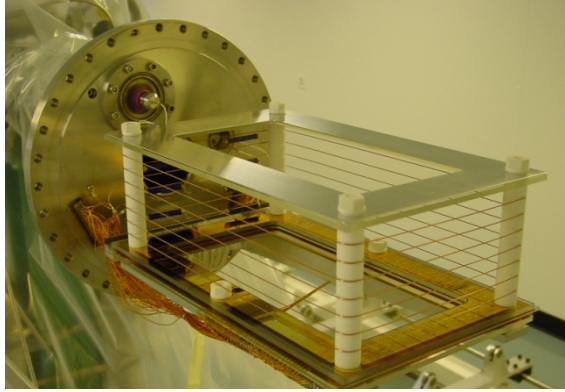
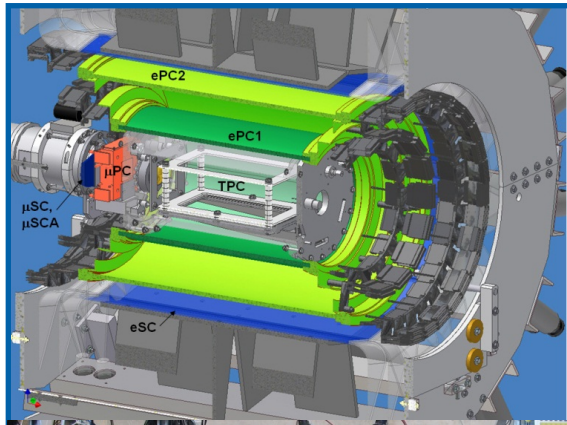
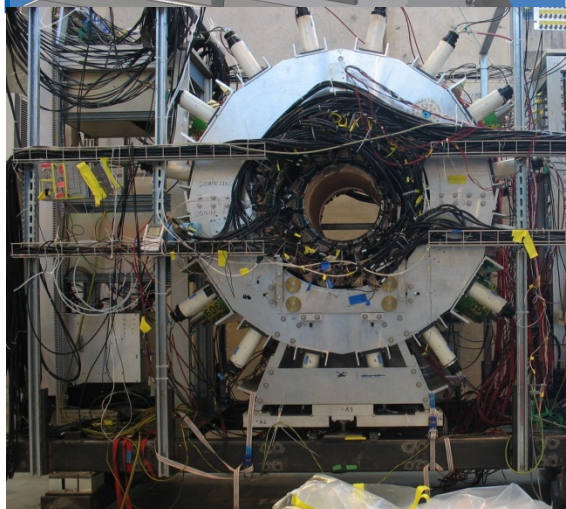


Fermilab

Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

Muon capture on the proton: Final results from the MuCap experiment



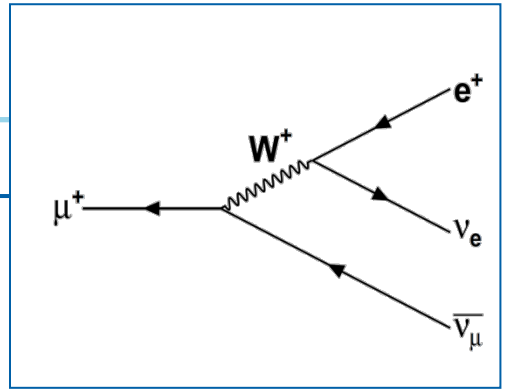


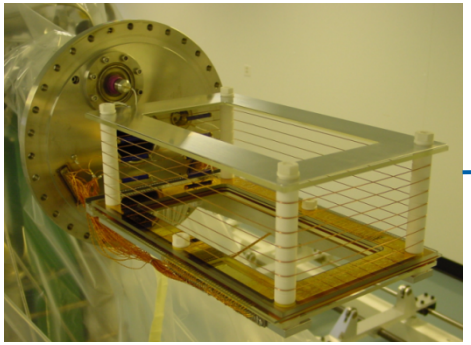
- Brendan Kiburg
- Fermi National Accelerator Laboratory (this research performed as a member of University of Illinois, University of Washington)

- NuFact 2015, Rio de Janeiro, Brazil
- August 12, 2015

Overview

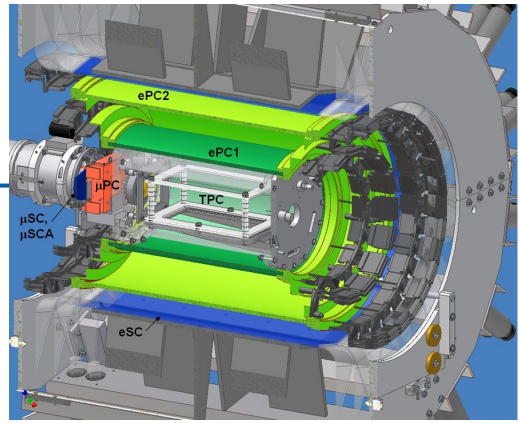
Weak Interaction Physics

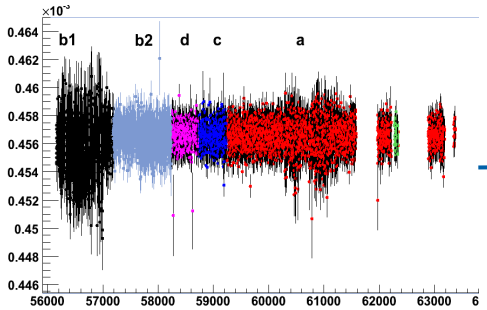




Experimental Requirements

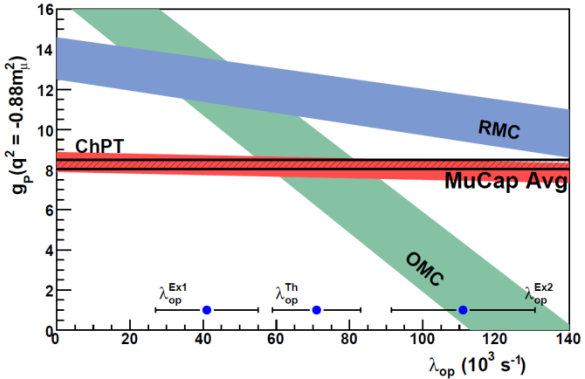
Technique



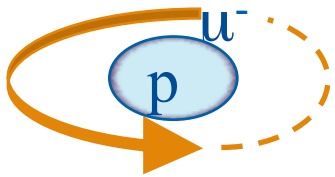


MuCap Analysis

Results



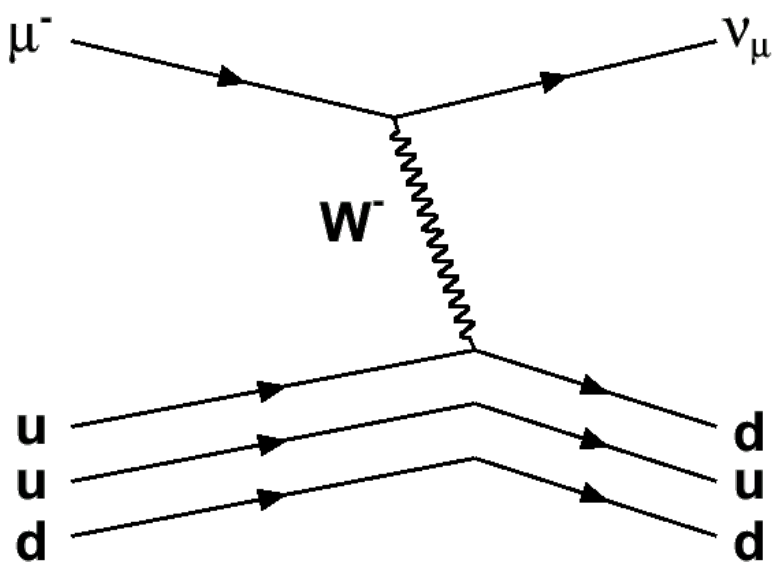
A negative muon can be captured by a proton



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

Rate Λ_S

- Current-current weak interaction



- Leptonic and hadronic left-chiral projections

$$M_{fi} = \frac{G_F V_{ud}}{\sqrt{2}} L_\alpha J^\alpha$$

$$L_\alpha = \bar{u}_\nu \gamma_\alpha \left(1 - \gamma_5\right) u_\mu$$

$$J^\alpha = \bar{q}_d \gamma^\alpha \left(1 - \gamma^5\right) q_u$$

The quarks involved in muon capture are embedded in a nucleon; the hadronic current must be modified

$$J^\alpha = \bar{u}_n \left(\underbrace{g_V \gamma^\alpha + \frac{i g_M}{2m_N} \sigma^{\alpha\nu} q_\nu + \frac{g_S}{m_\mu} q^\alpha}_{V^\alpha} - \underbrace{g_A \gamma^\alpha \gamma_5 - \frac{g_P}{m_\mu} q^\alpha \gamma_5 - \frac{i g_T}{2m_N} \sigma^{\alpha\nu} q_\nu \gamma_5}_{A^\alpha} \right) u_p$$

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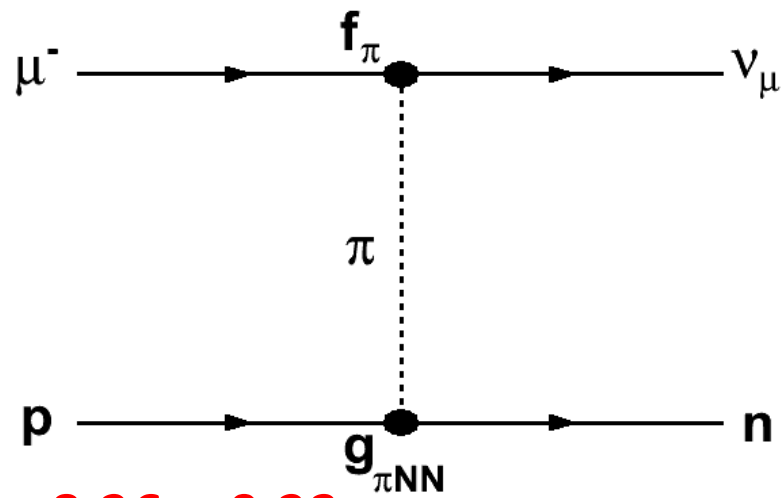
- CVC + G-Parity
  - g_S , $g_T \approx 0$
- CVC + Electron scattering
  - $g_V(q_\mu^2) = 0.976 \pm 0.001$
  - $g_M(q_\mu^2) = 3.583 \pm 0.003$
- Neutron beta decay
  - $g_A(q_\mu^2) = 1.2497 \pm 0.004$
    - Propagate $g_A(0) = 1.2723 \pm 0.0023 \rightarrow q^2$
    - K.A. Olive et al. (Particle Data Group), Chin. Phys. C, 38, 090001 (2014).
- This leaves g_P
  - Known with ≈50% uncertainty

Modern theory makes precise predictions for g_P

- Chiral Perturbation Theory (ChPT)
  - Effective field theory
  - Systematic low-energy expansion valid for q small compared to chiral scale



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

g_P = (8.74 ± 0.23) – (0.48 ± 0.02) = 8.26 ± 0.23

V. Bernard, L. Elouadrhiri, and U. G. Meissner,, J. Phys. G28 (2002) R1–R35

ChPT leading order one loop two-loop <1%

See Kammel and Kubodera. Annu. Rev. Nucl. Part. Sci. 2010. 60:327-53

- ChPT makes a precise prediction for g_P (2.8%)

Modern theory makes precise predictions for g_P

- Chiral Perturbation Theory (ChPT)
  - Effective field theory
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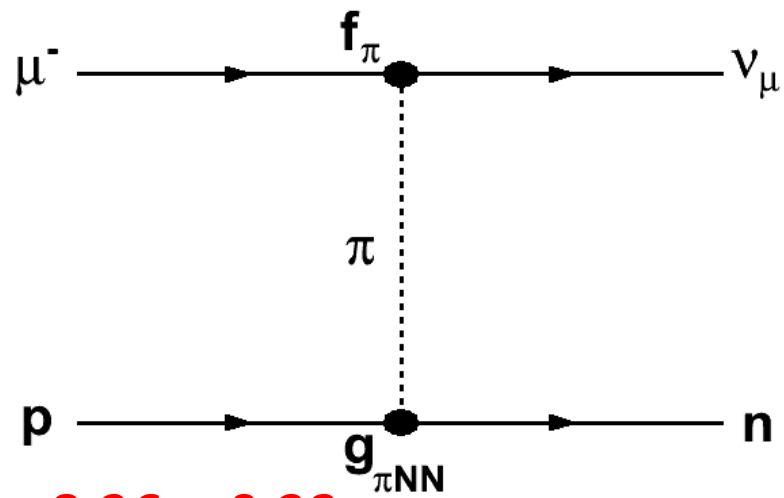

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ChPT leading order one loop two-loop <1%

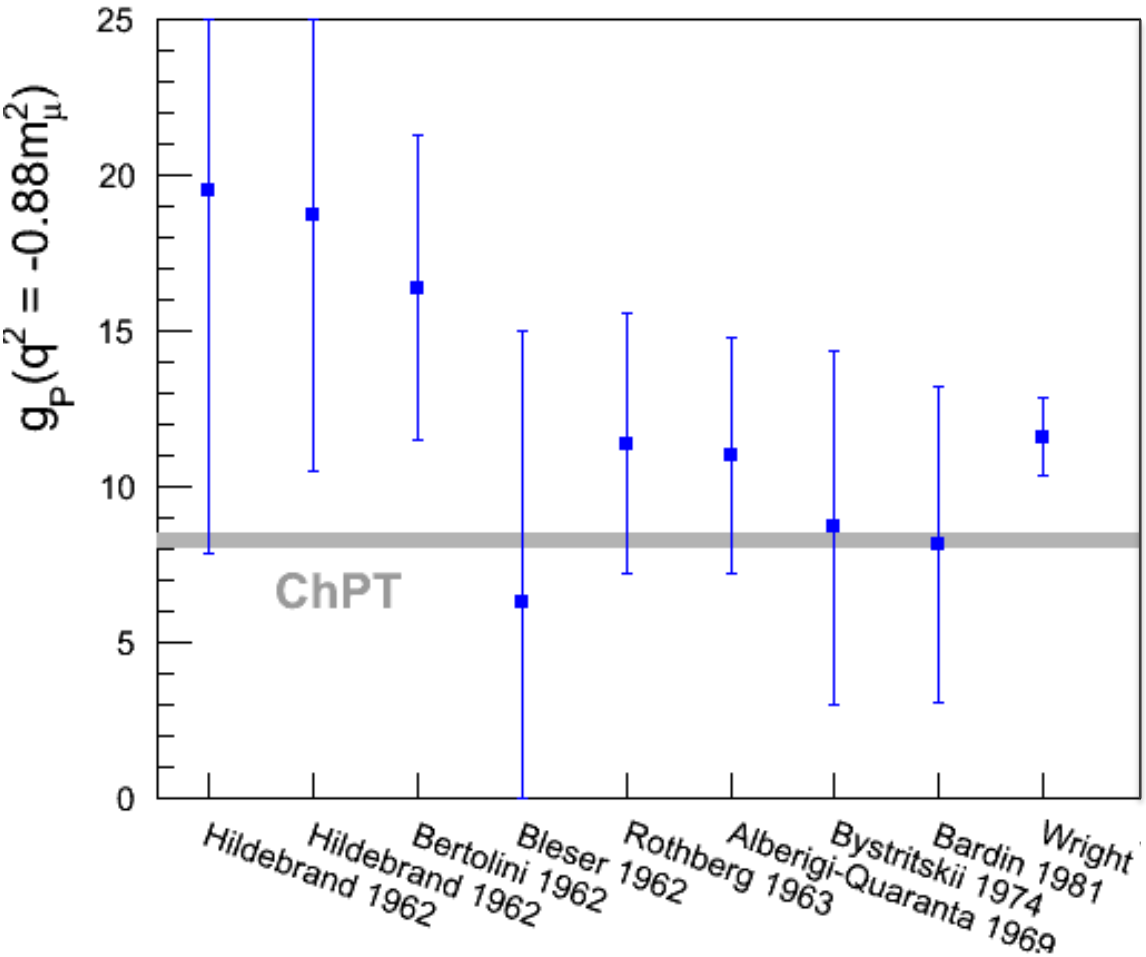
$$M_{fi} = \frac{G_F V_{ud}}{\sqrt{2}} L_\alpha J^\alpha$$

Theory Prediction

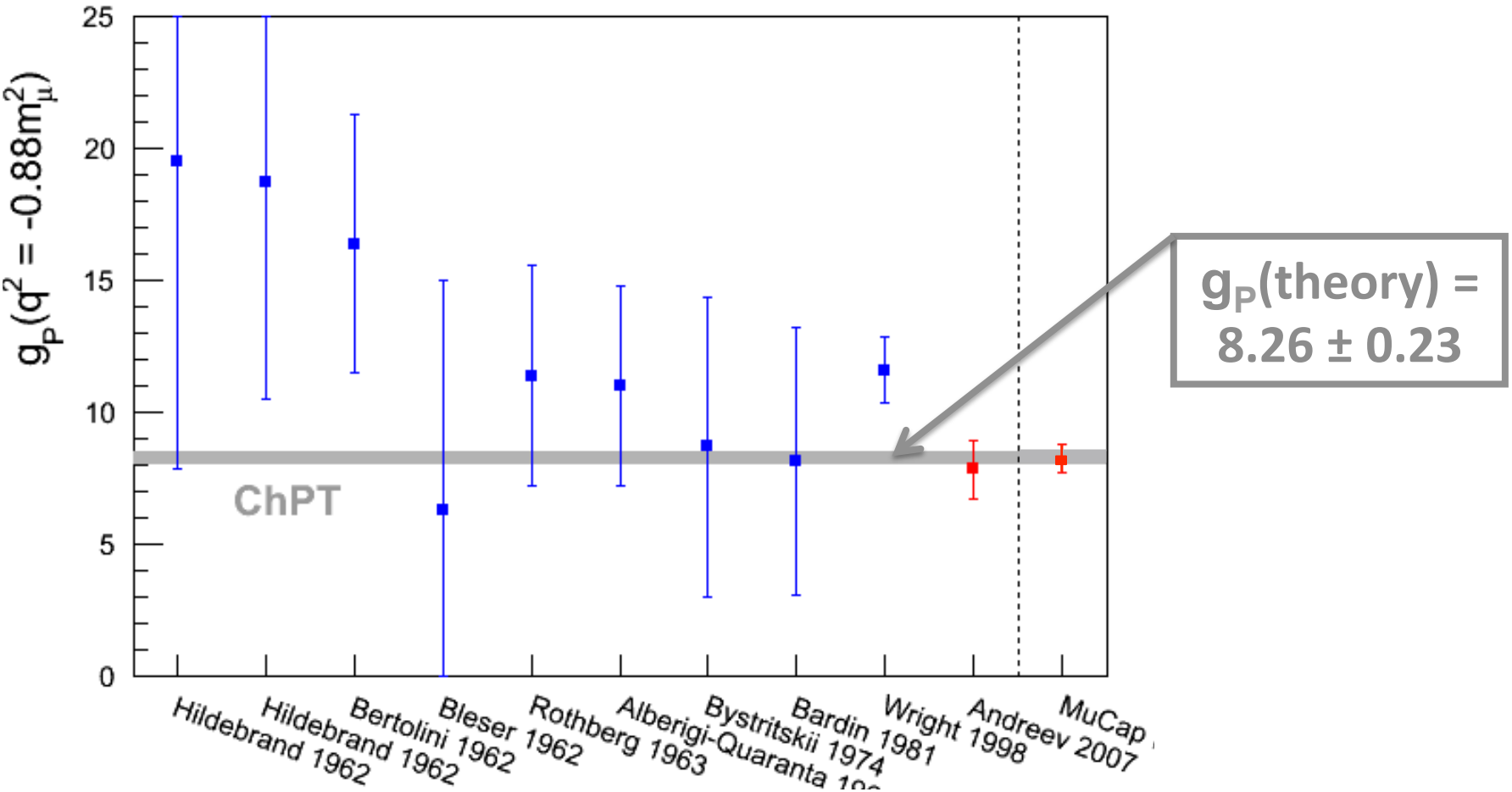
Λ_S = 712.7 ± 4.6 s^{-1}(0.65%)

Evaluation of Czarnecki, Marciano and Sirlin PRL 99,032003 (2007) in Andreev et al. PRL 110,012504(2013)

Experimental determinations of g_P prior to MuCap were far less precise

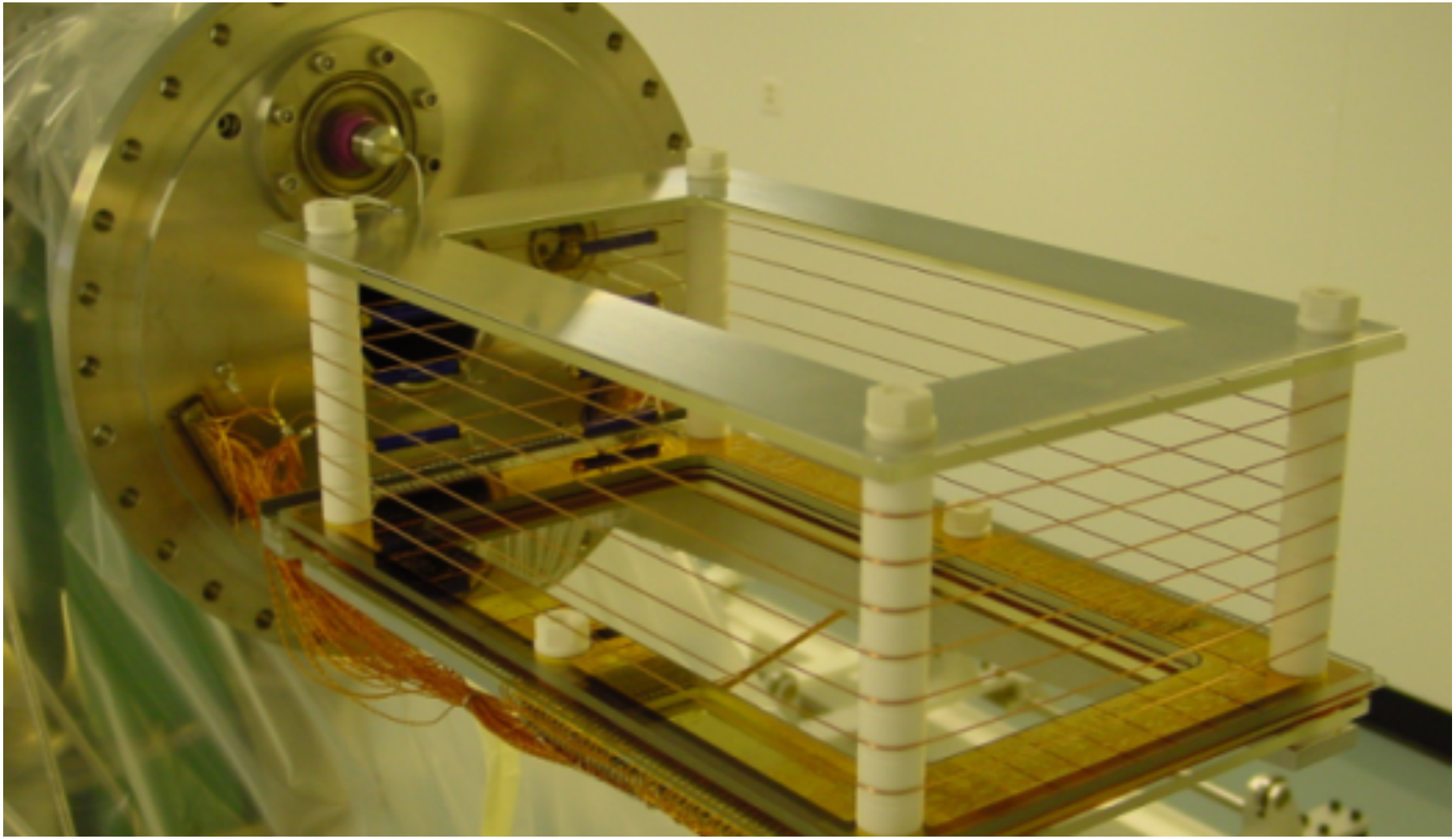


Precise and unambiguous MuCap result confirms chiral perturbation theory prediction



