ПРЕЦИЗИОННОЕ ИЗМЕРЕНИЕ СКОРОСТИ ЗАХВАТА МЮОНА В ВОДОРОДЕ И ОПРЕДЕЛЕНИЕ ПСЕВДОСКАЛЯРНОГО ФОРМ ФАКТОРА ПРОТОНА g_P

PNPI participants in MuCAP collaboration*) :

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Precision Measurement of Muon Capture on the Proton

“μCap experiment”

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

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

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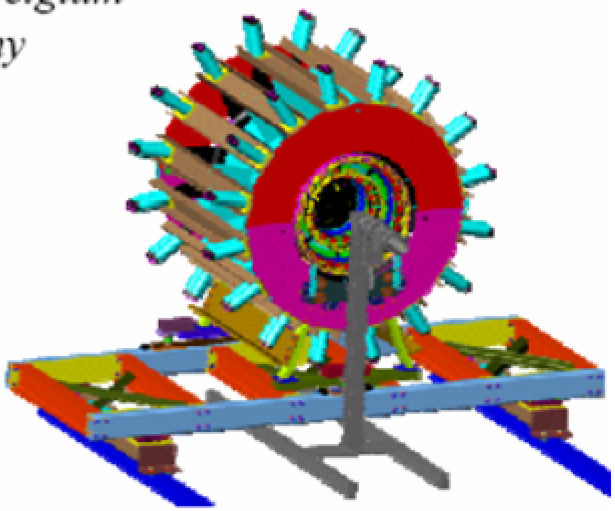


@ PSI

Исследования на мюонном канале Швейцарской мезонной фабрики

Мюонный катализ ядерного

dd- и dt- синтеза.

Мюонный захват легкими ядрами:

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

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

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

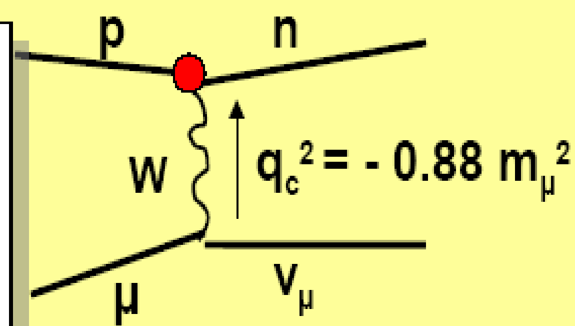
Muon Capture on Proton

$$\mu^- + p \rightarrow (\mu^- p)_{1S} \xrightarrow{\Lambda_S} \nu_\mu + n \qquad BR=0.16\%$$

MuCap goal: to measure μp-capture rate Λ_S with 1% (or better) precision

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

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



μp-capture offers a unique probe of the nucleon's electroweak axial structure

Стандартная Модель и структура нуклонов

$$g_V = 0.9755 \pm 0.0005$$

$$g_a = 1.245 \pm 0.003$$

$$g_m = 3.582 \pm 0.003$$

$$g_P(th) = 8.26 \pm 0.23$$

$$g_P(OMC) = 6 - 12$$

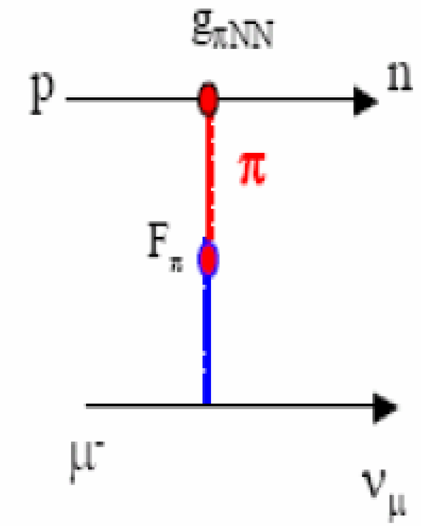
$$g_P(RMC) = 12.2 \pm 0.9 \pm 0.4$$

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:

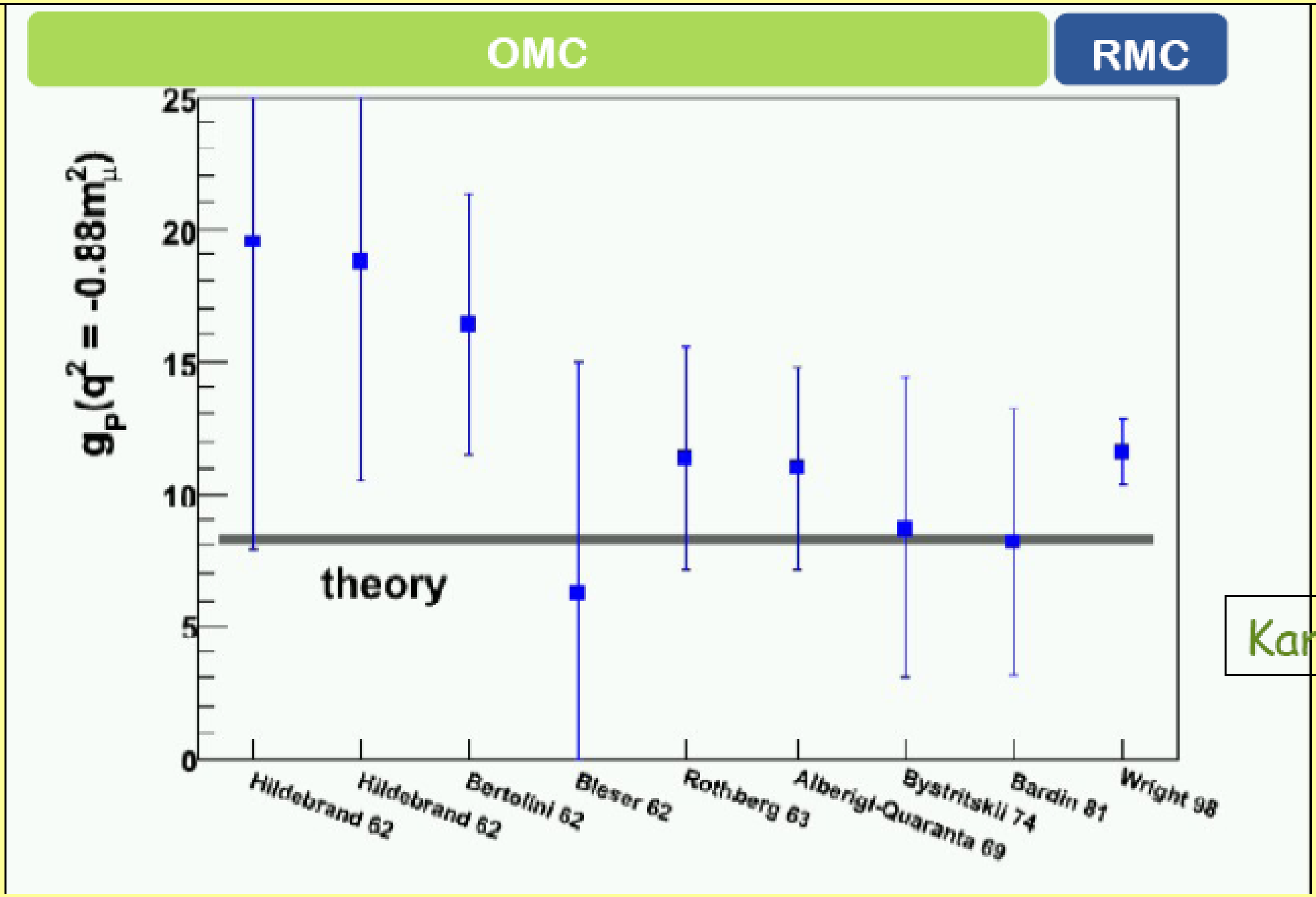
$$g_P(q^2) = \frac{2 m_\mu g_{\pi NN} F_\pi}{m_\pi^2 - q^2} - \frac{1}{3}\, g_A(0) m_\mu M\, r_A^2$$

