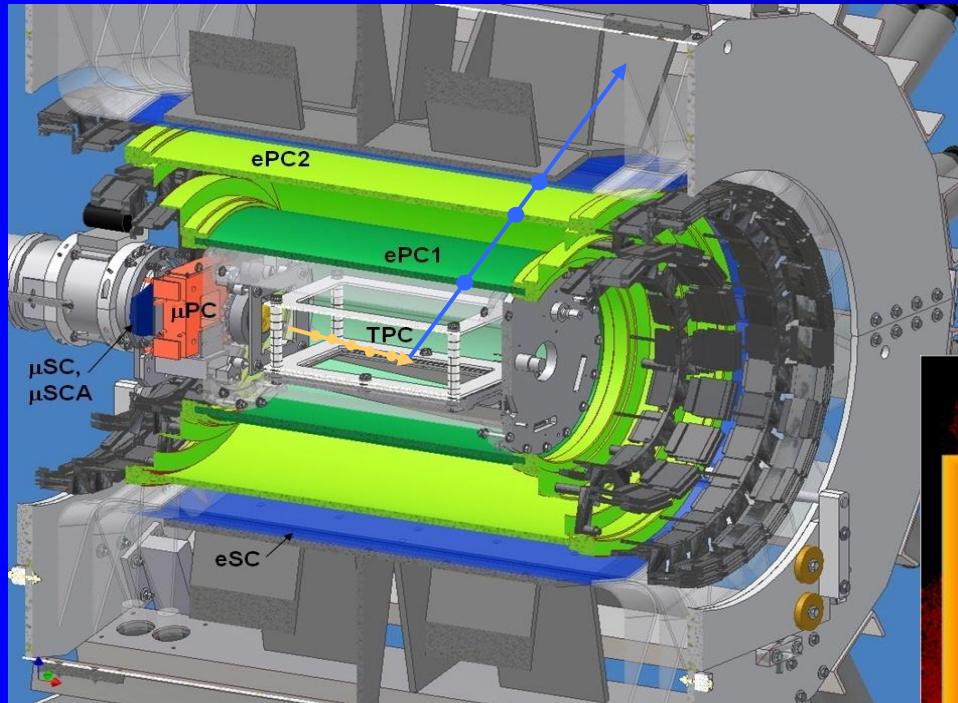


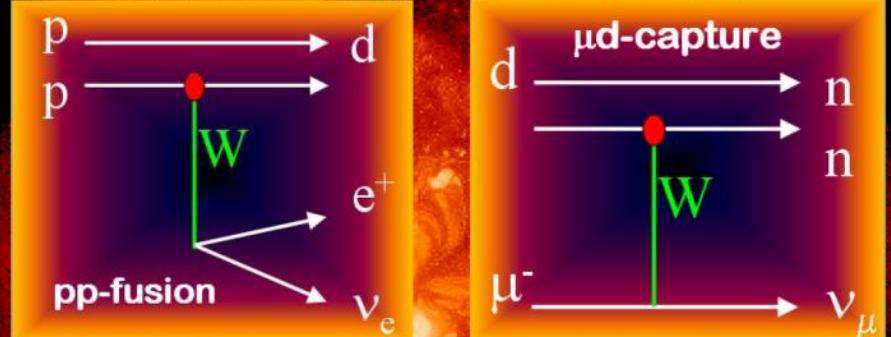
Muon capture @ PSI



g_P

Peter Winter

University of Washington



model-independent connection via EFT

L_{1A} / d_R

Outline

$\mu^- p$

Muon capture on the proton (MuCap)

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

$\mu^- d$

Muon capture on the deuteron (MuSun)

- Motivation and general overview
- Current status

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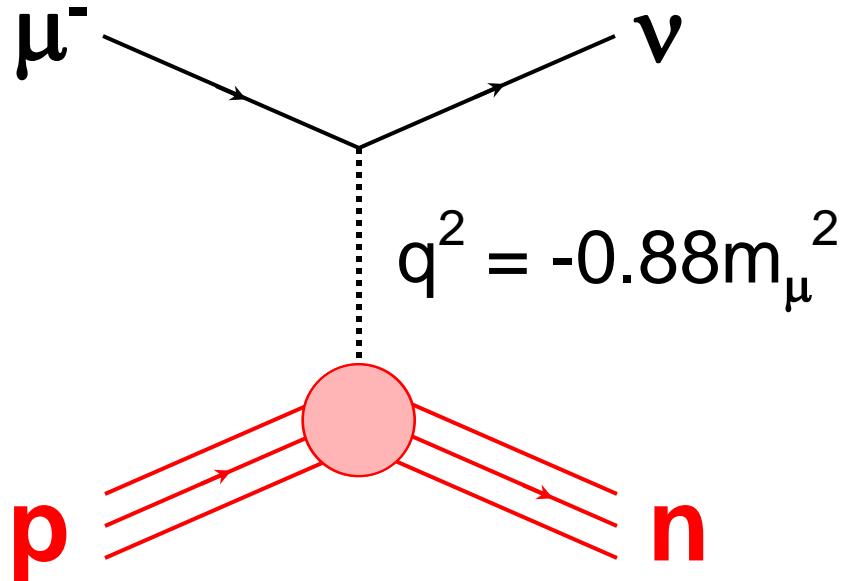
$\mu^- d$

Muon capture on the deuteron (MuSun)

- Motivation and general overview
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Nucleon form factors

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



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

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

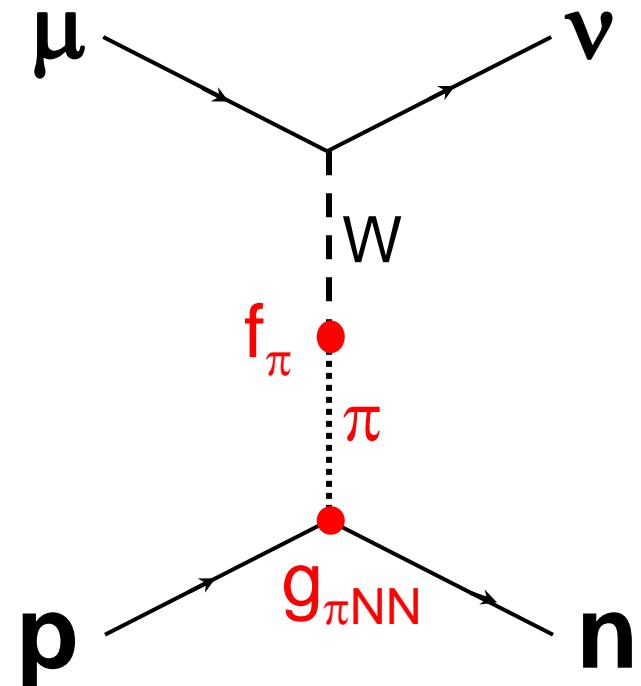
$g_A(q^2)$ measured in neutron decay

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:

- β decay: Not sensitive since g_P term $\sim q$
- ν 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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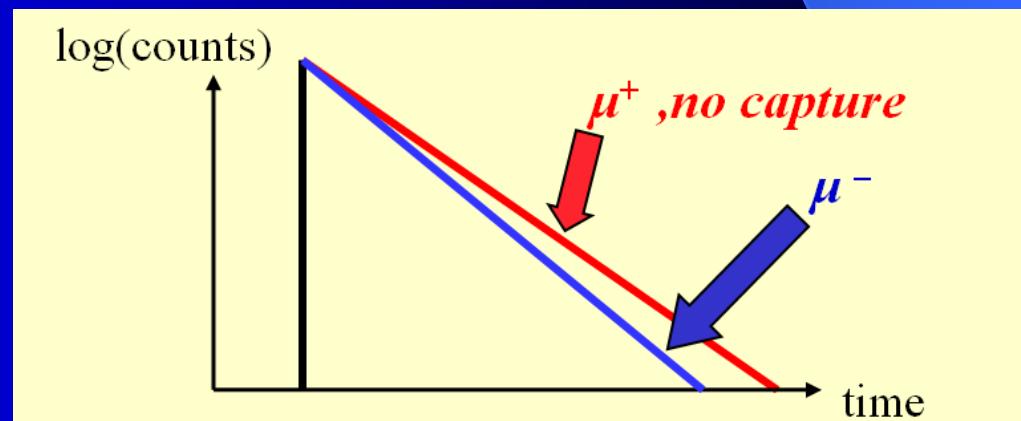
OMC: Methods to measure

Neutron experiments:

- Measure outgoing neutrons N_N
- Requires knowledge of neutron efficiency
- Separation of decay γ 's from neutrons
- Typical experiments 8-13% precision in Λ_S

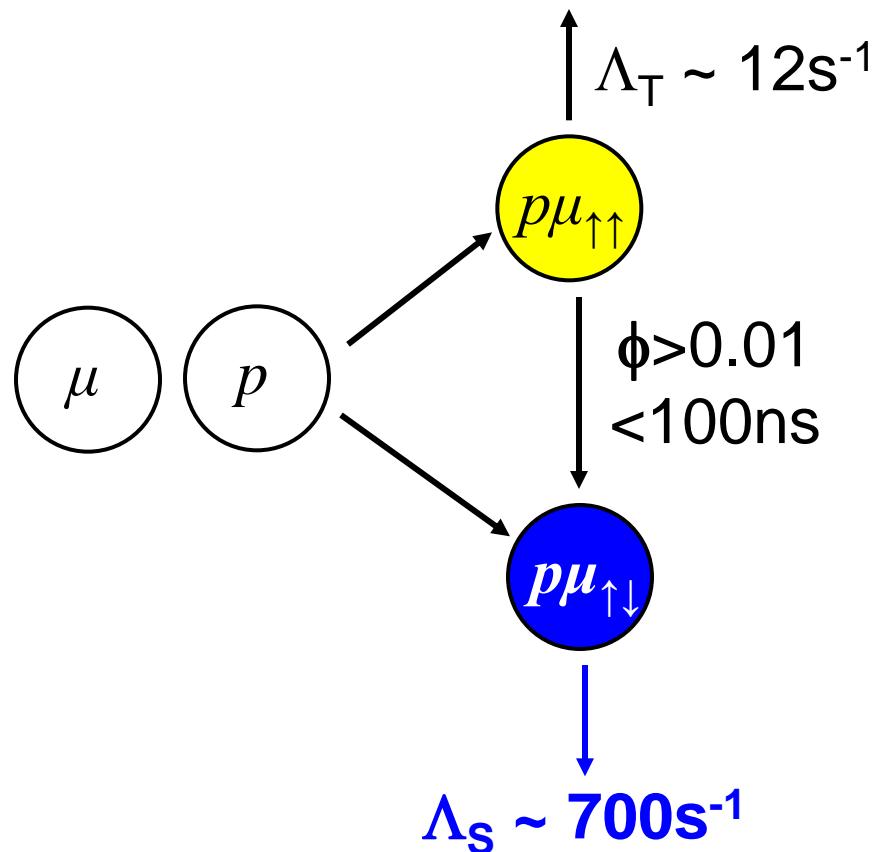
Lifetime method:

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

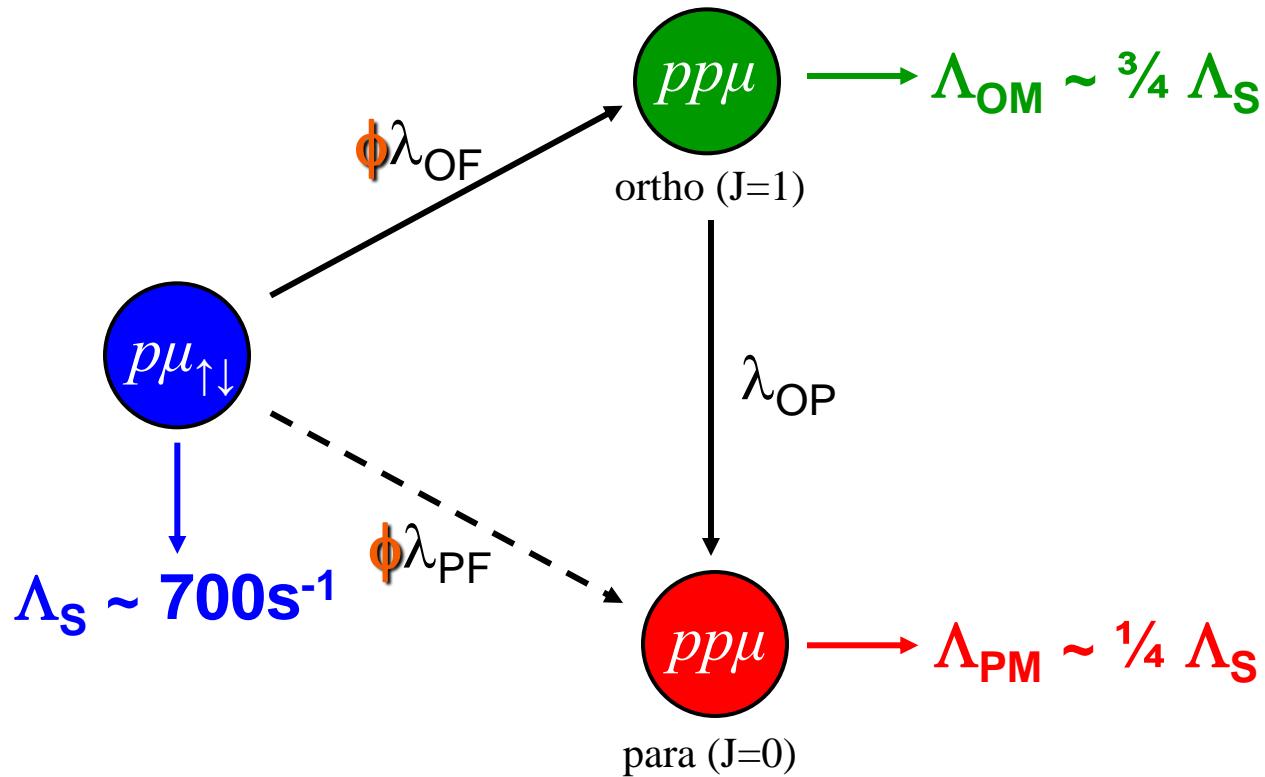


Muon kinetics

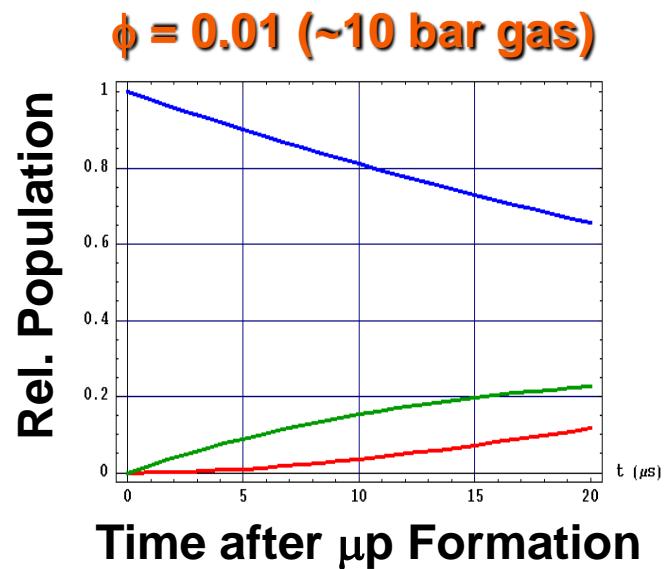
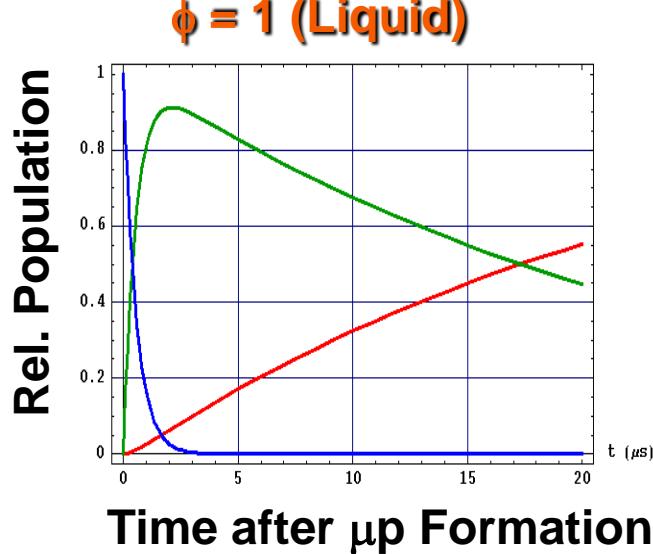
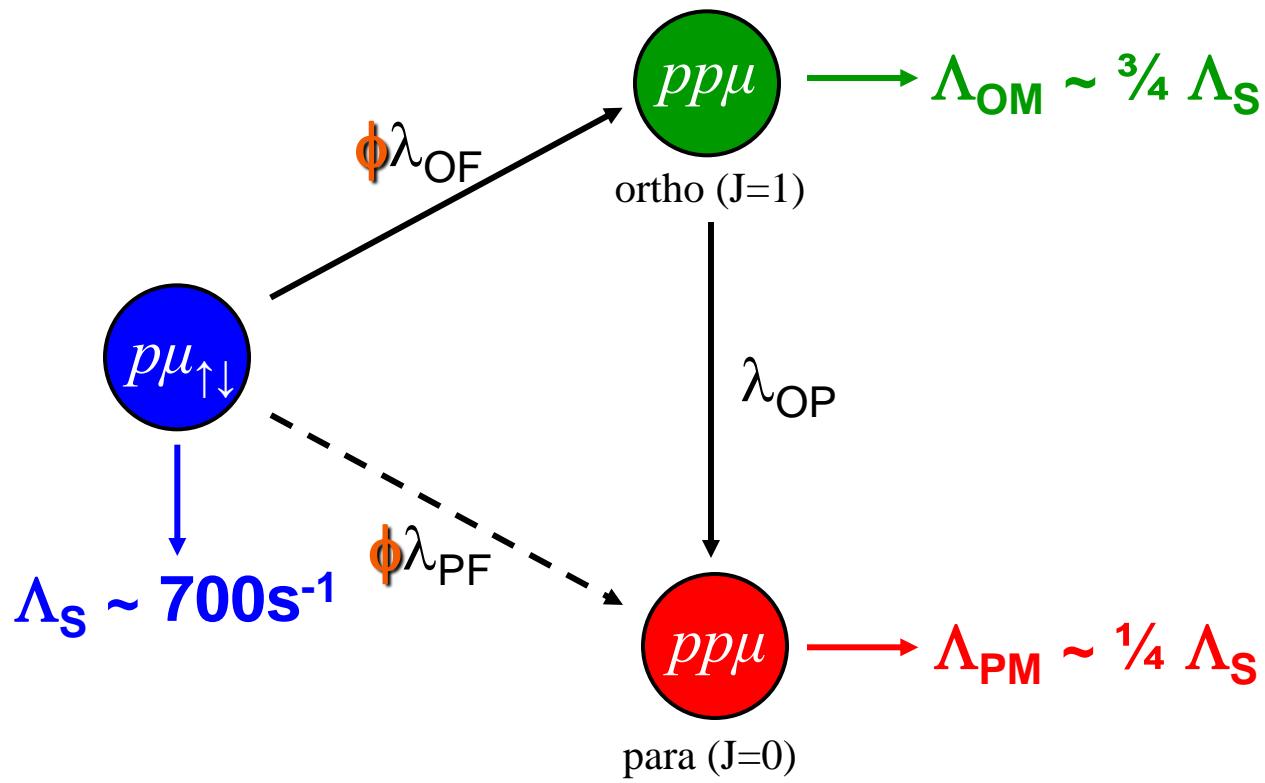
ϕ : Hydrogen density, (LH₂: $\phi=1$)



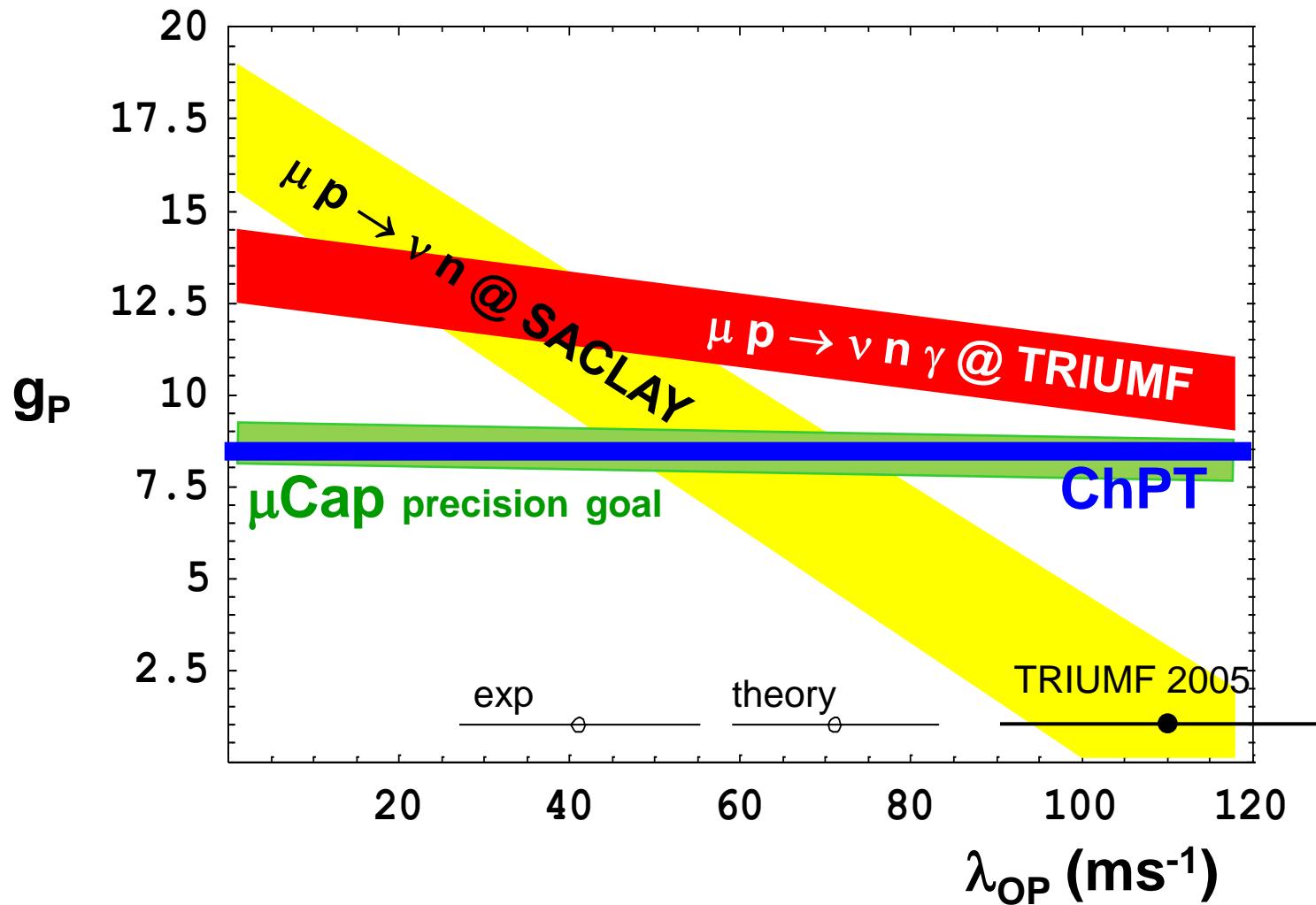
Muon kinetics



- $pp\mu$ formation depends on density ϕ
- Interpretation requires knowledge of Λ_{OM} , Λ_{PM} and λ_{OP}

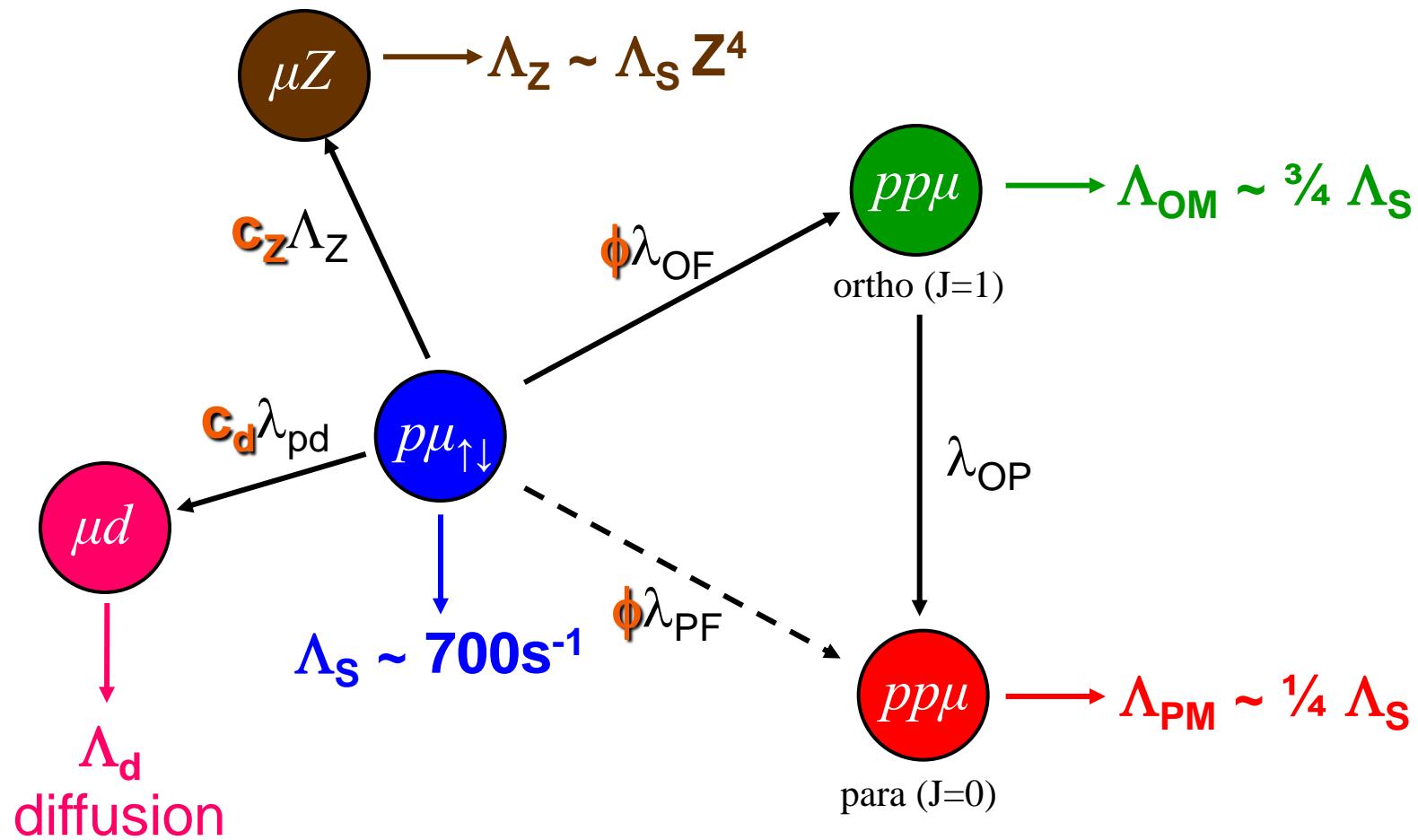


Previous results



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

Requirement of clean target



⇒ Isotopically and chemically pure H₂, ideally:
 $c_d < 1 \text{ ppm}$, $c_z < 10 \text{ ppb}$

