First Physics Results from the MuCap Experiment at PSI

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www.npl.uiuc.edu/exp/mucapture

MuCap Collaboration

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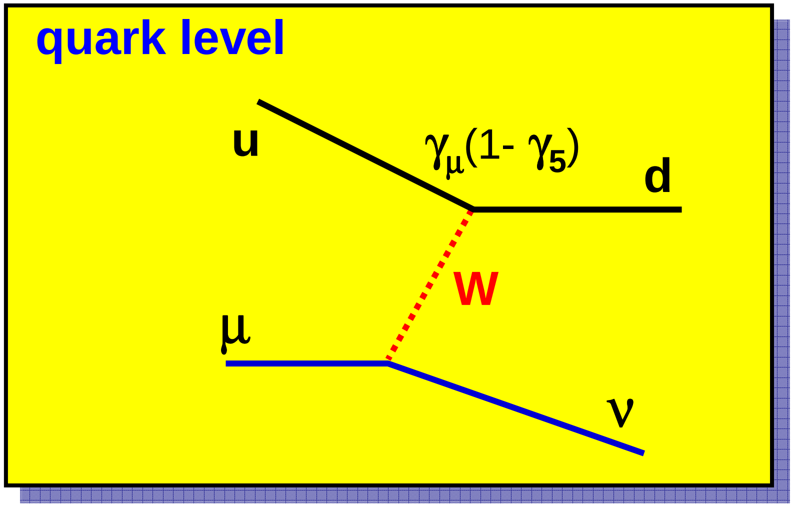
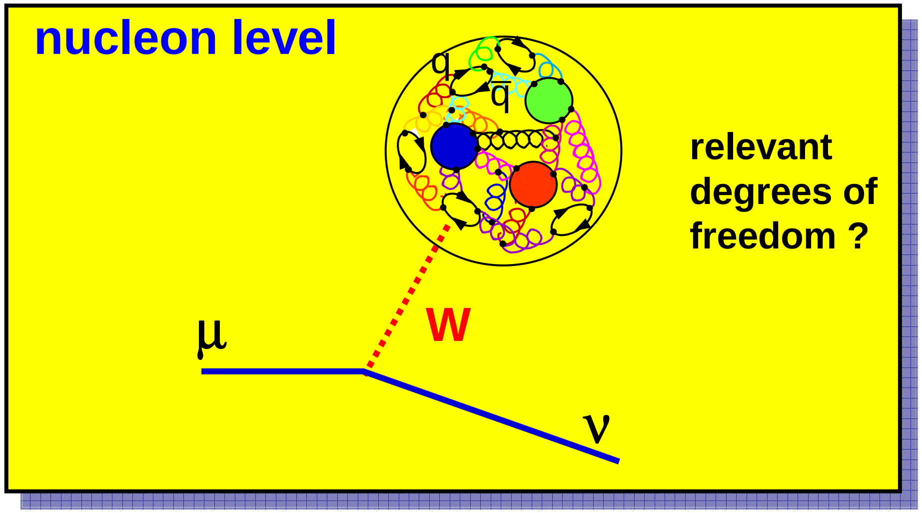
- **Physics Context**
- **Muon Capture on the Proton Theory – Experiment**
- **μCap and First Results**

Topics in Nuclear Physics
DNP, October 28, 2006

Nuclear Physics Context

- **EW current key probe for nucleon structure** — **charged current**





- **Understanding hadrons from fundamental QCD**
  - **lattice QCD**
  - **chiral effective field theory (ChPT)**

    π Goldstone boson of spontaneously broken symmetry, sys. expansion in q/Λ
    model independent predictions
    fundamental properties and symmetry tests
    interesting processes (astrophysics)
    interface to lattice calculations
    …

Muon Capture and Axial Nucleon Structure

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

rate Λ_S

$$\mathcal{M} = \frac{-iG_F V_{ud}}{\sqrt{2}} \overline{u}(p_\nu)\gamma_\alpha(1-\gamma_5)u(p_\mu)\overline{u}(p_f)\tau_- \left[V^\alpha - A^\alpha\right] u(p_i)$$

Lorentz, T invariance

$$V_\alpha = g_V(q^2)\,\gamma_\alpha + \frac{i\,g_M(q^2)}{2\,M_N}\,\sigma_{\alpha\beta}\,q^\beta$$

$$A_\alpha = g_A(q^2)\,\gamma_\alpha\,\gamma_5 + \frac{g_P(q^2)}{m_\mu}\,q_\alpha\,\gamma_5$$

+ second class currents suppressed by isospin symm.

Conserved Vector Current CVC

Vector form factors $q^2 = -0.88\ m_\mu^2$

$g_V = 0.9755(5)$ $g_M = 3.5821(25)$

strong program JLab, Mainz, ...

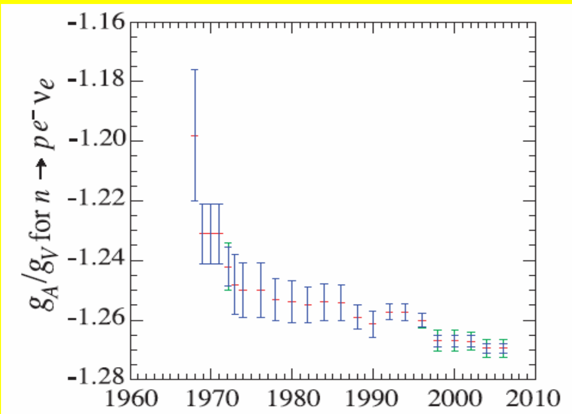
Main motivation for μCap studies

Axial form factors $q^2 = -0.88\ m_\mu^2$

$g_A = 1.245(4)$ $\mathbf{g_P = 8.3 \pm 50\%}$

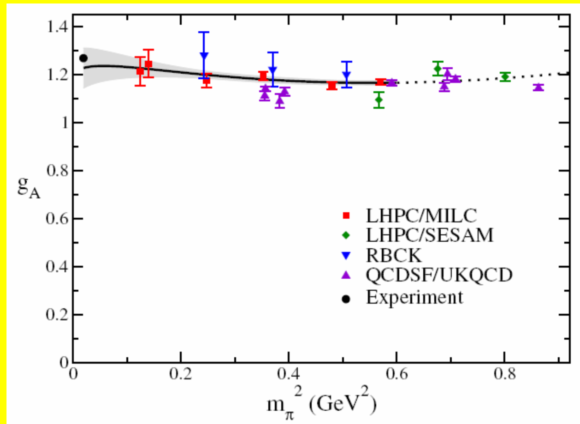
Axialvector Form Factor g_A

Exp. History



PDG 2006

Lattice QCD



Edwards et al. LHPC Coll (2006)

Axial radius

ν+N scattering

$$M_A = (1.026 \pm 0.021)\ GeV$$

$$\sqrt{< r_A^2 >} = (0.666 \pm 0.014)\ fm$$

consistent with π electroproduction (with ChPT correction)

Bernard et al. (2002)

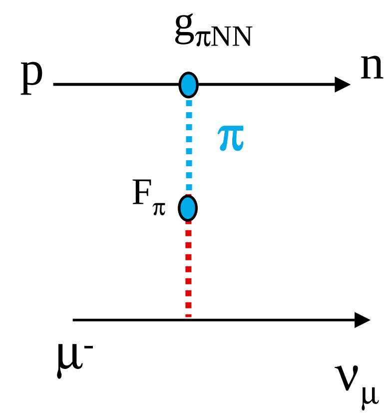
$$g_A(q^2) = g_A(0)(1 + \frac{1}{6} < r_A^2 > q^2)$$

$$g_A(0) = 1.2695 \pm 0.0029$$

$$g_A(-0.88 m_\mu^2) = 1.245 \pm 0.004$$

introduces 0.4% uncertainty to Λ_S (theory)

Pseudoscalar Form Factor g_P



g_P determined by chiral symmetry of QCD:

$$g_p(q^2) = \frac{2m_\mu g_{\pi NN}(q^2) F_\pi}{m_\pi^2 - q^2} - \frac{1}{3} g_a(0) m_\mu m_N r_A^2$$

g_P=	(8.74 ± 0.23)	– (0.48 ± 0.02)	=	**8.26 ± 0.23**
PCAC	pole term	Adler, Dothan, Wolfenstein		
ChPT	leading order	one loop	two-loop <1%	

