Muon Physics around the world and at the Intensity Frontier

Peter Winter

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Myself

- My funny accent is from the fact that I was born in Germany
- Studied physics at Bonn University
- PhD on meson production at the COoler SYnchrotron COSY at Research Center of Julich, Germany
- Postdoc at University of Illinois Urbana-Champaign and University of Washington in Precision Muon Physics Group
- Assistant Physicist at Argonne since August 2012 working on the New g-2 at Fermilab

Overview

- The Muon and the Big Picture
- Muon Beams
- Recent Muon Experiments
  - TWIST, Muon Spin Resonance, Lamb shift, **MuLan, MuCap/MuSun**
- Muons at Fermilab and the Intensity Frontier
  - CLFV: **MEG** (μ^+ -> $e^+\gamma$), μ3e, **Mu2e**, COMET
  - **New g-2**
  - Future Muon experiments with Project-X

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PART 1

PART 2

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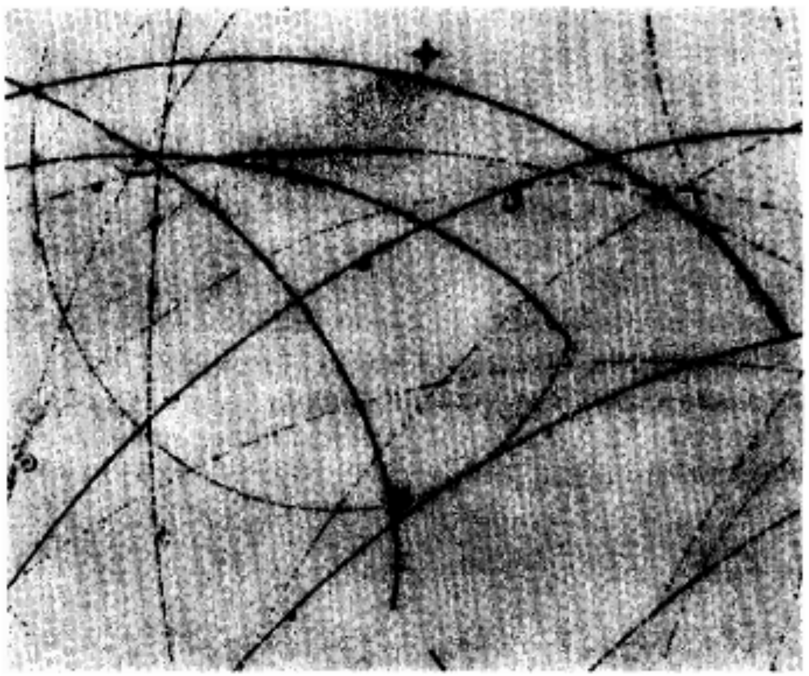
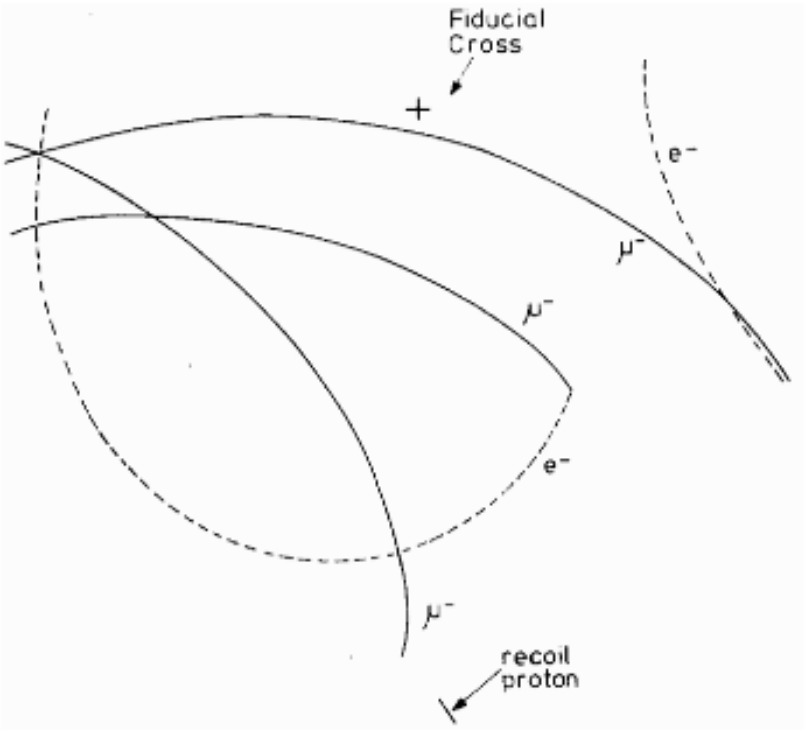
The Muon in a nutshell

- Discovered in cosmic rays in 1936 by Anderson and Neddermeyer



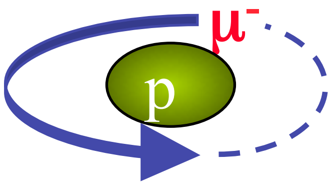
(a) Photograph.

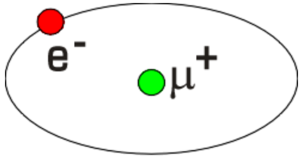


(b) Sketch.

The Muon in a nutshell

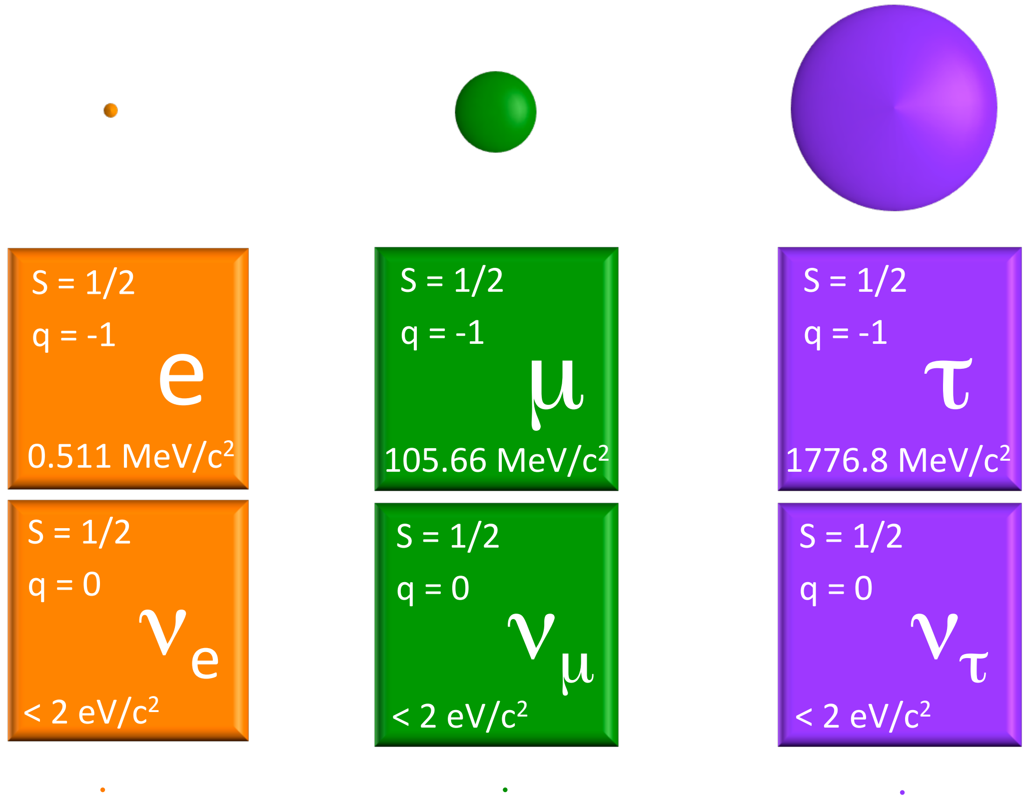
- Discovered in cosmic rays in 1936 by Anderson and Neddermeyer
- Big brother of the electron, $m_\mu = 207 \cdot m_e$
- Weak decay gives "long" lifetime (μs): beams and probe
- Main decay $\mu \rightarrow e\, \nu_e\, \nu_\mu$ (parity violating)
- Polarized muon beams from pion decay
- Hydrogen-like states ($\mu^- p$, $\mu^- d$, muonium: $\mu^+ e^-$)





- Enhanced sensitivity to new physics $\sim(m_\mu/m_e)^2$
- Lepton number violation ($\mu \rightarrow e$) extremely small in SM

The Muon is part of the 2nd lepton family



* Size of sphere represents mass of particle, neutrinos are still exaggerated!

Muon sources

So where do we get muons from?

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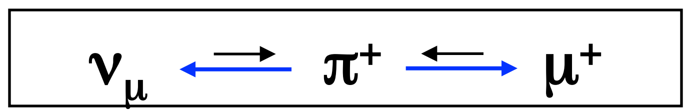

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* From 4-momentum conservation for pion at rest:

$$p_\mu = (m_\pi^2 - m_\mu^2) / 2m_\pi = 29.8\ \text{MeV/c}$$

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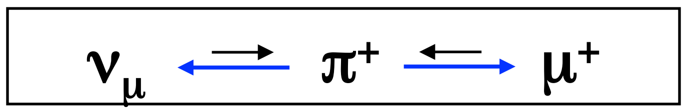

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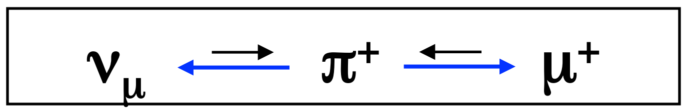

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3. Since pion has S=0 and neutrino has left-handed helicity, the decay muons are highly polarized
4. Collect decay muons in secondary beam channel to bring to experiment

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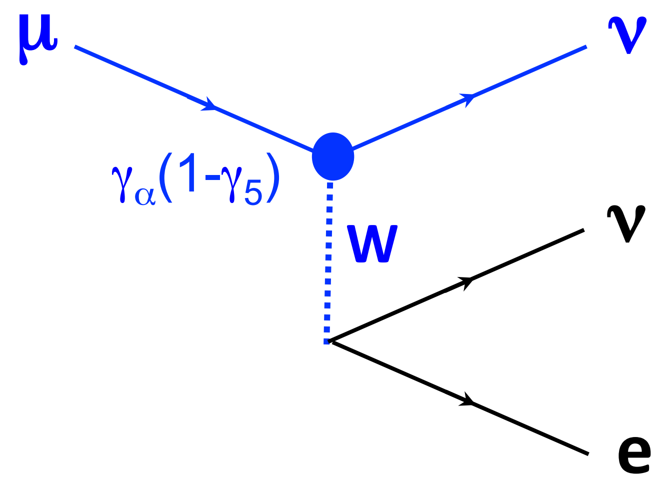
Muon decay



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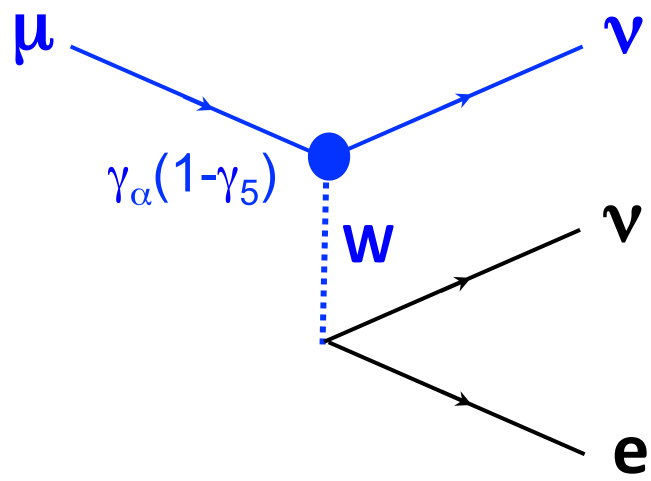
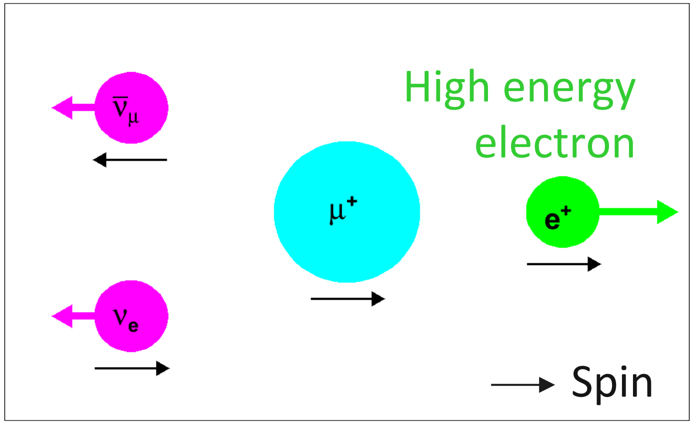
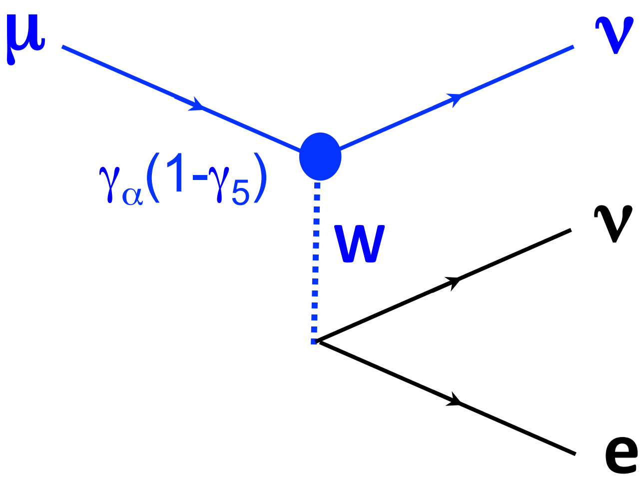
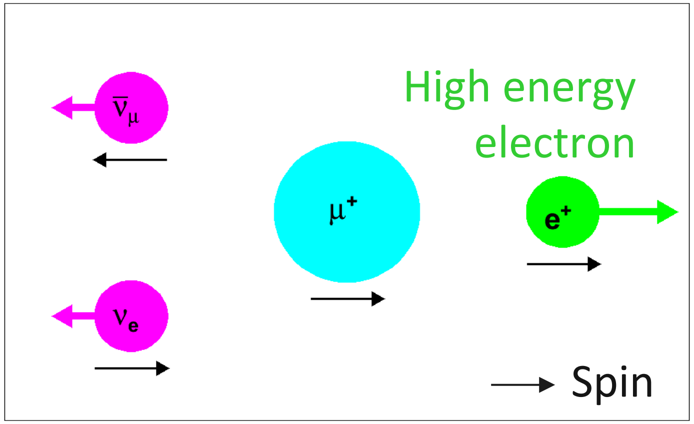




Muon decay

- Main decay channel: $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$
- Due to V-A structure of the weak leptonic current the decay is parity violating
- High energy positrons are emitted in direction of the μ^+ spin
- The decay is „self-analyzing“ in the sense that the decay electrons incorporate the muon spin

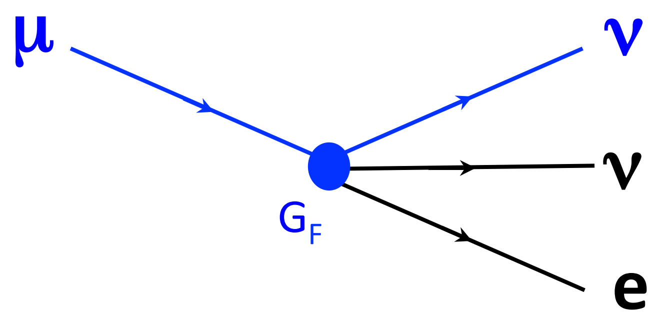




Muon decay

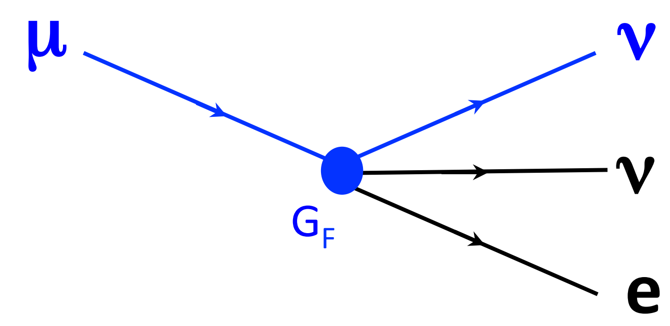
- Fermi's Golden rule allows to deduce:*

$$\Gamma = \frac{1}{\tau} \approx \frac{G_F^2 \, m_\mu^5}{192\pi^3}$$



* You can find derivations on the web: A lot of math and some assumptions and hours later...
Higher order corrections needed to make this an equality, see MuLan opening slides later

Muon decay #2



- Fermi's Golden rule allows to deduce:

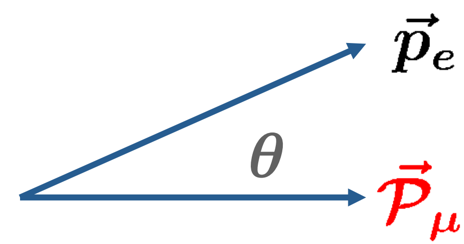
$$\Gamma = \frac{1}{\tau} \approx \frac{G_F^2\, m_\mu^5}{192\pi^3}$$

- Differential decay spectrum (parametrized by Michel parameters):

$$\frac{d^2\Gamma}{x^2 dx d(\cos\theta)} \propto (3-3x) + \frac{2}{3}\rho(4x-3) + 3\eta\frac{x_0}{x}(1-x)$$

$$+ P_\mu \xi \cos\theta\left[(1-x) + \frac{2}{3}\delta(4x-3)\right]$$

$$x = \frac{E_e}{E_{e,\max}}$$



Angle with respect to (positive) muon spin

In the Standard Model:

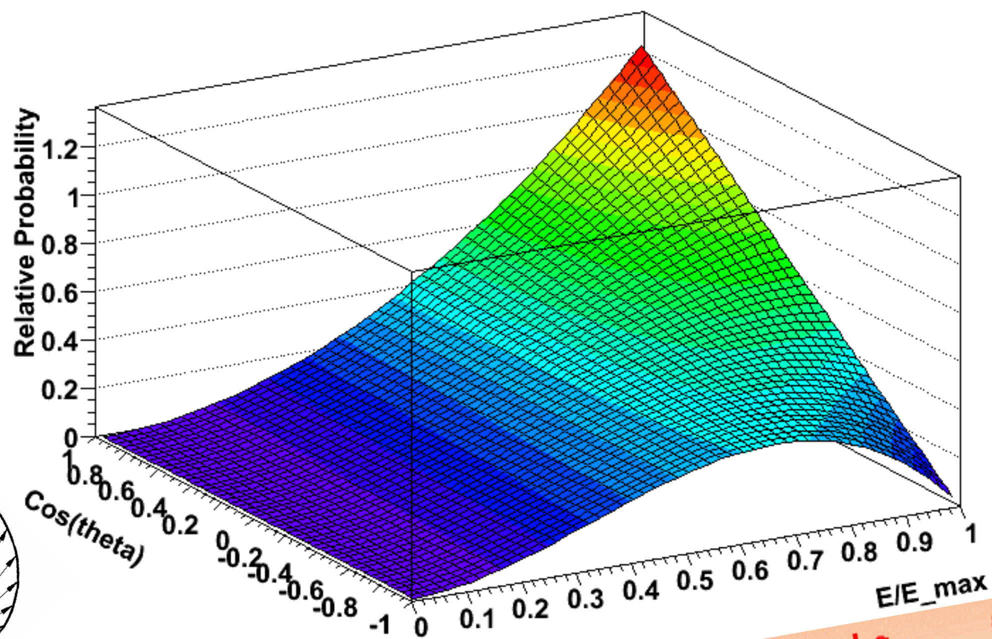
$\rho = 0.75$ $\eta = 0$

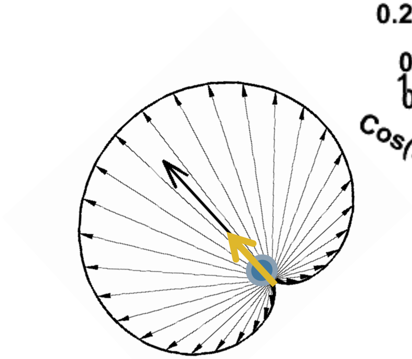
$P_\mu \xi = 1$ $\delta = 0.75$

Muon decay

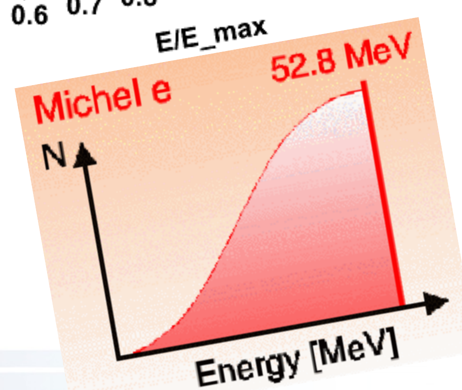
- Differential decay spectrum simplifies in SM to:

$$\frac{d^2\Gamma}{x^2 dx\ d(\cos\theta)} \propto \left[(3-2x) - P_\mu \cos\theta\ (1-2x)\right]$$



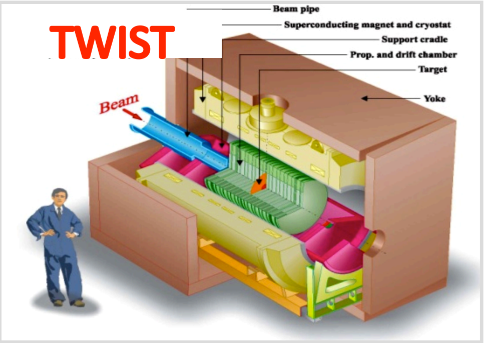


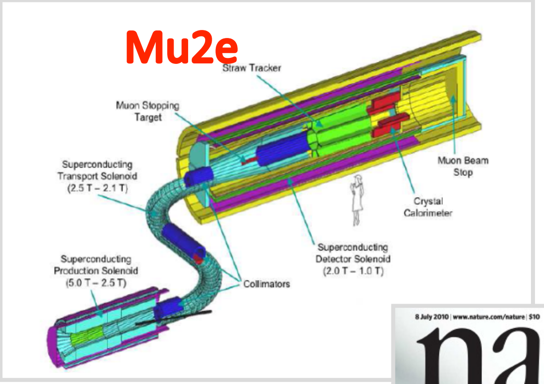
$$1 + P_\mu \cos\theta$$



Muon Physics: Worldwide Effort

- **Lifetime – Fermi constant**
  - 2 "precision" experiments: **MuLan & FAST** at PSI
- **Decay parameters**
  - **TWIST** at Triumf: Michel parameters ρ, δ, η, $P_\mu\xi$
- **Muon Capture**
  - **MuCap** at PSI: g_P, pseudoscalar coupling
  - **MuSun** at PSI: basic EW interaction in 2N system
- **Lepton Flavor Violation**
  - $\mu \rightarrow e\gamma$ – **MEG** at PSI taking data now
  - μe conversion **Mu2e** at FNAL
  - **COMET** at JParc, Japan
  - **µ3e** at PSI
- **Anomalous magnetic moment (g-2)**
  - **E821** at BNLand new **g-2 E989** at FNAL
- **Search for Electric Dipole Moment**
  - **E821** at BNL and new **g-2 E989** at FNAL
- **Lorentz / CPT violation tests**
  - **E821** at PSI: precession vs. sidereal day
- **Proton charge radius**
  - **Muonic Lamb shift** at PSI experiment
  - **MuSE** at PSI





Different categories of muon experiments

1. Measurement of Standard Model parameters:
   - Masses: $\mathbf{M_Z}$ $\mathbf{M_W}$ $\mathbf{M_H}$ $\mathbf{m_b}$ $\mathbf{m_t}$ $\mathbf{m_e}$ $\mathbf{m_u}$ $\mathbf{m_v}$ **…**
   - Couplings: α_{QED} α_{Strong} G_F G_{grav}
   - Structure of interactions: $SU(3)_C \times SU(2)_L \times U(1)_Y$