Outline

$\mu^- p$

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$\mu^- d$

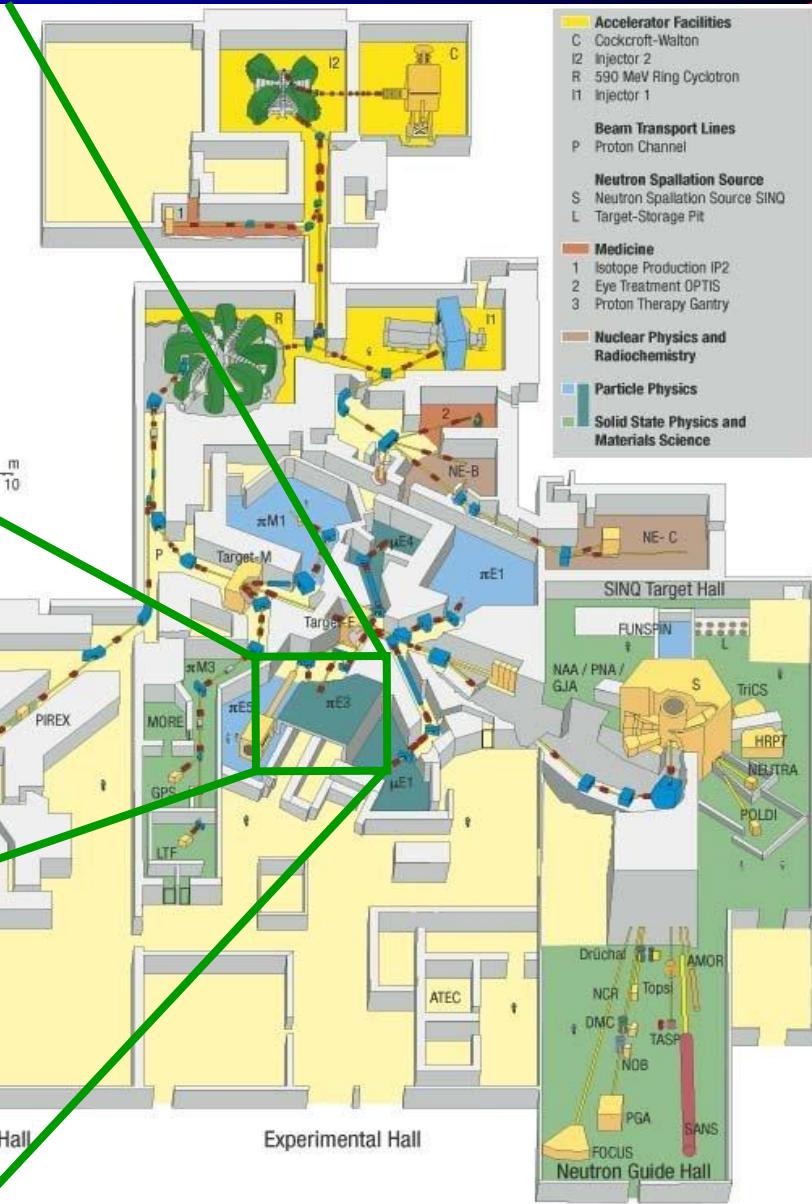
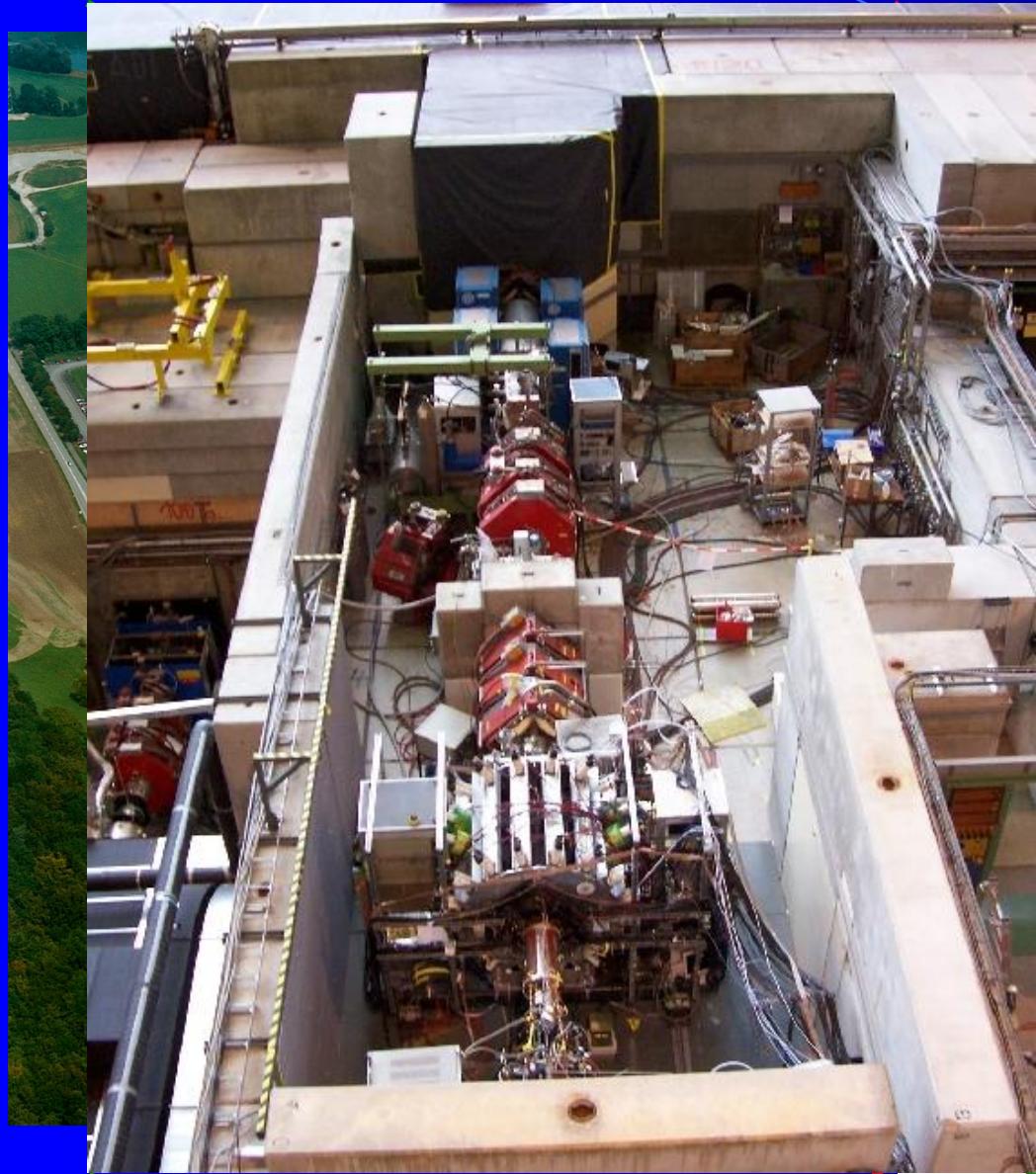
Muon capture on the deuteron (MuSun)

- Motivation and general overview
- Current status

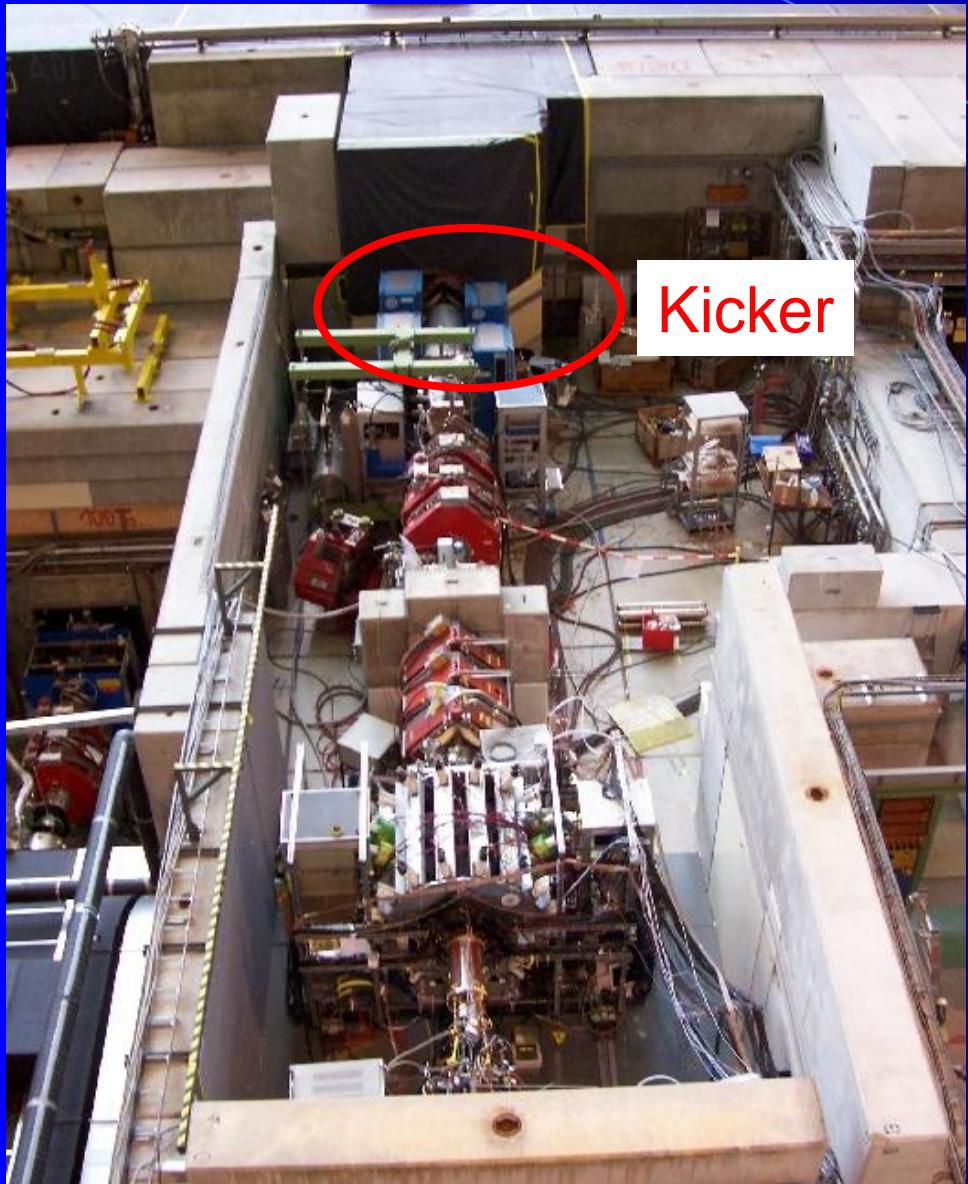
MuCap in a nutshell

- Lifetime method:
 $10^{10} \mu$ decays $\Rightarrow \Lambda_S$ to 1% precision
- Low gas density \Rightarrow Capture mostly from F=0
- Active gas target (TPC) \Rightarrow Clean μ stop
- Ultra pure gas system with in-situ monitoring
 $c_Z \sim 10 - 30 \text{ ppb}$ ($Z = \text{N}_2, \text{H}_2\text{O}$)
- Isotopically pure hydrogen gas
 $c_d \sim 100 \text{ ppb}$ (deuterium separation)

