Muon Capture and Muon Lifetime

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muon capture on proton

$\mu^- + \mathbf{p} \rightarrow \nu_\mu + \mathbf{n}$

Λ **to 1 %**

Nucleon form factors, chiral symmetry of QCD

μ Cap experiment

g_P to < 7% (3%)

muon capture on deuteron

$\mu^- + \mathbf{d} \rightarrow \nu_\mu + \mathbf{n} + \mathbf{n}$

Λ **to 1 %**

Basic EW two nucleon reaction, calibrate ν-d reactions

μD project

muon decay

$\mu^+ \rightarrow \mathbf{e}^+ + \nu_\mathbf{e} + \overline{\nu}_\mu$

$\tau_{\mu+}$ **to 1 ppm**

Fermi Coupling Constant

μ Lan experiment

G_F to < 1ppm

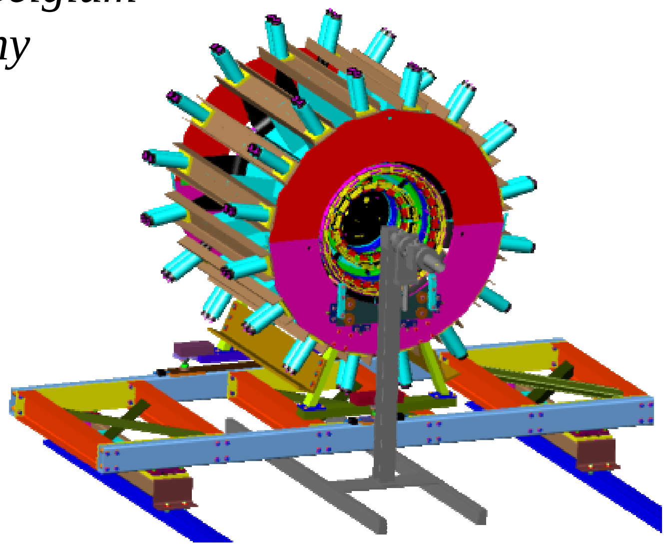
Precision Measurement of Muon Capture on the Proton

“mCap experiment”

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

www.npl.uiuc.edu/exp/mucapture/

Petersburg Nuclear Physics Institute (PNPI), Gatchina,Russia
Paul Scherrer Institut, PSI, Villigen, Switzerland
University of California, Berkeley, UCB and LBNL, USA
University of Illinois, Urbana-Champaign, USA
Universite Catholique de Louvain, Belgium
TU Munich,Garching, Germany
Boston University, USA
University of Kentucky, USA



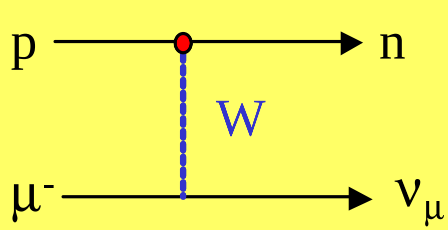
@ PSI

Scientific case: μ+p capture

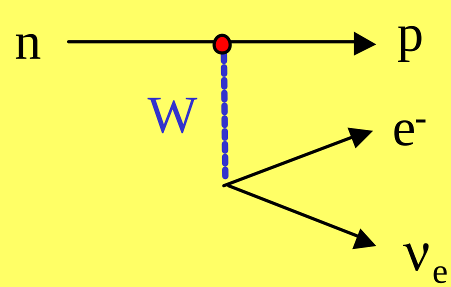
μ capture probes axial structure of nucleon

μ capture

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



β decay



hadronic vertex dressed by QCD Þ **q^2 dependent form-factors**

dual role of m

- μ acts as well defined probe of hadronic structure
  QCD tests, **pseudoscalar form-factor g_P, chiral symmetry**
- Standard Model symmetries of lepton-quark interaction

Nucleon charged current at $q^2 = -0.88\, m_\mu^2$

$J_a = V_a - A_a$

$V_a = g_V(q^2)\, g_a \quad + \; ig_M(q^2)/2M\; s_{ab}\, q^b \; + \; g_S(q^2)/m\; q_\alpha$

$A_a = g_A(q^2)\, g_a\, g_5 + \; g_P(q^2)\, q_a/m\; g_5 \quad + ig_T(q^2)/2M\; \sigma_{\alpha\beta}\, q^\beta\, \gamma_5$

nucleon weak formfactors g_V, g_M, g_A

- determined by SM symmetries and data
- contribute <0.4% uncertainty to L_S

$\mathbf{g_V = 0.9755(5)}$

$\mathbf{g_M = 3.5821(25)}$

$\mathbf{g_A = 1.245(3)}$

remains

$\mathbf{g_P = ?}$

- Vector current in SM determined via CVC
  $g_V(0)=1$, $g(q^2)=1+q^2\, r^2/6$, $r_V^2=0.59$ fm^2
  $g_M(0)=\mu_p-\mu_n-1=3.70589$, $r_M^2=0.80$ fm^2
  q^2 dependence from e scatt.
- Axial vector FF from experiment
  $g_A(0)=1.2670(35)$, $r_A^2=0.42\pm0.04$ fm^2
  q^2 dependence from quasi-elastic ν scattering,
  π e-production
- 2nd class FF g_S, g_T forbidden by G symmetry, e.g.
  $g_T/g_A=-0.15 \pm 0.15$ (exp),
  -0.0152 ± 0.0053(QCD sum rule, up-down mass difference)
- error from V_{ud} = 0.16 %

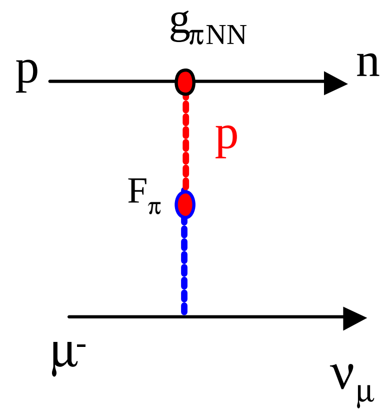
μCap

pseudoscalar form factor g_P

PCAC:

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

$g_P = 8.7$



heavy baryon chiral perturbation theory:

$$g_P(q^2) = \frac{2 m_\mu g_{\pi NN} F_\pi}{m_\pi^2 - q^2} - \frac{1}{3} g_A(0) m_\mu M r_A^2$$

$g_P = (8.74 \pm 0.23) - (0.48 \pm 0.02) = 8.26 \pm 0.23$

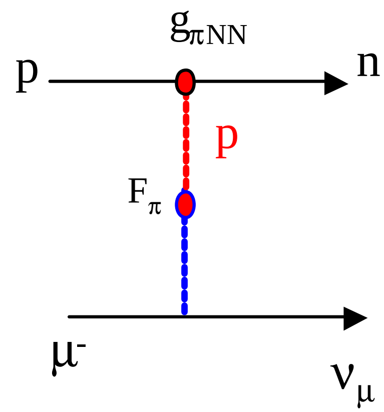
Λ calculations O(p^3) show good convergence: 100 % LO, 25 % NLO, 3 % NNLO
delta effect small

$g_{\pi NN}$
13.31(34)
13.0(1)
13.05(8)

author	year	g_P	Λ_S	Λ_T	comment
Primakoff	1959		664(20)	11.9(7)	smaller g_A
Opat	1964		634	13.3	smaller g_A
Bernard et al	1994	8.44(23)			
Fearing et al	1997	8.21(9)			
Govaerts et al	2000	8.475(76)	688.4(38)	12.01(12)	
Bernard et al	2000/1		687.4 (711*)	12.9	NNLO, small scale
Ando et al	2001		695 (722*)	11.9	NNLO

