PAUL SCHERRER INSTITUT

Wir schaffen Wissen – heute für morgen

Paul Scherrer Institut

Johny Egger, **Malte Hildebrandt**, Claude Petitjean

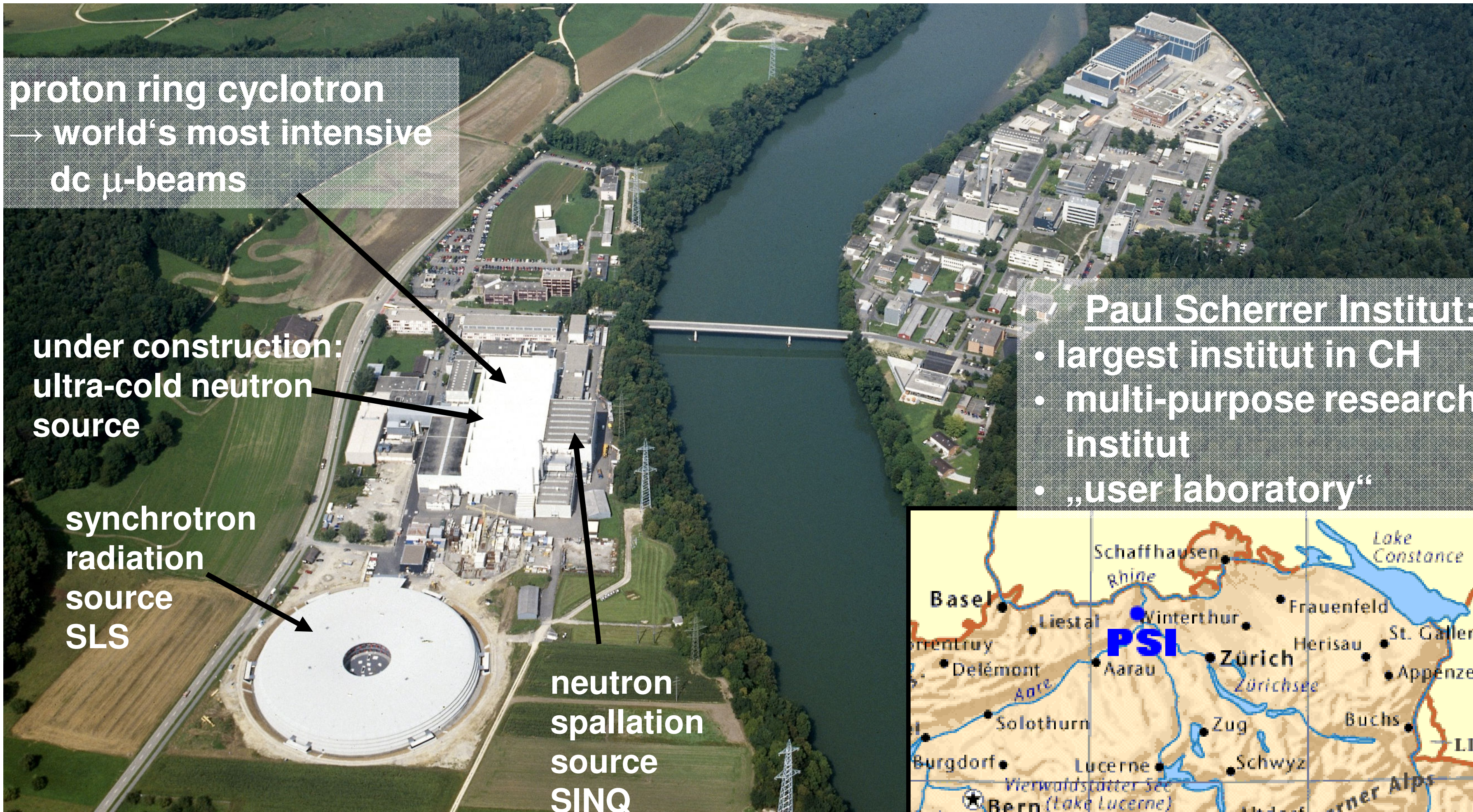
on behalf of the MuCap Collaboration

The 10 bar Hydrogen Time Projection Chamber of the MuCap Experiment

Vienna Conference on Instrumentation, 16th February 2010

MuCap at PSI

- MuCap Experiment
  - designed, constructed and performed by an international collaboration (US, Ru, B, D, CH)
  - located at the Paul Scherrer Institut, Switzerland



MuCap Experiment

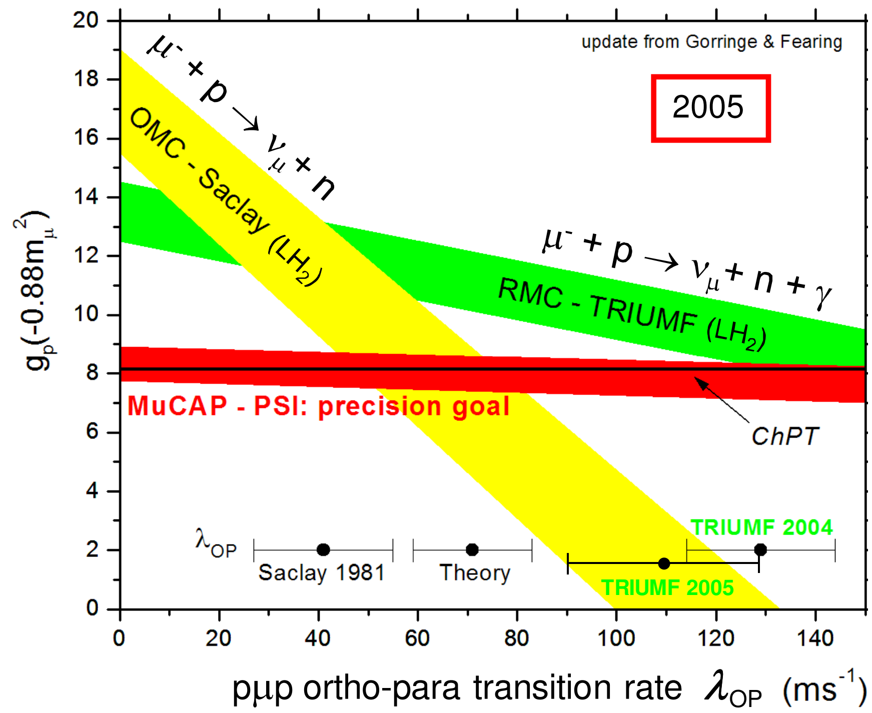
- Goal: measurement of the **singlet capture rate Λ_s** of the reaction

$$(p\,\mu^-)_{\uparrow\downarrow} \rightarrow n + \nu_\mu$$ (nuclear muon capture on the free proton)

to 1 % precision

- This allows to determine the *weak nucleonic charged-current pseudoscalar induced form factor* g_p to 7 % precision.

The HBChPT prediction for g_p is ~3 % precise!



- Realisation: measurement in 10 bar (gaseous) H_2 ($\rho = 0.012 \cdot \rho_{liquid}$)

→ pμp formation is slow, all captures proceed from μp singlet state

Lifetime Measurement

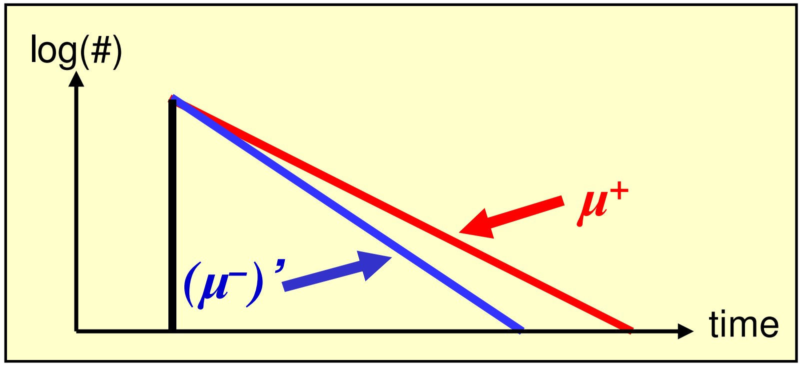
- measuring principle: lifetime measurement
- for μ^-, muon capture on the proton competes with muon decay:

$$(p\mu^-)_{\uparrow\downarrow} \rightarrow n\ \nu_\mu \qquad (0.15\,\%)$$

$$\mu^- \rightarrow e^-\ \nu_\mu\ \bar{\nu}_e \qquad (99.85\,\%)$$

- the rate of muon capture decreases the μ^- vacuum lifetime, which is measured seperately with μ^+:

$$\mu^+ \rightarrow e^+\ \bar{\nu}_\mu\ \nu_e \qquad (100\,\%)$$



$$\Lambda_S \approx \left(\tau_{(\mu^-)'}\right)^{-1} - \left(\tau_{\mu+}\right)^{-1}$$

$$\approx \lambda_{(\mu^-)'} - \lambda_{\mu^+}$$

- Λ_s to ±1 % needs slopes of 10 ppm precision $\rightarrow$ 10^{10} events for each: μ^+ and μ^-

Requirements for MuCap

- ultra-clean H_2 gas target (10 bar): Z>1 impurities on level <0.1 ppm
  → low outgasing material, heating, UHV, filling through palladium filter
- deuterium-depleted hydrogen („protium“): <1 ppm deuterium

- 100 % μ-stop identification in 10 bar H_2
  3-D reconstruction, no wall stops

- clean e identification + tracking → 2 cylindrical MWPC
  scintillator hodoscope

