LEAP 2013 UPPSALA

$\bar{H}^+$ production from collisions between positronium & keV antiprotons for GBAR

Pauline COMINI
Paul-Antoine HERVIEUX
François BIRABEN

for the GBAR *collaboration*

CEA-Saclay Service de Physique des Particules

+ Institut de Physique et de Chimie des Matériaux de Strasbourg

+ Laboratoire Kastler-Brossel

FRANCE

For the next 20 minutes

GBAR Context

Cross sections

Estimations

For the next 20 minutes

GBAR Context

(Why and) How producing $\overline{\mathrm{H}}^+$?

Cross sections

Estimations

For the next 20 minutes

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Cross sections

Theoretical calculations of $\bar{H}$ and $\bar{H}^+$ production

Estimations

For the next 20 minutes

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(Why and) How producing $\overline{\mathrm{H}}^+$?

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Theoretical calculations of $\overline{\mathrm{H}}$ and $\overline{\mathrm{H}}^+$ production

Estimations

Simulating the reaction chamber

And now…

GBAR Context

(Why and) How producing $\overline{H}^+$?

Cross sections

Estimations

$\bar{H}^+$ production for GBAR

GBAR CONTEXT

- *See talk by P. Indelicato*

Weak Equivalence Principle for Antimatter ?

Free fall experiment

Ultra-low energy

(1 m.s^{-1} ; neV)

Ion cooling

($\bar{H}^+$)

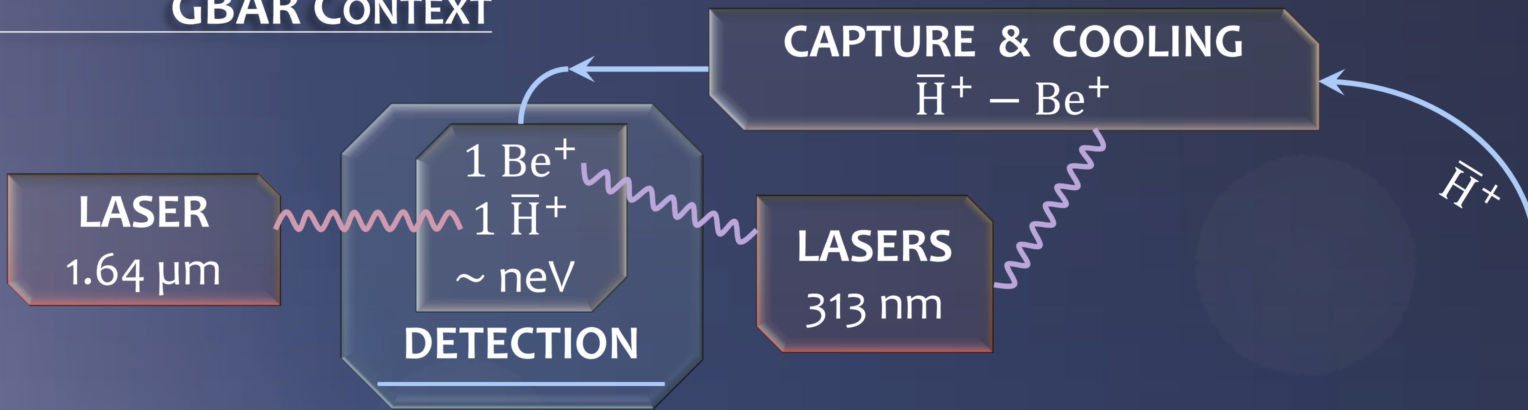
Neutral Antihydrogen

($\bar{H}$)

Photodetachment

$\bar{H}^+$ production for GBAR

GBAR Context



$\bar{H}^+$ production for GBAR

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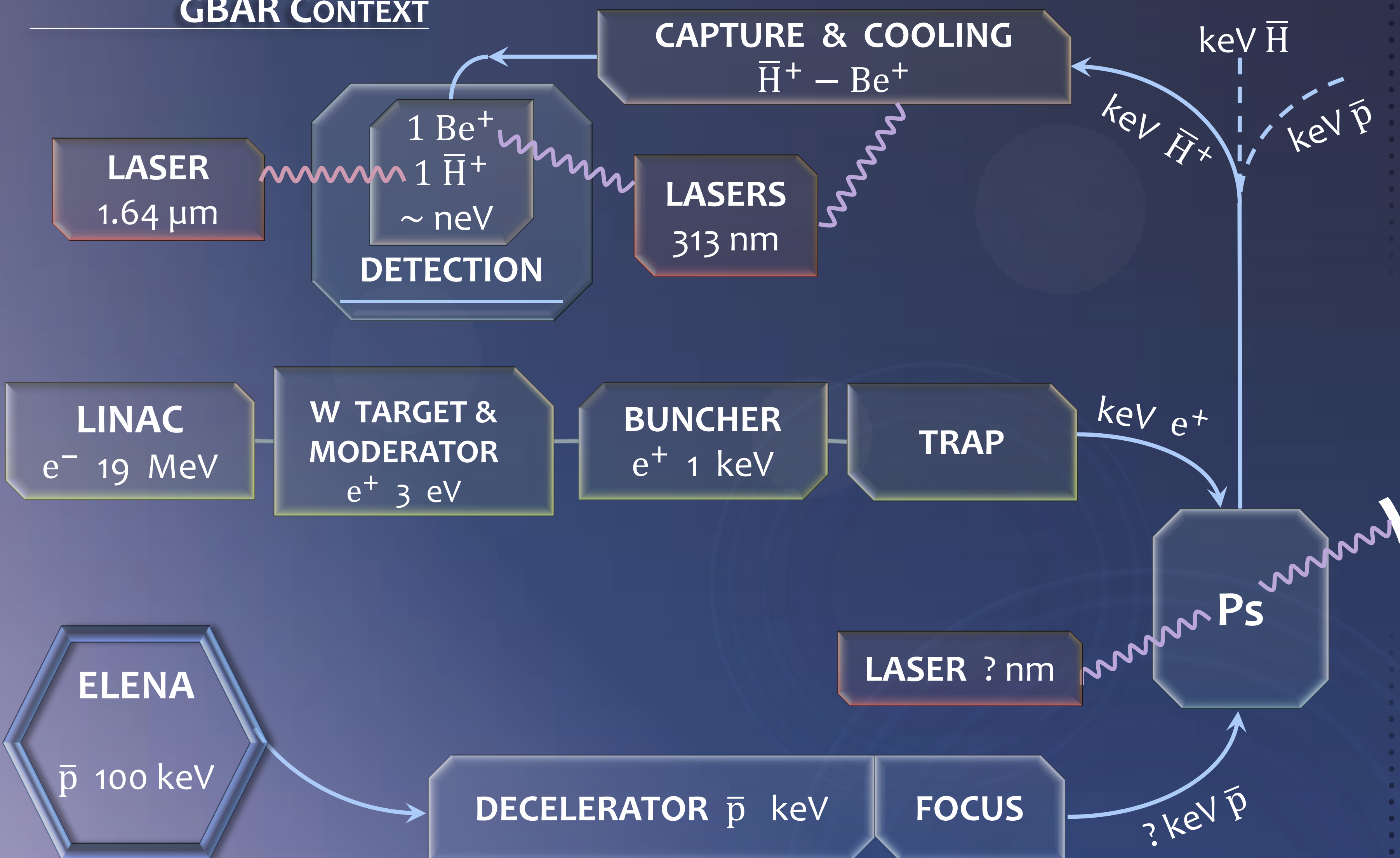