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2. Search for Physics Beyond the Standard Model:
   - TWIST: Michel Parameters ρ, δ, η, $P_\mu\xi$
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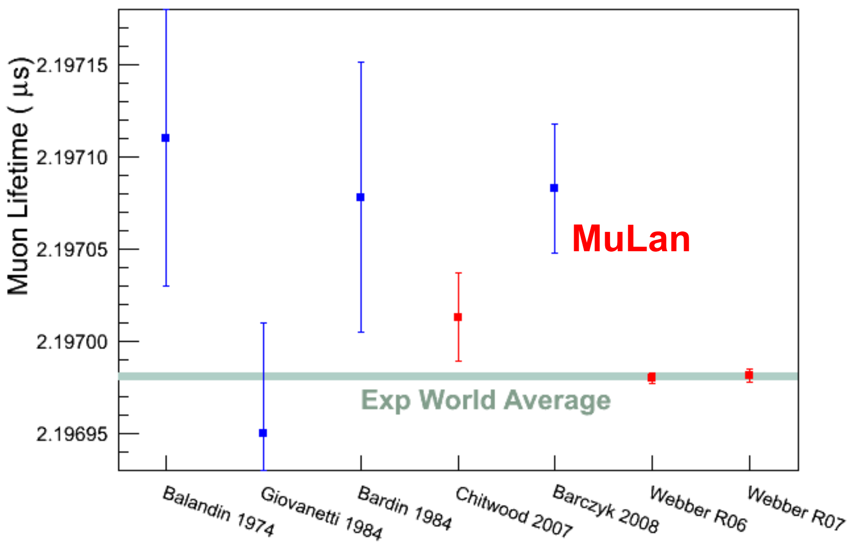
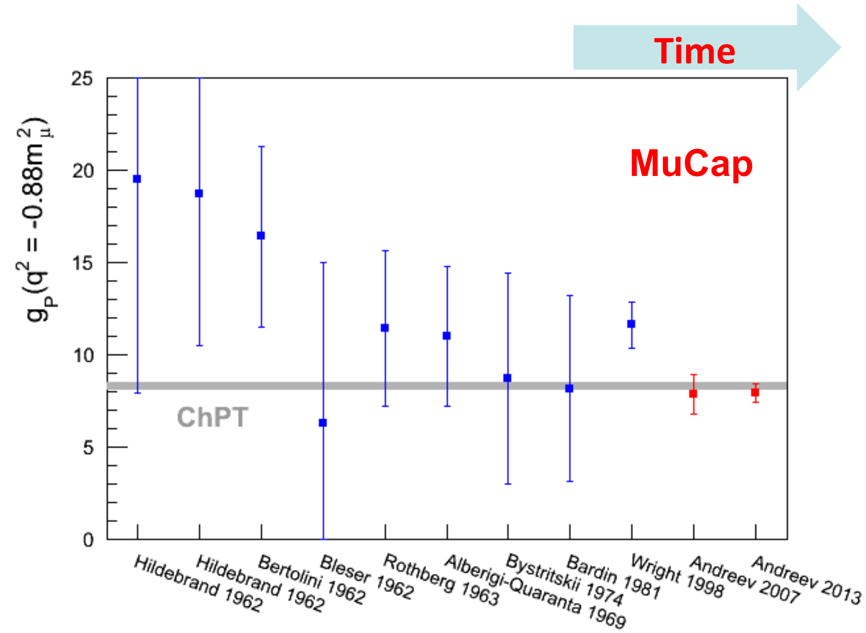
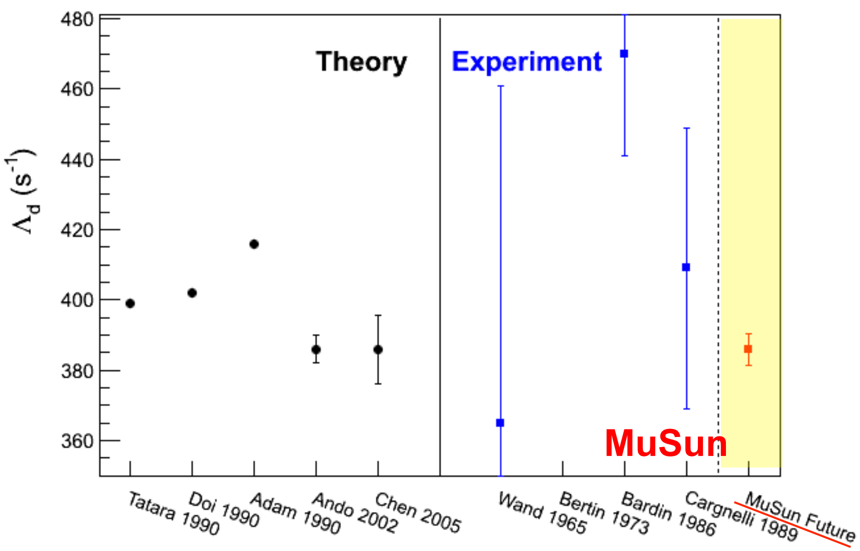
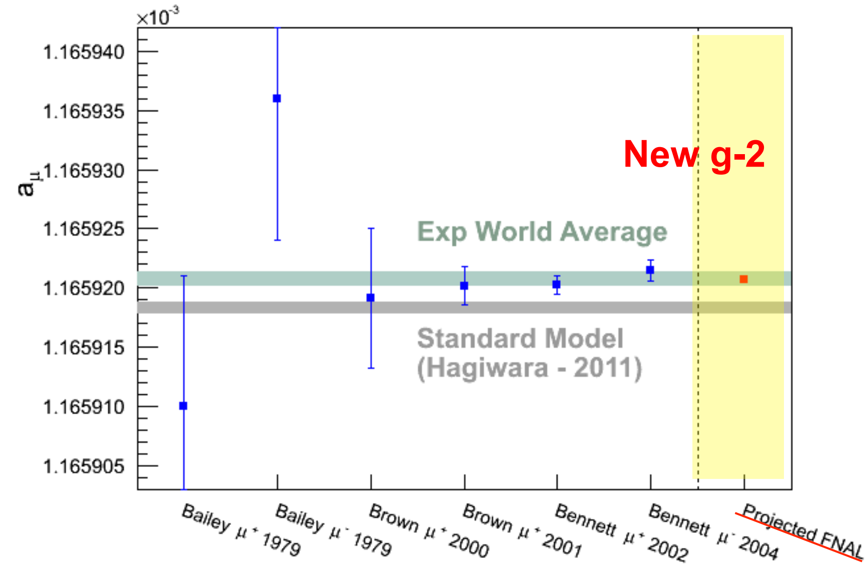
3. Applied material research:
   - Muon spin Resonance (muSR) to probe magnetic properties

Precision Muon Physics at the Parts-Per-Million Level









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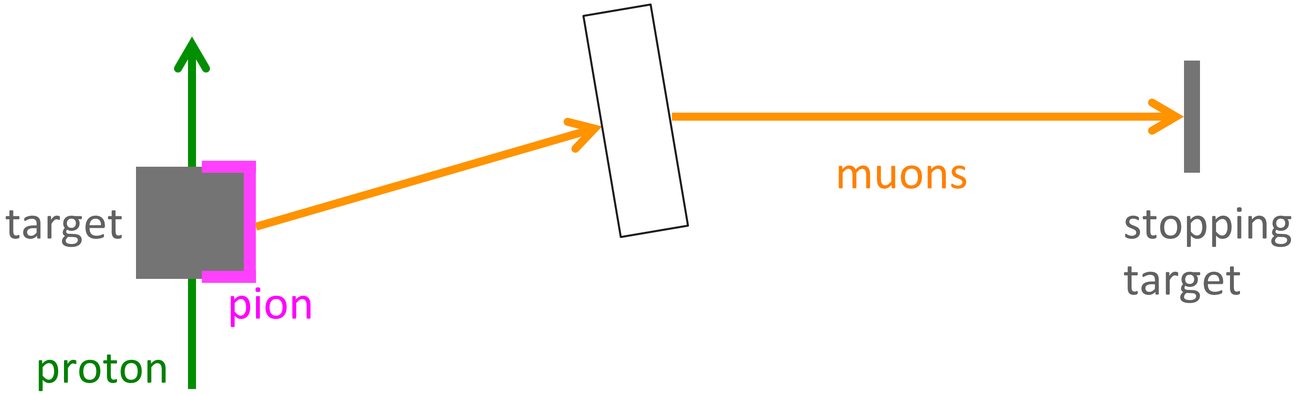
Muon beams: Surface muons (p_μ = 29.8 MeV/c)

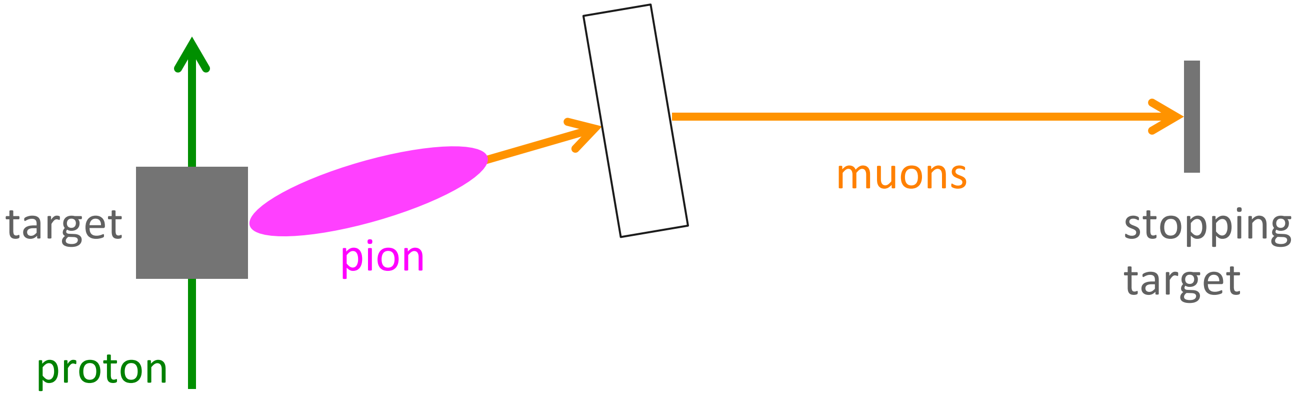


- A fraction of pions come to rest near surface
- Decay surface muons have momenta of ~29.8 MeV/c
- Well defined source
- High polarization of close to 100%
- No negative surface muons (π^- undergo nuclear capture)
- Positron contamination might require separator
- Short range R_μ allows thin muon stopping targets:

$$R_\mu \propto p^{3.5} \Rightarrow \frac{\Delta R_\mu}{R_\mu} \sim \sqrt{(3.5\frac{\Delta p}{p})^2 + (\Delta R_{str})^2}$$

A.E. Pifer et al., NIM 135, 39

Muon beams: Cloud muons

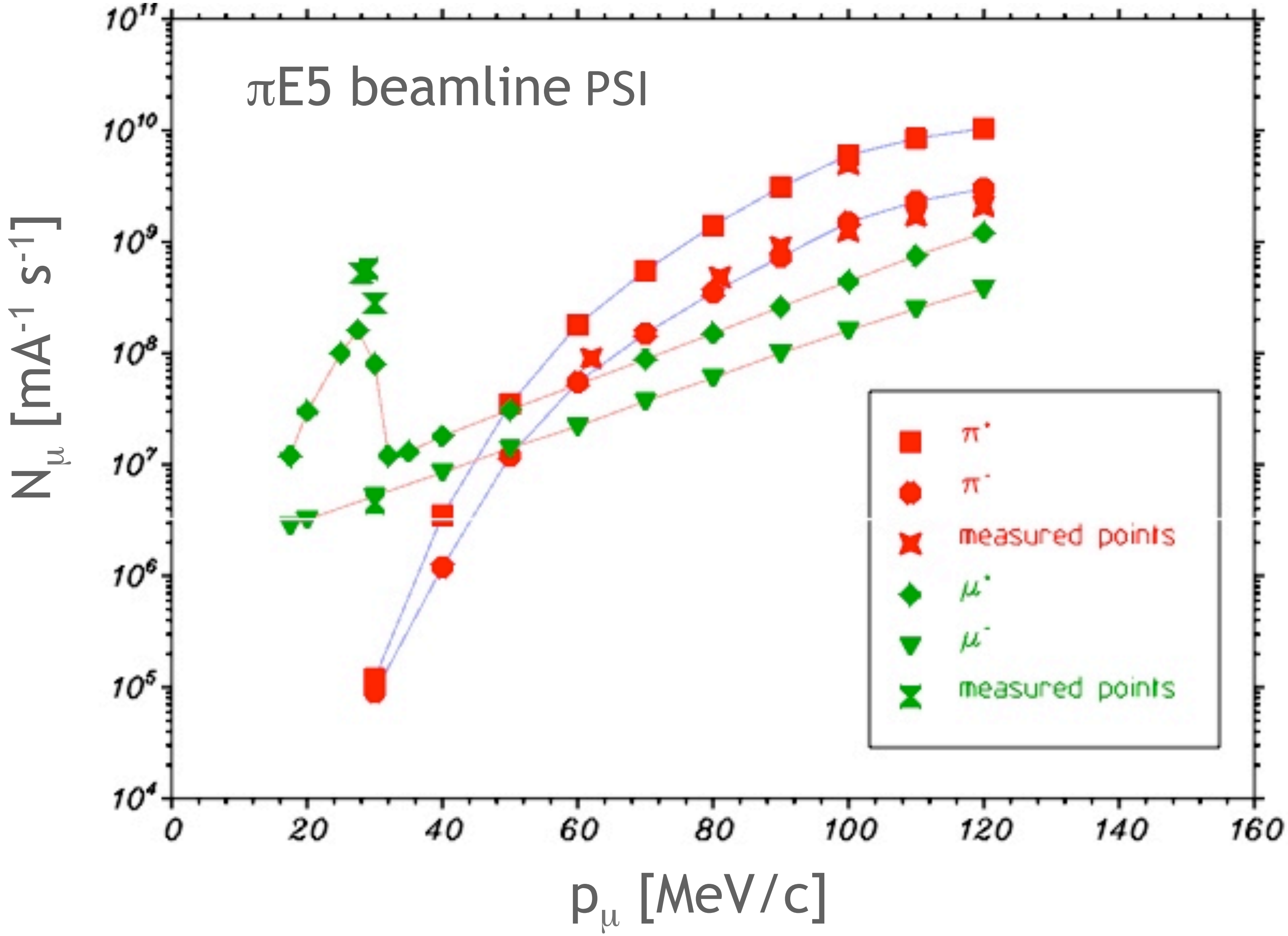


- Decay of pions in flight
- Cloud muons have wide range of momenta
- Usually low muon polarization
- Beam contaminated with $\pi^{\pm}$ and $e^{\pm}$
- Stopping target needs to be thicker with higher momentum

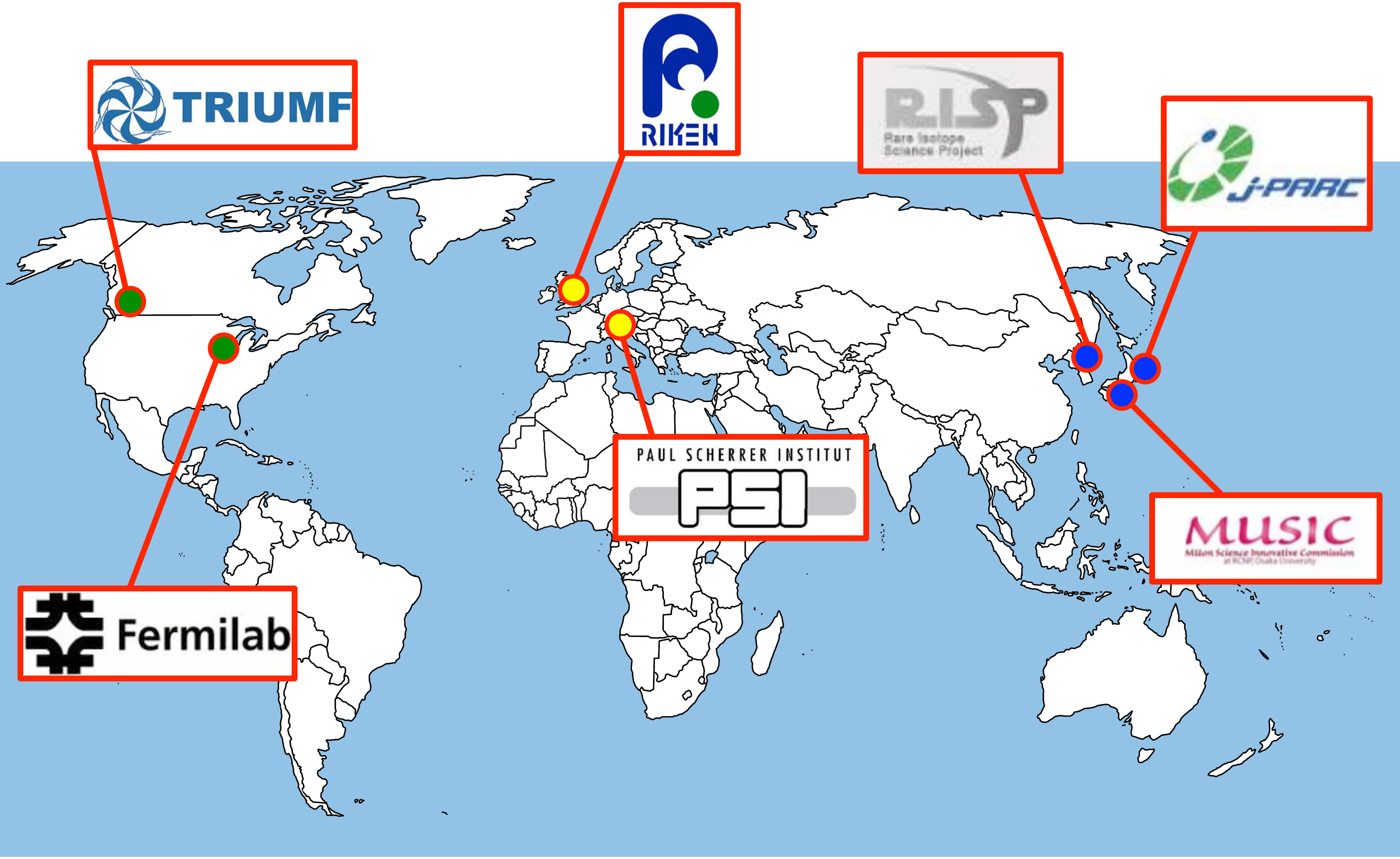
A.E. Pifer et al., NIM 135, 39

Muon production yields

http://aea.web.psi.ch/beam2lines/



Muon facilities

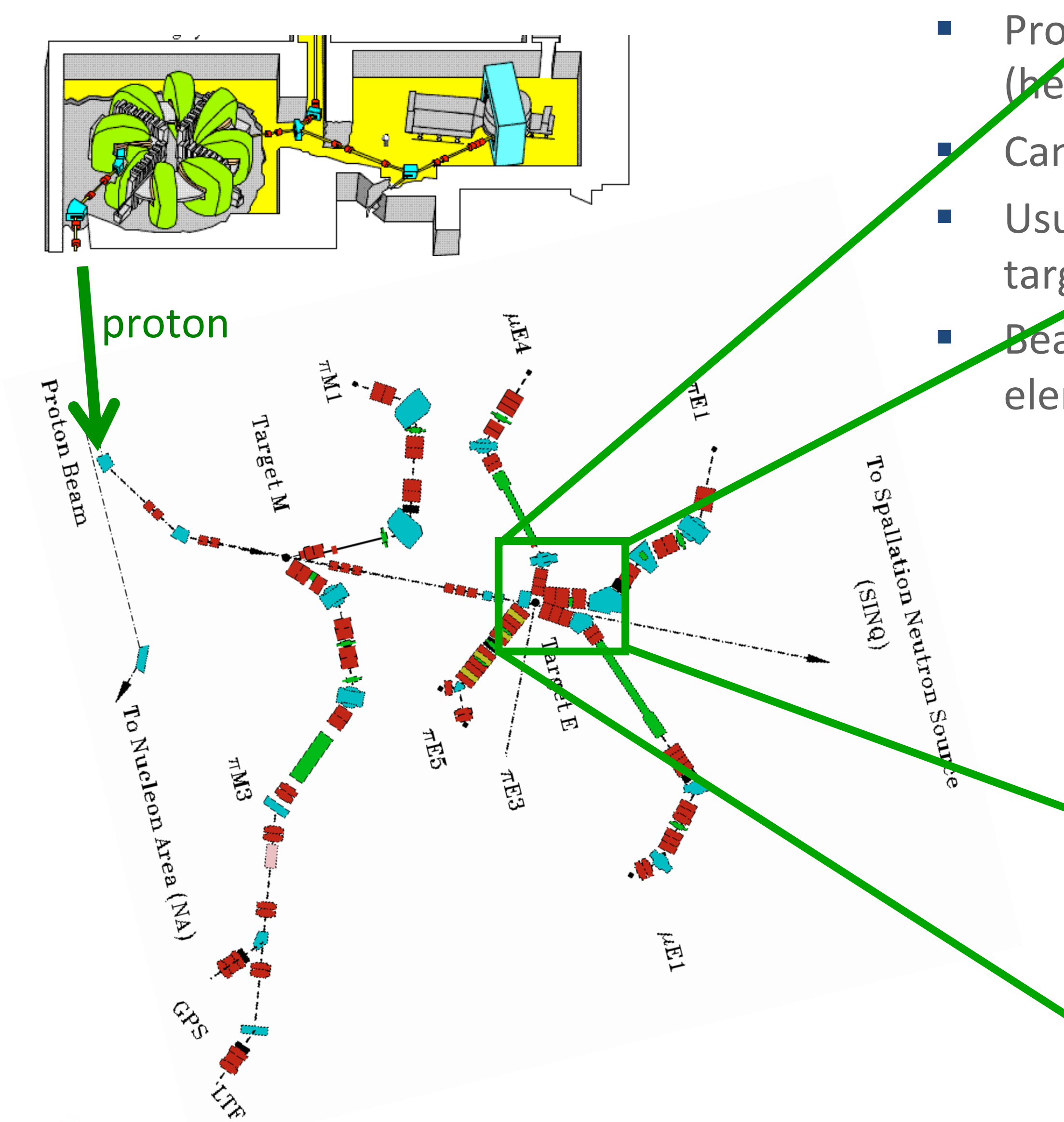


Throughout my talk

Fermilab

Small indicator of the **facility** where the experiment is located.

Two types of proton targets



- Proton (here r
- Can us
- Usually ... n target
- Beamli ... g elemen

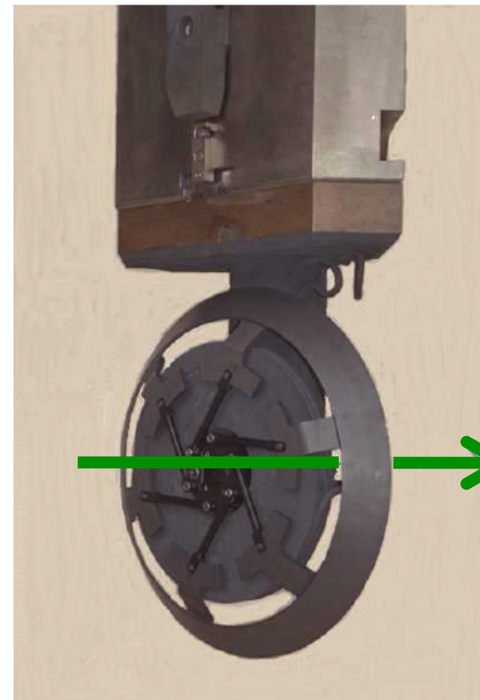
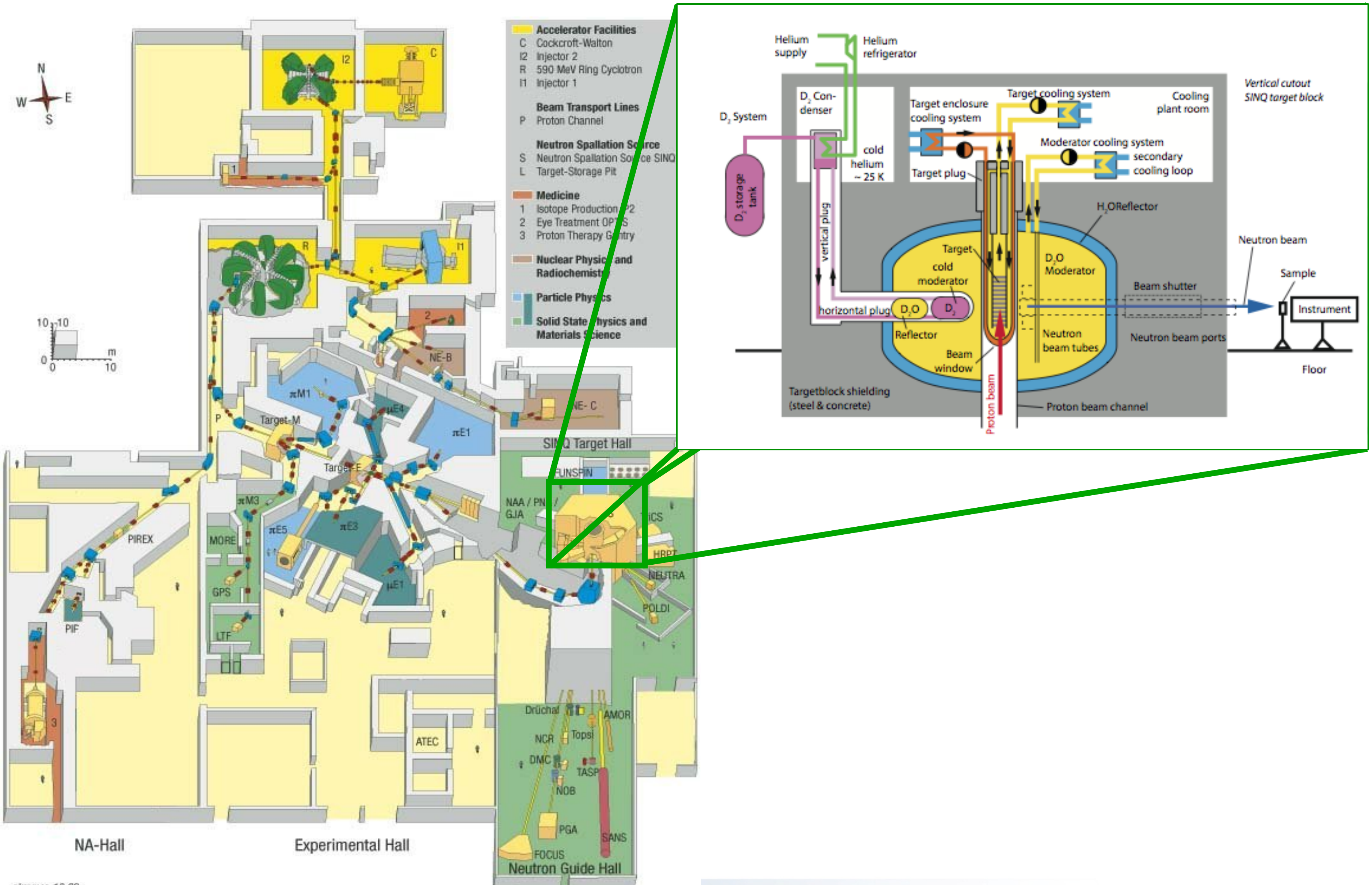


