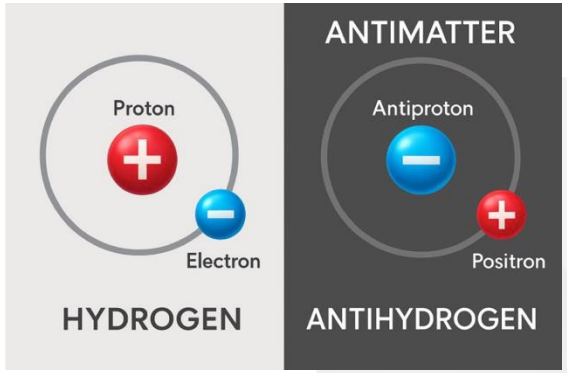
First measurement of a charge-exchange reaction cross-section for antihydrogen production

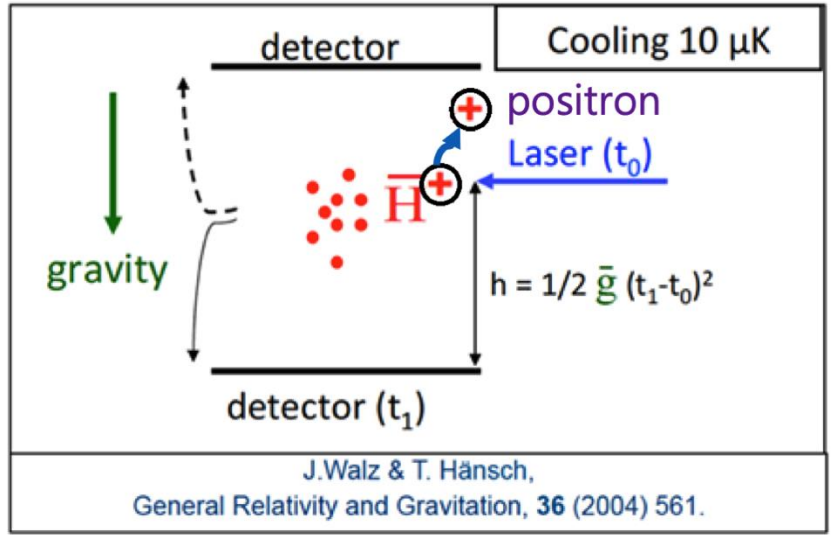
Sarah GEFFROY – IJCLab
on behalf of the GBAR collaboration

Gravitational **B**ehavior of **A**ntihydrogen at **R**est

Antihydrogen is antimatter

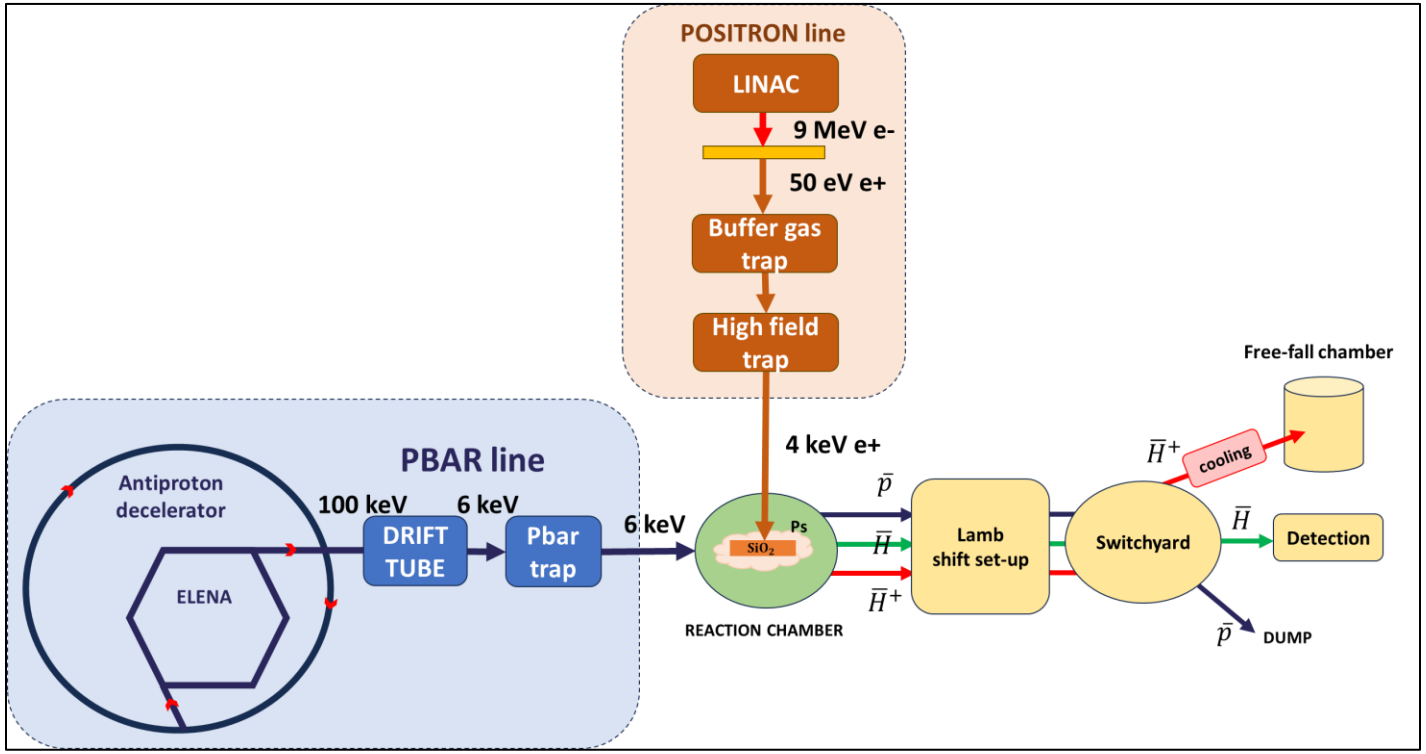


Do matter and antimatter fall the same way?



Study of a free-fall of an antihydrogen atom.

The GBAR experiment

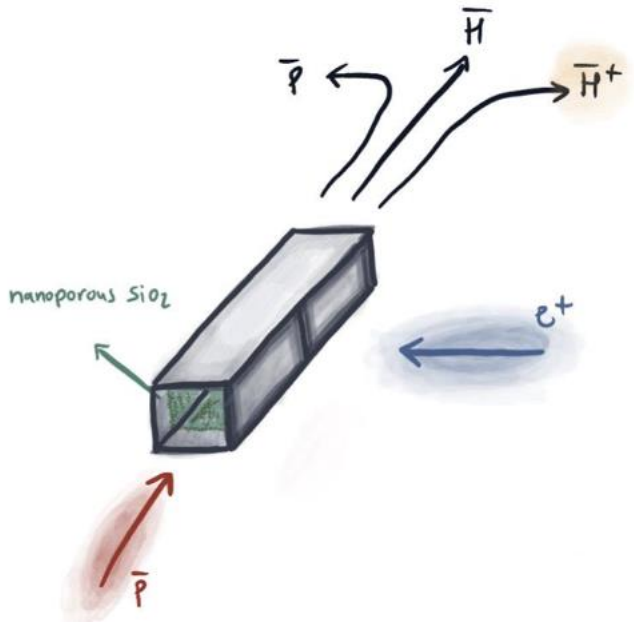


General scheme of the experiment

Two successive charge-exchange reactions:

$$\bar{p} + Ps \rightarrow \bar{H} + e^-$$
$$\bar{H} + Ps \rightarrow \bar{H}^+ + e^-$$