- high data rate → dc muon beams at PSI

- high statistics: $>10^{10}$ events for μ^+ and μ^-

- μSR under control for μ^+: 50-100 Gauss magnetic field

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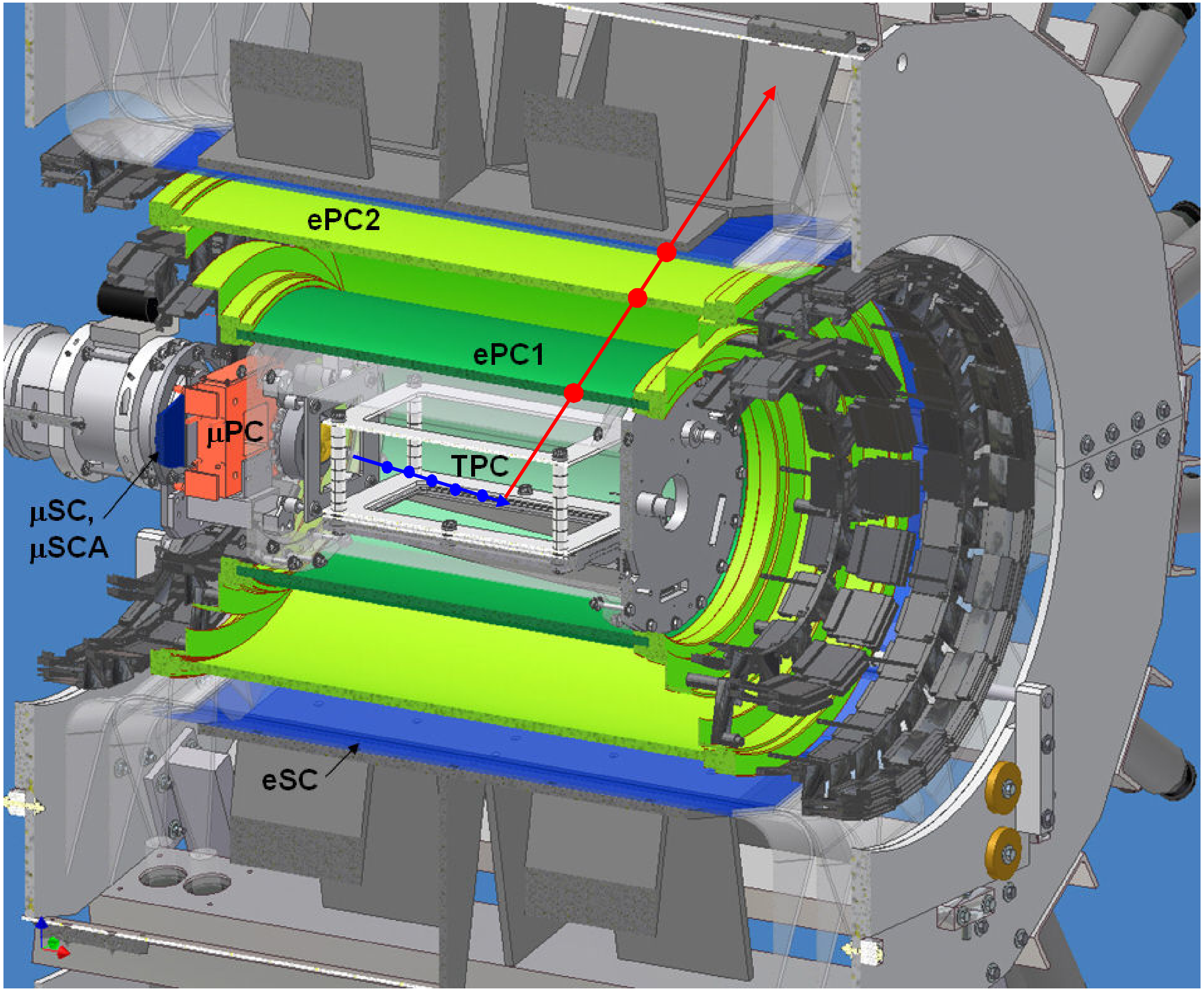
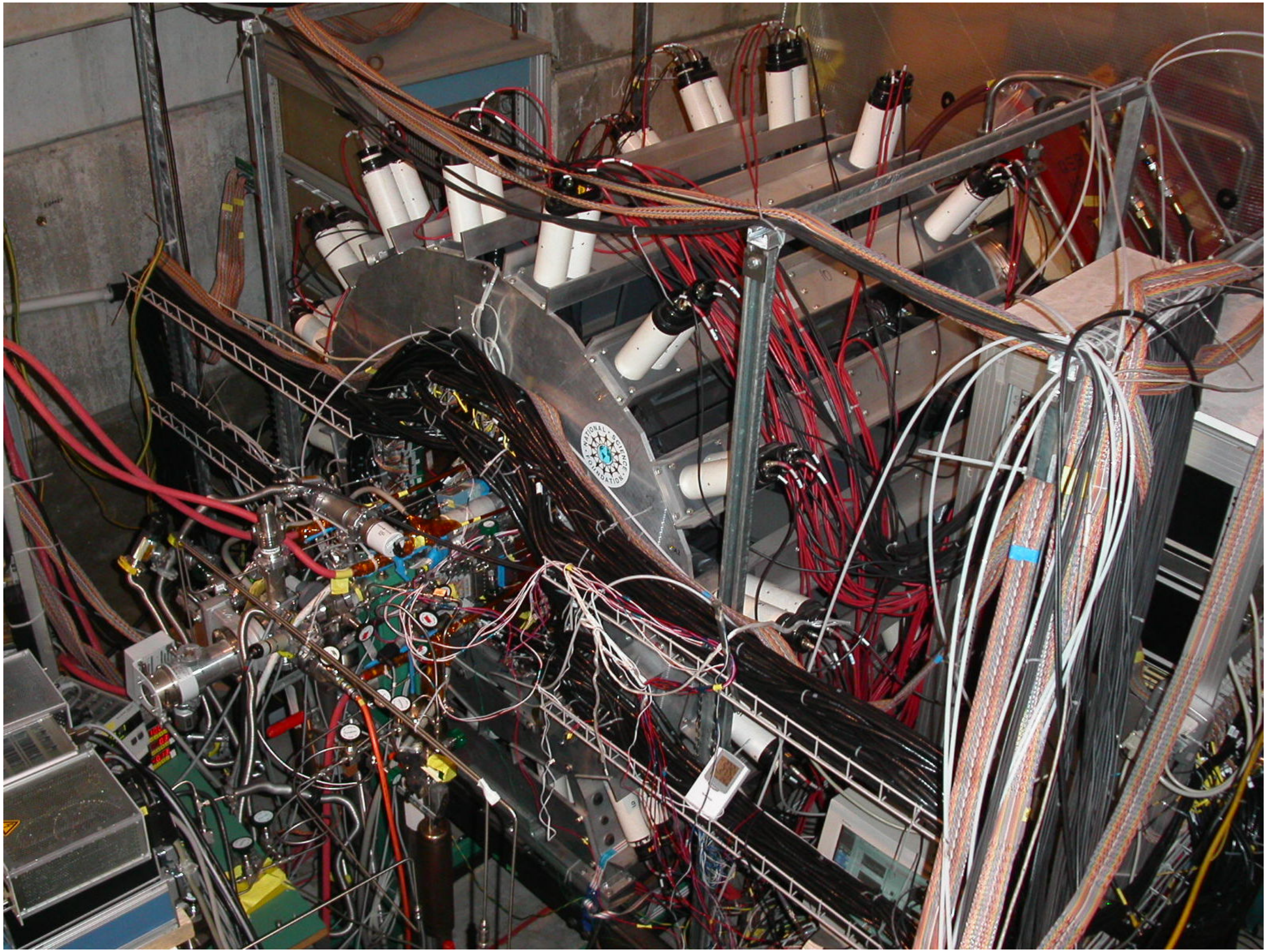
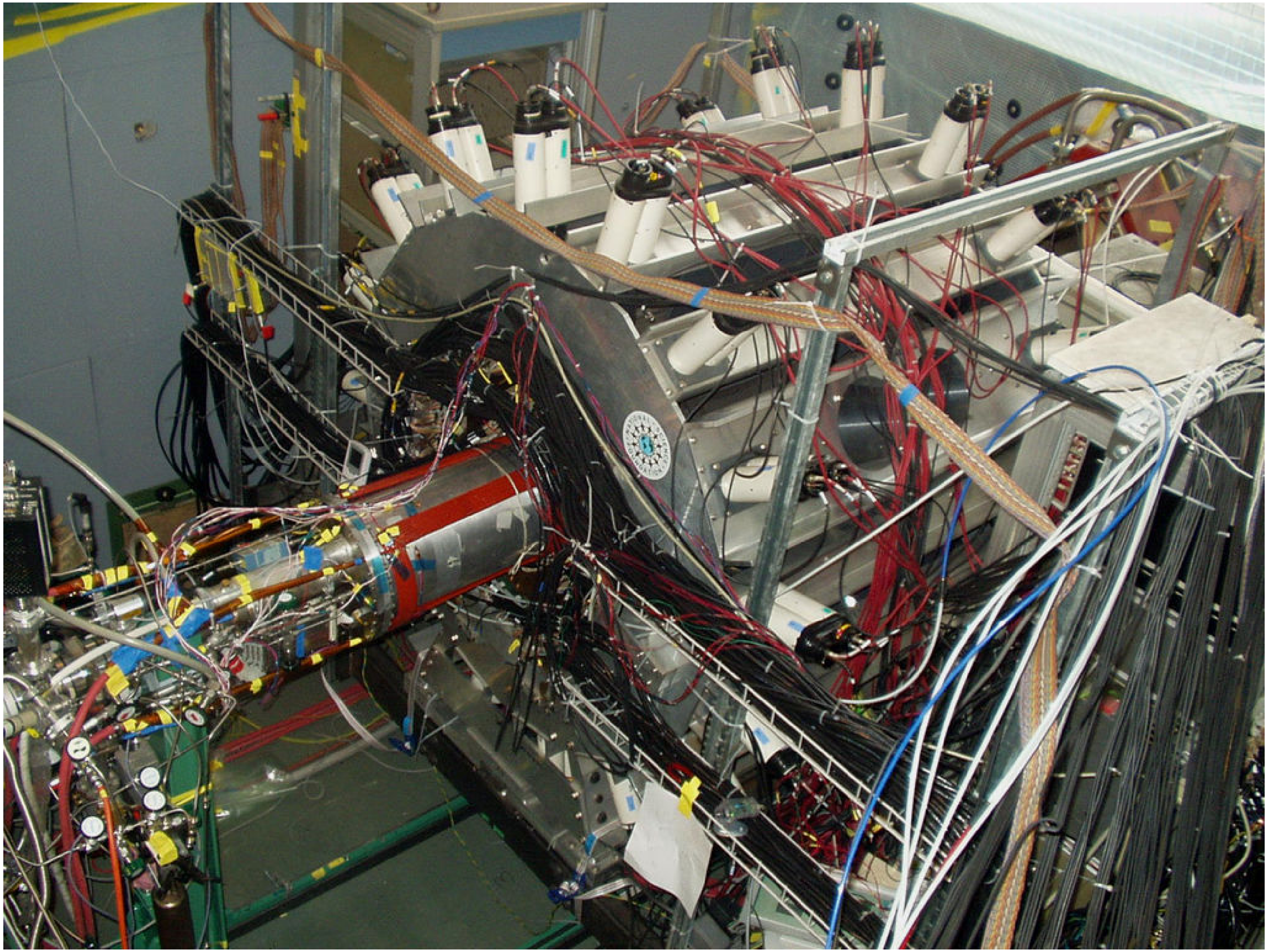
MuCap – Technical Drawing



