ÖAW Austrian Academy of Sciences

MARIETTA BLAU INSTITUTE FOR PARTICLE PHYSICS

Precision spectroscopy of $\overline{\mathrm{H}}$, H and D

Eberhard Widmann, MBI Vienna
ASACUSA Collaboration *https://cern.ch/asacusa*

New Exotica Workshop, ECT* Trento, 14 Oct 2026

Slides partially contributed by Ross Sheldon

Content

- Introduction
- Antihydrogen in-beam hyperfine spectroscopy
  - Status of beam production
- Hydrogen HFS spectroscopy
  - Magnetic field orientation dependence
- Deuterium HFS spectroscopy
  - Sidereal variations

Antihydrogen experiments motivation

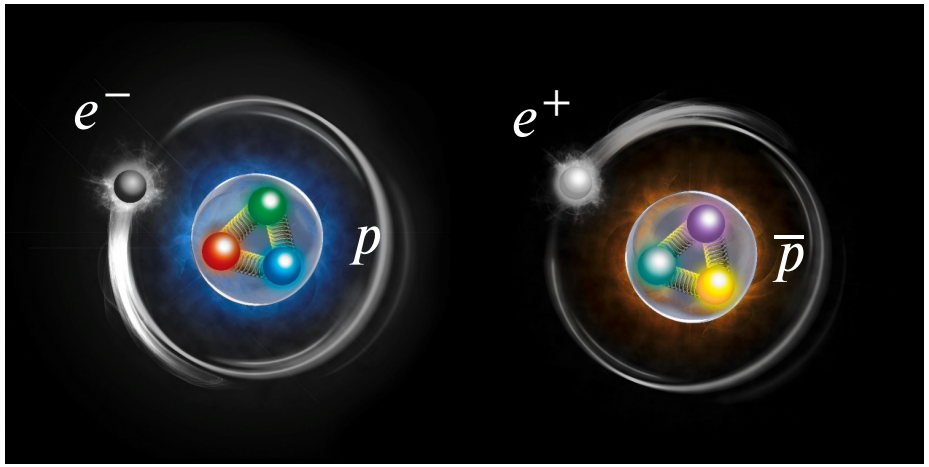


ASACUSA collaboration
https://cern.ch/asacusa

MBI, Milano, Brescia, Tokyo,
RIKEN, Aarhus, Imperial College London

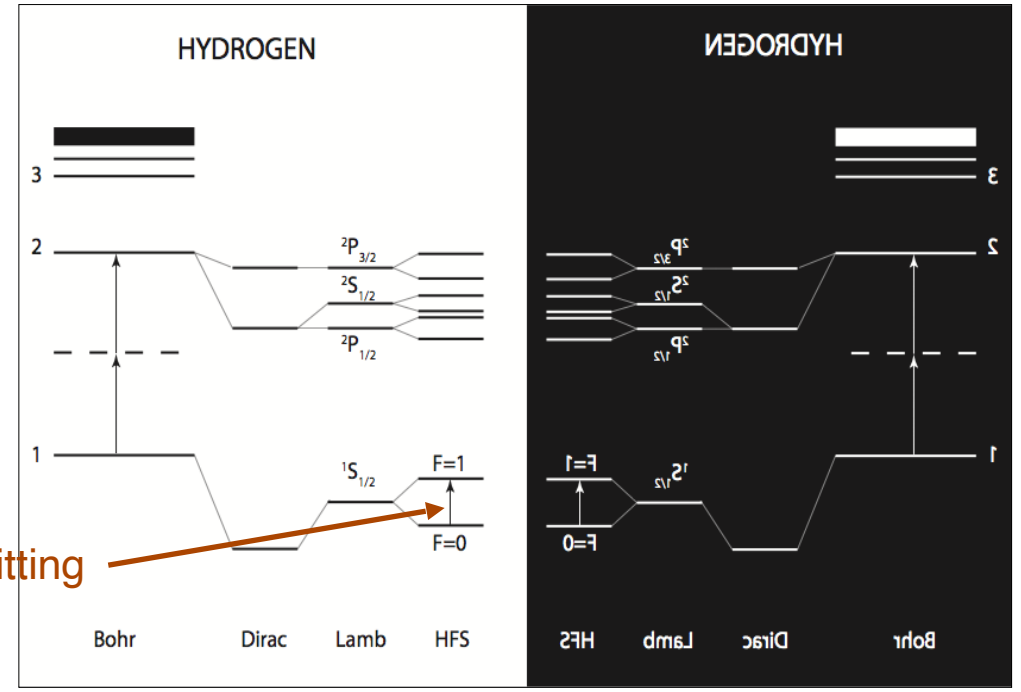
- Matter-Antimatter Symmetry
  - Charge conjugation-Parity-Time reversal: CPT
  - CPT theorem based on properties of QFT
    - *Lüders, Pauli, Bell, Jost 1955*
  - CPTV points to BSM physics

Anti-CPT theorem:
- CPT violation implies Lorentz Invariance Violation
- *Greenberg, O. W. PRL **89**, 1–4 (2002).*



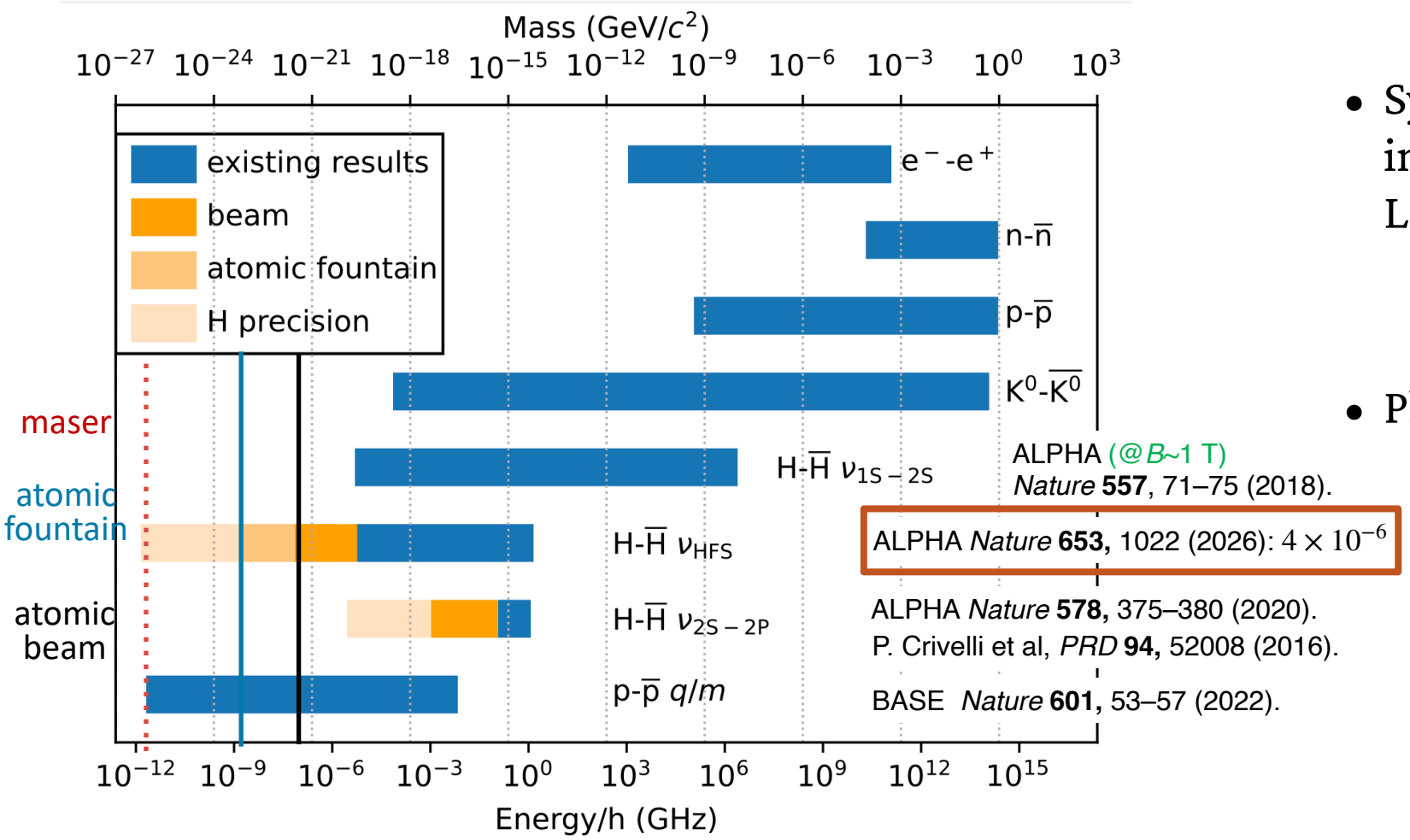
1S-2S
2 photon
λ=243 nm
Δf/f=10^{-14}

Ground state
hyperfine splitting
f = 1.4 GHz
Δ*f*/*f*=10^{-12}



Comparison of CPT tests -2026

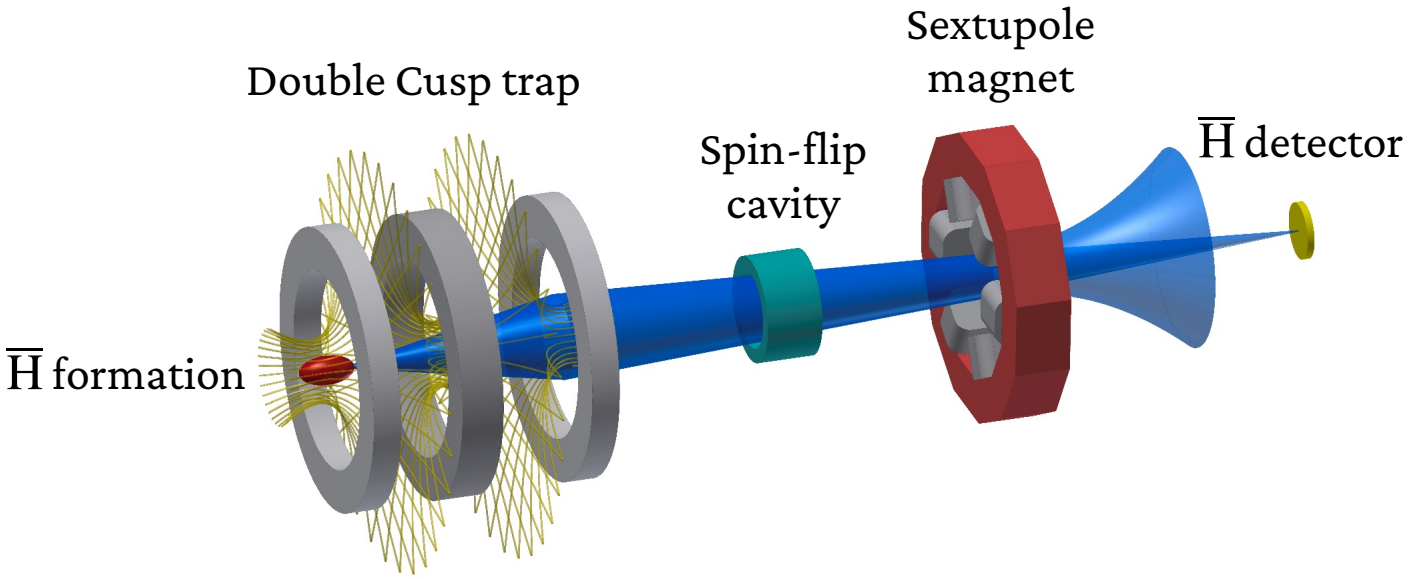
- Mass & frequency

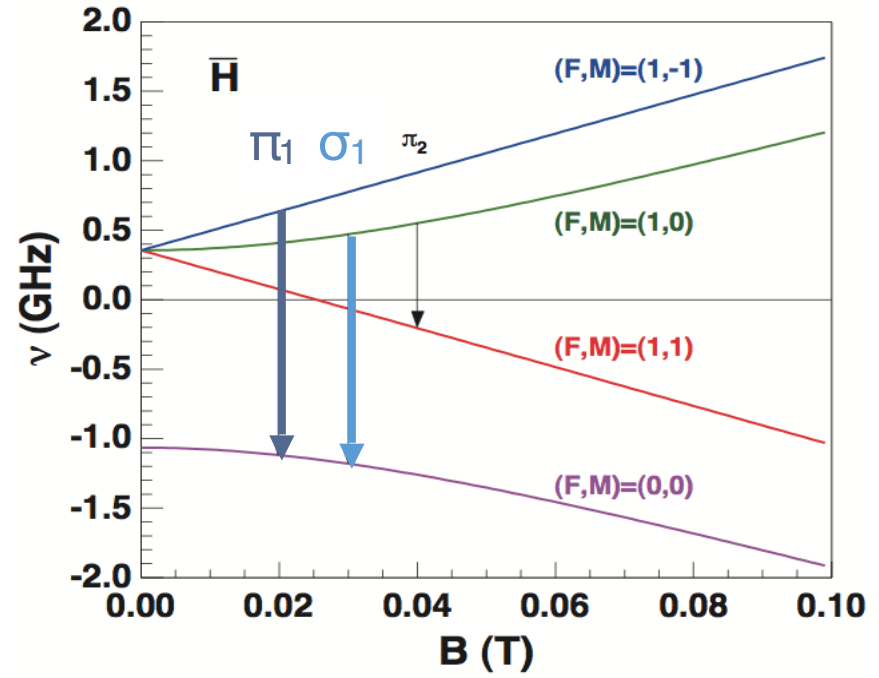


- Synopsis: CPT violating interaction appears at the level of Lagrangian
  - Relevant scale: absolute energy
- Plot
  - Right edge: value
  - Bar length: relative precision
  - Left edge: absolute sensitivity
  - Source: PDG

EW, Phys. Part. Nuclei **53**, 790–794 (2022).
arXiv:2111.04056 [hep-ex]