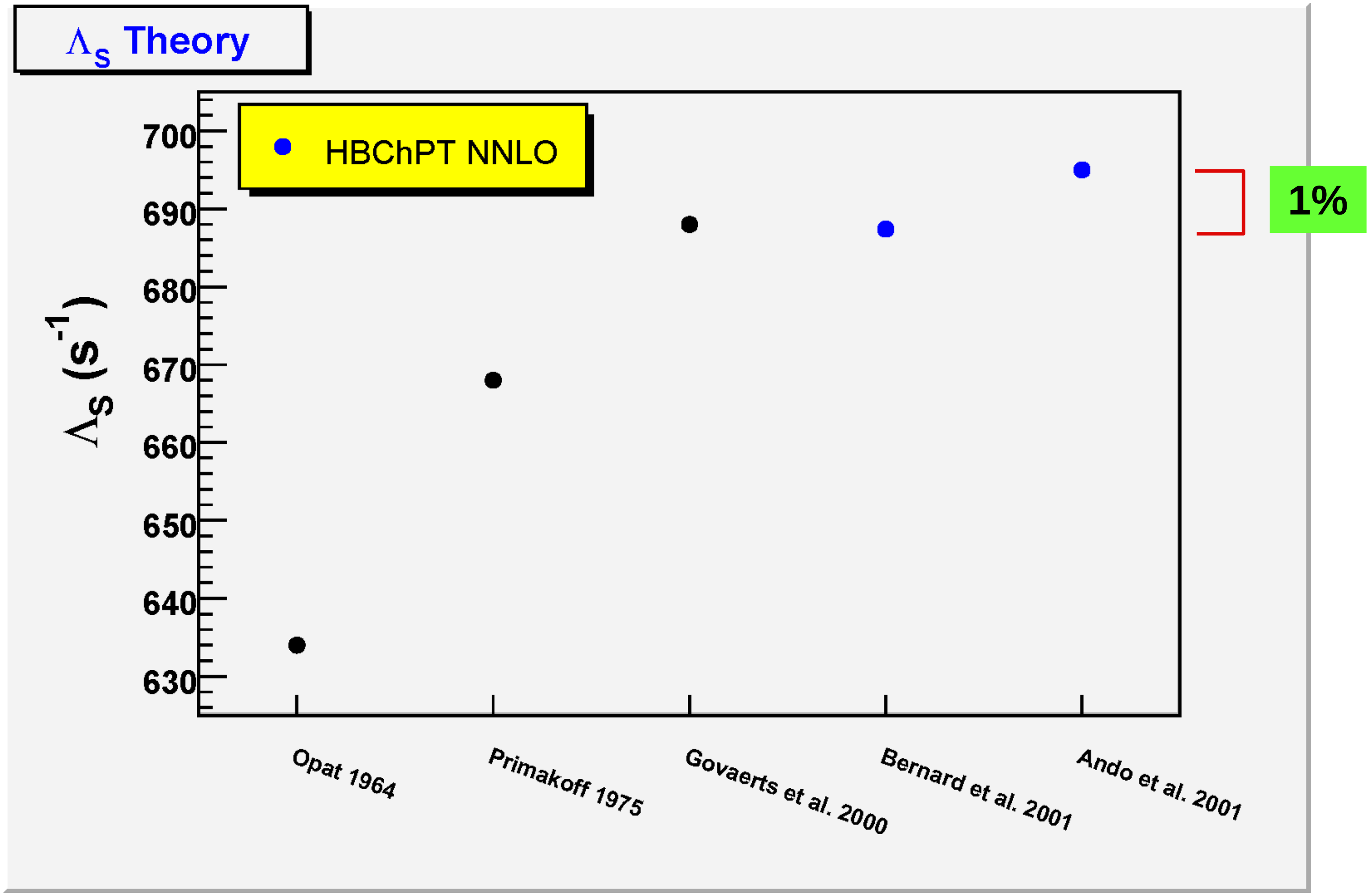
N. Kaiser Phys. Rev. C67 (2003) 027002

- **g_P basic and experimentally least known weak nucleon form factor**
- **solid QCD prediction via ChPT (2-3% level)**
- **basic test of QCD symmetries**

to V, A or P.

Recent reviews:
T. Gorringe, H. Fearing, Rev. Mod. Physics 76 (2004) 31
V. Bernard et al., Nucl. Part. Phys. 28 (2002), R1

Λ_S Calculations



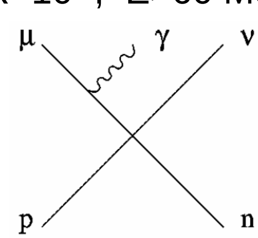
Processes to Determine g_P

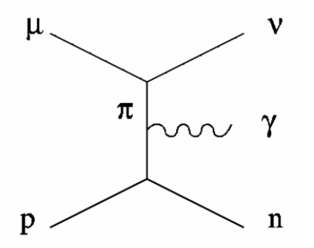
- $\mu^- + p \rightarrow \nu_\mu + n$ **OMC rate Λ_S** BR~10^{-3}

8 experiments, typical precision 10-15%, Saclay 4%

- $\mu^- + p \rightarrow \nu_\mu + n + \gamma$ **RMC** BR~10^{-8}, E>60 MeV

279±25 events
BR_γ(k>60MeV)=(2.10±0.21)x10^{-8}
Wright et al. (1998)





…

- $\mu^- + {}^3He \rightarrow \nu_\mu + {}^3H$

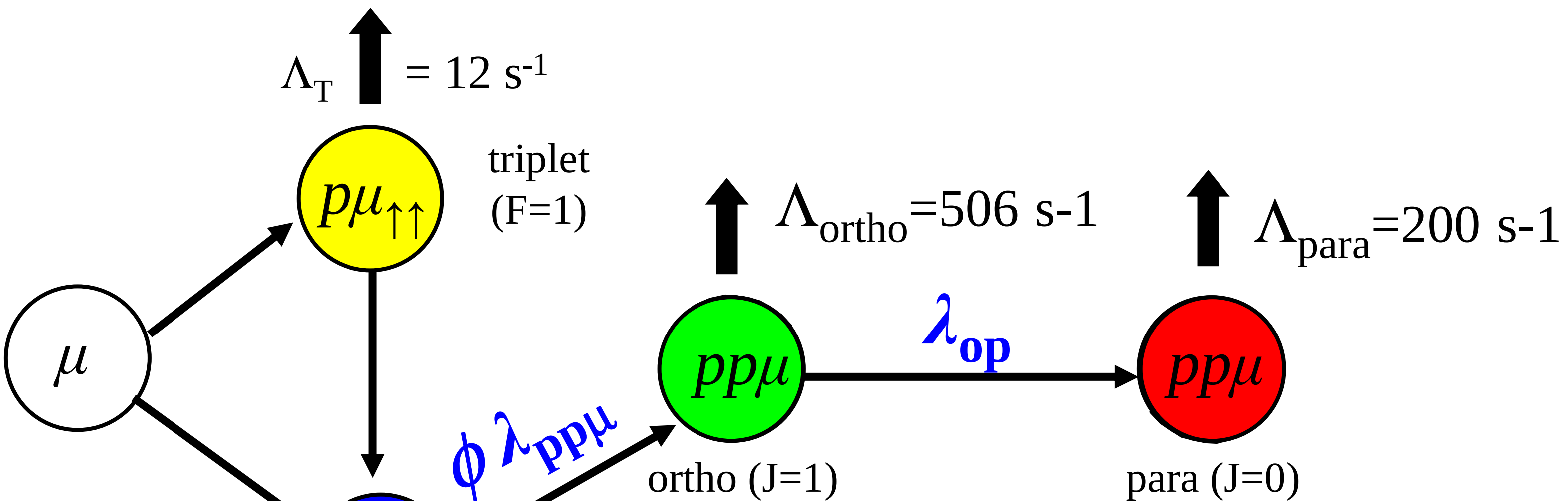
	authors	Λ_{stat} (s^{-1})	comment
theory 1993	*Congleton & Fearing*	1304	1B
theory 1996	*Congleton & Truhlik*	1502 ± 32	1B + 2B
exp 1998	*Ackerbauer et al*	1496.0 ± 4.0	^{3}He TPC
theory 2002	*Marcucci et al.*	1484 ± 8	1B+2B, T beta constraint