*NLO result

pseudoscalar form factor g_P



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

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g_P

1. **fundamental and least known weak nucleon FF**
2. **solid theoretical prediction at 2-3% level**
3. **basic test of QCD symmetries**

Recent reviews:

T. Gorringe, H. Fearing, ***Induced pseudoscalar coupling of the proton weak interaction***, nucl-th/0206039, Jun 2002

V. Bernard et al., ***Axial Structure of the Nucleon***, Nucl. Part. Phys. 28 (2002), R1

Experimental information on g_P

Ordinary **M**uon **C**apture $m^- + \mathbf{p}$ ® $n_m + \mathbf{n}$

BR~10^{-3}, 8 experiments 1962-82, BC, neutron, electron detection

"in principle" most direct g_P measurement

Radiative **M**uon **C**apture $m^- + \mathbf{p}$ ® $n_m + \mathbf{n} + g$

BR~10^{-8}, TRIUMF (1998), E_γ>60 MeV, 297 ± 26 events

closer to pion pole → ***3x sensitivity of OMC***

theory more involved (min substitution, ChPT)

- Muon capture in nuclei

  m + ^{3}**He** ® n + ^{3}**H** Λ_{st}=1496 ±4 s^{-1} PSI (1998)

  $g_p = g_p^{th}$ (1.08 ±0.19) error dominated by 3-N theory

  correlation measurements

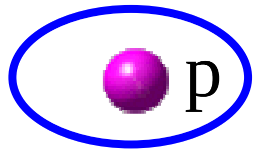
- Neutrino scattering

- π electro production at threshold

μCap

experimental challenges

$\mu^- p\ (\uparrow\downarrow) \rightarrow \nu_\mu + n$



m^- ® $\mathbf{e+\bar{n}_e+n_m}$

(Rich) physics effects

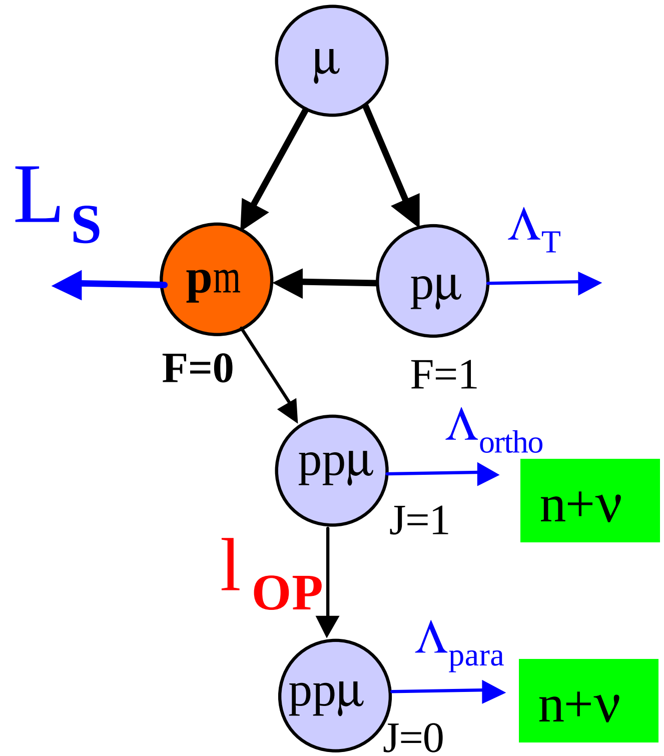
- **Interpretation:**
  where does capture occur **?**

  Critical because of strong spin dependence of V-A interaction

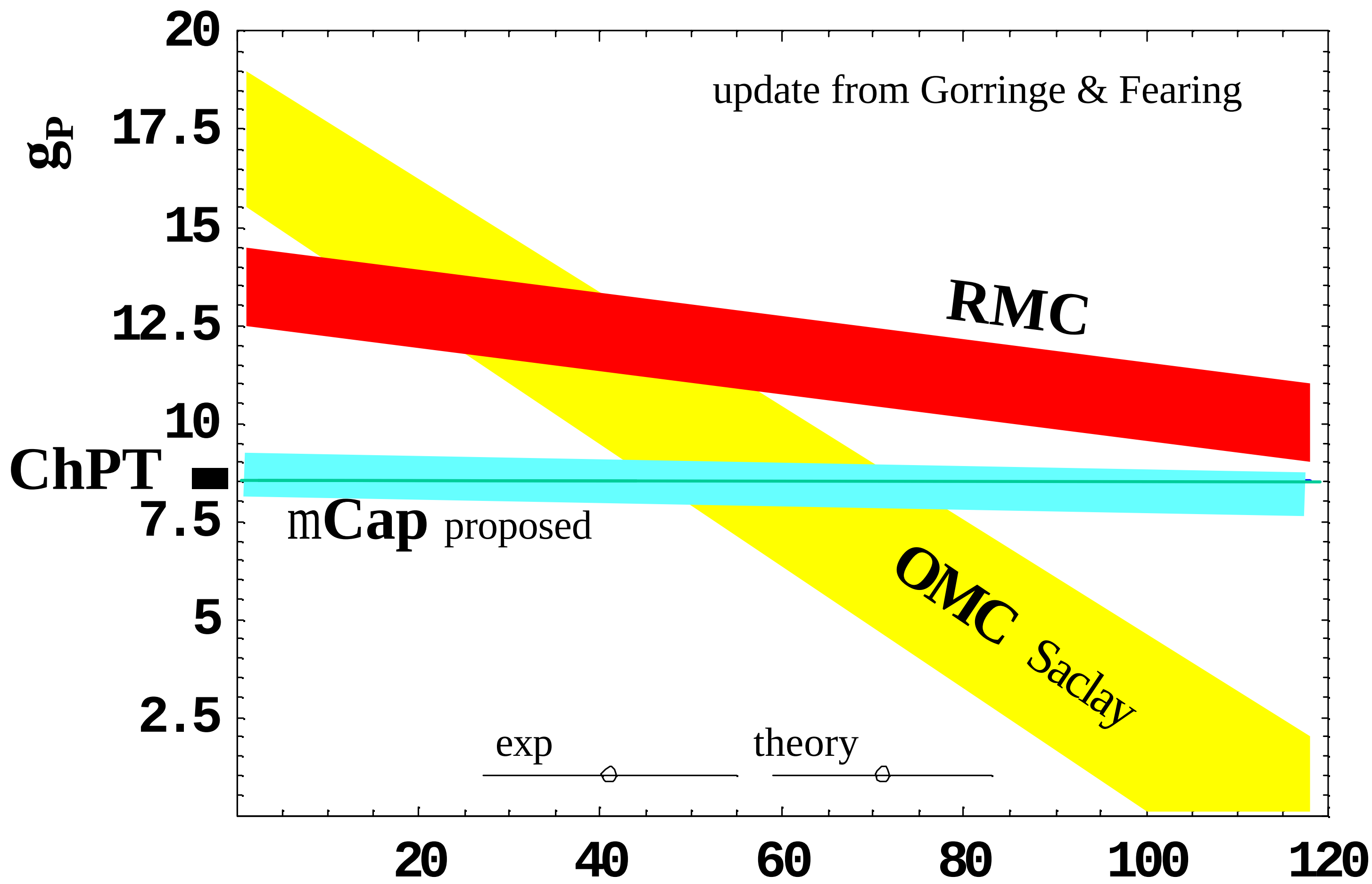
- **Background:**
  Wall stops and diffusion
  Transfer to impurities m**p+Z** ® m**Z +p**