The facility: π E3 beamline at PSI

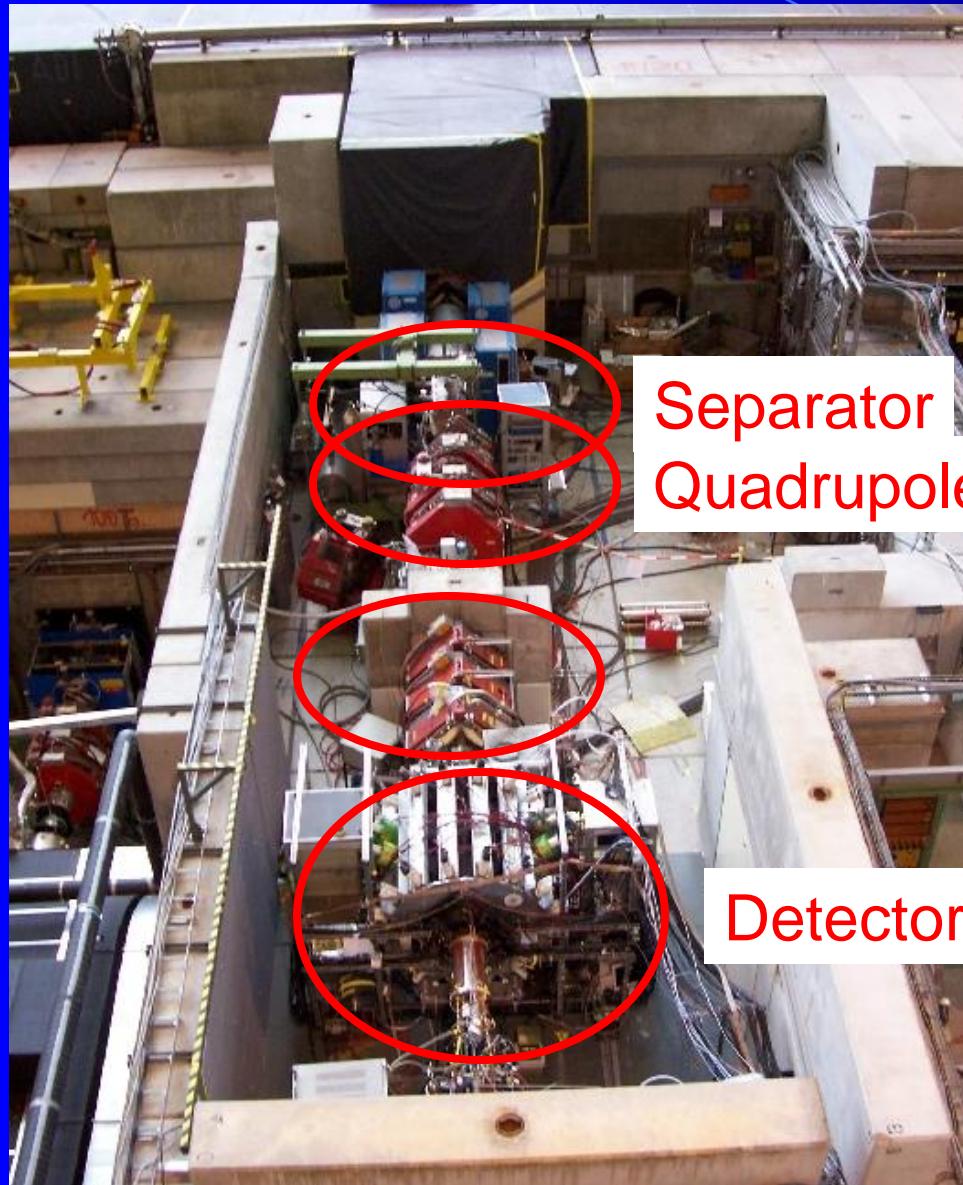


The Kicker

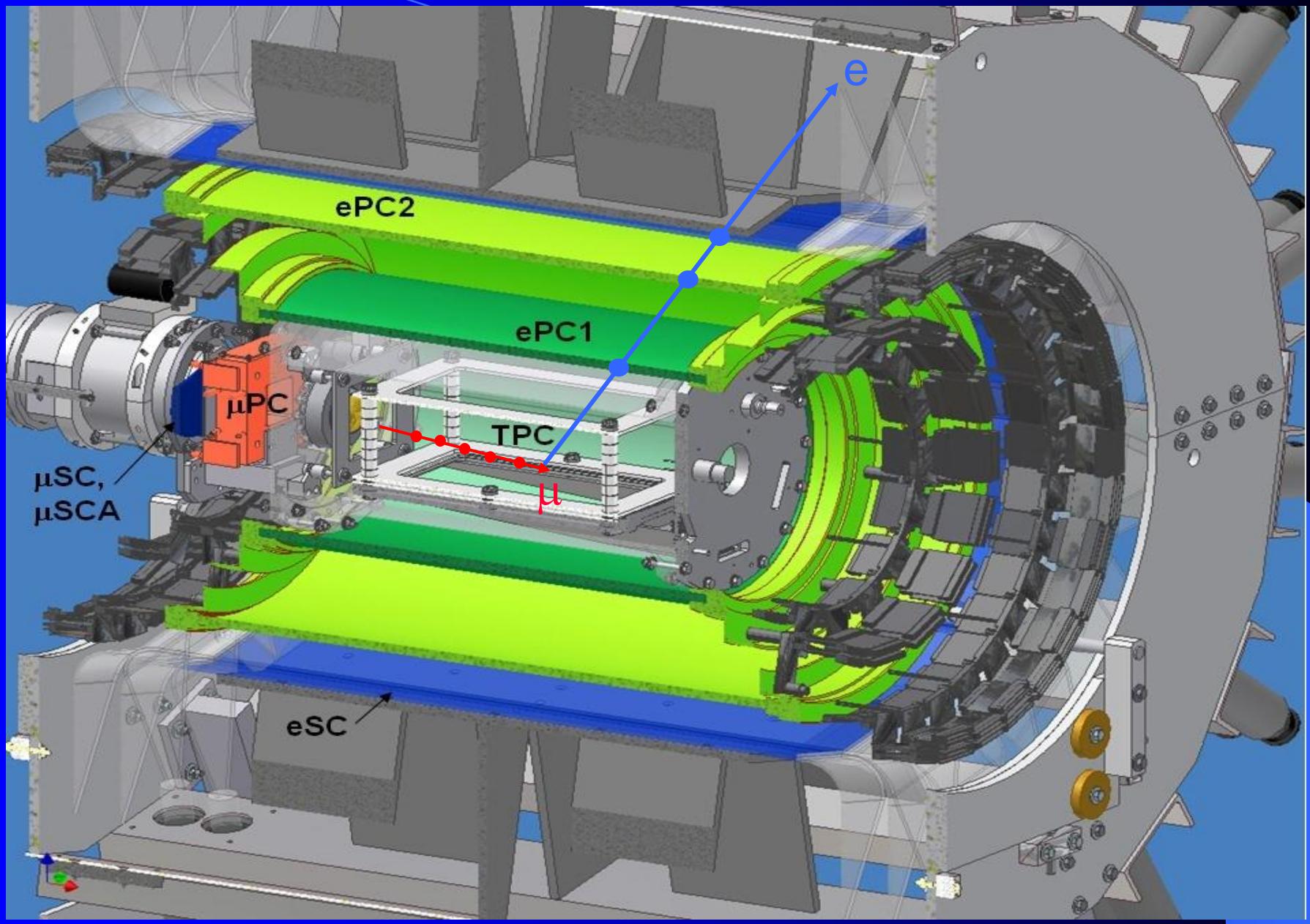


- Design at TRIUMF
- MOSFET based
- 50 ns switching time

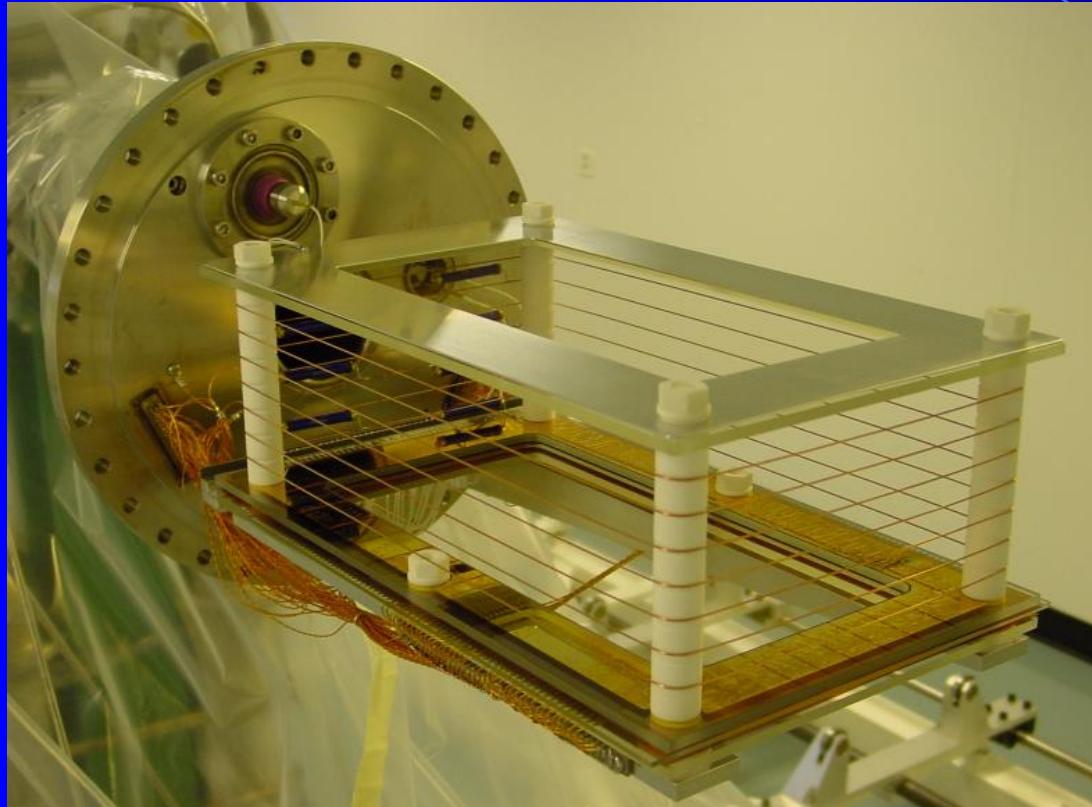
Other elements



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



TPC - the active target



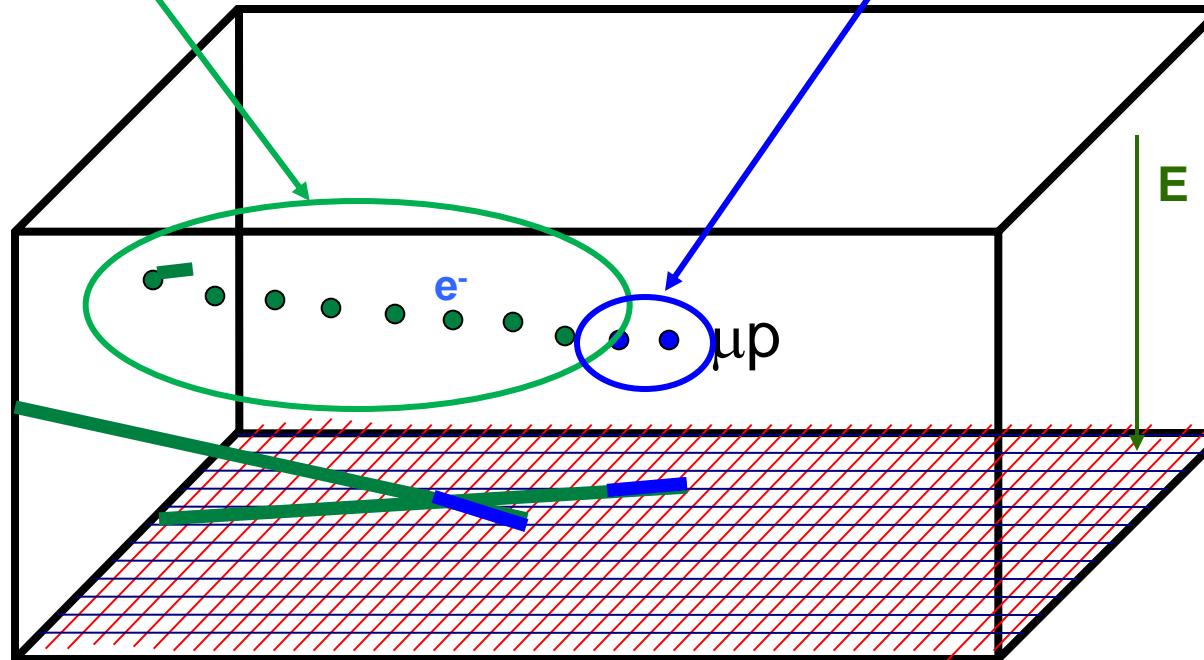
- 10 bar ultra-pure H₂
- 2.0 kV/cm drift field
- ~ 5.4 kV on 3.5 mm anode half gap
- bakeable glass/ceramic materials

Operation with pure H₂ challenging, R&D @ PNPI, PSI

TPC - the active target

μ^- entrance: lower energy loss

μ^- stop: Bragg peak



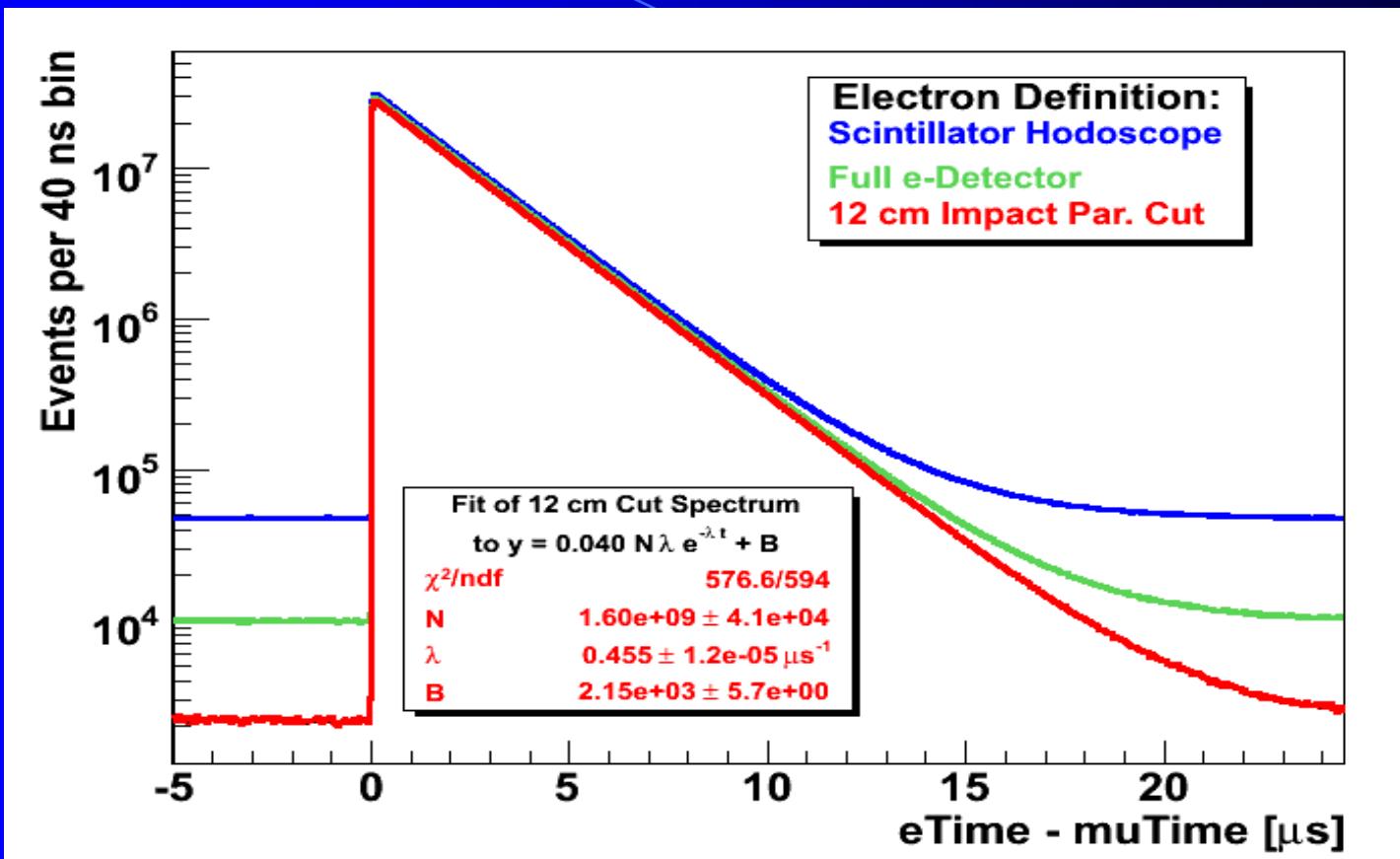
xz projection
from **anodes**
and **strips**