MuCap – Measuring Position



MuCap – Service Position

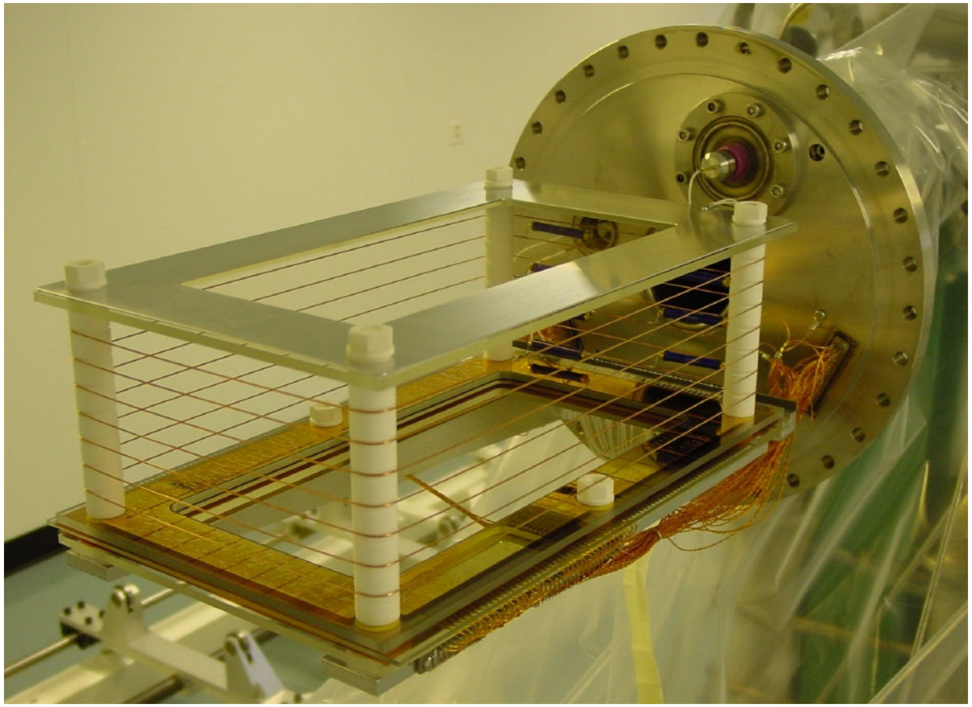


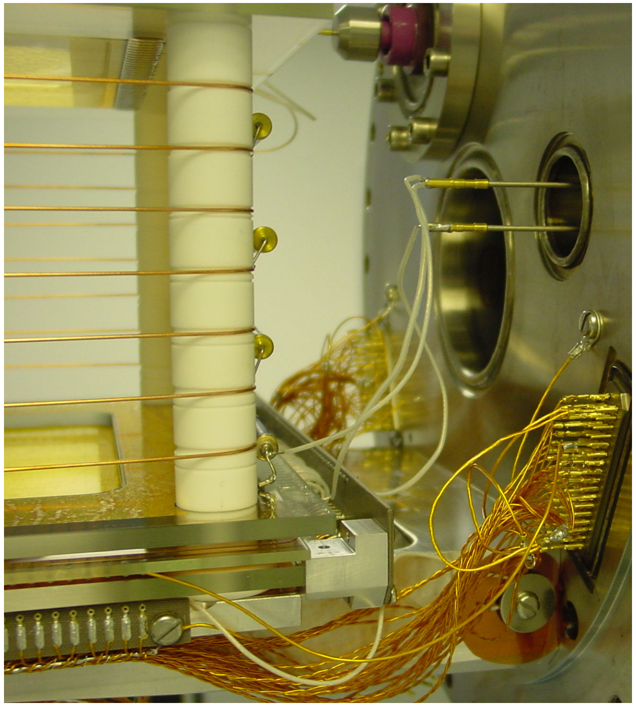
High-pressure Hydrogen TPC – 1

Time Projection Chamber: 3-D reconstruction of muon tracks

- operated in 10 bar H_2 (target and detector)
- sensitive volume $(15 \times 12 \times 30)\,\mathrm{cm}^3$ with E_{TPC}
- multi-wire proportional chamber $(15 \times 12 \times 2 \cdot 0.35)\,\mathrm{cm}^3$ with E_{MWPC}

75 anode wires
$2 \cdot 140$ cathode wires
} 2-D readout + t_{Drift} → 3-D reconstruction





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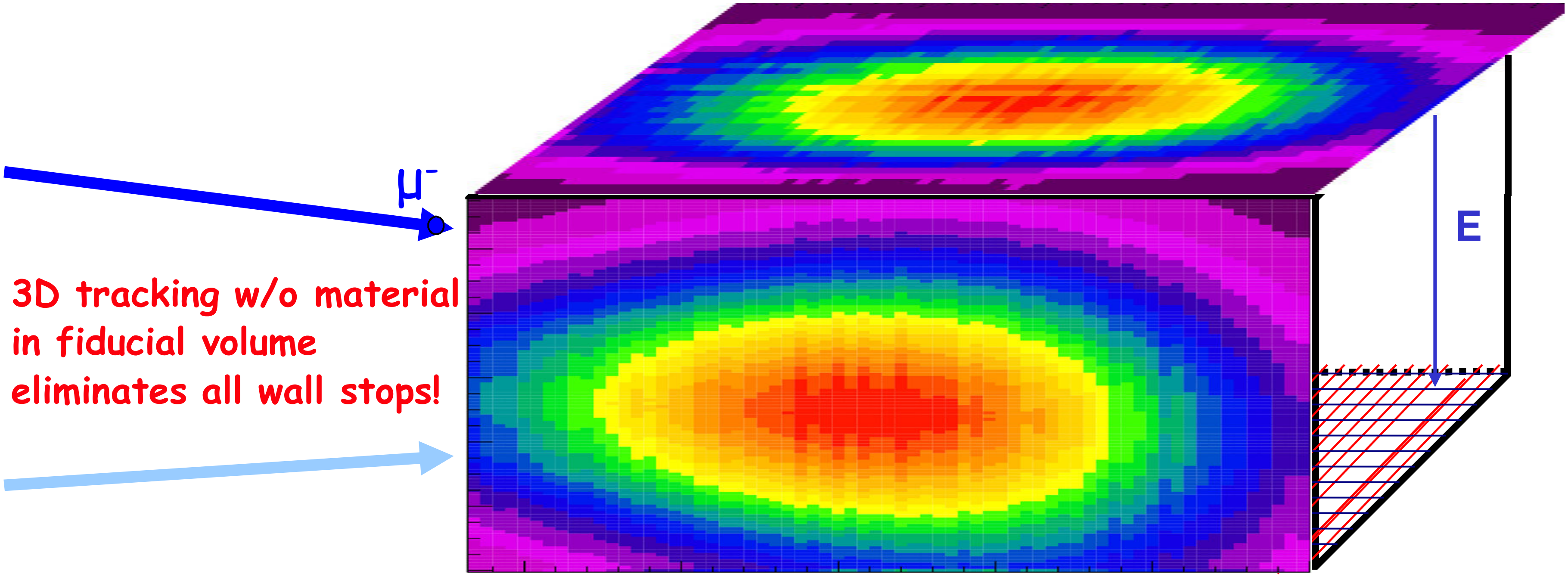
140 cathode wires
} 2-D readout + t_{Drift} → 3-D reconstruction

observed muon stopping distribution

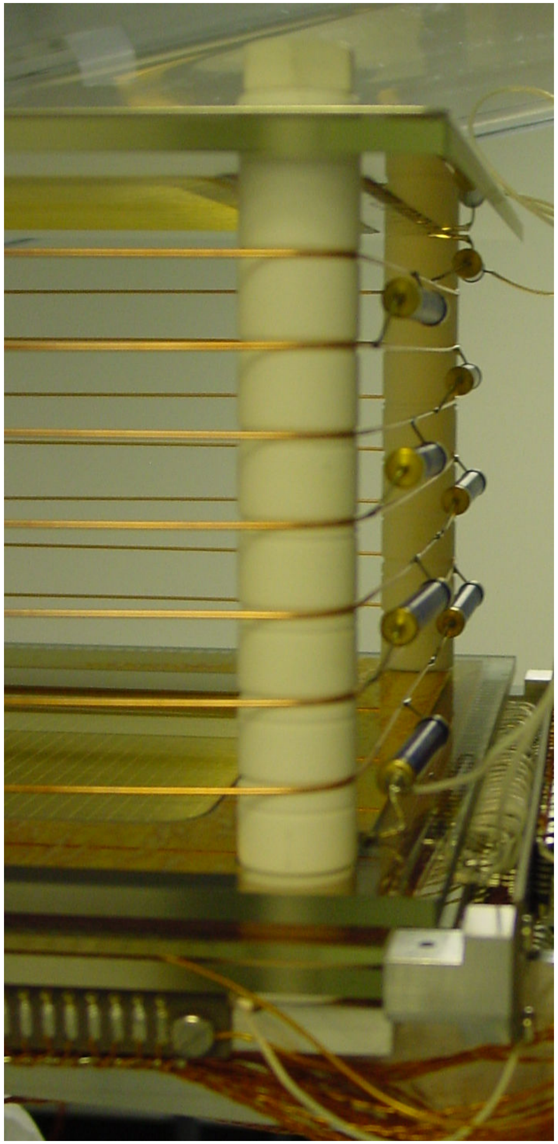


3D tracking w/o material in fiducial volume eliminates all wall stops!

