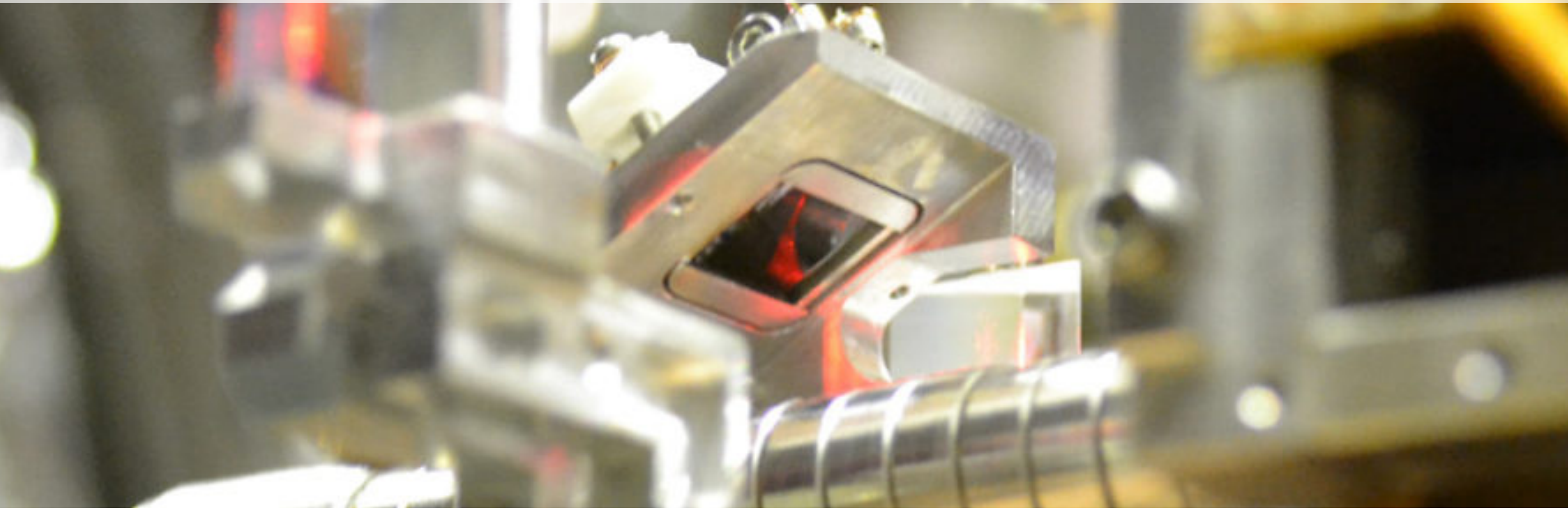
AVA Topical Workshop - Low energy facility design and optimization through diagnostics



LOW ENERGY ANTIPROTONS AND POSITRONIUM MANIPULATION, DETECTION AND DIAGNOSTICS FOR PULSED ANTIHYDROGEN PRODUCTION

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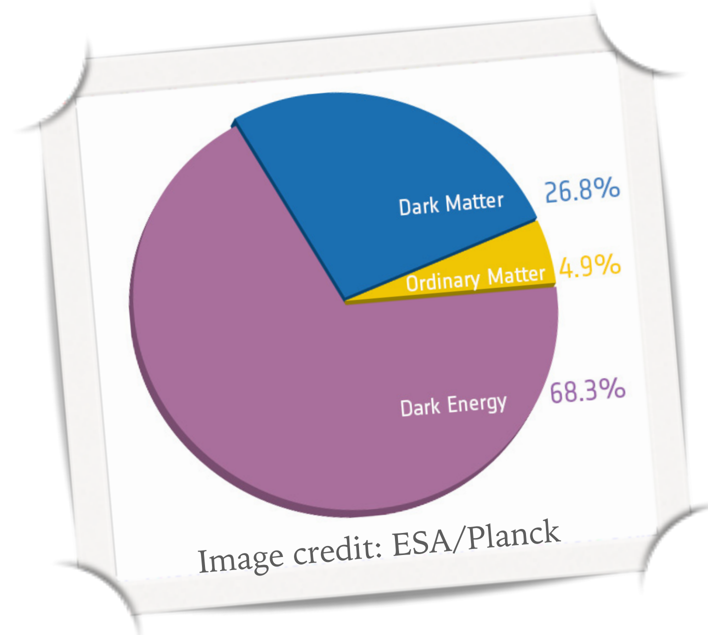
ANTIMATTER

- **Baryon asymmetry vs hadronization epoch**
  - ✳ No hints of antimatter in the baryonic sector

- **Look for fundamental sources of asymmetries**
  - ✳ Test of fundamental CPT symmetry
    Matter and antimatter should have equal properties (masses, lifetime, |charges|, g-factor...)
  - ✳ Test of Weak Equivalence Principle (WEP) with antimatter
    "*The behaviour of a body in an external gravitational field should not be affected by its composition*"
    Inertial mass and gravitational mass are identical

Any difference between matter and antimatter will necessarily have consequences…

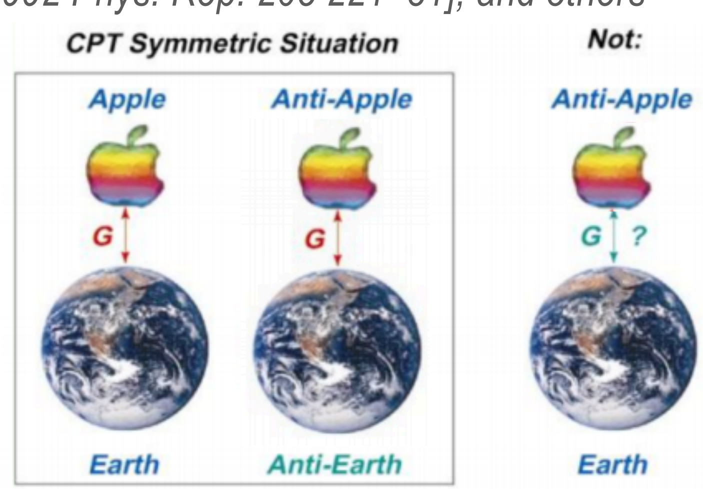
GRAVITY



- **Currently no direct experimental WEP test available for antimatter**
  - ∗ Normal matter: $\frac{\delta g}{g} = 10^{-13}$ *[J.G. Williams et al. Phys. Rev. D 53, 6730, 1996]*

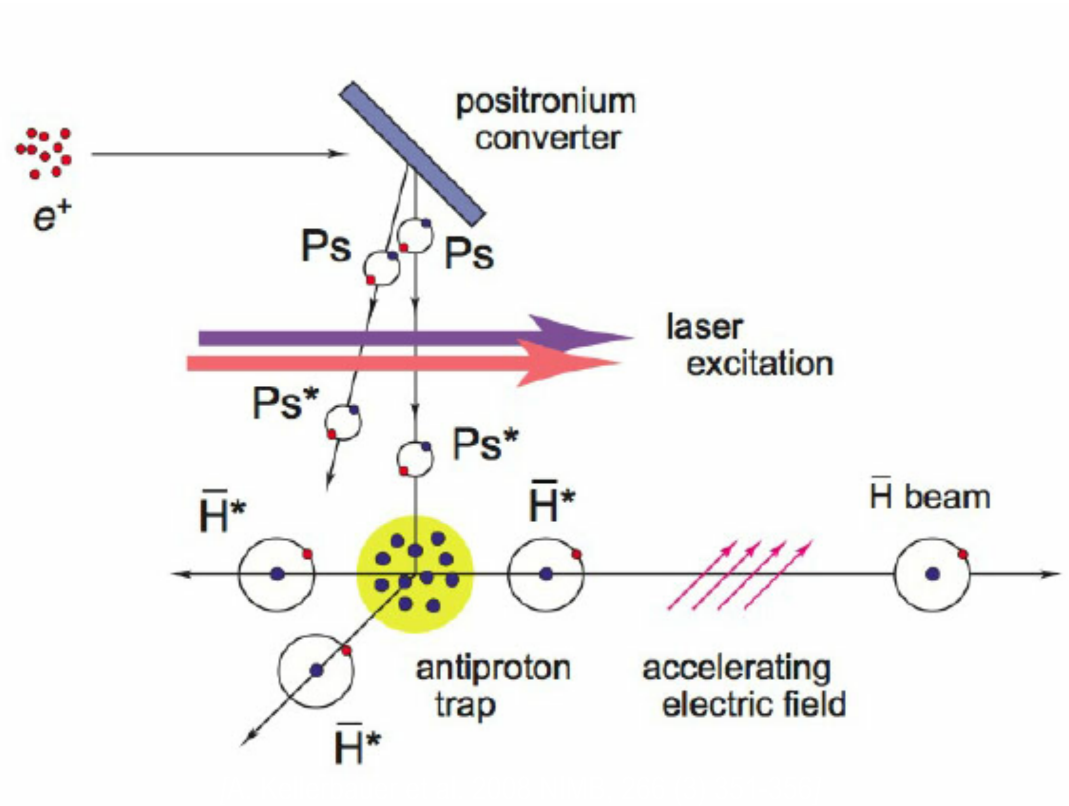
- **Three main hypothesis for gravitational interaction with antimatter**
  - ∗ Normal gravity (Einstein's Equivalence Principle, EEP)
    EEP=Weak Equivalence Principle + Local Lorentz Invariance + Local Position Invariance
  - ∗ Antigravity
    CPT invariance combined with General Relativity *[Villata M. 2011 EPL 94 20001]*
    -> Would imply General Relativity not universally applicable [Cabbolet, M.J.T.F, *Astrophys Space Sci (2012) 337:5–7]*
  - ∗ Slight violations of the EEP
    Quantum scalars and vector fields may be allowed when QFT extended to include gravitation
    -> Possibility of a non-identical gravitational interaction between matter and antimatter
    [Scherk J 1979 Phys. Lett. B 88 265], [Goldman T et al 1986 Phys. Lett. B 171 217], [Nieto M and Goldman T 1992 Phys. Rep. 205 221–81], and others

⇨
- ☐ Insights for quantum gravity?
- ☐ Connection to Dark Energy?
- ☐ …



APPROACH

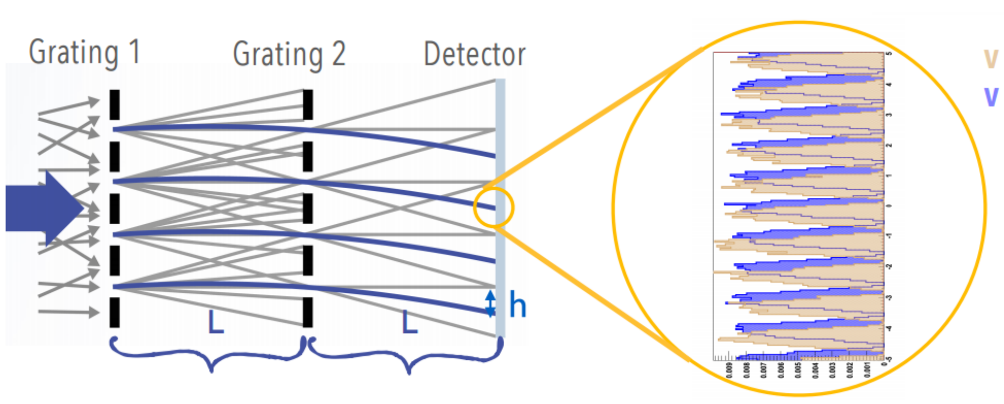
- **Measure the gravitational acceleration for antihydrogen in Earth gravitational field**
  - Pulsed antihydrogen formation via resonant charge exchange reaction with positronium (Ps)
  - Acceleration into cold pulsed antihydrogen beam
  - Direct measurement of the free fall of antihydrogen with position detector



Horizontally flying antihydrogen @500 m/s with a flight path of 1 m

⇨ Deflection due to gravity $h = 20\ \mu m$

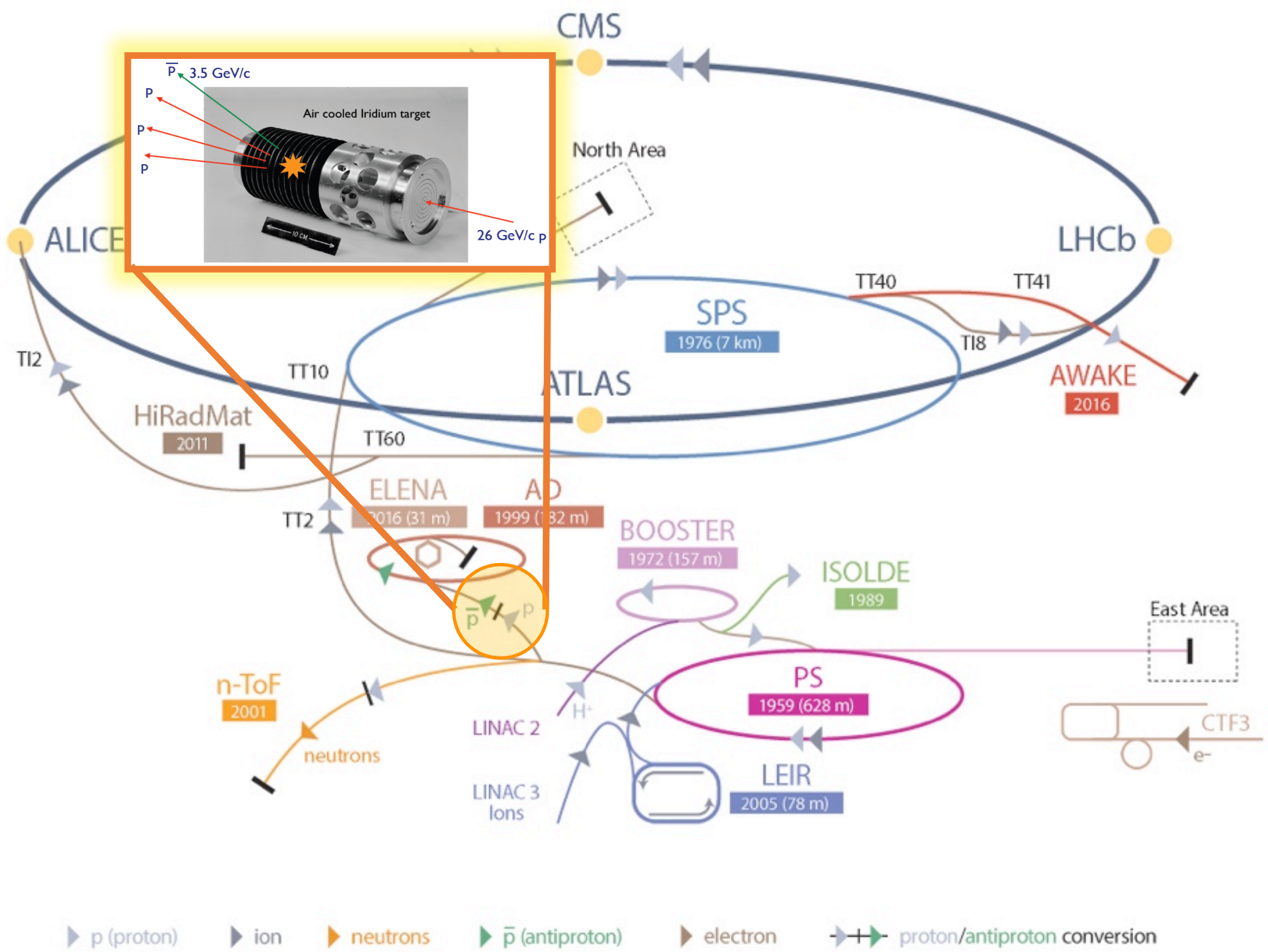
1% precision with ~$10^3\ \bar{H}$ detected