- **Rate and statistics (BR = 10^{-3})**

- m**SR effect for** m^+



Muon Capture and g_P

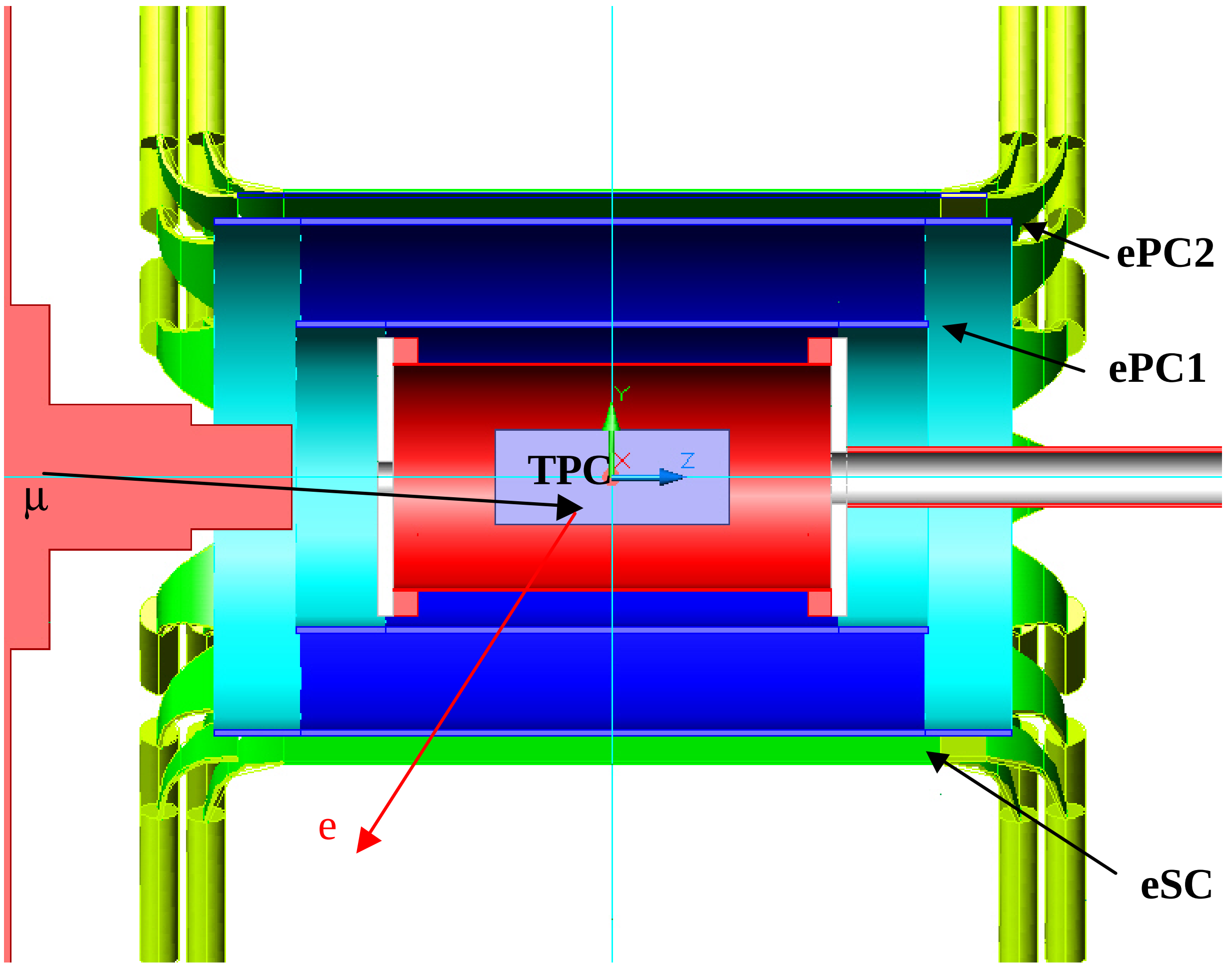


- OMC not precise, ambiguous interpretation
- RMC 4s discrepancy exp/th
- no overlap theory & OMC & RMC

mCap experimental strategy

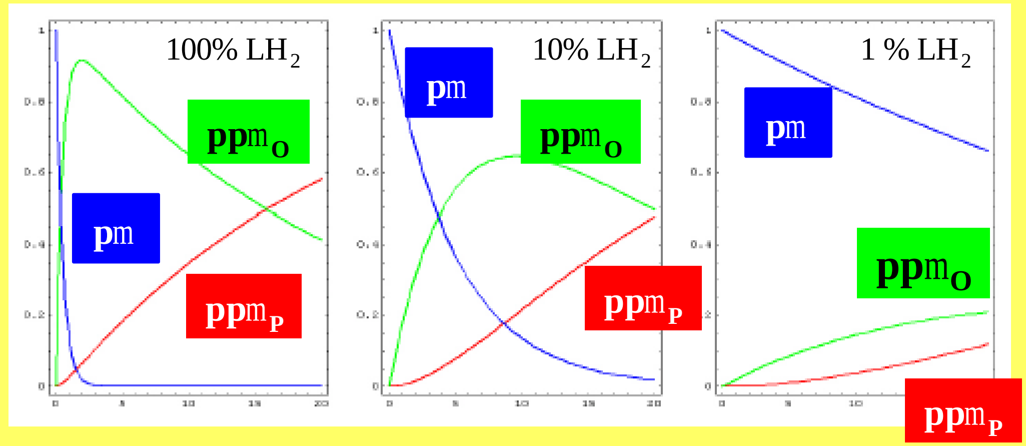
New idea: **active target of ultra-pure H_2 gas 10 bar**

measure t_{m+} **and** t_{m-} Þ $L_S = 1/t_{m-} - 1/t_{m+}$, t_m **to** 10^{-5}



experimental strategy

Physics



time (μs)

- **Unambigous interpretation**
  At low density (1% LH_2) mostly capture from m**p(F=0)** atomic state.

- **Clean muon stop definition:**
  Wall stops and diffusion eliminated by 3-D muon tracking

