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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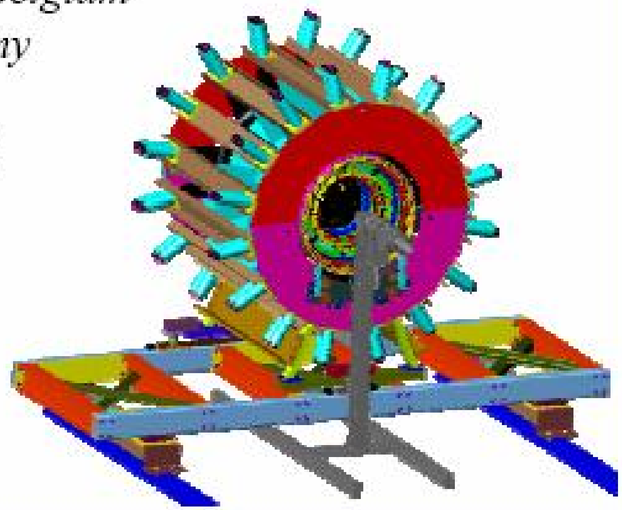
University of Illinois, Urbana-Champaign, USA
Universite Catholique de Louvain, Belgium
TU Munich,Garching, Germany
Boston University, USA
University of Kentucky, USA



@ PSI

ГРУППА МЕЗОЯДЕРНЫХ РЕАКЦИЙ

- Вед.н.с. к.н. - Семенчук Г.Г.
- Ст.н.с. к.н. - Маев Е.М.
- Ст.н.с. - Петров Г.Е.
- Ст.н.с. к.н. - Воропаев Н.И.
- Н.с. - Балин Д.В.
- Н.с. - Смиренин Ю.В.

  Н.с. - Маев О.Е.
- Инж. пр. - Фотиева Е.В.
- Инж.оп.пр. - Дубограй В.С.
- Монт. р/а - Еремеев А.Д.


Группа Шапкина
Протий-газ
Хим. очистка и
анализ примесей
Отдел Крившича
MWPC’s, TPC
mCap
ПИЯФ
ГМР
Лаборатория
Васильева
Система
рециркуляции
Лаборатория
Алексеева
(ОНИ)
Протиевая вода
ФТИ им. Иоффе
Анализ
примесей D2

- **Стандартная Модель и структура нуклонов**
- $G_v = 0.9755 \pm 0.0005$
- $G_a = 1.245 \pm 0.003$
- $G_m = 3.582 \pm 0.003$

$Gp(th) = 8.26 \pm 0.23$

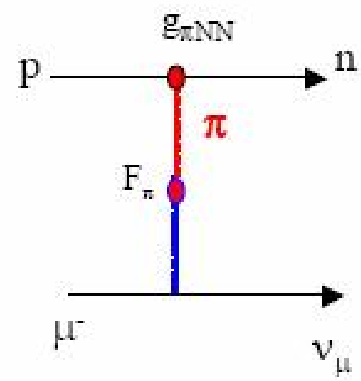
- $Gp = 6 - 12$
- $Gp\ (RMC) = 12.2 \pm 0.9 \pm 0.4$

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 % LO, 25 % NLO, 3 % NNLO

delta effect small

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

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

*NLO result

μCap

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)

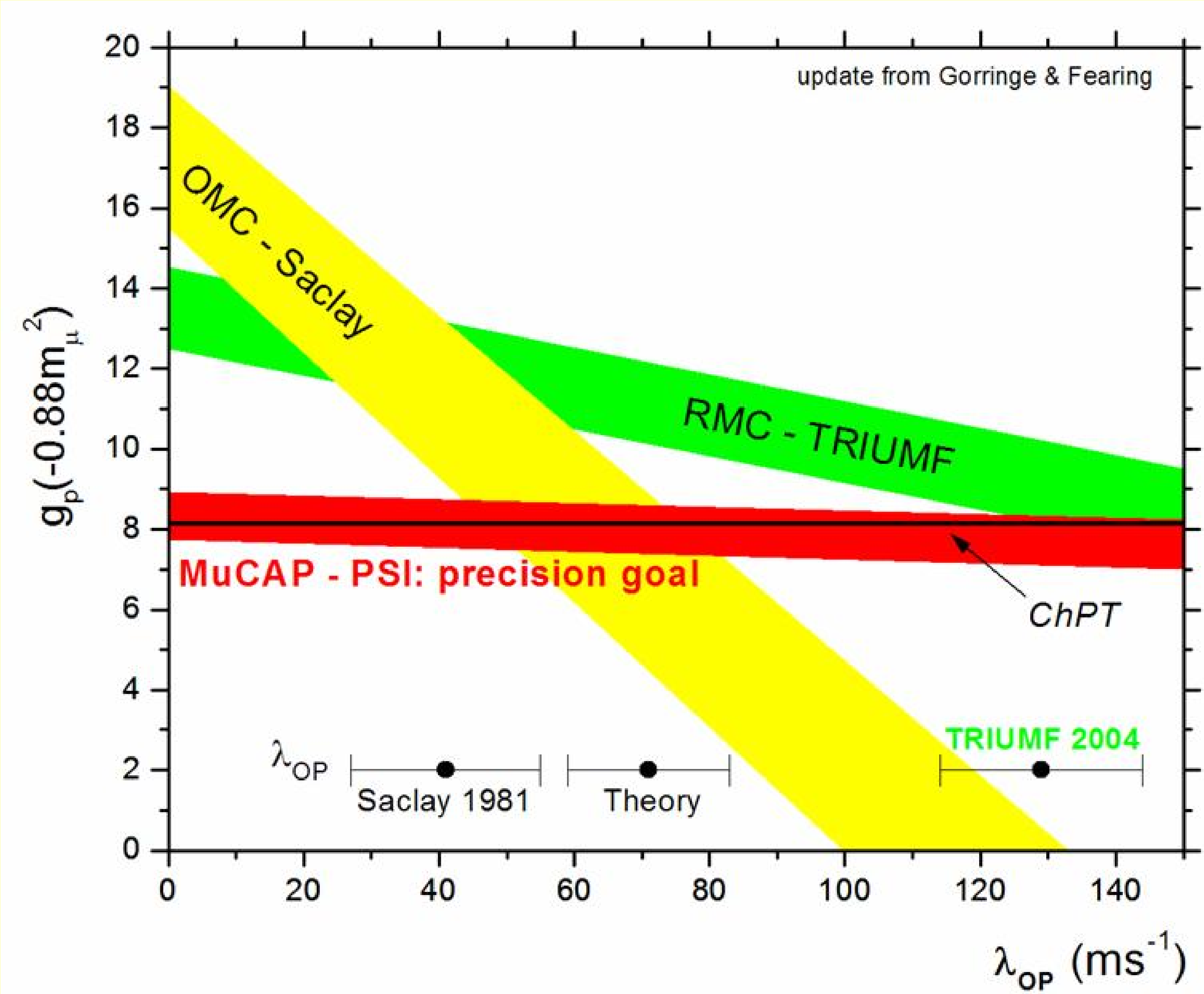
$g_P = g_P^{th}$ (1.08 ±0.19) error dominated by 3-N theory

correlation measurements

Table 1 presents the available experimental data on the OMC rate, Λ_c. Most of the measure-

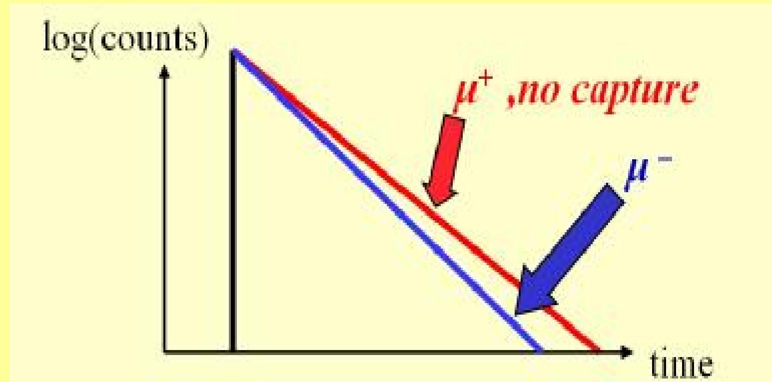
Year	Exptl.place	H_2-target	$\Lambda_c \pm \delta\Lambda_c$ s^{-1}	$\delta\Lambda_c/\Lambda_c$	Ref.	Method
1962	Chicago	liquid	428±85	20%	[12]	neutron detection
1962	Columbia	liquid	515±85	17%	[13]	-"-
1962	CERN	liquid	450±50	11%	[14]	-"-
1963	Columbia	liquid	464±42	9%	[15]	-"-
1969	CERN	gas, 8 atm	651±57	9%	[16]	-"-
1974	Dubna	gas, 41atm	686±88	13%	[17]	-"-
1981	Saclay	liquid	460±20	4.5%	[18]	life time measurement
1981	Saclay	liquid	531±33*)	6%	[19]	-"-

Table 1: Present status of $p\mu$ capture measurements.
*) corrected for ortho-para transitions in the $pp\mu$ molecule.



update from Gorringe & Fearing
OMC - Saclay
RMC - TRIUMF
MuCAP - PSI: precision goal
ChPT
TRIUMF 2004
λOP
Saclay 1981
Theory
gp(-0.88mμ2)
λOP (ms-1)
0
2
4
6
8
10
12
14
16
18
20
0
20
40
60
80
100
120
140

Стратегия MuCap эксперимента



n **Измерение времени жизни** t_{m-}
с точностью 10ppm, регистрация
10^{10} m→enn распадов
® $L_S = 1/t_{m-} - 1/t_{m+}$ **~ 1%**