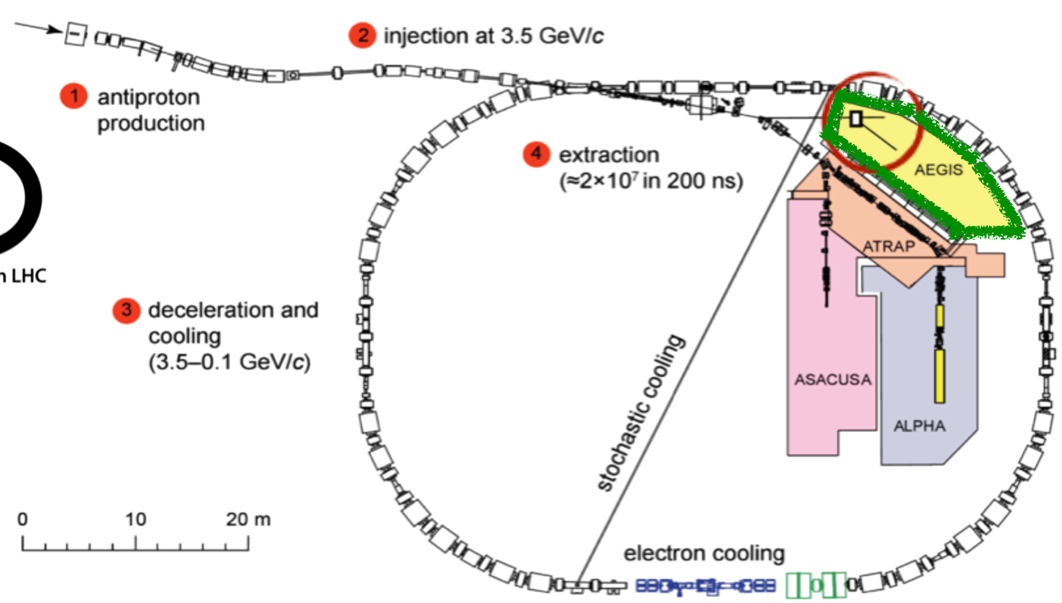


$$h = \frac{g}{a}\left(\frac{L}{v_h}\right)^2$$

[AEgIS proposal, http://cdsweb.cern.ch/record/1037532]

ANTIPROTONS

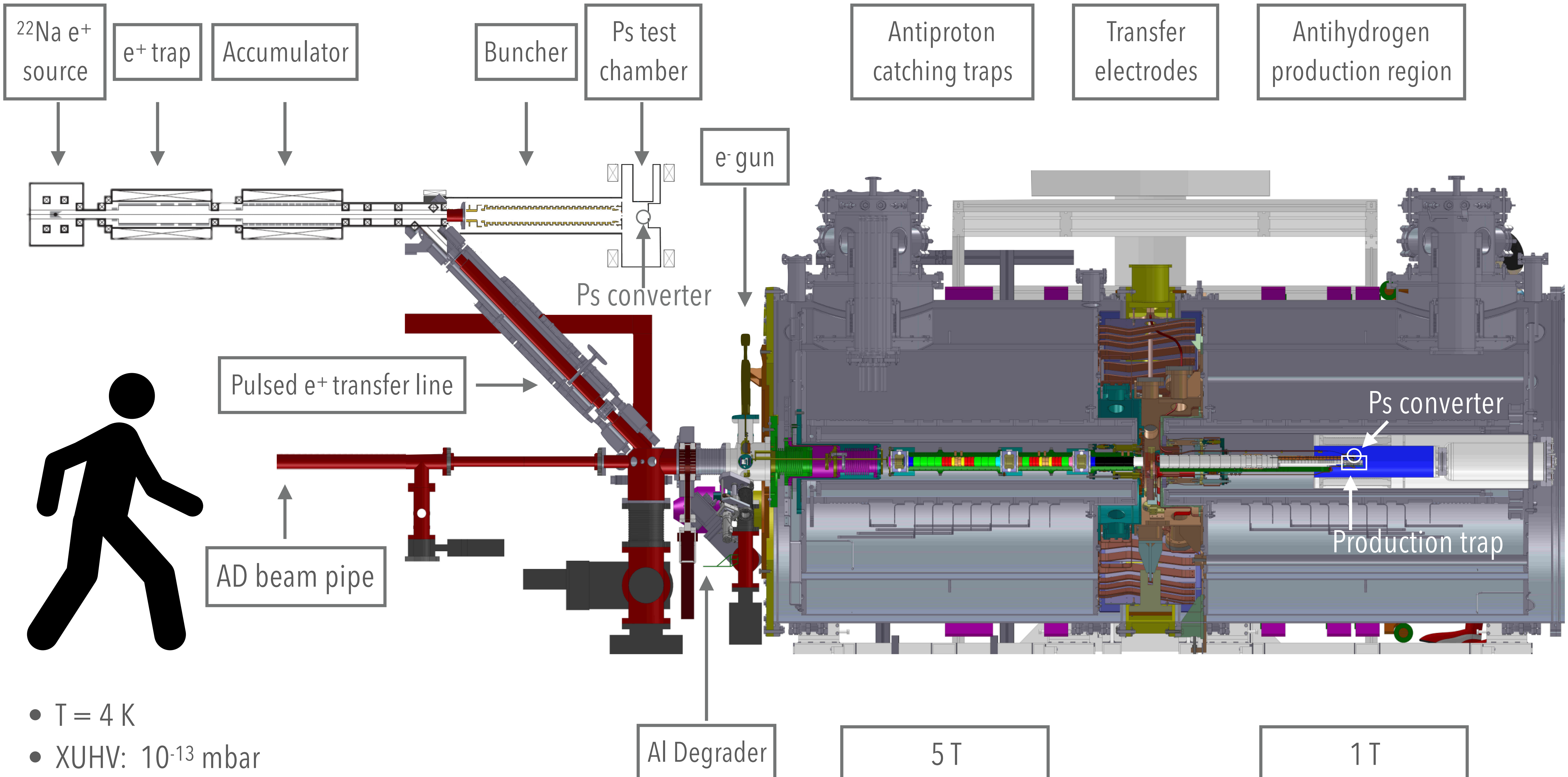




Much Cooler than LHC

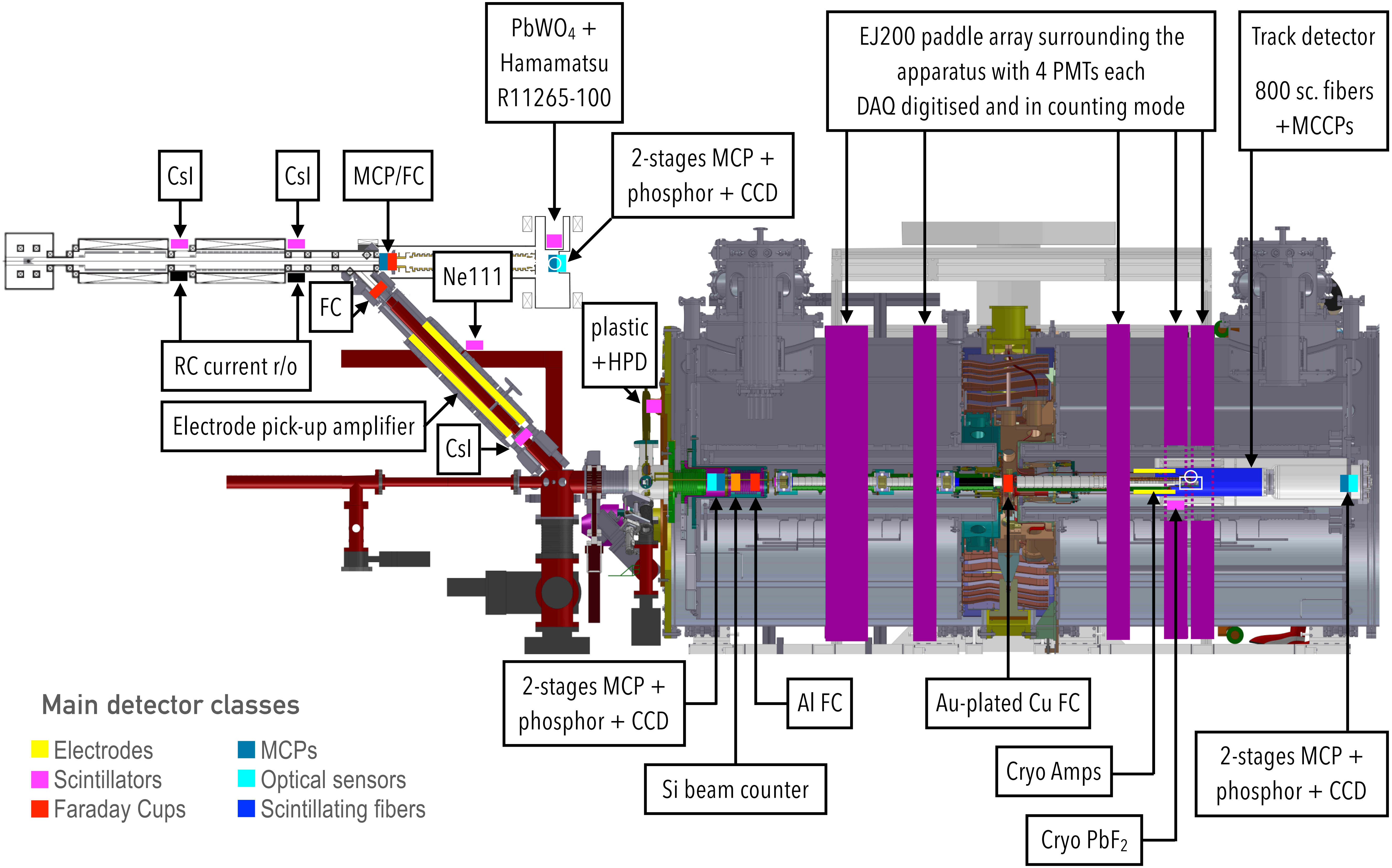
- **The Antiproton Decelerator at CERN**
  - Delivers 3×10^7 antiprotons few 10 ns every 110 s
  - 5.3 MeV, 100 MeV/c
- **Coming soon: ELENA**
  - Further deceleration to 100 keV

APPARATUS



- T = 4 K
- XUHV: 10^{-13} mbar
- 1.5×10^7 low (broad) energy antiprotons
- 4.5×10^5 antiprotons trapped at 9 kV, 1.3% efficiency

DETECTION SYSTEM



Main detector classes

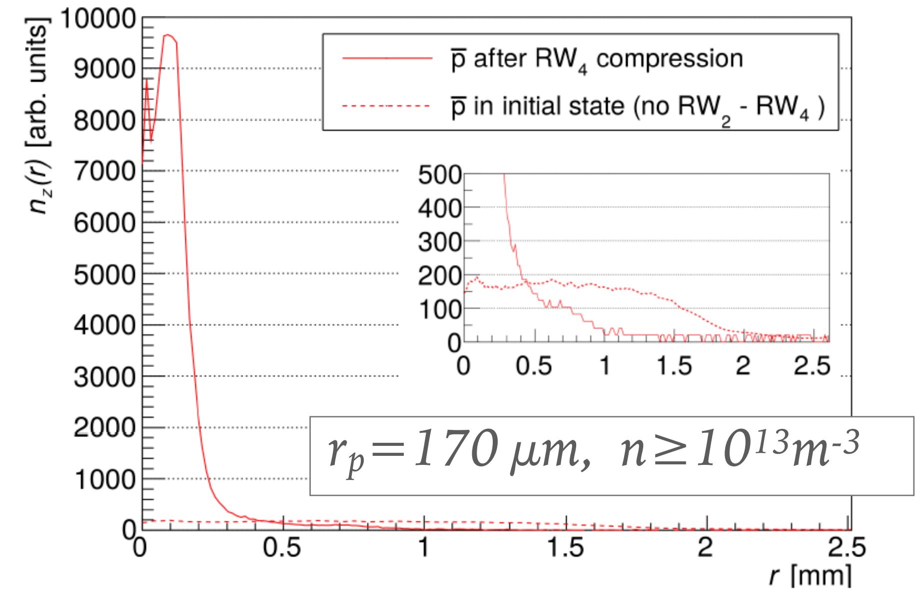
- Electrodes
- Scintillators
- Faraday Cups
- MCPs
- Optical sensors
- Scintillating fibers

$\bar{p}$ CATCHING

5T

- Multiring Penning/Malmberg catching traps
  - Used for antiproton catching, cooling, storage and transfer
  - 1 m length, 15 mm radius, B= 4.46 T

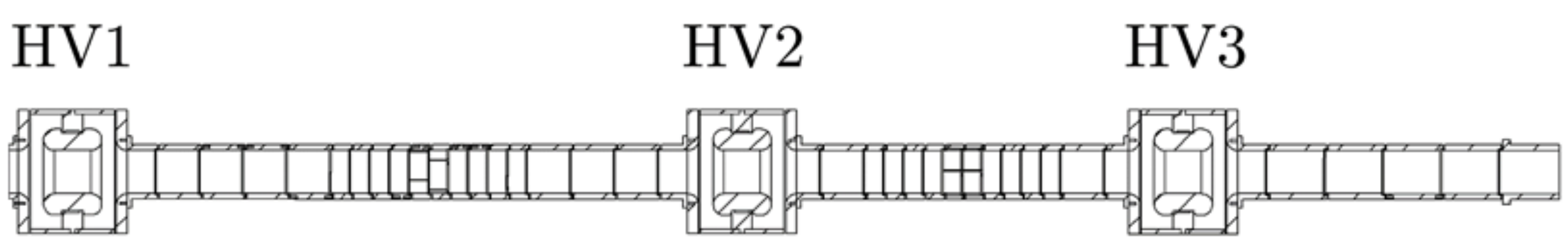
- Routinely catching antiprotons coming from AD
  - ~4.5x10^5 per AD shot (~3x10^7)
  - Strong dependence on steering and AD's general health



