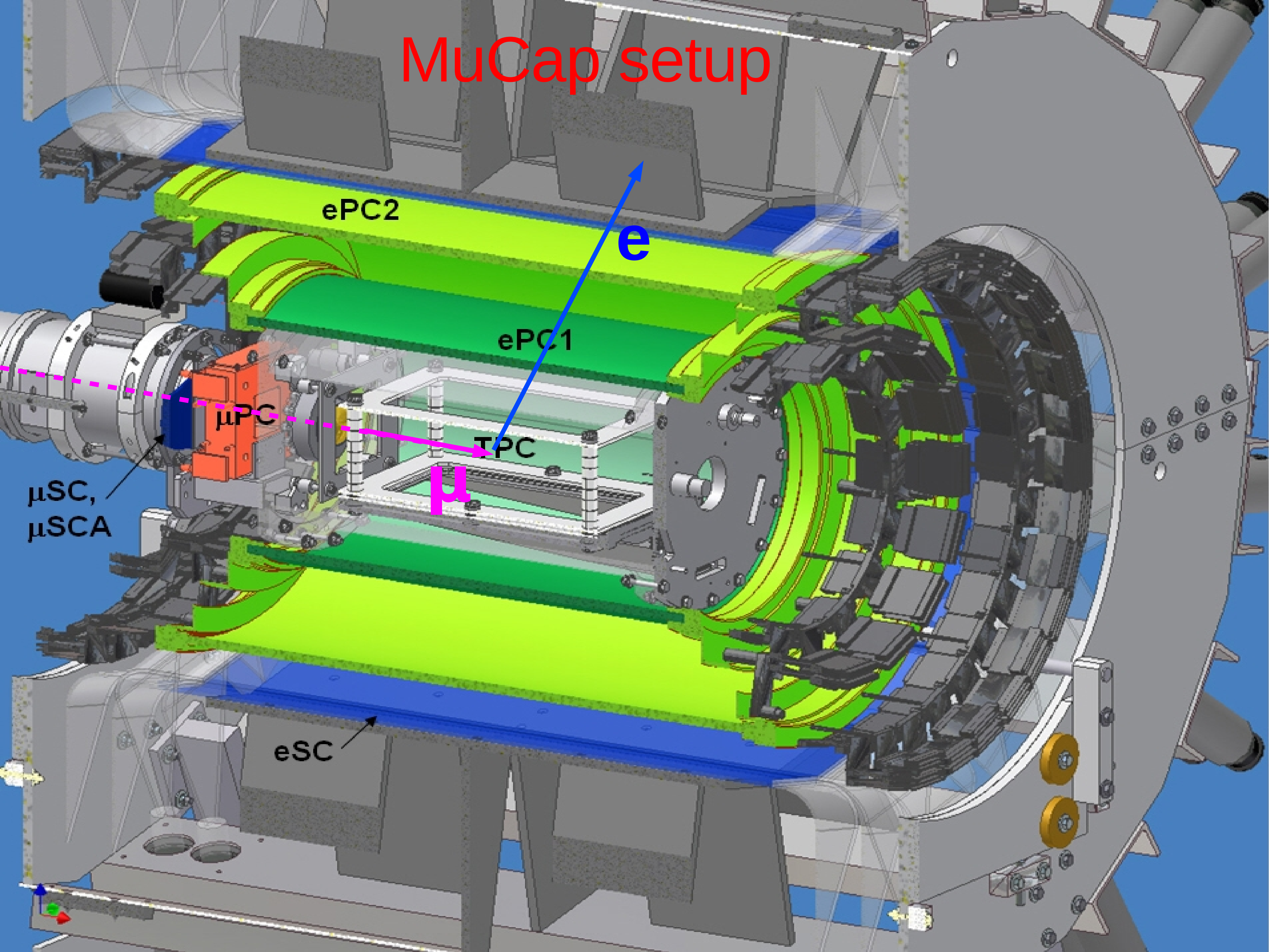


φ = 1 (Liquid)

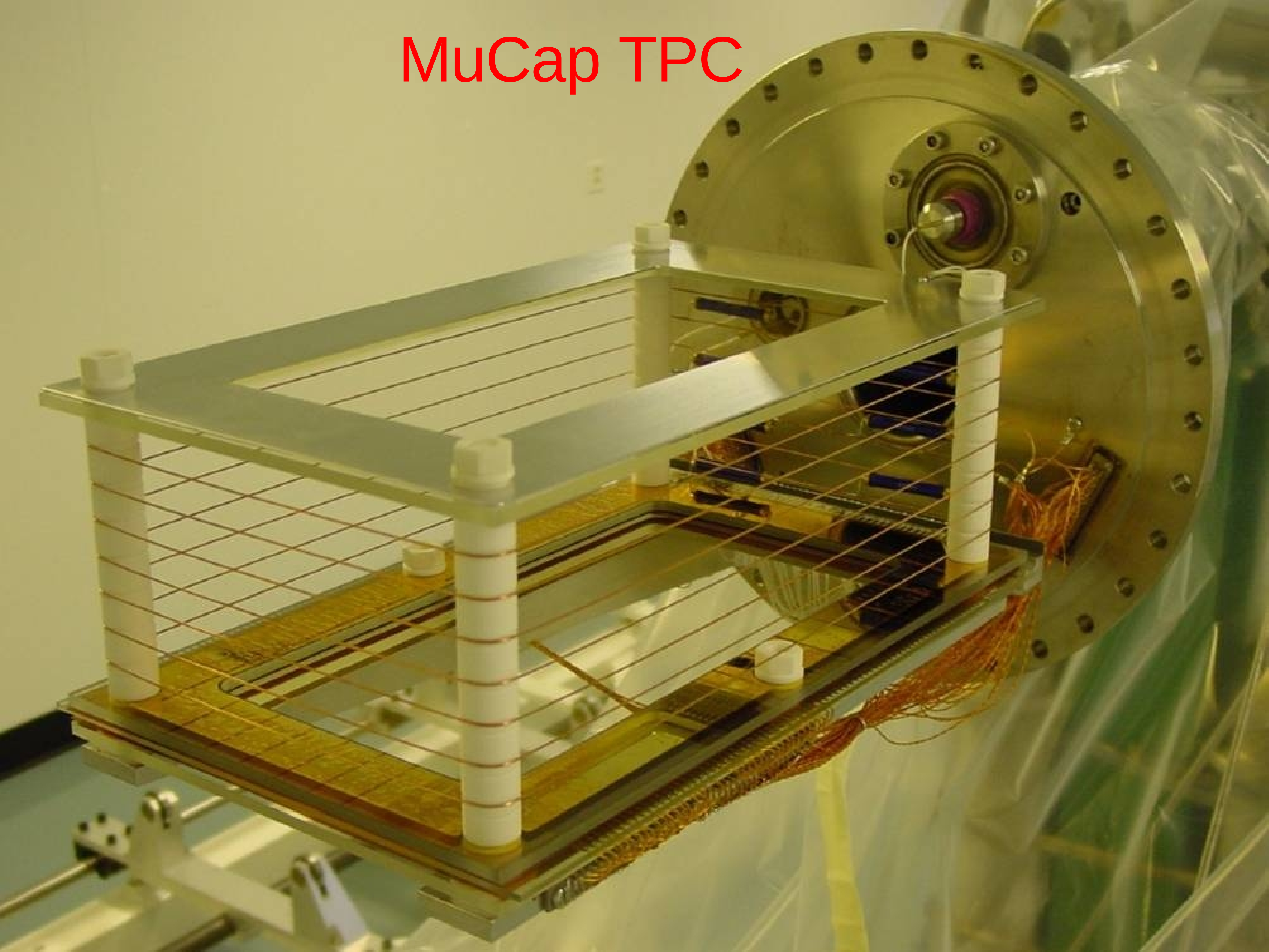


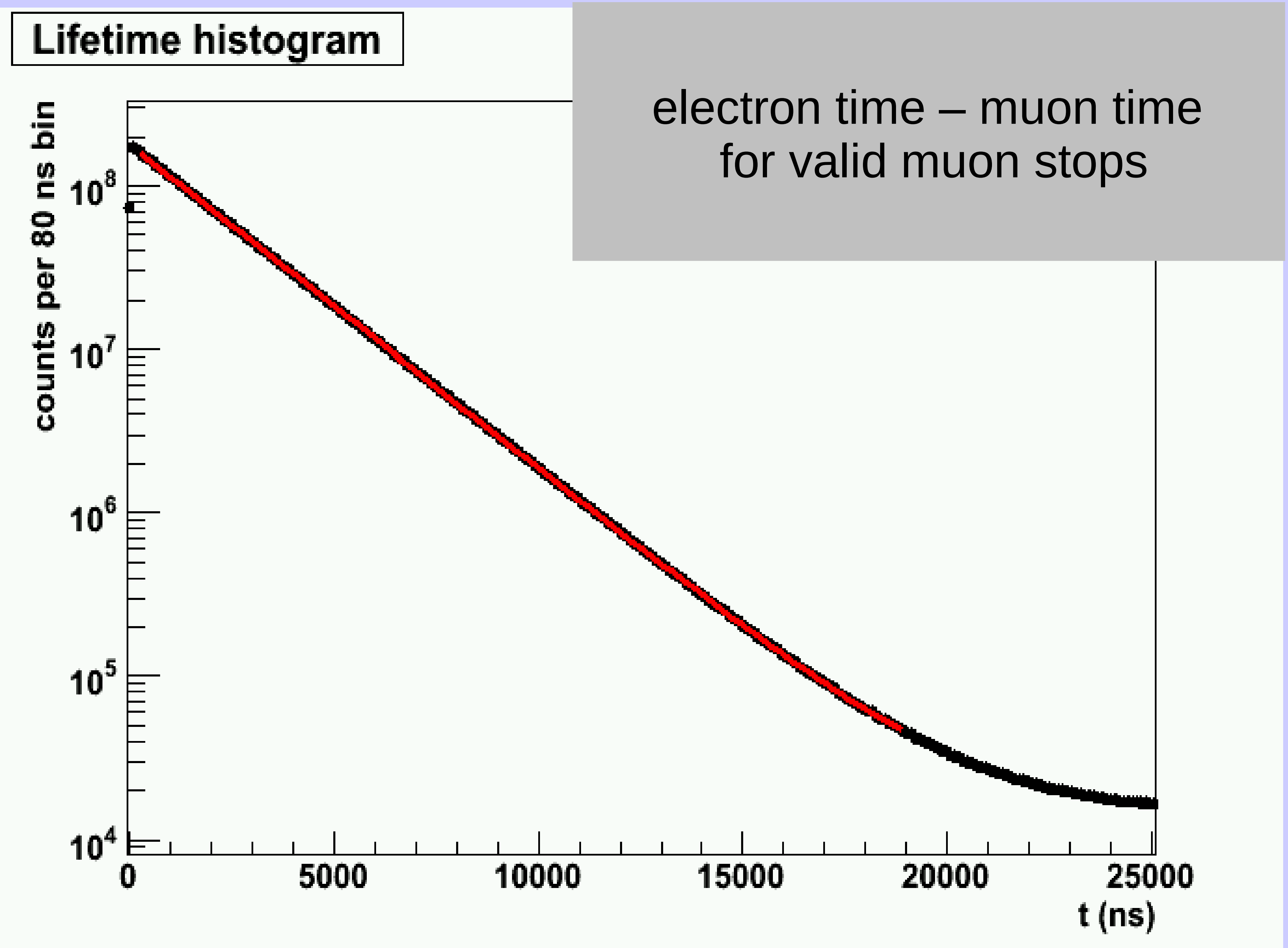
φ = 0.01 (~10 bar gas)

