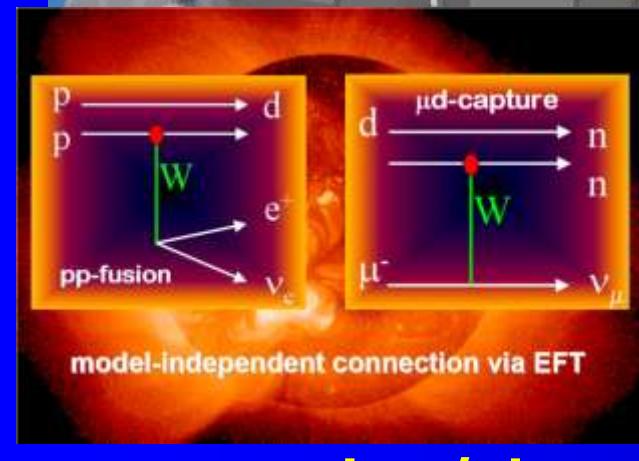
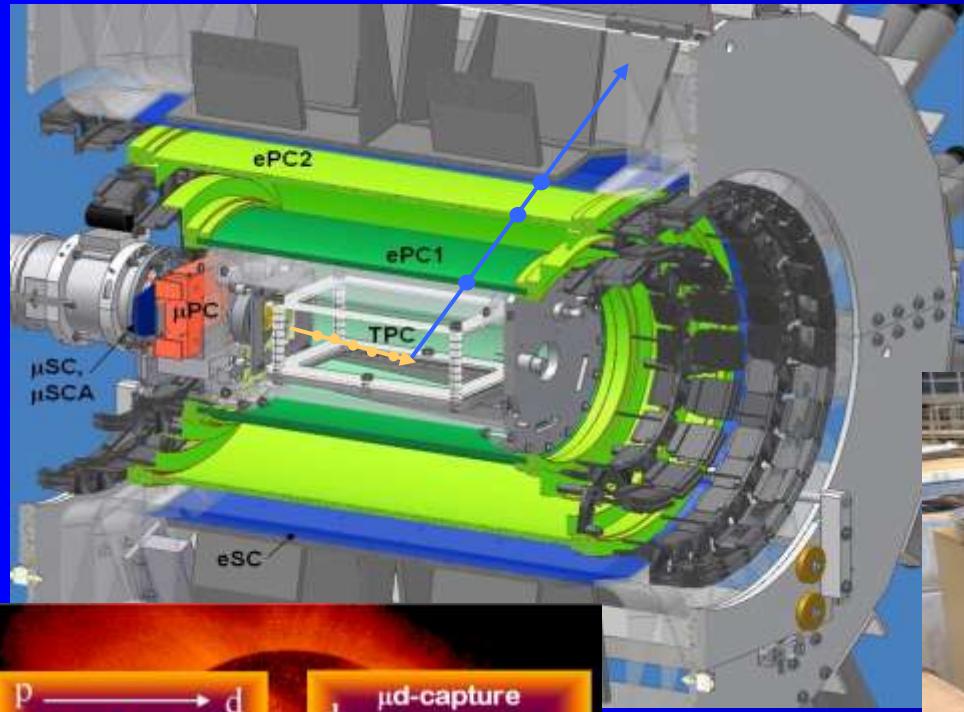


# In a muon's lifetime: From Fermi's constant to calibrating the sun

Peter Winter

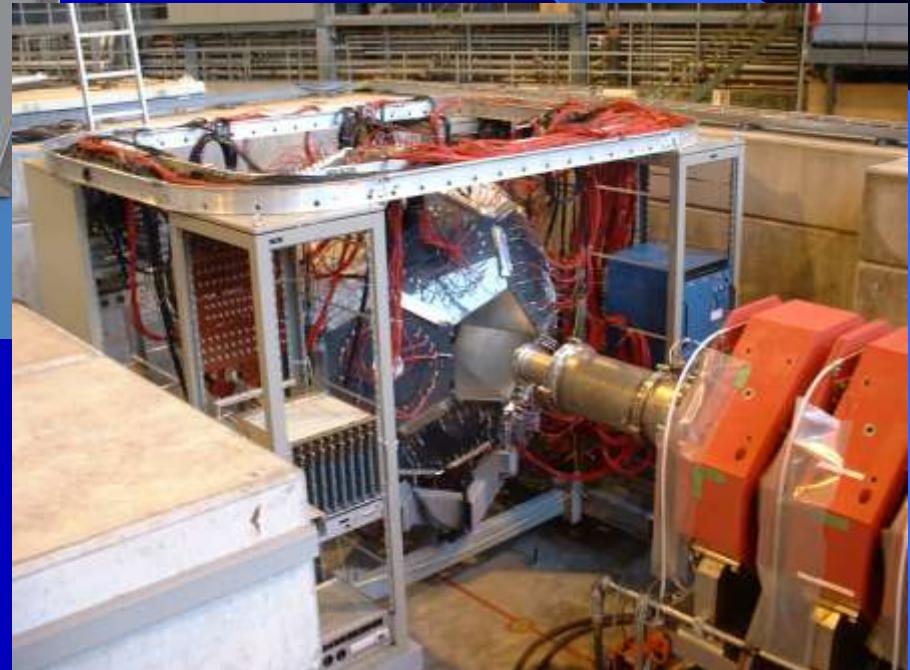
University of Washington



$g_P$

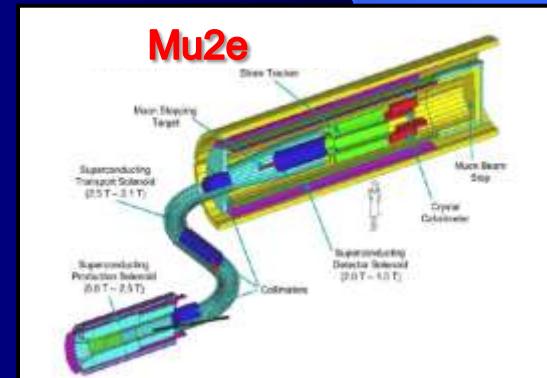
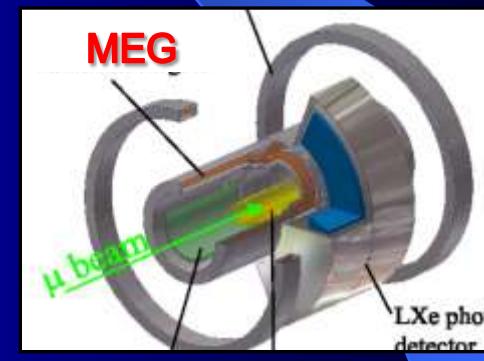
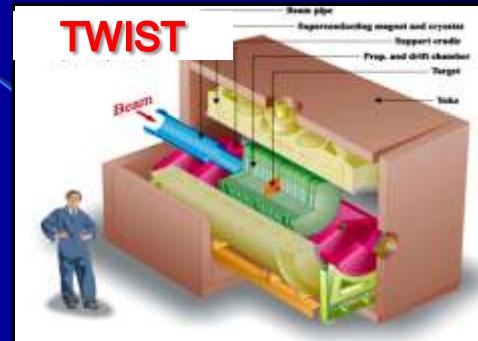
$\tau_\mu$

$L_{1A} / d_R$



# Muon physics efforts worldwide

- Lifetime – Fermi constant
  - 2 “precision” experiments: **MuLan & FAST**
- Decay parameters
  - Michel – **TWIST**  $\rho, \delta, \eta, P_{\mu\xi}$
  - Transverse polarization ( $\eta$ ) – PSI
- Capture
  - **MuCap**:  $g_P$ , pseudoscalar coupling
  - **MuSun**: basic EW interaction in 2N system
- Anomalous magnetic moment ( $g-2$ )
  - New **g-2** experiment in planning
- Lepton Flavor Violation
  - $\mu \rightarrow e\gamma$  – **MEG** at PSI taking data now
  - $\mu e$  conversion –  $\mu A \rightarrow eA$  **Mu2e** at FNAL new high-priority project
- EDM
  - **E821** PRD in prep  $\sim 10^{-21} \text{ e}\cdot\text{cm}$
  - Modest efforts toward small dedicated ring at PSI
- Lorentz / CPT violation tests
  - **E821** g-2 PRL 2007; precession vs. sidereal day
- Muonic Lamb shift (QED)
  - Finite size effects aids to hydrogen Lamb shift effort



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- Motivation and outlook

# Three electro-weak input parameters

- Fine structure constant

$\Delta\alpha / \alpha \approx 0.37$  ppb [Gabrielse et al, 2008]

- Neutral weak boson mass

$\Delta M_Z / M_Z \approx 23$  ppm [LEP EWWG 2005]

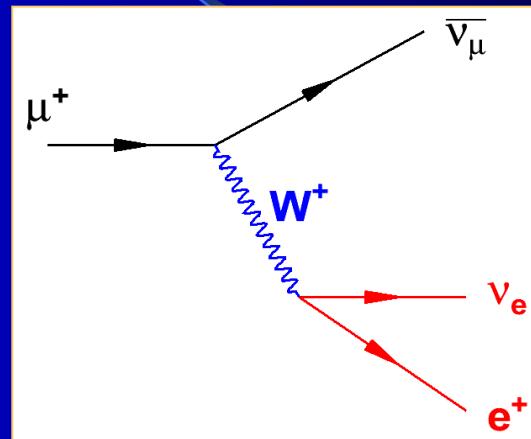
- Fermi constant

$\Delta G_F / G_F \approx 9$  ppm [Giovanetti et al, 1984,  
Bardin et al., 1984]

# Fermi constant $G_F$

Implicit to all EW precision physics

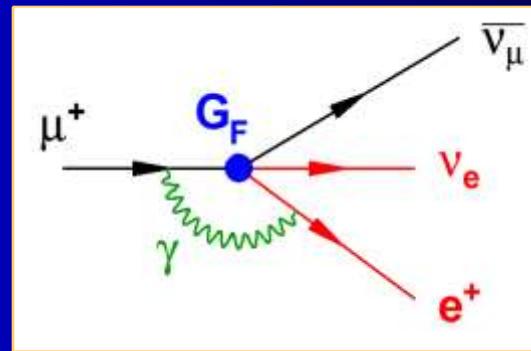
$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2} (1 + \Delta r(m_t, m_H, \dots))$$



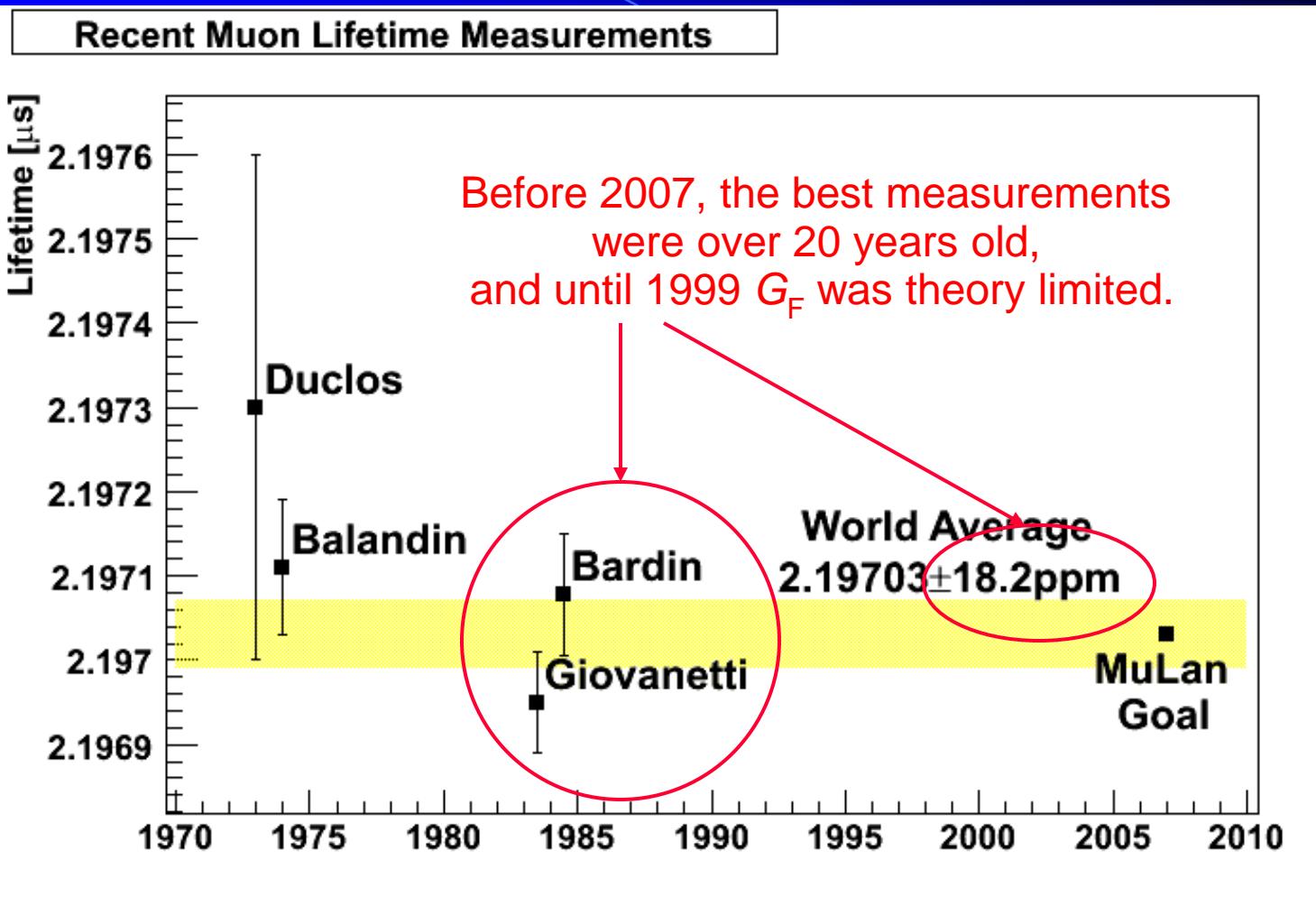
Most precisely determined by muon decay

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

PS, QED and hadr. rad.



# Brief history of $\tau_\mu$



G. Bardin et al., Phys. Lett. B 137, 135 (1984)

K. Giovanetti et al., Phys. Rev. D 29, 343 (1984)

# Extraction of $G_F$ no longer theory limited

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

Future:    0.5 ppm    1 ppm

<0.3 ppm

Lifetime error is  
the limit

2 loop QED corrections

T. van Ritbergen and R. G. Stuart, Nucl. Phys. B564, 343 (2000)  
A. Pak and A. Czarnecki, PRL 100, 241807 (2008)

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# The facility: $\pi$ E3 beamline at PSI

The image consists of two main parts: a photograph of the experimental hall and a detailed site map of the PSI facility.

**Photograph:** An aerial view of the experimental hall showing various scientific instruments, equipment, and infrastructure. A scale bar indicates distances up to 10 meters.

**Site Map:** A detailed diagram of the PSI facility layout. It includes:

- Accelerator Facilities:** Cockcroft-Walton (C), Injector 2 (I2), 590 MeV Ring Cyclotron (R), Injector 1 (I1).
- Beam Transport Lines:** Proton Channel (P).
- Neutron Spallation Source:** Neutron Spallation Source SINQ (S), Target-Storage Pit (L).
- Medicine:** Isotope Production IP2 (1), Eye Treatment OPTIS (2), Proton Therapy Gantry (3).
- Nuclear Physics and Radiochemistry:** NE-B, NE-C.
- Particle Physics:** PIREX, MORE, UTF, PI-EE, rEE, πE3, πE1, πM1, πM2, πM3, πE4.
- Solid State Physics and Materials Science:** FUNSPIN, NAA / PNA / GJA, TrICs, HRPT, NEUTRA, POLDI, Driftcell, NCR, Tops, DMC, TASPF, NQB, PGA, FOCUS, AMOR, SANS.
- Experimental Hall:** ATEC, ATEC.
- Neutron Guide Hall:** SINQ Target Hall.

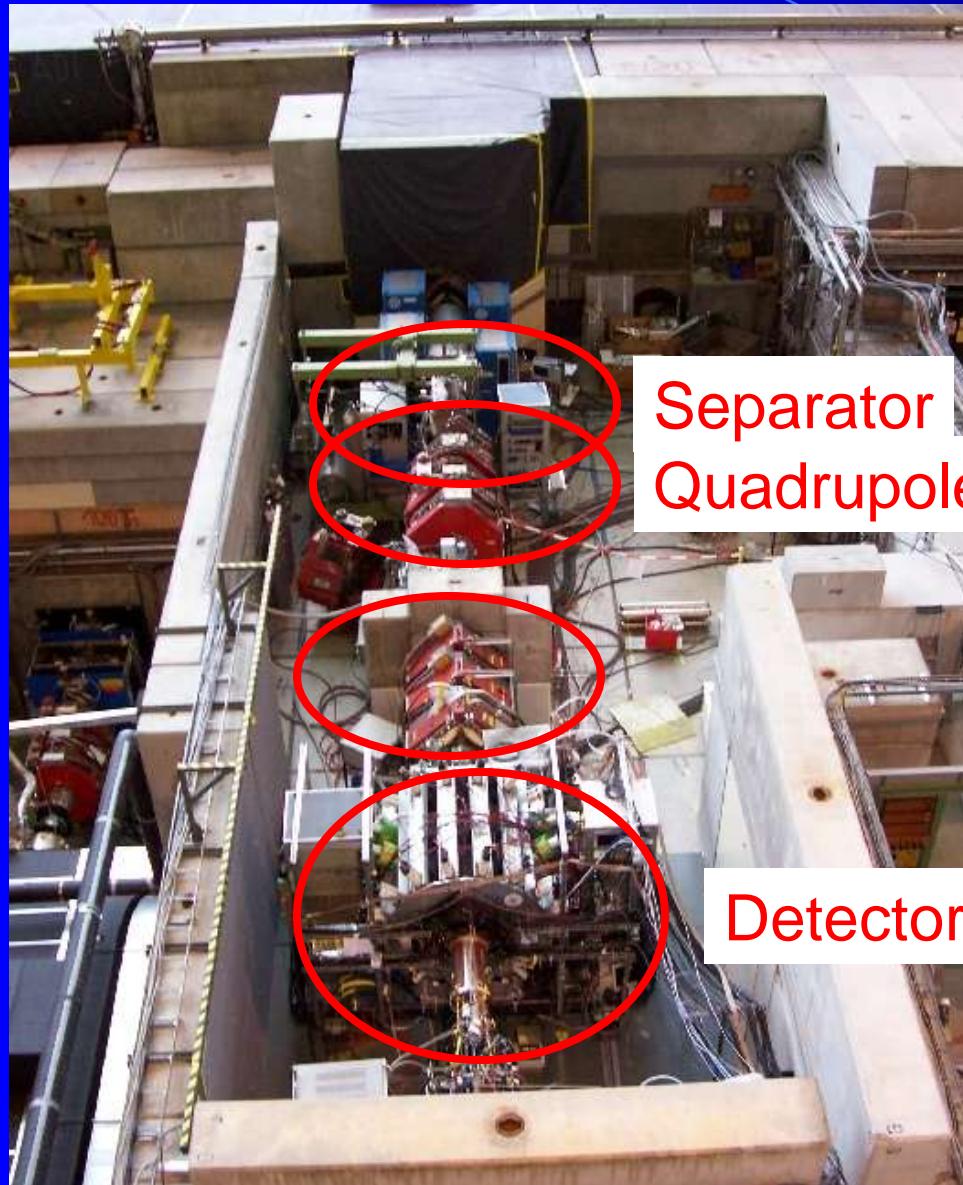
A green line connects the experimental hall photograph to the site map, highlighting the location of the  $\pi$ E3 beamline.