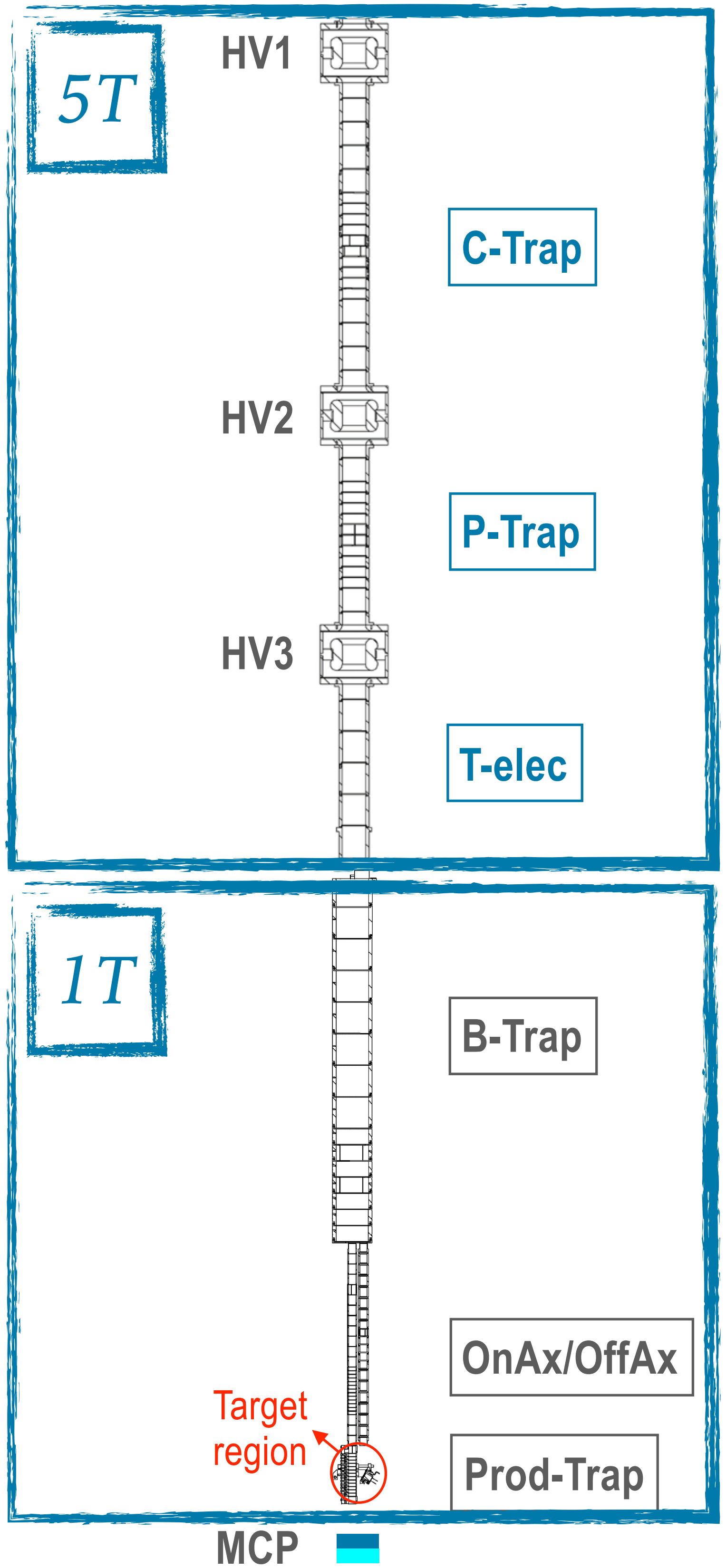
[Aghion S. et al., 2018 Eur. Phys. J. D 72 76]

- Accumulation and compression of several AD shots
  - Trade-off between stability and performances.
  - Linear growth of antiprotons cooled and compressed with number of AD shots
  - Best: 8 AD shots

Lowest antiproton cloud radius + highest density ever!



$\bar{\mathrm{P}}$ COMPRESSION



Catch antiprotons from AD

Preload electrons to cool down

Remove the hottest fraction

Move potentials

Cool down

Apply compression

Lower one edge of the well

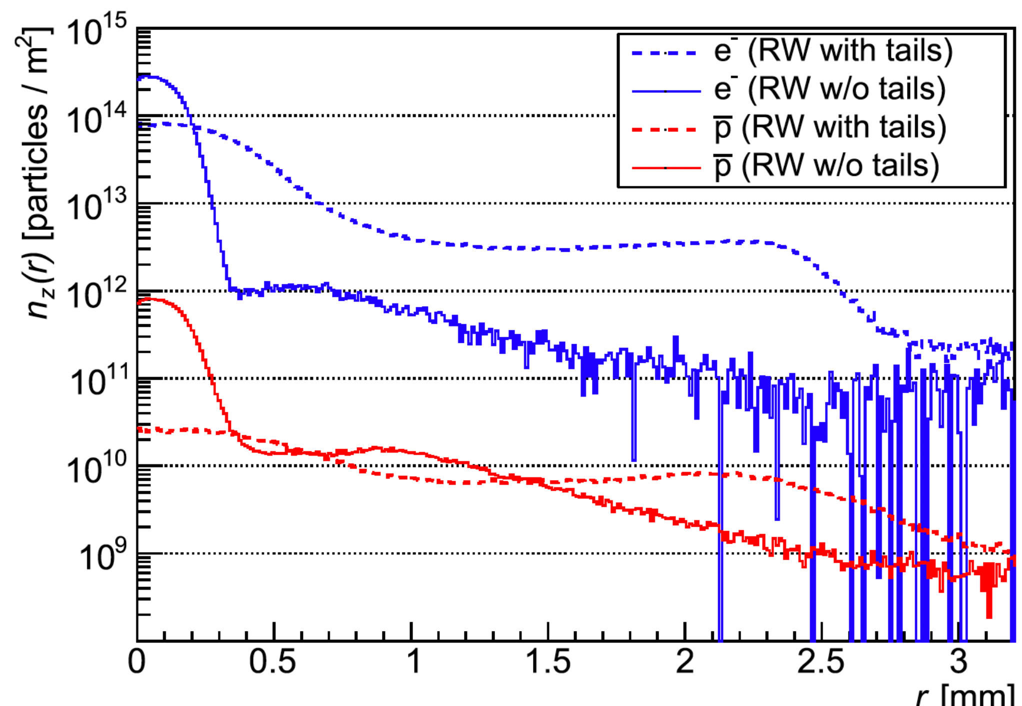
Transfer

In-flight recenter (segm. electr.)

Plasma cloud moves along the field line towards the MCP at end of the apparatus

5T

- Remove significant part of the electrons
- Apply RW technique on multispecies plasma
- Use additional electron reduction
- Repeat in compression stages to reach lower radii
- Fight against electron tails!



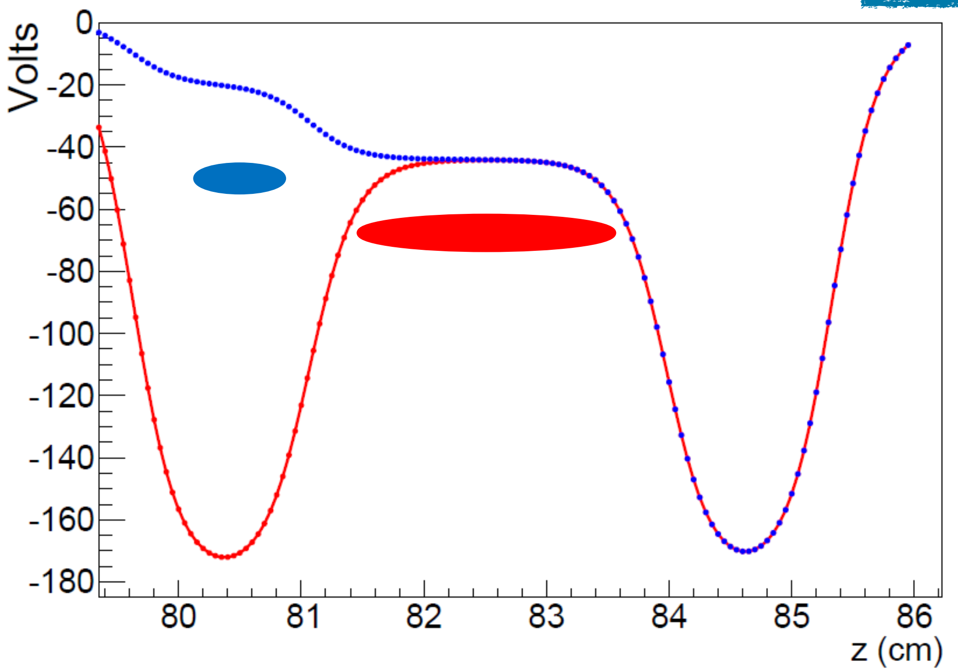
- Destructive measurement
  Detection= MCP + Phosphor + CCD
- The MCP measures radial distribution integrated along the trap axis
- Image intensity will be proportional to the number of particles

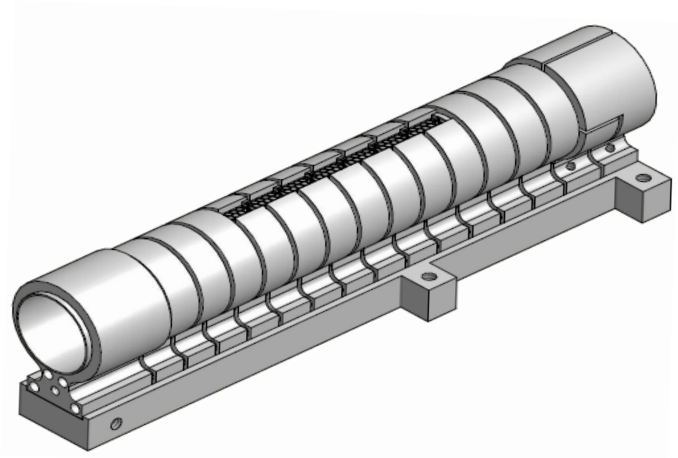
[Aghion S. et al., 2018 Eur. Phys. J. D 72 76]

H̄ PRODUCTION

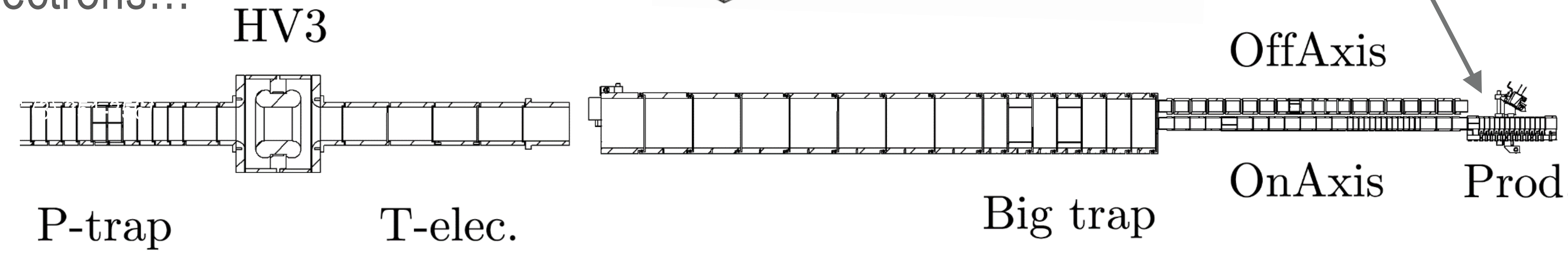
1T

- **Transport towards the production region**
  - Ballistic transfer: 1.5 m, radially compressed cloud
  - In-flight dynamical centring and recatching (90% efficiency)
- **Cooling antiprotons in the final trap**
  - Prepare electron plasma (~10^7), send to the antiproton well
    -Fast pulses (~10 ns) to open/close the trap
  - RW cloud compression for few tens of seconds
- **Get the best antiproton cloud condition**
  - Reduce the number of electrons
  - Limit the radial transport, reduce radial velocity
  - Cannot remove all the electrons…