$\bar{H}^+$ production for GBAR

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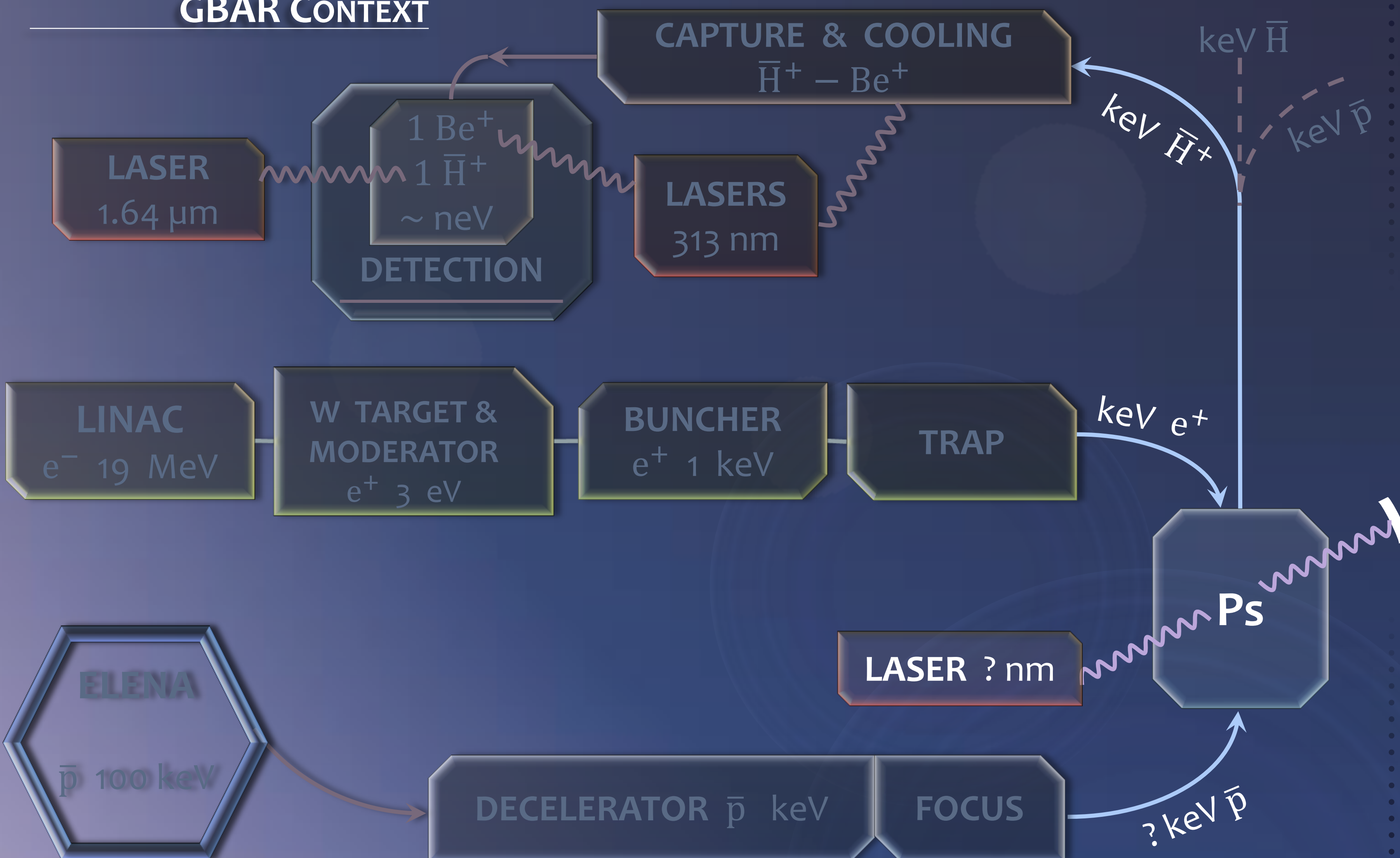


AND NOW...

GBAR Context

Cross sections

Theoretical calculations of $\overline{\mathrm{H}}$ and $\overline{\mathrm{H}}^+$ production

Estimations

Antiatomic reactions

- Inside GBAR's reaction chamber

$$\bar{\mathrm{p}} + \mathrm{Ps}(n_p, l_p, m_p) \longrightarrow \bar{\mathrm{H}}(n_h, l_h, m_h) + \mathrm{e}^- \qquad (1.A)$$

$$\bar{\mathrm{H}}(n_h, l_h, m_h) + \mathrm{Ps}(n_p, l_p, m_p) \longrightarrow \bar{\mathrm{H}}^+ + \mathrm{e}^- \qquad (2.A)$$

- Time reversal + charge conjugation

$$\mathrm{H}(n_h, l_h, m_h) + \mathrm{e}^+ \longrightarrow \mathrm{p} + \mathrm{Ps}(n_p, l_p, m_p) \qquad (1.B)$$

$$\mathrm{H}^- + \mathrm{e}^+ \longrightarrow \mathrm{H}(n_h, l_h, m_h) + \mathrm{Ps}(n_p, l_p, m_p) \qquad (2.B)$$