MuCap setup



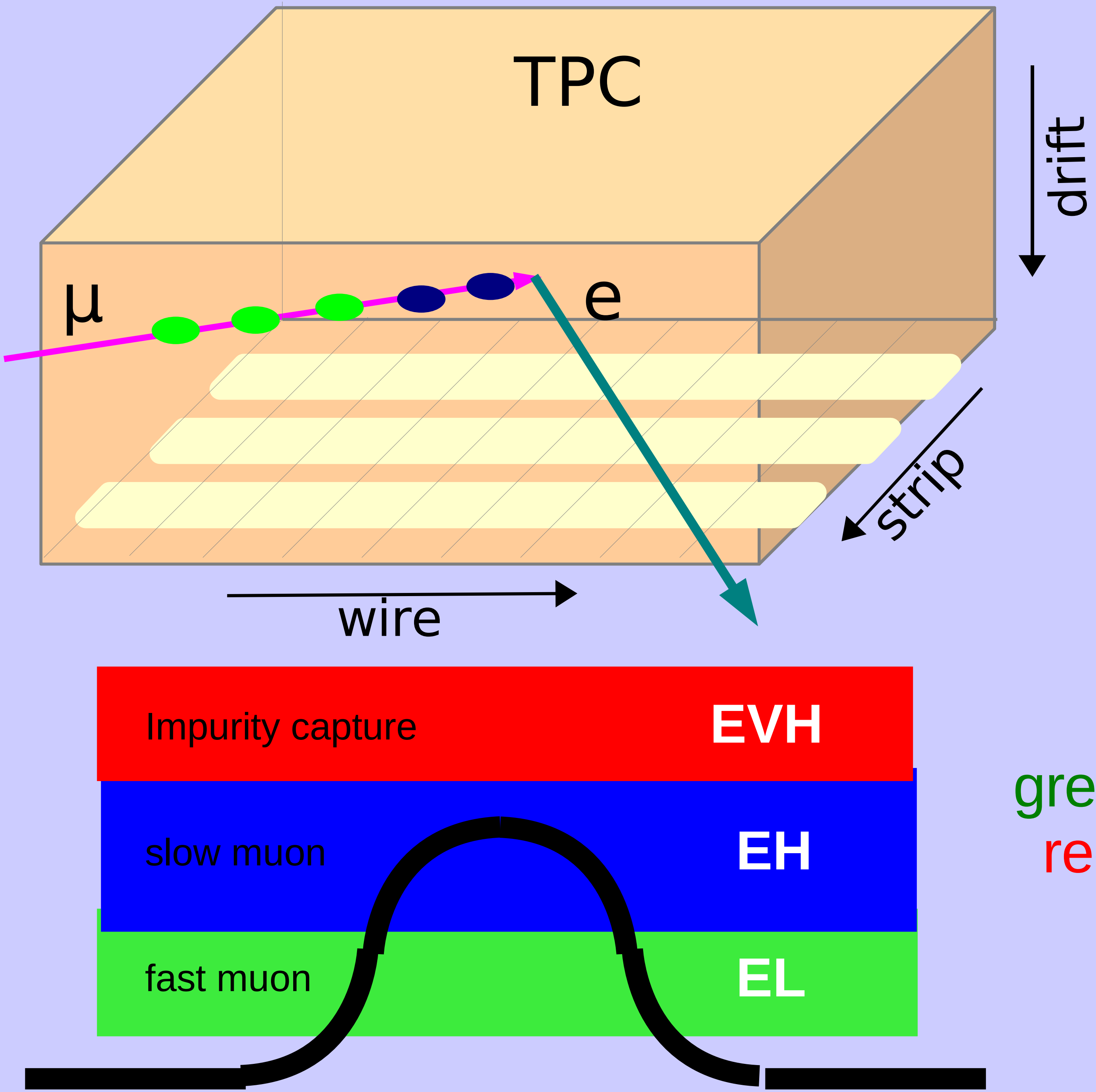
MuCap TPC





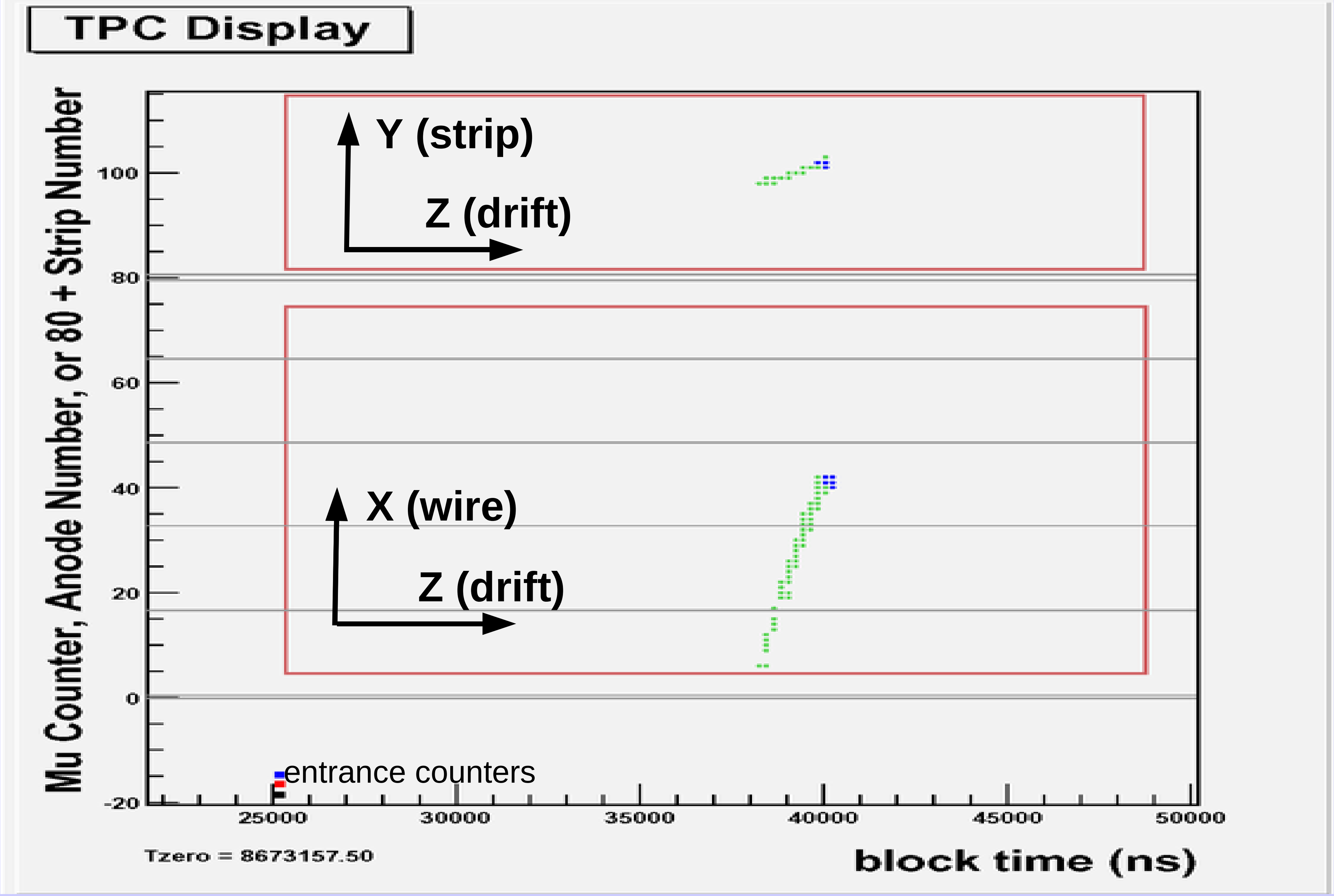
electron time – muon time
for valid muon stops