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

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

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

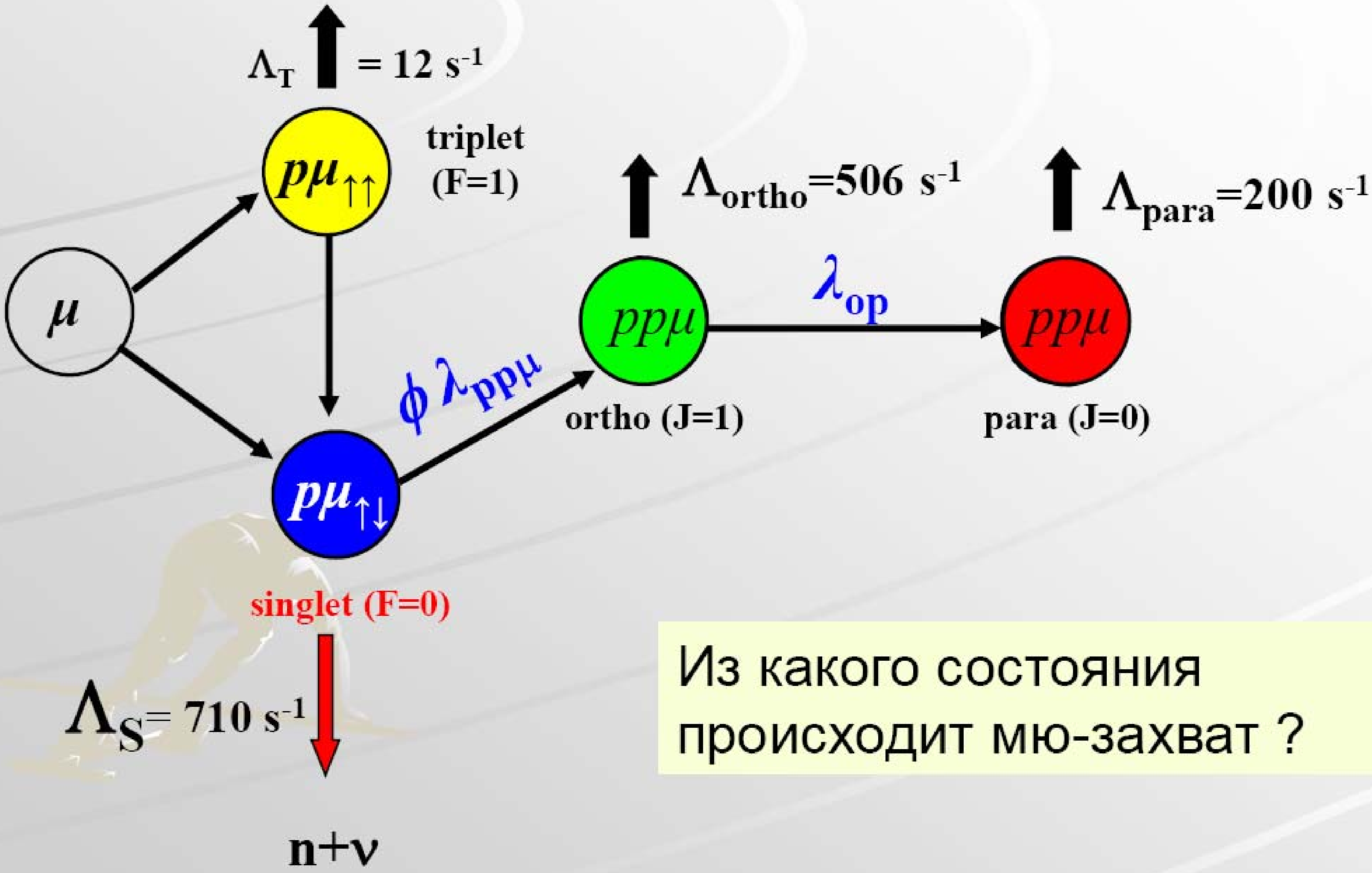
50 years of effort to determine gP



Kammel&Kubod

" Radiative muon capture in hydrogen was carried out only recently with the result that the derived *gP* was almost 50% too high. If this result is correct, it would be a sign of new physics... "

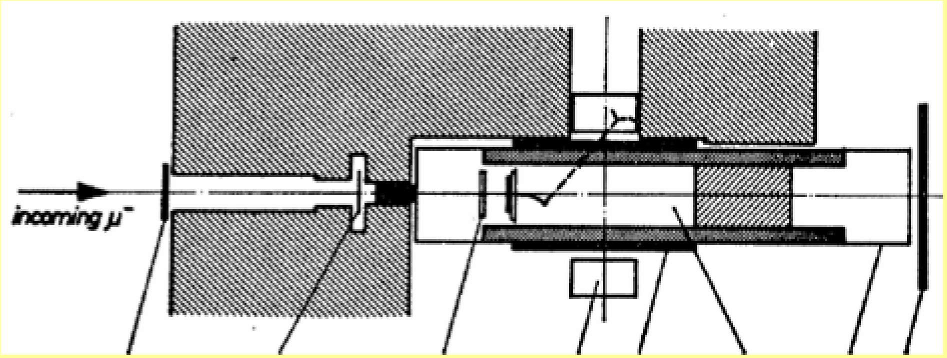
— *Lincoln Wolfenstein (Ann.ReNucl.Part.Sci. 2003)*



Из какого состояния происходит мю-захват ?

Pioneers of muon capture experiments

Emilio Zavattini 1927-2007



1969 Bologna-Pisa-CERN

H2 –target 8 atm

g_p = 11.0 ± 3.8

1973 Dubna group

H2 –target 41 atm

g_p =8.7 ± 5.7

Expt. Problems

- Wall effects
- Background
- Neutron detection efficiency

Стратегия эксперимента MuCap

- H2 газовая мишень 10 atm

$(\mu^{-}p)_{1S}$

- Имеряется время жизни мюона $\Lambda_S = 1/\tau_{\mu+} - 1/\tau_{\mu-}$

10^{-5} точность для μ^{-} and для $\mu+$

$\rightarrow \delta\Lambda_S/\Lambda_S = 1\%$

$>10^{10}$ распадов мюона

Высокая скорость набора

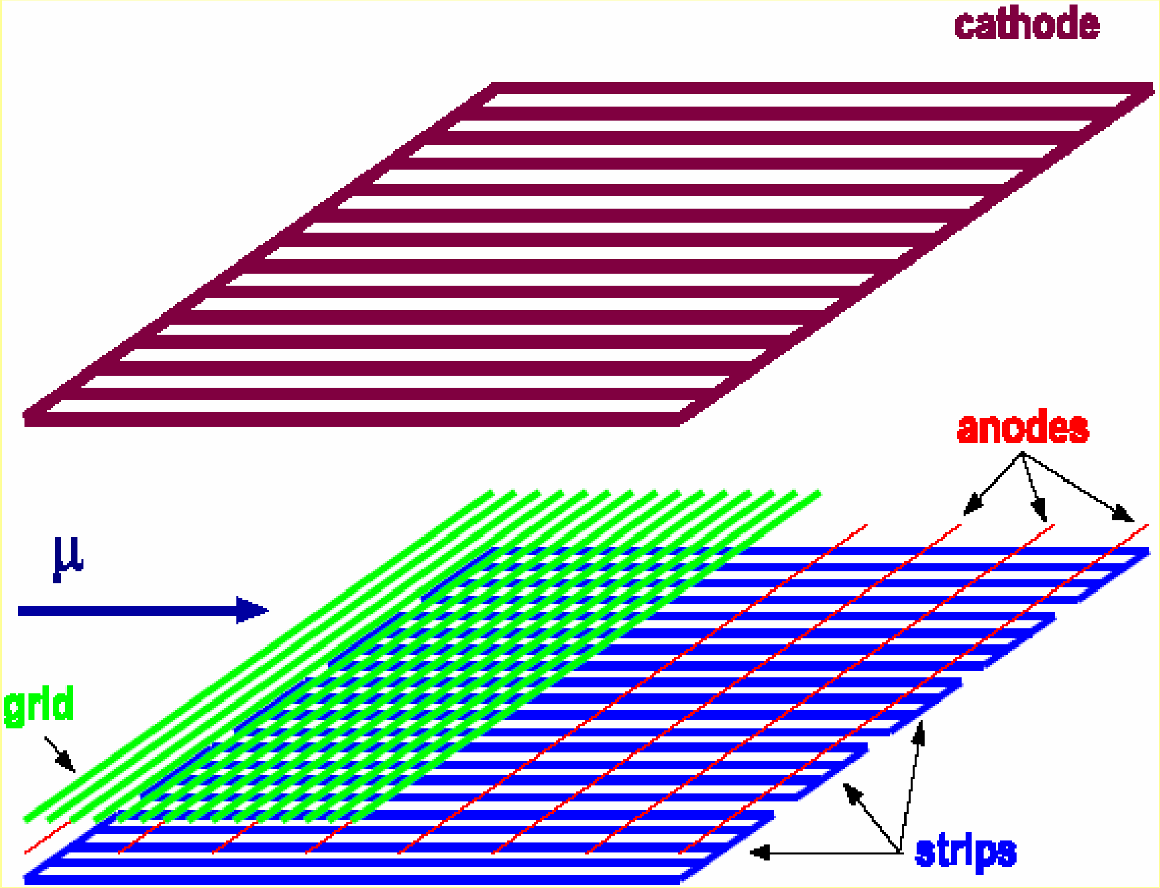
- Надежное выделение точки остановки мюона

