Moriond EW 2023 – 21/03/2023

Status of the GBAR experiment
First results of antihydrogen production

Corentin Roumegou
on behalf of the GBAR collaboration

The Weak Equivalence Principle

The effect of gravitation on a body in free fall
is independent from its nature and composition

- Verified with a precision of 10^{-15} for matter *
- Effect of gravity on antimatter ? ▶ $\bar{\mathrm{g}}$
- Only result from ALPHA collaboration: -65 < $\left(\bar{\mathrm{g}}/\mathrm{g}\right)$ < 110 **

* P. Touboul et al. (MICROSCOPE Collaboration), *Physical Review Letters* **129**, 121102 (2022)
** ALPHA Collaboration, *Nature Communications* **4** 1785 (2013)

The GBAR experiment

Gravitational Behaviour of Antihydrogen at Rest

- Creation of an Antihydrogen ion $\overline{\mathrm{H}}^+$

The GBAR experiment

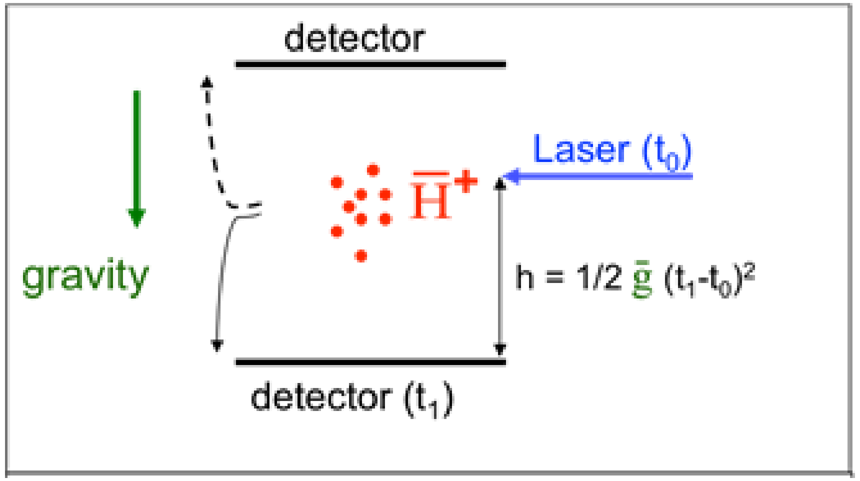
Gravitational Behaviour of Antihydrogen at Rest

- Creation of an Antihydrogen ion $\overline{\mathrm{H}}^+$
- Cooled to µK temperatures

The GBAR experiment

Gravitational Behaviour of Antihydrogen at Rest

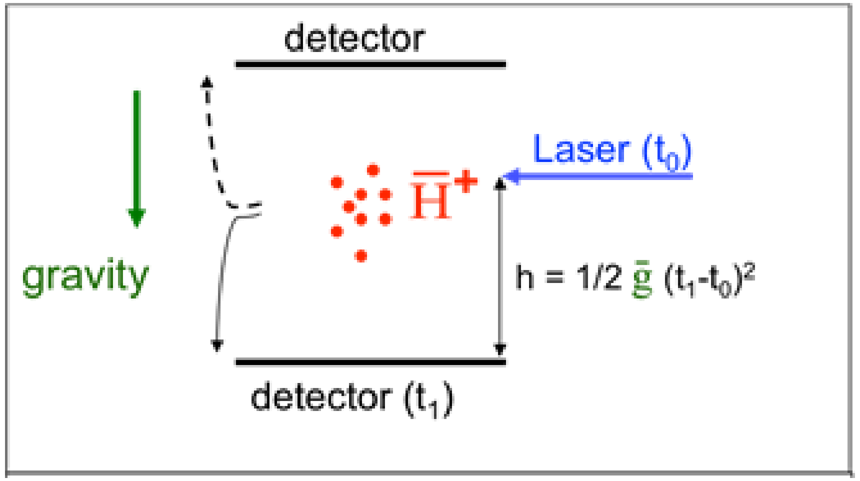
- Creation of an Antihydrogen ion $\overline{\mathrm{H}}^+$
- Cooled to μK temperatures
- Photo-detachment
- $\overline{\mathrm{H}}$ free-fall



The GBAR experiment

Gravitational Behaviour of Antihydrogen at Rest

- Creation of an Antihydrogen ion $\overline{\mathrm{H}}^+$
- Cooled to μK temperatures
- Photo-detachment
- $\overline{\mathrm{H}}$ free-fall
- Measure of $\bar{g}$



$\overline{\mathrm{H}}^{+}$ production

Double charge-exchange reaction

$$(1)\quad \mathrm{Ps} + \bar{\mathrm{p}} \longrightarrow \overline{\mathrm{H}} + \mathrm{e}^{-}$$

$e^{-}e^{+}$ $\qquad$ $\bar{p}$ e^{+}

$$(2)\quad \overline{\mathrm{H}} + \mathrm{Ps} \longrightarrow \overline{\mathrm{H}}^{+} + \mathrm{e}^{-}$$

$\bar{p}$ e^{+} $\qquad$ $e^{-}e^{+}$ $\qquad$ e^{+} $\bar{p}$ e^{+}

$\bar{H}^+$ production

Double charge-exchange reaction

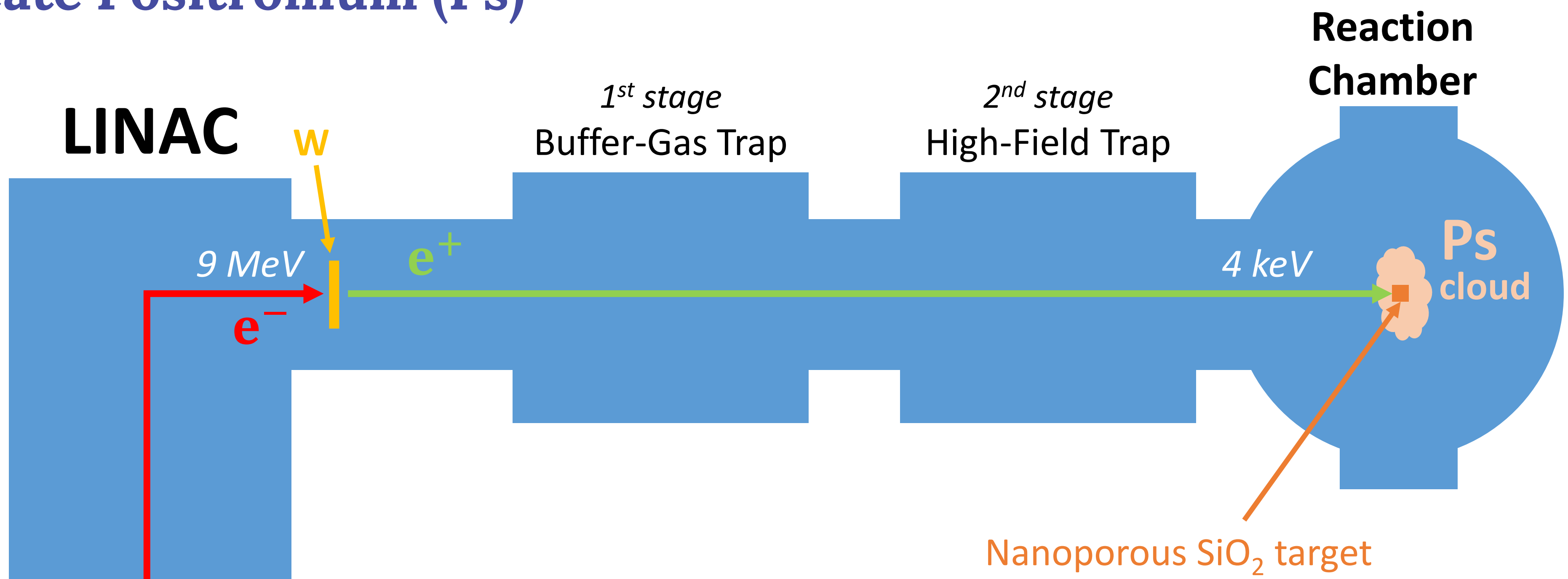
$$(1) \quad \boxed{Ps + \bar{p}} \longrightarrow \bar{H} + e^-$$