TABLE 1. Some Parameters For The Targets

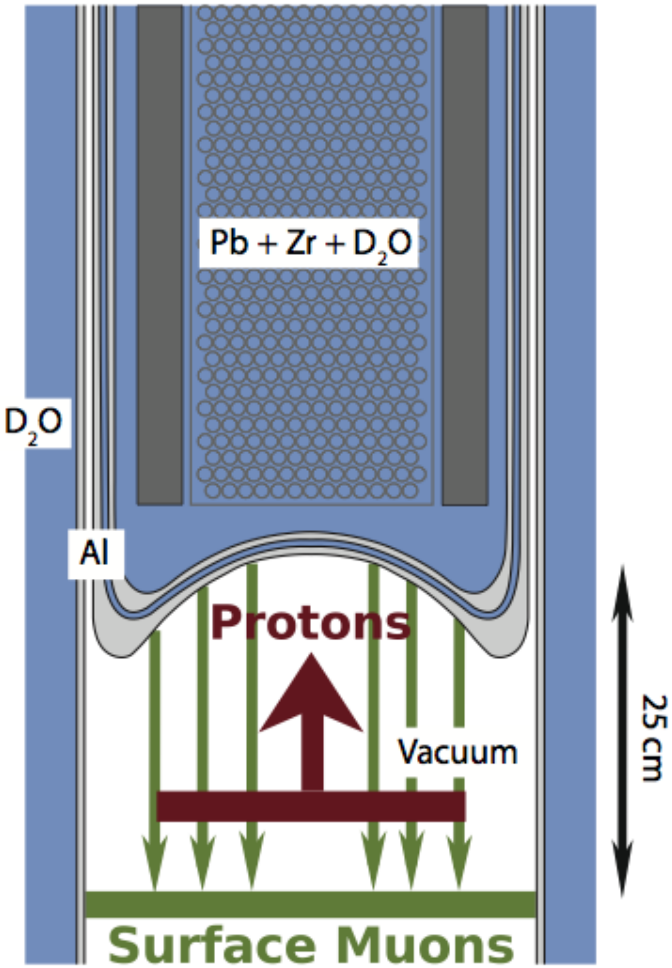
Meson Production Target	M	E
Mean Diameter (mm)	320	450
Target Length (mm)	5.2	60
Target Width (mm)	20	6
Graphite Density (g/cm^3)	1.8	1.8
Proton Beam Losses (%)	1.6	18
Power Deposition (KW/mA)	2.4	30
Irradiation Damage Rate (dpa/Ah)	0.11	0.1
Operating Temperature (K)	1100	1700
Rotational Speed (Turns/s)	1	1

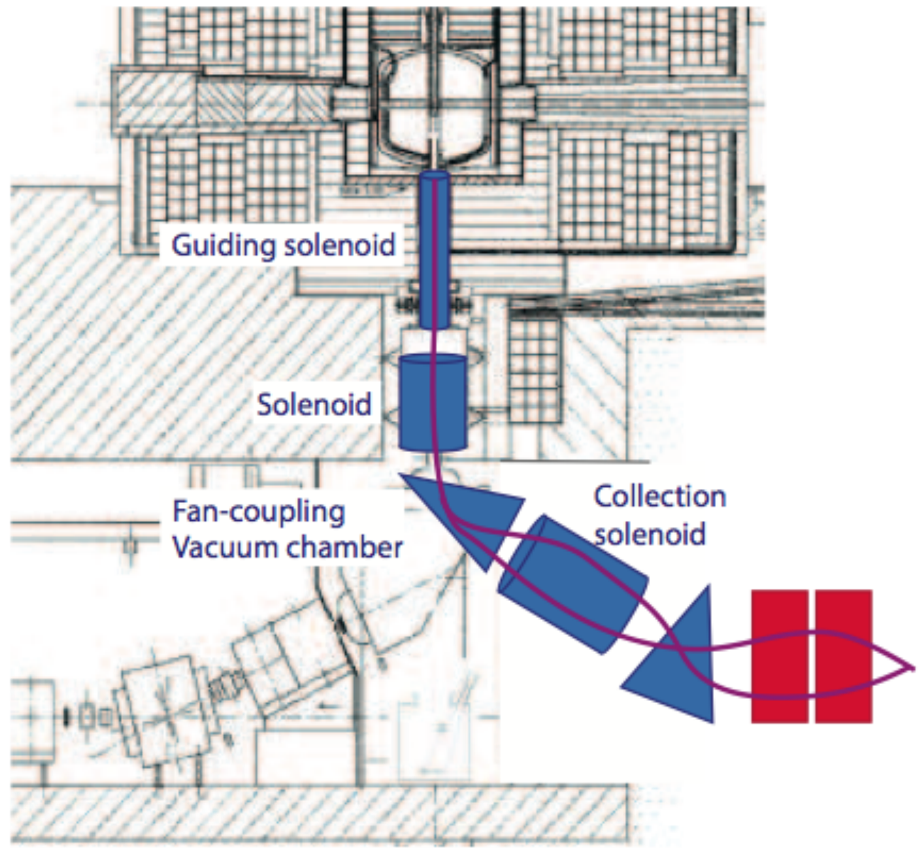
Two types of proton targets



r.kramer 10-99

Proposal: High intensity muon beam





Muon beams

Laboratory/ Beam line	Energy/ Power	Present Surface μ^+ rate (Hz)	Future estimated μ^+/μ^- rate (Hz)
PSI (CH)	(590 MeV, 1.3 MW, DC)		
LEMS	"	$4 \cdot 10^8$	
$\pi E5$	"	$1.6 \cdot 10^8$	
HiMB	(590 MeV, 1 MW, DC)		$4 \cdot 10^{10} (\mu^+)$
J-PARC (JP)	(3 GeV, 1 MW, Pulsed) currently 210 KW		
MUSE D-line	"	$3 \cdot 10^7$	
MUSE U-line	"		$2 \cdot 10^8 (\mu^+)$ (2012)
COMET	(8 GeV, 56 kW, Pulsed)		$10^{11} (\mu^-)$ (2019/20)
PRIME/PRISM	(8 GeV, 300 kW, Pulsed)		$10^{11-12} (\mu^-)$ ($>$ 2020)
FNAL (USA)			
Mu2e	(8 GeV, 25 kW, Pulsed)		$5 \cdot 10^{10} (\mu^-)$ (2019/20)
Project X Mu2e	(3 GeV, 750 kW, Pulsed)		$2 \cdot 10^{12} (\mu^-)$ ($>$ 2022)
TRIUMF (CA)	(500 MeV, 75 kW, DC)		
M20	"	$2 \cdot 10^6$	
KEK (JP)	(500 MeV, 2.5 kW, Pulsed)		
Dai Omega	"	$4 \cdot 10^5$	
RAL -ISIS (UK)	(800 MeV, 160 kW, Pulsed)		
RIKEN-RAL		$1.5 \cdot 10^6$	
RCNP Osaka Univ. (JP)	(400 MeV, 400 W, Pulsed)		
MUSIC	currently max 4W		$10^8 (\mu^+)$ (2012) means $> 10^{11}$ per MW
DUBNA (RU)	(660 MeV, 1.65 kW, Pulsed)		
Phasatron Ch:I-III		$3 \cdot 10^4$	

Muon experiments: Beam rates

Experiment	Beam	Momentum	Rates [1/s]	Beamline
TWIST	μ^+	29.8 MeV/c	<5 * 10^3	TRIUMF
Muon lamb shift	π^- μ^-	100 MeV/c ~1 MeV/c	~10^8 ~2.5 * 10^2	πE5 @ PSI
MuLan	μ^+	29.8 MeV/c	8 * 10^6	πE3 @ PSI
MuCap / MuSun	μ^-	34 MeV/c	1 * 10^5	πE3 @ PSI
MEG	μ^+	29.8 MeV/c	3 * 10^7	πE5 @ PSI
MEG upgrade	μ^+	29.8 MeV/c	7 * 10^7	πE5 @ PSI
$\mu^+ \to e^+e^-e^+$ (Ph. I)	μ^+	29.8 MeV/c	<1 * 10^8	πE5 @ PSI
$\mu^+ \to e^+e^-e^+$ (Ph. II)	μ^+	29.8 MeV/c	2 * 10^9	HIMB @ PSI
Mu2e	μ^-	~40 MeV/c	10^{10}	FNAL

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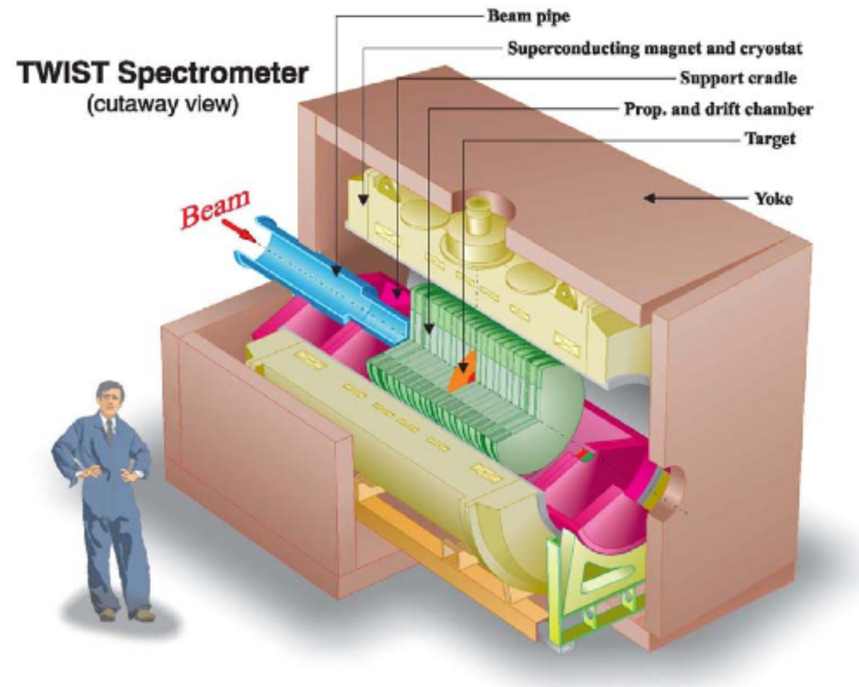
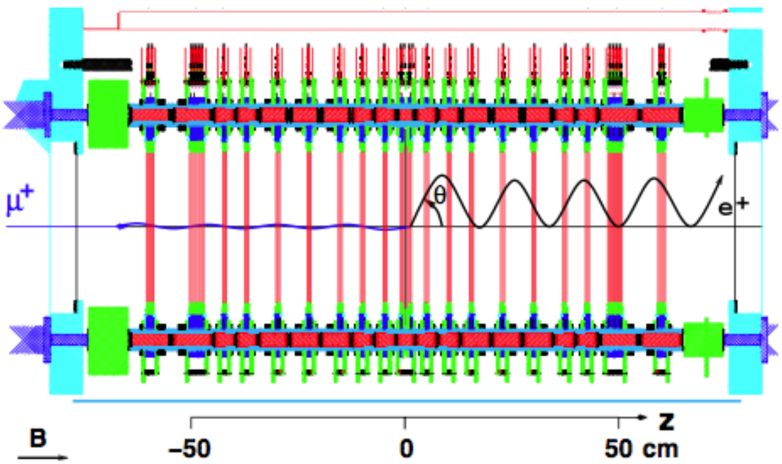
TWIST: Triumf Weak Interaction Symmetry Test

- Precise measurement of the Michel parameters
- Compare to SM predicition:

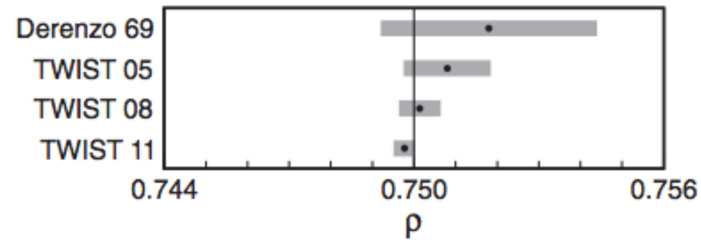
$$\rho = 0.75 \qquad \eta = 0$$
$$P_\mu \xi = 1 \qquad \delta = 0.75$$

- Sensitive to contributions from weak right-handed particles
- Highly polarized μ^+ beam stopped in Ag or Al target in a very symmetric detector
- Track e^+ in well-known, uniform field
- Analysis relies on comparison with detailed simulations





TWIST: Results

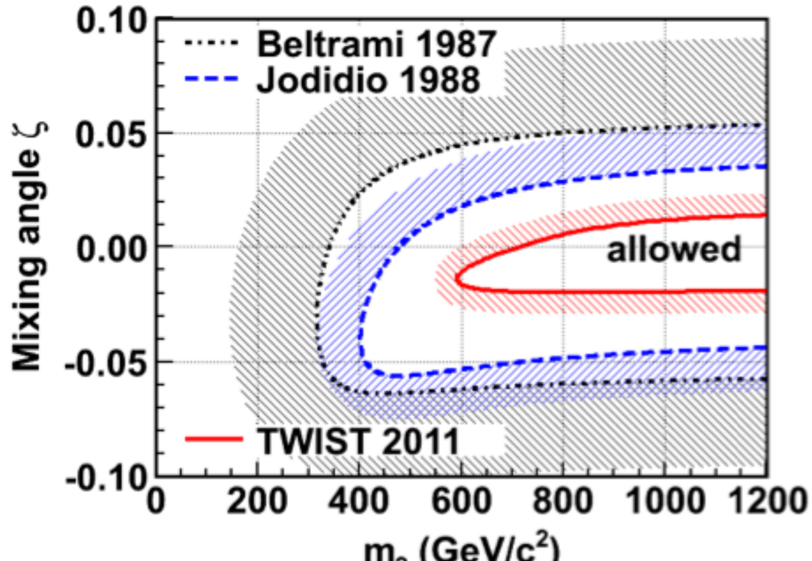


ρ = 0.74977 ± 0.00012 (stat) ± 0.00023 (syst)

δ = 0.75049 ± 0.00021 (stat) ± 0.00027 (syst)

This puts limits on specific Left-Right-Symmetric (LRS) models

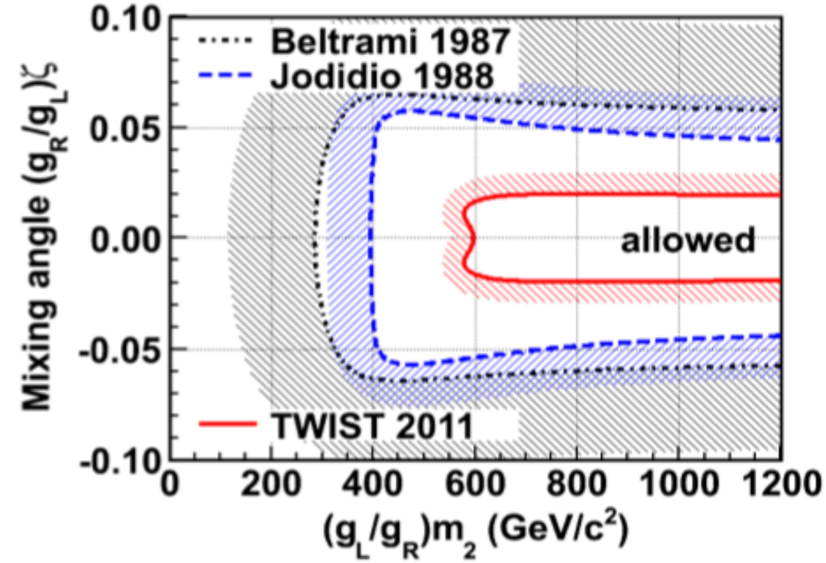
"manifest" LRS, 90%CL



m_2 > 592 GeV/c²

-0.020 < ζ < +0.017

generalized or non-manifest LRS, 90%CL

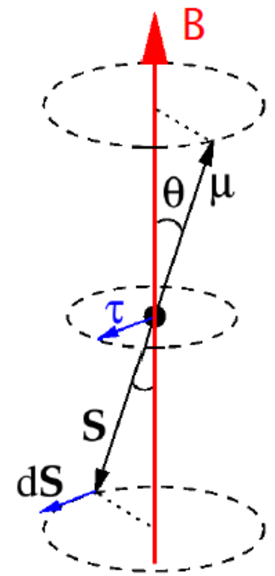


$(g_L/g_R)m_2$ > 578 GeV/c²

-0.020 < $(g_R/g_L)\zeta$ < +0.020

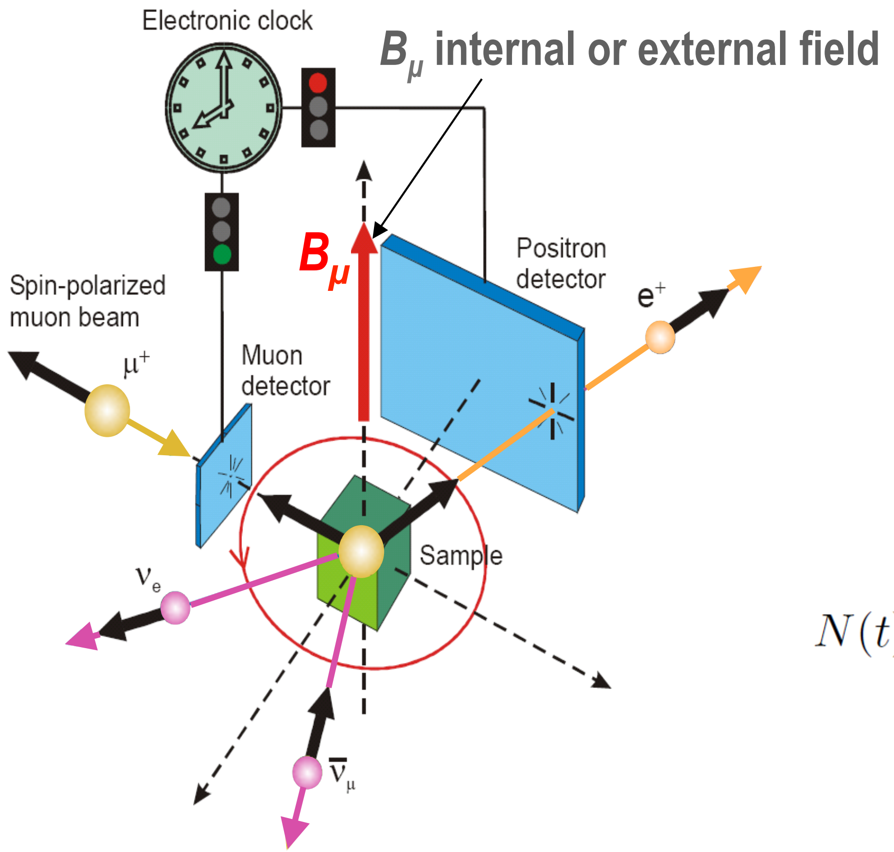
Muon Spin Resonance

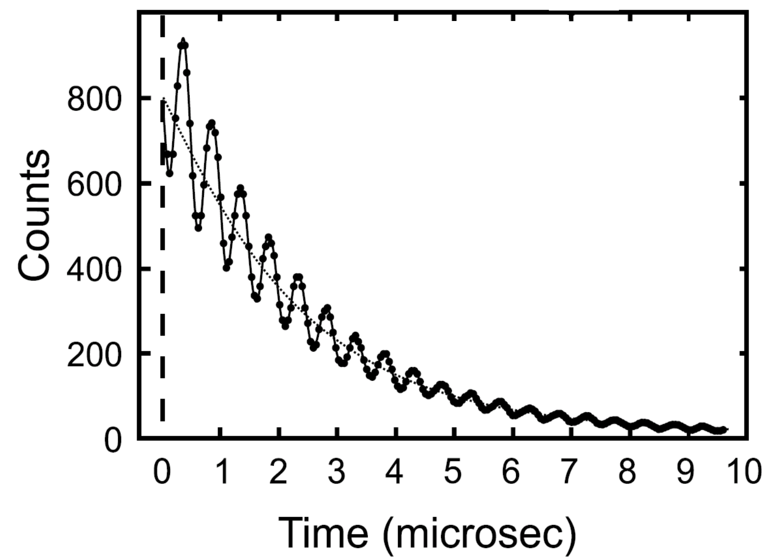
- Basic principle:
  - Stop low energy polarized μ^+ in sample
  - Muon spin precesses in internal or external magnetic field (Larmor precession)
  - Observe this precession via decay electron time spectrum (remember light house effect)



*Plots taken from colloquium by A. Suter at Fermilab

A typical MuSR experiment





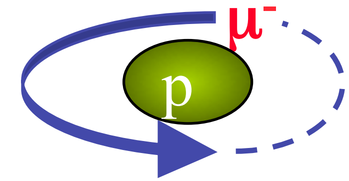
$$N(t) = N_0 \exp(-t/\tau_\mu)\,[1 + a\,G(t)] + \mathrm{Bkg}$$

***G(t)* contains the physics**

- Muon momentum selects different sample depth (sub-mm down to nm)
- Study properties related to sample magnetism, superconductivity, chemistry and semiconductor physics

*Plots taken from colloquium by A. Suter at Fermilab

Muonic Hydrogen Lamb Shift - Proton Charge Radius



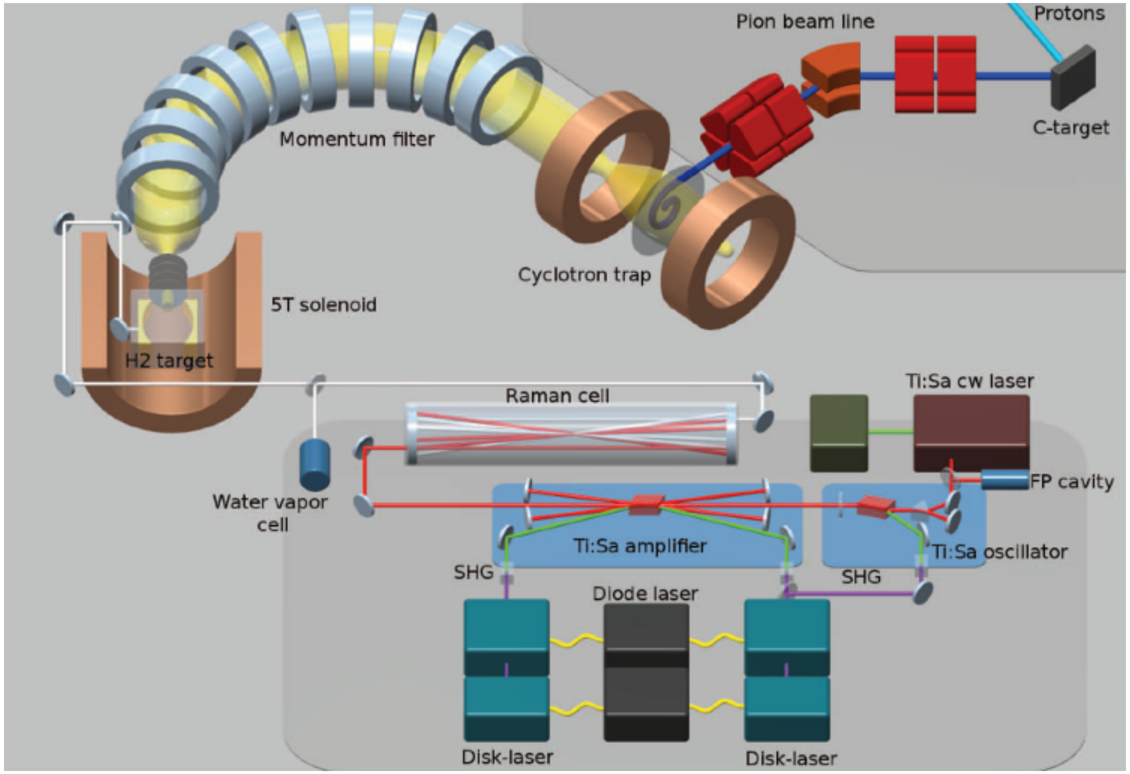
- Muon forms hydrogen-like atoms
- Bohr radius is 186 times smaller than in hydrogen
- The muon overlaps much more with the proton and can probe its charge structure
- Energy levels are changed due to proton's charge distribution
- Measure the 2S – 2P transition in $\mu^- p$ (muonic Lamb shift)
- Extract proton charge radius r_p from this transition

$$\Delta E(2S-2P) = 209.978(5) - 5.226\, r_p^2 + 0.$$

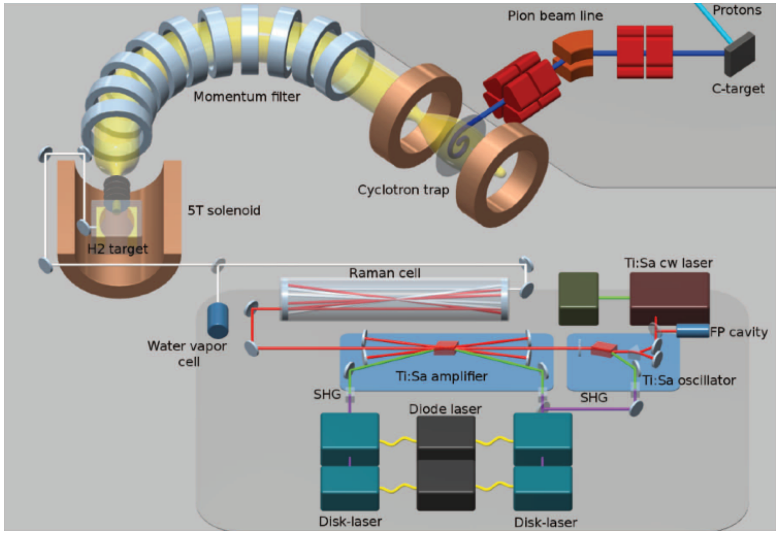
- Knowledge of the charge and magnetic distributions inside the proton are needed for precision tests of bound-state QED