Нет стеночных эффектов

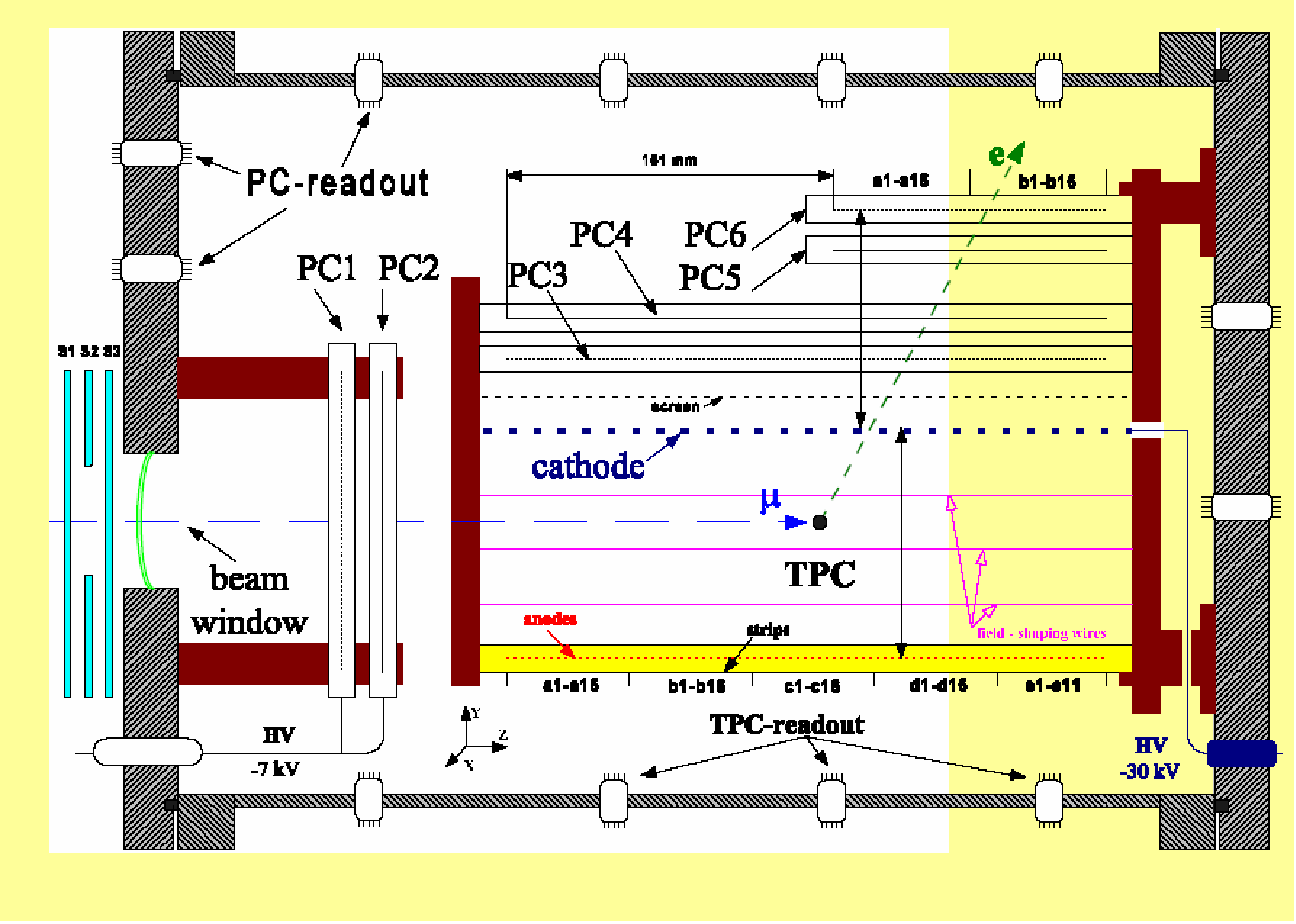
- Низкий уровень фона

$< 10^{-4}$

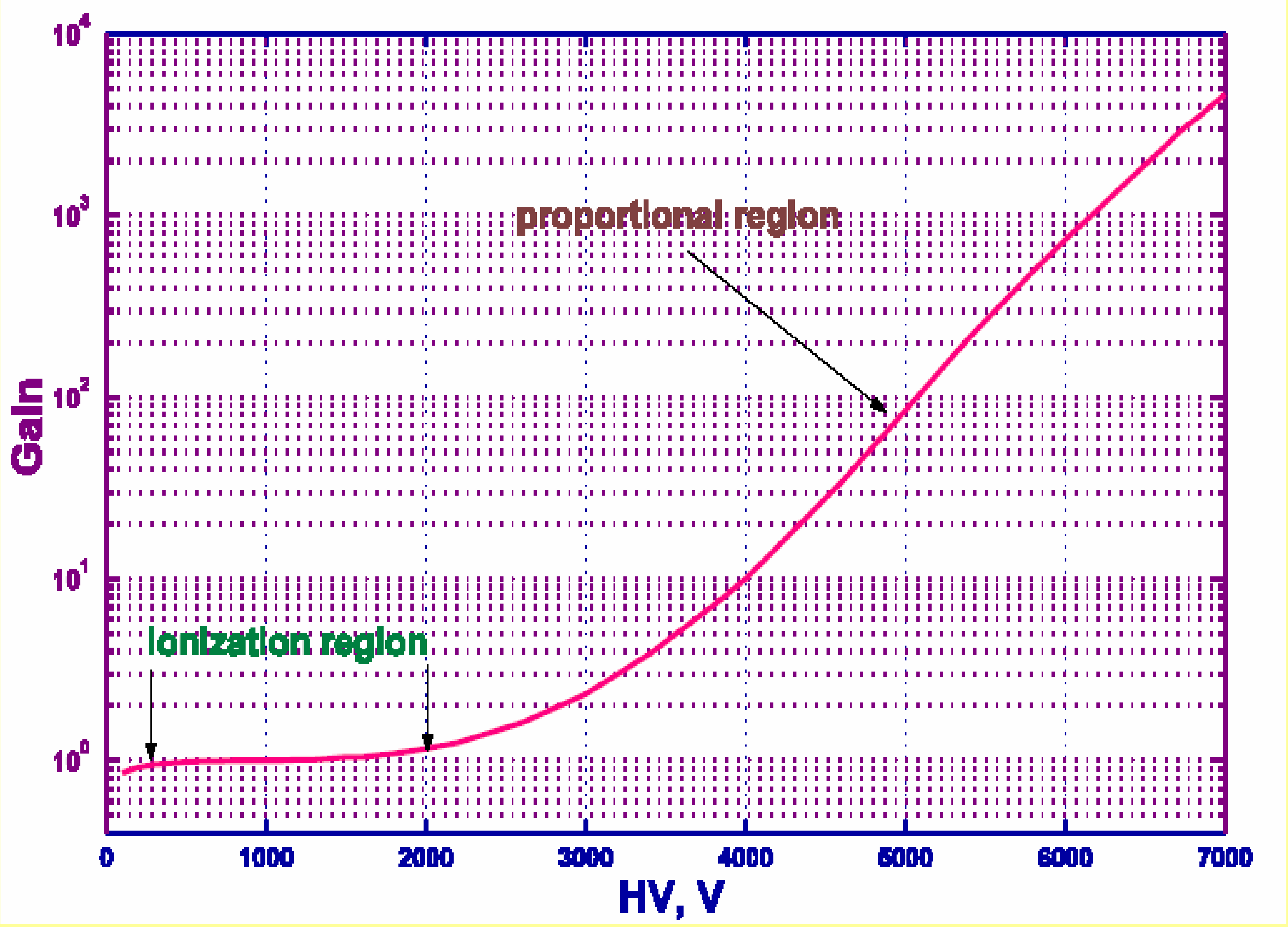
Schematic view of the TPC



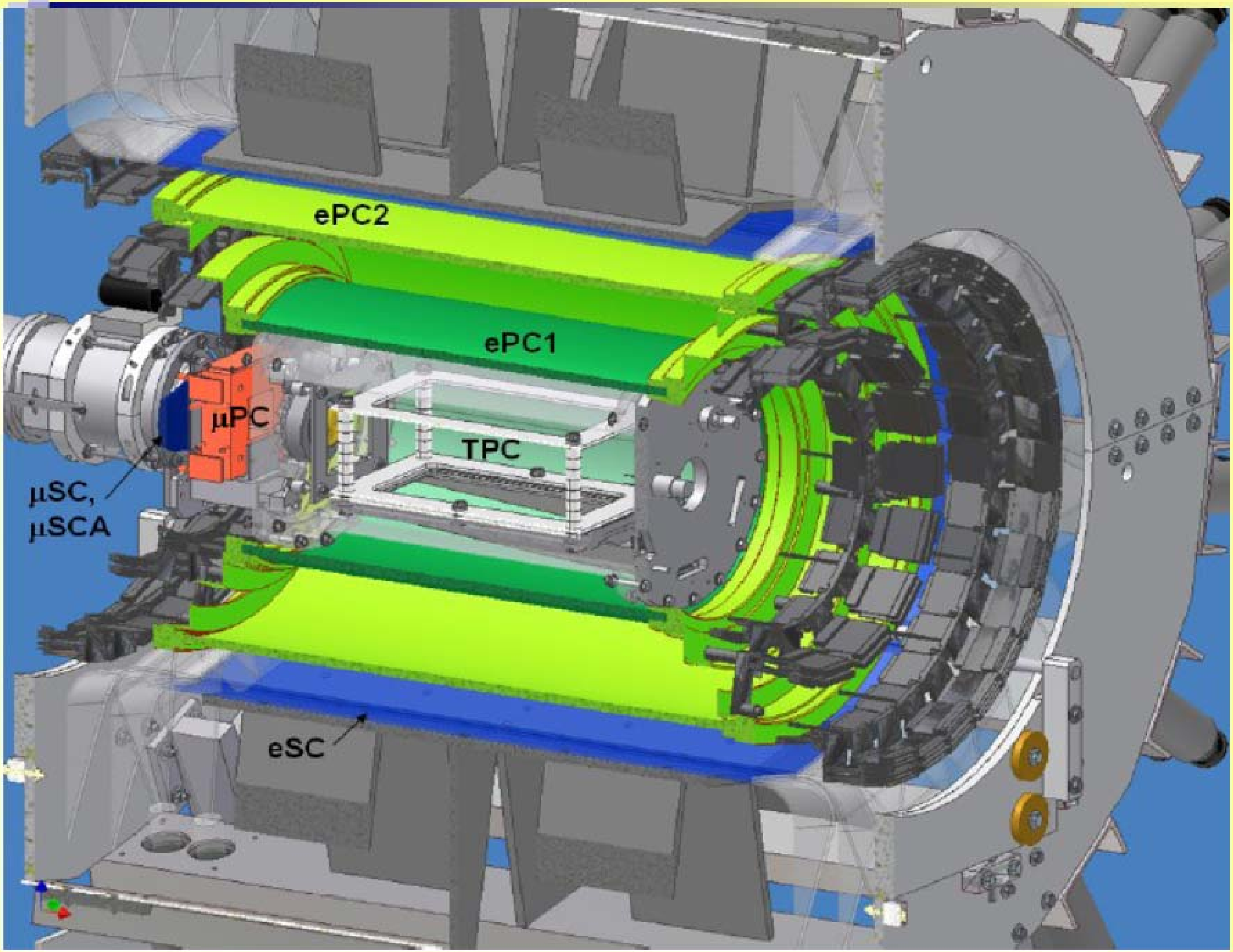
The trajectories of charged particles are measured in 3D space with resolution (rms) 1-2 mm.

