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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Boston University, USA
University of Kentucky, USA

PRECISION MEASUREMENT OF THE RATE OF MUON CAPTURE IN HYDROGEN GAS AND DETERMINATION IN THE PROTON'S PSEUDOSCALAR COUPLING g_P

PNPI participants in MuCAP collaboration*) :

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

$Gp(th) = 8.26 \pm 0.23$

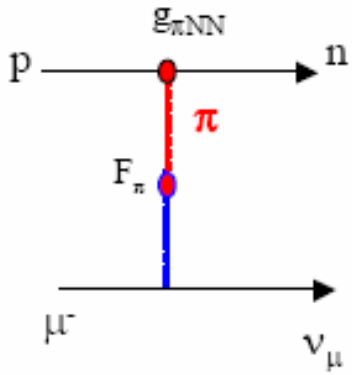
- $Gp = 6 – 12$
- $Gp\ (RMC) = 12.2 \pm 0.9 \pm 0.4$

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 % 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

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

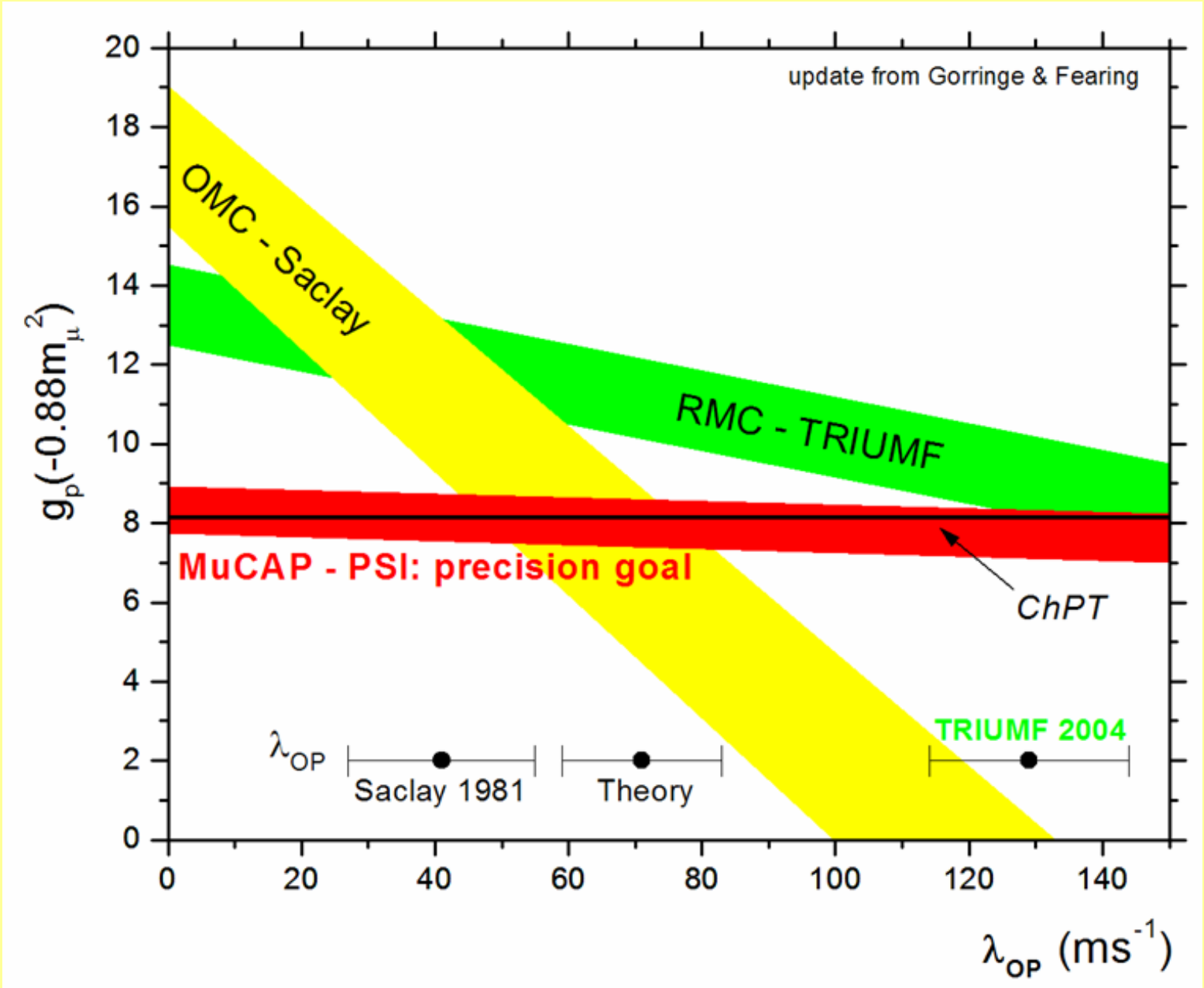
$\mu + {}^3He \rightarrow \nu + {}^3H$ Λ_{st}=1496 ±4 s^{-1} PSI (1998)
$g_p = g_p^{th}$ (1.08 ±0.19) error dominated by 3-N theory
correlation measurements

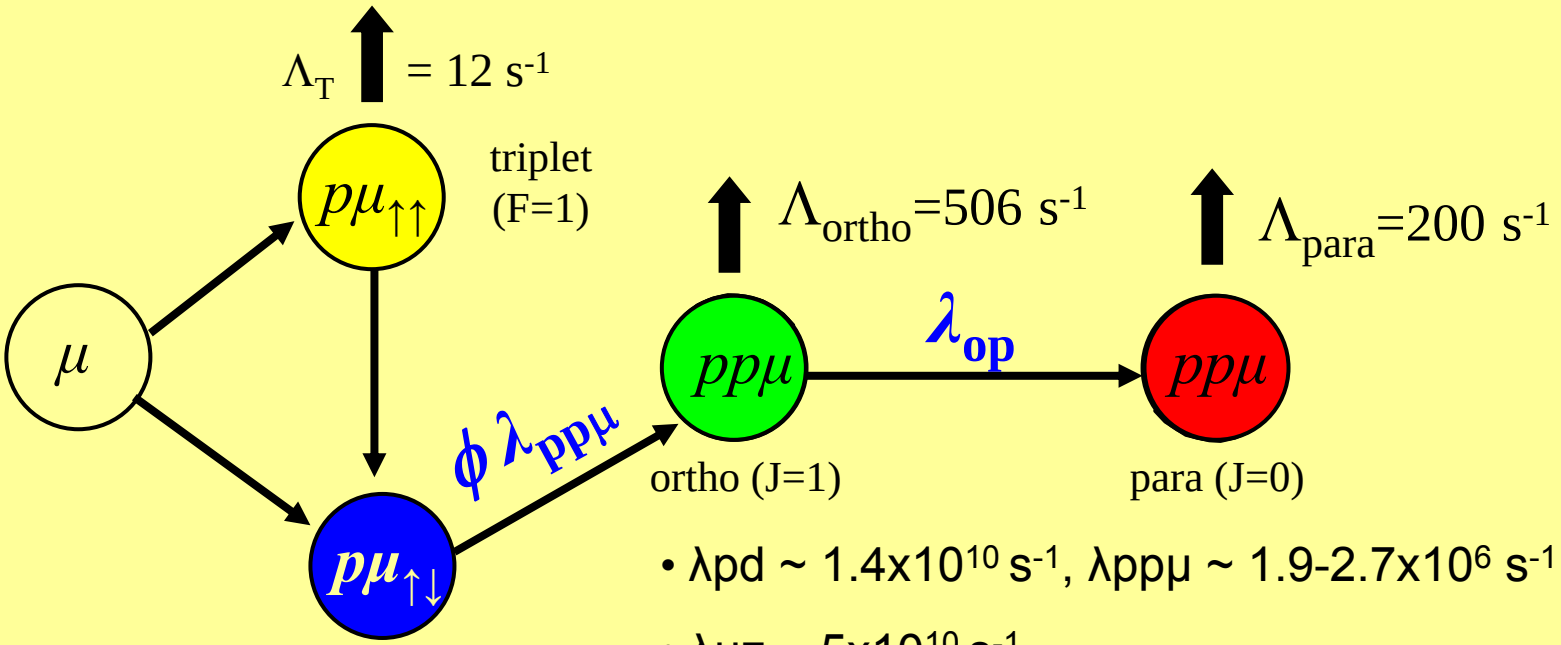
Table 1 presents the available experimental data on the OMC rate, Λ_c. Most of the measure-

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]	-"-

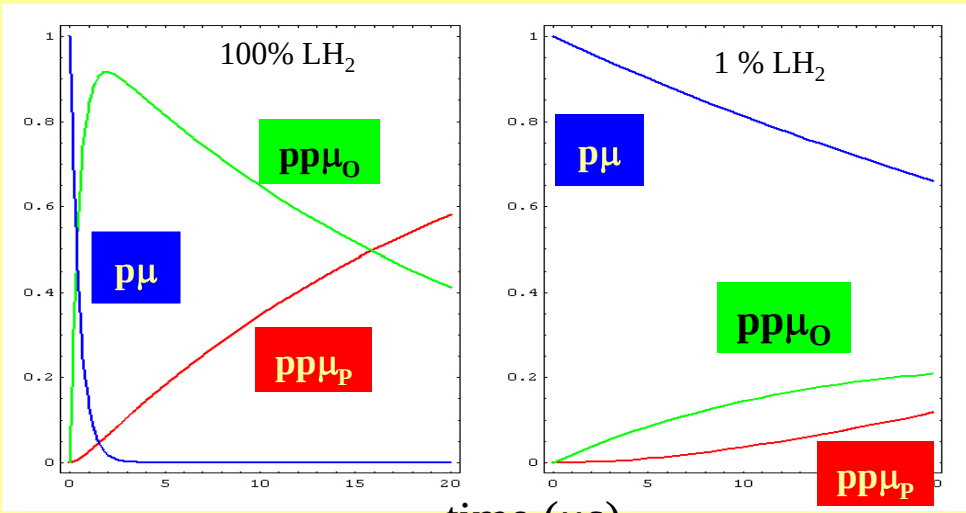
Table 1: Present status of $p\mu$ capture measurements.
*) corrected for ortho-para transitions in the $pp\mu$ molecule.