In-beam HFS spectroscopy of $\overline{\mathrm{H}}$: Rabi

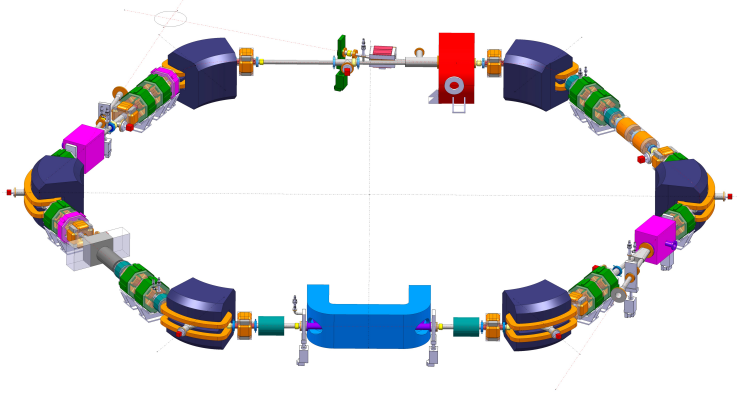




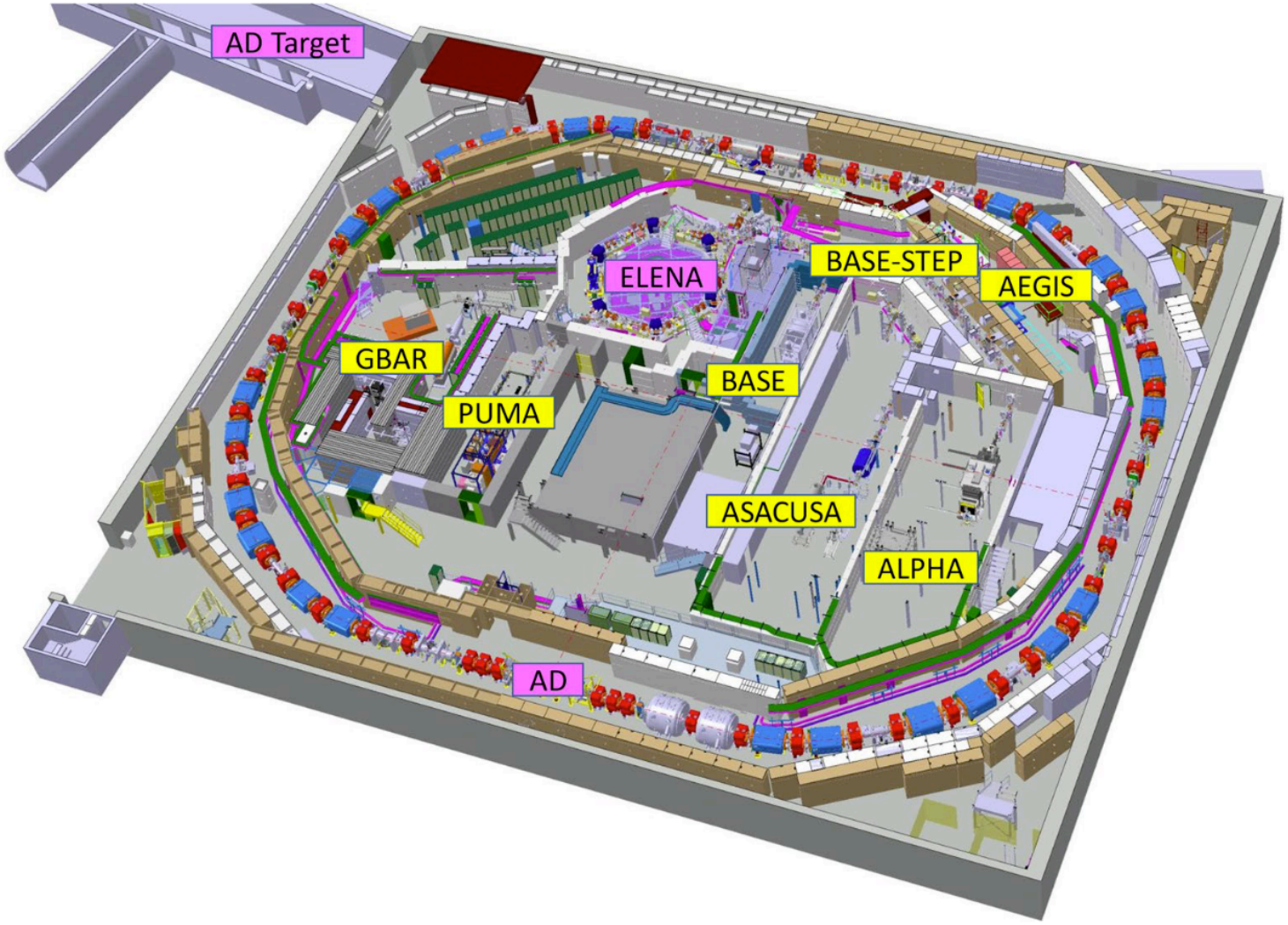
- Goals
  - In-beam measurement of ground-state hyperfine structure of antihydrogen to ppm-level and below
  - Advantage: free from B field gradients
  - Produce polarised, slow (T<100 K) $\overline{\mathrm{H}}$ beam

- Resolution: line width $\Delta\nu \sim 1/T$
  - $v = 1000$ m/s ($T = 50$ K), $L = 10$ cm:
  - $\Delta\nu/\nu \sim 7 \times 10^{-6}$ → center to ~ppm
  - > 100 $\overline{\mathrm{H}}$/s in 1S state into 4π needed
  - event rate 1 / minute: background from cosmics, annihilations upstreams

Antimatter facility: AD/ELENA @ CERN

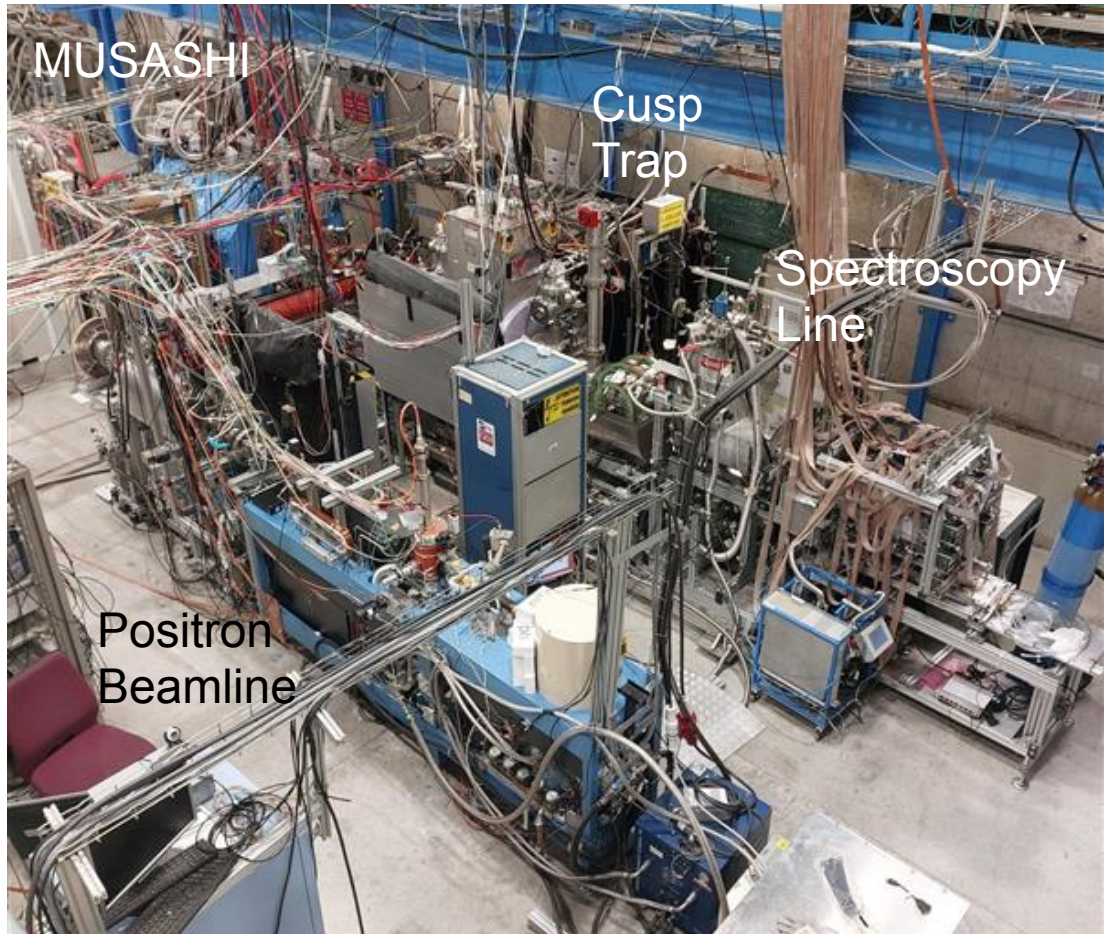


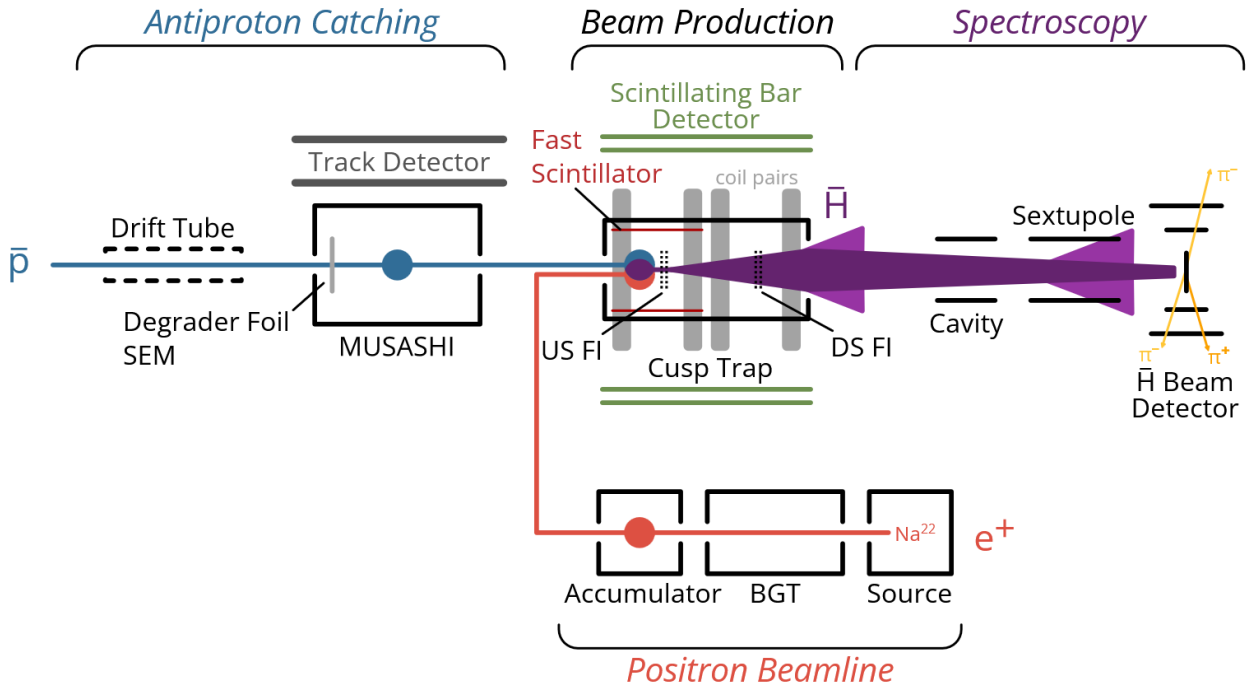
Energy range, MeV	5.3 - 0.1
Intensity of ejected beam	1.8×10^7
$\varepsilon_{x,y}$ of extracted beam, π·mm·mrad, [95%], standard	4 / 4
Δp/p of extracted beam, [95%], standard	$8 \cdot 10^{-3}$



ELENA operation started Aug. 2021

ASACUSA Experiment@AD/ELENA





ASACUSA SPSC Report for 2025, SPSC-SR-377

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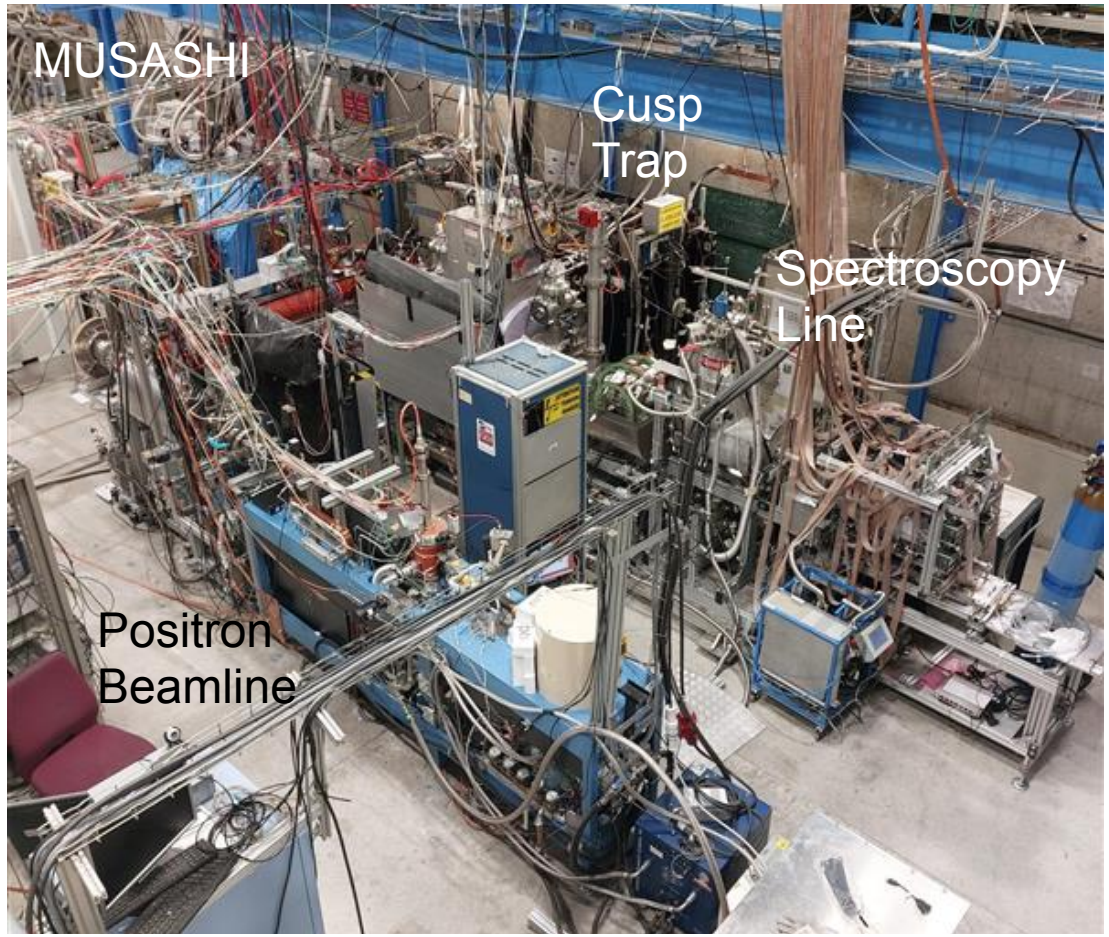