# The Kicker



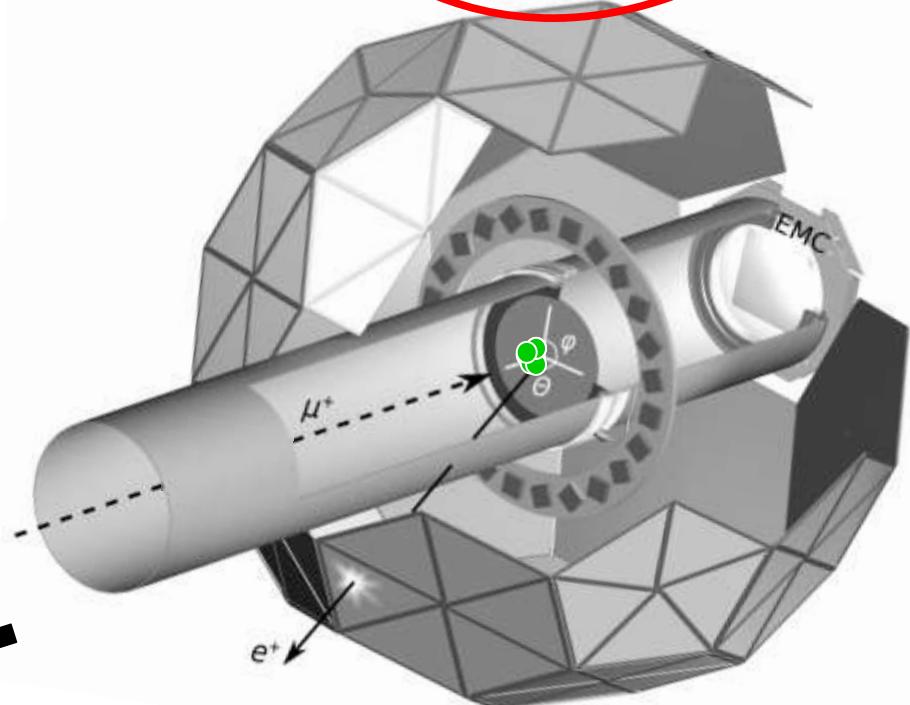
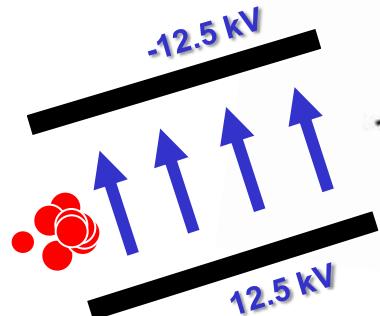
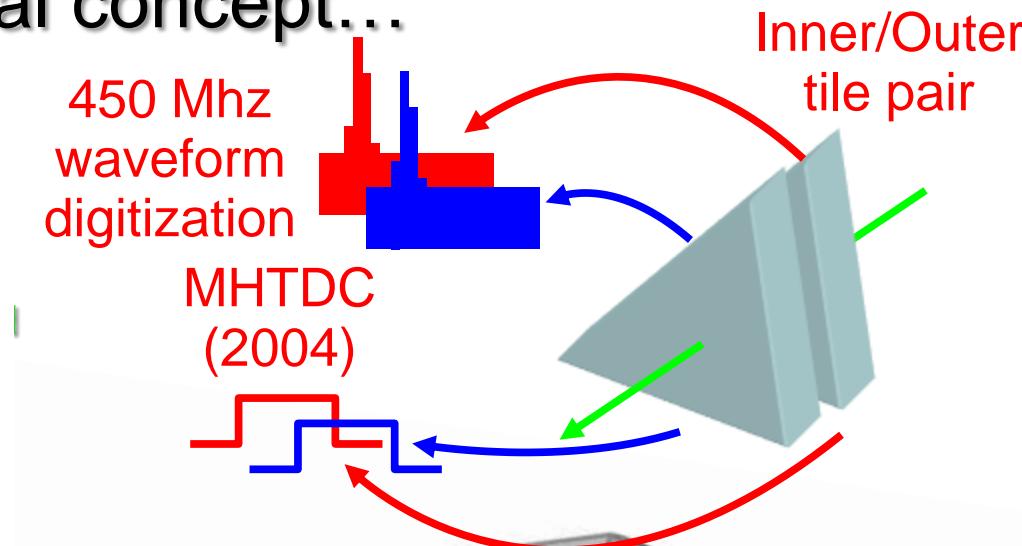
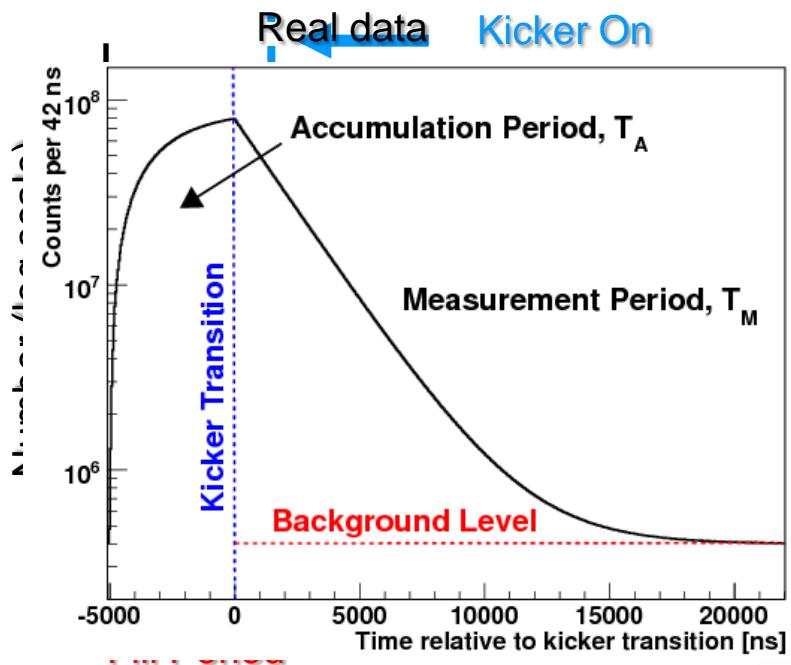
- Design at TRIUMF
- MOSFET based
- 50 ns switching time

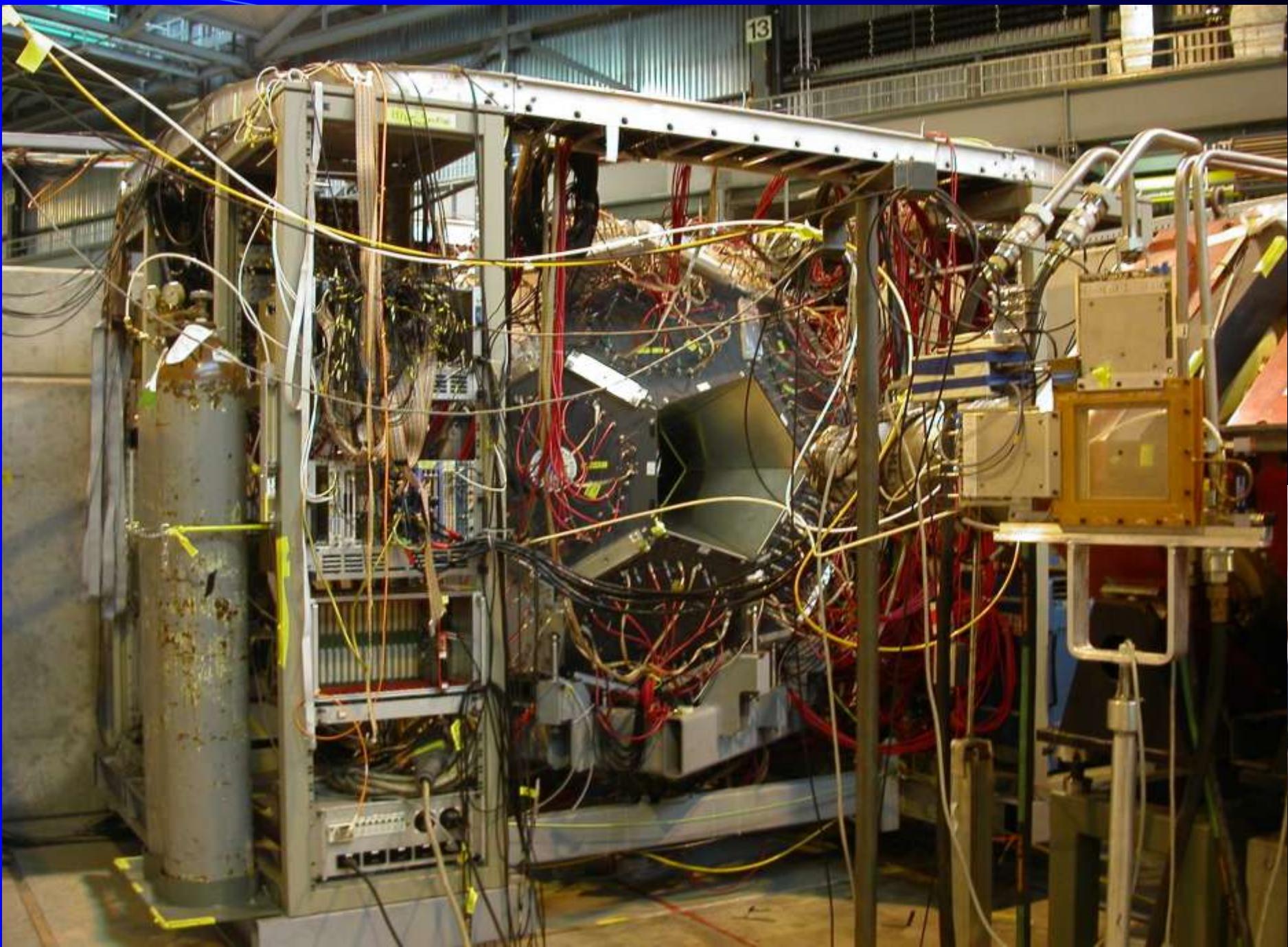
# Other elements



**Separator:**  
Suppression of  
 $e^+$  or  $e^-$  in beam

# The experimental concept...





# Outline

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## Muon capture on the deuteron (MuSun)

- Motivation and outlook

# Main systematics

Any early-to-late effect:

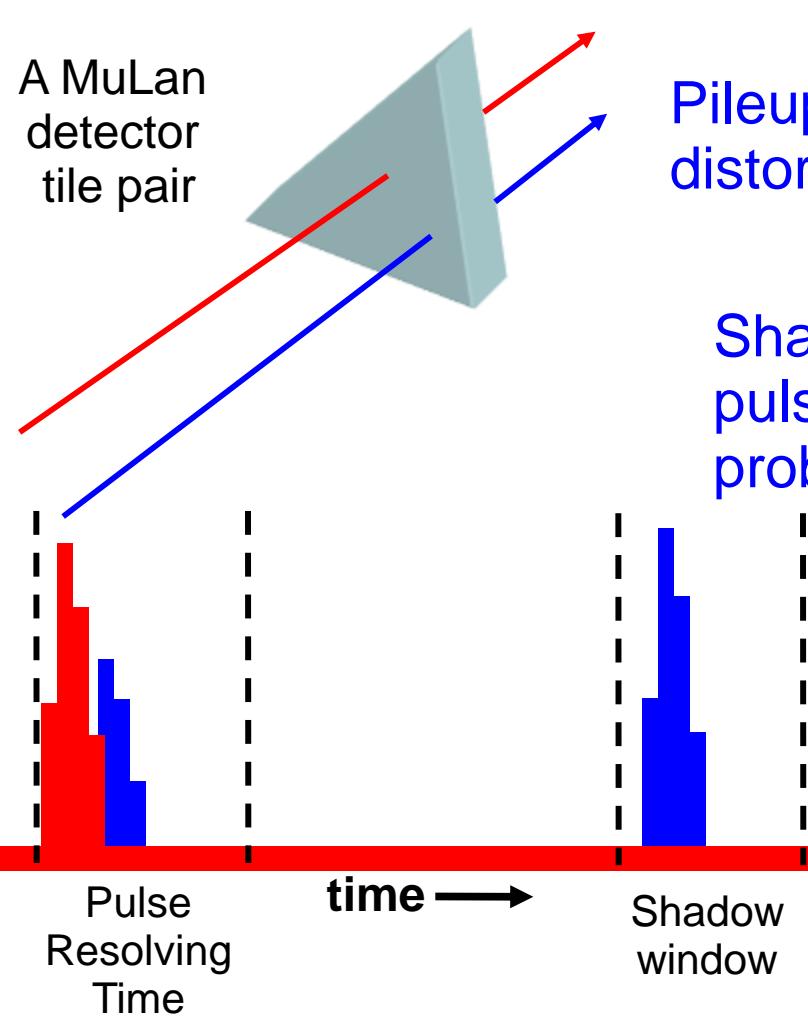
## *Instrumental issues*

- Pileup pulses
- Non-flat background
- PMT gain change
- ....

## *Physics issues*

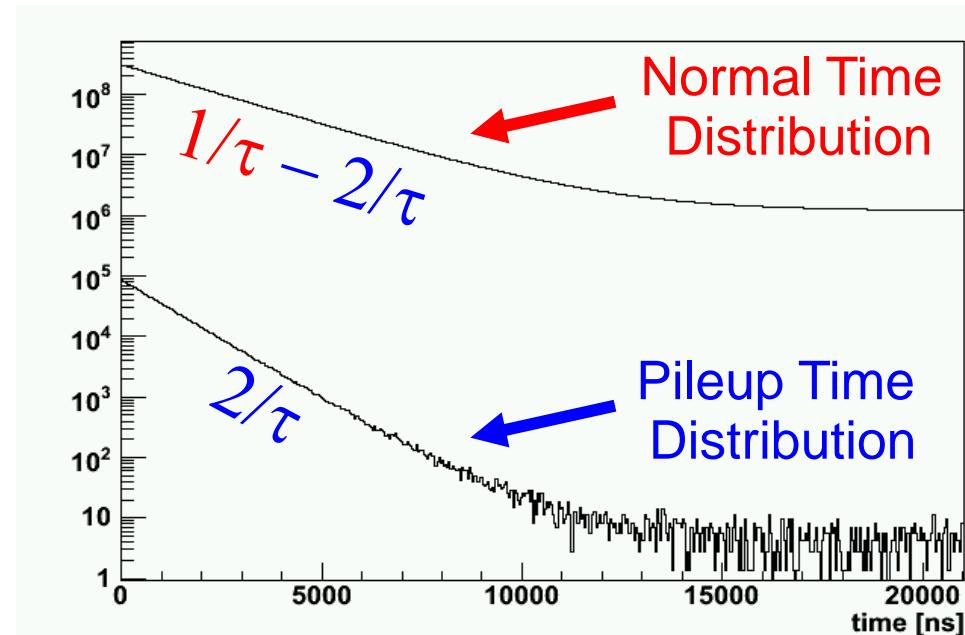
- Polarization
- Longitudinal relaxation
- ....

# Pileup corrected from the data



Pileup pulses measurably distort the lifetime

Shadow and pileup pulses have the same probability distribution!



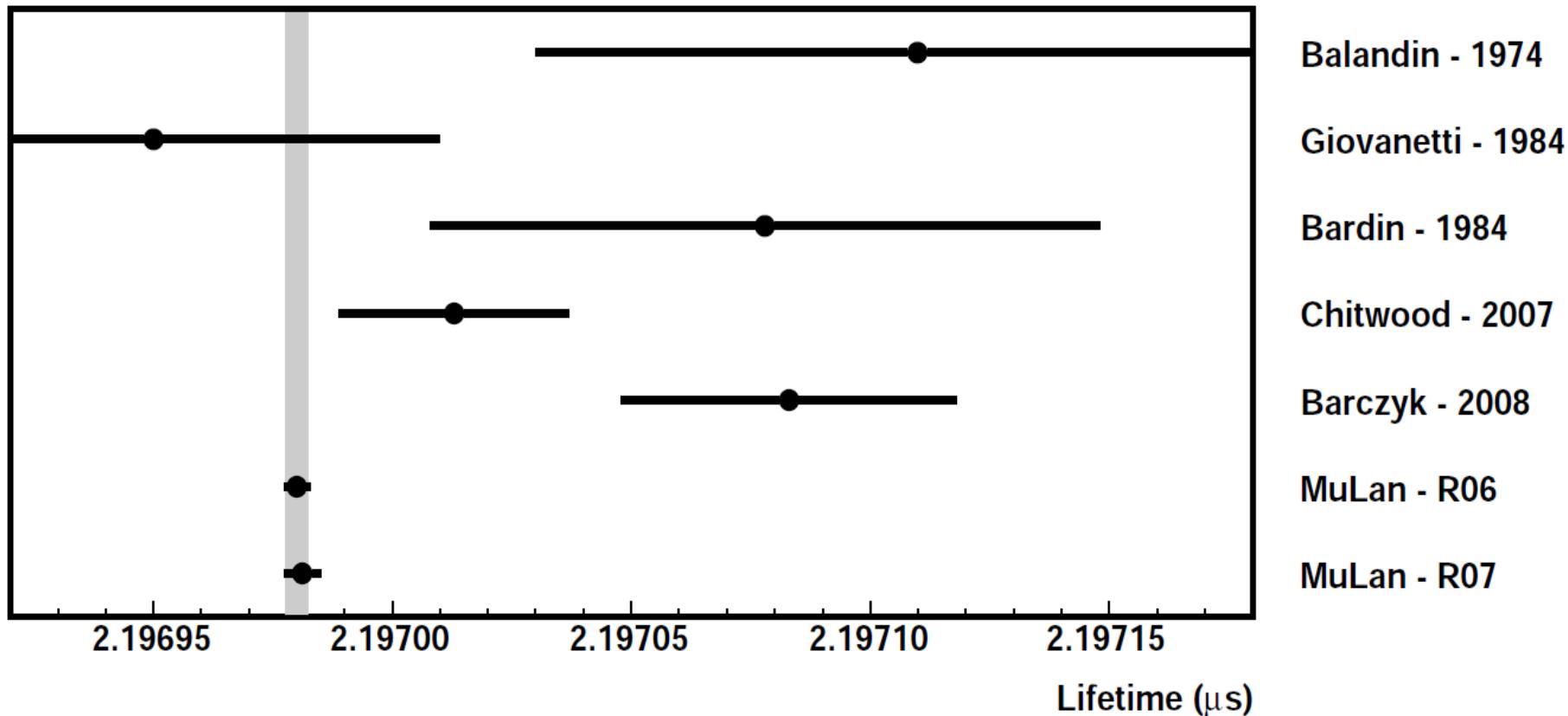
# Results final statistics

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

$$\tau_{\mu}(R06) = 2196979.9 \pm 2.5 \pm 0.9 \text{ ps}$$

$$\tau_{\mu}(R07) = 2196981.2 \pm 3.7 \pm 0.9 \text{ ps}$$

$$G_F = 1.1663818(7) \times 10^{-5} \text{ GeV}^{-2} \text{ (0.6 ppm)}$$



D.B. Chitwood et al., Phys. Rev. Lett. 99, 03201 (2007)  
D. Webber et al., in preparation for publication (2010)

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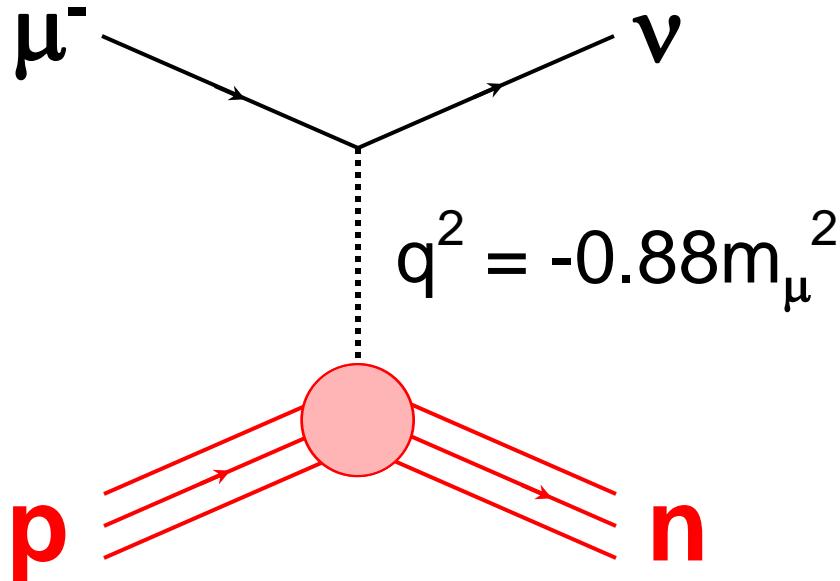
- Motivation and general overview
- MuCap experiment
- Systematics and results

## Muon capture on the deuteron (MuSun)

- Motivation and outlook

# Nucleon form factors

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



$$M \sim G_F V_{ud} \cdot \bar{\psi}_v \gamma_\alpha (1 - \gamma_5) \psi_\mu \cdot \bar{\psi}_n (V^\alpha - A^\alpha) \psi_p$$

# Nucleon form factors

$$M \sim G_F V_{ud} \cdot \Psi_v \gamma_\alpha (1 - \gamma_5) \Psi_\mu \cdot \Psi_n (V^\alpha - A^\alpha) \Psi_p$$

$$\begin{aligned} V^\alpha = & g_V(q^2) \gamma^\alpha \\ & + i g_M(q^2) \sigma^{\alpha\beta} q_\beta / 2M_N \\ & + \cancel{g_S(q^2) q^\alpha / m_\mu} \end{aligned}$$

Conserved Vector Current and isospin symmetry

$$\Rightarrow g_S(q^2) = 0$$

$g_V, g_M$ : strong program JLab, Mainz, ...