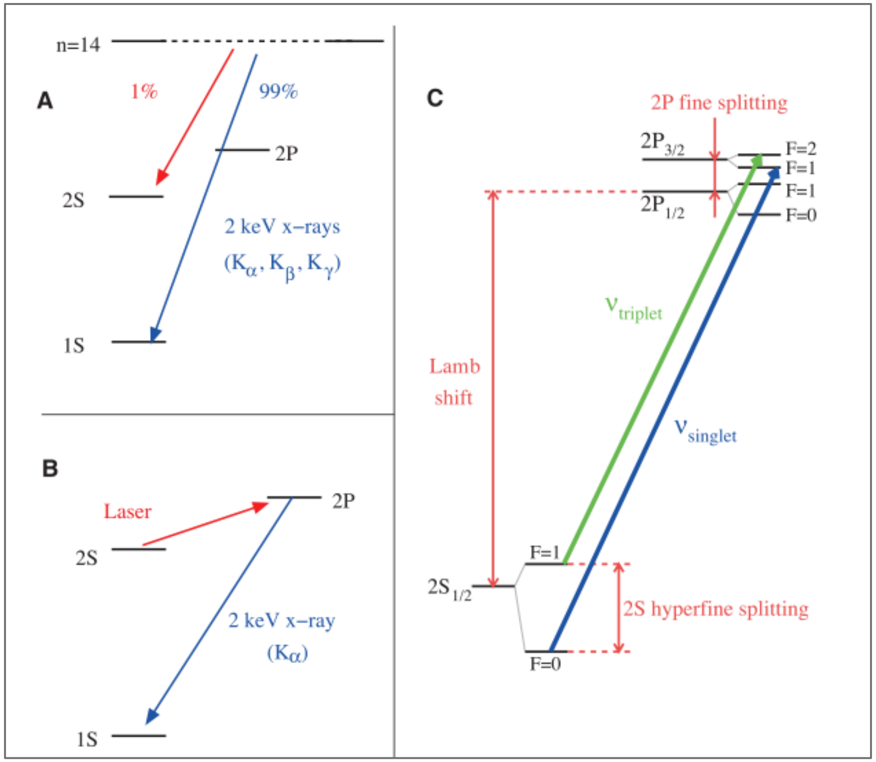
Muonic Lamb Shift - Experimental technique

- Negative pions are captured in cyclotron trap and decay into MeV muons
- Thin foil slows muons
- Toroidal field guides keV muons to 1 mbar hydrogen target
- Muons captured in excited μp atom (n≈14)



Muonic Lamb Shift - Experimental technique





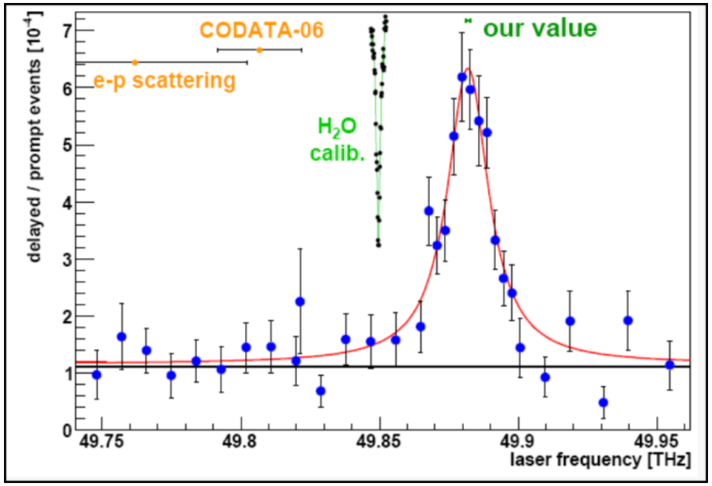
A. Excited μp atoms deexcite to 1S ground state (99%) and meta-stable 2S (1%)

B. Delayed (0.9 μs) laser induces 2S – 2P transition followed by immediate deexcitation via 1.9 keV X-ray (2P – 1S) transition

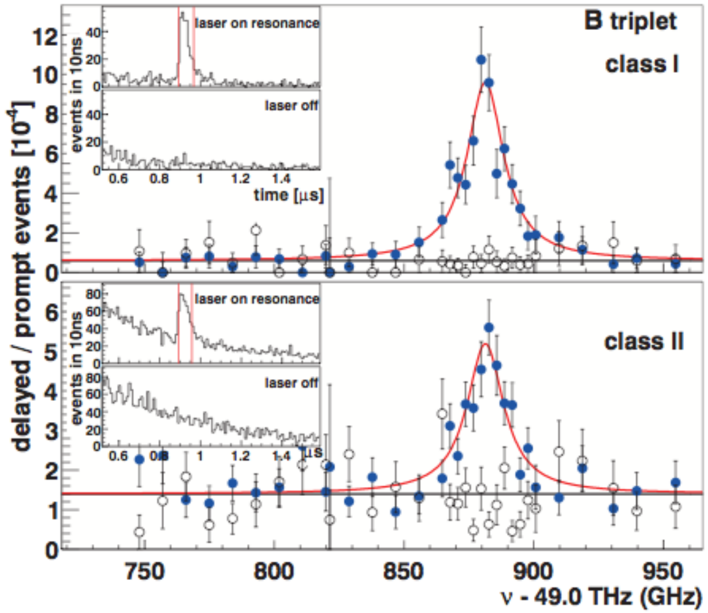
C. Transitions measured: $\nu_{triplet}$ (6 μm) and $\nu_{singlet}$ (5.5 μm)

D. Laser calibration well known water absorption lines

Muonic Lamb Shift - Results



Pohl et al., Nature 466 (2010)



Antonigni et al., Science 339 (2013)

- **Difference** in the observed charge radius, r_P, compared to H spectroscopy and elastic electron scattering is **now 7σ**!
- This proton radius puzzle is still unsolved and has triggered many papers
- Several effects (both in the measurement and theory) were investigated but none could explain this large discrepancy
- Lamb shift measurement in μ^3He^+ and μ^4He^+ will help to disentangle the origin of the puzzle

Precision muon lifetime measurements

- MuLan: μ^+ lifetime

- MuCap: μ^- lifetime in hydrogen
- MuSun: μ^- lifetime in deuterium

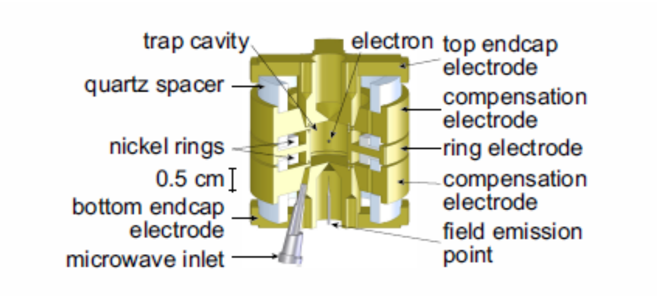
You will see that the motivation is however VERY different for the MuLan and MuCap/MuSun

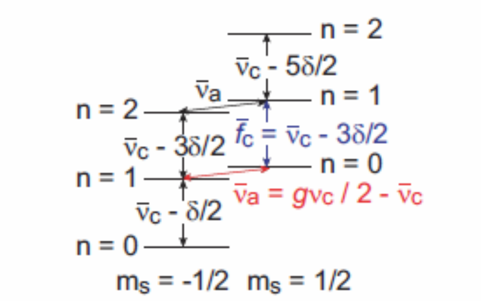
Precision muon lifetime measurements

- MuLan: μ^+ lifetime
- MuCap: μ^- lifetime in hydrogen
- MuSun: μ^- lifetime in deuterium

Electroweak Theory needs 3 input parameters

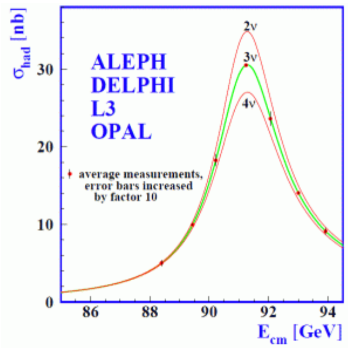
1. Fine structure constant α (0.00037 ppm)





Ultra precise penning trap: Hanneke et al. PRL 100 (2008) 120801

2. Neutral weak boson mass M_Z (23 ppm)



Phys. Rept. 427: 257—454, 2006

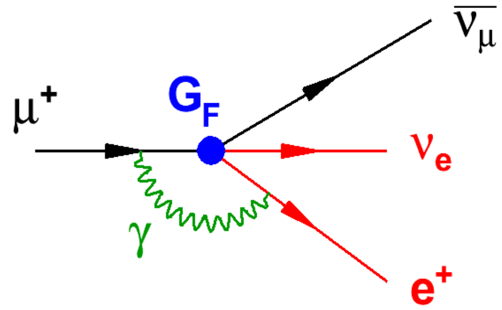
3. Fermi constant G_F (9 ppm)

Fermi constant GF: weak interaction strength

Most precisely determined by muon decay

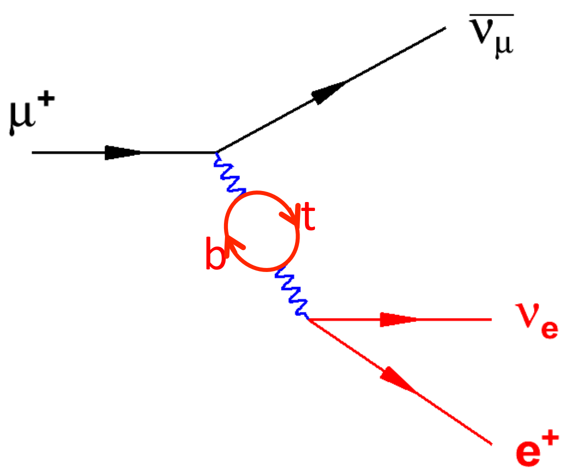
$$\frac{1}{\tau_{\mu^+}} = \frac{{G_F}^2 m_\mu^5}{192\pi^3}\,(1 + \mathbf{q})$$

PS, QED and hadr. rad. *



Implicit to all EW precision physics

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



Fermi constant GF: weak interaction strength

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

MuLan: **0.5 ppm** **1 ppm** **<0.3 ppm**

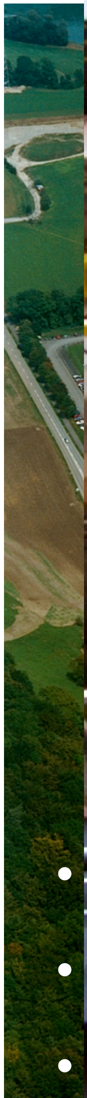
<0.14 ppm

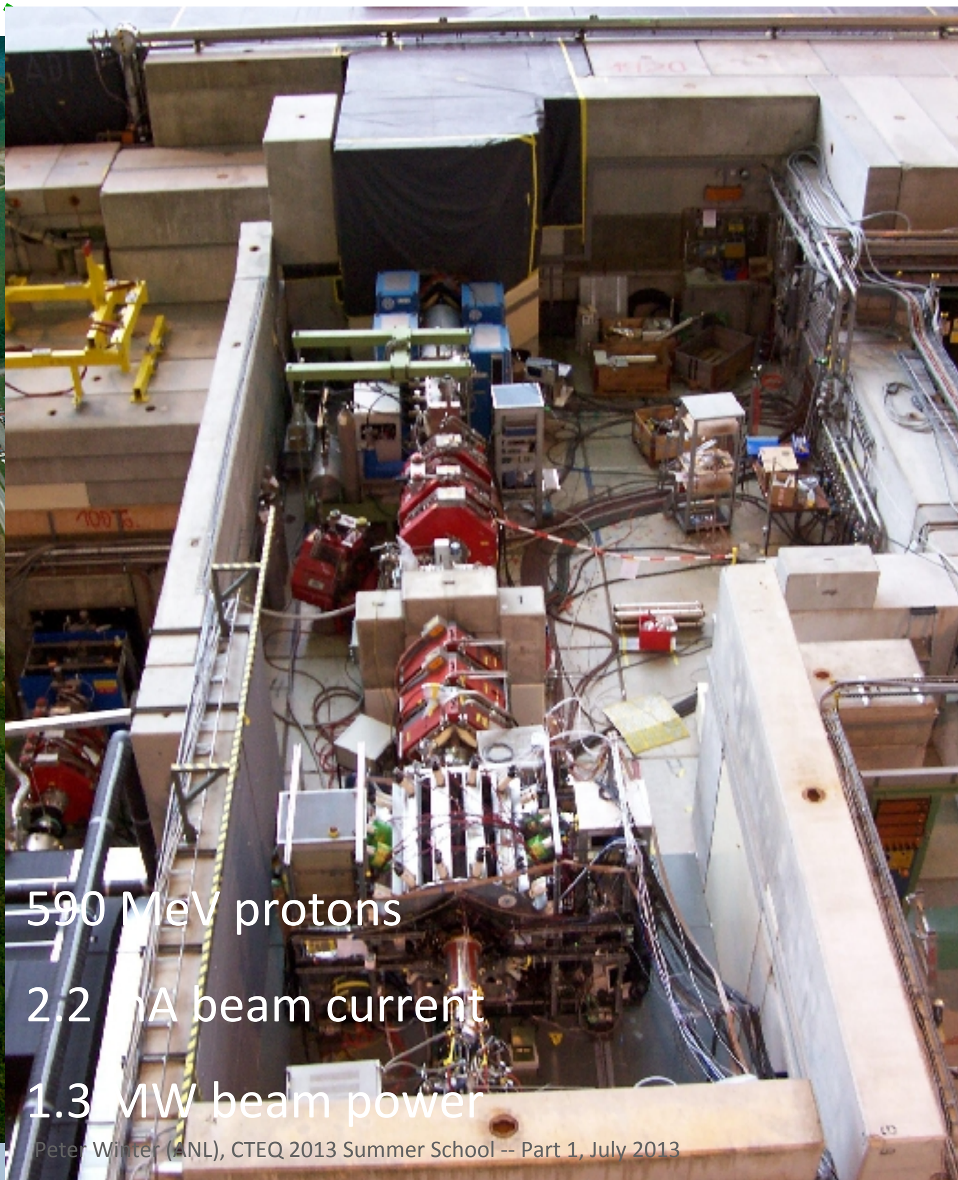
Lifetime error is the limit

van Ritbergen and Stuart:
2 loop QED corrections

Recently Pak and Czarnecki:
Finite electron mass (0.5ppm shift in G_F)

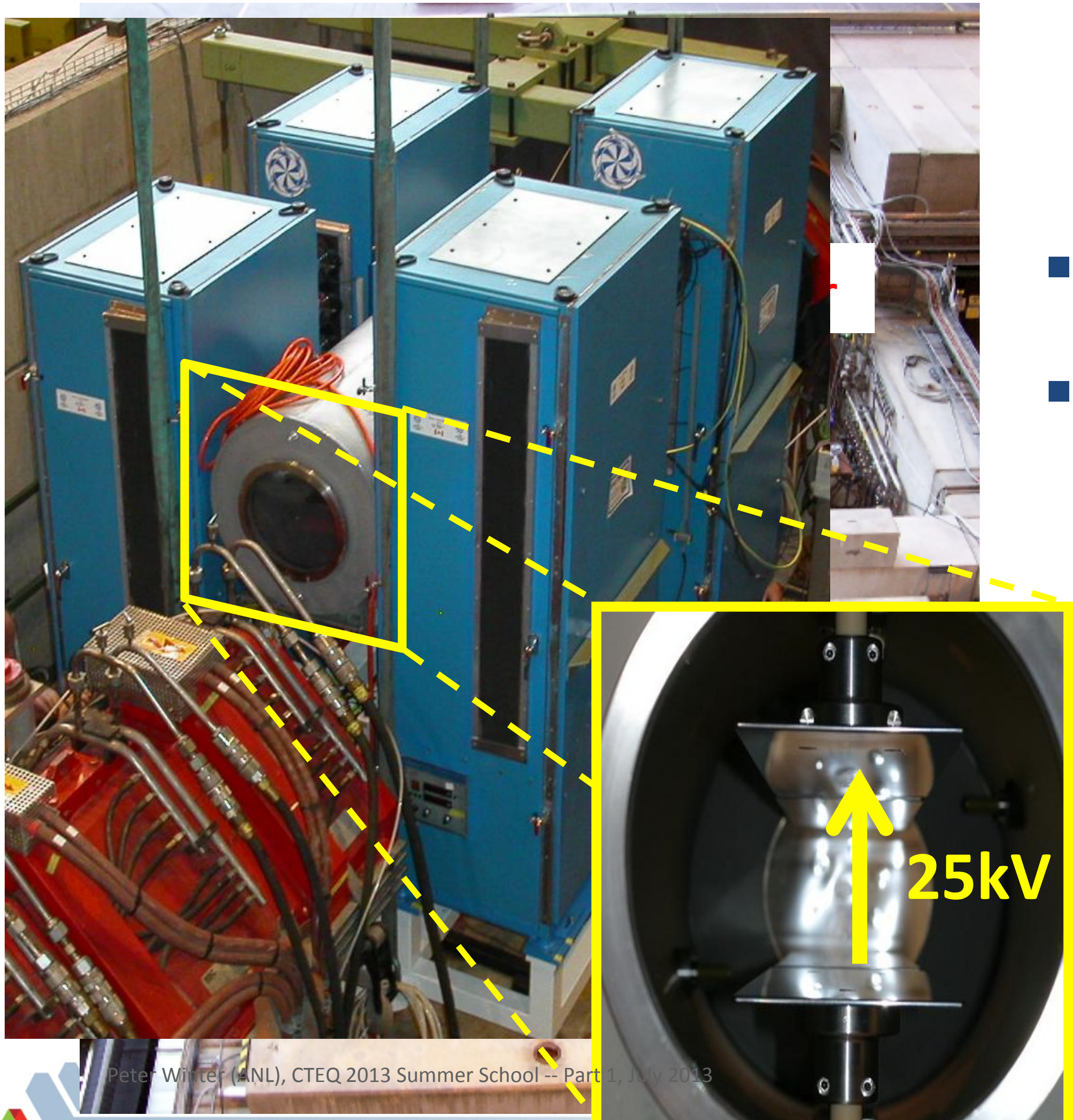
The facility: πE3 at PSI





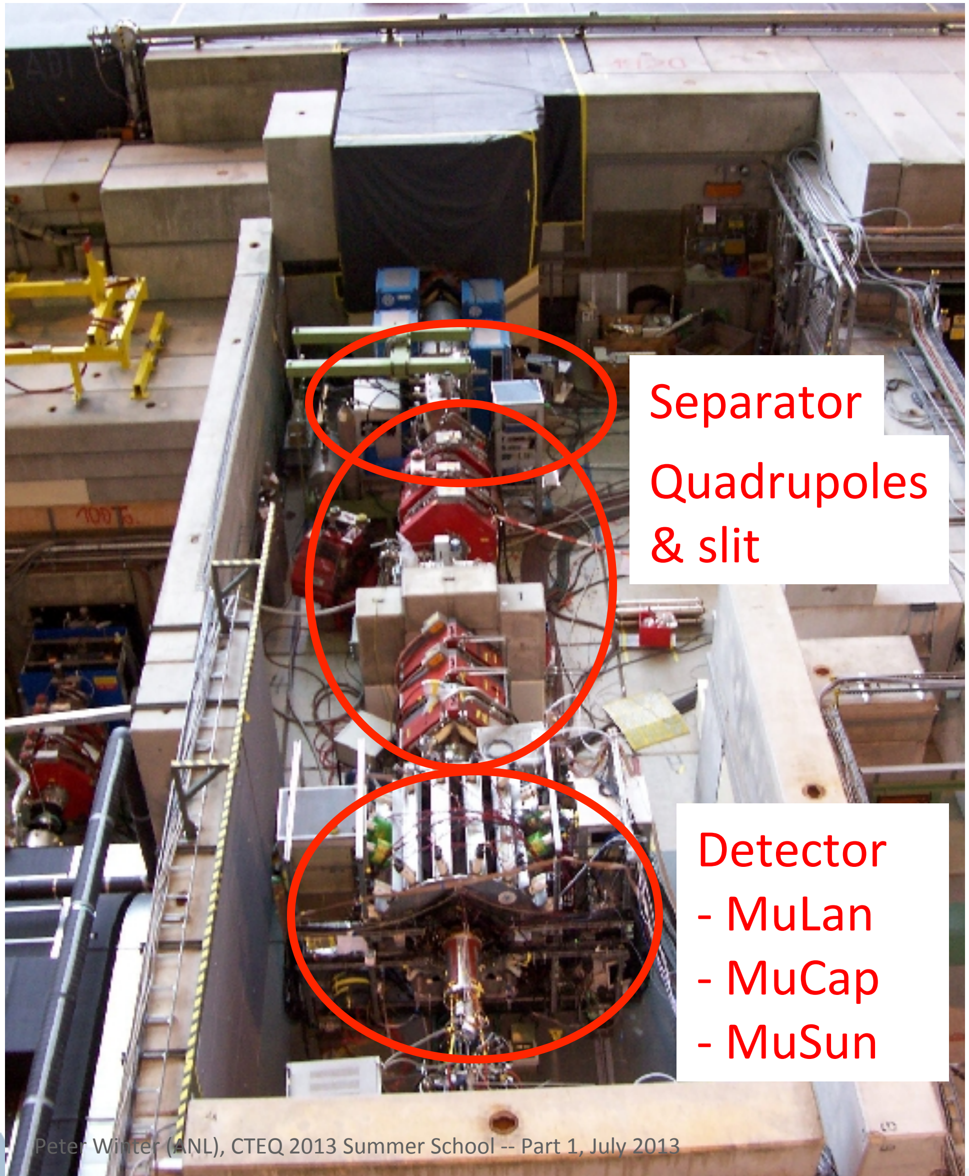
- 590 MeV protons
- 2.2 mA beam current
- 1.3 MW beam power