→ We need **positronium** & **antiprotons**

$$(2) \quad \bar{H} + Ps \longrightarrow \bar{H}^+ + e^-$$

GBAR experiment design

Positron line → create Positronium (Ps)



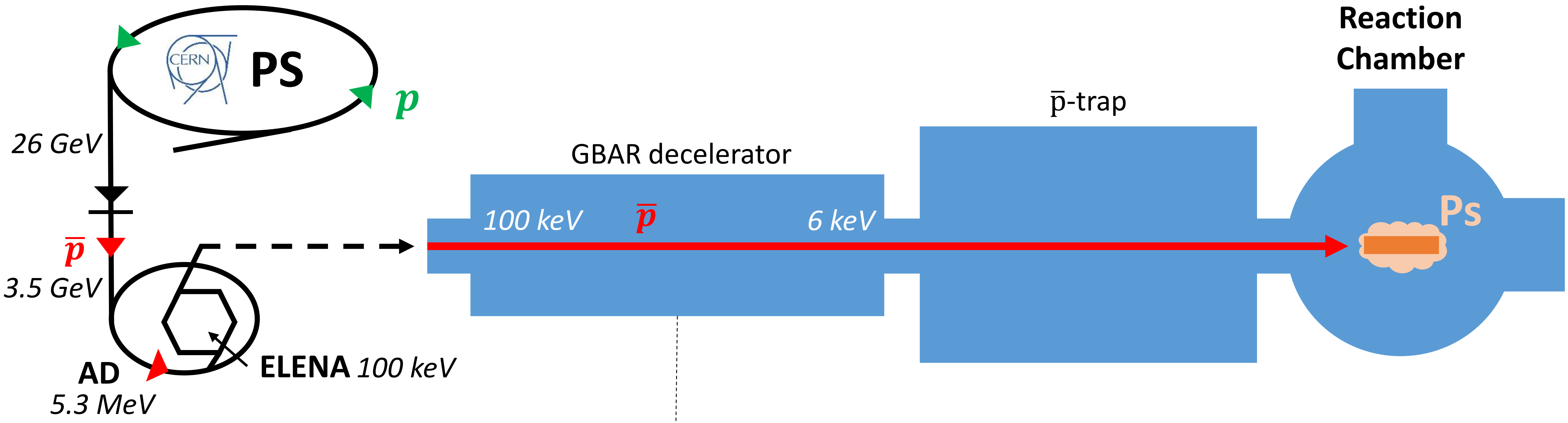
M. Charlton et al., *NIMA* **985** 164657 (2021)
P. Blumer et al., *NIMA* **1040** 167263 (2022)

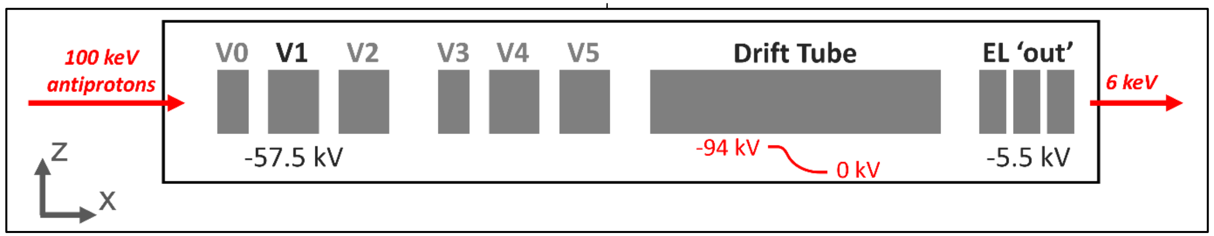
End of 2022 run : [Preliminary]

- **1.7 x 10^8** e^+ accumulated / $\bar{p}$ cycle
- **(7.3 ± 0.7) x 10^7** e^+ on target
- **(9.1 ± 2.1) x 10^6** o-Ps interacting with $\bar{p}$ / shot

GBAR experiment design

Antiproton line ($\bar{p}$)





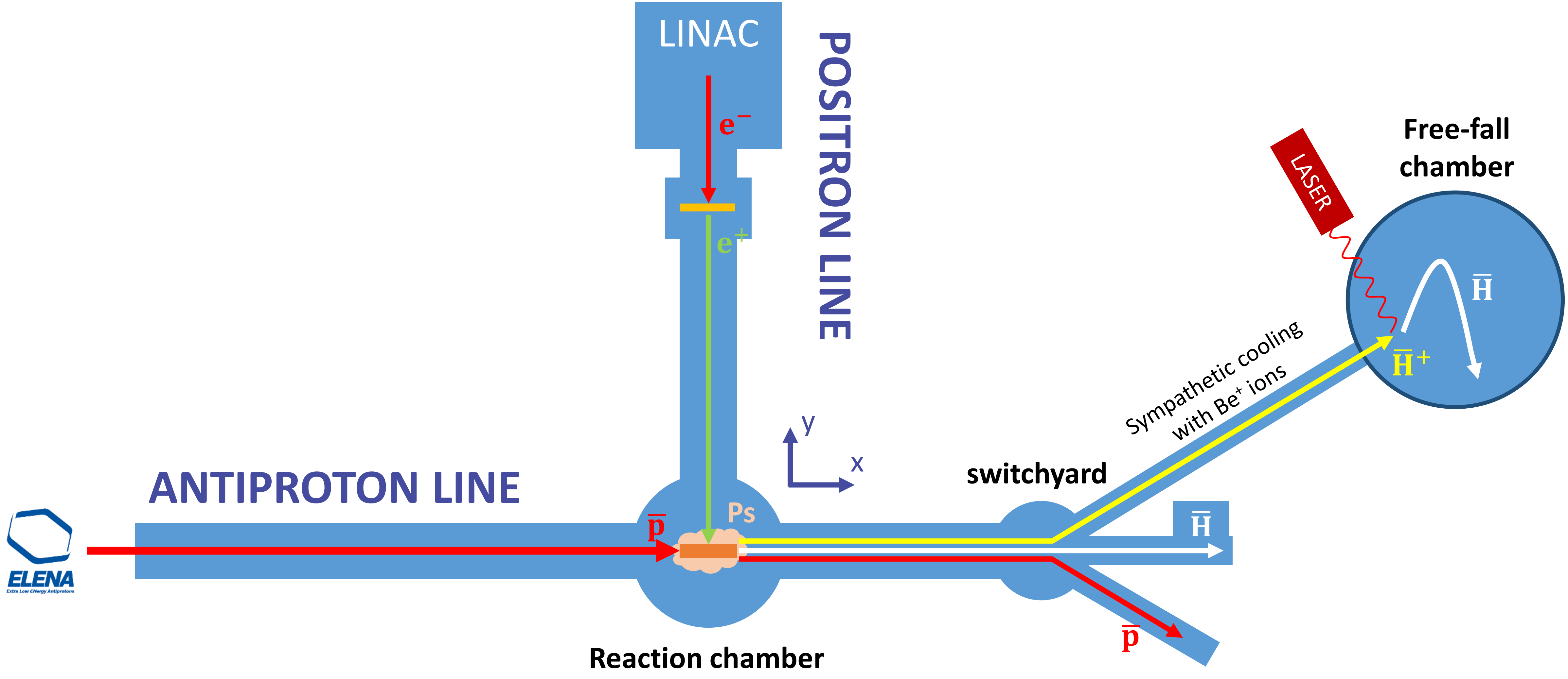
A. Husson et al., *NIMA* **1002** 165245 (2021)