# Nucleon form factors

$$M \sim G_F V_{ud} \cdot \Psi_v \gamma_\alpha (1 - \gamma_5) \Psi_\mu \cdot \Psi_n (V^\alpha - A^\alpha) \Psi_p$$

$$\begin{aligned} A^\alpha = & g_A(q^2) \gamma^\alpha \gamma_5 \\ & + i \cancel{g_T(q^2)} \cancel{\sigma^{\alpha\beta}} \cancel{q_\beta} / 2M_N \gamma_5 \\ & + g_P(q^2) q^\alpha / m_\mu \gamma_5 \end{aligned}$$

Second class current suppressed by isospin  
 $\Rightarrow g_T(q^2) = 0$

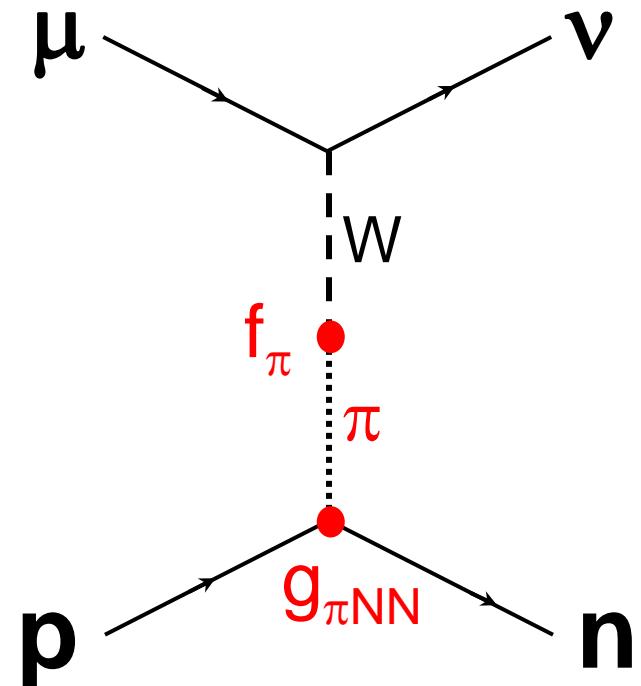
$g_A(q^2)$  measured in neutron decay

# Pseudoscalar form factor $g_P$

$$g_P(q^2) = -\frac{2m_N m_\mu g_A(0)}{q^2 - m_\pi^2} -$$

PCAC pole term  
(Adler, Dothan, Wolfenstein)

$$g_P = 8.26 \pm$$



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

Recent reviews:

T. Gorringe, H. Fearing, Rev. Mod. Physics 76 (2004) 31

V. Bernard et al., Nucl. Part. Phys. 28 (2002), R1

# How to access $g_P$ ?

In principle any process directly involving axial current:

- $\beta$  decay: Not sensitive since  $g_P$  term  $\sim q$
- $\nu$  scattering difficult to measure



Muon capture most direct source for  $g_P$

# Experiments: Observed Processes

- Ordinary muon capture (OMC):  $\mu^- p \rightarrow \nu n$
- Radiative muon capture (RMC):  $\mu^- p \rightarrow \nu n \gamma$
- $\mu^- {}^3\text{He} \rightarrow \nu {}^3\text{H}$  or other nuclei

# Experiments: Observed Processes

- Ordinary muon capture (OMC):  $\mu^- p \rightarrow \nu n$
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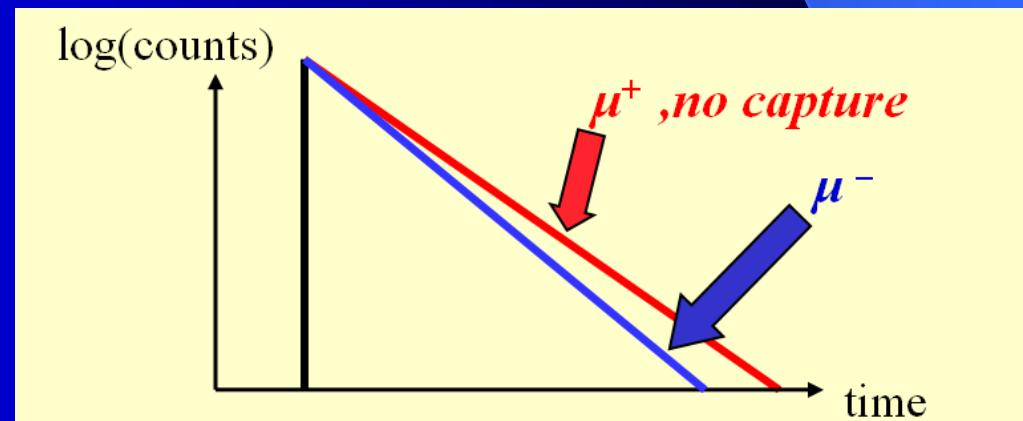
# OMC: Methods to measure

Neutron experiments:

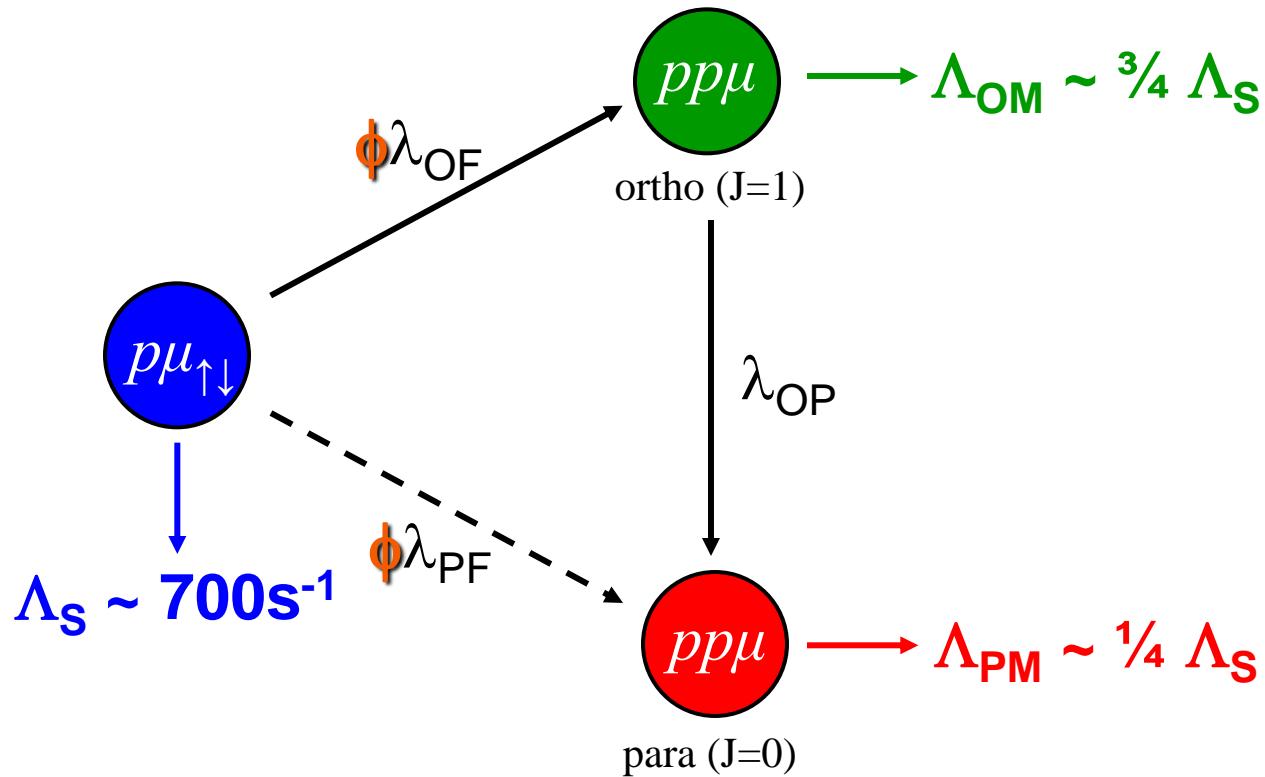
- Measure outgoing neutrons  $N_N$
- Requires knowledge of neutron efficiency
- Separation of decay  $\gamma$ 's from neutrons
- Typical experiments 8-13% precision in  $\Lambda_S$

Lifetime method:

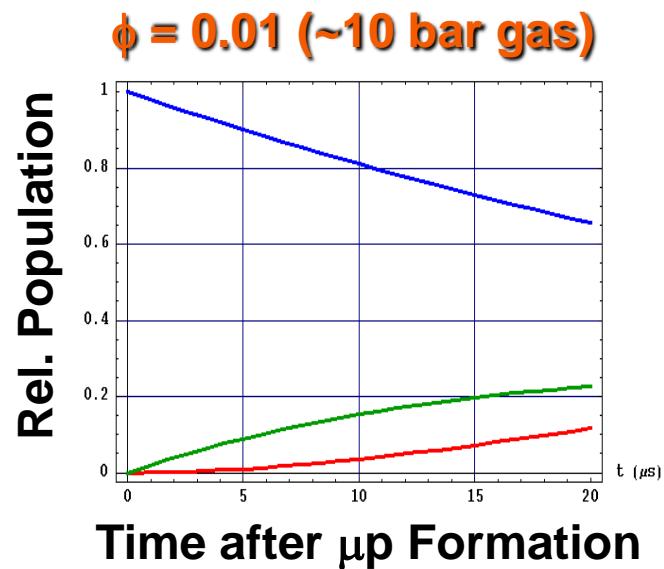
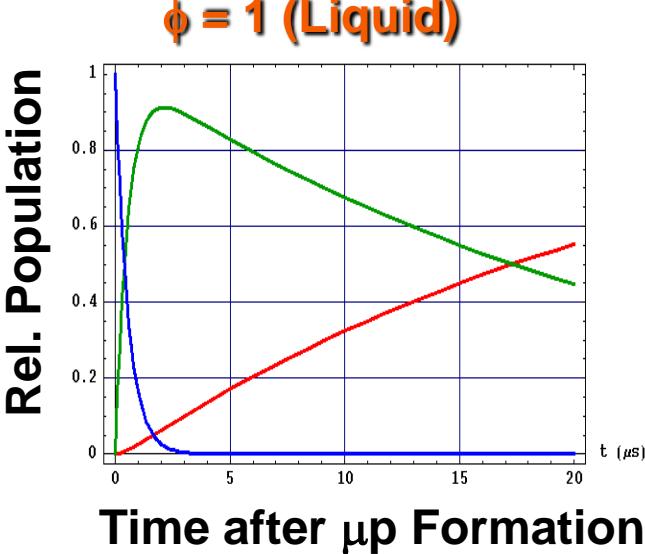
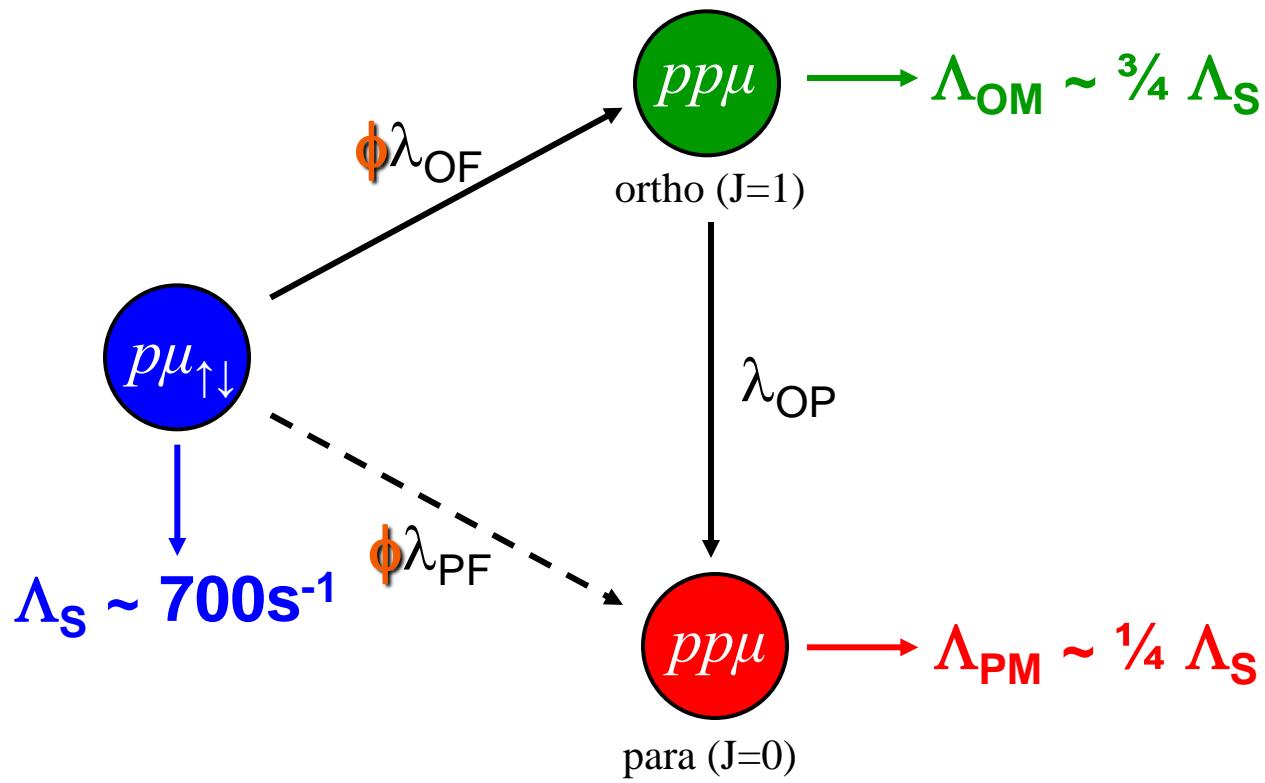
$$- \Lambda_S \approx 1/\tau_- - 1/\tau_+$$



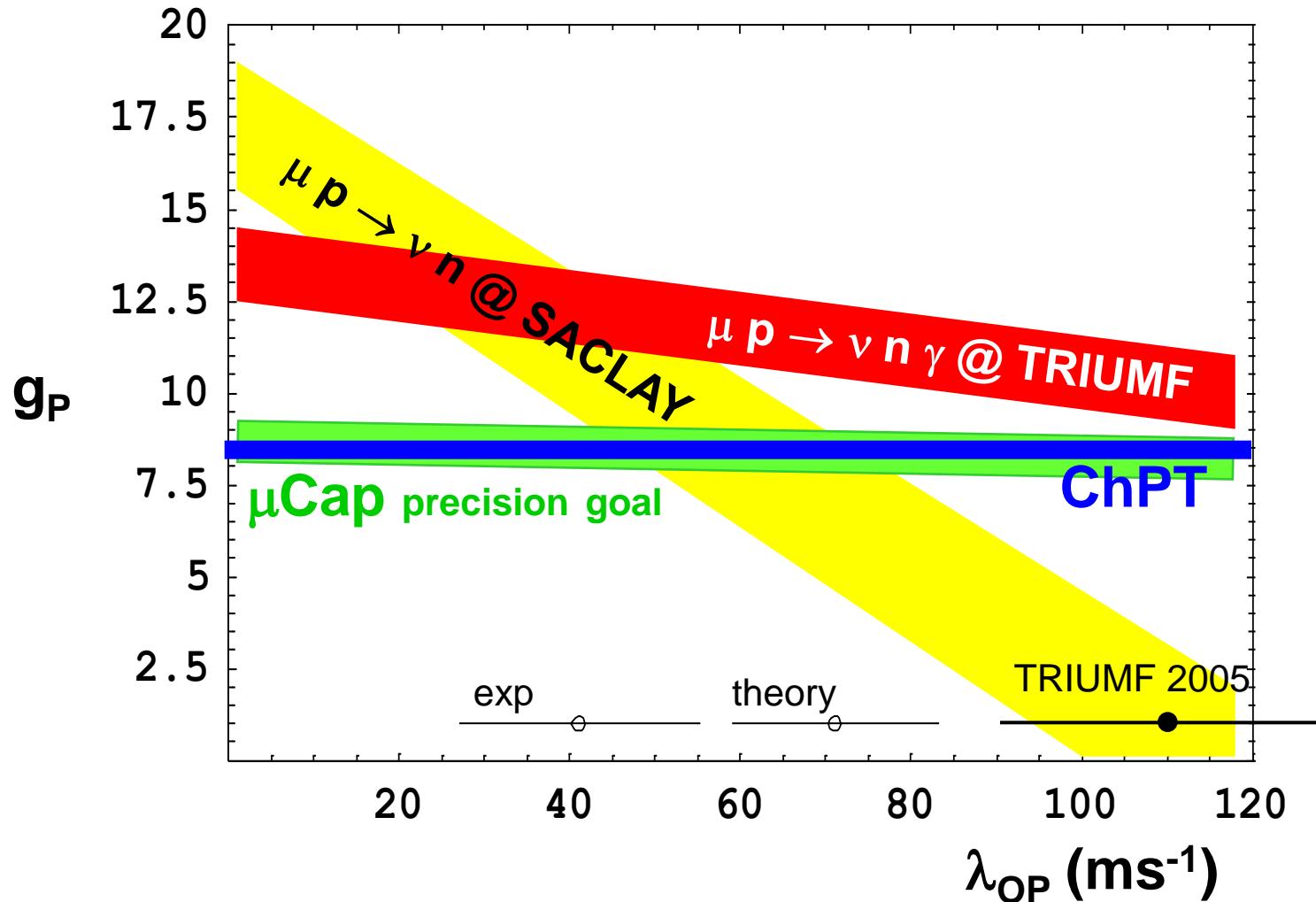
# Muon kinetics



- $pp\mu$  formation depends on density  $\phi$
- Interpretation requires knowledge of  $\Lambda_{OM}$ ,  $\Lambda_{PM}$  and  $\lambda_{OP}$