The electrostatic kicker

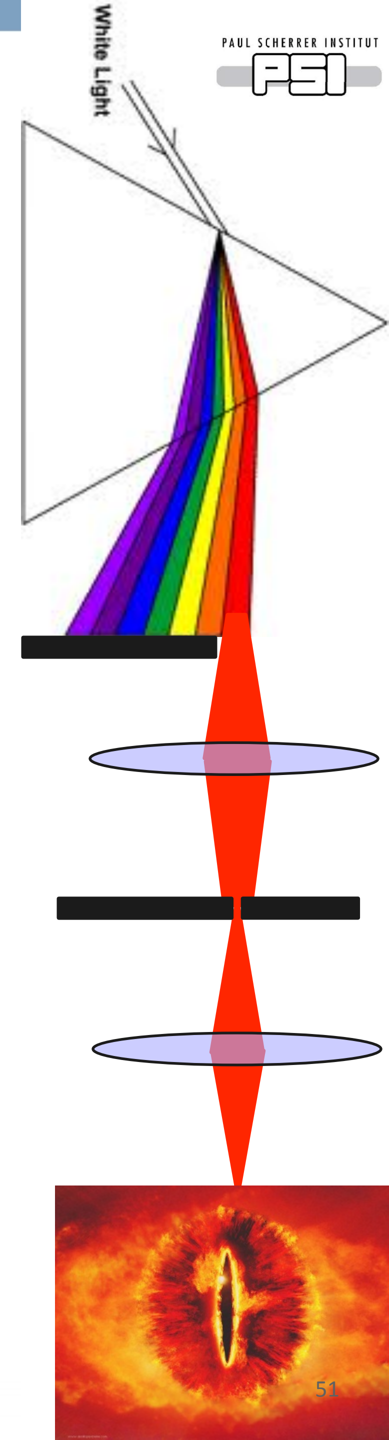


- Design at TRIUMF
- 50 ns switching time

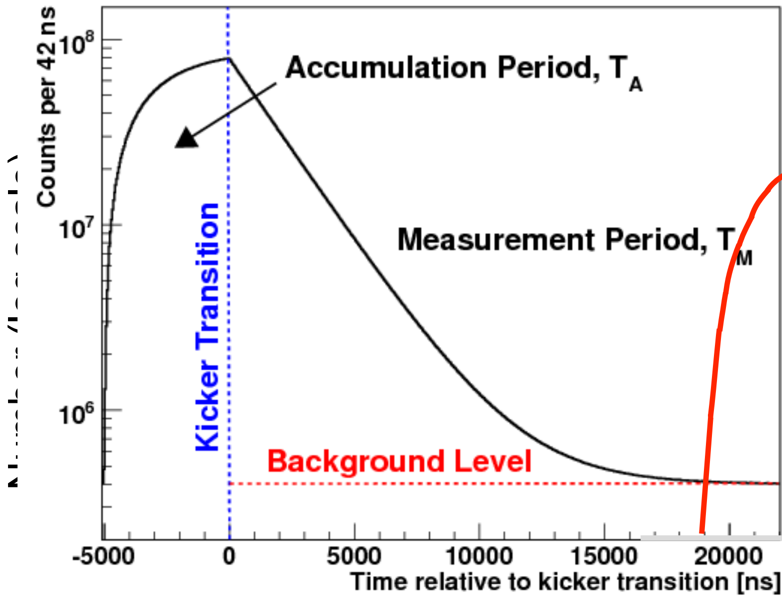
Other beamline elements



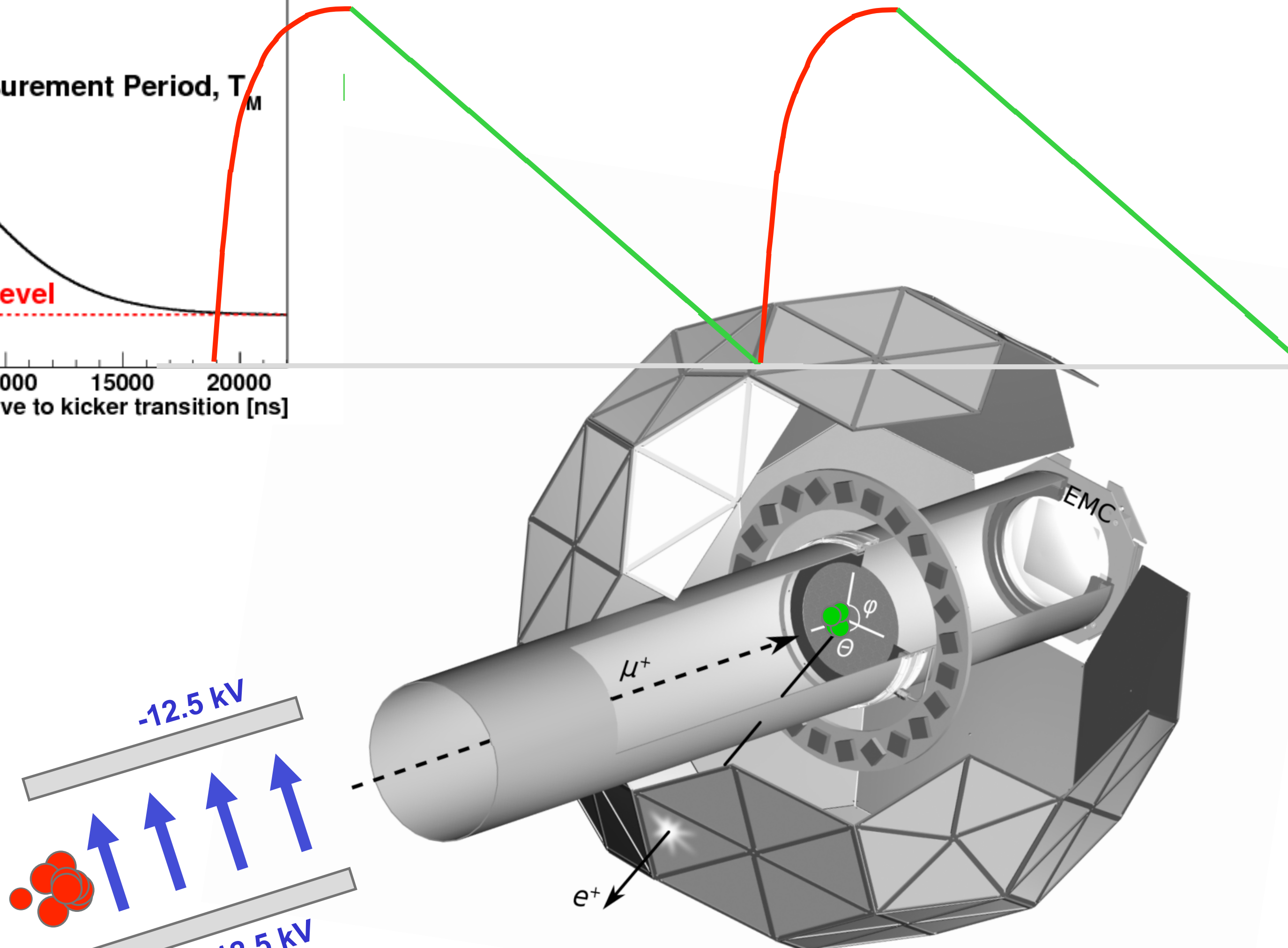
E x B separation of electrons



The MuLan concept in one slide…



Fill Period



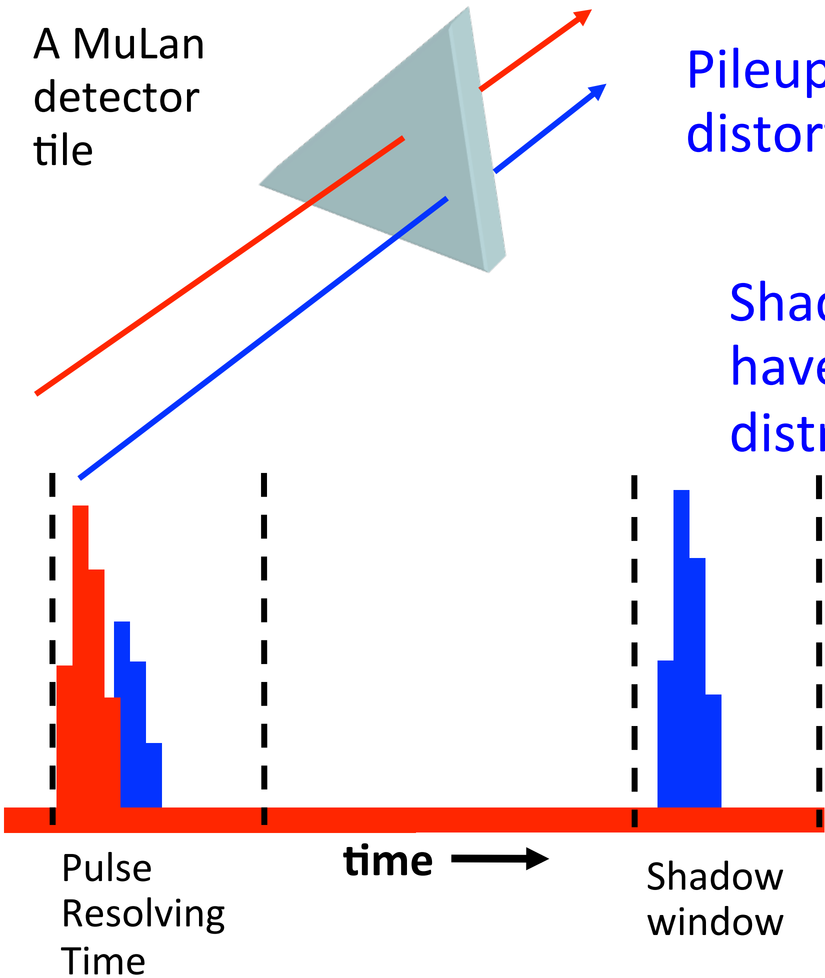
Final result for 2 x 10^{12} muon decays

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

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

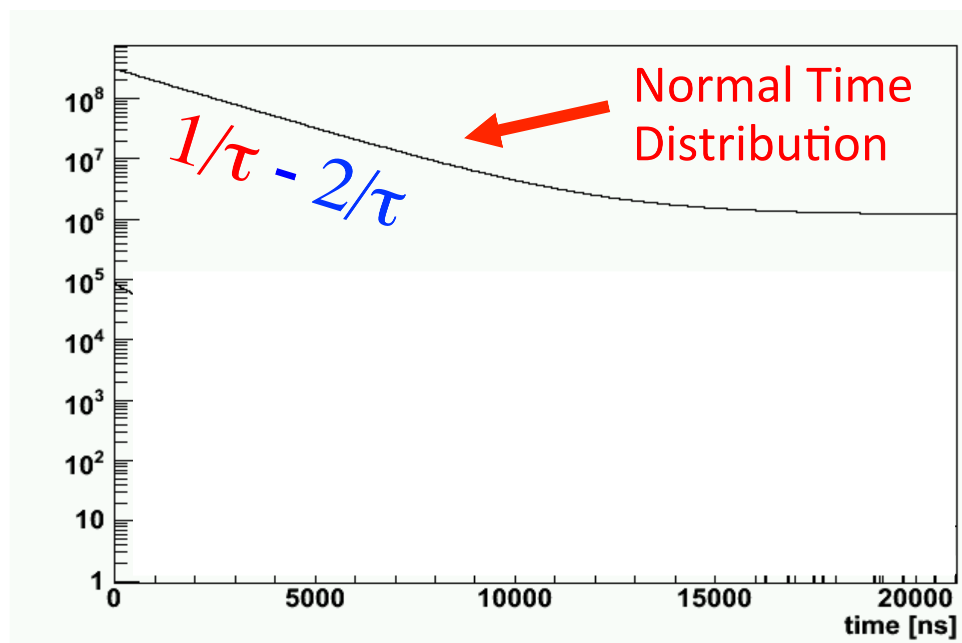
$$\tau_\mu(\mathrm{R07}) = 2196981.2 \pm 3.7 \pm 0.9 \text{ ps}$$

One example: Pileup systematic

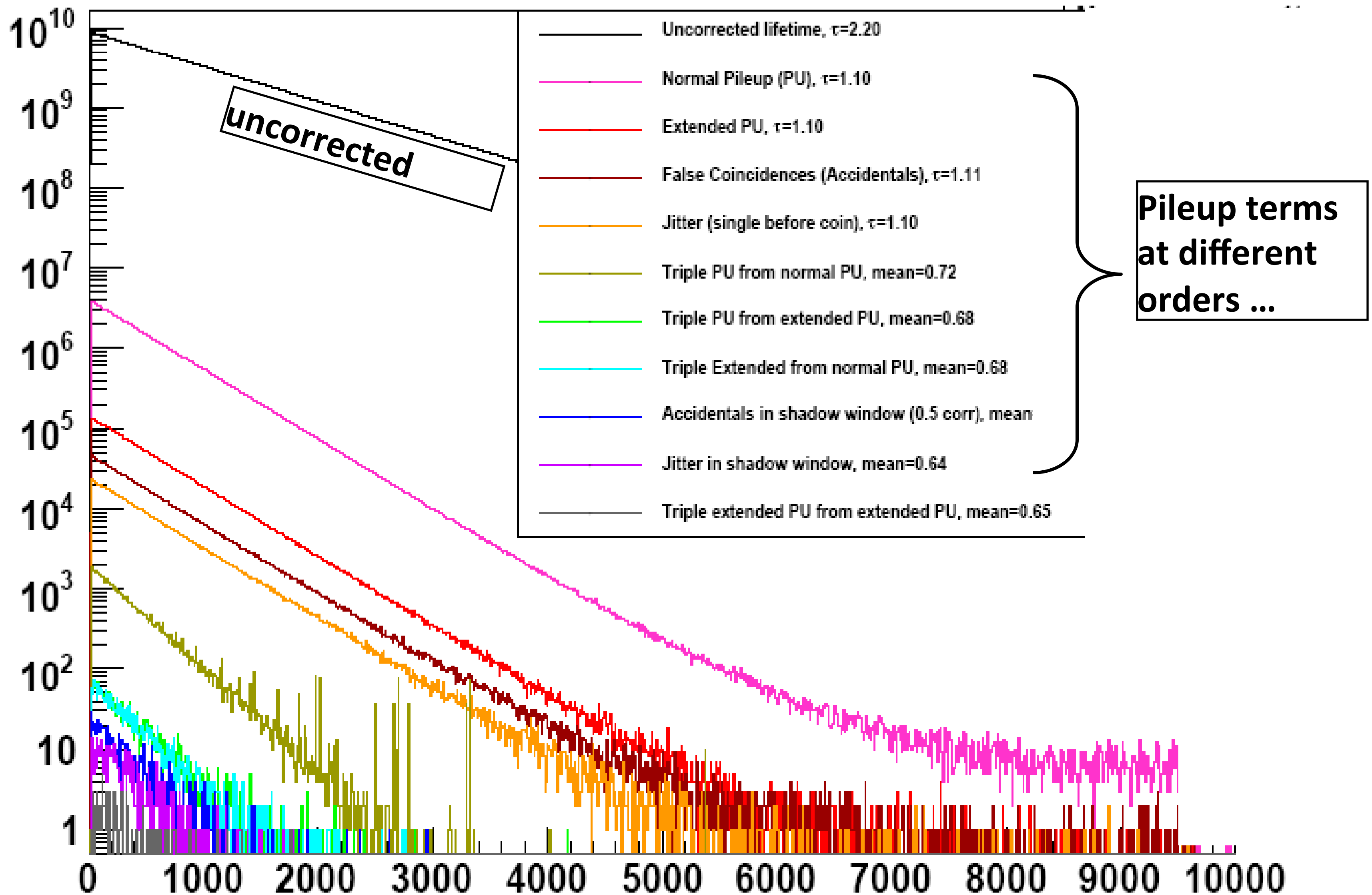


Pileup pulses measurably distort the lifetime

Shadow and pileup pulses have the same probability distribution!



It only takes one grad student and many months to figure it all out at the sub-ppm level...



Important: Double blinding technique

500 MHz precise master clock

Detune clock

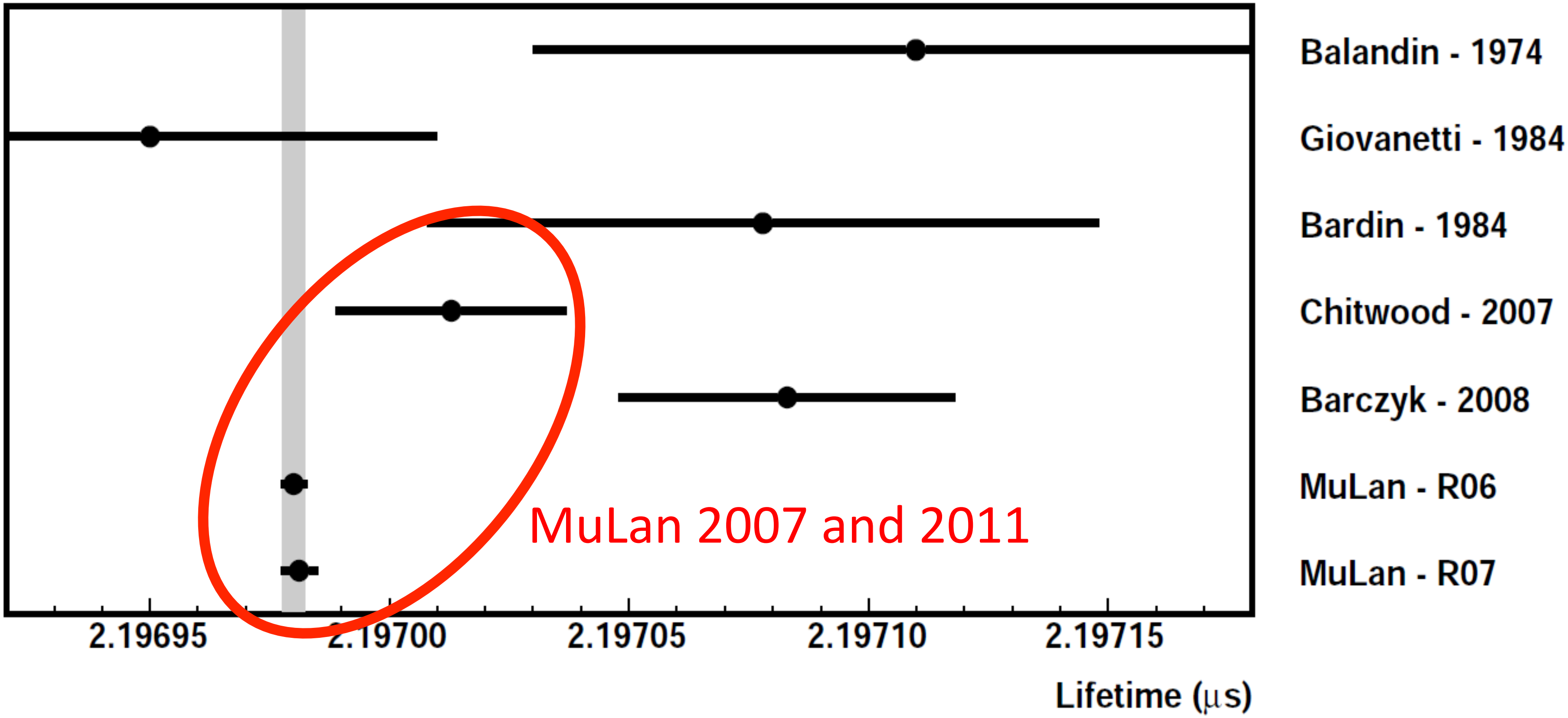
Hide from analyzers

Analyzers add secret offset

Commonly used in most precision experiments to prevent bias.

Master secret offset only removed after all systematics evaluated!

G_F = 1.1663818(7) x 10-5 GeV-2 (0.6 ppm)



D.B. Chitwood et al., Phys. Rev. Lett. 99, 03201 (2007)

D. Webber et al., Phys. Rev. Lett. 106, 041803 (2011)

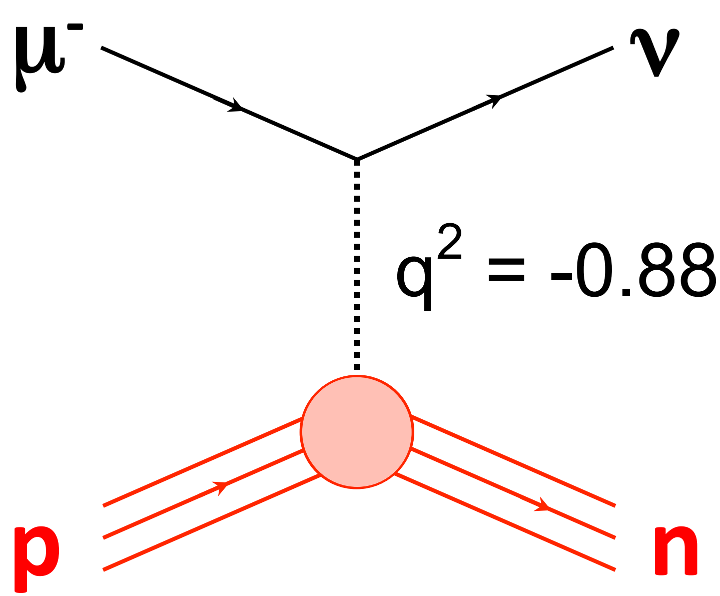
V. Tishchenko et al., Phys. Rev. D. 87, 052003 (2013)

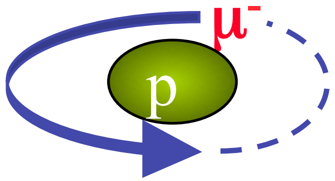
Precision muon lifetime measurements

- MuLan: μ^+ lifetime
- MuCap: μ^- lifetime in hydrogen
- MuSun: μ^- lifetime in deuterium

Nucleon form factors

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





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

Observable: Singlet capture rate Λ_S

Nucleon form factors

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

$$V^\alpha = g_V(q^2)\,\gamma^\alpha + i\, g_M(q^2)\,\sigma^{\alpha\beta} q_\beta / 2M_N$$

$$A^\alpha = g_A(q^2)\,\gamma^\alpha \gamma_5 + g_P(q^2)\, q^\alpha / m_\mu \gamma_5$$

$$\frac{\Delta\Lambda_S}{\Lambda_S} \Rightarrow \frac{\Delta g_P}{g_P}$$

.6%

.1%

.8%

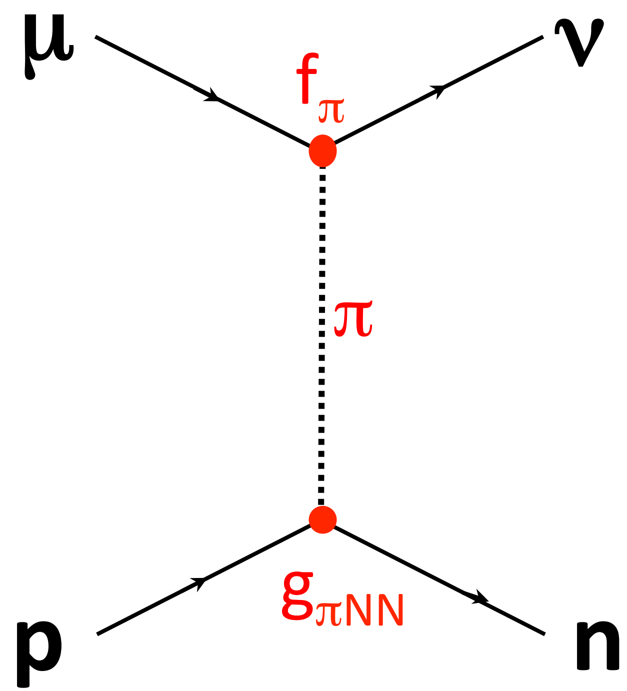
$$\frac{\delta\Lambda_S}{\Lambda_S} = 2\frac{\delta V_{ud}}{V_{ud}} + 0.466\frac{\delta g_v}{g_v} + 0.151\frac{\delta g_m}{g_m} + 1.567\frac{\delta g_a}{g_a} - 0.179\frac{\delta g_p}{g_p}$$

Note: Here, we neglected second class currents g_S and g_T that are small.

Well known, contribute only 0.45% uncertainty to Λ_S

Pseudoscalar form factor g_P

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



PCAC pole term

(Adler, Dothan, Wolfenstein)

$g_P = 8.26 \pm$

- ChPT based on the spontaneous symmetry breaking
- solid QCD prediction via ChPT (2-3% level)
- basic test of chiral symmetries and low energy QCD

Recent review: Kammel, P. and Kubodera, K., Annu. Rev. Nucl. Part. Sci. 60 (2010), 327

So how do we measure the rate Λ_S of $\mu^- p \rightarrow n \nu$?

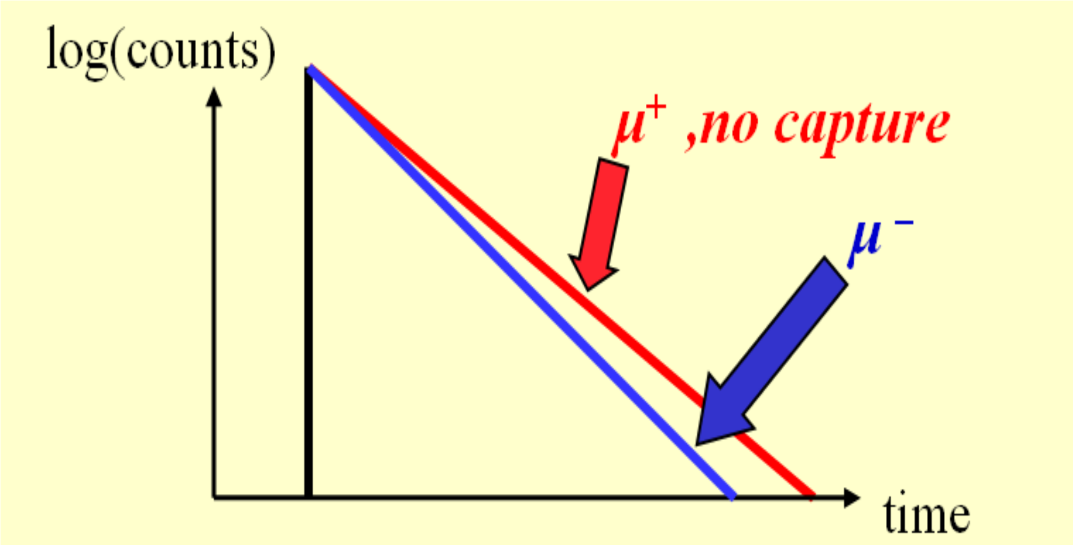
Direct method:

- Measure outgoing neutrons
- Typical experiments ~10% precision in Λ_S

Lifetime method:

$\Lambda_S \approx \lambda^- - \lambda^+$

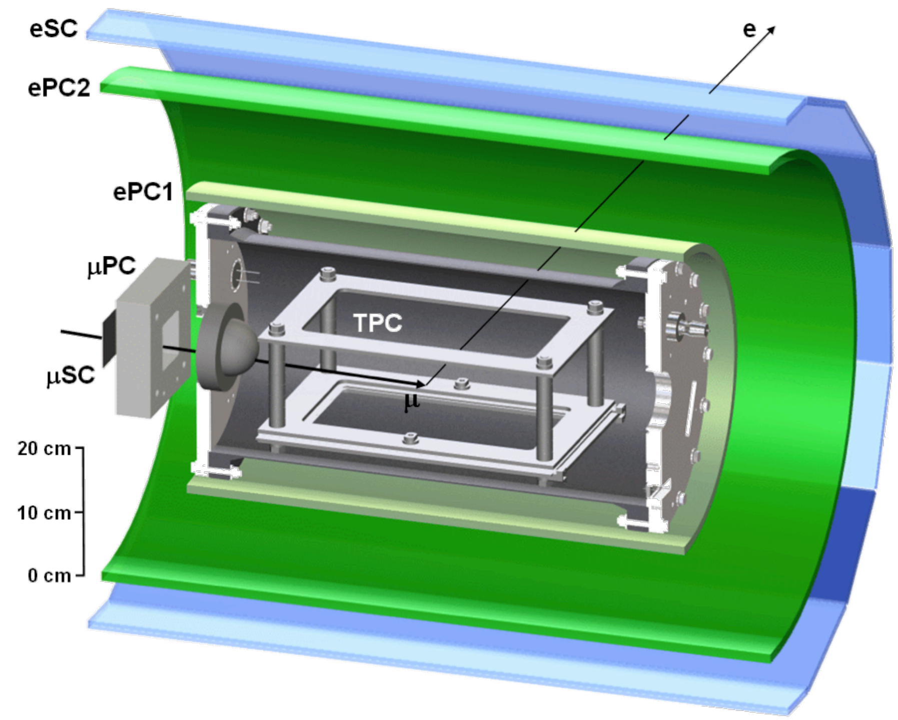
$\Lambda_S = 0.15\% \lambda^-$!



