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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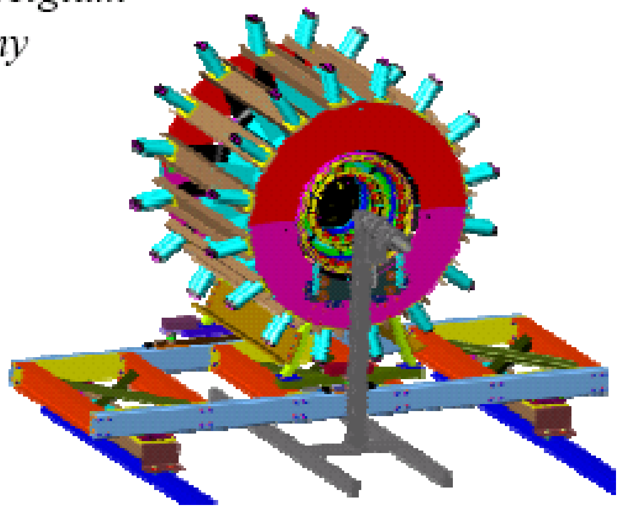


@ PSI

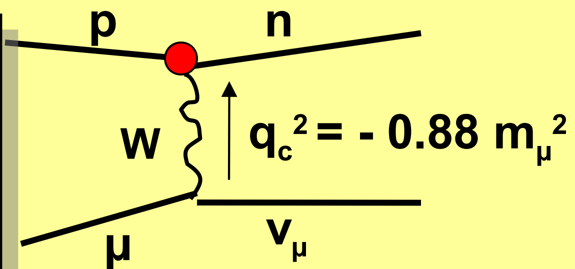
Muon Capture on Proton

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

MuCap goal: to measure μp-capture rate Λ 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

Muon capture on proton

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

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

Стандартная Модель и структура нуклонов

$g_v = 0.9755 \pm 0.0005$

$g_a = 1.245 \pm 0.003$

$g_m = 3.582 \pm 0.003$

$g_P(th) = 8.26 \pm 0.23$

$g_P(OMC) = 6 – 12$

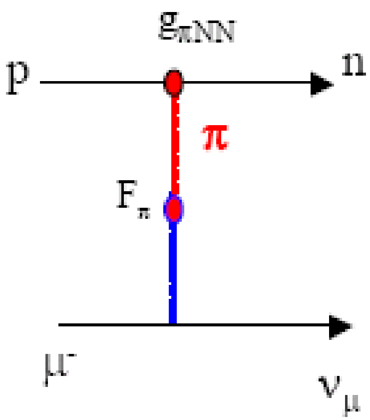
$g_P\,(RMC) = 12.2 \pm 0.9 \pm 0.4$

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)

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

Muon capture on proton
Sensitivity to Form Factors

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

Experimental information on g_P

Ordinary Muon Capture $\mu^- + p \rightarrow \nu_\mu + n$

BR~10^{-3}, 8 experiments 1962-82, BC, neutron, electron detection
"in principle" most direct g_P measurement

Radiative Muon Capture $\mu^- + p \rightarrow \nu_\mu + n + \gamma$

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

  $\mu + {}^3He \rightarrow \nu + {}^3H$ Λ_{st}=1496 ±4 s^{-1} PSI (1998)
  $g_P = g_P^{th}$ (1.08 ±0.19) error dominated by 3-N theory

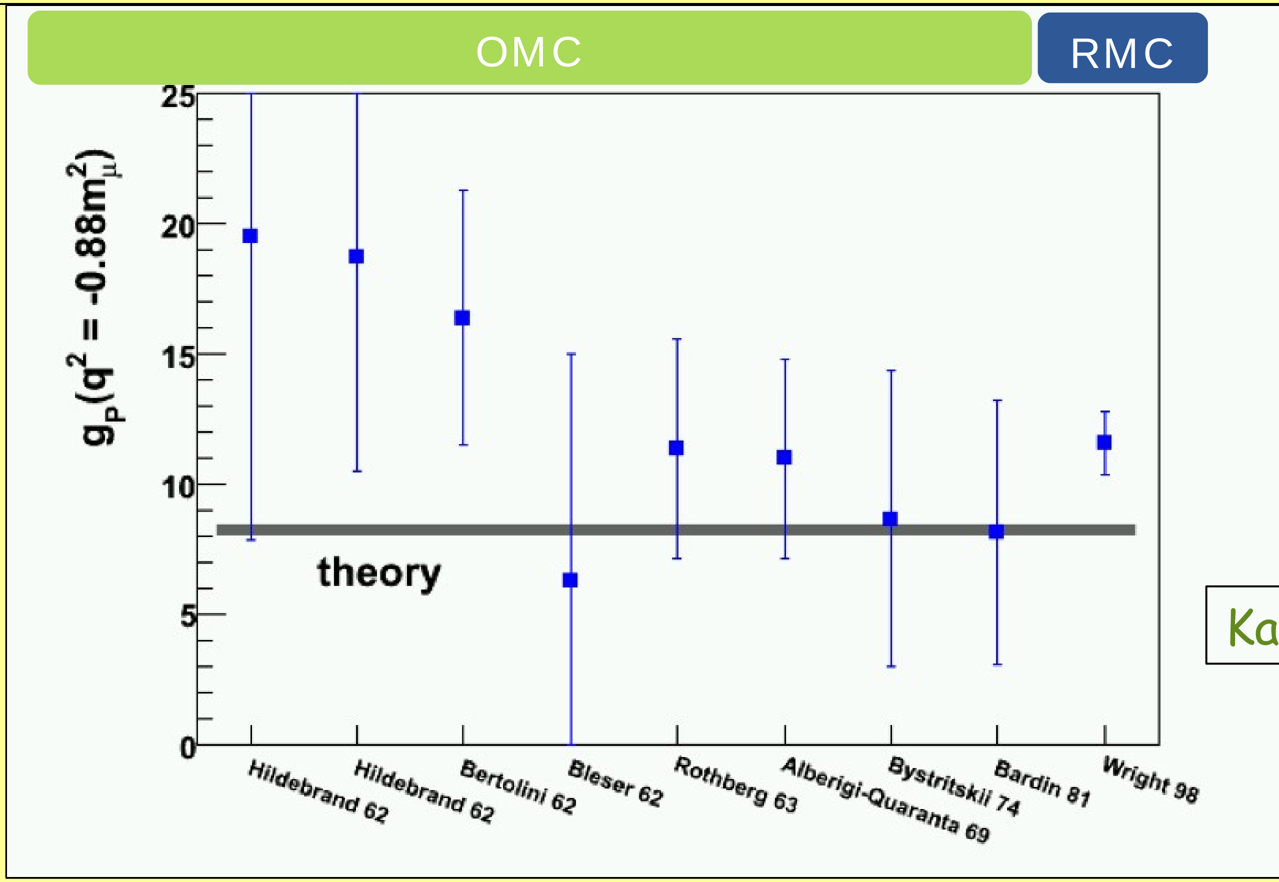
  correlation measurements

- π electro production at threshold

µCap

Ref.	n/n_o	Δt (μs)	S:O:P	Rate (s^{-1})	$g_p(-0.88m_\mu^2)$
Ordinary muon capture					
Hildebrand (1962)	1.0	0.0	0.15:0.77:0.07	420±120	19.5±11.6
Hildebrand and Doede (1962)	1.0	0.0	0.15:0.77:0.07	428±85	18.7±8.2
Bertolini *et al.* (1962)	1.0	0.0	0.15:0.77:0.07	450±50	16.4±4.9
Bleser *et al.* (1962)	1.0	1.0	0.01:0.88:0.11	515±85	6.3±8.7
Rothberg *et al.* (1963)	1.0	1.2	0.01:0.88:0.12	464±42	11.4±4.2
Alberigi-Quaranta *et al.* (1969)	0.014	0.9	1.00:0.00:0.00	651±57	11.0±3.8
Bystritskii *et al.* (1974)	0.072	1.4	1.00:0.00:0.00	686±88	8.7±5.7
Bardin *et al.* (1981a) (original τ_+)	1.0	2.5		460±20	7.9±3.0
(new τ_+)				435±17	10.6±2.7
Radiative muon capture					
Wright *et al.* (1998) (original theory)	1.0	0.365	0.06:0.85:0.09	$(2.10\pm0.21)\times10^{-8}$	12.4±0.9±0.4
(new theory)					12.2±0.9±0.4