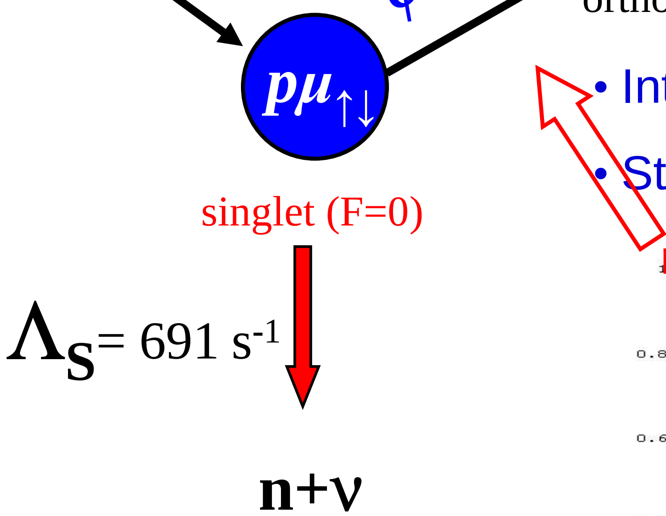
$$g_P(-0.954 m_\mu^2) = 8.53 \pm 1.54$$

rad. corrections?

- **pion electroproduction**

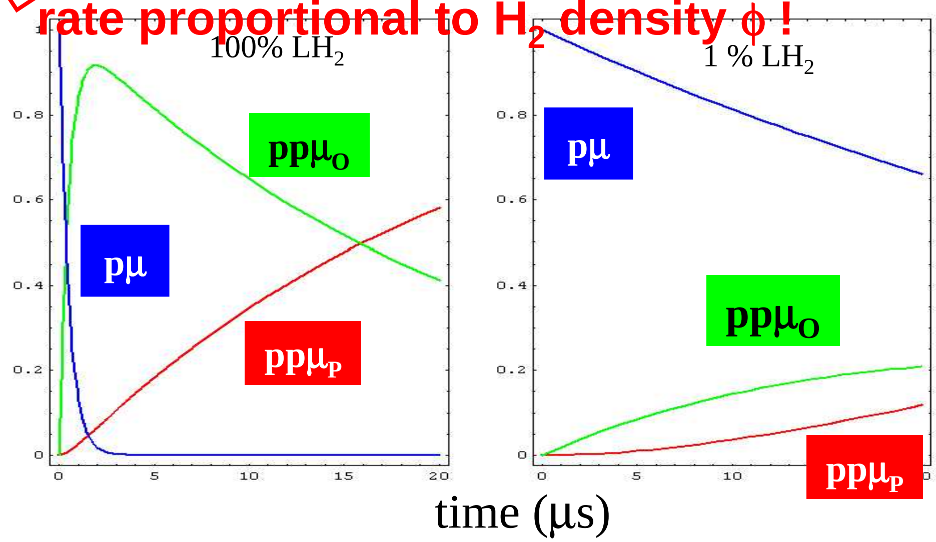
Muon capture and muon molecular processes



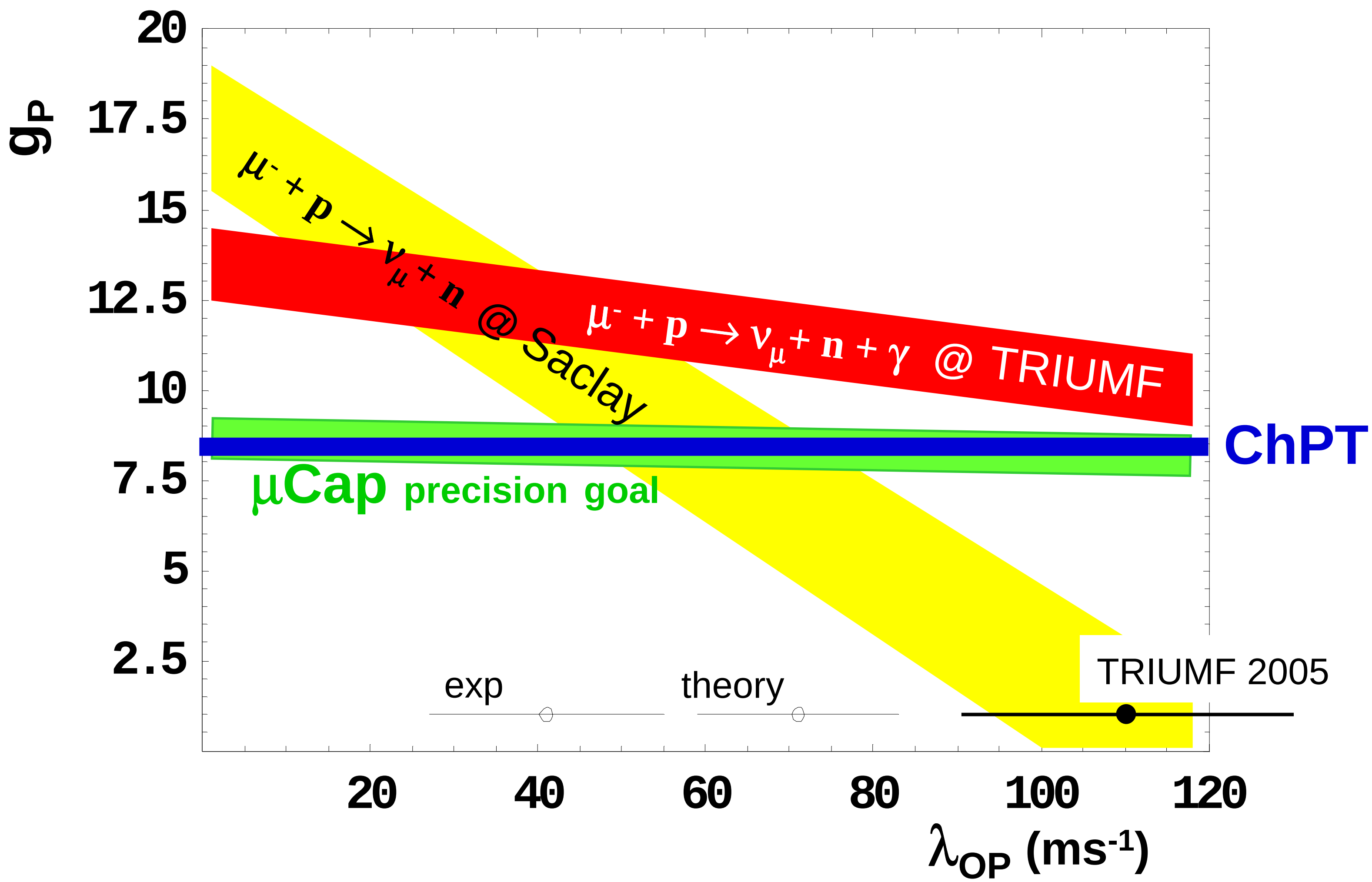


- Interpretation requires knowledge of ppμ population
- Strong dependence on hydrogen density ϕ

rate proportional to H_2 density ϕ !