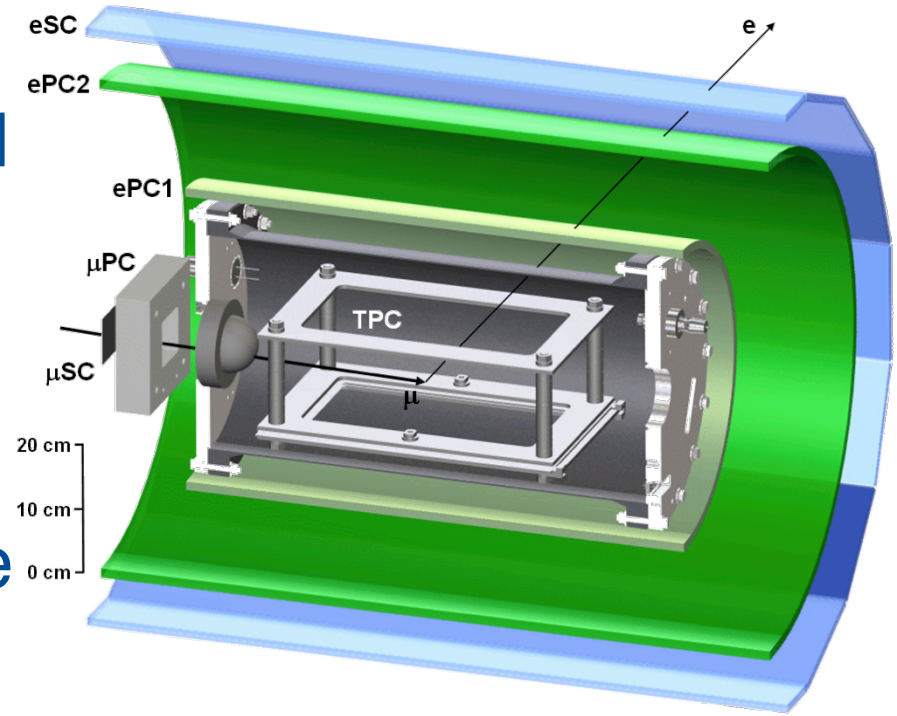
g_P(MuCap) = 8.14 ± 0.55

Experimental Requirements

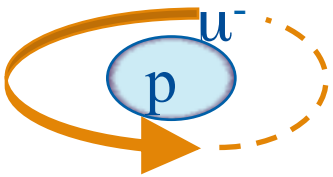


MuCap experimental requirements

- Use a low-energy muon beam
- Stop in a specially prepared pure hydrogen target
- Image the stopping muon (TPC)
- Measure the disappearance rate
- Compare to the positive muon lifetime (MuLan)



Lifetime method determines the capture rate Λ_S



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

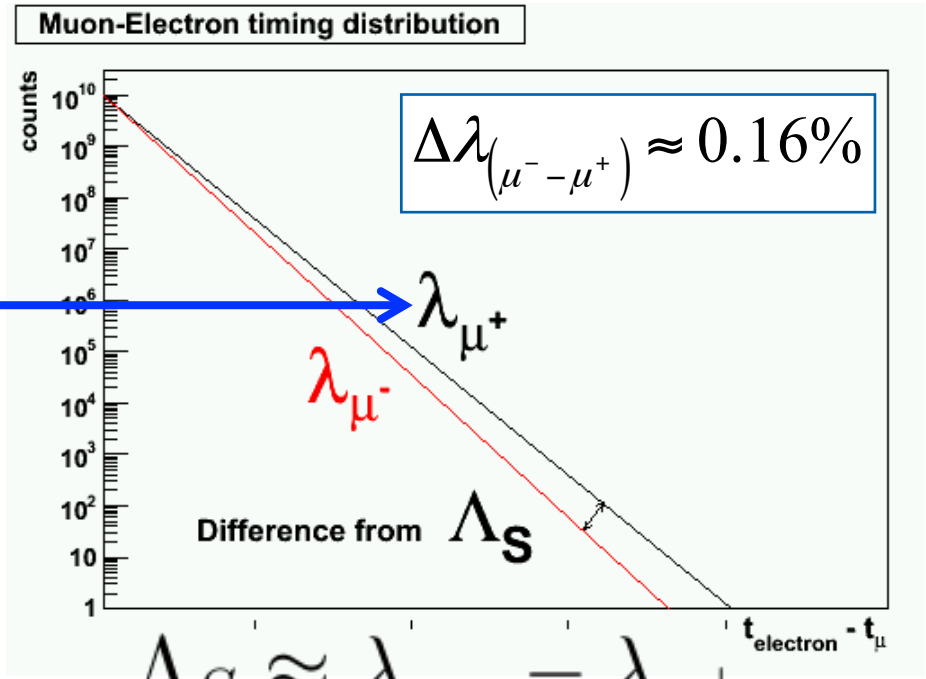
(Λ_S~700 s^{-1})

$$\mu^- + p \rightarrow p + e^- + \bar{\nu}_e + \nu_\mu$$

($\lambda_{\mu+}$ ~455000 s^{-1})

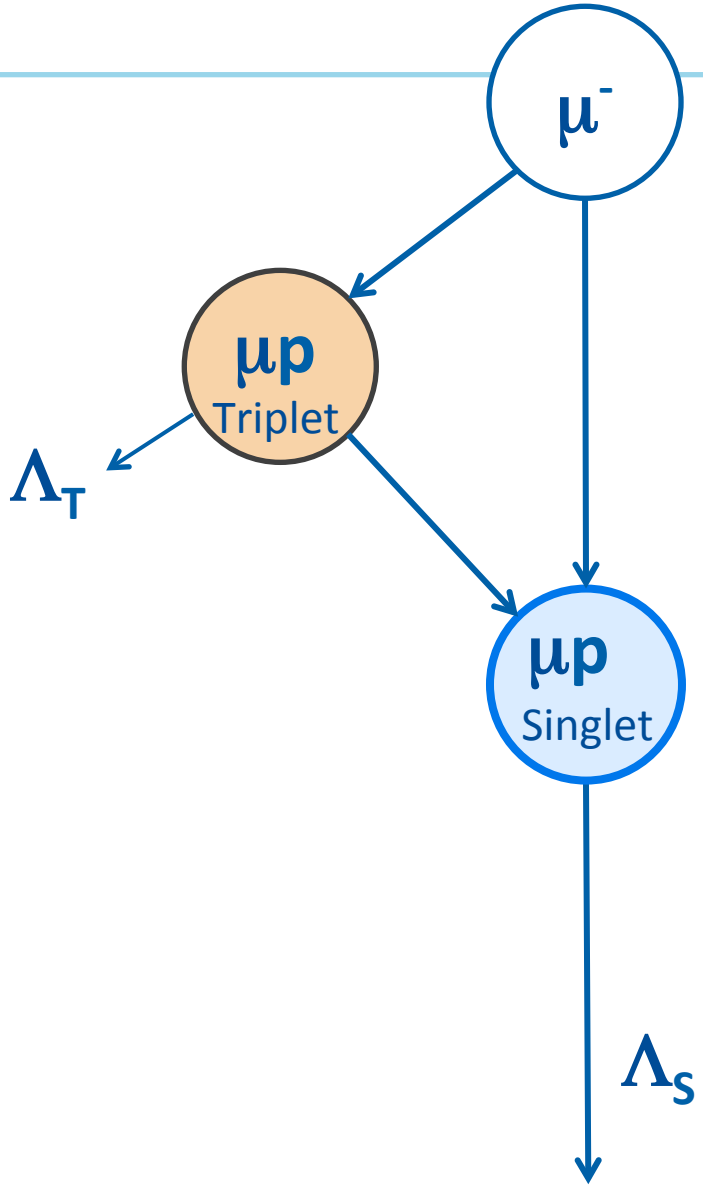
MuCap observes the electron from muon decay.

MuLan!



$$\Lambda_S \approx \lambda_{\mu^-} - \lambda_{\mu^+}$$

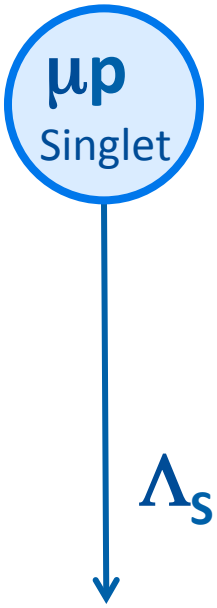
The muon kinetics are rich



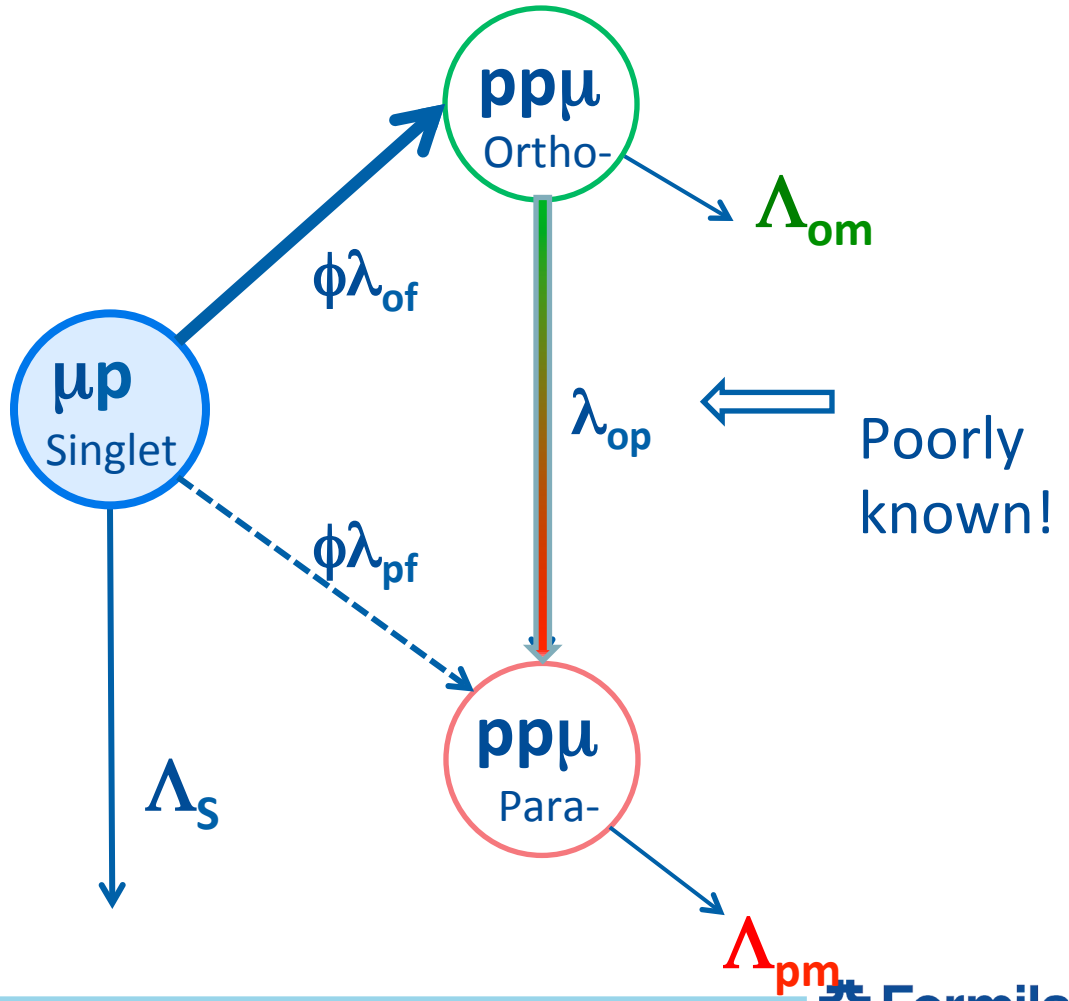
- Decay from any state
- Atomic capture
- Populate singlet state ≈10 ns

- $\Lambda_S \sim 700\ s^{-1}$
- $\Lambda_T \sim 12\ s^{-1}$
- Strong spin dependence due to V-A interaction

The Simple Goal

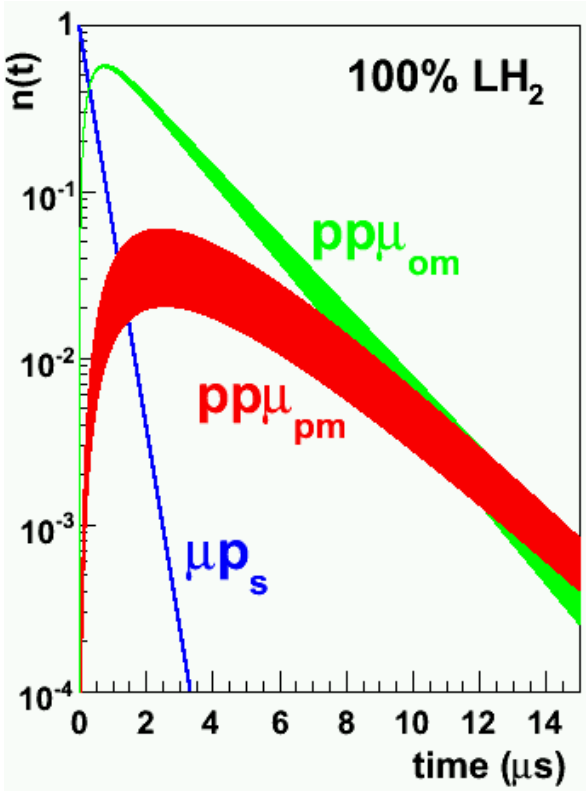


Reality is More Complicated

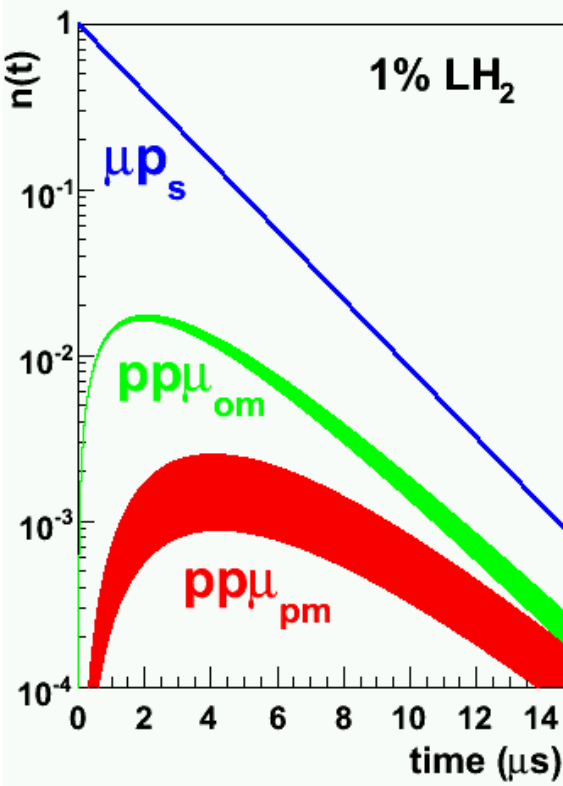


Molecular formation distorts the disappearance rate of the μp system, in a time-dependent way

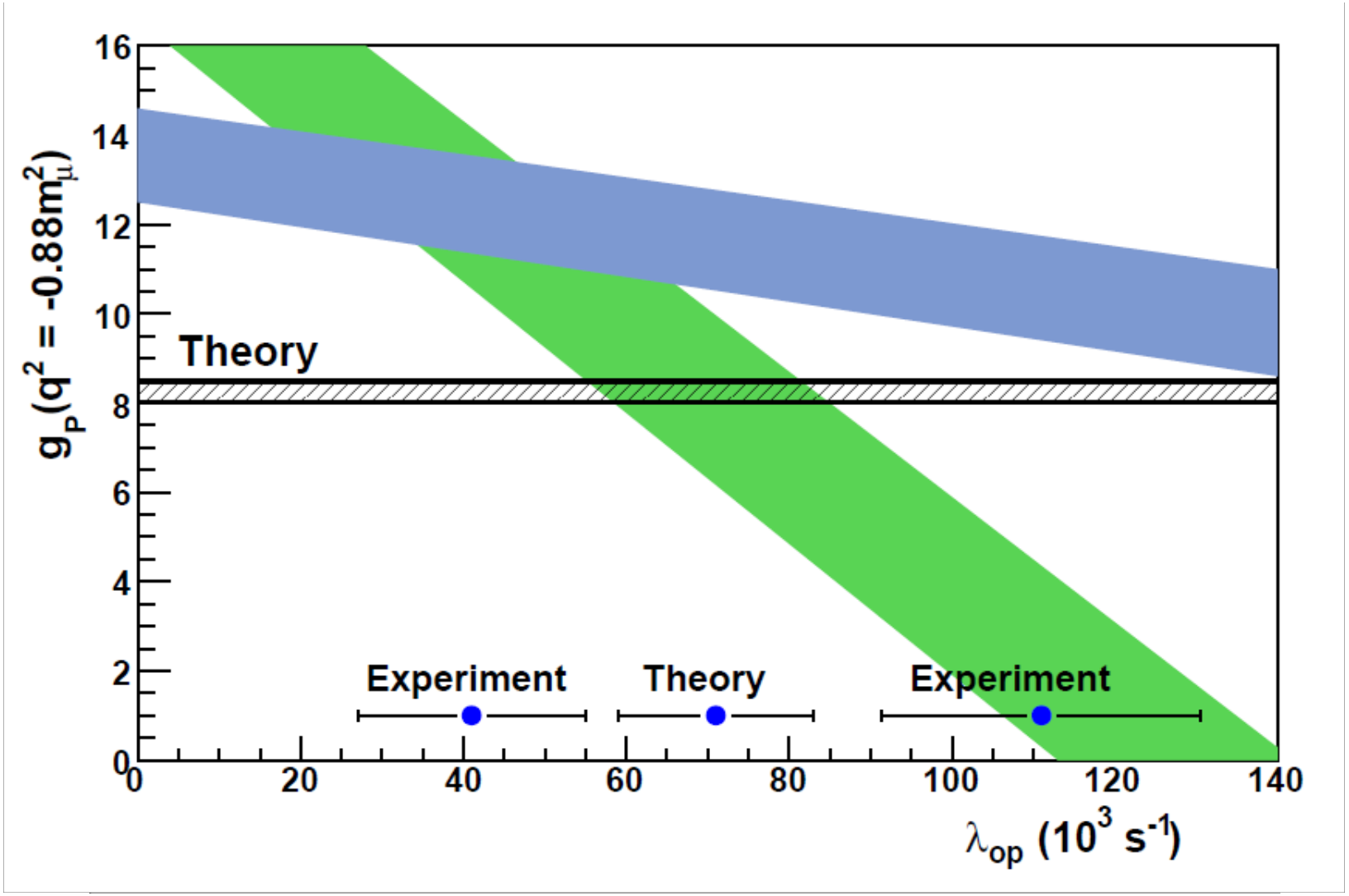
- Capture rate depends on spin configuration
  - $\Lambda_S \sim 700\ s^{-1}$
  - $\Lambda_{OM} \sim 540\ s^{-1}$
  - $\Lambda_{PM} \sim 210\ s^{-1}$



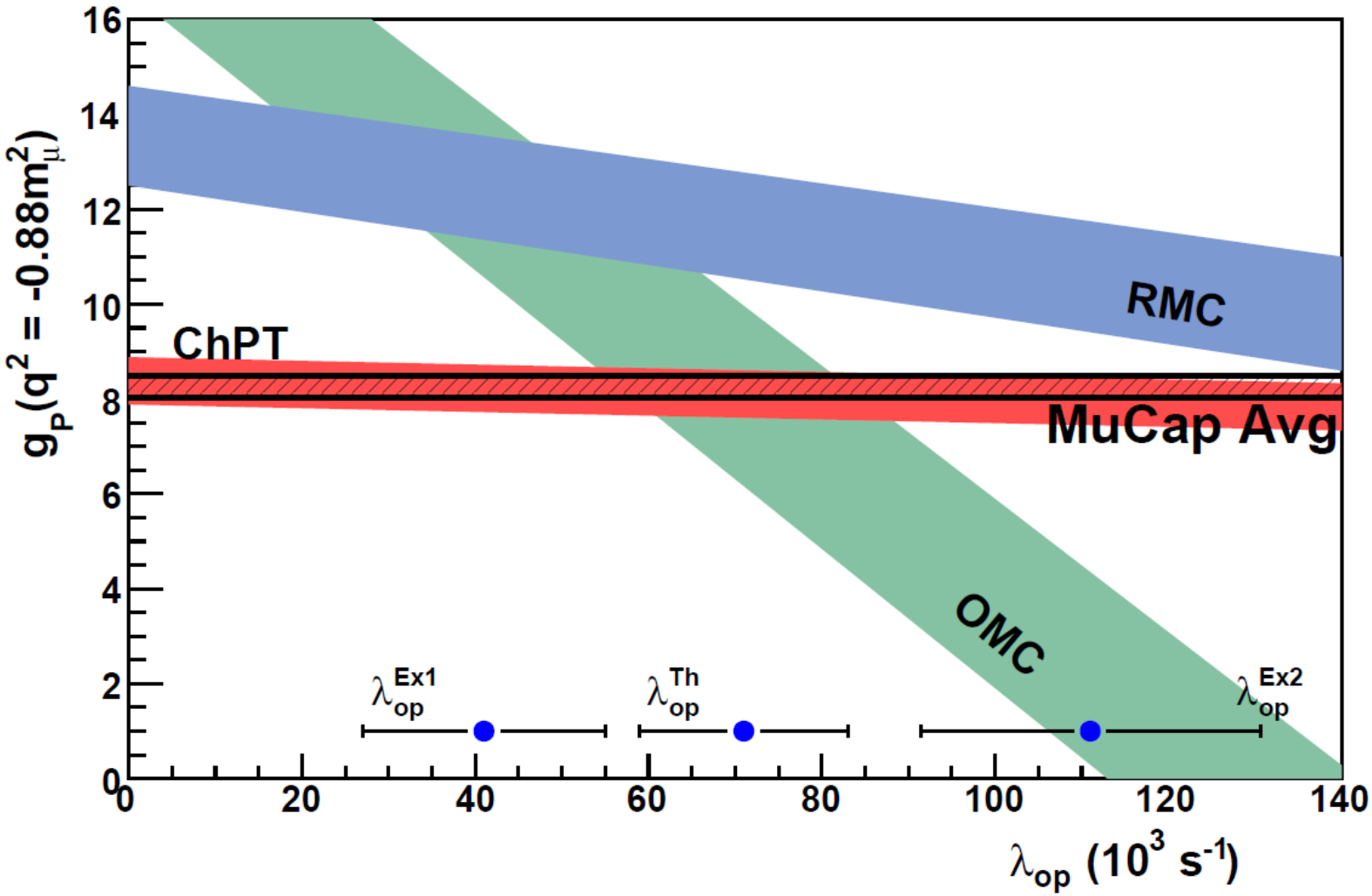
- Relative population is a function of hard-to-measure kinetic rates (λ_{of} , λ_{op})
- Molecular formation rate scales with hydrogen density, ϕ
  - Choose lower ϕ
  - Measure λ_{of}