Validation of μ stops in H_2 gas

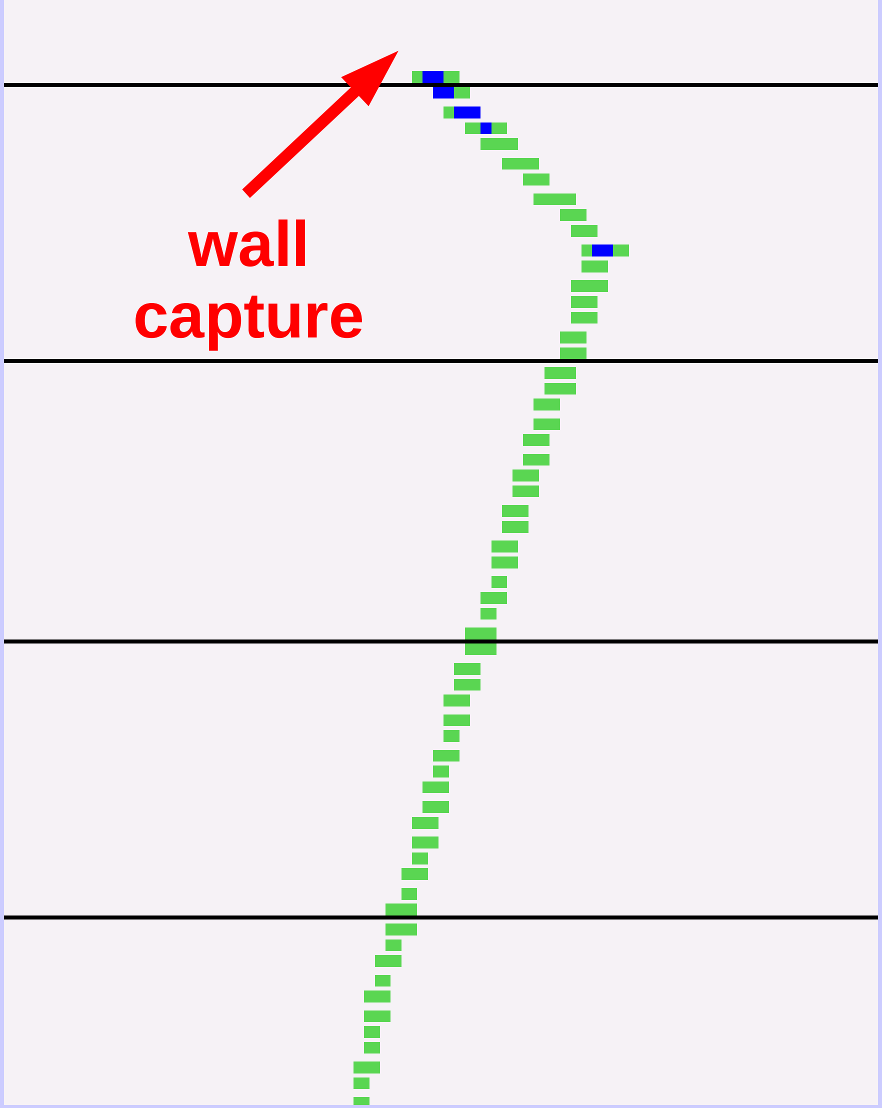


green, blue, red pixels

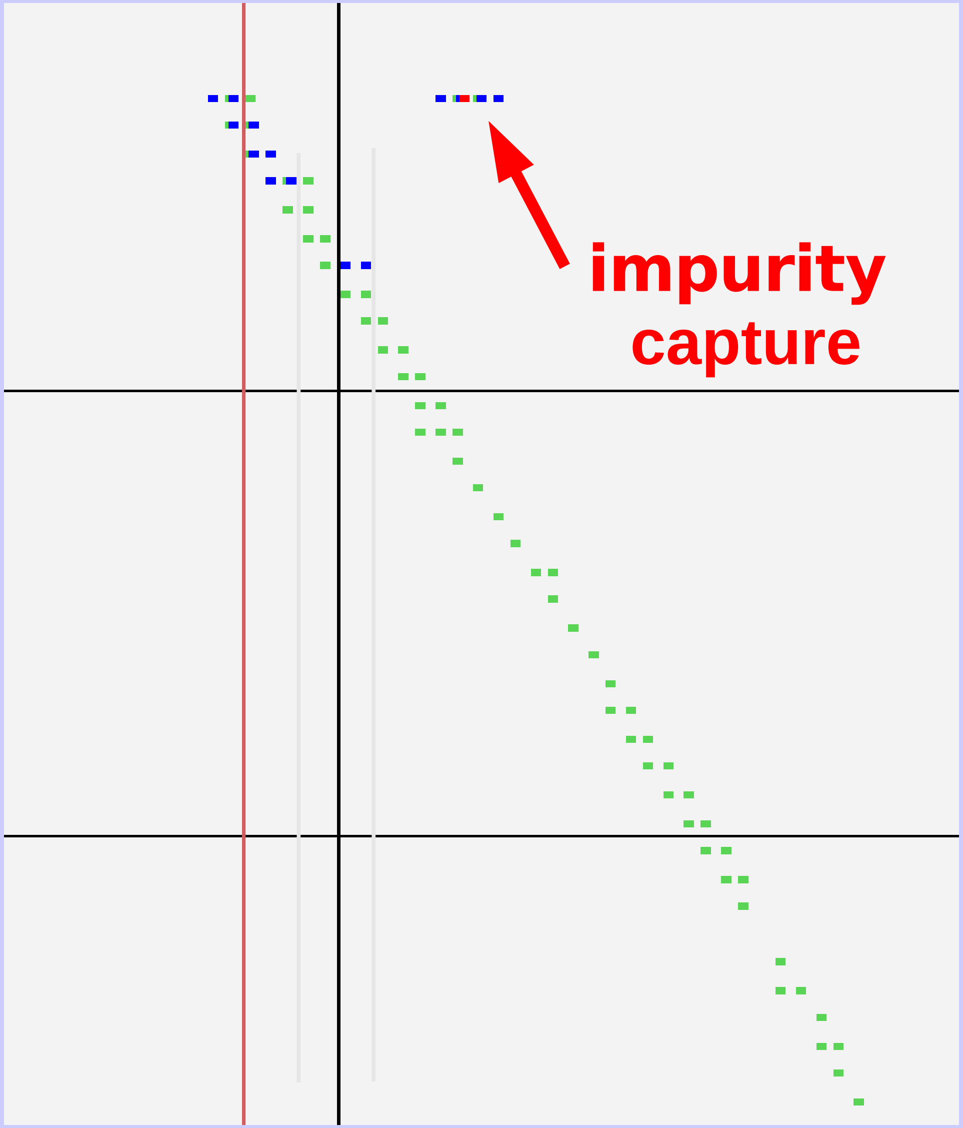
Validation of μ stops in H_2 gas



- worrisome systematics -
muon capture on Z>1 materials
e.g. walls and impurities



μ scatter event

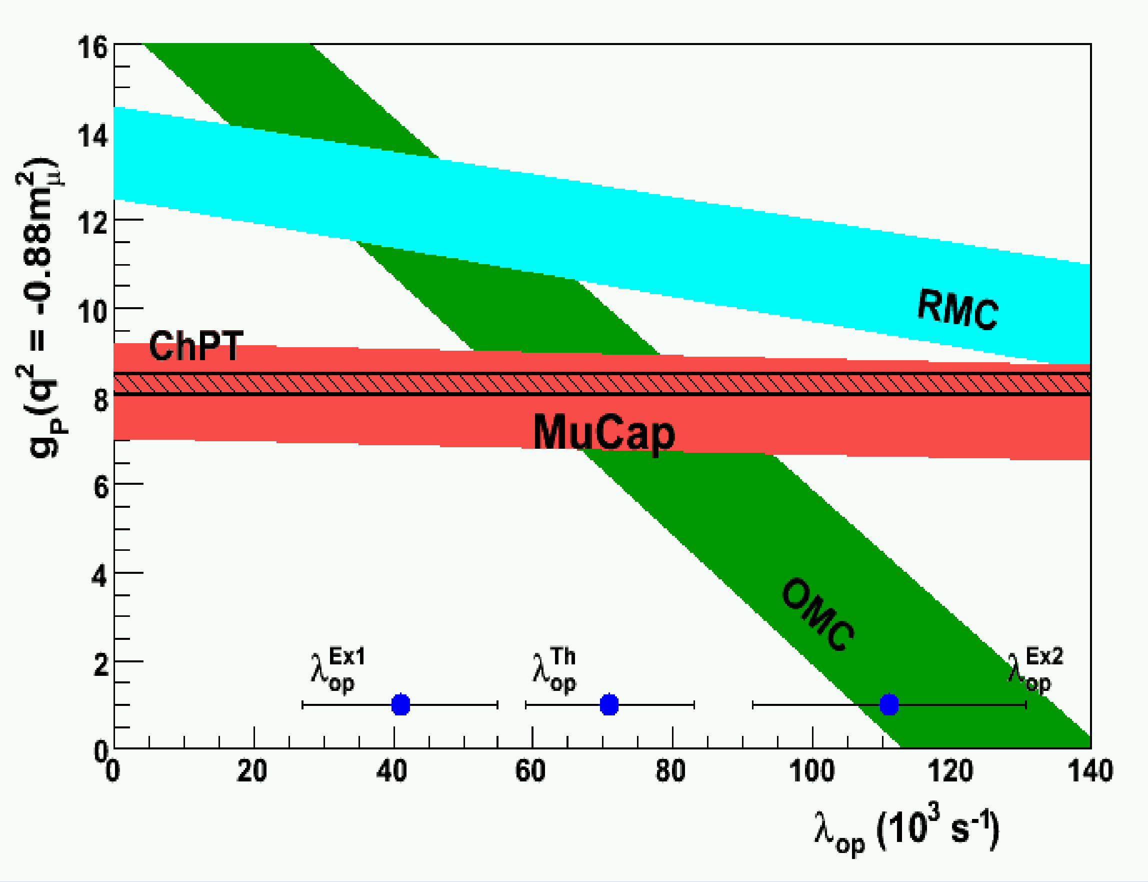


μ transfer event

MuCap Results

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

g_p (q^2 = -0.88m^2_μ) = 7.8±1.1



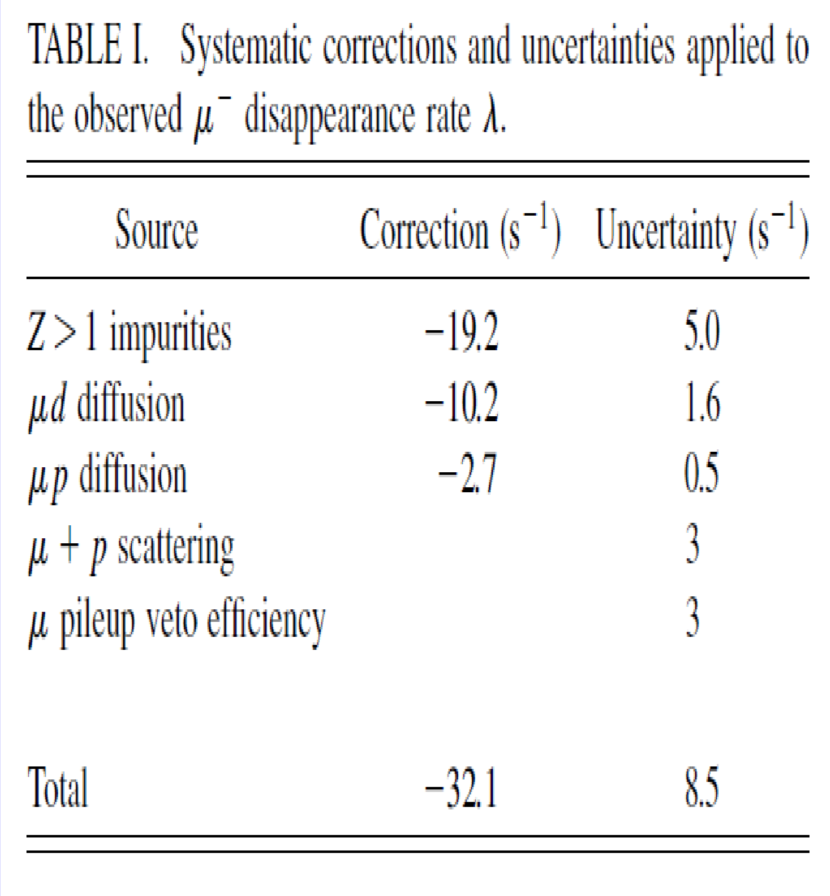


TABLE I. Systematic corrections and uncertainties applied to the observed μ^- disappearance rate λ.