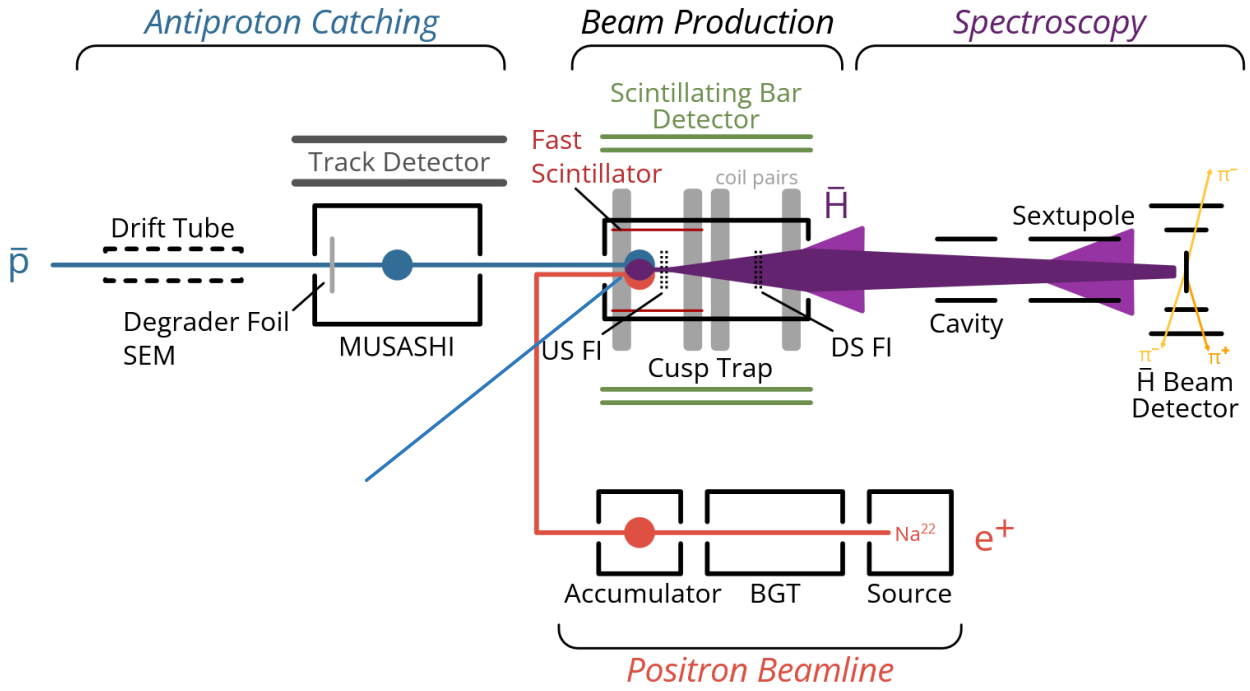

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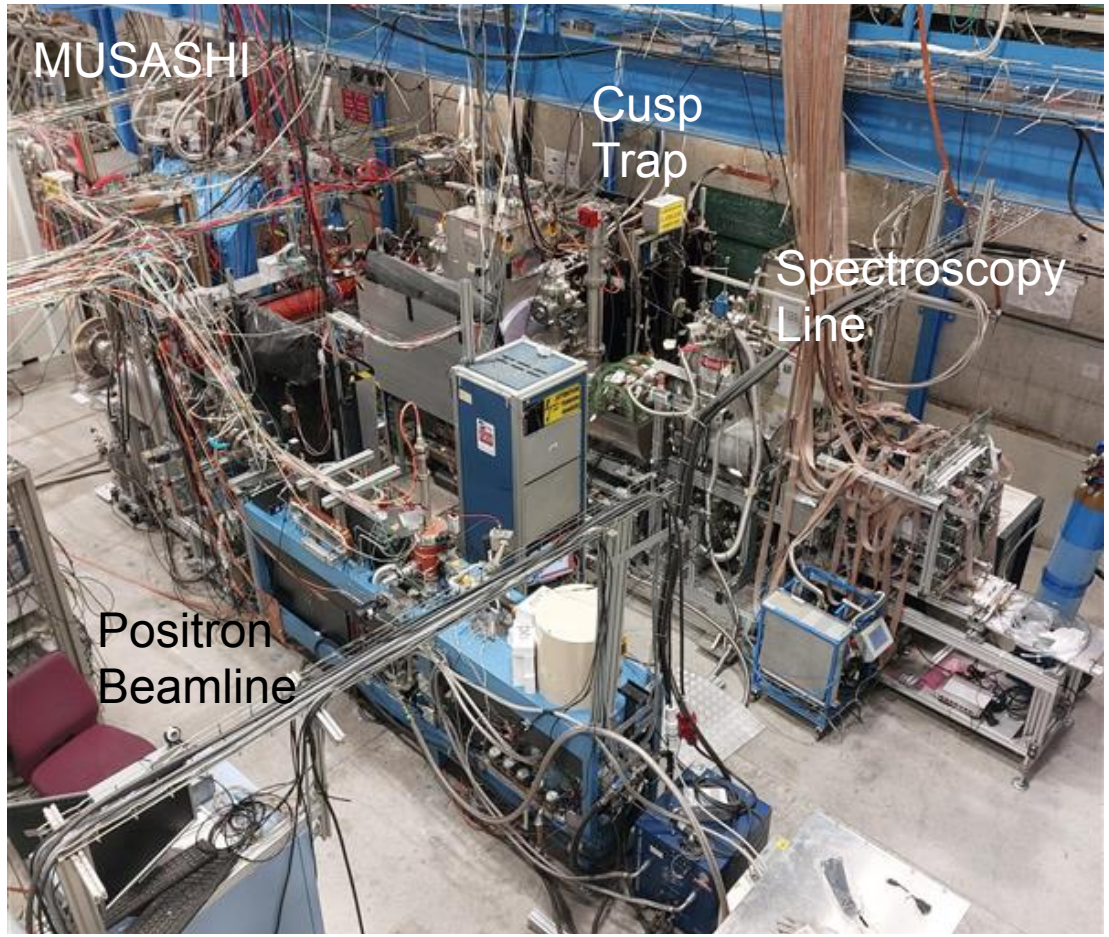