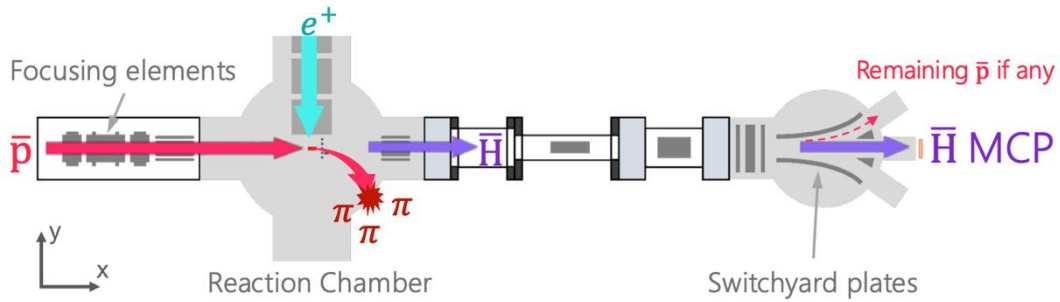
Antihydrogen production



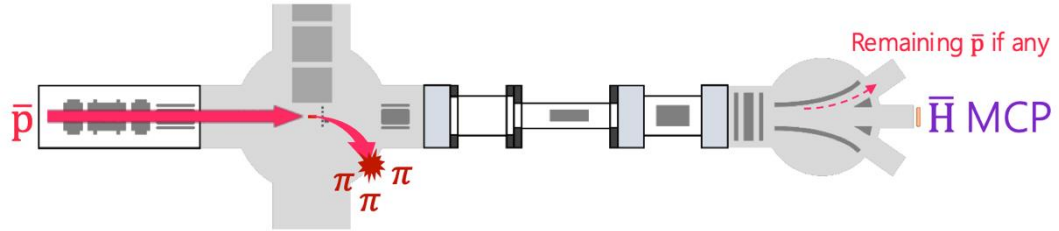
$$5 \times 10^{11}\ oPs\ cm^{-3}\ density$$
$$+ \longrightarrow 0.5\ \bar{H}$$
$$5 \times 10^{6}\ \bar{p}\ at\ 6\ keV$$

P. Pérez & A. Rosowsky, Nucl. Inst. Meth. A 532, 523 (2004)

MIXING



BACKGROUND



Cross-section measurement

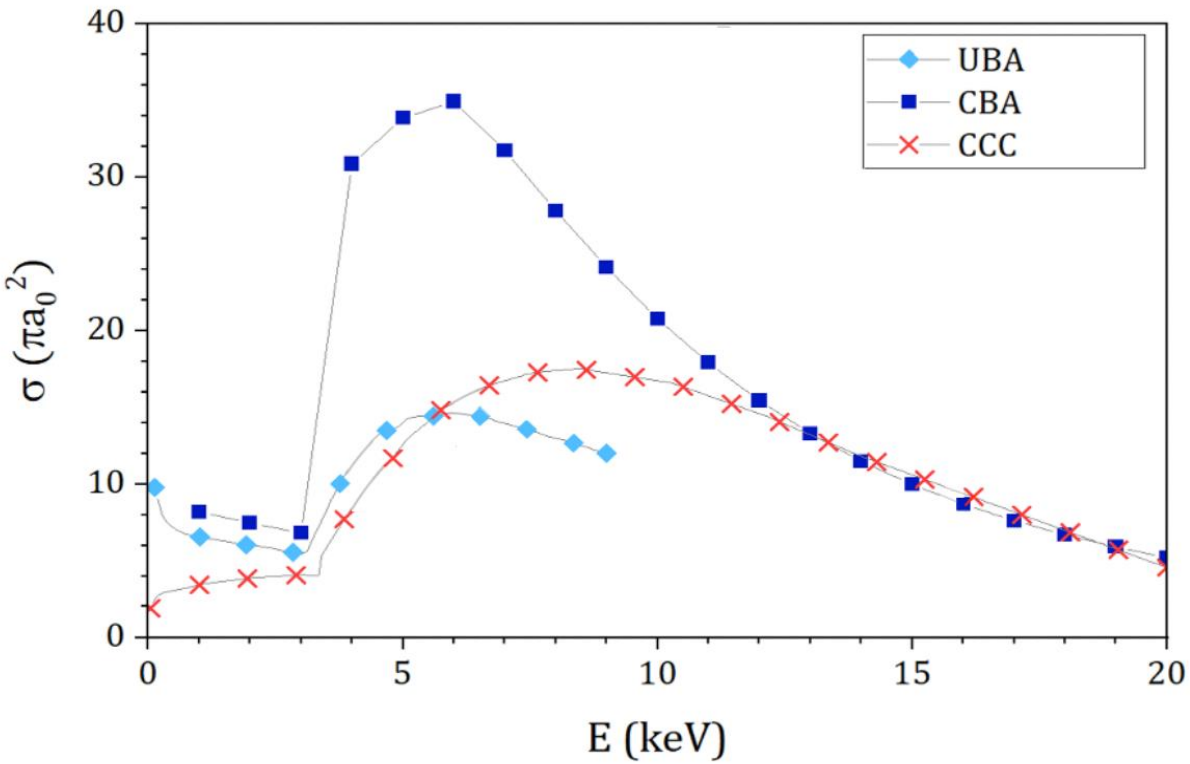
Number of antihydrogen atoms produced

$$\sigma(\bar{v}_{\bar{p}}) = \frac{N_{\bar{H}}}{N_{\bar{p}} N_{oPs}} \times \frac{1}{I_{overlap}}$$

Number of antiprotons sent

Overlap between $\bar{p}$ & oPs

Number of orthopositronium



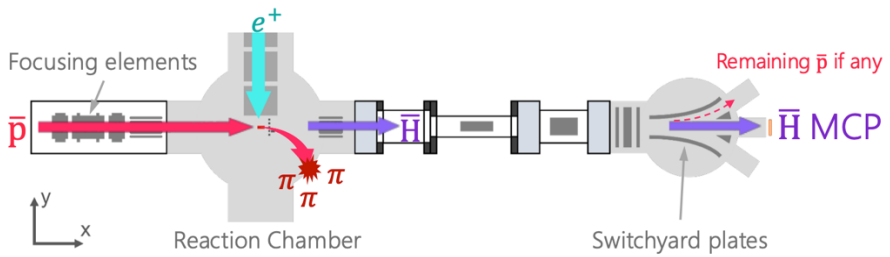
Theory predictions for the cross-section