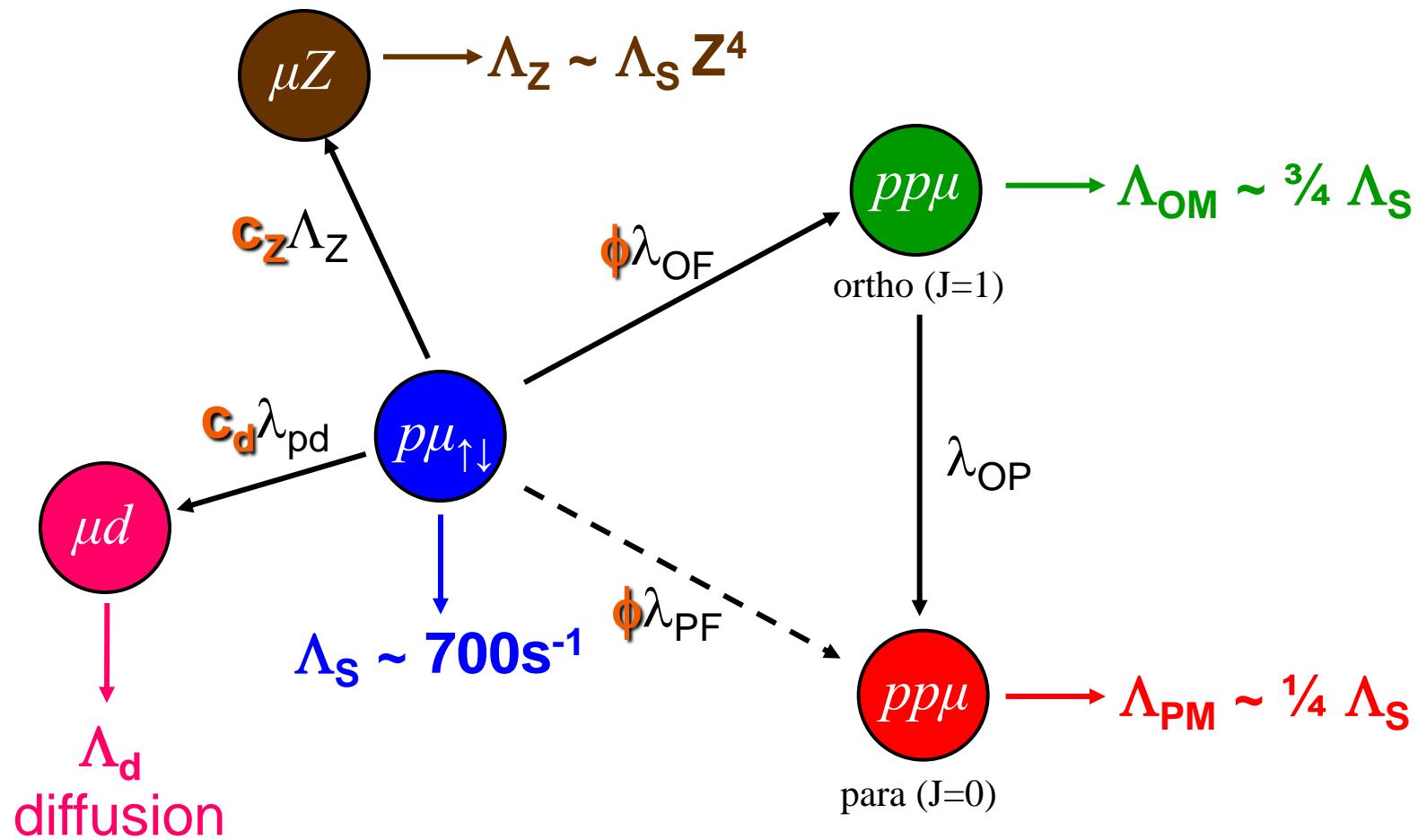


# Previous results



- no overlap theory, OMC & RMC
- large uncertainty in  $\lambda_{OP} \Rightarrow g_P \pm 50\%$

# Requirement of clean target



⇒ Isotopically and chemically pure H<sub>2</sub>, ideally:  
 $c_d < 1 \text{ ppm}$ ,  $c_z < 10 \text{ ppb}$

# Outline

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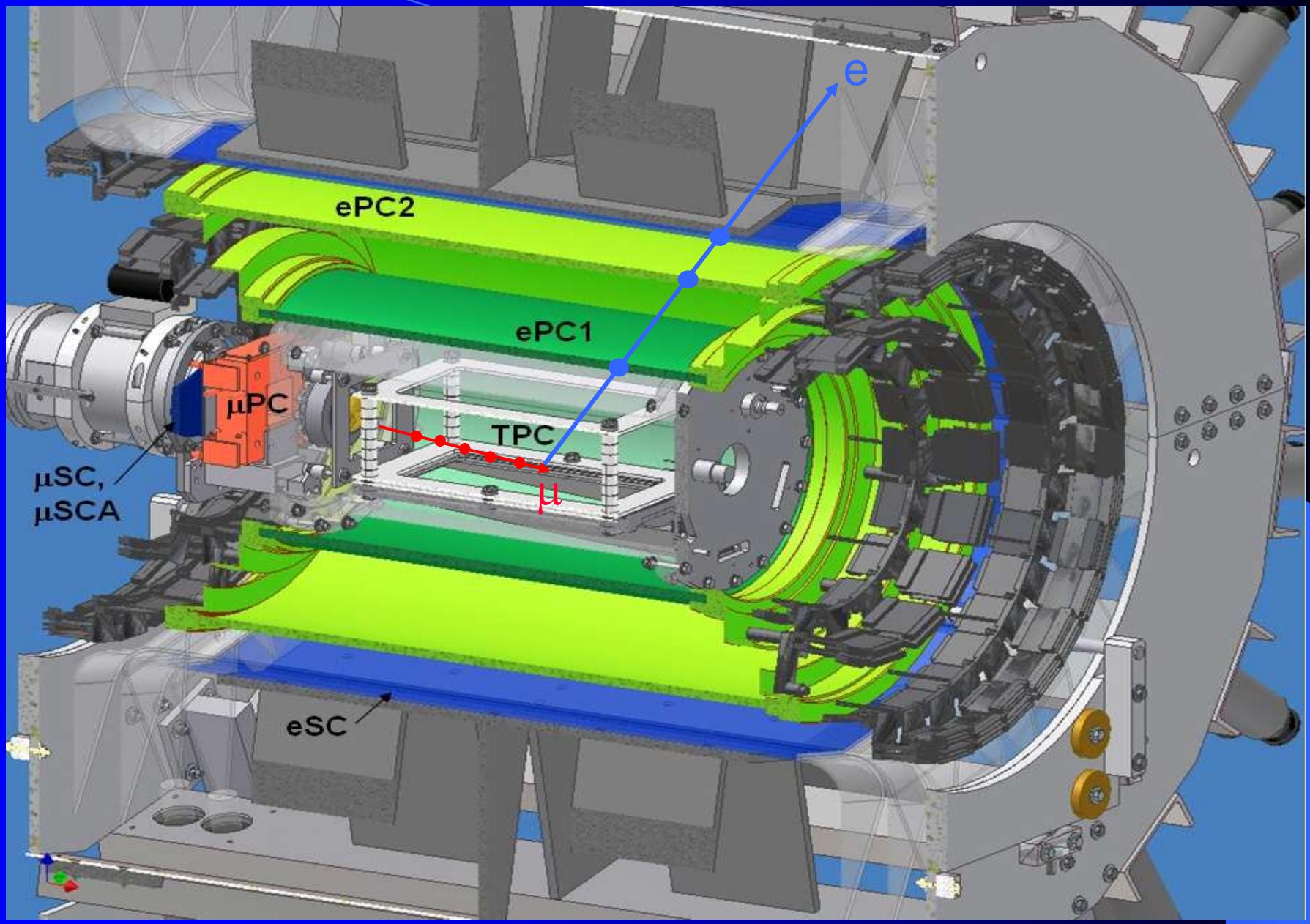
- Motivation
- MuLan experiment
- Main systematics and result

## Muon capture on the proton (MuCap)

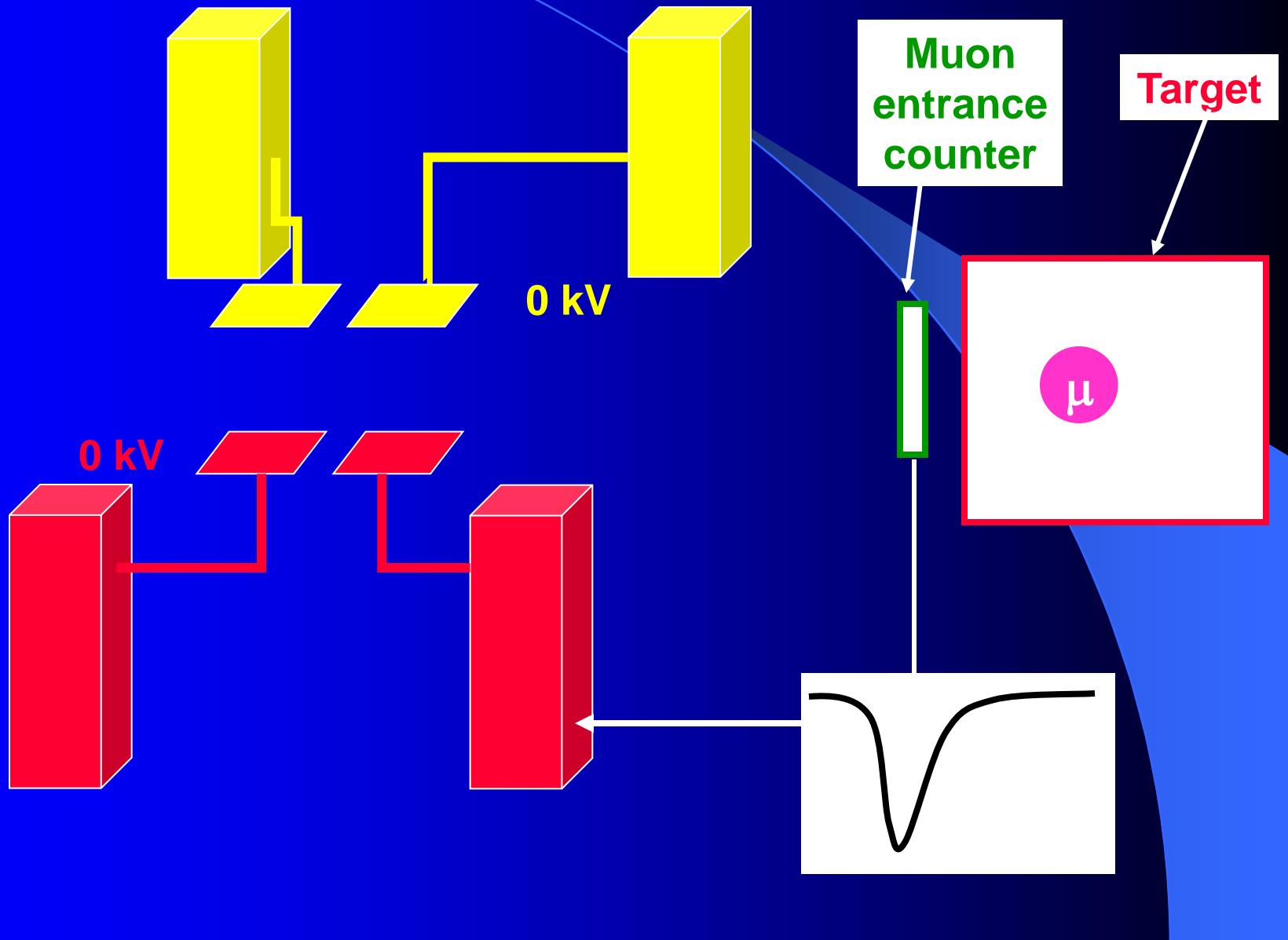
- Motivation and general overview
- MuCap experiment
- Systematics and results

## Muon capture on the deuteron (MuSun)

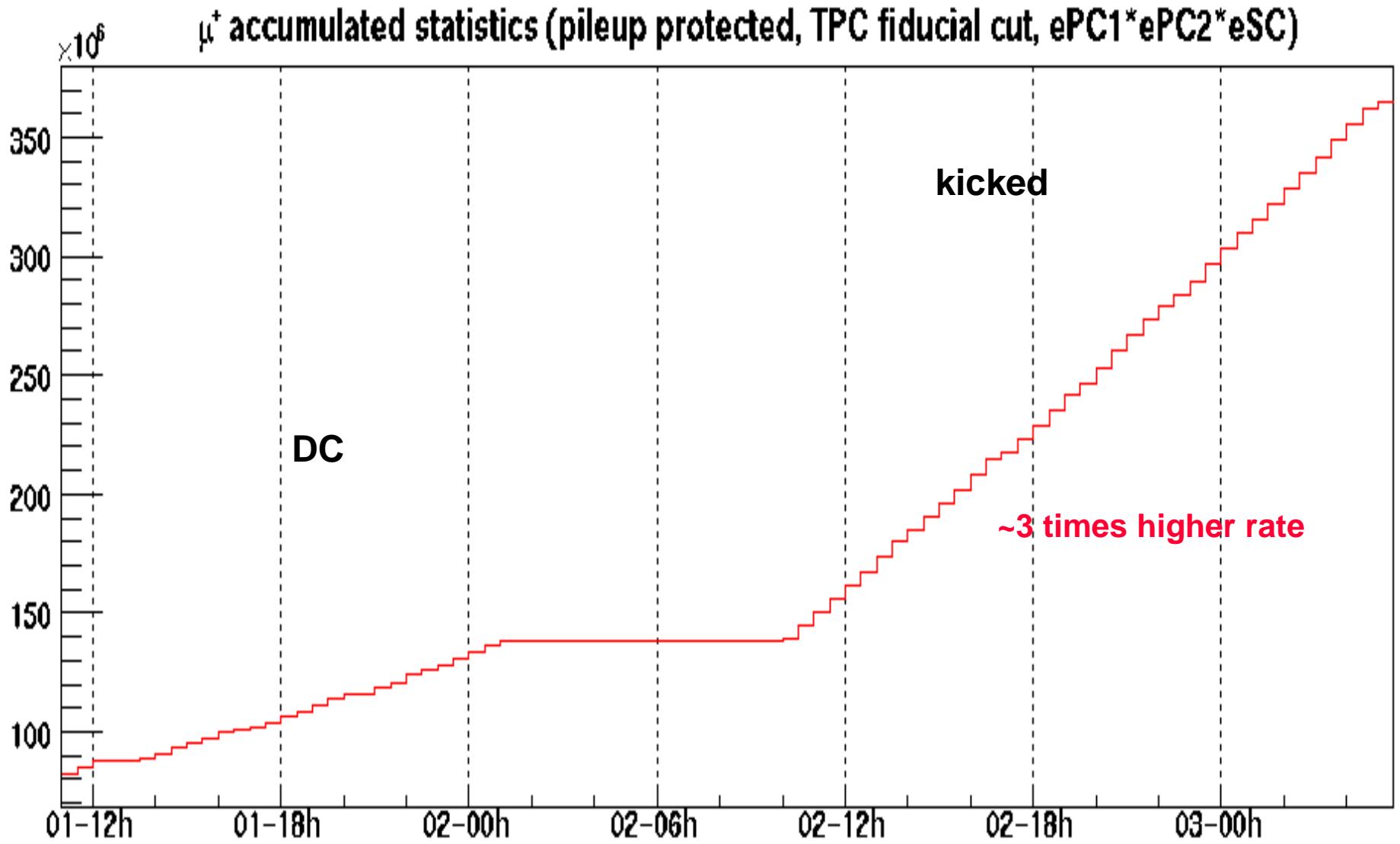
- Motivation and outlook



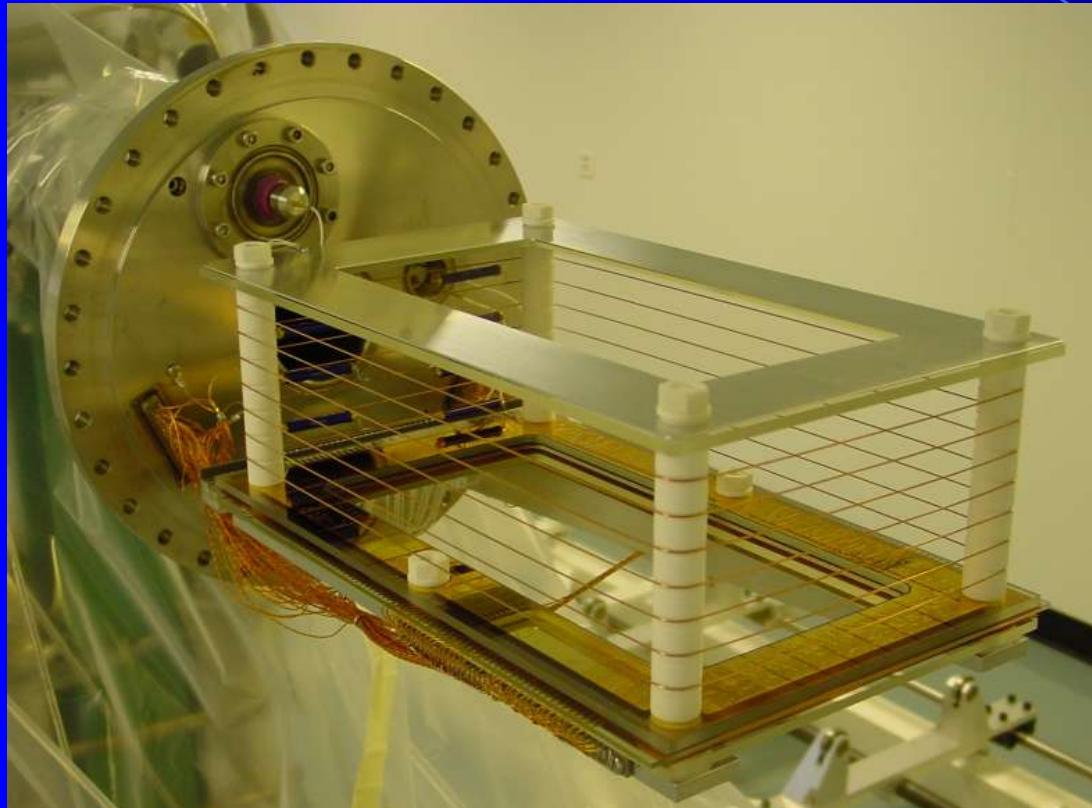
# One muon at a time



# One muon at a time



# TPC - the active target



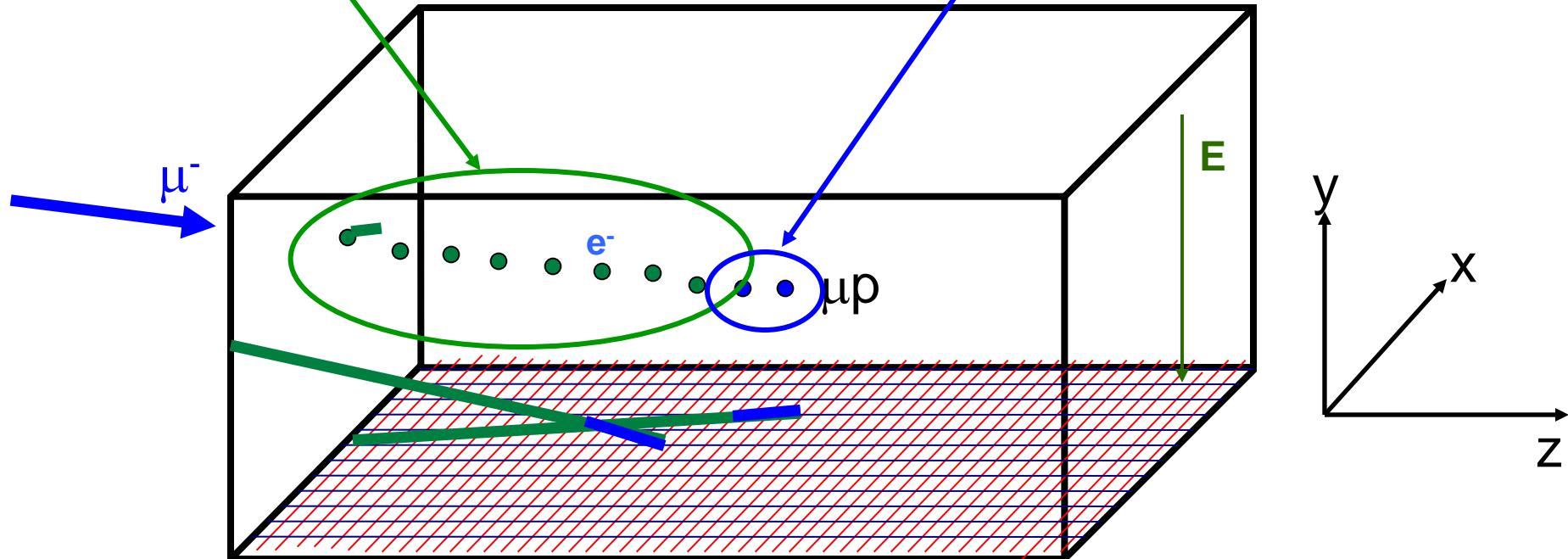
- 10 bar ultra-pure H<sub>2</sub>
- 2.0 kV/cm drift field
- ~ 5.4 kV on 3.5 mm anode half gap
- bakeable glass/ceramic materials