End of 2022 run : [Preliminary]

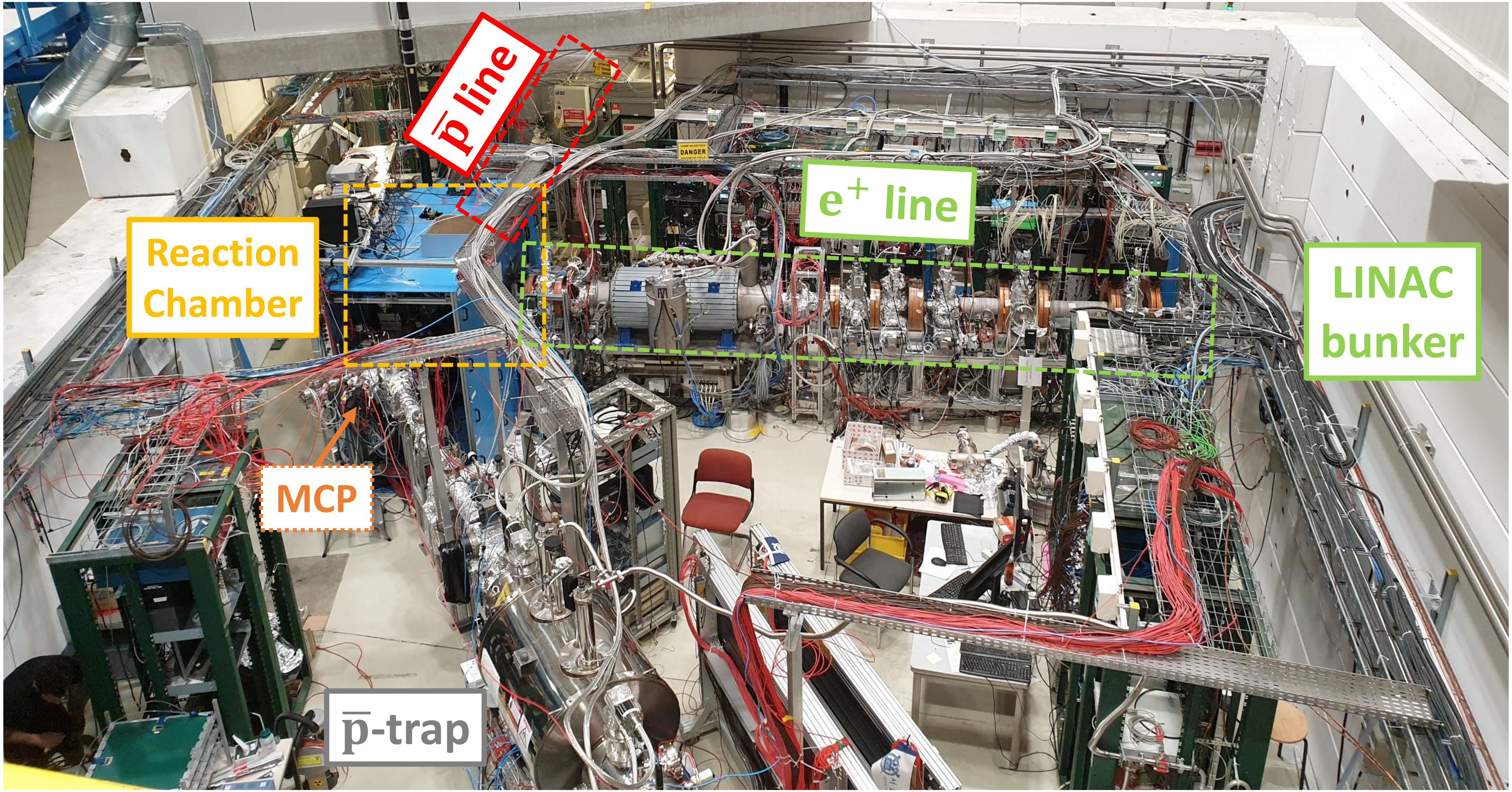
- ~ **7 x 10^6** $\bar{p}$ from ELENA / cycle
- ~ **3 x 10^6** $\bar{p}$ interacting on target