High-pressure Hydrogen TPC – 2

"Drift part"

- **drift cathode wire plane**, $\mathbf{U_{drift}}$ **= -29.4 kV**
  50 µm (100 µm) gold-plated W (3% Re), 1 mm wire spacing
- sensitive volume $(15\times12\times30)\,\mathrm{cm}^3 \rightarrow$ $\mathbf{E_{TPC}=2\,kV/cm}$
- 4 Macor pillars (glas ceramics)
- 7 field forming wires (1 mm copper), resistor chain



MWPC

- **1 anode wire plane with 4 mm wire spacing**
  25 µm (50 µm, 100 µm) gold-plated W (3% Re), **GND**
- **2 cathode wire planes with 1 mm wire spacing**
  50 µm (100 µm) gold-plated W (3% Re), $\mathbf{U_{cath}}$ **= -5.4 kV**
  perpendicular to anode wires
  read out: 4 wires combined to one "cathode strip"
- capton frames between anode and cathode frames to avoid edge effects (125 µm thick)
- **half gap 3.5 mm** $\rightarrow$ $\mathbf{E_{MWPC}=15\,kV/cm}$

High-pressure Hydrogen TPC – 3

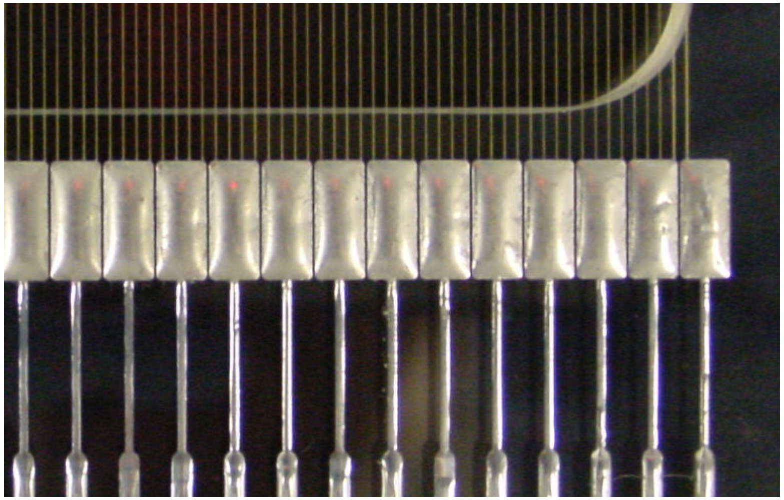
selection of materials

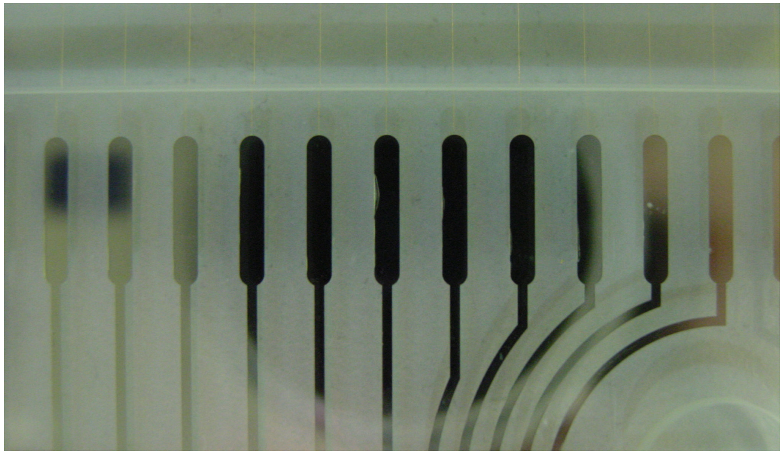
- muon transfer and muon capture to high-Z impurities is enhanced
  → reduce impurities

- to reach impurity level <0.1 ppm
  → all materials low outgasing:
  glass, ceramics, capton, teflon, …

- bakable up to 110℃
  → borofloat glas (thermal expansion)
  → special coating for soldering pads
  - titanium undercoating
  - 0.5 μm gold
  - 2 μm nickel
  - 100 nm gold

  → no cracking or separation of the pads during heating cycles





High-pressure Hydrogen TPC – 4

gas system

an elaborated high vacuum and gas handling system was constructed:

- turbomolecular pump combined with oil-free forevacuum pump, huge diameter tube for pumping, stainless steel tubes and valves, vacuum connections sealed with metallic gaskets, mass spectrometer, etc.
  → residual pressure $<10^{-7}$ mbar
- gas handling: stainless steel bottles, hydride storage beds, zeolite bed
- **several ports for gas sampling** or **injection of precise defined admixtures of impurity gases**
- **protium:**
  - electrolysis of commercially bought protium water ($c_D \approx 1.44$ ppm)
  - isotope separation column to produce ultra-depleted protium ($c_D < 70$ ppb)
- **gas filling through palladium filter**, in addition **gas circulation and cleaning system** (CHUPS) V.A.Ganzha *et al.*, NIM A 578 (2007) 485-497

High-pressure Hydrogen TPC – 5

gaseous physics

- TPC acts as an active muon stop detector
  → 10 bar H_2 operate as target and detector

  but: gaseous physics and operation of the detector is rather challenging
  ↔ hydrogen is not suitable gas for operating gaseous detector!
  - low breakdown voltage
  - no absorption of ultraviolet photons (no "quenching")
- large dynamic range: e_{decay}: 5 keV/cm → μ-stop: 220 keV/few mm
- high-gain operation: up to 10^4

→ limited world-wide experience in high-pressure, high-gain and longterm operation with ultra-pure hydrogen in proportional chambers

- some basic parameters were established in E612 Fermilab: measurement of inclusive cross section for $\gamma\, p \rightarrow X\, p$ in 15 bar H_2
  T.J.Chapin *et al.*, NIM 197 (1982) 305-315 and NIM 225 (1984) 550-556

High-pressure Hydrogen TPC – 6

conditions of TPC operation

- beam test with TPC-prototypes (PNPI Gatchina)
  E.M.Maev *et al.*, NIM A 478 (2002) 158-162 and NIM A 515 (2003) 288-291
- beam test with μPC2 (MWPC with same geometry as „TPC-MWPC")
- ^{90}Sr measurements in laboratory (Bragg peak)
- operation of „PSI"-TPC in μE4 and πE3 (secondary beam lines at PSI)

allowed to distinguish between following „operation" modes:

E_{Drift}:	2 kV/cm	→	$v_{drift} \approx 0.5$ cm / μs
E_{MWPC}:	> 4.8 kV/0.35 cm (gain ~50)	→	μ stop μ capture to impurities
	> 5.3 kV/0.35 cm (gain ~200)	→	Alvarez-μ from pμd fusion e_{Auger} from muonic atom (N, O)
	> 6.3 kV/0.35 cm (gain ~3000)	→	decay e

→ main data taking: gain ~100-300 due to longterm stability issues

High-pressure Hydrogen TPC – 7

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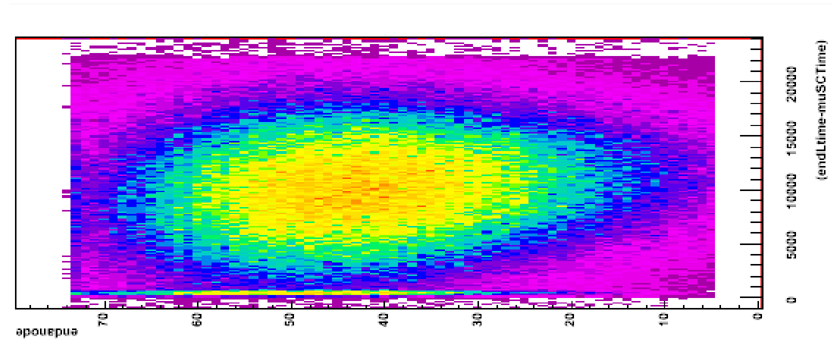
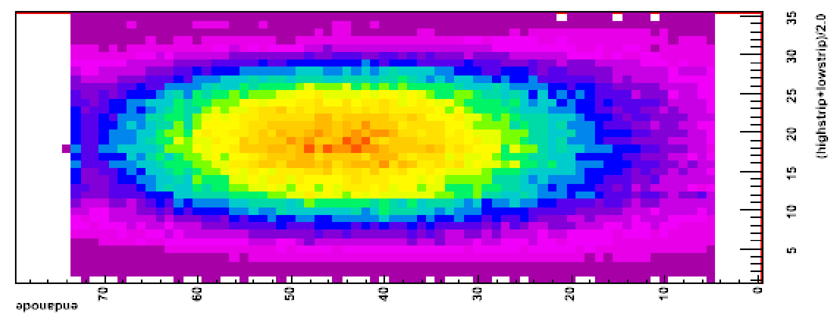
μ capture to impurities

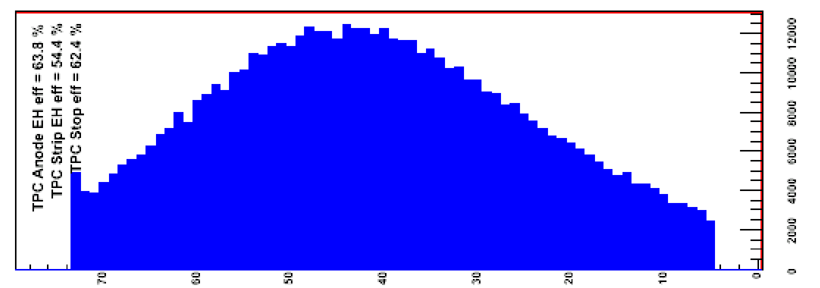
MuCap Online Histograms

- πE3, μ^-, μ^+ ~28 MeV/c
- beam rate ~25 kHz
  muon-on-demand („kicker“)
  - pileup protection
  - dead time, efficiencies
- good μ-stops in TPC ~3.5 kHz
  → $0.3 \cdot 10^9$ / day