Quiz: How precise do you have to measure λ^- if you want to know Λ_S to 1%?
Note: λ^+ is known to 1 ppm from MuLan, so negligible!
Correct: 15 ppm (1% * 0.15% = 0.000 015)

MuCap key elements

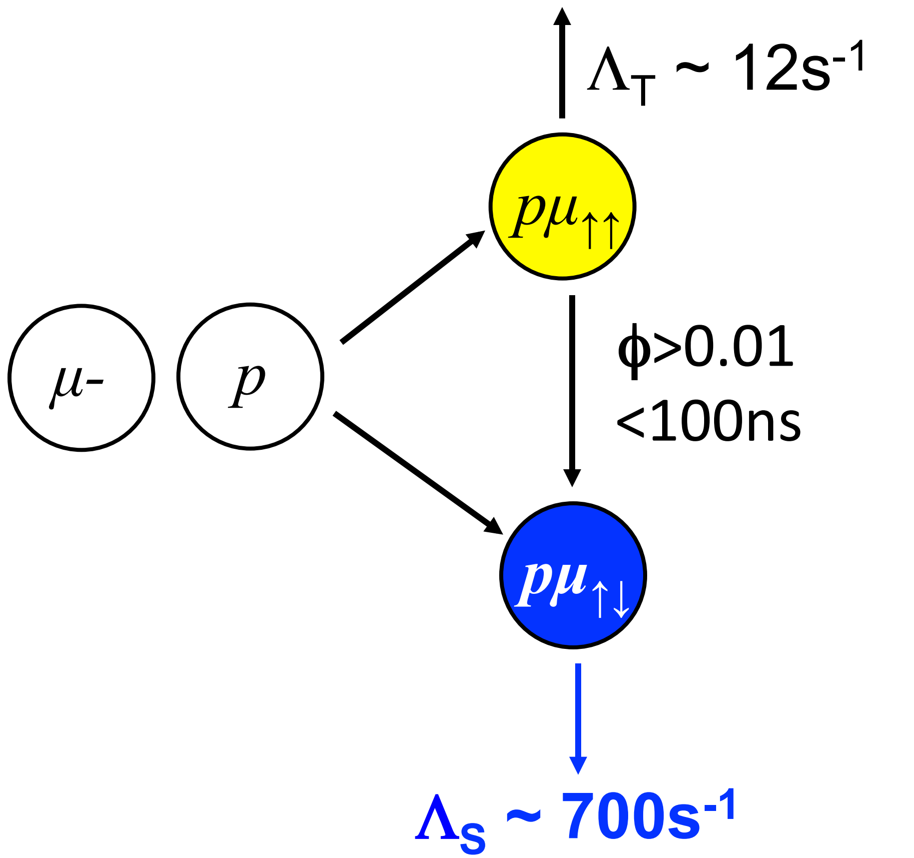
- Lifetime method
- Low gas density
- Active gas target (TPC)



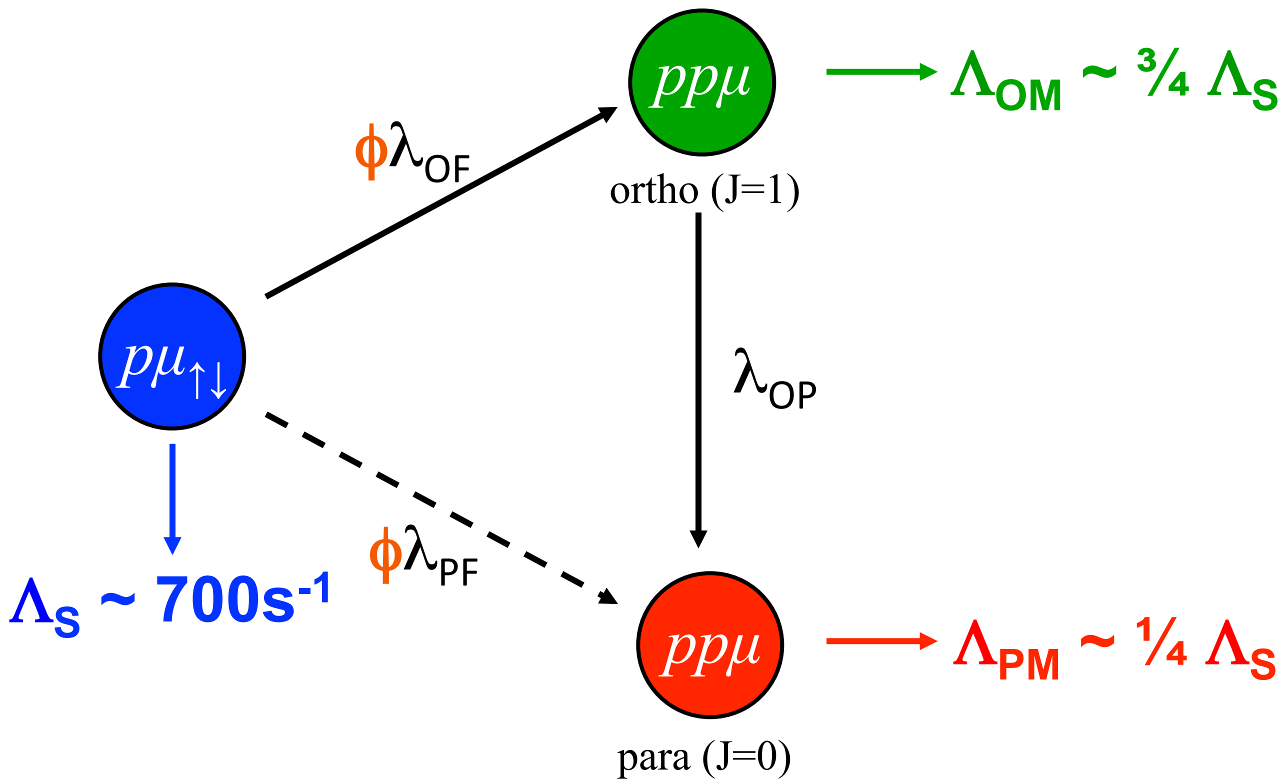
- Ultra pure gas system with in-situ monitoring
- Isotopically pure hydrogen gas

A muon in a hydrogen environment

ϕ: Hydrogen density, (LH_2: ϕ=1)

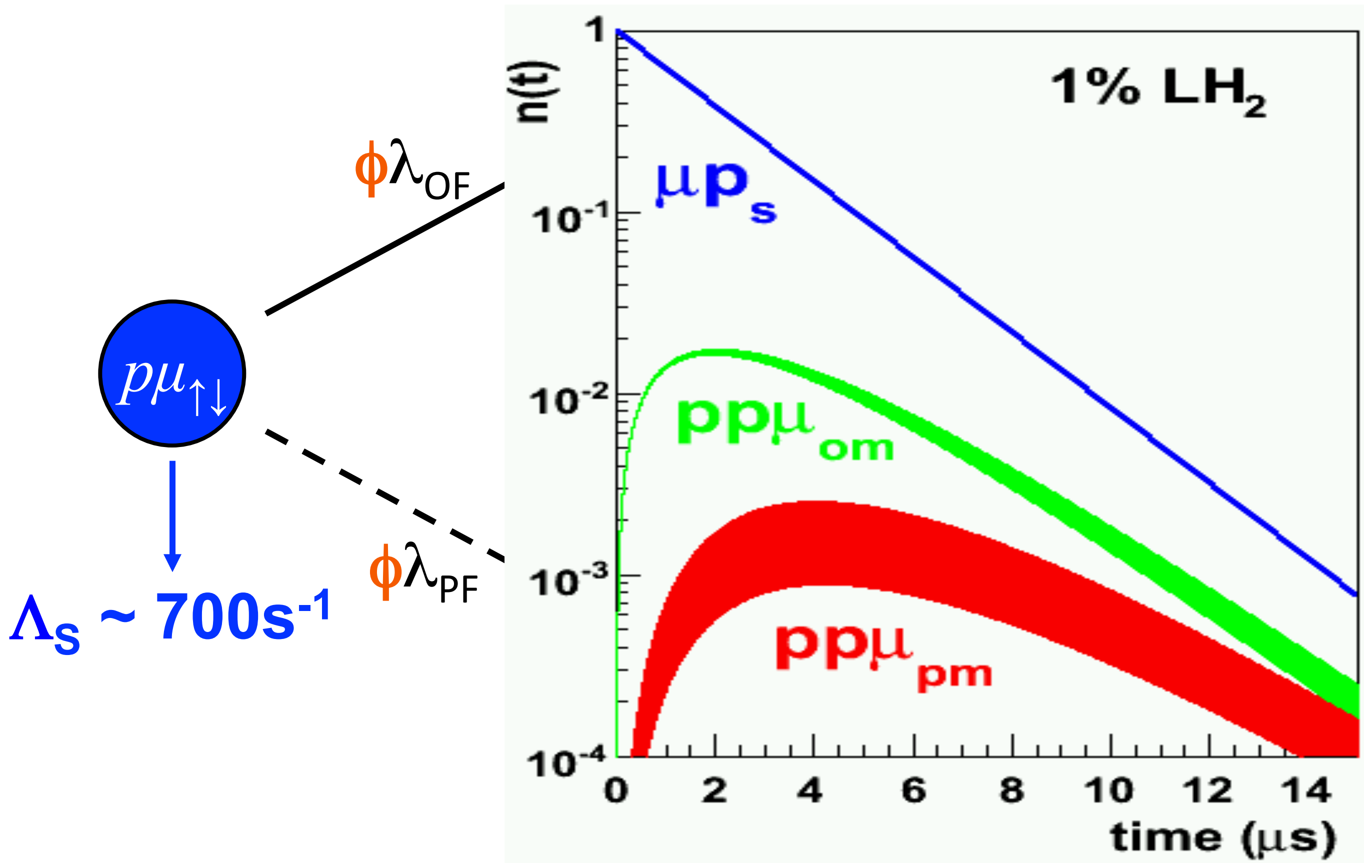


A muon in a hydrogen environment



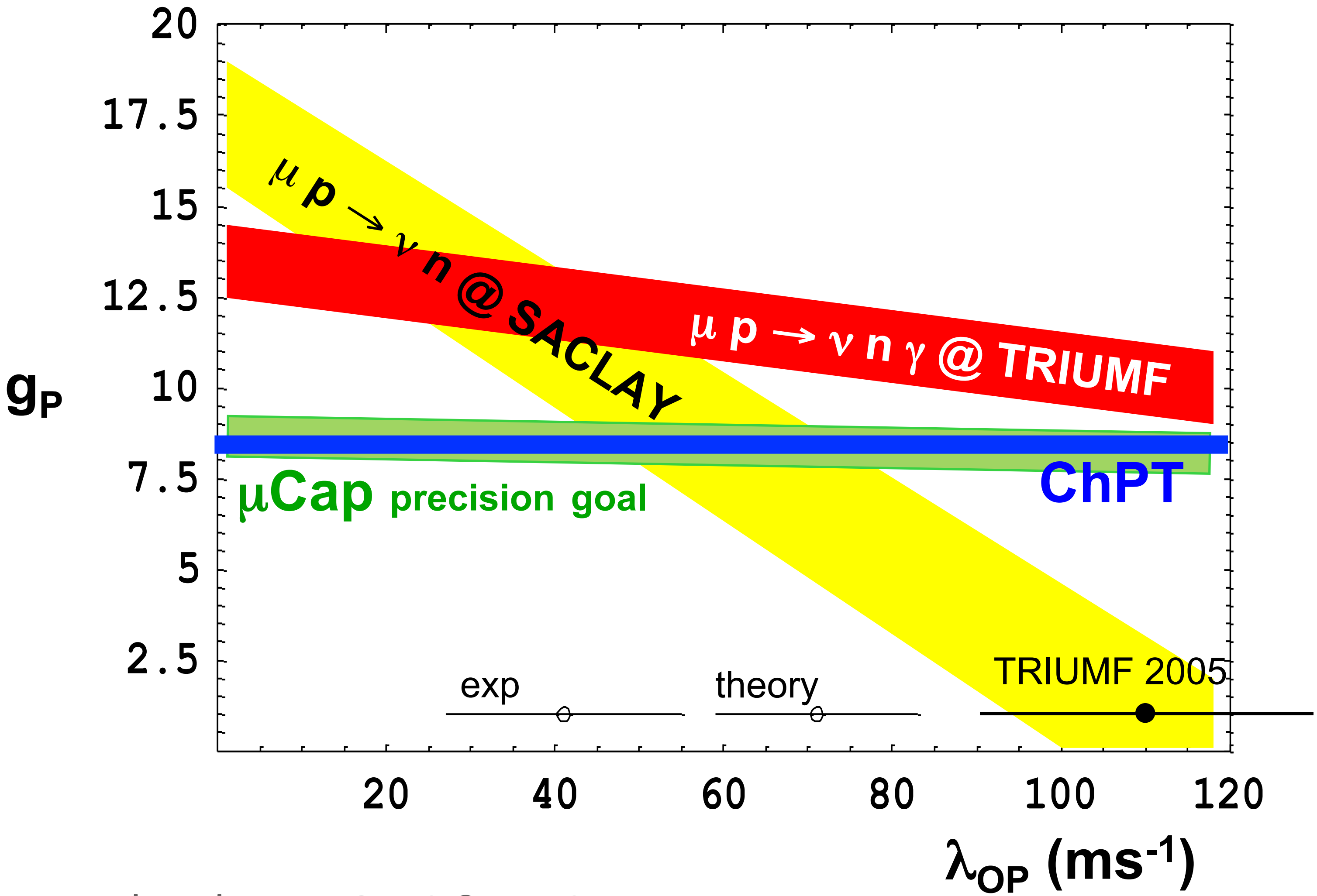
- Molecular ppμ formation depends on density ϕ
- Interpretation requires knowledge of λ_{OF} and λ_{OP}

A muon in a hydrogen environment



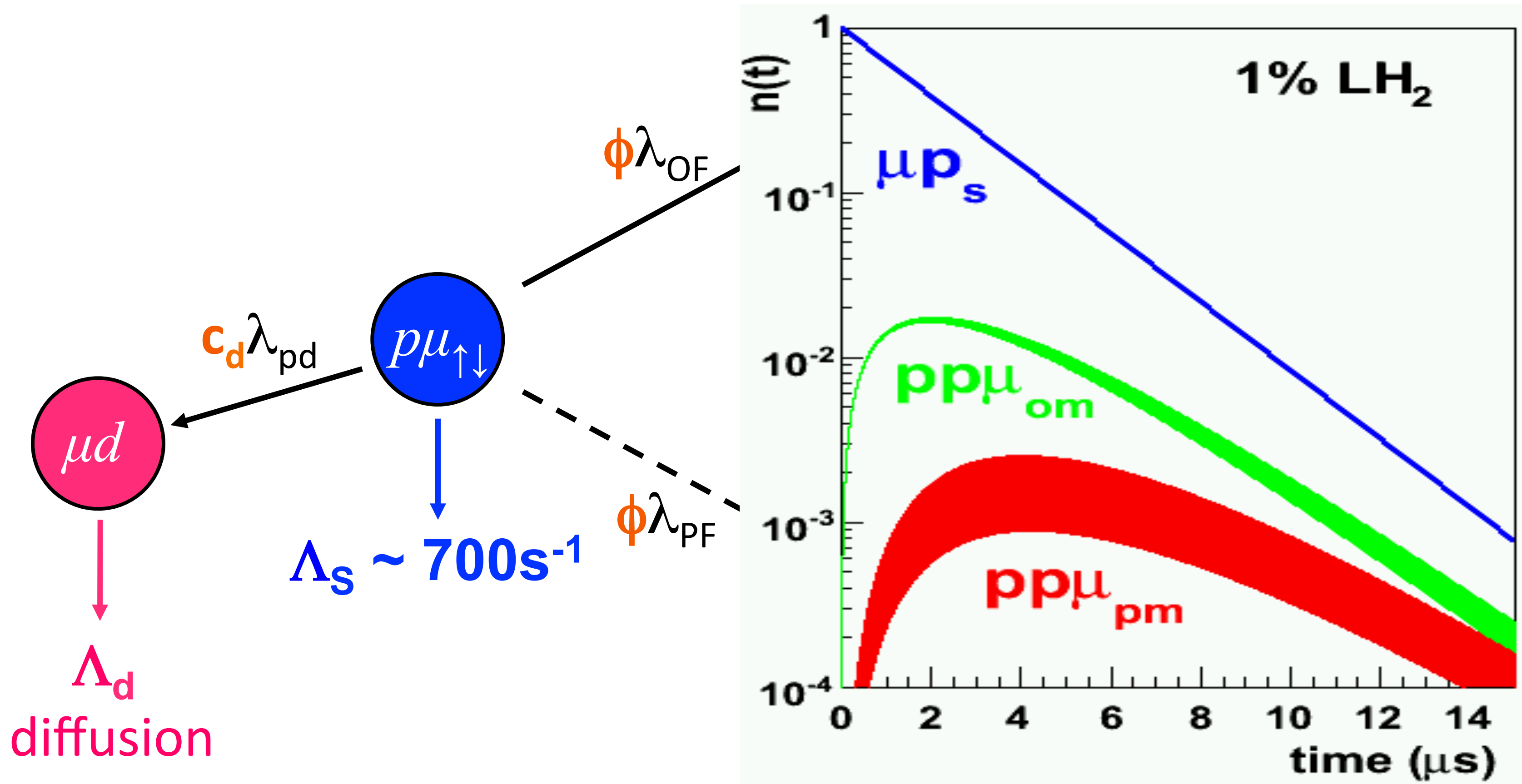
- MuCap solution: Low gas density ϕ (10 bar at room temperature) reduces molecular states!

Previous results suffer from molecular states



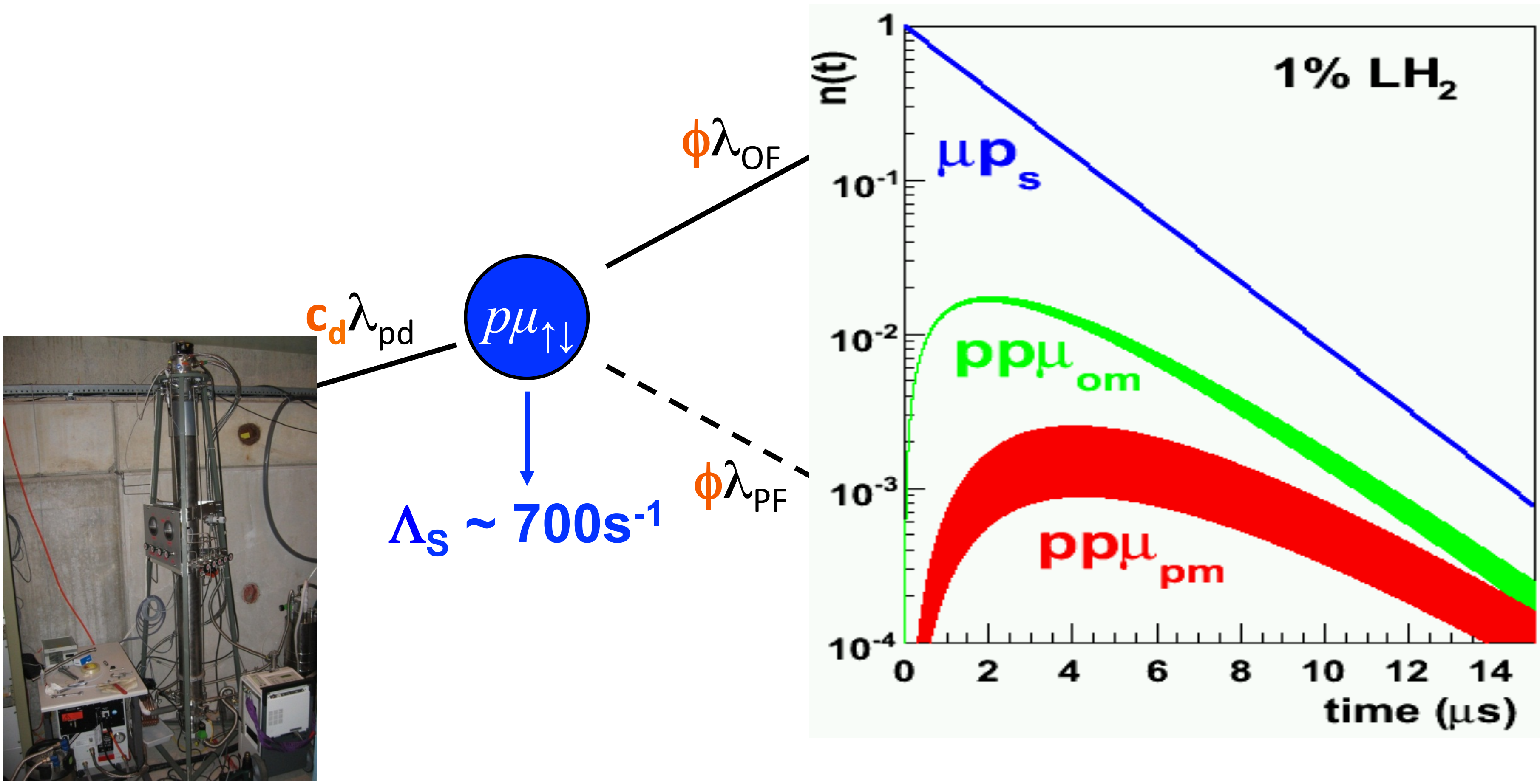
- No overlap theory, OMC & RMC
- Large uncertainty in $\lambda_{OP} \Rightarrow g_P \pm 50\%$

A muon in a hydrogen environment



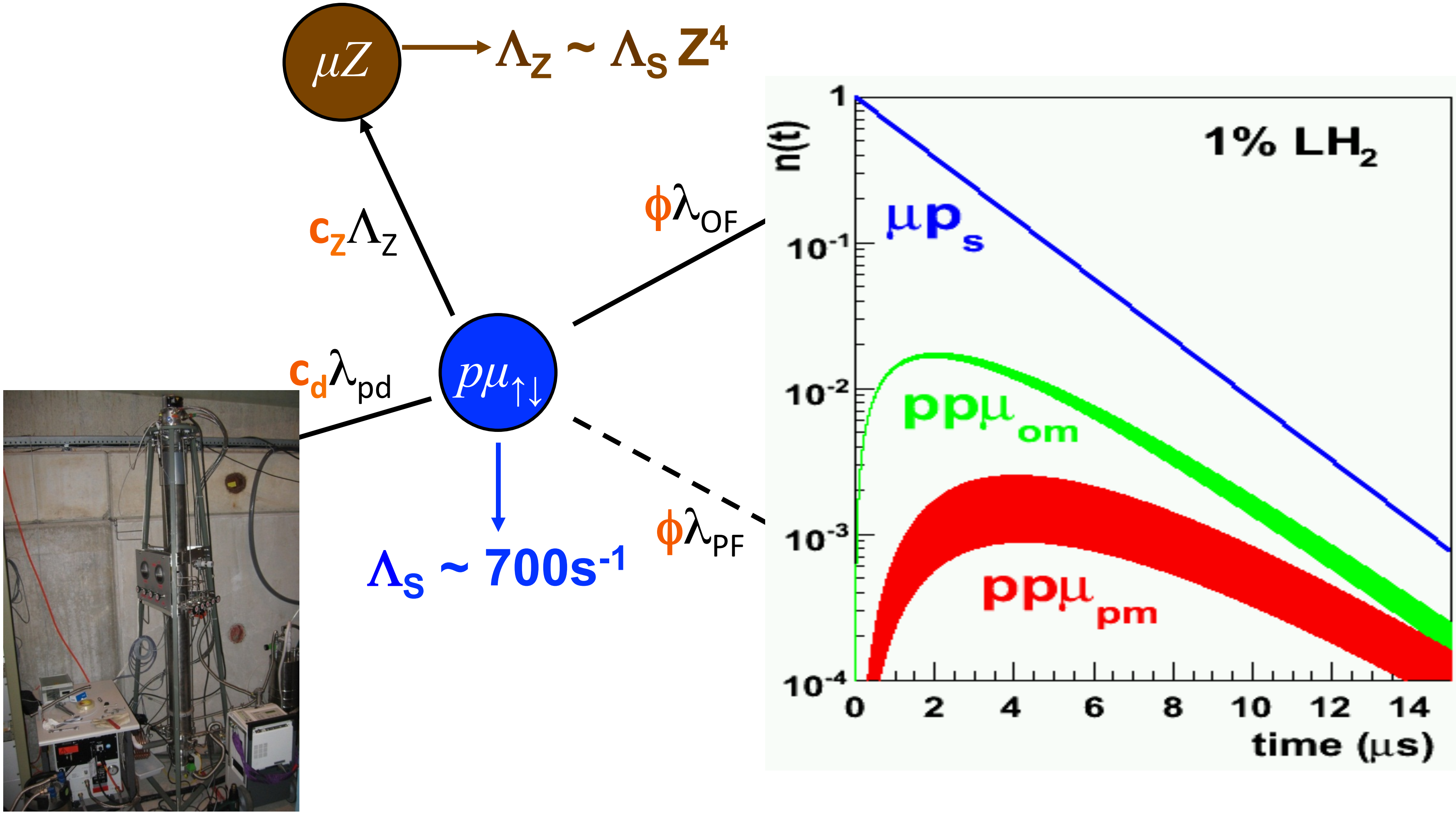
- μ^-d atoms can drift out of your hydrogen target due to a so-called Ramsauer-Townsend minimum in the scattering cross section.

