ALICE
EIC_NET
FAMU
J_LAB12
LEA
MAMBO
N-ToF

Esperimenti di GR3-Pavia, sommario finanziamenti per il 2023

Sigla	FTE	Assegnazioni totali (k€)	Missioni (k€)	Cons (k€)	Inv (k€)	Altro (k€)	
ALICE	5.6	25	25	-`	-	-	
EIC_NET	0.1	4.5	4.5	-	-	-	
FAMU	1.8	29.5	26.5	3	-	-	
JLAB12	3.8	14	14	-	-	-	
LEA	6.6	99	48	-	-	51	
MAMBO	1.6	10.5	6.5	-	4	-	
n-ToF	1	6	3	-	-	3	
TOTALE	20.5	188.5	127.5	3	4	54	
DOTAZIONI			12.5	10.5	17	2	

ALICE

A Large Ion Collider Experiment

ALICE

Gianluigi Boca, Germano Bonomi, Susanna Costanza, Ramona Lea, Davide Pagano, Rohaan Deb, Nicolò Valle, Nicola Zurlo

Anagrafica (2023)

Nome	Qualifica	MOF-A	Percentuale
Boca Gianluigi	PA	NO	70
Bonomi Germano	PO	SI	70
Costanza Susanna	RTD B	SI	70
Lea Ramona	RTD B	SI	100
Pagano Davide	PA	SI	100
Rohaan Deb	PhD	SI	100
Urioni Marta	PhD	SI	70
Valle Nicolò	Post-doc	SI	50
Zurlo Nicola	PA	SI	80

Principali attività del gruppo nel 2023

- PWG-LF (Ramona e Rohaan)
    - Ramona: PWG conveneer (fino ad aprile 2024), Analisi produzione di nuclei, di particelle dotate di stranezza, e di correlazione tra mesoni e barioni, Paper committee member/chair di 4 paper, Responsabile del capitolo 5 del *review paper* di ALICE
    - Rohaan: Analisi degli spettri di pi/K/p prodotti in collisioni Pb-Pb con i dati del Run3 di ALICE
- PWG-HF (Susanna)
    - analisi del mesone D^0 in collisioni pp a $\sqrt{s}$ = 13 TeV → risultati pubblicati su J. High Energ. Phys. 2023, 86 (2023) doi:10.1007/JHEP12(2023)086
- Inner Tracking System (ITS) (Nicolò)
    - Sviluppo e mantenimento di task per la calibrazione online di ITS
    - Analisi di performance durante la presa dati piombo-piombo
    - Responsabilità: ITS Run Coordinator (Nicolò), Deputy: gennaio-giugno; Main: luglio-dicembre
    - Paper sulla calibrazione di ITS, in stato di revisione finale. Firmato da ITS Collaboration

Principali attività del gruppo nel 2023

- Statistical group (Davide)
  - Working group dedicato alle questioni inerenti la statistica (trattazione incertezze sistematiche, intervalli di confidenza, limiti, etc.)
    Chair (Davide)

- Hyperloop (tutti)
  - Il cluster Brescia-Pavia è uno dei 4 istituti che si occupano della gestione dei *treni* (ovvero i job che vanno eseguiti sulla grid)
  - Rientra nella attività di *service work*

- Masterclass (Susanna e Nicolò)
  - Rientra nella attività di *service work*

- Turni di presa dati in ACR al CERN-P2(Gianluigi, Nicolò, Rohaan, Nicola)

Partecipazione alla presa dati 2023

- Crediti dovuti come cluster (7 M&O nel 2023): **50.94**
    - 1 credito è di norma equivalente a 1 turno di presa dati (8 h)
    - Soglia per essere il regola: **38.2** (75% del dovuto)
    - Crediti ottenuti: **48.5**
- In aggiunta si è svolto attività di expert on call per l'ITS (Nicolò)
- Run Manager (Nicolò), in agosto/settembre 2023

Talks

- *Constraining coupled channels dynamics using femtoscopic correlations with ALICE at LHC,* contributed talk, HADRON2023 - 20th International Conference on Hadron Spectroscopy and Structure
- *A Monolithic Active Pixel Sensor-based Inner Tracking System for ALICE,* invited talk, TERASCALE WORKSHOP, Heidelberg 2023

Publications

ALICE accomplished 66 peer-reviewed publications in 2023, our group main contributions were to:

- *Charm production and fragmentation fractions at midrapidity in pp collisions at sqrt(s) = 13 TeV*, J. High Energ. Phys. 2023, 86 (2023). doi:10.1007/JHEP12(2023)086, https://arxiv.org/abs/2308.04877
- S. Costanza for the ALICE Collaboration, *Open heavy flavour production in small systems with ALICE*, Nucl. Part. Phys. Proc., Vol. 324–329, 2023, 12-15, doi:10.1016/j.nuclphysbps.2023.01.004
  Proceedings of QCD22 Conference
- *Enhanced deuteron coalescence probability in jets* Phys. Rev. Lett. 131 (2023) 042301 arXiv:2211.15204
- *Constraining the KN coupled channel dynamics using femtoscopic correlations at the LHC* Eur. Phys. J. C 83 (2023) 340, arXiv:2205.15176

EIC_NET

EIC_NET-Pavia

Anagrafica

Coordinatore locale: M. Radici (fino al 31/12/2023)
S. Costanza (dal 01/01/2024)

Nome	Qualifica	FTE
Boca Gianluigi	PA UniPV	0
Costanza Susanna	RTD B UniPV	0.2
Delcarro Filippo	Assegnista UniPV	0.1 (dal 01/01/2024)
Radici Marco	Primo Ricercatore (INFN)	0.1

EIC_NET-Pavia

Contributo sperimentale

Software & Computing activities (just started)

- G. Boca: reconstruction of secondary vertices
- S. Costanza: studies of acceptance effects on TMDs extraction (SIDIS working group)

Experimental activities related to Silicon Vertex Tracker (SVT)