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

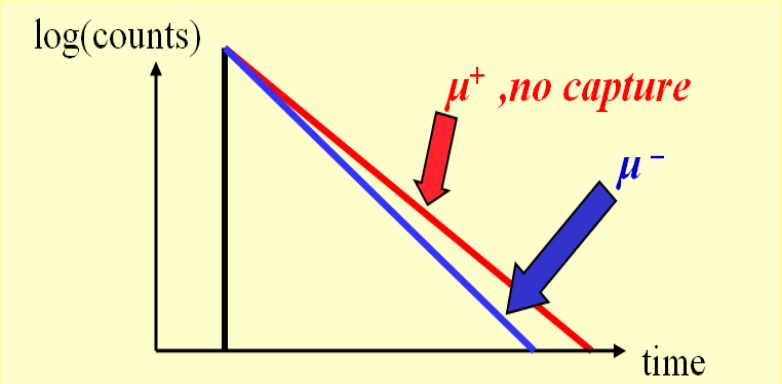

update from Gorringe & Fearing
OMC - Saclay
RMC - TRIUMF
MuCAP - PSI: precision goal
ChPT
TRIUMF 2004
λOP
Saclay 1981
Theory
gp(-0.88mμ2)
λOP (ms-1)
0
2
4
6
8
10
12
14
16
18
20
0
20
40
60
80
100
120
140



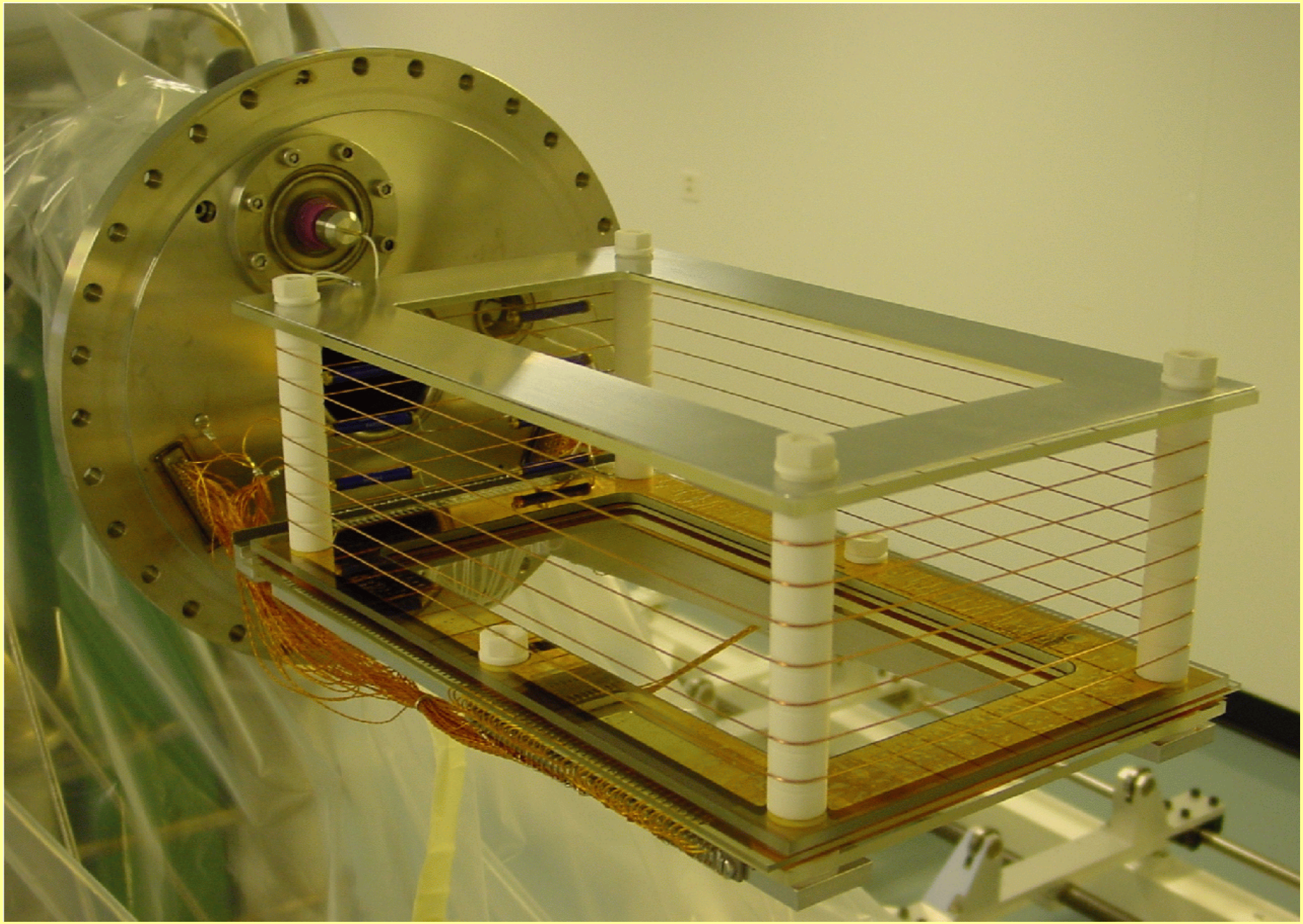
- λpd ~ 1.4x10^{10} s^{-1}, λppμ ~ 1.9-2.7x10^{6} s^{-1}
- λμz ~ 5x10^{10} s^{-1}