Operation with pure H<sub>2</sub> challenging, R&D @ PNPI, PSI

# TPC - the active target

$\mu^-$  entrance: lower energy loss

$\mu^-$  stop: Bragg peak



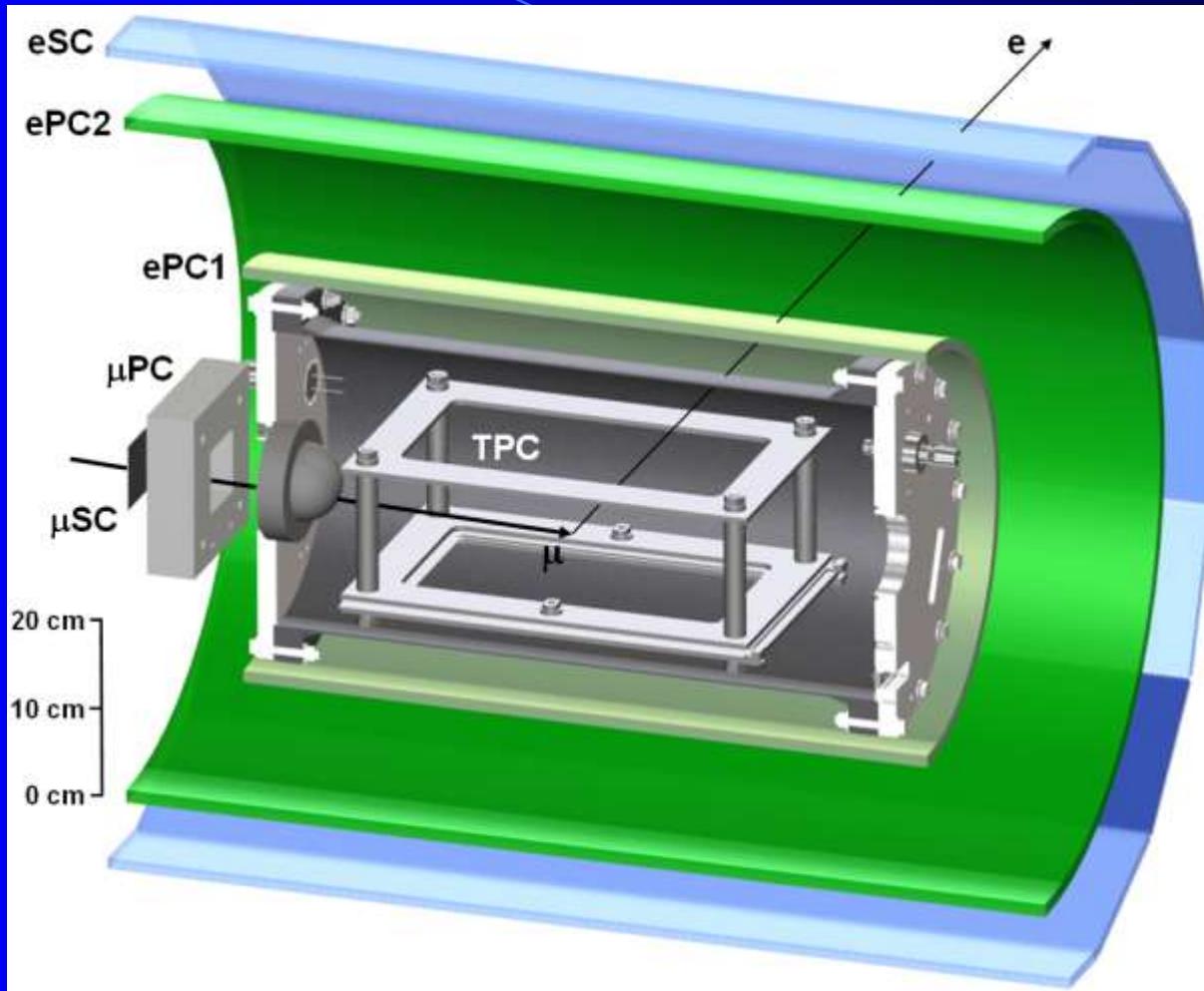
xz projection  
from **anodes**  
and **strips**

zy projection  
from **anodes**  
and **drift time**

xy projection  
from **strips**  
and **drift time**

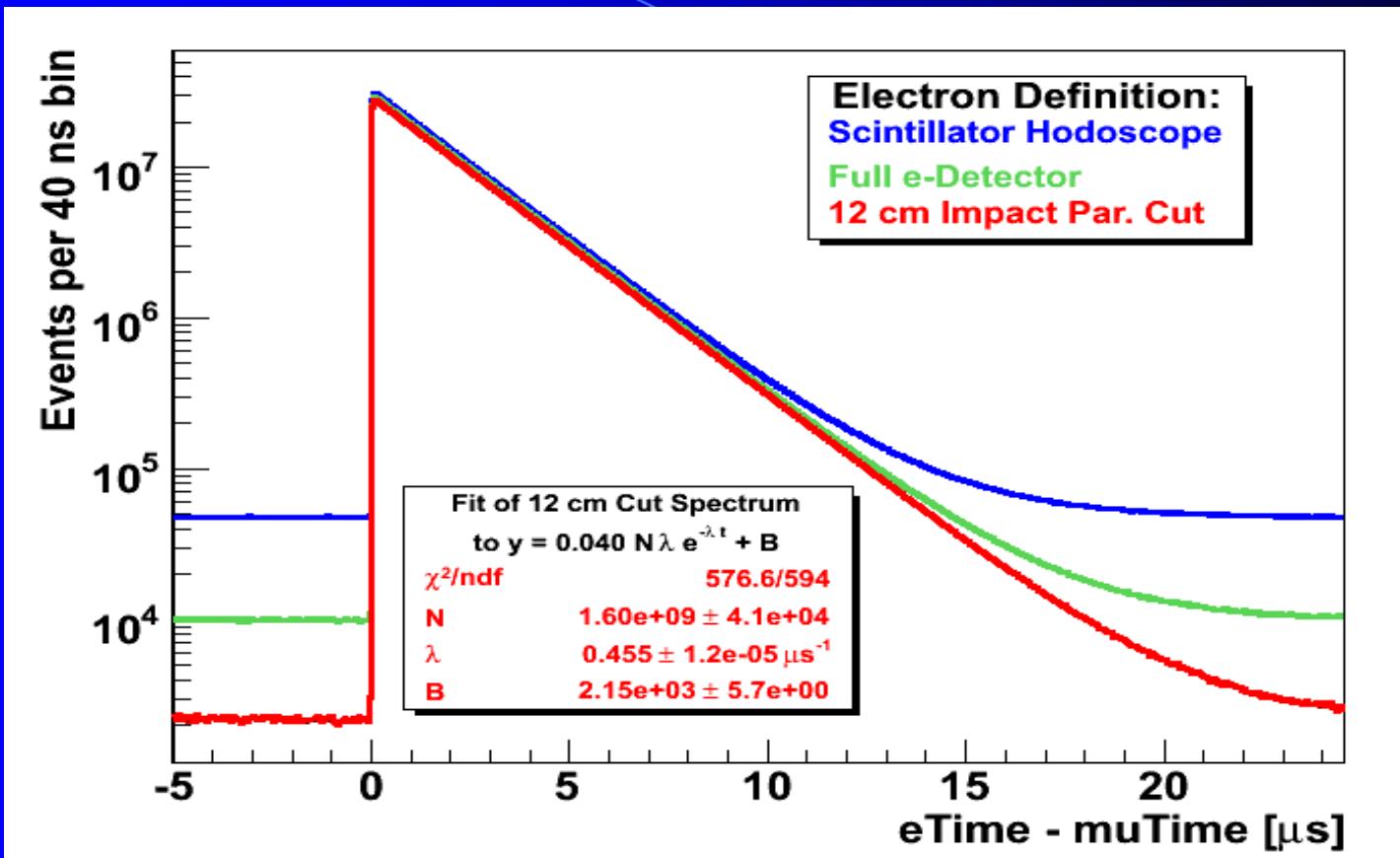
- 3d tracking without material in fiducial volume
- Clean muon stop definition away from high-Z

# Electron detectors

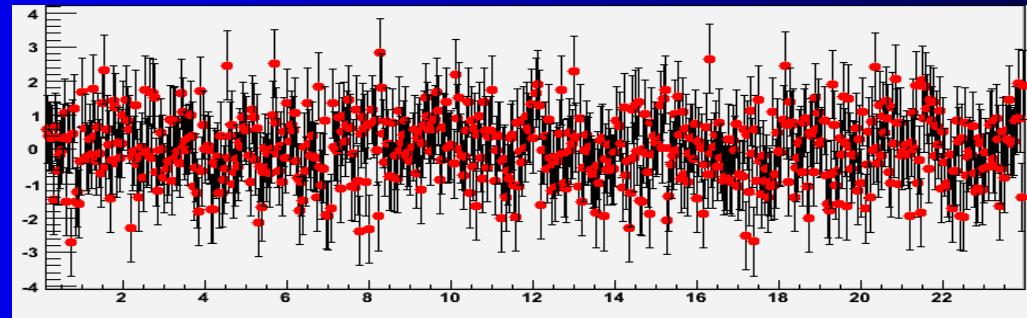


- Timing from scintillator (eSC)
- Full 3d tracking with wire chamber (ePC1 and ePC2)

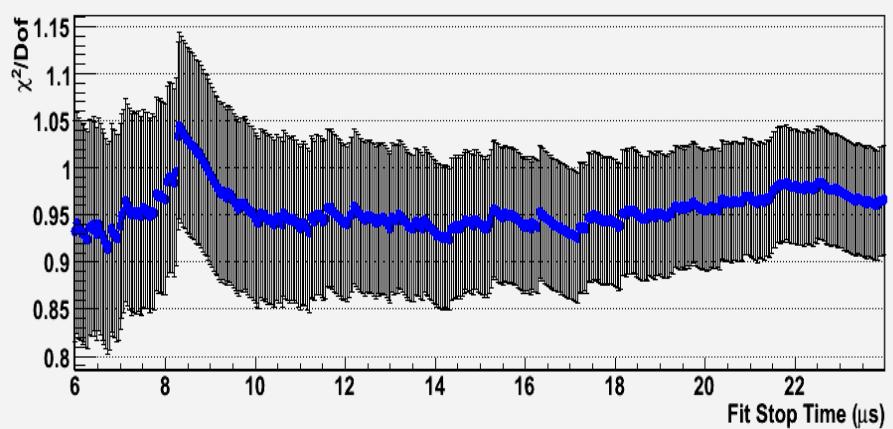
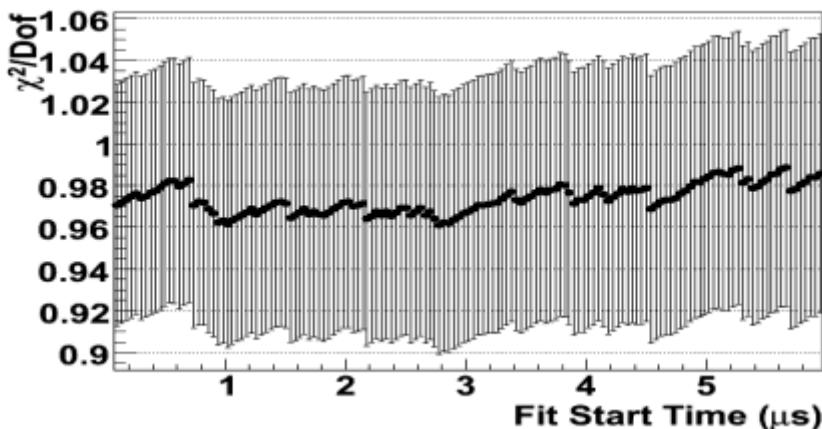
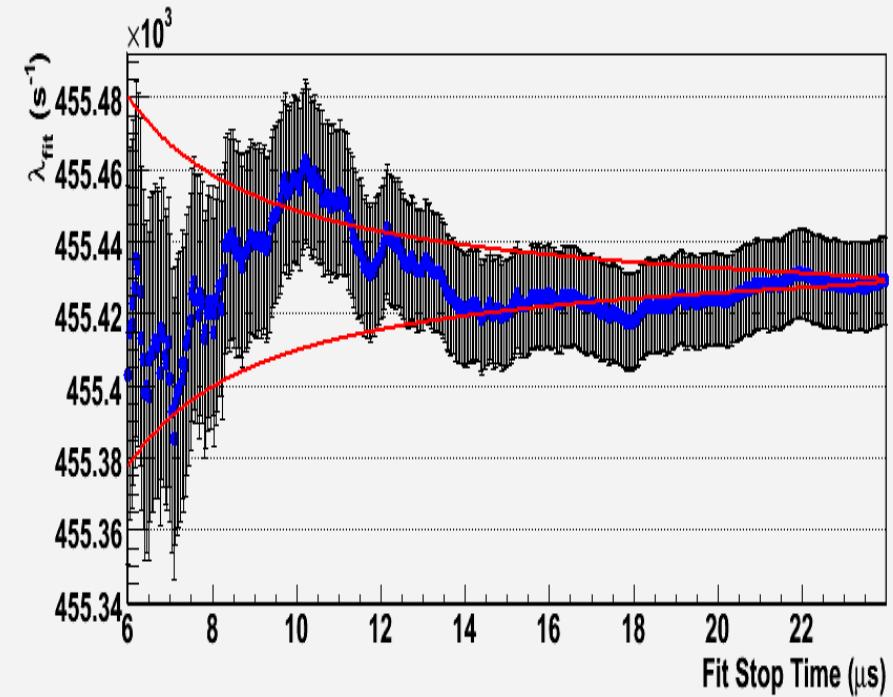
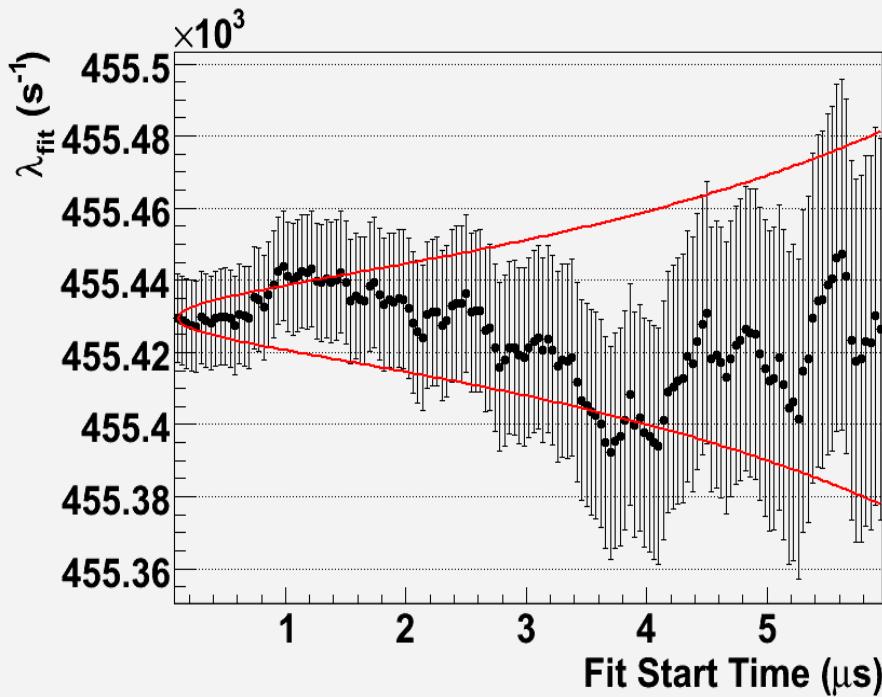
# Lifetime spectra



Normalized  
residuals

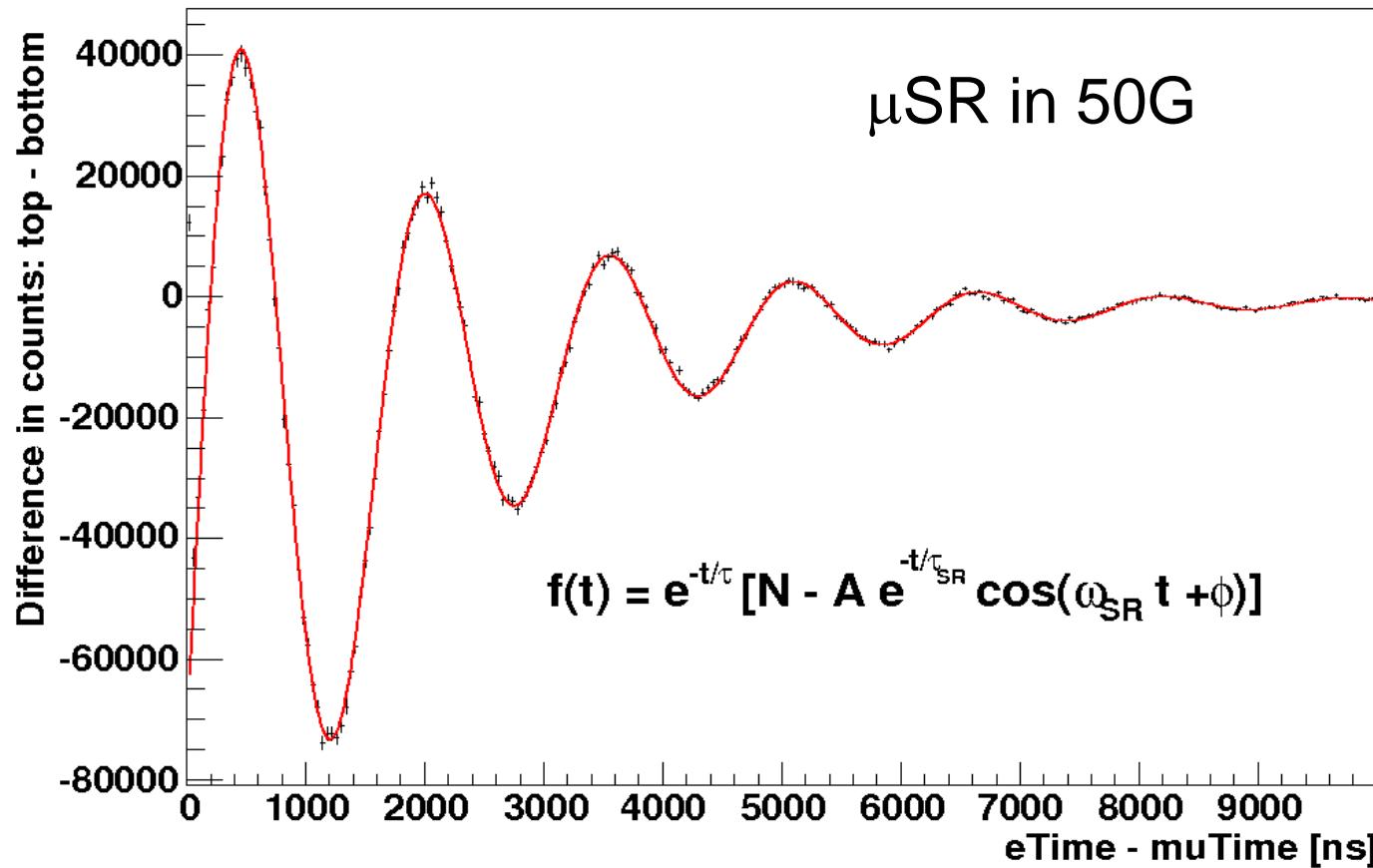


# Consistency checks



# $\mu^+$ as reference

Difference spectrum for top and bottom electron scintillators



- Measurement with  $\mu^+$  has identical detector systematics
- Cross check with world average  $\tau_+$ :  
~1ppm precision in the future (MuLan and FAST @ PSI)