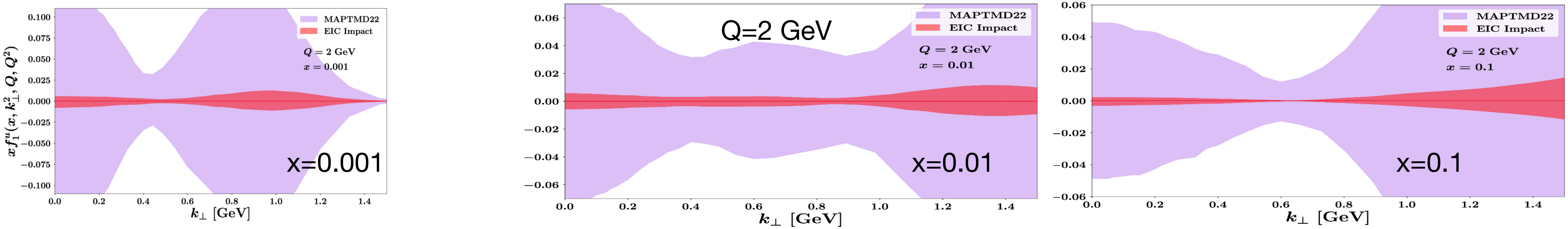
- eRD111 and eRD113 FY24 DoE grants → € 22.750,00 for a new post-doc
- Activities in collaboration with INFN Bari, Padova and Trieste: ageing test in climate chamber, half-layer/barrel transportation

Contributo teorico

Prominent roles in EIC Users Group structure:

- M. Radici: Chair of the Steering Committee (former Vice-Chair till 31-05-2023) member of the Council Board, of the Charter Committee; convener of SIDIS Working Group in the ePIC Collaboration (till apr 2023)
- also A. Bacchetta: convener of the EICUG Theory Working Group

Theoretical support to EIC simulation activities (see next slide)



EIC impact (Yellow Report 10x100 configuration) on unpolarized quark TMD(x,k_T;Q) from MAP22 fit

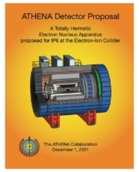
M. Radici, talk at "Int. Workshop on Hadron Struct. & Spectroscopy (IWHSS 2023)", 25-28/06/23, Praga

Other related publications:

Snowmass 2021 White Paper: Electron Ion Collider for High Energy Physics

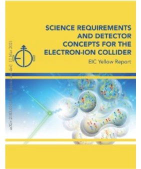
P. Abdul Khalek,.., M. Radici et al., arXiv:2203.13199

EIC Detector proposal by the **ATHENA** proto-Collaboration
(M. Radici co-convener of SIDIS Working Group)



J. Adam,.., M. Radici et al. (ATHENA Collaboration), JINST 17 (22) 10, P10019, arXiv:2210.09048

Science requirements and detector concepts for the Electron-Ion Collider:
EIC Yellow Report (M. Radici co-editor; B. Pasquini co-convener of Excl. WG)



R. Abdul Khalek,.., M. Radici et al., Nucl. Phys. A1026 (22) 122447, arXiv:2103.05419

Precision studies of QCD in the low energy domain of the EIC

V.D. Burkert,.., M. Radici et al., Prog. Part. Nucl. Phys. 131 (23) 104032, arXiv:2211.15746

The case for an EIC Theory Alliance: Theoretical Challenges of the EIC

R. Abir,.., M. Radici et al., arXiv:2305.14572

FAMU

Consuntivi FAMU 2023

CdS, giugno 2024

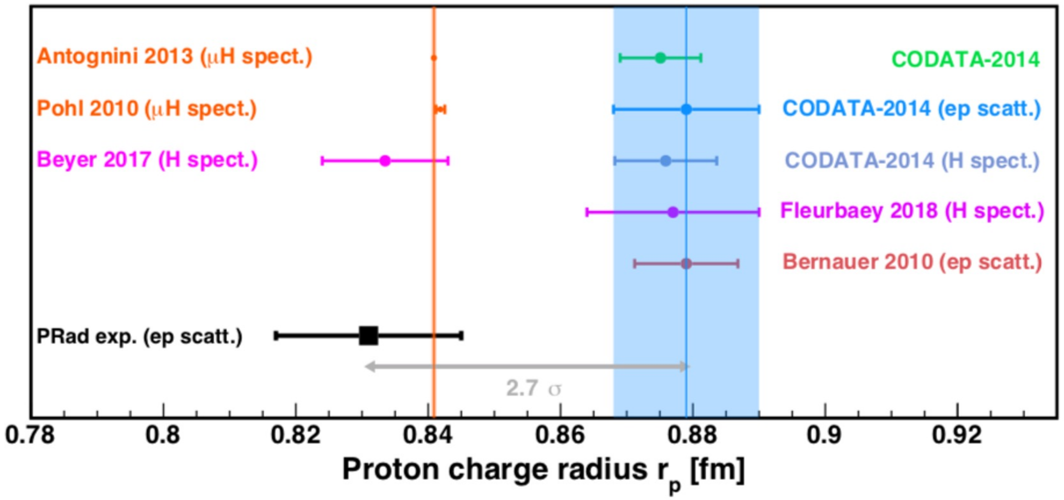
La Collaborazione FAMU (2023)

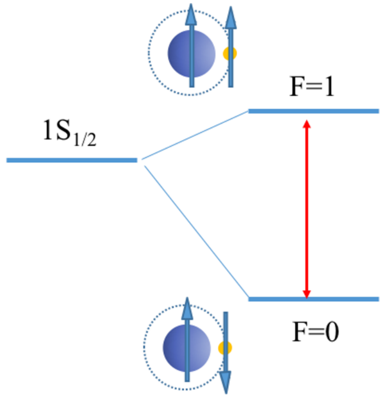
- Spokesperson: *Andrea Vacchi (Univ. Udine)*
- Responsabile Nazionale: *Cecilia Pizzolotto (INFN Trieste)*
- Sezioni INFN di: *Bologna, Milano, Milano Bicocca, Pavia, Roma 3, Trieste, Napoli (Caserta)*
- Collaborazioni estere: *Krakow (Pol.), Sofia (Bul.), RIKEN (Jap.). RAL (UK)*
- **FAMU-Pavia**: 1.8 *FTE, 6 persone (1 PA, 2 ricercatori, 2 tecnologi, 1 dottorando)*

FAMU: un recap sugli obiettivi

- Gli atomi muonici sono sistemi atomici legati simili all'idrogeno, con raggio di Bohr 200 volte più piccolo rispetto ai normali atomi elettronici. Ciò si traduce in una sovrapposizione tra le funzioni d'onda muonica e nucleare causando spostamenti dei livelli di energia atomica.