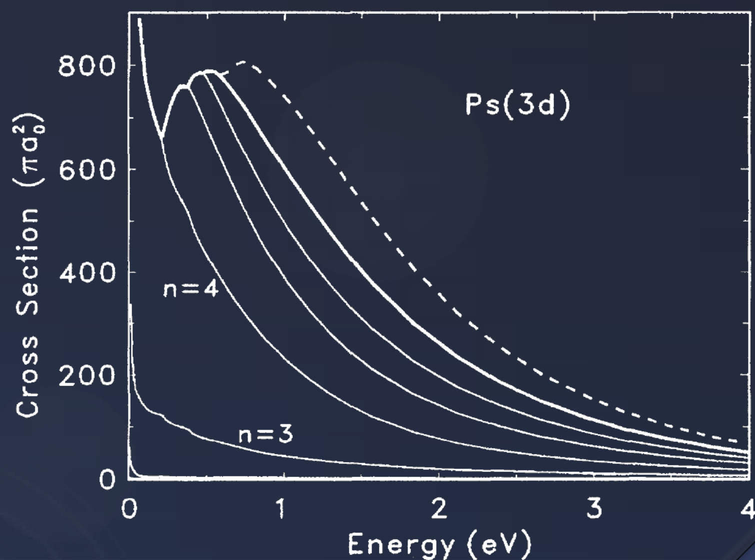
AVAILABLE RESULTS : REACTION 1.

- Theoretical example

$$\bar{p} + Ps(n_p, l_p) \rightarrow \bar{H}(n_h, l_h) + e^-$$

J Mitroy, *Phys. Rev. A* **52** (1995) 2859

Importance of $\bar{H}$ excited state
Interest in excited Ps & low energy $\bar{p}$



- Experimental work

Nothing with $\bar{p}$ … yet

$$p + Ps(1s) \rightarrow H(n_h, l_h) + e^+$$

J P Merrison *et al.*, *Phys. Rev. Lett.* **78** (1997) 2728

- Reverse reaction

$$e^+ + H(1s) \rightarrow p + Ps(n_p, l_p)$$

Zhou *et al.*, *Phys. Rev. Lett.* **78** (1997) 2728

$\bar{H}^+$ production for GBAR

Available results : Reaction 2.

- Scarce theoretical studies

  $$H(1s) + Ps(n_p, l_p) \rightarrow H^- + e^+$$

  H(1s)
  Ps(1s) to Ps(2p)

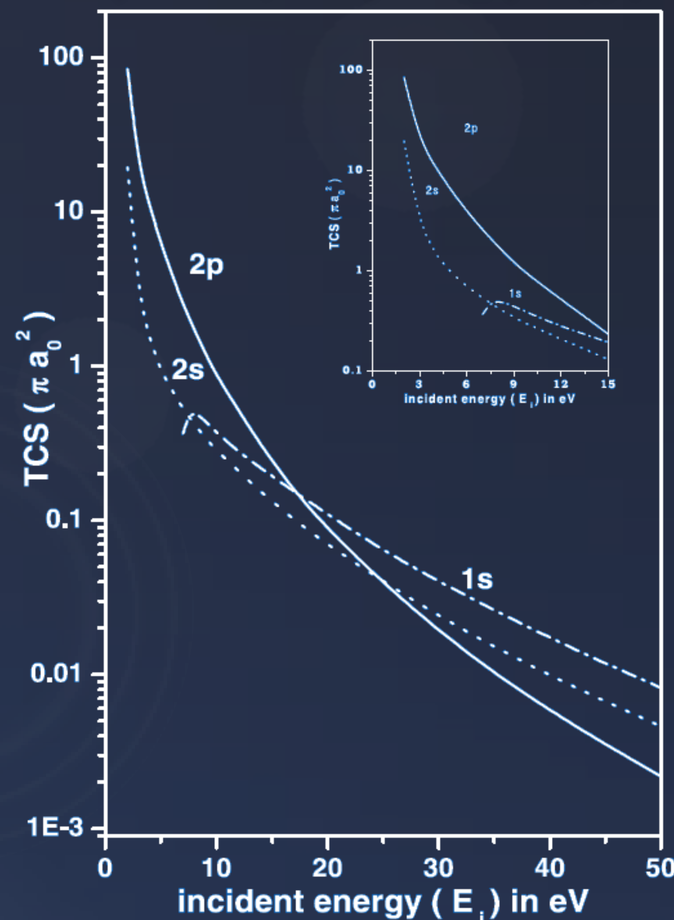
  Interest in excited Ps
  & low energy $\bar{p}$

- No experimental work

- Need some efforts !

  $n_p \geq 3, n_h \geq 2$ missing

S Roy & C Sinha, *Eur. Phys. J. D* **47** (2008) 327



Collisional model for both reactions

$$\mathrm{H}(n_h, l_h, m_h) + \mathrm{e}^+ \rightarrow \mathrm{p} + \mathrm{Ps}(n_p, l_p, m_p) \quad \text{(3-body)}$$

$$\mathrm{H}^- + \mathrm{e}^+ \rightarrow \mathrm{H}(n_h, l_h, m_h) + \mathrm{Ps}(n_p, l_p, m_p) \quad \text{(4-body)}$$

Microreversibility

Invariance by charge conjugaition

+

- Continuum Distorted Wave - Final State (*CDW-FS*)
  - Perturbative theory
  - Exact boundary conditions
  - In particular, final state treatment (Coulomb w. f. for Ps)
  - 3-body [1] and 4-body [2] formulations

[1] O A Fojòn *et al.*, *Phys. Rev. A* **54** (1996) 4923
[2] J Hanssen *et al.*, *Phys. Rev. A* **63** (2001) 012705

CDW-FS RESULTS

- 3-body

$$\bar{p} + Ps(n_p, l_p) \longrightarrow \bar{H}(n_h, l_h) + e^-$$

- Presented for
  - 0 to 30 keV $\bar{p}$ energy
  - $1 \leq n_p \leq 3$
  - $1 \leq n_h \leq 5$
  - Sum over m_p and m_h states

More details in the forthcoming publication

- 4-body

$$\bar{H}(n_h, l_h) + Ps(n_p, l_p) \longrightarrow \bar{H}^+ + e^-$$

- Presented for
  - 0 to 30 keV $\bar{p}$ energy
  - $1 \leq n_p \leq 3$
  - $n_h = 1$
  - Sum over m_p states

More details in the forthcoming publication

CDW-FS results : Reaction 1.

