TRIUMF

Canada's national laboratory
for particle and nuclear physics
and accelerator-based science

Machine Learning for Antihydrogen Detection at ALPHA

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TRIUMF - on behalf of the ALPHA collaboration

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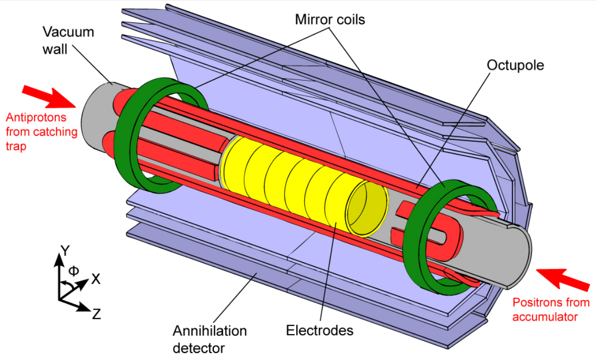
Outline

Antihydrogen $\overline{\text{H}}$ is a tool to explore fundamental symmetries

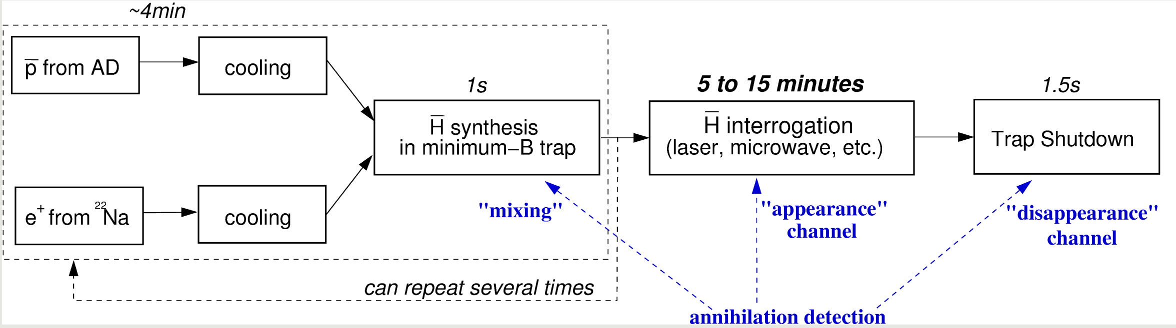
- Charge-Parity-Time (CPT) invariance
  - mass of antiparticles and particles, e.g., $|M(\text{K}^0) - M(\overline{\text{K}^0})|/M < 6 \times 10^{-19}$
    E. Abouzaid *et al.*, Phys. Rev. **D83**, 092001 (2011)
  - absolute value of the charges, e.g., $|Q(e^+) + Q(e^-)|/e < 4 \times 10^{-8}$
    e.g., C. Patrignani *et al.* (PDG), Chin. Phys. C, **40**, 100001 (2016)
  - **spectra of antiatoms and atoms**: $|\nu_{\text{1S-2S}}(\text{H}) - \nu_{\text{1S-2S}}(\overline{\text{H}})|/\nu_{\text{1S-2S}} < 2 \times 10^{-10}$
    M. Ahmadi *et al.*, Nature **541**, 506-510 (2017)
- Weak Equivalence Principle
  - Measurement of the gravitational acceleration of $\overline{\text{H}}$ is coming soon...

The ALPHA apparatus



1 T solenoid and laser path not shown

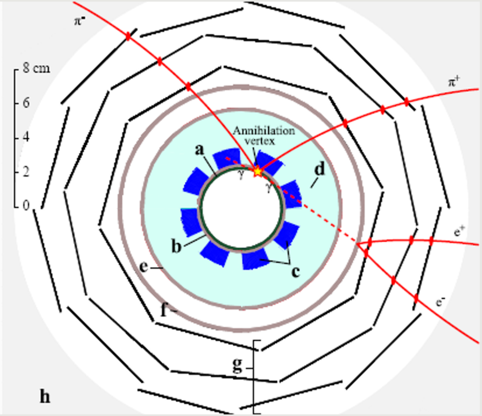
C. Amole *et al.*, Nucl. Instrum. Meth. **A735**, 319-340 (2014).