50 years of effort to determine gP



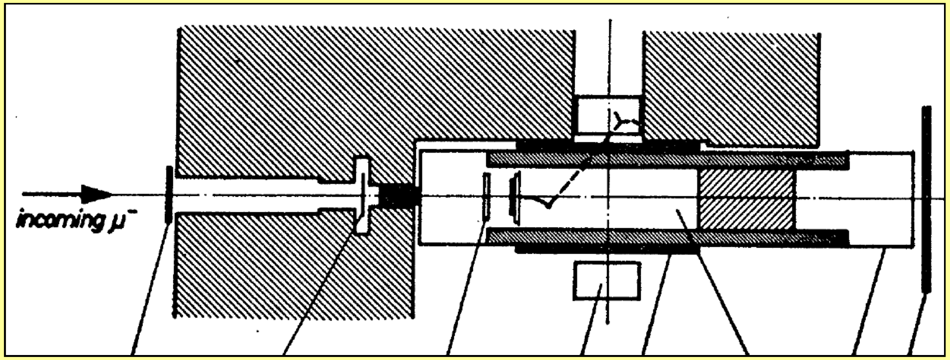
Kammel&Kubodera

“ 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)*

Pioneers of muon capture experiments

Emilio Zavattini 1927-2007



1969 Bologna-Pisa-CERN

H2 –target 8 atm

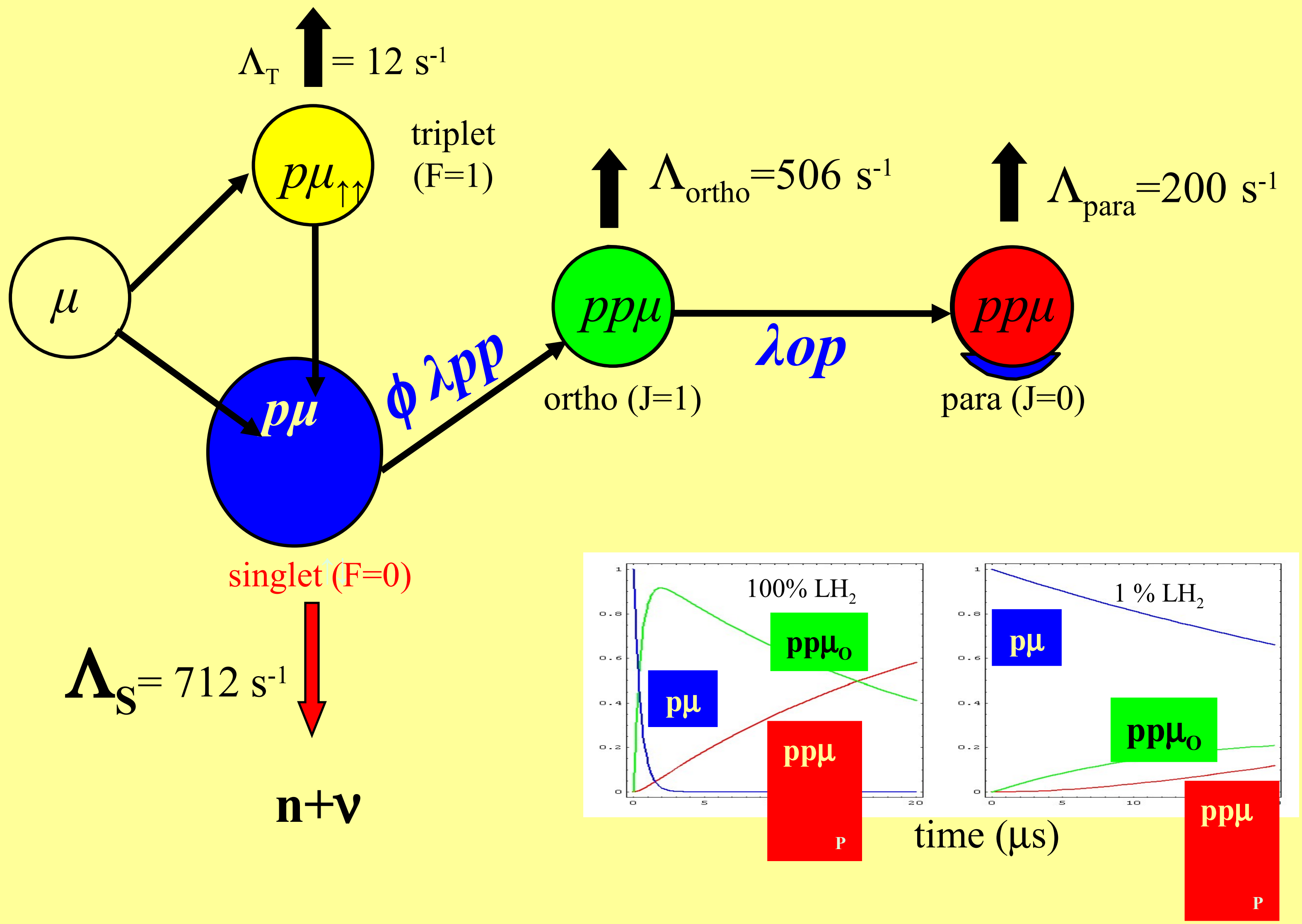
g_p **= 11.0 ± 3.8**

1973 Dubna group

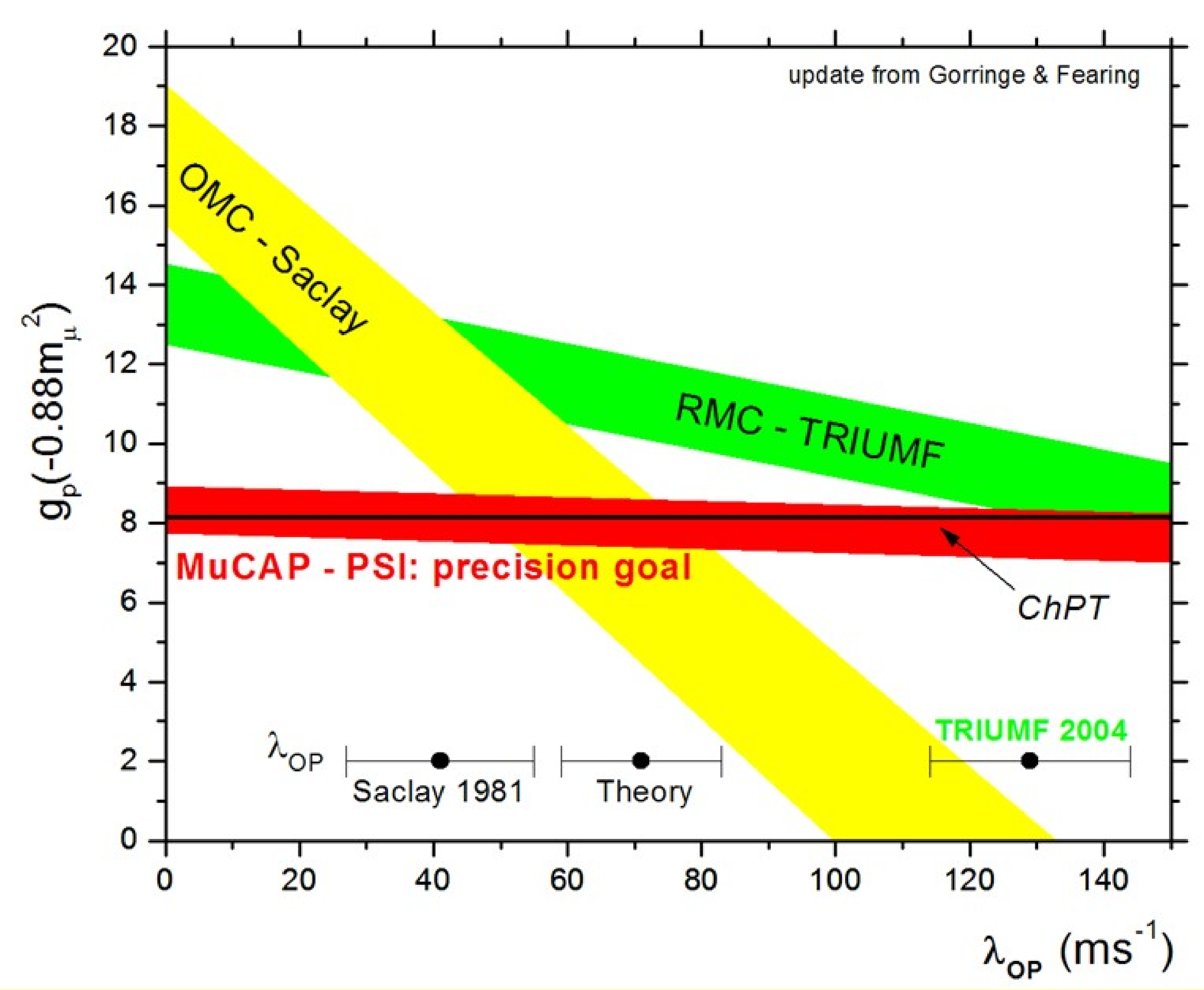
H2 –target 41 atm

g_p **=8.7 ± 5.7**

Expt. Problems
- Wall effects
- Background
- Neutron detection efficiency

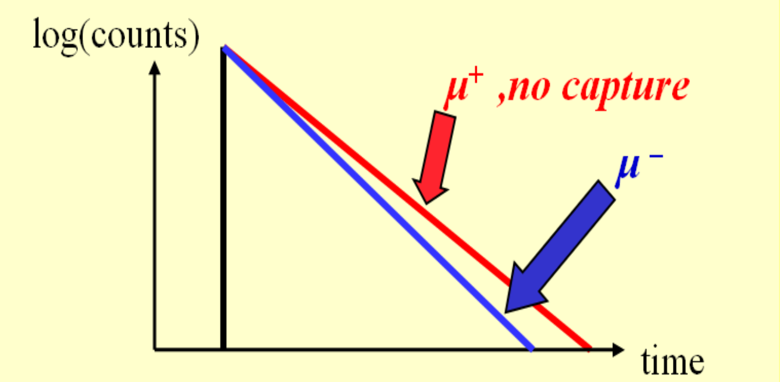


Λ_T = 12 s^{-1}
$p\mu_{\uparrow\uparrow}$
triplet
(F=1)
Λ_{ortho}=506 s^{-1}
Λ_{para}=200 s^{-1}
μ
$pp\mu$
$pp\mu$
λop
$\phi\ \lambda pp$
$p\mu$
ortho (J=1)
para (J=0)
singlet (F=0)
Λ_S= 712 s^{-1}
n+ν
100% LH_2
$pp\mu_O$
pμ
ppμ
P
1 % LH_2
pμ
$pp\mu_O$
ppμ
P
time (μs)


update from Gorringe & Fearing
OMC - Saclay
RMC - TRIUMF
MuCAP - PSI: precision goal
ChPT
TRIUMF 2004
λ_{OP}
Saclay 1981
Theory
$g_p(-0.88m_\mu^2)$
λ_{OP} (ms^{-1})
0
20
40
60
80
100
120
140
2
4
6
8
10
12
14
16
18

Стратегия MuCap эксперимента

- **Измерение времени жизни (τ)**
  с точностью 10ppm, регистрация
  $\mu \rightarrow e\nu\nu$ распадов (10^10)



- **Однозначность интерпретации**
  захват из F=0 состояния μp атома при плотности 1% LH2
- **Использование методики активной мишени (TPC)**
  с точной регистрацией координат и времени остановок мюонов, реконструкция треков электронов к точке распада.
- **Использование ультрачистого водорода Cz < 10ppb**
- **Контроль примесей по реакциям: $\mu p + Z \rightarrow \mu Z + p$, Cz~10ppb.**
- **Обеспечение изотопической чистоты водорода**
  $\mu p + d \rightarrow \mu d + p$ + 134eV, примесь Cd <1ppm, диффузия μd ~cm

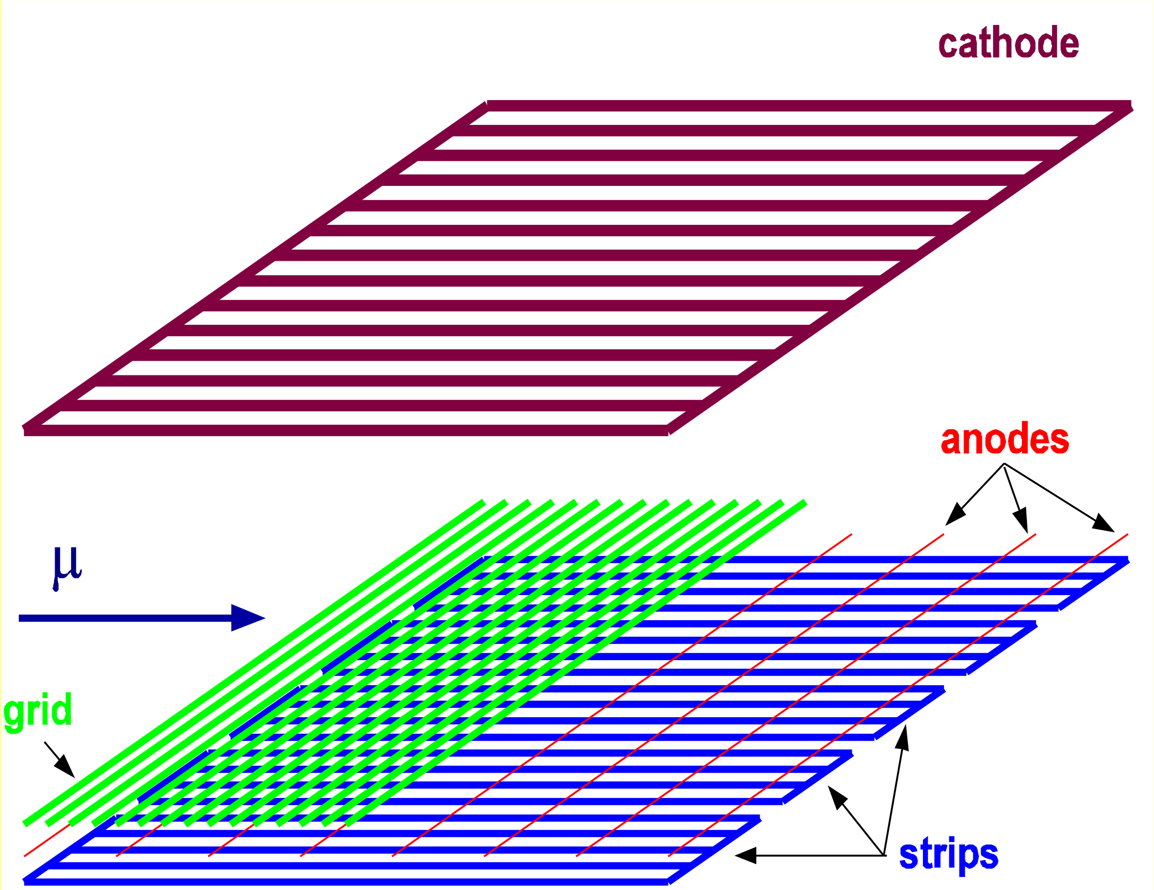
PSI meson factory

600MeV protons
2mA extracted proton beam
100% duty factor
High intensity muon channels
Muon-on-request mode