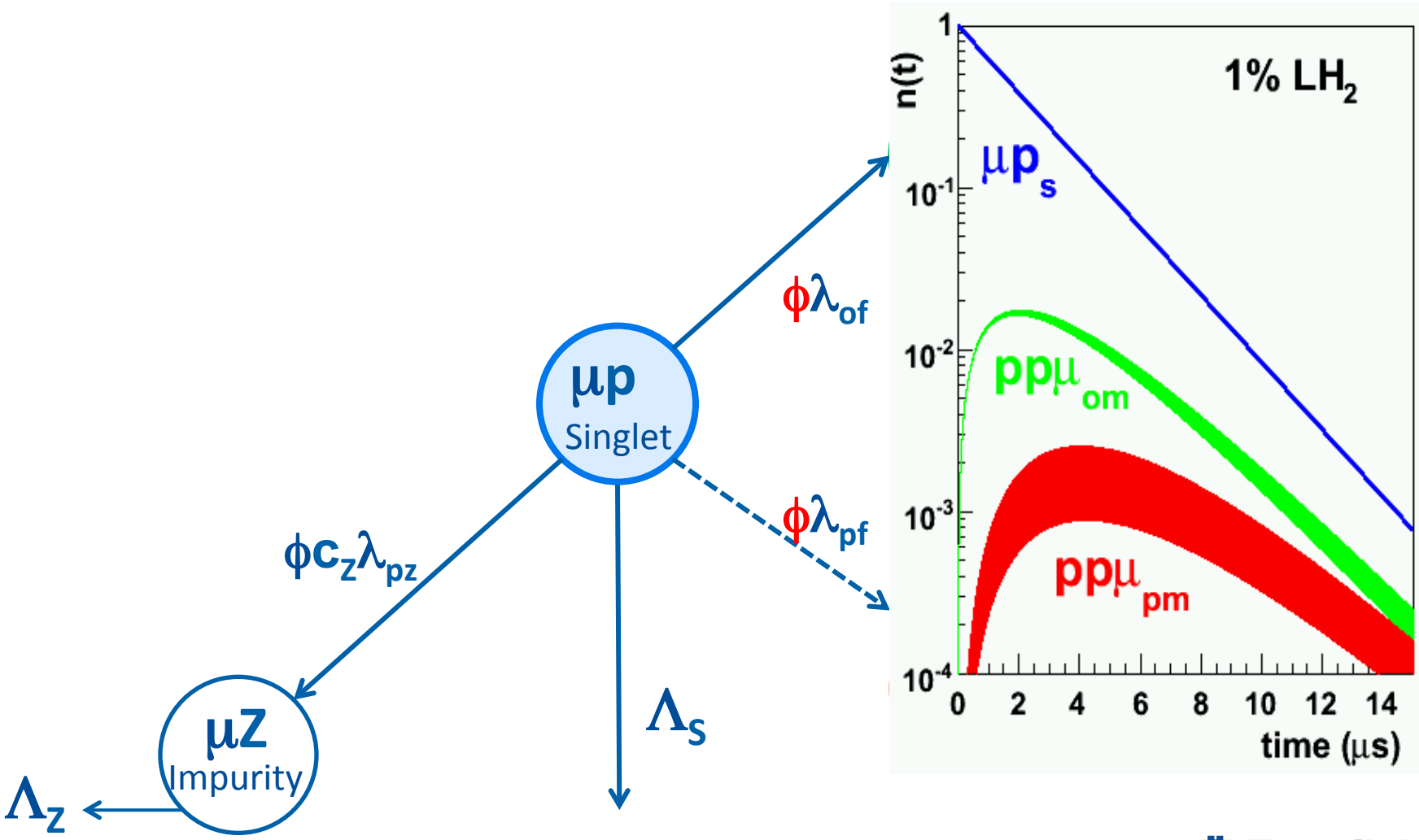
Past experiments were very sensitive to a poorly known parameter of muon chemistry, λ_{op}



MuCap mostly insensitive to molecular transition rate λ_{op}



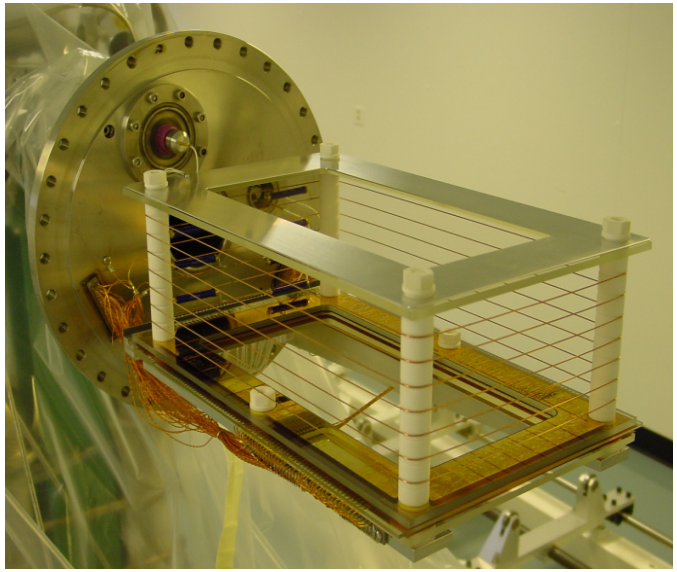
MuCap is designed to be mostly insensitive to the molecular complexities



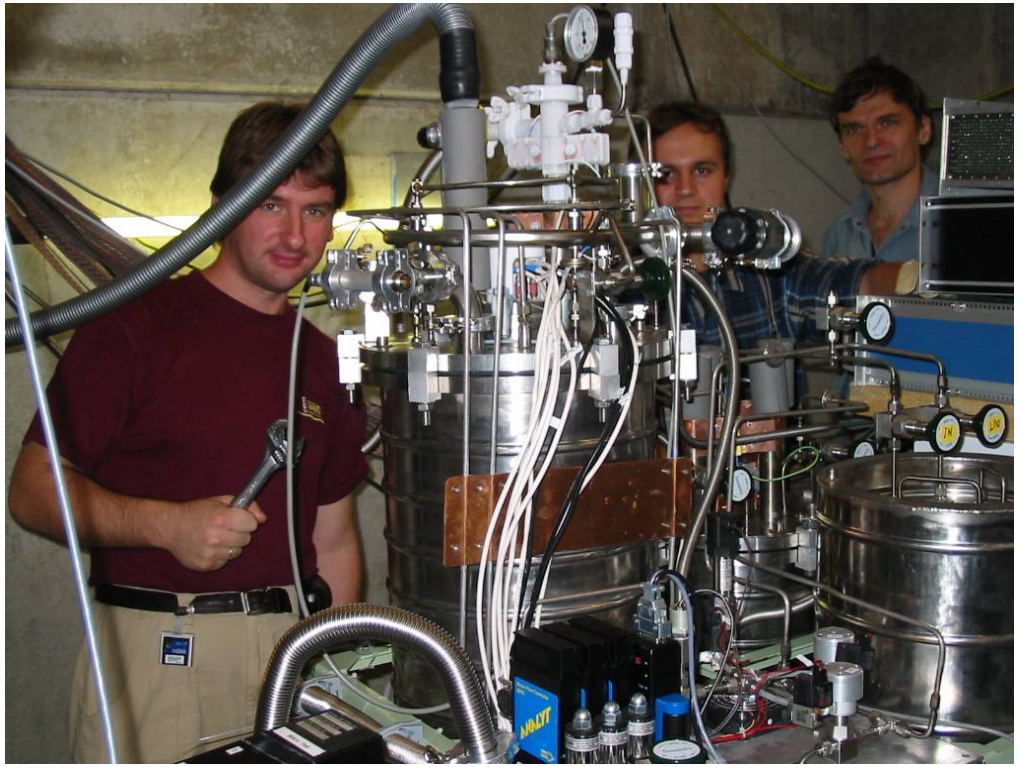
Z > 1 impurities have a larger capture rate and need to be removed from the target

$$\Lambda_Z \propto Z^4$$

- Z>1 all relevant
- Active TPC
- No materials in fiducial volume



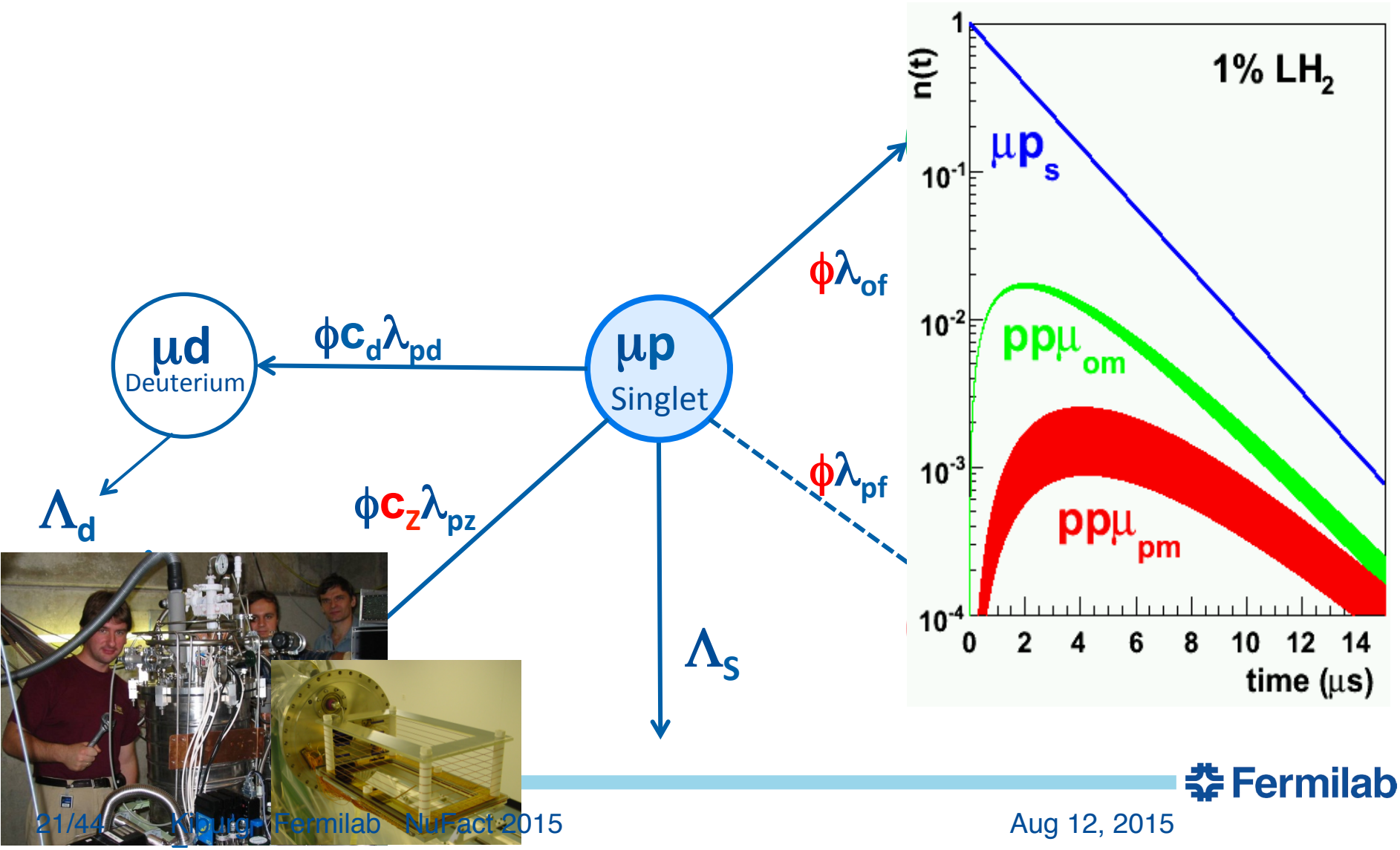
- CHUPS purifies the gas continuously



- c_N < 7 ppb
- c_{H_2O} < 10 ppb

See: Ganzha et. al. NIM A 578, 2007.

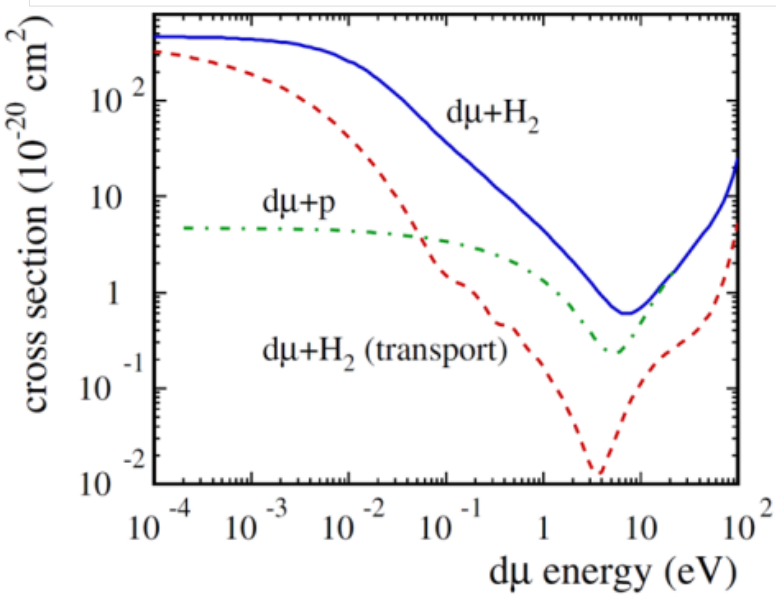
Chemically pure hydrogen gas is used



μd diffusion

Stopping μ forms μd atom w/ ~45 eV

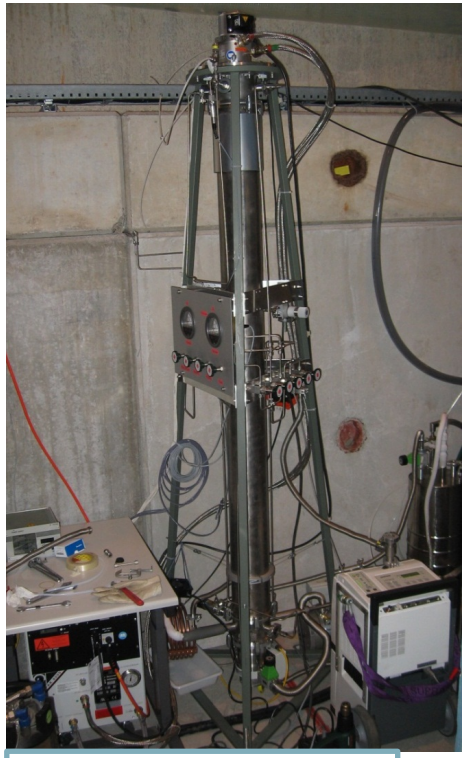
Ramsauer-Townsend minimum



- "Good" muon stop
- μd diffusion (cm / τ_μ)
- High-Z capture

Cryogenic distillation column

Isotopic separation

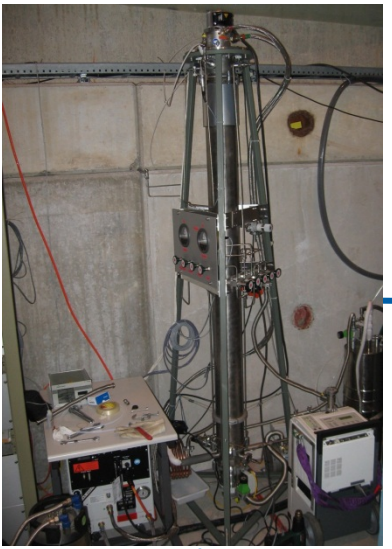


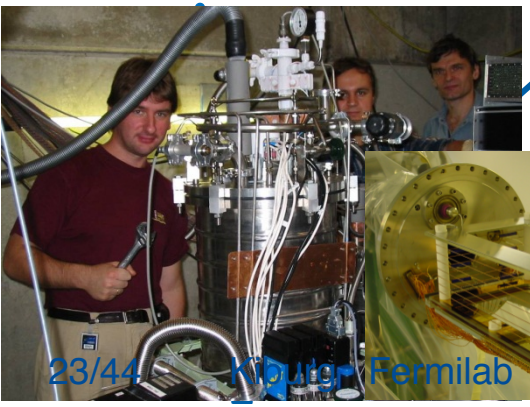
c_d < 6 ppb

See: Aleekseev, NHA Annu. Hydrog. Conf (2008)

See: M. Döbeli et. Al, NIM B266 p. 1820-1823 (2008).