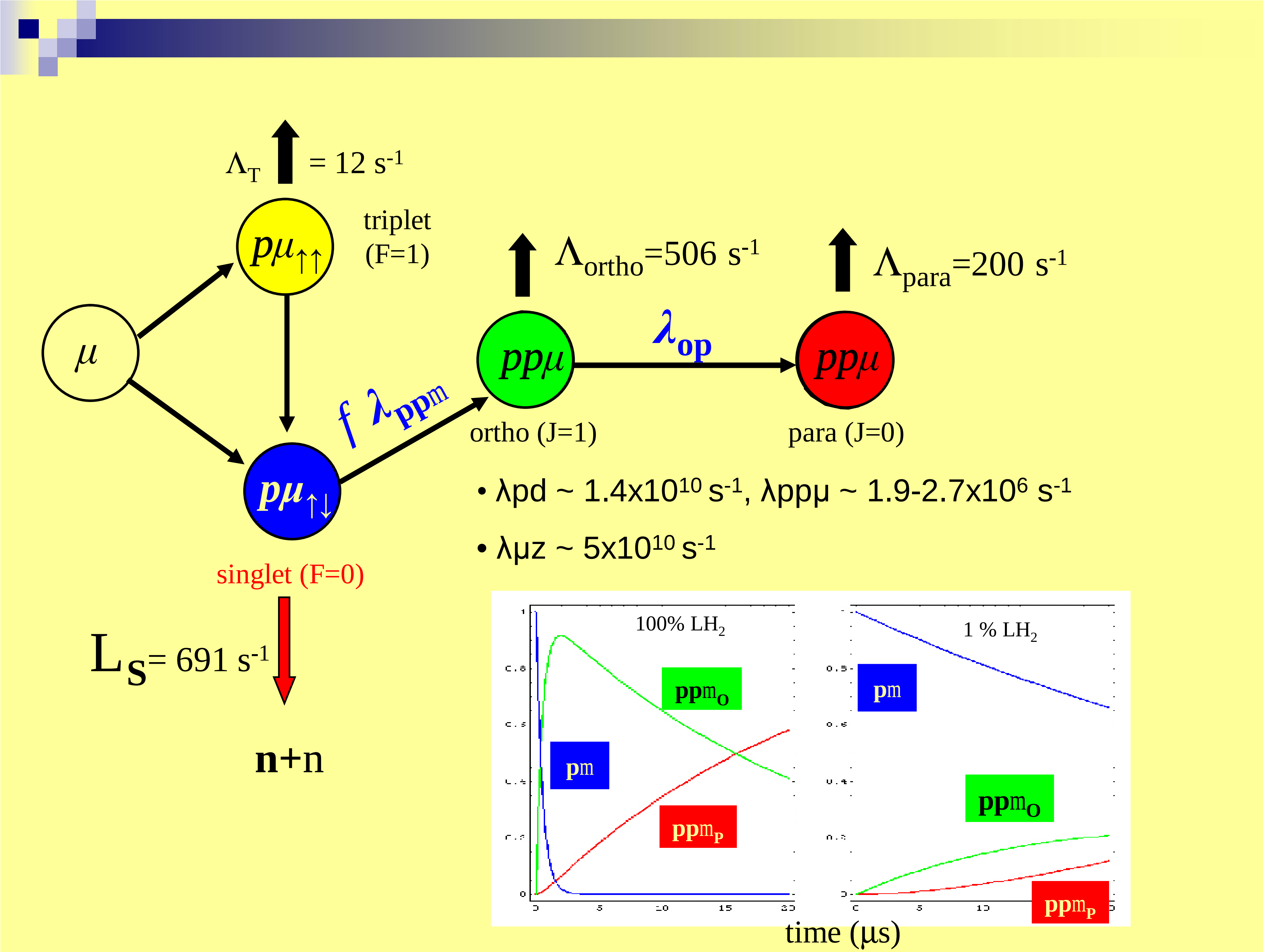
n **Однозначность интерпретации**
захват из F=0 состояния mp атома при плотности LH_2 1%

n **Использование методики активной мишени (TPC)**
с точной регистрацией координат и времени остановок мюонов, реконструкция треков электронов к точке распада

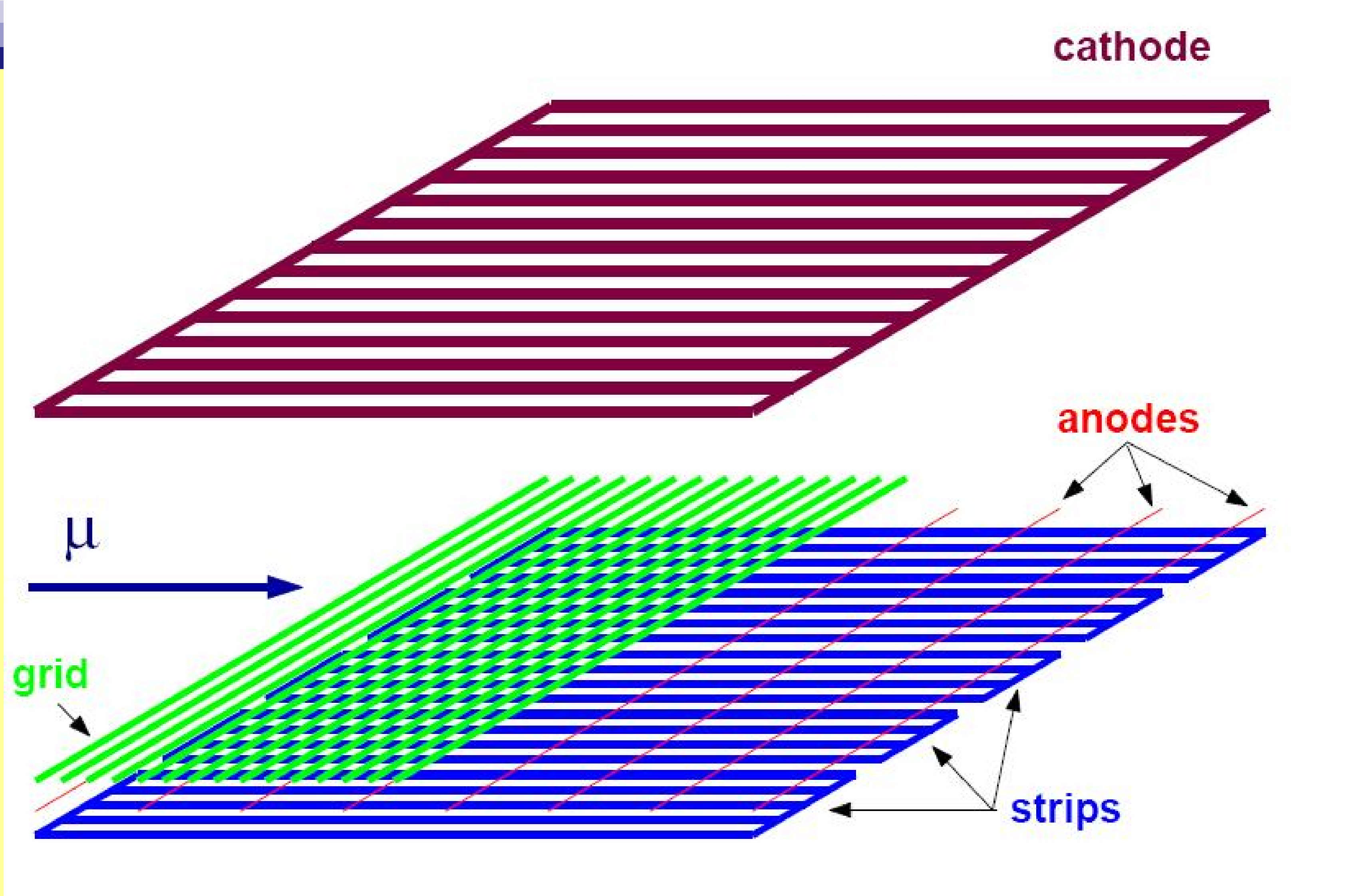
n **Использование ультрачистого водорода** $C_z < 10^{-8}$

n **Контроль примесей по реакциям:** **mp + Z ® mZ + p, ~10 ppb N_2**

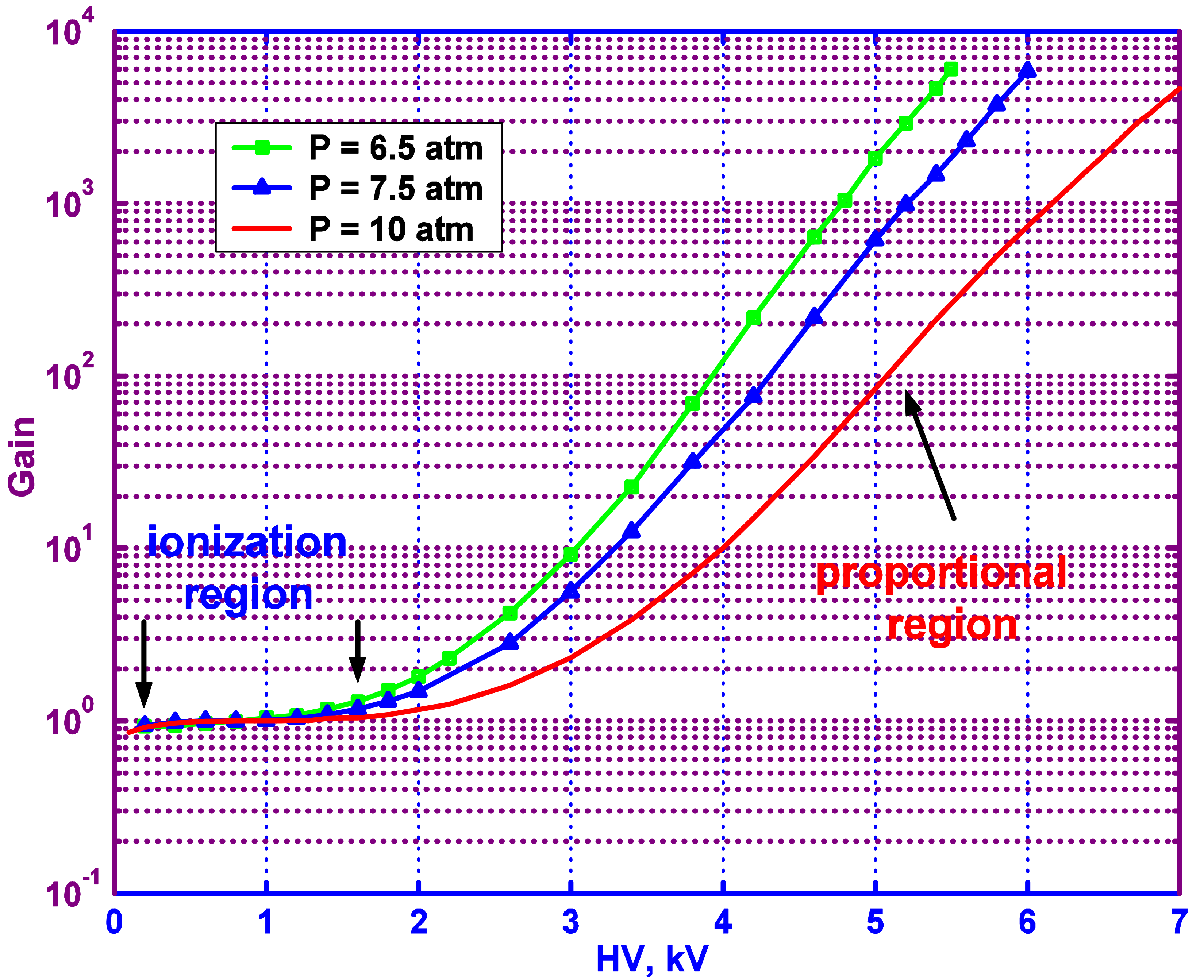
n **Обеспечение изотопической чистоты водорода**
mp + d ® md + p + 134 eV, примесь D_2~1 ppm, диффузия md ~cm