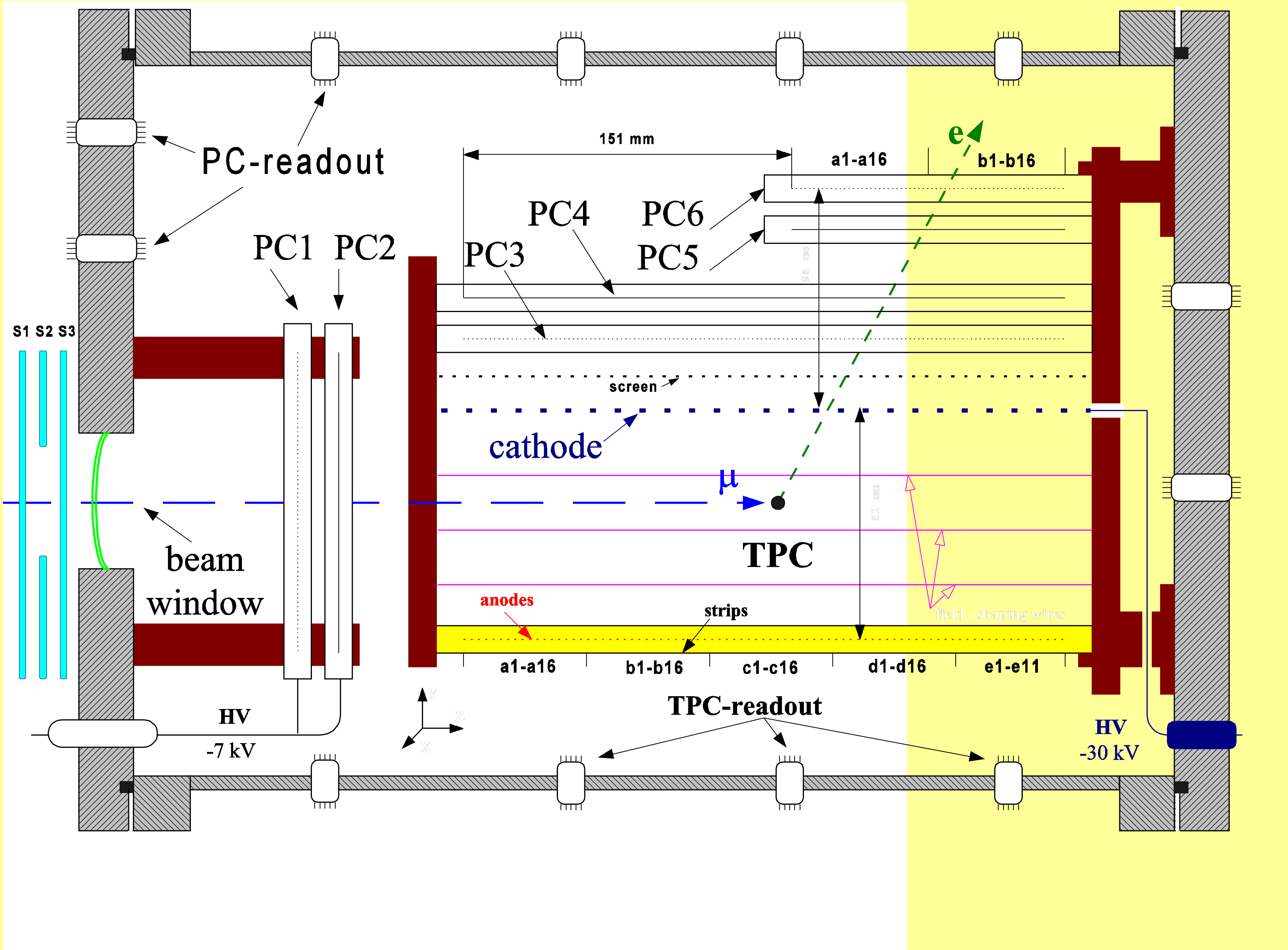
PNPI in PSI since 1986

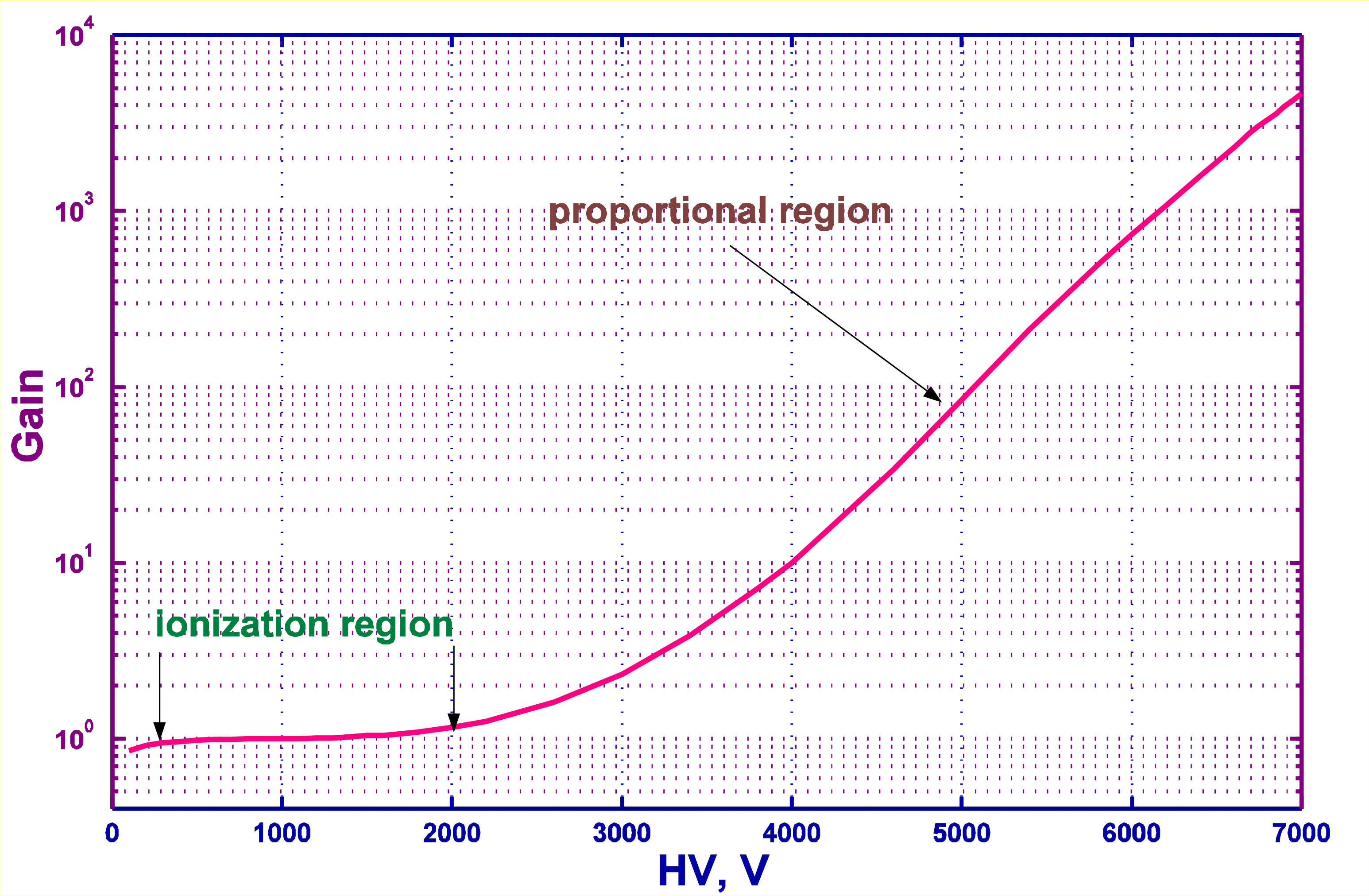
- **Muon catalyzed dd-and dt-fusion experiments** (completed)
- **Muon capture on He-3** (completed)
- **Muon capture on proton** (completed)
- **Muon capture on deuteron** (in progress)