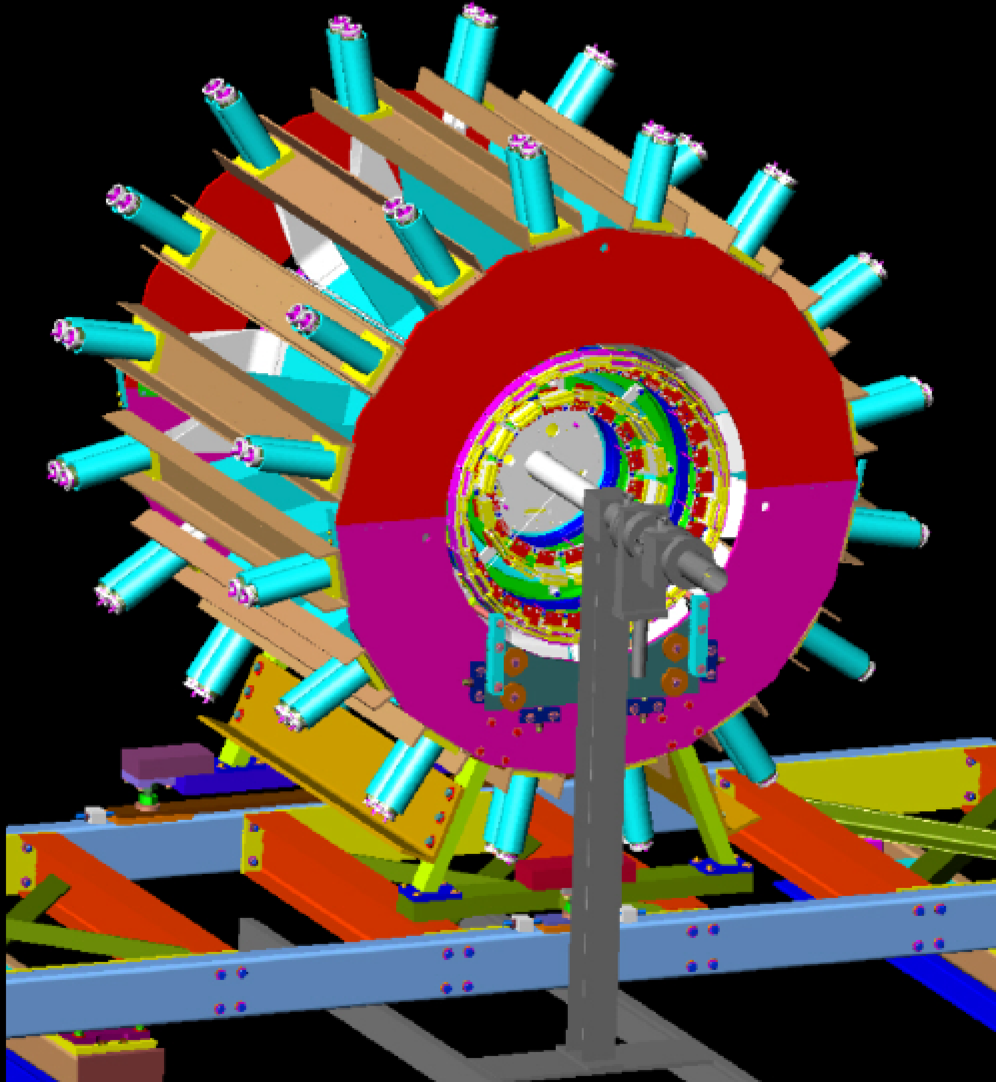
- **In situ gas impurity control** ($c_Z<10^{-8}$, $c_d<10^{-6}$)
  hydrogen chambers bakeable to 150 C, continuous purification
  TPC monitors capture on impurity and transfer to deuterium
  10^{-8} sensitivity with gas chromatograph

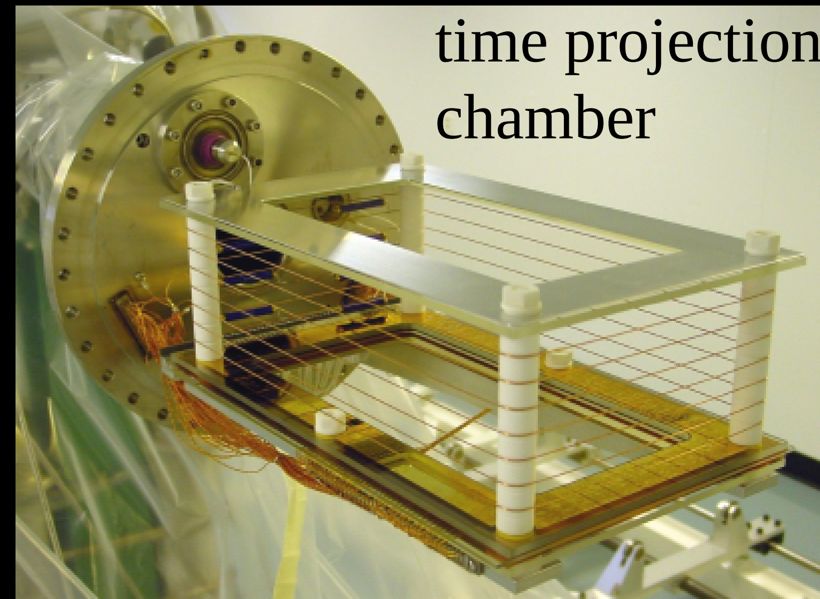
- m^+**SR**: calibrated with tranverse field 70 G