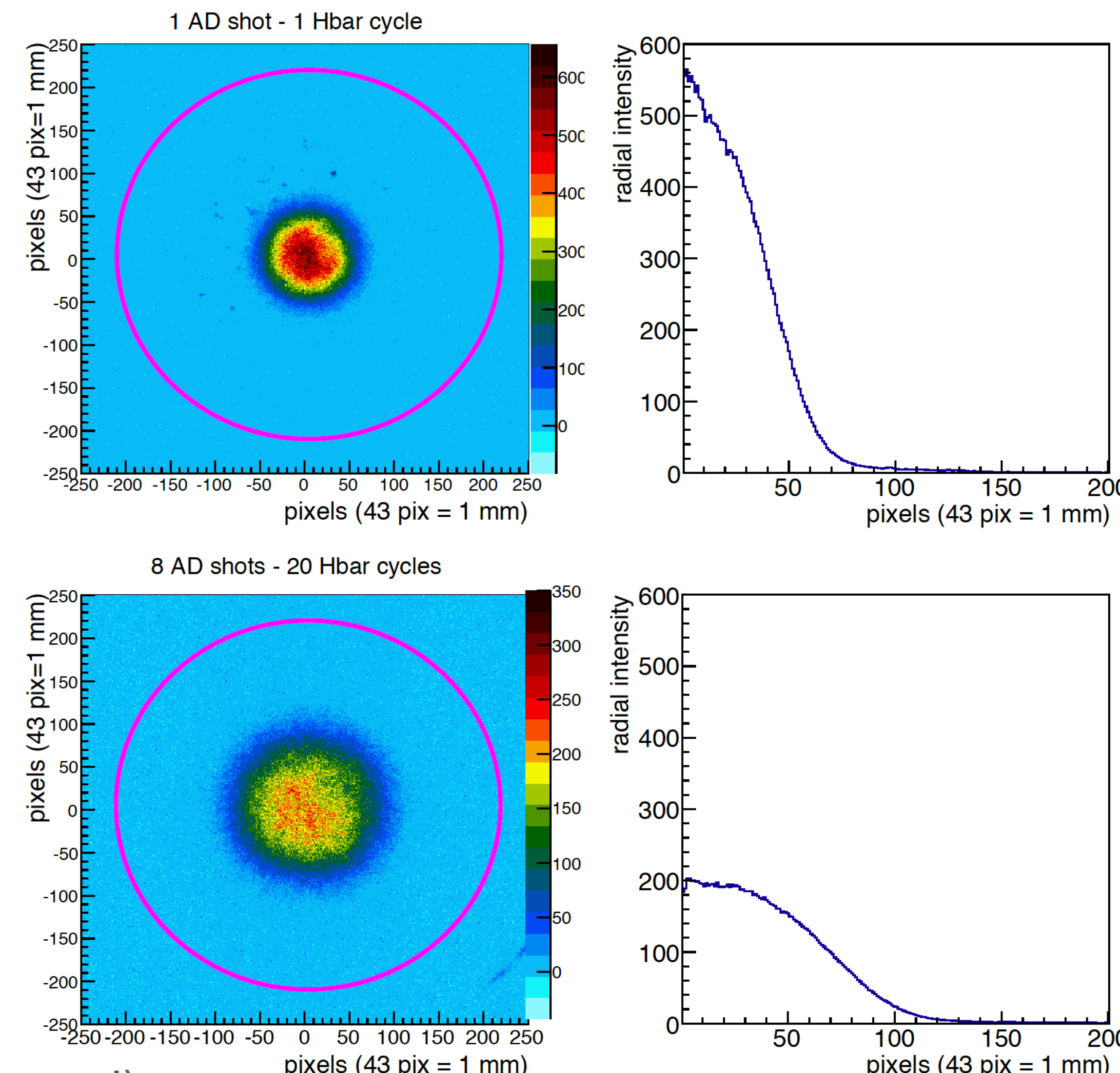


Non-standard trap design
Radial transport

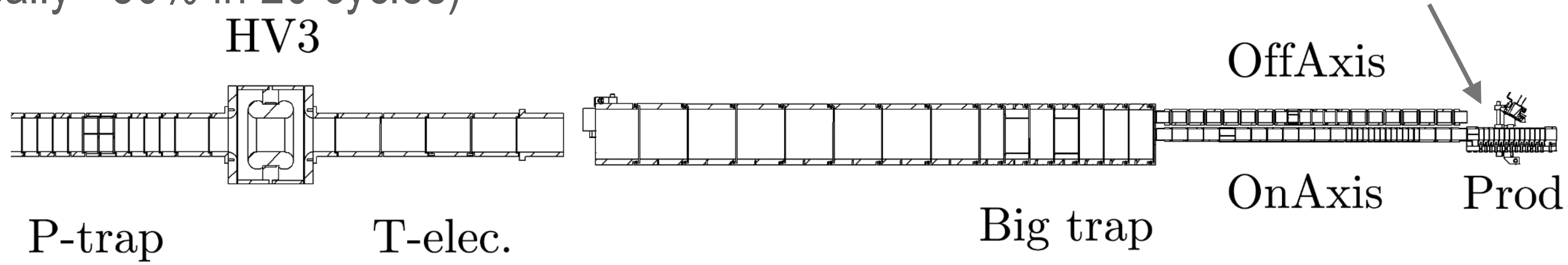


H̄ PRODUCTION

- **Multiple antihydrogen production cycles**
  - Up to 10^6 antiprotons available for each production cycle
  - Up to 60 production cycles per stored antiproton cloud
  - Improving time efficiency and production efficiency
- **Multispecies non-neutral plasma**
  - Antiprotons and electrons in the same cloud
  - Accurate choice of parameters (e.g. to avoid centrifugal separation)
- **Antiproton plasma lifetime mainly affected by**
  - Radial expansion rate (plasma angular moment not conserved)
  - Losses in the residual gas
  - Control of the losses (typically ~30% in 20 cycles)

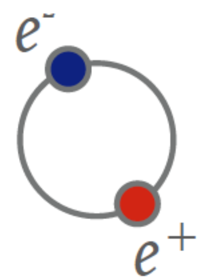


Non-standard trap design
Radial transport



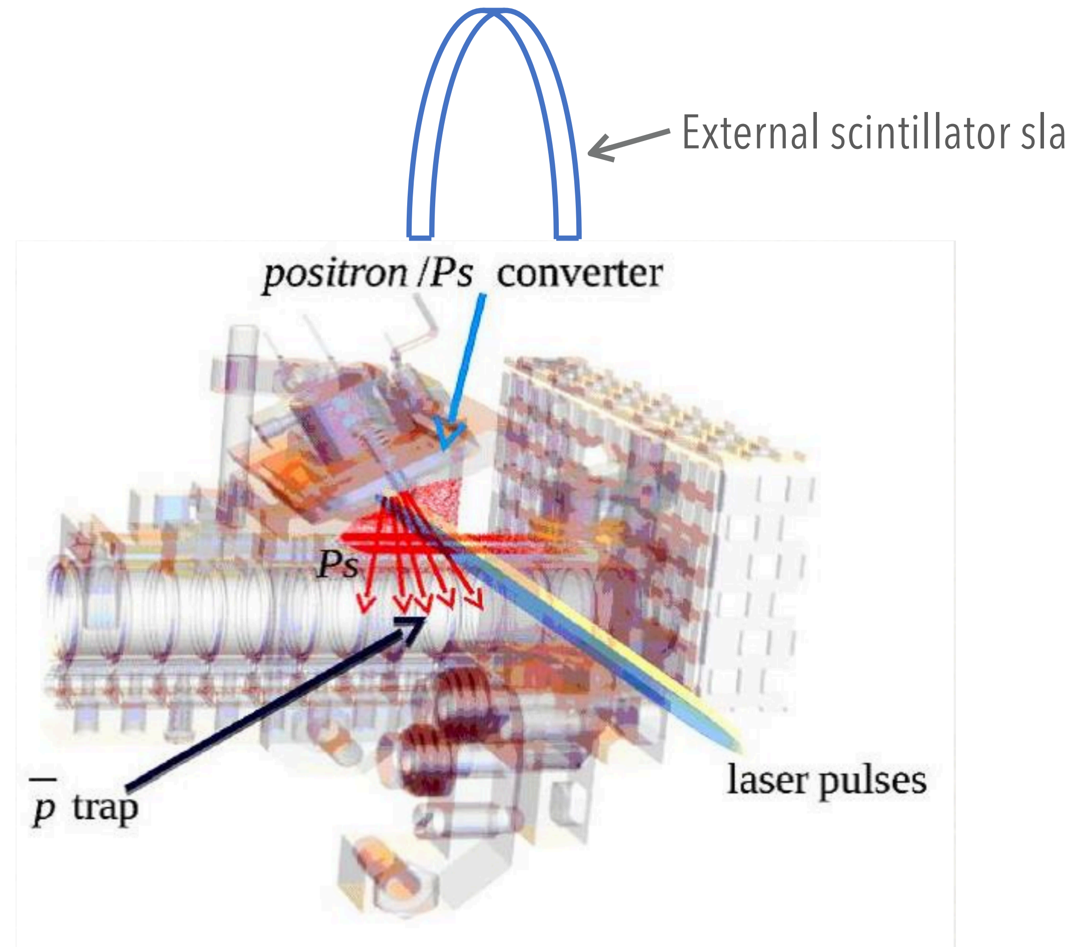
1T

POSITRONIUM

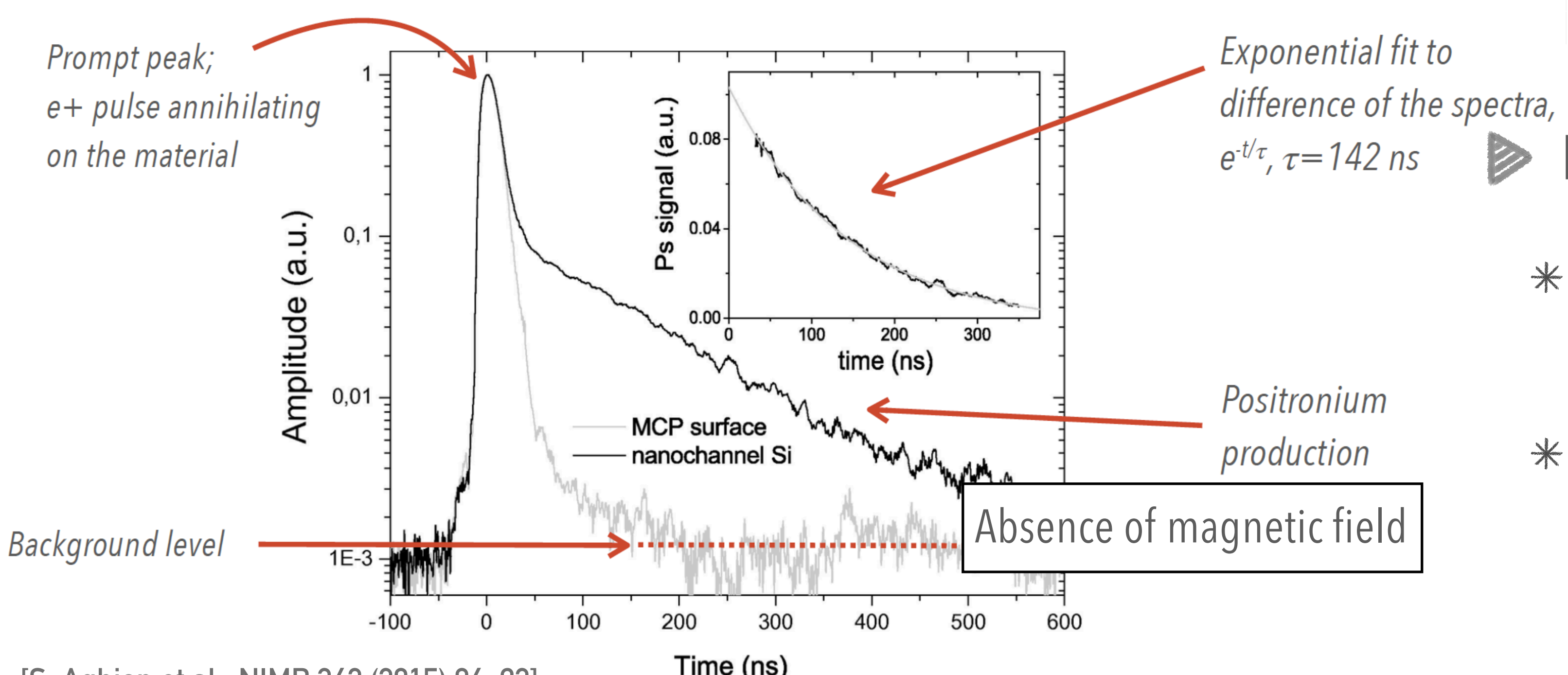


- Bound state of positron and electron
  - ✳ Hydrogen-like pure leptonic atom
  - ✳ Two spin configurations, different lifetimes

State	Spin configuration	Name	Lifetime	Decay
1^1S	↑↓−↓↑	*para-positronium (p-Ps)*	125 ps	2γ
1^3S	↑↑, ↓↓, ↑↓+↓↑	*ortho-positronium (o-Ps)*	142 ns	3γ



Single-Shot Positron Annihilation Lifetime Spectroscopy (SSPALS)



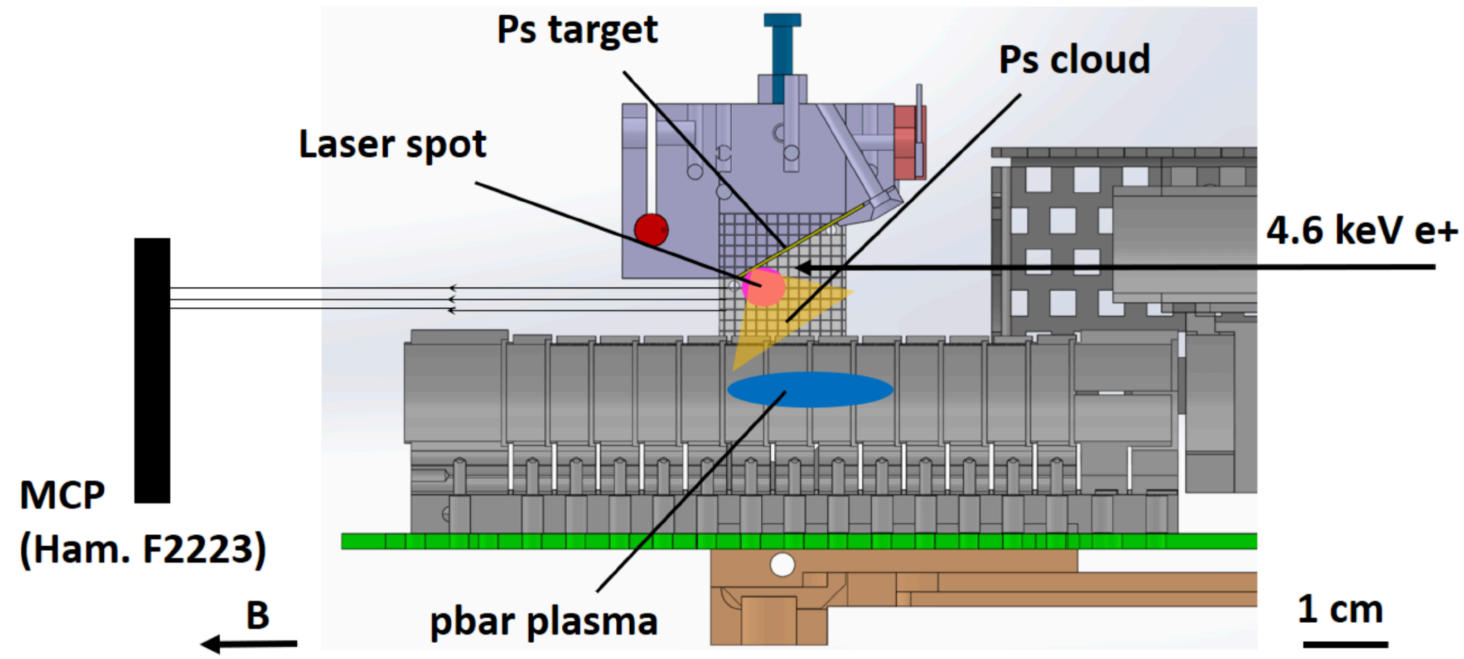
[S. Aghion et al., NIMB 362 (2015) 86–92]

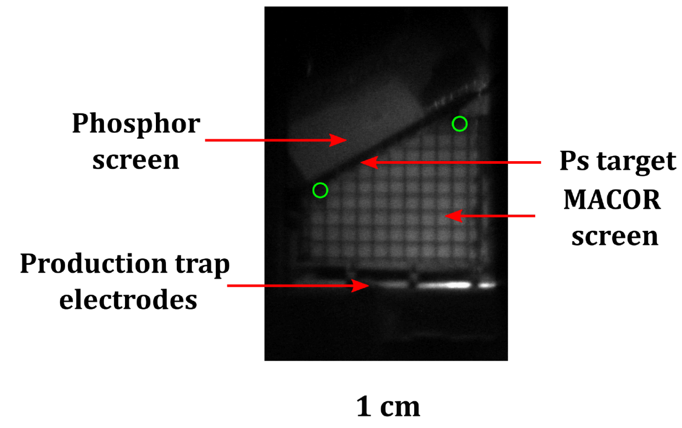
- Laser excitation to Rydberg states
  - ✳ Rydberg Ps for longer lifetime and higher antihydrogen production rate
  - ✳ Antihydrogen production cross section