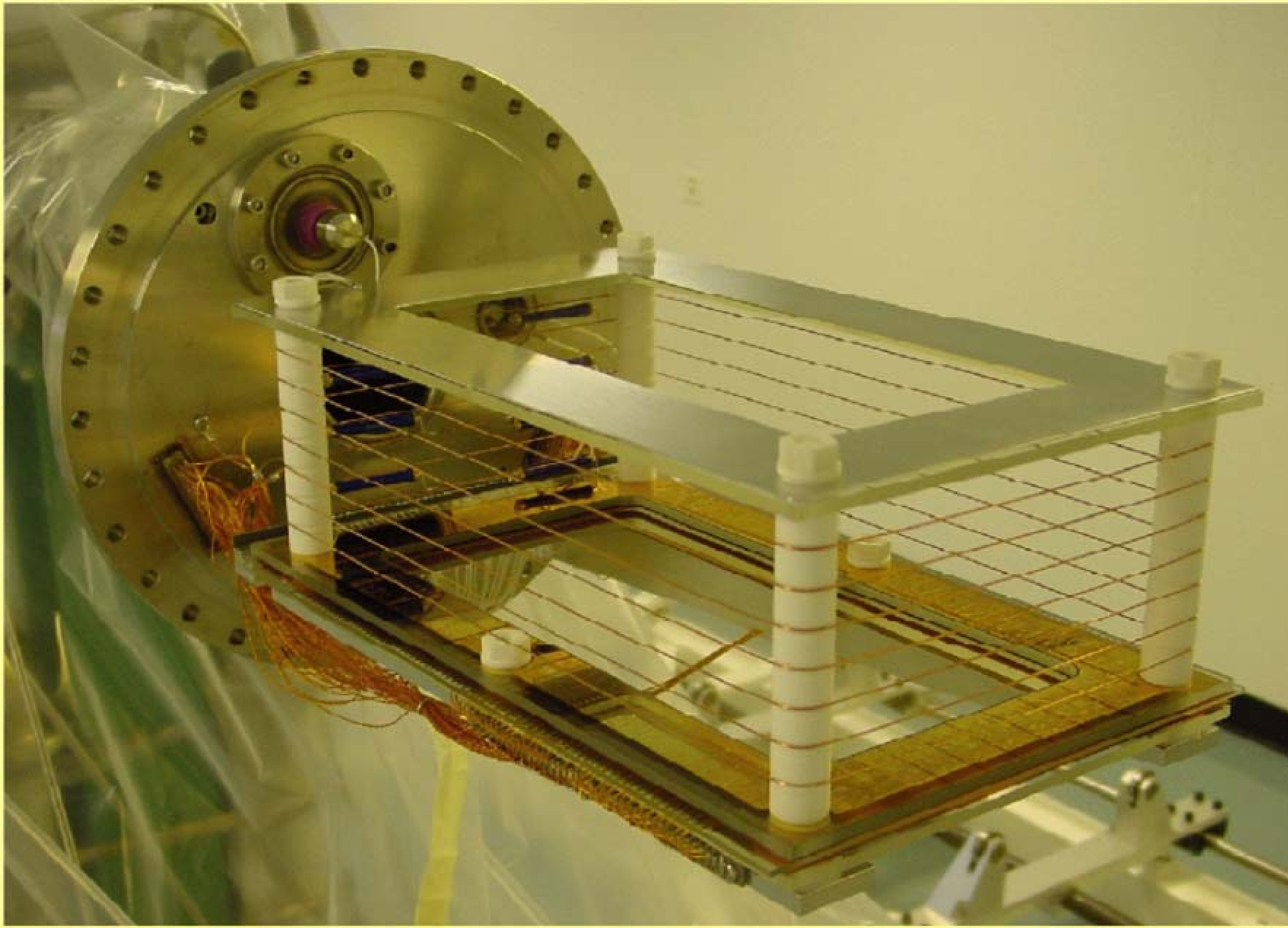


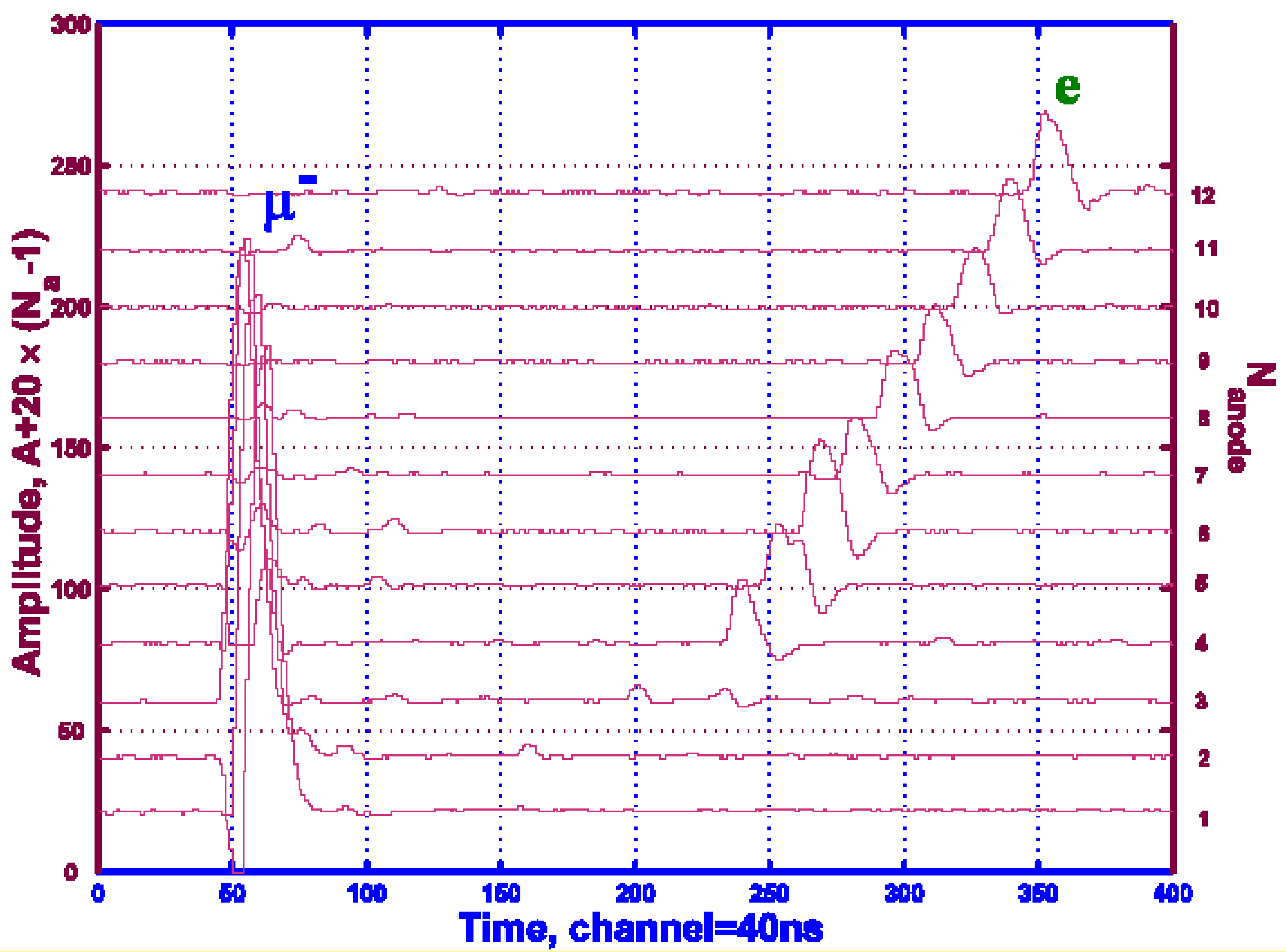
PC-readout
PC1
PC2
PC3
PC4
PC5
PC6
a1-a16
b1-b16
screen
cathode
μ
e
TPC
beam
window
anodes
strips
field - shaping wires
a1-a16
b1-b16
c1-c16
d1-d16
e1-e11
TPC-readout
HV
-7 kV
HV
-30 kV
S1 S2 S3
Y
Z
X



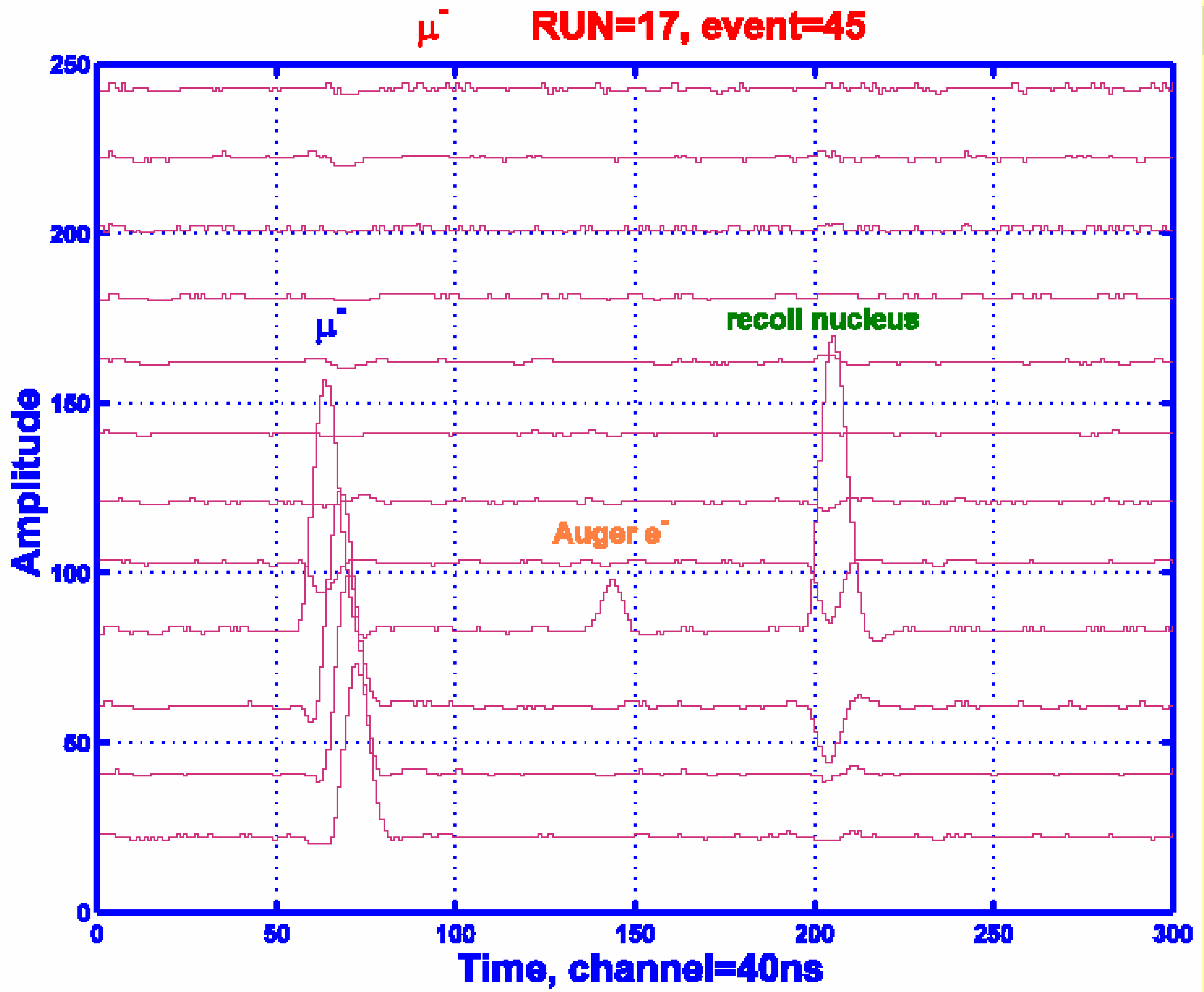
Gain
10^4
10^3
10^2
10^1
10^0
proportional region
Ionization region
0
1000
2000
3000
4000
5000
6000
7000
HV, V