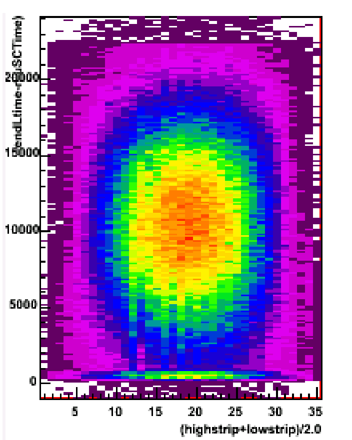
← μ

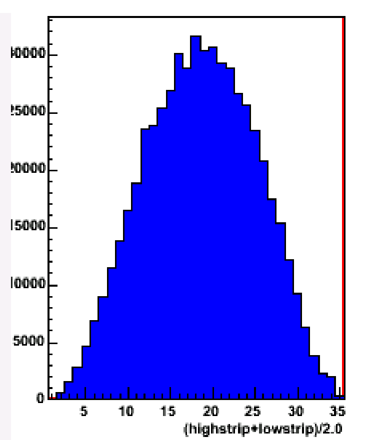




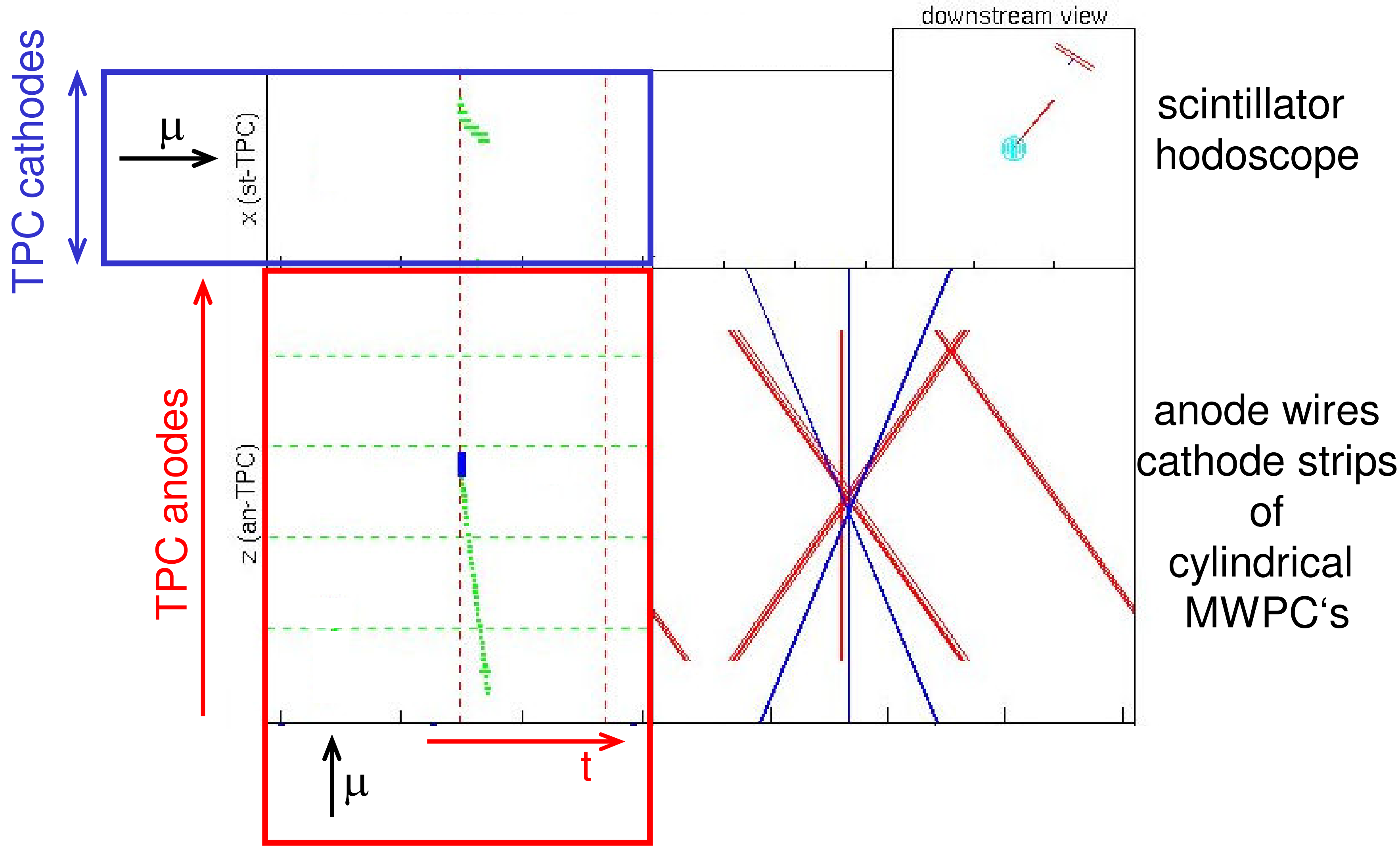


$\otimes \mu$

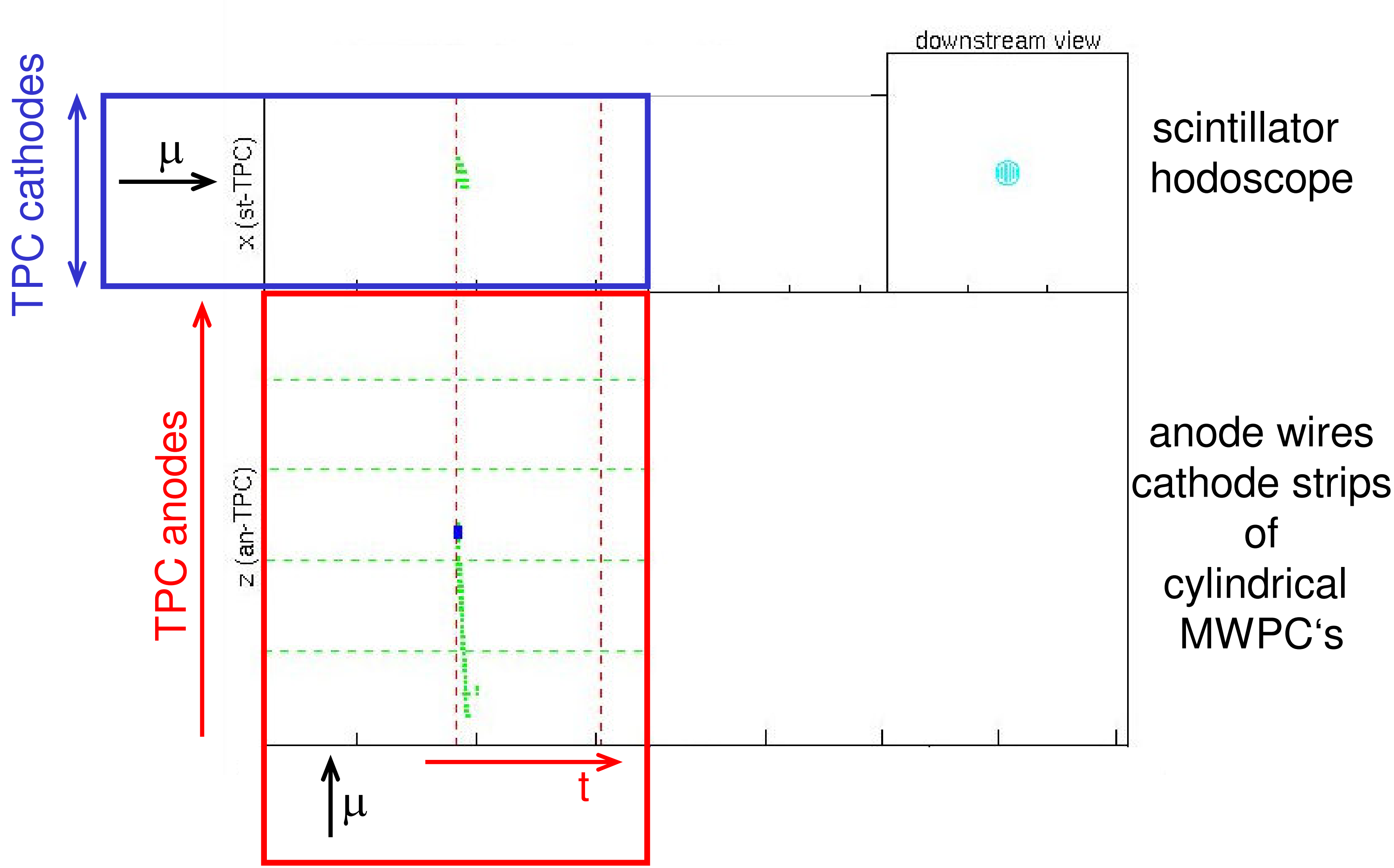




MuCap Event Display – μ Decay



MuCap Event Display – μ Capture by p



High-pressure Hydrogen TPC – 7

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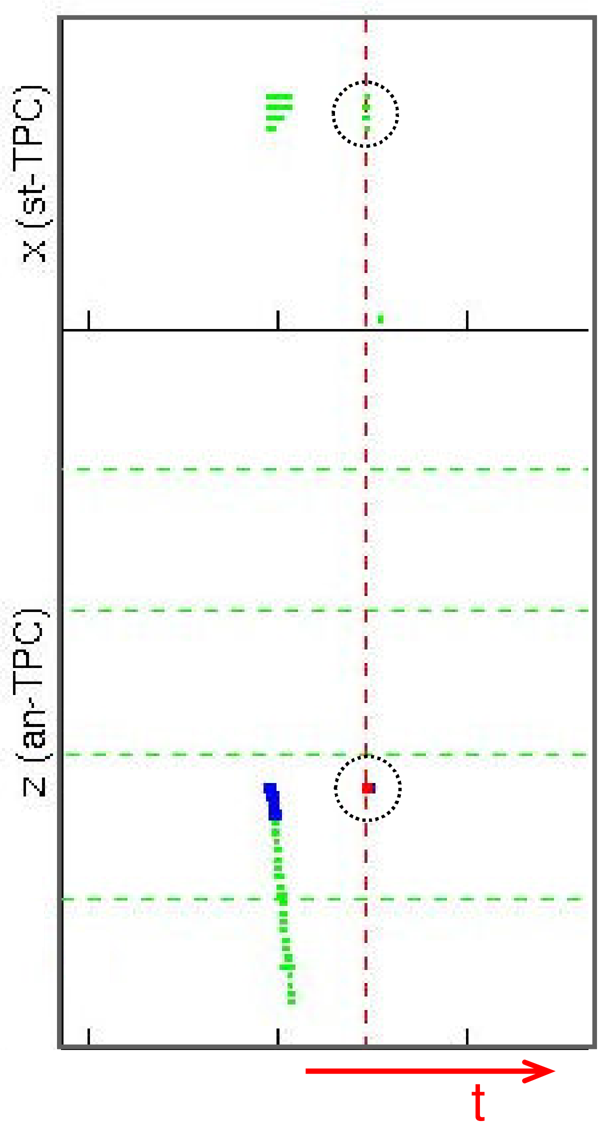
→ μ capture to impurities