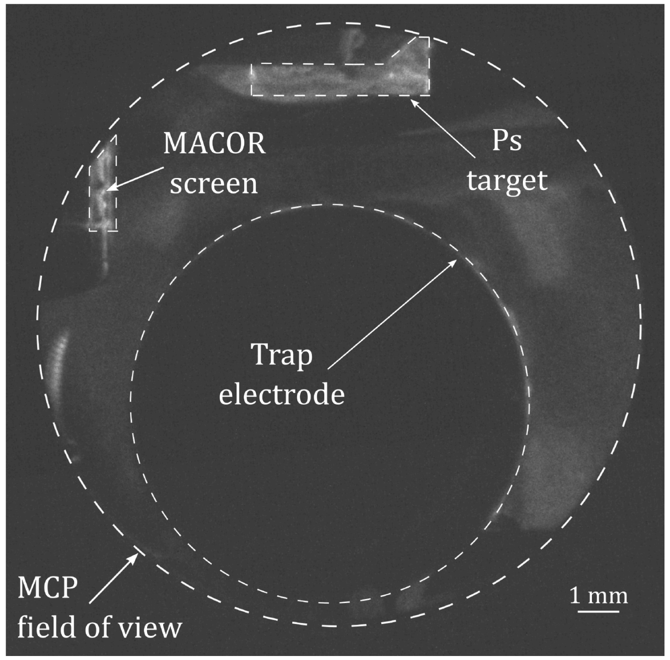
$$\boxed{\sigma \propto n_{Ps}^4} \quad \sigma(n_{Ps} = 18) \approx 10^{-10}\ cm^2$$

PS NEW DIAGNOSTICS

- **Improved visibility in the target region**
  - Target region modified to allow for significantly improved diagnostics
  - Mount the target as close as possible to the production trap
- **Rework of the laser diagnostics**
  - New CMOS camera from outside vacuum for imaging of laser excitation position relative to positron implantation point
  - Optical fibres for positioning coupled to a PMT for timing information
    + Phosphor, Macor with meshgrid
- **MCP added to the Ps diagnositcs**
  - Move the MCP to add Ps cloud path to its view for imaging of released positrons and electrons

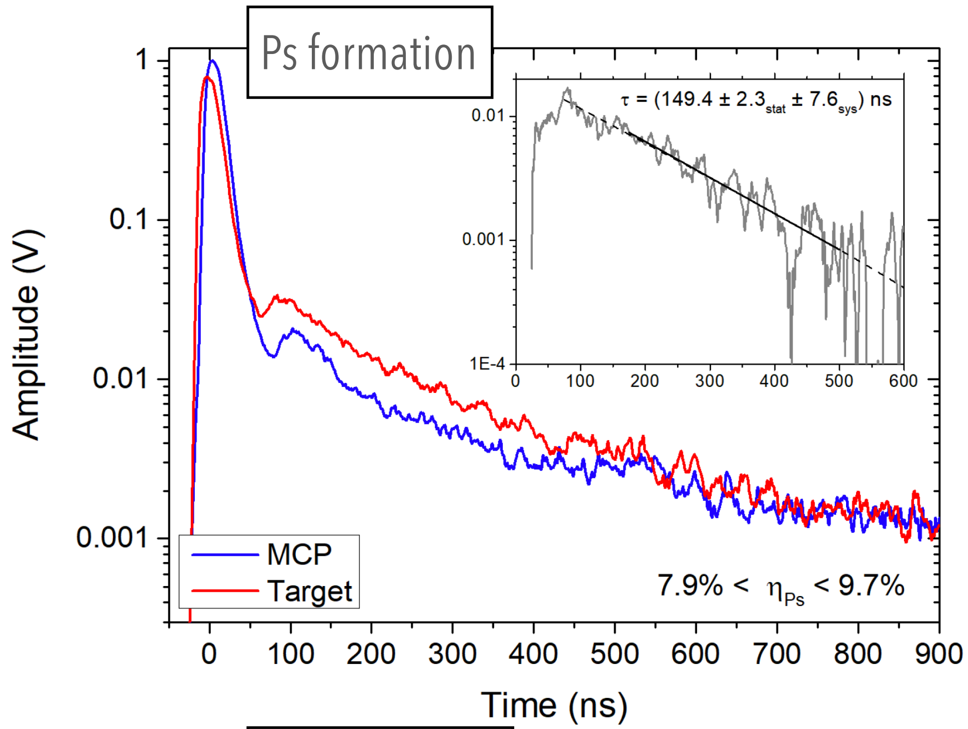


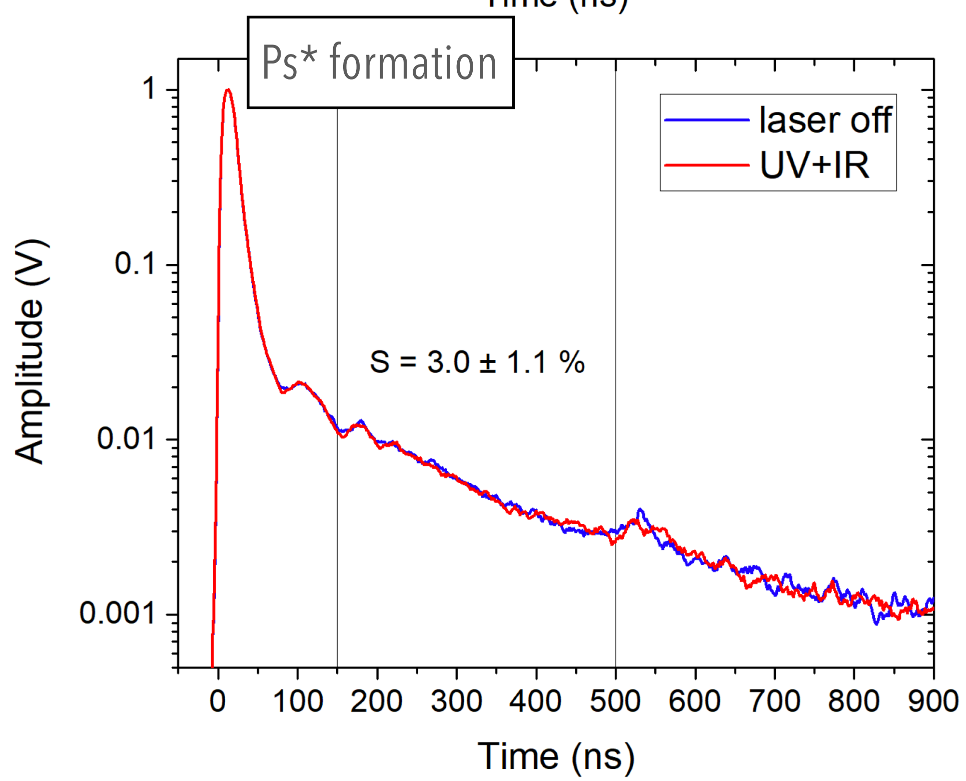




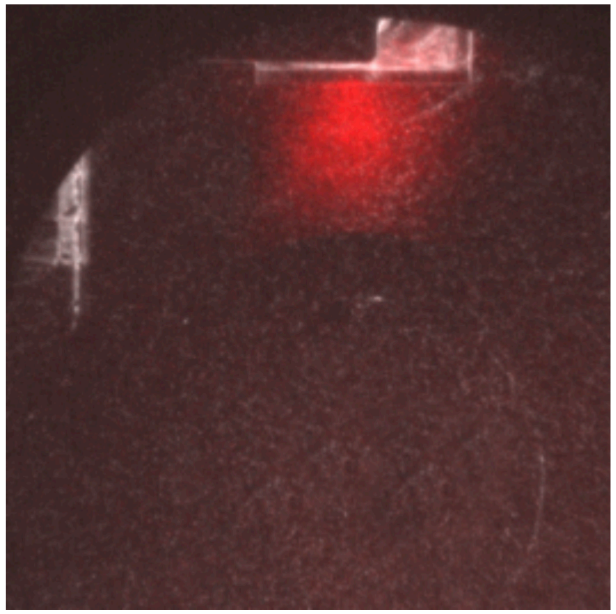
PS CHARACTERISATION IN 1T

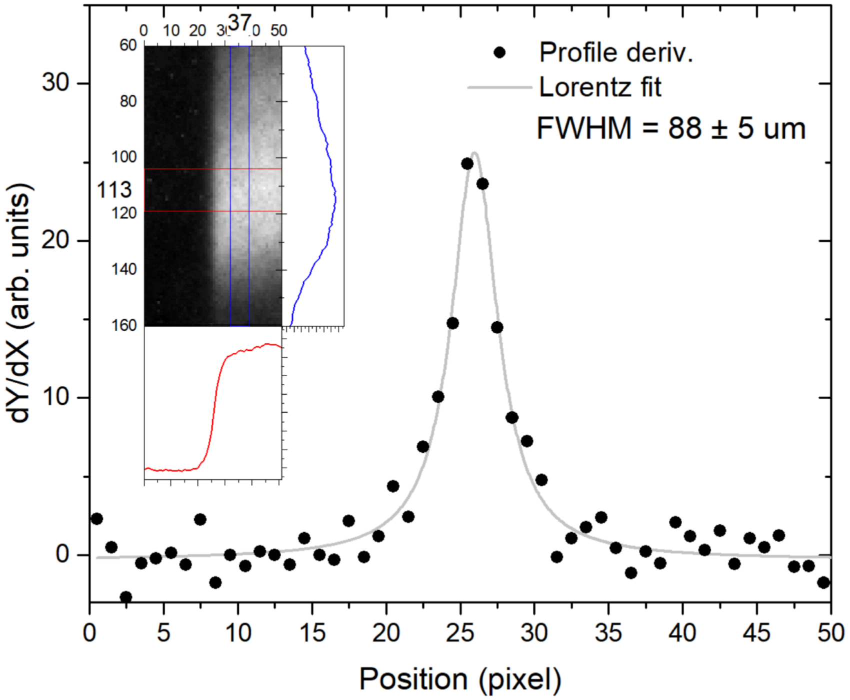
- Before: SSPALS (hundreds of shots)

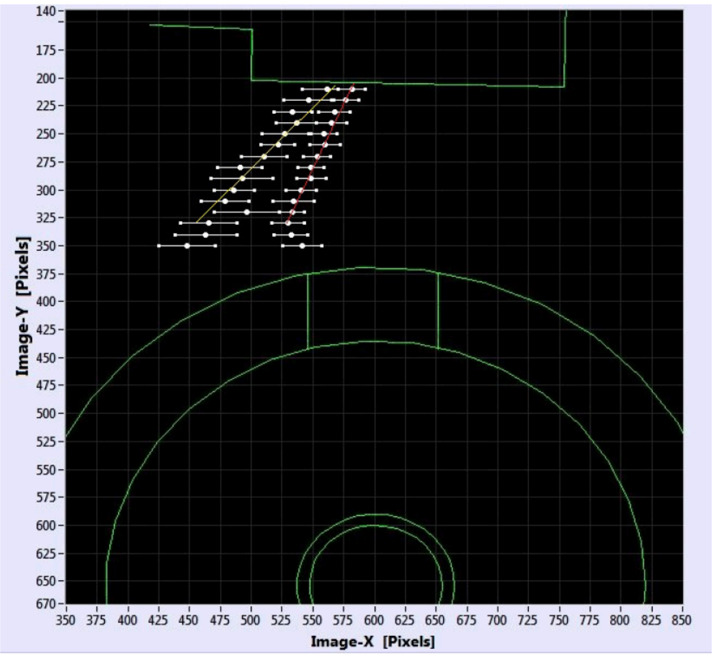


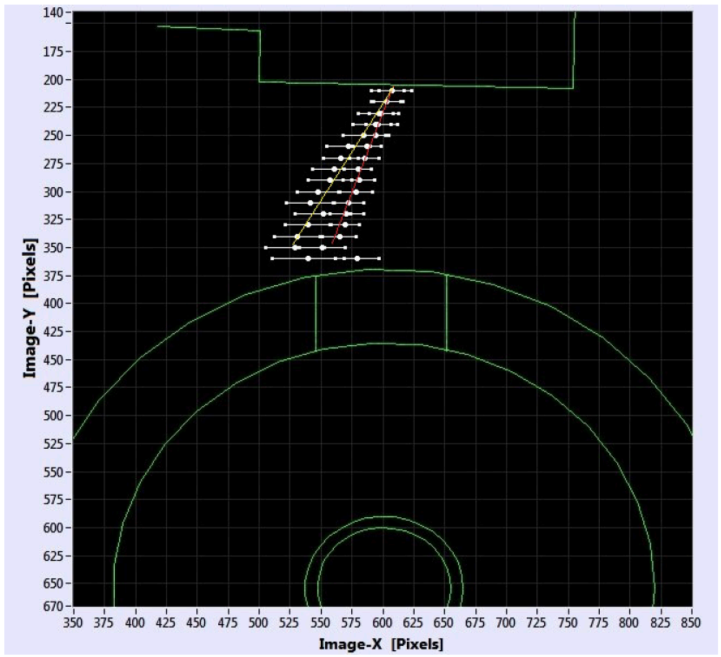


- Now: photoionisation (few shots)





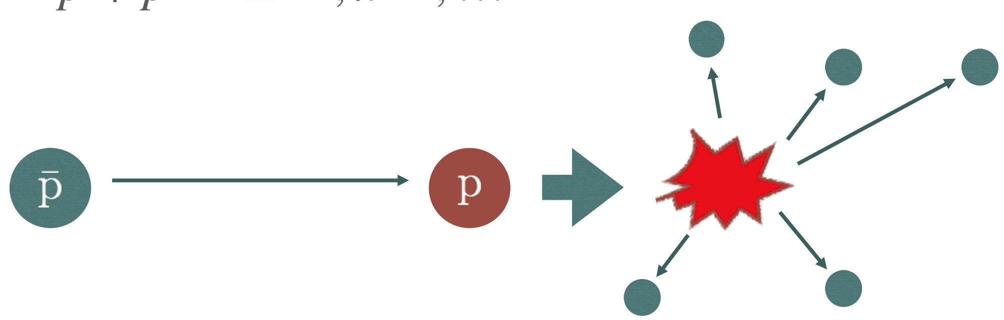




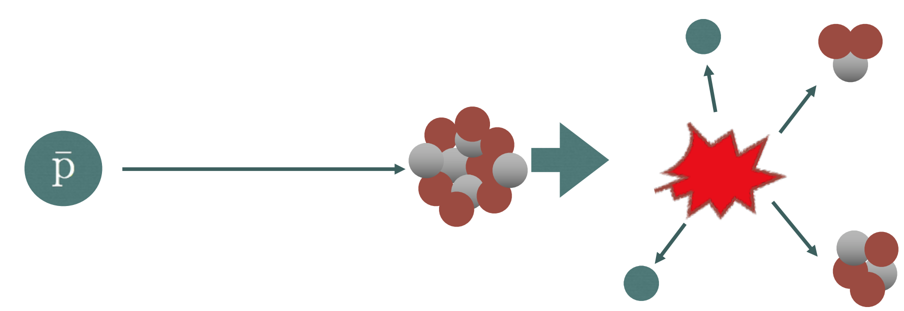
$\bar{H}$ DETECTION

- **Antihydrogen detection is detection of antiproton annihilation on trap electrodes (Au plated)**
  - Very low energies for antiproton annihilation have been reached only recently
    Need for experimental data to corroborate theoretical/simulations models
  - The cartoon:

$\bar{p} + p \rightarrow K^{\pm,0}, \pi^{\pm,0}, \ldots$



$\bar{p} + Au \rightarrow n\pi^{\pm,0} + X$



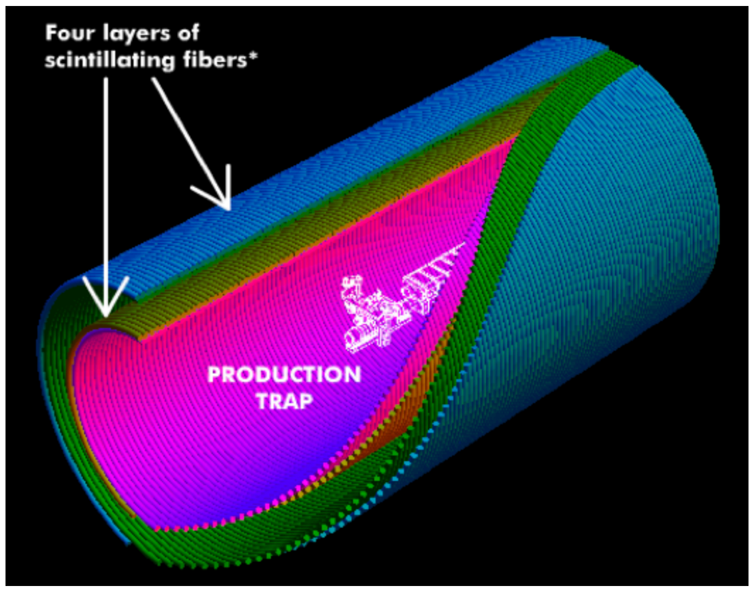
X= nuclear recoils, p, t, n, α, ^{3}He, ^{4}He, ^{6}He, ^{8}He, Li…

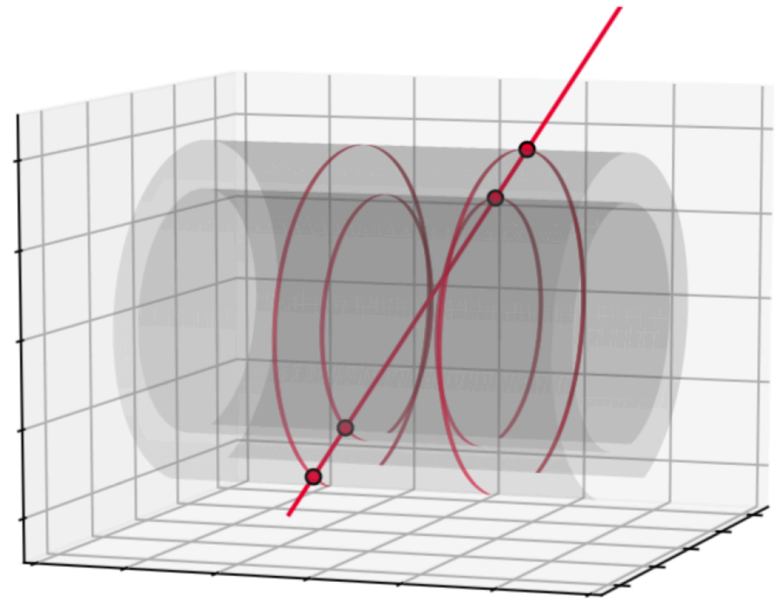
- **Several sources of background and undesirable effects**
  - **Environmental**
  - **Procedure-induced** (e.g. antiproton losses, positron burst, etc…)
  - **All other possible systematics**

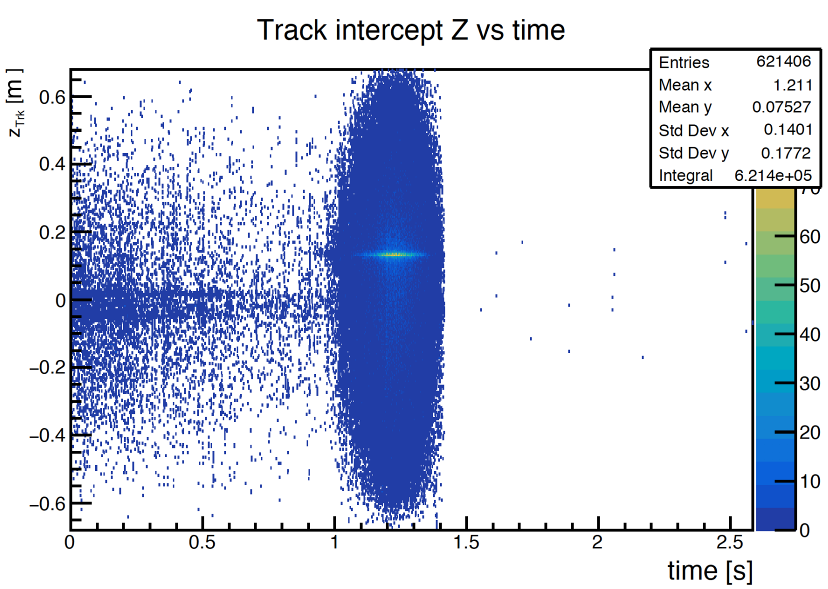
Severely affects detectors relatively long time needed for recovery

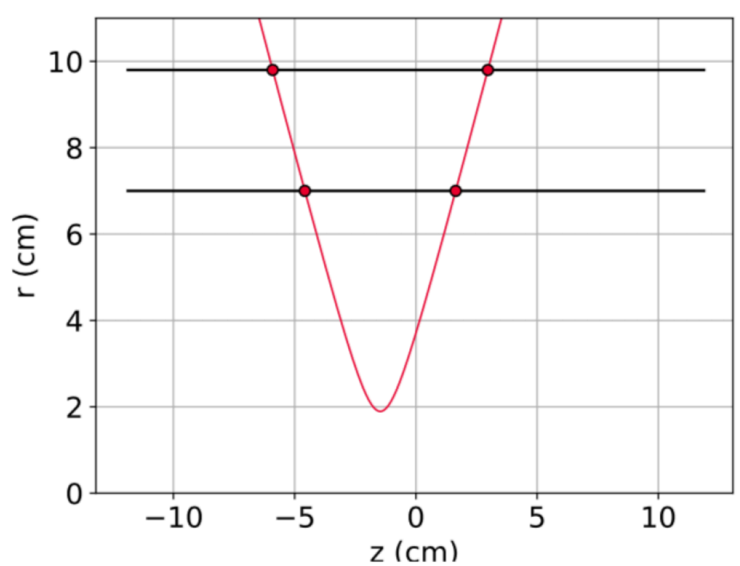
H̄ DETECTORS

The Fast Annihilation Cryogenic Tracker (FACT) detector





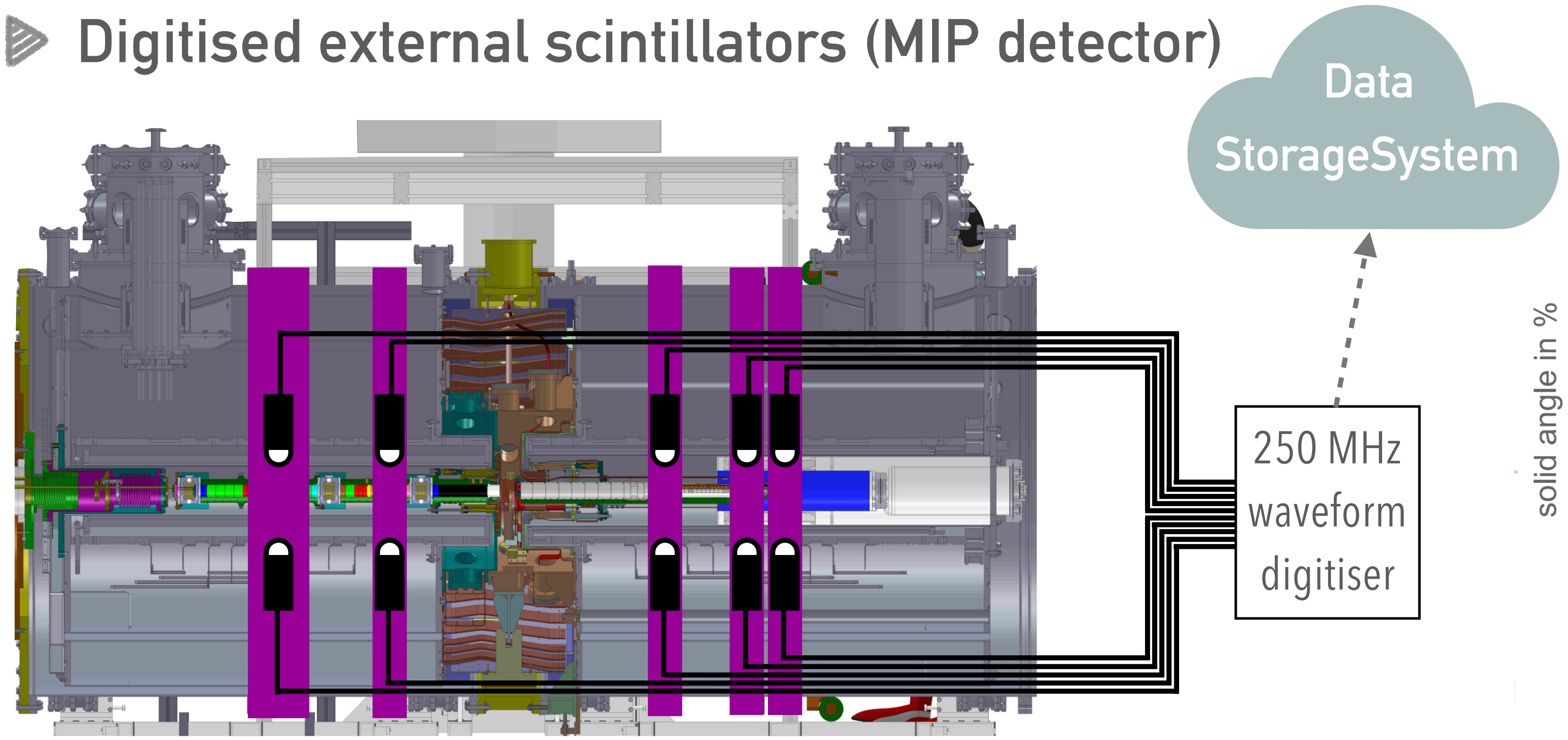


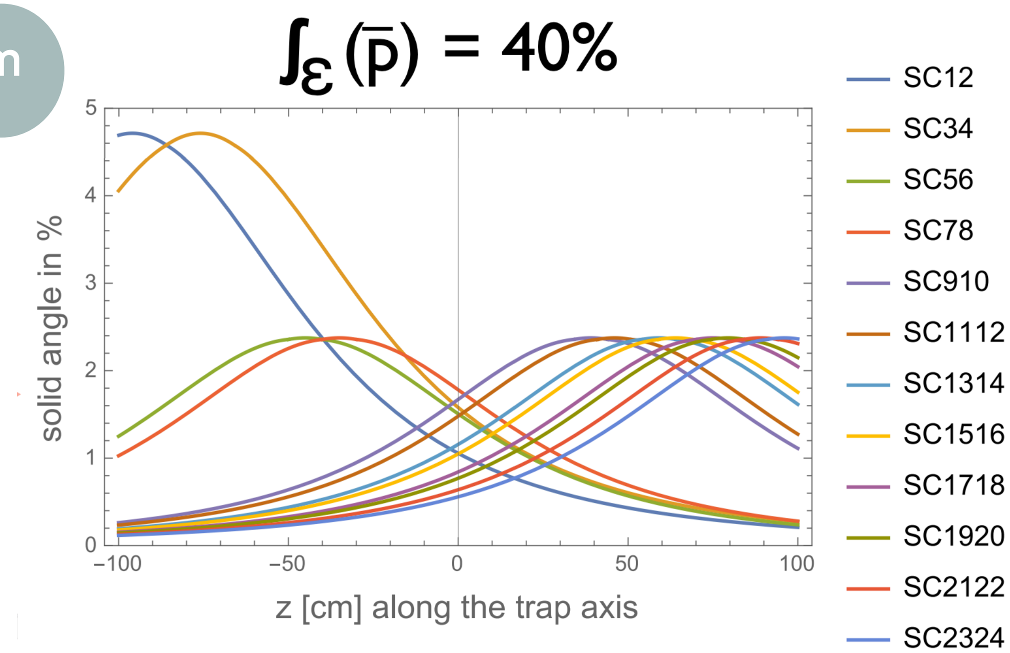


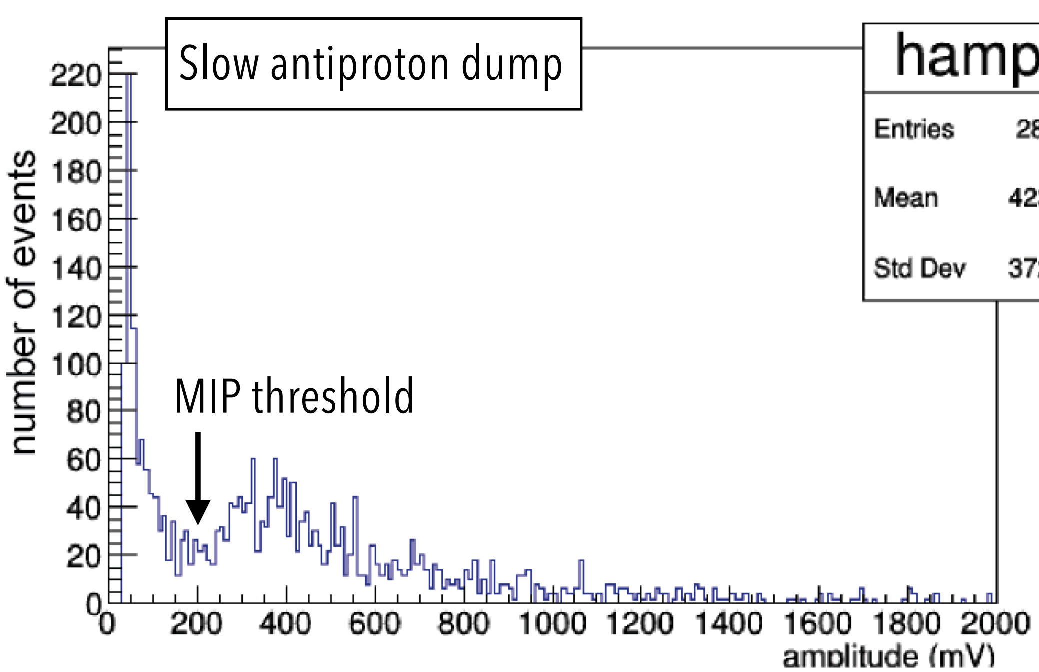
- ✳ 4 layers of 1 mm diameter scintillating fibres
- ✳ Cryogenic optical coupling
- ✳ Arrays of 1 mm diameters Hamamatsu MPPC (Multi Pixel Photon Converter)
- ✳ 100 Geiger mode Avalanche Photo Diodes (APD) each
- ✳ R/O via fast discriminator with TTL output to 16+1 FPGAs (48 MPPC each)
- ✳ Challenging operating requirements
  - 4K environmental temperature
  - 1T solenoidal magnetic field