ePC2
ePC1
μPC
TPC
μSC,
μSCA
eSC

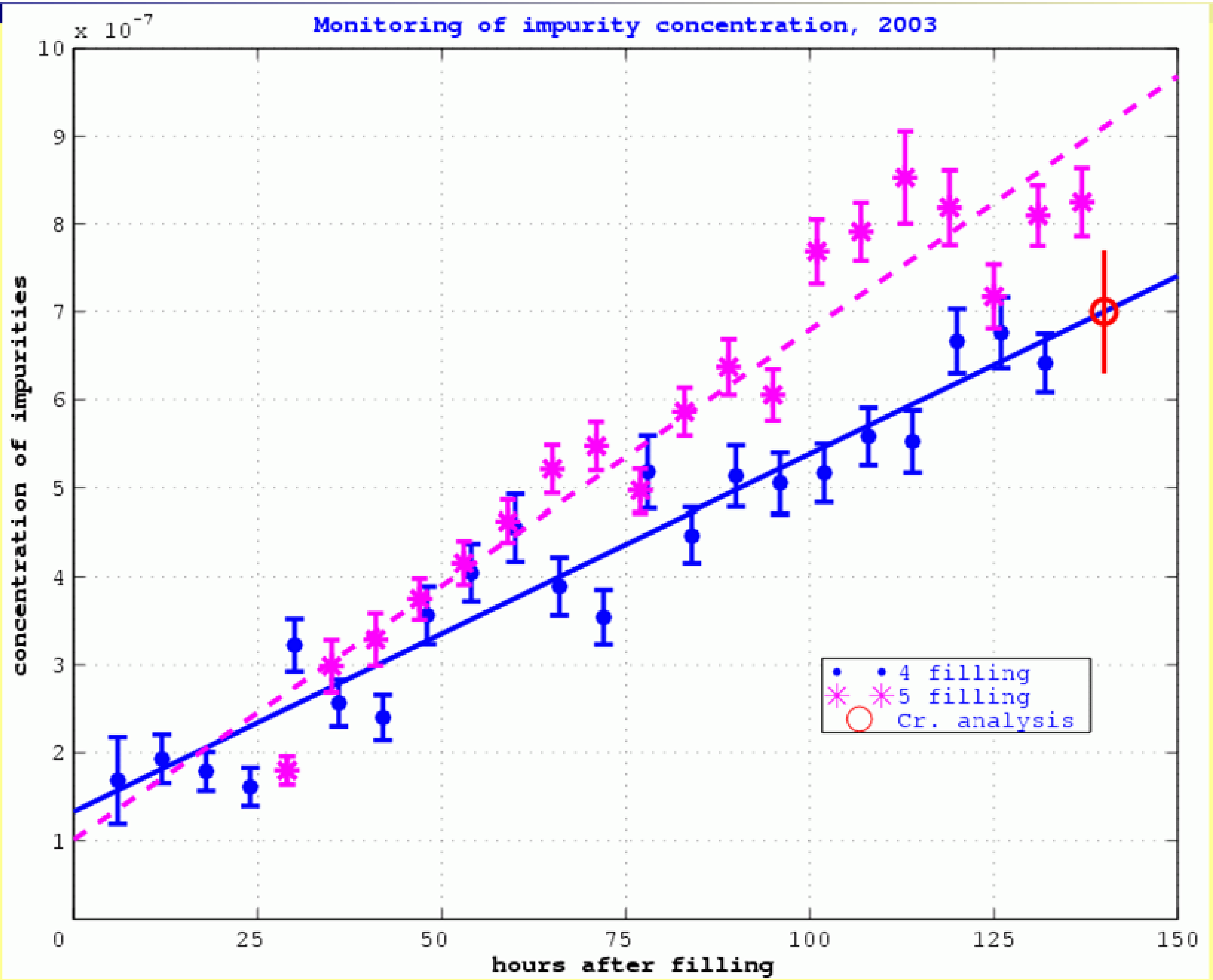




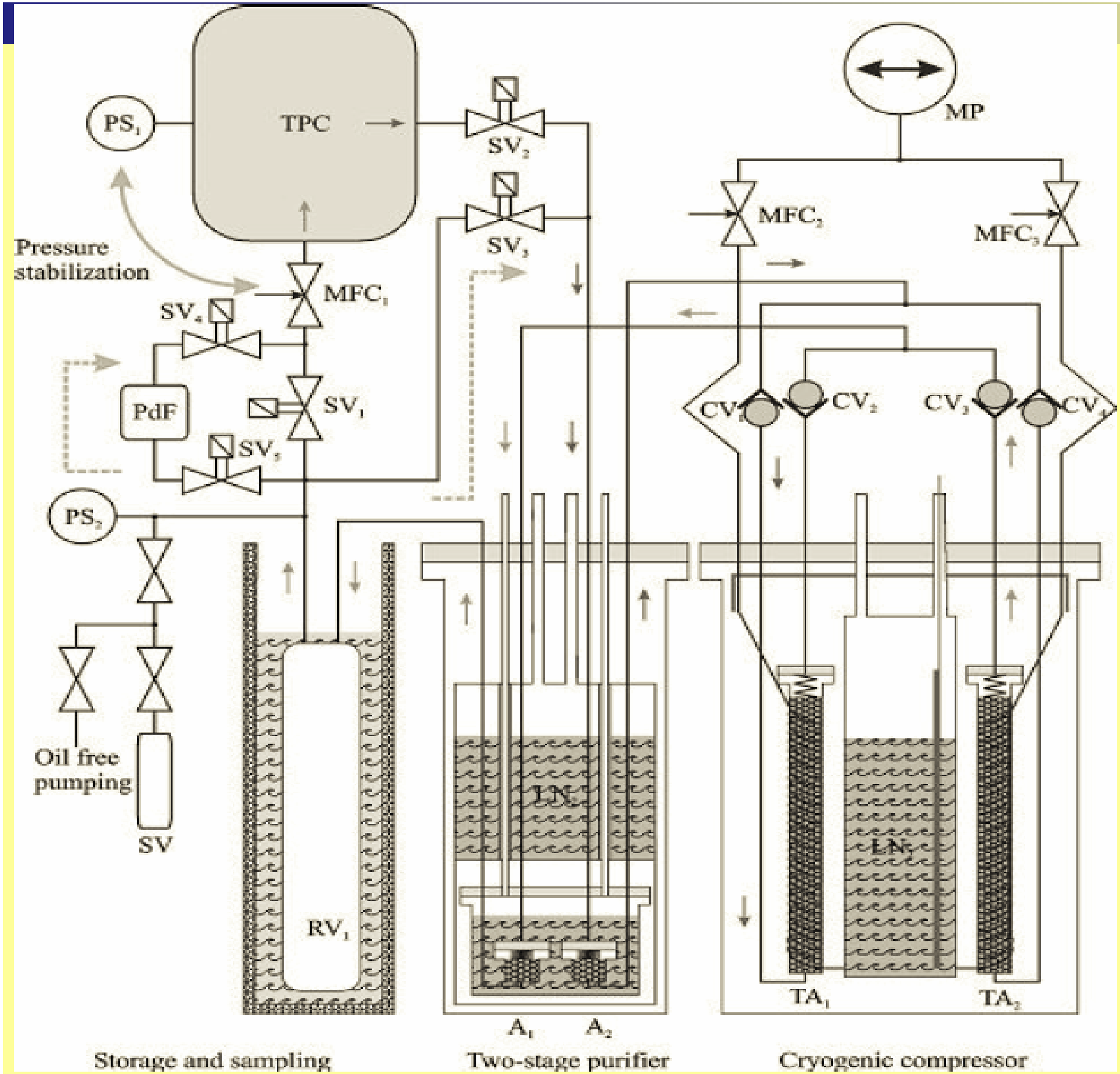
The signal on TPC anode wires from μ-e decay event