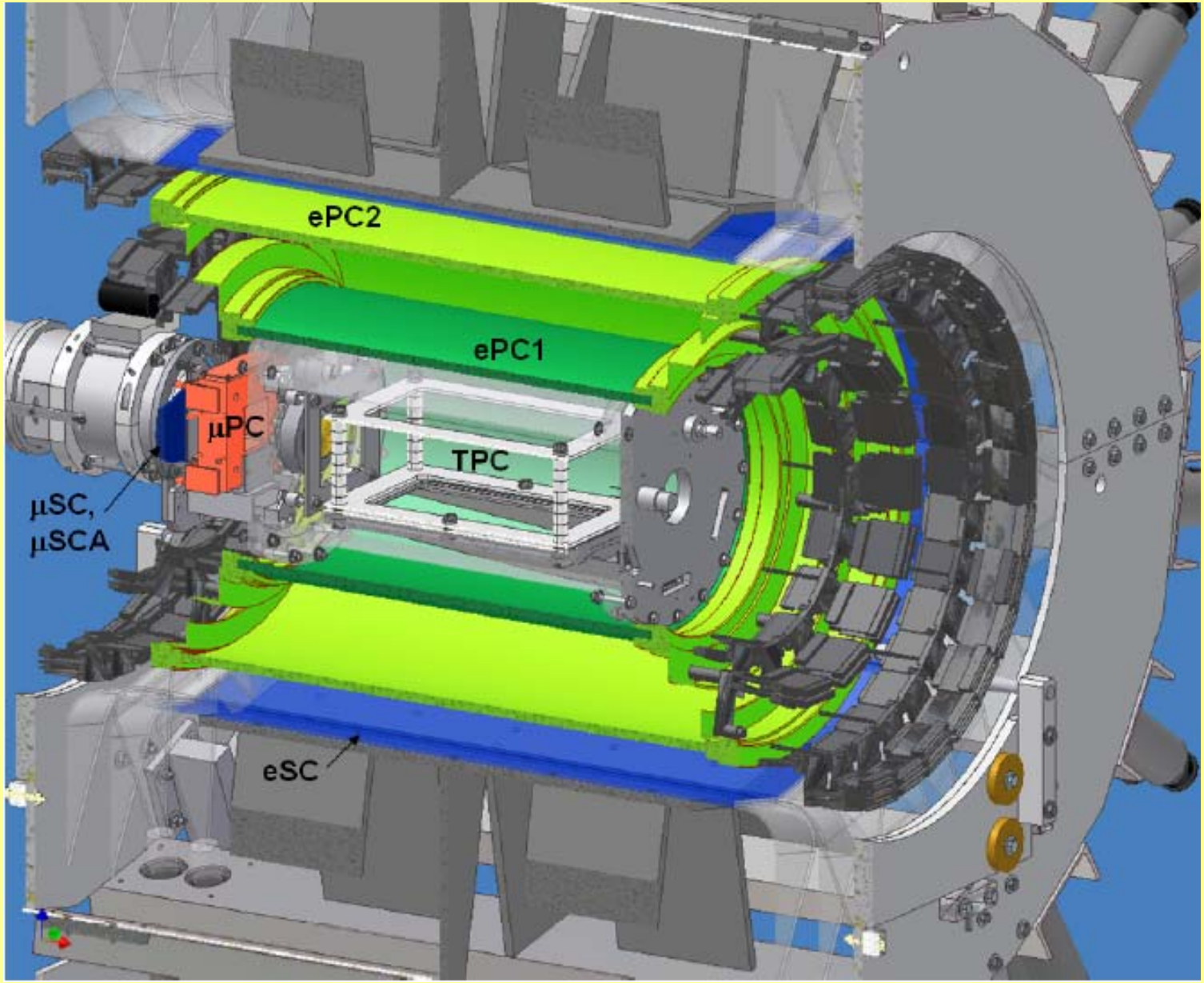


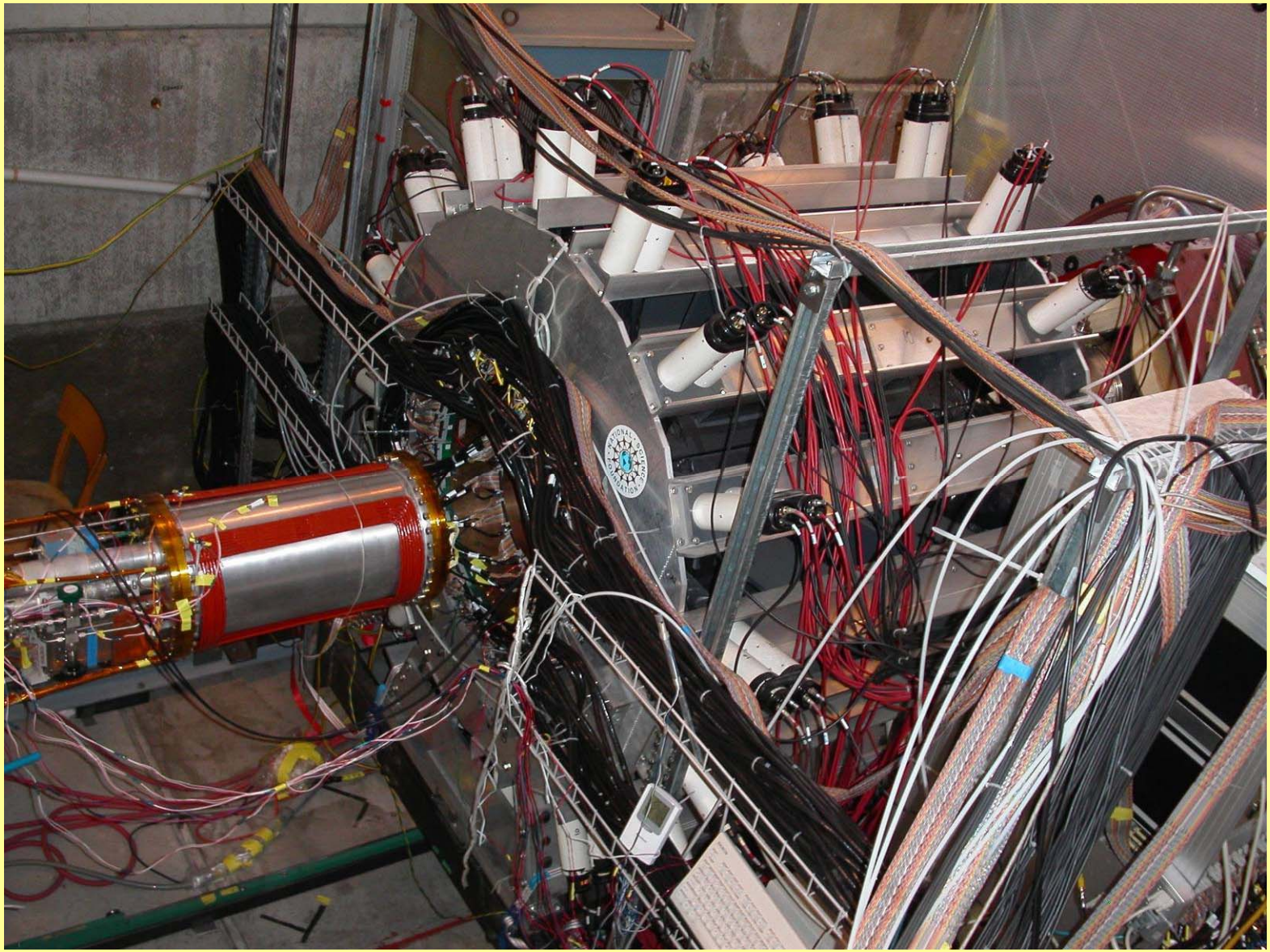
Стратегия MuCap эксперимента

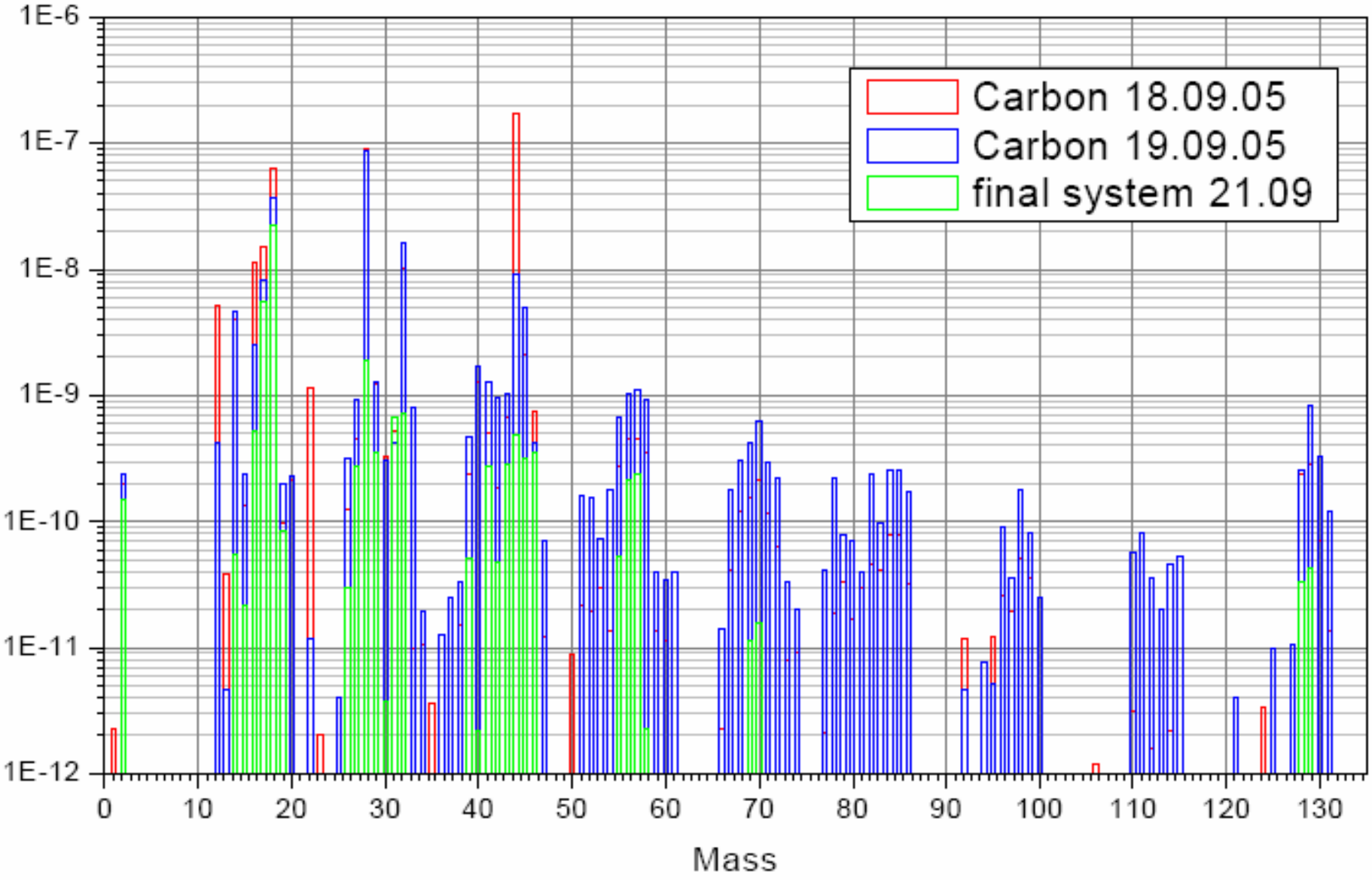


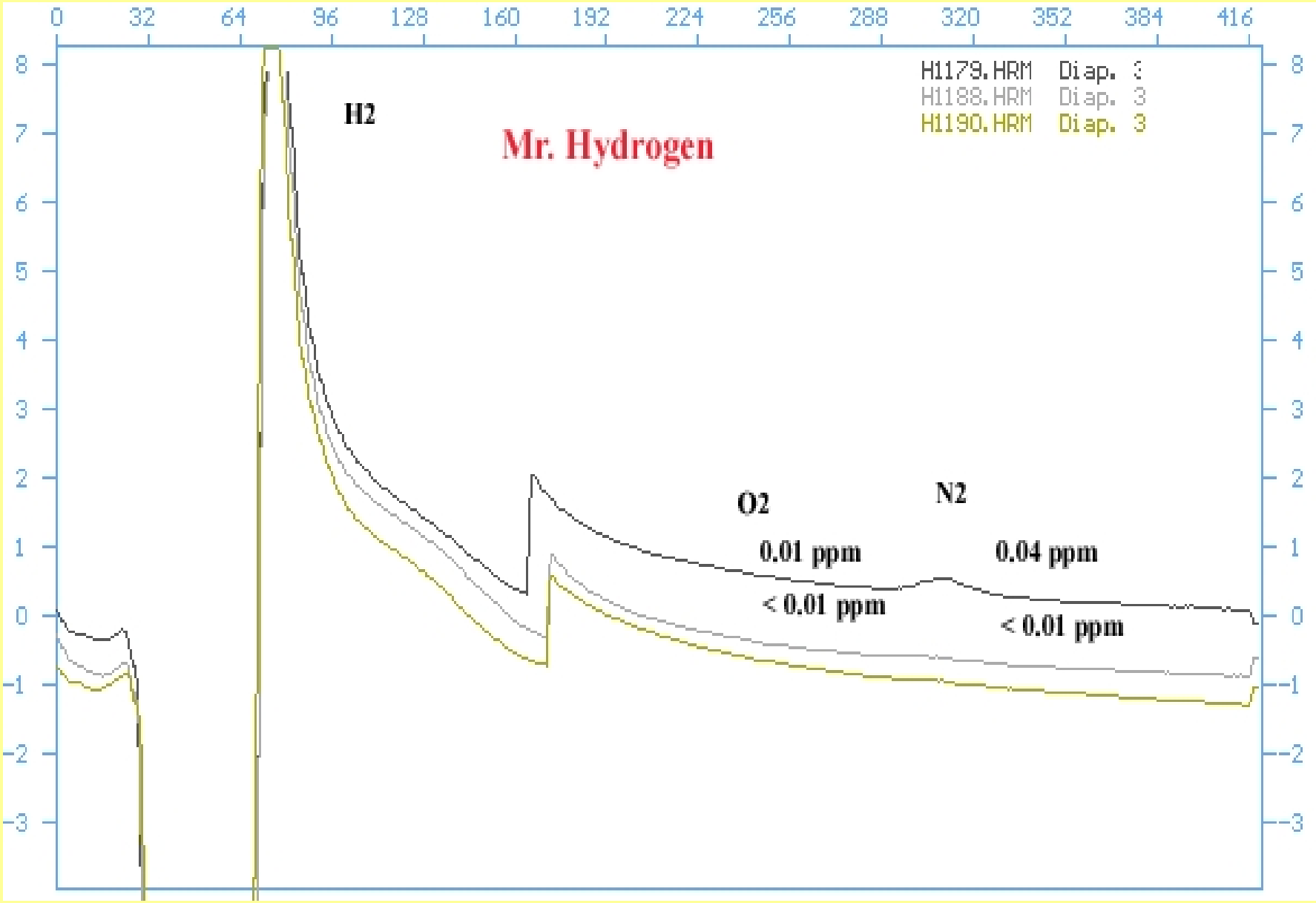
- **Измерение времени жизни $\tau_{\mu-}$**
  с точностью 10ppm, регистрация
  10^{10} $\mu \rightarrow e\nu\nu$ распадов
  $\rightarrow \Lambda_S = 1/\tau_{\mu-} - 1/\tau_{\mu+} \sim 1\%$
- **Однозначность интерпретации**
  захват из F=0 состояния μp атома при плотности LH_2 1%
- **Использование методики активной мишени (TPC)**
  с точной регистрацией координат и времени остановок мюонов, реконструкция треков электронов к точке распада
- **Использование ультрачистого водорода $C_z < 10^{-8}$**
- **Контроль примесей по реакциям: $\mu p + Z \rightarrow \mu Z + p$, ~10 ppb N_2**
- **Обеспечение изотопической чистоты водорода**
  $\mu p + d \rightarrow \mu d + p + 134$ eV, примесь D_2~1 ppm, диффузия μd ~cm