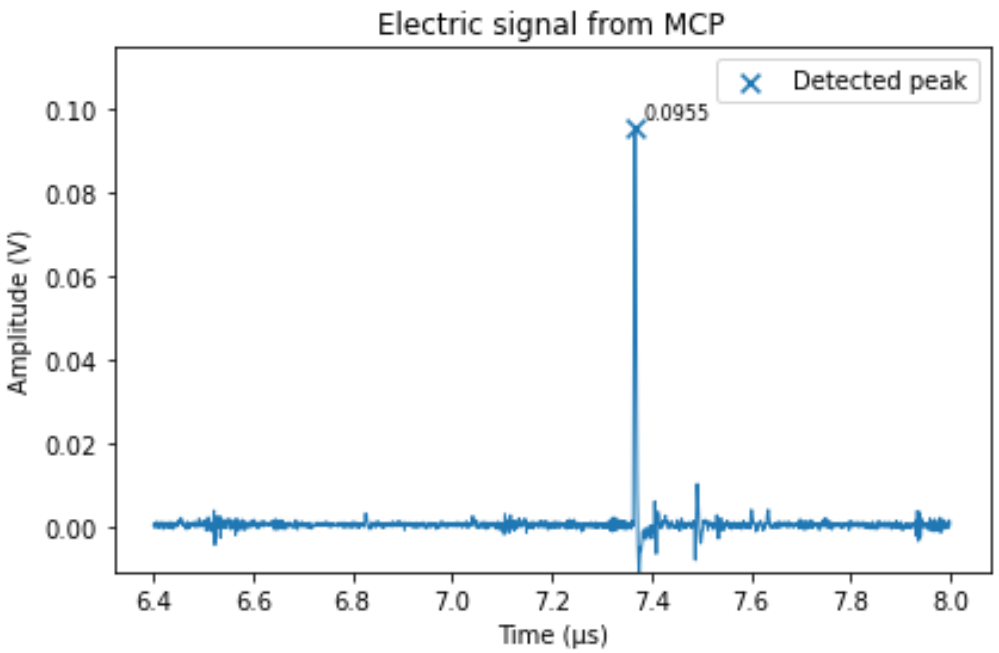
$$I_{overlap} = \frac{\bar{v}_{\bar{p}}}{V_{cavity}} \int F_{\bar{p}}(t) \cdot F_{oPs}(t) \cdot dt$$

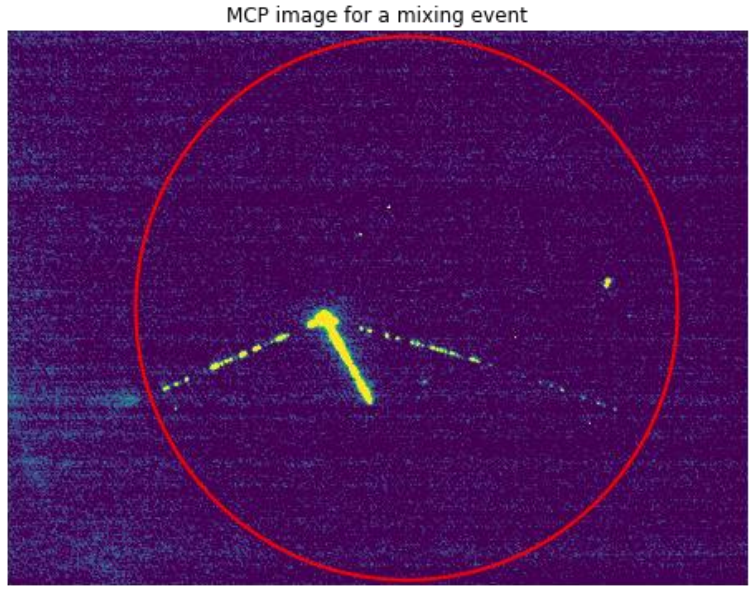
Cross-section measurement

$$\sigma(\bar{v}_{\bar{p}}) = \frac{N_{\bar{H}}}{N_{\bar{p}}\, N_{oPs}} \times \frac{1}{I_{overlap}}$$

$N_{\bar{H}}$:Number of antihydrogen atoms produced



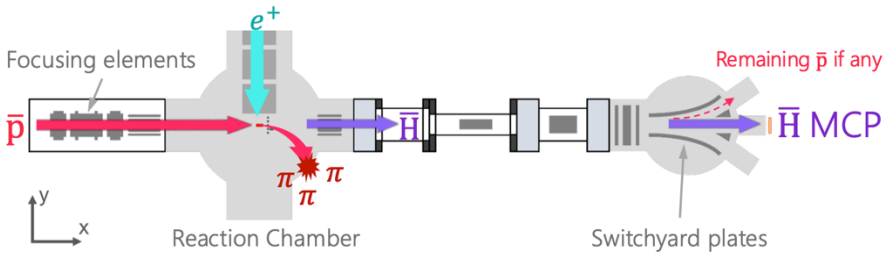




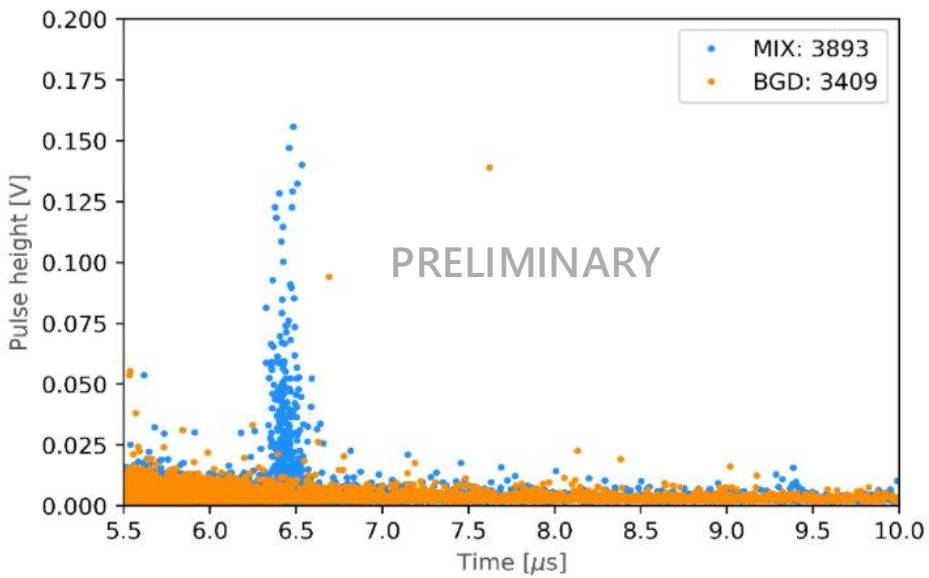
Cross-section measurement

$$\sigma(\bar{v}_{\bar{p}}) = \frac{N_{\bar{H}}}{N_{\bar{p}}\, N_{oPs}} \times \frac{1}{I_{overlap}}$$