GBAR experiment design

Mixing $\bar{p}$ and Ps & measuring $\bar{H}$ freefall

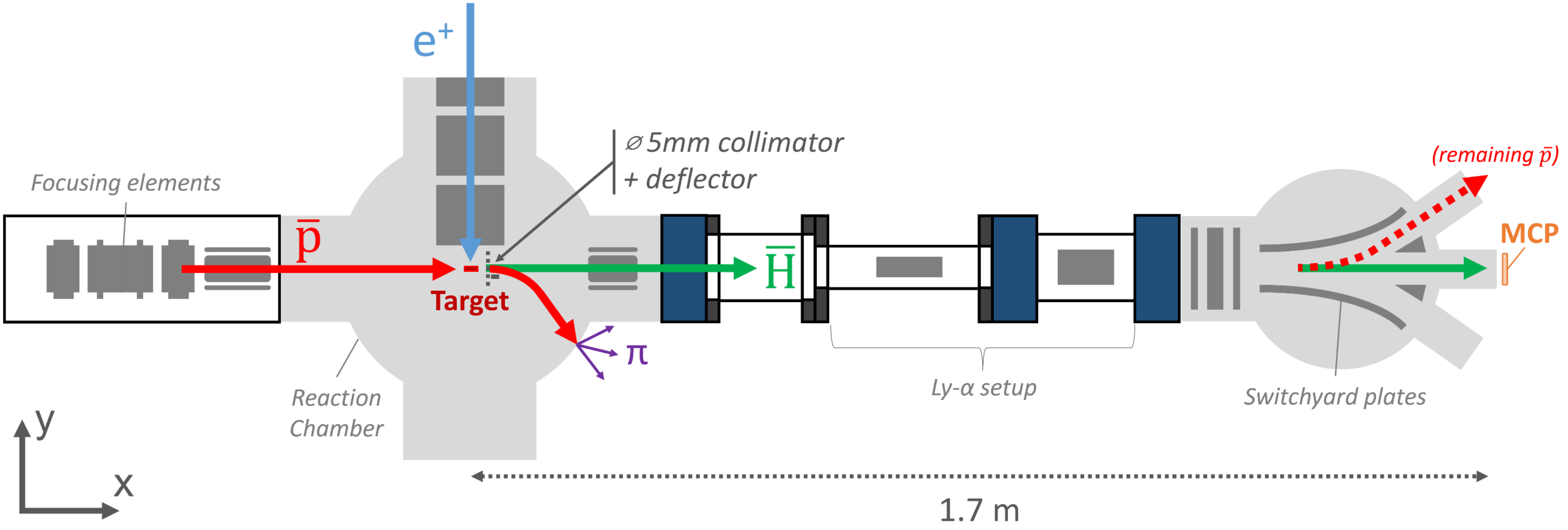


2022 experimental setup



2022 running scheme

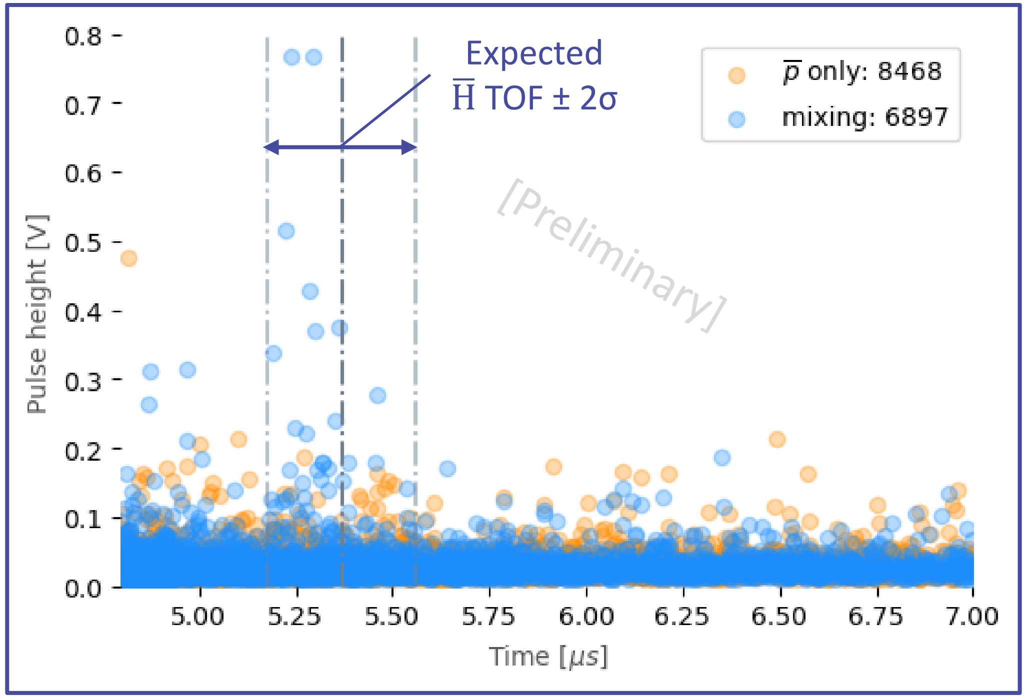
- Detect $\bar{\mathrm{H}}$ on MCP *(MicroChannel Plate)* → electric signal
- Background mainly from $\bar{\mathrm{p}}$ annihilations in reaction chamber (→ pions faster than antihydrogen)

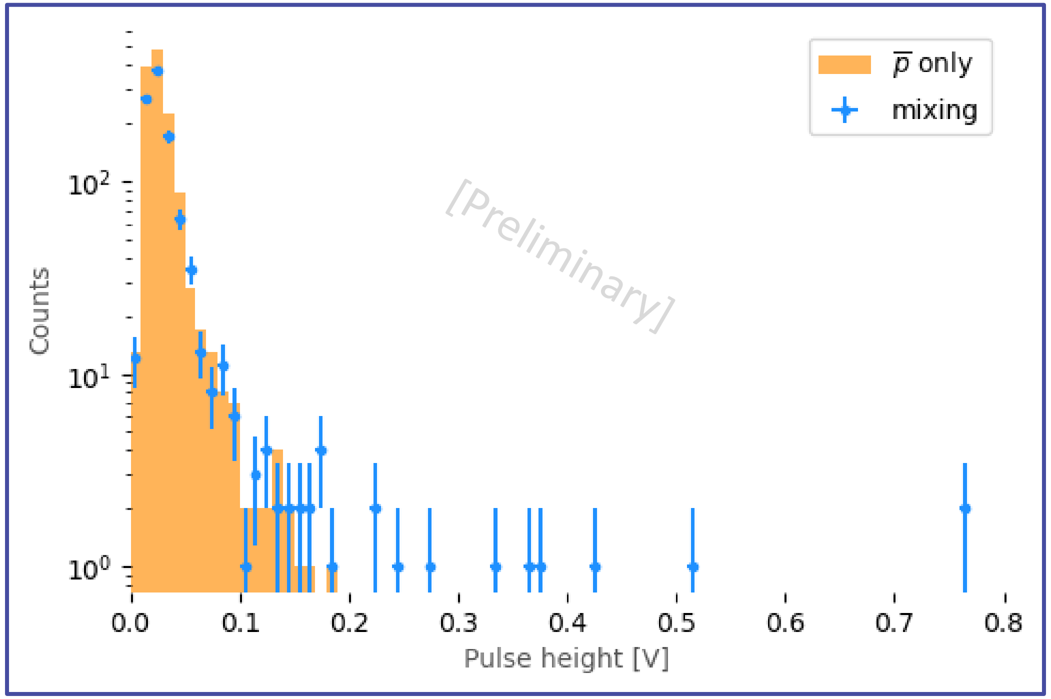


Data taking

- Data taking during 2022 beamtime:
  - 8468 shots with **antiprotons only** – no positrons (→ *"$\bar{p}$ only"*) ▶ Background
  - **Positronium** background is negligible
  - 6897 shots with **both antiprotons and positrons/positronium** (→ *"mixing"*) ▶ Expect to see $\bar{\mathrm{H}}$

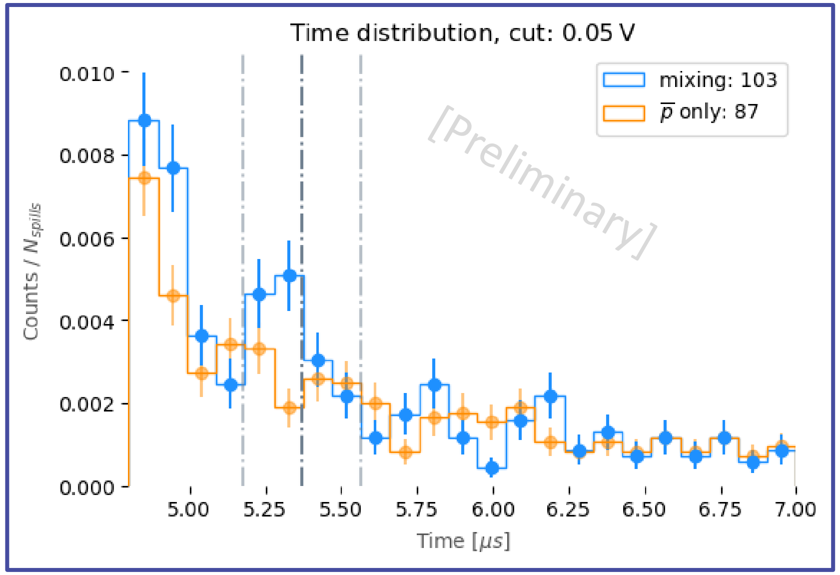
- A few particles reach MCP in the expected time window → distinguishable pulses