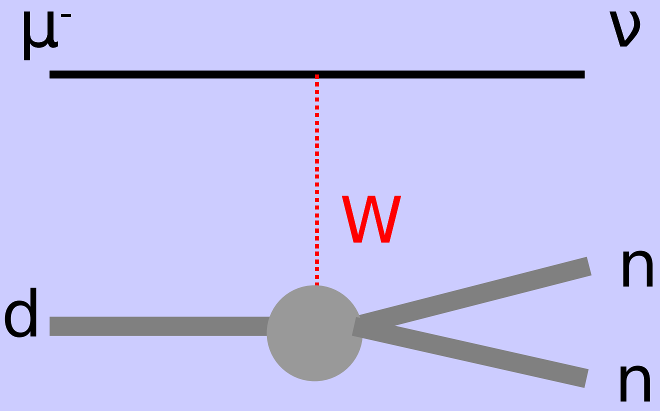
Source	Correction (s^{-1})	Uncertainty (s^{-1})
$Z > 1$ impurities	−19.2	5.0
μd diffusion	−10.2	1.6
μp diffusion	−2.7	0.5
$\mu + p$ scattering		3
μ pileup veto efficiency		3
Total	−32.1	8.5

goal for 2006/2007 datasets is Λ_s to ±5s^{-1}

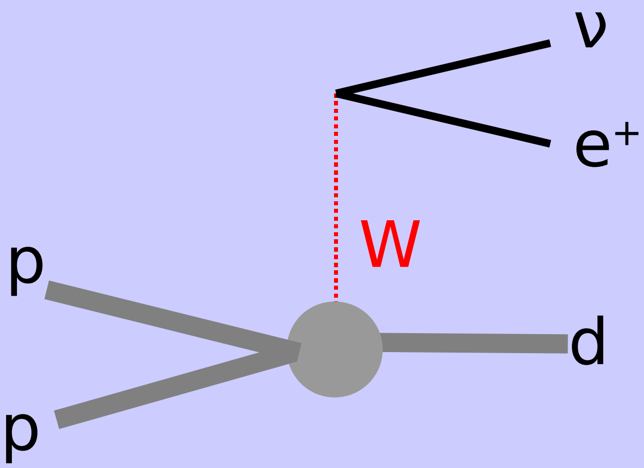
MuSun -the μ^-d lifetime, elementary weak nuclear interaction, and solar hydrogen burning.

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

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



proton-proton fusion,
$p p \rightarrow d e^+ \nu$



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-body weak axial current (L_{1A})

Why we determine Λ_d, L_{1A}?

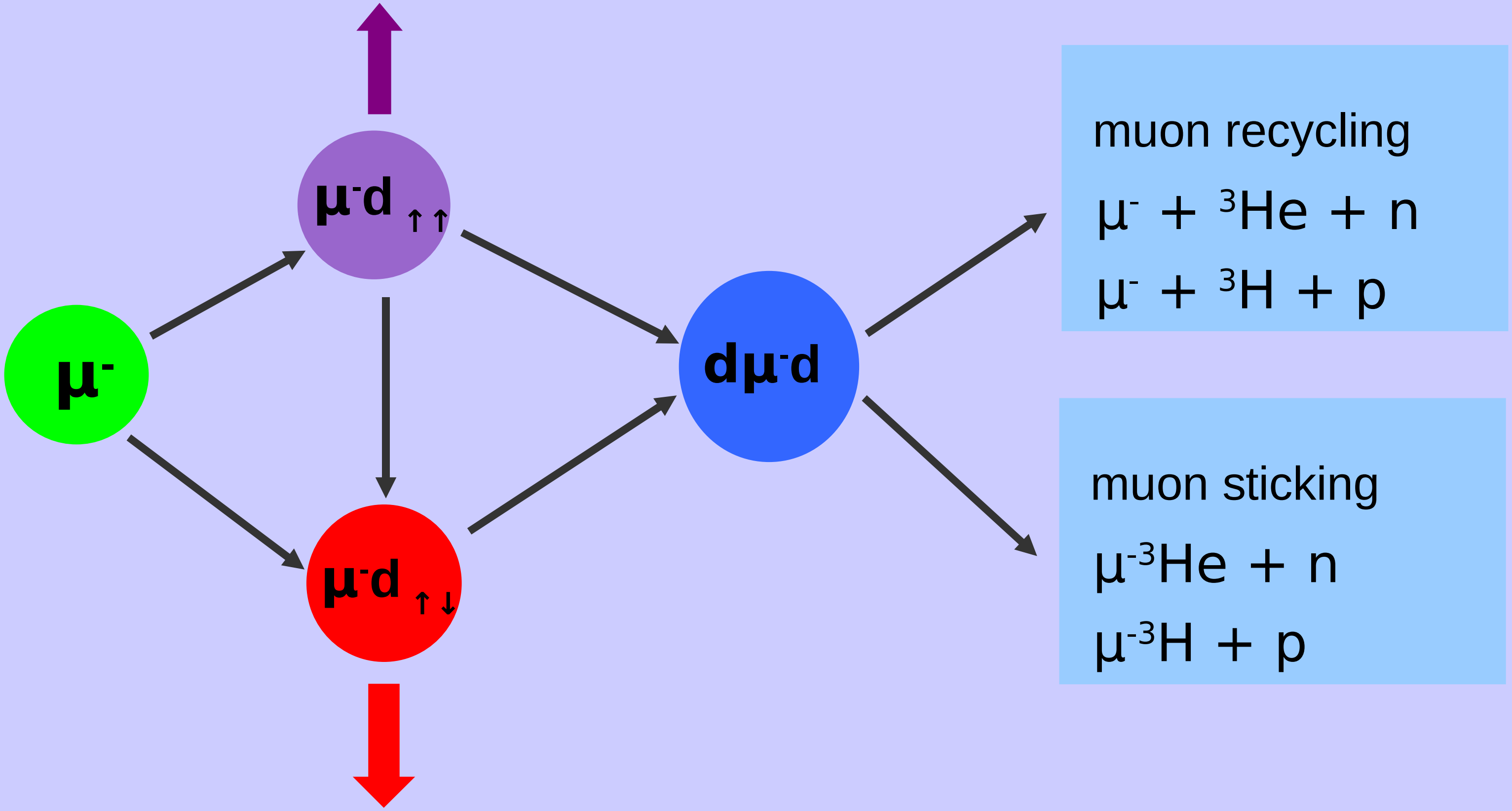
elementary weak nuclear interaction where precision measurement and precision calculation are possible.

$\mu^- d \rightarrow \nu nn$ reaction related to weak processes of intense interest in solar physics (pp fusion) and neutrino physics (νd interactions).