- Ps states comparison

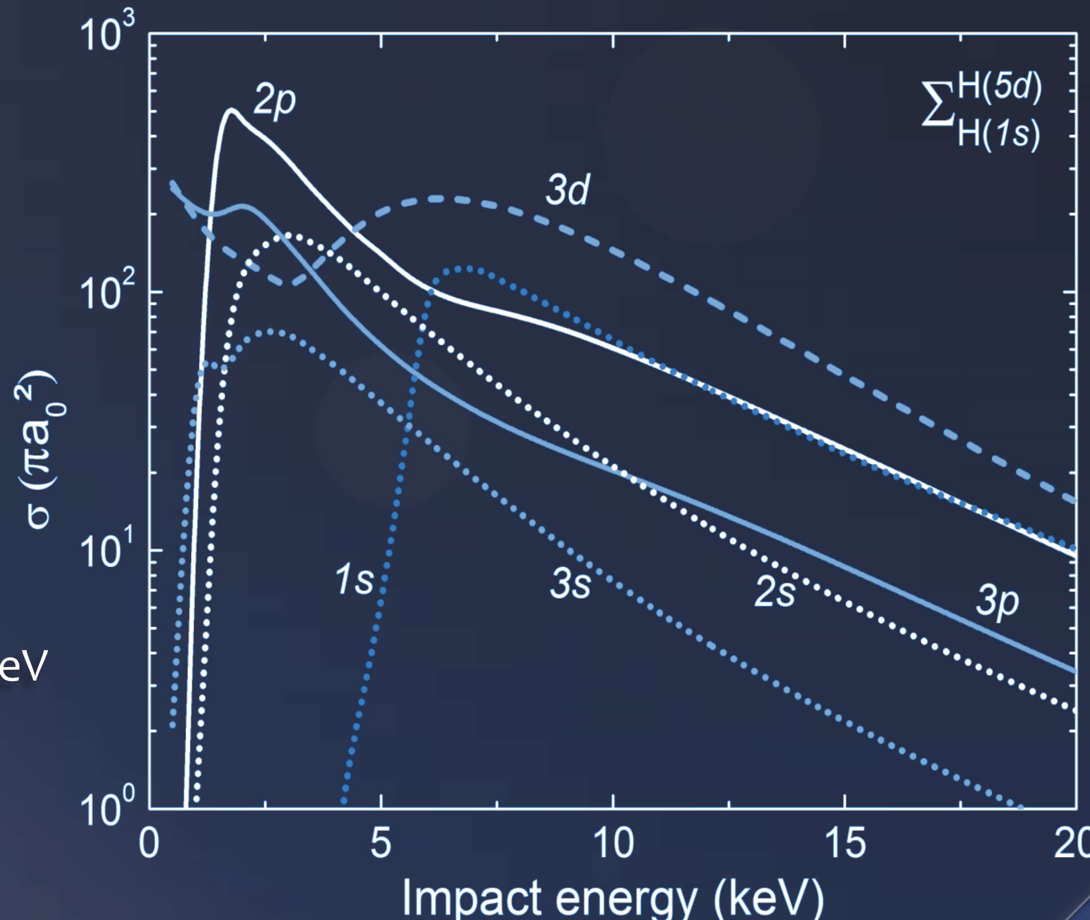
  Sum over $\overline{\mathrm{H}}$ states

- Below 6 keV :

  Ps excitation required

  Ps(2*p*) for 2 to 4 keV

  Ps(3*p*), Ps(3*d*) below 1.5 keV



$\bar{H}^+$ production for GBAR

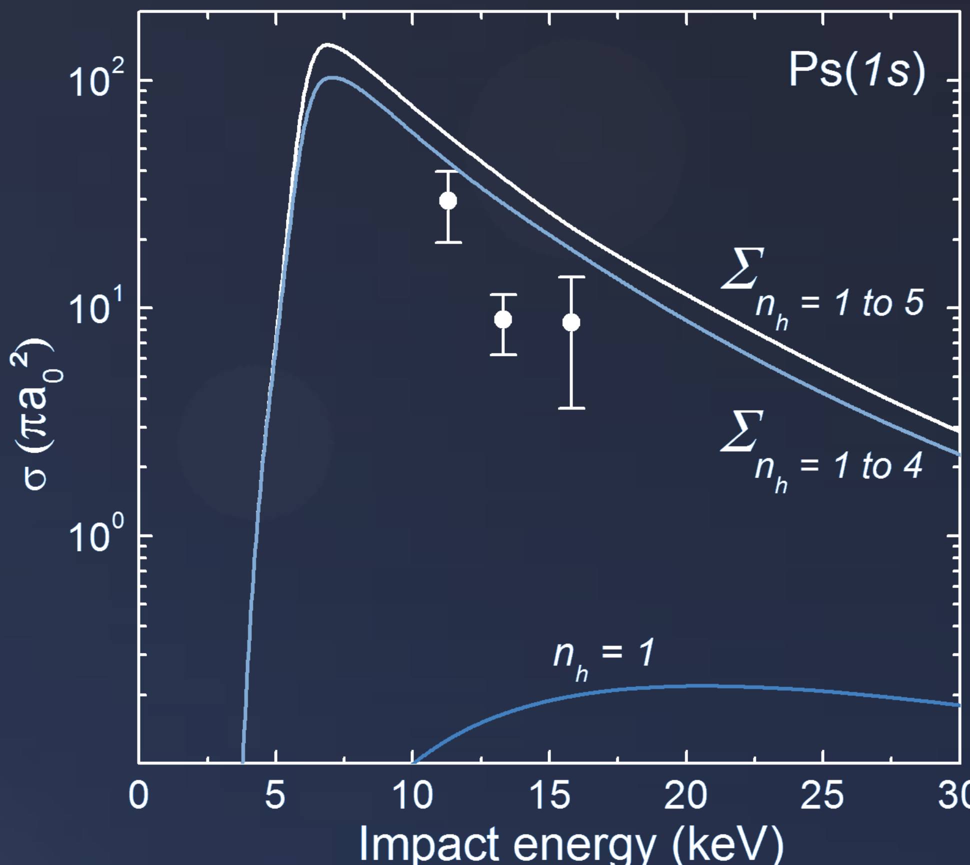
CDW-FS results : Reaction 1.

- Particular case : Ps(*1s*)
- $\bar{H}$(*1s*) production negligible

Excited $\bar{H}$ produced

- Comparison with experimental data :

Slightly overestimated
But right order of magnitude



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CDW-FS results : Reaction 2.