Schematic view of the TPC

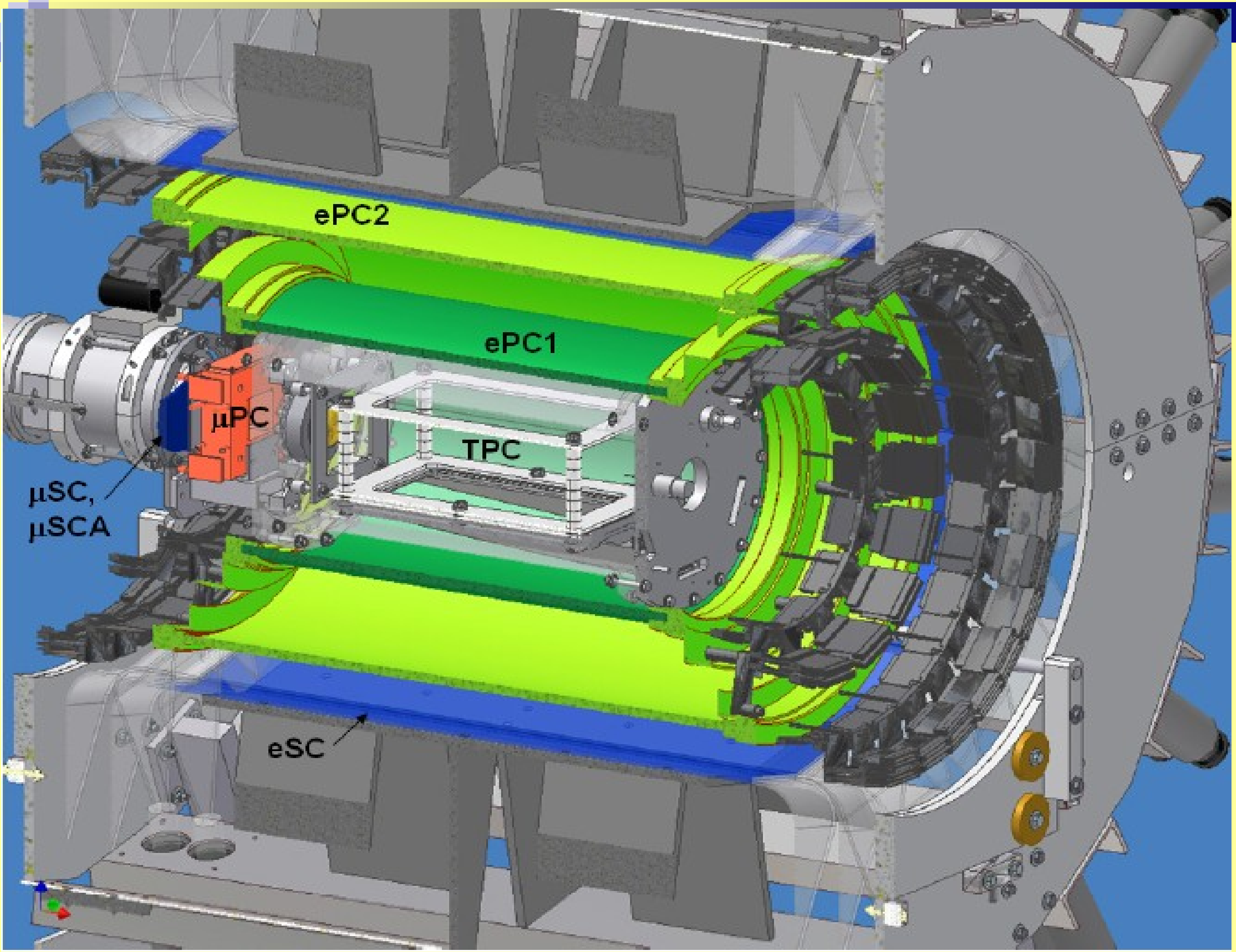


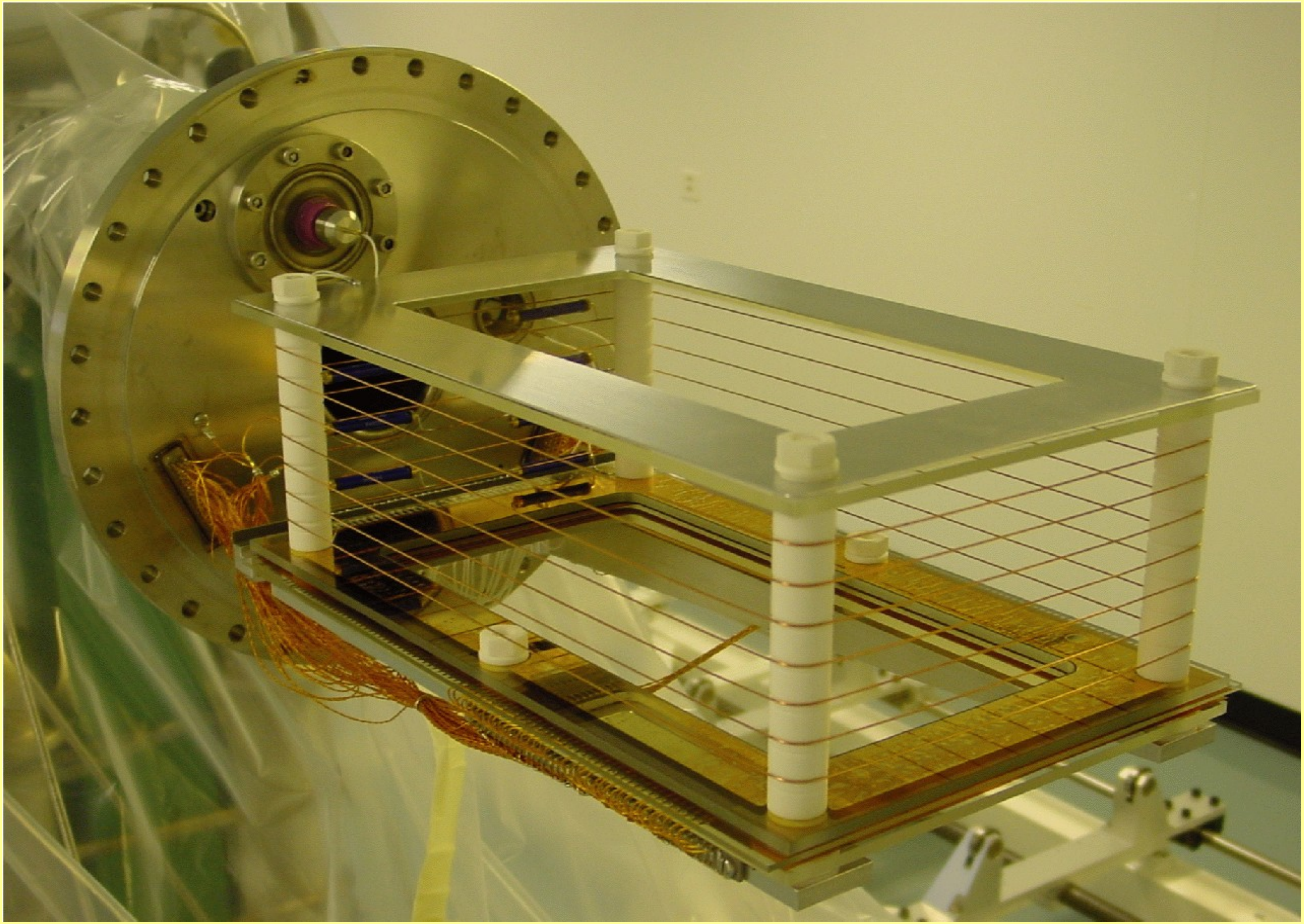
The trajectories of charged particles are measured in 3D space with resolution (rms) 1-2 mm.

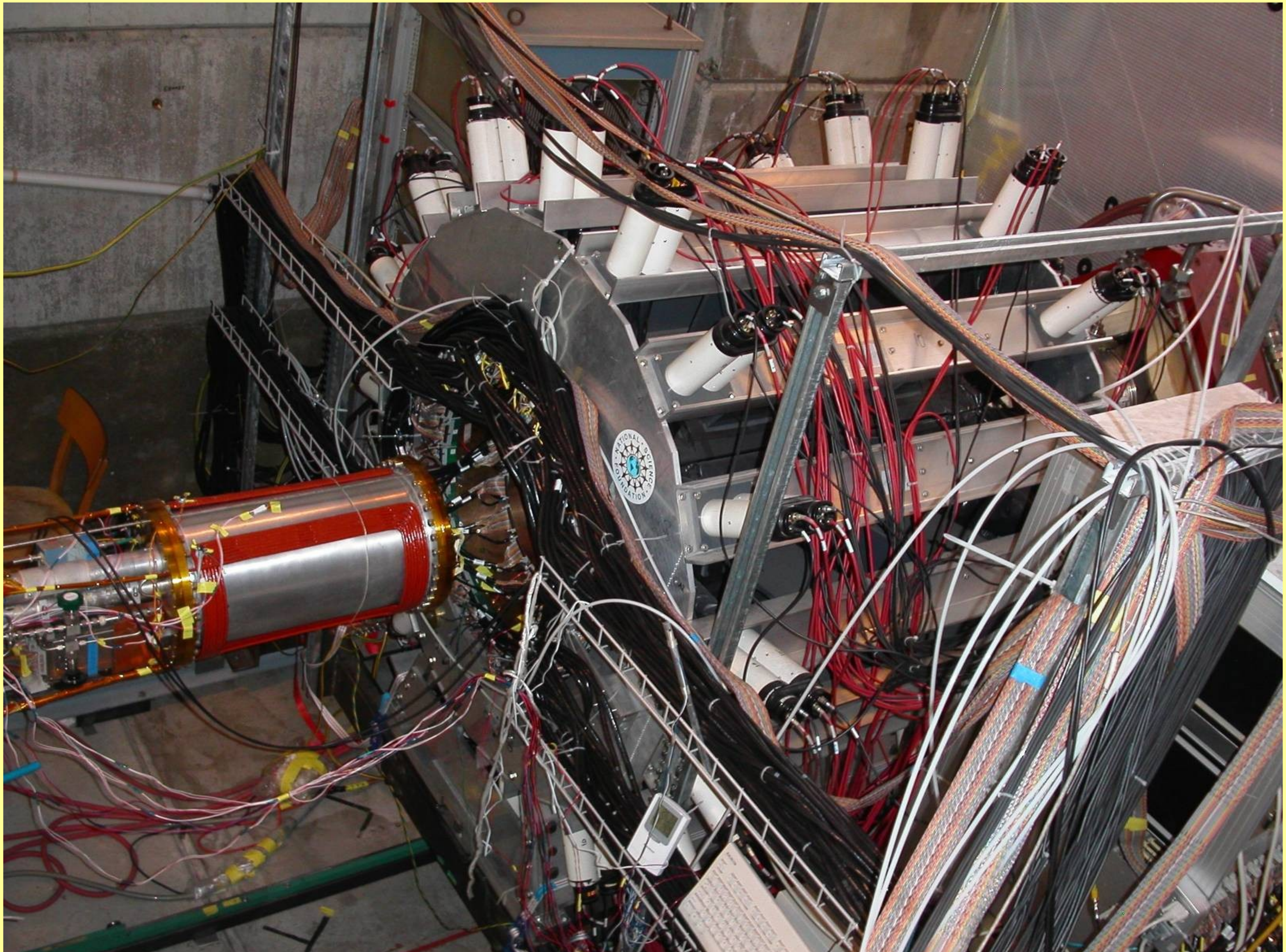

PC-readout
151 mm
a1-a16
b1-b16
e
PC4
PC6
PC3
PC5
PC1
PC2
S1 S2 S3
screen
cathode
μ
beam
window
TPC
anodes
strips
field - shaping wires
a1-a16
b1-b16
c1-c16
d1-d16
e1-e11
HV
-7 kV
TPC-readout
HV
-30 kV

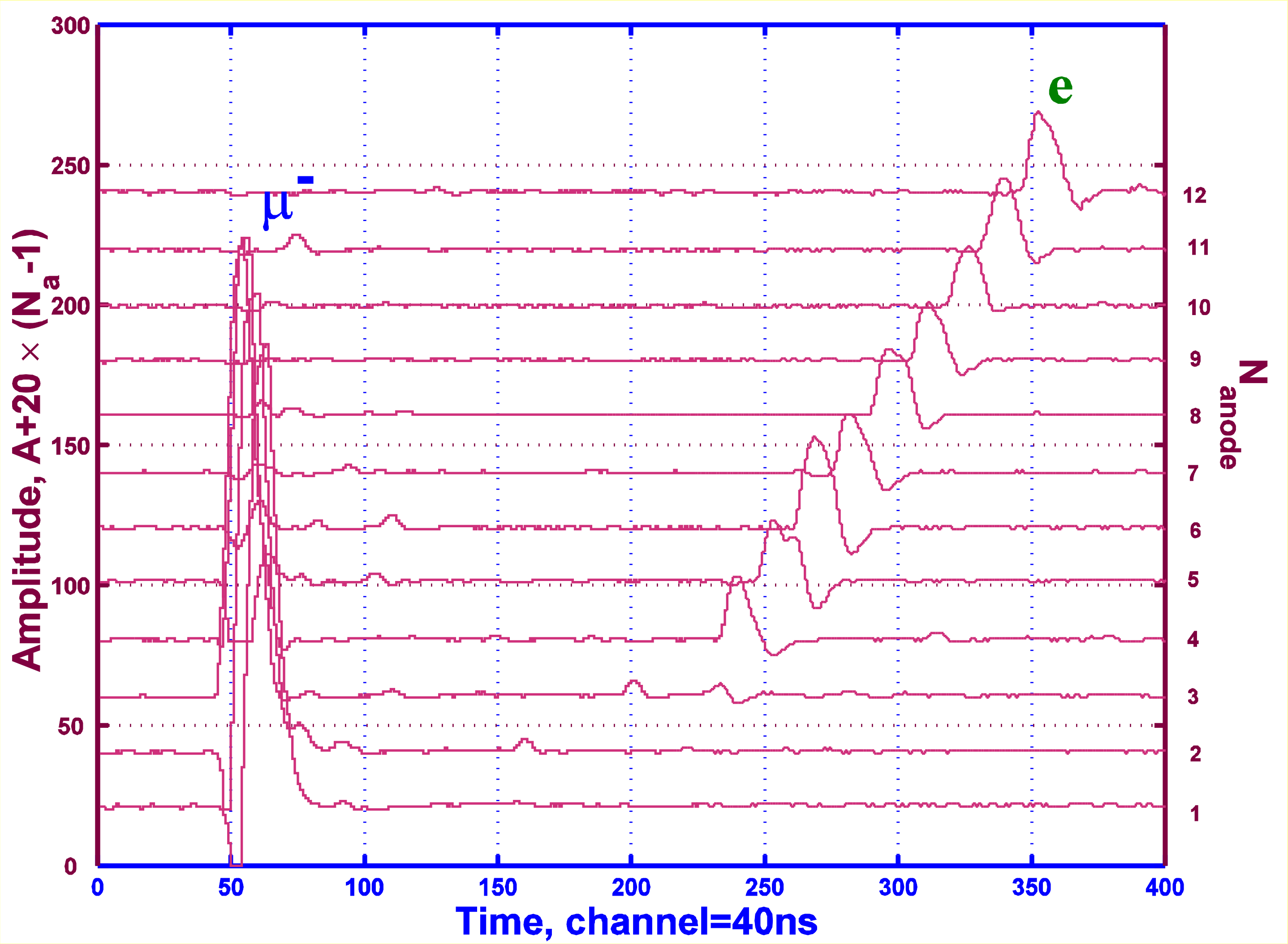


Gain
HV, V
proportional region
ionization region
10^4
10^3
10^2
10^1
10^0
0
1000
2000
3000
4000
5000
6000
7000