Experiment	Protocol for $\bar{H}$ Interrogation: Counting		
Laser 1S-2S	On-Resonance 243 nm	Off-Resonance 200 kHz	No Laser
Electric charge	Oscillating E field		No Field
Microwave	On-Resonance 28 GHz	Off-Resonance 10 MHz	No Microwave

$\overline{\text{H}}$ Annihilation Detector

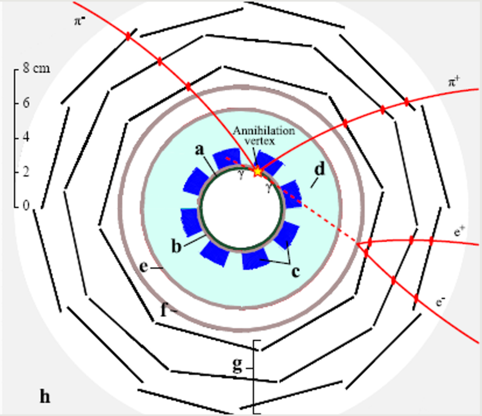
Cross-section view of ALPHA



- a Electrodes/UHV region (Al and Au-plated)
- b Mirror coil(s) for $\overline{\text{H}}$ axial confinement
- c Octupole for $\overline{\text{H}}$ radial confinement
- d Liquid He space
- e Cryostat wall (steel) and heat shield (Cu)
- f OVC wall (steel)
- g **Annihilation detector**
  - Double-sided silicon detector.
  - 3 layers, 72 hybrids modules.
  - Track annihilation products: mostly $\pi^{\pm}$ with $\langle p \rangle \approx 100 - 300\,\text{MeV}$
- h 1 T solenoid

Tracking and Vertexing

Cross-section view of ALPHA



$\overline{\text{H}}$ annihilation position $\Longleftrightarrow$ the *vertex*

The vertex is $\overline{\text{H}}$ signature

1. Hits position from strips on the detector modules
2. Identification of the tracks from hits
3. Tracks fit to helices
4. Selection of tracks - choose the ones due $\pi^{\pm}$
5. Annihilation vertex is the point where the tracks pass closest to each other

Background is due to cosmic rays $\mu^{\pm}$

Rate: $\approx 10\,\text{Hz}$

With “cuts analysis” rate: $\approx 47\,\text{mHz}$

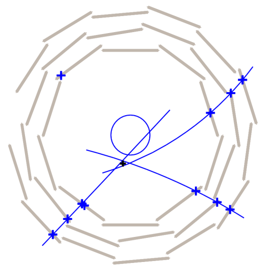
Typical $\overline{\text{H}}$ trapping rate: 10 per cycle

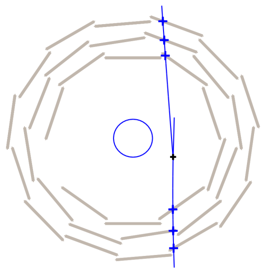
Even considering the *shortest* “appearance channel”: **14 cosmic rays** can be detected.

Without strong(er) background suppression, **the signal is therefore washed out**.

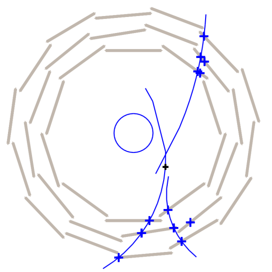
A Classification Problem

$\overline{\text{H}}$ annihilation





Cosmic ray: easy



Cosmic ray: hard

Training Samples

Training is performed on real data - not on Monte Carlo

Background sample: cosmic rays ≈1.6M events

Dedicated runs without antiparticles in the apparatus

Signal sample: "hot" $\overline{\mathrm{H}}$ (mixing) ≈208k events

Annihilation recorded during $\overline{\mathrm{H}}$ synthesis (1 s every cycle).
The z distribution can be very different for physics measurements.