The careful choice of operating conditions makes this experiment possible





$\phi c_d \lambda_{pd}$

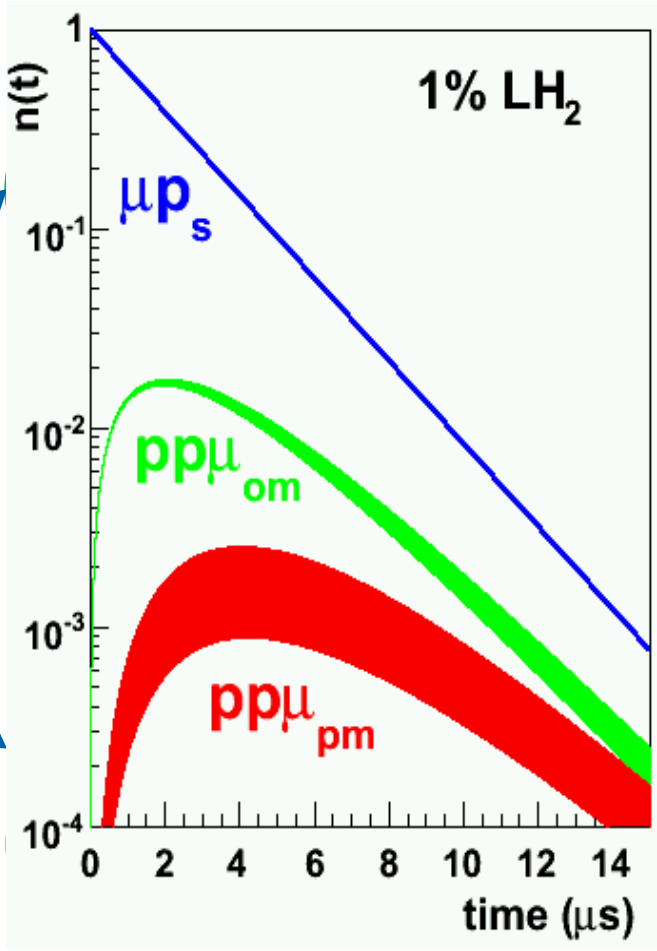
$\phi c_z \lambda_{pz}$

μp
Singlet

$\phi \lambda_{of}$

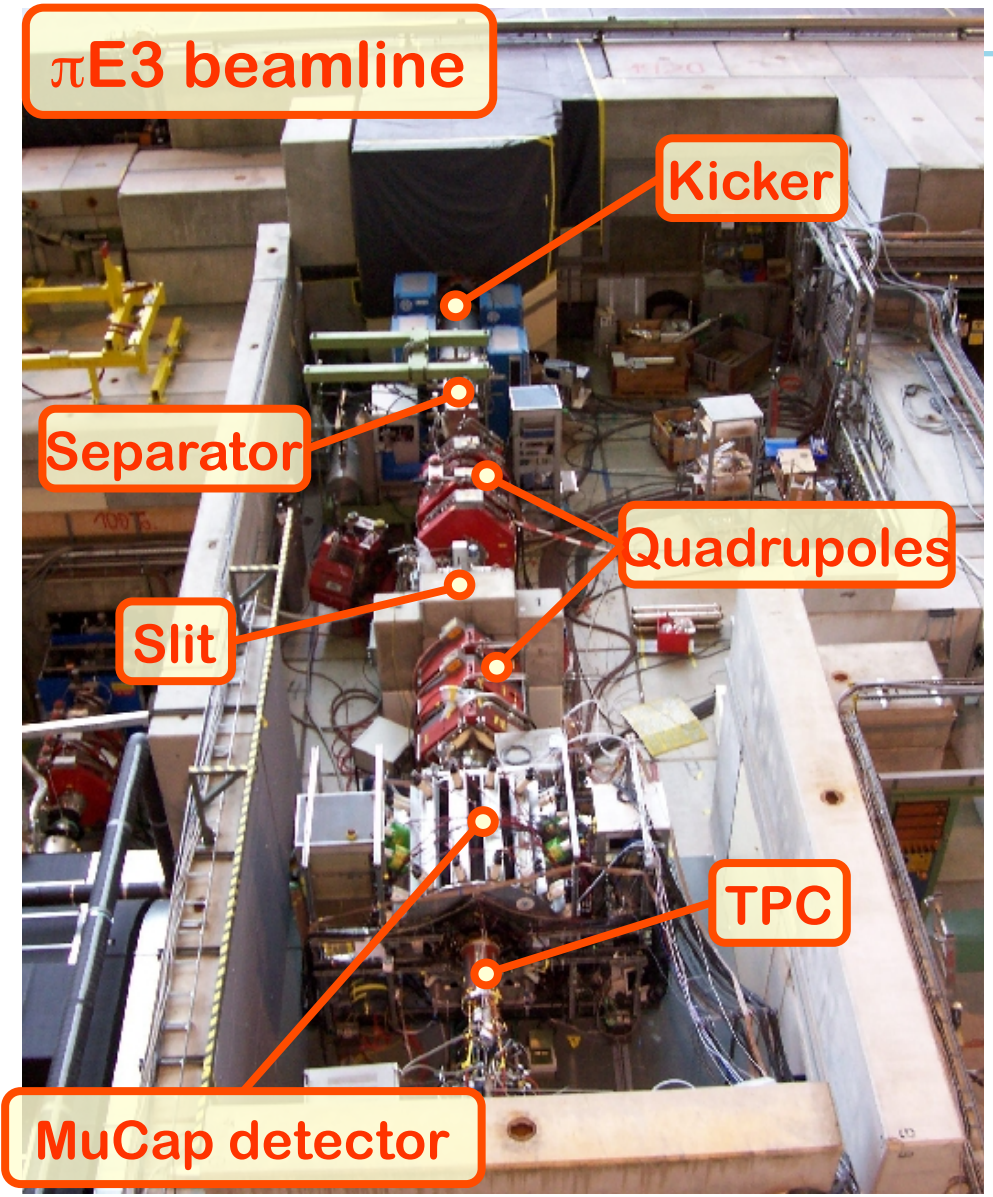
$\phi \lambda_{pf}$

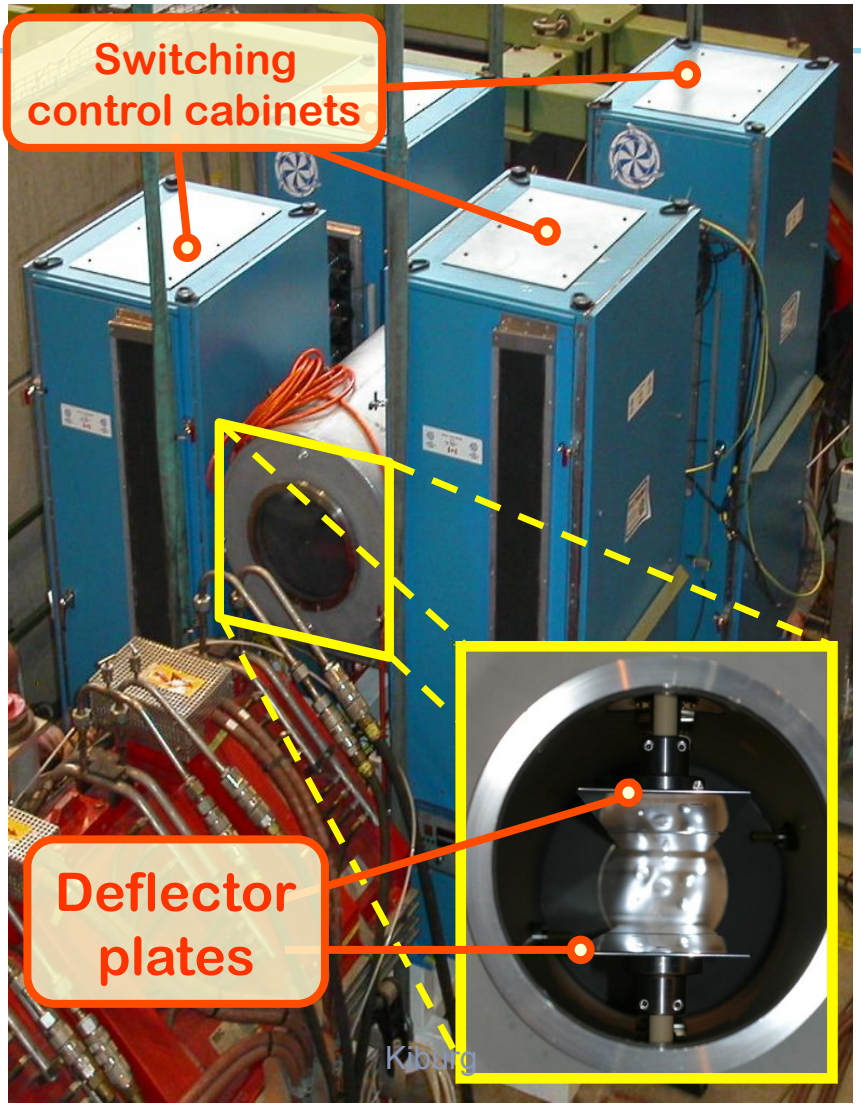
Λ_S



Fermilab

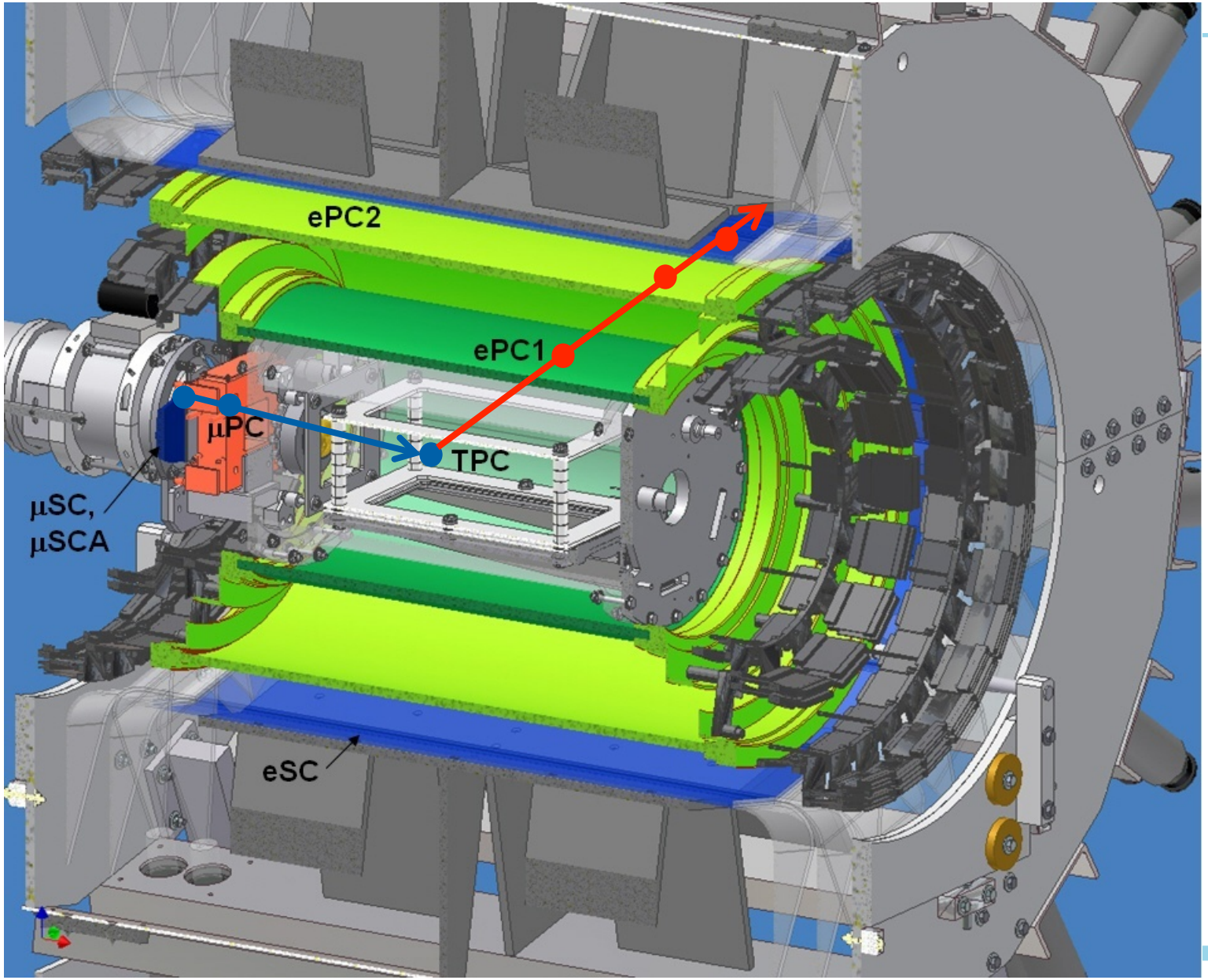
MuCap used the 1.3 MW, 2.2 mA πE3 beamline at PSI

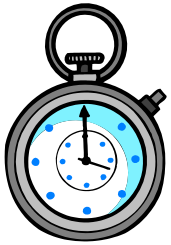




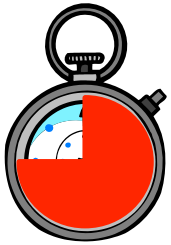
Muon On Request Mode

The MuCap Detector





$t_\mu = 0$

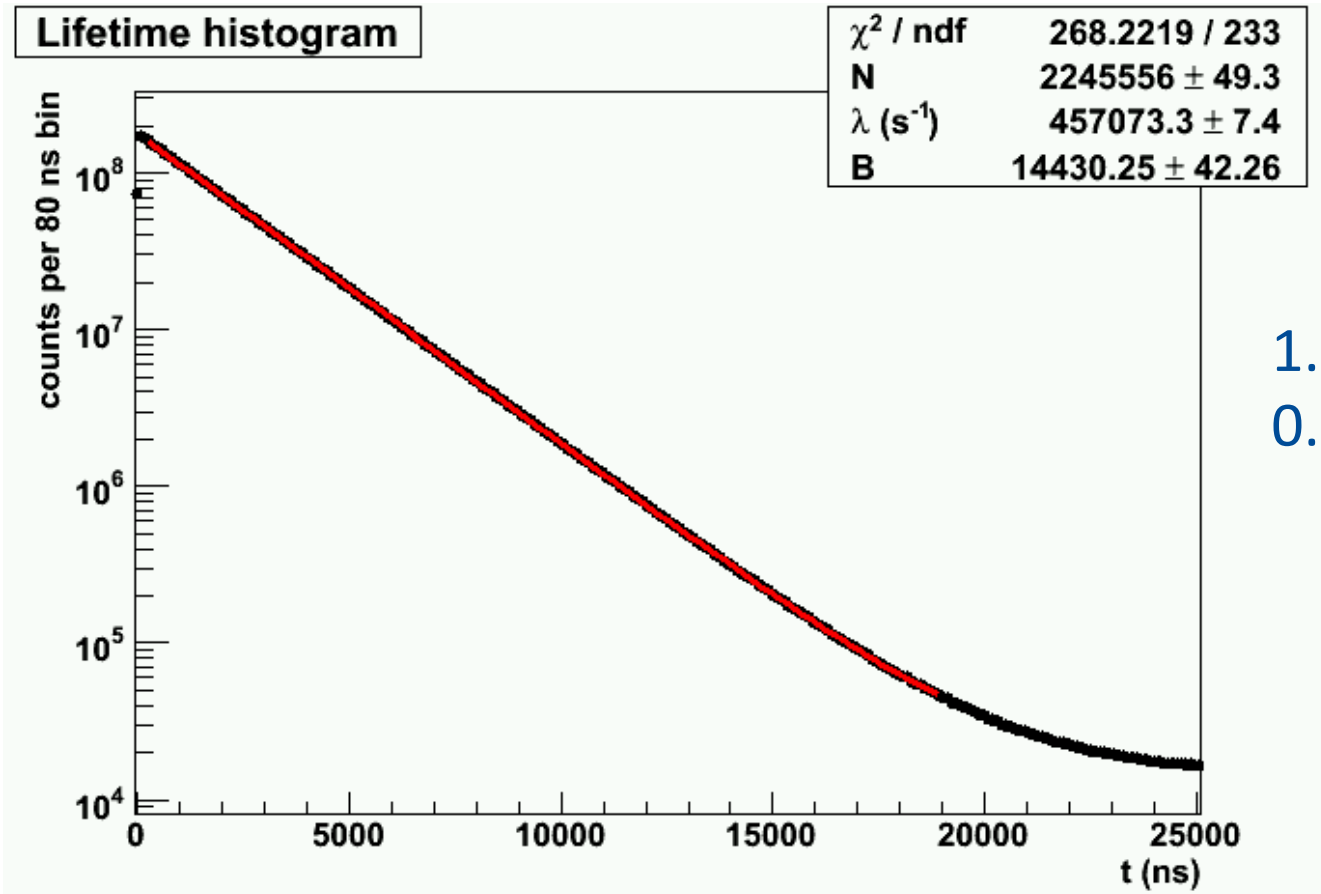


$t = t_{el}$

15 cm

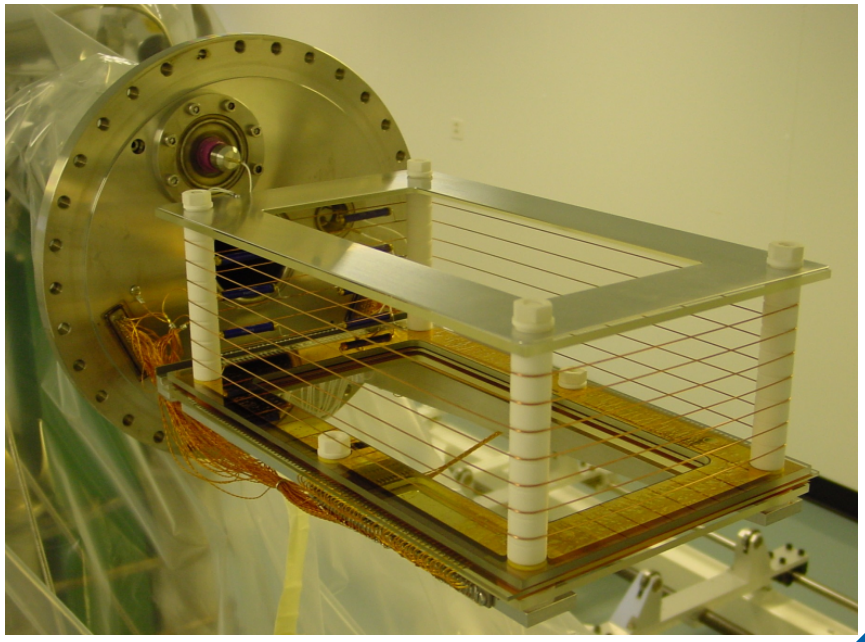
The decay time is histogrammed and fit with an exponential plus background

$$N(t) = N_0 \cdot w \cdot \lambda \cdot e^{(-\lambda t)} + B$$

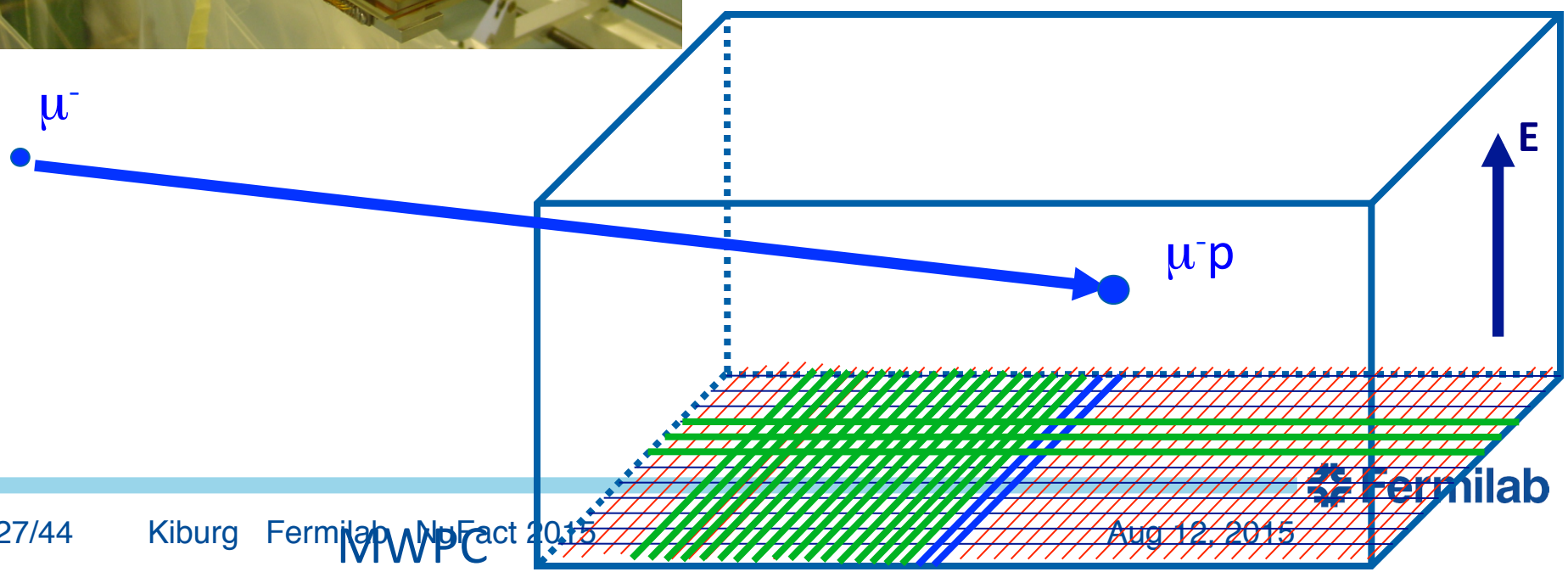


1.21×10^{10} μ^- e^- pairs
0.60×10^{10} μ^+ e^+ pairs

The TPC images the muon stop



- 10 bar ultra-pure H_2
- Bakeable glass/ceramic materials
- No materials in the fiducial volume



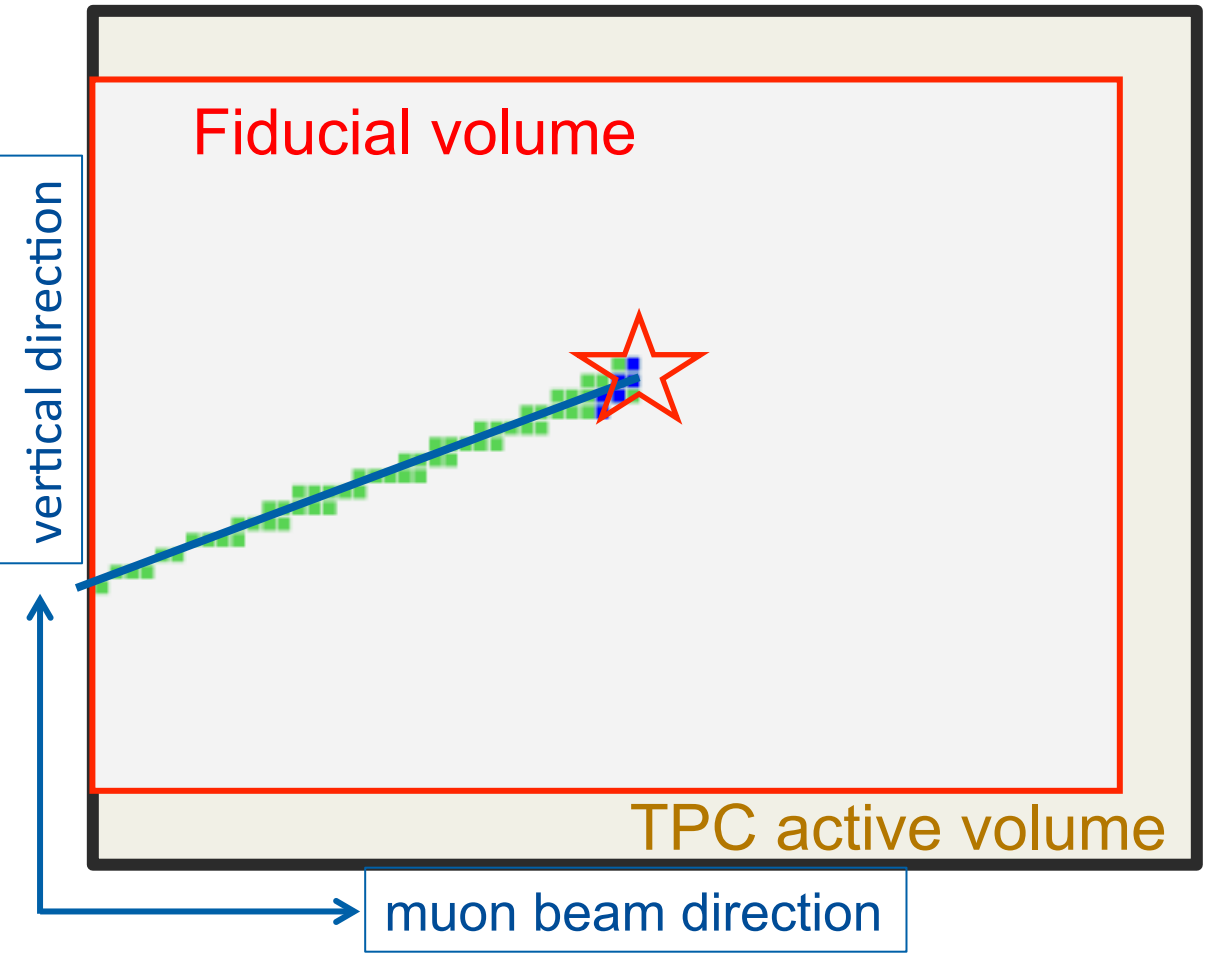
Sample Event

Low-energy threshold ~10 kEV (just above noise)

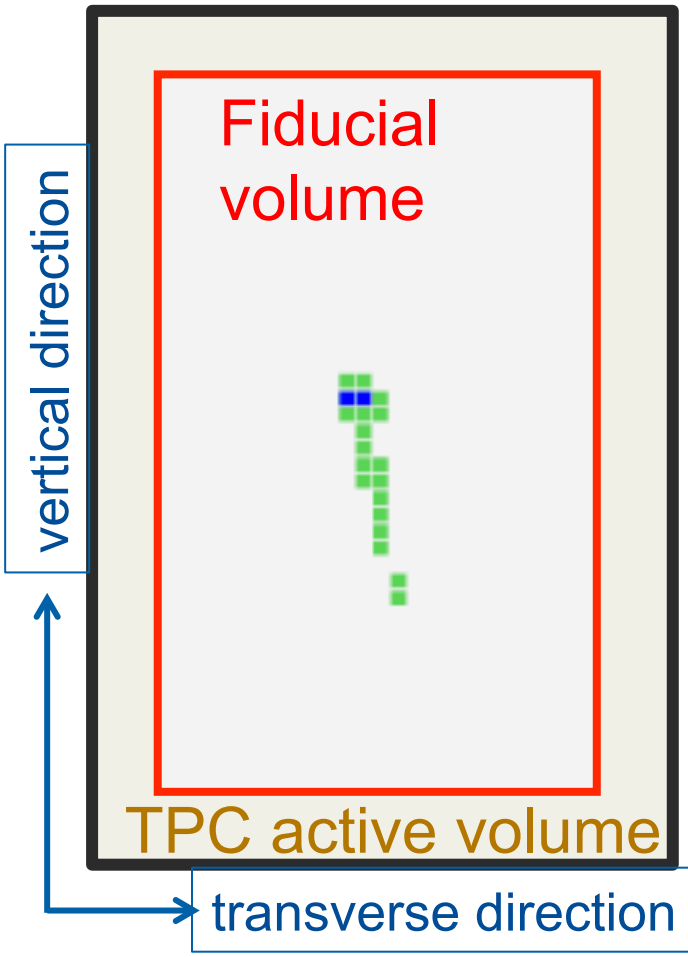
High-energy threshold ~70 kEV (stopping muon)

Very-High-energy threshold ~300 kEV (impurity capture)

TPC side view

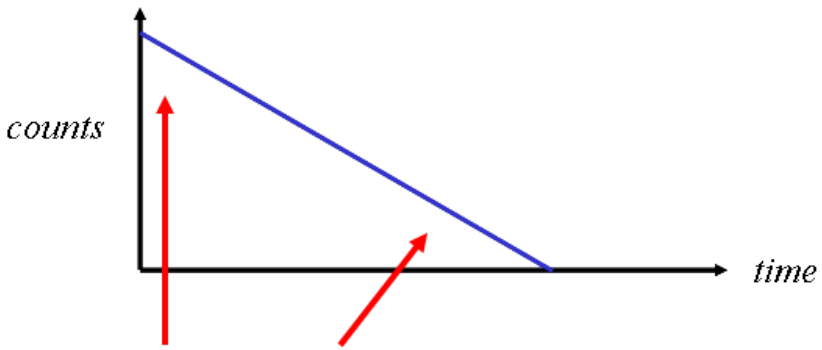


Front face view



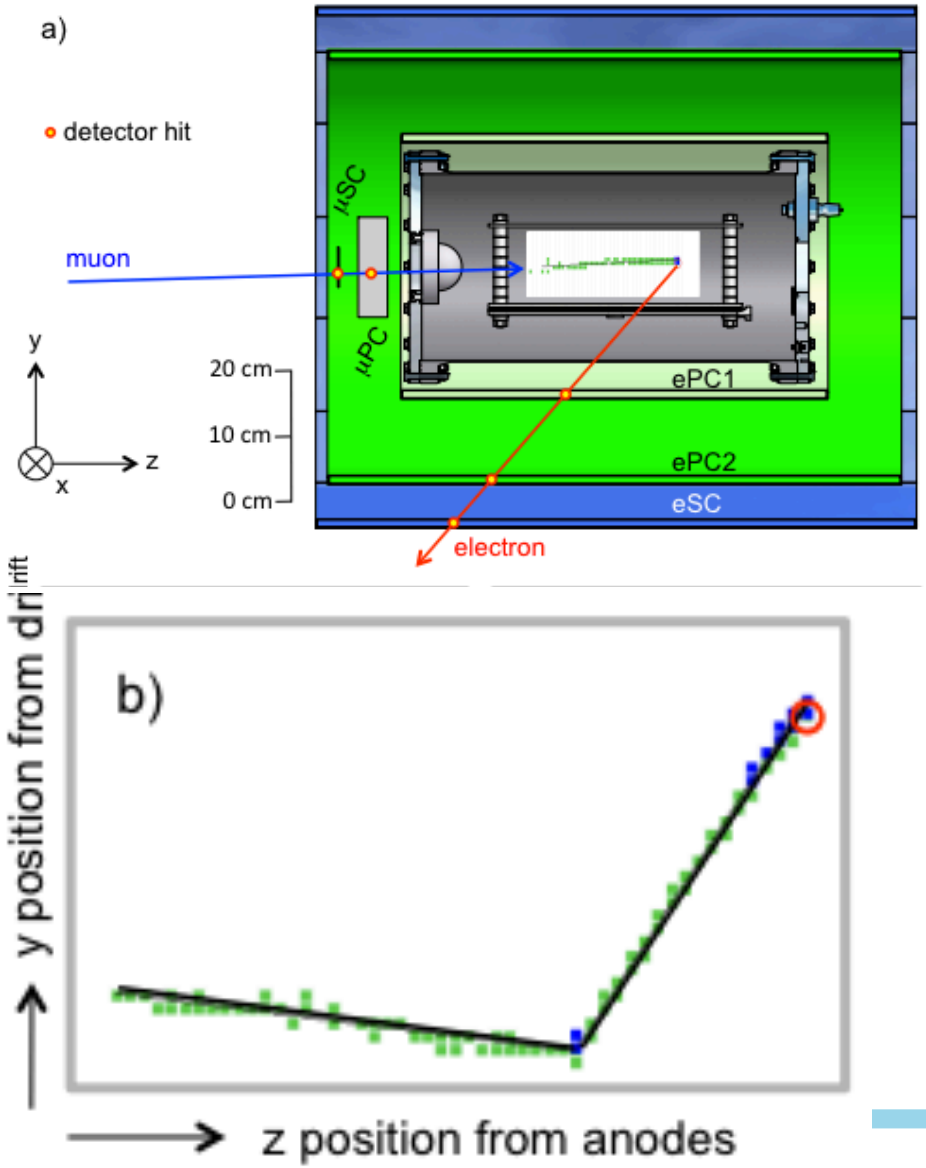
How would we get the capture rate wrong?