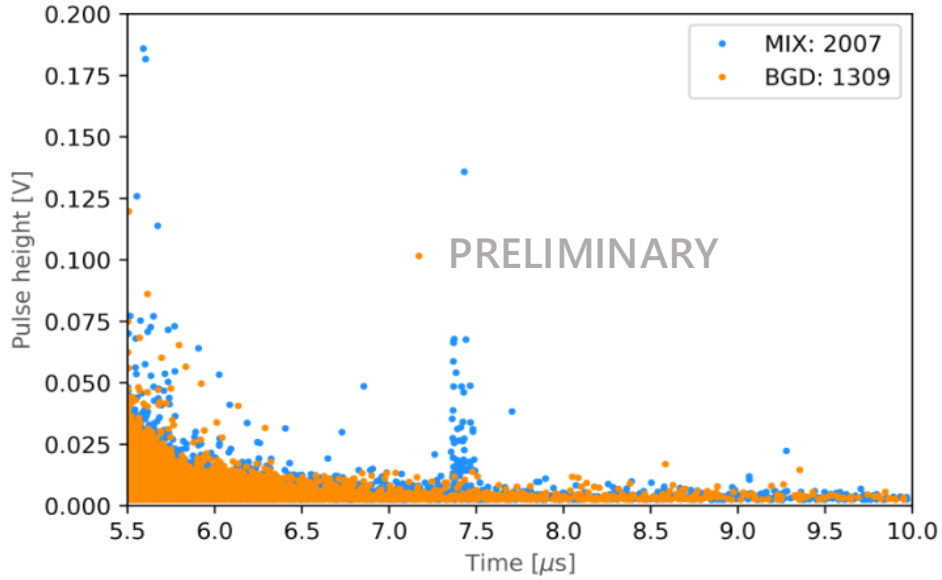
$N_{\bar{H}}$:Number of antihydrogen atoms produced



$6\ keV$: 357,1 $\pm$ 39.9 $\bar{H}$ *candidates*



$4\ keV$: 76.8 $\pm$ 18.5 $\bar{H}$ *candidates*



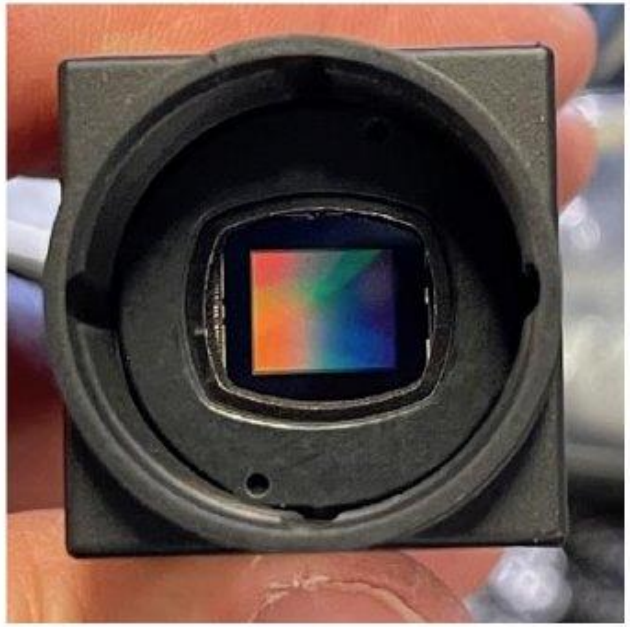
Cross-section measurement

$$\sigma(\bar{v}_{\bar{p}}) = \frac{N_{\bar{H}}}{N_{\bar{p}} N_{oPs}} \times \frac{1}{I_{overlap}}$$

$N_{\bar{p}}$:Number of antiprotons

$$Number\ of\ tracks\ on\ CMOS\ sensor \rightarrow Number\ of\ \bar{p}\ going\ through\ the\ cavity$$

CMOS sensor



CMOS hit per antiproton annihilation on target estimated by GEANT IV simulation and cross-checked with ELENA numbers from beam monitor.

Back-scattering of antiprotons on MCP studied and estimated (8%).

$6\ keV : 850000\ \bar{p}\ per\ shot$
$3893\ shots$

$4\ keV : 450000\ \bar{p}\ per\ shot$
$2007\ shots$

Cross-section measurement

$$\sigma(\bar{v}_{\bar{p}}) = \frac{N_{\bar{H}}}{N_{\bar{p}}\, N_{oPs}} \times \frac{1}{I_{overlap}}$$

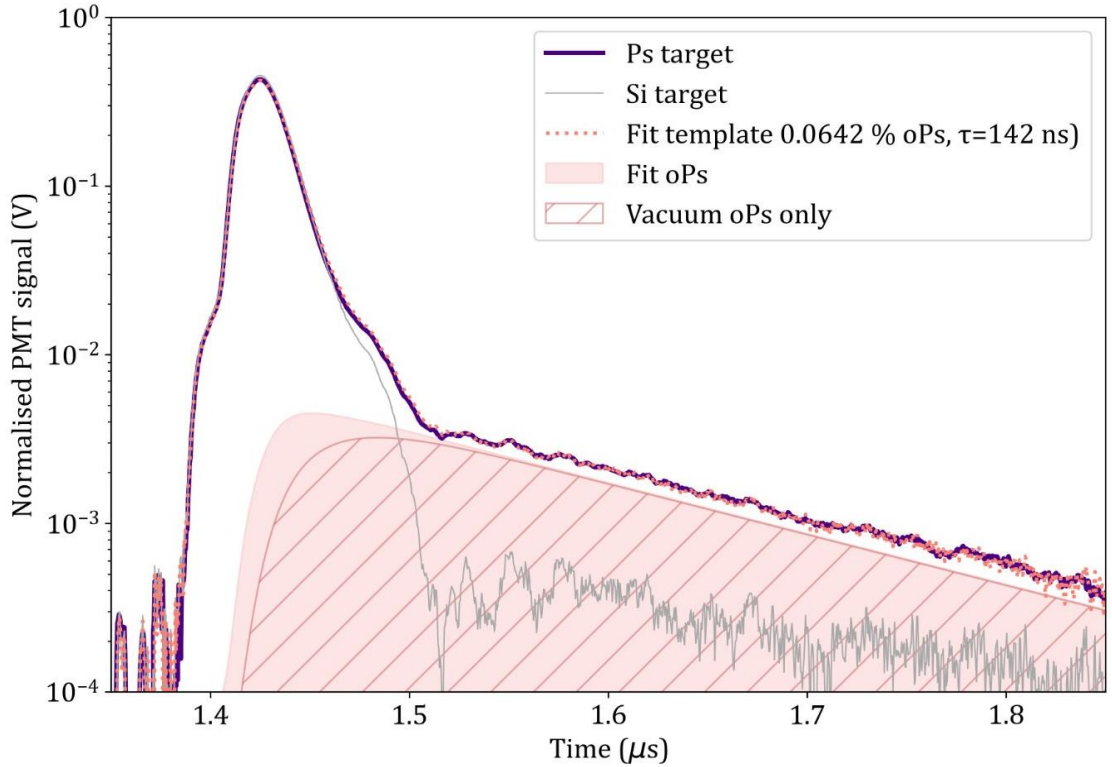
N_{oPs} : Average number of orthopositronium

$$N_{oPs} = f_{oPs}\, \mathrm{N_{e+}}$$

with $\mathrm{N_{e+}}$ the number of positrons entering in the cavity
f_{oPs} the fraction converted into oPs