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- Systematics and results

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- Motivation and outlook

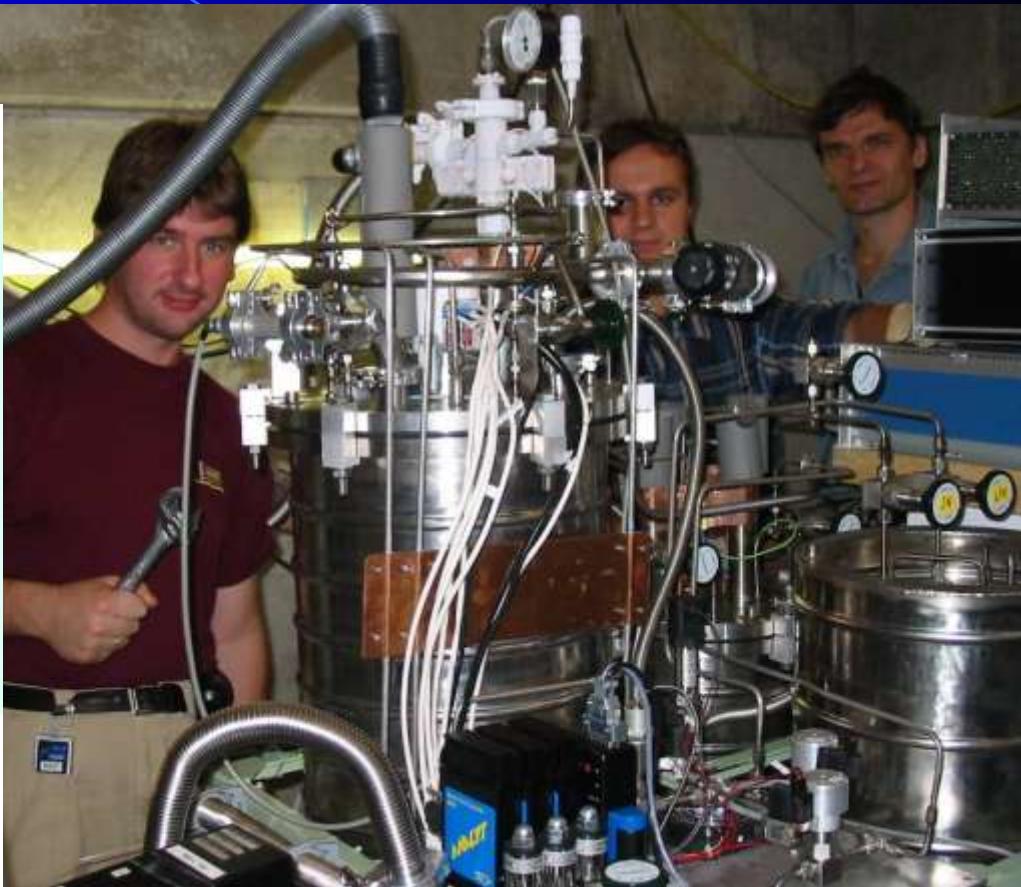
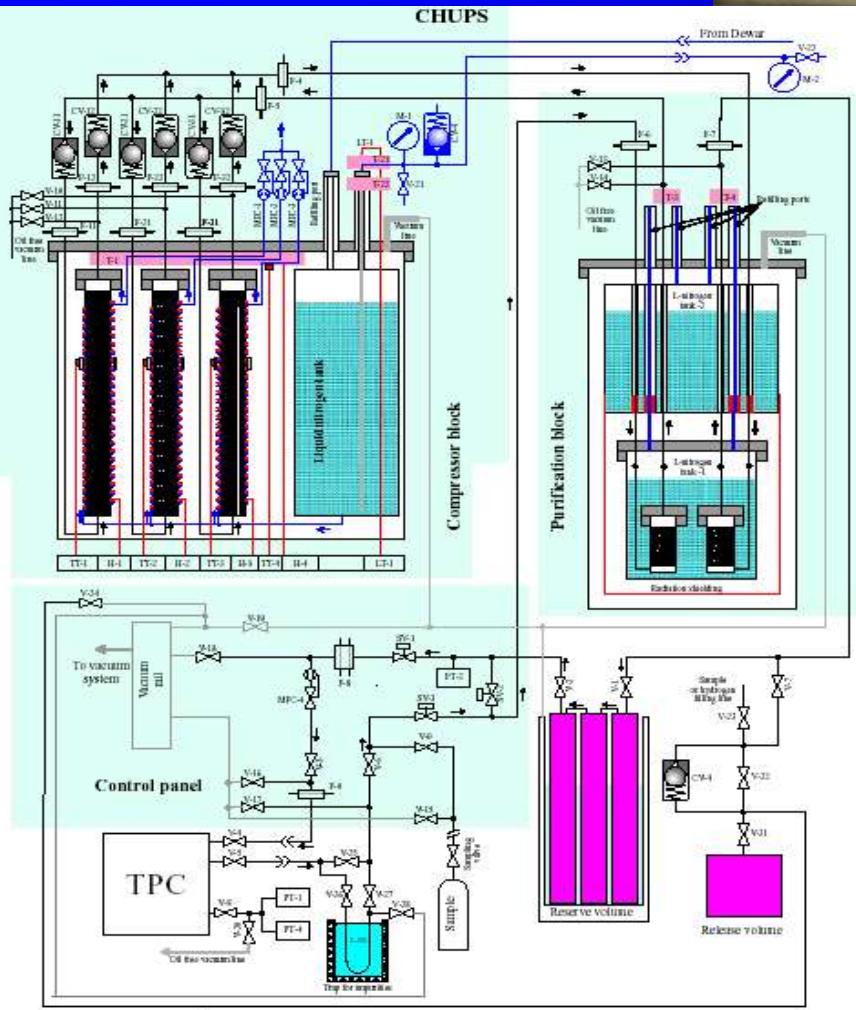
# Internal corrections to $\lambda_-$

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

(statistical uncertainty of  $\lambda_-$ : 13.7  $s^{-1}$ )

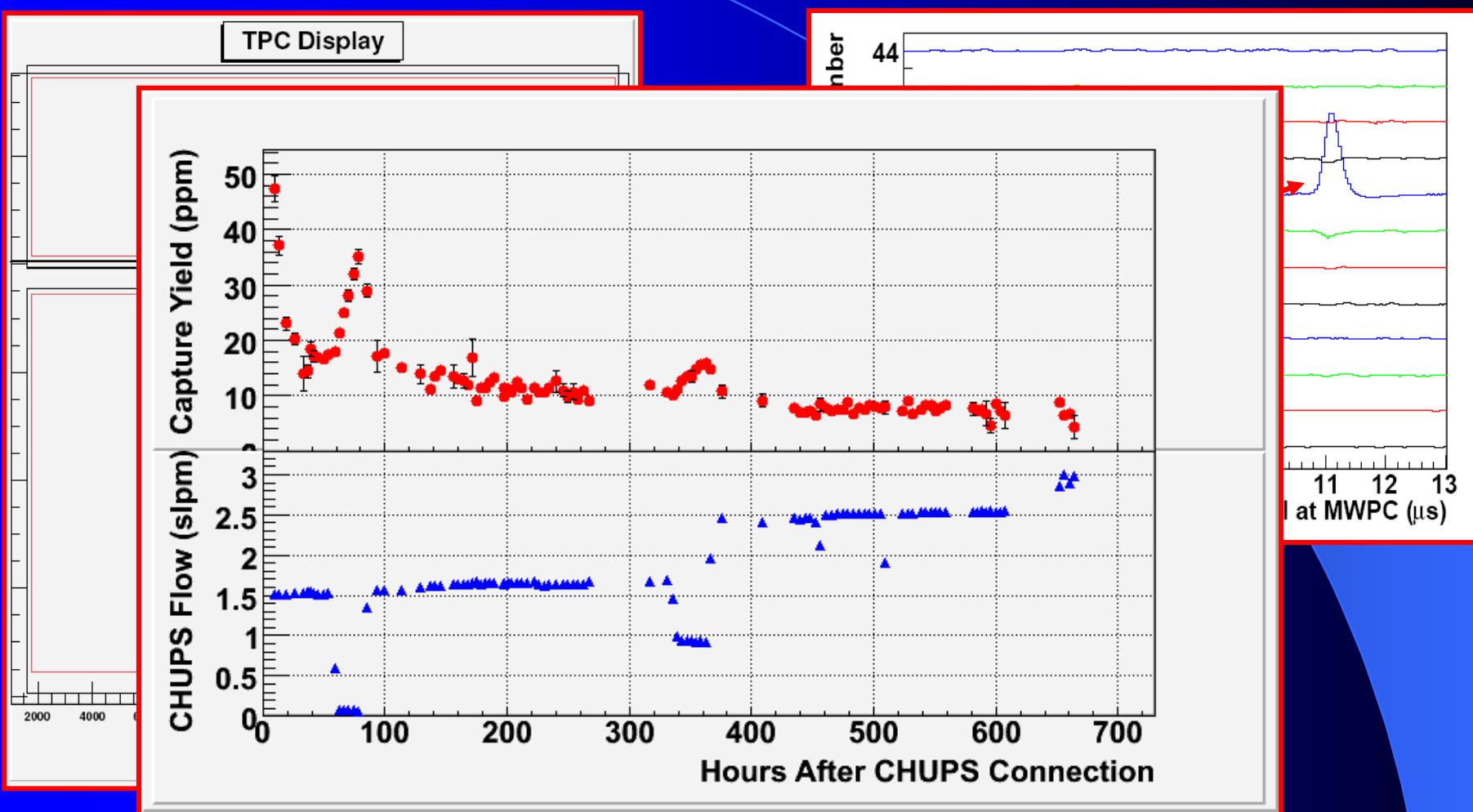
# CHUPS

# Continuous H<sub>2</sub> Ultra-Purification System



$c_{N_2}, c_{O_2} < 10 \text{ ppb}$

# Impurity monitoring



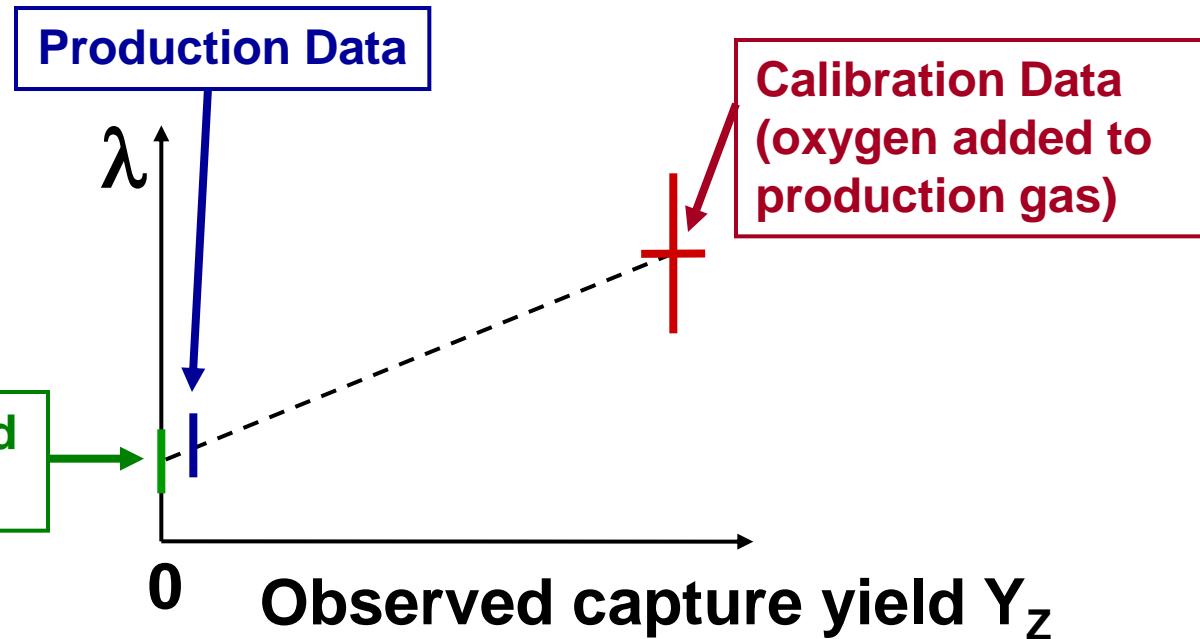
2004 run:

$c_N, c_O < 7 \text{ ppb}$ ,  $c_{H_2O} \sim 30 \text{ ppb}$

2006/2007 runs:

$c_N, c_O < 7 \text{ ppb}$ ,  $c_{H_2O} \sim 10 \text{ ppb}$

# Final high-Z impurity correction



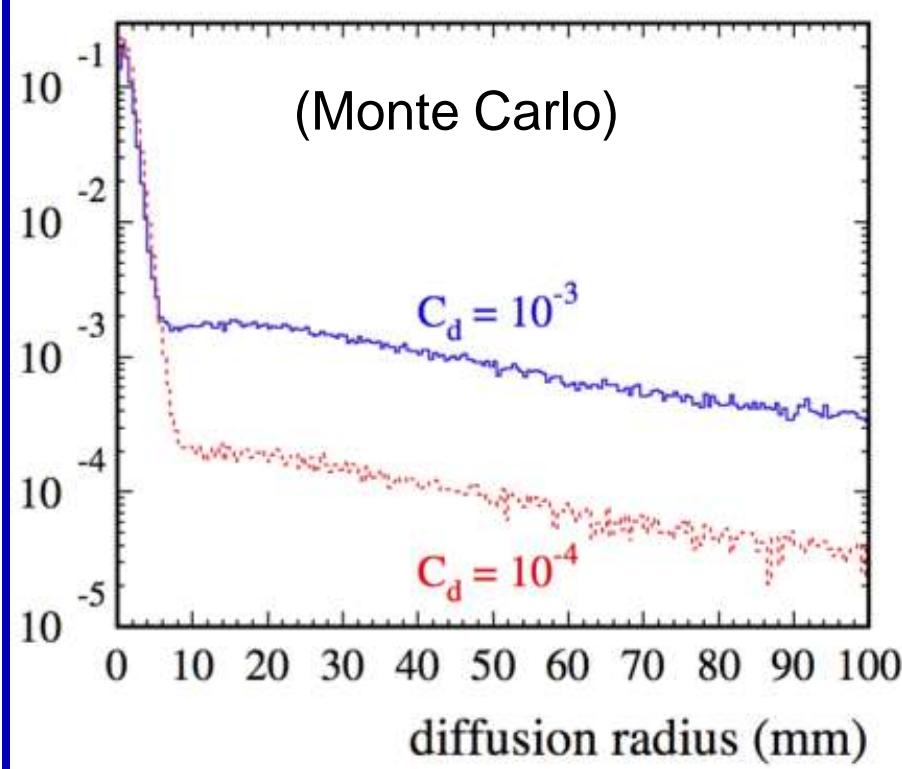
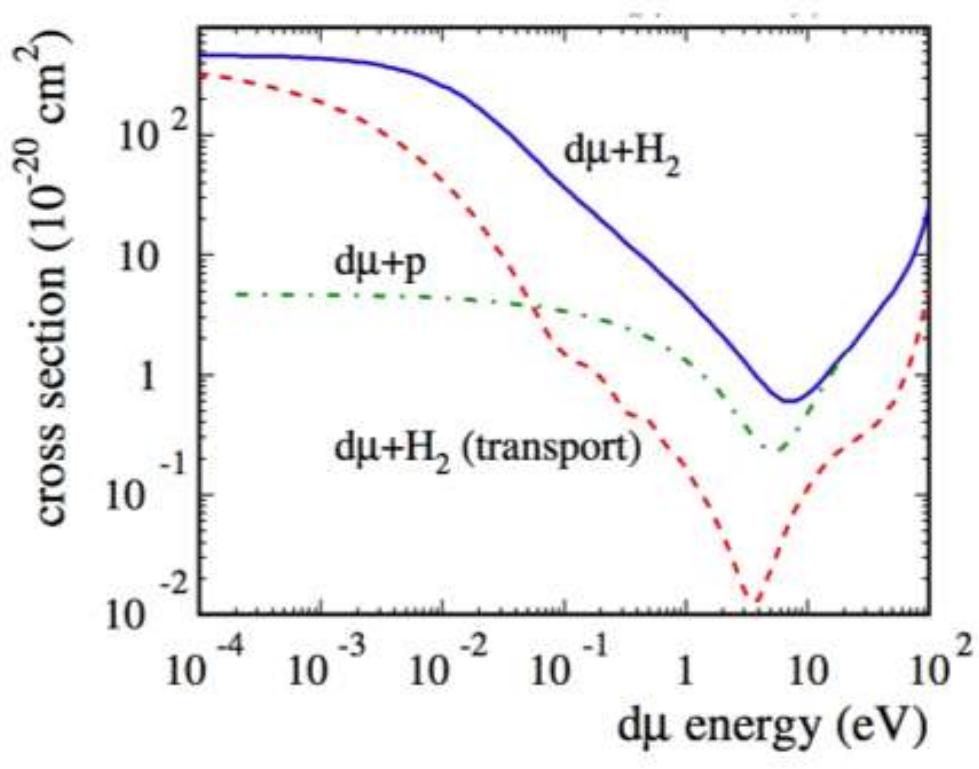
Lifetime deviation is linear with the  $Z>1$  capture yield.