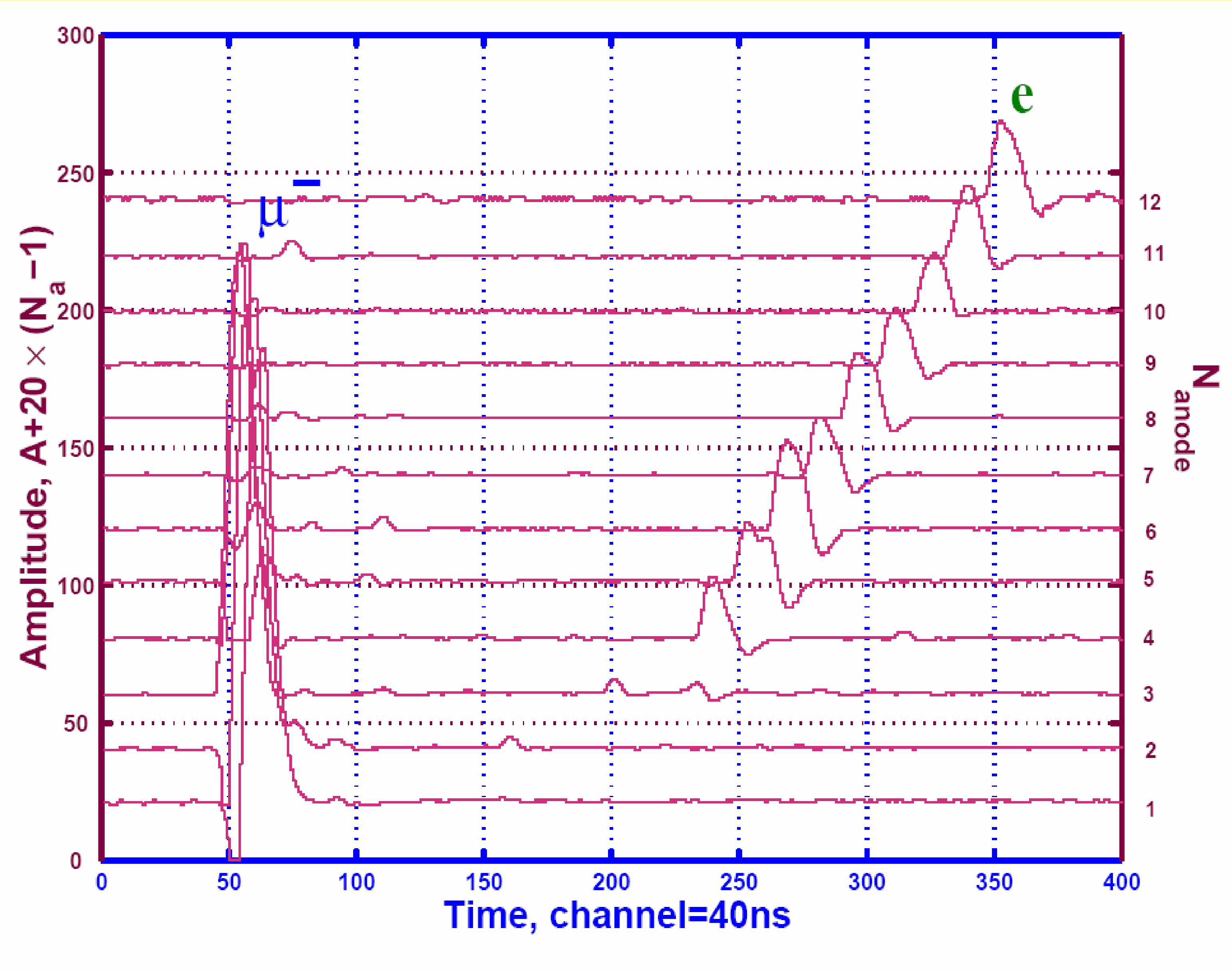
Λ_T = 12 s^{-1}
$p\mu_{\uparrow\uparrow}$
triplet
(F=1)
μ
Λ_{ortho}=506 s^{-1}
Λ_{para}=200 s^{-1}
$pp\mu$
λ_{op}
$pp\mu$
f λ_{ppm}
ortho (J=1)
para (J=0)
$p\mu_{\uparrow\downarrow}$
• λpd ~ 1.4x10^{10} s^{-1}, λppμ ~ 1.9-2.7x10^{6} s^{-1}
• λμz ~ 5x10^{10} s^{-1}
singlet (F=0)
L_S= 691 s^{-1}
n+n
100% LH_2
ppm_O
pm
ppm_P
1 % LH_2
pm
ppm_O
ppm_P
time (μs)



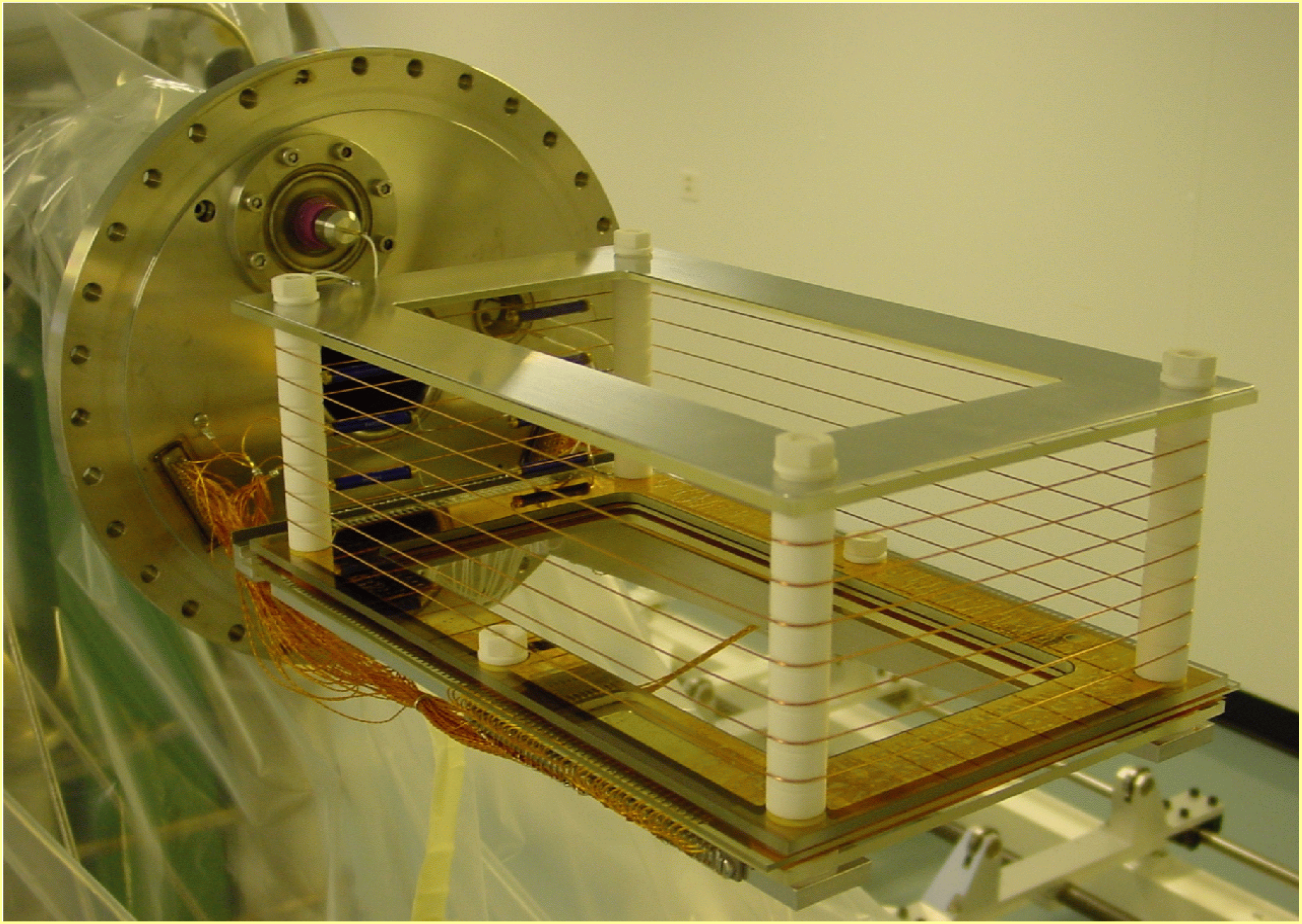
Верхний катод- 300мкм,Fe,шаг- 3мм, U~ 25-30 кВ,дрейф 0.7см/мкс
Катодная плоскость-80 мкм,Fe,шаг-1мм, зазор- 2x3.5 мм,U~5-6.4 кВ
Аноды- 25 мкм,W(Au),шаг-4мм,75 каналов. Стрипы – 34 канала