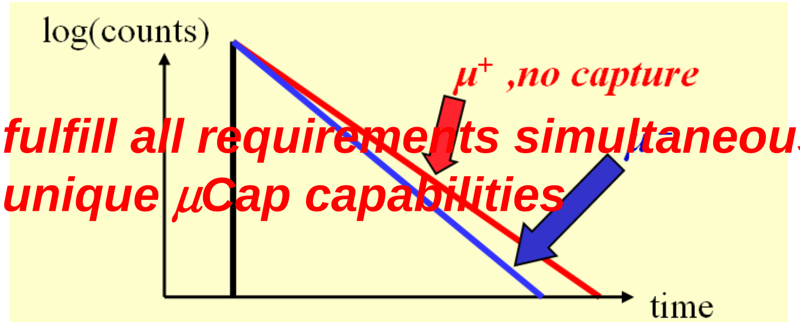


Precise Theory vs. Controversial Experiments



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

μCap Experimental Strategy



fulfill all requirements simultaneously
unique μCap capabilities

- **Lifetime method**
  10^{10} $\mu \rightarrow e\bar{\nu}\nu$ decays
  measure $\tau_{\mu-}$ to 10ppm,

  $\rightarrow \Lambda_S = 1/\tau_{\mu-} - 1/\tau_{\mu+}$ **to 1%**

- **Unambiguous interpretation**
  capture mostly from F=0 μp state at 1% LH_2 density

- **Clean μ stop definition in active target (TPC)**
  to avoid: μZ capture, 10 ppm level

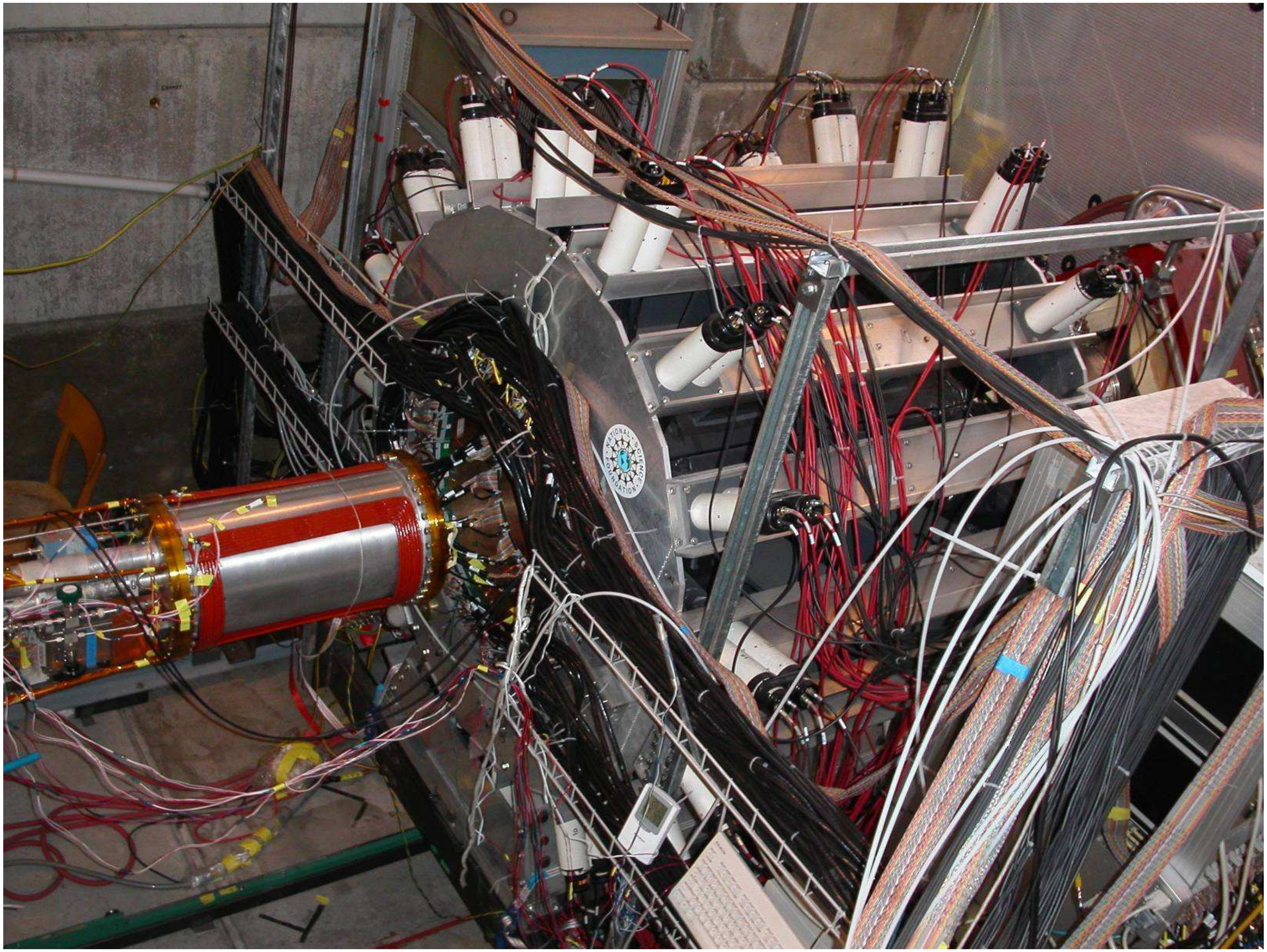
- **Ultra-pure gas system and purity monitoring**
  to avoid: $\mu p + Z \rightarrow \mu Z + p$, ~10 ppb impurities

- **Isotopically pure "protium"**
  to avoid: $\mu p + d \rightarrow \mu d + p$, ~1 ppm deuterium