- Le misurazioni ad alta precisione delle frequenze di transizione negli atomi muonici possono essere utilizzate quindi come sonde precise delle proprietà a bassa energia dei nuclei.

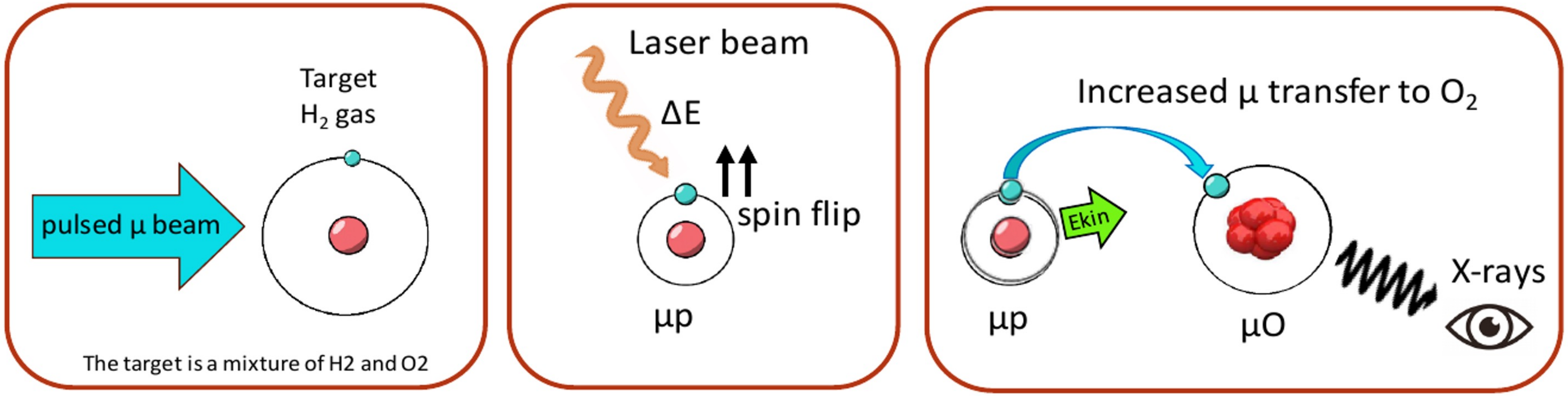




Misura dello splitting iperfine (hfs) nello stato base dell'idrogeno muonico con precisione ~ 10^{-5}

- ➢ Misura del raggio Zemach del protone con precisione dell'1%.
- ➢ benchmark per modelli del protone.

FAMU: metodologia



- Create muonic hydrogen and wait for its thermalization;
- Shoot laser at the hyperfine splitting energy (λ_0 ~ 6.8μm)
  - and change spin state of μ -p from 1^1S_0 to 1^3S_1 ,
  - spin is flipped: $\mu^- p(\uparrow\downarrow) \rightarrow \mu^- p(\uparrow\uparrow)$;
- De-excitation and acceleration of μ^- p (~120 meV)
- If μ^-p are accelerated, the μ^- transfer to Oxygen increases (O_2 has an energy-dependent rate);
- The hyperfine splitting energy is determined by varying the wavelength of the laser beam and search the maximum number of oxygen X-rays

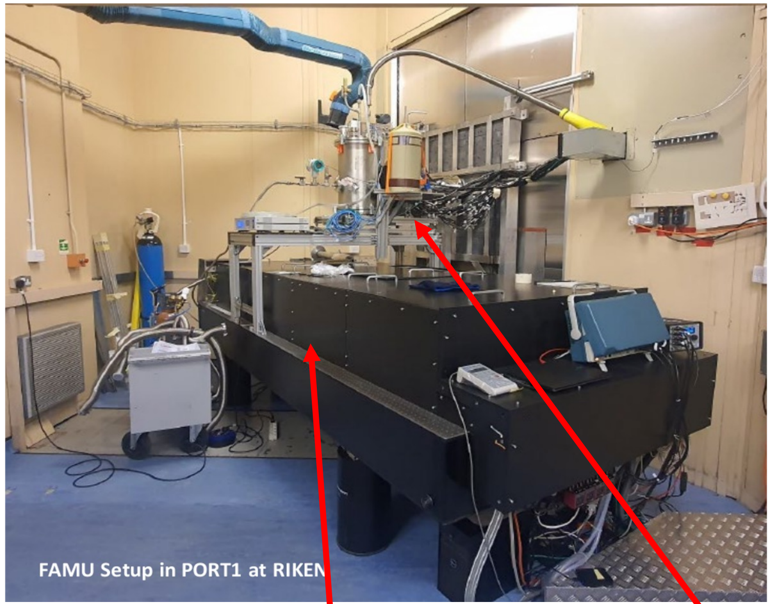
2023: primi run di fisica

- Installazione e test del setup (lavori gruppo PV principalmente sui rivelatori LaBr3, HPGe e odoscopio di fascio) da gennaio a luglio 2023

- 17-23 Luglio 2023: run di commissioning (~ 50 ore).