Involve effects of poorly known two-body weak currents

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

μ chemistry, a complication



muon recycling

$\mu^- + {}^3He + n$

$\mu^- + {}^3H + p$

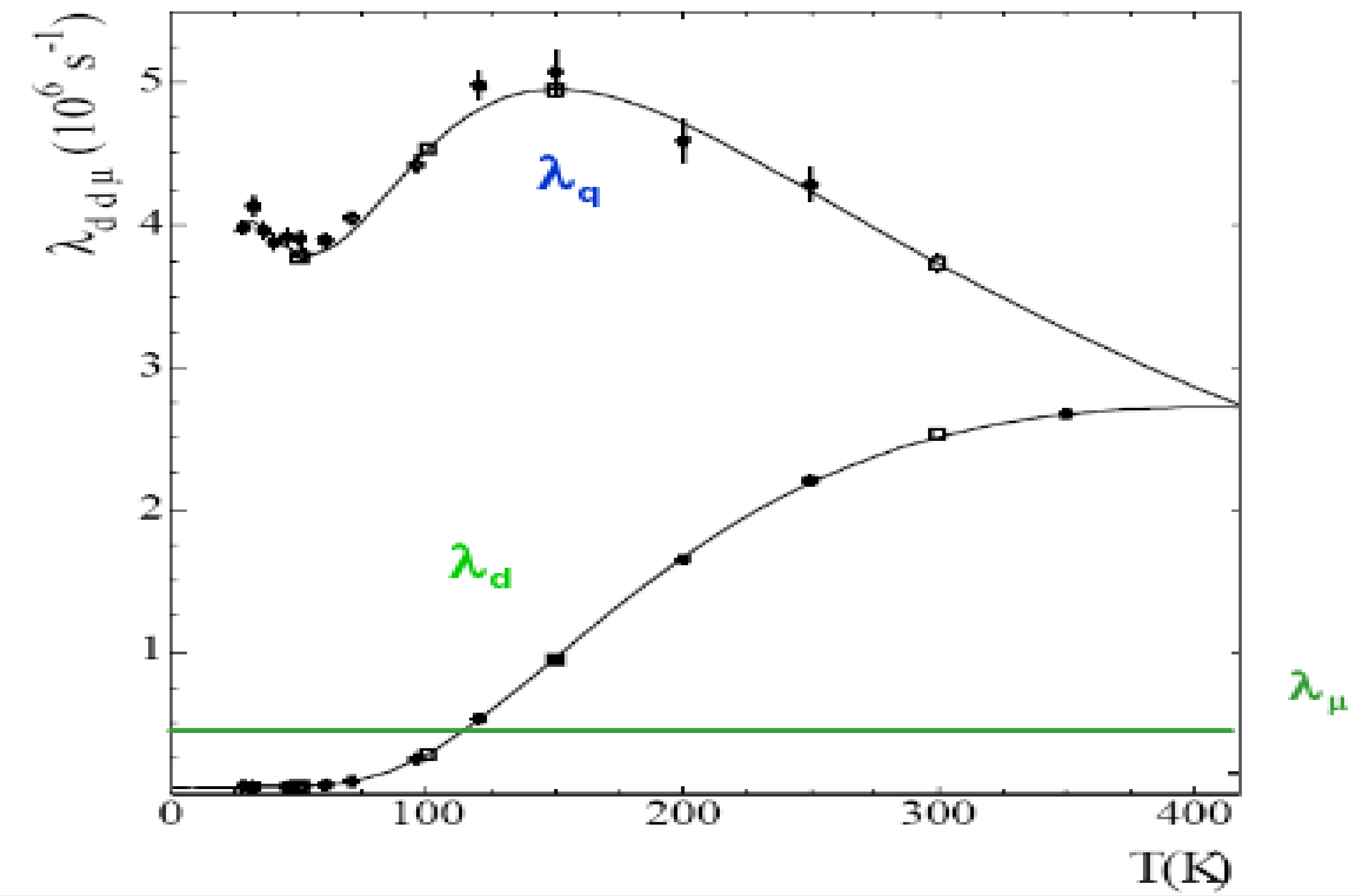
muon sticking

$\mu^-{}^3He + n$

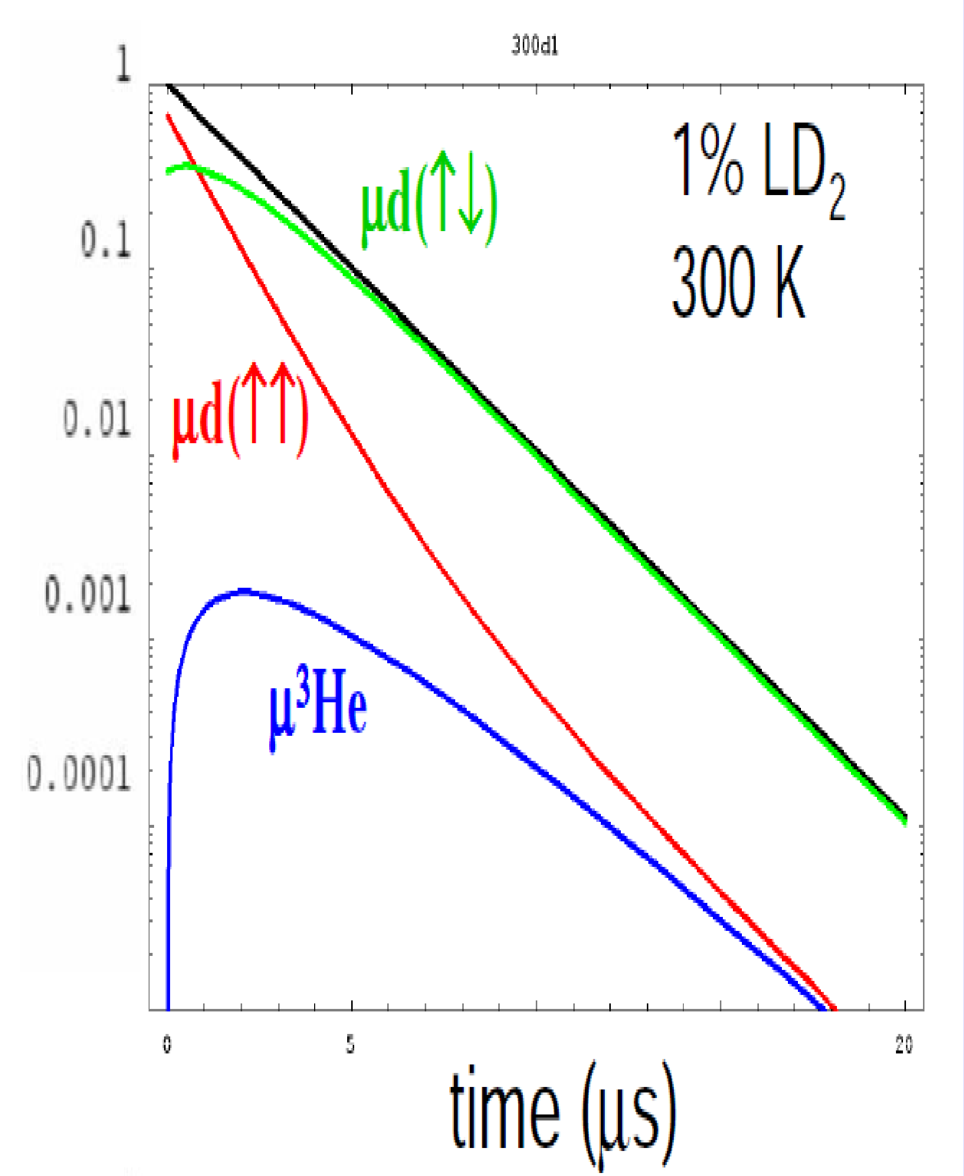
$\mu^-{}^3H + p$

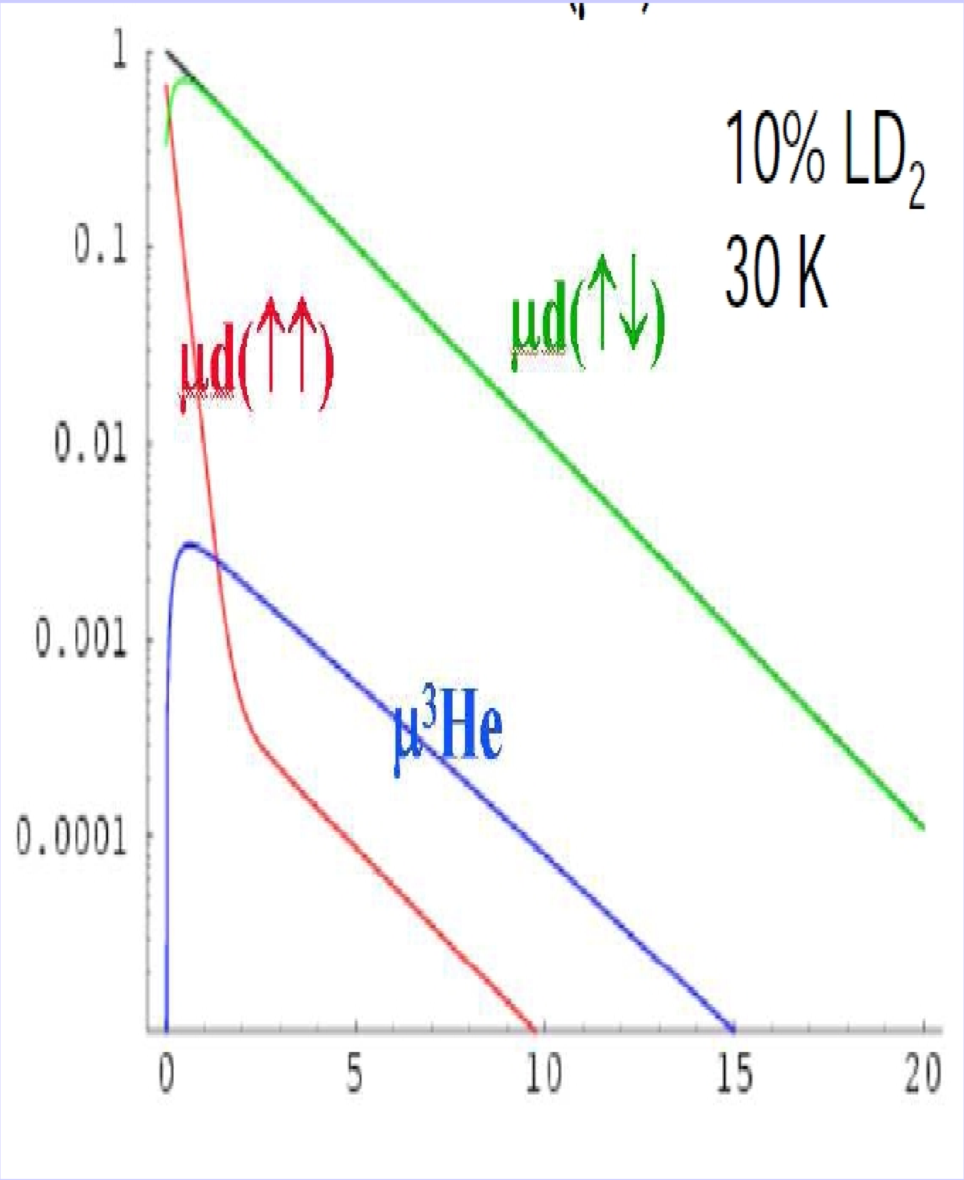
use ulltra-pure (chemically, isotopically)
30 Kelvin, 5% liquid density D_2 gas

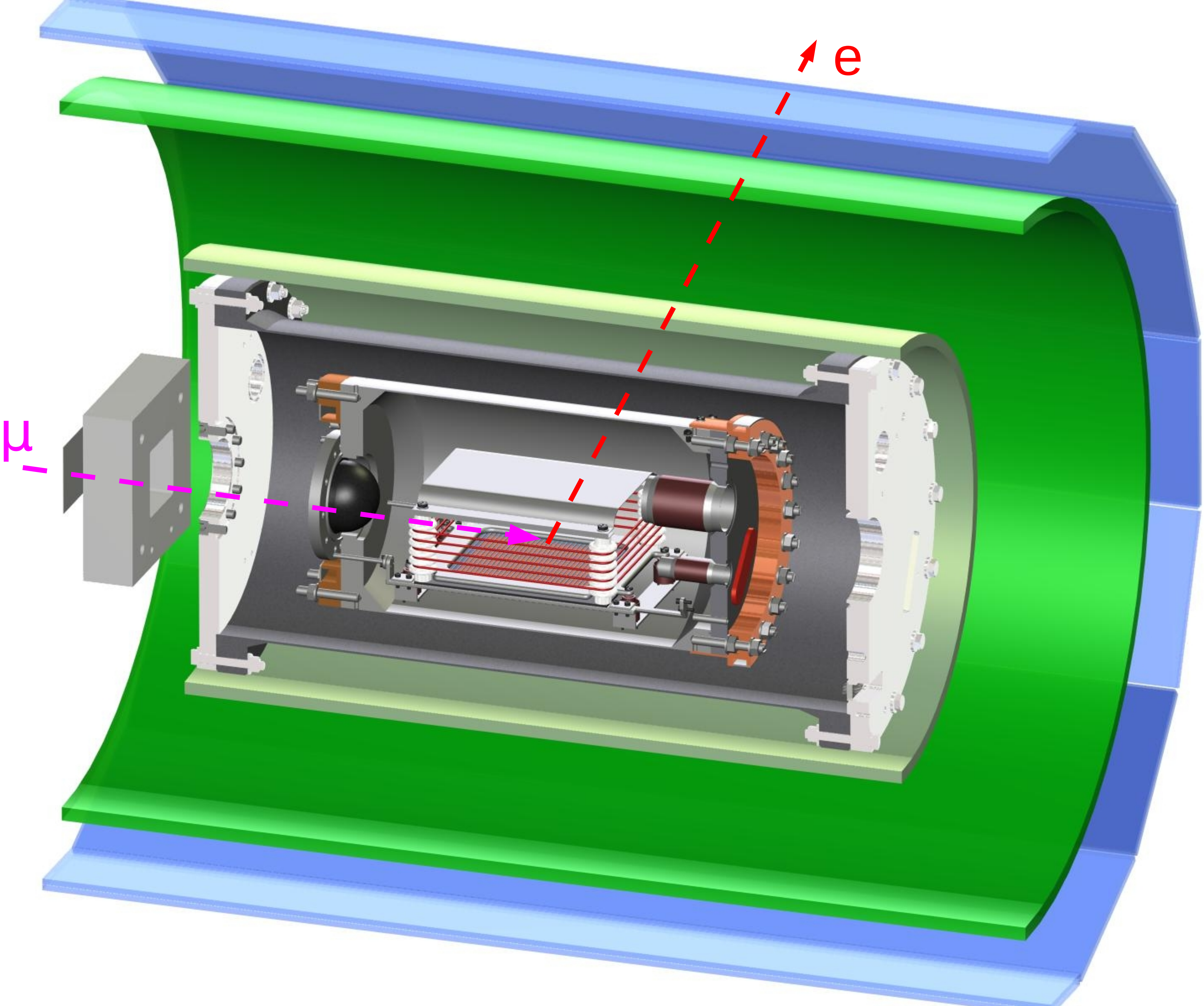
temperature dependence of dμd formation.