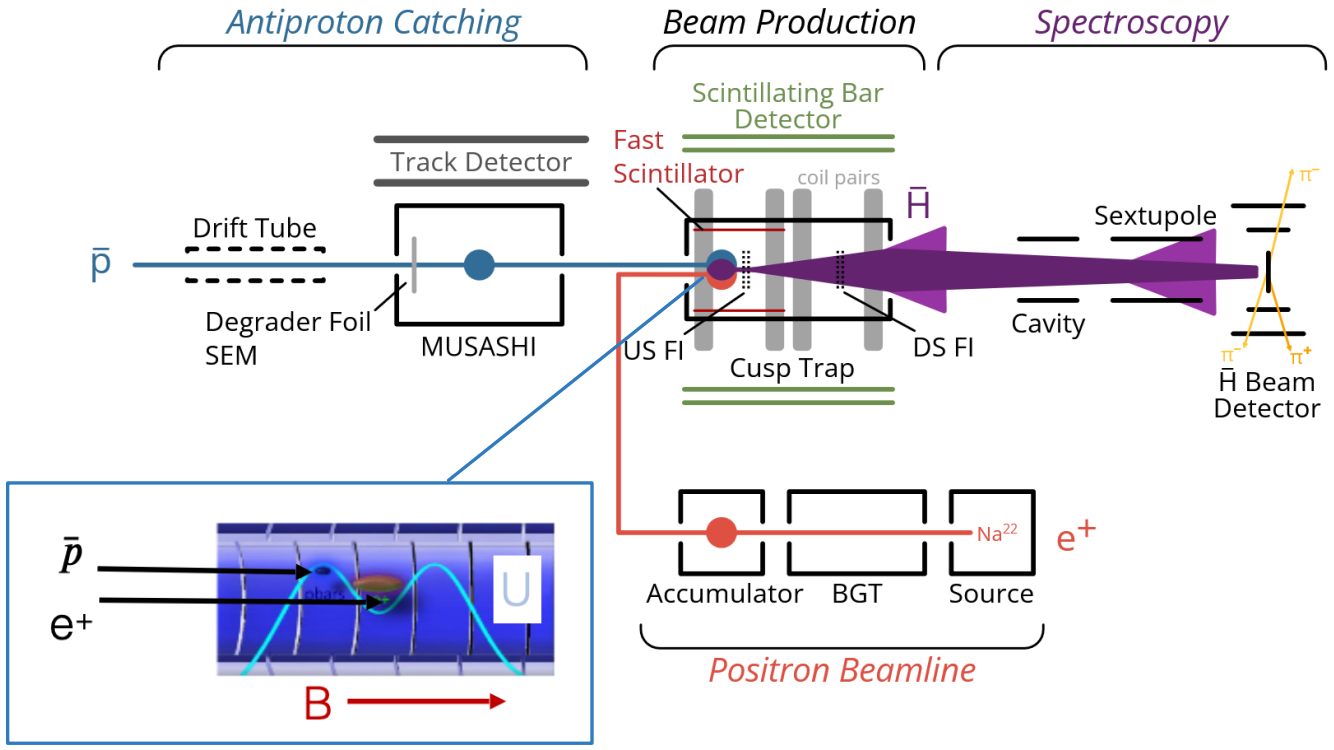

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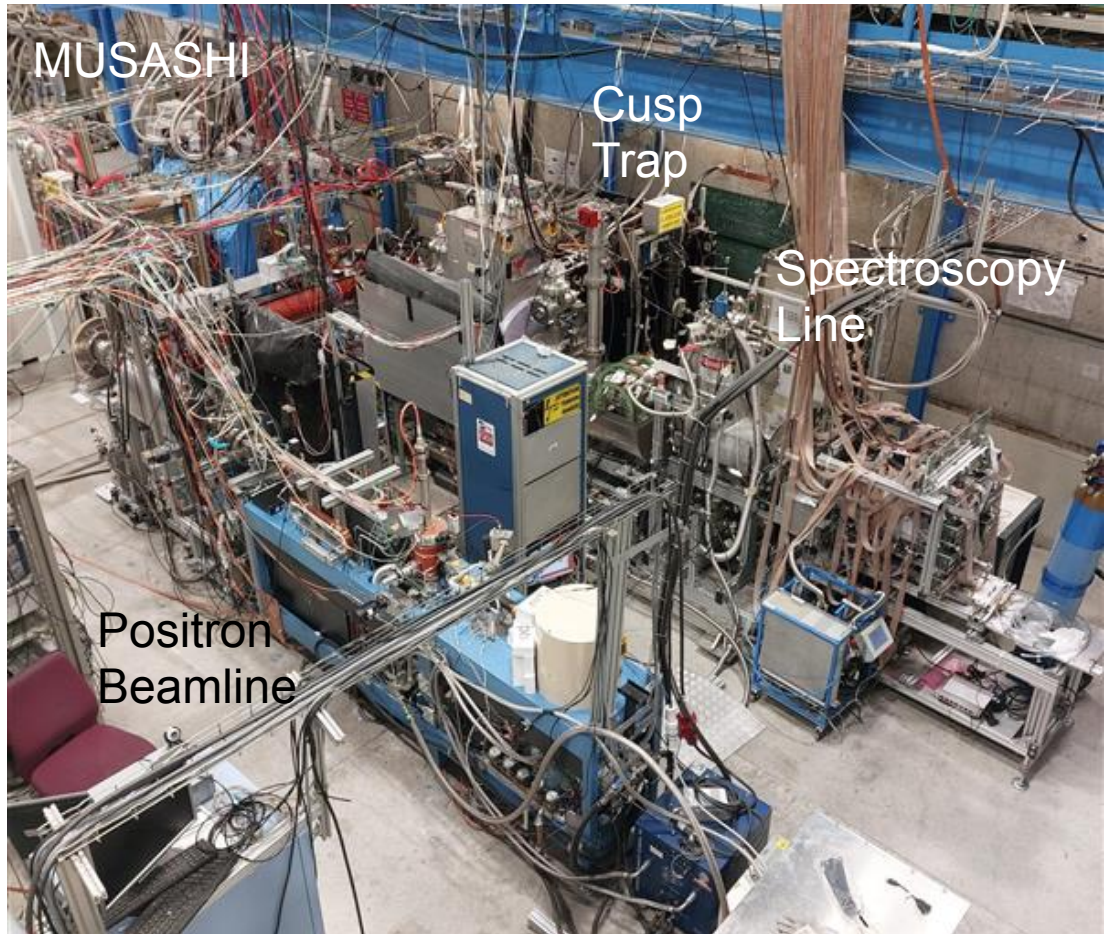
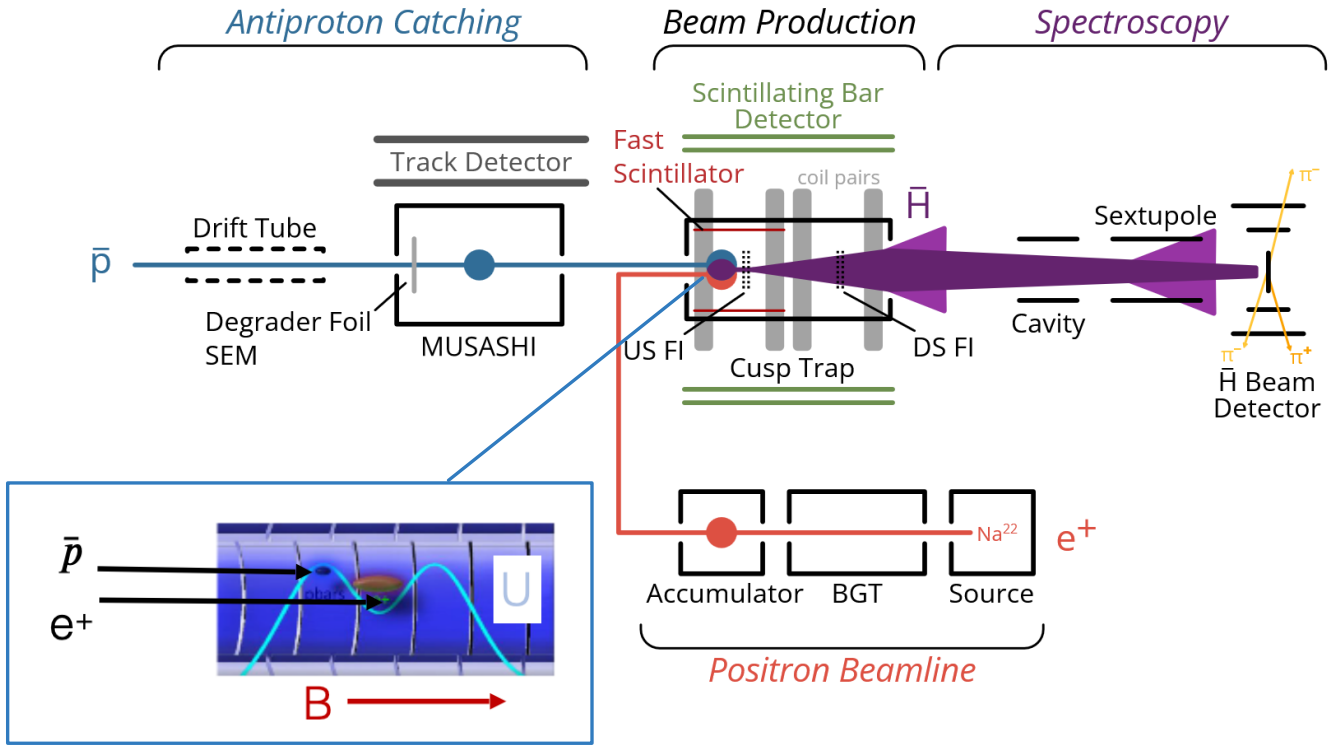
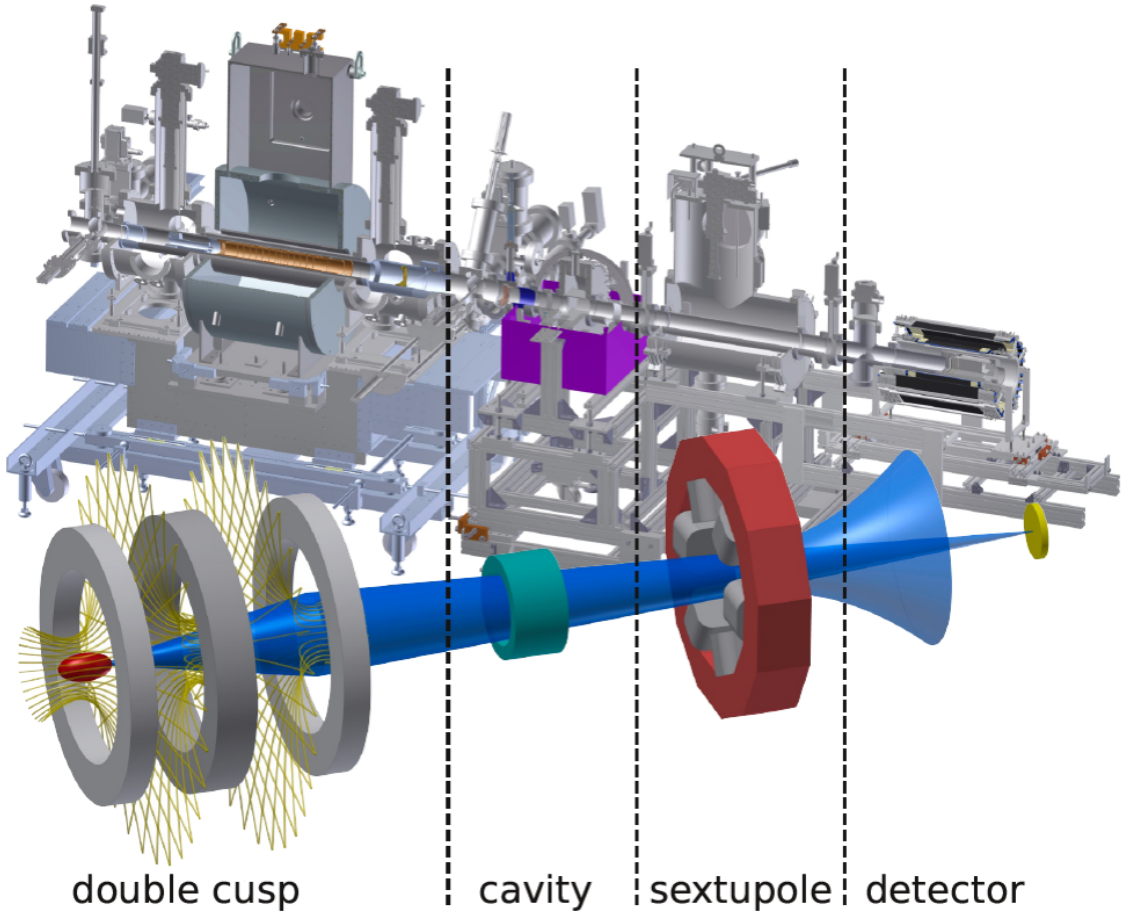




Formation in nested Penning trap

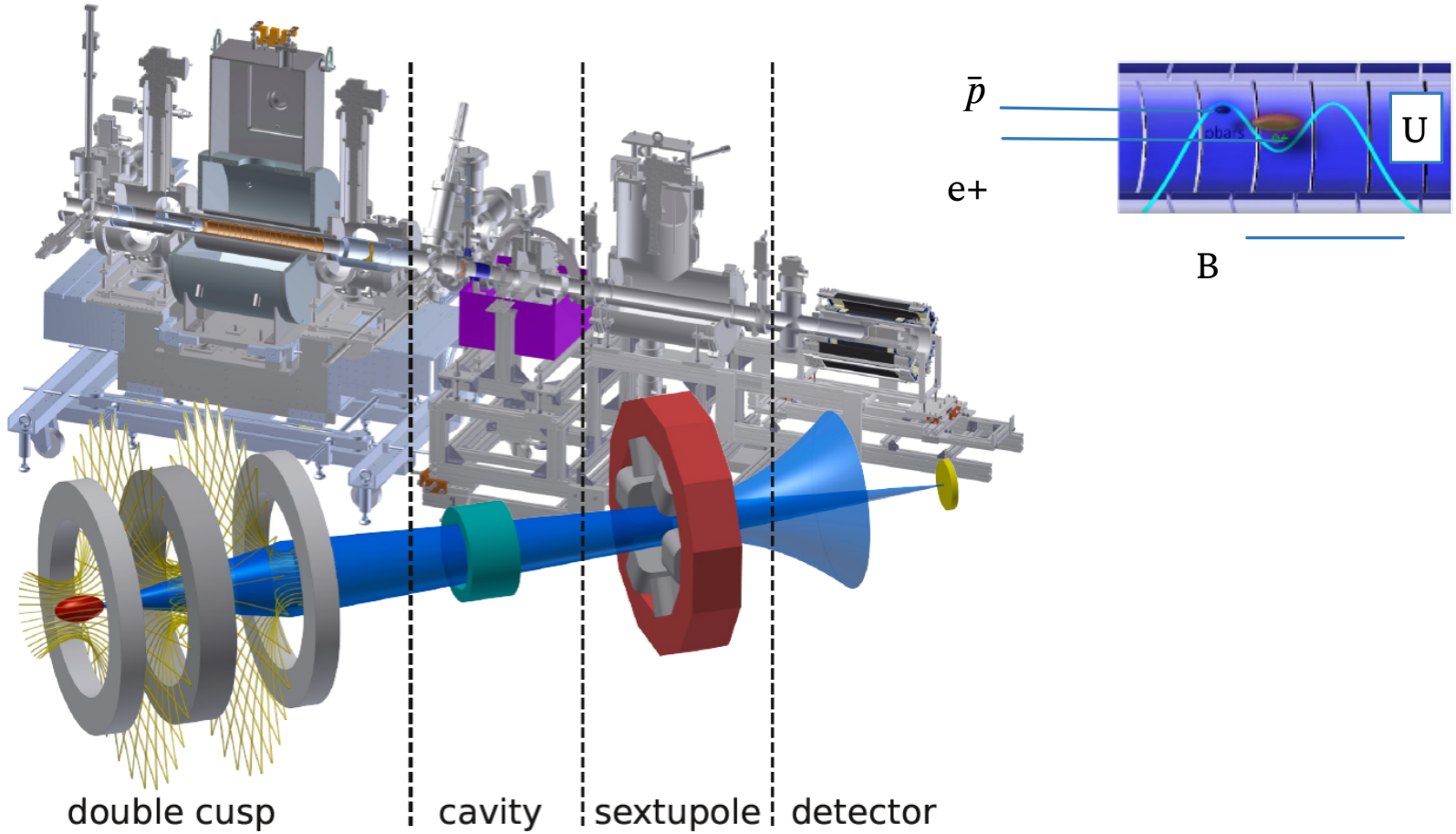
ASACUSA SPSC Report for 2025, SPSC-SR-377

ASACUSA Antihydrogen beam for HFS



ASACUSA Antihydrogen beam for HFS

- $\bar{H}$ production 1st time in 2010 in nested Penning trap
  - Three body recombination (→Rydberg states)



ASACUSA Antihydrogen beam for HFS

- $\bar{H}$ production 1st time in 2010 in nested Penning trap
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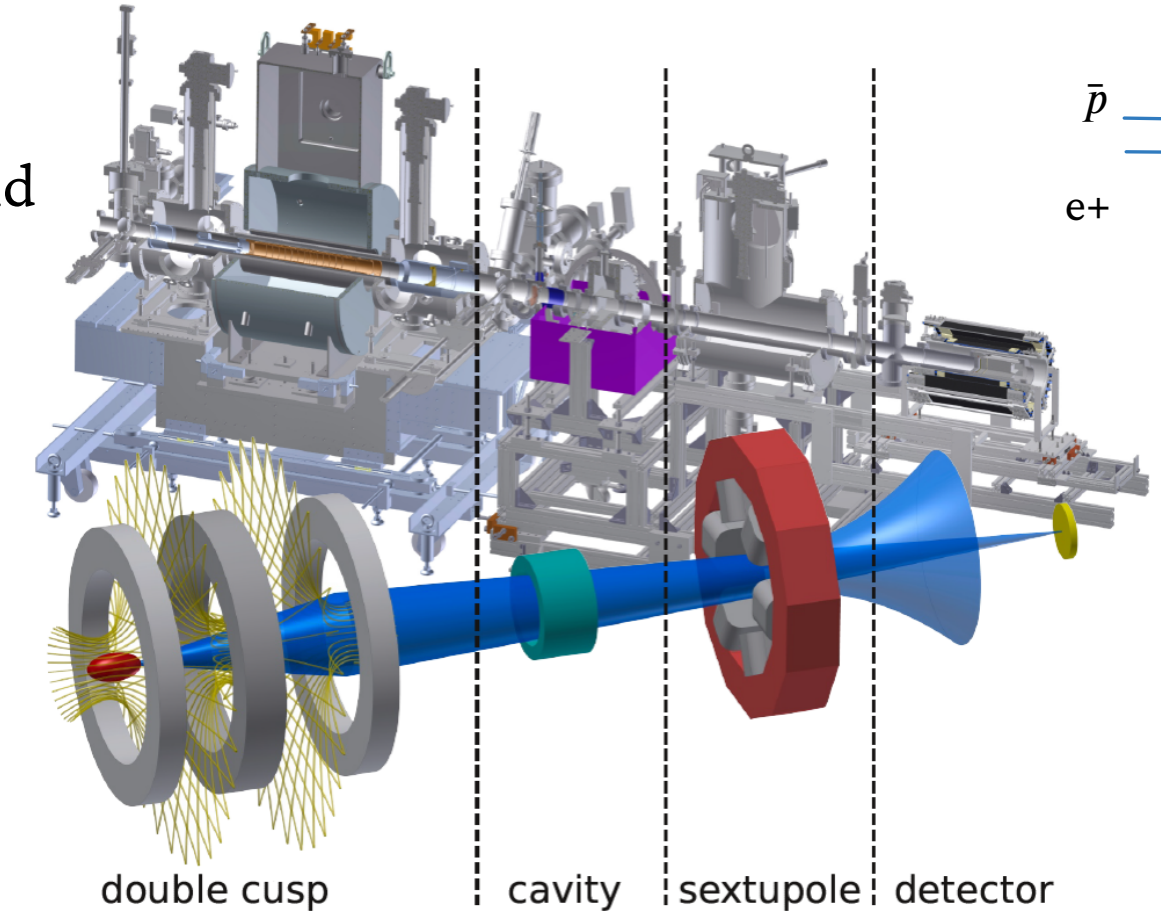
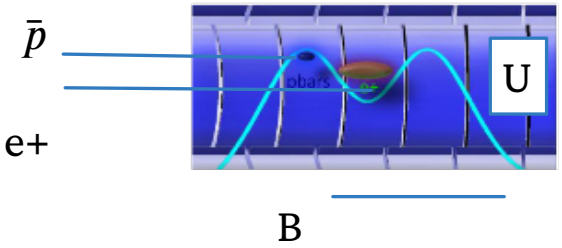
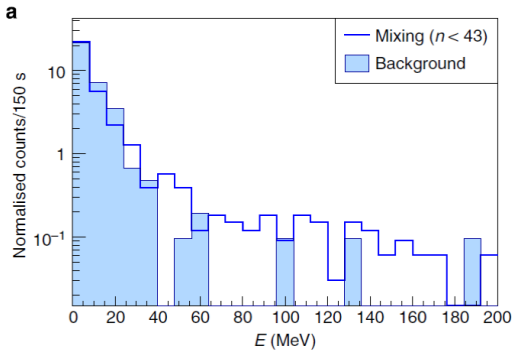
- 1st observation of beam in field free region 2014
  - n≤43: 6 $\overline{H}$/15 min
  - n≤29: 4 $\overline{H}$/15 min