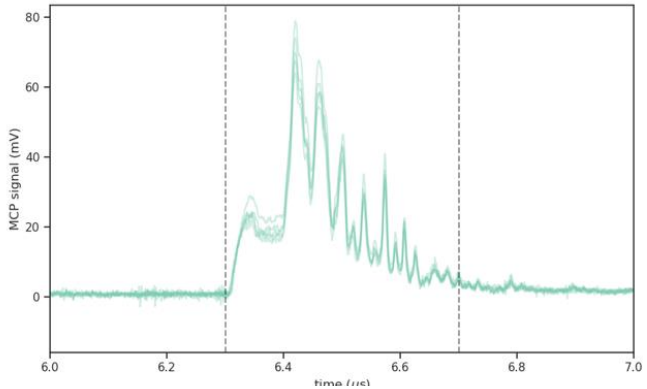
$$6\ keV : 8{,}69 \times 10^{6}\ oPs$$

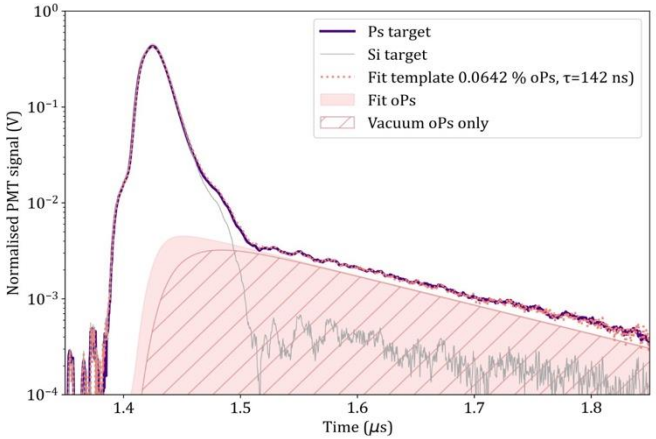
$$4\ keV : 9{,}26 \times 10^{6}\ oPs$$



Cross-section measurement

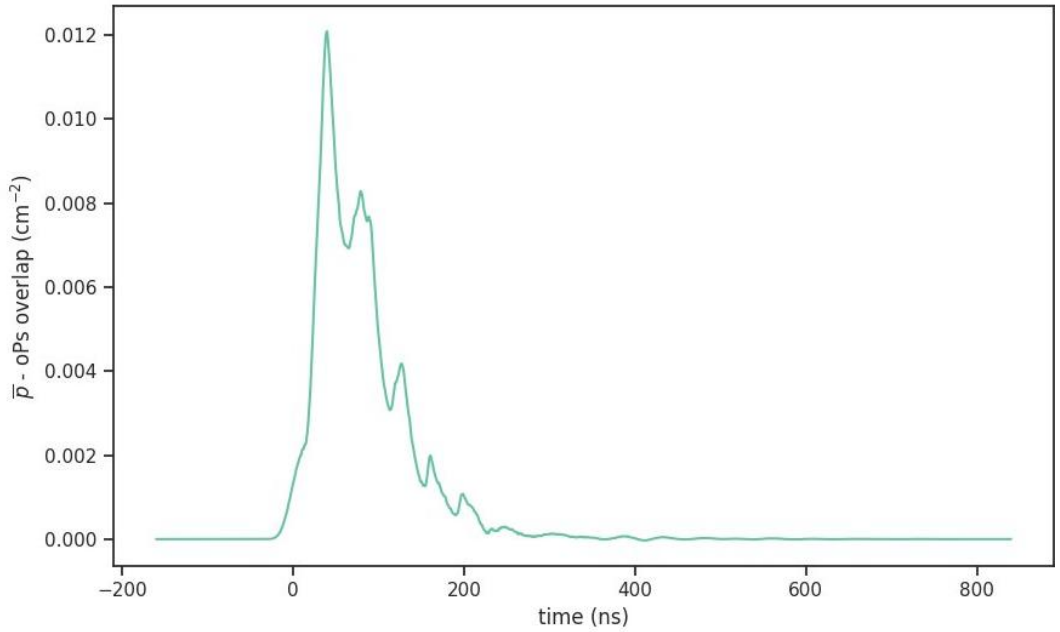
$$\sigma(\bar{v}_{\bar{p}}) = \frac{N_{\bar{H}}}{N_{\bar{p}}\, N_{oPs}} \times \frac{1}{I_{overlap}} \qquad I_{overlap} = \frac{\bar{v}_{\bar{p}}}{V_{cavity}} \int F_{\bar{p}}(t) \cdot F_{oPs}(t) \cdot dt$$