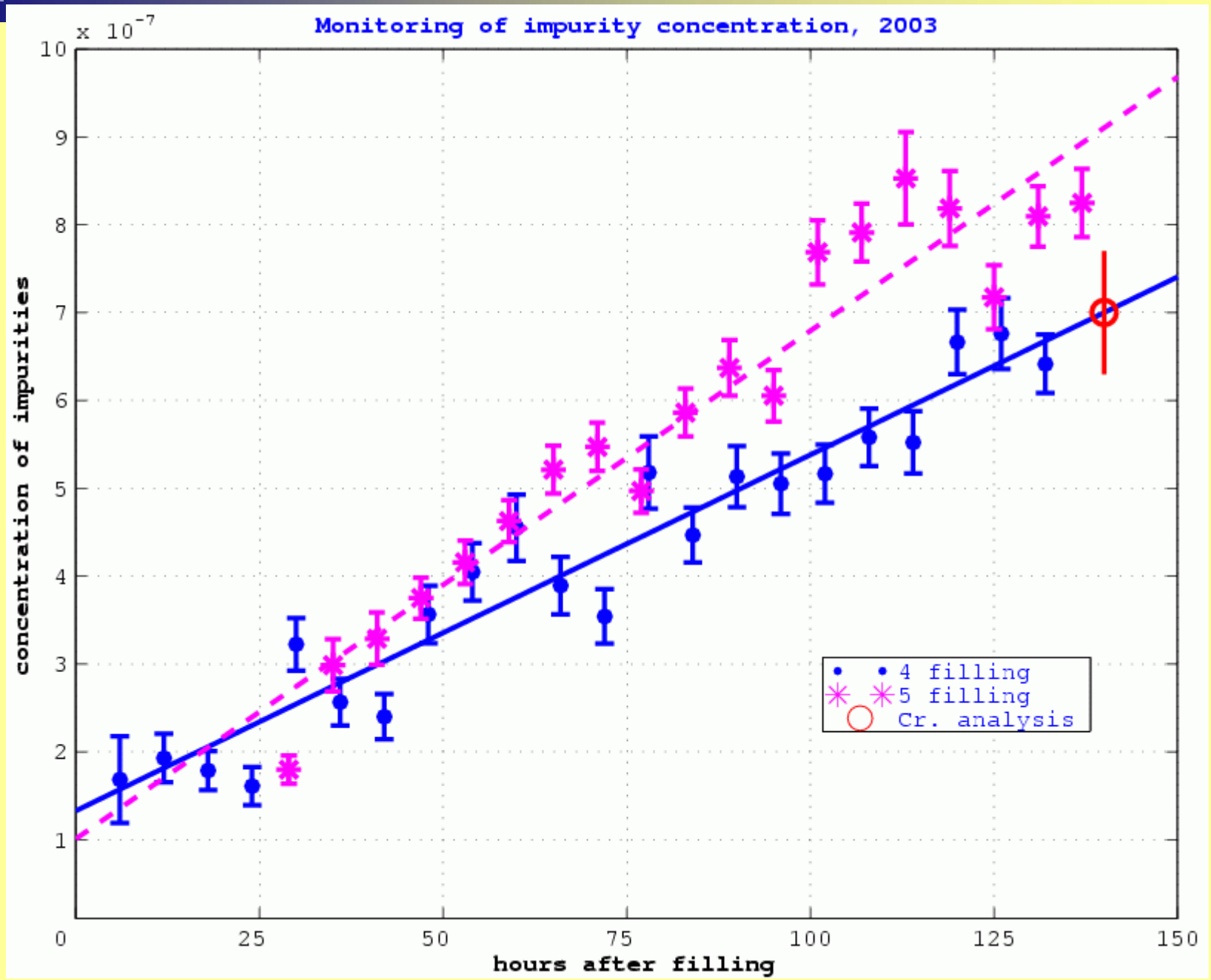


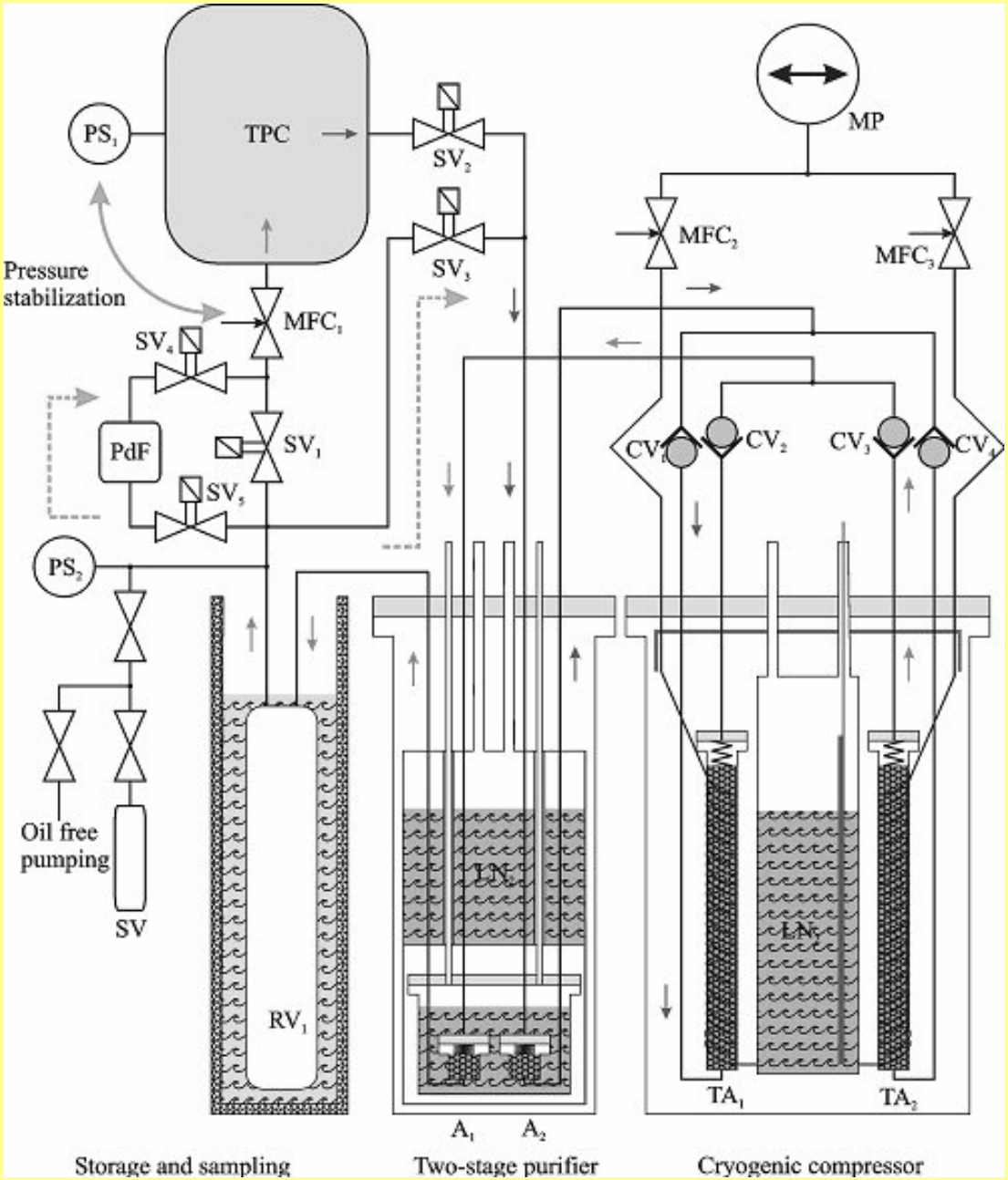

ePC2
ePC1
µPC
TPC
µSC,
µSCA
eSC

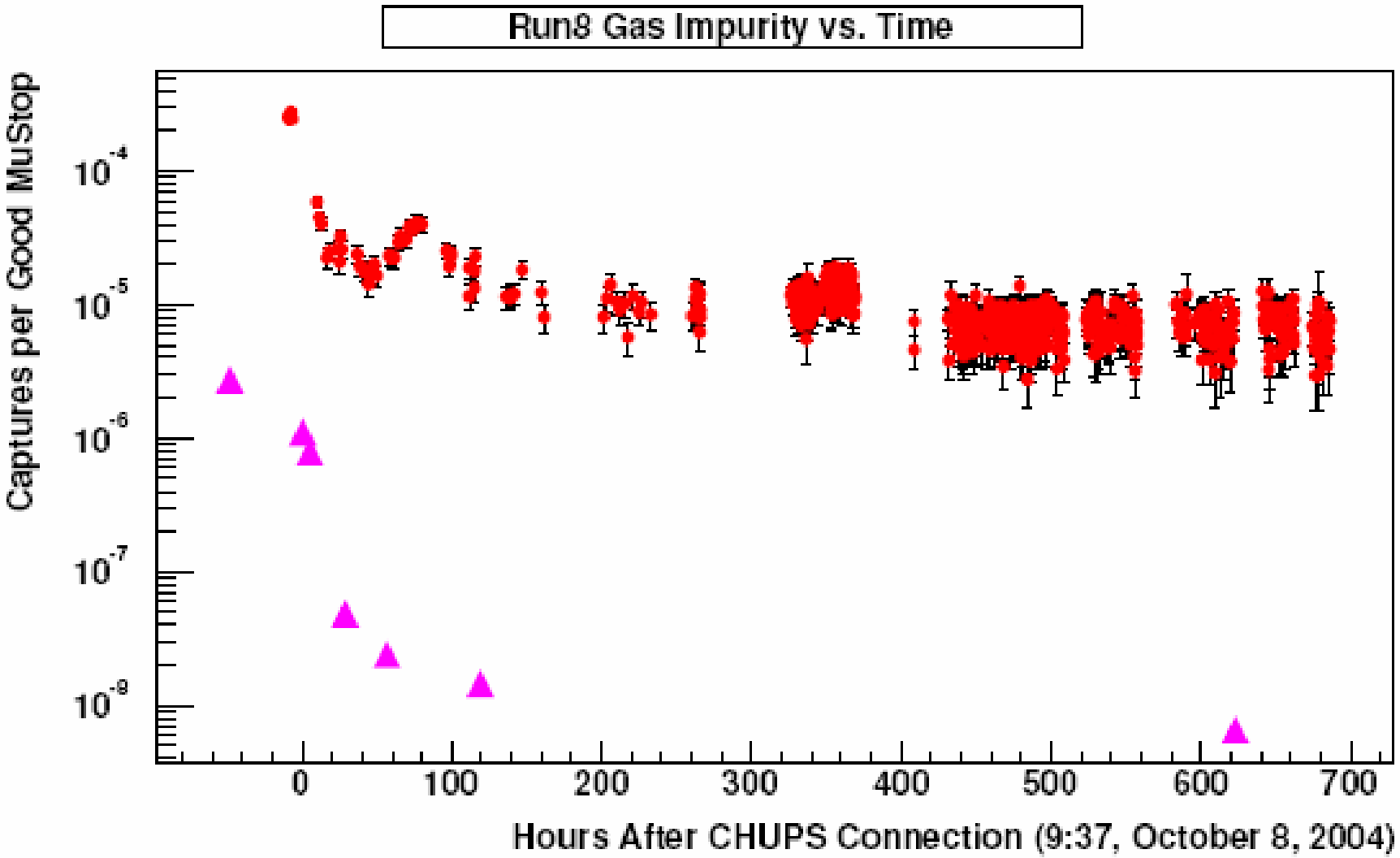



Carbon 18.09.05
Carbon 19.09.05
final system 21.09
1E-6
1E-7
1E-8
1E-9
1E-10
1E-11
1E-12
0
10
20
30
40
50
60
70
80
90
100
110
120
130
Mass


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