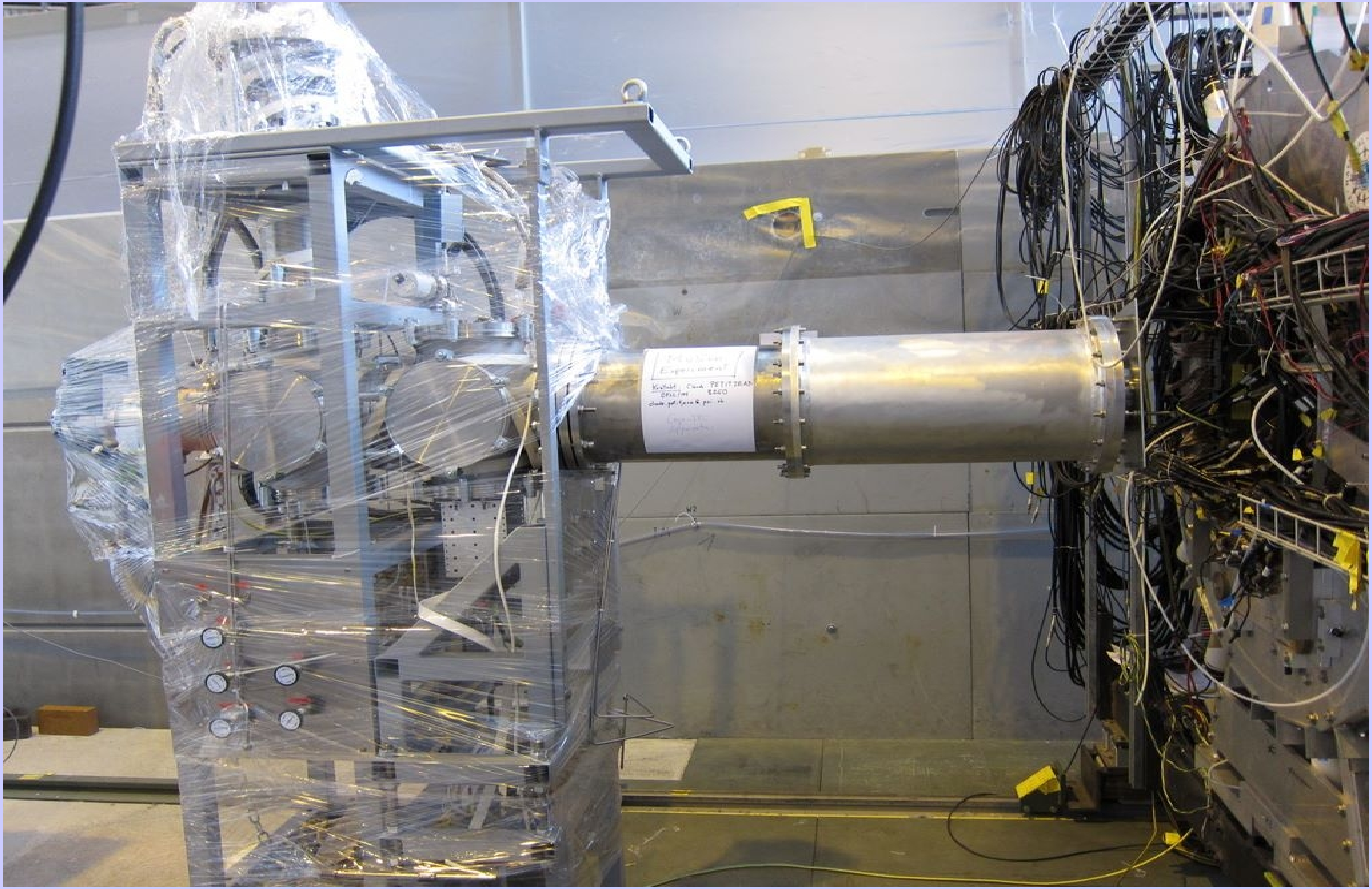
Relative populations of doublet atoms, quadruplet atoms, μ^{-3}He atoms in warm/cold gas