A muon in a hydrogen environment



- MuCap solution: Distill deuterium out of gas: **c_d < 6 ppb**!!! We should apply for world's cleanest gas record!

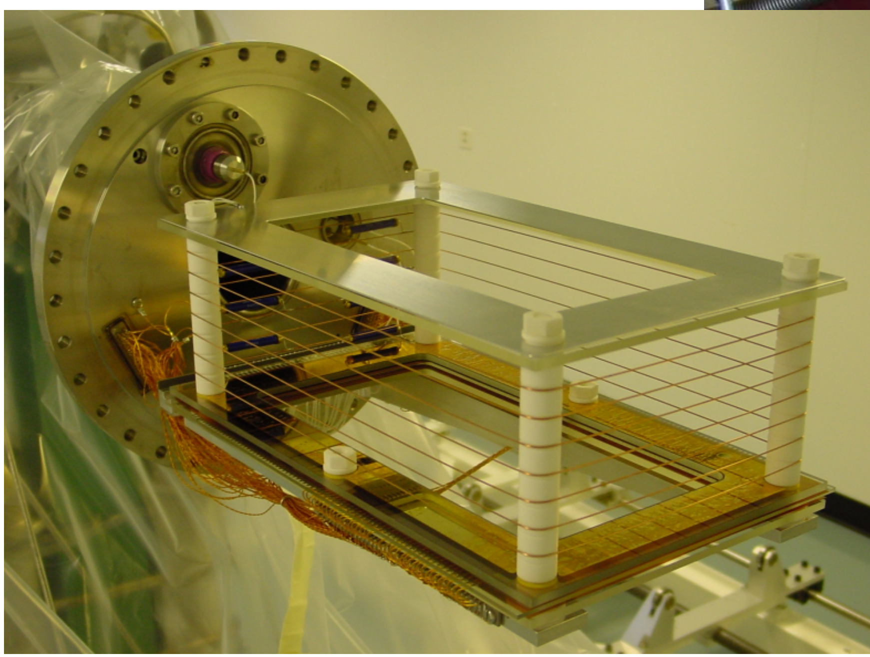
A muon in a hydrogen environment

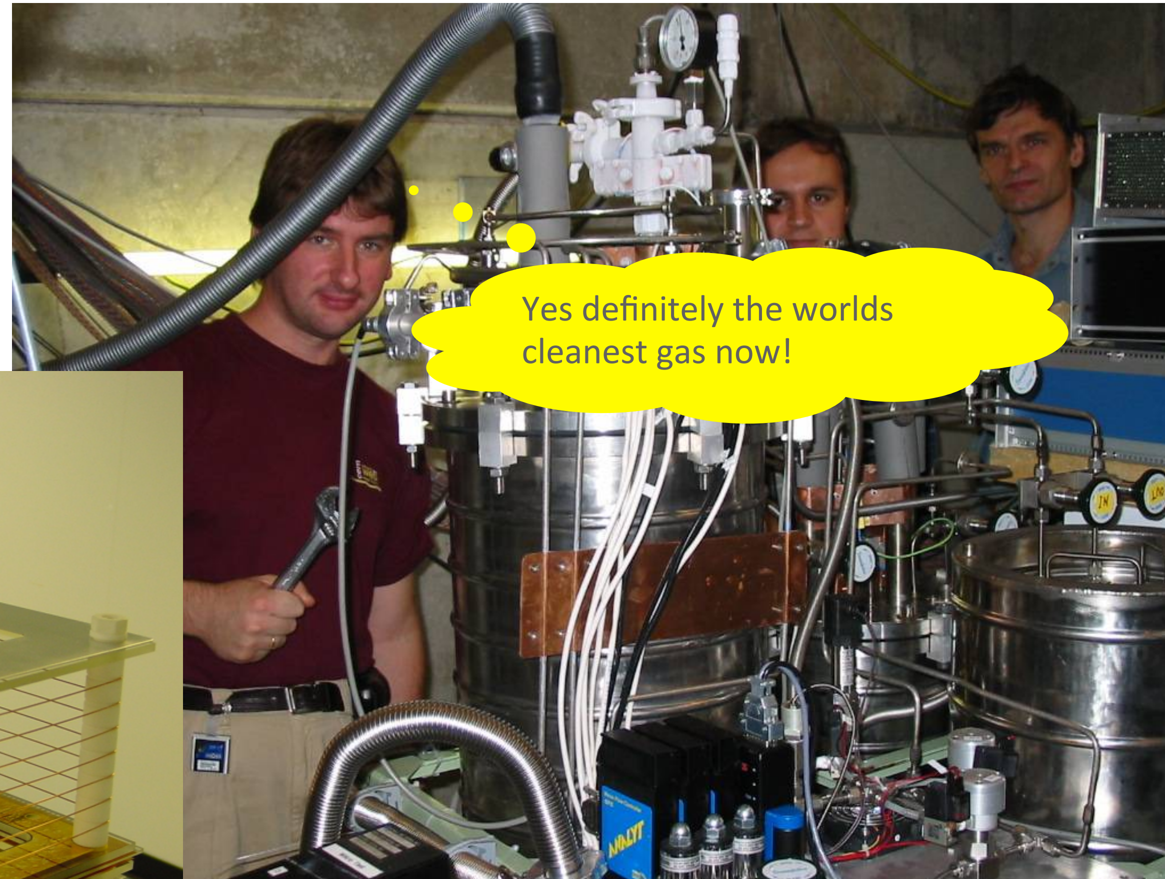


High-Z impurities in MuCap

Circulating H_2 Ultra-Purification System

- Active target (TPC)
- No materials in fiducial volume

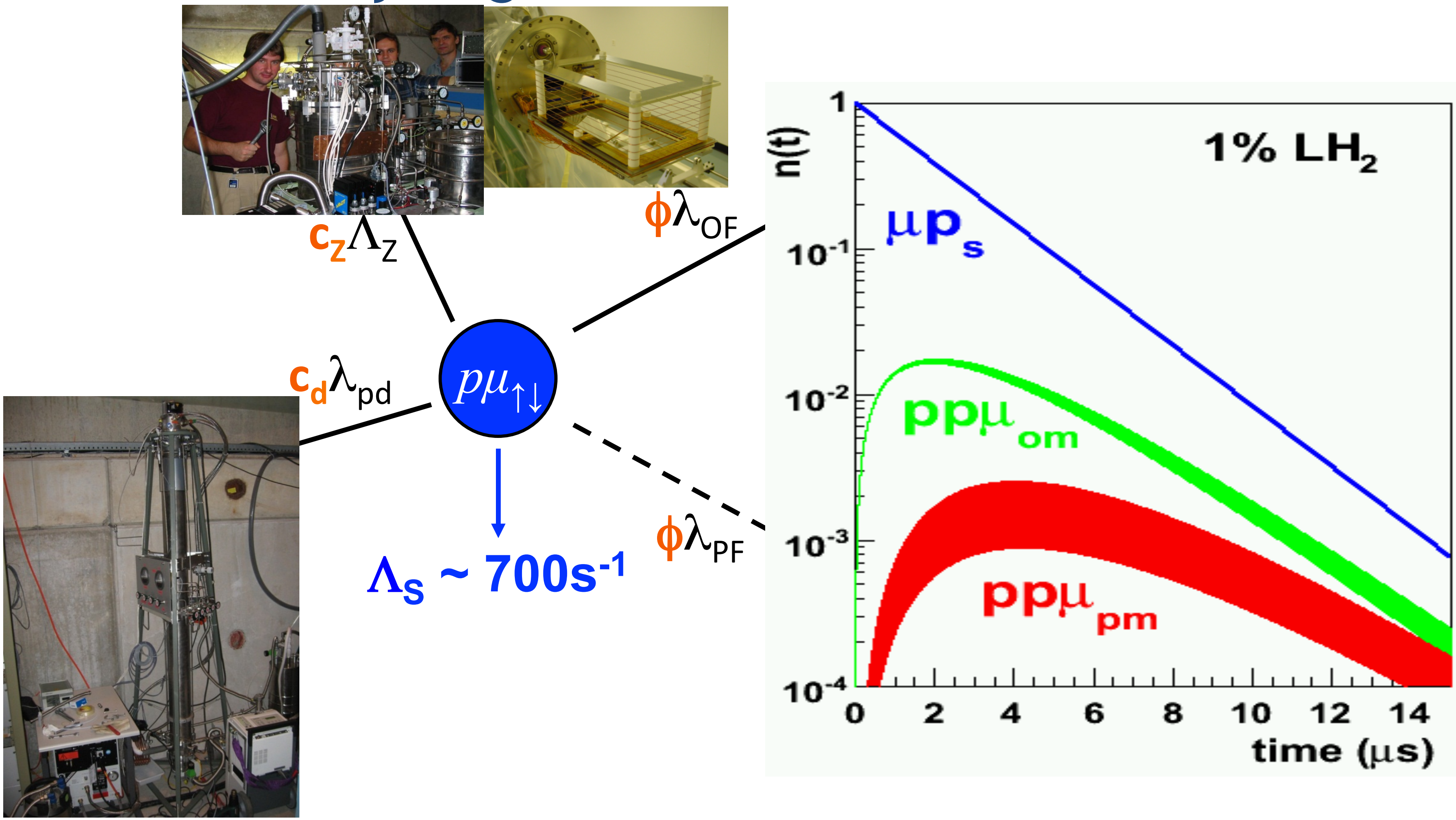




c_N, c_{H2O} < 10 ppb

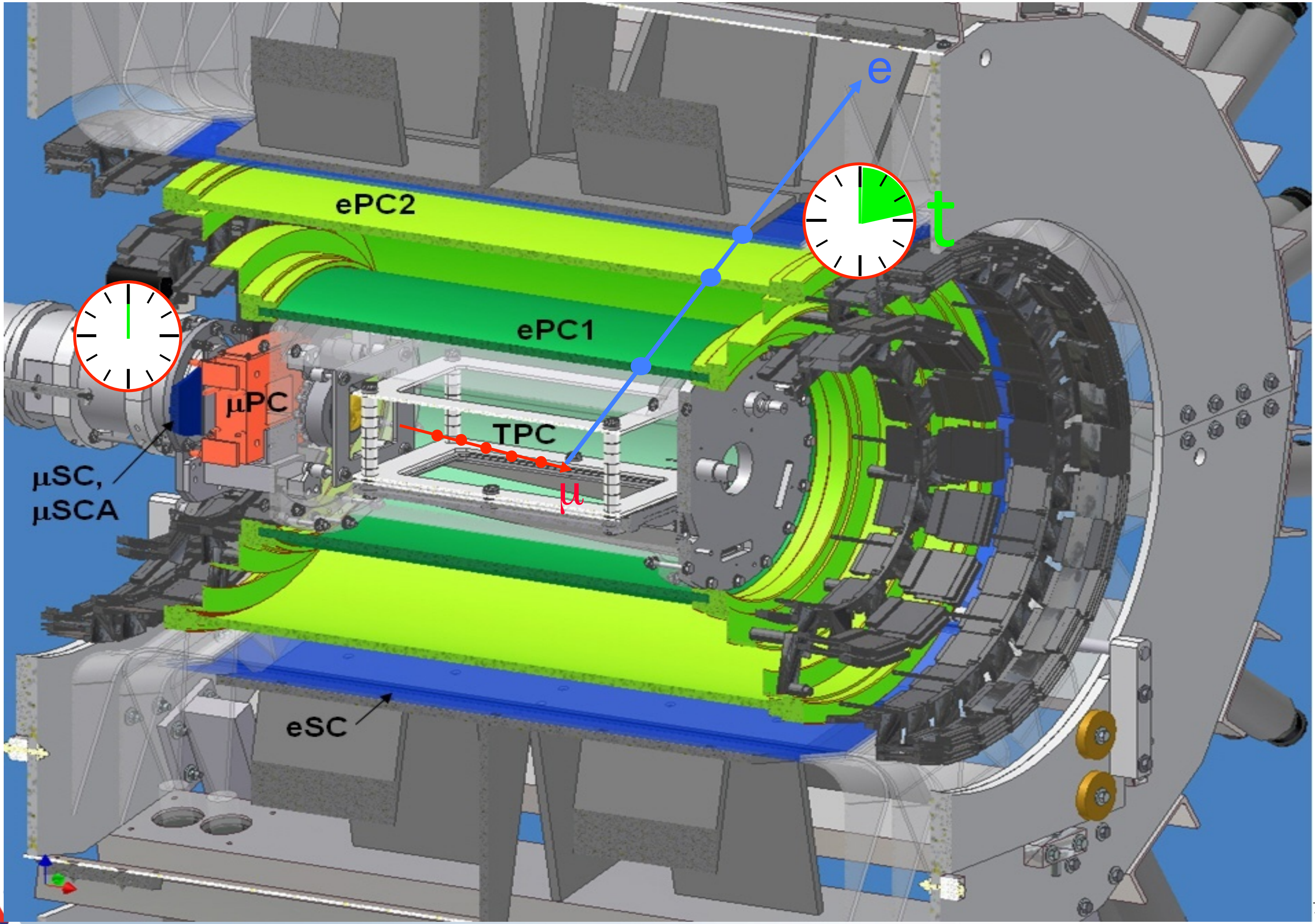
Nucl. Instr. & Meth. A578 (2007), 485

A muon in a hydrogen environment

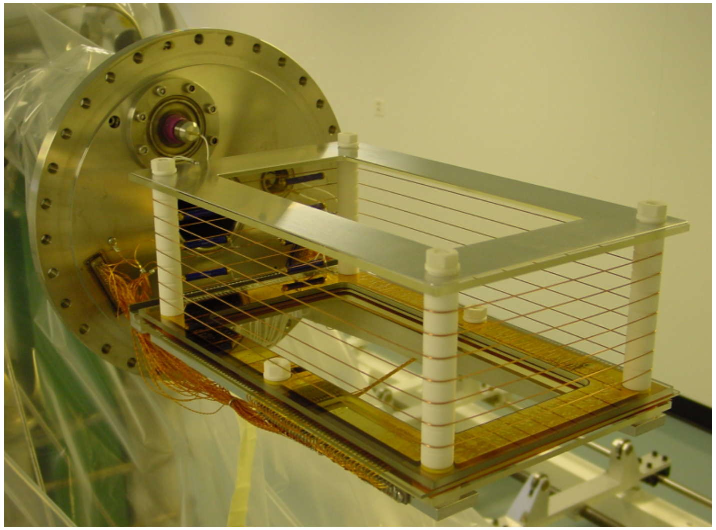


So MuCap design ensures that we measure the rate Λ_S of the singlet state!

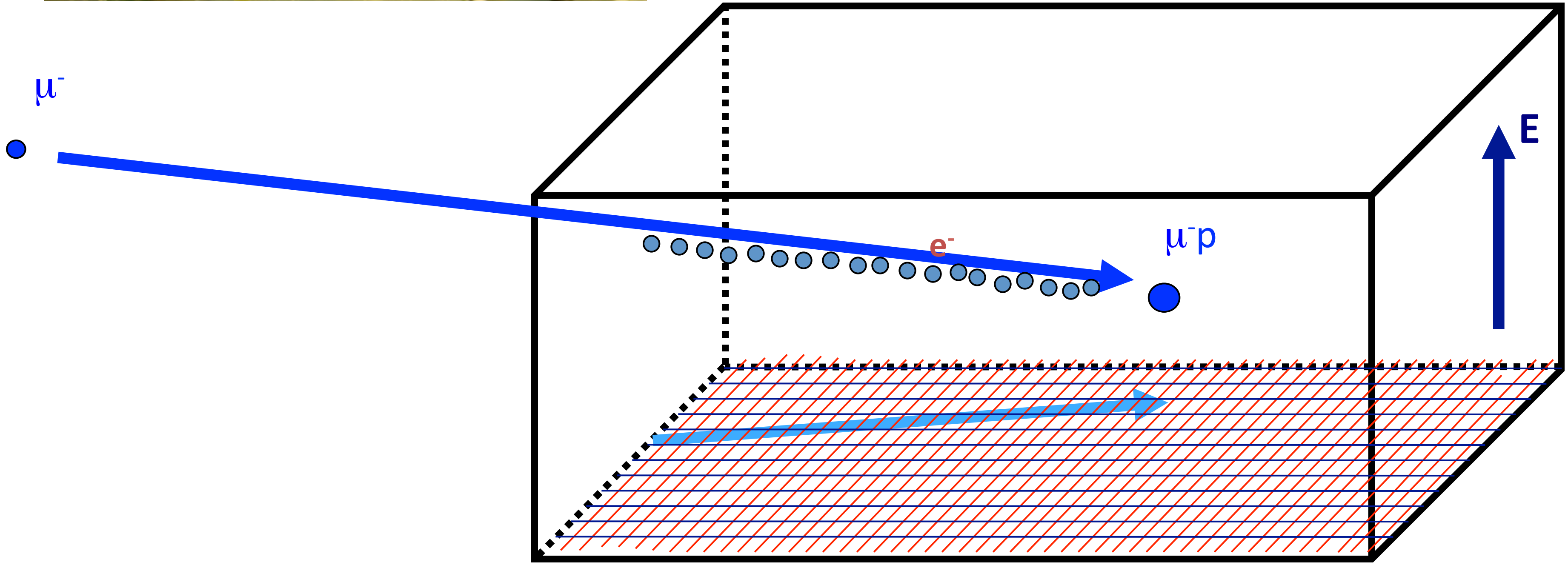
The experiment MuCap



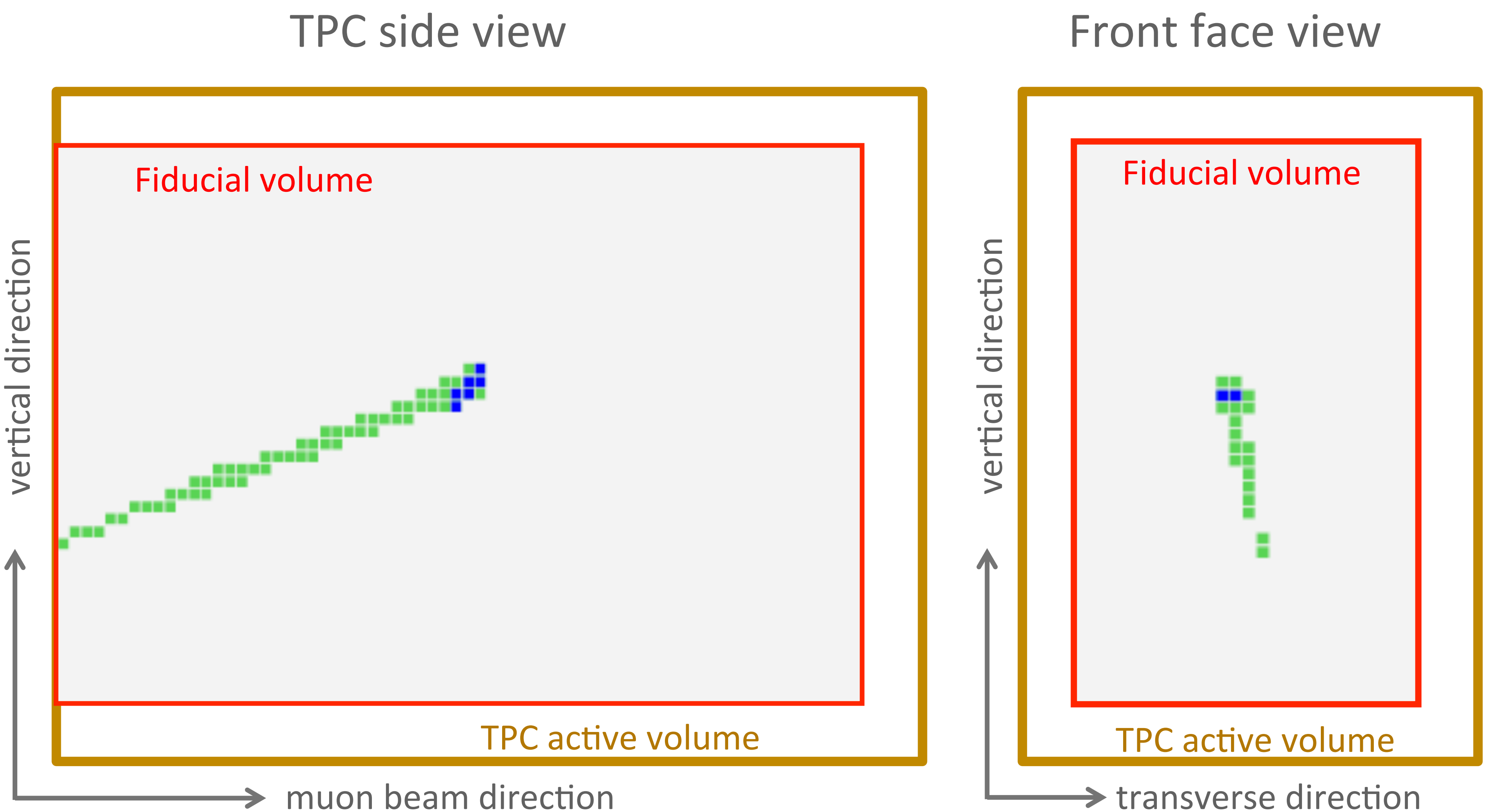
Novel technique: Hydrogen time projection chamber



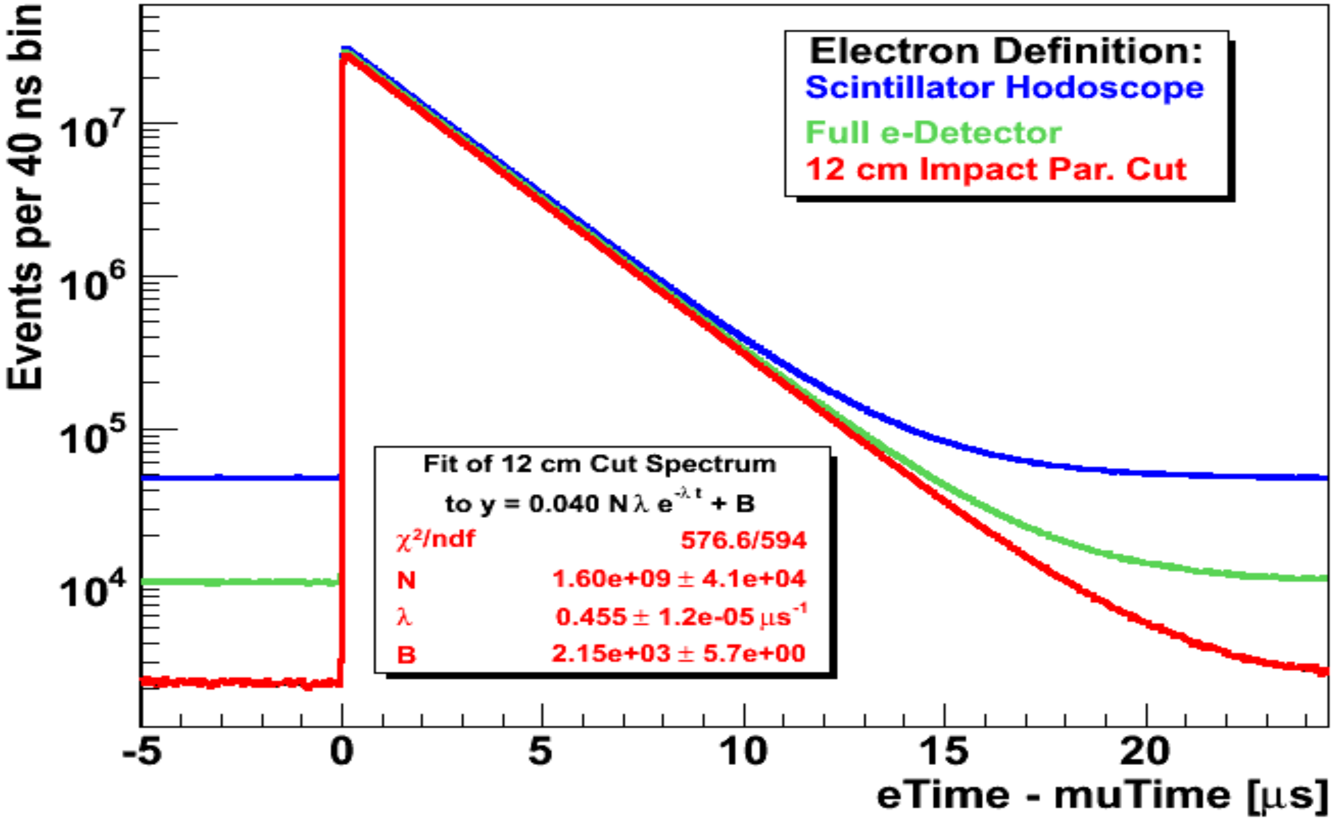
- 10 bar ultra-pure H_2
- No materials in fiducial volume
- 3D muon track reconstruction