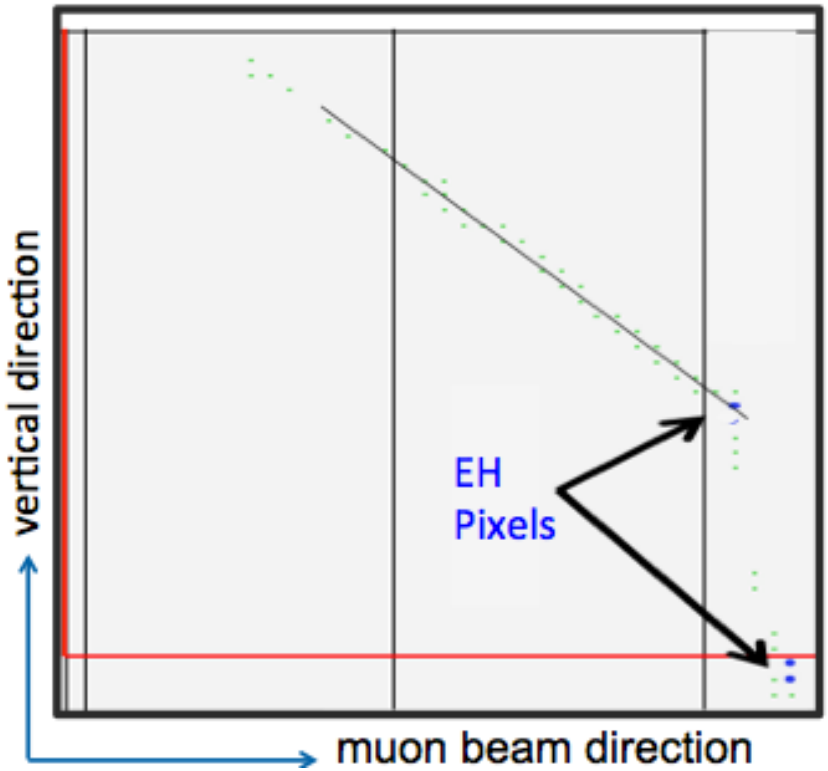
- Acceptance of events that fake a good stop, but actually stop in other materials
  - Deuterium Diffusion
  - Muon Scatter Events



- Any “early-to-late” changes in muon acceptance
  - If the decay electron changes the probability that we identify the muon stop as “good” in a time-dependent way

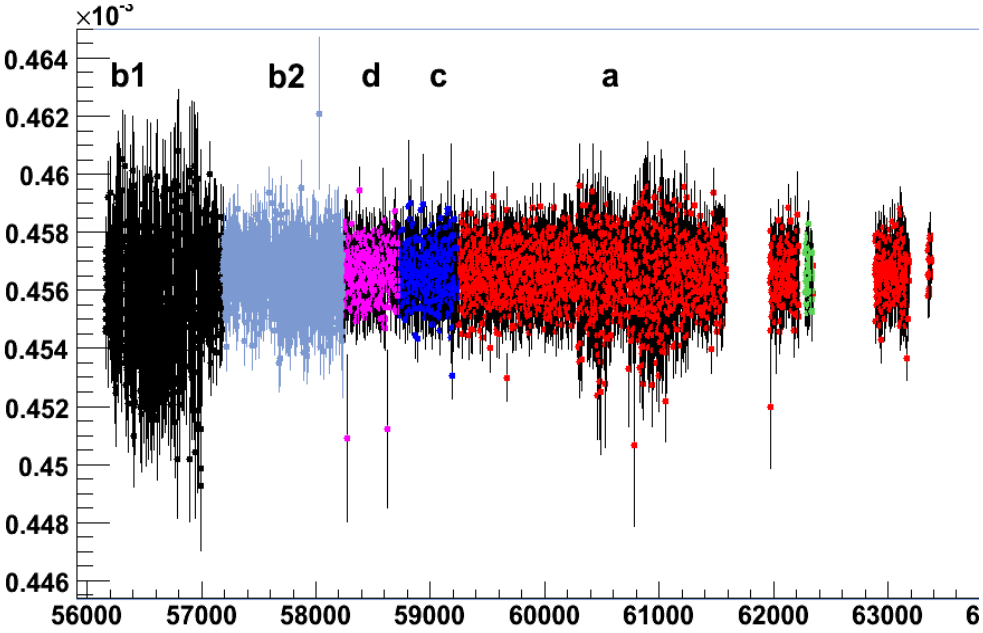
Ideal event, acceptable scatter, unacceptable scatter





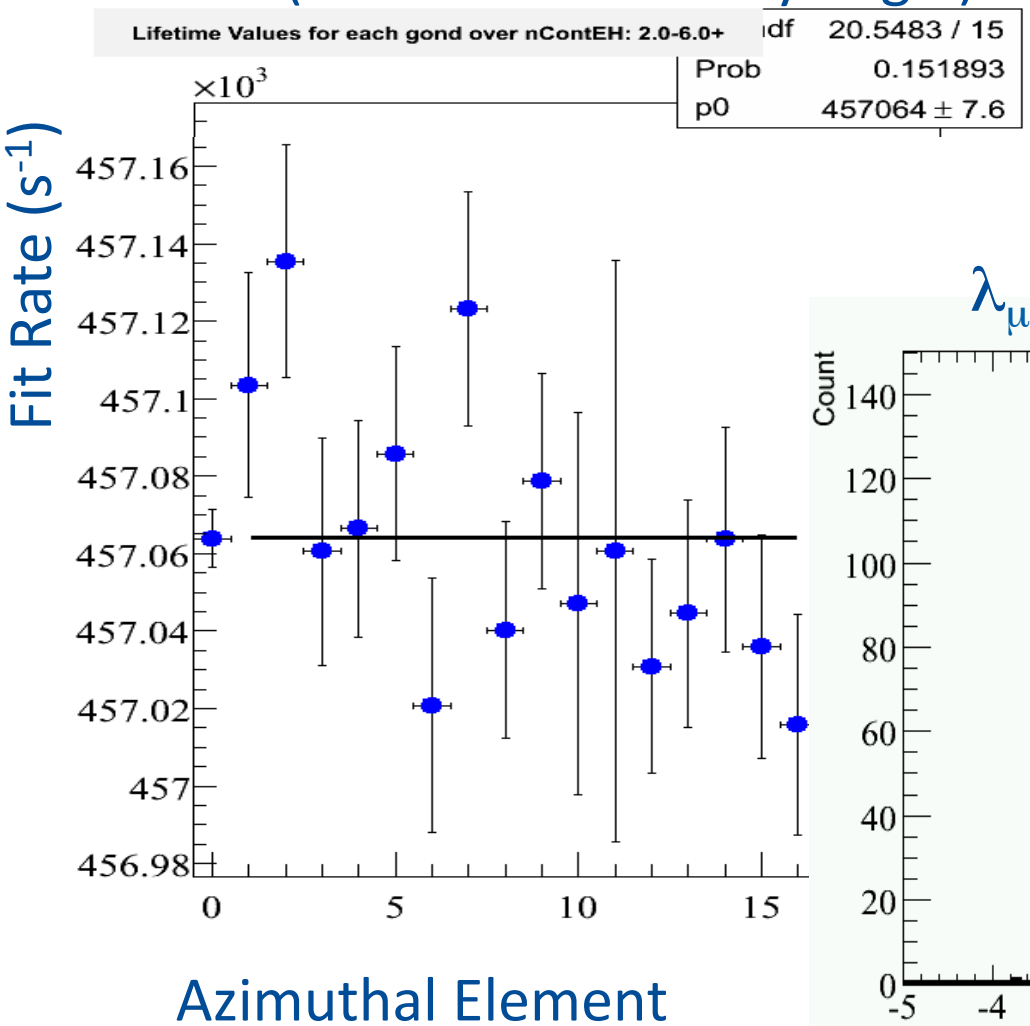
1 EH Pixel @ scatter, 2+ at stop

Consistency Checks

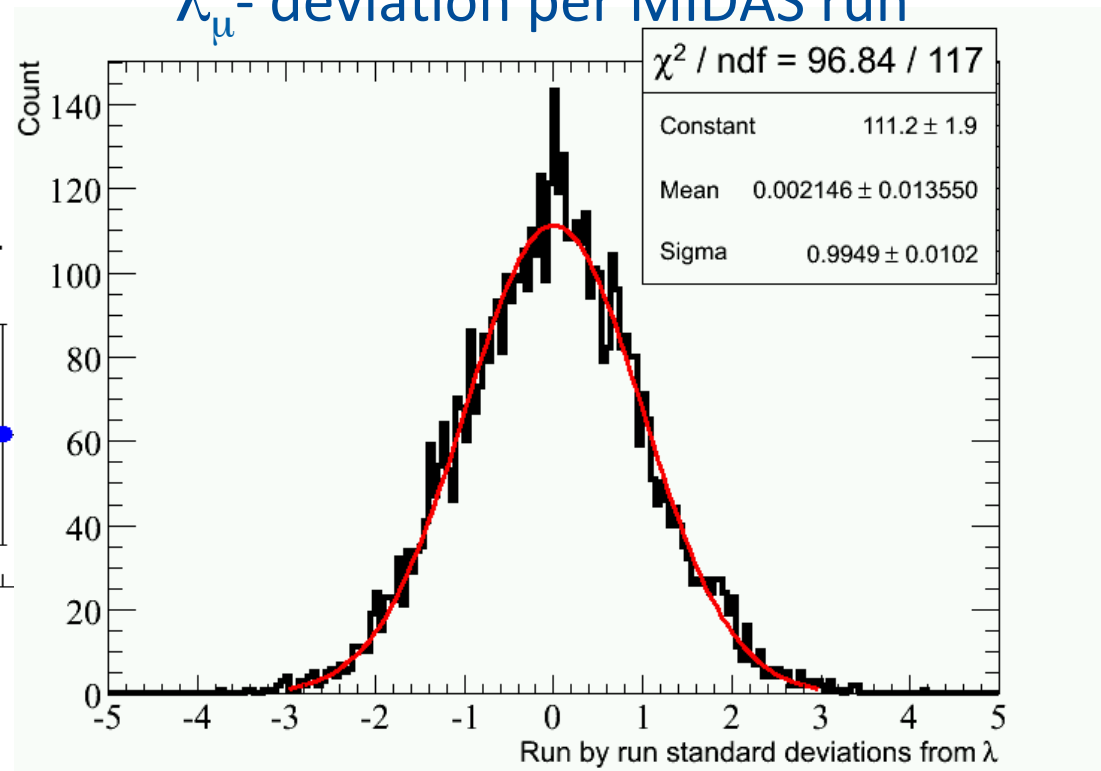


Scanned versus different cut variables

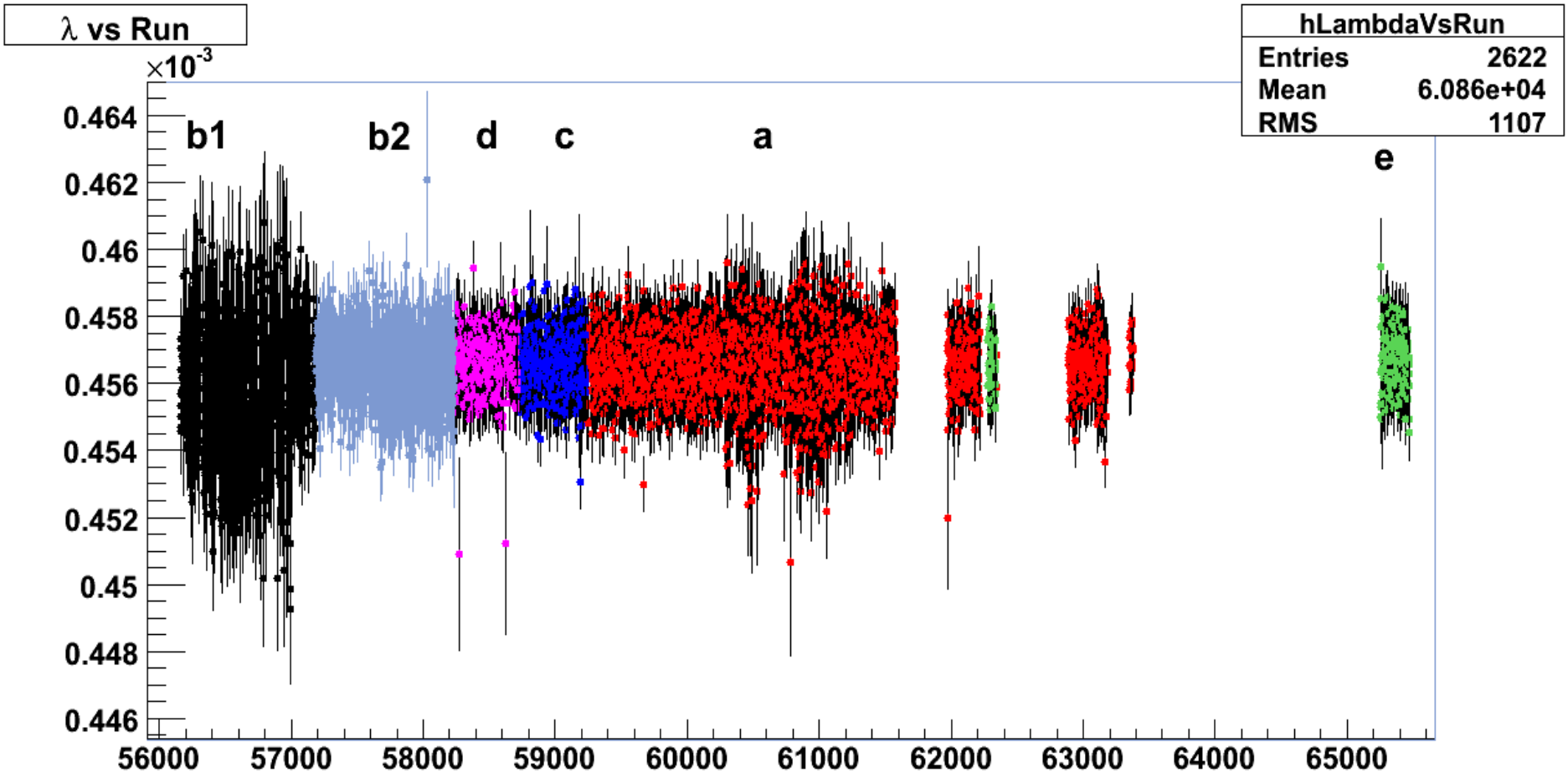
Azimuth (transverse e⁻ decay angle)



λ_μ- deviation per MIDAS run

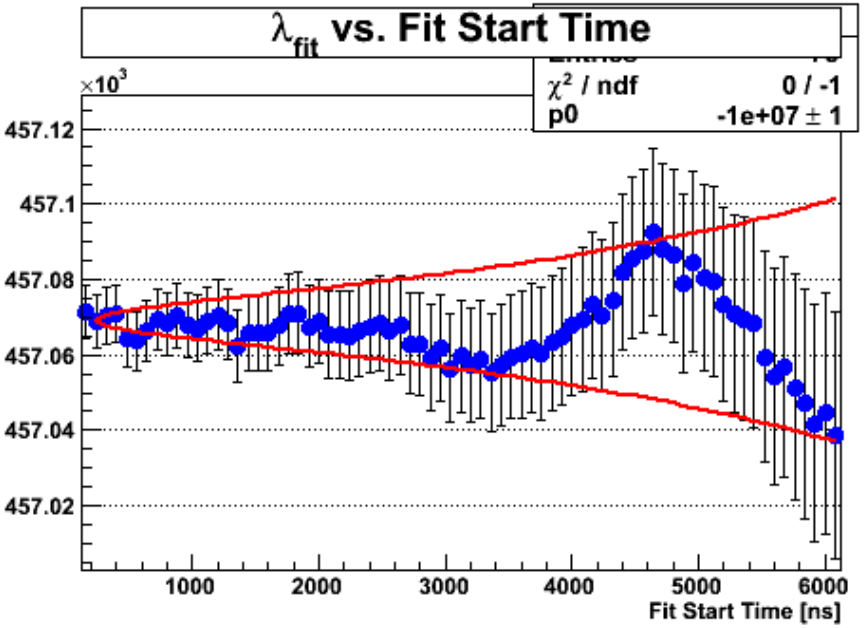


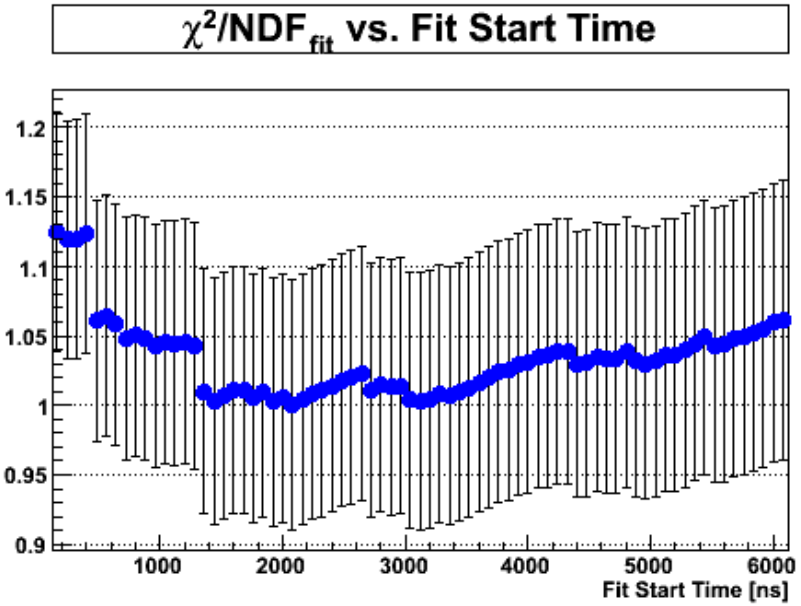
The disappearance rate is independent of run

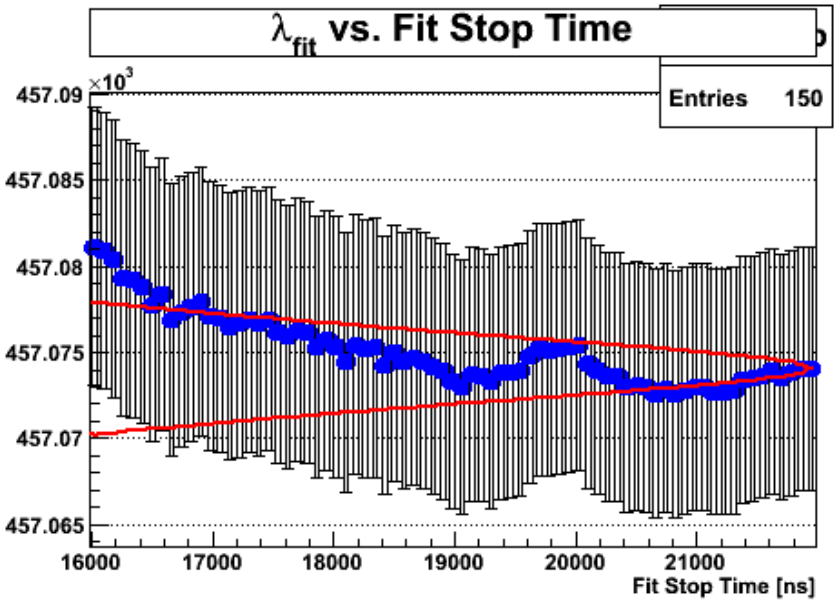


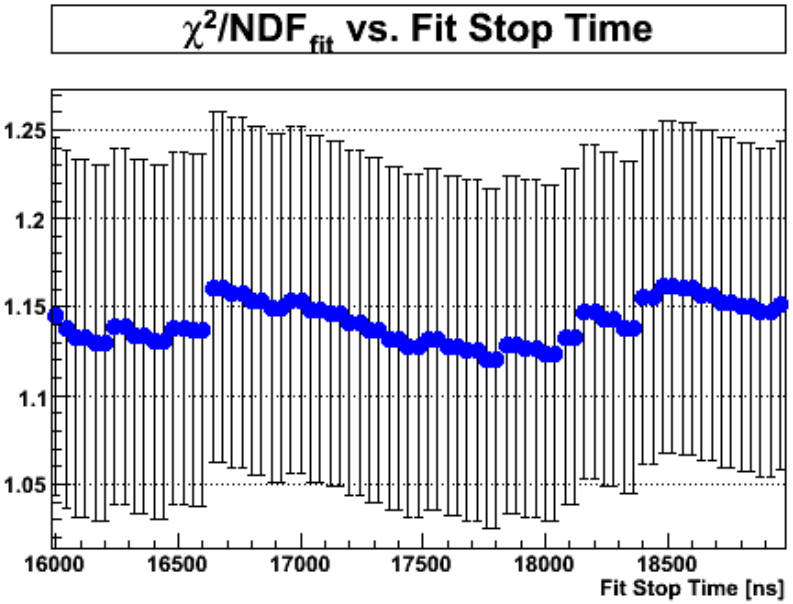
Different color points represent slightly different electron detector high voltage conditions