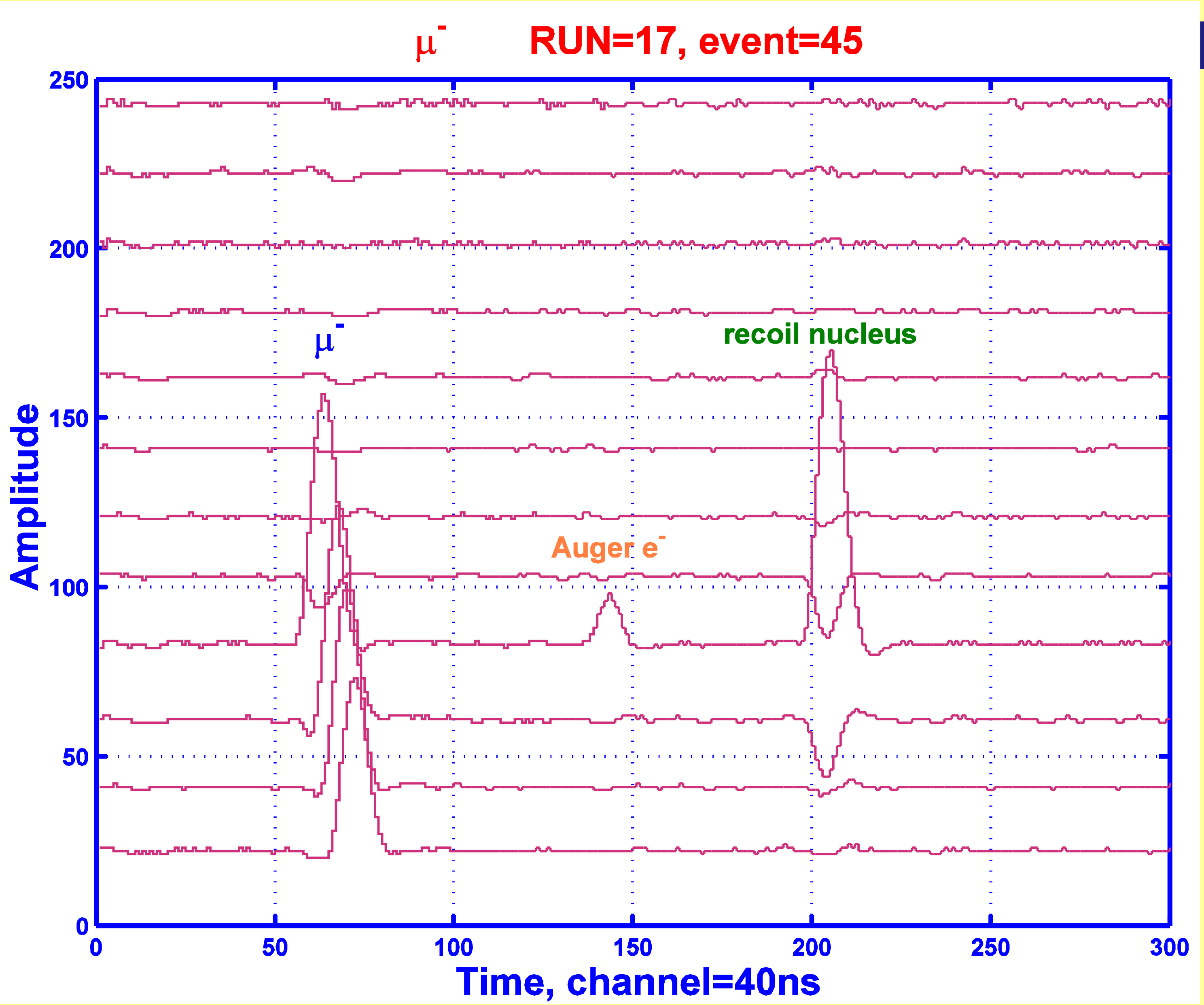

ePC2
ePC1
μPC
TPC
μSC,
μSCA
eSC



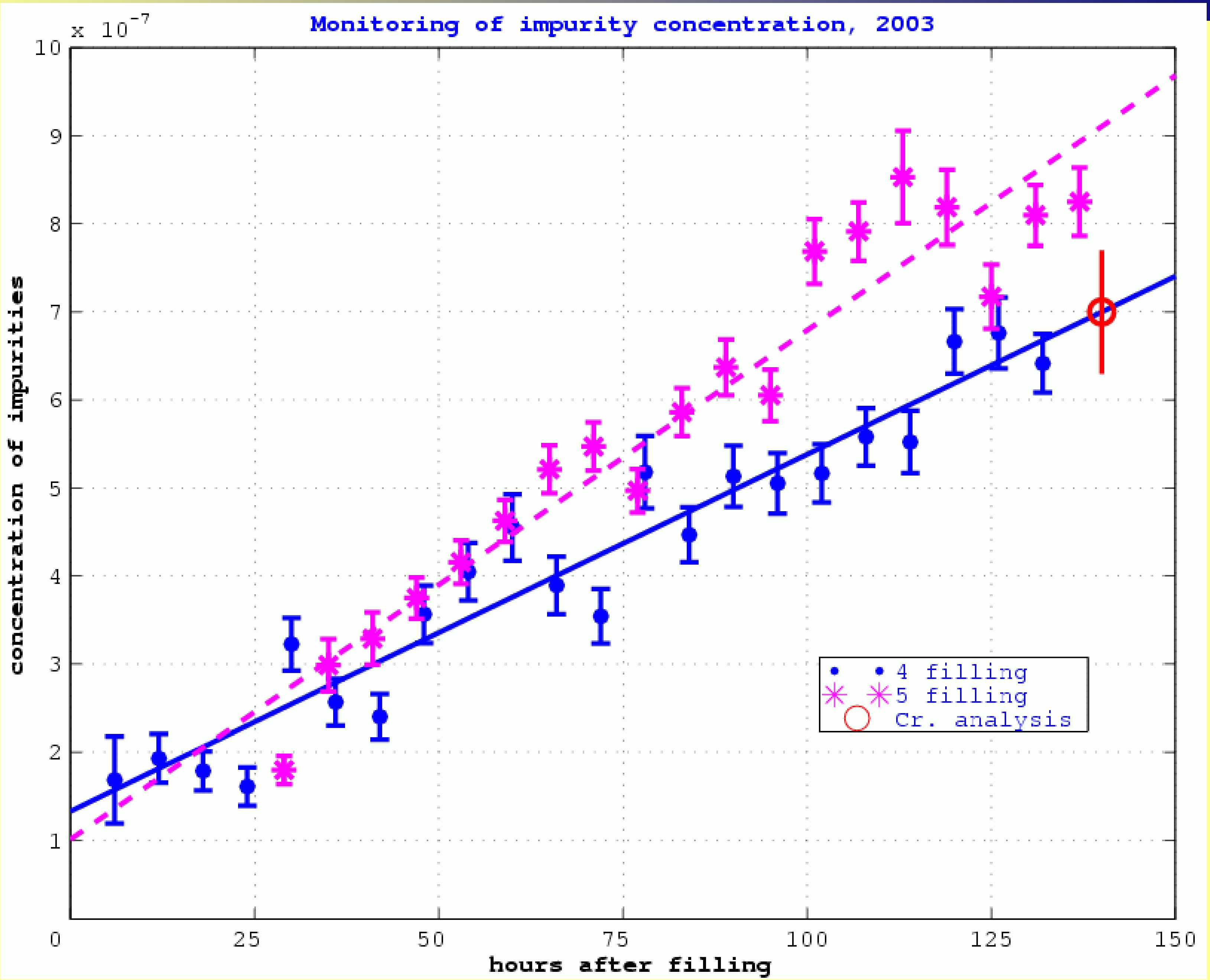

NATIONAL SCIENCE FOUNDATION

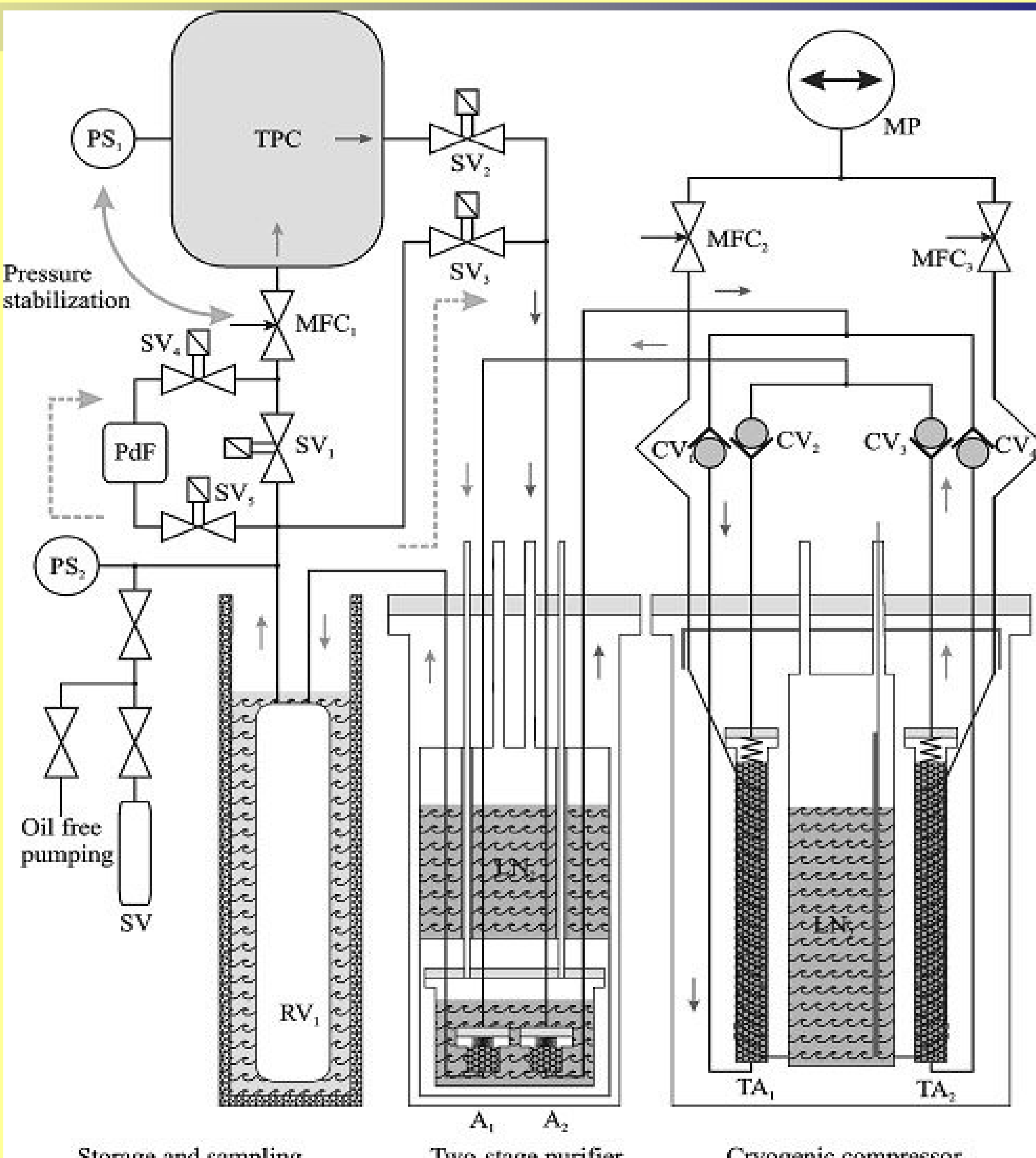


The signal on TPC anode wires from μ-e decay event

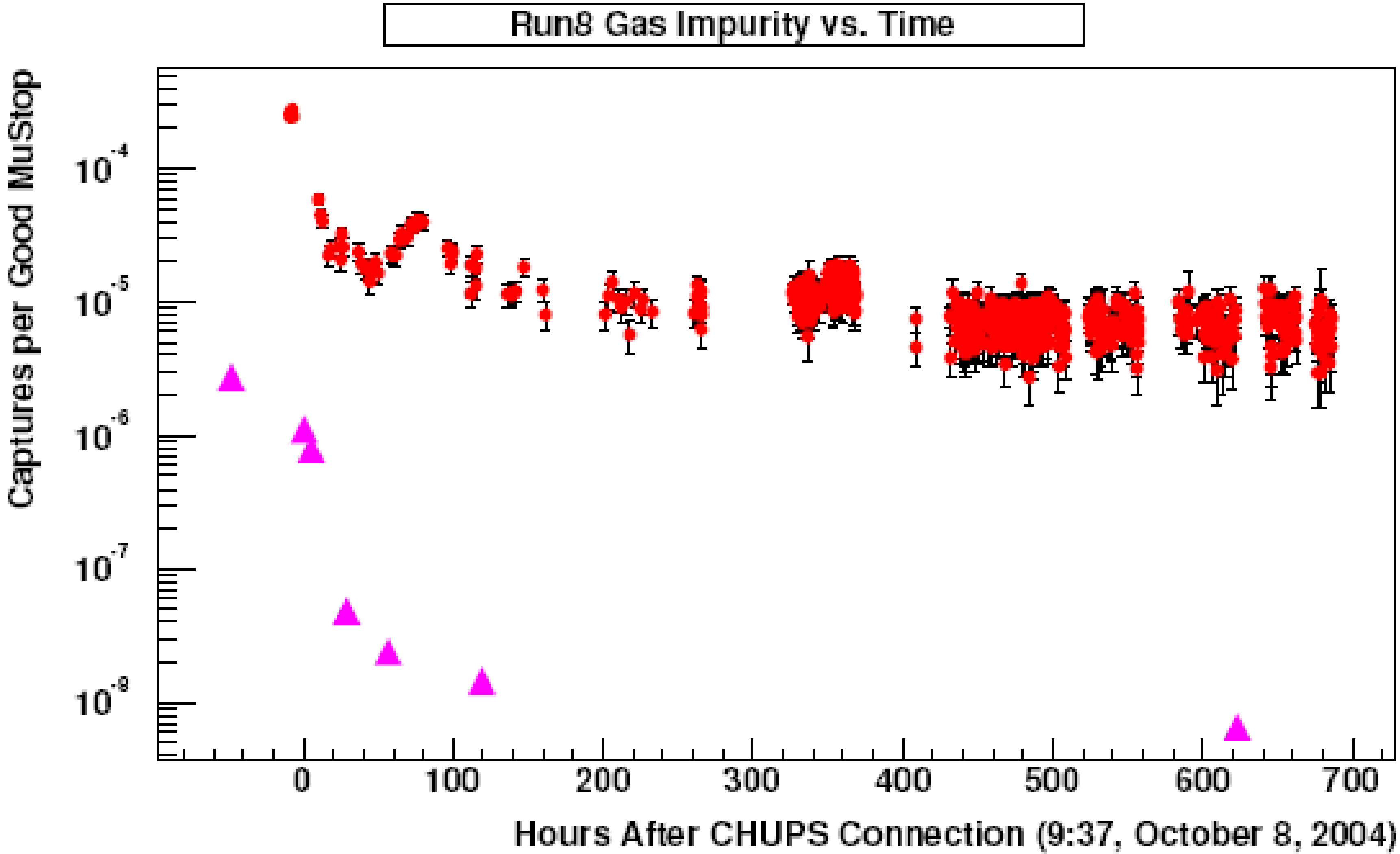


Display of a typical event with μ-capture reaction on impurity

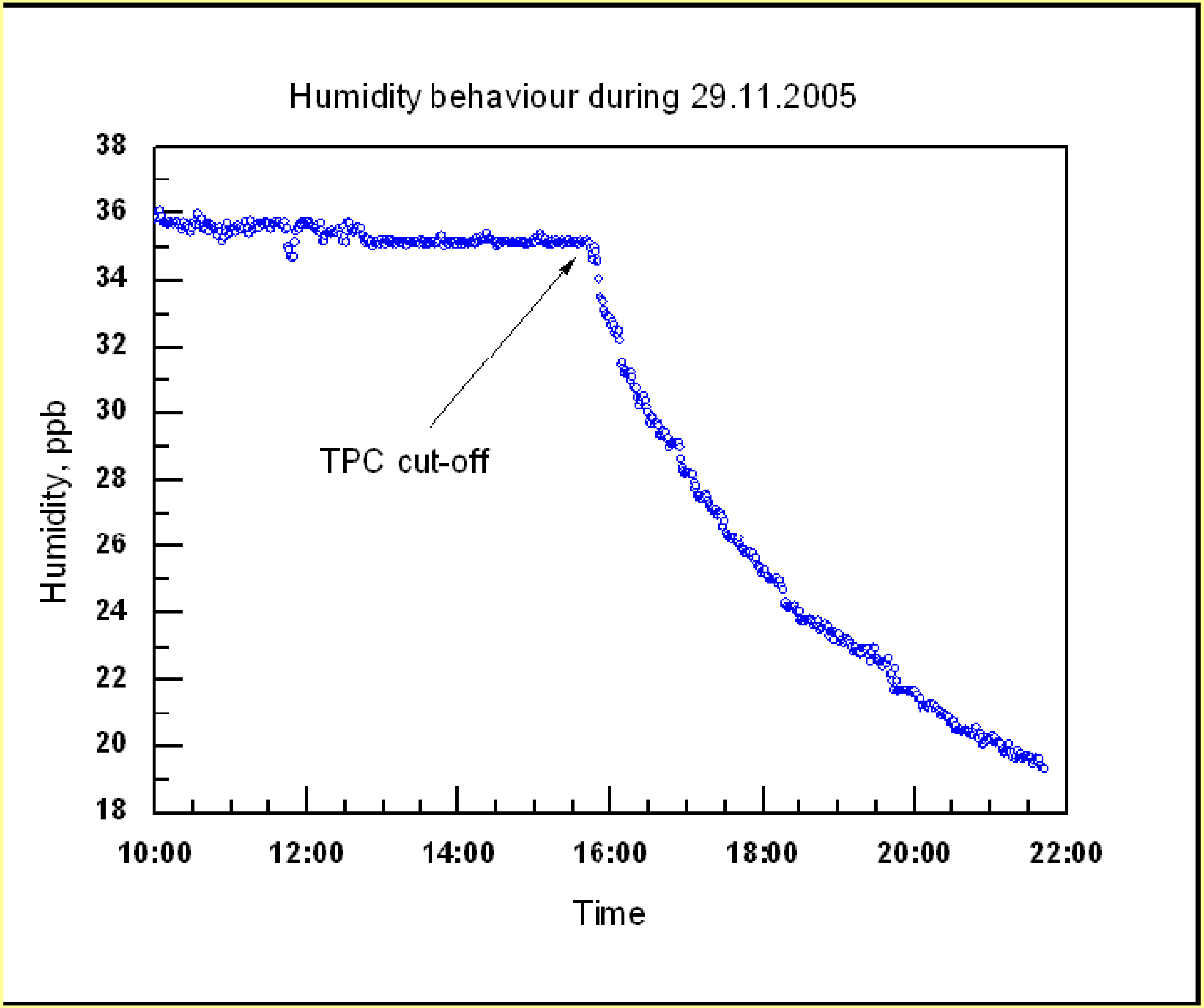

Monitoring of impurity concentration, 2003
x 10^{-7}
concentration of impurities
hours after filling
0
25
50
75
100
125
150
1
2
3
4
5
6
7
8
9
10
4 filling
5 filling
Cr. analysis



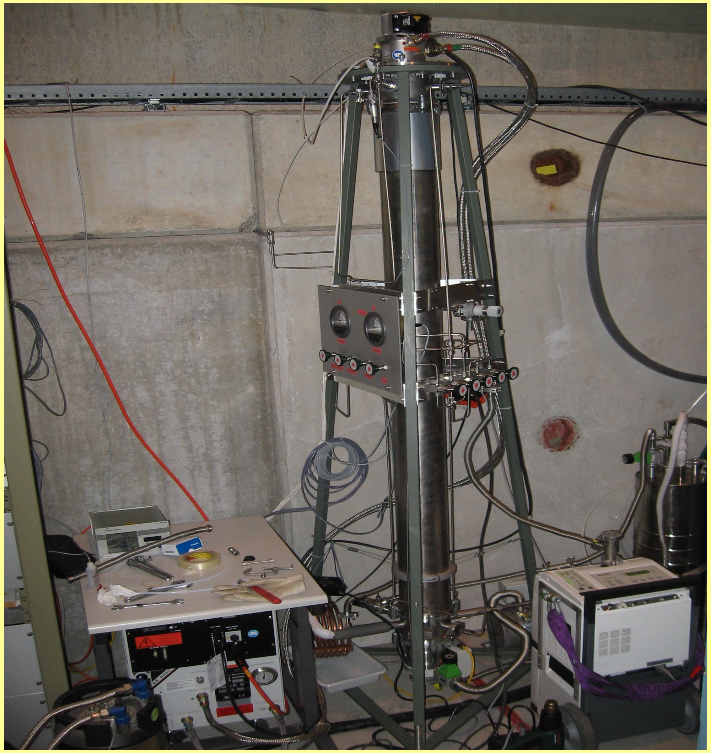
PS1
TPC
SV2
SV3
MP
MFC2
MFC3
Pressure stabilization
MFC1
SV4
PdF
SV1
SV5
PS2
CV1
CV2