Muon Capture by Impurities



- muon transfer and muon capture to high-Z impurities is enhanced

→ gas circulation and cleaning system (CHUPS)
V.A.Ganzha *et al.*, NIM A 578 (2007) 485-497

~10 ppb N_2, <1 ppb O_2/Ar, ~18 ppb H_2O

→ calibration runs to estimate corrections to $\tau_{(p\mu^-)}$

- admixture of 21 ppm nitrogen
  ↔ captures per μ-stop vs. gas chromatography
  → ~10 ppb N_2 ~1 ppm correction to $\tau_{(p\mu^-)}$

- „introduction“ of ~10 ppm H_2O
  ↔ captures per μ-stop vs. humidity sensor
  → ~18 ppb H_2O ~13 ppm correction to $\tau_{(p\mu^-)}$

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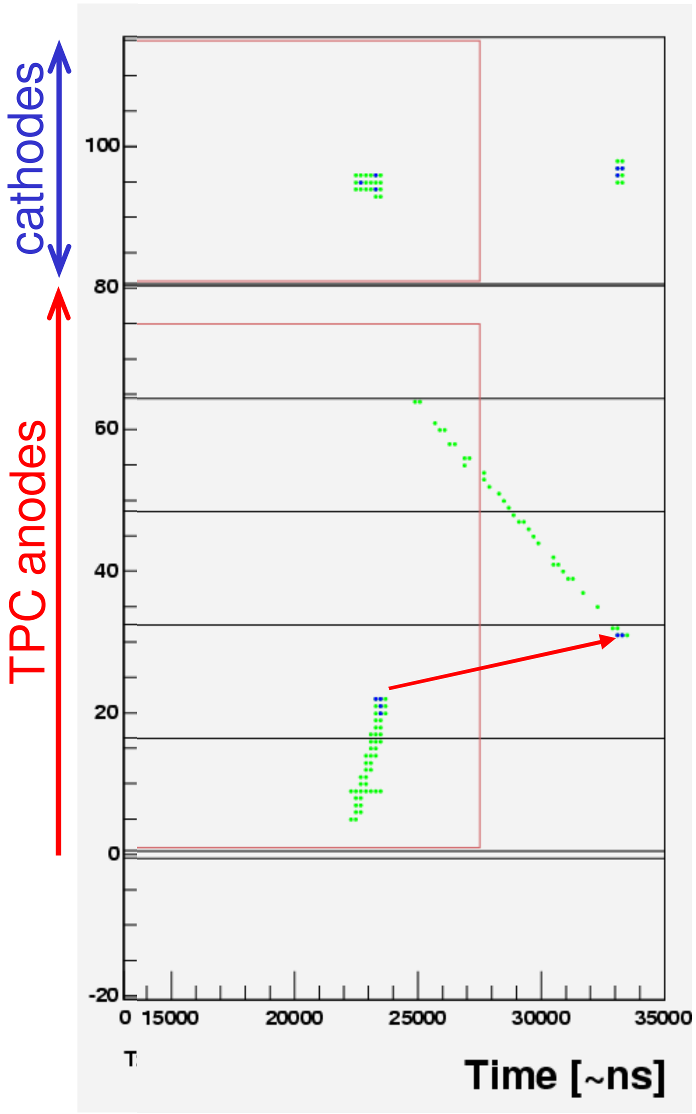
e_{Auger} from muonic atom (N, O)

„Alvarez“ Muon



- μd diffusion with remaining deuterium
- deuterium “detection tool“:

  → μ-catalysed pd fusion with emission of conversion μ („Alvarez“ muon)

- process chain in hydrogen isotopes:

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

  $\mu p + d \rightarrow \mu d + p$ (pd transfer)

  → large diffusion (cm)

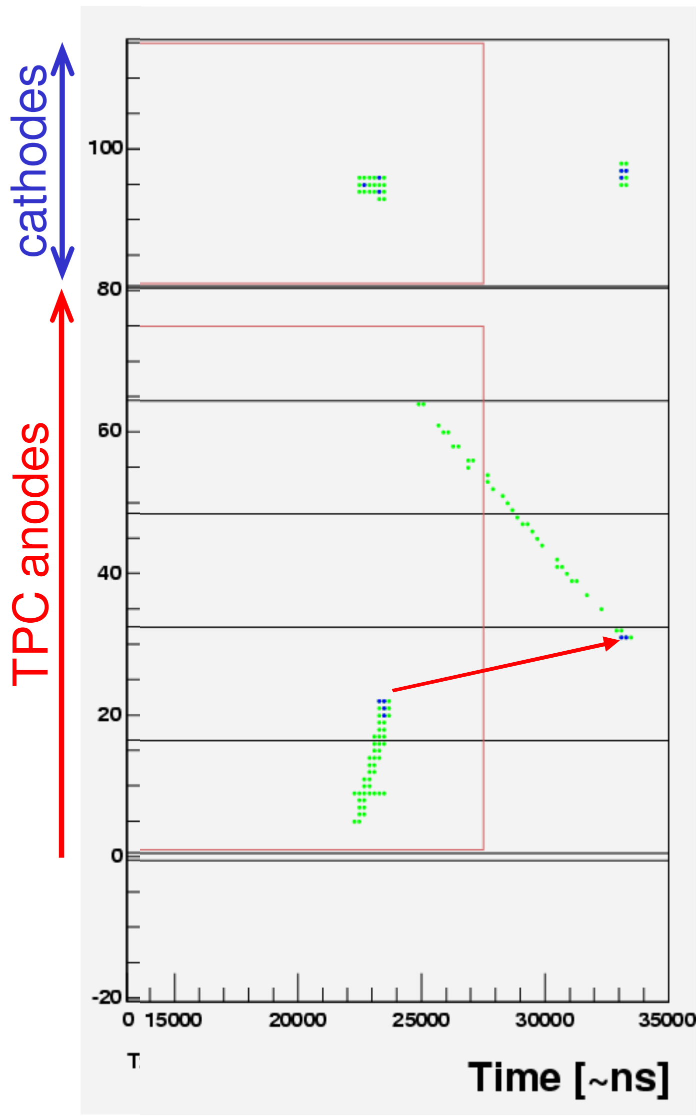
  $\mu d + p \rightarrow p\mu d$ (molecule formation)

  $p\mu d \rightarrow {}^3He$ (0.2 MeV) + μ^- (5.3 MeV)

- μd diffusion is time dependent!

  → distorts live time measurement

„Alvarez“ Muon



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- 2004, 2005: $c_D = (1.45 \pm 1.15)$ ppm

  → correction to $\tau_{(p\mu^-)}$ of -10 ppm

High-pressure Hydrogen TPC – 7

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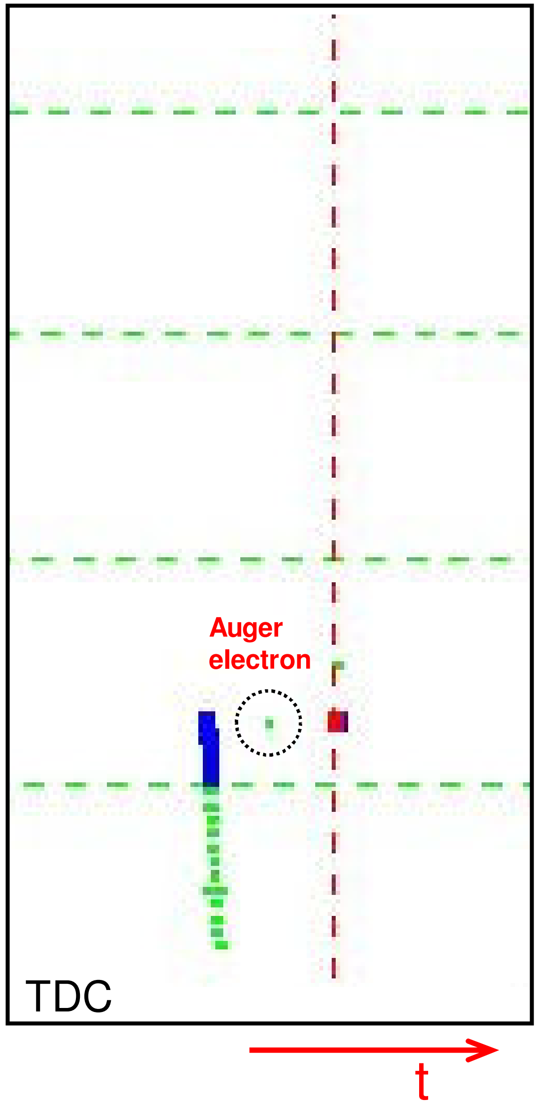
Auger Electron



remark:
- not necessary for MuCap experiment
- but example and proof of the capability of the TPC