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

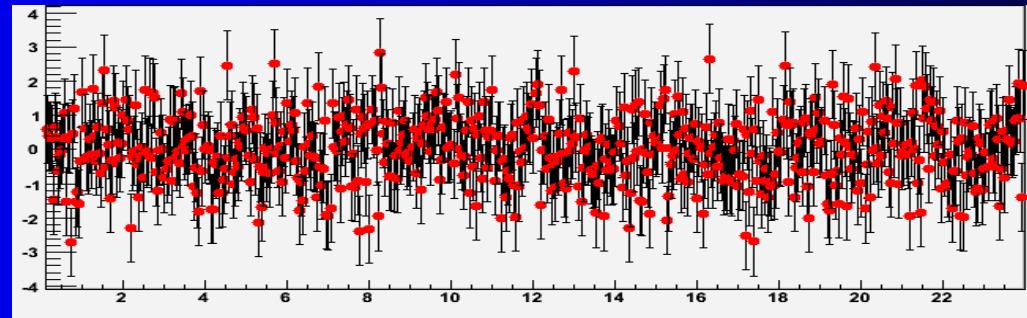
xy projection
from **strips**
and **drift time**

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

Lifetime spectra



Normalized
residuals



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$\mu^- d$

Muon capture on the deuteron (MuSun)

- Motivation and general overview
- Current status

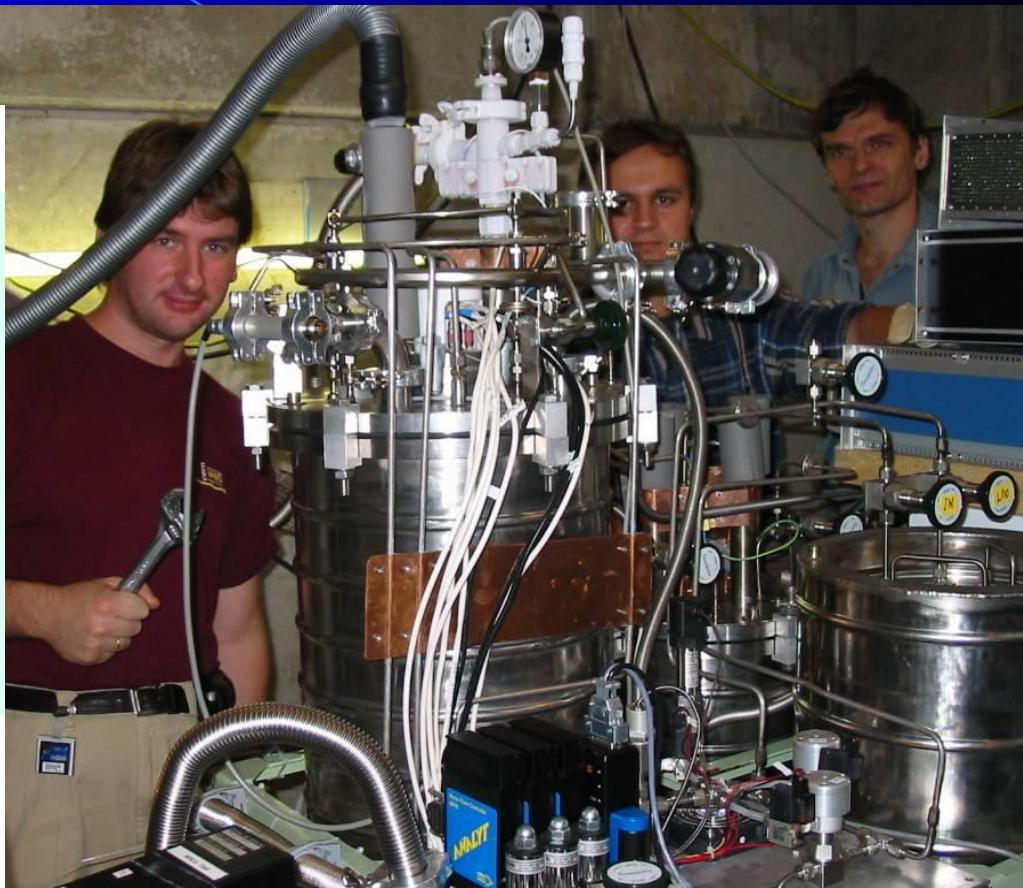
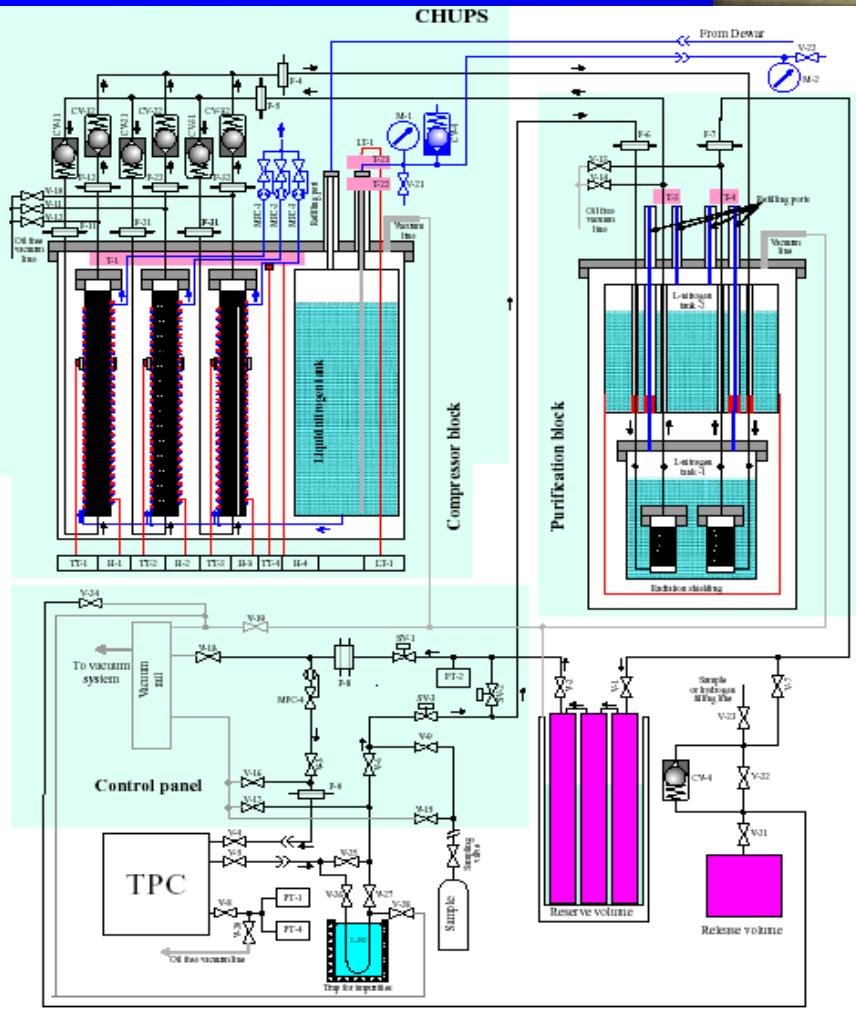
Internal corrections to λ_-

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

(statistical uncertainty of λ_- : 13.7 s^{-1})

CHUPS

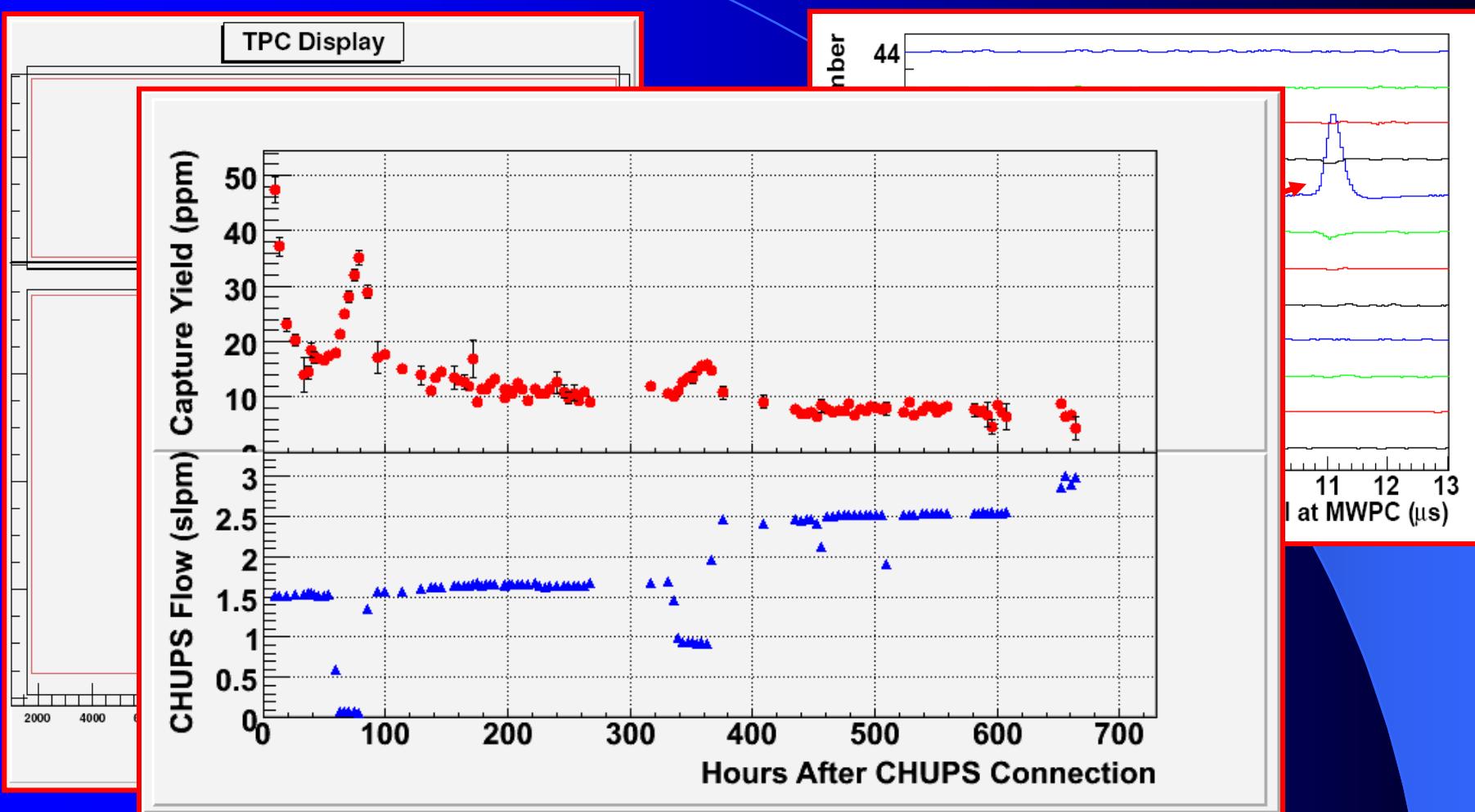
Continuous H₂ Ultra-Purification System



$C_{N2}, C_{O2} < 10 \text{ ppb}$

NIM A578 (2007), 485

Impurity monitoring



2004 run:

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

2006 / 2007 runs:

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

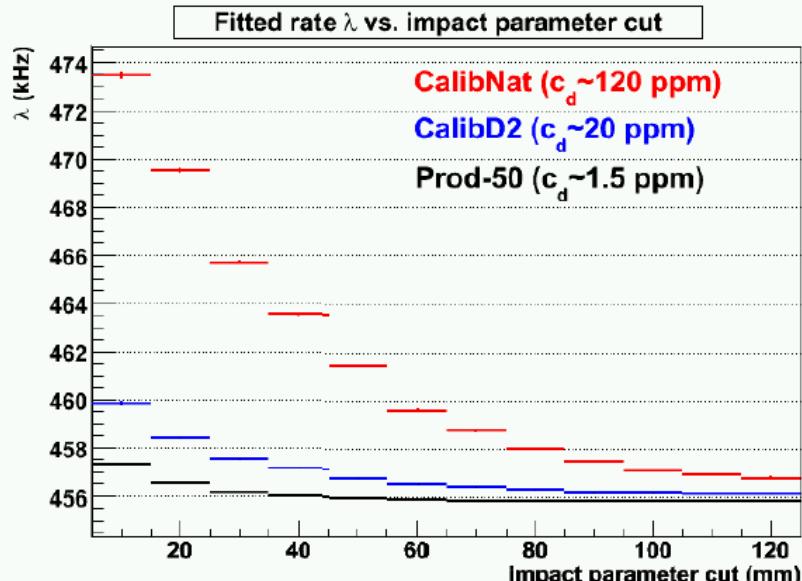
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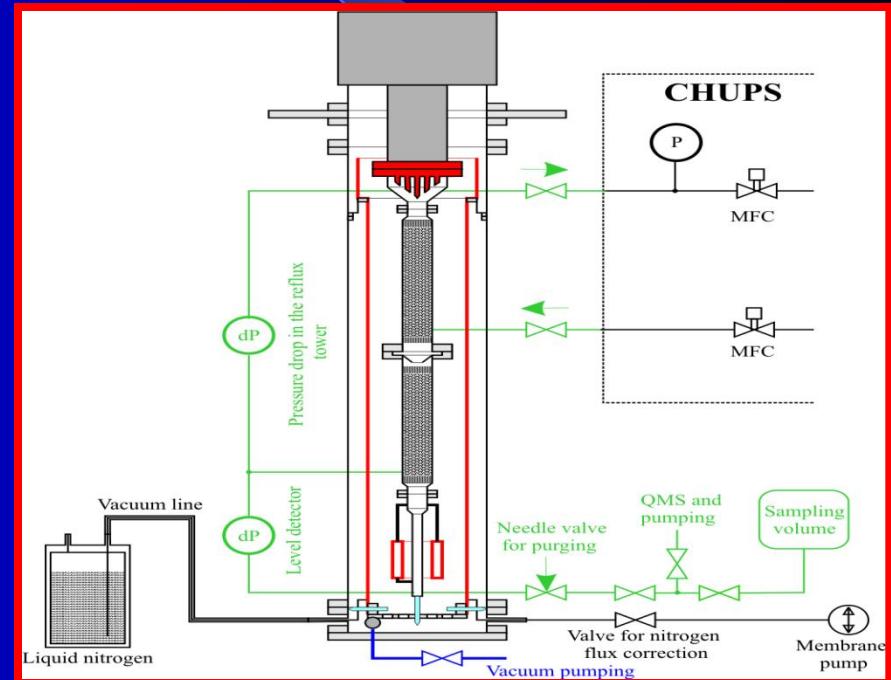
MuCap's unique capability