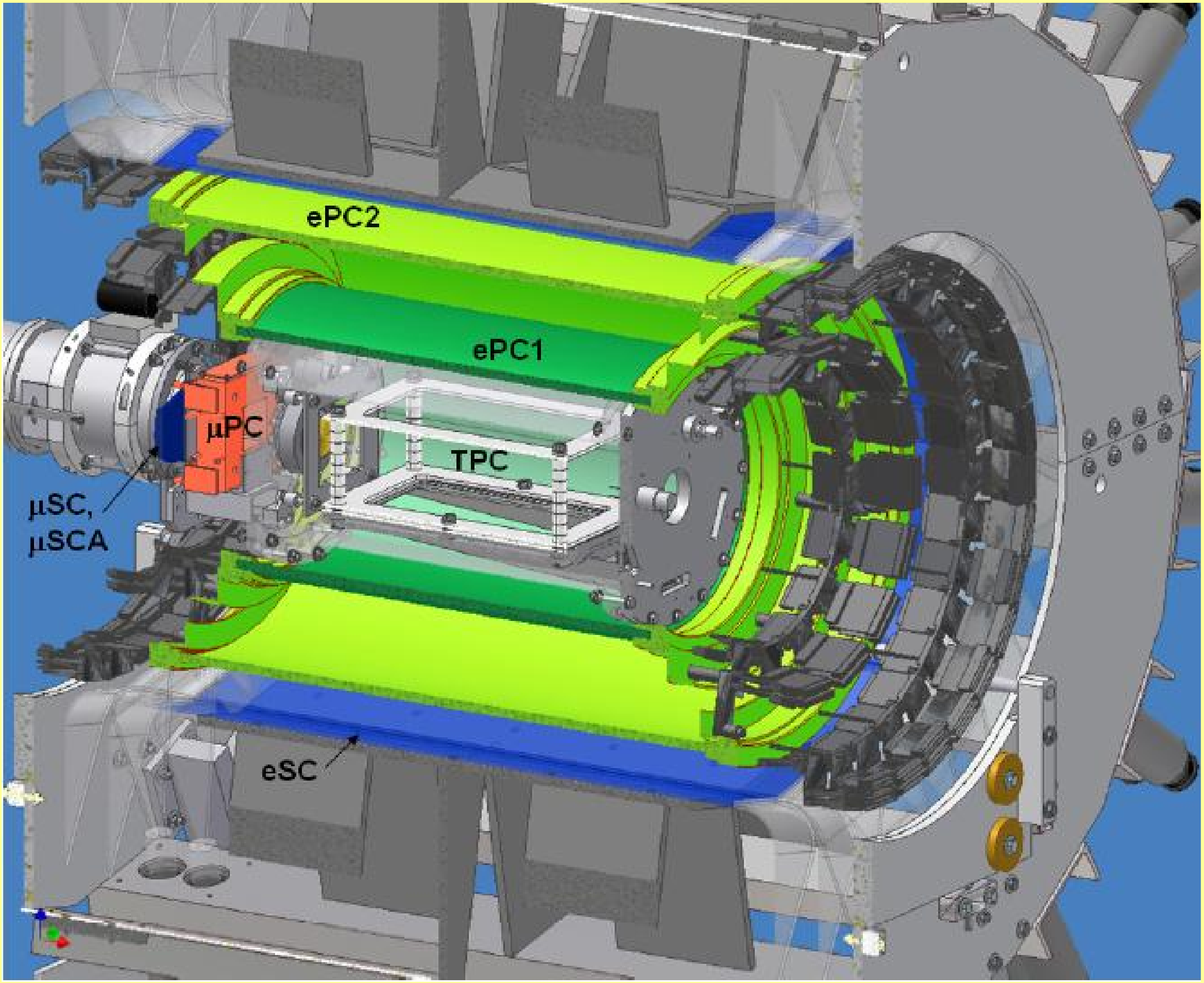


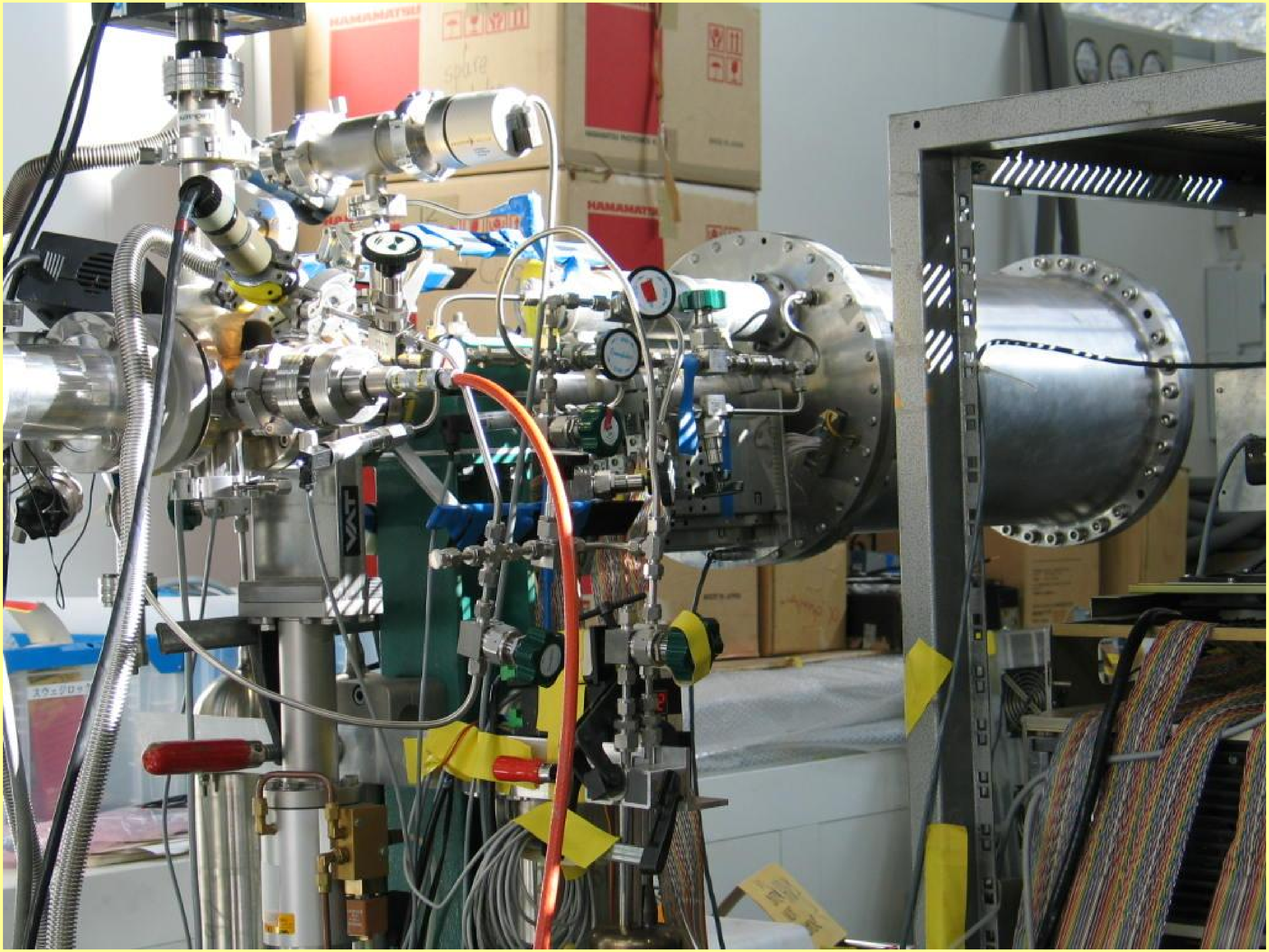
P = 6.5 atm
P = 7.5 atm
P = 10 atm
ionization region
proportional region
Gain
HV, kV
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
0
1
2
3
4
5
6
7

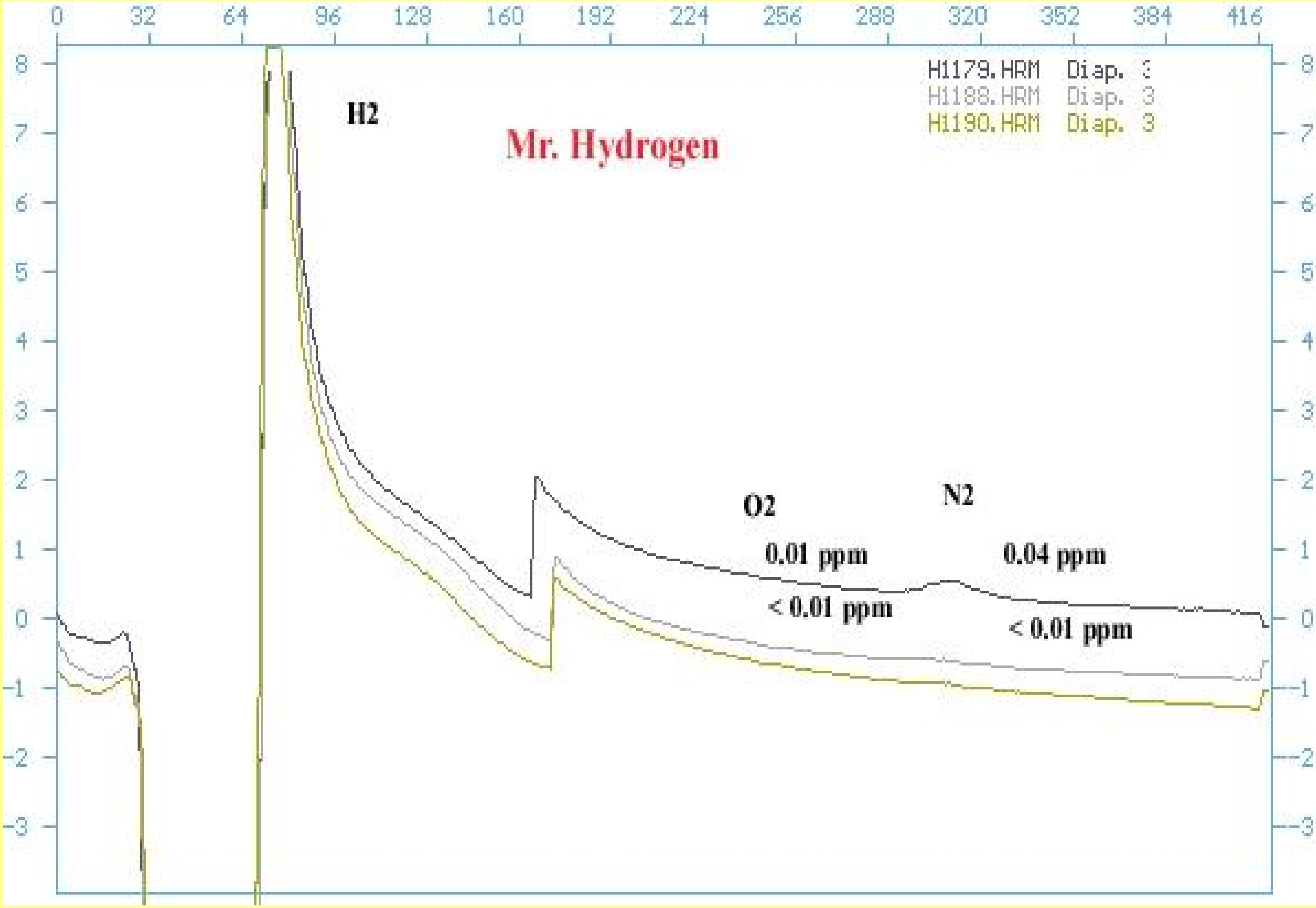


e
μ⁻
Amplitude, $A+20\times(N_a-1)$
Time, channel=40ns
N_{anode}
0
50
100
150
200
250
300
350
400
12
11
10
9
8
7
6
5
4
3
2
1




ePC2
ePC1
μPC
TPC
μSC,
μSCA
eSC


HAMAMATSU
HAMAMATSU
VAT



H2
Mr. Hydrogen
H1179.HRM Diap. 3
H1188.HRM Diap. 3
H1190.HRM Diap. 3
O2
N2
0.01 ppm
0.04 ppm
< 0.01 ppm
< 0.01 ppm