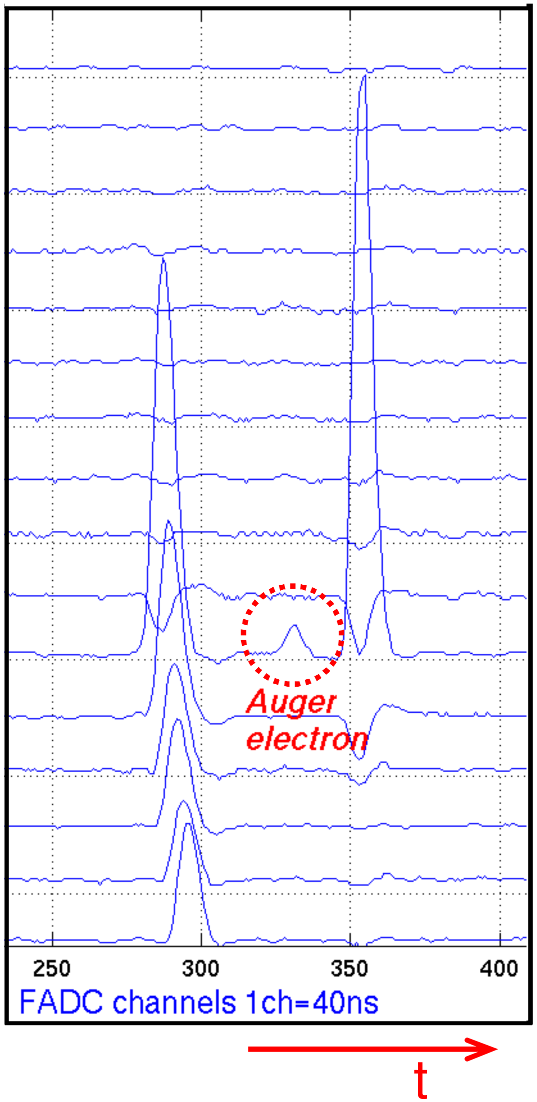
- Auger electron from de-excitation of impurity muonic atom (e.g. N, O)

→ distinguish between $\lambda_{transfer}$ and $\lambda_{capture}$

$\Delta T(\mu\text{-stopp} - e_{Auger})$ → muon transfer rate

$\Delta T(e_{Auger} - \mu\text{-capture})$ → muon capture rate

Auger Electron



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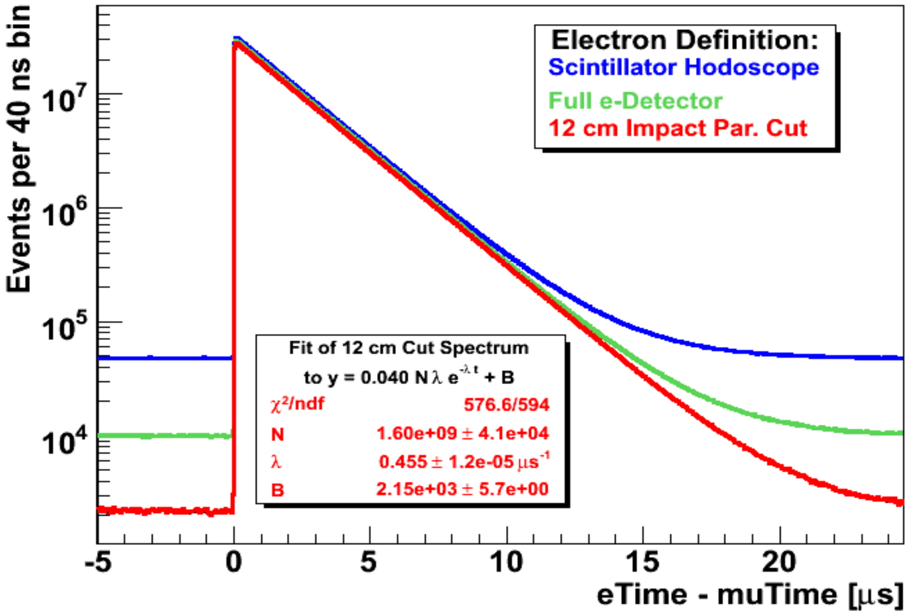
Corrections to Lifetime $\lambda_{Experiment}$



$$\lambda_{(\mu^-)'} = \lambda_{Experiment} \quad + \textit{corrections}$$

$\Delta\lambda_Z$ muon capture to Z>1 impurities: Λ_Z (C,N,O) ~(40-100)$\cdot\Lambda_S$

$\Delta\lambda_{\mu d}$ large diffusion for µd atoms: Ramsauer Townsend minimum

$\Delta\lambda_{\mu p}$ small diffusion, but magnified by e scattering in pressure vessel

new world average (incl. MuLan)

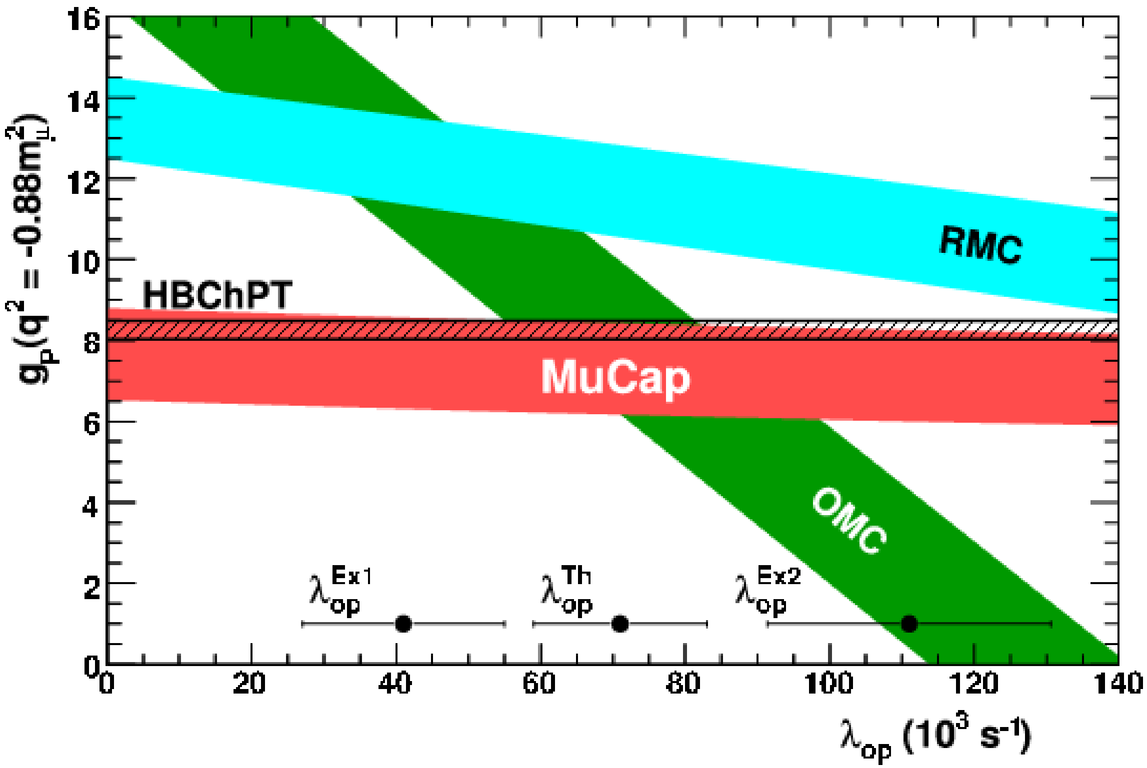
$$\Lambda_s = \lambda_{(\mu^-)'} - \lambda_{\mu^+} - \Delta\lambda_{\mu p} - \Delta\lambda_{p\mu\mu}$$

nuclear recoil correction to µ decay rate in the bound µp state (from literature)

captures from pµp states: $\Lambda_{p\mu p} < \Lambda_{\mu p}$
$\rightarrow$ $\lambda_{p\mu p}$ was measured in run 2007

Measurement of the Muon Capture Rate in Hydrogen Gas and Determination of the Proton's Pseudoscalar Coupling g_p

Andreev *et al.*, Phys.Rev.Lett. 99, 032002 (2007)



OMC
Bardin *et al.*, Nucl.Phys. A 352, 365 (1981)

RMC
Wright *et al.*, Phys.Rev. C 57, 373 (1998)

λ_{op}^{Ex1}
Bardin *et al.*, Phys.Lett. B 104, 320 (1981)

λ_{op}^{Ex2}
Clark *et al.*, Phys.Rev.Lett. 96, 073401 (2006)

λ_{op}^{Th}
Balakov *et al.*, Nucl.Phys. A 384, 302 (1982)

HBChPT
Bernard *et al.*, Phys.Rev. D 50, 6899 (1994)
Bernard *et al.*, J.Phys. G 28, R1 (2002)

HBChPT: $g_p = 8.26 \pm 0.23$

MuCap: $g_p = 7.3 \pm 1.1$

run 2004: $1.6 \cdot 10^9$ fully tracked decay events
(13% of total MuCap μ^- statistics)

→ result of run 2005-2007 will follow in 2010

Summary

- The MuCap experiment developed a new methode to measure the capture rate Λ_s of the nuclear muon capture on the free proton.
  → central idea: the use of an active hydrogen target
- The measurement principle is a lifetime measurement.
  → requirement: 100 % μ-stop identification, 3-D reconstruction of μ tracks
- The MuCap experiment developed a new Time Projection Chamber (TPC) which is operated with 10 bar hydrogen and acts as target and detector.
- To achieve a ppb impurity level the TPC was constructed using only low outgasing materials and prior to physics data taking the complete setup was heated up to 110º C under high vacuum for several weeks.
- An elaborated high vacuum and gas handling system was constructed.
- During several physics data taking run periods, the TPC worked as a fully efficient μ-stop detector and as a “detection” tool, e.g. for muon capture events on impurities or for “Alvarez” muons from pμd fusion.