N. Kuroda et al, Nat. Commun. 5, 3089 (2014).



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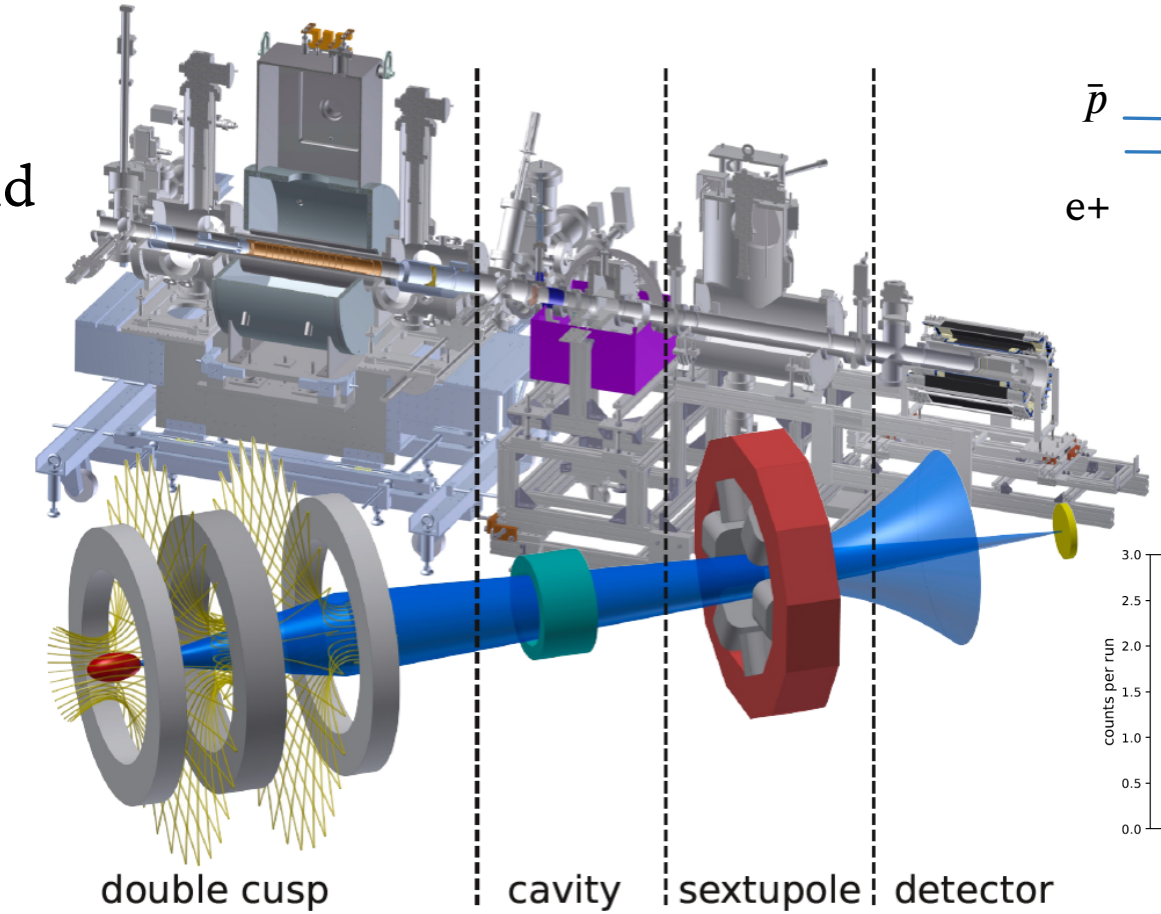
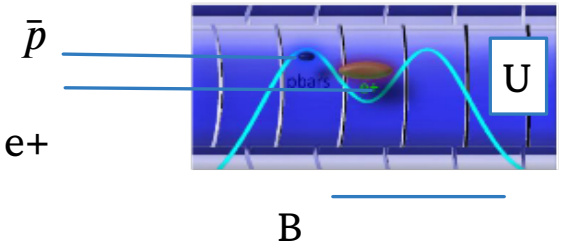
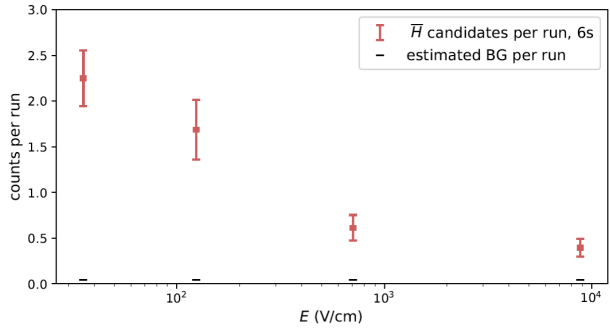
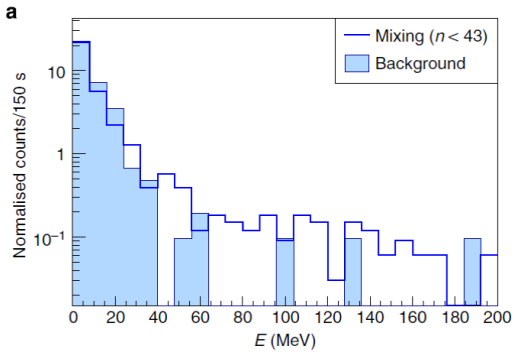




Measurement of n distribution 2021



B. Kolbinger et al.
EPJ D 75, (2021) 91.



N. Kuroda et al, Nat. Commun. 5, 3089 (2014).

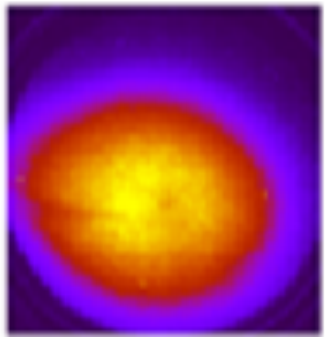
Plasma properties

E. D. Hunter et al. Phys. Plasmas **33** (2026)

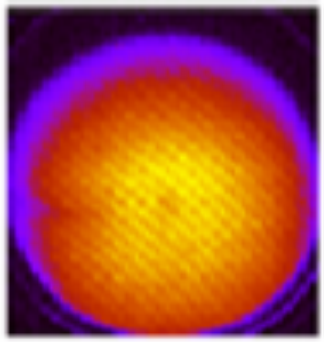
	Number ($x10^6$)	Temperature (K)	Density* ($x10^8$ cm^{-1})
Antiprotons	2.89 ± 0.04	1700 ± 200	0.8 ± 0.1
Positrons	100 ± 2	50 ± 20	2.0 ± 0.5

*numerical solver

Antiprotons



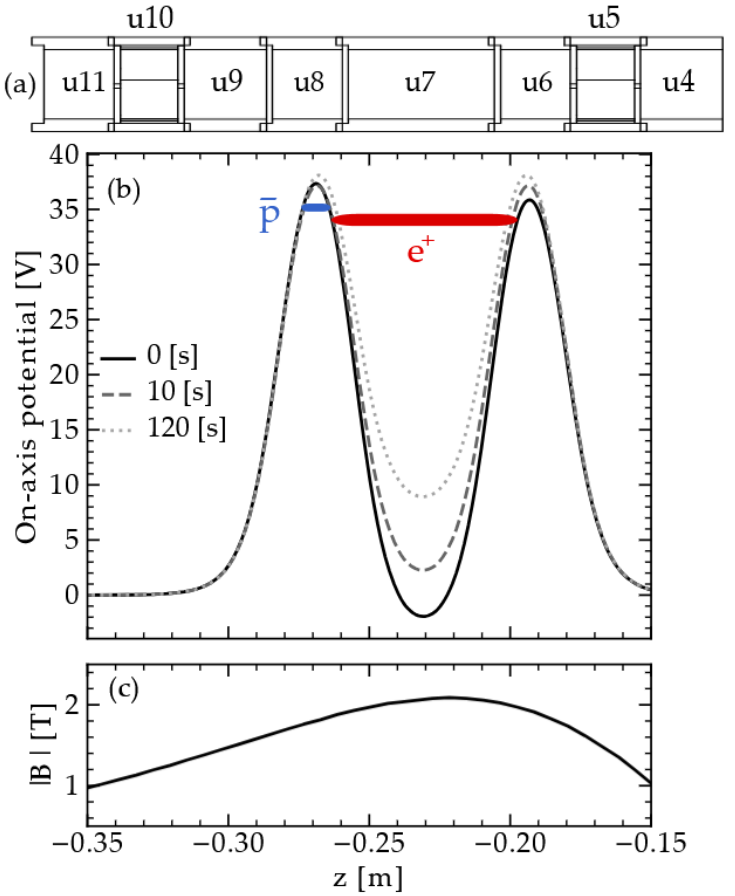
Positrons



2024 data

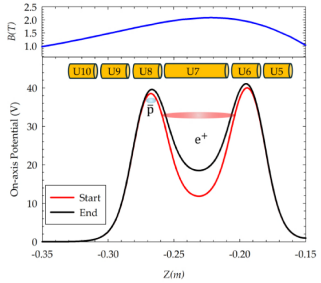
2025 Mixing parameters

- >7 million antiprotons
- 130 million positrons
- Similar temperature
- Mixing duration 120 s
- Full cycle ~18 minutes
- 100 beam-like $\overline{H}$ per cycle



ASACUSA SPSC Report for 2025, SPSC-SR-377

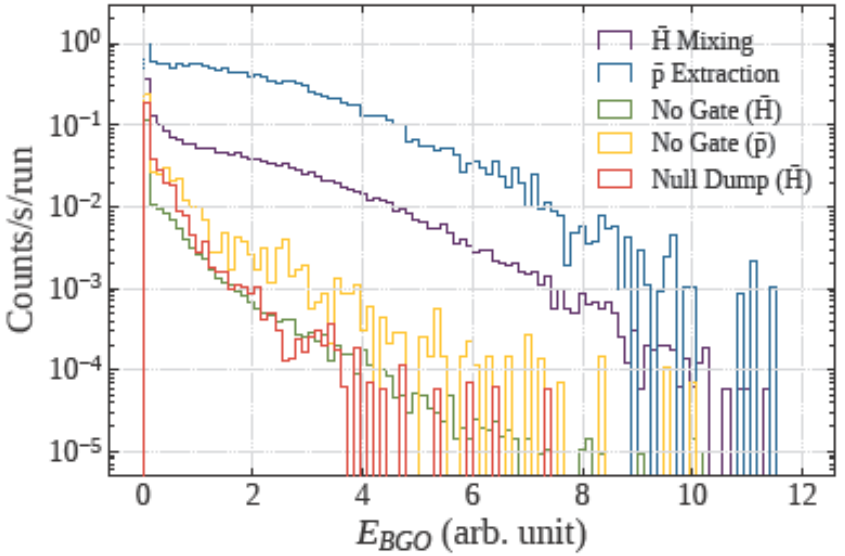
Beam intensity

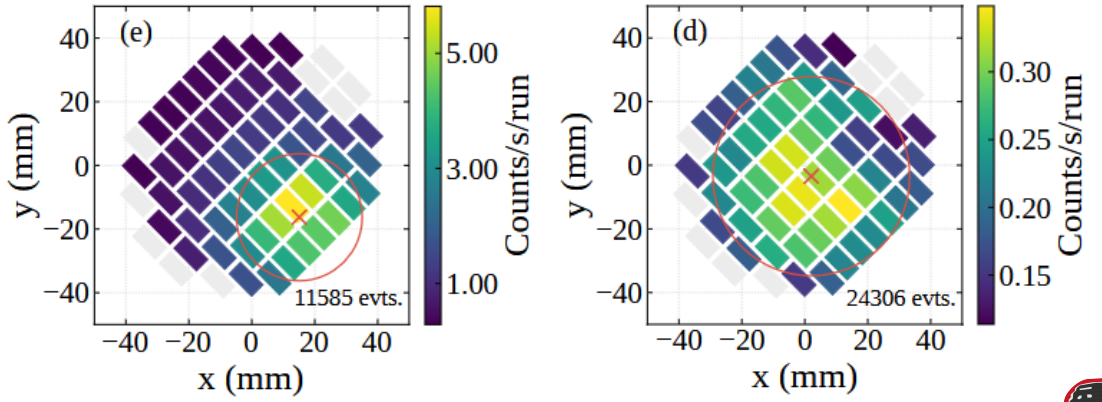


- 2.3 ± 0.2 million $\overline{H}$ per 60s mixing
- Of which 300 $\overline{H}$ beam-like
  - Factor 100 improvement
  - Short beam line: after Cusp
- On the order of solid angle selection
- Observe difference between $\bar{p}$ (left) & $\overline{H}$ (right) beam spot

2024 data

E. D. Hunter et al. In Preparation





Beam velocity

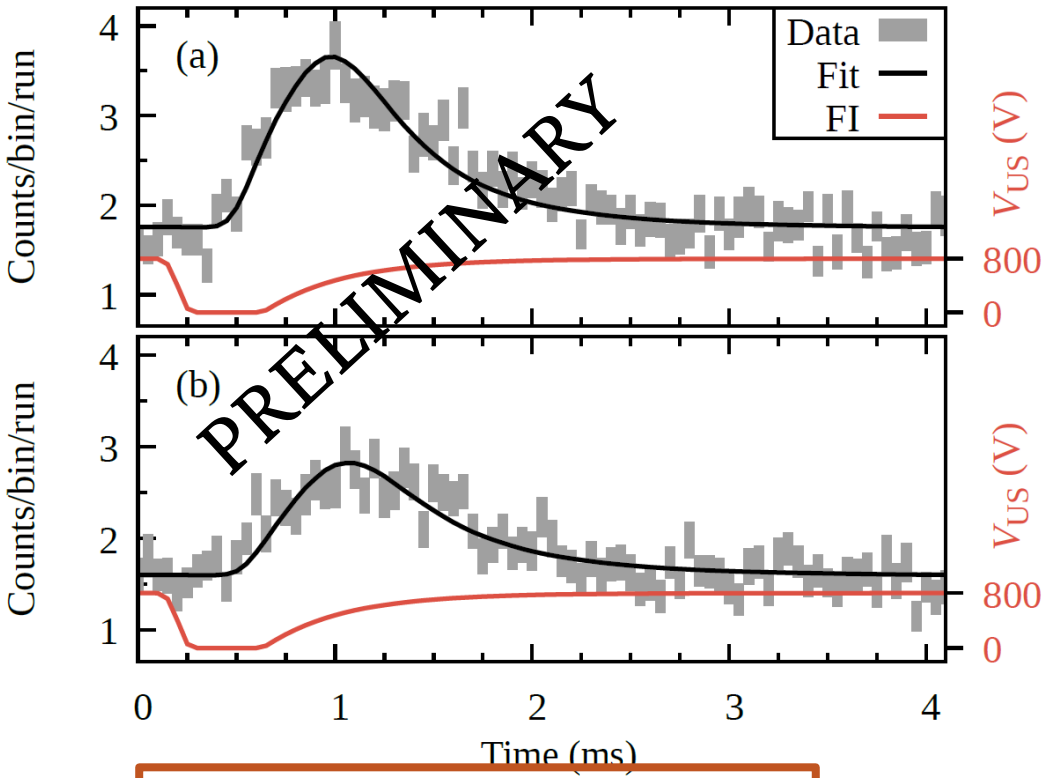
- Field ionisation → n
- Pulses → velocity