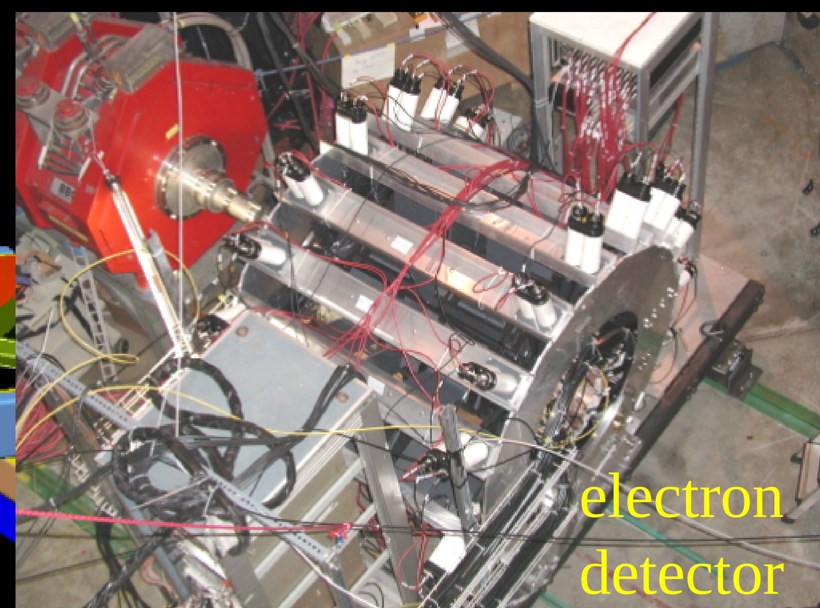
Statistics

- **10^{10} statistics**: Complementary analysis methods

μCap detector



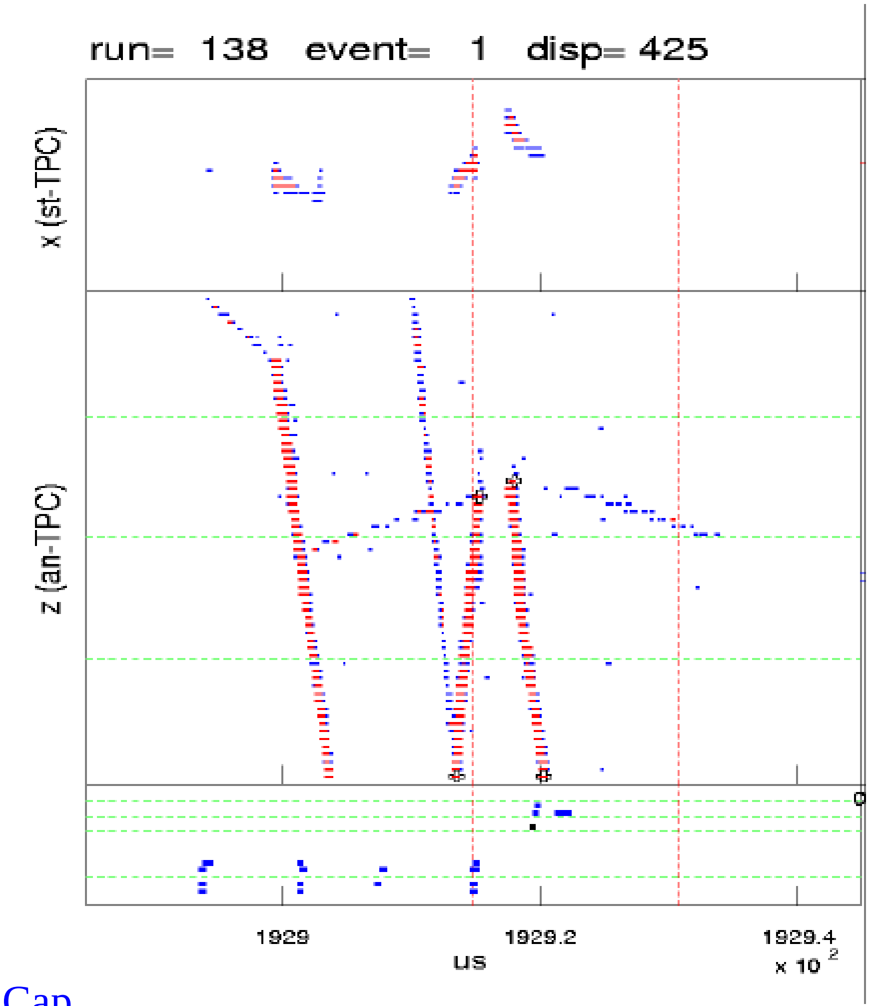




μCap

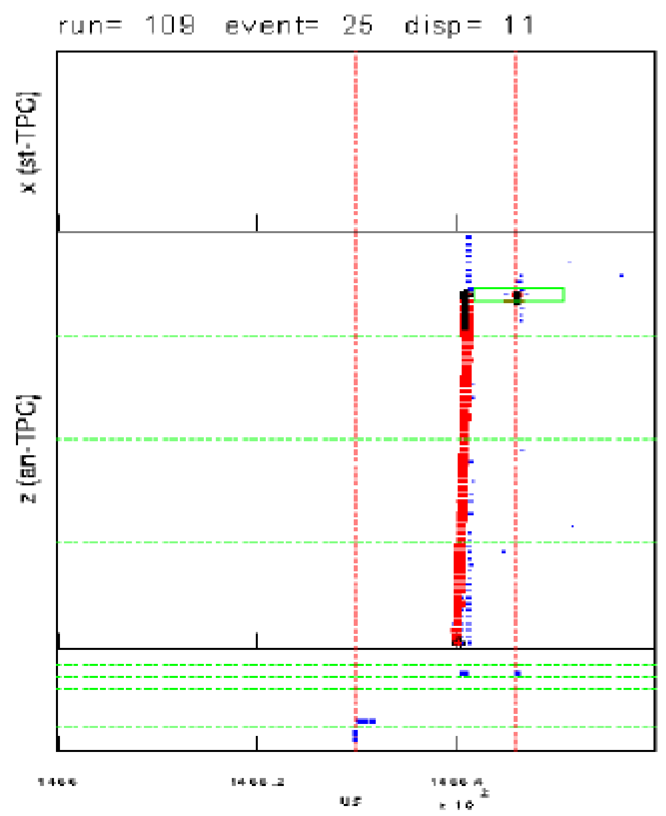
TPC tracking

muon decay



rare impurity capture

$\mu + Z \rightarrow Z' + n + \nu$



μCap

mCap status and plans

Planned schedule mCap I

- technical proposal spring 2001, received “high priority status”
- development final detector components and high purity chambers, 2001-2002
- commissioning fall 2002, spring 2003
- data run 2003, 2004 (Λ_S 3%, 1%)

mCap II with muon-on-request beam* (2004, 2005)
chopper development and μ^+ result from μLan

- goal Λ_S to 0.3 %, g_P 2-3%

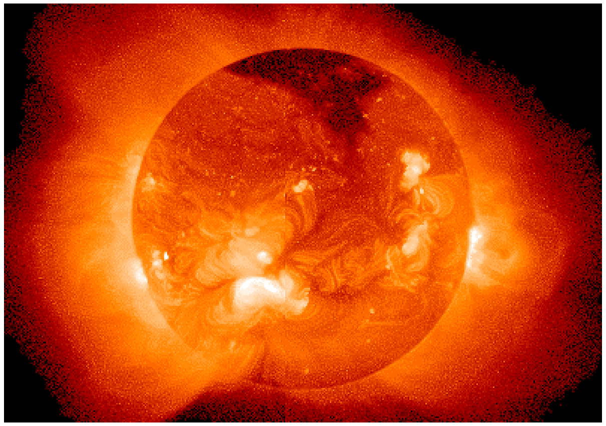
    20-30x exp improvement
    Λ_S similar precision as τ_n
    exp challenges: statistics, purity, atomic physics

*P.K. et al, PSI letter of intent 1998

mD project

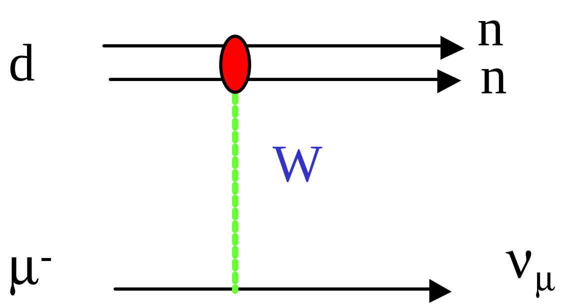
m + d ® n + n + n

P.K and J.W.Chen et al.

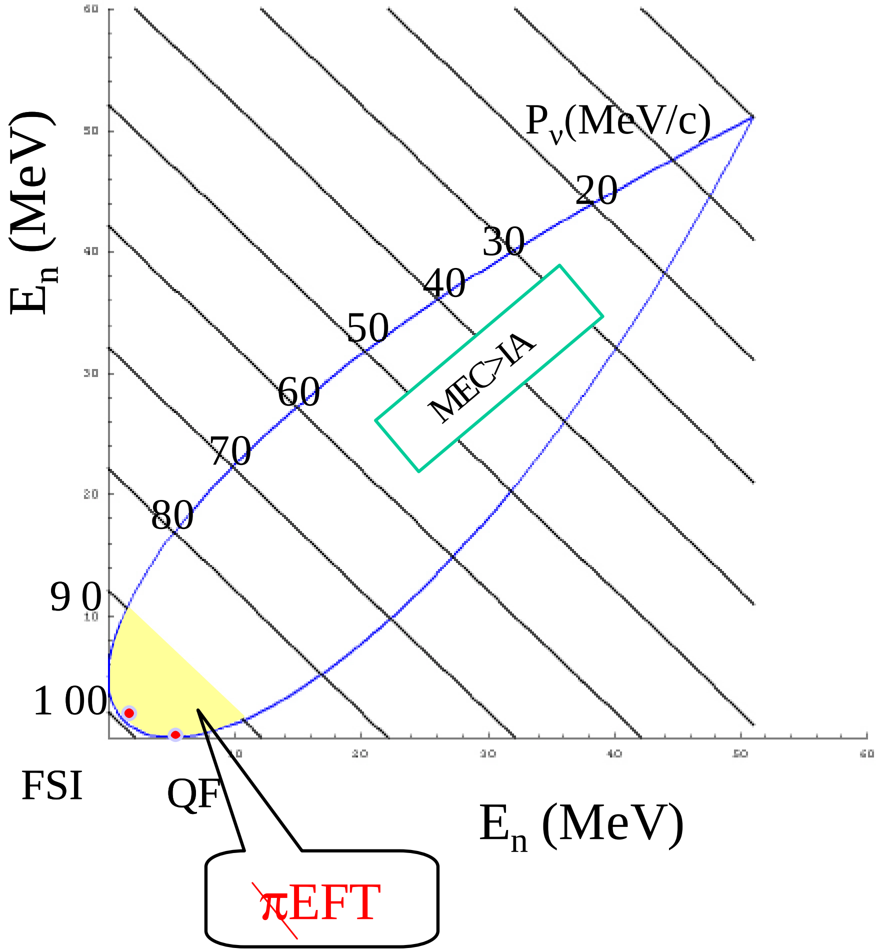


- fundamental EW 2-body reaction
- high astrophysics impact: “calibrate the sun”
- 10x precision improvement feasible by μCap techniques

Physics motivation



- nucleon FF dependence similar to μ+p
  g_P dependence ~20%
- 2-N physics important (d wavefunction, a_{nn}, …)
- MEC's contribute, dominantly Δ isobar current
  EFT: two-body currents parametrized by
  LEC L_{1A} (isovector, axial) 4N vertex
- 3 body final state