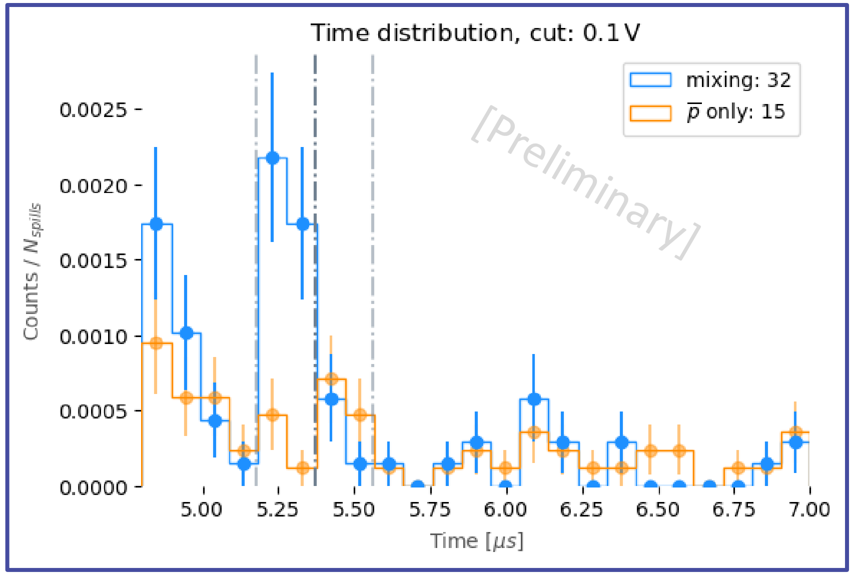


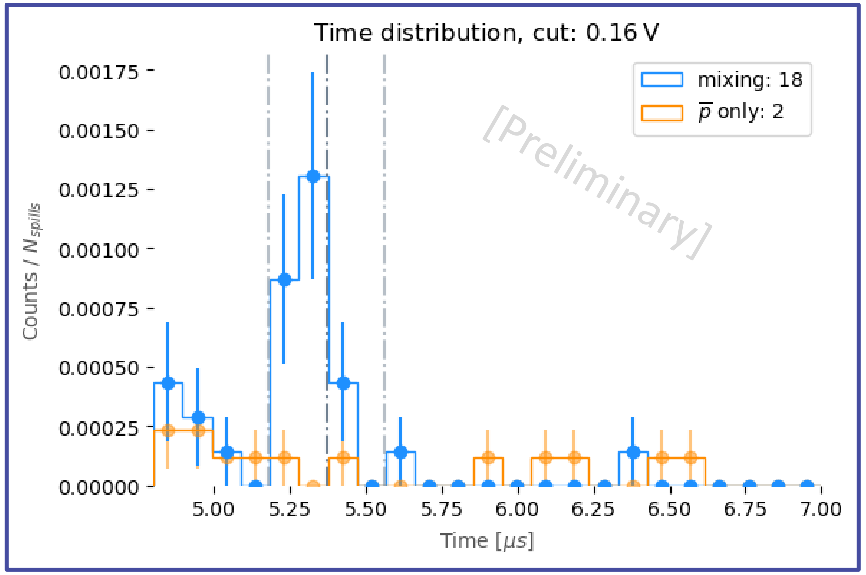


Preliminary results

- Compare number of events with high pulse height in time window for mixing vs background







“ We produced antihydrogen ”

▶ Confidence level > 3σ

GBAR collaboration - Acknowledgments

P. Adrich[1], P. Blumer[2], G. Caratsch[2], M. Chung[3], P. Cladé[4], P. Comini[5], P. Crivelli[2], O. Dalkarov[6], P. Debu[5], A. Douillet[4,7], D. Drapier[4], P. Froelich[8,*], S. Guellati-Khelifa[4,9], J. Guyomard[4], P-A. Hervieux[10], L. Hilico[4,7], P. Indelicato[4], S. Jonsell[8], J-P. Karr[4,7], B. Kim[11], S. Kim[12], E-S. Kim[13], Y.J. Ko[11], T. Kosinski[1], N. Kuroda[14], B.M. Latacz[5,**], B. Lee[12], H. Lee[12], J. Lee[11], E. Lim[13], L. Liszkay[5], D. Lunney[15], G. Manfredi[10], B. Mansoulié[5], M. Matusiak[1], V. Nesvizhevsky[16], F. Nez[4], S. Niang[15,**], B. Ohayon[2], K. Park[10], N. Paul[4], P. Pérez[5], C. Regenfus[2], S. Reynaud[4], C. Roumegou[15], J-Y. Roussé[5], Y. Sacquin[5], G. Sadowski[5], J. Sarkisyan[2], M. Sato[14], F. Schmidt-Kaler[17], M. Staszczak[1], K. Szymczyk[1], T.A. Tanaka[14], B. Tuchming[5], B. Vallage[5], D.P. van der Werf[18], A. Voronin[6], D. Won[12], S. Wronka[1], Y. Yamazaki[19], K-H. Yoo[3], P. Yzombard[4]

(GBAR Collaboration)

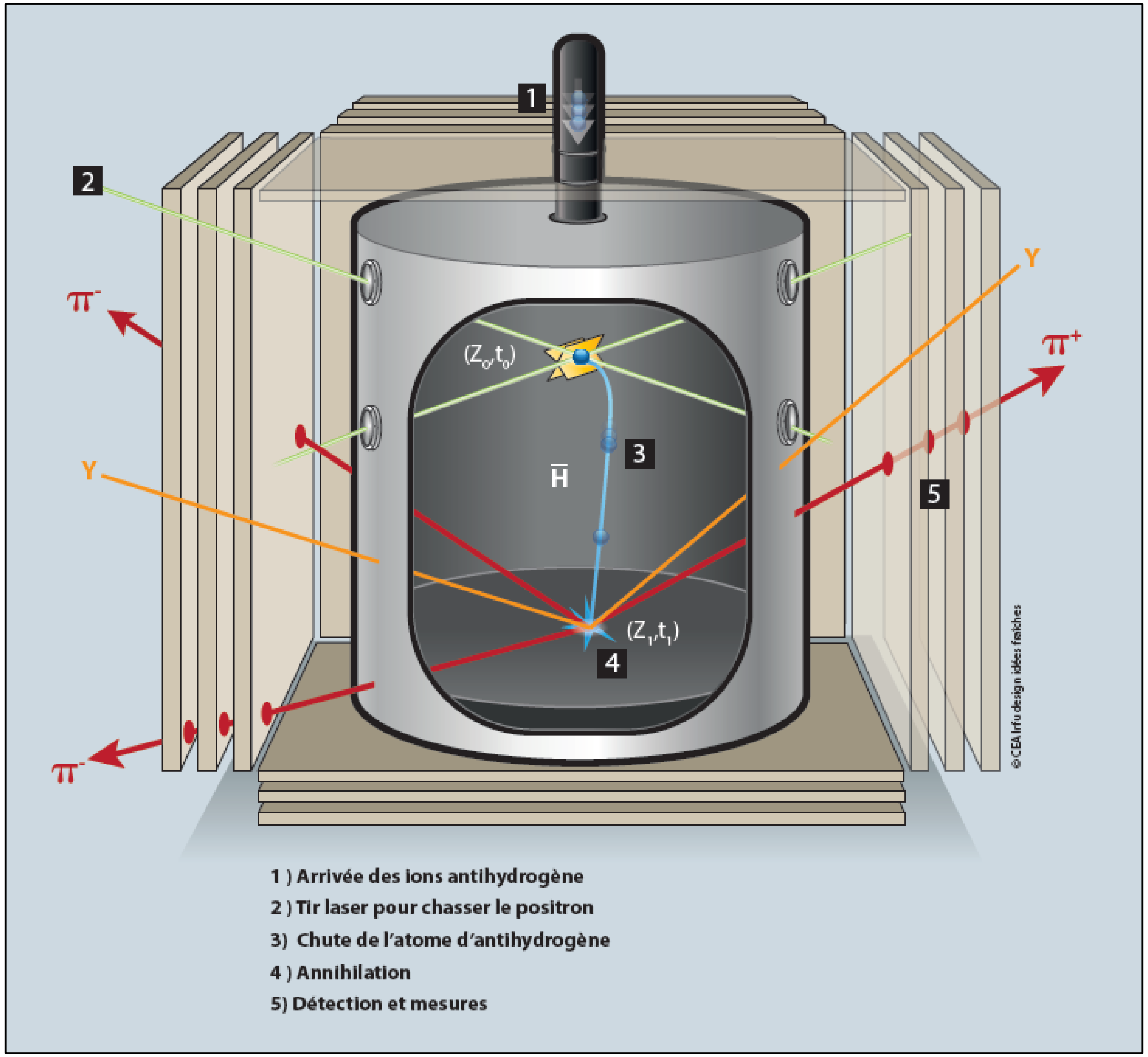
Any questions?