- Fit model
  - 1D Maxwell-Boltzman – axial $\bar{p}$
  - 2D Maxwell-Boltzman – transverse e^+

- Beam selection
- Time in plasma
- Plasma rotation

- Lower n → lower average velocity

n > 27: $\langle v \rangle$ = 3000 ± 200 m/s

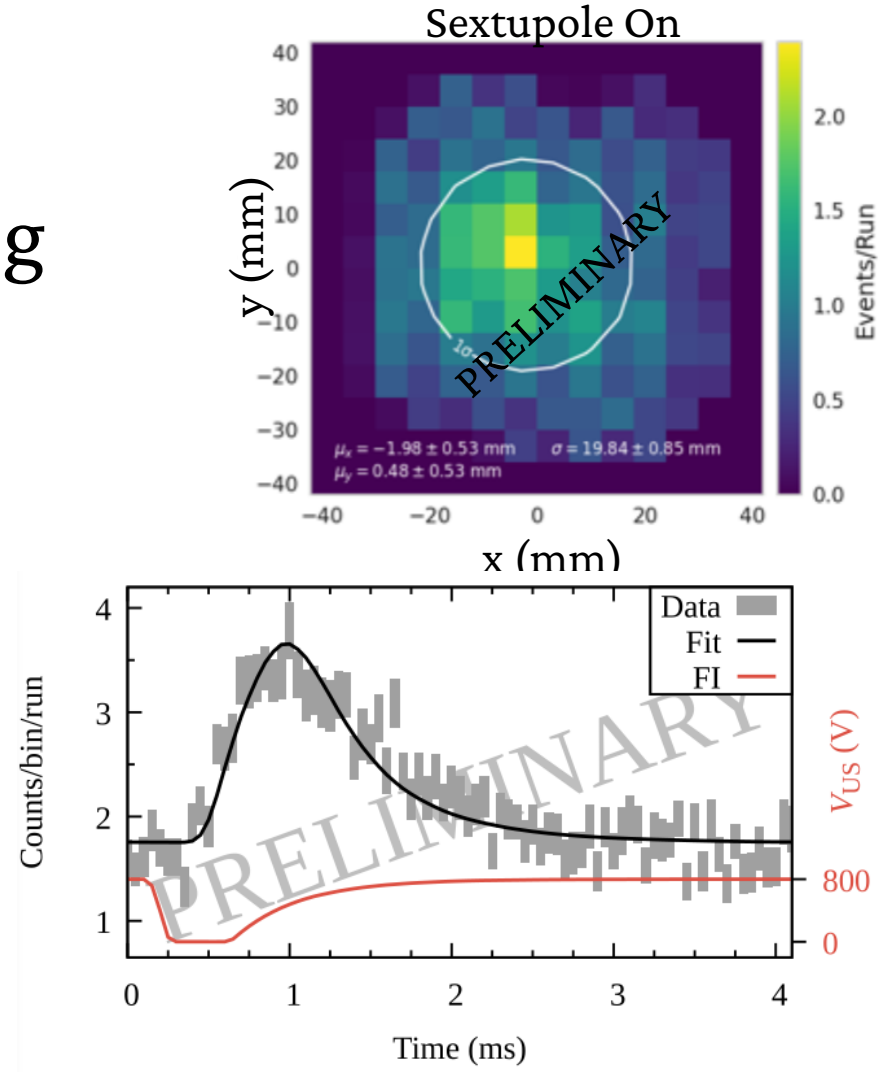


27 < n < 36: $\langle v \rangle$ = 2500 ± 100 m/s

E. D. Hunter et al. In Preparation

Conclusions

- We have atoms we could use
- Next step: make them useful
- Beam and plasma optimisation ongoing
  - Colder plasmas → more $\overline{\mathrm{H}}$
  - Denser positrons → slower/lower-n $\overline{\mathrm{H}}$
- Improve signal-to-noise ratio
  - Remove central atoms : beam blocker
  - Remove Rydberg atoms: FI
  - Improve polarisation
    - Slower, lower-n $\overline{\mathrm{H}}$
    - Separate formation and polarisation regions
      - Deeexcite Rydberg $\overline{\mathrm{H}}$



H,D: Standard Model Extension

$$\mathcal{L} \supset \frac{1}{2}\overline{\Psi_w}(\gamma^\mu i\partial_\mu - m_w + \hat{Q}_w)\Psi_w + \text{h.c.} \qquad w{=}e,p,n$$

$\hat{Q}_w$: sum of all Lorentz invariance and CPT violating terms compatible with QFT: low-energy manifestation of unknown theory at M_{Pl}

V.A. Kostelecký and M. Mewes, PRD 88 096006 (2013)

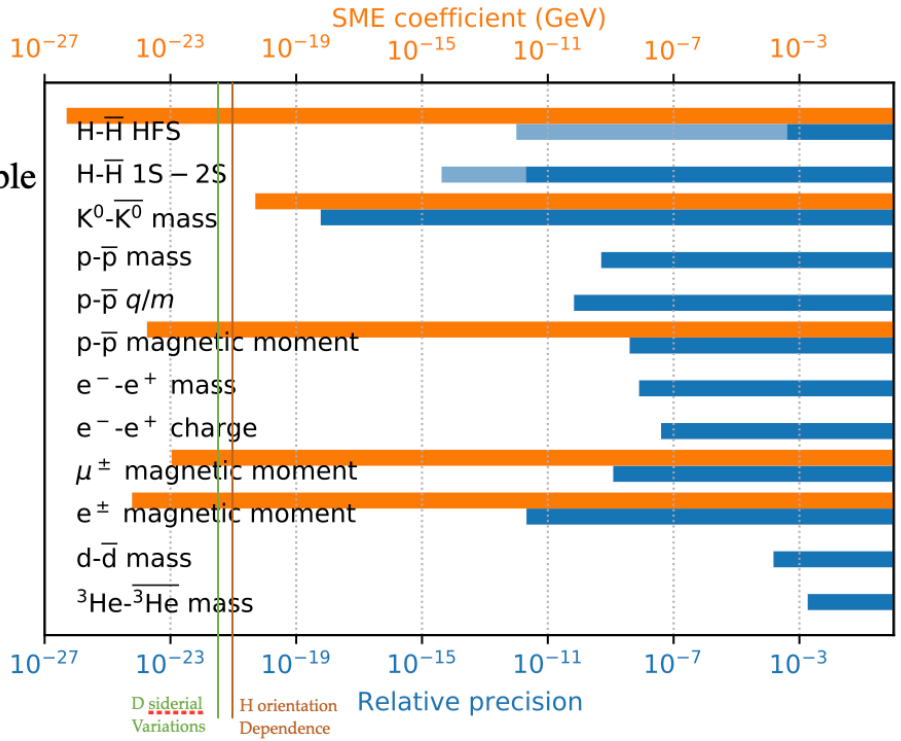
$$\mathcal{H}^0_{\text{w}} = -\sum_{kjm} |\boldsymbol{p}|^k \, {}_0Y_{jm}(\hat{\boldsymbol{p}})\, \mathcal{V}^{\text{NR}}_{w\,jkm} \qquad p\text{: particle momentum}$$

$$\mathcal{H}_{\text{wr}} = -\sum_{kjm} |\boldsymbol{p}|^k \, {}_0Y_{jm}(\hat{\boldsymbol{p}})\, \mathcal{T}^{\text{NR(0B)}}_{w\,jkm},$$

$$\mathcal{H}_{\text{w}\pm} = -\sum_{kjm} |\boldsymbol{p}|^k \, {}_{\pm1}Y_{jm}(\hat{\boldsymbol{p}})\, (i\mathcal{T}^{\text{NR(1E)}}_{w\,jkm} \pm \mathcal{T}^{\text{NR(1B)}}_{w\,jkm})$$

$$\mathcal{V}^{\text{NR}}_{wkjm} = c^{\text{NR}}_{wkjm} - a^{\text{NR}}_{wkjm}, \qquad \text{CPT odd}$$

$$\mathcal{T}^{\text{NR(qP)}}_{wkjm} = g^{\text{NR(qP)}}_{wkjm} - H^{\text{NR(qP)}}_{wkjm};$$



ALPHA HFS result not sensitive to SME

E. Widmann, Phys. Part. Nucl. 53, 790 (2022)
Source: PDG & arXiv:0801.0287v17

Siderial variations: constrained by maser to mHz

$$\mathcal{K}^{\text{NR,lab}}_{w\,k10} = \mathcal{K}^{\text{NR,Sun}}_{w\,k10}\cos\vartheta - \sqrt{2}\,\text{Re}\,\mathcal{K}^{\text{NR,Sun}}_{w\,k11}\sin\vartheta\cos\omega_\oplus T_\oplus + \sqrt{2}\,\text{Im}\,\mathcal{K}^{\text{NR,Sun}}_{w\,k11}\sin\vartheta\sin\omega_\oplus T_\oplus.$$

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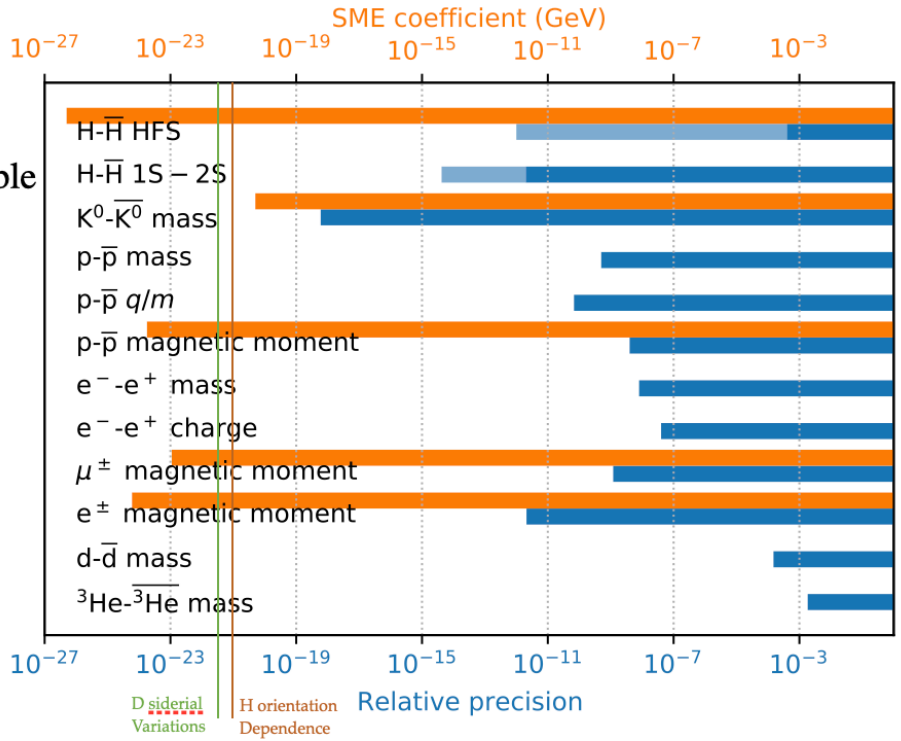

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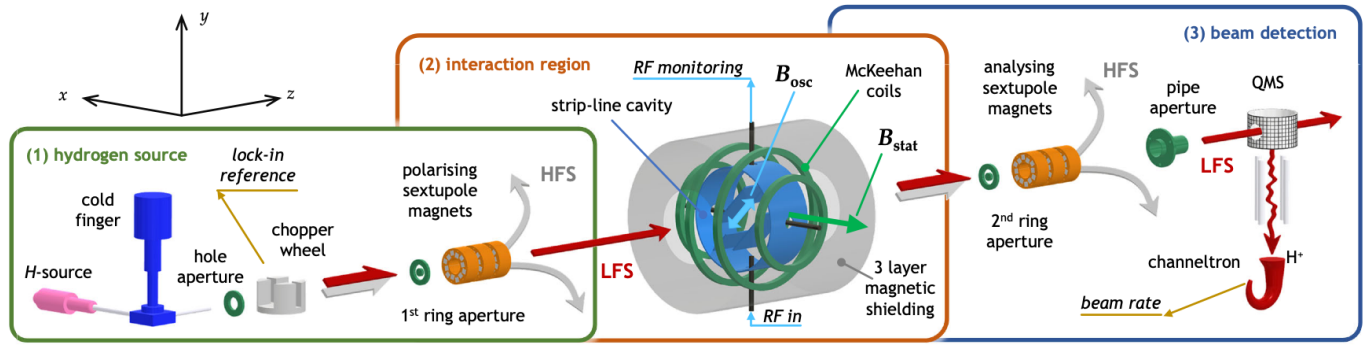
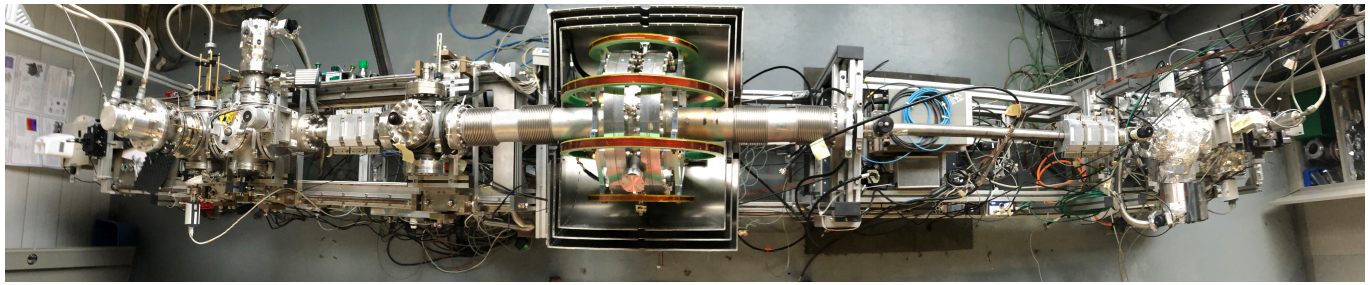
Orientation dependence: previously unconstrained