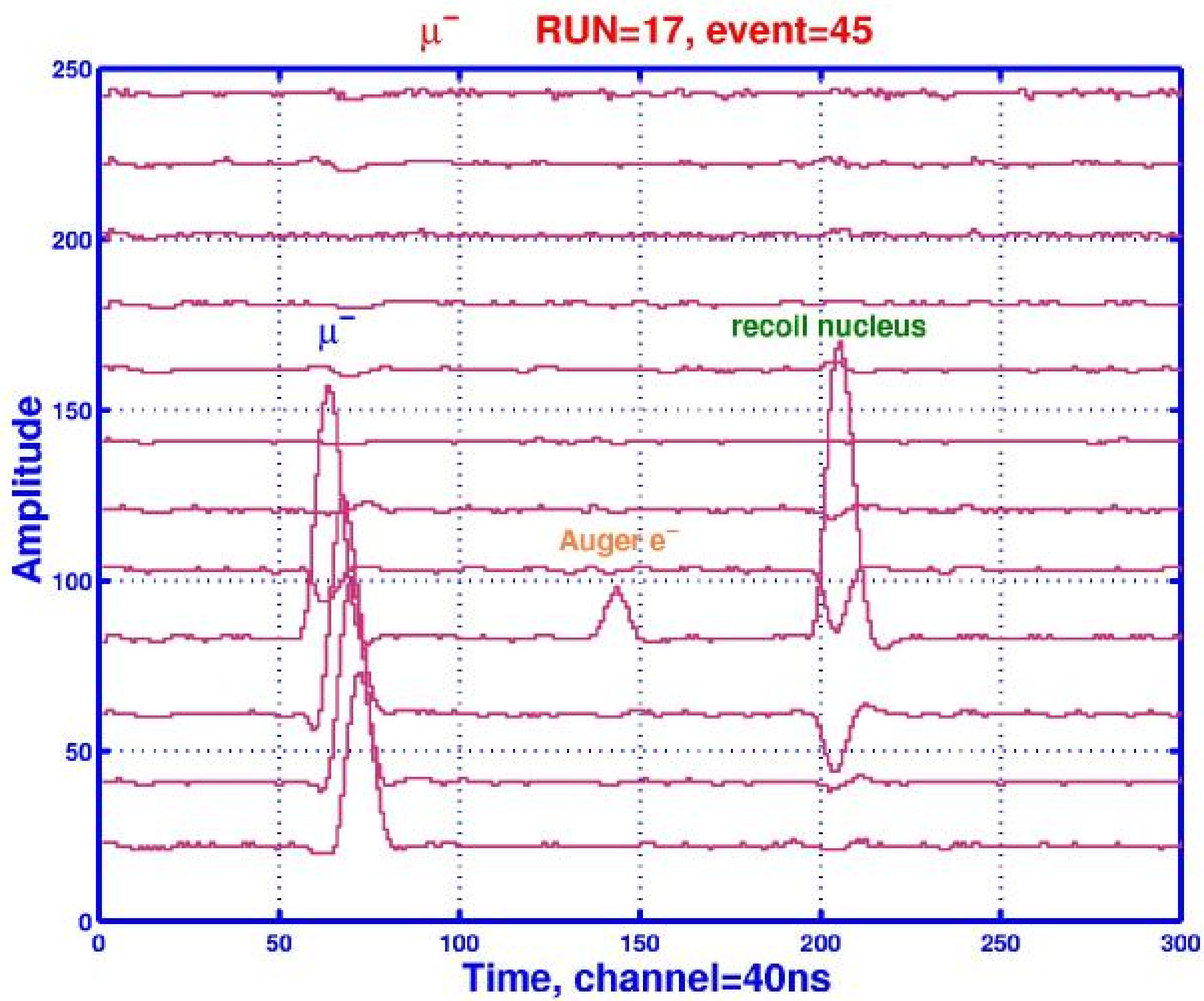
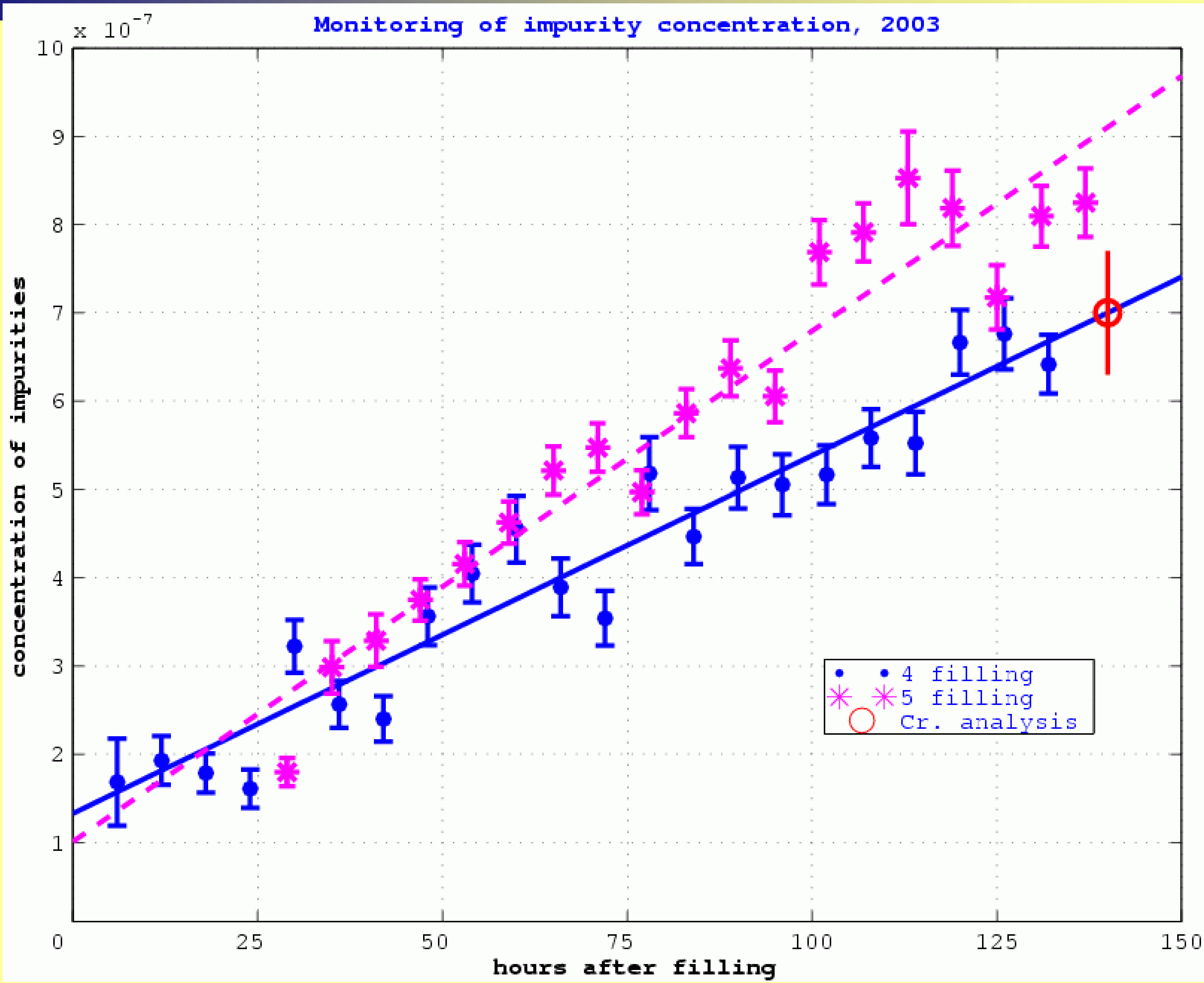
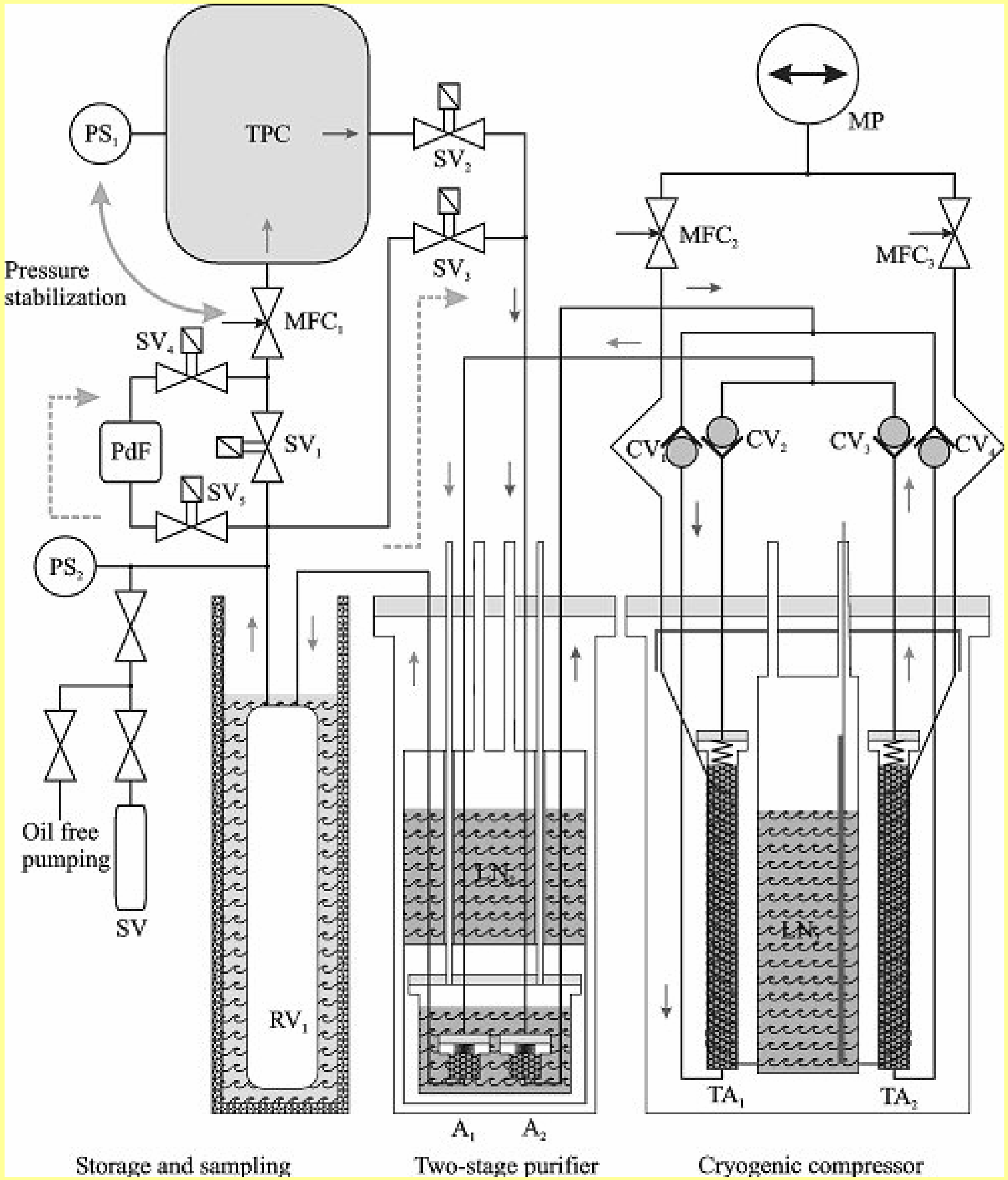
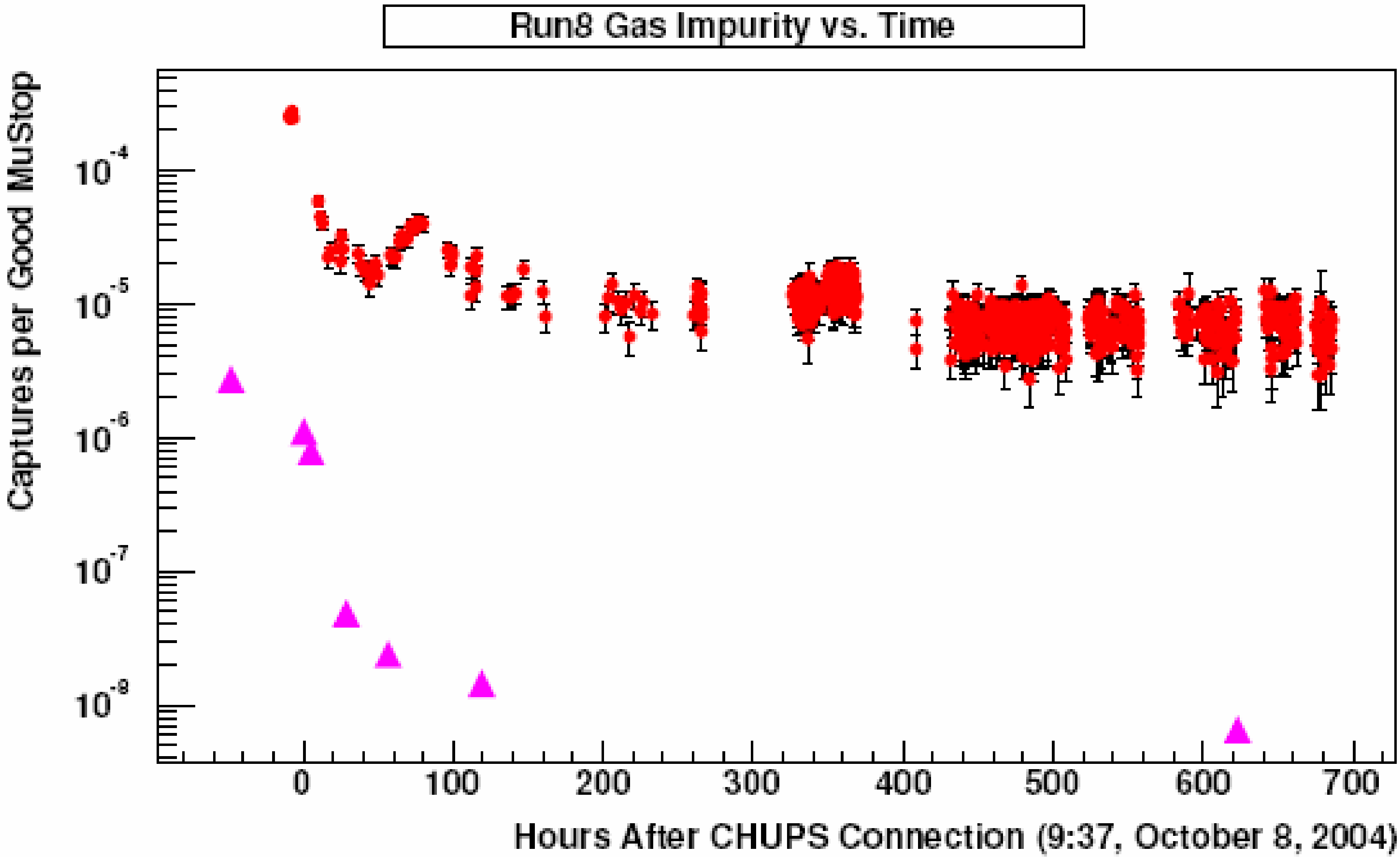