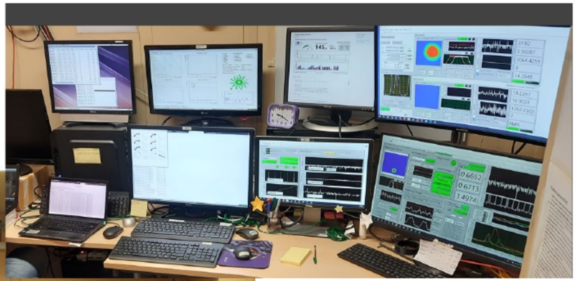
- 12-18 Ottobre 2023: primo run di fisica (scan 5 frequenze laser)

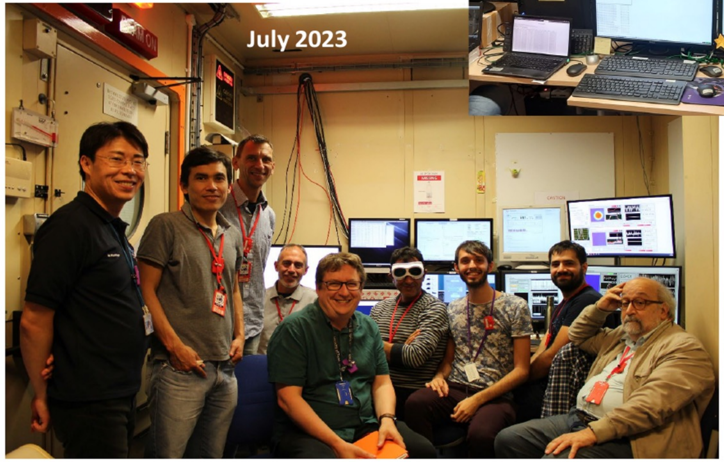
- 7-18 Dicembre 2023: secondo run di fisica (9 frequenze laser)