# Internal corrections to $\lambda_-$

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Unseen $\mu + p$ scatters ( $\Delta\lambda_{sc}$ )	0.0	3.0
$\mu$ stop definition ( $\Delta\lambda_{tr}$ )	0.0	2.0
$\mu$ pileup veto inefficiency ( $\Delta\lambda_\kappa$ )	0.0	3.0
Analysis methods ( $\Delta\lambda_{Ana}$ )	0.0	5.0
Total	-32.6	$\pm 8.4$

(statistical uncertainty of  $\lambda_-$ : 13.7  $s^{-1}$ )

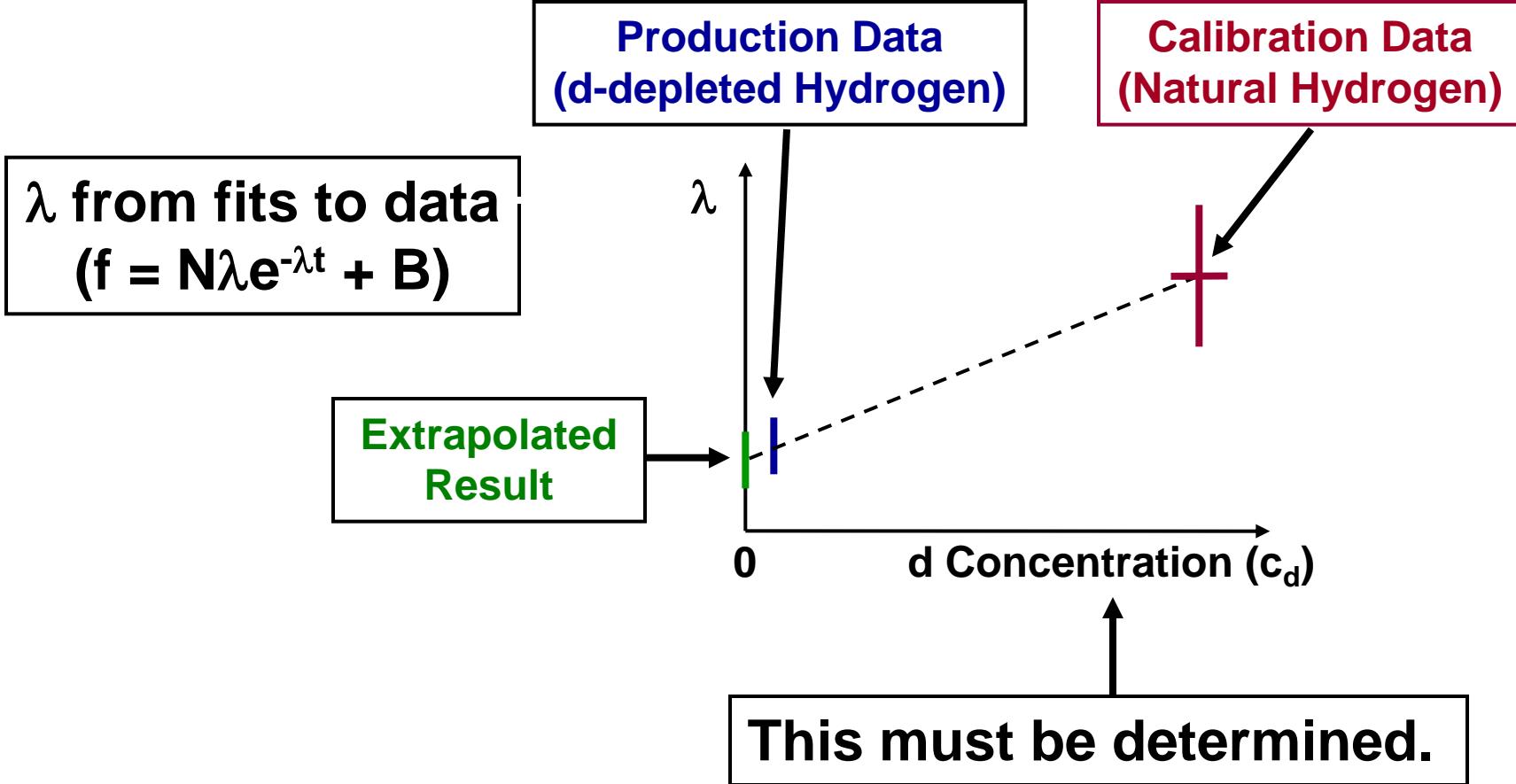
# $\mu d$ diffusion



- Ramsauer-Townsend minimum in the scattering cross section
- $\mu d$  can diffuse  $\sim 10$  cm before muon decay, possibly into walls

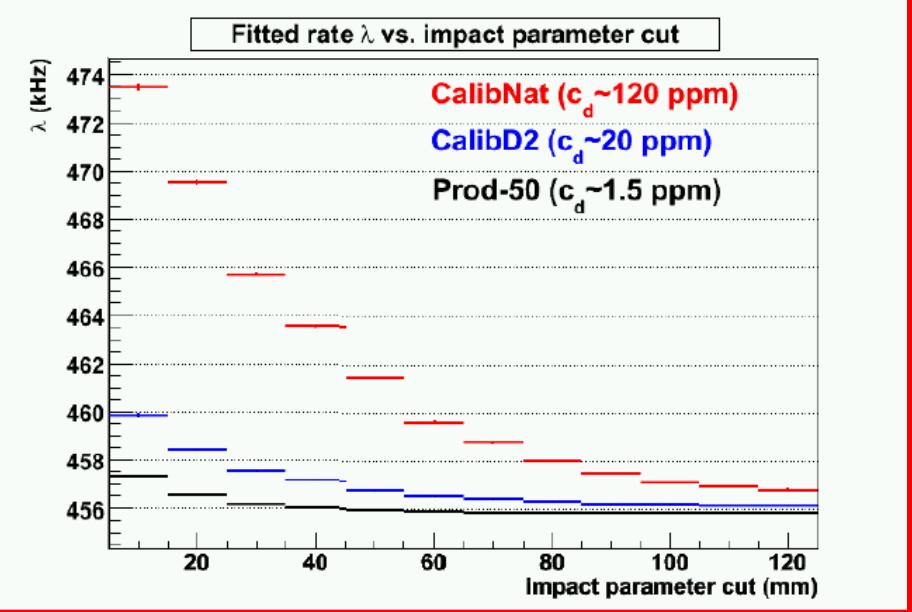
# Deuterium correction

Again zero extrapolation procedure



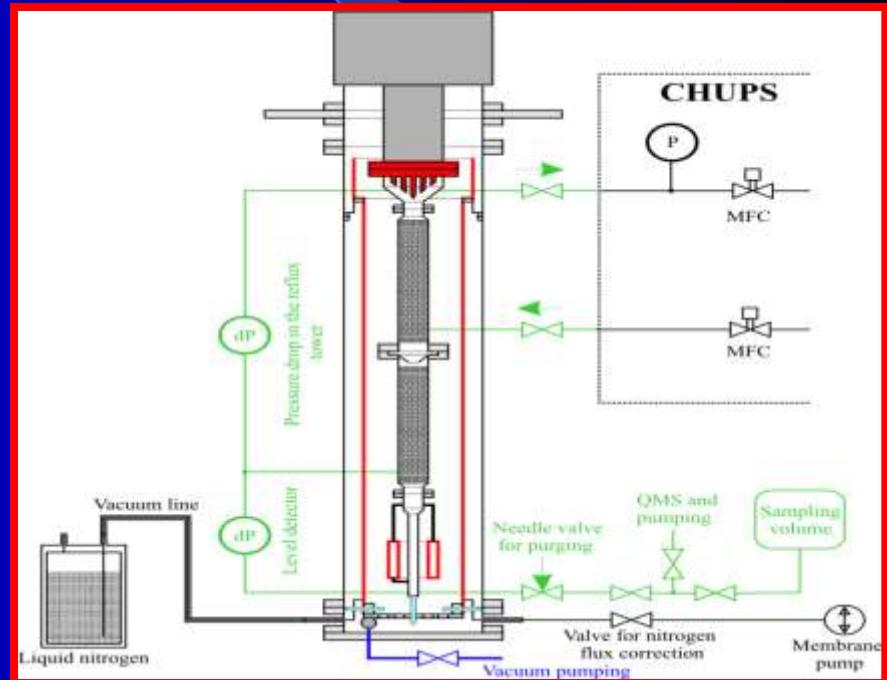
# $\mu$ d: MuCap's unique capability

- Data:  $\lambda$  versus impact parameter cut



$$\underline{c_d = 1.49 \pm 0.12 \text{ ppm}}$$

On site purification since 2006



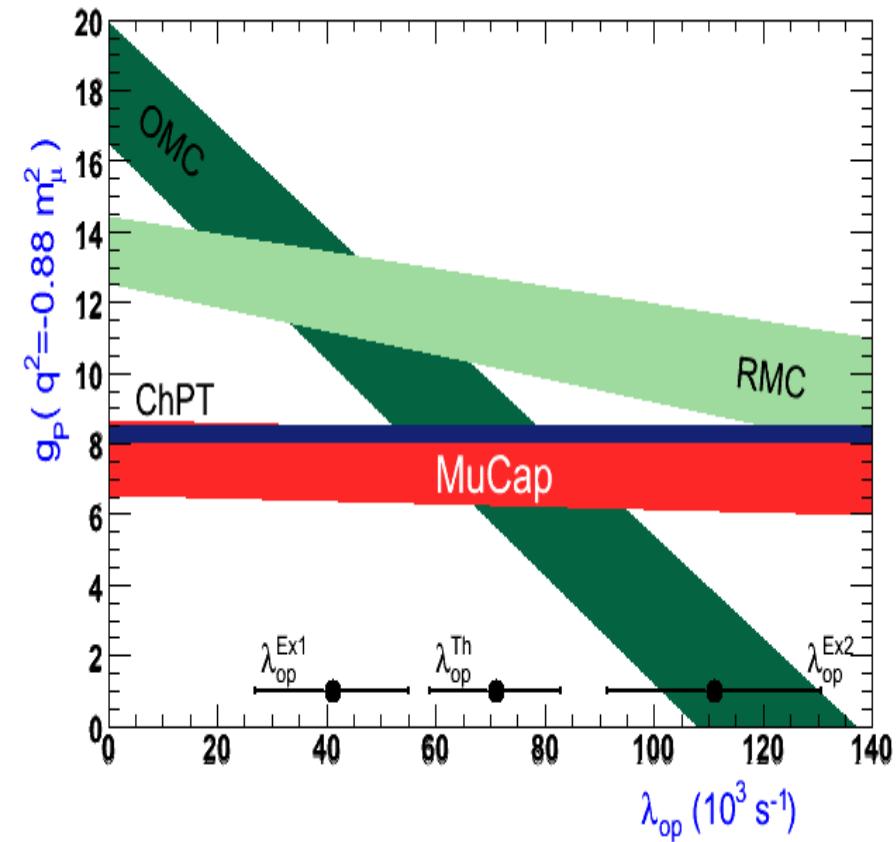
- AMS, ETH Zurich

$$\underline{c_d = 1.44 \pm 0.15 \text{ ppm}}$$

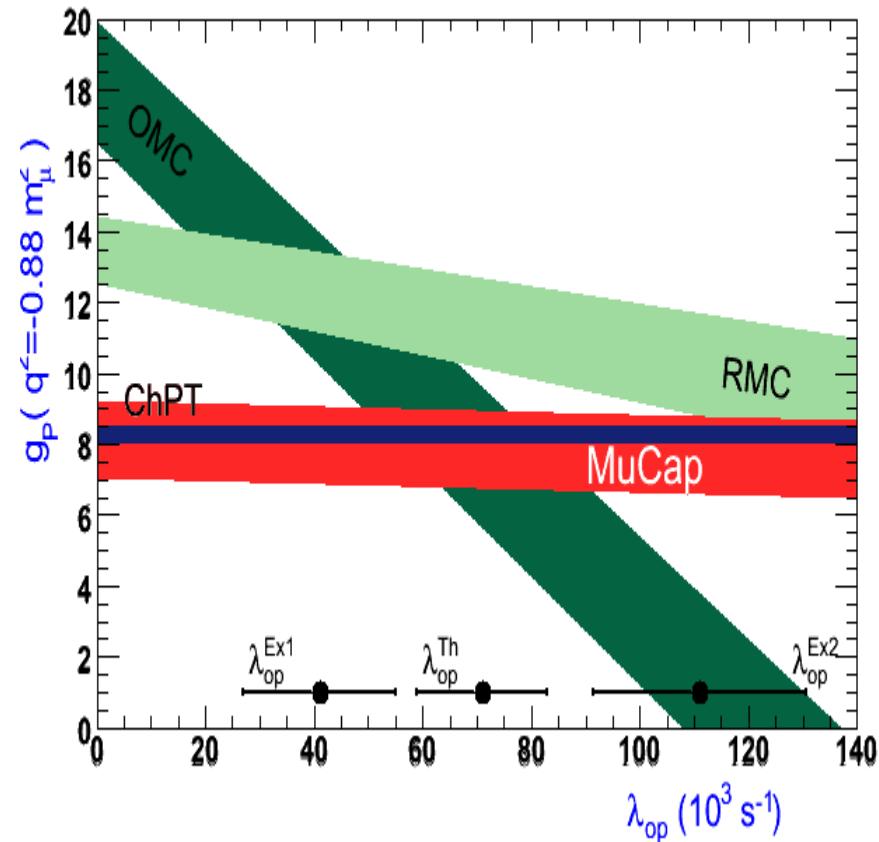
World Record:  $c_d < 100 \text{ ppb}$

# Precise and unambiguous MuCap result

Using previous  $\tau_\mu$  world average



Using new MuCap  $\tau_\mu$  average



Mon Mar 1 14:59:22 2010

Sat 9 13:38:01 2010

V.A. Andreev et al., Phys. Rev. Lett. 99, 03202 (2007)

# Outline

## Muon Lifetime Analysis (MuLan)

- Motivation
- MuLan experiment
- Main systematics and result

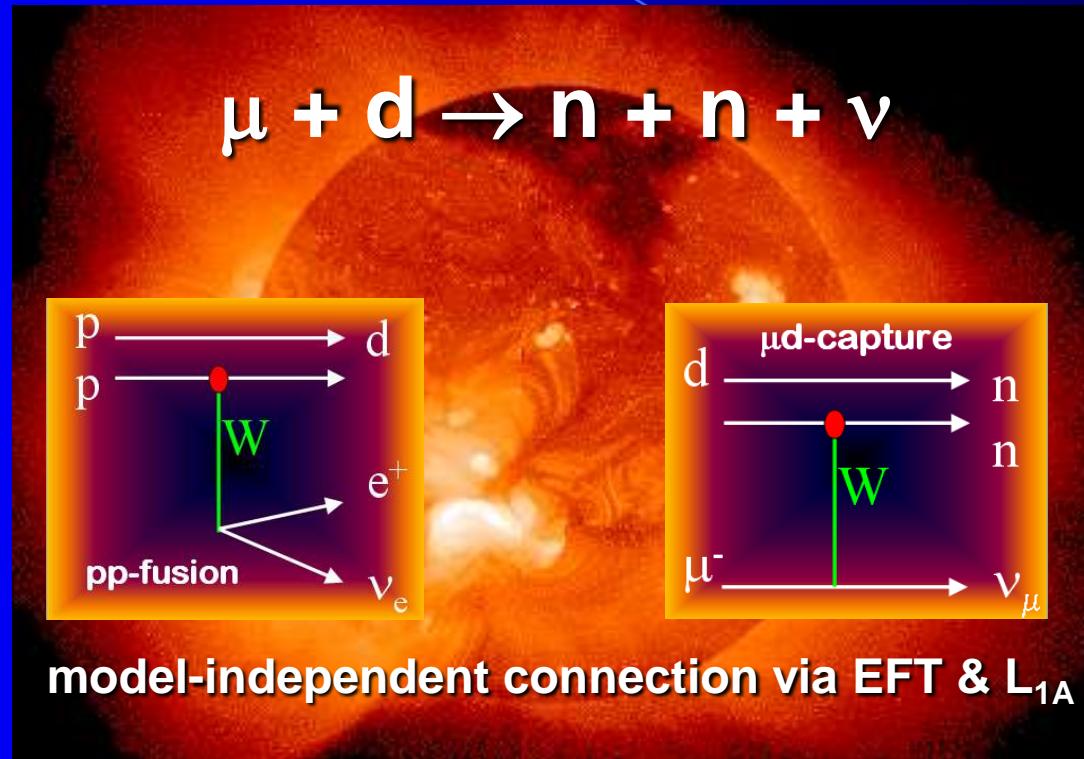
## Muon capture on the proton (MuCap)

- Motivation and general overview
- MuCap experiment
- Systematics and results

## Muon capture on the deuteron (MuSun)

- Motivation and outlook

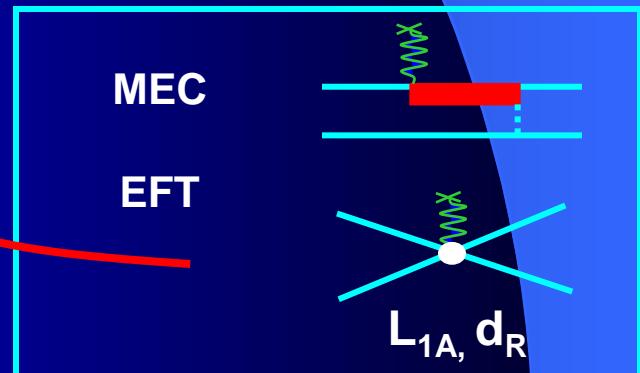
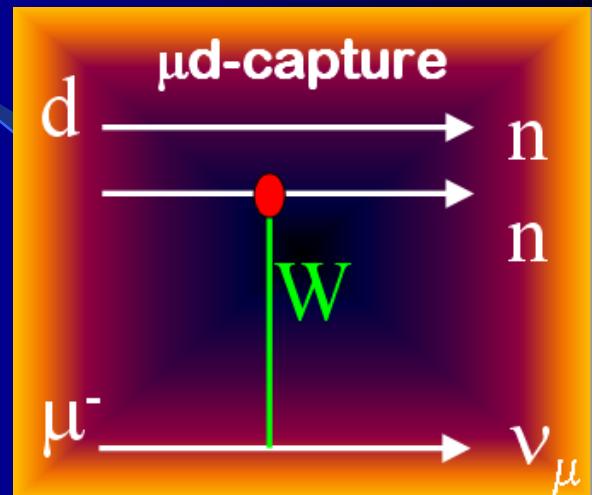
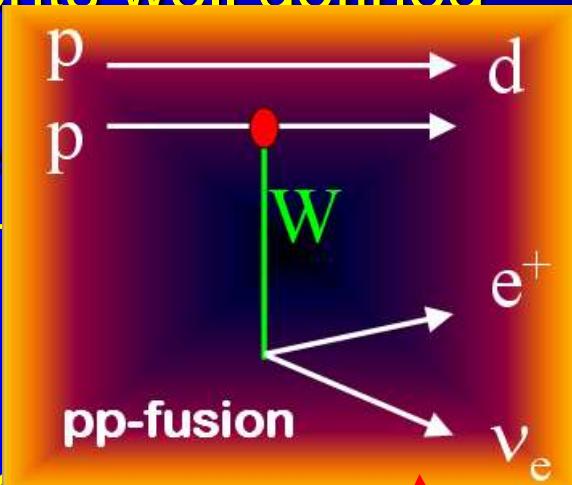
# MuSun: "Calibrating" the sun