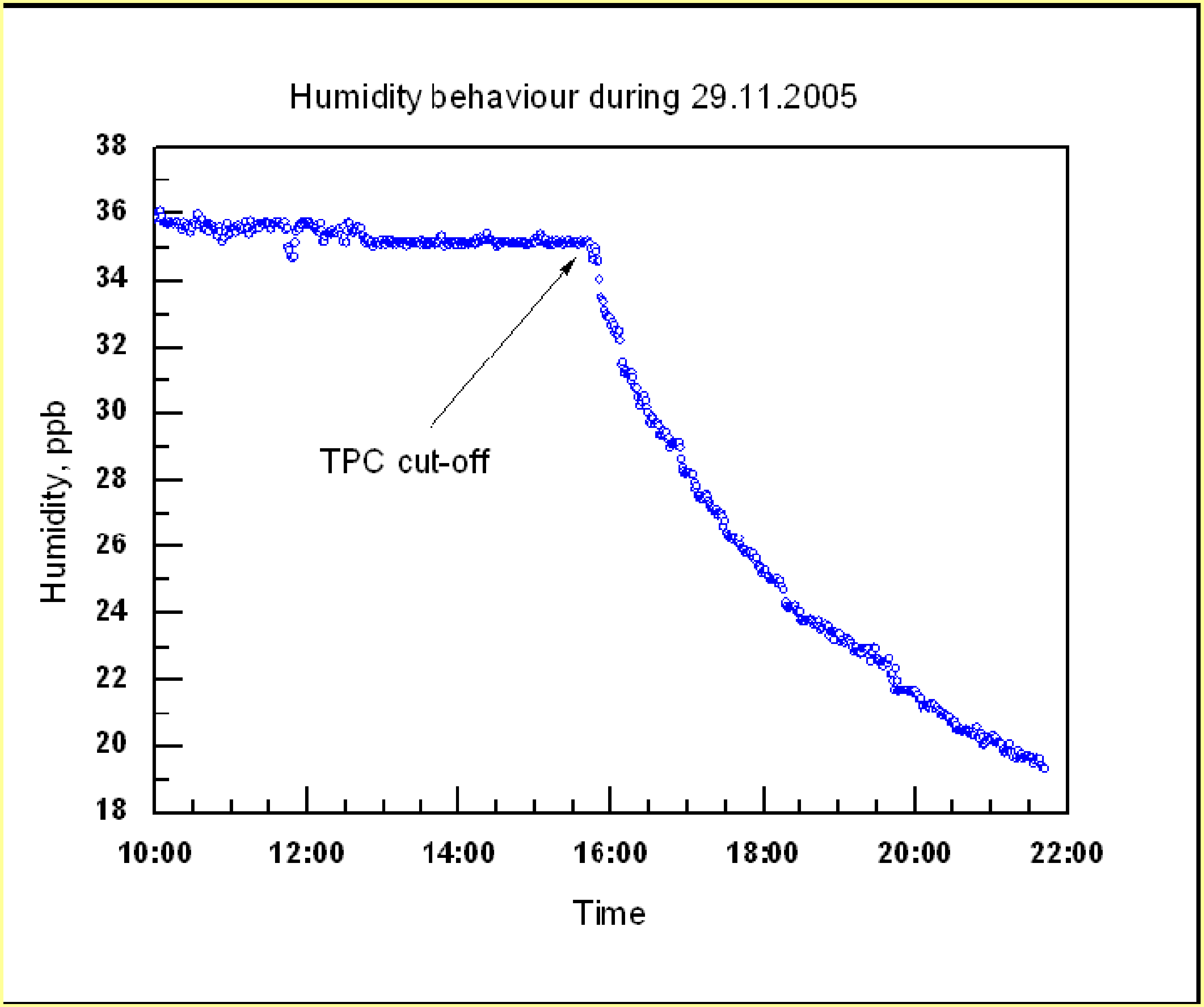
Figure 3: Display of flash ADC's showing typical event with signals from muon, Auger electron and signal from recoil nucleus.


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

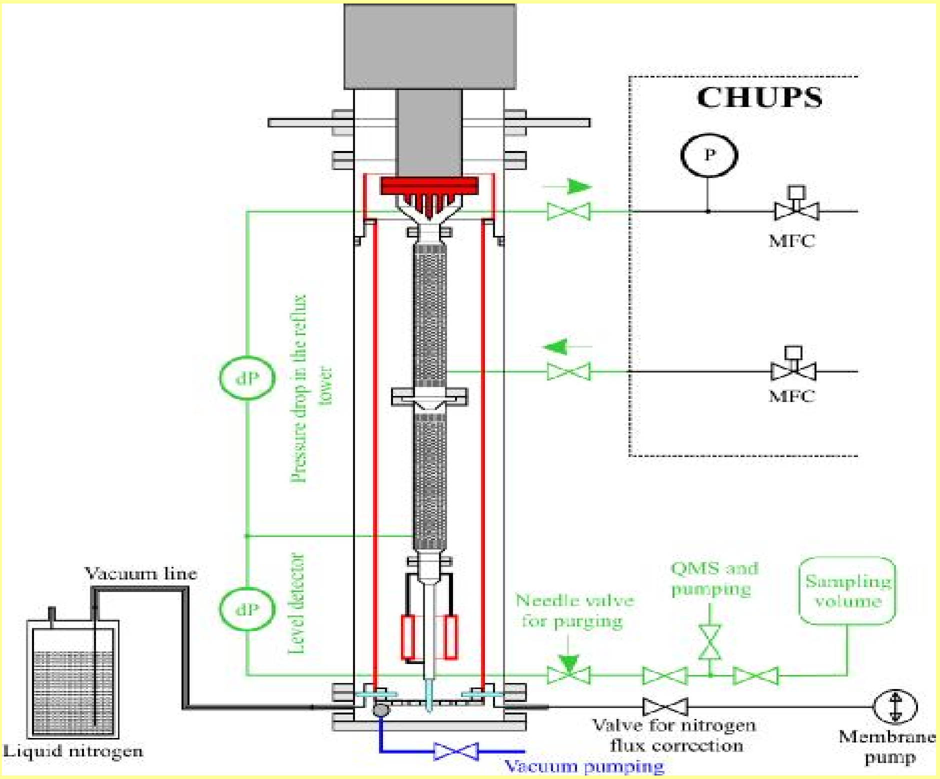


TPC
PS1
SV2
SV3
MP
MFC2
MFC3
Pressure stabilization
MFC1
SV4
PdF
SV1
SV5
PS2
CV1
CV2
CV3
CV4
Oil free pumping
SV
LN2
LN2
RV1
TA1
TA2
A1
A2
Storage and sampling
Two-stage purifier
Cryogenic compressor


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
10:00
12:00
14:00
16:00
18:00
20:00
22:00
Time
TPC cut-off

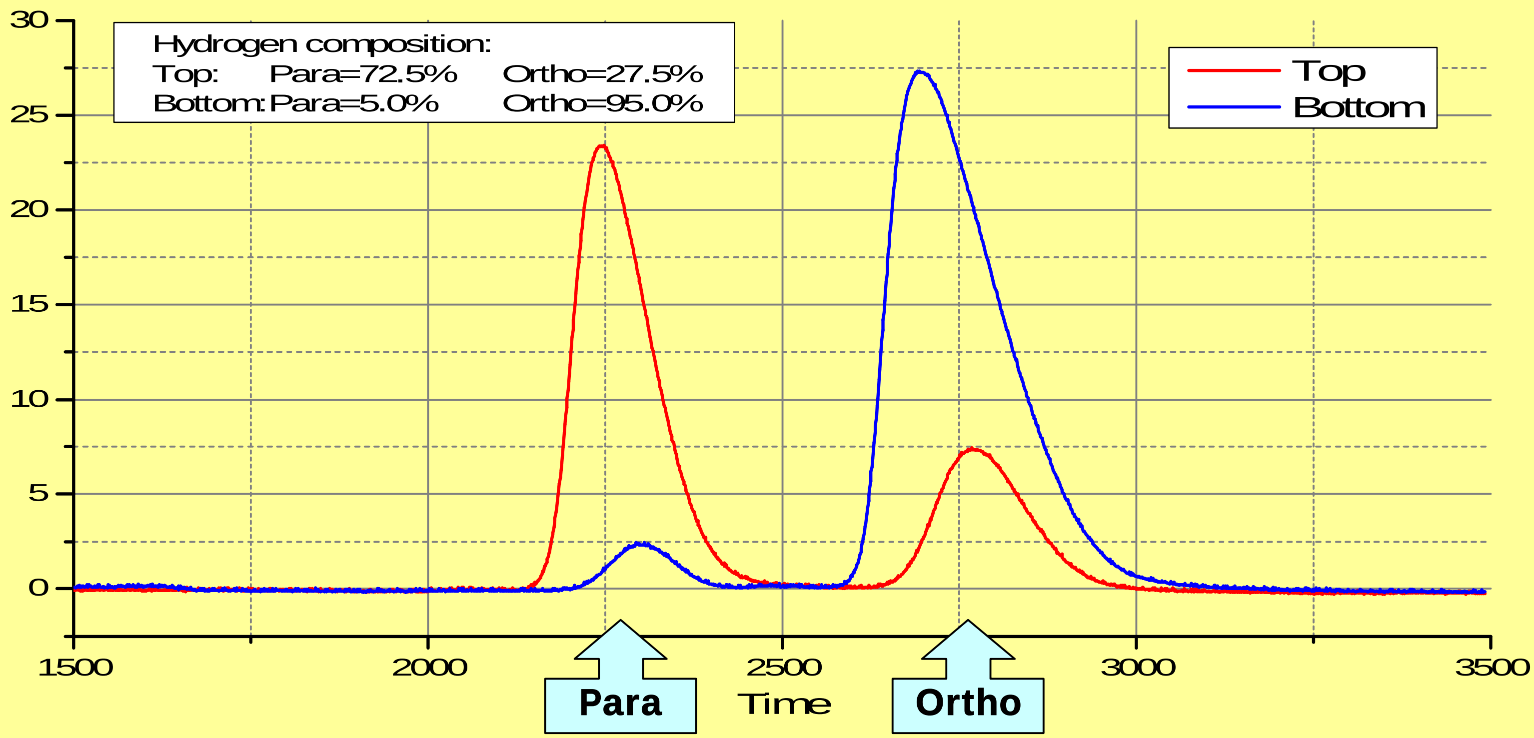
IV. the new protium isotope separation facility: production of ultra-depleted protium



1) sample #74 from column after separation run: cd < 0.14 ppm
(twice analyzed April-15 & May-18)
2) 3 stp-ltr protium sample from run-10 gas cd < 0.07 ppm
3) 0.5 stp-ltr sample with end-of-run-8 gas cd = 1.44±0.13 ppm

Ortho-Para Hydrogen Chromatogram

(Natural hydrogen, Column pressure = 1.2 bar; Reboiler power = 10W)



main results of ETH protium gas analysis

during two measurement cycles, April-15 and May-18, 2006,
10 hydrogen/protium samples were analyzed with the small ETH Tandem with unprecedented precision yielding the following results:

1) sample #74 from column after separation run: c_d < 0.14 ppm
(twice analyzed April-15 & May-18)

2) 3 stp-ltr protium sample from run-10 gas c_d < 0.07 ppm

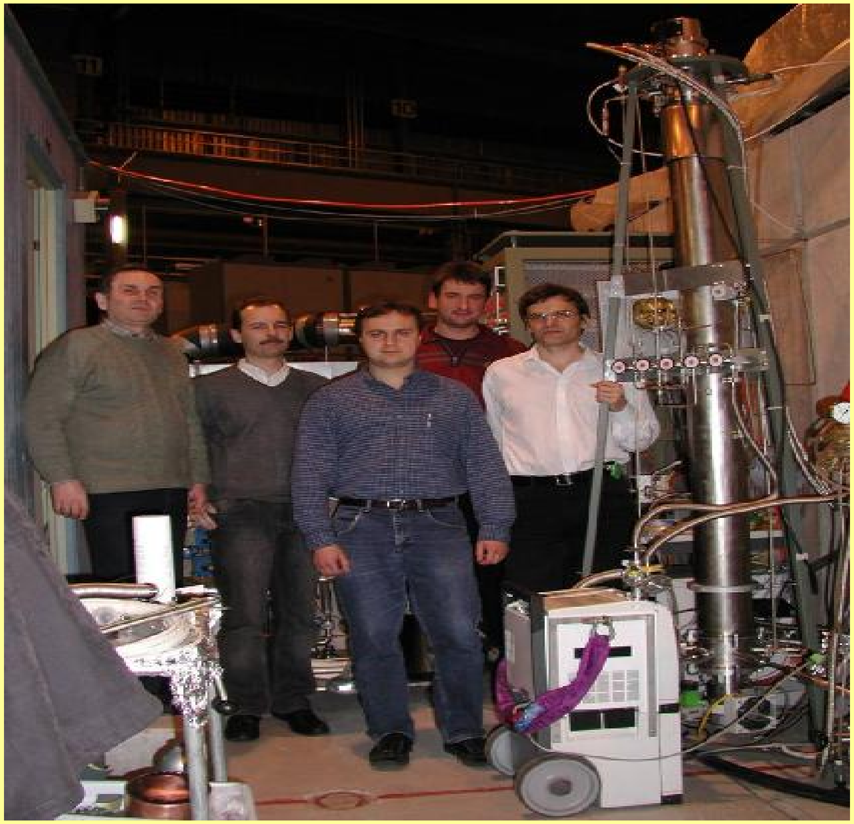
3) 0.5 stp-ltr sample with end-of-run-8 gas c_d = 1.44±0.13 ppm
(after applying small corr. of 0.13 ppm)

4) protium sample with run-9 gas c_d = 1.45±0.14 ppm

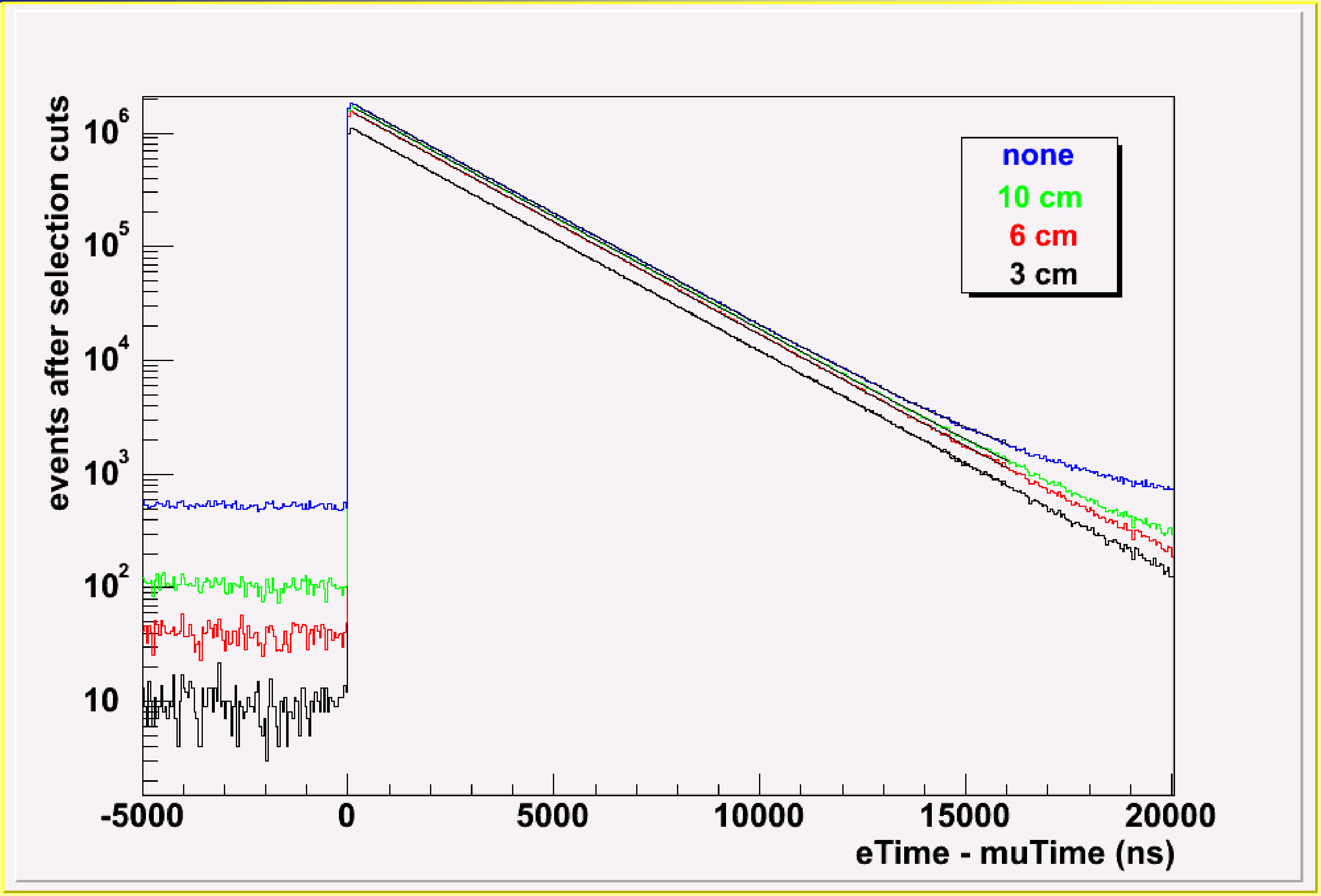
5) deuterium enriched sample #50 ("feed through, no purging", calculated enrichment factor 41 c_d = 76.9±1.6 ppm
→ back-calculation gives for run-8+run-9 gas c_d = 1.40±0.03 ppm
(systematic error not yet determined)

6) "natural" hydrogen from new 2006-bottle c_d = 126.9±1.9 ppm
agrees with Saurer result 04/04/06 old bottle c_d = 126.9 ppm
but disagrees with Saurer 01/26/05 old bottle c_d = 117.6 ppm

CHUPS + cryogenic separation column



Status report for the period March – April 2006



Histogram shows dramatic accidental suppression in the lifetime spectrum due to m-e impact parameter cuts (cut radius given in the legend).

Общая набранная статистика

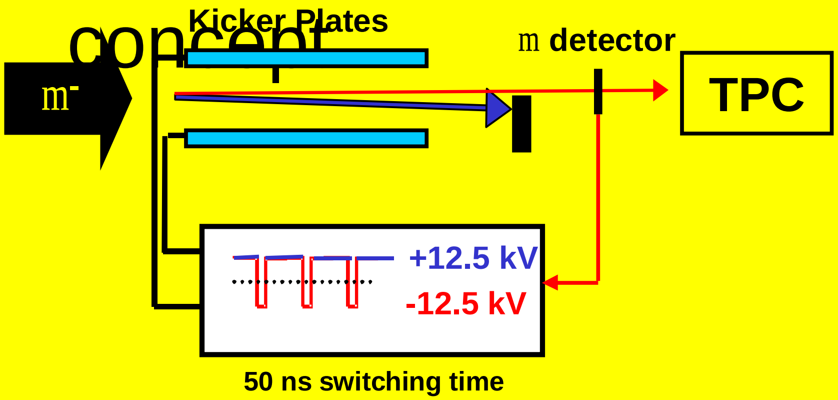
Год	$\mu^+ \times 10^9$	$\mu^- \times 10^9$	D_2(ppm)	H_20 (ppm)
2004	0.2	2.0	~1.5	0.07
2005	1.4	3.5	~1.5	0.036
2006	4.0	8.0	<0.07	0.02
	5.6	13.5		