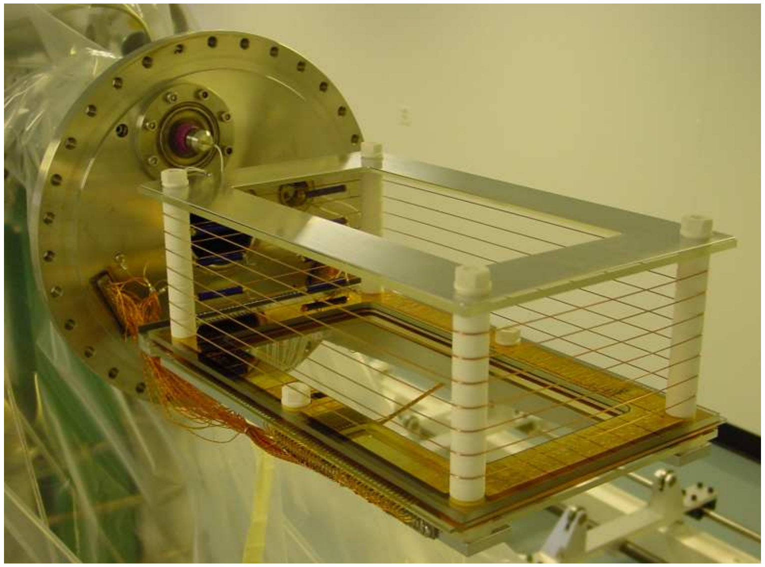
  diffusion range ~cm

μCap Detector

Reality 2004



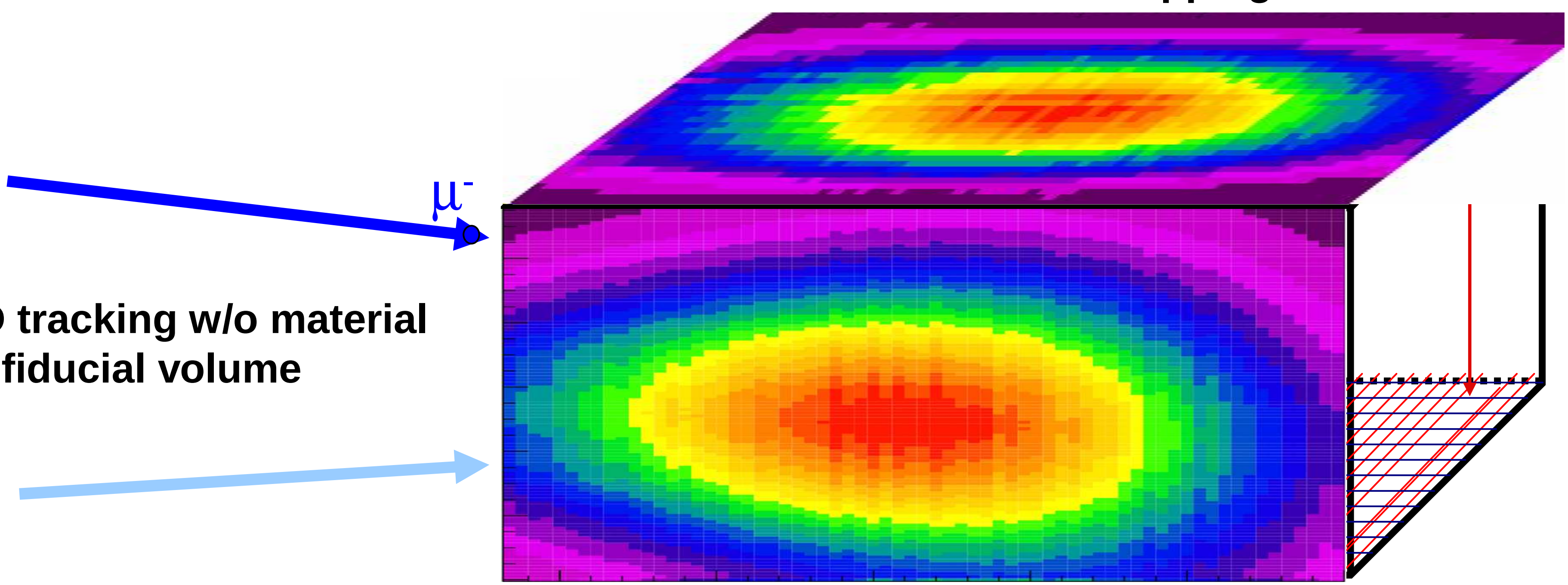
Muon Stops in Active Target



10 bar ultra-pure hydrogen, 1.16% LH_2
2.0 kV/cm drift field
~5.4 kV on 3.5 mm anode half gap
bakeable glass/ceramic materials

Operation with pure H_2 challenging, R&D @ PNPI, PSI

Observed muon stopping distribution



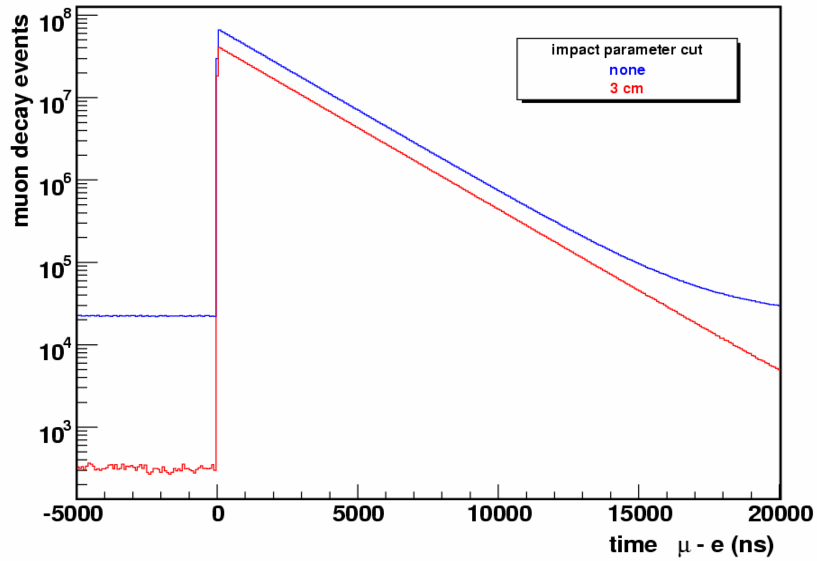
3D tracking w/o material in fiducial volume