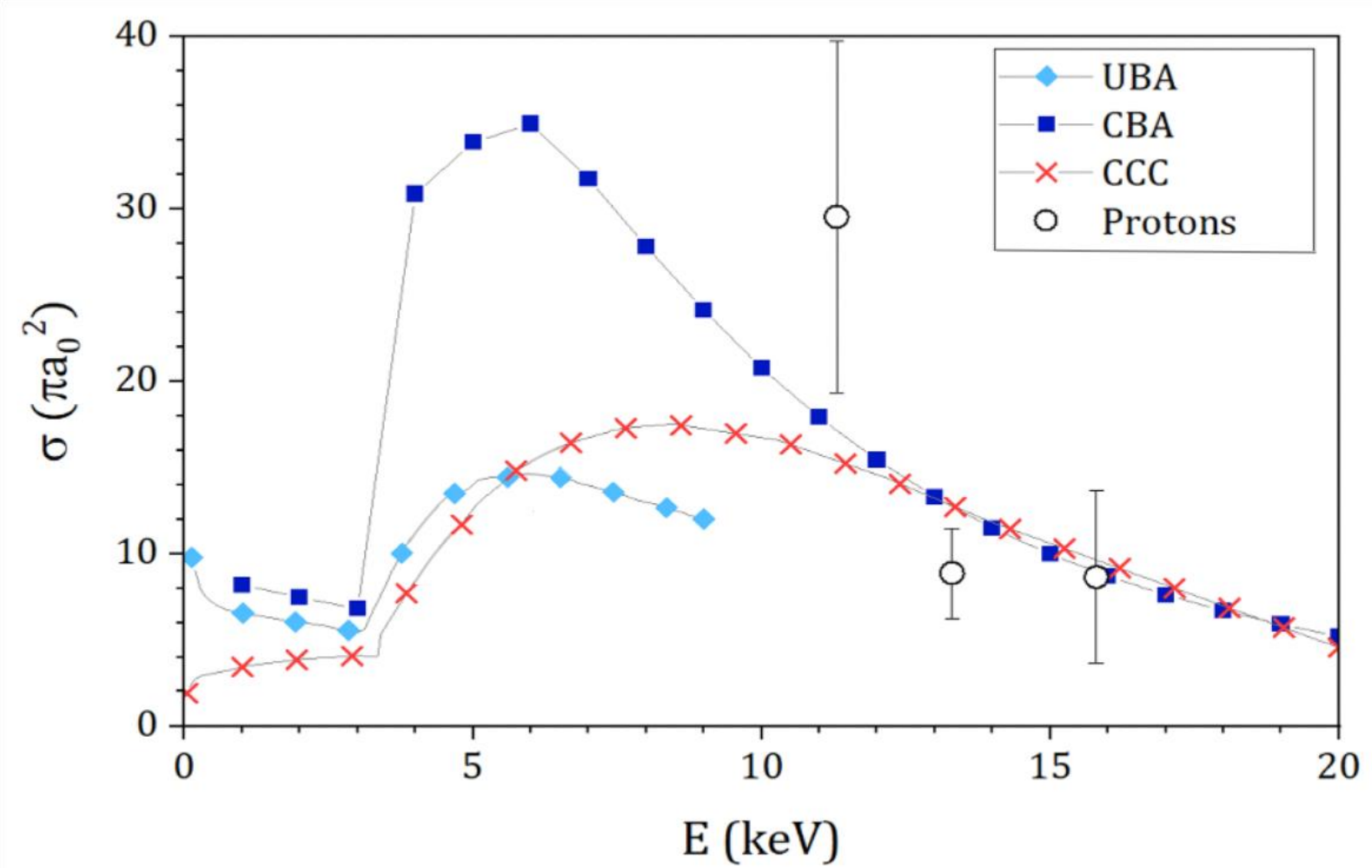
Antiproton pulse

oPs pulse



$6\ keV : 9{,}39\ cm^{-2}$ $4\ keV : 9{,}18\ cm^{-2}$

Cross-section measurement



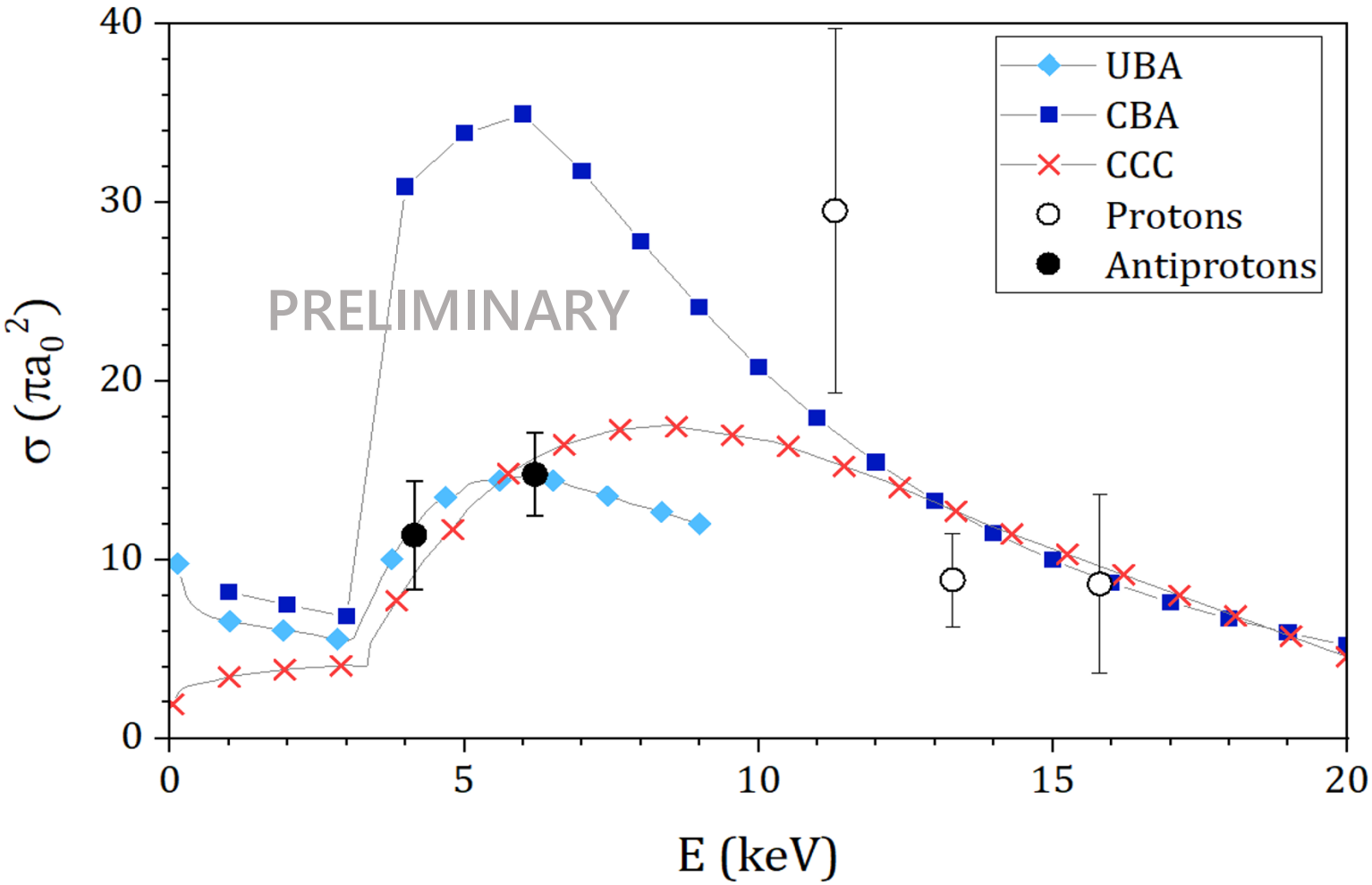
UBA: J. Mitroy, PRA 52, 2859 (1995)

CBA: K. Lévêque-Simon and P.A. Hervieux, PRA 107, 052813 (2023)

CCC: C. M. Rawlins et al., PRA 93, 012709 (2016)

Protons: Merrison, J.P., et al.: Phys. Rev. Lett. 78, 2728–2731 (1997)