CV3
CV4
Oil free pumping
SV
RV1
LN2
LN2
A1
A2
TA1
TA2
Storage and sampling
Two-stage purifier
Cryogenic compressor

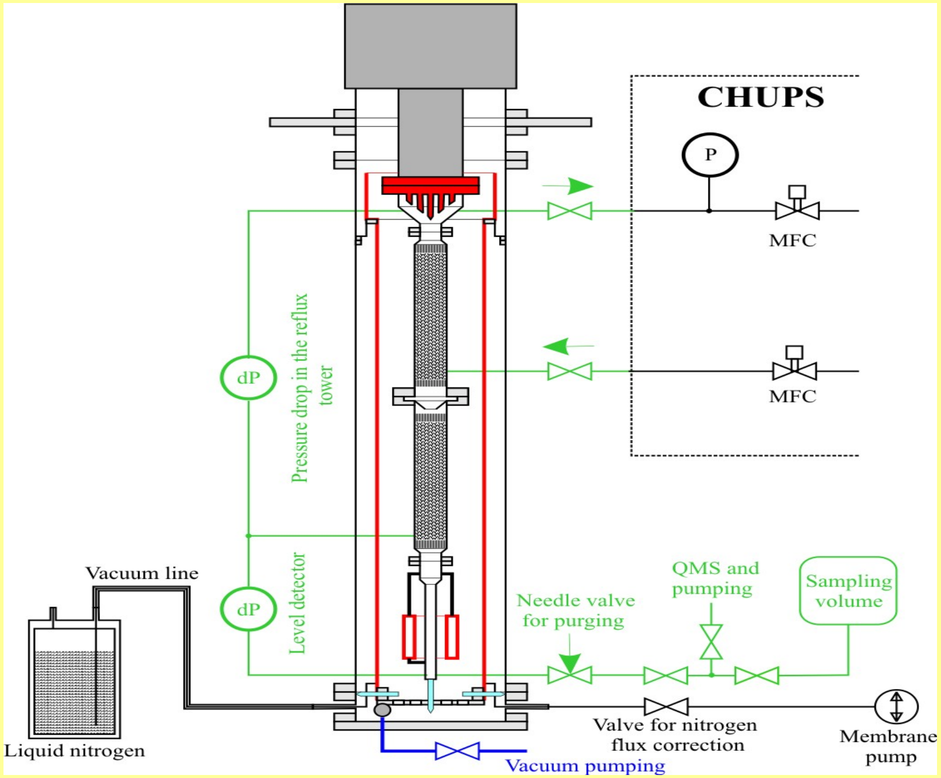


Run8 Gas Impurity vs. Time
Captures per Good MuStop
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
0
100
200
300
400
500
600
700
Hours After CHUPS Connection (9:37, October 8, 2004)


Humidity behaviour during 29.11.2005
Humidity, ppb
38
36
34
32
30
28
26
24
22
20
18
TPC cut-off
10:00
12:00
14:00
16:00
18:00
20:00
22:00
Time

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

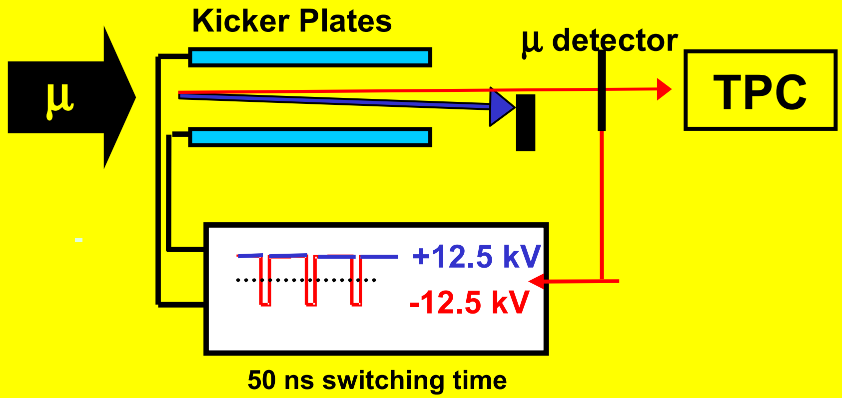


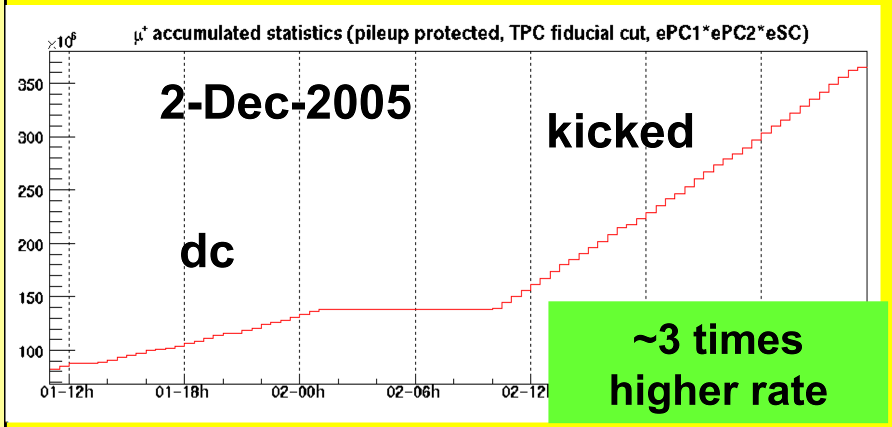


1)	Cd = 1440 ppb	(2004)
2)	Cd < 60 ppb	(2006)
3)	Cd < 6 ppb	(2007)