$\not{\pi}$EFT: Class of axial current reactions related by single unknown parameter L_{1A}

- basic solar fusion reaction

$$p + p \rightarrow d + e^+ + \nu$$

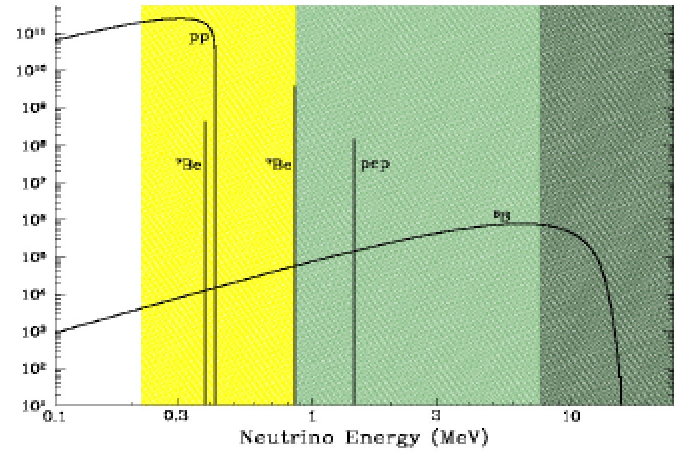
- key reactions for solar neutrino detection and supernova neutrino

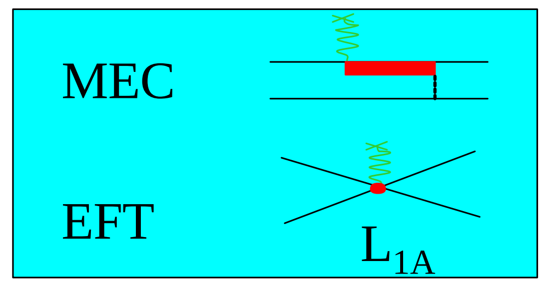
$$\nu + d \rightarrow p + p + e$$

$$\nu + d \rightarrow p + n + \nu$$

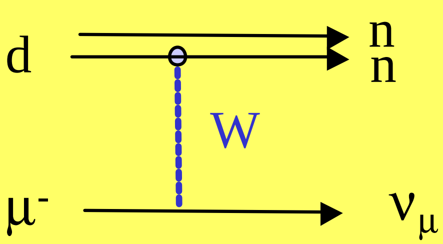
- short distance, axial two body currents,

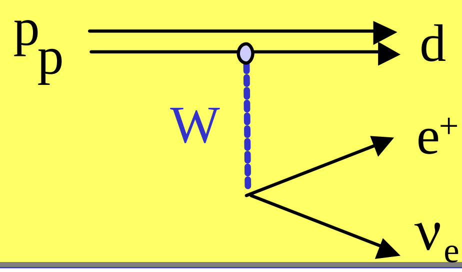
  ab-inito $\not{\pi}$EFT(NNLO) vs. SNPA vs. MEEFT





μd capture close terrestrial analogue





- **soft enough ?**
- **precision measurement possible ?**

L_{1A} estimates

Butler, Chen, Vogel

process	value (fm^3)	status
theory		
Dim.arguments	±5	
2 nucleon		
$\nu_e+d \rightarrow e^-+p+p$	±2	Orland ??
$\nu+d \rightarrow e^++n+n$	3.6 ±5.5	reactor, optimistic
$\nu+n+p$		
ES,CC,NC	?	SNO self calibration
$\mu+d \rightarrow n+n+n$	**±1.5 ?**	**1% Λ measurement theory uncertainty?**
3 nucleon		
$^3H \rightarrow {}^3He+e^++n$	6.5 ± 2.4	
$\mu{}^3He \rightarrow {}^3H+\nu$	?	g_P from other source
astro		
Helioseismology	7.0 ± 5.9	pp fusion, but no other SoMo uncertainties

- Ando et al (2002)
  - EFT with T decay constraint
  - uncertainty **~1%**
  - 2 body currents 6.5%
  - High E_{nn} contribution negligible
  - → **1% experiment on Λ_d measures L_{1A} to ~20%**
- Chen (private comm):
  - $\not\pi$EFT, q < 10MeV/c, higher order?

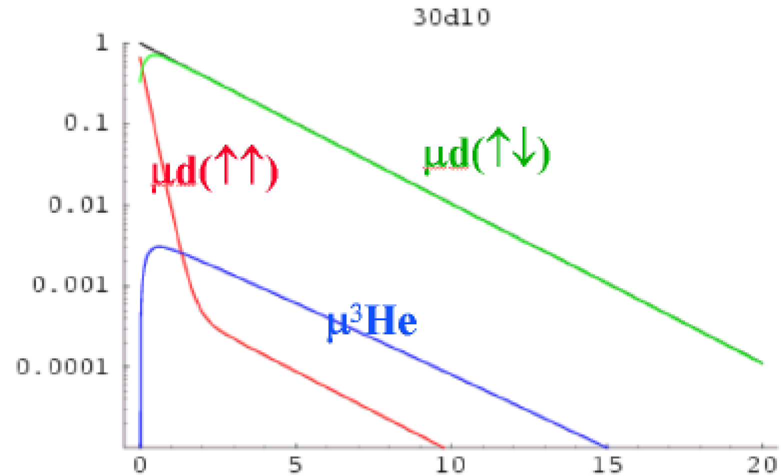
μD

1% precision experiment possible? yes

- **measurement of absolute rate <1% (mD I)**

  Basic lifetime method, new TPC

  Kinetics requires optimized target conditions 80K, 5% density



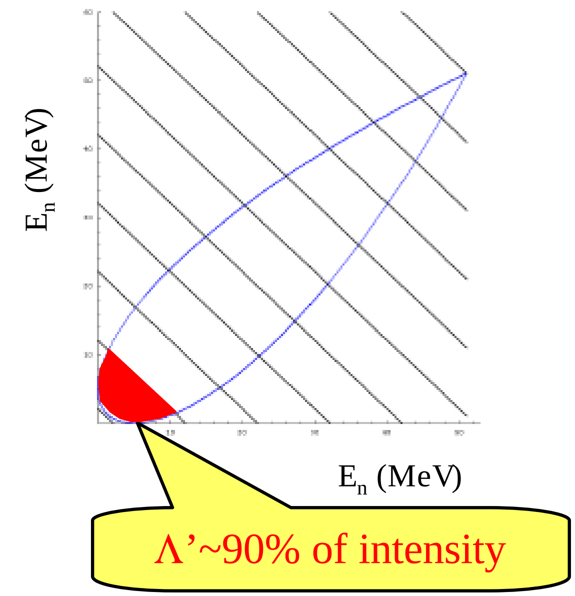
- **measurement of Dalitz Plot 5 % (T_n>10MeV) (mD II)**