Cross-section measurement



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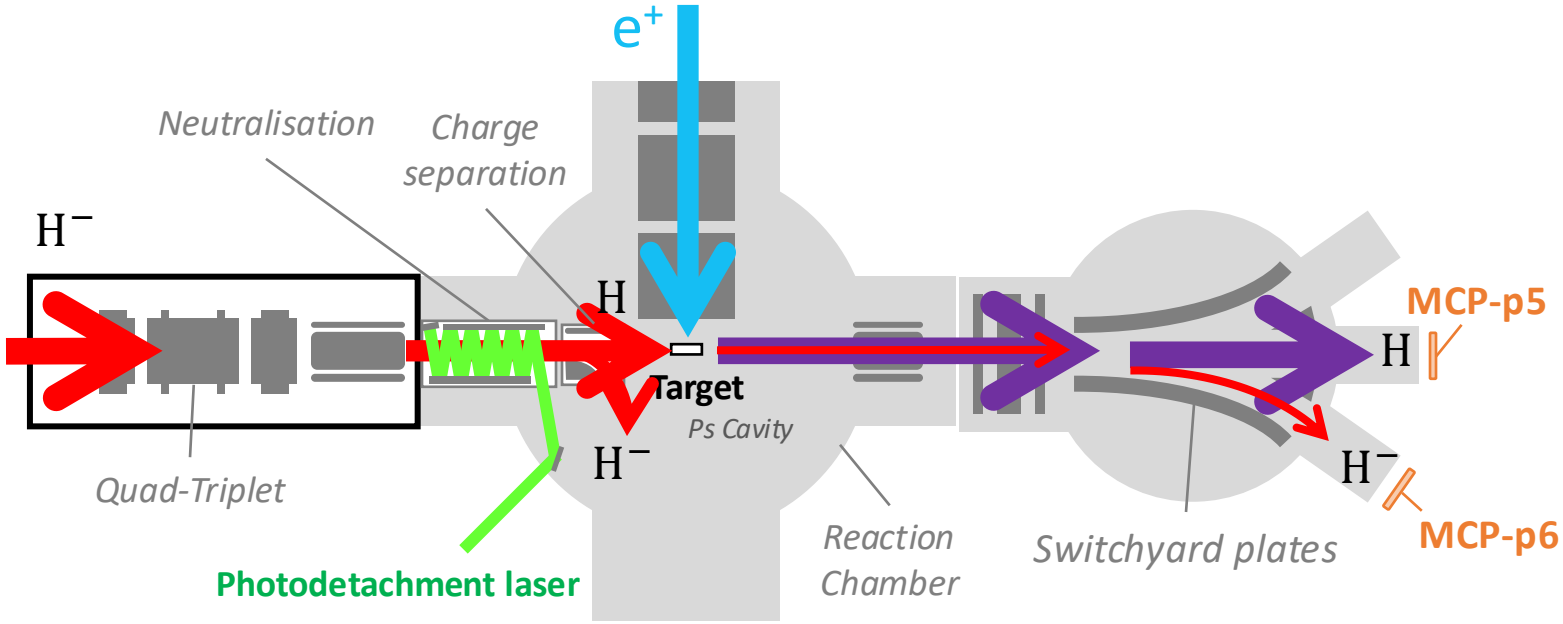
Antimatter : $\bar{H} + Ps \rightarrow \bar{H}^{+} + e^{-}$

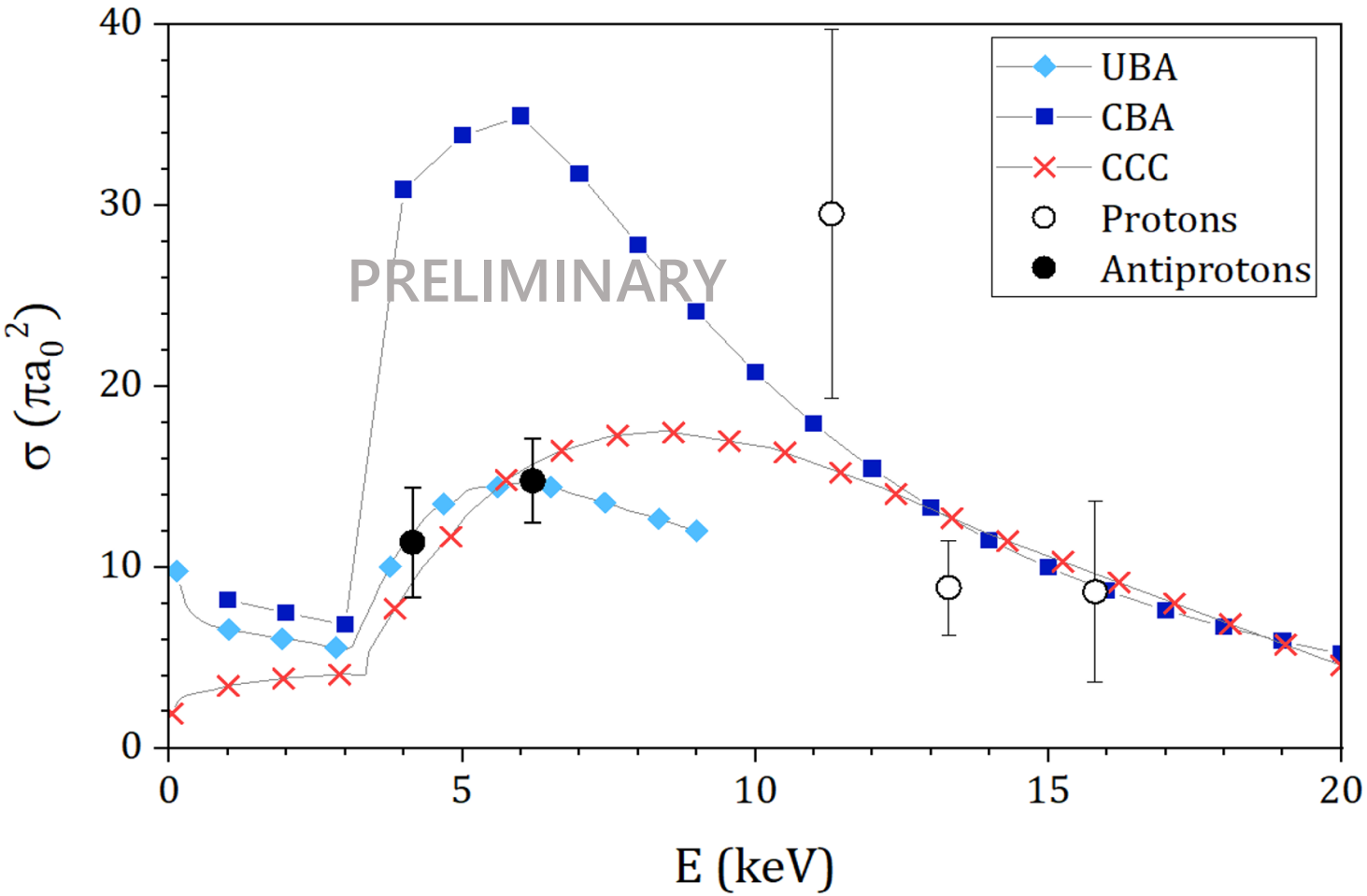
Matter : $H + Ps \rightarrow H^{-} + e^{+}$



Adapted from: Yamashita *et al.*, *Phys Rev A* **105**, 052812 (2022)

Many thanks to you for your attention
&
to the GBAR collaboration

Cross-section measurement



$\sigma(6keV) = 1{,}303 \times 10^{-15} cm^2$

$\sigma(4keV) = 1{,}0 \times 10^{-15} cm^2$

$N_{\bar{H}}$:Number of antihydrogen atoms produced

$$N_{\bar{H}produced} = \frac{N_{\bar{H}candidates}}{1 - f_{BS}} \frac{1}{\varepsilon_{det,MCP}}$$

with f_{BS} the backscattering fraction and $\varepsilon_{det,MCP}$ the detection efficiency of our MCP.

Type of analysis	Energy	$N_{\bar{H}produced}$
Electric signal analysis	6 keV	357,1 ± 39,9 (stat) ± 31,9 (sys)
	4 keV	76,8 ± 18,5 (stat) ± 6,9 (sys)
Cluster image analysis	6 keV	373,8 ± 39,9 (stat) ± 33,4 (sys)
	4 keV	74,3 ± 21,1 (stat) ± 6,6 (sys)

$N_{\bar{p}}$: Number of antiprotons

$$N_{\bar{p}} = \frac{1}{\varepsilon_{det,CMOS}} N_{clusters\ average}\, N_{shots\ mixing}$$

With:

- $N_{clusters\ average}$ the average of tracks in our sensor,
- $N_{shots\ mixing}$ the number of mixing shots,
- $\varepsilon_{det,CMOS}$ the detection efficiency of our CMOS sensor.