- MuCap 2004 data:



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

On site purification since 2006

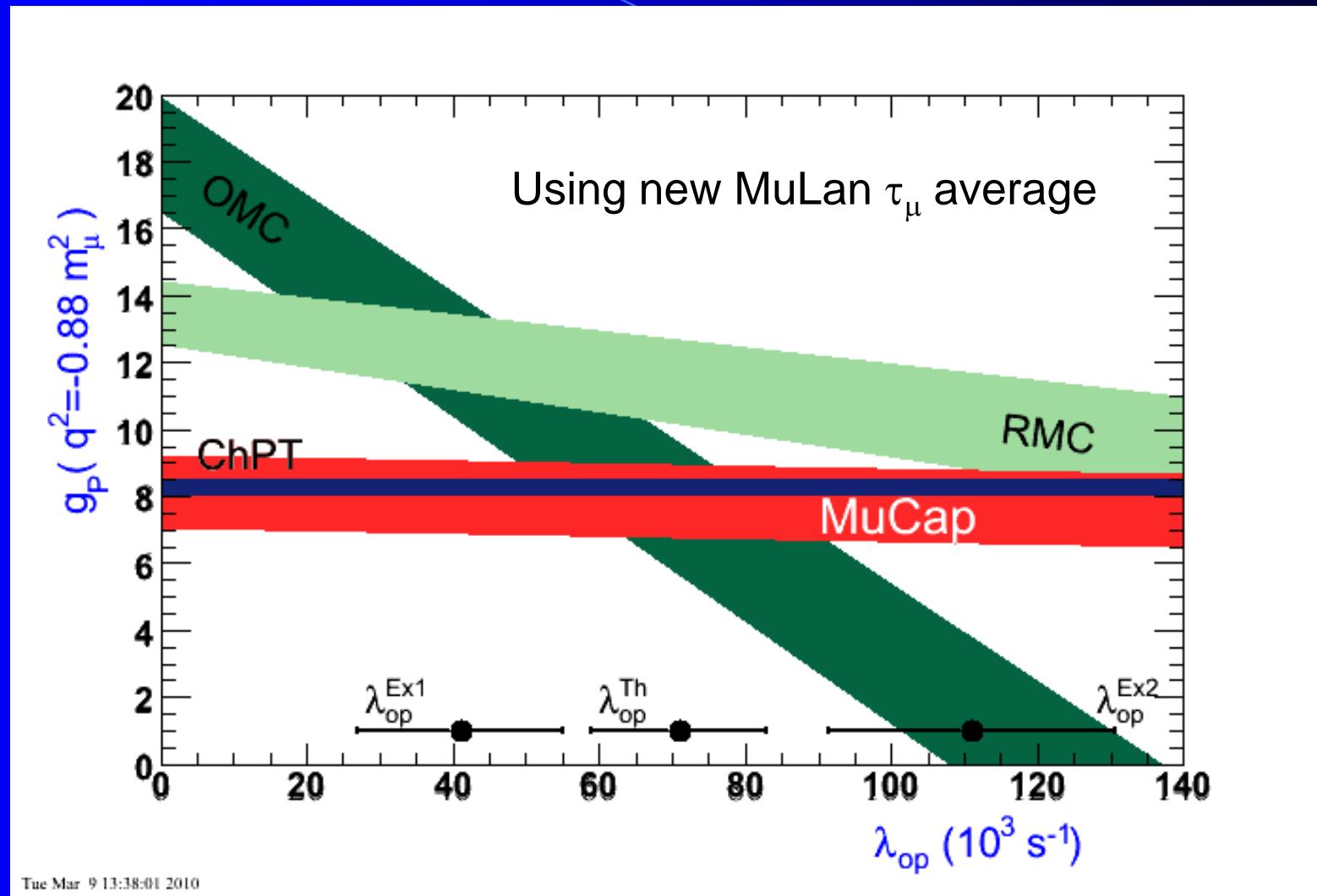


- AMS, ETH Zurich

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

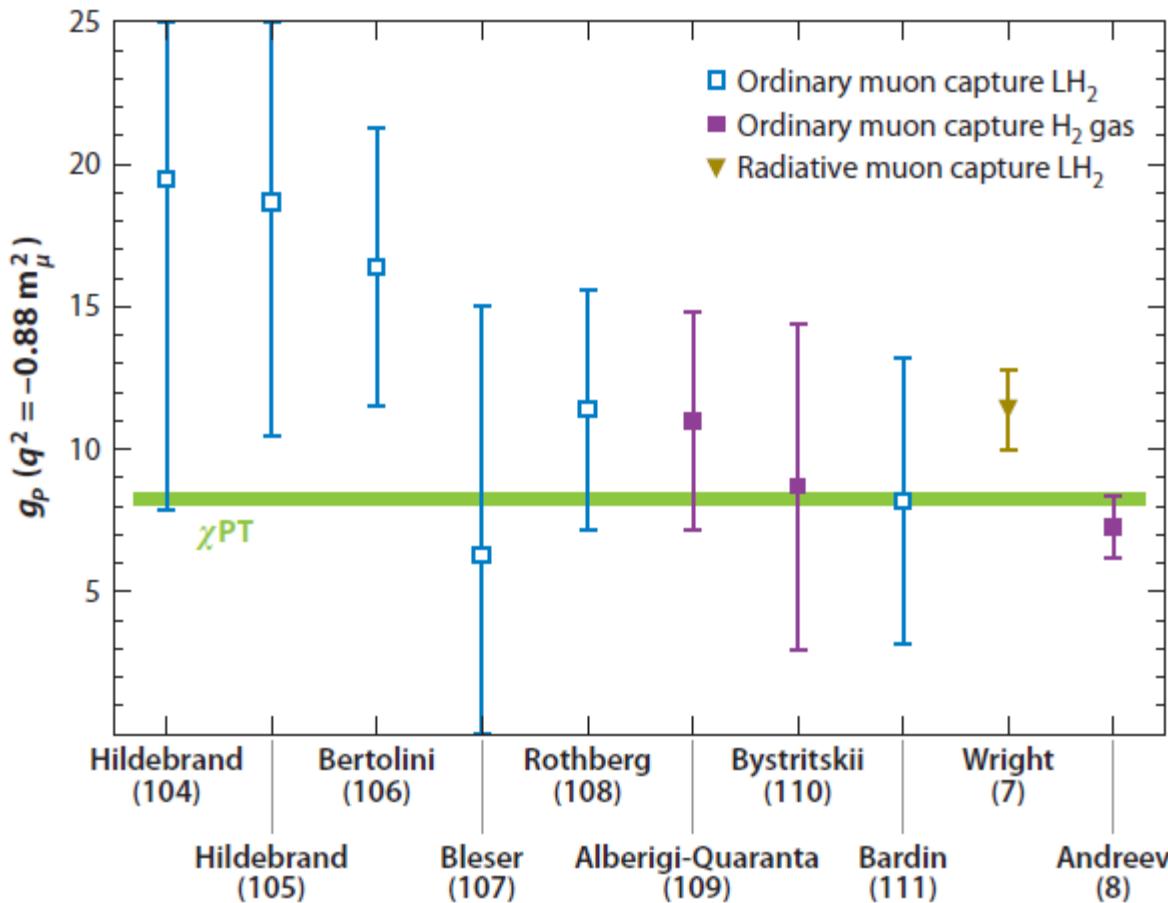
World Record: $c_d < 100 \text{ ppb}$

Precise and unambiguous MuCap result



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

g_P evaluation

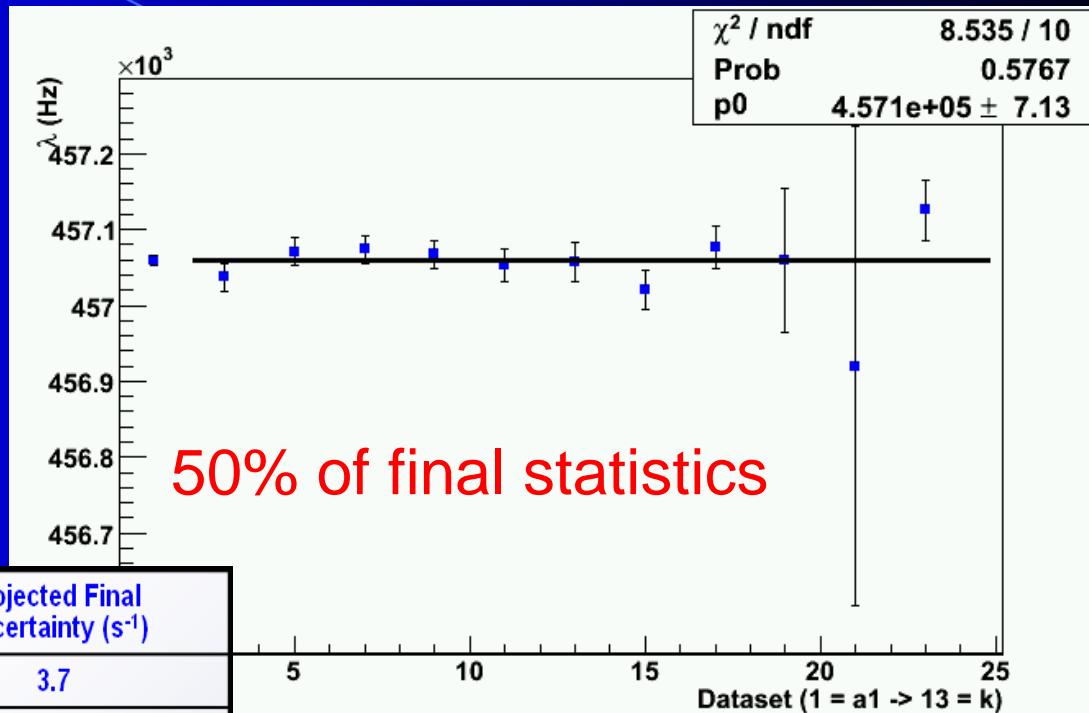


Recent muon capture review:

P. Kammel and K. Kubodera, Ann. Rev. Nucl. Part. Sci., Vol 60 (2010)

Final analysis (10^{10} muon decays)

- Many hardware upgrades (readout, purification, kicker)
- 10x higher statistics



Source	2007 Uncertainty (s^{-1})	Projected Final Uncertainty (s^{-1})
Statistical	13.7	3.7
$Z > 1$ impurities	5.0	2
μd diffusion	1.6	0.5
μp diffusion	0.5	0.5
$\mu + p$ scattering	3	1
μ pileup veto eff.	3	1
Analysis Methods	5	2
Muon kinetics	5.8	2
Systematic	10.7	3.8
Total	17.4	5.3

- Analysis far advanced (many subtle effects studied)
- Unblinding expected in first half of 2011

Outline

$\mu^- p$

Muon capture on the proton (MuCap)

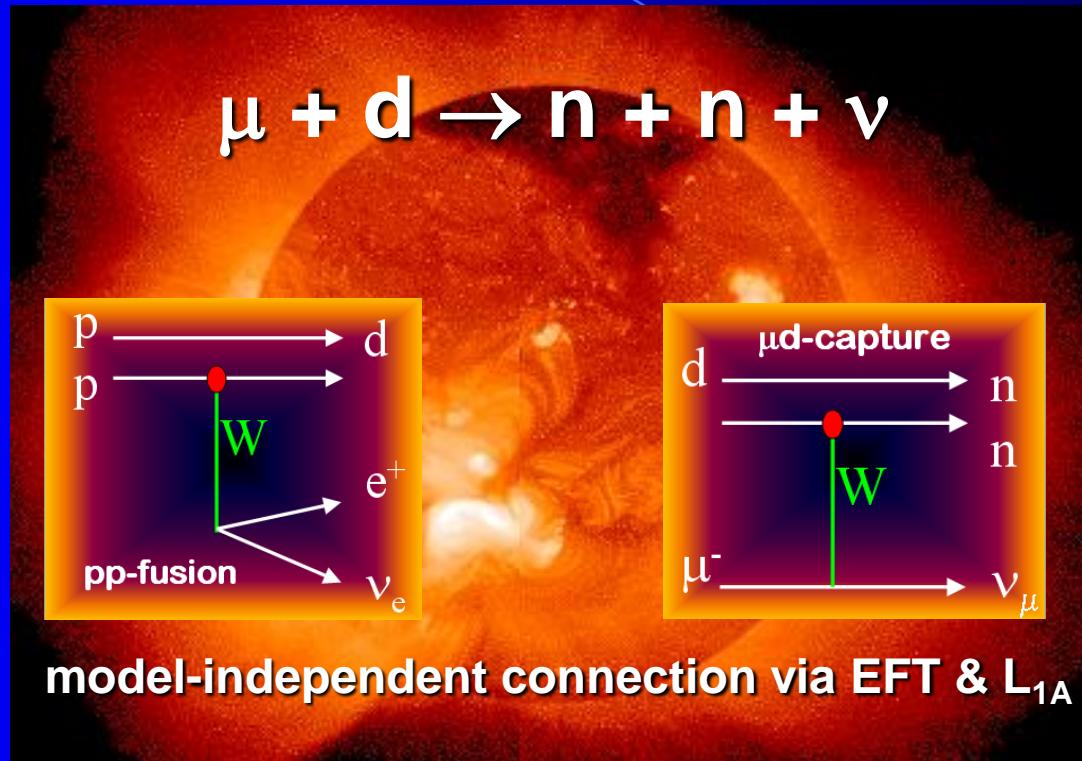
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Muon capture on the deuteron (MuSun)