Start and stop-time-scans demonstrate consistency

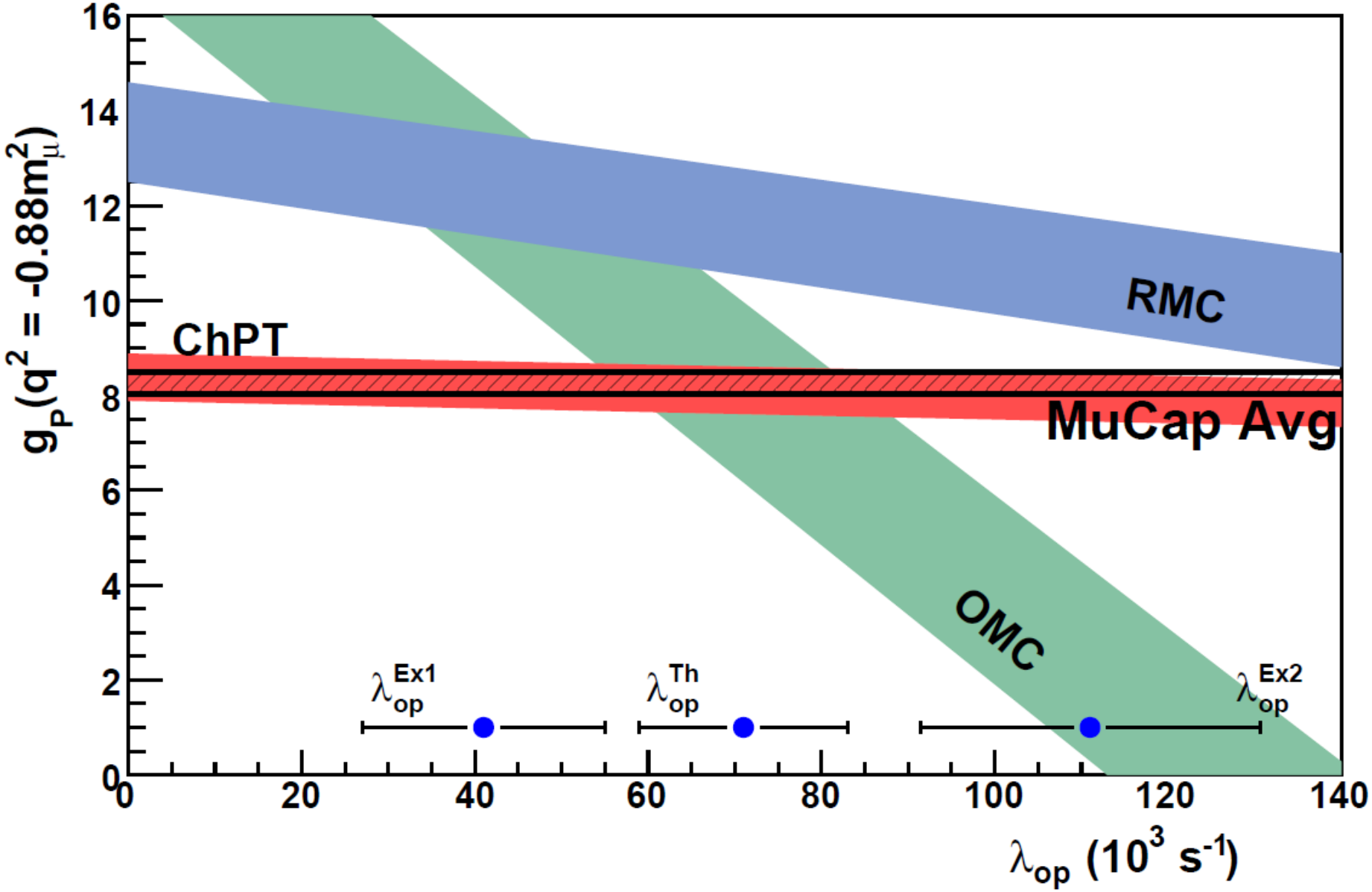








Results


16
14
12
10
8
6
4
2
0
0
20
40
60
80
100
120
140
$g_P(q^2 = -0.88m_\mu^2)$
λ_{op} (10^3 s^{-1})
RMC
ChPT
MuCap Avg
OMC
λ_{op}^{Ex1}
λ_{op}^{Th}
λ_{op}^{Ex2}

Applied correction and systematic errors

Effect	Corrections and uncertainties [s^{-1}] R06	R07
$Z > 1$ impurities	-7.8 ± 1.87	-4.54 ± 0.93
μ-p scatter removal	-12.4 ± 3.22	-7.2 ± 1.25
μp diffusion	-3.1 ± 0.10	-3.0 ± 0.10
μd diffusion	± 0.74	± 0.12
Fiducial volume cut	± 3.00	± 3.00
Entrance counter ineff.	± 0.50	± 0.50
Electron track def.	± 1.80	± 1.80
Total λ_{μ^-} corr.	-23.30 ± 5.20	-14.74 ± 3.88
μp bound state: $\Delta\lambda_{\mu p}$	-12.3 ± 0.00	-12.3 ± 0.00
$pp\mu$ states: $\Delta\Lambda_{pp\mu}$	-18.40 ± 1.90	-18.40 ± 1.90

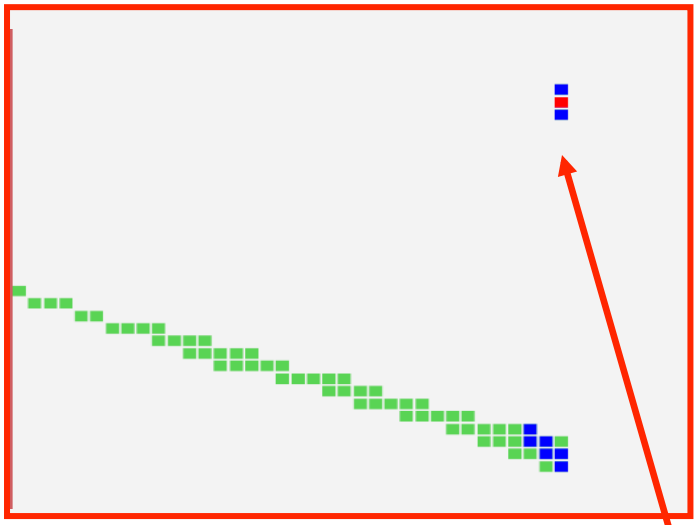
Muon disappearance

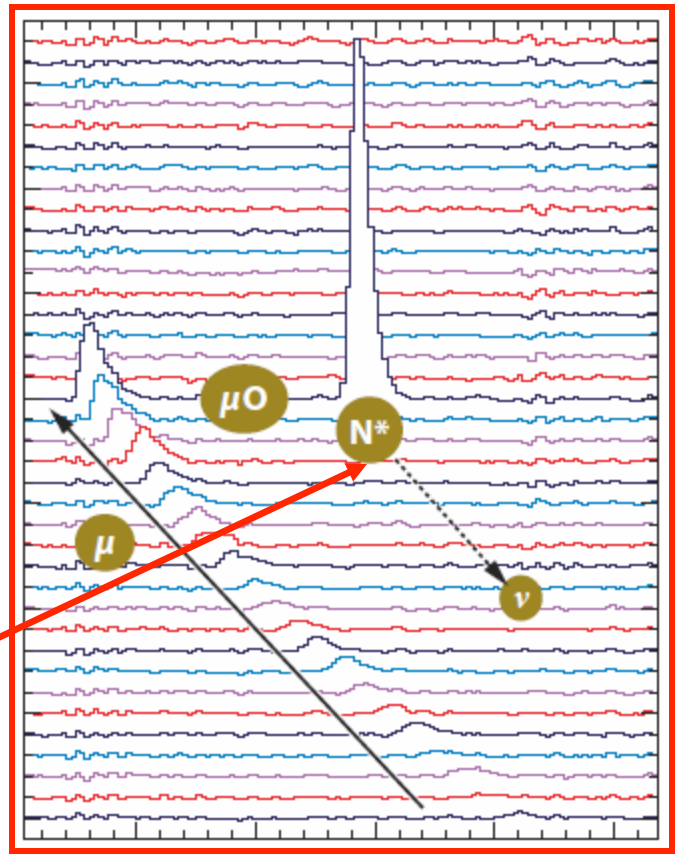
Λ_S interpretation

Measured molecular formation rate, published in 2015 producing 0.7 s^{-1} shift for final Λ_S result

See: Andreev et al., Phys. Rev. C91, 2015.

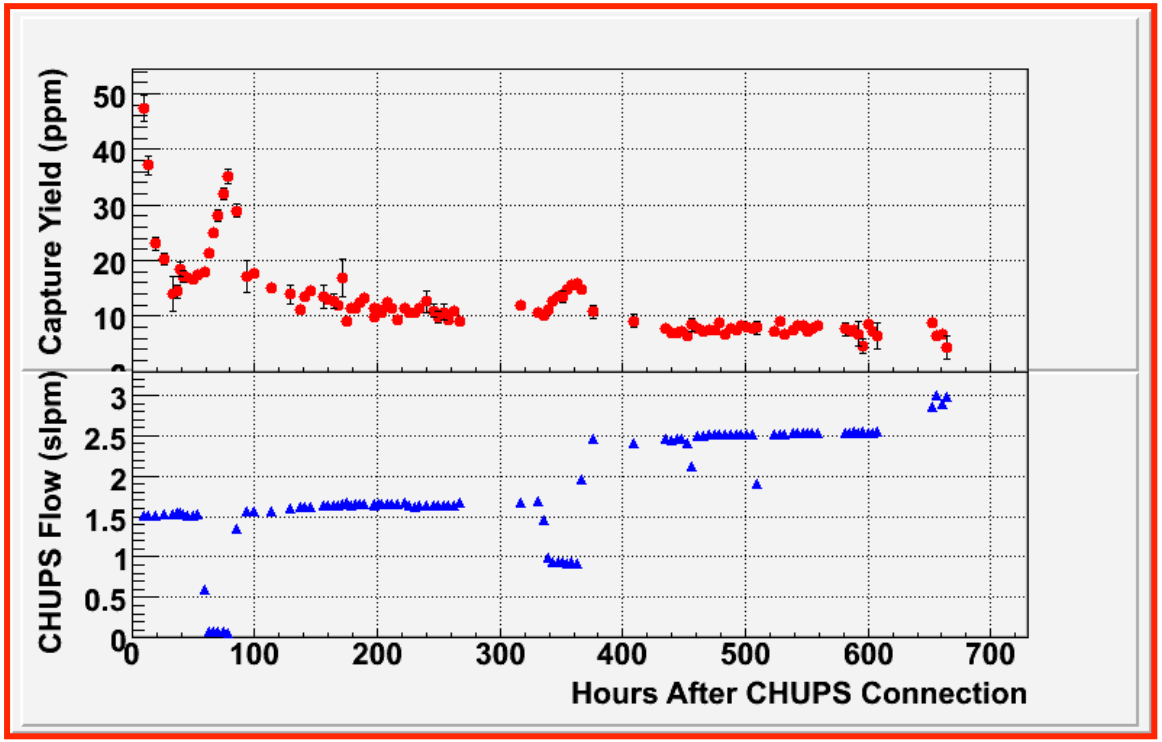
Impurity Monitoring





Imp. Capture:
$\mu^- Z \rightarrow (Z\text{-}1)\ n\ \nu$

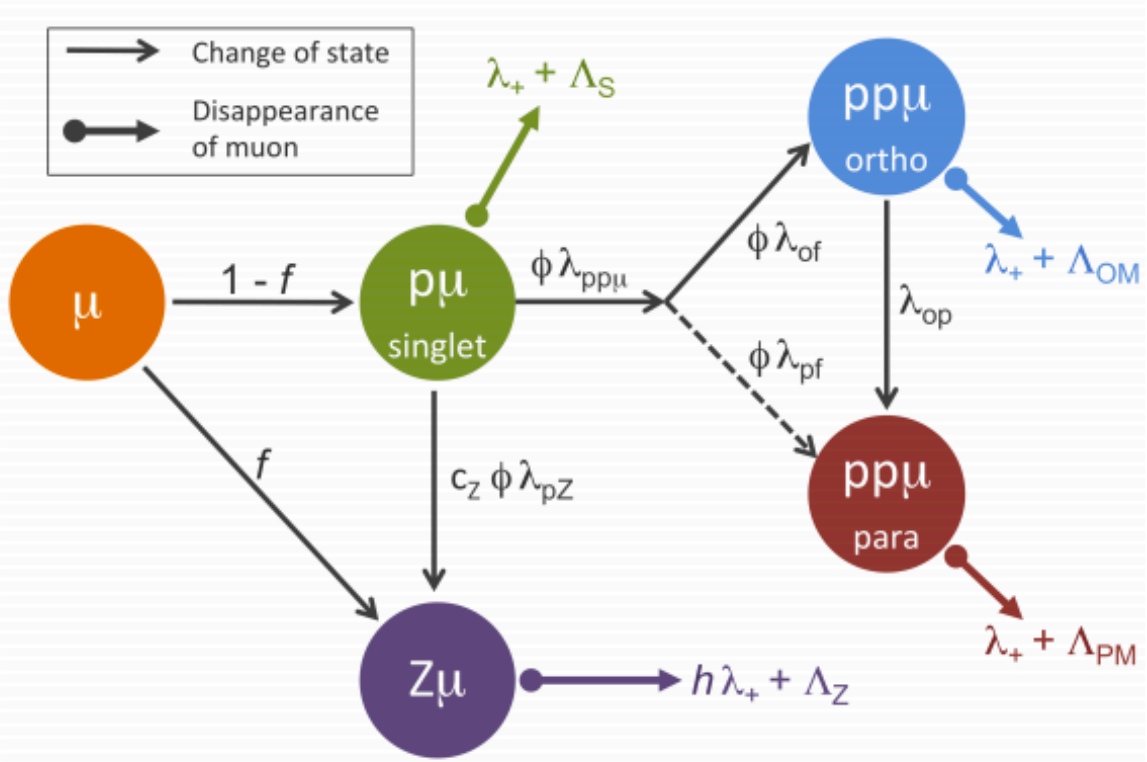
Z > 1 Impurities suppressed to ~10 ppb level



- Production Data contains final purity:
  - c_N < 7 ppb
  - c_{H2O}~10 ppb
- Calibration data with 20 ppm Nitrogen/ H2O impurities
  - Measure large capture yield
  - Extrapolate to 0ppb impurity
  - Shift production lambda by about 8 s^{-1}

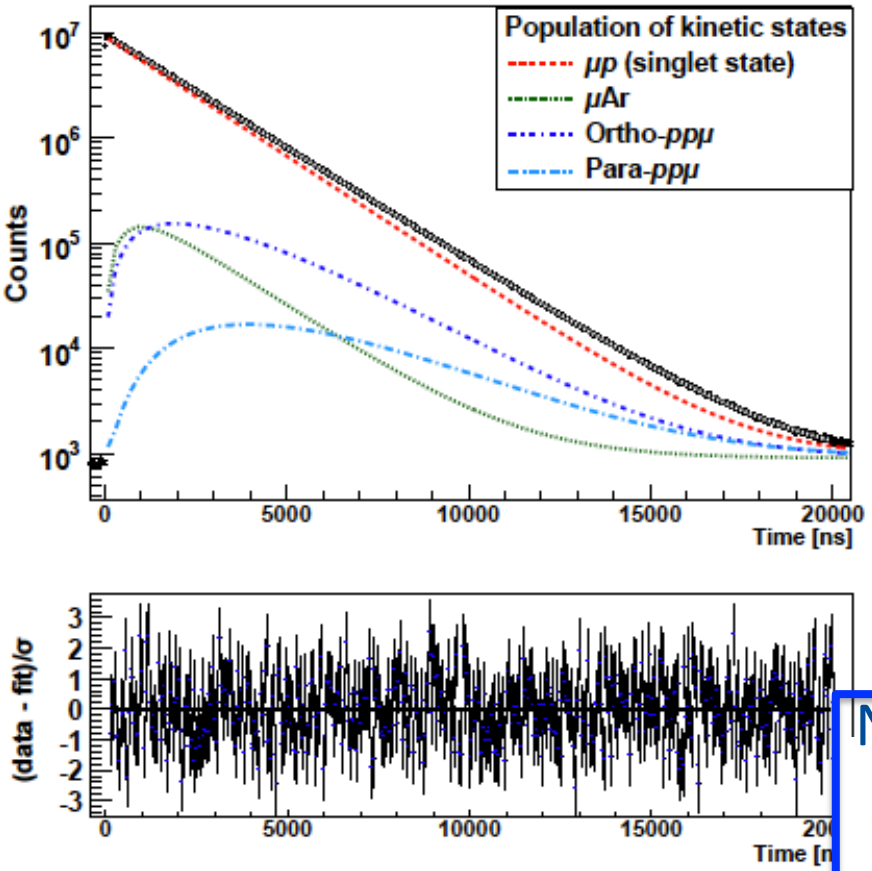
Measurement of the Molecular Formation Rate

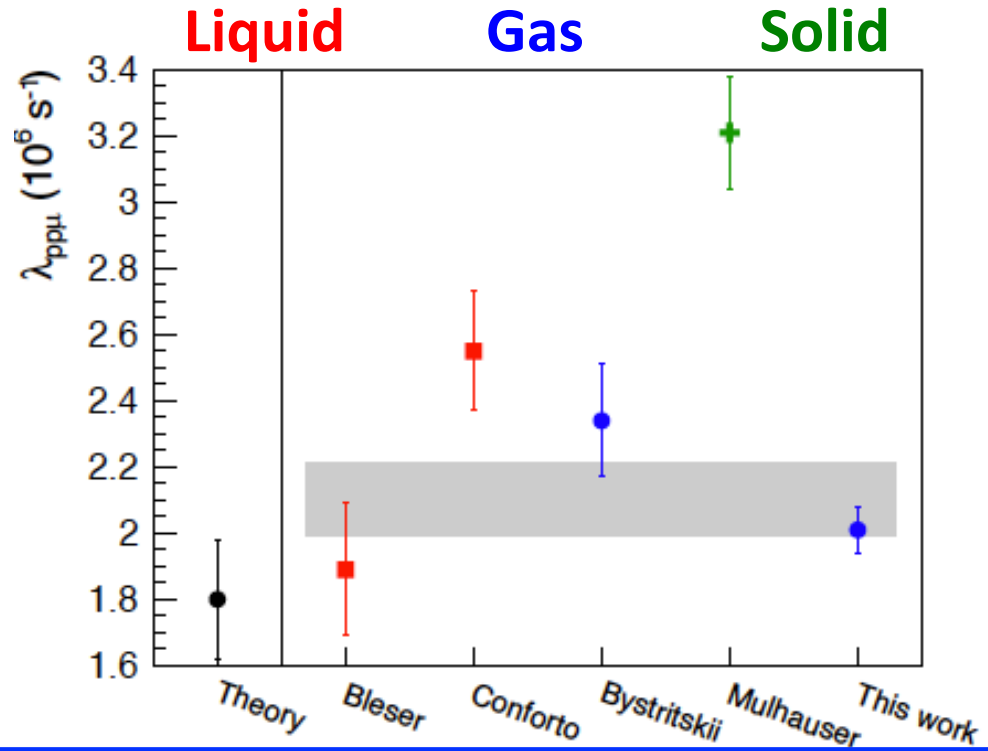
- Despite ϕ=0.01LH_2 density, must still correct for formation of molecules
- Implies we must know how quickly muonic molecules form
- Molecules form ~ $\phi\lambda_{pp\mu} = \phi(\lambda_{of} + \lambda_{pf})$
- Dope protium with 20 ppm Argon, competes with molecular formation



Measurement of the Molecular Formation Rate

- Electron time spectrum allows extraction of the various states as a function of time





Normalized Molecular Formation Rate:

$$\lambda_{pp\mu}^{\mathrm{MuCap}} = 2.01 \pm 0.06_{\mathrm{stat}} \pm 0.03_{\mathrm{syst}} \times 10^6\ \mathrm{s}^{-1},$$

External Corrections to λ_{μ^-}

$$\lambda_{\mu^-} = (\lambda_{\mu^+} + \Delta\lambda_{\mu p}) + \Lambda_S + \Delta\lambda_{p\mu p}$$

bound state effect

molecular formation
PRC 2015 refines
pμp correction

Λ_S (MuCap) = 715.6 ± 5.4$_{stat}$ ± 5.1 $_{syst}$ s^{-1}

Λ_S (theory) = 712.7 ± 3 ± 3 s^{-1}

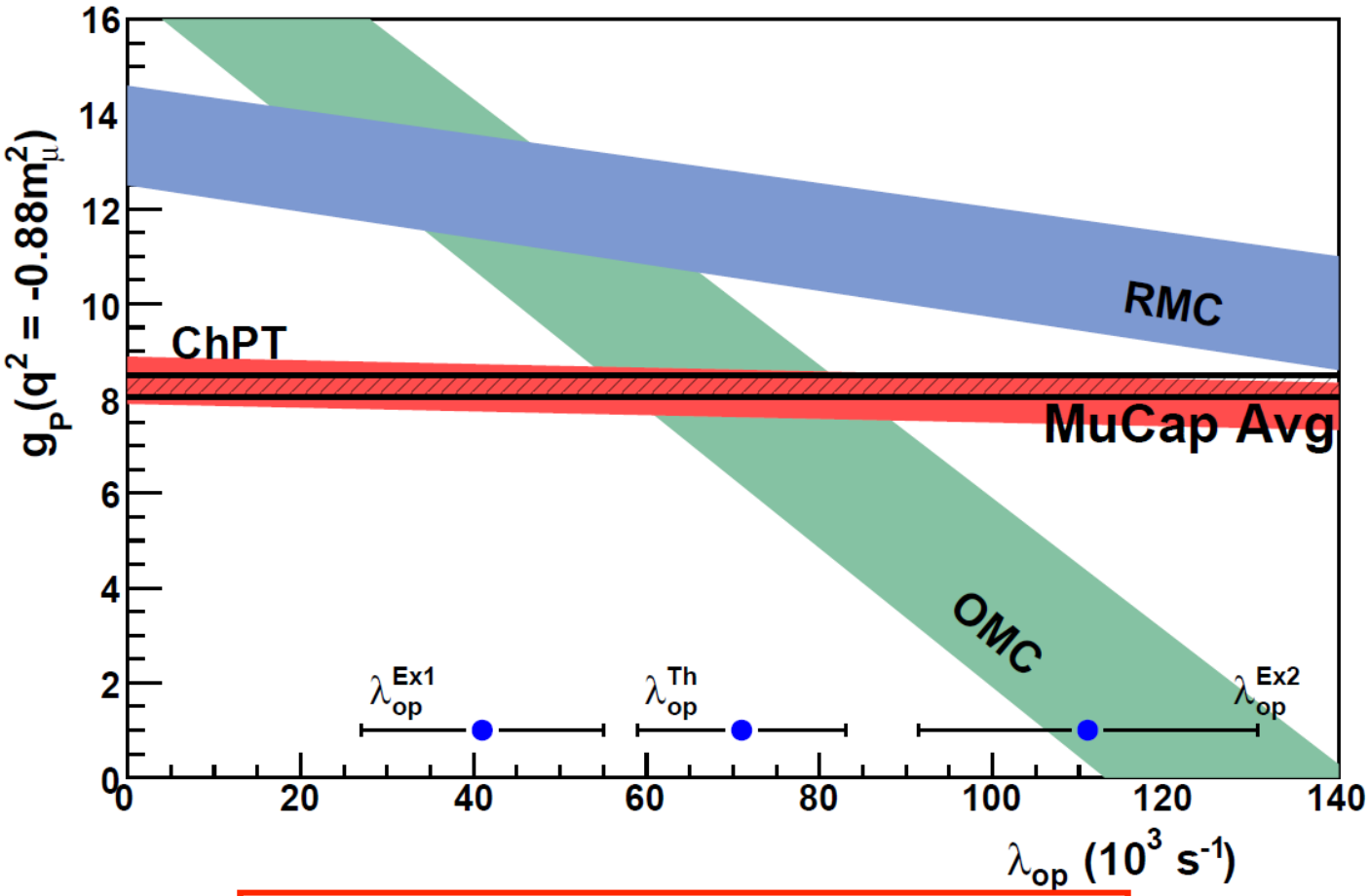
Updated $g_A(0)$ =1.2723 from PDG 2014

$$\Lambda_S^{\mathrm{Th}}(g_A, g_P) = (712.7 \pm 3.0 \pm 3.0) \times \left[1 + 0.6265(g_A - g_A^{\mathrm{PDG}}) - 0.0108(g_P - g_P^{\mathrm{Th}})\right]^2 \ \mathrm{s}^{-1}, \quad (9)$$

g_P(MuCap) = 8.14 ± 0.55

g_P(theory) = 8.26 ± 0.23

Precise and unambiguous MuCap result confirms chiral perturbation theory



$$g_P(\text{MuCap}) = 8.14 \pm 0.55$$

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

Thanks to an energetic collaboration and to the NuFact organizers for the opportunity to present our results

V.A. Andreev, T.I. Banks, R.M. Carey, T.A. Case, D. Chitwood, S.M. Clayton, K.M. Crowe, J. Deutsch, J. Egger, S.J. Freedman, V.A. Ganzha, T. Gorringe, J. Govaerts, F.E. Gray, D.W. Hertzog, M. Hildebrandt, P. Kammel, B. Kiburg, S. Knaack, P. Kravtsov, A.G. Krivshich, B. Lauss, E.M. Maev, O.E. Maev, F. Mulhauser, C.S. Özben, C. Petitjean, G.E. Petrov, R. Prieels, G.N. Schapkin, G.G. Semenchuk, M. Soroka, V. Tichenko, A. Vasilyev, A.A. Vorobyov, M. Vznuzdaev, P. Winter

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University of Washington (formerly UIUC), USA
Université Catholique de Louvain, Belgium
TU München, Garching, Germany
University of Kentucky, Lexington, USA
Boston University, USA

http://muon.npl.washington.edu/exp/MuCap/

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Fermilab

List of Papers from MuCap Data

- Ganzha et al. *A Circulating hydrogen ultra-high purification system for the MuCap experiment,* Nucl. Instrum. Meth. A578, 2007.
- Andreev et. al. *Measurement of the rate of muon capture in hydrogen gas and determination of the proton's pseudoscalar coupling* g_P, Phys. Rev. Lett 99, 2007 (032002).
- M. Döbeli et al. *Detection of trace deuterium in depleted protium by MeV ion beam techniques* Nucl. Instr. and Meth. B266 p. 1820-1823 (2008).
- Alekseev I, et al. (Deuterium Remov. Unit MuCap Exper.) Presented at NHA Annu. Hydrog. Conf., Sacramento. http://nha.confex.com/nha/2008/techprogram/MEETING.HTM (2008)
- Andreev et al. *Measurement of Muon Capture on the Proton to 1% Precision and Determination of the Pseudoscalar Coupling* g_P, Phys. Rev. Lett 110, 2013.
- Egger et al. *A high-pressure hydrogen time projection chamber for the MuCap experiment*, Eur. Phys. Journ. A, Vol 50, Num 10, 2014.
- Andreev et al. *Measurements of the Formation Rate of Muonic Hydrogen Molecules*, Phys. Rev. C91, 2015.