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


PS1
TPC
SV2
MP
SV3
MFC2
MFC3
Pressure stabilization
MFC1
SV4
PdF
SV1
CV1
CV2
CV3
CV4
SV5
PS2
Oil free pumping
SV
LN2
LN1
RV1
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)

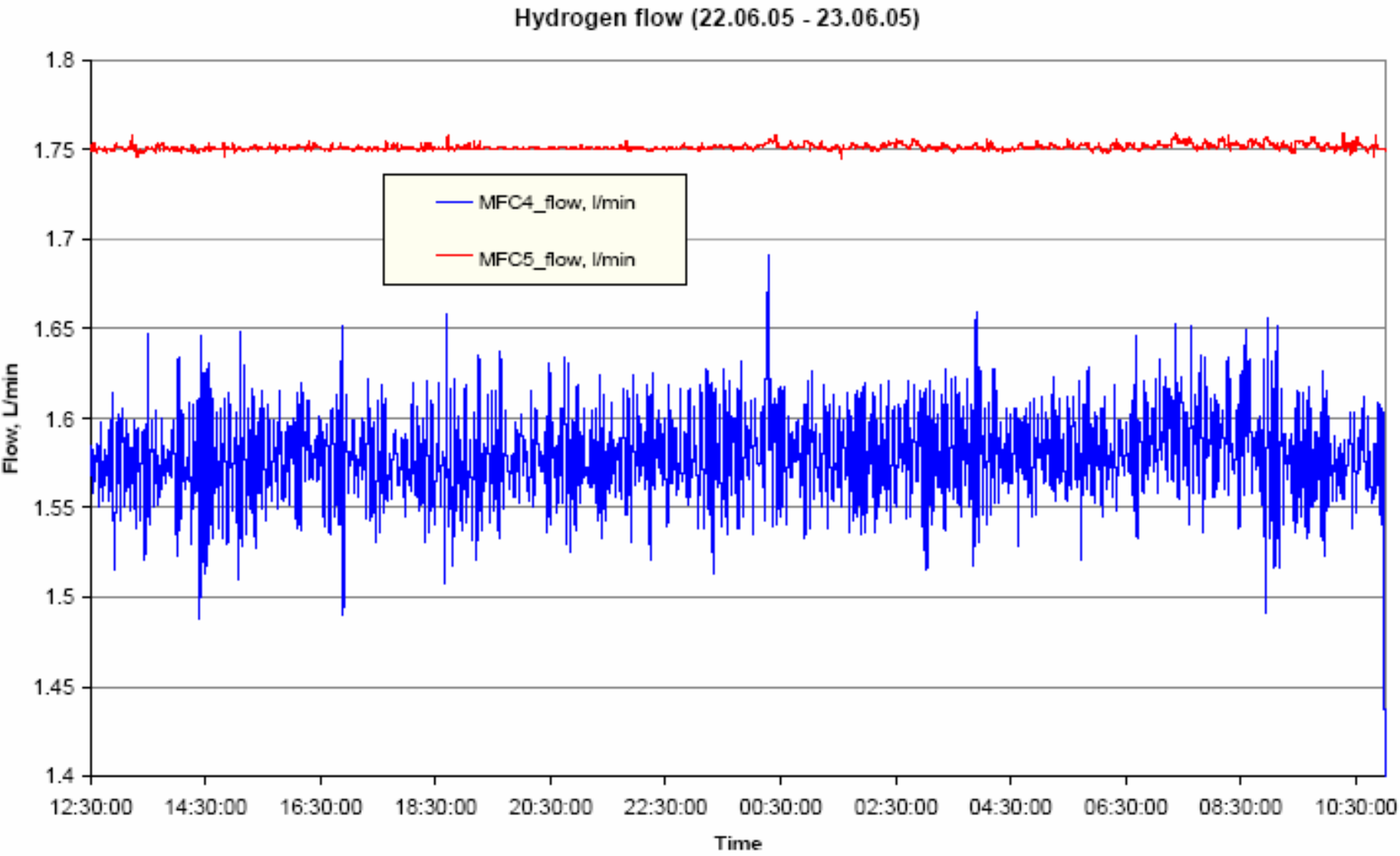
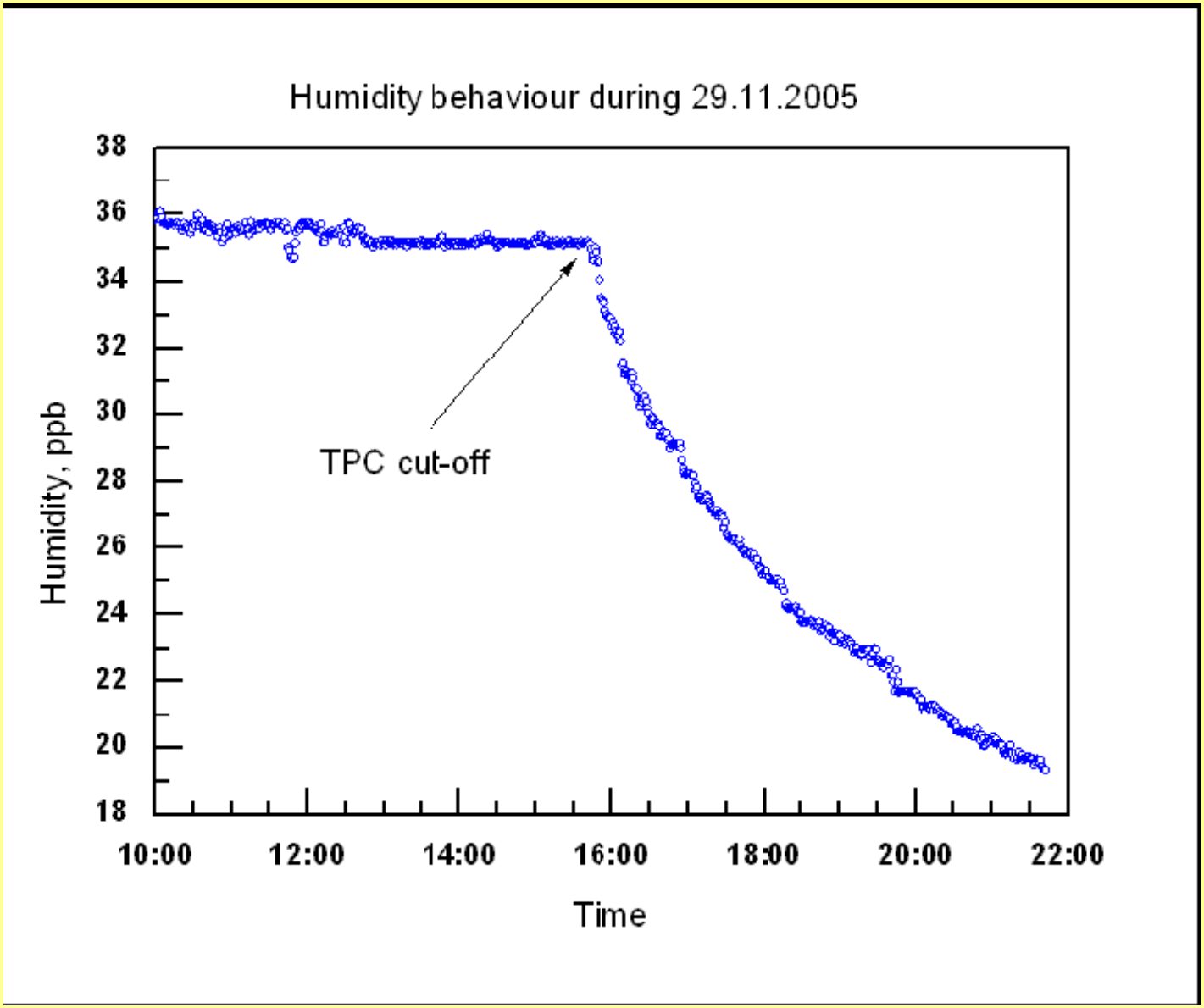


Fig. 4. TPC inlet (MFC4) and outlet (MFC5) flows.