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- Current status

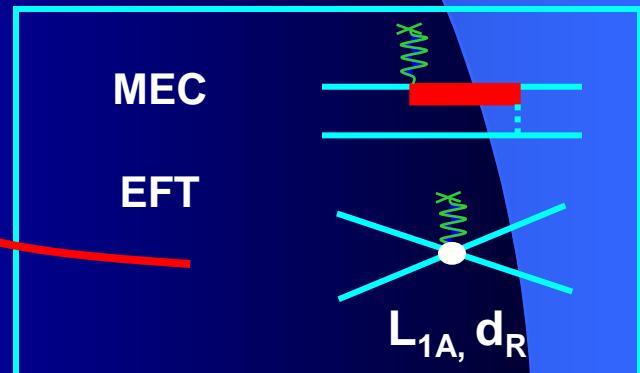
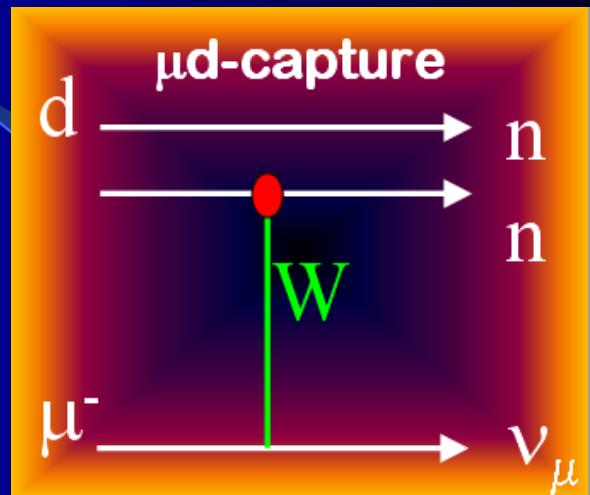
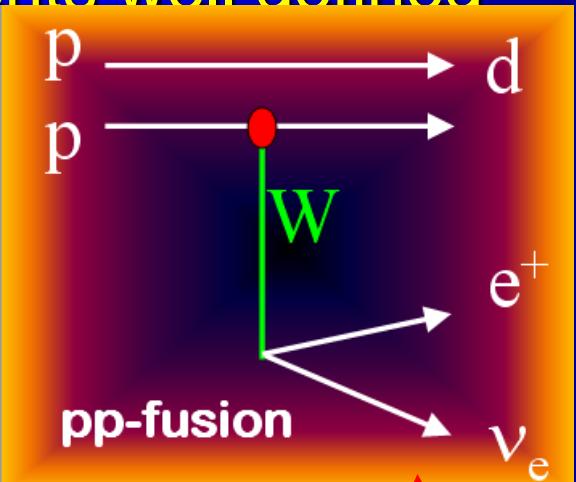
MuSun: "Calibrating" the sun



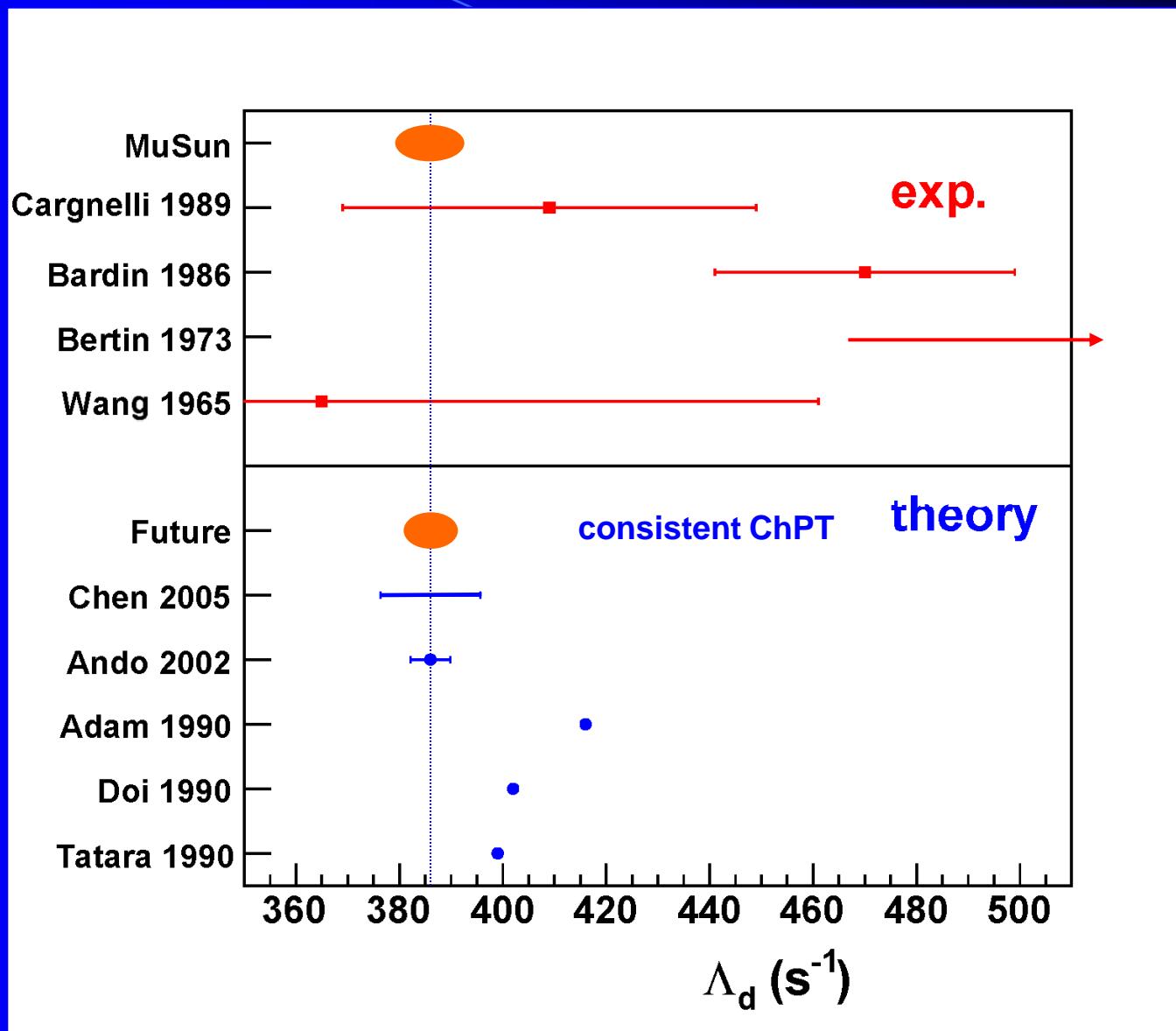
Aim: Measure rate Λ_d from $\mu d(\uparrow\downarrow)$ to $< 1.5 \%$

Theory

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



Precise experiment needed



Outline

$\mu^- p$

Muon capture on the proton (MuCap)

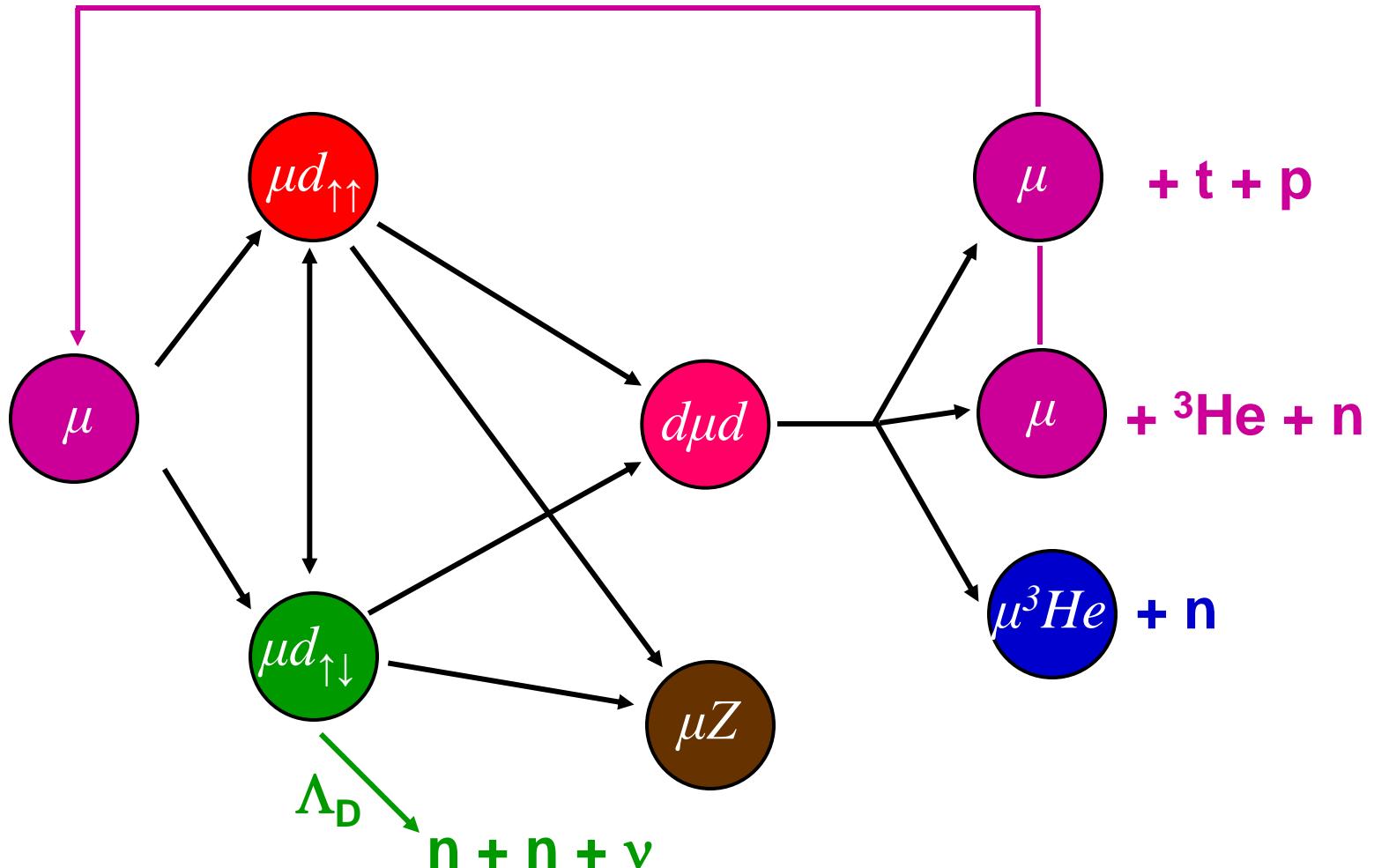
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$\mu^- d$

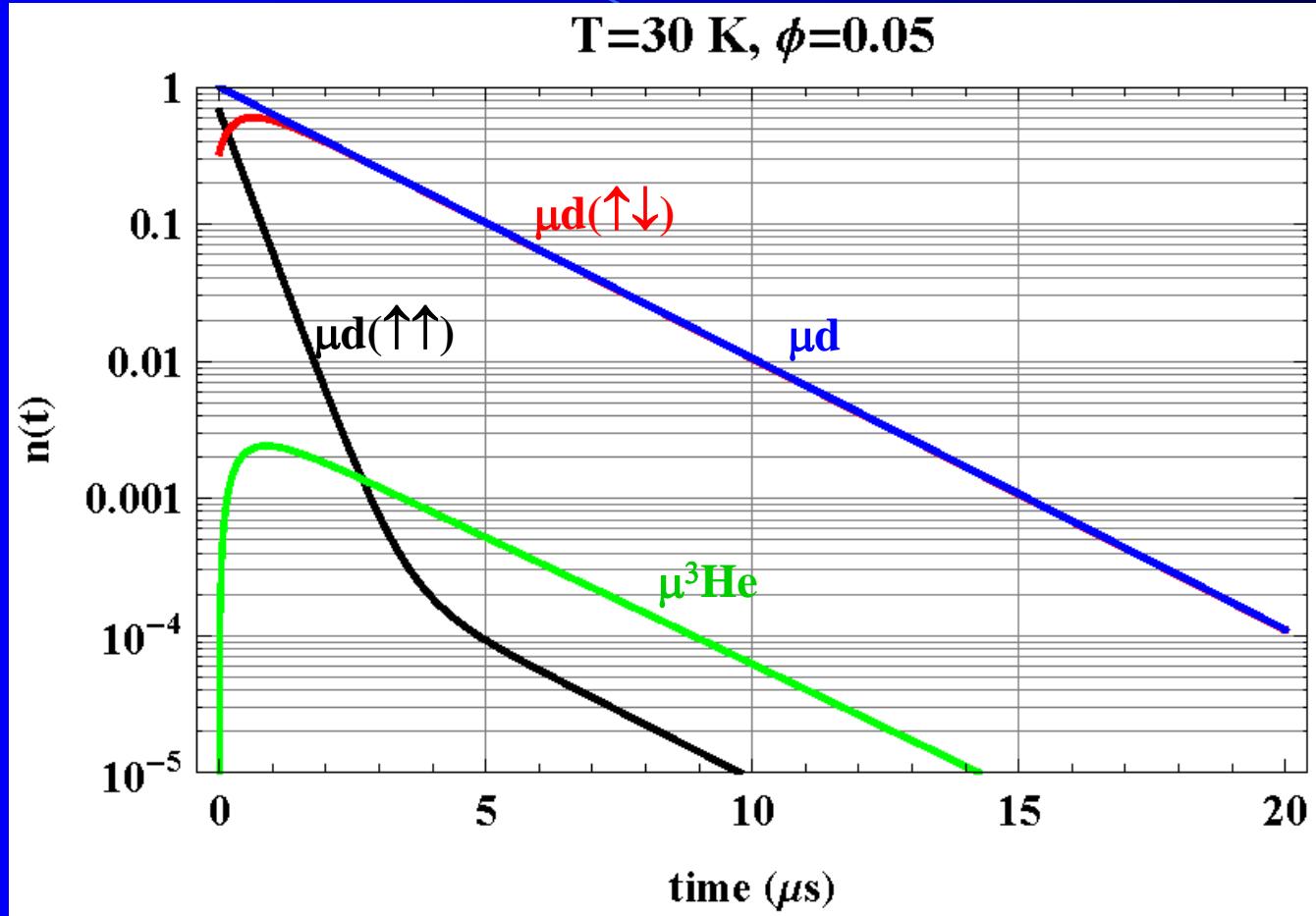
Muon capture on the deuteron (MuSun)