Time Spectra

μ-e impact parameter cut

huge background suppression

diffusion (deuterium) monitoring

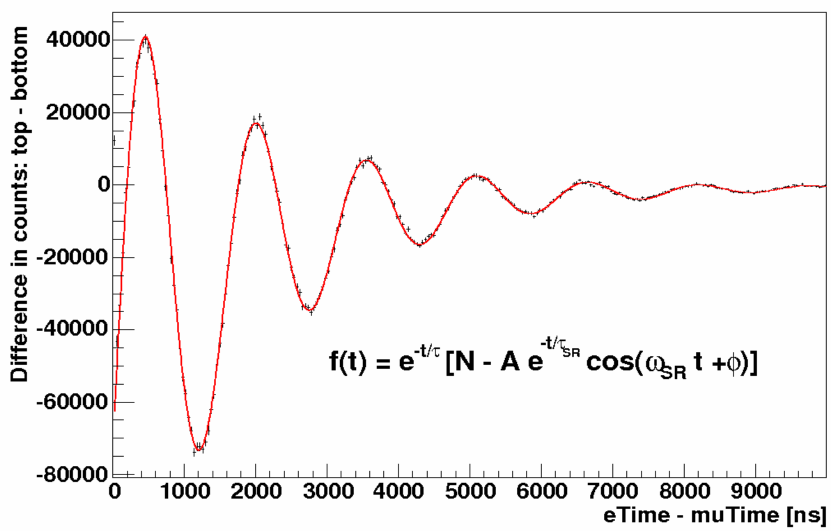


μ^-

μ^+ as reference

identical detector systematics

different physics



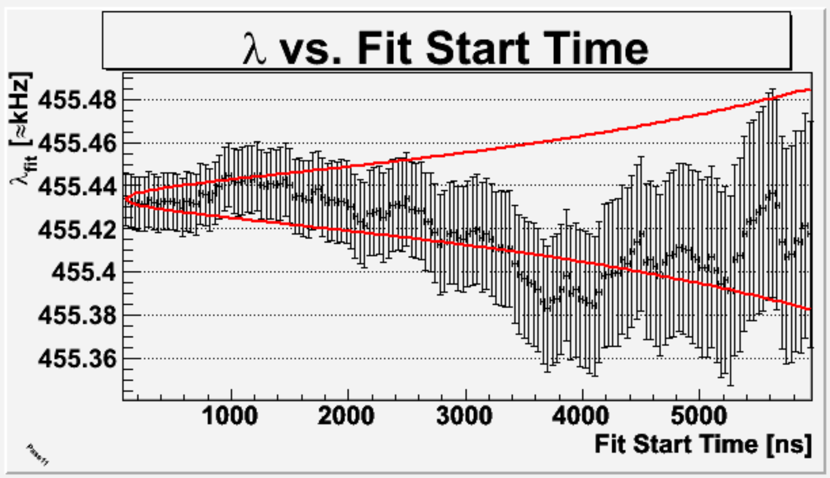
μ^+

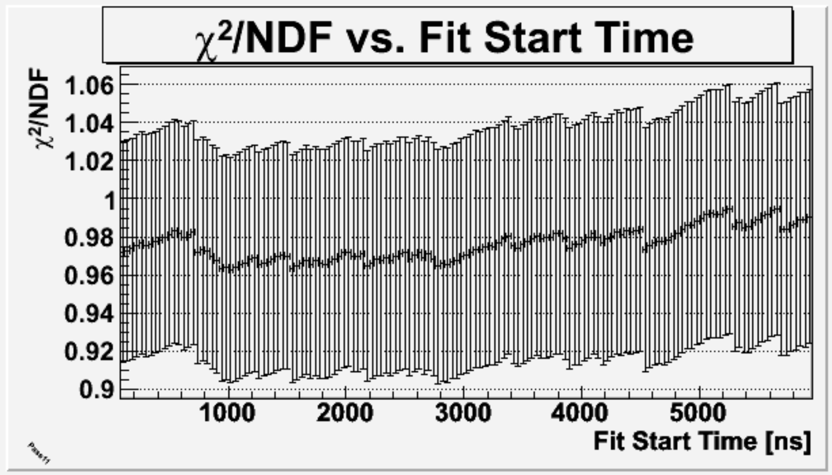
μSR
in 50G

blinded master clock frequency

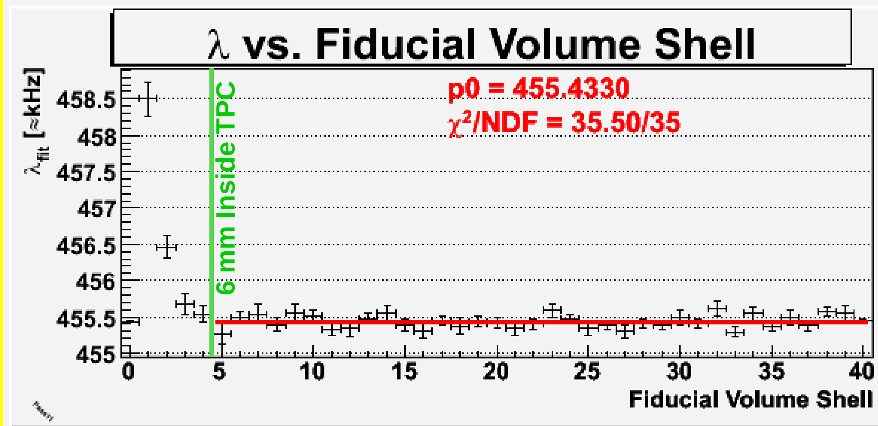
Consistency Studies

Start time fit

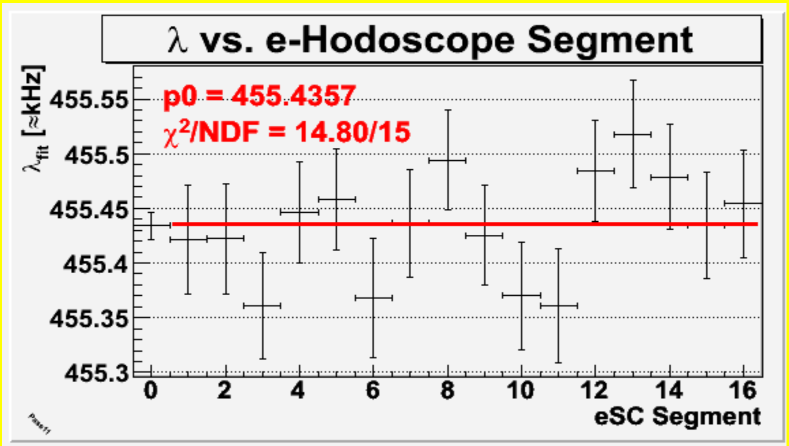




TPC fiducial cuts



Event selection cuts



μCap Unique Capabilities: Impurities

rare impurity capture $\mu Z \rightarrow (Z\text{-}1)+n+\nu$

Λ_Z **(C, N, O) ~ (40-100) x** Λ_S

~10 ppb purity required

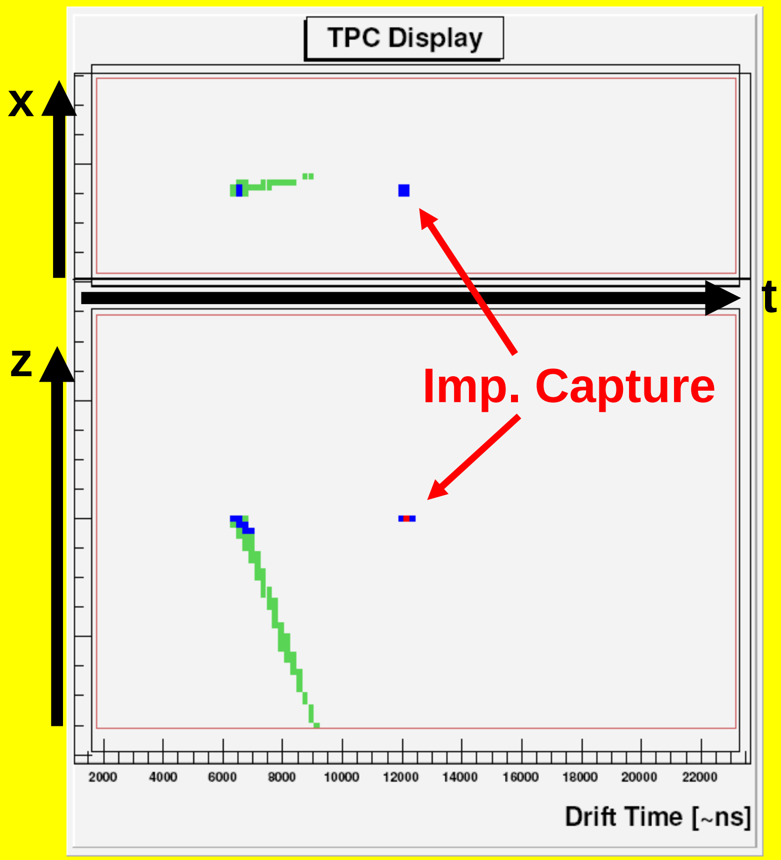
Hardware

Circulating Hydrogen Ultrahigh Purification System

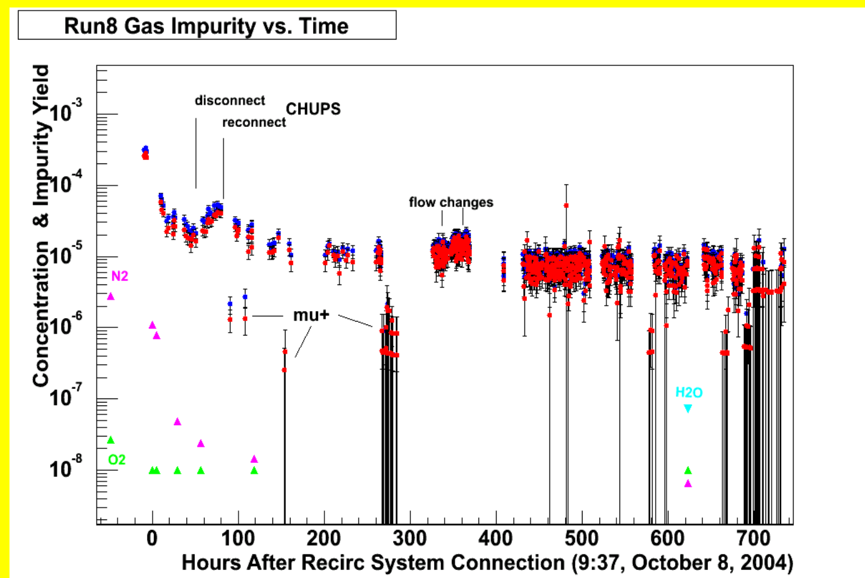
Gas chromatography

CRDF 2002, 2005

Diagnostic in TPC



Results



- **c_N, c_O < 7 ppb, c_{H_2O}~30 ppb**
- **correction based on observed capture yield**

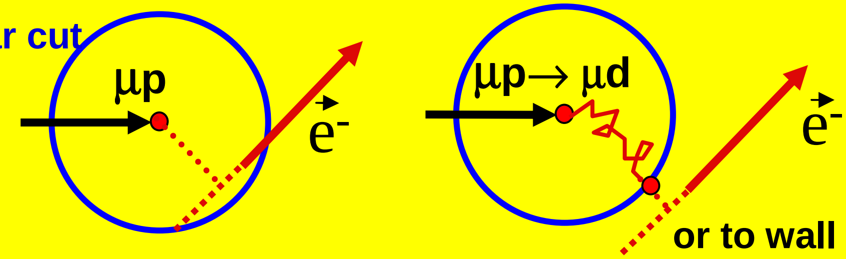
μCap Unique Capabilities: μp, μd diffusion

μp + d → μd + p (134 eV)

large diffusion range of μd

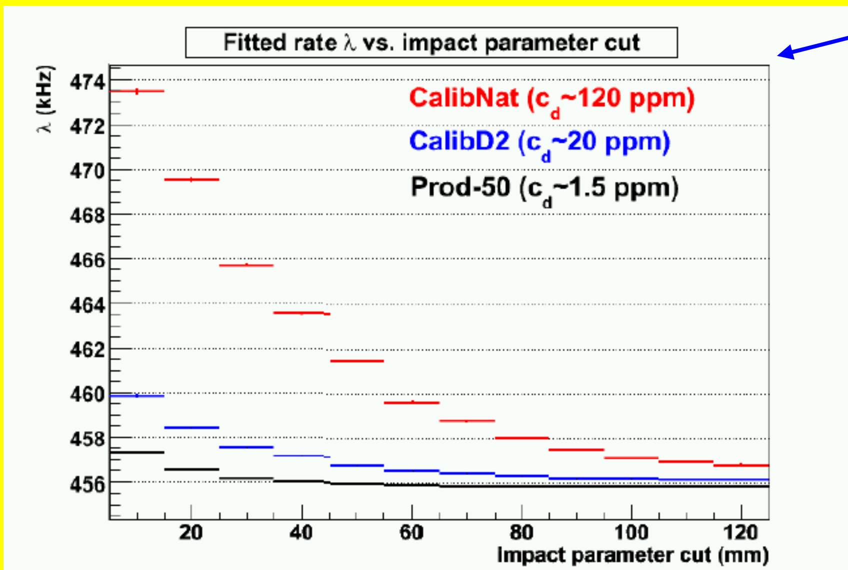
< 1 ppm isotopic purity required

μ-e impact par cut



Diagnostic:

- λ vs. μ-e vertex cut



- AMS, ETH Zurich

Results

- Directly from data

  c_d= 1.49 ± 0.12 ppm

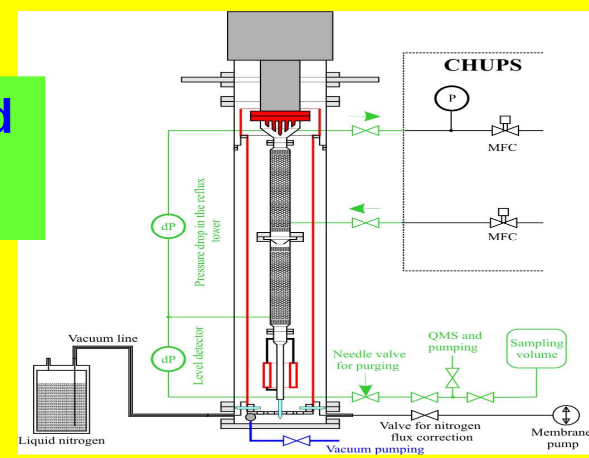
- AMS (2006)

  c_d= 1.44 ± 0.15 ppm

On-site isotopic purifier 2006 (PNPI, CRDF)

World Record

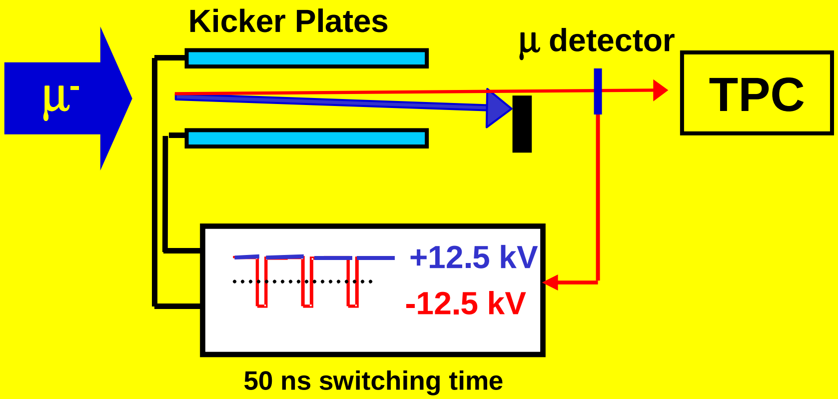
c_d < 0.1 ppm

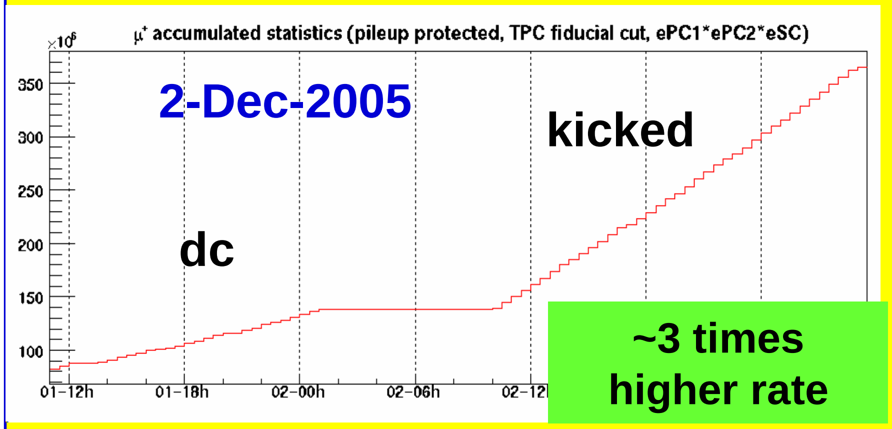


μCap Unique Capabilities: Muon-On-Demand

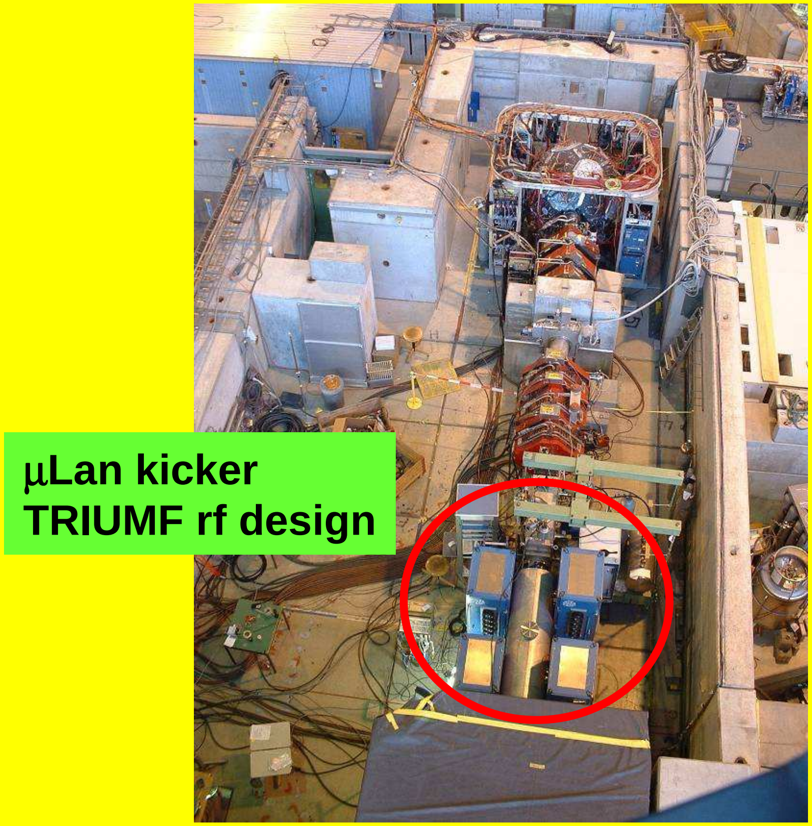
Single muon requirement (to prevent systematics from pile-up)
limits accepted μ rate to ~ 7 kHz,
while PSI beam can provide ~ 70 kHz