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

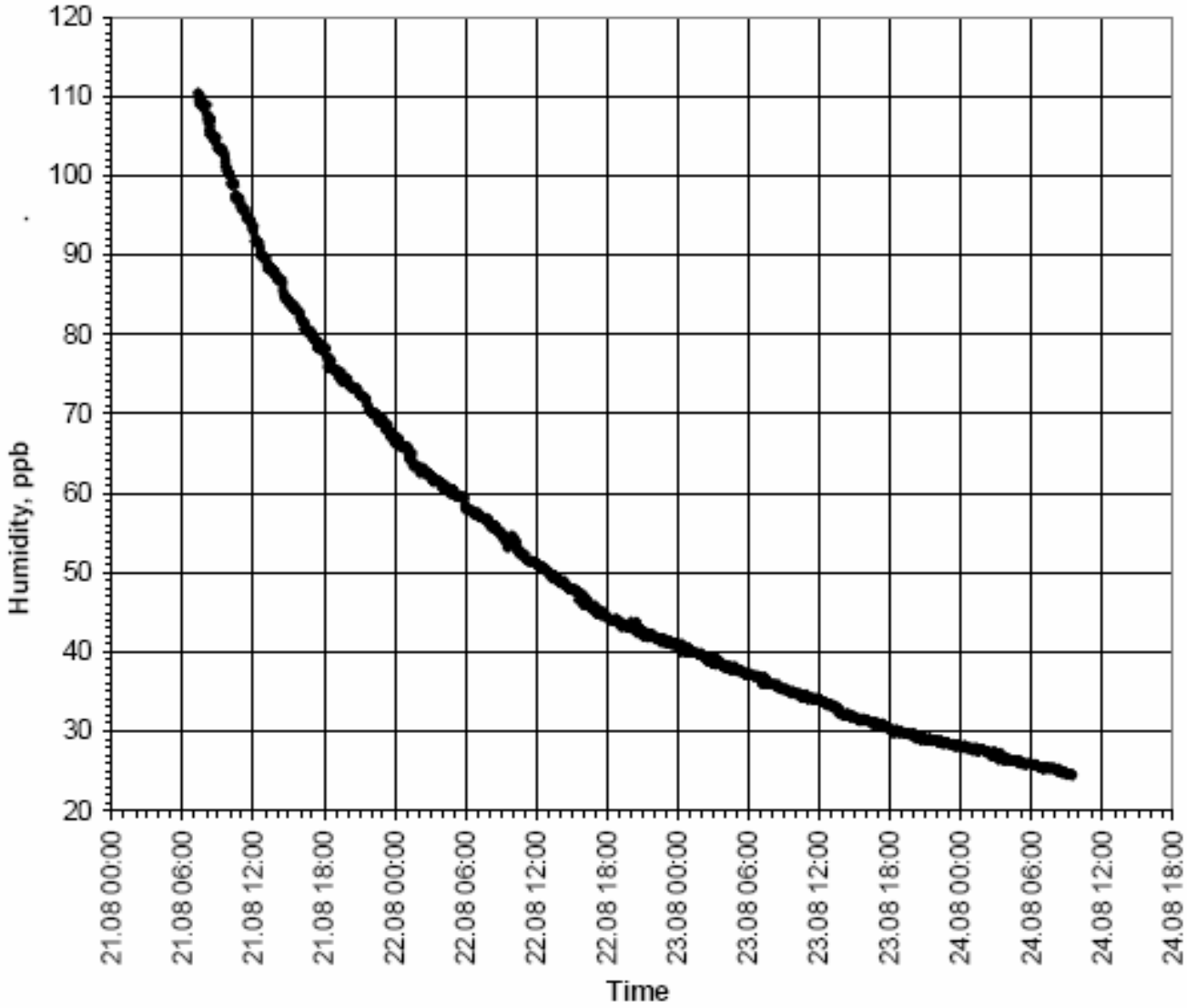
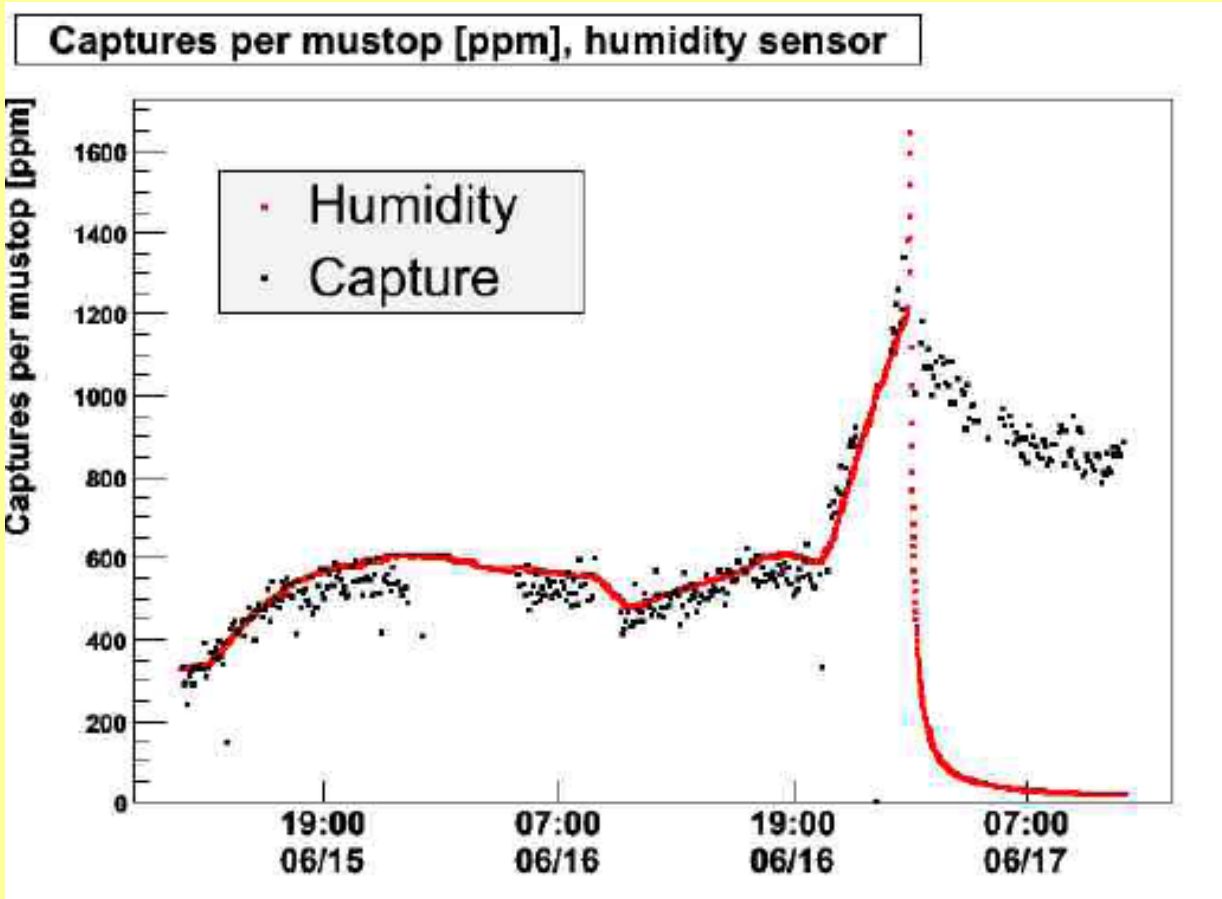
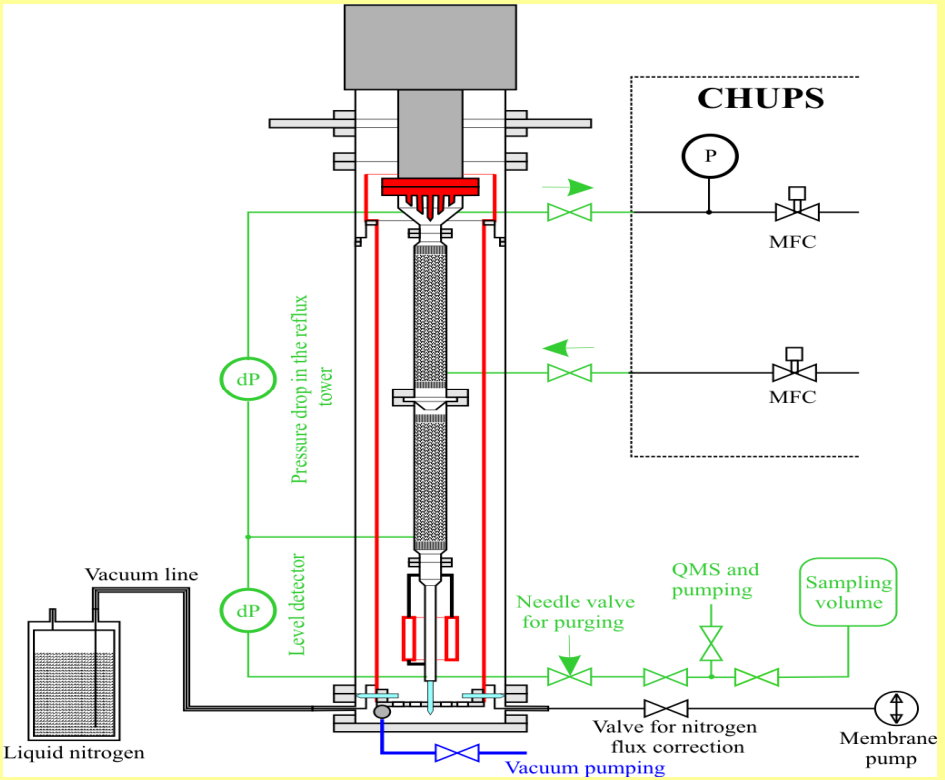


Fig. 2. Humidity decrease with TPC.