  Neutron detector array

  Kinematics determined by angle and δt

- **subtract to determine rate for relevant low energy part L'**

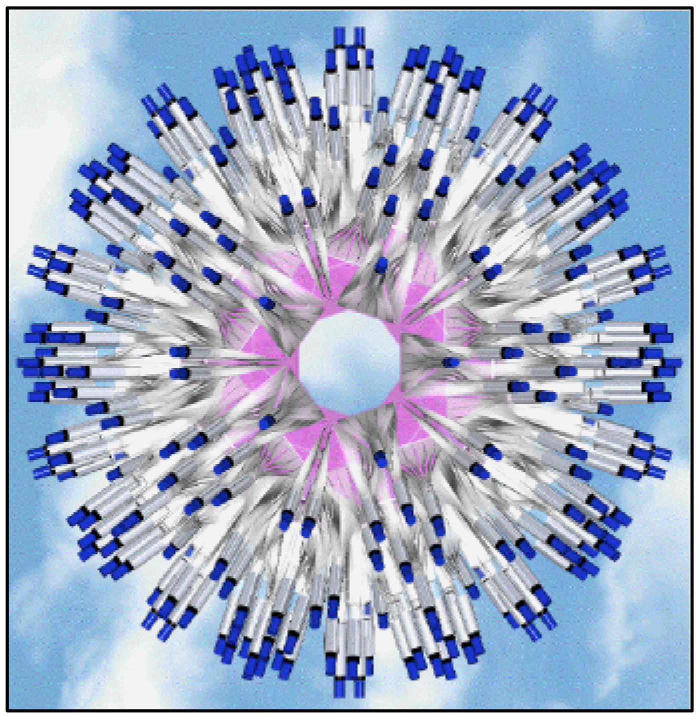
- measure full DP if sufficient physics motivation



μD

mLan experiment:
Precision Muon Lifetime Measurement

University of California at Berkeley
Boston University
University of Illinois at Urbana-Champaign
James Madison University
University of Kentucky



Scientific case: m^+ lifetime + G_F

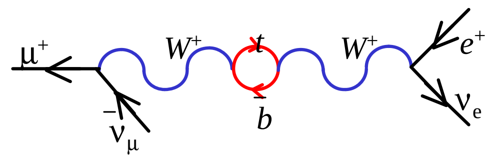
$$\frac{1}{t_m} = \frac{G_F^2 m_m^5}{192 p^3}(1+\Delta q)$$

radiative corrections,
higher order QED

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

precision EW physics
quantum loops

- **fundamental constant of nature**
- **dominant theoretical error (16 ppm) reduced to <0.3 ppm** (2-loop, '99)
- **impressive predictive power in EW sector**
- **dramatic improvement in other EW parameters**

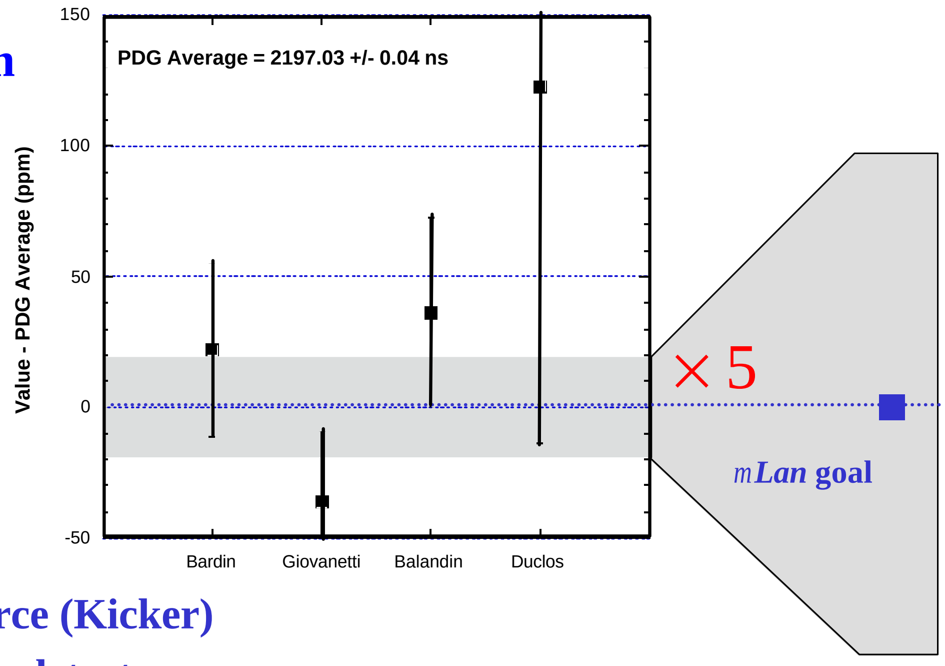


quantity	*symbol*	*value(error)*	*(ppm)*
Fermi constant	G_F	1.16637(1) 10^{-5} GeV^2	9
Fine-structure constant	$\alpha(0)$	1/137.03599976(50)	0.0037
	$\alpha(M_Z^2)$	1/127.934(27)	210
Z boson mass	M_Z	91.1876(21) GeV/c^2	22

experimental efforts at RAL (Riken) and PSI (FAST, mLAN)

mLan summary*

- **Determine m^+ *lifetime* to 1 ppm**
  - **This yields G_F to <1 ppm**
  - ***Helps* g_p determination from m^+ / m^- lifetime difference**

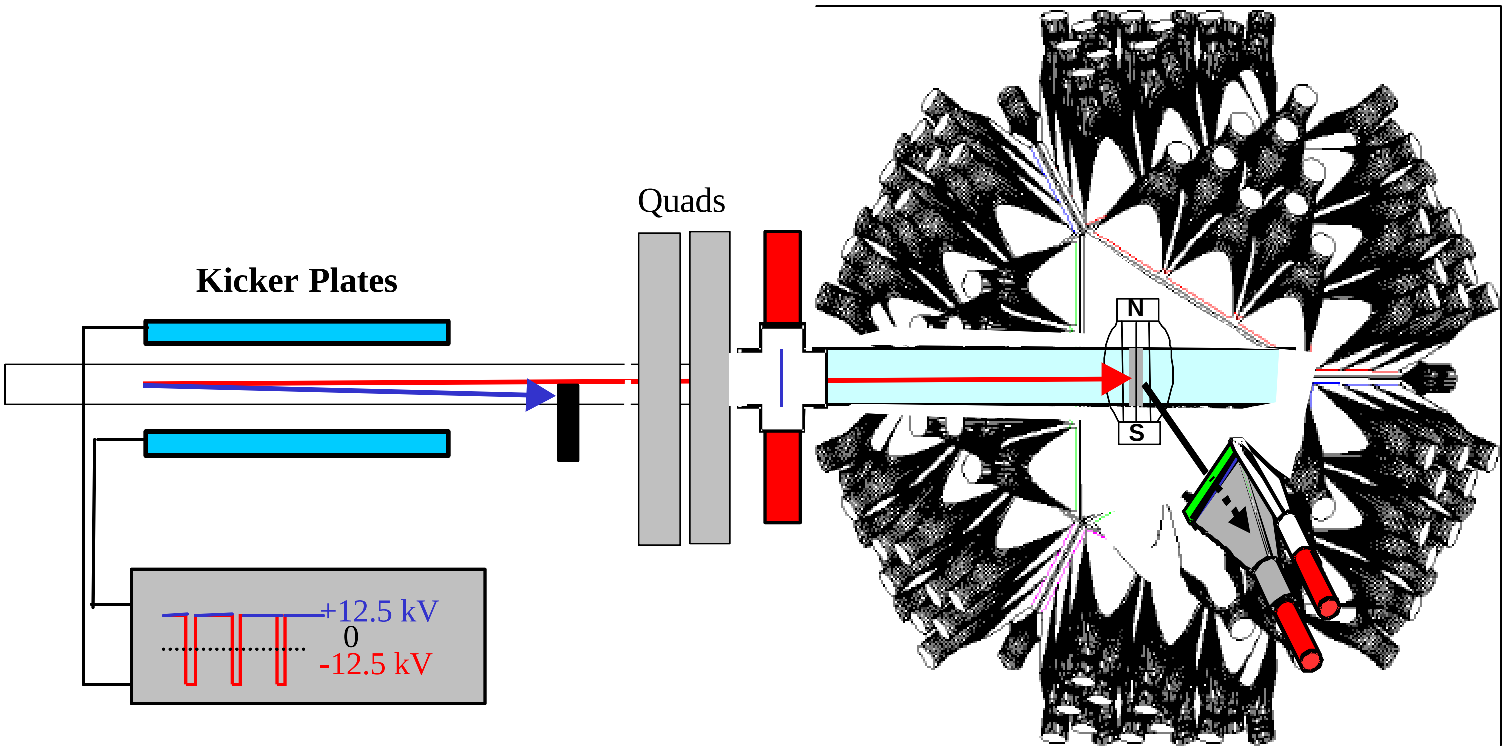


- **Require**
  - **10^{12} good events**
  - **Pulsed low-energy muon source (Kicker)**
  - **Symmetric, segmented timing detector**