Supplemental Slides

Spontaneous Symmetry Breaking connects g_P to the pion

- Vector (CVC)

$$\partial_\alpha V^\alpha = 0$$

- Axial (PCAC)

$$\partial_\alpha A^\alpha = 0 \text{ (chiral limit)}$$

AXIAL VECTOR CURRENT CONSERVATION IN WEAK INTERACTIONS*

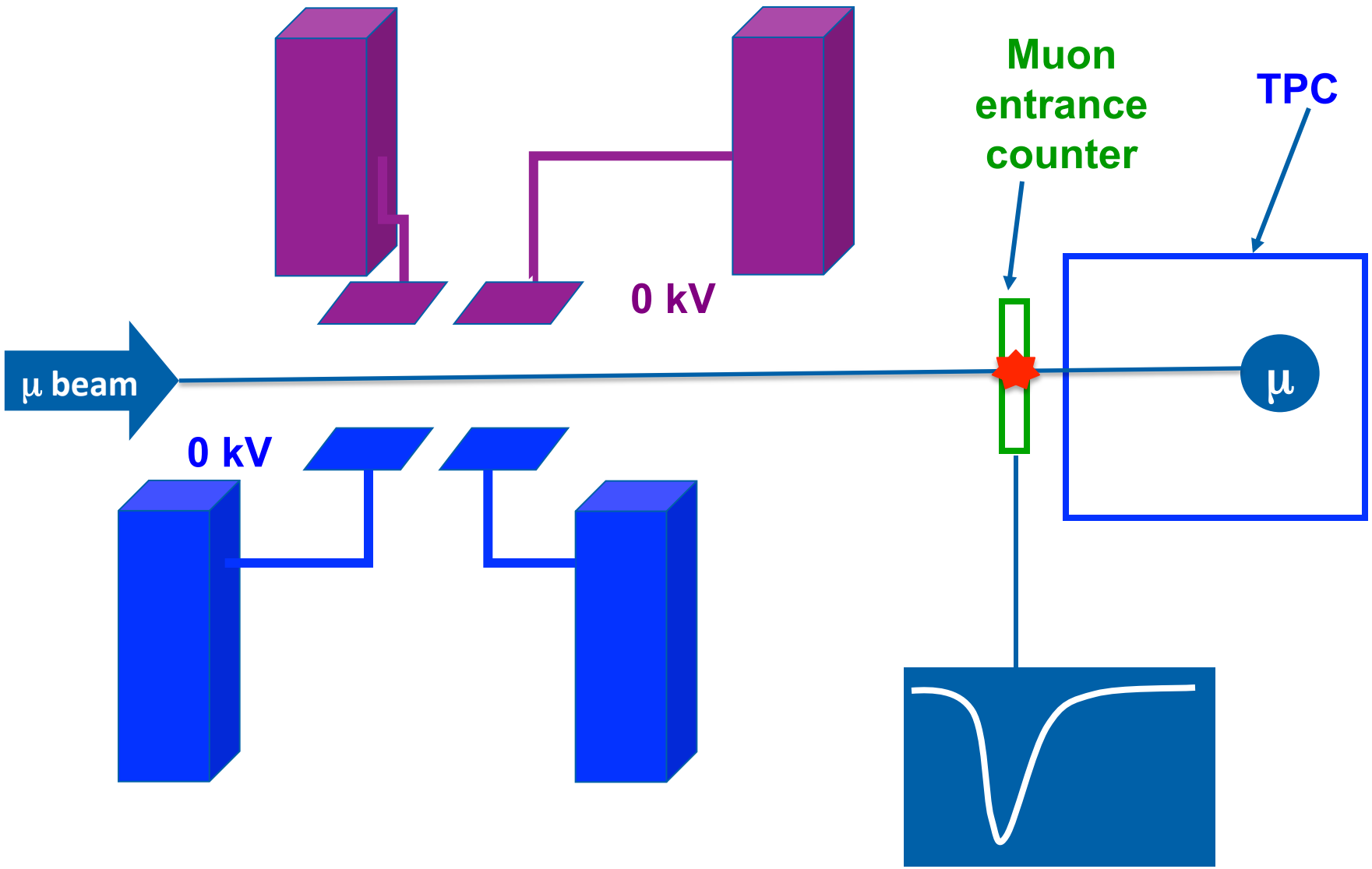
Yoichiro Nambu
Enrico Fermi Institute for Nuclear Studies and Department of Physics
University of Chicago, Chicago, Illinois
(Received February 23, 1960)

$\Downarrow$

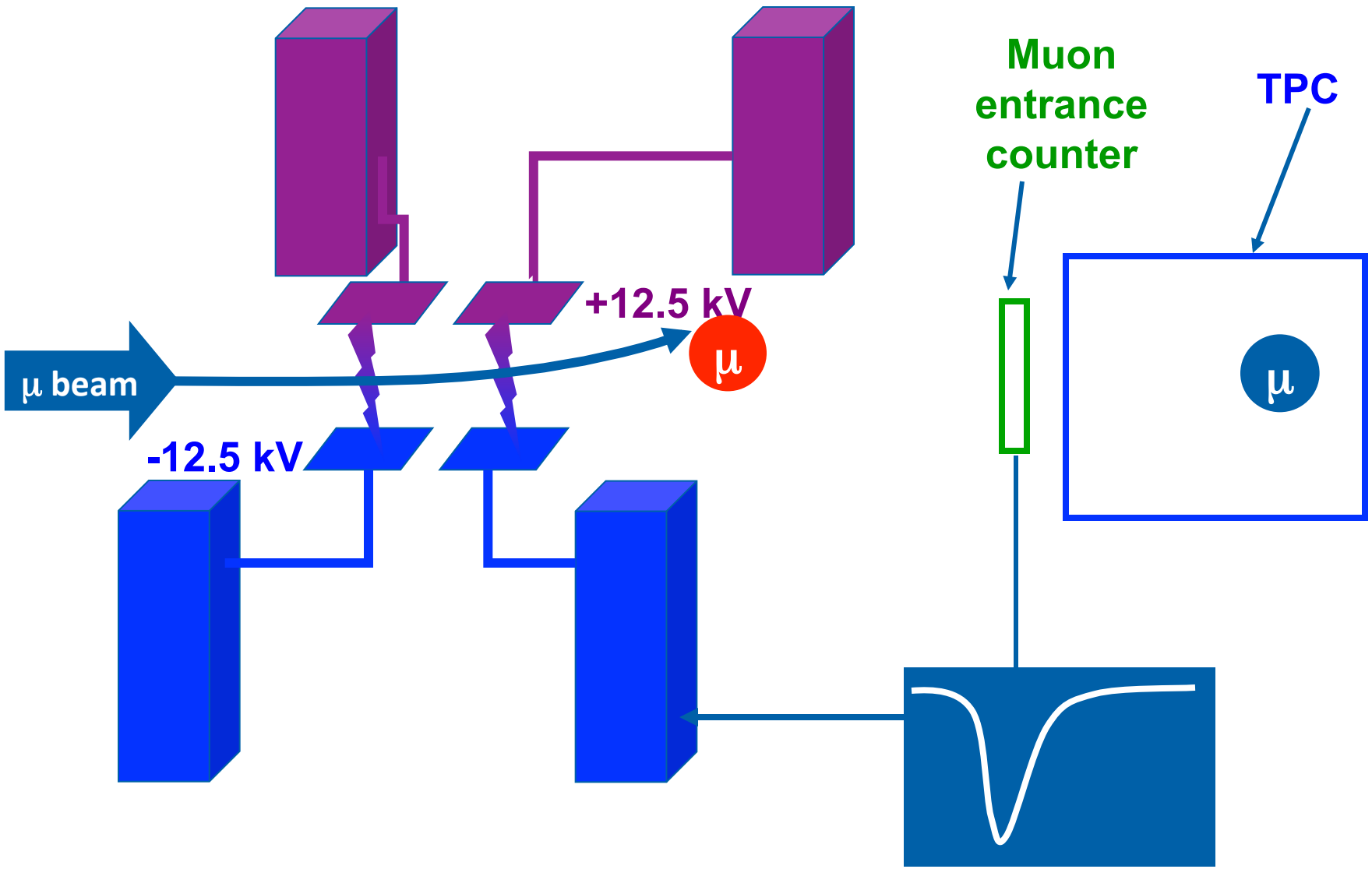
2008 Nobel Prize

- Nambu
  - If Axial Current Conserved:
    - Chiral symmetry is spontaneously broken
    - A massless pseudoscalar exists
  - With Explicit Chiral breaking, only partially conserved
    - The (massive) pion is the pseudo-Nambu-Goldstone boson
- Historic milestone
  - Foundation for the generation of particle masses
  - Led to the development of chiral perturbation theory, low-energy effective field theory of fundamental QCD

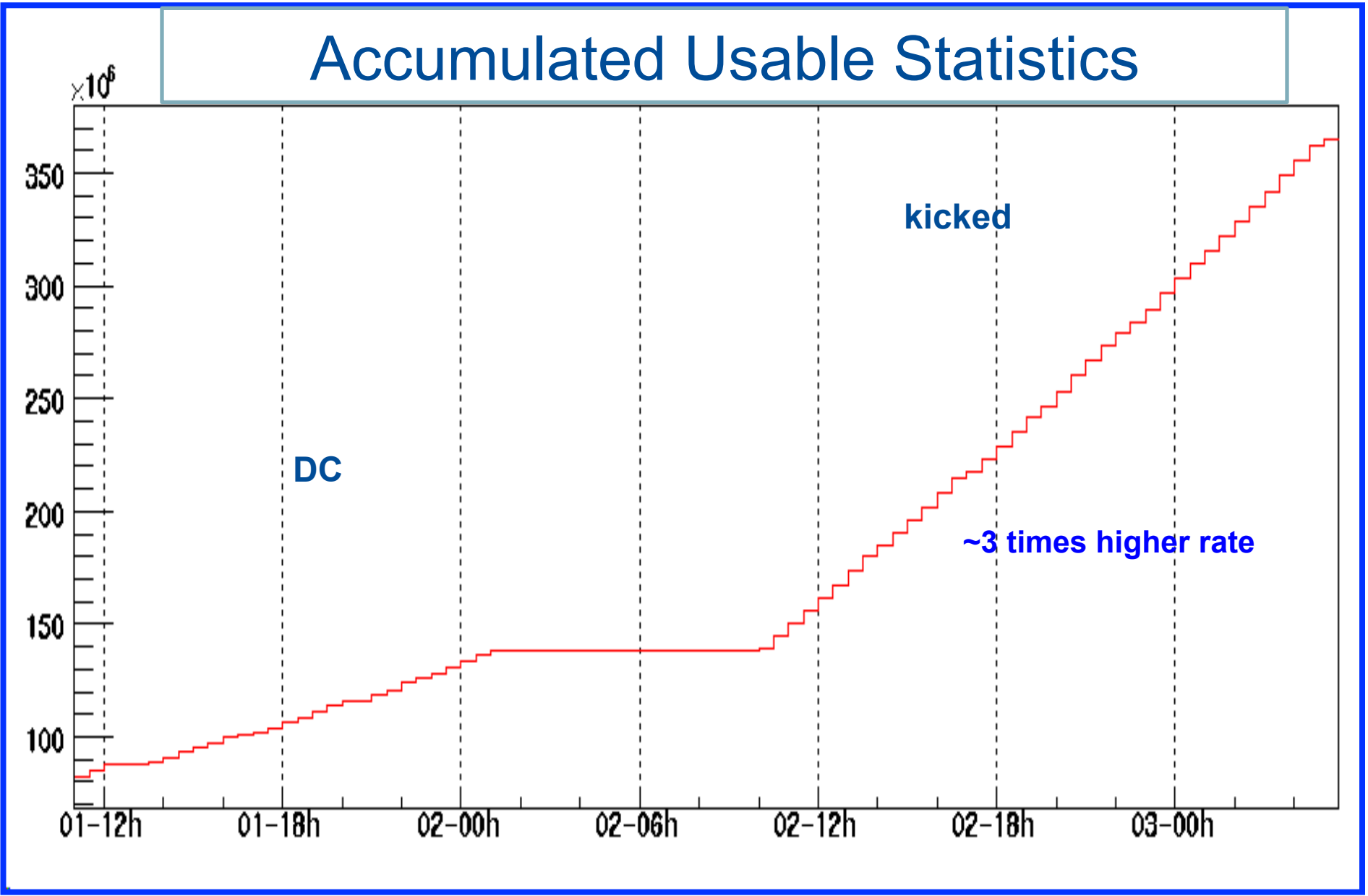
One muon at a time

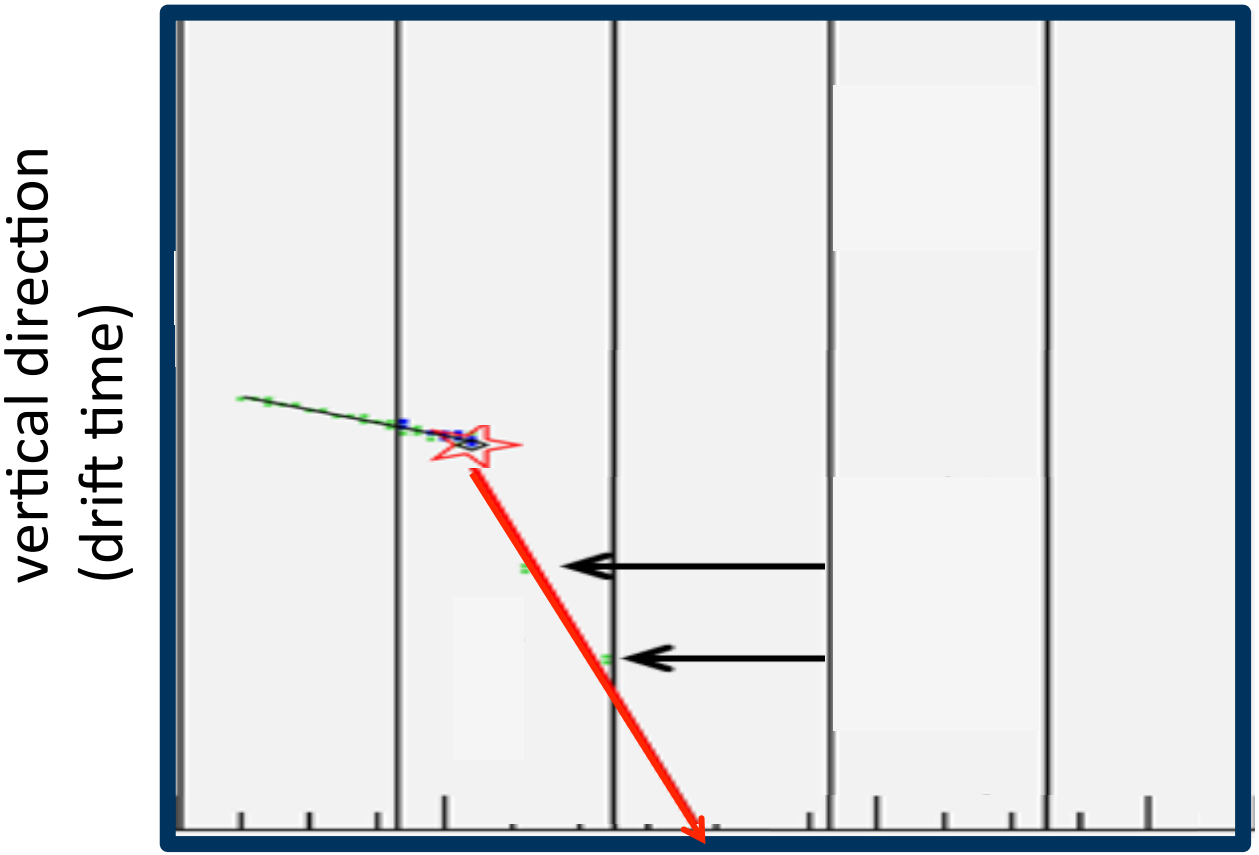


One muon at a time

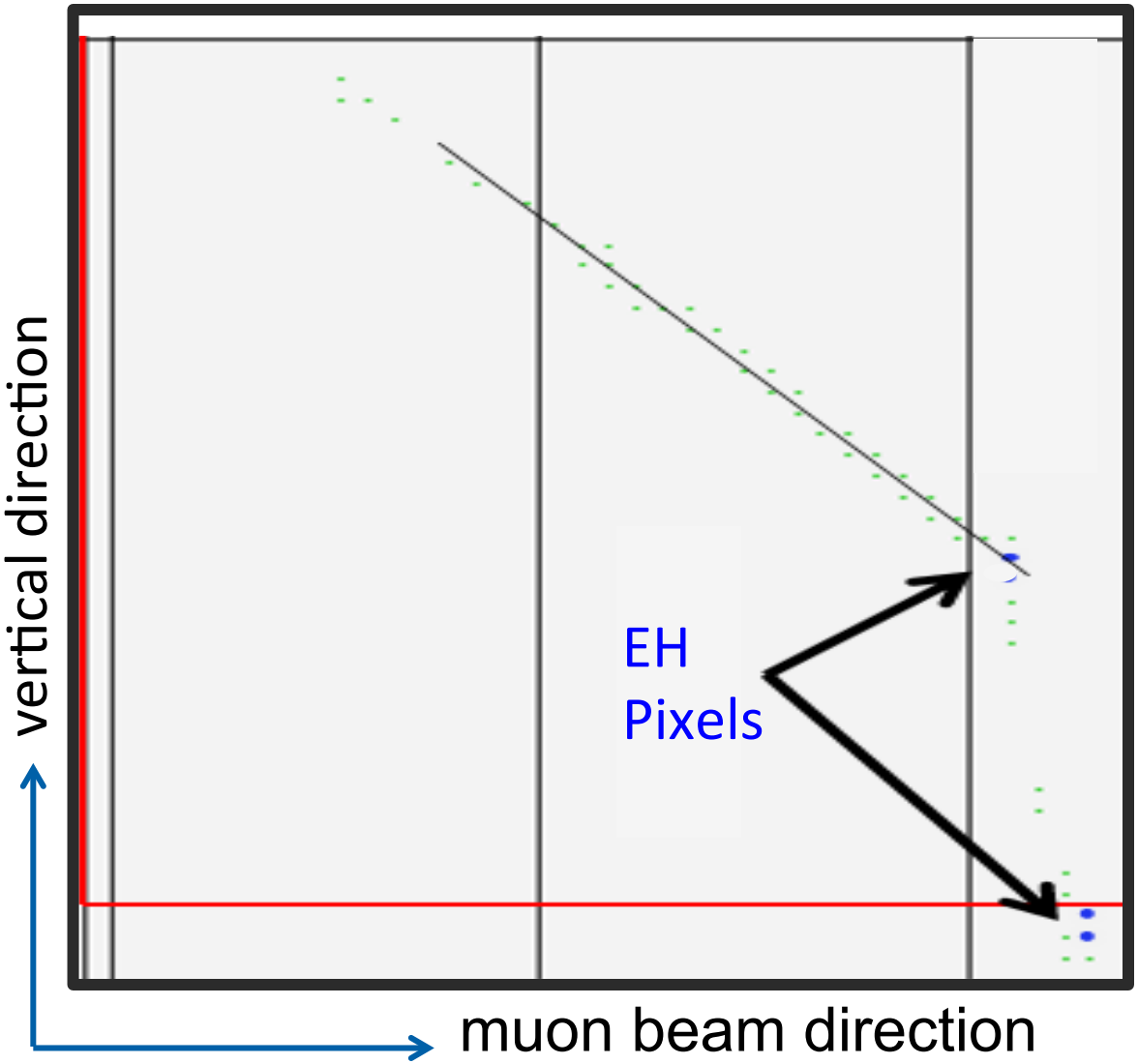


One muon at a time



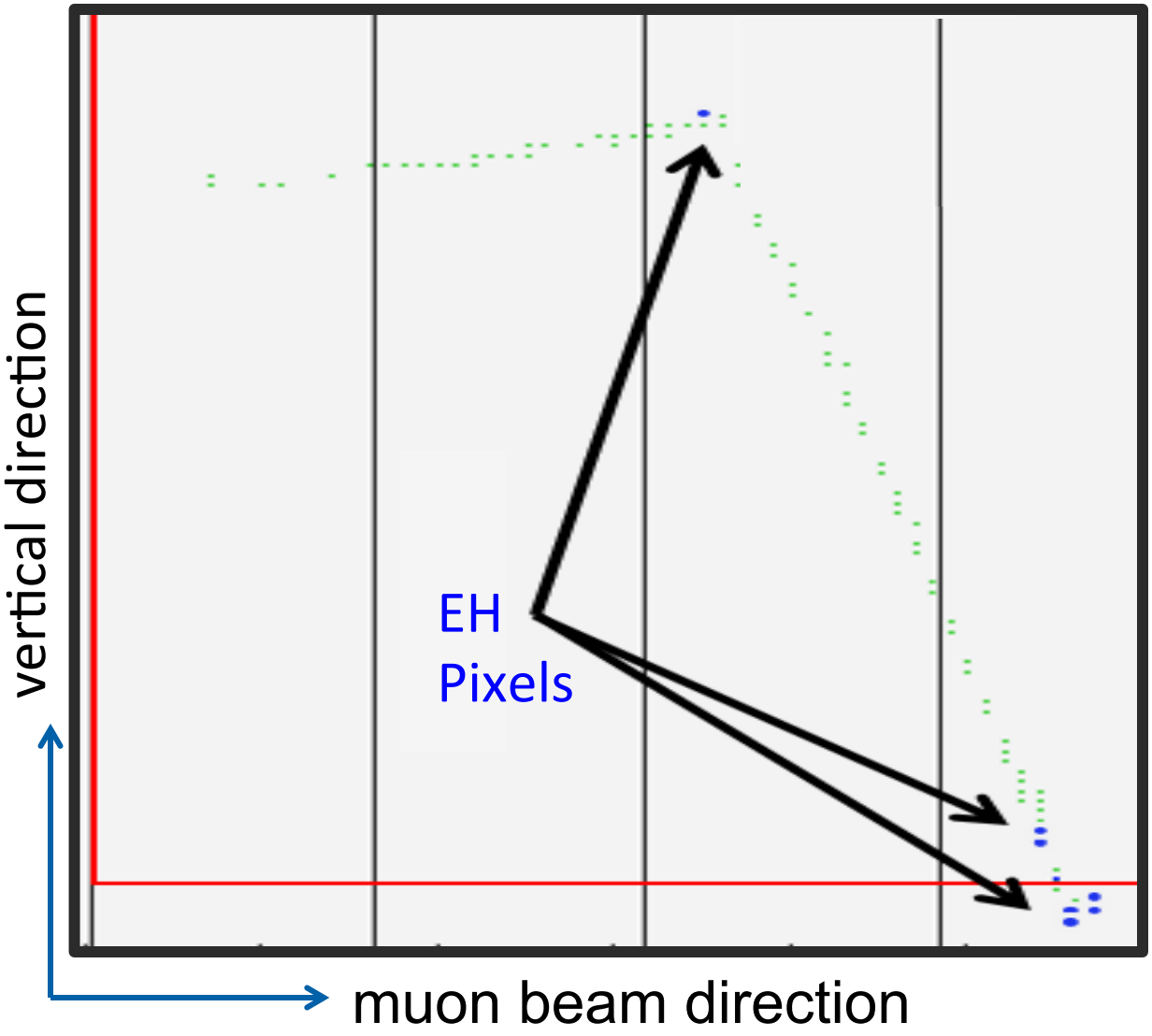

vertical direction
(drift time)
muon beam
direction

Muons that fake a stop in the fiducial volume but actually stop in the surrounding Z > 1 materials have the wrong capture rate