- Ps states comparison

$n_h \geq 2$ states : negligible

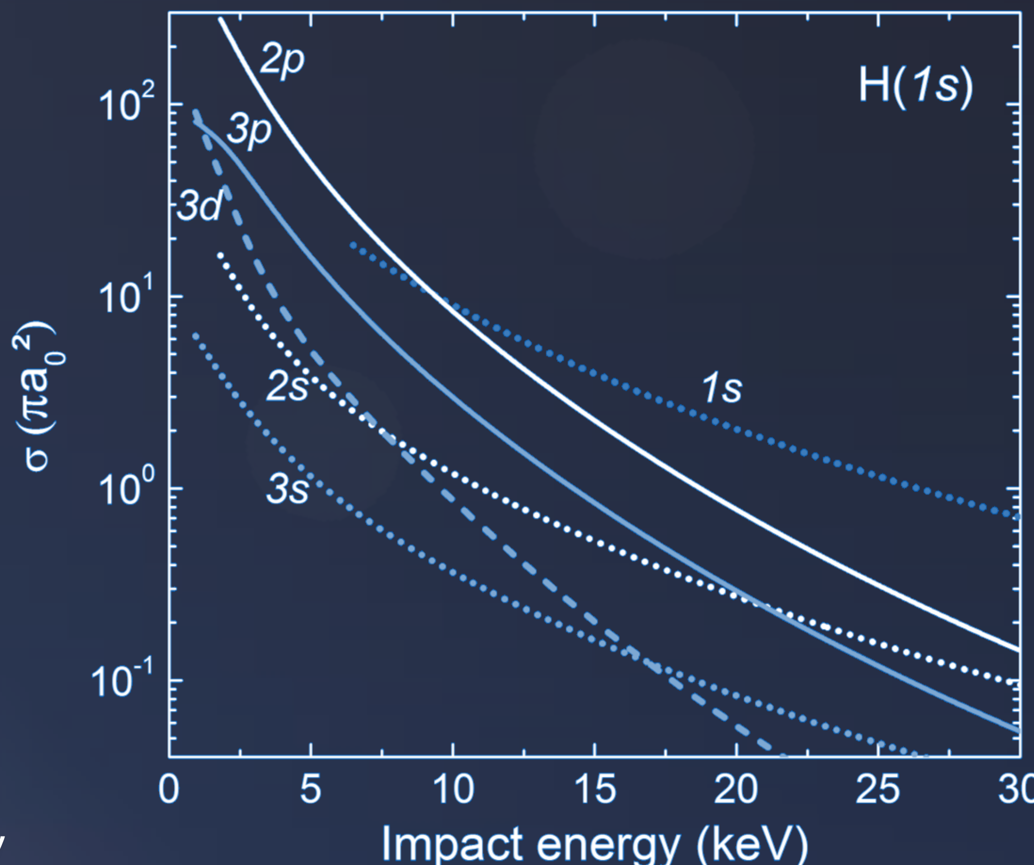
$\bar{H}(1s)$ needed

- Below 6 keV :

Ps excitation required

Ps(2p) from 1 to 6 keV

Ps(3p), Ps(3d) below 1 keV



* w. f. for H⁻ : C Le Sech, *J. Phys. B: At. Mol. Opt. Phys.* **30** (1997) L47

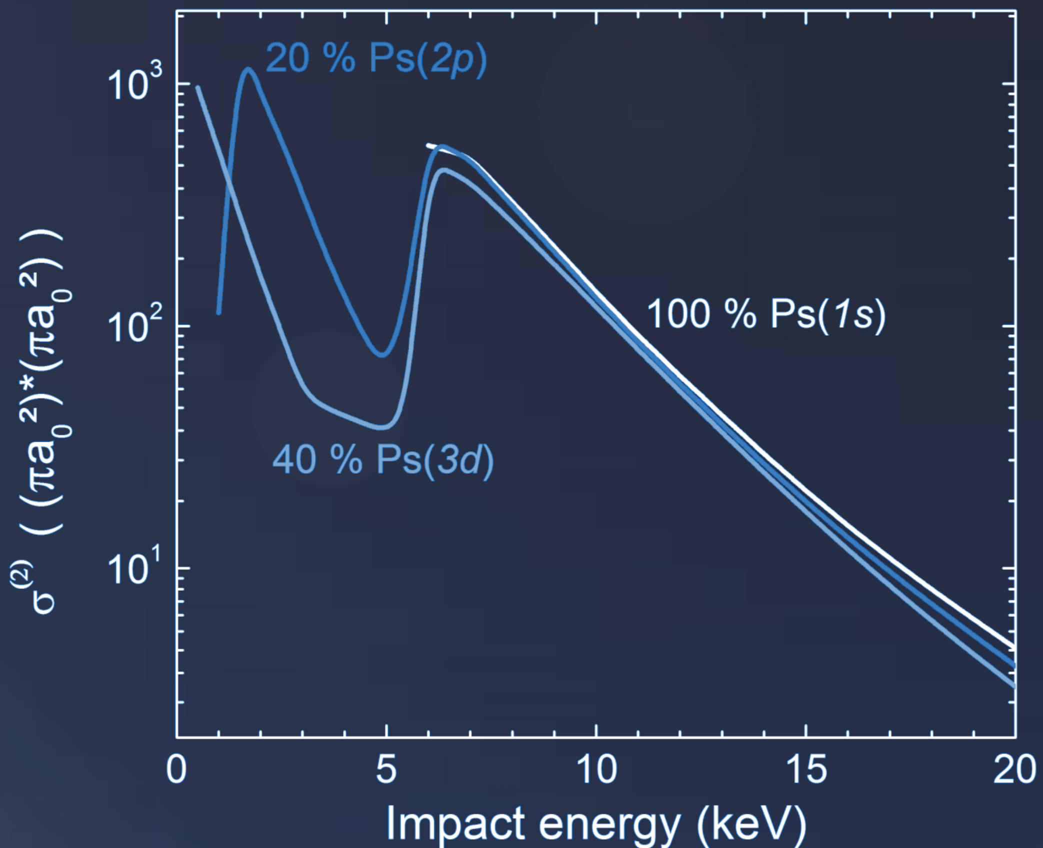
CDW-FS results : Reaction 1. + Reaction 2.

- Overall cross sections
- Assuming :

  Constant % of excited Ps
  20 % of $\bar{H}(1s)$ for Reaction 2.