Energy	$\mathbf{N_{\bar{p}}}$
6 keV	8,50 ± 0,22 (stat) ± 0,20 (sys) 10^5 × 3893
4 keV	4,50 ± 0,12 (stat) ± 0,10 (sys) 10^5 × 2007

N_{oPs} : Number of ortopositronium

$$N_{\bar{p}} = \frac{1}{\varepsilon_{det,CMOS}} N_{clusters\ average}\, N_{shots\ mixing}$$

With:

- $N_{clusters\ average}$ the average of tracks in our sensor,
- $N_{shots\ mixing}$ the number of mixing shots,
- $\varepsilon_{det,CMOS}$ the detection efficiency of our CMOS sensor.

Energy	$N_{\bar{p}}$
6 keV	8,50 ± 0,22 (stat) ± 0,20 (sys) 10^5 × 3893
4 keV	4,50 ± 0,12 (stat) ± 0,10 (sys) 10^5 × 2007

$I_{overlap}$: Overlap between $\bar{p}$ & oPs

$$I_{overlap} = \frac{\bar{v}_{\bar{p}}}{V_{cavity}} \int F_{\bar{p}}(t) \cdot F_{oPs}(t) \cdot d$$

With:

- $\bar{v}_{\bar{p}}$ the mean velocity of antiprotons,
- V_{cavity} the volume of the cavity,
- $\int F_{\bar{p}}(t) \cdot F_{oPs}(t) \cdot dt\ \varepsilon_{det,CMOS}$ the overlap function.

Energy	$\bar{v}_{\bar{p}}$
6 keV	1,088867 ± 0,00054 (stat) ± 0,00436 (sys) mm/ns
4 keV	0,89296 ± 0,00179 (stat) ± 0,00357 (sys) mm/ns

V_{cavity}
65,8 ± 2,7 (sys) mm^3

Cross-section measurement

$$\sigma(\bar{v}_{\bar{p}}) = \frac{N_{\bar{H}}}{N_{\bar{p}}\, N_{oPs}} \times \frac{1}{I_{overlap}} \qquad I_{overlap} = \frac{\bar{v}_{\bar{p}}}{V_{cavity}} \int F_{\bar{p}}(t) \cdot F_{oPs}(t) \cdot dt$$

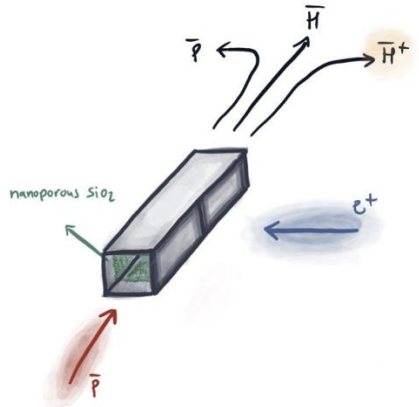
$\bar{v}_{\bar{p}}$: mean velocity of $\bar{p}$

Time of flight measurement between two detectors.

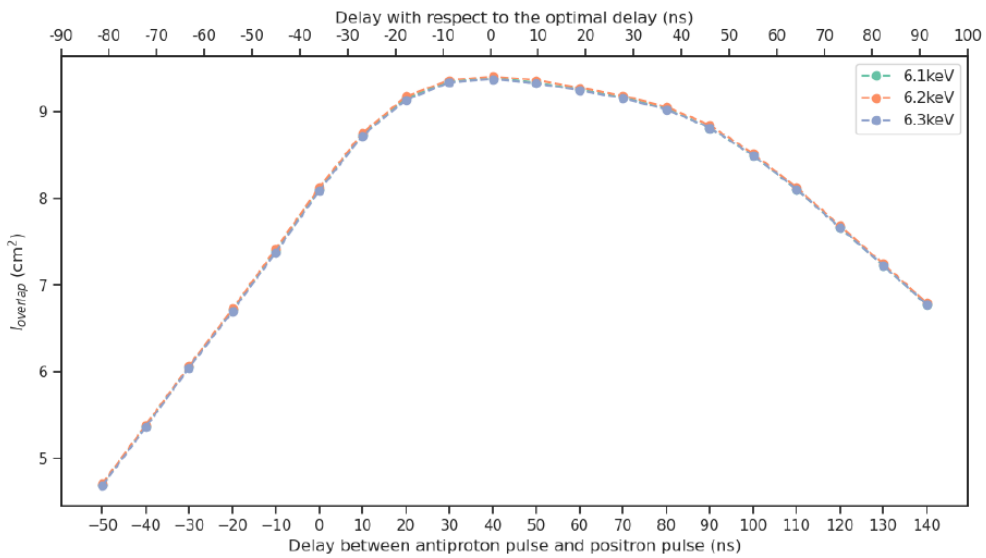
$6\ keV : 1{,}088867\ mm/ns$ $\qquad$ $4\ keV : 0{,}89296\ mm/ns$

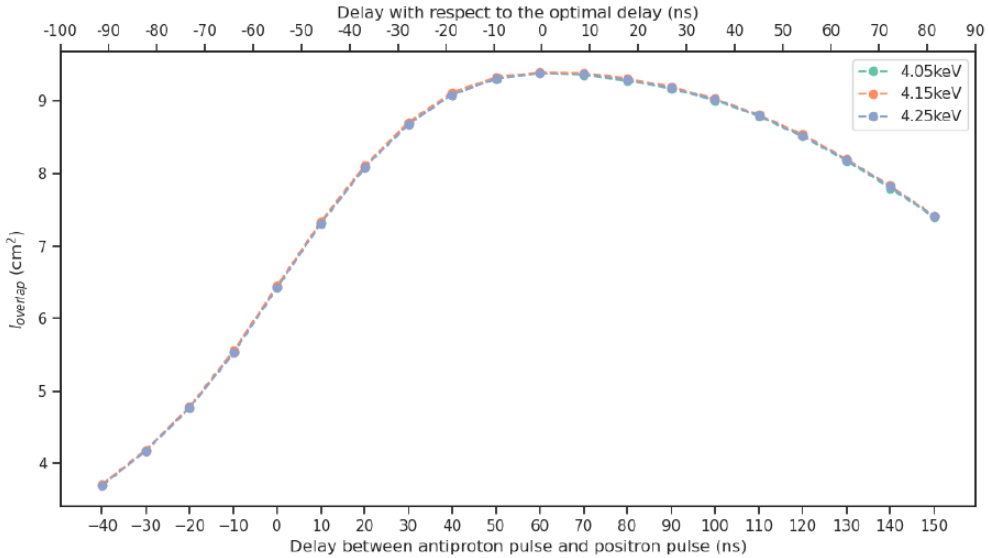
V_{cavity}: volume of the cavity

$$V_{cavity} = 65{,}8\ mm^3$$



$I_{overlap}$: Overlap between $\bar{p}$ & oPs





Energy	$I_{overlap}$
6 keV	9,39 ± 0,03 (stat) ± 0,32 (sys) cm^{-2}
4 keV	9,18 ± 0,28 (stat) ± 0,38 (sys) cm^{-2}

Beam spots contained in MCP