Captures per mustop [ppm], humidity sensor
Captures per mustop [ppm]
Humidity
Capture
1600
1400
1200
1000
800
600
400
200
0
19:00
06/15
07:00
06/16
19:00
06/16
07:00
06/17

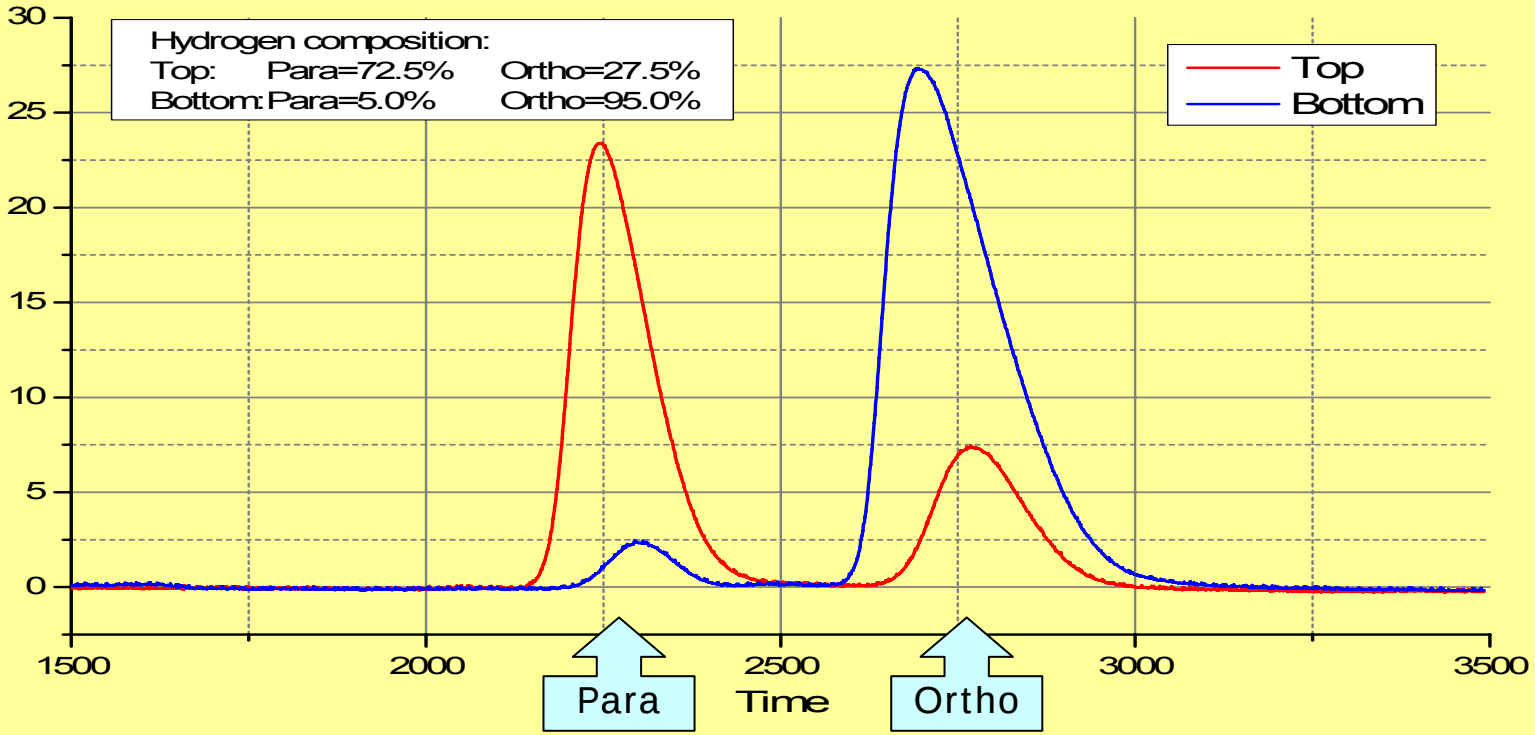
IV. the new protium isotope separation facility: production of ultra-depleted protium



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

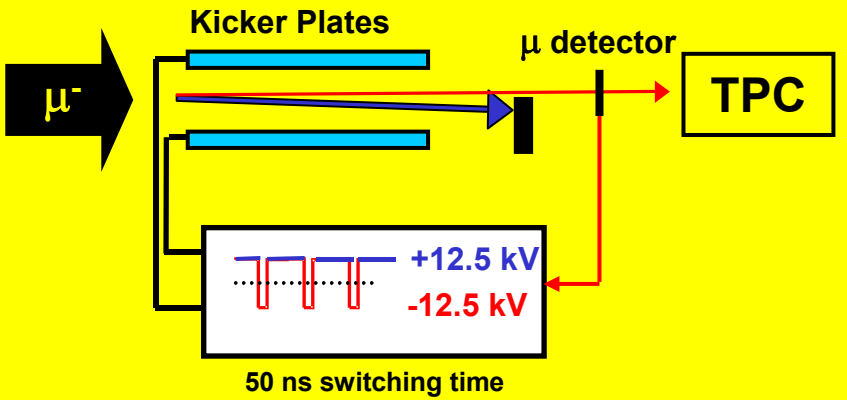
Ortho-Para Hydrogen Chromatogram

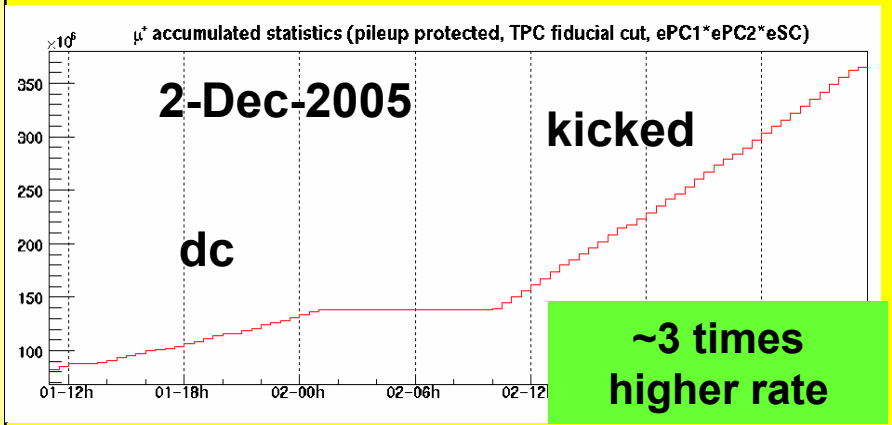
(Natural hydrogen, Column pressure = 1.2 bar; Reboiler power = 10W)



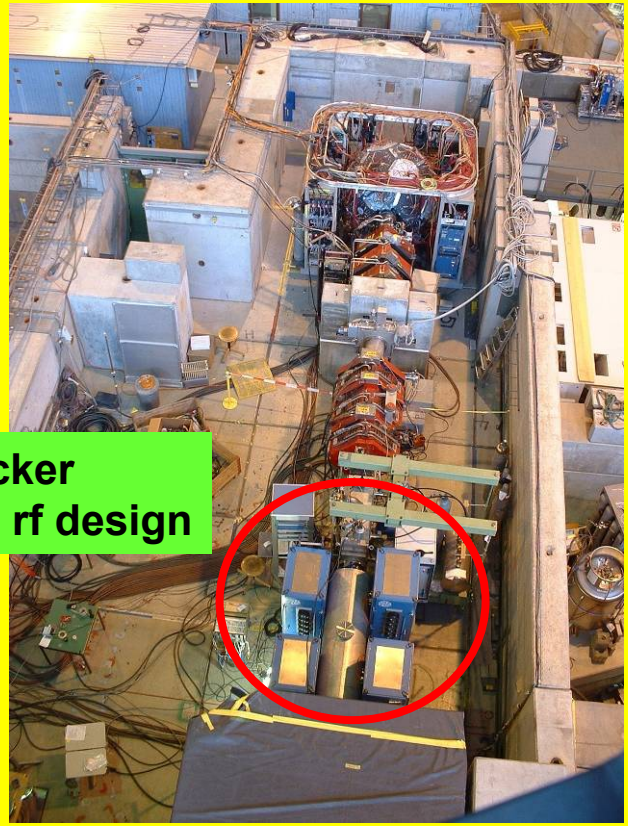
- Single muon requirement (to prevent systematics from pile-up)
- limits accepted μ rate to ~ 7 kHz,
- while PSI beam can provide ~ 70 kHz