- Results suggest :

  Ps(3*p*), Ps(3*d*) at 1 keV
  Ps(2*p*) at 2 keV
  Ps(1*s*) at 6 keV



And now…

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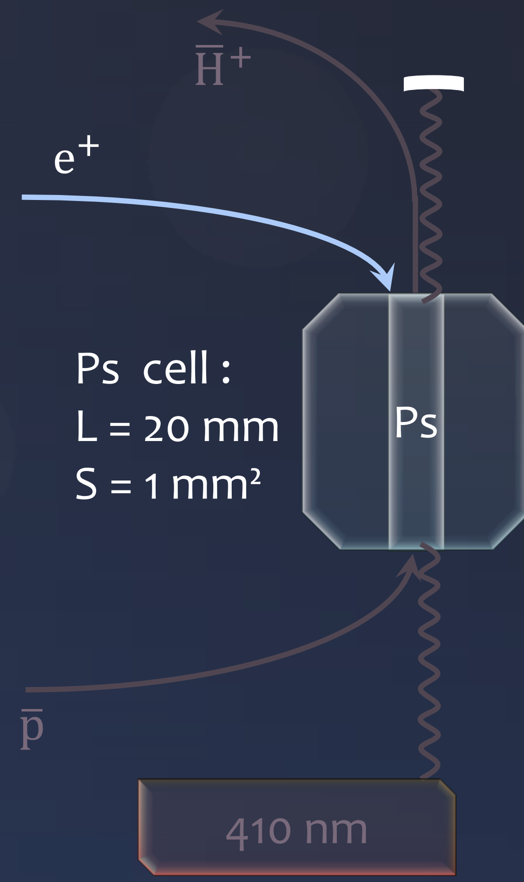
Cross sections

Simulating the reaction chamber

Estimations

Description of the simulation

- t = 0 : implantation of e^+
  Ps production begins ($7.4\ 10^9$ o-Ps)
  FWHM = 75 ns



Description of the simulation

- t = 0 : implantation of e^{+}
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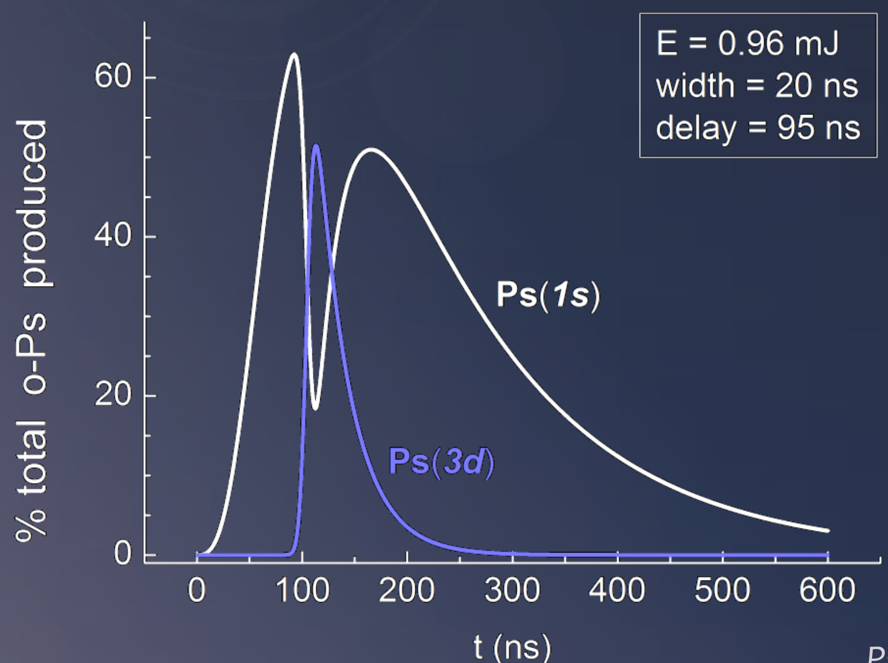
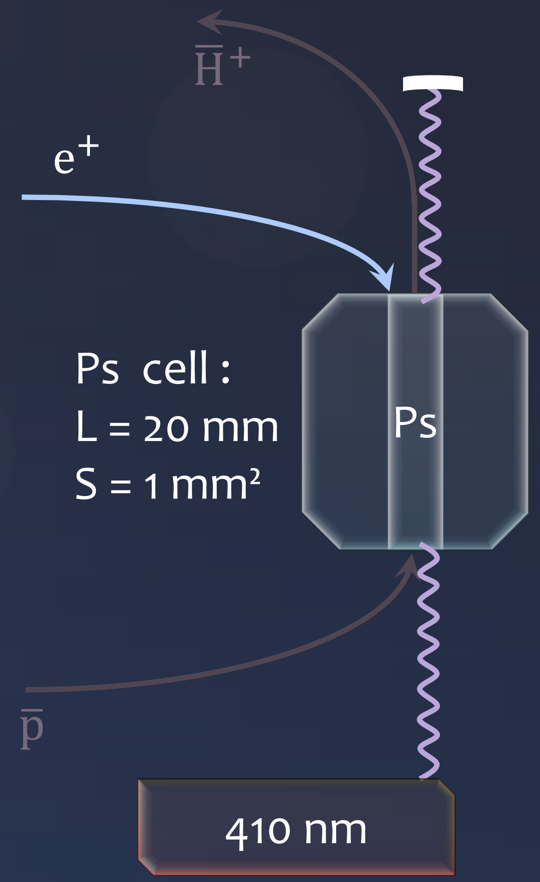
- t = delay_laser : laser excitation begins
  Production of Ps(3d)





Ps populations calculated with Bloch equations

Description of the simulation

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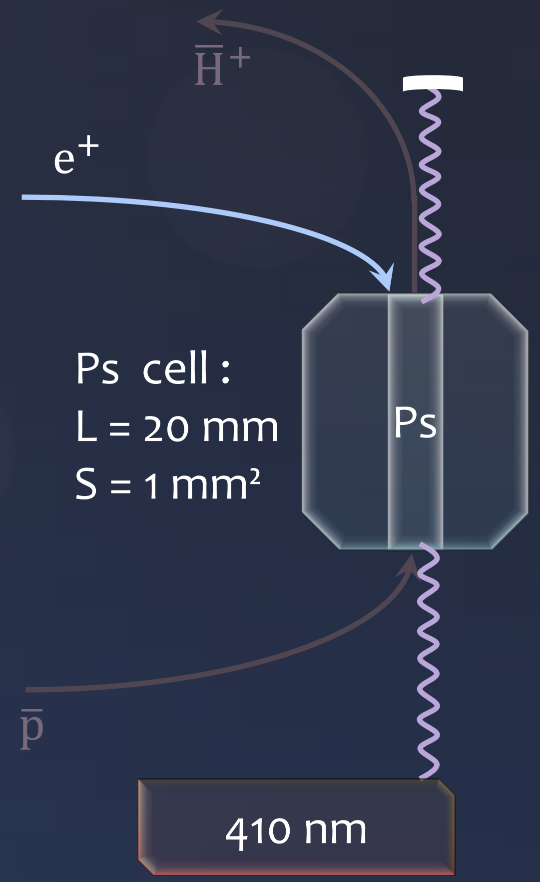
- t = delay_laser : laser excitation begins
  Production of Ps(3d)
  delay laser (free)
  E laser pulse = 0.96 mJ
  FWHM = 20 ns