Classifier: **Bagged Decision Tree** from SPR package
http://statpatrec.sourceforge.net
arXiv:physics/0507143 (2005)

1. number of hits N_{hit},
2. number of reconstructed tracks N_{helices},
3. number of reconstructed tracks used in vertexing $\tilde{N}_{\text{helices}}$,
4. squared residual δ,

$$\delta = \min_{i,j \in N_{\text{helices}}} \left\{ \sum_{h=1}^{6} (l_x(\tilde{t}_h) - x_h)^2 + (l_y(\tilde{t}_h) - y_h)^2 + (l_z(\tilde{t}_h) - z_h)^2 \text{ for } h \in i \text{ and } j \right\}$$

where

$$\mathbf{l}(t) = \begin{cases} u_x t + x_0 \\ u_y t + y_0 \\ u_z t + z_0 \, , \end{cases}$$

and

$$\tilde{t}_h = \frac{u_x(x_0 - x_h) + u_y(y_0 - y_h) + u_z(z_0 - z_h)}{|\mathbf{u}|^2} \, .$$

Discriminating Variables II

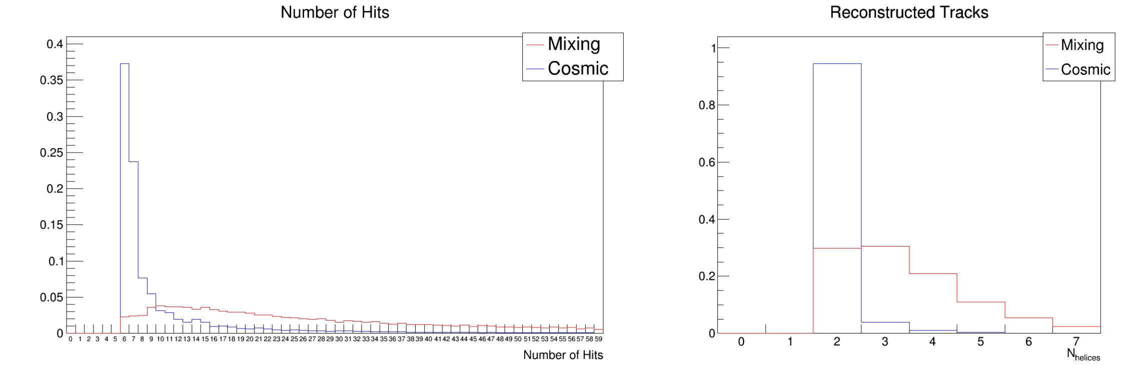
5. ϕ component of generalized sphericity tensor eigenvector Σ_ϕ,
6. z component of generalized sphericity tensor eigenvector Σ_z,
7. combination of two largest generalized sphericity tensor eigenvalues $\sqrt{\lambda_1^2 + \lambda_2^2}$,

$$S_{ab} = \frac{1}{N_{\text{helices}}} \sum_{i=1}^{N_{\text{helices}}} \frac{p_a^i \, p_b^i}{|\mathbf{p}_i|^2} ,$$

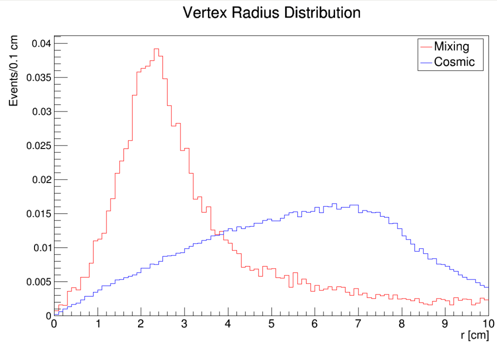
where $\mathbf{p}_i$ is the momentum of the i^{th} reconstructed track and $a, b = x, y, z$.
The eigenvalues λ_j of S with $j = 1, 2, 3$ are such that $\lambda_1 \geq \lambda_2 \geq \lambda_3$.