Backup Slides

Next steps - Perspectives

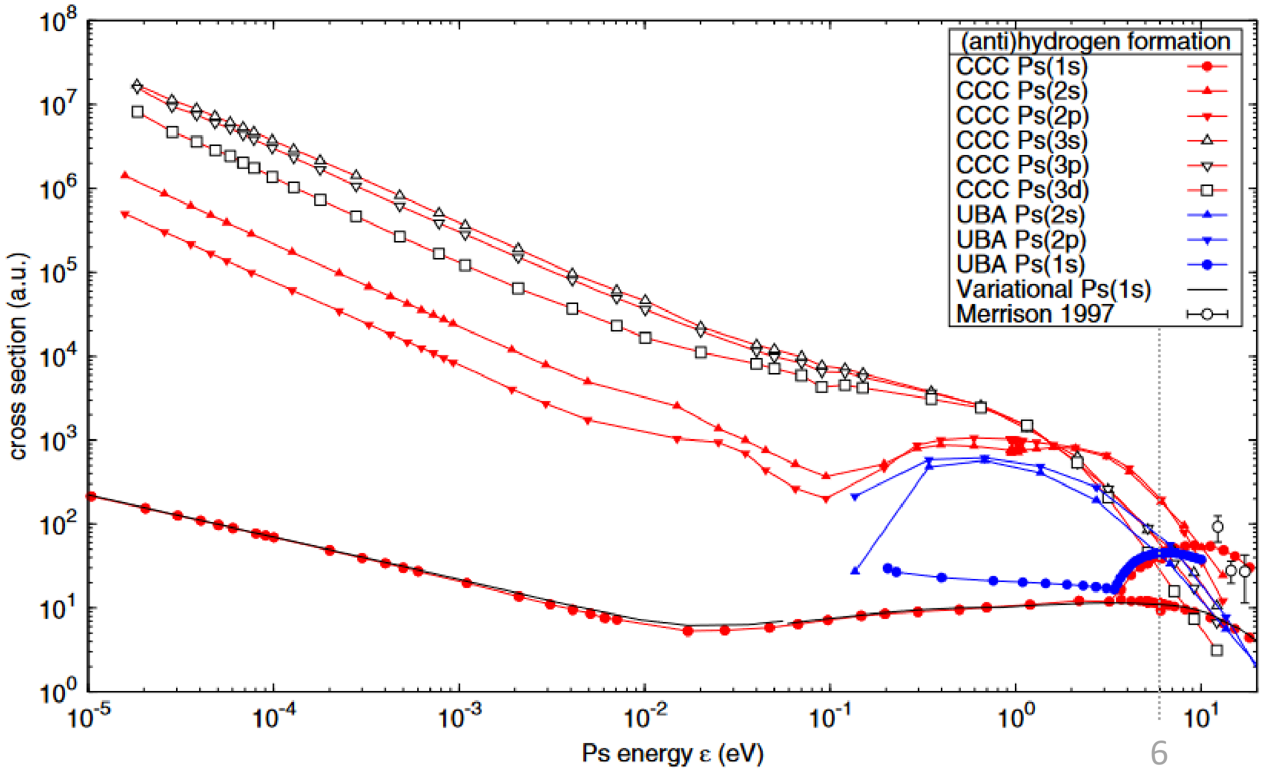
- Install $\bar{p}$-trap ▶ **Lower emittance, better $\bar{p}$ focusing into target**
- Increase LINAC frequency & improve transmission in positron line ▶ **More e^+ on target**
- **Lamb-shift** measurement for antihydrogen ▶ **CPT test**
- Produce antihydrogen ion and measure cross-section of 2nd reaction ▶ $\bar{\mathbf{H}}^+$
- Freefall measurement ▶ **Measure $\bar{\mathbf{g}}$** ($\frac{\Delta\bar{g}}{\bar{g}} \leq 1\%$)
- "Quantum free-fall of antihydrogen" ▶ **Measure $\bar{\mathbf{g}}$** ($\frac{\Delta\bar{g}}{\bar{g}} \leq 10^{-5}$)

Free-fall chamber scheme



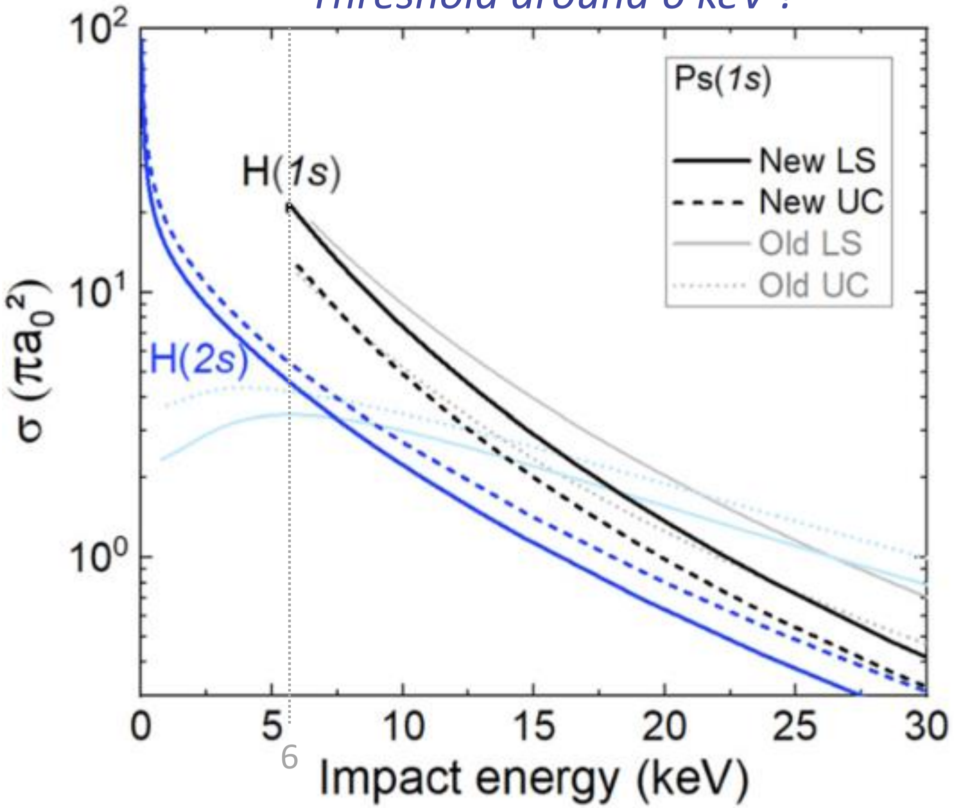
Cross sections theoretical calculations

(1) $\text{Ps} + \bar{p} \longrightarrow \bar{H} + e^-$



(2) $\bar{H} + \text{Ps} \longrightarrow \bar{H}^+ + e^-$

Threshold around 6 keV !