Scatters aren't always obvious

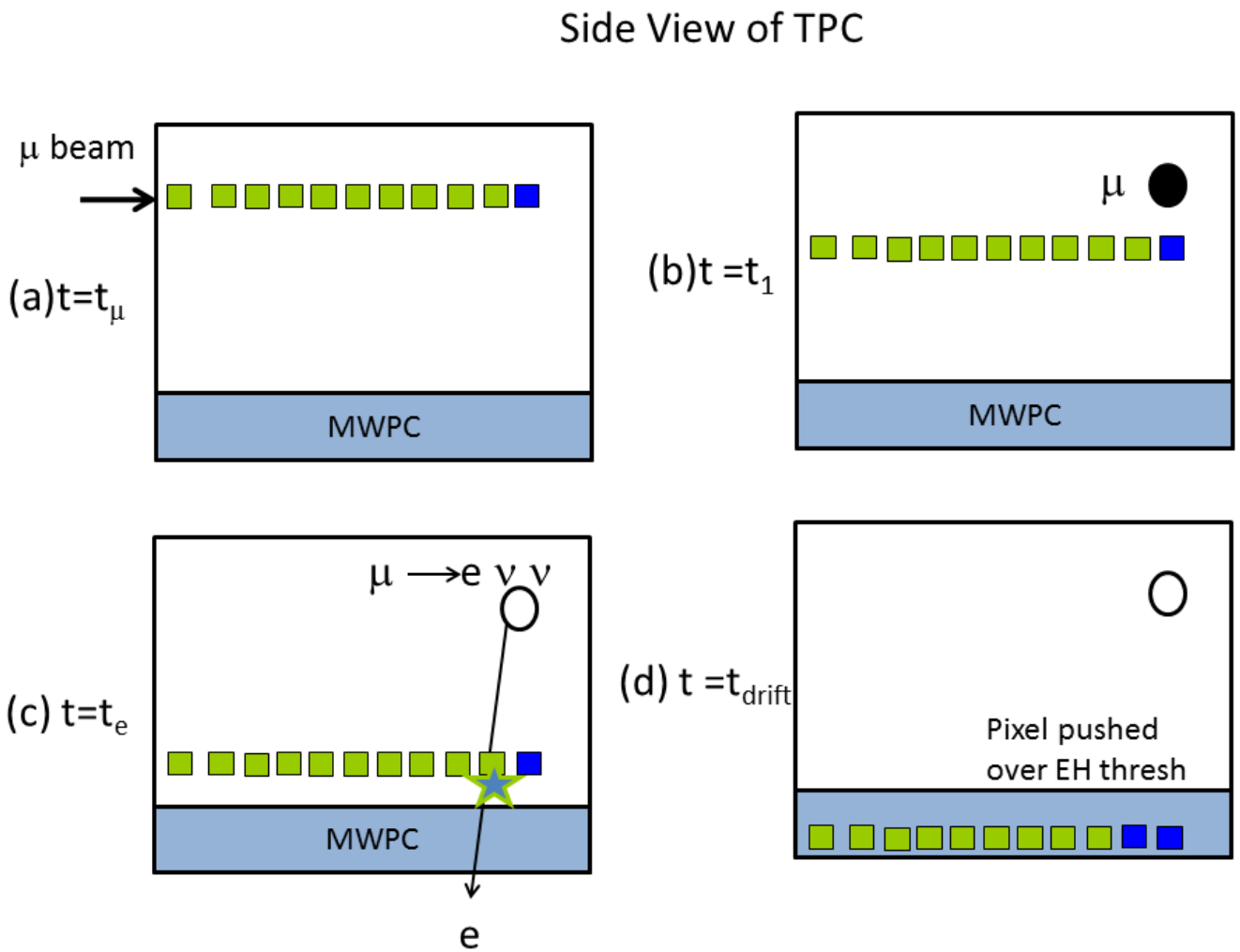
- Recoil proton from scatter
- Deposit energy on 1 anode
- Require > 1 blue pixels to eliminate scatters



Muon leaves the Fiducial Volume

And likely the active volume as well

Energy deposition from decay electrons can modify pixels in a muon track



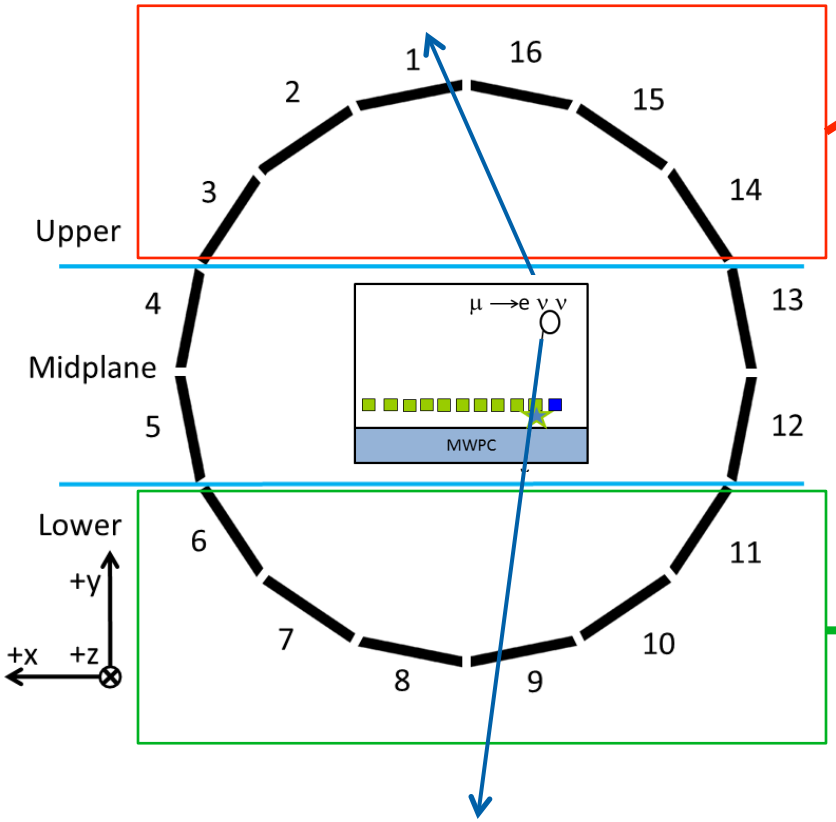
(a) μ enters TPC & Ionizes gas

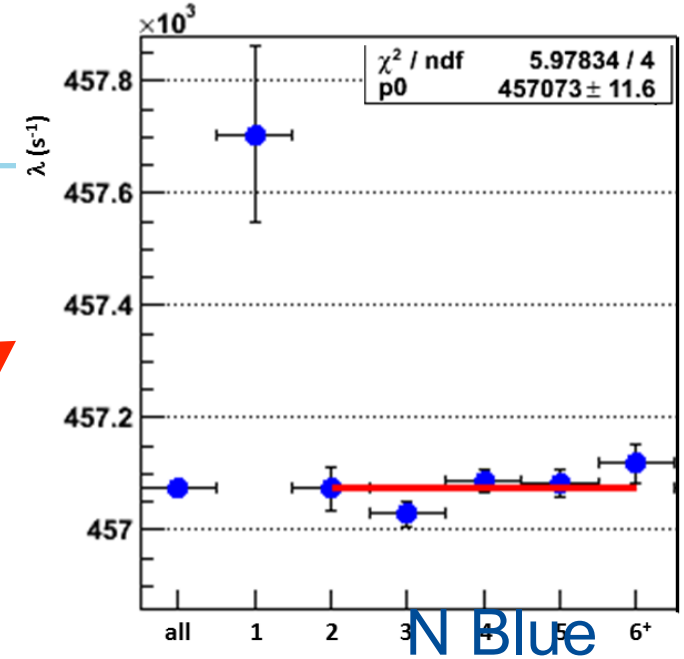
(b) Charge drifts towards MWPC

(c) Decay electron deposits energy

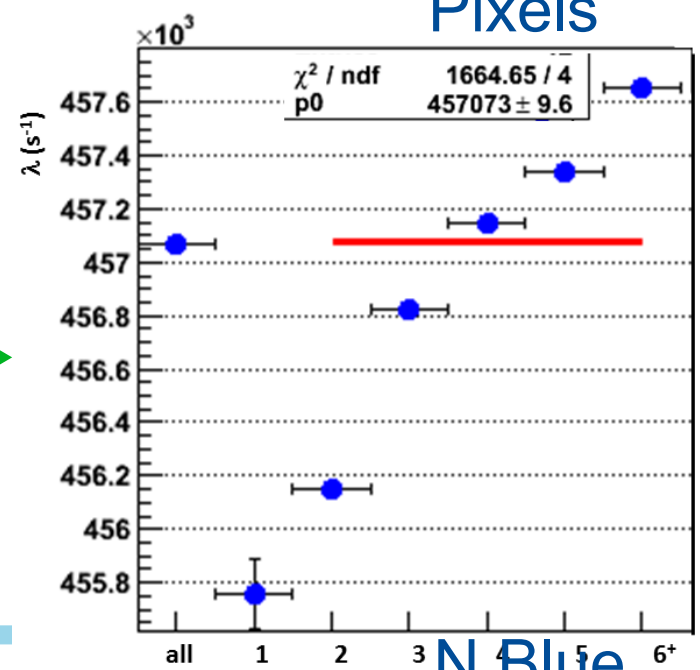
(d) Augments pixels

The interference is time- and space-dependent



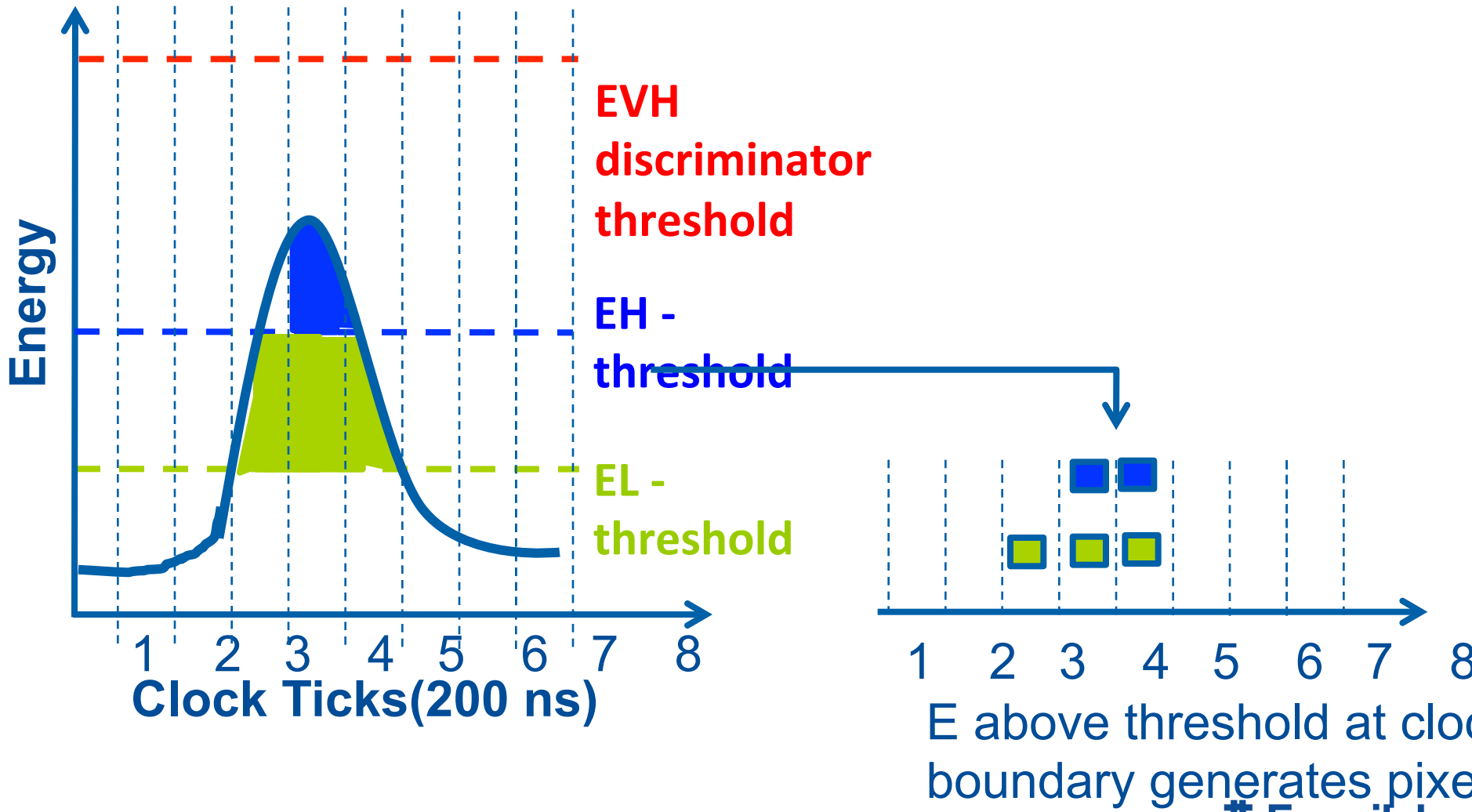


N Blue Pixels



N Blue Pixels

The collection of charge on anode wires generates pulses, which are digitized into pixels



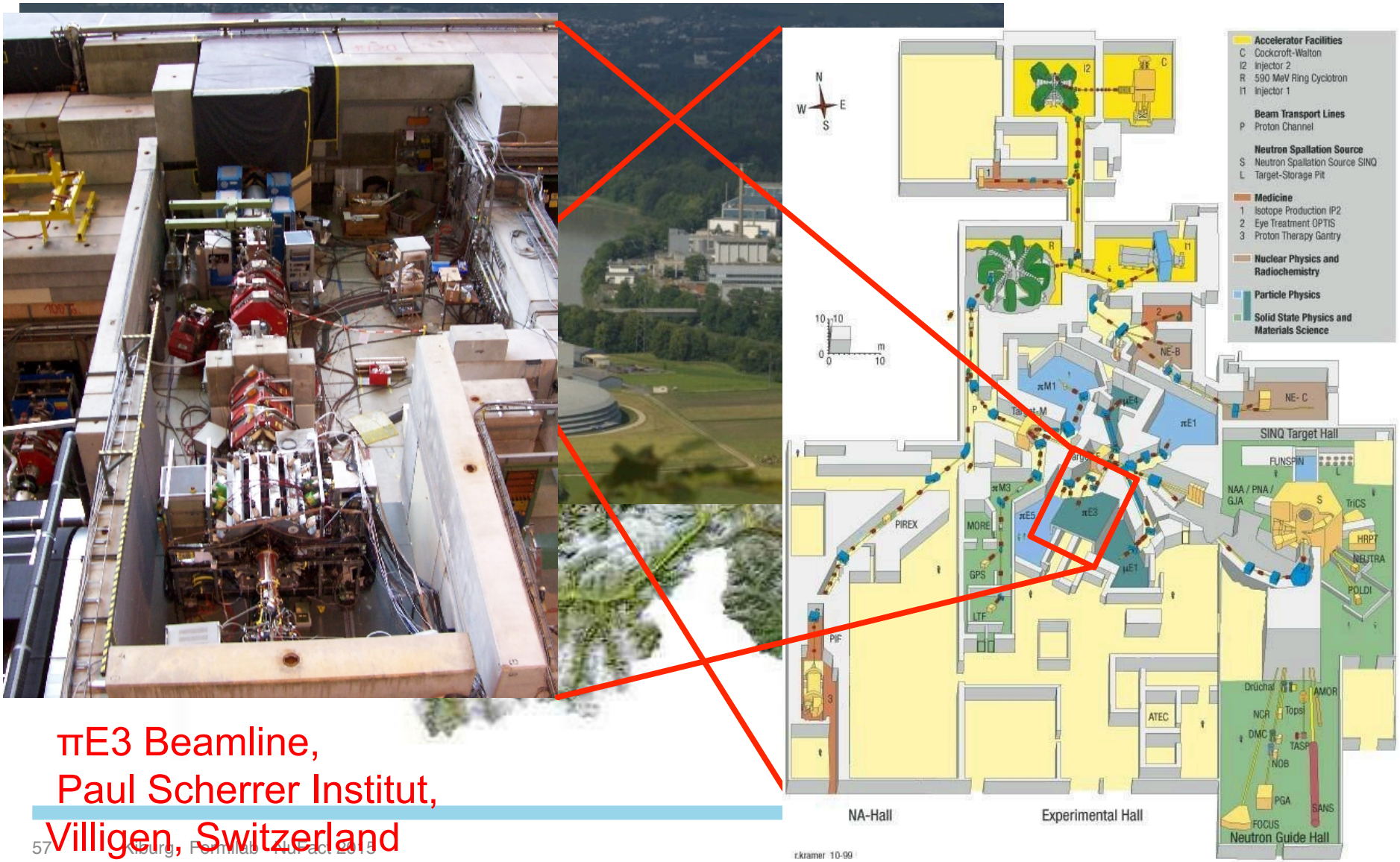
10 times increased statistics

Year	Statistics [10^{10} muon decays]		Comment
	μ-	μ+	
2004	0.16	0.05	published *
2006	0.55	0.16	This talk
2007	0.50	0.40	This talk
Total	**~1.21**	**~0.61**	**~60TB raw data**

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

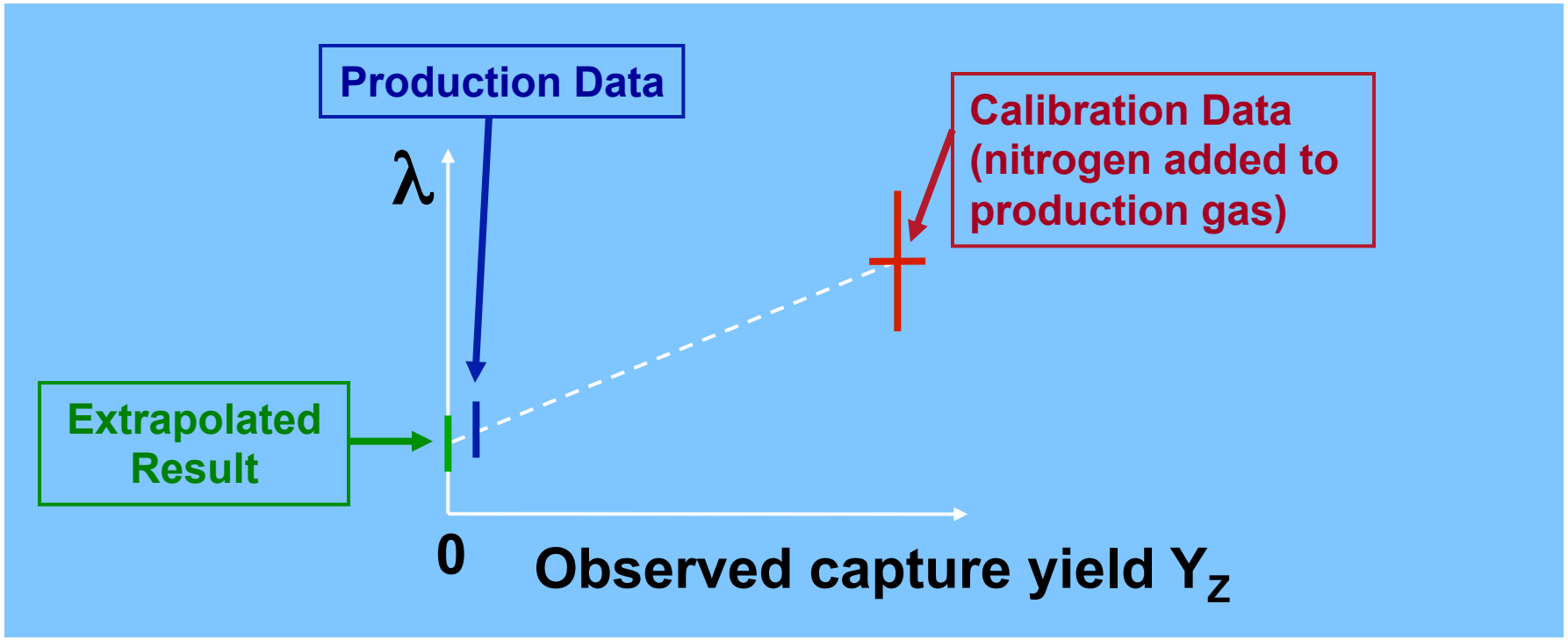
For 10 ppm, we need more than 10^{10} muons ...

- 1.3 MW beam; 2.2 mA, 590 MeV protons



πE3 Beamline,
Paul Scherrer Institut,
Villigen, Switzerland

High-Z Impurity Correction



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

Reinterpreting MuCap results with future gA/gP measurements

$$\Lambda_S^{\mathrm{MuCap}} = 714.9 \pm 5.4_{\mathrm{stat}} \pm 5.1_{\mathrm{syst}}\ \mathrm{s}^{-1}. \quad (8)$$

→ 715.6 after PRC 2015

This new result is in excellent agreement with recent theory [25–27]. From the latest calculation [27], we derive

$$\Lambda_S^{\mathrm{Th}}(g_A, g_P) = (712.7 \pm 3.0 \pm 3.0)\times \left[1 + 0.6265(g_A - g_A^{\mathrm{PDG}}) - 0.0108(g_P - g_P^{\mathrm{Th}})\right]^2\ \mathrm{s}^{-1}, \quad (9)$$

where all form factors are evaluated at q_0^2. Eqn. 9 quantifies the dependence of the theoretical capture rate on the choice of g_P, relative to value $g_P^{\mathrm{Th}} = 8.2$ used in Ref. [27], and on g_A, relative to the latest $g_A^{\mathrm{PDG}}(0) = 1.2701 \pm 0.0025$ [5]. The two uncertainties in the equation stem from limited knowledge of g_A and radiative corrections. Setting $\Lambda_S^{\mathrm{Th}}(g_A^{\mathrm{PDG}}, g_P^{\mathrm{MuCap}})$ to $\Lambda_S^{\mathrm{MuCap}}$ gives

→ 1.2723 after PDG 2014

$$g_P^{\mathrm{MuCap}}(q_0^2 = -0.88\, m_\mu^2) = 8.06 \pm 0.48 \pm 0.28, \quad (10)$$

→ 8.14 re-extracted