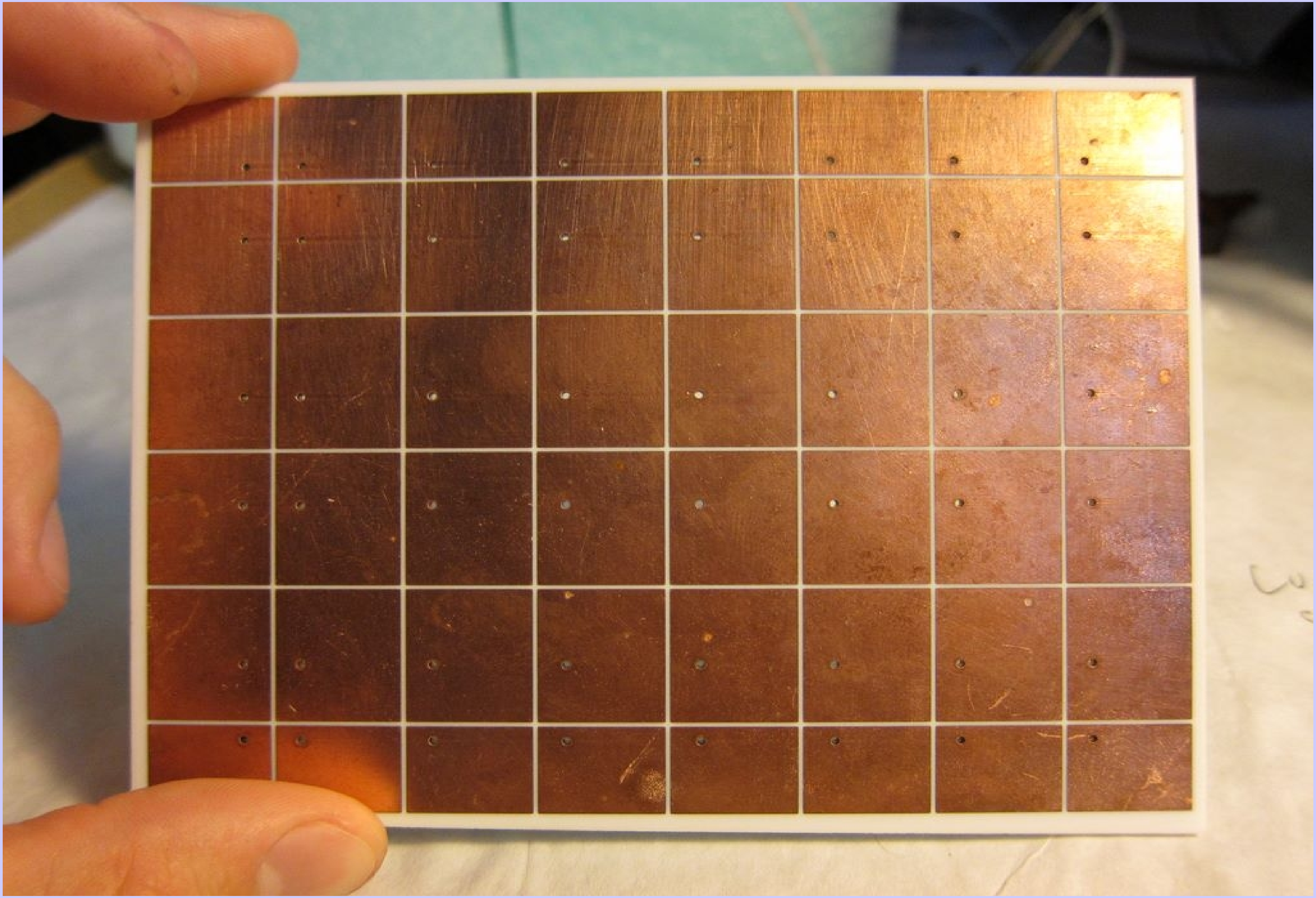



e
μ

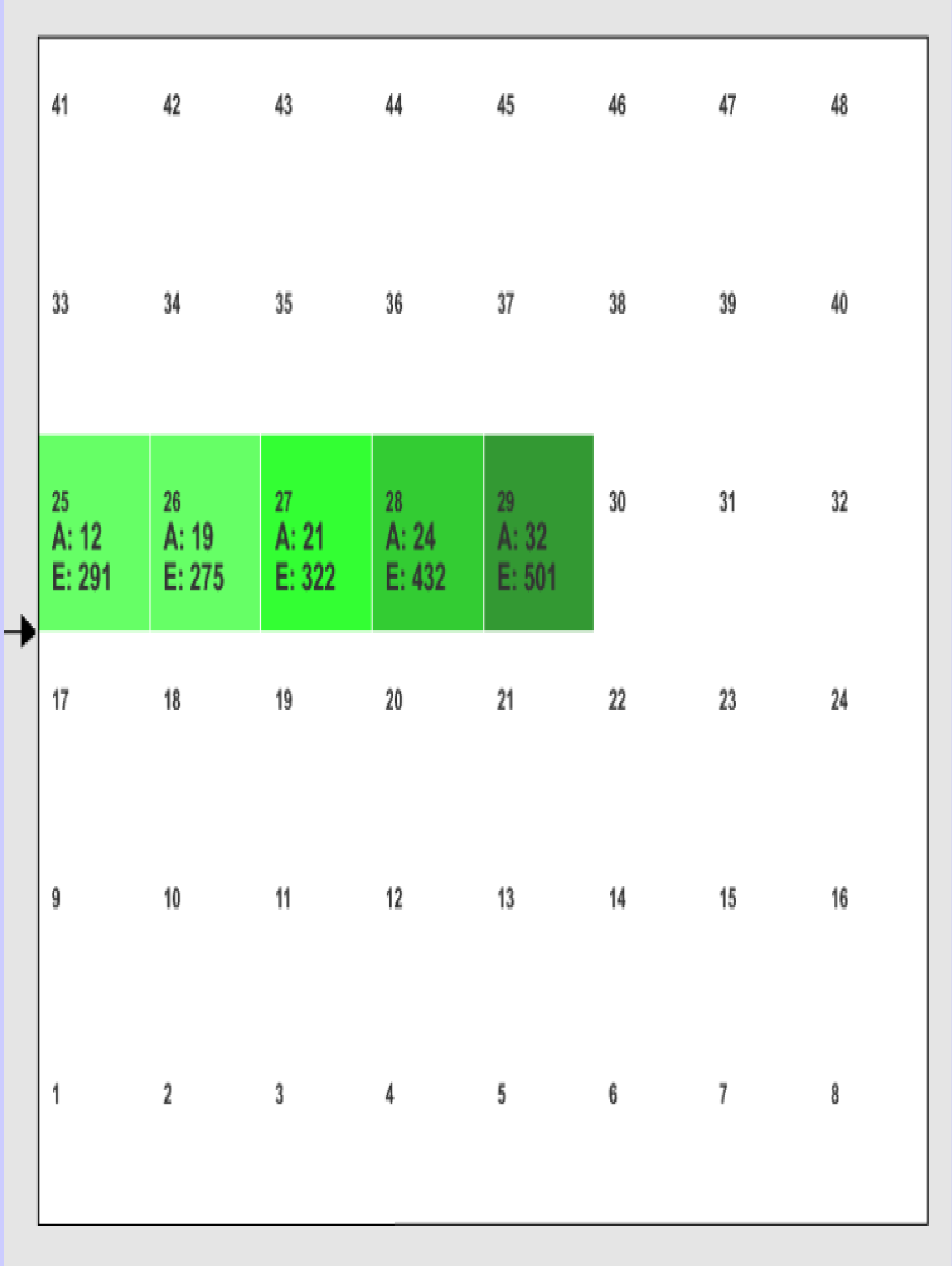
Cryogenic TPC assembly

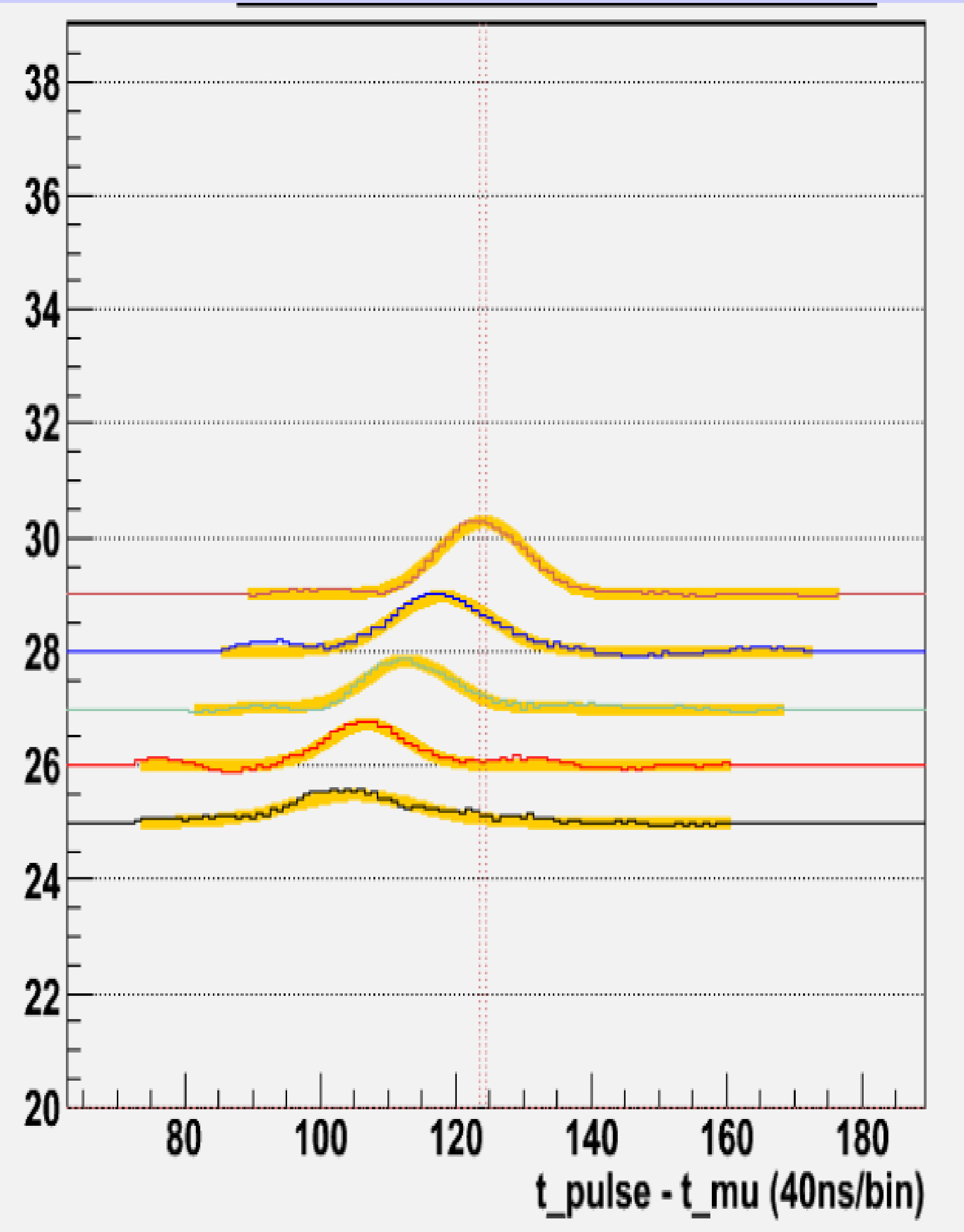


Cryogenic TPC design



Cryogenic TPC event





Conclusions

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

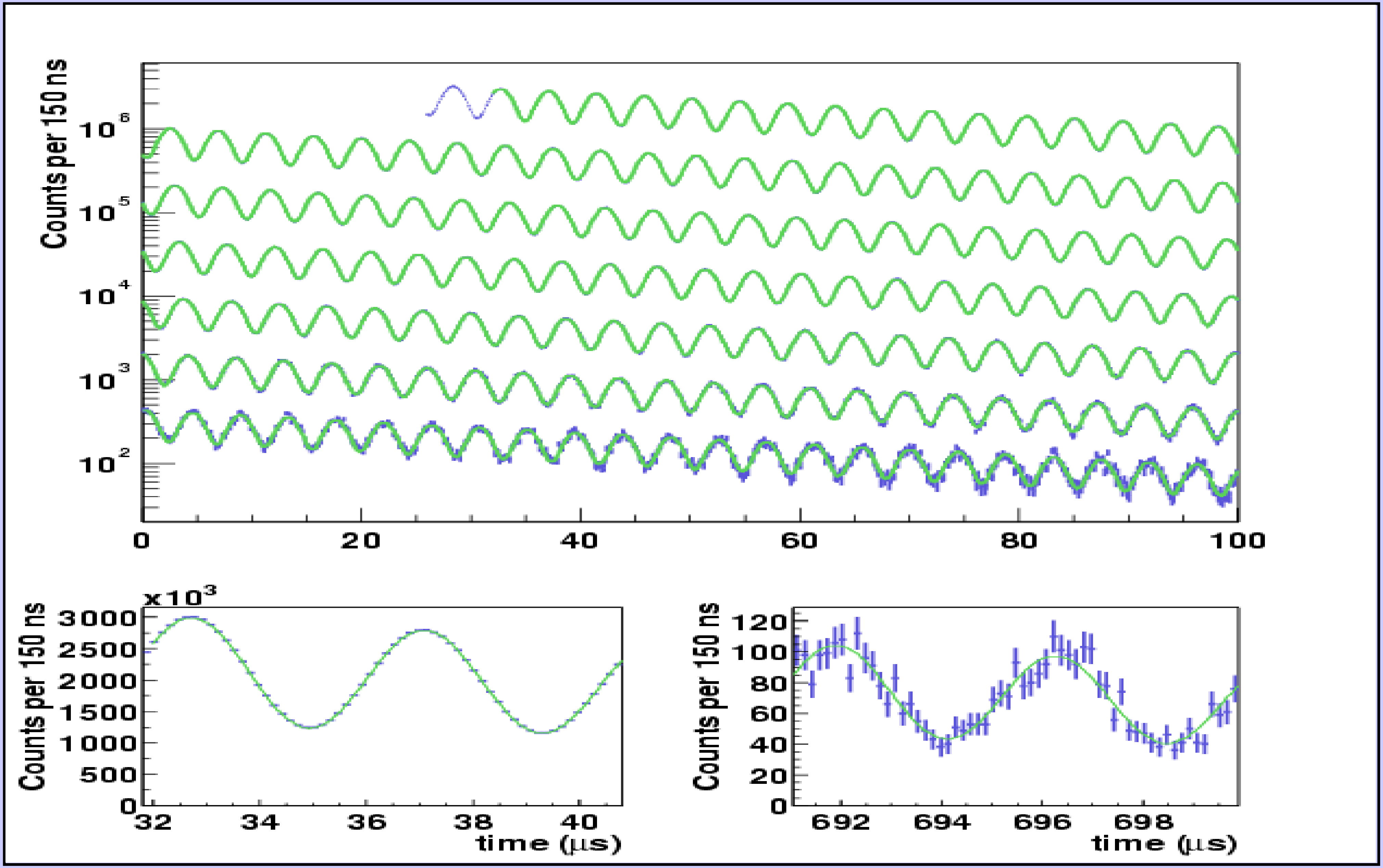
MuLan experiment - **τ_μ= 2196979.9 ± 2.5(stat) ± 0.9(sys) ps [2006], τ_μ= 2196981.2 ± 3.7(stat) ± 0.9(sys) ps [2007],** **G_F= 1.166 3788 (7) x 10^{-5} GeV^{-2}** - a thirty-fold improvement over earlier experiments.