Search for CPT and LIV with matter: H beam

MBI, LKB Paris, LAC Saclay

- CPT - Lorentz invariance
  - connected by Anti-CPT theorem
- Lorentz Invariance Violation
  - Orientation dependence
  - Sidereal variations due to rotation of Earth





Hydrogen beam @Bat 275 CERN

Moved to Laboratoire Aimé Cotton U Paris Saclay for D beam

H beam result

- H/D source: rf discharge
  - Cold nozzle T~35 K
  - $T_{\mathrm{H}} \sim 50$ K, $v_{\mathrm{H}} \sim 1000$ m/s
- H beam parameter
  - Cavity L = 10.5 cm ($\lambda/2$)
  - Line width
    - $\Delta\nu \sim 1/t_L \sim 9.5$ kHz
  - Achieved precision for transition frequency $\delta\nu_\pi < 1$ Hz

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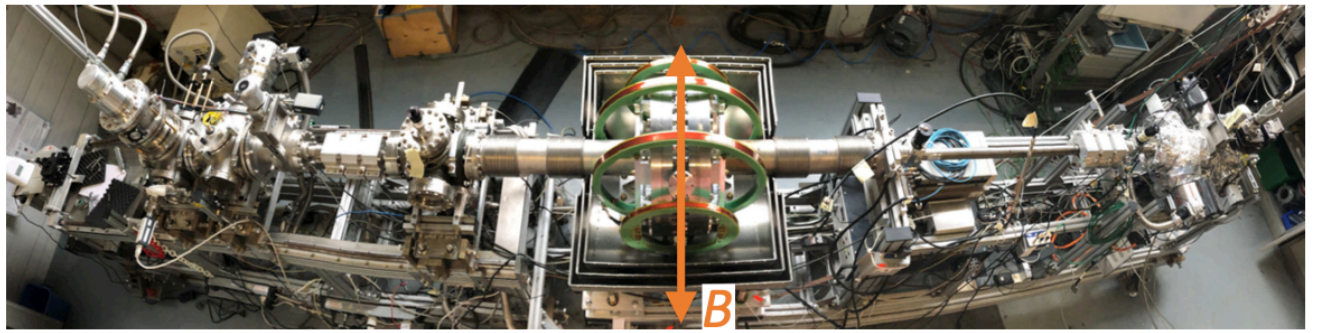
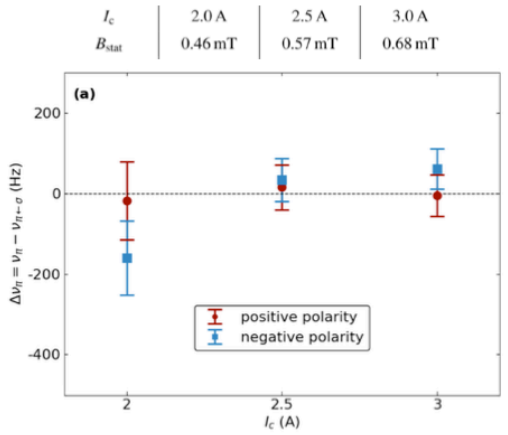
  - Achieved precision for transition frequency $\delta\nu_\pi < 1$ Hz

Hydrogen beam: orientation dependence



π transition

- $\nu_\pi(\vec{B}) - \nu_\pi(-\vec{B})$ is proportional to SME coefficients
  V.A.Kostelecký & A.J. Vargas, PRD 92, 056002, (2015).
  - Error 51 Hz
- Simultaneous measurement of ν_σ, ν_π yields improved value for zero field hyperfine splitting
  - $\delta\nu_{HF} = 0.63$ Hz (440 ppt)

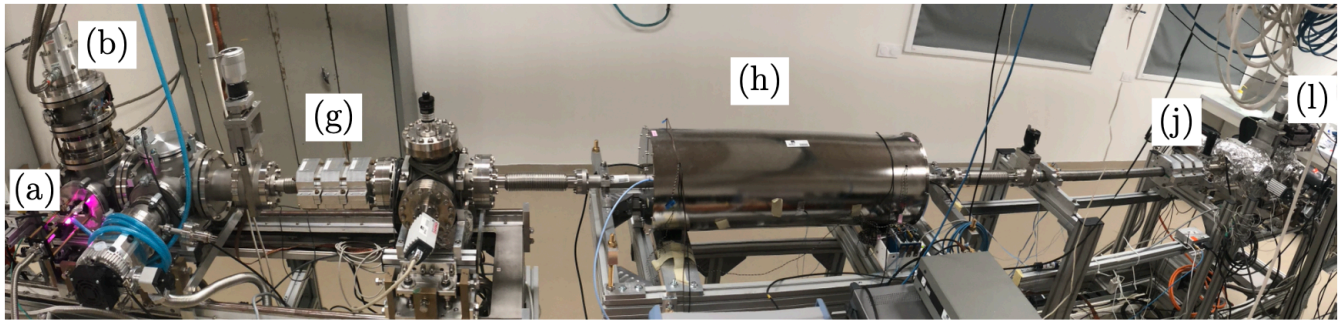


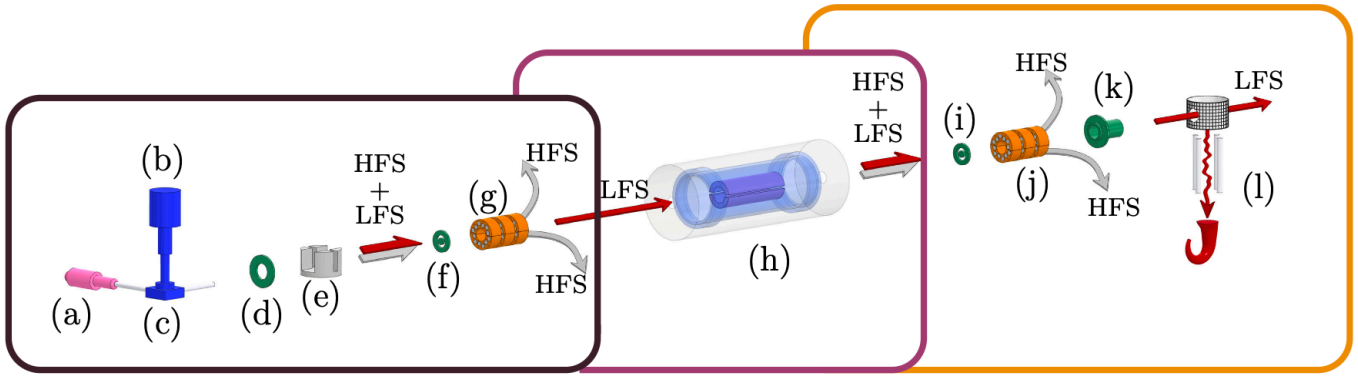
Coefficient $\mathcal{K}$	Constraint on $\lvert\mathcal{K}\rvert$
proton	
$H^{NR(0B),Sun}_{p010}$, $g^{NR(0B),Sun}_{p010}$	$< 1.2 \times 10^{-21}$ GeV
$H^{NR(1B),Sun}_{p010}$, $g^{NR(1B),Sun}_{p010}$	$< 5.8 \times 10^{-22}$ GeV
$H^{NR(0B),Sun}_{p210}$, $g^{NR(0B),Sun}_{p210}$	$< 8.4 \times 10^{-11}$ GeV^{-1}
$H^{NR(1B),Sun}_{p210}$, $g^{NR(1B),Sun}_{p210}$	$< 4.2 \times 10^{-11}$ GeV^{-1}
$H^{NR(0B),Sun}_{p410}$, $g^{NR(0B),Sun}_{p410}$	< 1.2 GeV^{-3}
$H^{NR(1B),Sun}_{p410}$, $g^{NR(1B),Sun}_{p410}$	< 0.6 GeV^{-3}
electron	
$H^{NR(0B),Sun}_{e010}$, $g^{NR(0B),Sun}_{e010}$	$< 7.7 \times 10^{-19}$ GeV
$H^{NR(1B),Sun}_{e010}$, $g^{NR(1B),Sun}_{e010}$	$< 3.8 \times 10^{-19}$ GeV
$H^{NR(0B),Sun}_{e210}$, $g^{NR(0B),Sun}_{e210}$	$< 5.5 \times 10^{-8}$ GeV^{-1}
$H^{NR(1B),Sun}_{e210}$, $g^{NR(1B),Sun}_{e210}$	$< 2.8 \times 10^{-8}$ GeV^{-1}
$H^{NR(0B),Sun}_{e410}$, $g^{NR(0B),Sun}_{e410}$	$< 8.0 \times 10^{2}$ GeV^{-3}
$H^{NR(1B),Sun}_{e410}$, $g^{NR(1B),Sun}_{e410}$	$< 4.0 \times 10^{2}$ GeV^{-3}

First limits on this type of coefficients
Nowak, L. et al. arXiv.2403.17763

Nowak, L., et al. *Physics Letters* ***B*** **858** (2024), 139012.

Deuterium beam at LAC

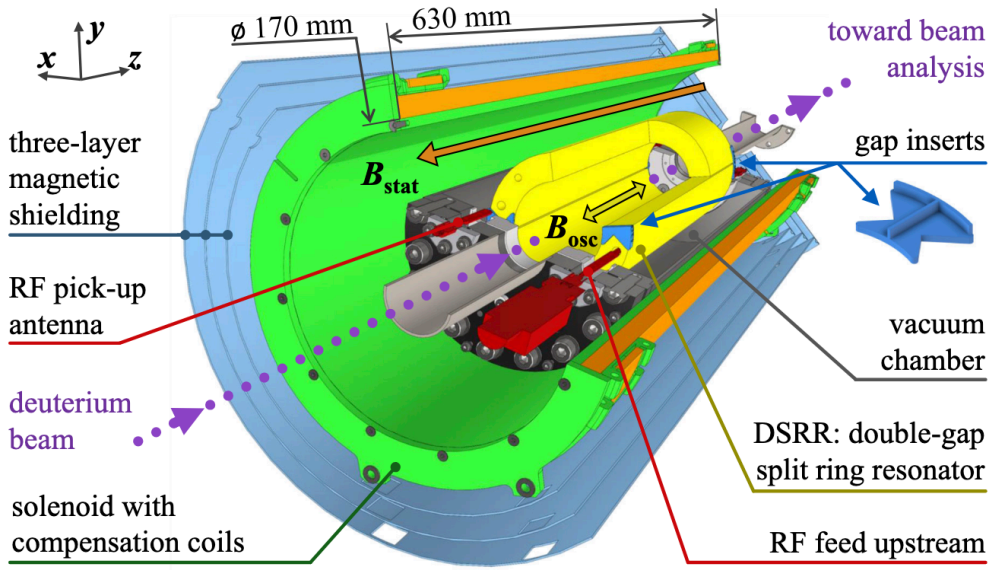




(a) Deuterium Plasma	(b) Coldhead	(c) Aluminium Sandwich
(d) Hole Aperture	(e) Chopper Wheel	(f) 1st ring aperture
(g) Polarizing magnets	(h) Spectrometer	(i) 2nd ring aperture
(j) Analysis magnets	(k) Pipe aperture	(l) QMS + Channeltron

D source: nozzle @ 27 K

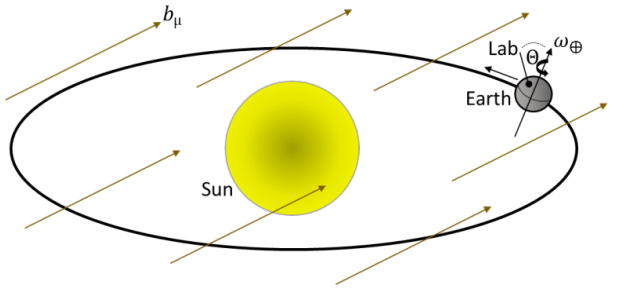
$v_D \sim 700$ m/s

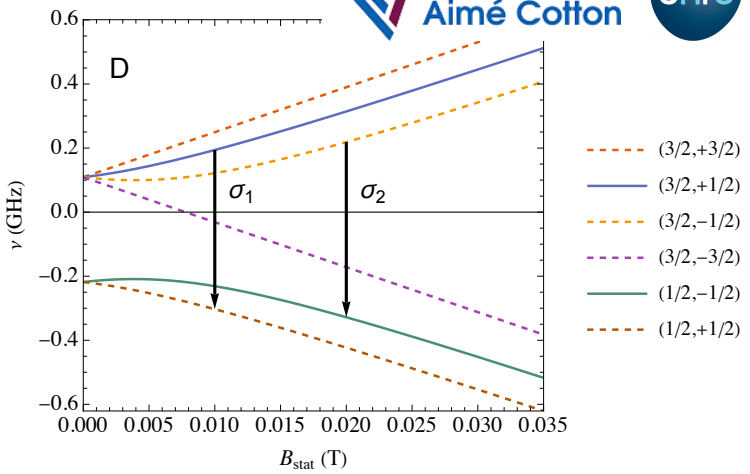


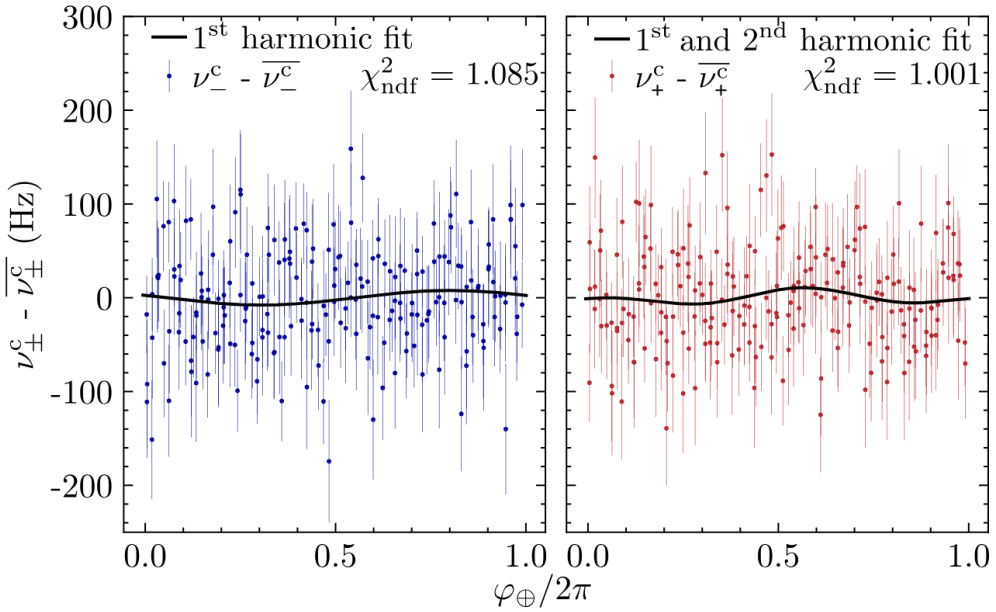
Deuterium beam: sidereal variations

Deuterium hyperfine structure

- Increased sensitivity due to relative momentum p-n in d
- Important for coefficients at higher order in momentum