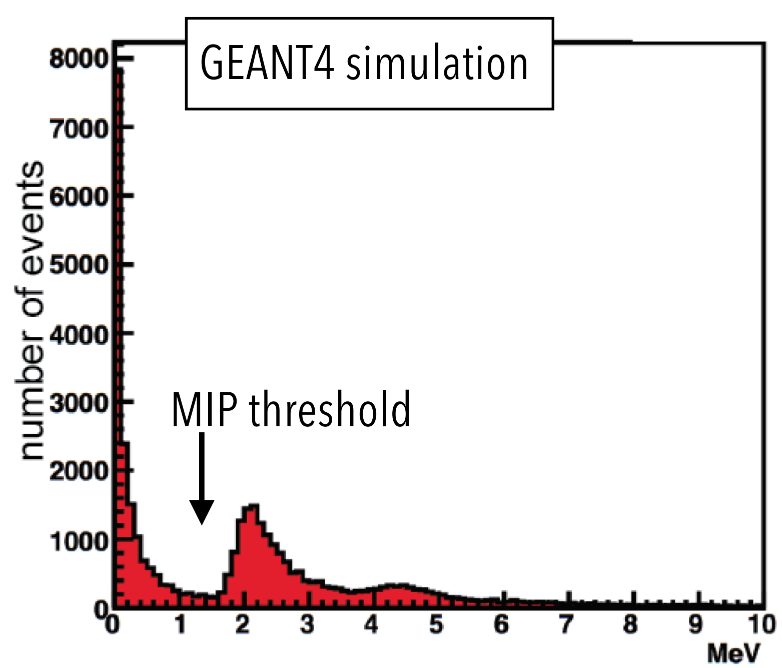
H̄ DETECTORS

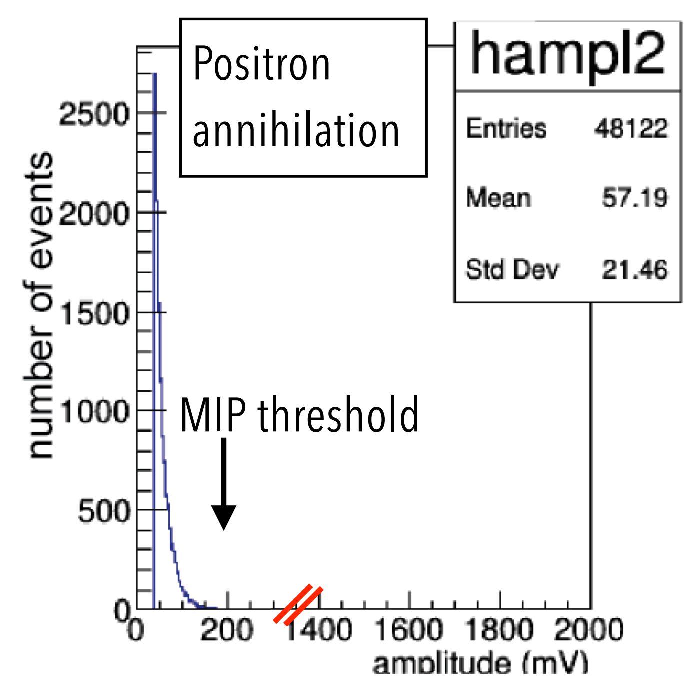
- Digitised external scintillators (MIP detector)



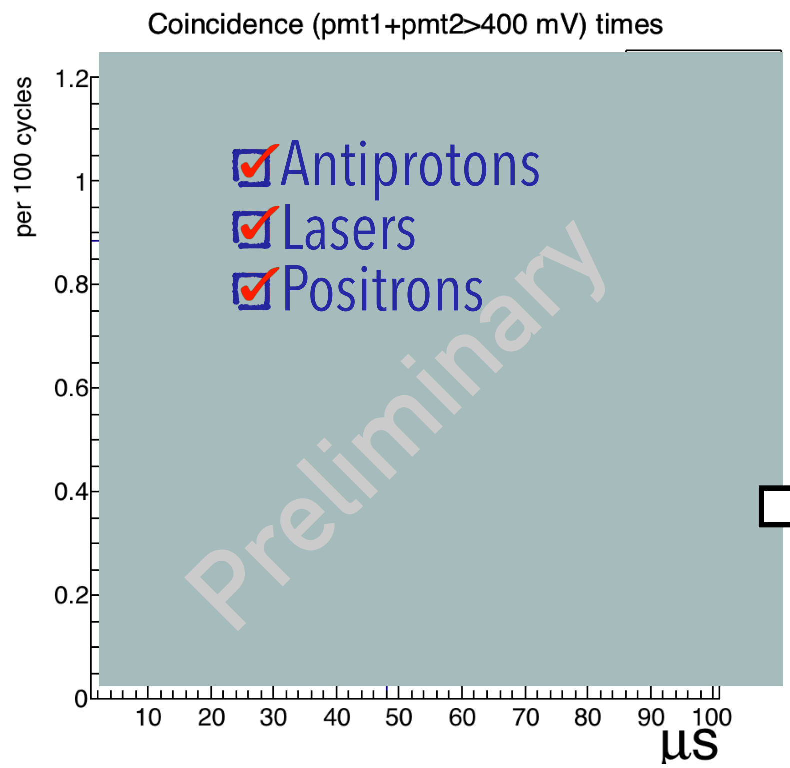


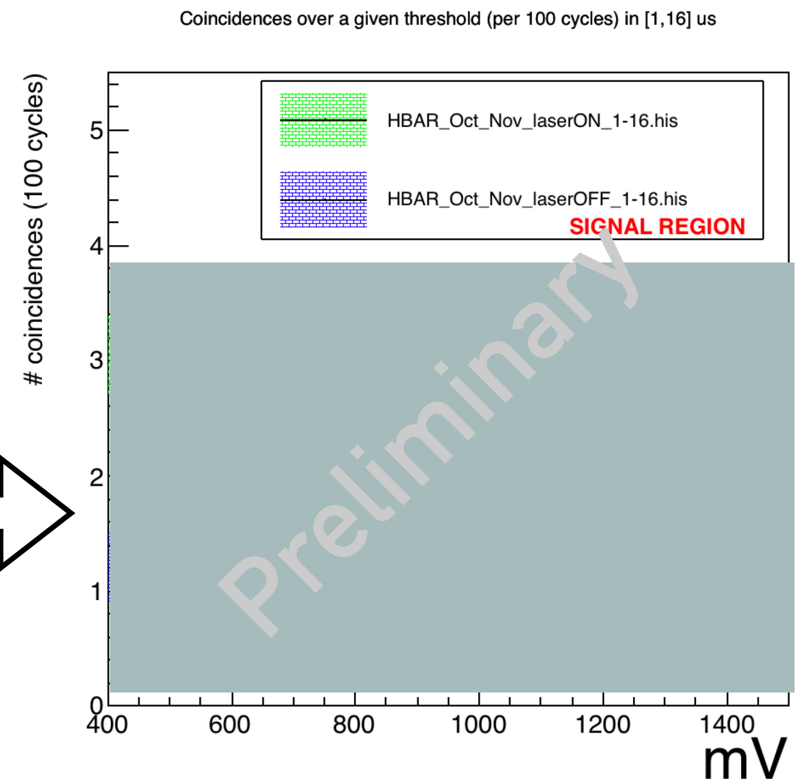




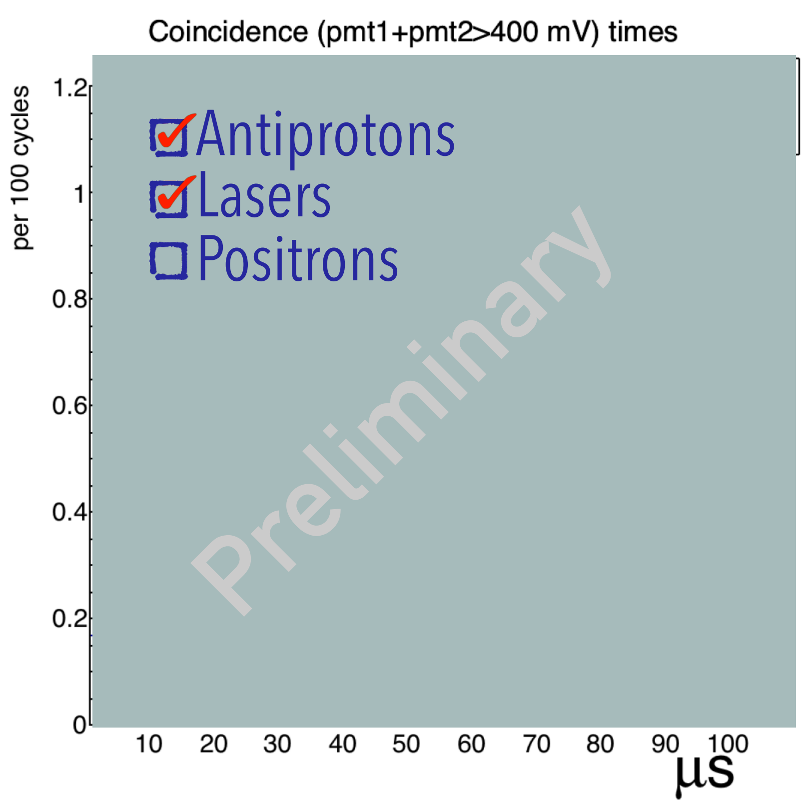


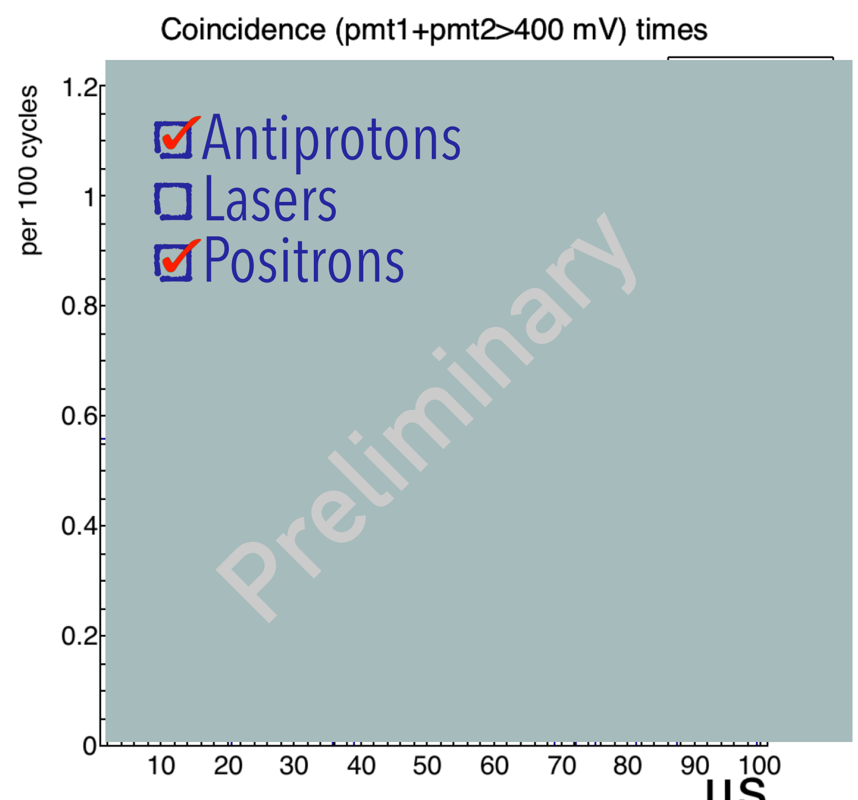
H̄ ANALYSIS

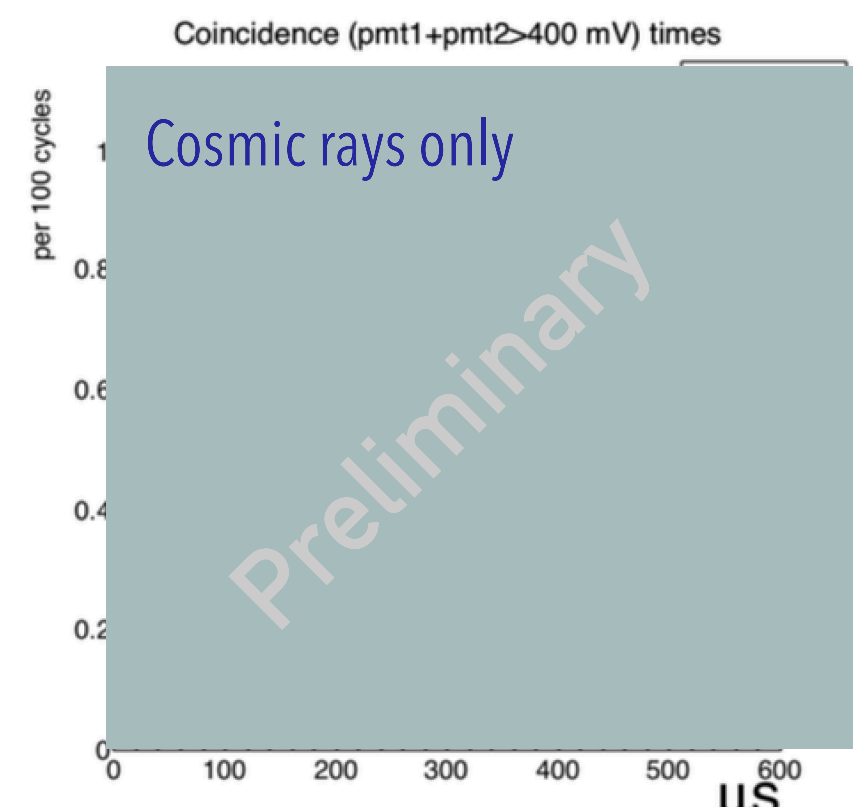




- **Same measurement protocol for several combinations**
- **Robustness check**
  - Vary scintillator array MIP threshold
  - Several data takings campaigns dedicated to all the backgrounds and systematics