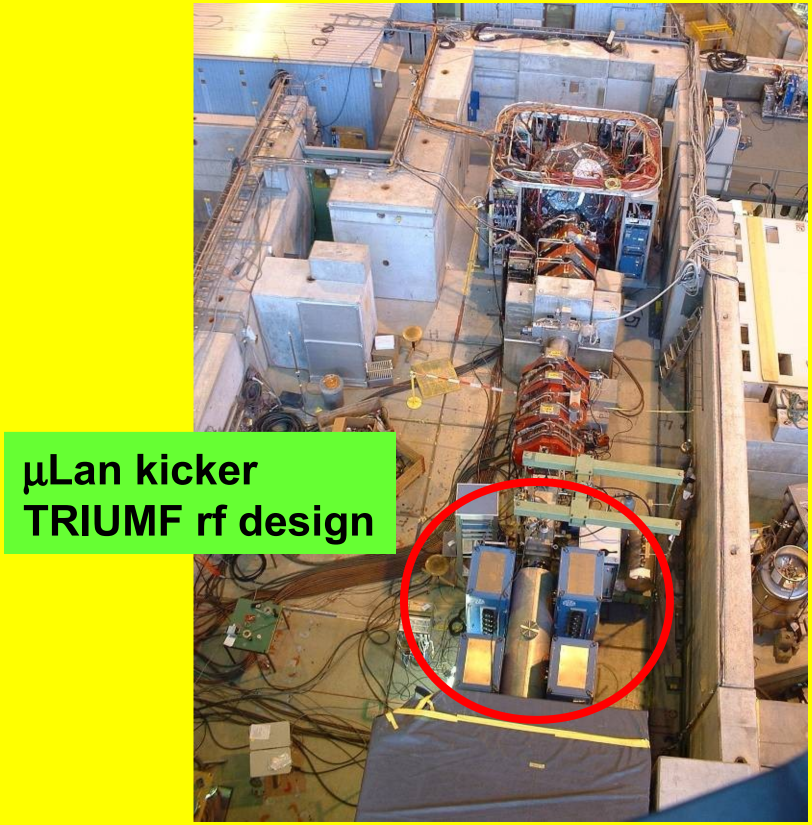
- Single muon requirement (to prevent systematics from pile-up)
- limits accepted μ rate to ~ 7 kHz,
- while PSI beam can provide ~ 70 kHz