Display of a typical event with μ-capture reaction on impurity

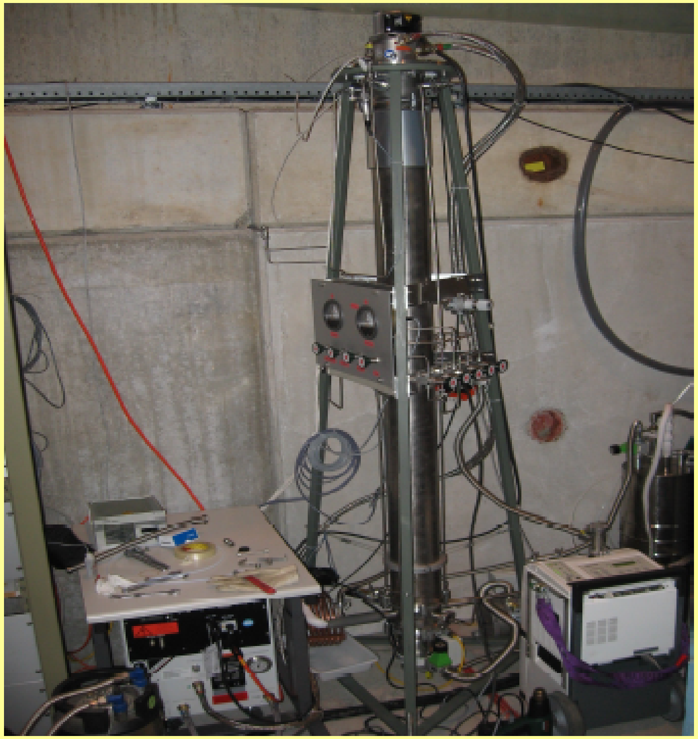


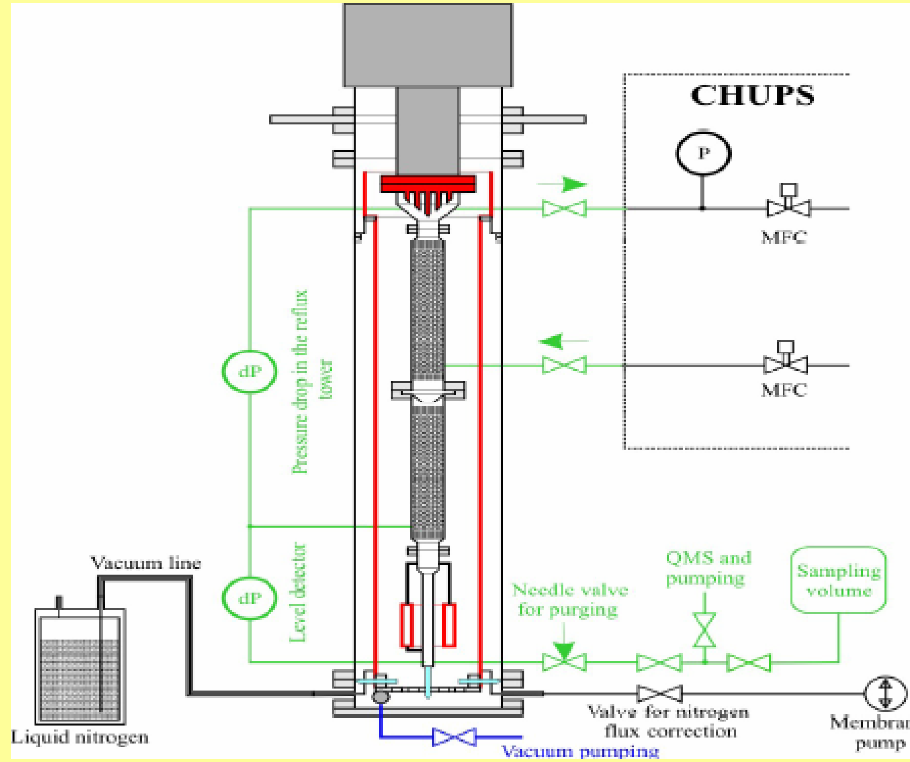
Monitoring of impurity concentration, 2003
x 10^-7
10
9
8
7
6
5
4
3
2
1
0
25
50
75
100
125
150
concentration of impurities
hours after filling
4 filling
5 filling
Cr. analysis



TPC
PS1
PS2
SV2
SV3
MFC1
SV4
SV1
SV5
PdF
Pressure stabilization
MP
MFC2
MFC3
CV1
CV2
CV3
CV4
LN2
RV1
Oil free pumping
SV
A1
A2
TA1
TA2
Storage and sampling
Two-stage purifier
Cryogenic compressor

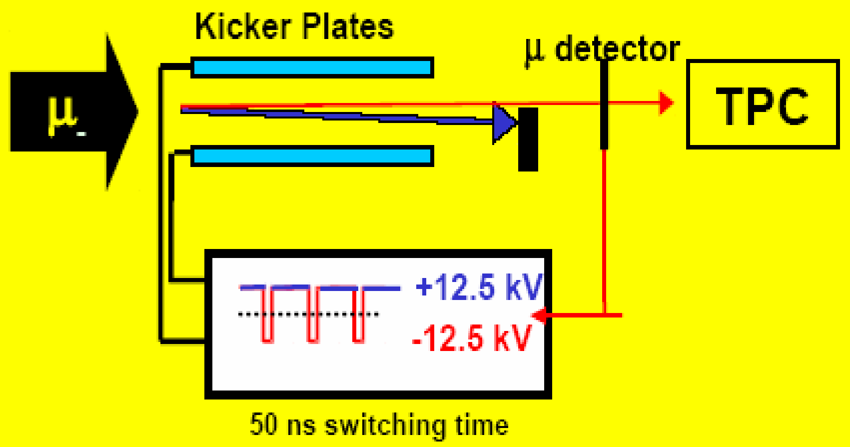
IV. the new protium isotope separation facility: production of ultra-depleted protium

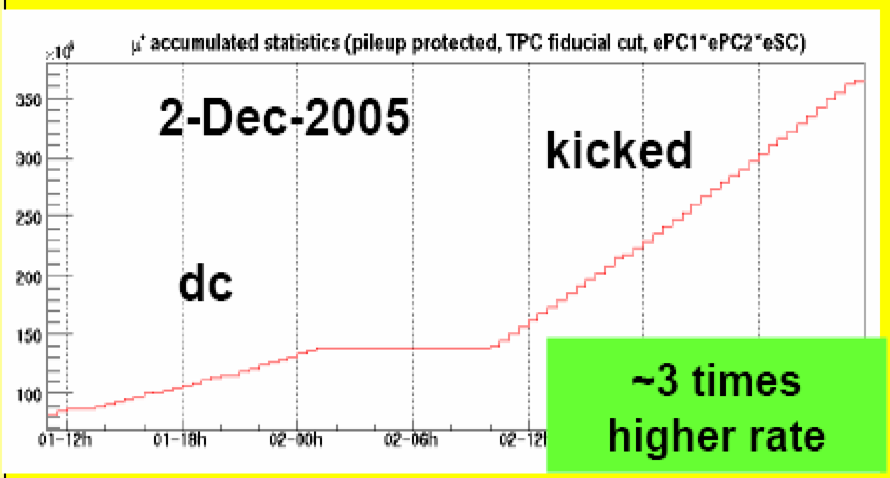




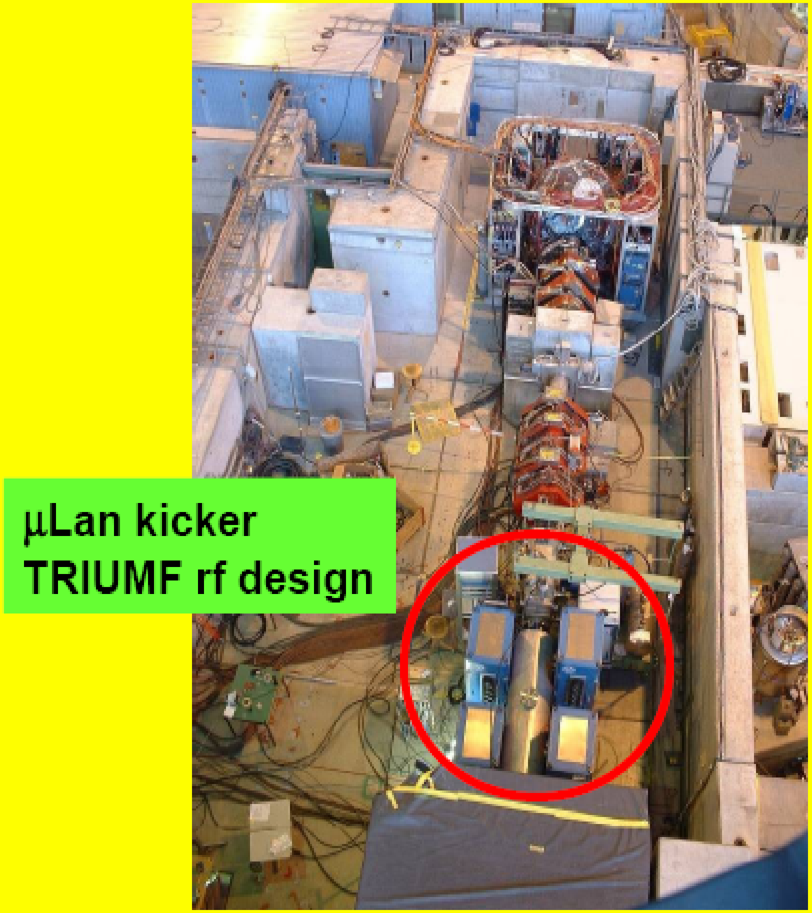
1) Cd = 1440 ppb (2004)
2) Cd < 60 ppb (2006)
3) Cd < 6 ppb (2007)