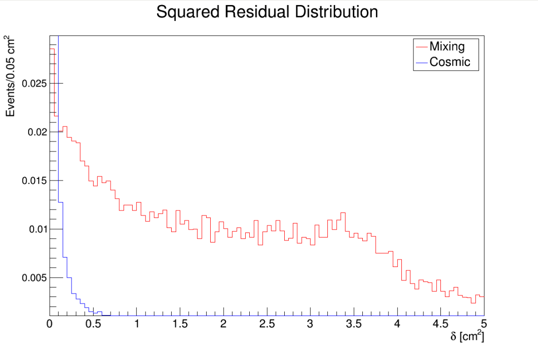
8. ϕ component of the reconstructed vertex,
9. r component of the reconstructed vertex.

Discriminating Variables 1 and 2

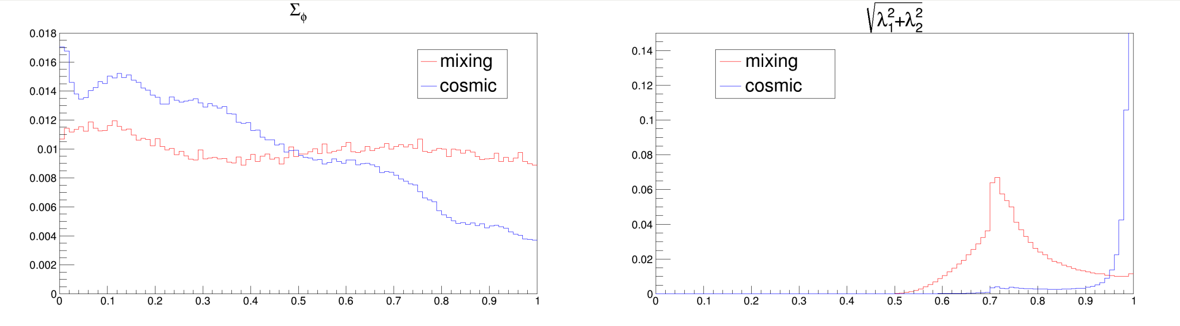


Discriminating Variables 4 and 9

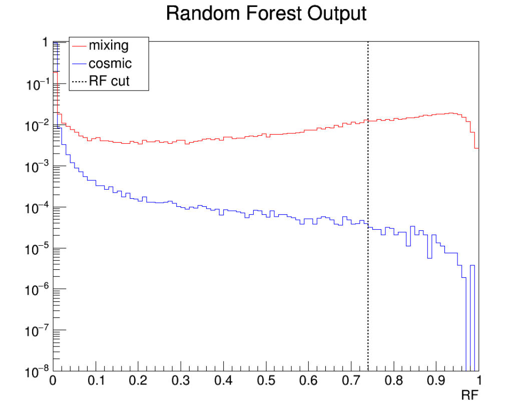




Discriminating Variables 5 and 7



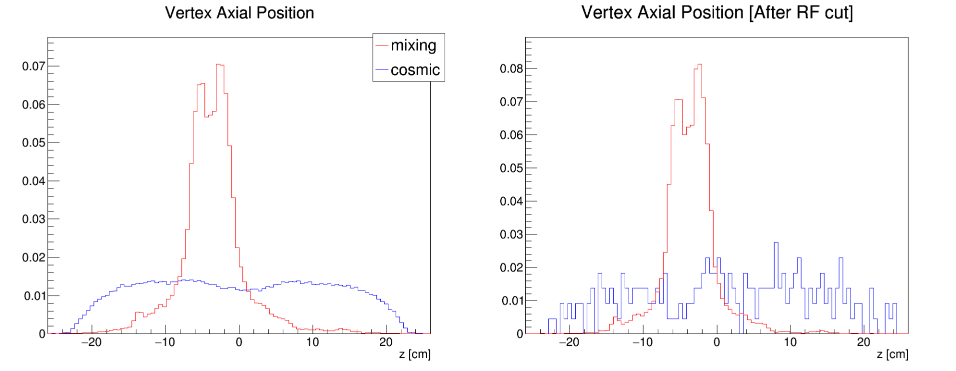
Classifier Trained



- 100 replicas, 4 variables, 16 events/leaf
- Bump Hunting to maximize Punzi significance $\frac{S}{\frac{3}{2}\sigma+\sqrt{B}}$ arXiv:physics/0308063v2 (2003)
- Background Rate: **4 mHz** ($\pm$7%)
- Signal Acceptance: (37.6 ± 0.2)% of test sample or $\approx$ 50% of "disappearance" channel