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

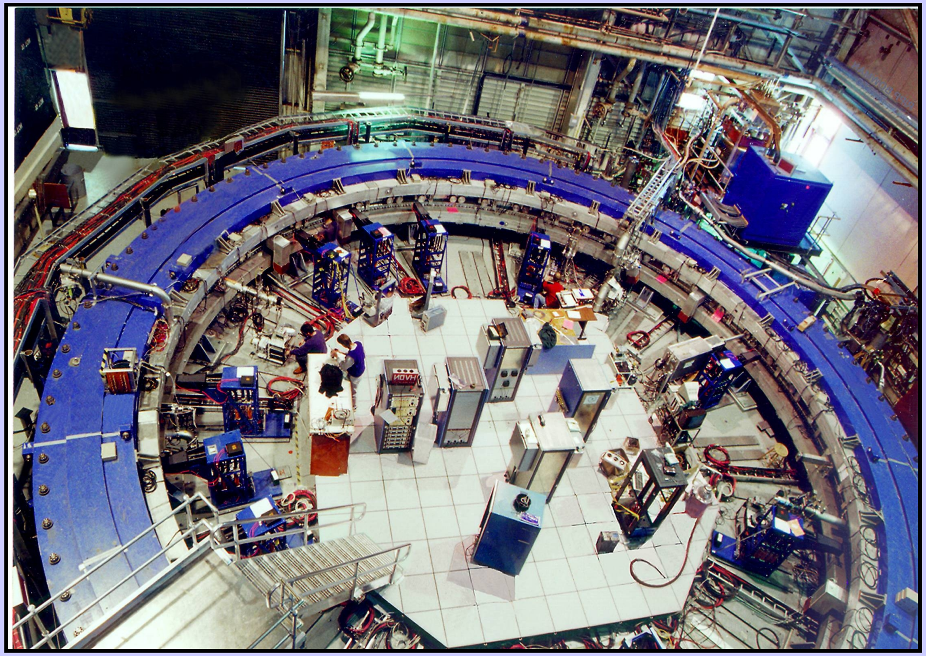
MuSun experiment – **goal of Λ_S to ±1.5%** - precision measurement of two-nucleon weak interaction of great interest to solar physics, neutrino physics and two-body weak currents.

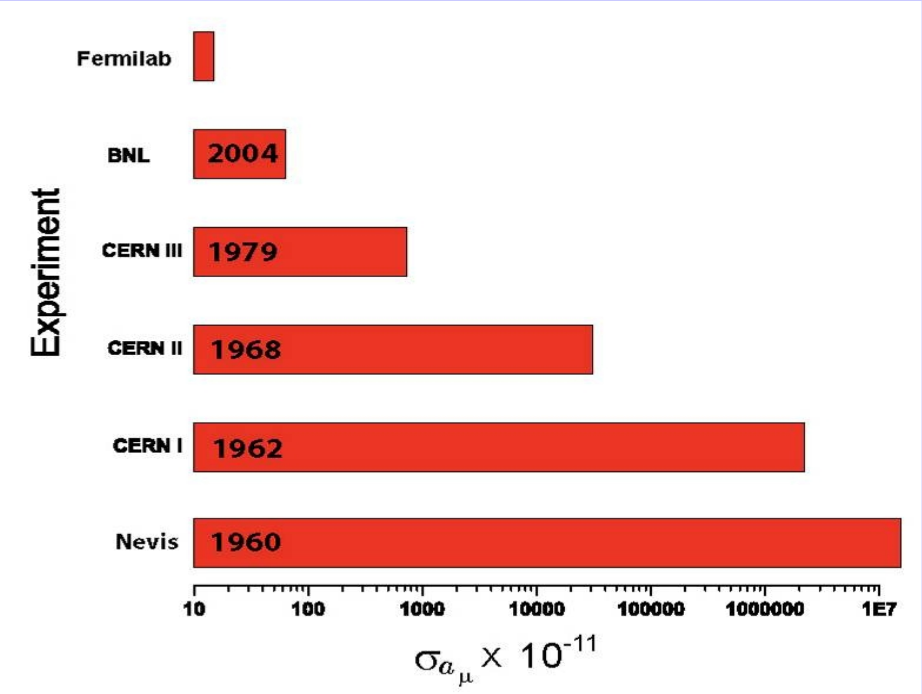
Advertisement

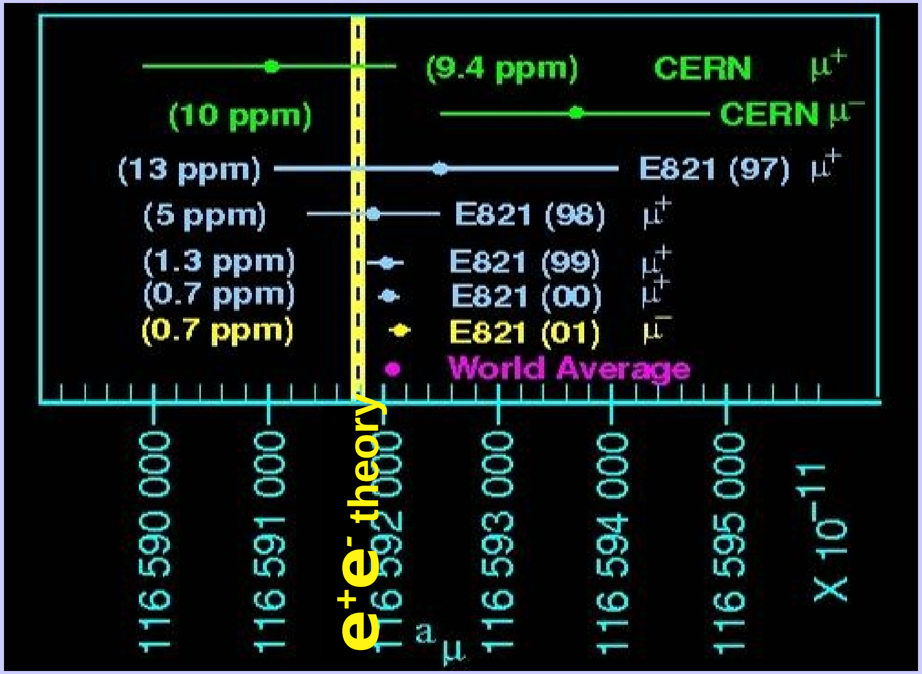
new g-2 expt on muon campus at Fermilab



g-2 @ FNAL




Fermilab
BNL
2004
CERN III
1979
CERN II
1968
CERN I
1962
Nevis
1960
Experiment
10
100
1000
10000
100000
1000000
1E7
$\sigma_{a_\mu} \times 10^{-11}$


(9.4 ppm) CERN μ^+
(10 ppm) CERN μ^-
(13 ppm) E821 (97) μ^+
(5 ppm) E821 (98) μ^+
(1.3 ppm) E821 (99) μ^+
(0.7 ppm) E821 (00) μ^+
(0.7 ppm) E821 (01) μ^-
World Average
116 590 000
116 591 000
116 592 000
116 593 000
116 594 000
116 595 000
X 10^{-11}
a_μ
e^+e^- theory

g-2 @ FNAL

muon storage ring from BNL to FNAL by barge and helicopter

Extras

Relation to Standard Model

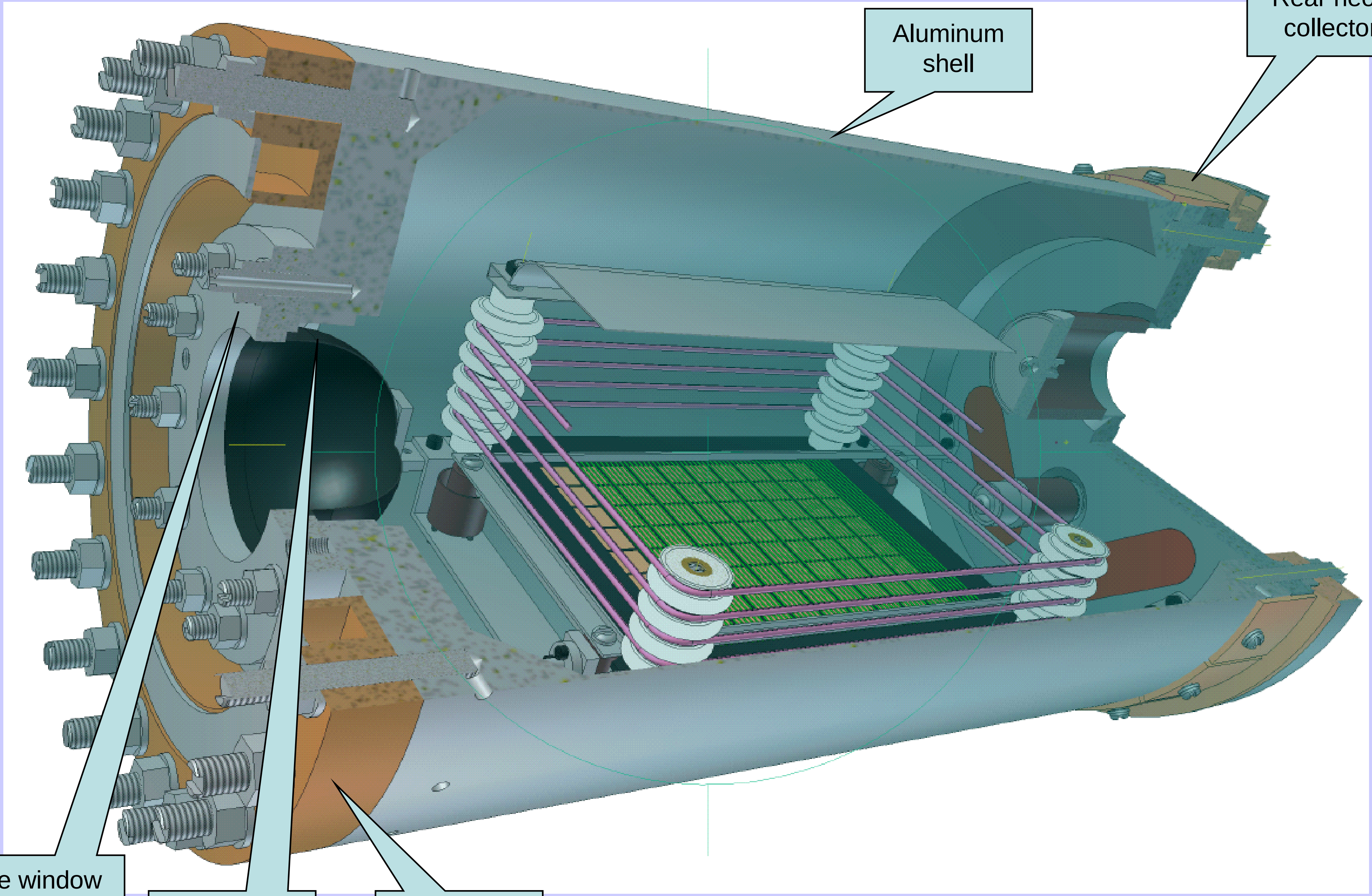
$$\sqrt{4\pi\alpha} = g\,g'/\sqrt{g^2+g'^2}$$

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

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

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

Cryogenic TPC design



Aluminum shell

Rear neon collector

Be window flange

Be window

Front neon collector