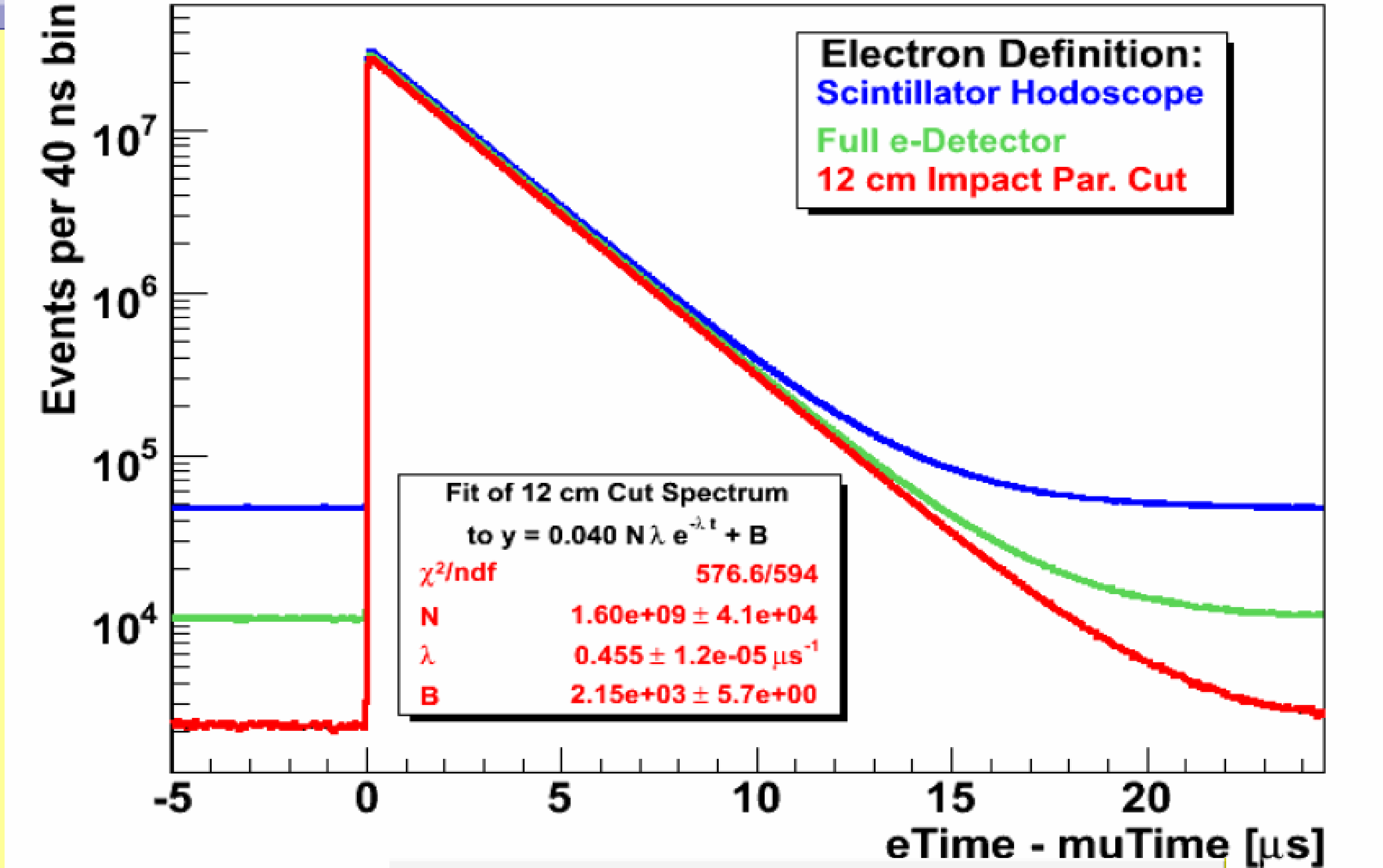
■ Muon-On-Demand concept



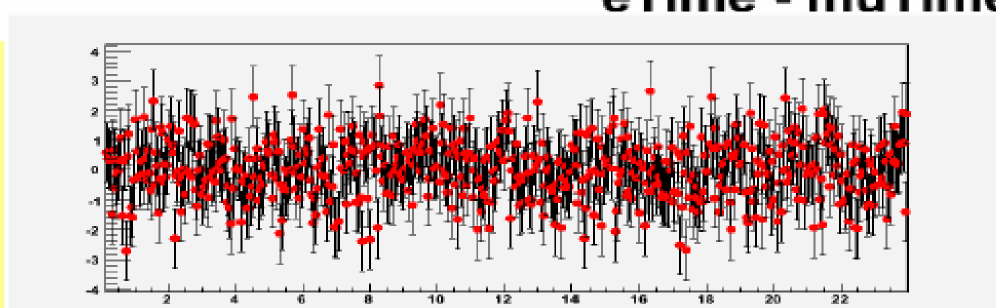


■ Beamline





Normalized residuals



Общая набранная статистика

Год	μ+ (10^9)	μ- (10^9)	Cd(ppb)	H_2O(ppb)
2004	0.2	2.0	~1400	~70
2005	1.4	3.5	~1400	36
2006	1.56	8.6	<60	18
2007	5.4	6.0	<6	8.7

TABLE: Applied corrections and systematic errors.

Effect	Corrections and uncertainties [s-1] R06	R07
Z > 1 impurities	7.8 + - 1.9	4.5 + - 0.9
mu-p scatter removal	12.4 + - 3.2	7.2 + - 1.3
mu-p diffusion	3.1 + - 0.1	3.0 + - 0.1
mu-d diffusion	+ - 0.7	+ - 0.1
Fiducial volume cut	+ - 3.0	+ - 3.0
Entrance counter ineff.	+ - 0.5	+ - 0.5
Electron track def.	+ - 1.8	+ - 1.8
Total corr. $\lambda_{\mu-}$	23.3 + - 5.2	14.7 + - 3.9
mup bound state ($D_{\mu p}$)	12.3 + - 0.0	12.3 + - 0.0
ppmu states ($D_{pp\mu}$)	17.7 + - 1.9	17.7 + - 1.9

Результаты анализа данных за 2004-2007 год

$N_{\mu^-} = 1.2 \times 10^{10}$

$\lambda_{\mu^-} = 455851.4 \pm 12.5\text{stat} \pm 8.5\text{syst}\ \ s^{-1}$ **(MuCAP 2004).**

$\lambda_{\mu^-} = 455857.3 \pm 7.7\text{stat} \pm 5.1\text{syst}\ \ s^{-1}$ **(MuCAP 2006).**

$\lambda_{\mu^-} = 455853.1 \pm 8.3\text{stat} \pm 3.9\text{syst}\ \ s^{-1}$ **(MuCAP 2007).**

Muon Capture Rate λ_s

$$\lambda_s = \lambda_{\mu-} - (\lambda_{\mu+} - D_{\mu p}) + D_{pp\mu}$$

$D_{\mu p} = 12.3\ s^{-1}$ (μp bound state)

$D_{pp\mu} = 17.7\ s^{-1}$ ($\lambda_{pp\mu} = (1.94 \pm 0.06)\ \mu s^{-1}$)

Результаты анализа данных за 2004-2007 год

$$\lambda_{\mu+} = 455170.05 \pm 0.46\ s^{-1}$$ (μLAN experiment)

$$\lambda_{\mu-} = 455854.9 \pm 5.4stat \pm 4.7syst\ \ s^{-1}$$ (MuCap 2004-2007)

$$\Lambda_S^{MuCap}(aver.) = 714.9 \pm 5.4stat \pm 5.3syst\ \ s^{-1}$$

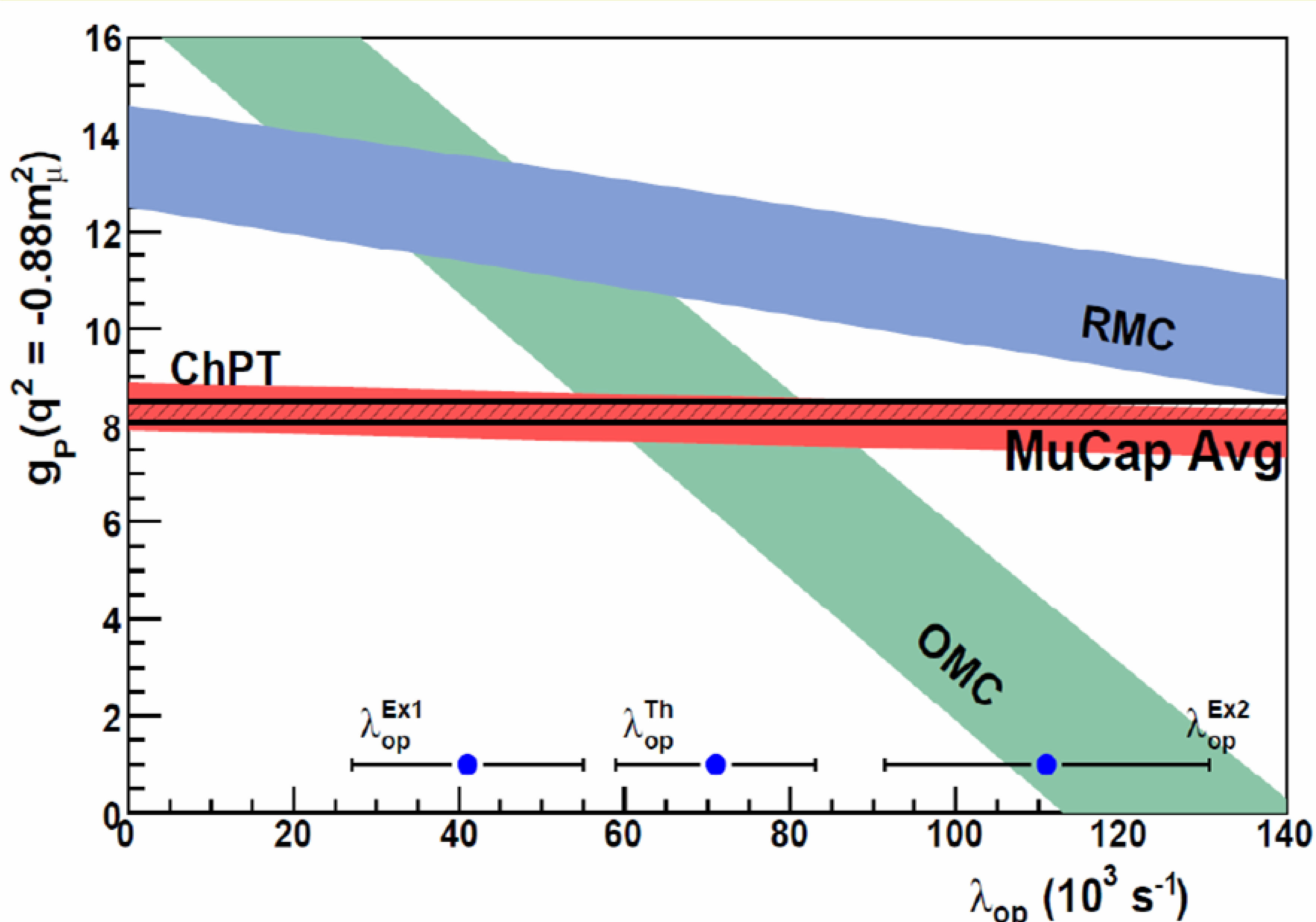
$$\Lambda_S^{Th} = 693.3\ s^{-1}(aver.) + 19.4 s^{-1}(r.c.) = 712.7 \pm 3.0 \pm 3.0\ s^{-1}$$