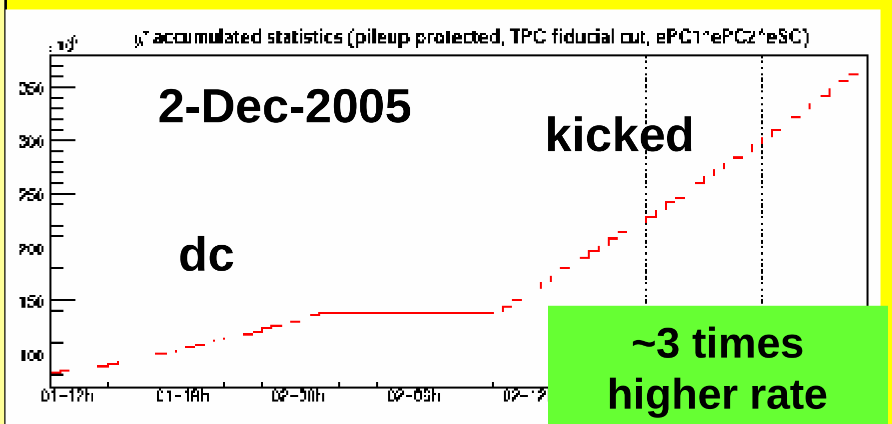
За 2006 год набрано данных ~ 25 Tb

μCap Unique Capabilities: Muon-On-Demand

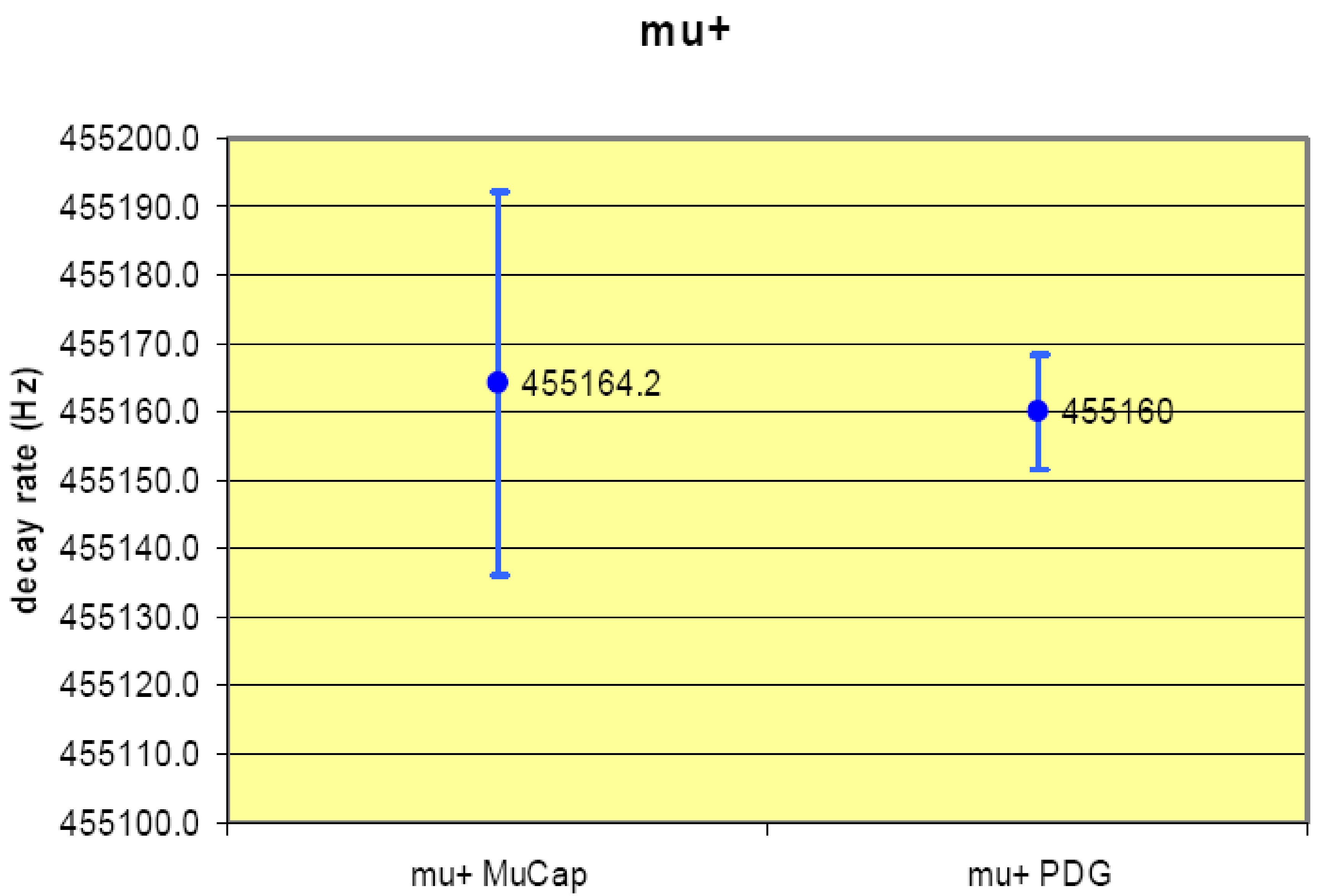
- Single muon requirement (to prevent systematics from pile-up)
- limits accepted μ rate to ~ 7 kHz,
- while PSI beam can provide ~ 70 kHz

- Muon-On-Demand concept

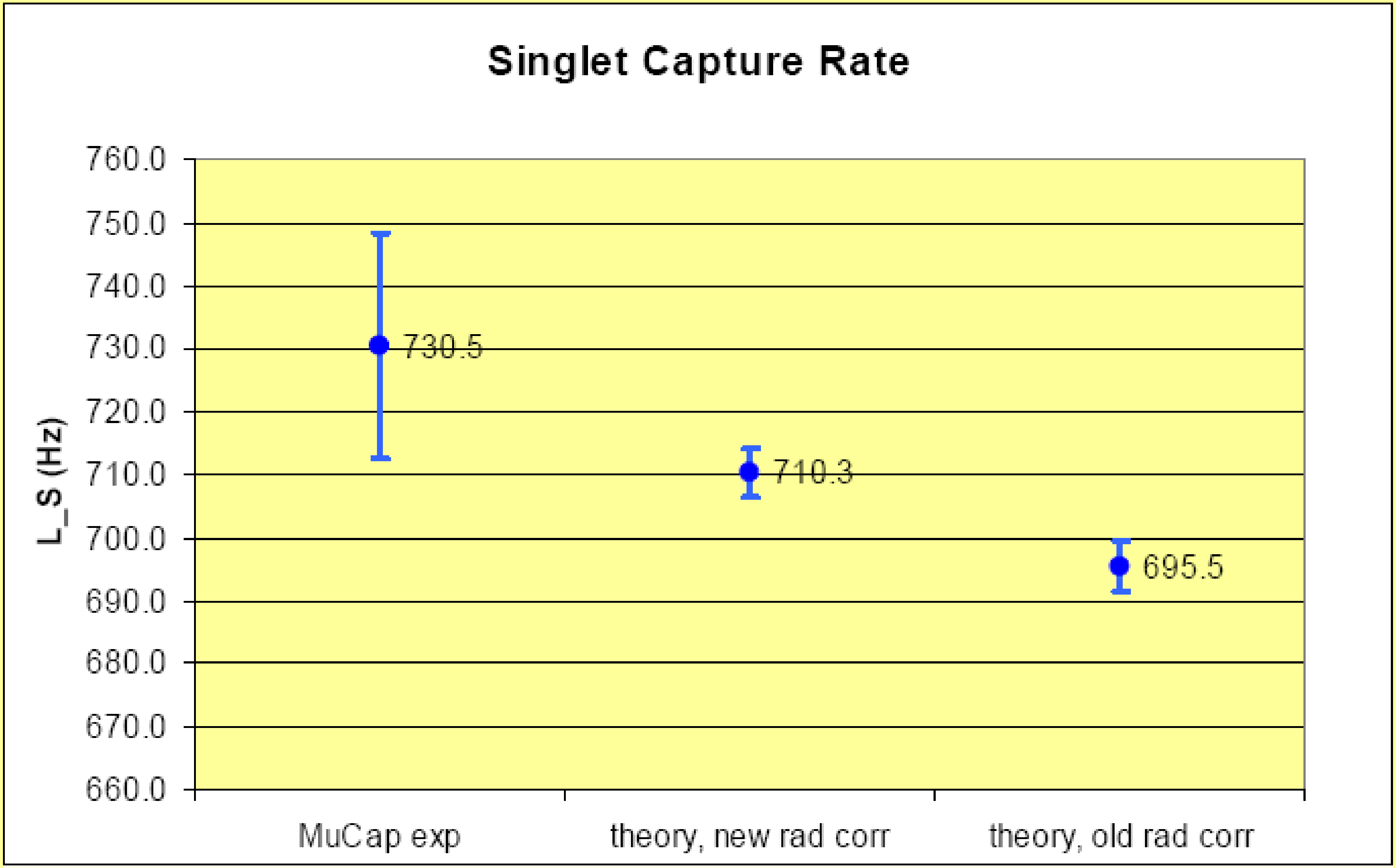


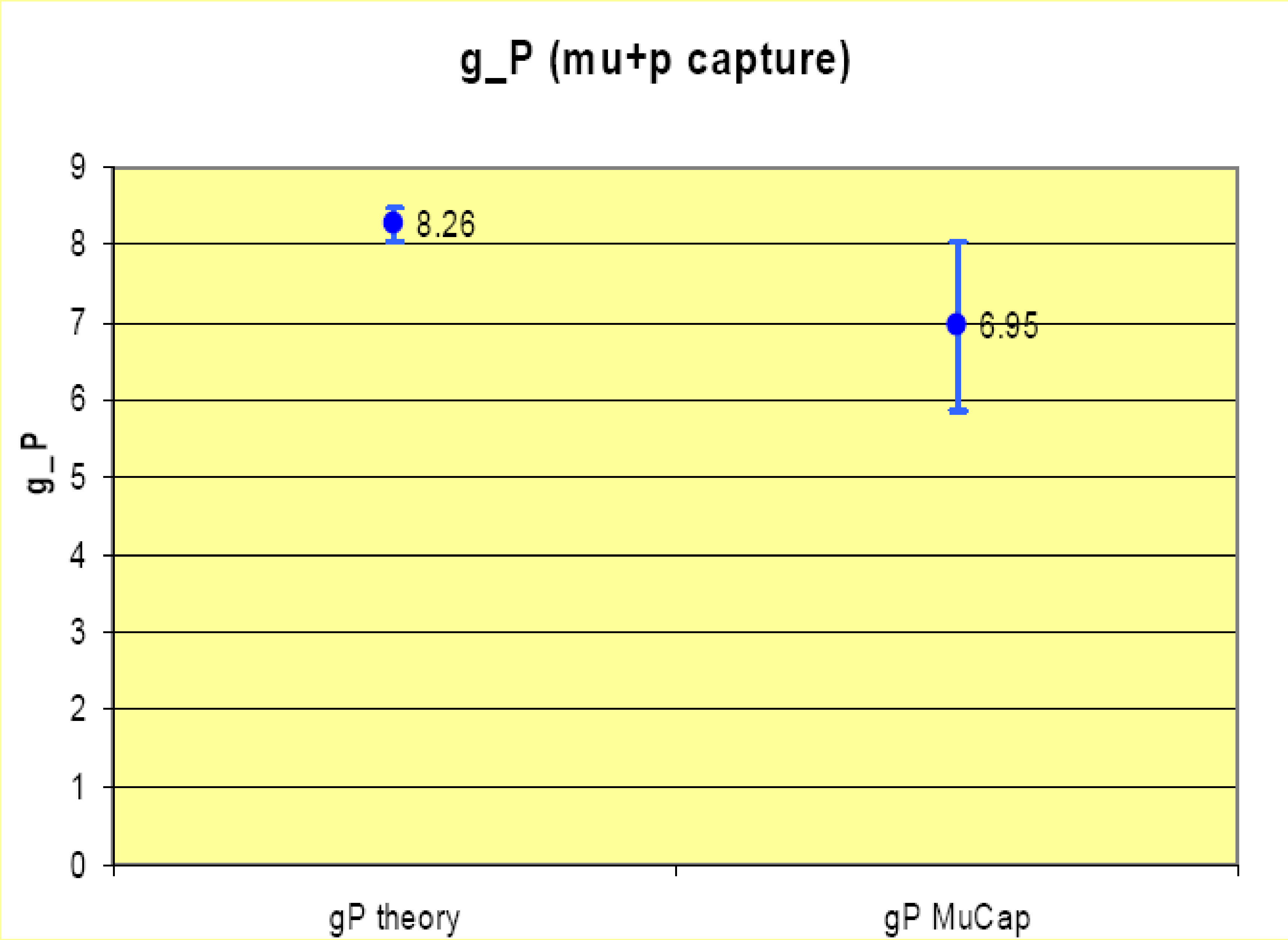


- Beamline



mu+
decay rate (Hz)
455200.0
455190.0
455180.0
455170.0
455160.0
455150.0
455140.0
455130.0
455120.0
455110.0
455100.0
455164.2
455160
mu+ MuCap
mu+ PDG


Singlet Capture Rate
L_S (Hz)
760.0
750.0
740.0
730.0
720.0
710.0
700.0
690.0
680.0
670.0
660.0
730.5
710.3
695.5
MuCap exp
theory, new rad corr
theory, old rad corr


g_P (mu+p capture)
g_P
9
8
7
6
5
4
3
2
1
0
8.26
6.95
gP theory
gP MuCap

Summary

preliminary

- **Preliminary results 2004 data**

	μ**Cap**	**theory***
Λ_S	**730 ± 18**	**707 - 715**
g_P	**6.95 ± 1.09**	**8.26 ±0.23**

- **2007 plans**
  - **10^{10} events μ^+ and μ^- and suppl. measurements in 2007**
    - → Λ_S **with 1% uncertainty**
  - **μ+d proposal planned for 2007**

including Czarnecki et al. rad. corrections

ФИНАНСЫ 2006

- Тема РАН – 600 т.руб + 550 т.руб
- Минобрнаука (поездки) – 37 К USD
- Грант CRDF ~49 K USD