Consistency! z distribution

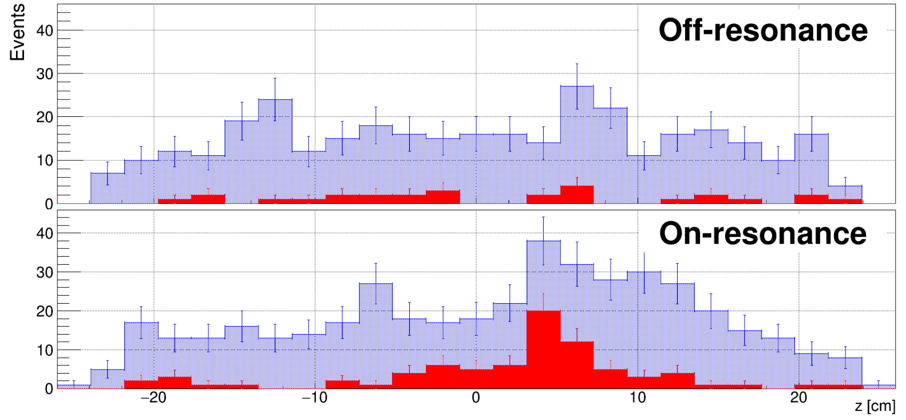
Test sample



Appearance Channel in Laser Experiment

Loss mechanism:

- ionization from 2S state
- decay to un-trappable state



"pass-cuts" MVA

Summary and Outlook

- ALPHA experiment offers new tool to search for new physics
- ALPHA relies upon $\overline{\mathrm{H}}$ identification by annihilation position reconstruction

- Background due to cosmic rays, strong suppression with MVA
- MVA trained on real data: both signal and background

- CPT test at 0.2 ppb level

- Current and future work:
  - Try TMVA
  - Increase the number of discriminating variables (17)
  - Use *deep learning* for reconstruction altogether.

Thanks to:

S. Stracka, A. Olin and J. T. McKenna
and to the ALPHA collaboration

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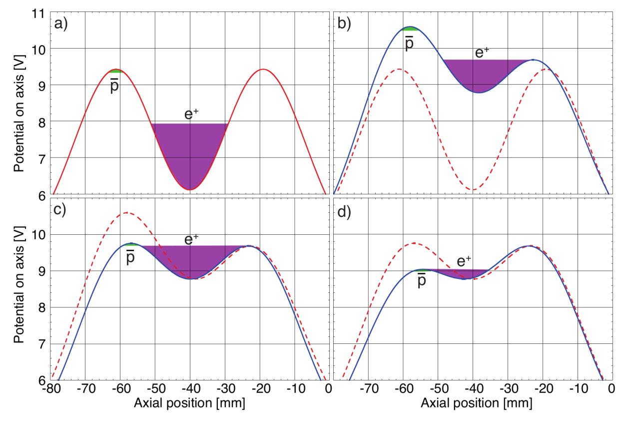
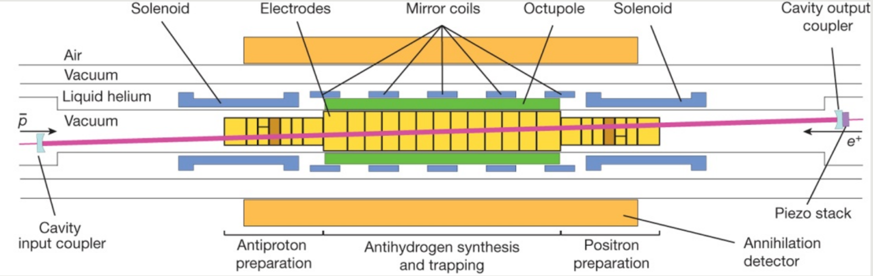
ADDITIONAL MATERIAL