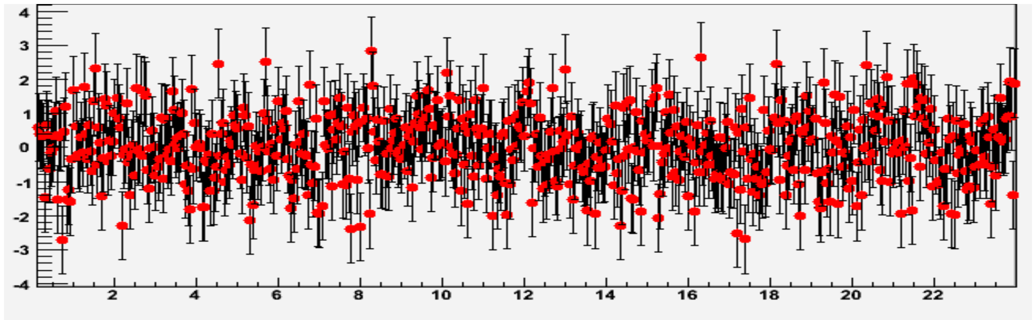
A typical good stopped muon



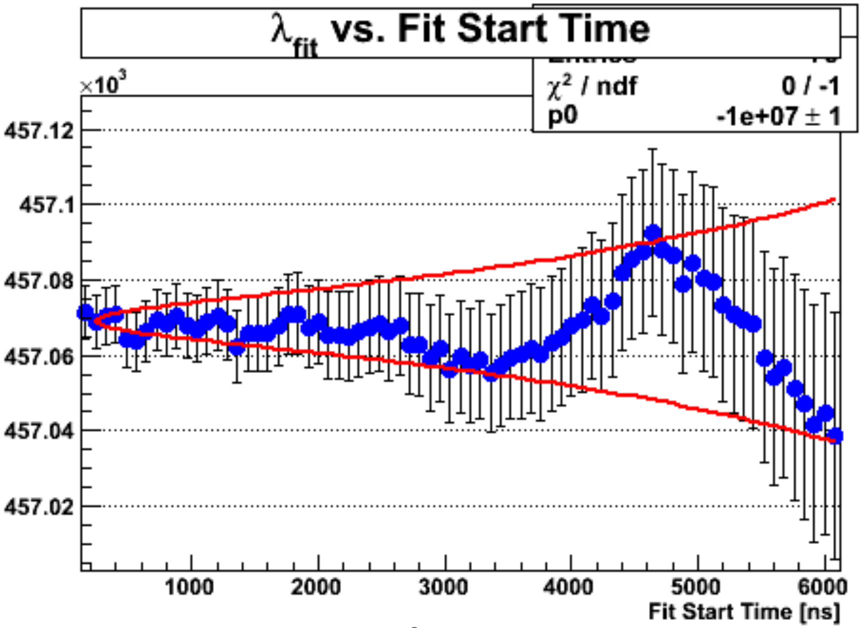
Lifetime spectrum

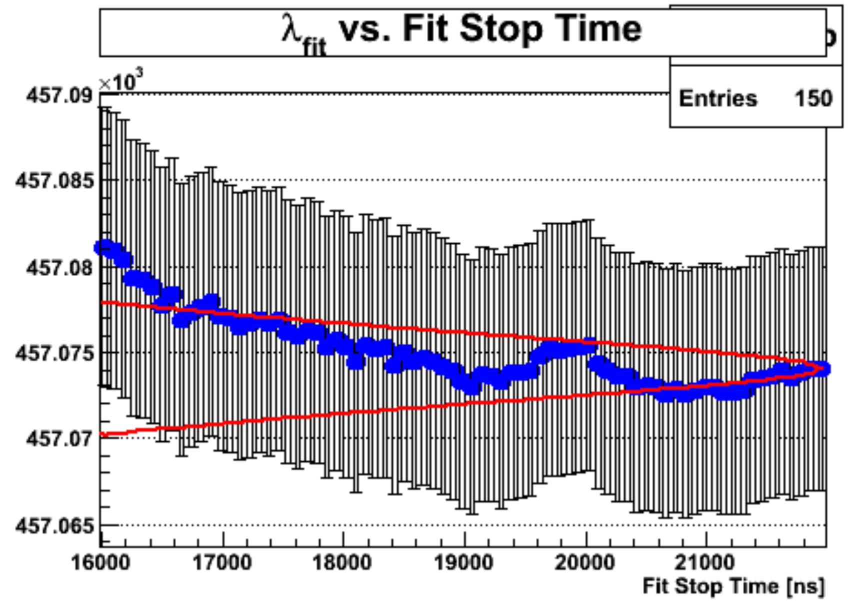


Normalized residuals

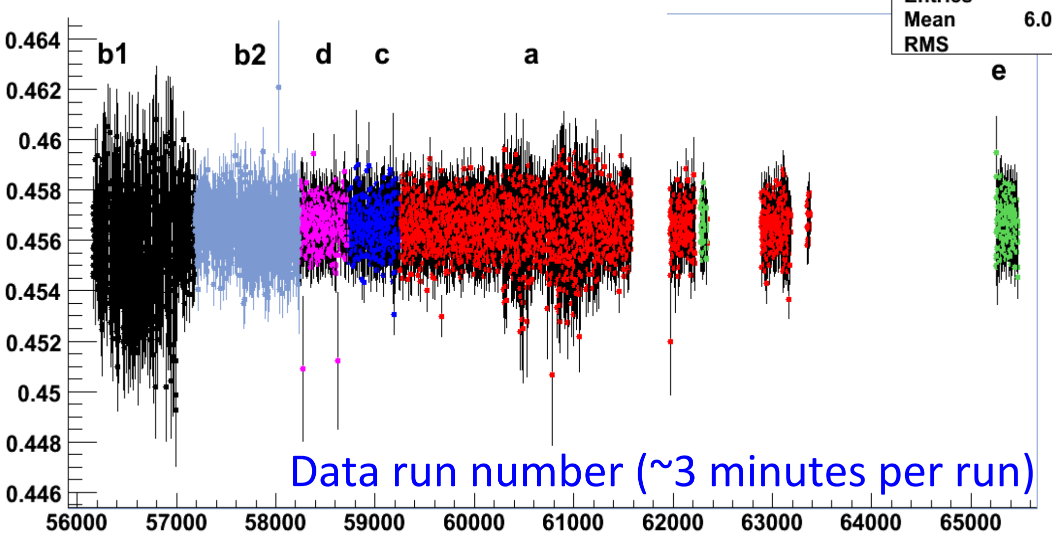


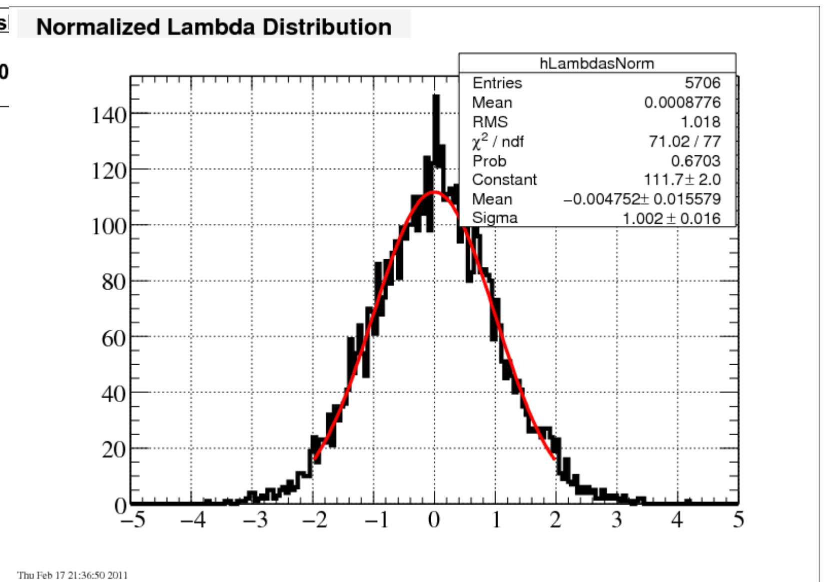
Perform many consistency checks





- Rate versus run duration



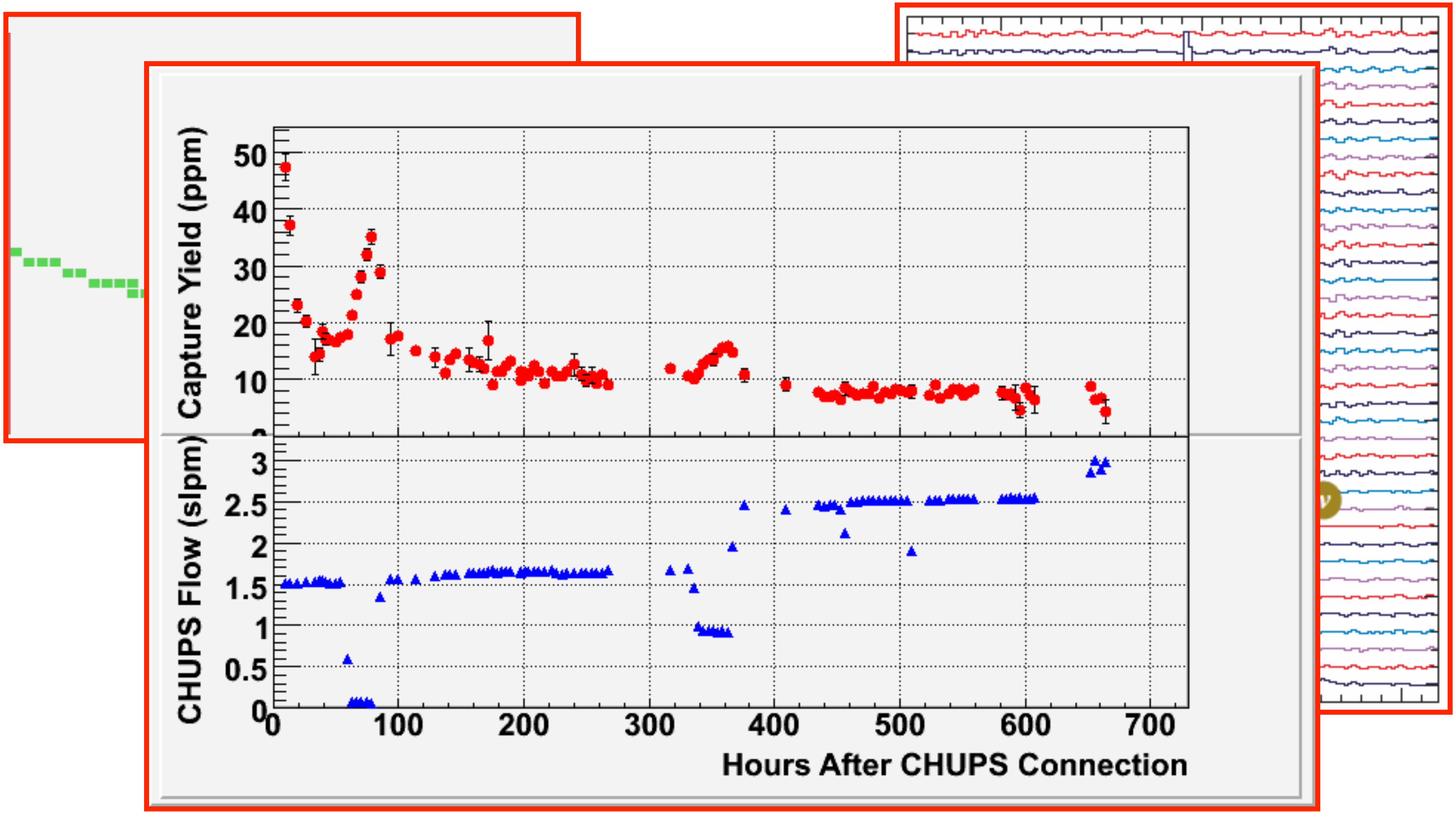


Precision measurements is all about systematics

$$\Lambda_S \text{ (MuCap)} = 714.9 \pm 5.4_{stat} \pm 5.1_{syst} \text{ s}^{-1}$$

Systematic errors	Run 2006		Run 2007		Comment
	λ (s^{-1})	$\delta\lambda$ (s^{-1})	λ (s^{-1})	$\delta\lambda$ (s^{-1})	
High-Z impurities	-7.8	1.87	-4.54	0.93	
μp scatter	-12.4	3.22	-7.20	1.25	
μp diffusion	-3.1	0.1	-3.0	0.1	
μd diffusion		0.74		0.12	
Fiducial volume cut		3		3	
Entrance counter inefficiencies		0.5		0.5	
Choice of electron detector def.		1.8		1.8	
Total	**-23.3**	**5.14§**	**-14.74**	**3.88§**	**§ = correlated**

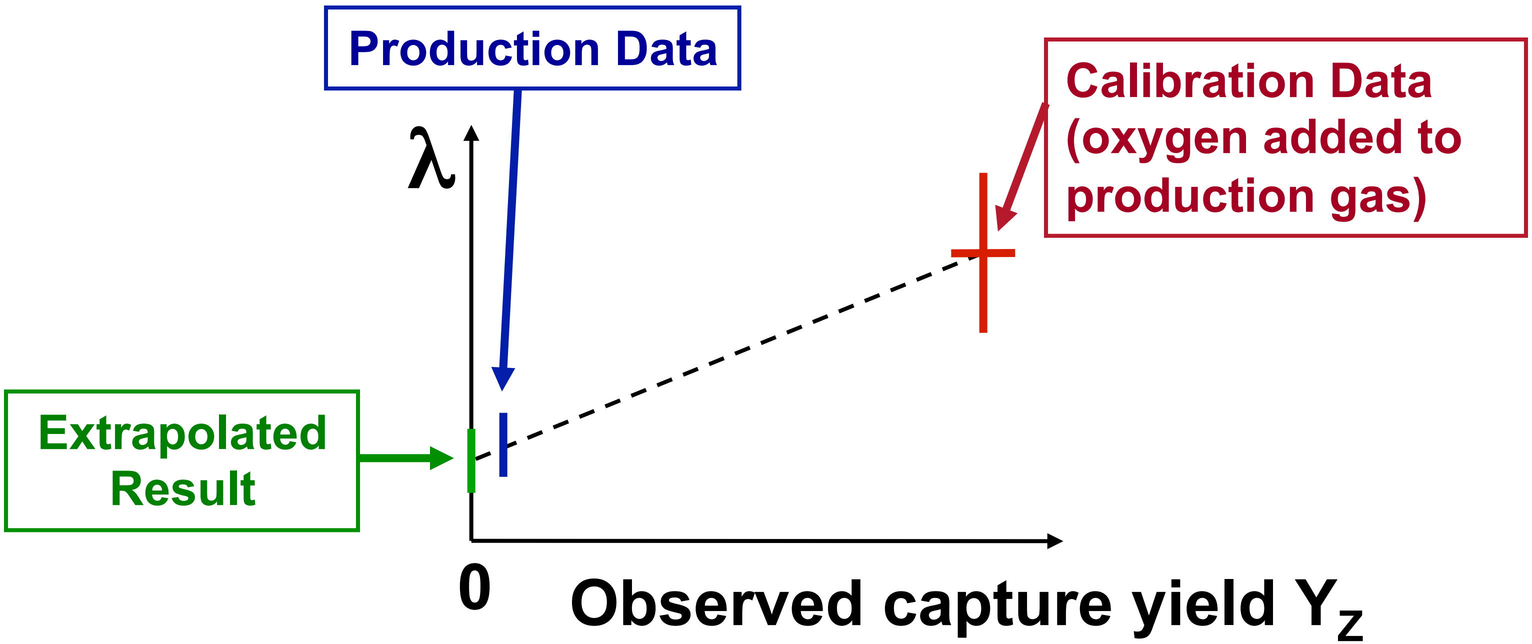
Impurity monitoring with data



2004 run: $c_N < 7$ ppb, c_{H2O}~30 ppb

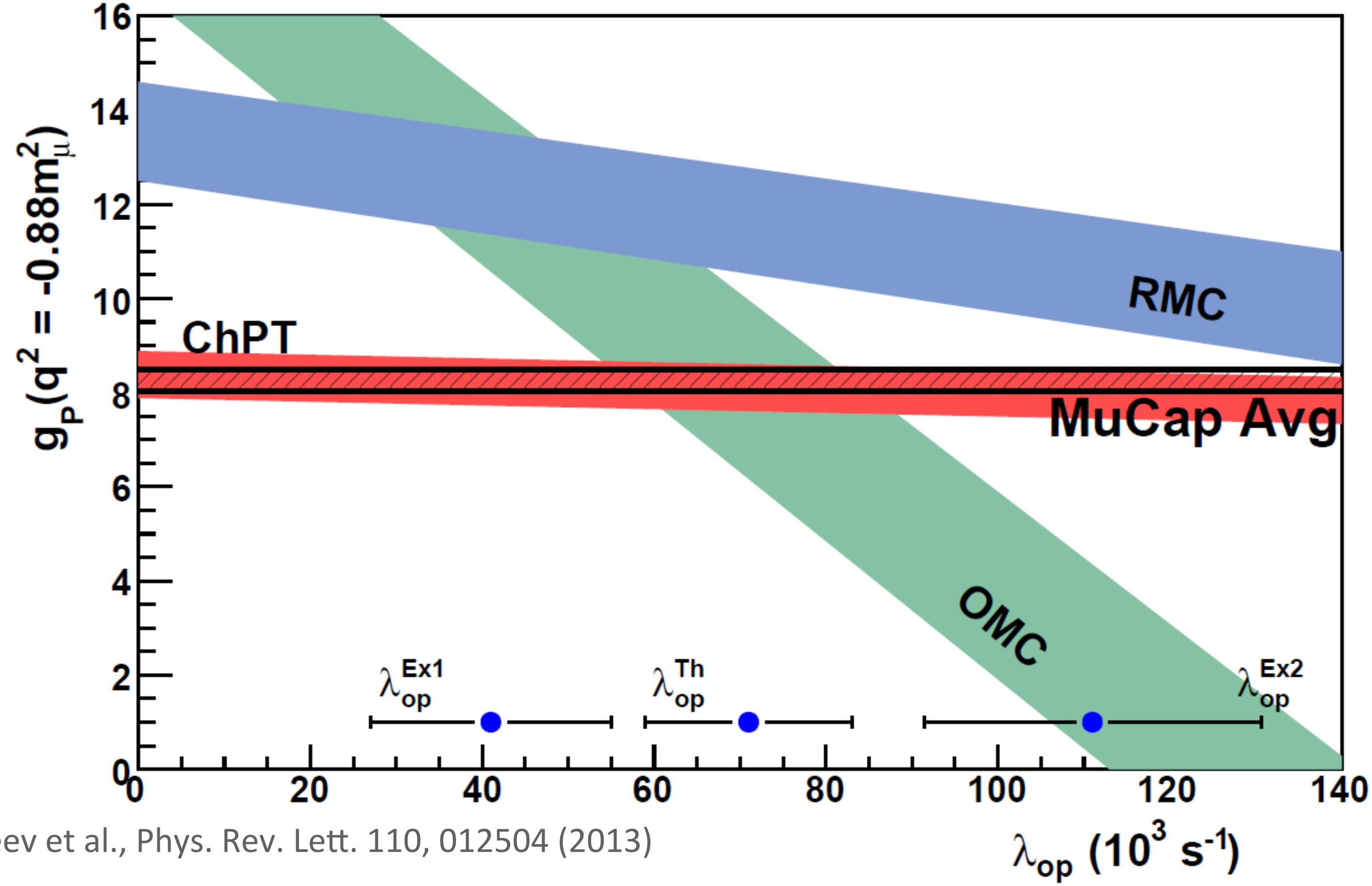
2006 / 2007 runs: $c_N < 7$ ppb, c_{H2O}~10 ppb

Apply correction from linear extrapolation



This works since lifetime deviation is linear for small impurity contamination

Pecise and unambiguous MuCap result



Andreev et al., Phys. Rev. Lett. 110, 012504 (2013)

$$g_P(\text{MuCap}) = 8.06 \pm 0.55$$

$$g_P(\text{theory}) = 8.26 \pm 0.23$$

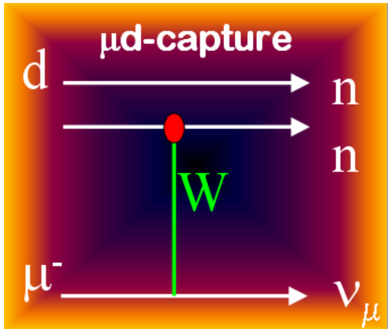
Precision muon lifetime measurements

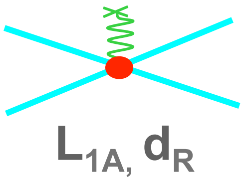
- MuLan: μ^+ lifetime

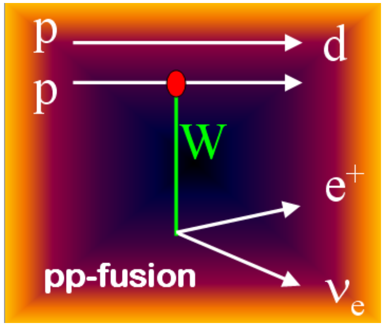
- MuCap: μ^- lifetime in hydrogen
- MuSun: μ^- lifetime in deuterium

MuSun: Muon capture on deuterium $\mu^- d \rightarrow n\, n\, \nu$

- After MuCap, next step to measure two nucleon system
- Effective field theory connects μ^-d capture to pp solar fusion or νd scattering via a single low energy constant L_{1A}, d_R







- Experimental conditions optimized at 30 K, i.e. need cryo-TPC
- Aim to measure doublet capture rate Λ_d to 1.5% precision
- Many upgrades compared to MuCap setup (cryo-TPC, full waveform digitization, cryo-preamplifiers, ...)
- Experiment aims to take full statistics end of this year and in 2014

Summary: Some lessons on muons

- Muons have very useful properties:
  - Long lifetime
  - Polarized beams available
  - Self-analyzing decay
- Muon physics is rich:
  - Measurement of SM parameters (e.g. MuLan, MuCap, Lamb shift)
  - Search for BSM (e.g. TWIST and tomorrow CLFV, g-2, ...)
  - Applied science (muSR)
- It's precision muon physics so it's all about systematics!

TWIST: Michel parameters and coupling constants

TRIUMF

- Fetscher and Gerber coupling constants (see PDG)

$$M = \frac{4G_F}{\sqrt{2}} \sum_{\substack{\gamma=S,V,T \\ \varepsilon,\mu=R,L}} g^{\gamma}_{\varepsilon\mu} \langle \bar{e}_\varepsilon | \Gamma^\gamma | (\nu_e)_n \rangle \langle (\bar{\nu}_\mu)_m | \Gamma_\gamma | \mu_\mu \rangle$$

SM

$$\rho = \frac{3}{4} - \frac{3}{4}[|g^V_{RL}|^2 + |g^V_{LR}|^2 + 2|g^T_{RL}|^2 + 2|g^T_{LR}|^2 + \mathbb{R}e\,(g^S_{RL}g^{T*}_{RL} + g^S_{LR}g^{T*}_{LR})]$$

0.75

$$\eta = \frac{1}{2}\mathbb{R}e[g^V_{RR}g^{S*}_{LL} + g^V_{LL}g^{S*}_{RR} + g^V_{RL}(g^{S*}_{LR} + 6g^{T*}_{LR}) + g^V_{LR}(g^{S*}_{RL} + 6g^{T*}_{RL})]$$

0

$$\xi = 1 - \frac{1}{2}|g^S_{LR}|^2 - \frac{1}{2}|g^S_{RR}|^2 - 4|g^V_{RL}|^2 + 2|g^V_{LR}|^2 - 2|g^V_{RR}|^2 + 2|g^T_{LR}|^2 - 8|g^T_{RL}|^2 + 4\mathbb{R}e(g^S_{LR}g^{T*}_{LR} - g^S_{RL}g^{T*}_{RL})$$

1

$$\xi\delta = \frac{3}{4} - \frac{3}{8}|g^S_{RR}|^2 - \frac{3}{8}|g^S_{LR}|^2 - \frac{3}{2}|g^V_{RR}|^2 - \frac{3}{4}|g^V_{RL}|^2 - \frac{3}{4}|g^V_{LR}|^2 - \frac{3}{2}|g^T_{RL}|^2 - 3|g^T_{LR}|^2 + \frac{3}{4}\mathbb{R}e(g^S_{LR}g^{T*}_{LR} - g^S_{RL}g^{T*}_{RL})$$

0.75

- Deviations from the SM values would be due to right-handed scalar, vector and tensor couplings g_{RL}, g_{RR}, g_{LR}

Let's ask a bit about you

- How many are graduate students?
- How many are postdocs?
- Who is theoretical and who is experimental?
- Who is working at the Energy Frontier?
- Who is working at the Cosmic Frontier?
- Who is working at the Intensity Frontier?
- Is anybody working or has worked on a Muon Experiment?