A.S. Kadyrov et al., *Physical Review Letters* **114**, 183201 (2015)
P. Comini et al., *New Journal of Physics* **23**, 029501 (2021)

Cross section measurement

1st reaction matter equivalent

$$Ps \quad + \quad p \quad \longrightarrow \quad H \quad + \quad e^+$$

Merrison et al., *Physical Review Letters* **78**, 2728 (1997)

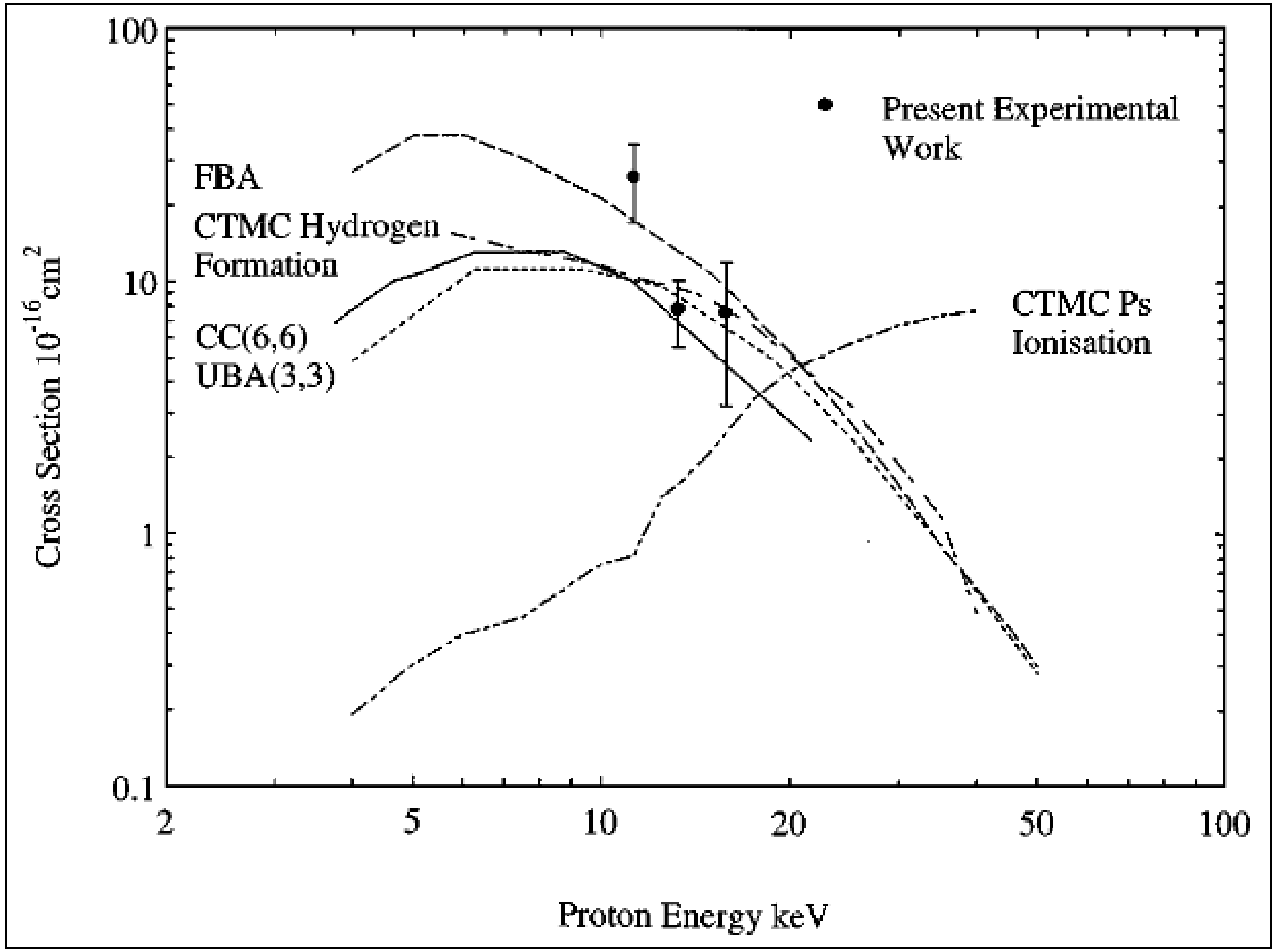


FIG: Total cross sections for formation of hydrogen by proton impact upon Ps(1s). Comparison is made between the present experimental values and various theoretical approximations.

Positronium background [Preliminary]

- 1 x 10^7 o-Ps per shot

Ps lifetime:	*p-Ps = 125 ps*
	o-Ps = 142 ns

3 gamma /o-Ps

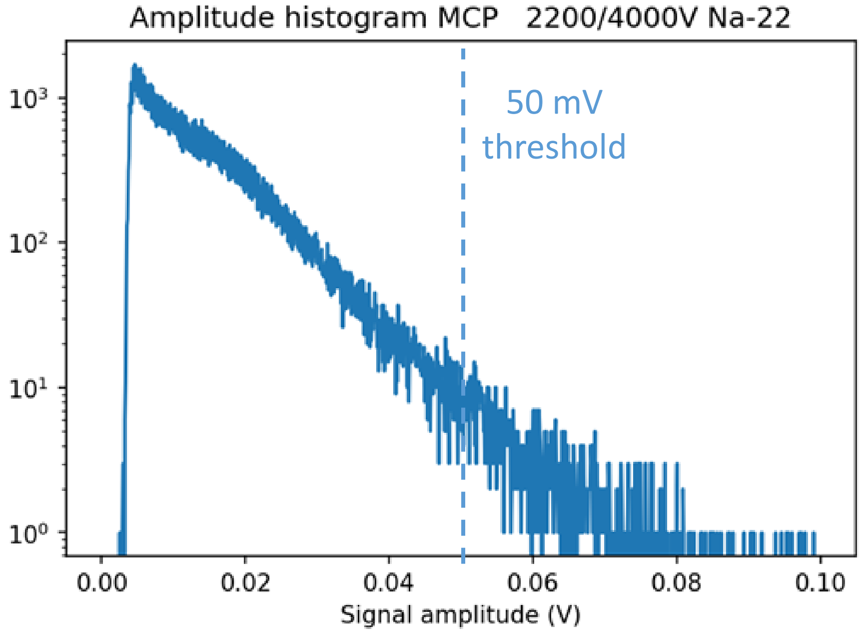
- o-Ps target to MCP = 1.6 µs TOF for pbar / Time window: 200 ns → detection starts at 1.4 µs
- #Gamma photons after this time: $3 \times e^{\frac{-1400}{142}} \times 10^7 = 1568$
- Solid angle of 4 cm diameter MCP: $\left.\frac{\pi \times 0.02^2}{1.7^2}\right/ 4\pi = 3.46 \times 10^{-5}$
- #Gammas on MCP after 1.4 µs: $1568 \times 3.46 \times 10^{-5} = 0.05$
- With 5 % detection efficiency (very good MCP with 10^7 gain !): 2.5×10^{-3} MCP signals per shot
- 6897 mixing shots → $6897 \times 2.5 \times 10^{-3} <$ **18 MCP signals**