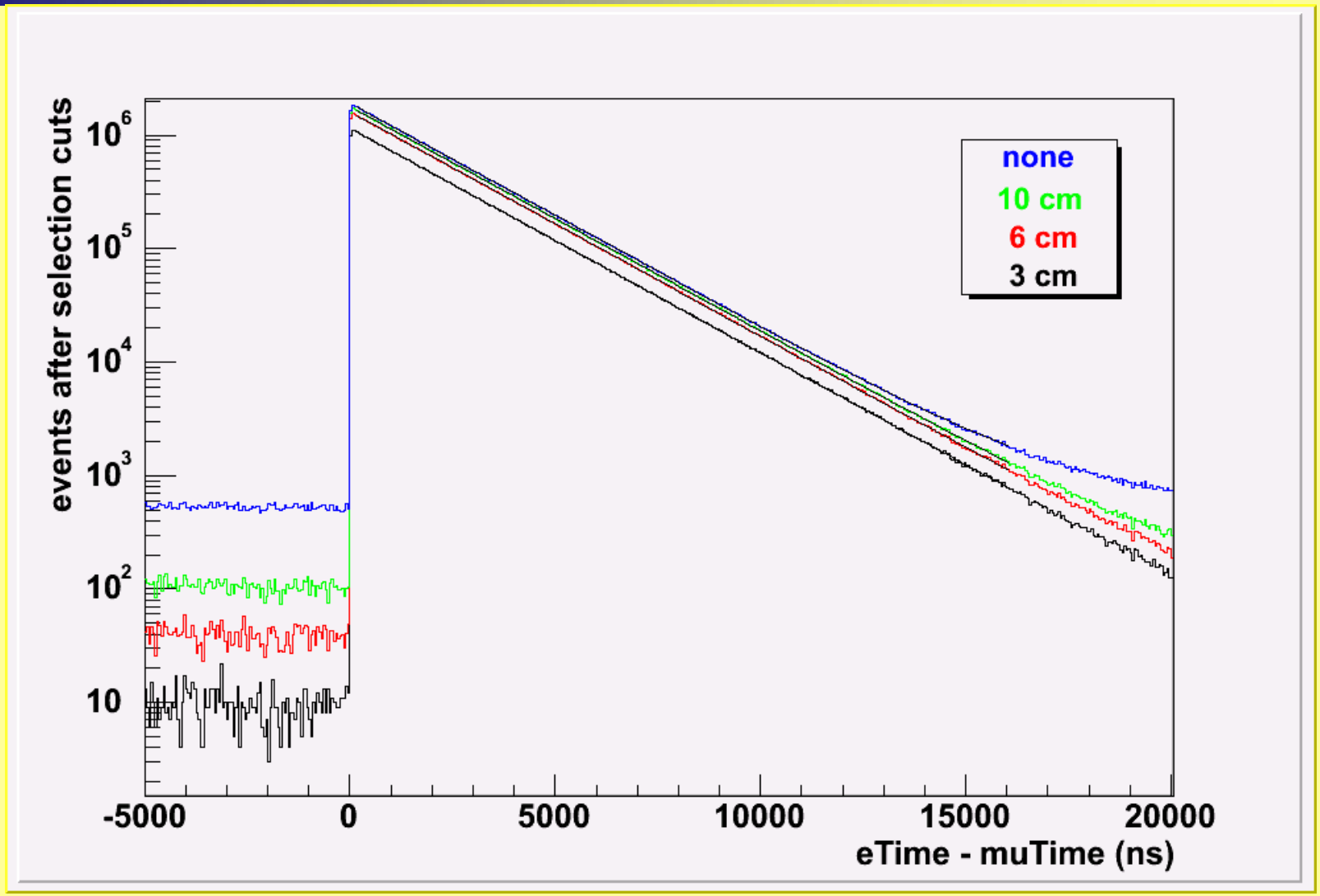
Muon-On-Demand concept



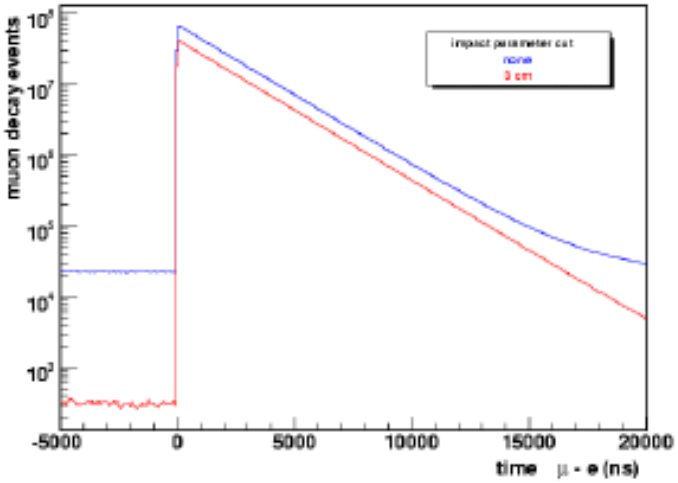


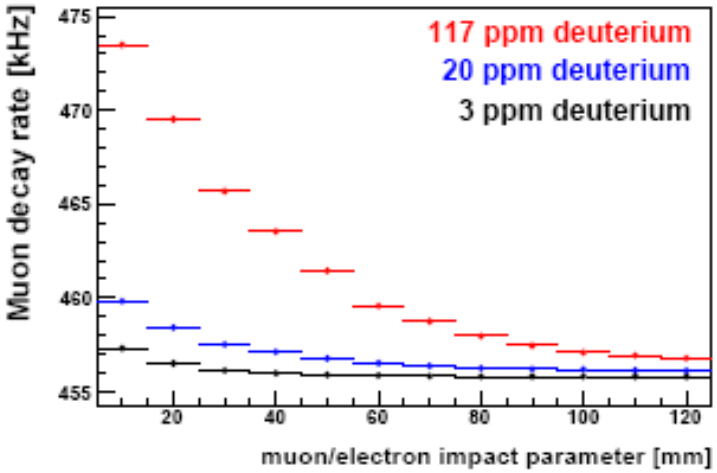
Beamline





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


muon decay events
time μ - e (ns)
-5000
0
5000
10000
15000
20000


Muon decay rate [kHz]
muon/electron impact parameter [mm]
117 ppm deuterium
20 ppm deuterium
3 ppm deuterium
475
470
465
460
455
20
40
60
80
100
120

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	1.56	8.6	<0.07	0.02
2007	5.4	6.0	<0.006	0.01
	8.56	20.1		

Общий объем данных за 2006-2007 гг. ~ 40 Tb

Анализ одного файла данных размером 1.6 Gb занимает примерно 1 час процессорного времени.

На данный момент в ПИЯФе есть 1Tb данных за 2006-2007 года.

Анализ этих данных потребует ~ 600 часов!!!!!

Результаты анализа данных за 2004 год

$N = 1.6 \times 10^9$

$\lambda_{\mu+}$ = 455162.2 ± 4.4 s^{-1} (μLAN experiment, to be published)

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

Λ_S^{MuCap} = 725.0 ± 13.7stat ± 10.7syst s^{-1}

Λ_S^{Th} = 691.2 s^{-1} (averaged) + 19.4s^{-1}(radiation correction)

$g_P^{MuCap} = g_P^{Th} + (dg_P/d\Lambda_S) \times (\Lambda_S^{MuCap} - \Lambda_S^{Th}) = 7.3 \pm 1.1$ (15%)

$g_P^{Th} = 8.26 \pm 0.23$ (2.8%)

Earlier, in 1998, we have studied the muon capture on ^{3}He. The muon capture rate in the channel $\mu^- + {}^3\mathrm{He} \rightarrow {}^3\mathrm{H} + \nu_\mu$ was measured with high precision : $\Lambda_c = 1496.0 \pm 4.0\ s^{-1}$.

This result have been used in some theoretical analyses (T.Gorringe and H.W.Fearing, 2004) for deriving the proton's pseudoscalar coupling g_P. They applied the microscopic theory based on impulse approximation supplemented by explicit calculations of the meson exchange corrections .
Their result was

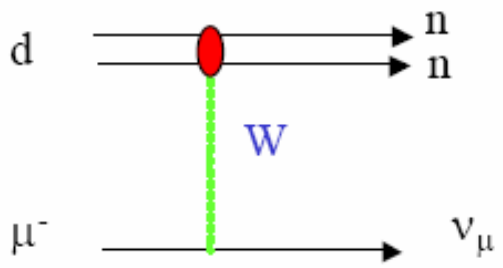
$g_P = 8.77 \pm 1.58$.

Публикации в 2007 году по теме «Мюон»

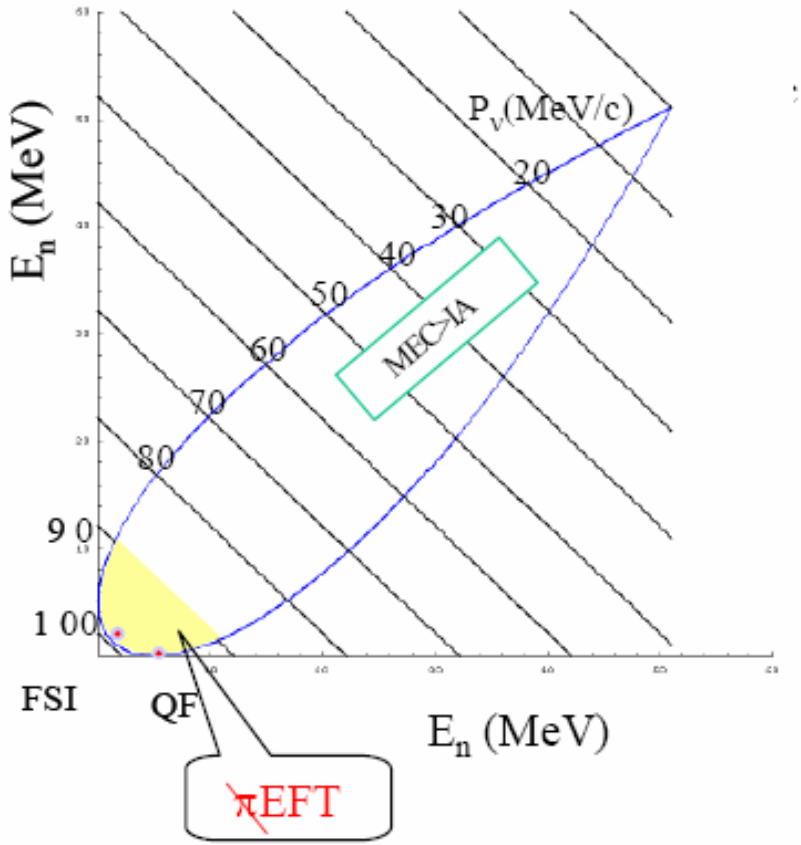
V.A. Andreev, T.I. Banks et al. “ Measurement of the Rate of Muon Capture in Hydrogen Gas and Determination of the Proton's Pseudoscalar Coupling gP.” Phys.Rev.Lett. 99, 032002 (2007)

V.A. Ganzha, P.A. Kravtsov et al. “A Circulating Hydrogen Ultra-High Purification System for the MuCap Experiment”
Nucl. Instr. Methods Phys. Res. A 578 (2007) 485-497

Physics motivation



- nucleon FF dependence similar to μ+p
  g_P dependence ~20%
- 2-N physics important (d wavefunction, a_{nn}, …)
- MEC's contribute, dominantly Δ isobar current
  EFT: two-body currents parametrized by LEC L_{1A} (isovector, axial) 4N vertex
- 3 body final state

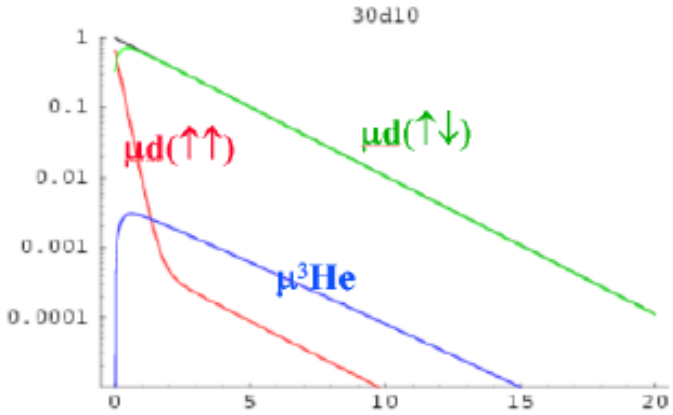


1% precision experiment possible? yes

- **measurement of absolute rate <1% (μD I)**

  Basic lifetime method, new TPC

  Kinetics requires optimized target conditions 80K, 5% density

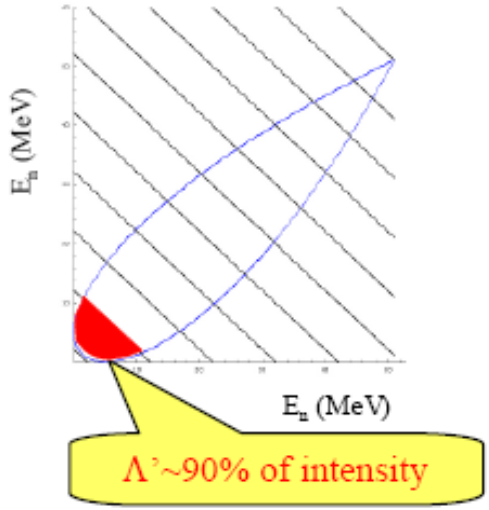


- **measurement of Dalitz Plot 5 % (T_n>10MeV) (μD II)**

  Neutron detector array

  Kinematics determined by angle and δt

- **subtract to determine rate for relevant low energy part Λ'**
- measure full DP if sufficient physics motivation



μD

ФИНАНСЫ 2007

- Тема РАН – 400 т.руб + 550 т.руб
- Грант CRDF ~49 K USD

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.