Muon-On-Demand concept





Beamline



Corrections & preliminary results data 2004

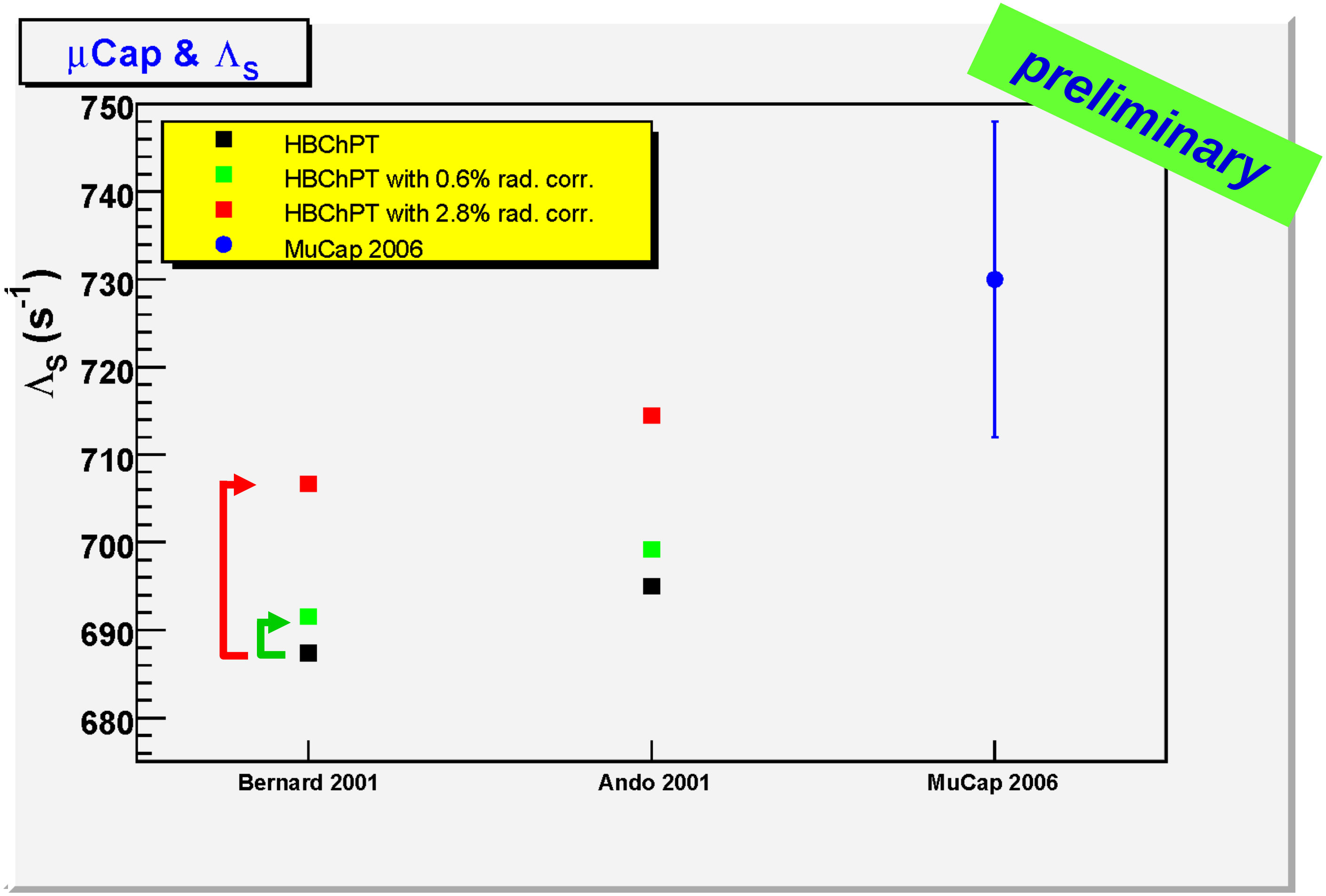
internal	correction (s^{-1})	uncertainty (s^{-1})
statistics		12
Z>1 impurities	-14	6
μ stop definition		2
μd diffusion	-12	1
μp diffusion	-3	1
μ+p scatter	-5	2
pileup	1	1
det combination		5
clock		3
total systematics	-33	9
total sys & stat	-33	15

external	correction (s^{-1})	uncertainty (s^{-1})
ppμ formation	19	4
λ_{OP} transition	5	2.3
$1/\tau$ in μp system	12	
$1/\tau$ PDG		8.3
total external	36	9.5

Unblinding

	MuCap			PDG
	events	$\lambda=1/\tau$ (s^{-1})	Λ_S(s^{-1})	$1/\tau$(s^{-1})
μ^-	0.16×10^{10}	455854 ± 15	730 ± 18	
μ^+	0.06×10^{10}	455164 ± 28		455160 ± 8.3

μCap and Λ_S calculations



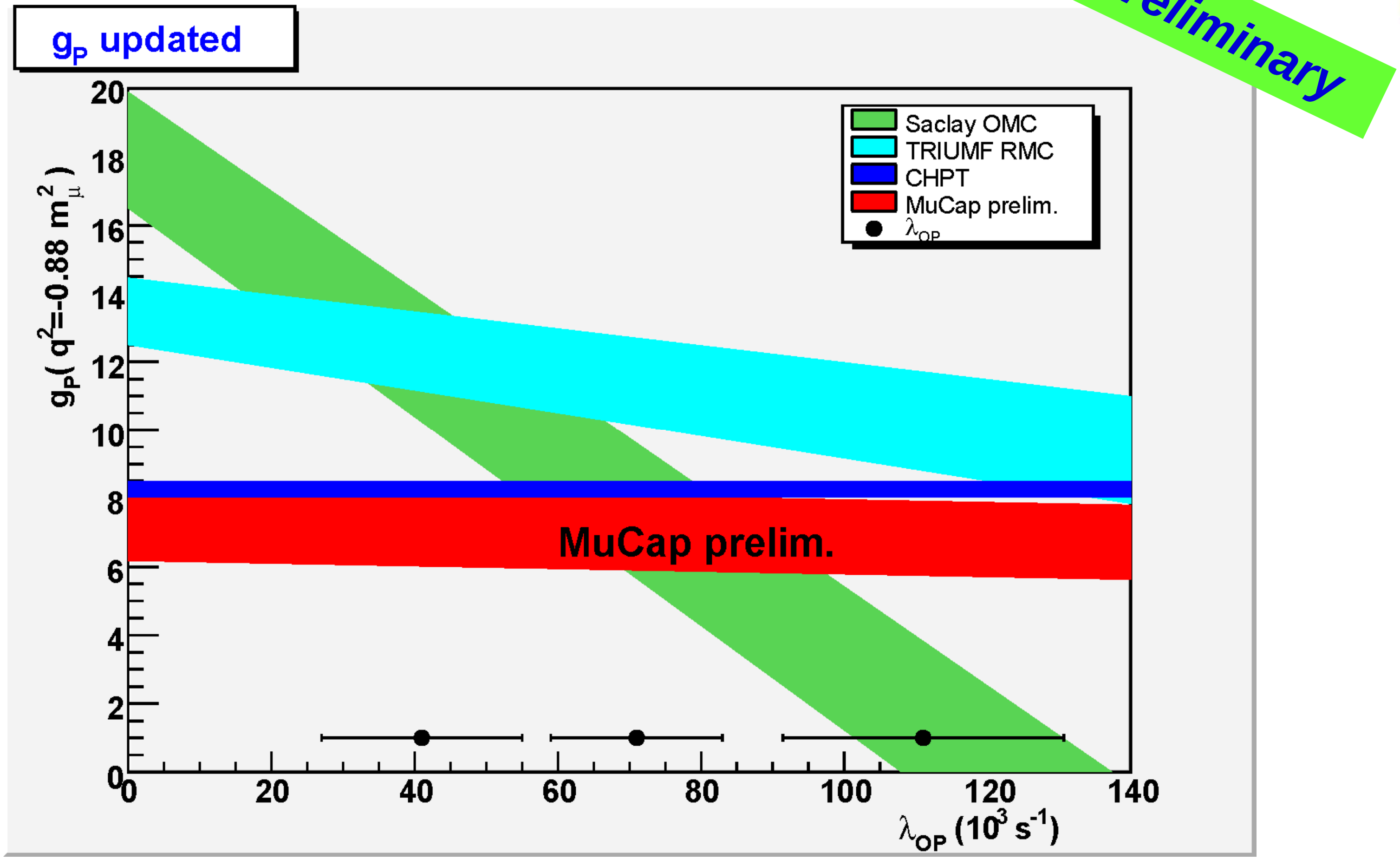
rad. corrections

- *Goldman (1972)*
- *Czarnecki Marciano Sirlin (2006)* *private comm. preliminary*

MuCap agrees within ~1σ with Λ_S theory

Thorough theory studies needed for next MuCap 1% stage !

μCap and g_P



- within one sigma of chiral prediction, no dramatic discrepancy
- nearly independent of molecular physics (λ_{OP})
- has overlap with old OMC, barely with recent RMC result
- final result ('06 and '07 data) will reduce error to 7%

Summary and Plans

preliminary

- **Preliminary results 2004 data**

	μCap	theory*
Λ_S	730 ± 18	707 - 715
g_P	6.95 ± 1.09	8.26 ± 0.23

- **2006 data and 2007 plans**
  - 10^{10} events μ^- achieved in 2006
  - 10^{10} events μ^+ and suppl. measurements in 2007

    ➡ Λ_S with 1% uncertainty
  - μ+d proposal planned for 2007

- **Ideas for ultrapure H_2 TPC welcome**

**including Czarnecki et al. rad. corrections*