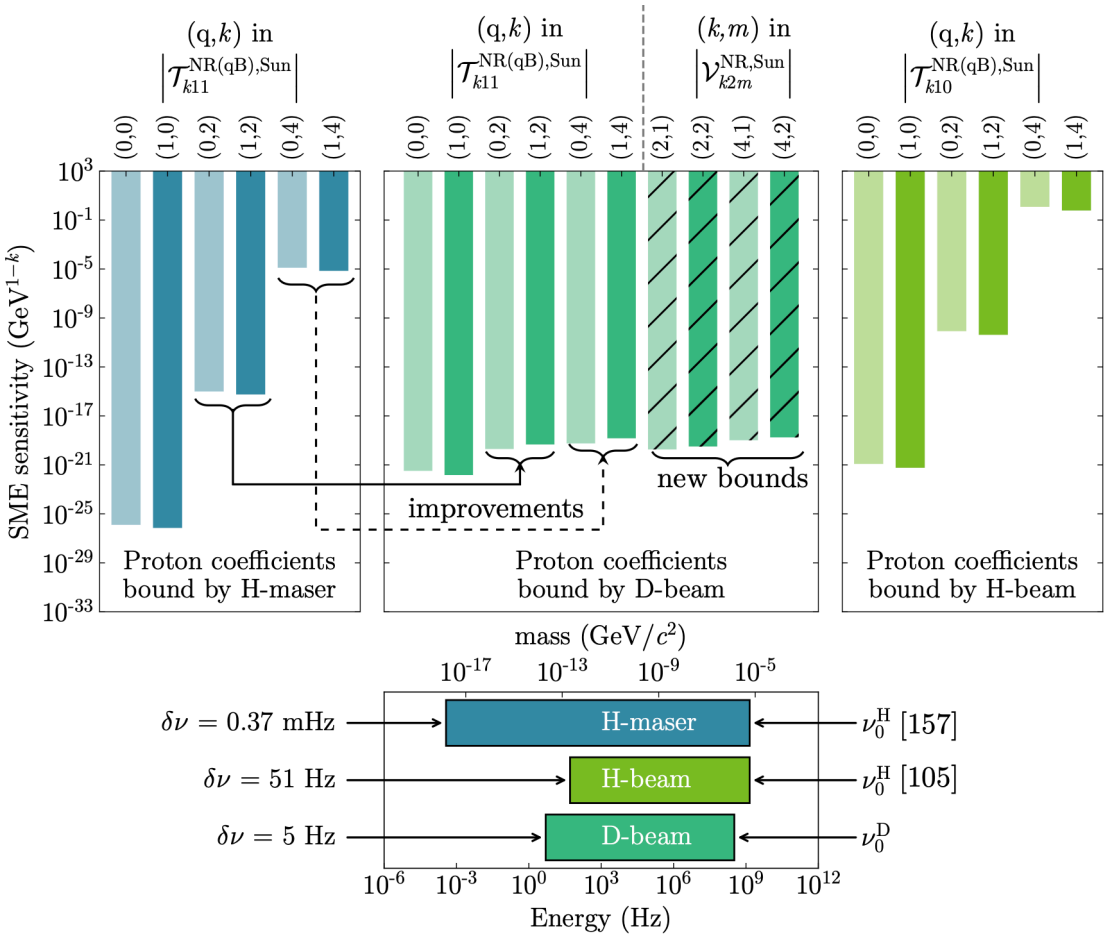




Spin-depend. coeff.	$\Re(\mathcal{T}^{Sun})$	$\Im(\mathcal{T}^{Sun})$	Units
$H^{NR(0B)}_{p_{211}}, -g^{NR(0B)}_{p_{211}}$	0.6 ± 1.6	1.9 ± 1.6	10^{-20} GeV^{-1}
$H^{NR(1B)}_{p_{211}}, -g^{NR(1B)}_{p_{211}}$	1.5 ± 3.7	4.4 ± 3.6	10^{-20} GeV^{-1}
$H^{NR(0B)}_{p_{411}}, -g^{NR(0B)}_{p_{411}}$	1.8 ± 4.6	5.4 ± 4.5	10^{-20} GeV^{-3}
$H^{NR(1B)}_{p_{411}}, -g^{NR(1B)}_{p_{411}}$	-0.5 ± 1.1	-1.4 ± 1.1	10^{-19} GeV^{-3}
Spin-independ. coeff.	$\Re(\mathcal{V}^{Sun})$	$\Im(\mathcal{V}^{Sun})$	**Units**
$c^{NR}_{p_{221}}, -a^{NR}_{p_{221}}$	1.6 ± 1.8	-0.9 ± 1.7	10^{-20} GeV^{-1}
$c^{NR}_{p_{222}}, -a^{NR}_{p_{222}}$	-2.3 ± 3.0	2.2 ± 3.0	10^{-20} GeV^{-1}
$c^{NR}_{p_{421}}, -a^{NR}_{p_{421}}$	-0.9 ± 1.0	0.5 ± 1.0	10^{-19} GeV^{-3}
$c^{NR}_{p_{422}}, -a^{NR}_{p_{422}}$	1.3 ± 1.7	-1.2 ± 1.7	10^{-19} GeV^{-3}

*A. Nanda et al., PRL **137**, 031802 (2026)*
Non-minimal non-relativistic SME coefficients of the proton

Deuterium beam & SME



$$\mathcal{L} \supset \frac{1}{2}\overline{\Psi_w}(\gamma^\mu i\partial_\mu - m_w + \hat{Q}_w)\Psi_w + \text{h.c.}$$

$\hat{Q}_w$: sum of all Lorentz invariance and CPT violating terms compatible with QFT: low-energy manifestation of unknown theory at M_{Pl}

V.A. Kostelecký and M. Mewes, PRD 88 096006 (2013)

$$\mathcal{H}^0_{\mathrm{w}} = -\sum_{kjm} |\boldsymbol{p}|^k \, {}_0Y_{jm}(\hat{\boldsymbol{p}})\, \mathcal{V}^{\mathrm{NR}}_{w\,jkm}$$

p: particle momentum

$$\mathcal{H}_{\mathrm{wr}} = -\sum_{kjm} |\boldsymbol{p}|^k \, {}_0Y_{jm}(\hat{\boldsymbol{p}})\, \mathcal{T}^{\mathrm{NR(0B)}}_{w\,jkm},$$

$$\mathcal{H}_{\mathrm{w}\pm} = -\sum_{kjm} |\boldsymbol{p}|^k \, {}_{\pm1}Y_{jm}(\hat{\boldsymbol{p}})\, (i\mathcal{T}^{\mathrm{NR(1E)}}_{w\,jkm} \pm \mathcal{T}^{\mathrm{NR(1B)}}_{w\,jkm})$$

$$\mathcal{V}^{\mathrm{NR}}_{wkjm} = c^{\mathrm{NR}}_{wkjm} - a^{\mathrm{NR}}_{wkjm},$$

$$\mathcal{T}^{\mathrm{NR(qP)}}_{wkjm} = g^{\mathrm{NR(qP)}}_{wkjm} - H^{\mathrm{NR(qP)}}_{wkjm}.$$

[157] M. A. Humphrey, et al., **PRA** 68, 063807, (2003)
[105] L. Nowak et al., PLB **858,** (2024)

Summary

- Slow atomic beams are useful tools to study fundamental symmetries and interactions
- Antihydrogen
  - Formation in nested Penning traps at low temperature (≤ 50 K)
  - *Direct test of CPT*
- Hydrogen, deuterium:
  - Standard: discharge and nozzles at ~ 6 K
  - New scheme at 100 mK in dilution cryostat
  - Further deceleration by Zeeman decelerator possible
  - *Test of LIV $\rightarrow$ CPT (model dependent)*

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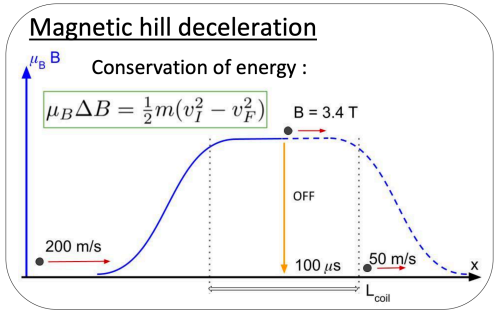

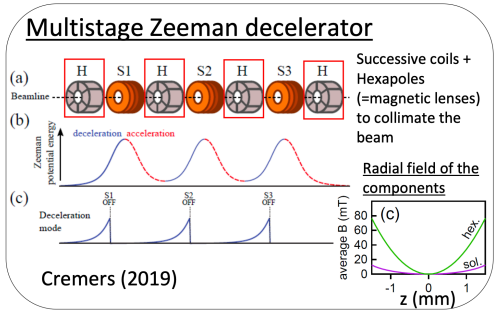

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* Co-spokespersons

ÖAW Austrian Academy of Sciences

MARIETTA BLAU INSTITUTE FOR PARTICLE PHYSICS

Thank you

H experiments @MBI

QR results

- More analysis, publish?
- Electron cloud influence
  - established? Can be measured (Kelvin probe)/controlled?

QR plans

- Smaller velocity band
  - Chopper, slits
- Single mirror + goniometer
- Many substrates
- Funding?

GQS results

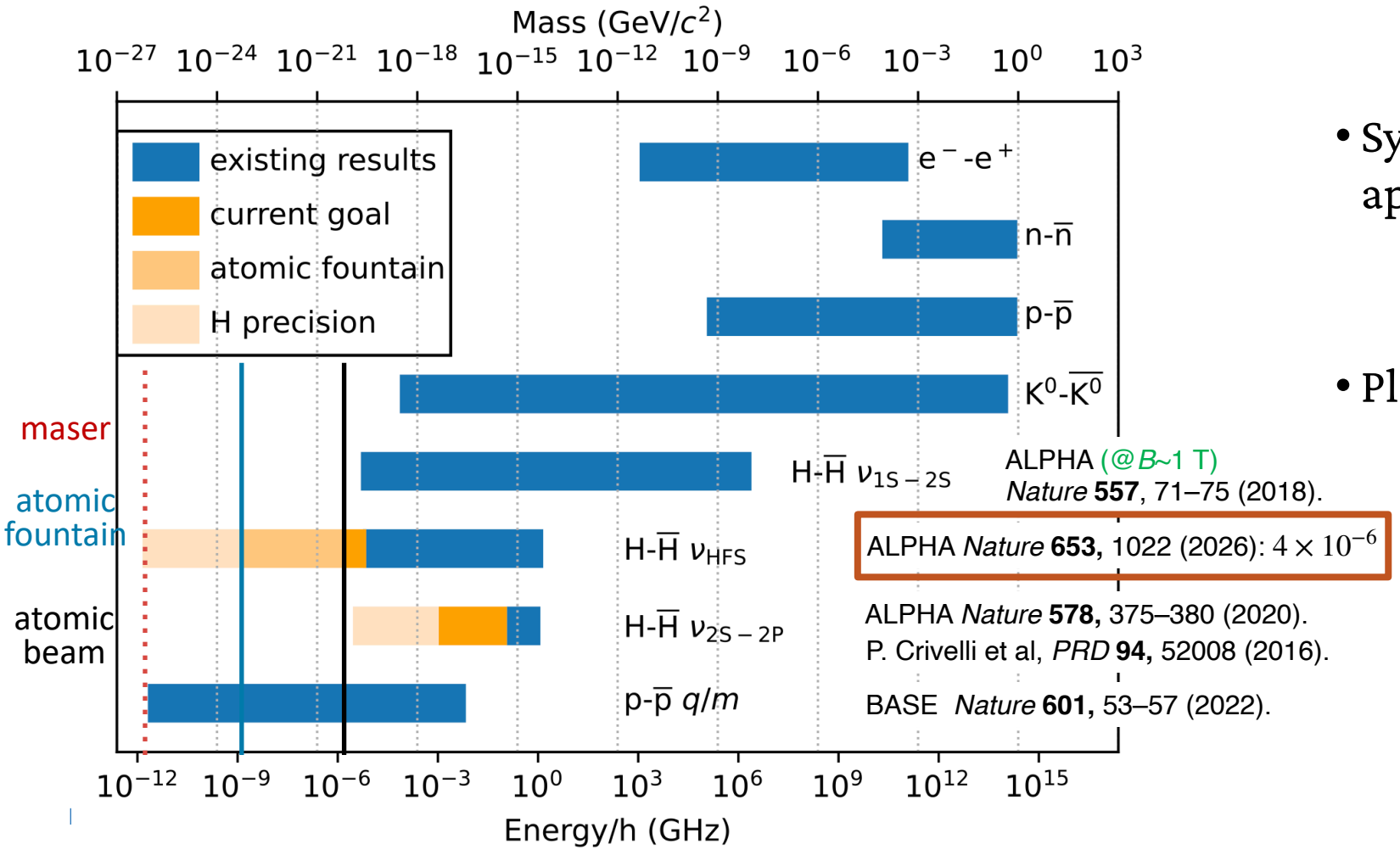
- No observation:
  - H velocity? CAPSENS calibration?
  - How to improve?
  - Go directly to far field measurement?

General improvements

- Source
  - Intensity, stability
- Compact setup on one table

Comparison of CPT tests -2026

- Mass & frequency



- Synopsis: CPT violating interaction appears at the level of Lagrangian
  - Relevant scale: absolute energy
- Plot
  - Right edge: value
  - Bar length: relative precision
  - Left edge: absolute sensitivity
  - Source: PDG

EW, Phys. Part. Nuclei **53**, 790–794 (2022).
arXiv:2111.04056 [hep-ex]

- Assess
  - asas
    - asas

- Assess
  - asas
    - asas
- Asas