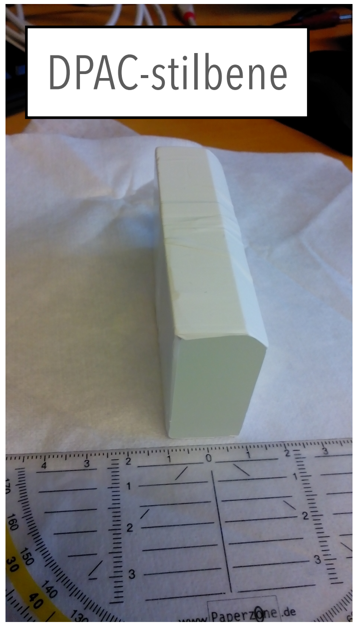


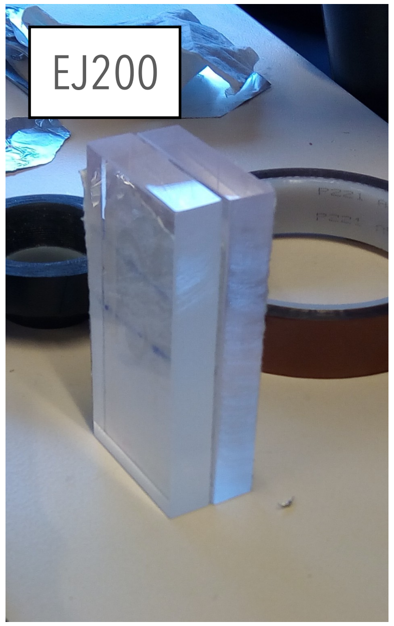


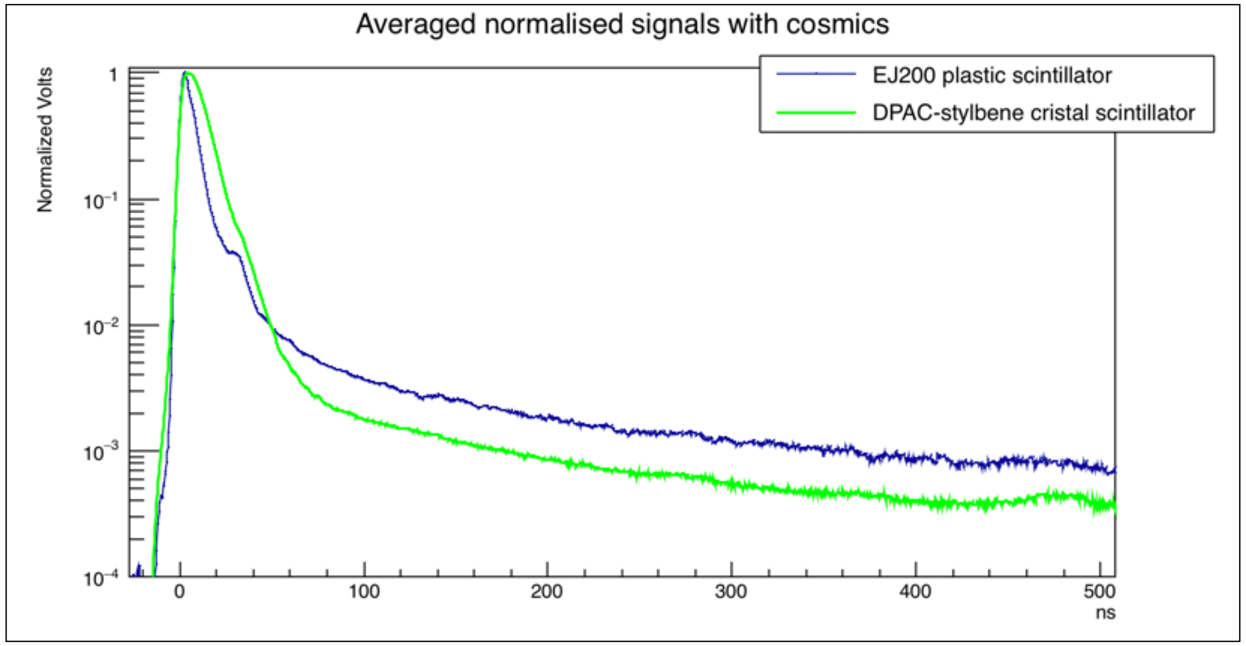


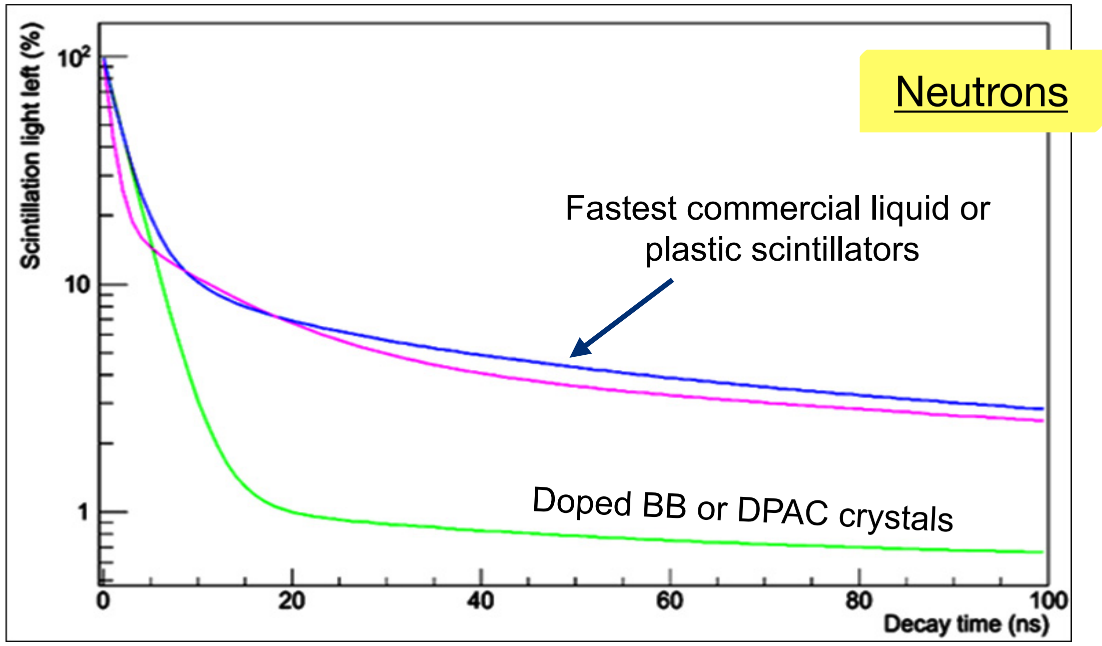
PS DETECTION

- Look for a better precision in positronium measurements
  - New diphenylacetylene (DPAC) crystal doped with stylbene, grown at LLNL
  - Very small delayed light component
  - Allows an even better sensitivity in the interesting time region
- SSPALS technique in 1T to improve Ps diagnostics
  - Possible modifications in the production trap



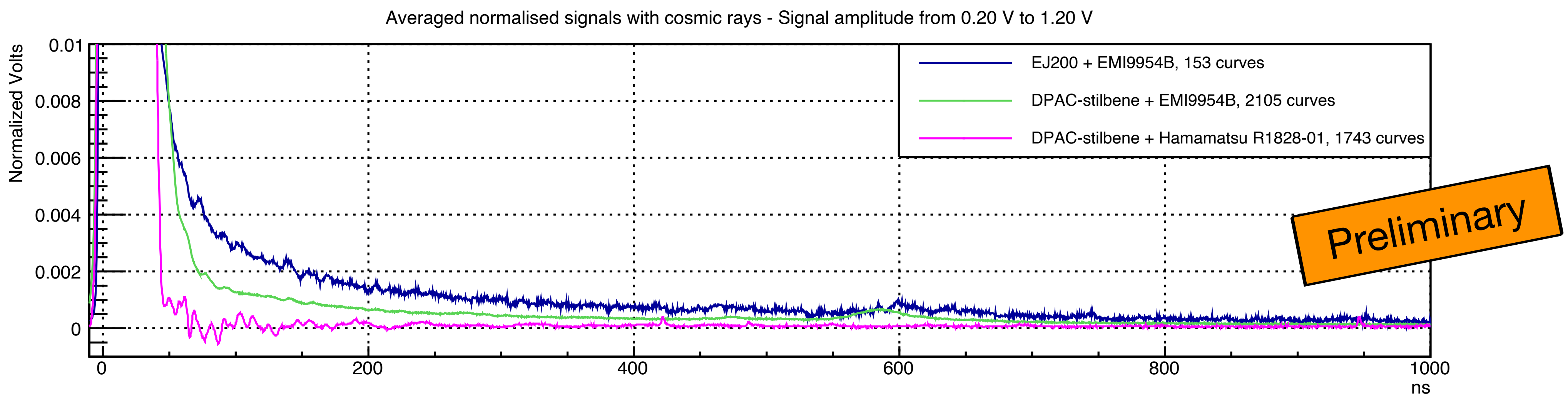


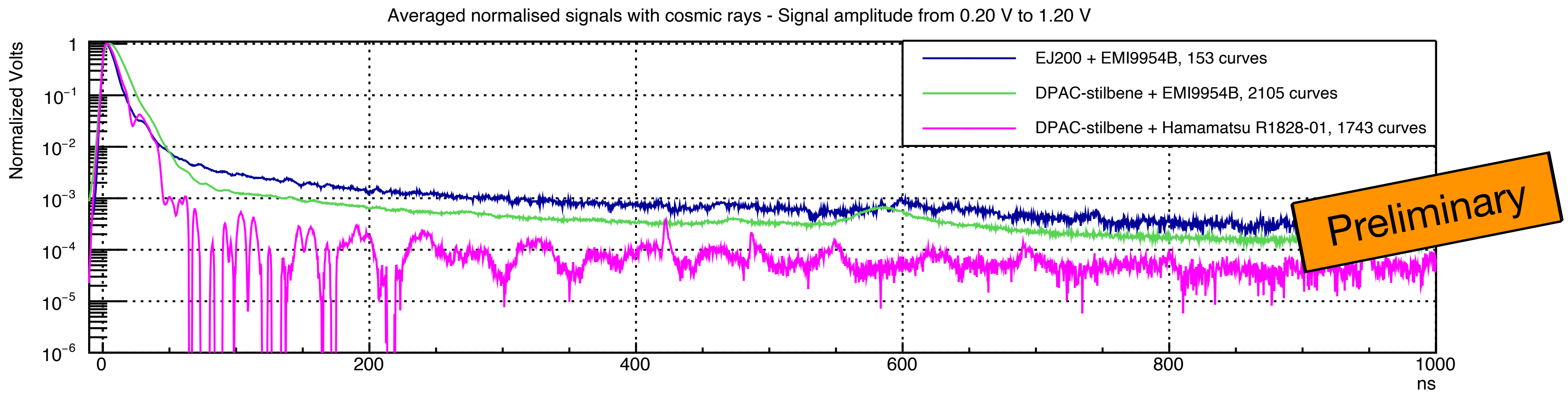


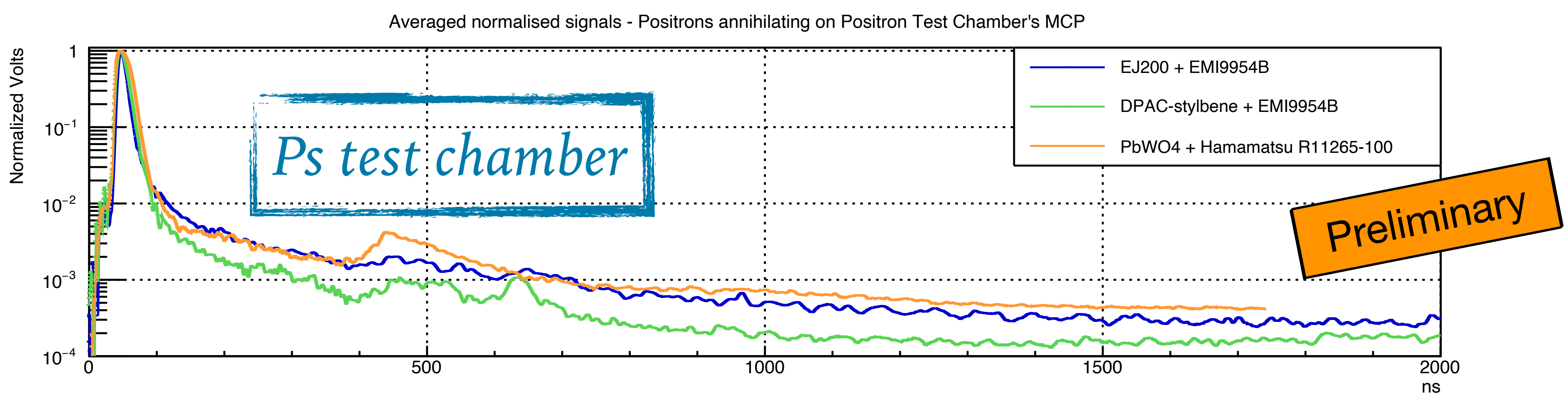


[Courtesy of N.P. Zaitseva, LLNL]

PS DETECTION







CONCLUSIONS

- AEgIS uses several classes of detectors implementing a wide range of techniques in the detection of charged particles, non-neutral plasmas, positronium and antihydrogen.
- A final procedure has been developed for the pulsed production of antihydrogen. AEgIS routinely captures antiprotons coming from AD and reaching the best compression ever. This contributes to a number of improvements in the plasma conditions which gave a substantially increase in the production rate. The introduction of a stacking procedure significantly increased the efficiency of the overall antihydrogen production procedure.
- Positronium is routinely formed both in a dedicated setup and inside the main apparatus, leading to the first Ps laser excitation to the Rydberg levels in a 1T magnetic field and to the detailed characterisation of the Ps source for antihydrogen production. A new diagnostics developed during last year allowed a precise characterisation of the travel path of the Ps cloud towards the antihydrogen production trap.
- A preliminary analysis of data taken during last year highlights a statistically significant signal compatible with pulsed formation of antihydrogen, while excluding major potential sources of background. Further analysis is under way.
- A new scintillator-based innovative detector promises a better precision in the diagnostics of positronium measurements to be implemented in the experiment during the LS2.

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