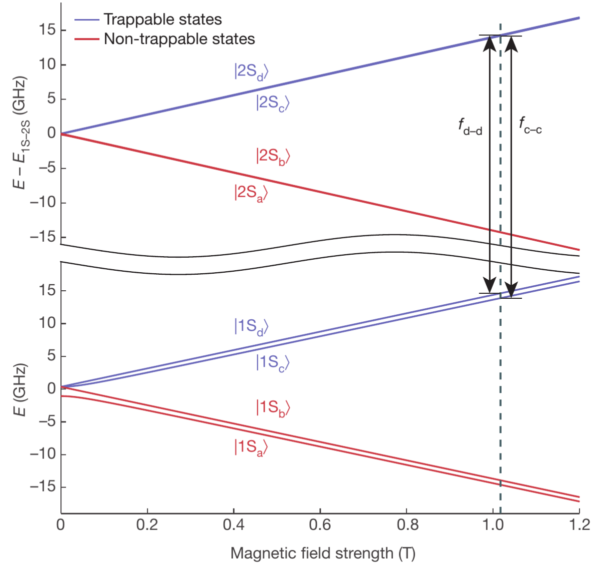
Antihydrogen synthesis sequence: MIXING



Dashed and solid curves represent electrostatic potentials before and after each step.

Laser Experiment Setup




Trappable states
Non-trappable states
|2S_d⟩
|2S_c⟩
|2S_b⟩
|2S_a⟩
|1S_d⟩
|1S_c⟩
|1S_b⟩
|1S_a⟩
f_d–d
f_c–c
E – E_1S–2S (GHz)
E (GHz)
15
10
5
0
–5
–10
–15
0
0.2
0.4
0.6
0.8
1.0
1.2
Magnetic field strength (T)

Counts in Laser Experiment

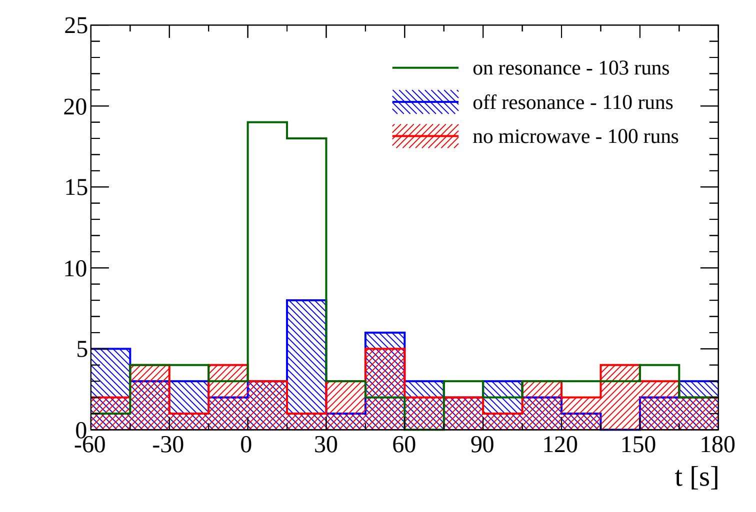
Disappearance channel

	Background	$\overline{\mathrm{H}}$events	Uncertainty
On-resonance	0.7	67	8.2
Off-resonance	0.7	159	13
No laser	0.7	142	12

Appearance channel

	Background	$\overline{\mathrm{H}}$ events	Uncertainty
On-resonance	28.4	79	8.9
Off-resonance	28.4	27	5.2
No Laser	28.4	30	5.5

Appearance Channel in Microwave Experiment



Disappearance Channel in Stochastic Heating Experiment