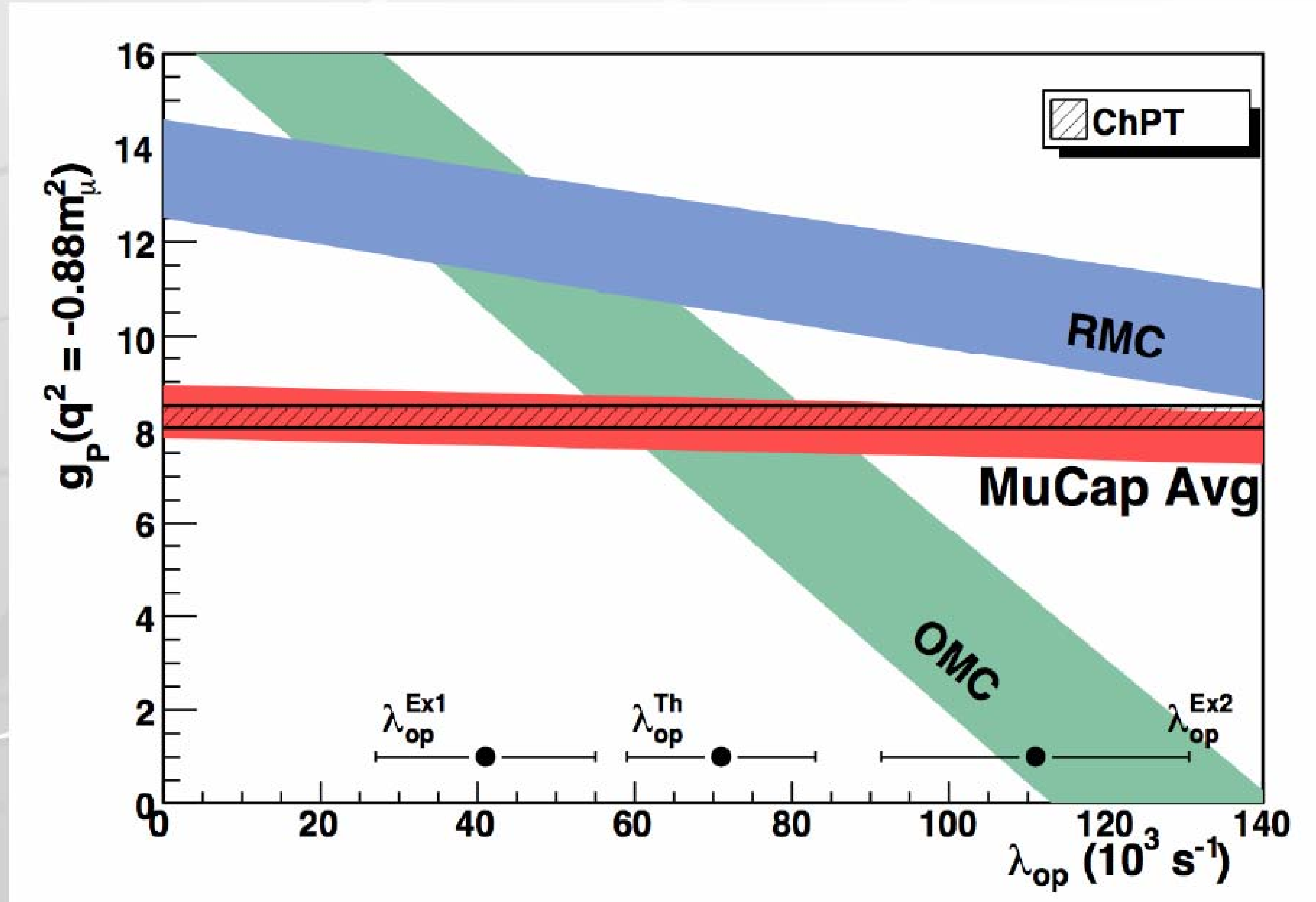
$$g_P^{MuCap} = g_P^{Th} - 0.065 \times (\Lambda_S^{MuCap} - \Lambda_S^{Th})$$

$$g_P^{MuCap} = 8.06 \pm 0.48(exp) \pm 0.28(th)$$

$$g_P^{Th} = 8.2 \pm 0.2\ (2.8\%)$$

Precise and unambiguous MuCap result solves longstanding puzzle





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

Earlier, in 1998, we have studied the muon capture on ^3He. The muon capture rate in the channel $\mu^- + {}^3He \rightarrow {}^3H + \nu_\mu$ was measured with high precision :

$$\Lambda_c = 1496.0 \pm 4.0\ s^{-1}\ (0.3\%)\ .$$

This result have been used in some theoretical analyses :
L.E. Marcucci et al. (2012) [1] and D. Gazit(2009) [2]
for deriving the Λ_c and the proton's pseudoscalar form factor g_P.

$$\Lambda_c = 1494 \pm 21 s^{-1}\ [1]\ \text{and}\ \ \Lambda_c = 1499 \pm 12\ s^{-1}\ ([2].$$

$$g_P = 8.13 \pm 0.6\ \ [2]$$

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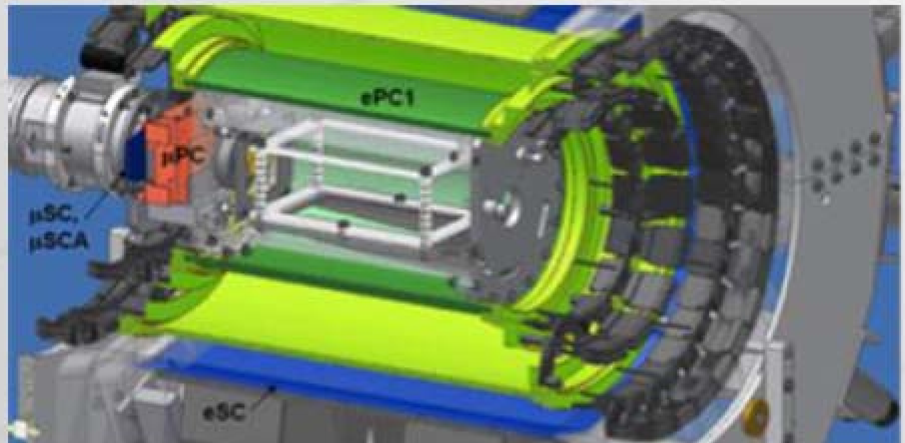
Synopsis: Sizing Up Quark Interactions



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

Measurement of Muon Capture on the Proton to 1% Precision and Determination of the Pseudoscalar Coupling *gP*

V. A. Andreev et al. (MuCap Collaboration)

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Even though the radioactive decay of nuclei is mainly driven by the weak force, interactions between the quarks that make up the protons and neutrons in the nucleus can also affect the process. Calculating these effects with quantum chromodynamics (QCD), the theory describing the strong force interactions between quarks, is, however, mathematically cumbersome at the low energies associated with the nucleus. Instead, calculations are more tractable using an effective QCD theory, in which interactions are between bound quarks (mesons, protons and neutrons). Now, researchers running the muon capture (MuCap) experiment at the Paul Scherrer Institute in Switzerland have **confirmed a long-standing prediction of the theory, known as chiral perturbation theory, boosting confidence that it can be used to accurately describe quark interactions in simple nuclei.** Muon capture is like a beta-decay process run in reverse: a muon (a particle with the same charge as an electron, but 200 times the mass) interacts with a proton to produce a neutron and a neutrino. Among other factors, a dimensionless quantity called the "pseudoscalar coupling," determines the rate of the reaction.

Chiral perturbation theory says the coupling factor has a value of Gp=8.26 , without a lot of wiggle room. But experimental data going back to the 1960s have shown the coupling could be anywhere between 2 and 14. The MuCap collaboration, which measures the rate of the muon capture process by stopping a beam of muons in a low-density gas of pure hydrogen, has analyzed 30 terabytes of data to extract the pseudoscalar coupling with unprecedented precision. The value of their result, reported in *Physical Review Letters*, is 8.06+/-0.55 —in excellent agreement with the theoretical prediction.

– Jessica Thomas

MuCap collaboration

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Paul Scherrer Institute (PSI), Villigen, Switzerland
University of California, Berkeley (UCB and LBNL), USA
University of Illinois at Urbana-Champaign (UIUC), USA
Université Catholique de Louvain, Belgium
TU München, Garching, Germany
University of Kentucky, Lexington, USA
Boston University, USA

Из поздравлений внутри MuCap коллаборации

"…….Success of our experiment is the result of lucky combination of several unique factors:

- unique experimental method,
- unique muon channel,
- unique MuCap collaboration."