Laser

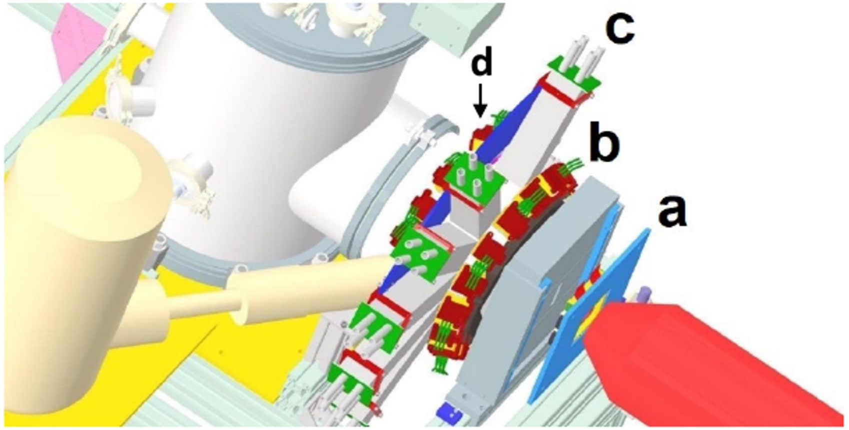
Target e rivelatori



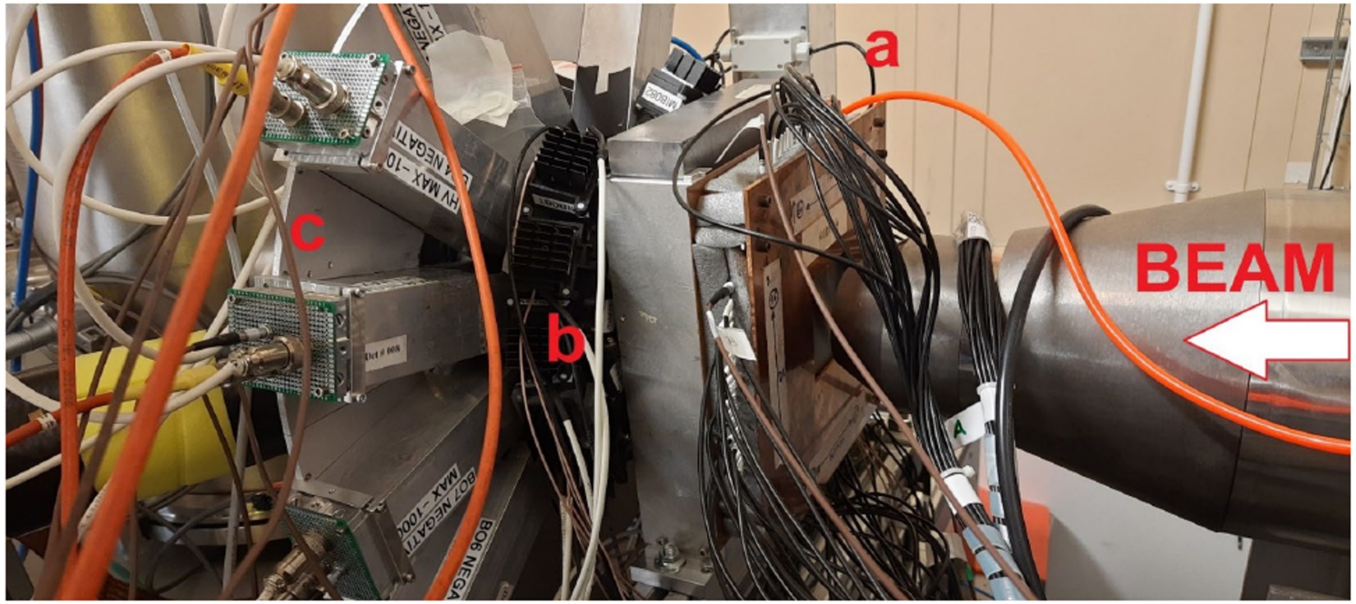


During beamtime:
2 shifters present 24h/24

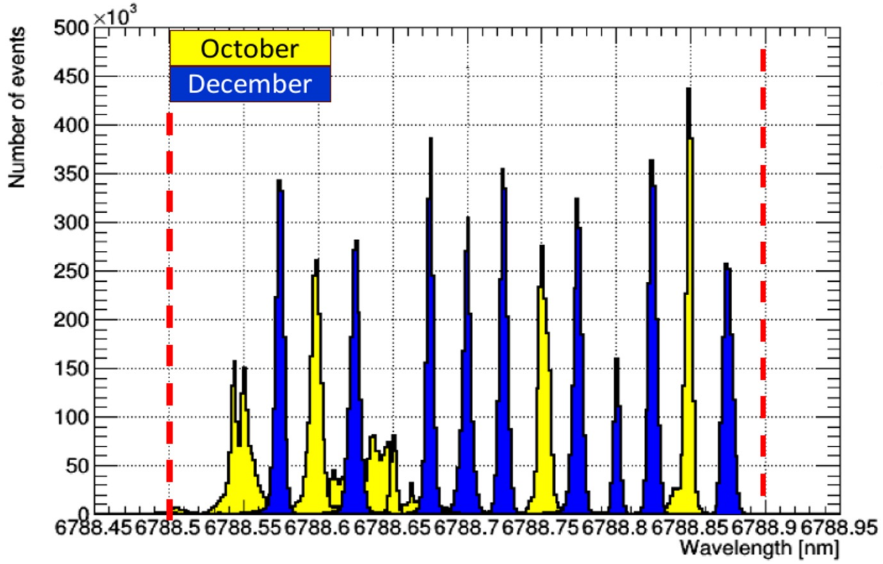
2023: primi run di fisica



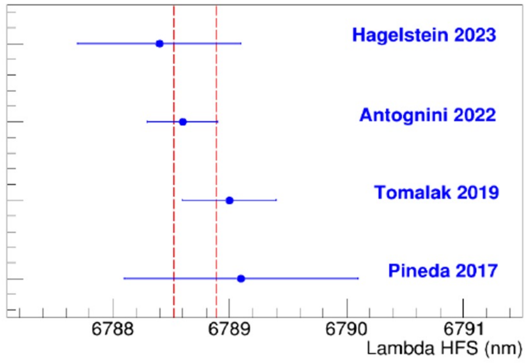
(a) the beam hodoscope, 1mm fibers
(b) the upstream crown of 1 inch $LaBr_3(Ce)$ crystals + SiPM
(c) the central crown with 6 PMT readout prototypes.
(d) (hidden) backstream crown with ½ inch $LaBr_3(Ce)$ + SiPM