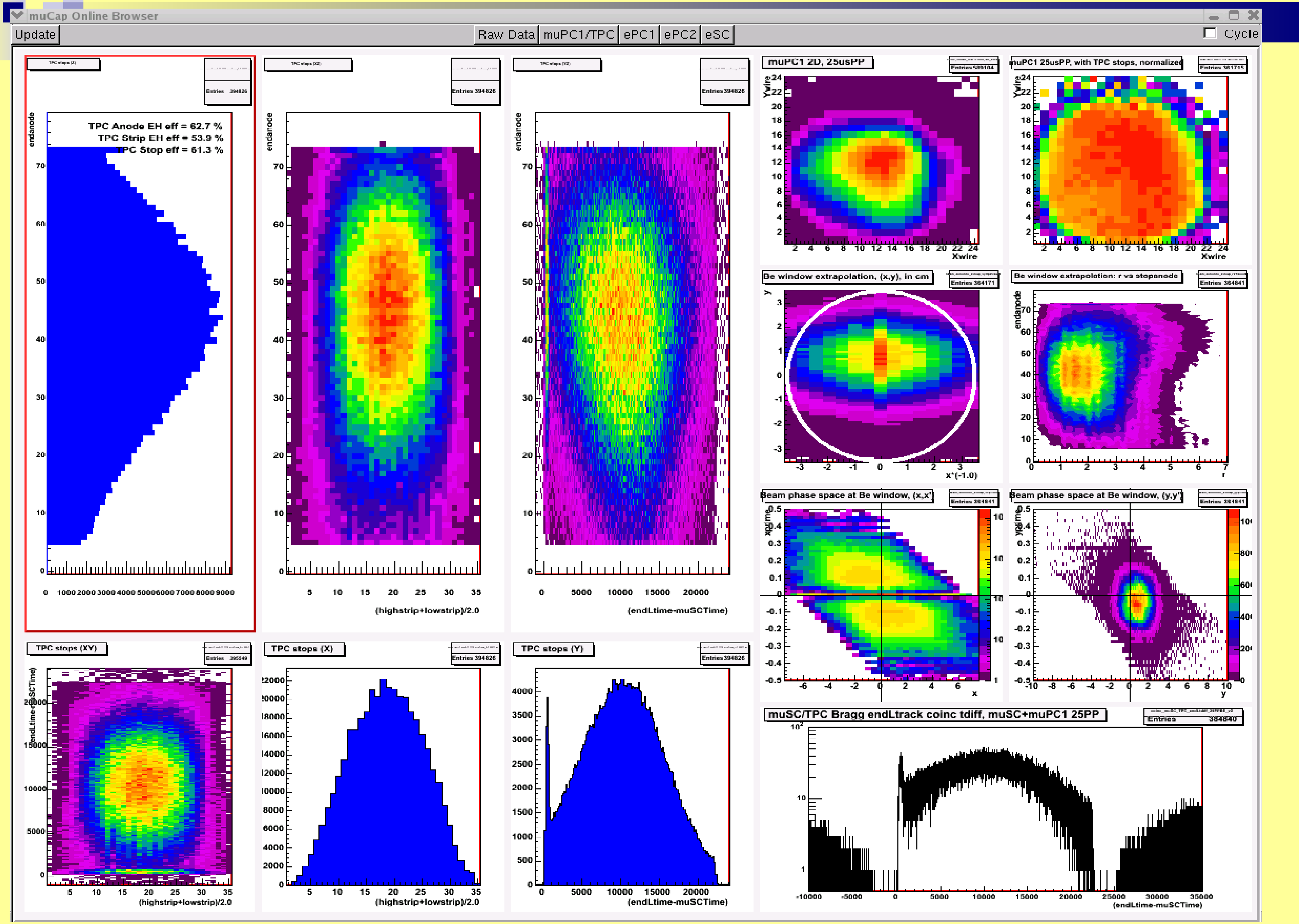
- Muon-On-Demand concept

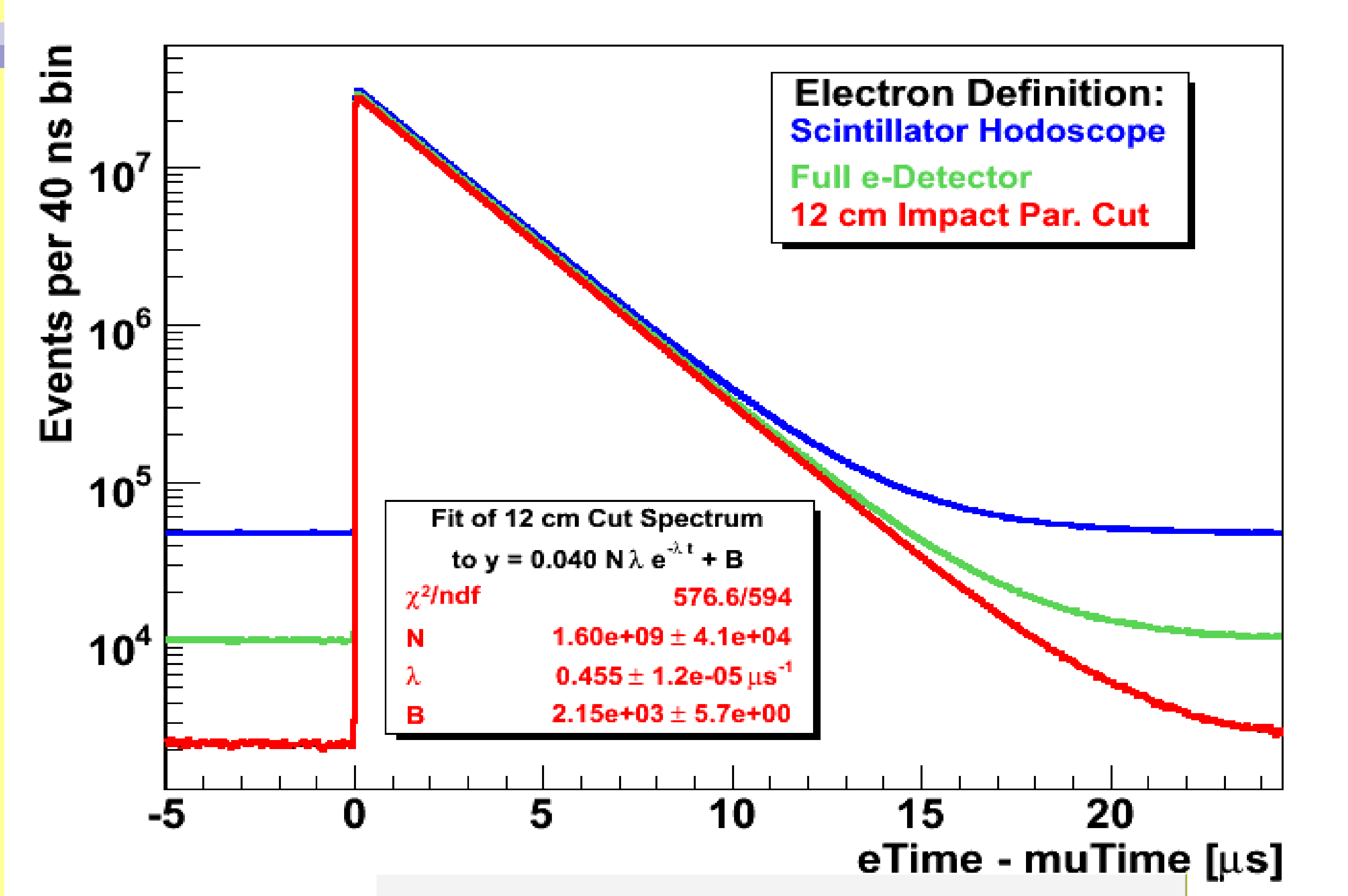




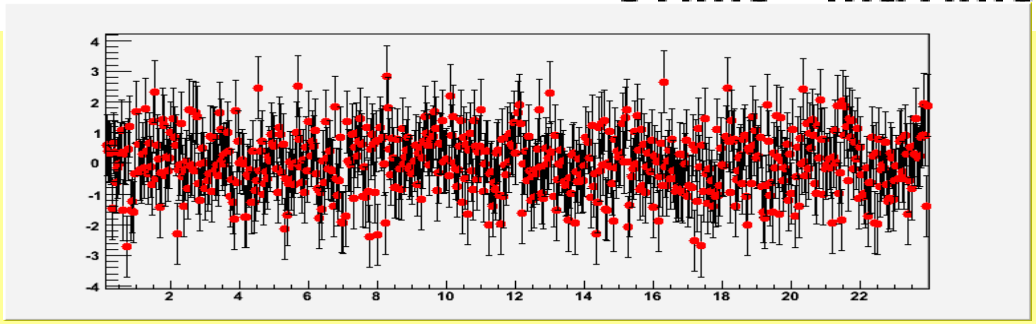
- Beamline



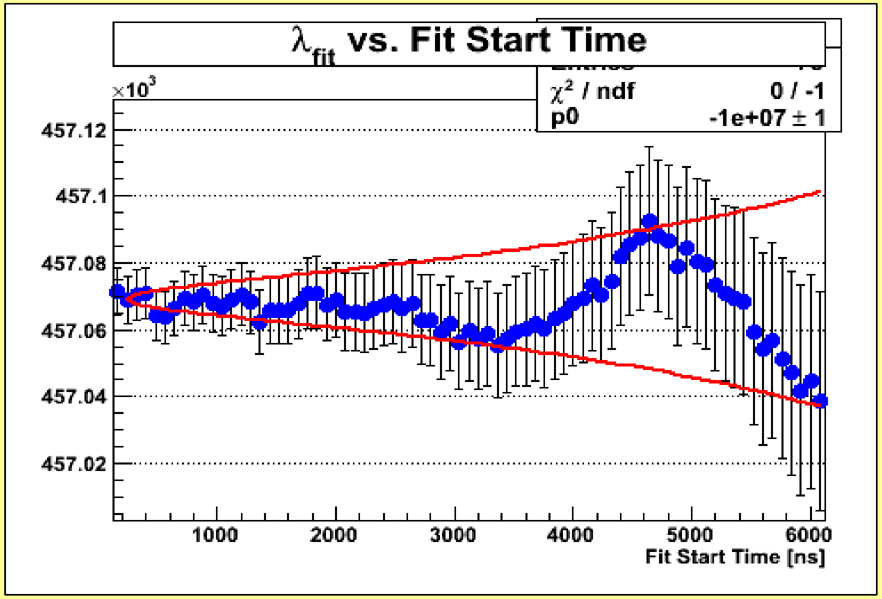

muCap Online Browser
Update
Raw Data
muPC1/TPC
ePC1
ePC2
eSC
Cycle
TPC Anode EH eff = 62.7 %
TPC Strip EH eff = 53.9 %
TPC Stop eff = 61.3 %
endanode
(highstrip+lowstrip)/2.0
(endLtime-muSCTime)
muPC1 2D, 25usPP
muPC1 25usPP, with TPC stops, normalized
Ywire
Xwire
Be window extrapolation, (x,y), in cm
Be window extrapolation: r vs stopanode
x*(-1.0)
Beam phase space at Be window, (x,x')
Beam phase space at Be window, (y,y')
TPC stops (XY)
TPC stops (X)
TPC stops (Y)
muSC/TPC Bragg endLtrack coinc tdiff, muSC+muPC1 25PP
Entries 384840

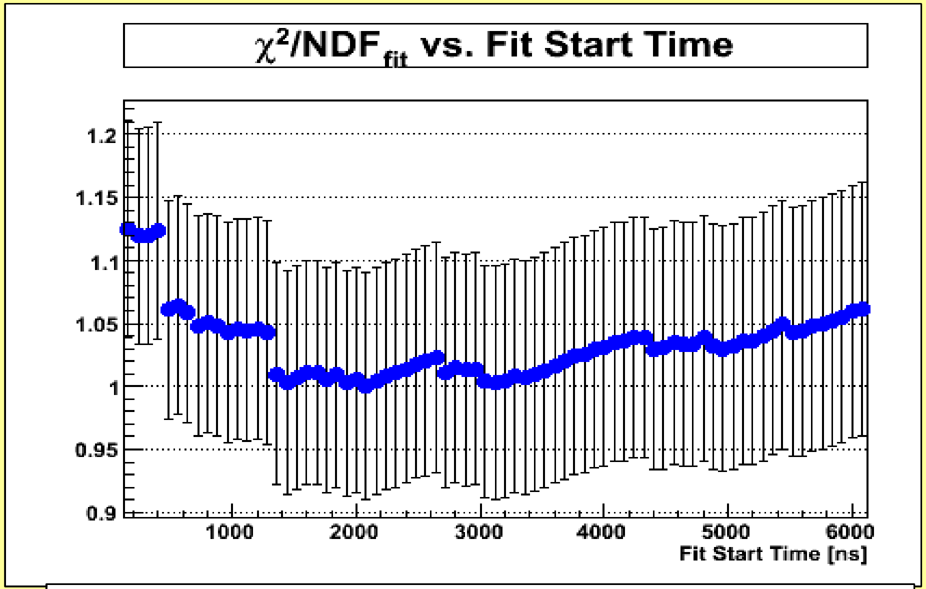


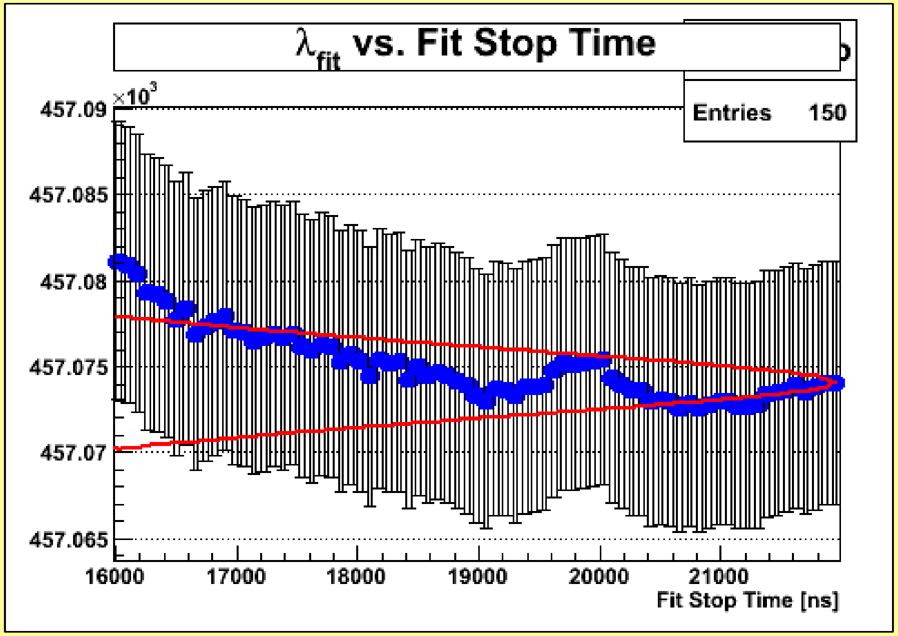
Normalized residuals

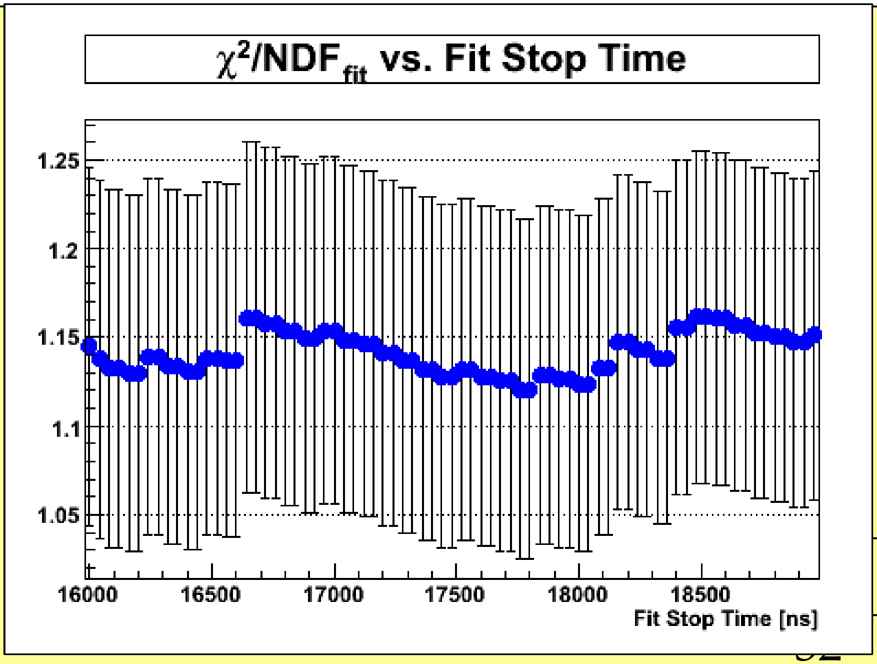


Start and stop-time-scans consistency









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
	8.56	20.1		

Общий объем данных за 2004-2007 гг. ~ 100 TB

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)

$Dpp\mu$ = 17.7 s-1 (λppμ =(1.94 ± 0.06)μs-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)**

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

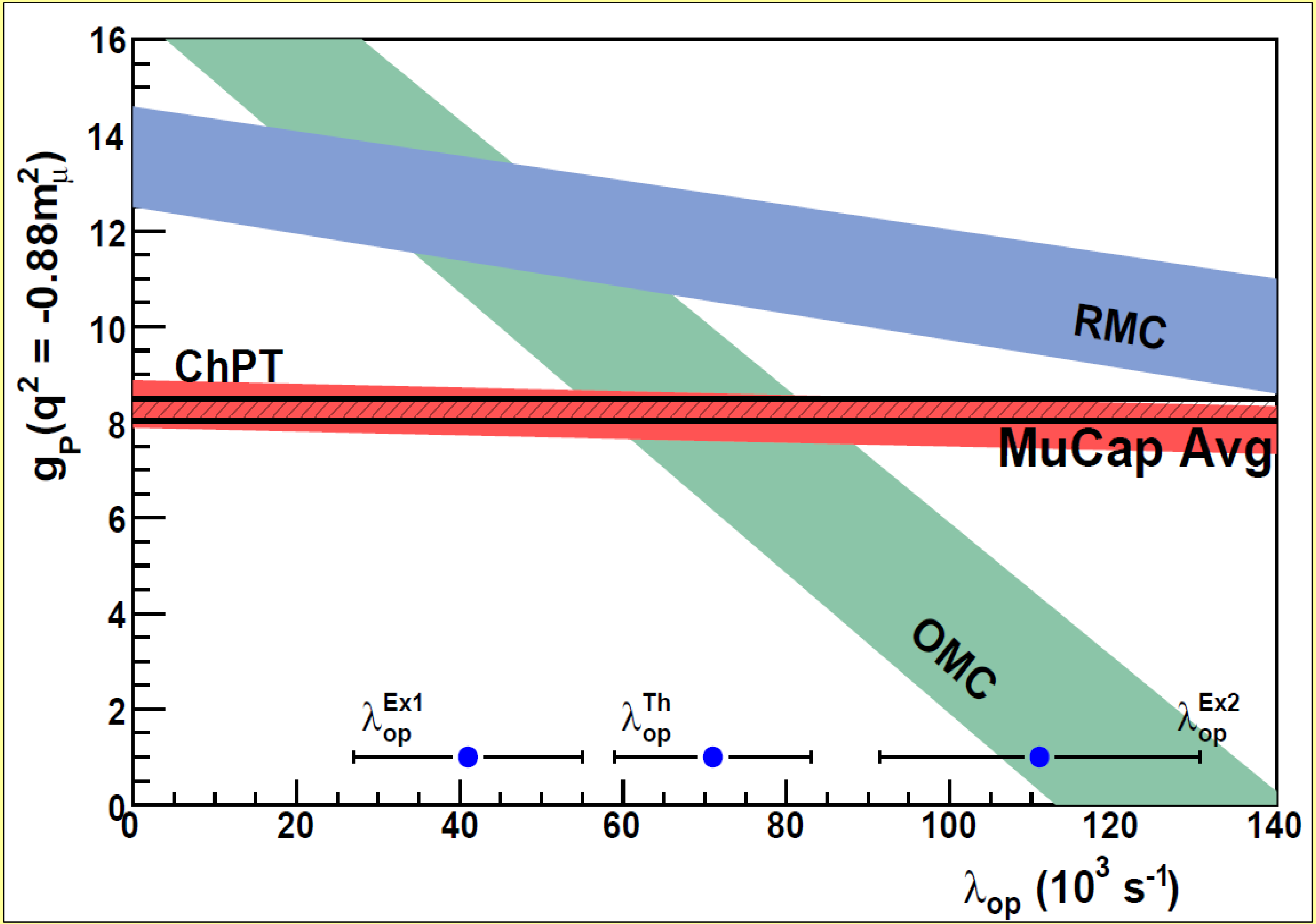
$\Lambda_S^{Th} = 693.3\ s^{-1}\ (aver.) + 19.4s^{-1}(r.c.) = 712.7 \pm 3.0 \pm 3.0\ s^{-1}$

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

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

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

Precise and unambiguous MuCap result solves longstanding puzzle



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.

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

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

MuCap collaboration

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