MuCap Collaboration

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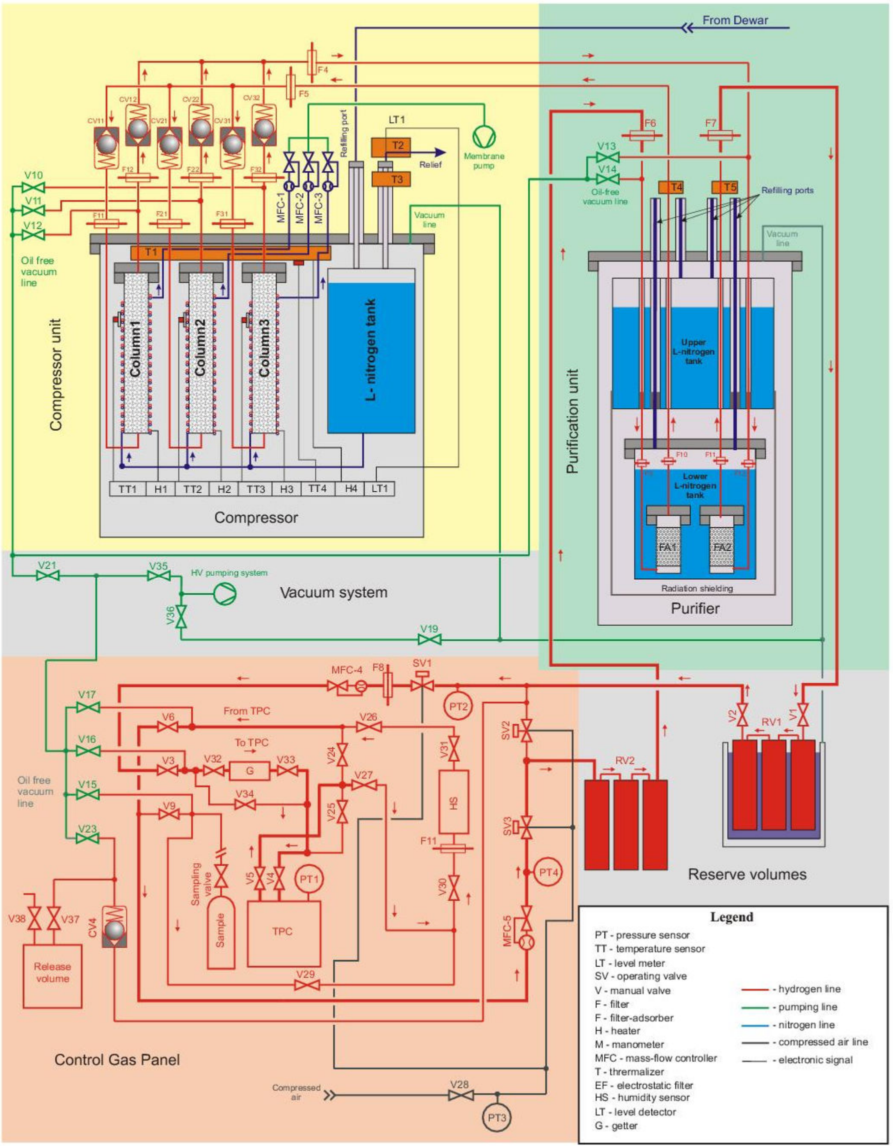
Backup Slides

Cryogenic Hydrogen Ultra-Purification System



gas circulation and cleaning system

V.A.Ganzha *et al.*, NIM A 578 (2007) 485-497

- operation at 10 bar (± <1 mbar)
- flux 0.5 – 3.5 l/min
- activ carbon, zeolith filters (LN_2)

→ ~10 ppb N_2, < 1 ppb O_2

gas chromatography

→ ~35 ppb H_2O (2005)

~18 ppb H_2O (2006)

humidity sensor (in situ)

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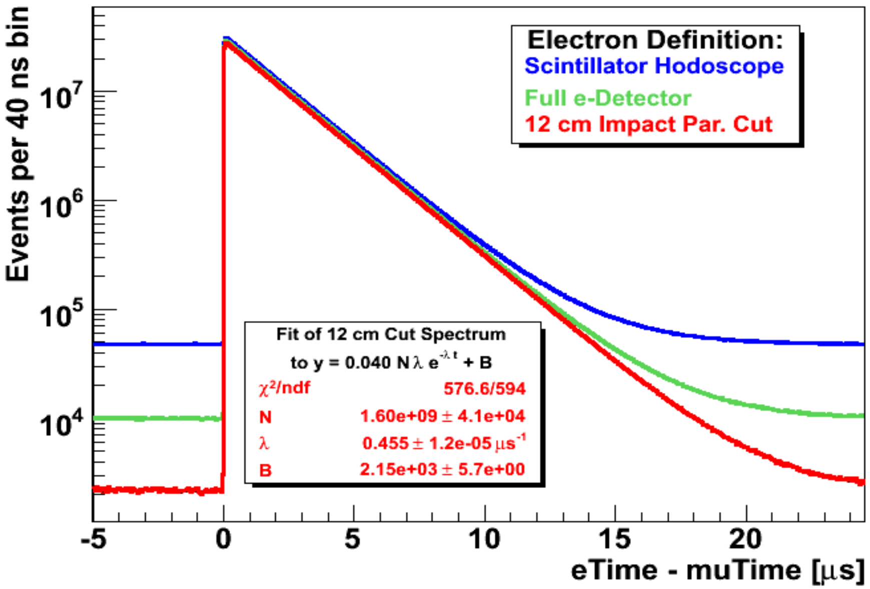
MuCap Result Λ_S



$$\lambda_{(\mu^-)'} = \lambda_{Experiment} \quad + corrections$$

$\Delta\lambda_Z$ -19.2 s^{-1}

$\Delta\lambda_{\mu d}$ -10.2 s^{-1}

$\Delta\lambda_{\mu p}$ -2.7 s^{-1}

$$\lambda_{(\mu^-)'} = 455\,851.4 \pm 12.5_{stat} \pm 8.5_{syst}\ s^{-1}$$

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

$\Delta\lambda_{\mu p}$ -12.3 s^{-1}

$\Delta\lambda_{p\mu p}$ -23.5 ± 4.3 ± 3.9 s^{-1}

λ_{μ^+} 455 162.2 ± 4.4 s^{-1}

MuCap: $\Lambda_S = 725.0 \pm 13.7_{stat} \pm 10.7_{syst}\ s^{-1}$

run 2004, 13% of total MuCap μ^- statistics

Andreev *et al.*, Phys.Rev.Lett. 99, 032002 (2007)

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PSI

25 Years of TPC

PARTICLE DETECTORS

The time projection chamber turns 25

Since its birth 25 years ago, the time projection chamber has developed into a mature technology that is used in many fields, as **Spencer Klein** describes.

A time projection chamber (TPC) provides a complete, 3D picture of the ionization deposited in a gas (or liquid) volume. It acts somewhat like a bubble chamber, albeit with a fast, all-electronic read-out. The TPC's 3D localization makes it extremely useful in tracking charged particles in a high-track-density environment, and for identifying particles through their ionization energy loss (dE/dx). To honour the 25th anniversary of the TPC, a symposium was organized at the Lawrence Berkeley National Laboratory on 17 October 2003, with workshops that included presentations on the past, present and future of the TPC.

The TPC was invented by Dave Nygren at the Lawrence Berkeley Laboratory (LBL) in the late 1970s. Its first major application was in the PEP-4 detector, which studied 29 GeV e^+e^- collisions at the PEP storage ring at SLAC. Since then TPCs have been used to study e^+e^- collisions at PEP, at the TRISTAN collider, at the KEK laboratory and at the Large Electron Positron (LEP) collider at CERN. A TPC could also be the central detector at future e^+e^- linear colliders.

The device has also figured in a number of experiments involving heavy-ion collisions at machines such as LBL's Bevalac and the Relativistic Heavy Ion Collider (RHIC) at Brookhaven; and now the ALICE collaboration is building a large TPC to study heavy-ion collisions at the Large Hadron Collider (LHC). TPCs have also been used in a whole host of non-accelerator experiments.

TPCs in particle physics

The PEP-4 TPC (figure 1) was built to combine charged-particle tracking with good particle identification by measuring the specific energy loss (dE/dx) of charged particles. This 2 m long cylindrical TPC had an inner diameter of 40 cm and an outer diameter of 2 m, and had most of the features of newer TPCs.

Charged particles from e^+e^- collisions in the centre of the TPC ionized molecules in a mixture of 80% argon and 20% methane gas at 8.5 atmosphere. A central membrane (the cathode) that was charged to −75 kV produced a strong electric field (figure 2, see p41). Under the influence of this field, ionization electrons drifted to one of the two end caps. A solenoidal magnetic field minimized the transverse diffusion and bent the charged particles to allow momentum measurement.

The end caps were divided into six sectors, each one containing a 183-anode multiwire proportional chamber (MWPC). Drifting electrons were accelerated in the strong electric fields around the wires and acquired enough kinetic energy to ionize the gas and produce an avalanche. A single drift electron produced about 1000 electrons in the wire.

The wire signals were sampled 10 million times per second to a 9-bit accuracy by an analogue storage unit based on a charge-coupled device (CCD). The signals were

charge on several adjacent pads, the ionization could be localized to approximately 250 µm. These pads were also read out by the CCD system.

Later TPCs used many of the techniques pioneered by PEP-4. Some notable examples were the ALEPH and DELPHI TPCs at LEP, the TOPAZ experiment at TRISTAN and the early vertex chambers for the CDF experiment at Fermilab. The ALEPH TPC at LEP was one of the larger examples, measuring 3.6 m in diameter and 4.4 m in

TPCs have also been used in a number of smaller experiments, such as in studies of muon decay and capture. The MuCap experiment at the Paul Scherrer Institute, for example, is building a 10 atmosphere hydrogen-gas TPC to measure muon lifetime.

CERN Courier, January / February 2004

Milestones in TPC development

- PEP4 at LBL@SLAC
- EOS at Bevelac@LBL
- E895 at AGS@BNL
- E907 at Fermilab
- TOPAZ at TRISTAN@KEK
- ALEPH at LEP@CERN
- DELPHI at LEP@CERN
- NA35, NA36, NA45 (Ceres), NA49 at SPS@CERN
- STAR at RHIC@BNL
- ICARUS at Gran Sasso