- **Run Plan**
  - **Beam tests and modeling:** **June 00, July 01, Dec. 01, July 02**
  - **Detector prototype tests:** **June 00, July 02**
  - **Install complete experiment:** **Summer/Fall 03**
  - **Running for physics data:** **Summer 04**
  - **Additional running:** **Summer 05**

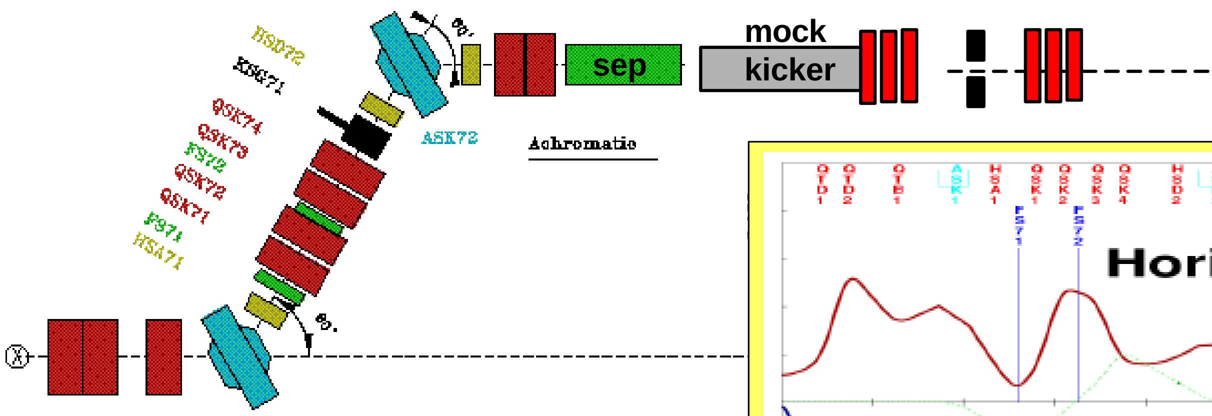
*Courtesy D. Hertzog

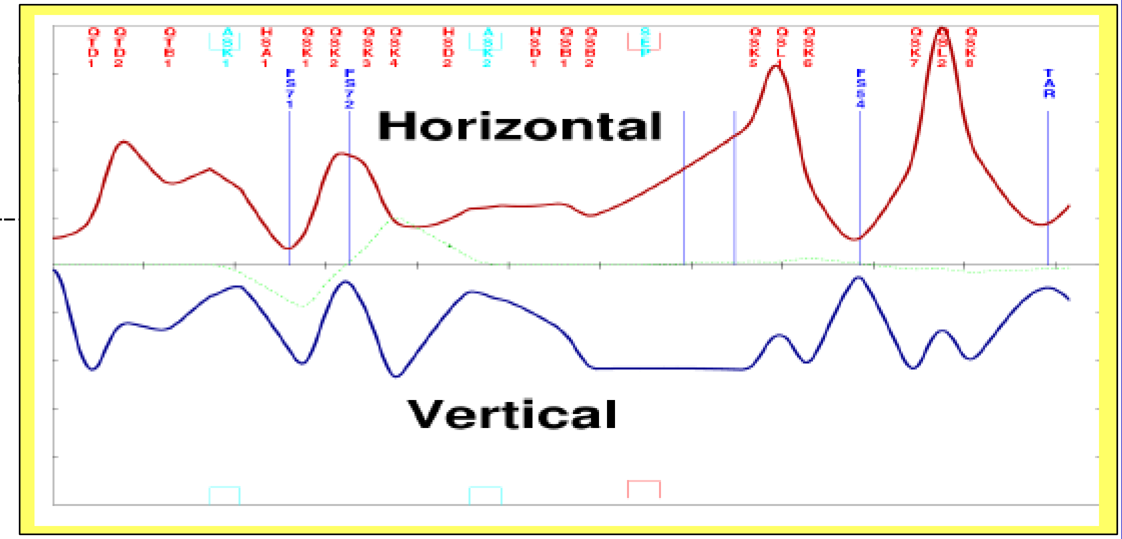
mLan concept



- statistics N_e=some 10^{12}
  in standard DC beams only one μ at a time,
  rate limitation, several years of measurement
  ⇨ **pulsed beam, radioactive source mode**

Beam development πE3

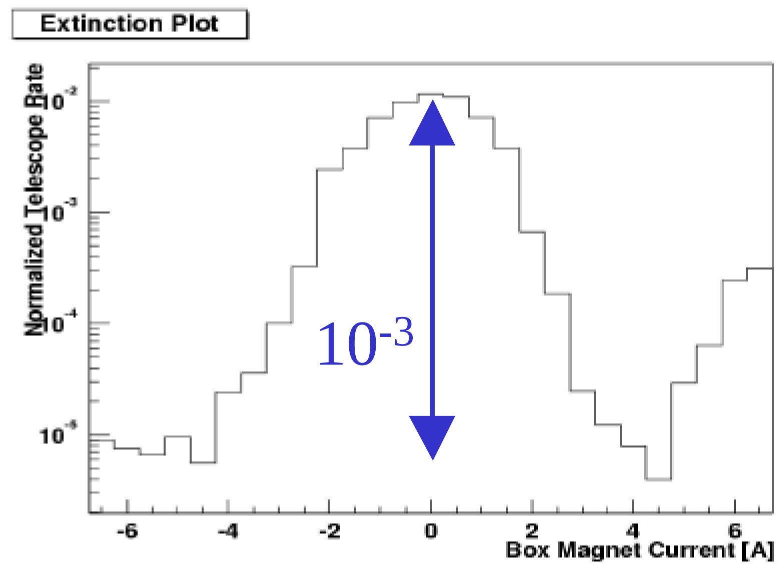




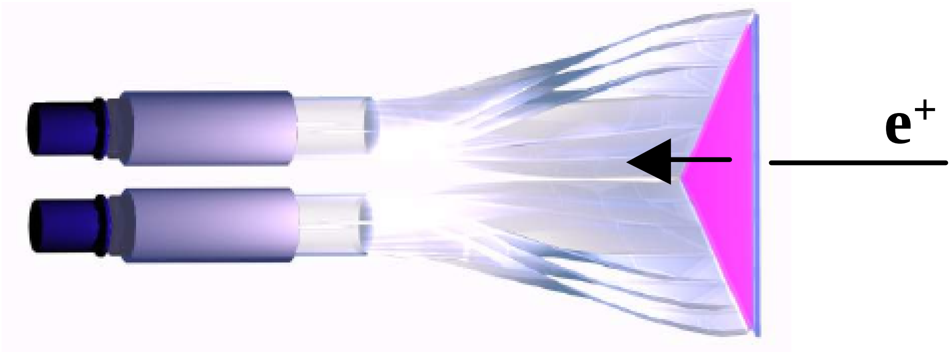
exp. milestone achieved ’02

extinction $3x10^{-4}$

rate ~30 MHz



Detectors and Structure



180 triangular double layer scintillators arranged in soccer ball geometry