2023: Lunghezze d’onda e spettri raccolti

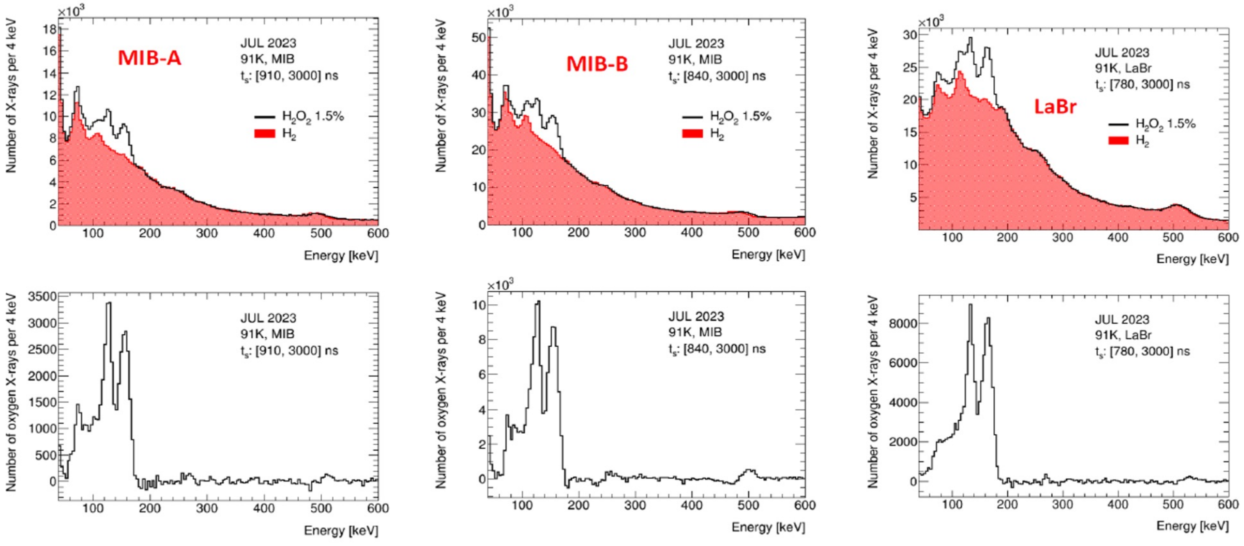


Theoretical prediction of the HFS energy for muonic hydrogen



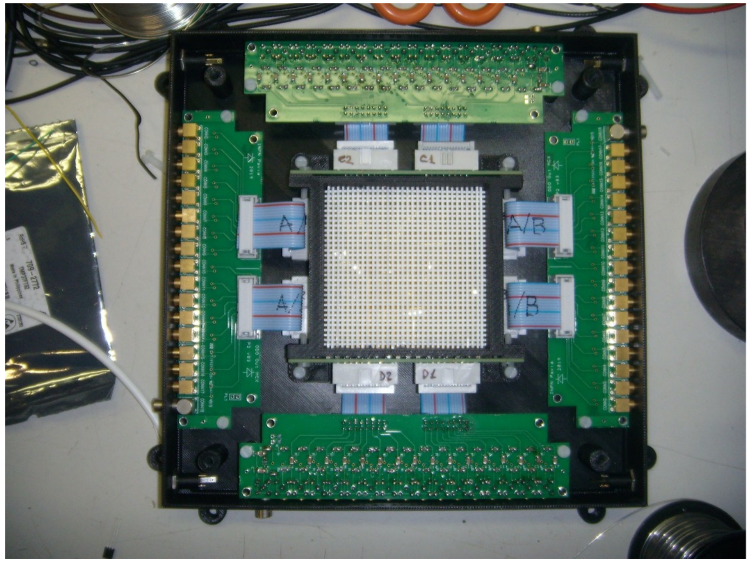
Central and forward crown

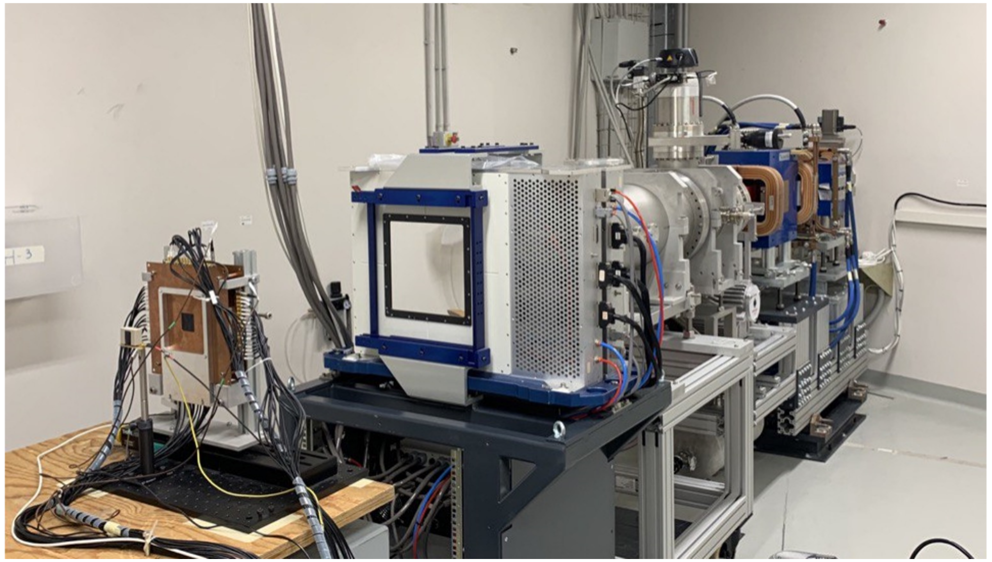
Central crown

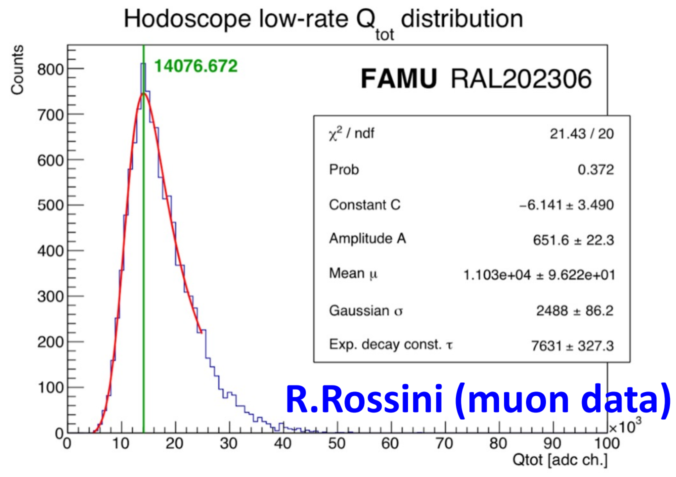


- Picchi dell’ossigeno muonico (run di commissioning)
- Analisi dati in corso…

Attività FAMU-PV 2023: test degli odoscopi (monitor del fascio di muoni) a CNAO e a RAL







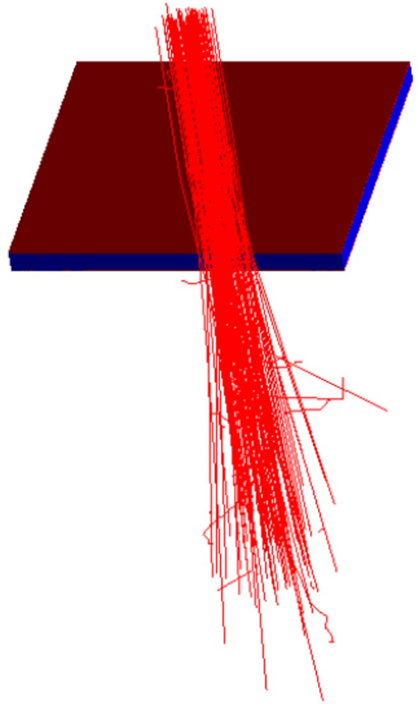
- caratterizzazione con fascio a basso flusso di protoni a CNAO / muoni a RAL .
- inter-calibrazione delle fibre.
- determinazione della carica depositata da una singola particella nel range energetico di lavoro in FAMU per poter stimare il flusso di muoni nell'esperimento.

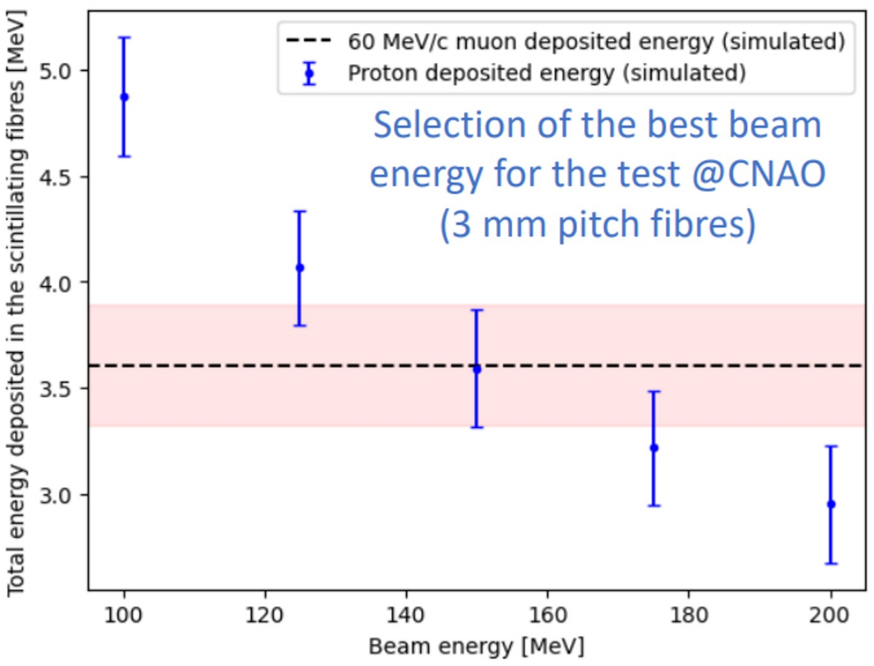
Attività FAMU-PV 2023: simulazione dell'odoscopio in Geant4

- Simulazione in Geant4 in prosecuzione dall'anno precedente.
- Attività di supporto sia per i test a CNAO con protoni a basso rate, sia per i run sperimentali ad alto rate di muoni a RAL.

Attività in prosecuzione nel 2024.