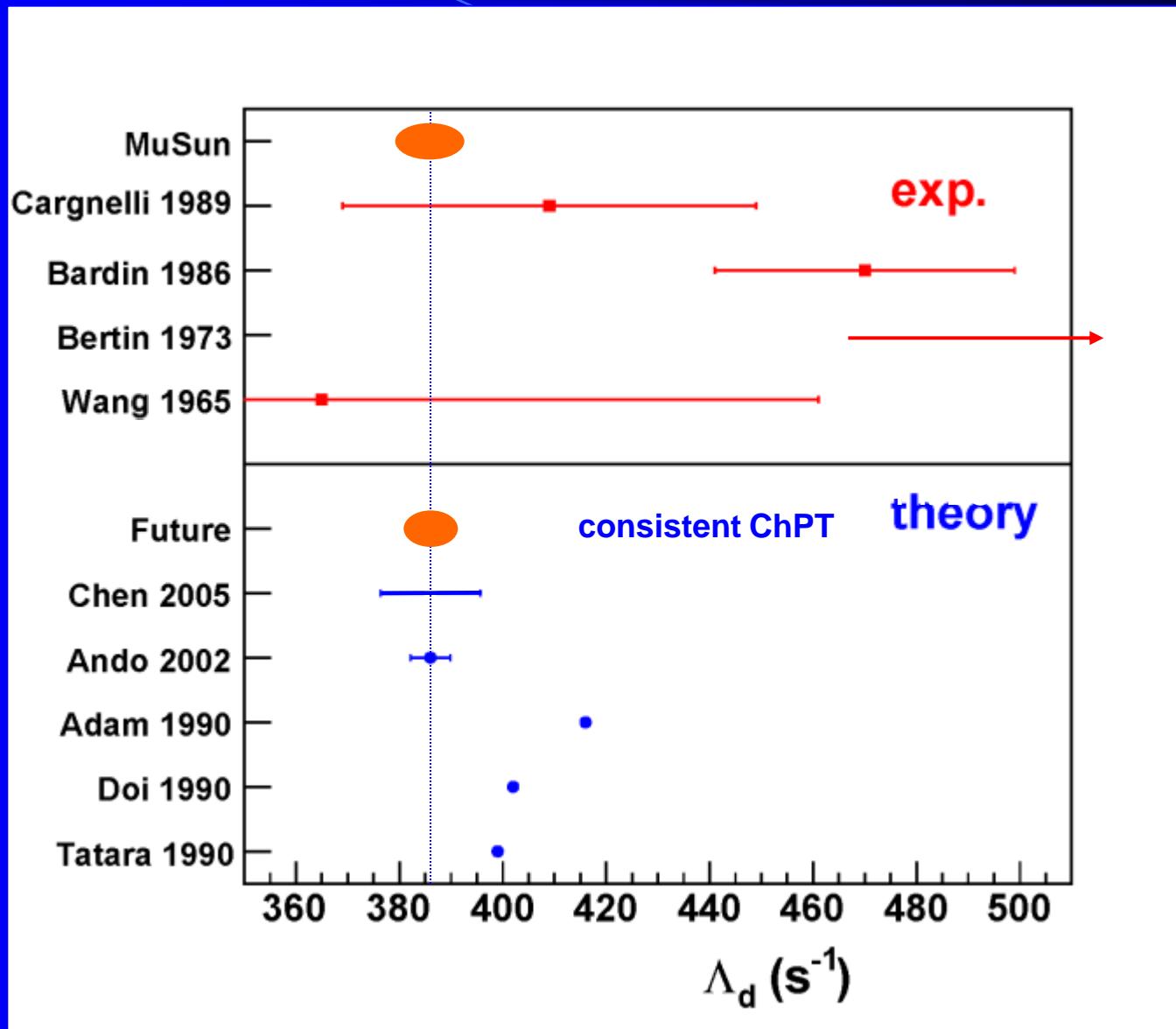
Aim: Measure rate  $\Lambda_d$  from  $\mu d(\uparrow\downarrow)$  to < 1.5 %

# Theory

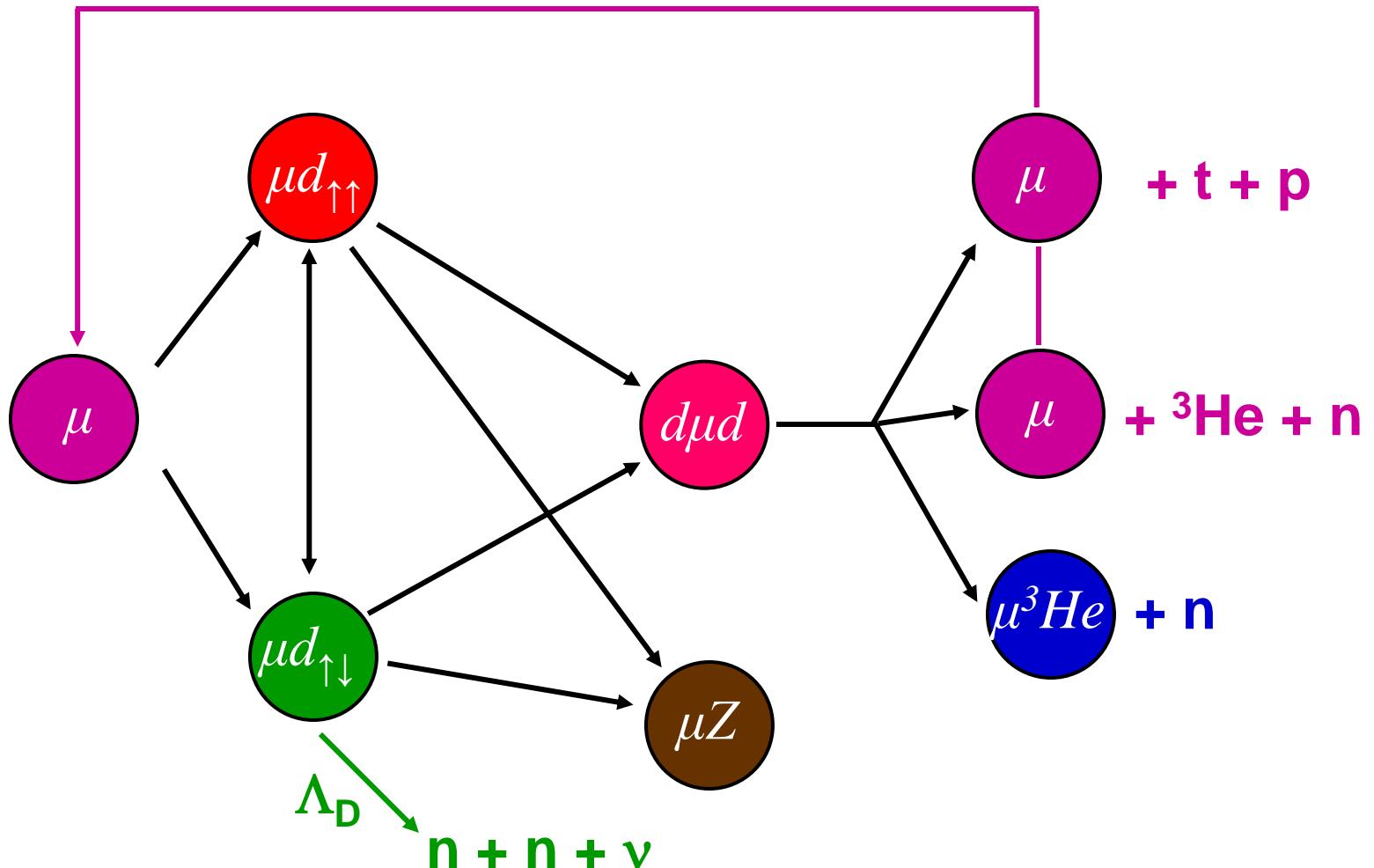
- One body currents well defined
- Two body currents constrained by
- Methods:  
Potential model + MEC  
 $\pi$ -less or hybrid EFT ( $L_{1A} / d_R$ )
- Muon capture soft enough to relate to solar reactions



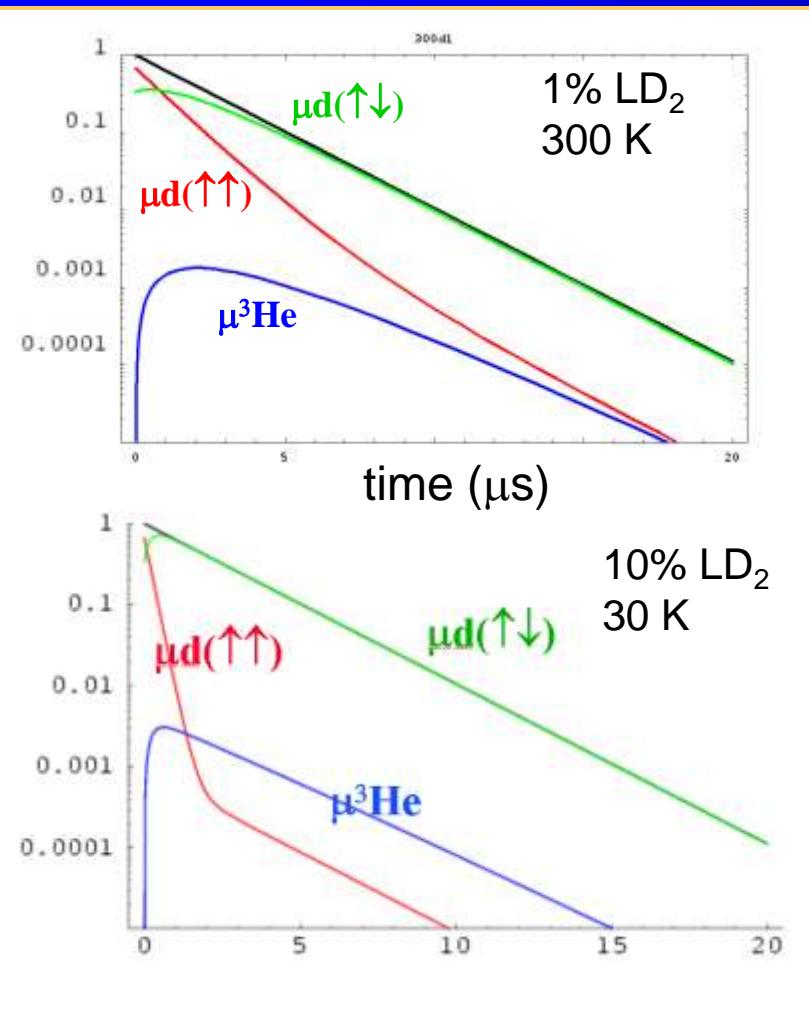
# Precise experiment needed



# $\mu d$ kinetics



# Approved proposal by PSI



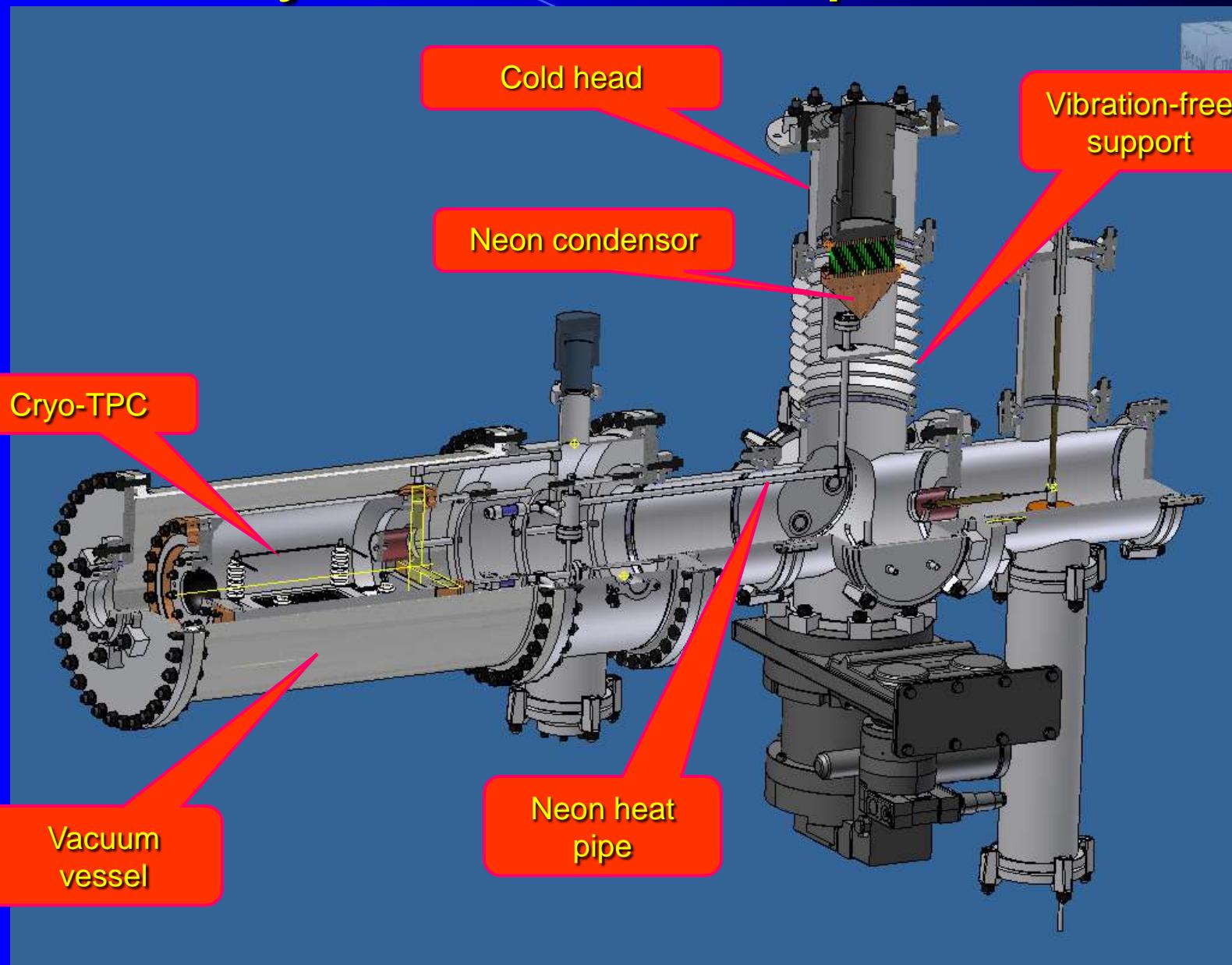
## Stage 1:

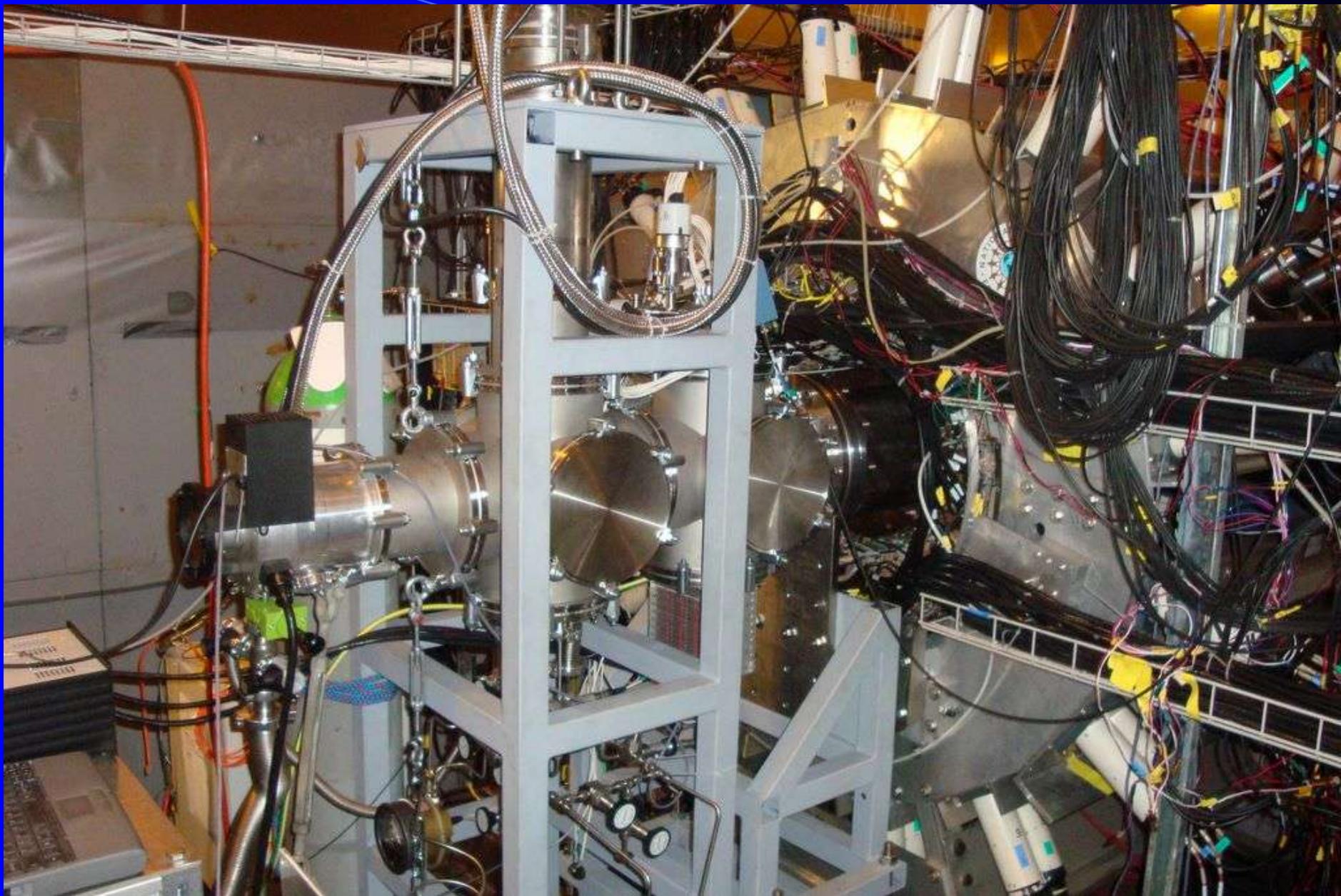
- MuCap setup with 1% LD<sub>2</sub> and 300 K
- Prove excellent energy resol.
- Understand fusion and impurity events
- Measure nitrogen transfer rate
- Run finished end of 2008

## Stage 2:

- Measure  $\Lambda_D$  at >5% LD<sub>2</sub> and 30 K
- Cryo TPC development

# Cryo-TPC development

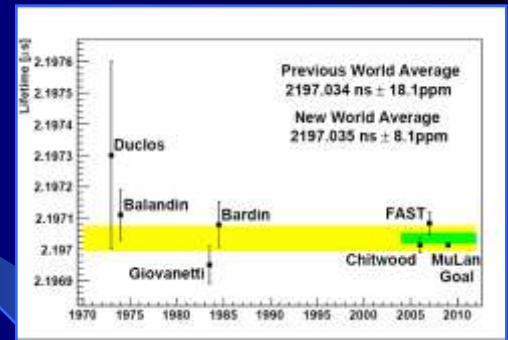




# Overall summary

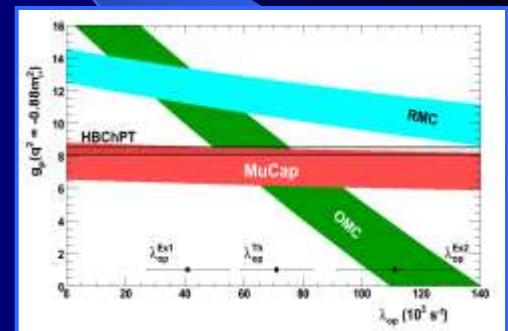
- MuLan:

- Factor ~25 improvement on  $G_F$  is final



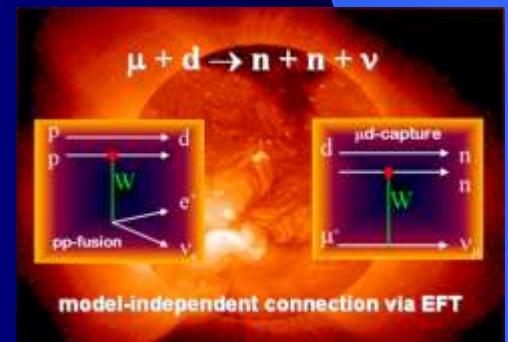
- MuCap:

- First precise  $g_P$  with clear interpretation
  - Consistent with ChPT expectation, clarifies long-standing puzzle
  - Factor 3 additional improvement on the way (unblinding in first half of 2011)



- MuSun

- Muon-deuteron capture with 10x higher precision
  - Calibrates basic astrophysics reactions and provides new benchmark in axial 2N reactions



Parts of the MuLan collaboration



Parts of the MuCap collaboration



- *Petersburg Nuclear Physics Institute, Gatchina, Russia*
- *Paul Scherrer Institute, CH*
- *University of California, Berkeley, USA*
- *University of Illinois at Urbana-Champaign, USA*
- *Université Catholique de Louvain, Belgium*
- *University of Kentucky, Lexington, USA*
- *Boston University, USA*
- *James Madison University, USA*
- *Regis University, Colorado, USA*