$\bar{H}^+$ production for GBAR

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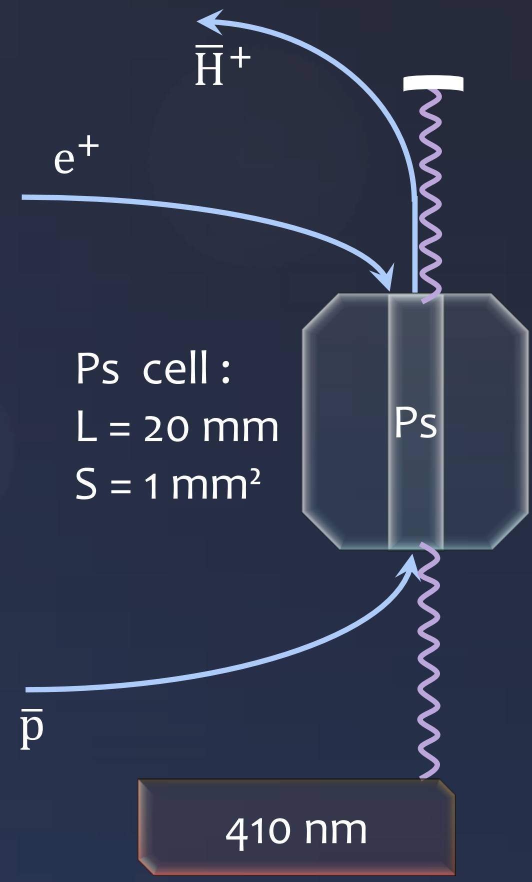
- t = delay_$\bar{p}$: $\bar{p}$ pulse injected (3.10^6 $\bar{p}$)

Free parameters :
  delay $\bar{p}$
  E $\bar{p}$ (mono-energetic to start)
  FWHM



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Free parameters :
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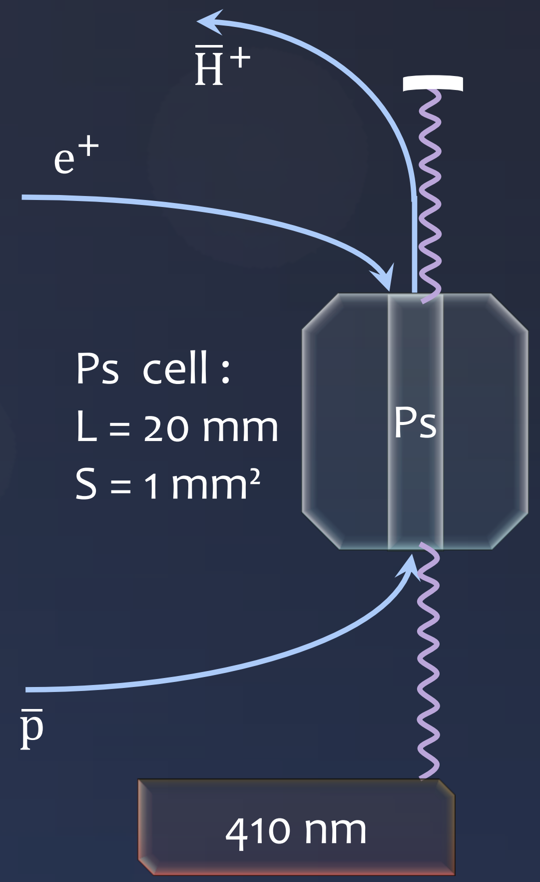
  FWHM

- $\bar{H}$ de-excitation + $\bar{H}^+$ photodetachment



Estimations for optimised delays

- **1 $\bar{H}^+/\bar{p}$ pulse expected**
- Best solution: **2 keV + Ps(2*p*)**
- At 6 keV, 33 % gain with Ps(3*d*)
- To be compared with GBAR proposal [1]: 0.3 $\bar{H}^+/\bar{p}$ pulse

	Ps % max	$\bar{p}$: E (keV)	$\bar{p}$: FWHM (ns)	$\bar{H}^+$/pulse
Ps(1*s*)	100	6	150	0.9
Ps(3*d*)	52	1	120	2.6
		1	***210***	***1.5***
		6	150	1.2
Ps(2*p*)	20	2	180	1.4
	30	***2***	***180***	***3***