R. Rossini





Attività FAMU-PV 2023: conferenze e pubblicazioni

16th Topical Seminar on Innovative Particle and Radiation Detectors , Siena, Italy (talk):

- R. Rossini: "Status of the FAMU experiment at RIKEN-RAL for a precision measurement of the Zemach radius of the proton in muonic hydrogen" (talk)
- R. Rossini: "Characterisation of a low-momentum high-rate muon beam monitor for the FAMU experiment at RIKEN-RAL" (poster)

- R. Rossini et al., "Characterisation of a scintillating fibre-based hodoscope exposed to the CNAO low-energy proton beam", NIMA
- R. Rossini et al., "Characterisation of muon and proton beam monitors based on scintillating fibres with a SiPM read-out", NIMA
- M. Bonesini et al., "Comparison of new SiPM devices for applications in High-Energy physics", NIMA
- M. Stoilov et al., "Experimental determination of the energy dependence of the rate of the muon transfer reaction from muonic hydrogen to oxygen for collision energies up to 0.1 eV", Phys. Rev. A
- M. Bonesini et al., "Improving the Time Resolution of Large-Area LaBr3:Ce Detectors with SiPM Array Readout", Cond. Matter
- A. Vacchi et al, "Investigating the Proton Structure: The FAMU Experiment", Nuclear Physics News
- M. Bonesini et al, "Large area LaBr3:Ce crystals read by SiPM arrays with improved timing and drift control", NIMA

JLAB12

Jlab12: Sigla che accorpa tutte la attività INFN al Thomas Jefferson Laboratory, Virginia. Centro di ricerca attorno ad un acceleratore di elettroni con varie sale bersaglio fisso. Noto per 20 anni attività fascio 6 GeV, poi upgrade a 12 GeV.

Gruppo Jlab PV/BS 2023 impegnato collaborazioni **CLAS** e **BDX**:

Ricercatori:

- Andrea Bianconi 100 %,
- Luca Venturelli 30 %,
- Valerio Mascagna 40 %,
- Giovanni Costantini 50 %,
- Stefano Migliorati 0
- Giulia Gosta 0

Tecnologi:

- Marco Leali 50 %,
- Luigi Solazzi 50 %.

Tot 3.2 FTE

(Migliorati, dottorato nel 2023 ed ora assegnista, e Gosta, assegnista nel 2023, non hanno percentuali in Jlab12 ma hanno collaborato a vari progetti Jlab).

Collaborazione **BDX** (+ spinoff):

Obiettivo di bandiera: Dark Matter leggera nel flusso secondario a valle del beam dump di Jlab.
Stato arte: in standby per la difficoltà a reperire fondi extra per ampliamento sito sotterraneo per apparato completo.

BDX-mini: versione prototipo, ha raccolto misure competitive su limiti superiori, destinate pubblicazione.

NuBDX: misure con neutrini e/o muoni, presenti a valle del beam dump. Fase simulazioni.

Positroni: La collaborazione BDX ha pubblicato studio su misure DM in caso realizzazione fascio positroni al Jlab.

Nostre attività in BDX:

- nuBDX: simulazione GEMC dello schermaggio attivo/passivo di neutroni.

CLAS: Collaborazione multipurpose su apparato sala B, misure sia esclusive a pochi adroni, sia semi-inclusive, polarizzazione elettroni ed L/T target (p, D → n, nuclei).

Attività recenti o in corso:
Ri-calibrazione (finalizzata “pass-2” = revisione dati 2019)
Prese dati con target polarizzato L.

Criticità:
Polarizzazione T: accantonato progetto iniziale “Dice” target HD. Ripiegherà su bersagli tradizionali --> ostacolo: ristrutturare campi magnetici e rivelatori in zona target.

Raccolta dati:
Raccolti dati fino a marzo 2023. Prevista intensa attività nei mesi estivi, questa in realtà per problemi vari è stata spostata all’autunno e alla primavera 2024. Prevista nuova sosta fino a settembre 2024.

Pubblicati
Si sono alternati articoli relativi ai dati raccolti in anni recenti con il nuovo accelratore (che ha funzionato a diverse energie tra I 2 e gli 11 GeV) ad articoli risultato delle vecchie prese dati dalla fase 6 GeV.

Attivita' 2023-24 del nostro gruppo in CLAS

Shift marzo 2023:
4 turni da 8 ore (M.Leali).
Shift marzo-maggio 2024:
45 turni da 8 ore (M.Leali, V.Mascagna, S.Migliorati)
Il forte sbilanciamento tra I due anni è dovuto ad un lungo break imprevisto del fascio nell'estate 2023, periodo nel quale erano programmati i nostri turni che sono stati spostati al 2024. Questo ha causato il prematuro quasi completo esaurimento dei fondi 2024, che sono risultati finora sufficienti solo grazie all'integrazione con fondi Probes.

Hardware:
- Lavoro/calibrazione su LTCC (Contatore Cherenkov ex CLAS-6 riadattato per CLAS12):
- Collaborazione con Ferrara lavoro/calibrazione RICH (altro Cherenkov, realizzato a Ferrara):
- Partecipazione lavori gruppo "high luminosity"

Review interne di analisi o draft:
2 review di articoli in via di sottomissione per pubblicazione, 1 review di proposta nuova analisi dati.

SPESE.

2023: Stanziati 14 keuro, spesi circa 2 keuro in 1 missione presa dati Hall B. 4 keuro di nostri fondi sono stati spostati ad altre sezioni per le loro necessità, il resto restituito.

2024: Stanziati 14 keuro. Spesi 13 keuro per 7 trasferte americane + 300 euro per un incontro in Italia. Utilizzati circa 2.5 keuro di integrazione Probes.

Pubblicazioni CLAS 2024

I. A. Skorodumina et al. (CLAS Collaboration), "Double-Pion Electroproduction off Protons in Deuterium: Quasi-Free Cross Sections and Final State Interactions", arXiv:2308.13962, accepted for publication in Phys. Rev. C

L. Clark et al. (CLAS Collaboration), "Photoproduction of the Σ^+ Hyperon Using Linearly Polarized Photons with CLAS", arXiv:2404.19404, submittted to Phys. Rev. C (2024).