- Motivation and general overview
- Current status

μd kinetics



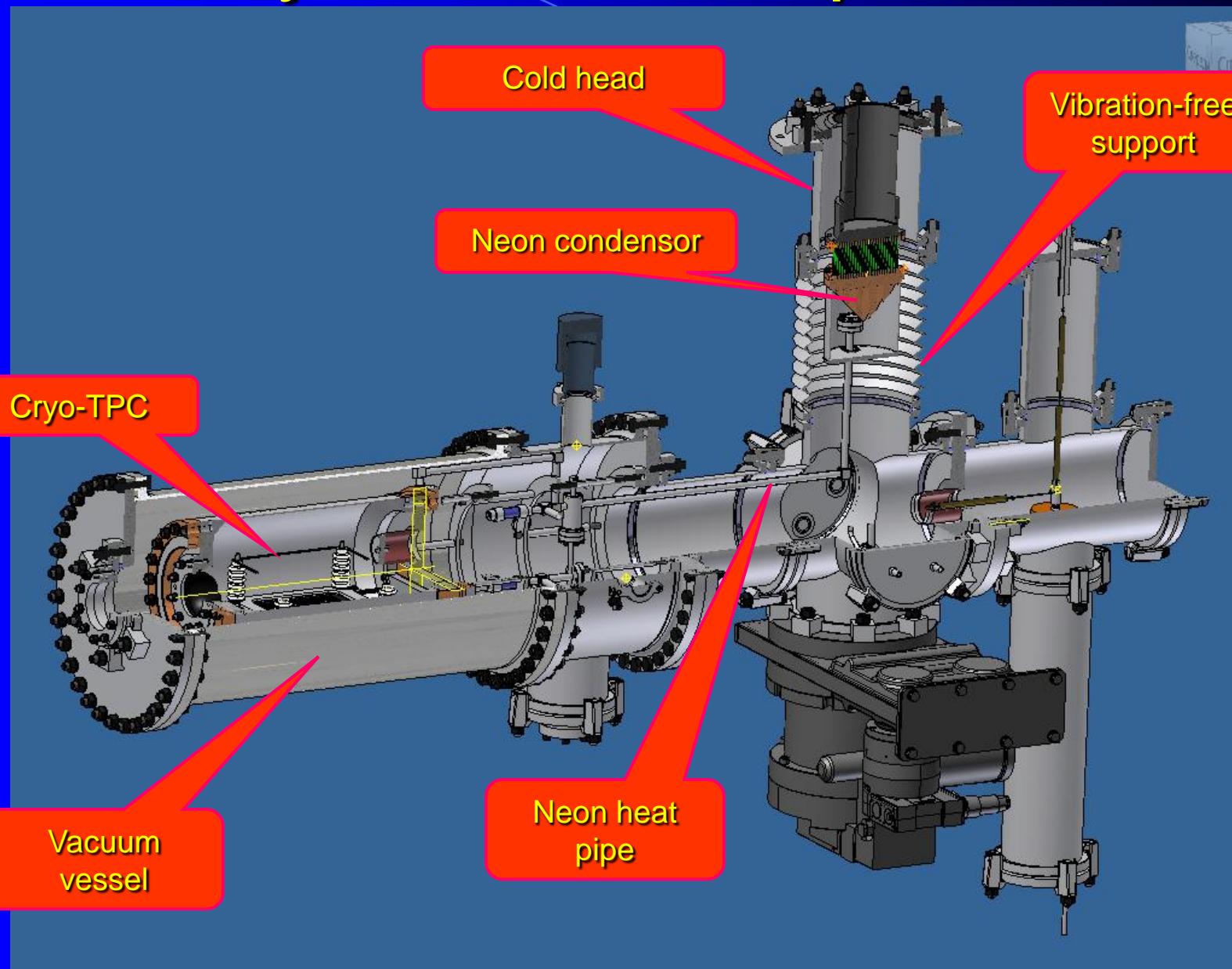
Optimized conditions



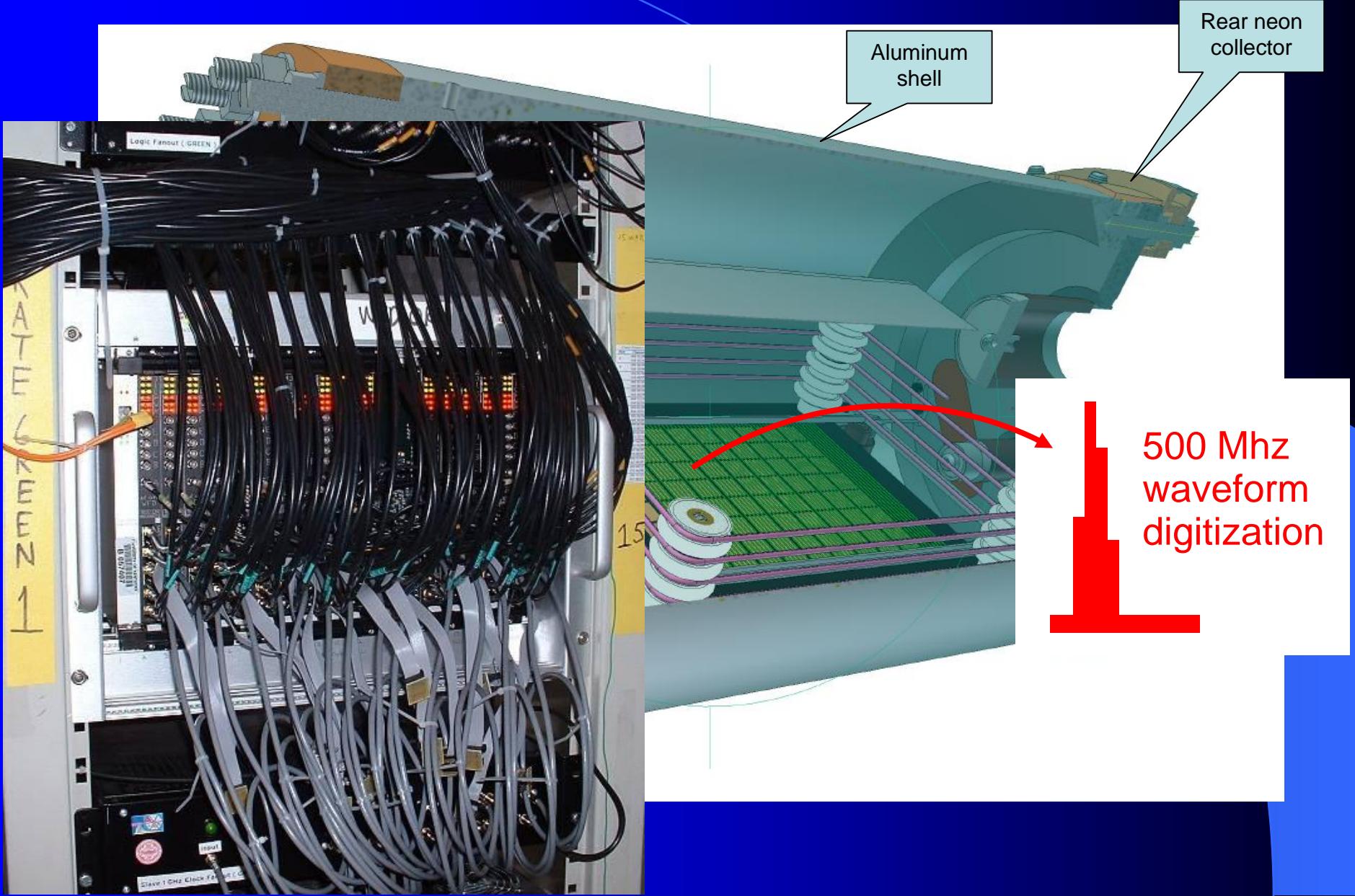
Clean interpretation at:

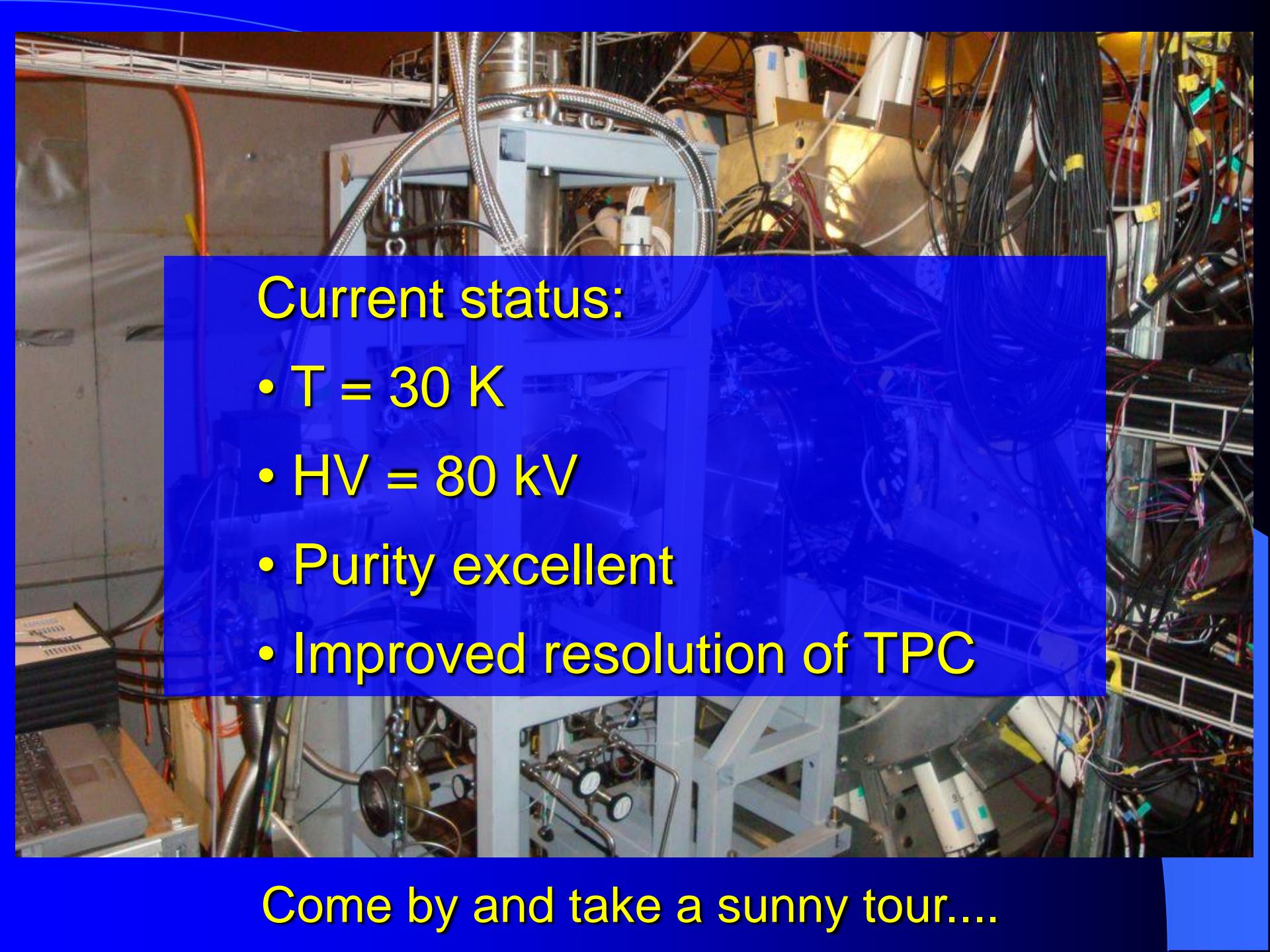
$T = 30 \text{ K}, \phi = 5\% \text{ LH}_2 \text{ density}$

Cryo-TPC development



Cryo-TPC development





Current status:

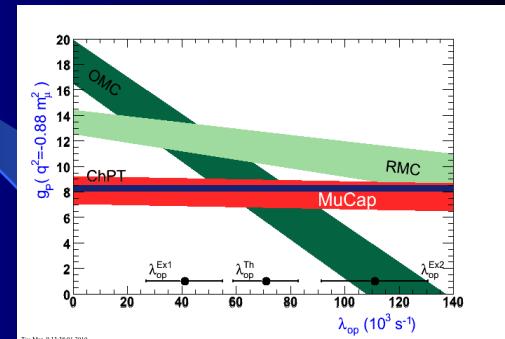
- $T = 30 \text{ K}$
- $\text{HV} = 80 \text{ kV}$
- Purity excellent
- Improved resolution of TPC

Come by and take a sunny tour....

Overall summary

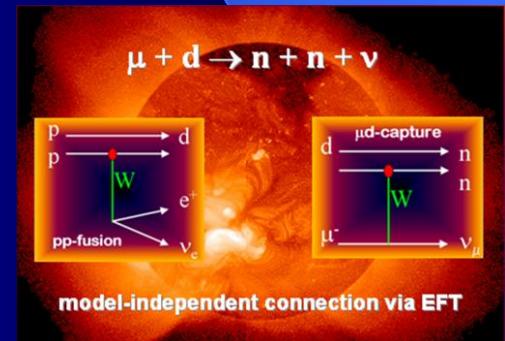
• MuCap:

- 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



Recent muon capture review:

P. Kammel and K. Kubodera, Ann. Rev. Nucl. Part. Sci., Vol 60 (2010)