[1] The GBAR Collaboration 2011 CERN-SPSC-2011-029, SPSC-342

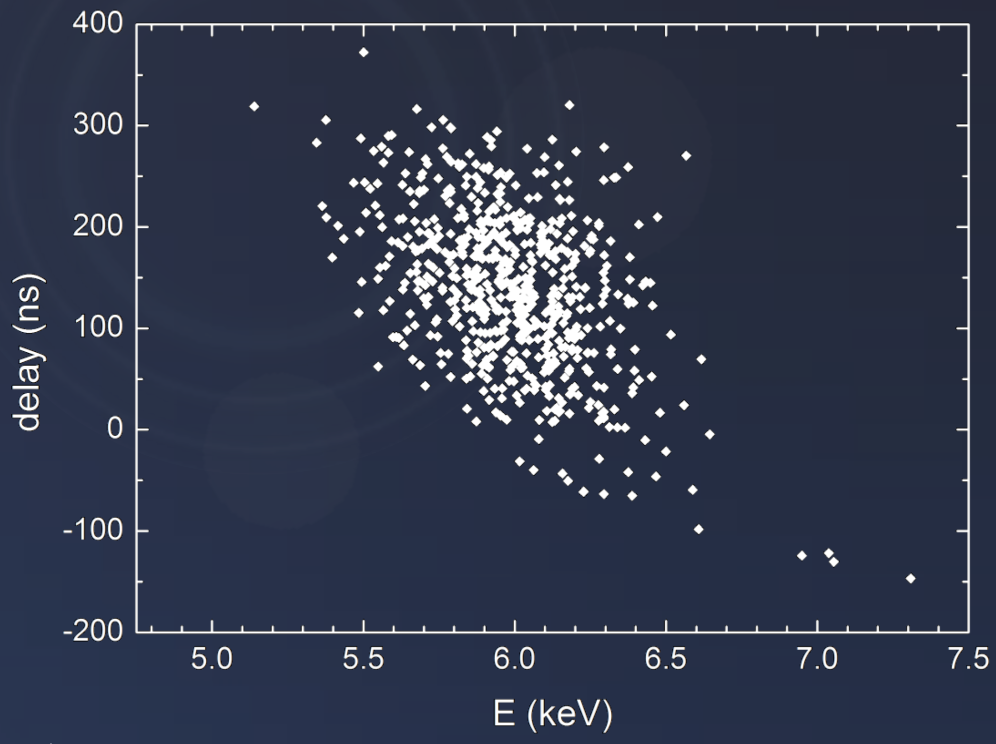
$\bar{H}^+$ production for GBAR

USING DATA FROM DECELERATOR SIMULATION

- *See talk by P. Dupré*
- 1000 $\bar{p}$ simulated
- 641 going through
- Mean E = 5987 eV

  E spread : ~ 450 eV (FWHM)
- Mean delay : ~ 140 ns

  Time spread : ~ 170 ns (FWHM)



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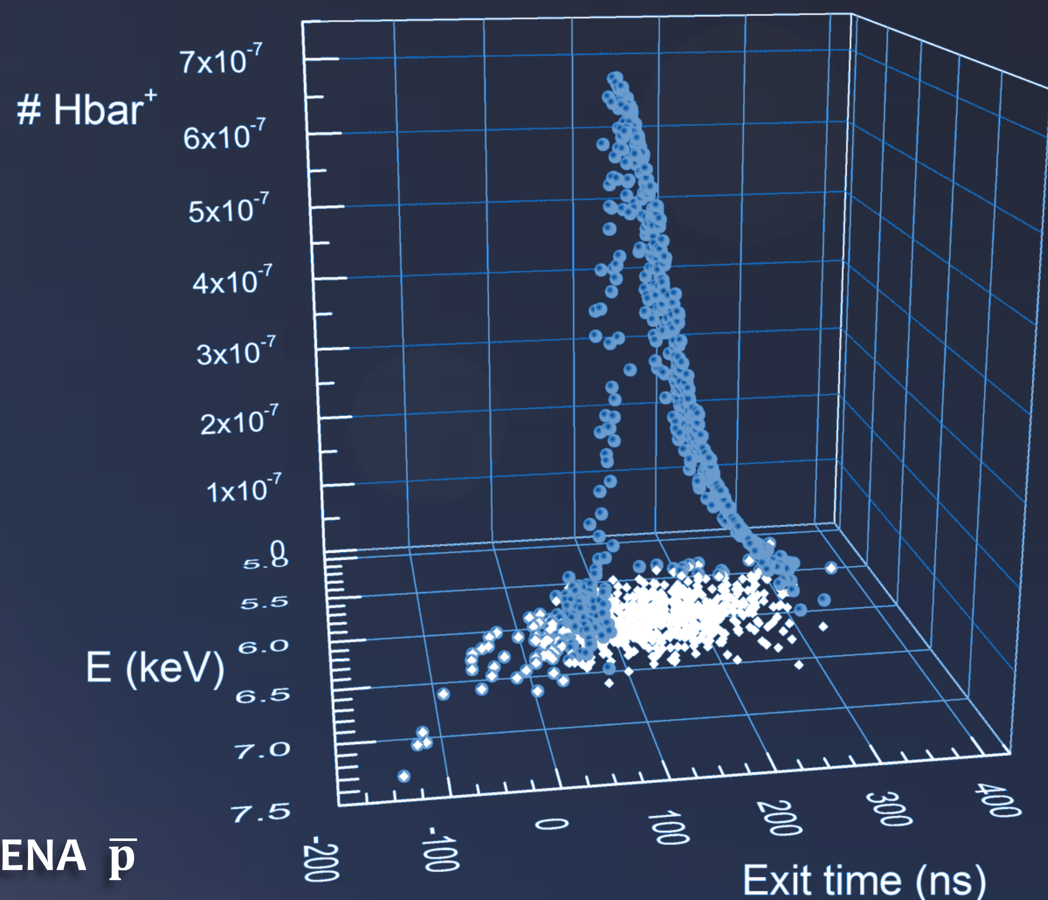


- 1.66 10^{-4} $\bar{H}^+$
- **0.75 $\bar{H}^+$ for 4.5 10^6 ELENA $\bar{p}$**

$\bar{H}^+$ production for GBAR

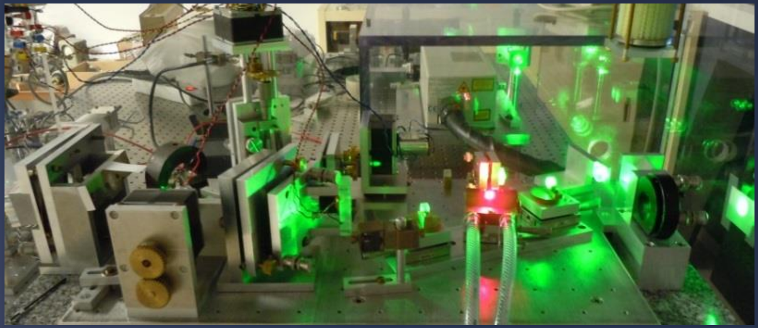
Conclusions

Summary & propects

- Cross sections available for $\overline{\mathrm{H}}^+$ production
- Ps up to 3d state ; $\overline{\mathrm{H}}$ up to n_h = 4 or 5
- *« One model to rule them all »*

- Simulation scheme with Ps excitation (3*d* ; rough estimation for 2*p*)
- About 1 $\overline{\mathrm{H}}^+/\,\bar{\mathrm{p}}$ pulse at 1, 2 and 6 keV
- 2 keV + Ps(2*p*) : factor 3 gain

- Improvement of the simulation
- Measurements of the cross sections for H^- ?
- Design of a laser for Ps(2*p*) excitation



Laser for Ps(3d) currently being built at LKB

THANK YOU FOR YOUR ATTENTION !

GBAR Collaboration

Irfu

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