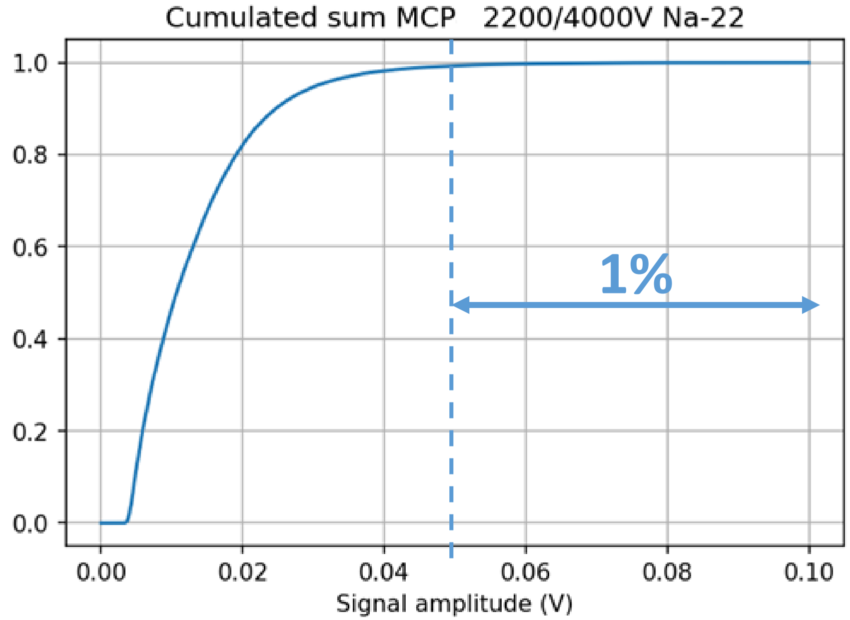
Positronium background [Preliminary]

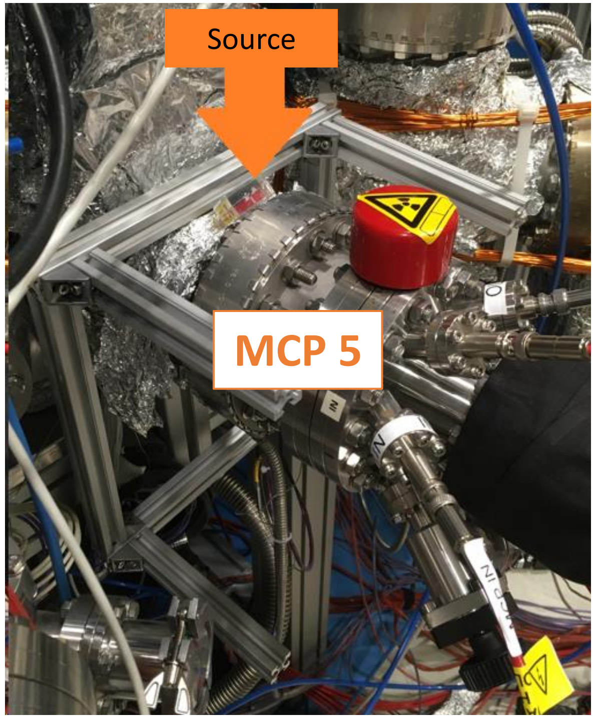
MCP efficiency for gammas

- < 18 MCP signals in 6897 mixing shots
- Signal above the 50 mV threshold: 1 % (see histogram) → 1% of 18

< 0.2 events for the 6897 mixing shots



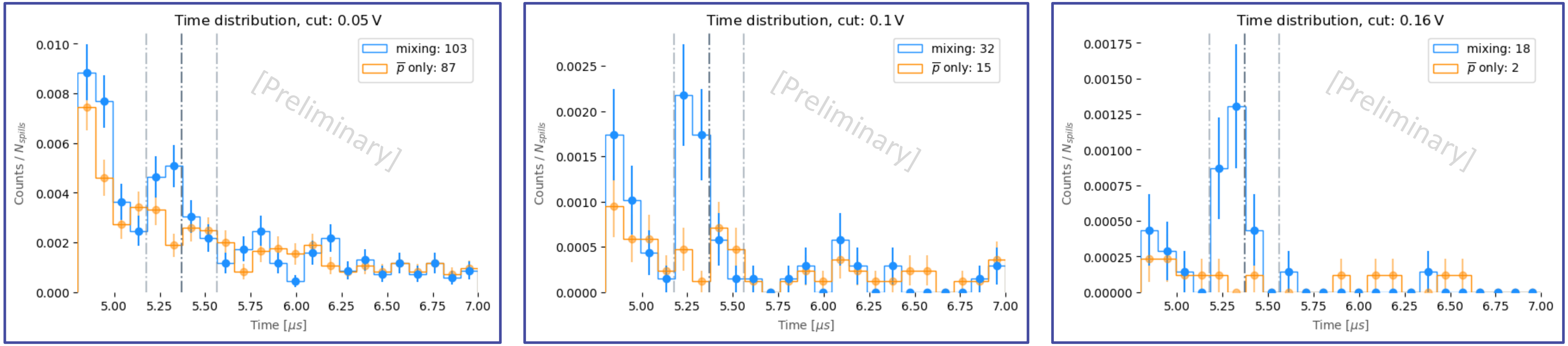




We used 22Na source to measure the amplitude distribution, but we do not expect a fundamentally different distribution for o-Ps annihilation photons

Significance [Preliminary]

NB: $\overline{H}$ production is around 3.8 µs
→ 1.6 µs TOF to MCP



Cut [V]	0.10	0.12	0.14	0.16	0.18	0.20
n	32	28	22	18	12	11
b	15	11	5	2	1	0
$\sigma_{binomial}$	3.26	3.42	3.87	4.14	3.48	3.79
$\sigma_{Li\&Ma}$	3.20	3.40	3.92	4.27	3.66	4.20

- $\sigma_{binomial}$: binomial test comparing Poisson means of two samples
- $\sigma_{Li\&Ma}$: $S = \sqrt{2}\sqrt{n \times log\left(\frac{\alpha+1}{\alpha}\frac{n}{n+b}\right) + b \times \left((\alpha+1)\frac{b}{n+b}\right)}$ [T-P. Li and Y-Q Ma, *The Astrophysical Journal* **272** 317-324 (1983)]

Pbar line scheme for 2022 run

- $\bar{p}$-trap at the end of the line
- Transfer line between decelerator and reaction chamber
- <u>Goals:</u> Detect $\bar{H}$ in switchyard MCP & test $\bar{p}$-trap