A. Kim et al. (CLAS Collaboration), "Beam Spin Asymmetry Measurements of Deeply Virtual π^0 Production with CLAS12", Phys. Lett. B 849, 138459 (2024)

Pubblicazioni CLAS 2023

S. Paul et al. (CLAS Collaboration), "Alignment of the CLAS12 Central Hybrid Tracker with a Kalman Filter", Nucl. Inst. and Meth. A 1049, 168032 (2023).

C. Kim et al. (CLAS Collaboration), "Measurements of the Helicity Asymmetry E for the $\gamma p \rightarrow p\, \pi^0$ Reaction in the Resonance Region", Eur. Phys. J. A. 59, 217 (2023).

S. Diehl et al. (CLAS Collaboration), "First Measurement of Hard Exclusive $\pi^- \Delta^{++}$ Electroproduction Beam Spin Asymmetries off the Proton", Phys. Rev. Lett. 131, 021901 (2023).

I. Korover et al. (CLAS Collaboration), "Observation of Large Missing-Momentum (e,e'p) Cross-Section Scaling and the Onset of Correlated-Pair Dominance in Nuclei", Phys. Rev. C 107, L061301 (2023).

G. Christiaens et al. (CLAS Collaboration), "First CLAS12 Measurement of DVCS Beam-Spin Asymmetries in the Extended Valence Region", Phys. Rev. Lett. 130, 211902 (2023).

T. Chetry et al. (CLAS Collaboration), "First Measurement of Λ Electroproduction off Nuclei in the Current and Target Fragmentation Regions", Phys. Rev. Lett. 130, 14 (2023).

S. Diehl et al. (CLAS Collaboration), "A Multidimensional Study of the Structure Function Ratio $\sigma_{LT'}/\sigma_0$ from Hard Exclusive π^+ Electroproduction off Protons in the GPD Regime", Phys. Lett. B 839, 137761 (2023).

H. Avakian et al. (CLAS Collaboration), "Observation of Correlations Between Spin and Transverse Momenta in Back-to-Back Dihadron Production at CLAS12", Phys. Rev. Lett. 130, 022501 (2023).

LEA

Low Energy Antimatter

sigla che comprende

AEGIS, ALPHA, ASACUSA

ovvero, esperimenti con antiprotoni a bassa energia

+

PsICO,QUPLAS

esperimenti con positronio, nessun partecipante di Pavia

LEA - Low Energy Antimatter

CONSUNTIVI 2023

CSN3

The LEA Collaboration

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E.Pasino, L. Povolo, M.Urioni →

← A. Del Vincio, M. Bayo, R.Fergusson, A. Chehaimi

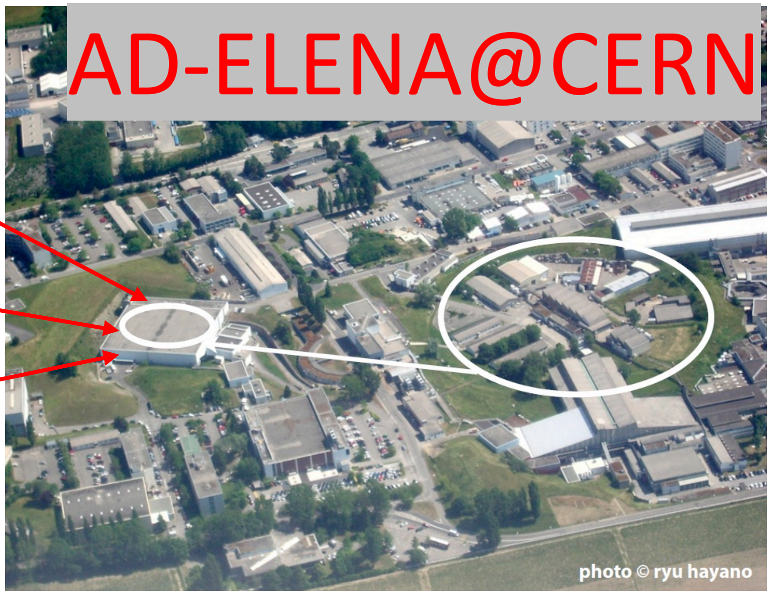
SEDE	NOMINATIVO	TIPO	CONTRATTO	QUALIFICA	RICERCATORI	TECNOLOGI	NOTE
PV	Baù Marco	ASSOC	Tecnologica Ricercatori/Prof...	Ricercatore B Temp...		50	
	Bonomi Germano	ASSOC	Incarico di Ricerca tecnolog...	Prof. Ordinario		30	
	Calosso Claudio Eligio	ASSOC	Tecnologica Ricercatori/Prof...	Ricercatore Confer...		50	
	Costantini Giovanni	ASSOC	Tecnologica Assegno universi...	Assegnista		50	
	Ferrari Marco	ASSOC	Scientifica Ricercatori/Prof...	Prof. Associato	50		
	Ferrari Vittorio	ASSOC	Scientifica Ricercatori/Prof...	Prof. Ordinario	50		
	Gosta Giulia	DIP	Assegno di Ricerca	Assegno di Ricerca	50		
	Leali Marco	ASSOC	Tecnologica Ricercatori/Prof...	Tecnico Categoria B		50	
	Mascagna Valerio	ASSOC	Tecnologica Ricercatori/Prof...	Ricercatore B Temp...	40		
	Migliorati Stefano	ASSOC	Tecnologica Dottorando con b...	Dottorando		100	
	Urioni Marta	ASSOC	Tecnologica Assegno universi...	Assegnista		50	% attiva dal 2023-12-01
	Venturelli Luca	ASSOC	Incarico di Ricerca scientif...	Prof. Ordinario	70		
	Zurlo Nicola	ASSOC	Incarico di Ricerca scientif...	Prof. Associato	20		
					2.8 fte 6 pers.	3.8 fte 7 pers.	
					6.60 fte / 13 pers. (media 0.51)		

PV (13 PERSONE - 6.6 FTE)

LEA Experiments

- AEgIS $\bar{p}$ e^+ Ps $\bar{H}$
- ALPHA $\bar{p}$ e^+ $\bar{H}$
- ASACUSA $\bar{p}$ e^+ $\bar{H}$

AD-ELENA@CERN



- PsICO e^+ Ps
- QUPLAS e^+ Ps

TIFPA-TN

L-NESS-CO

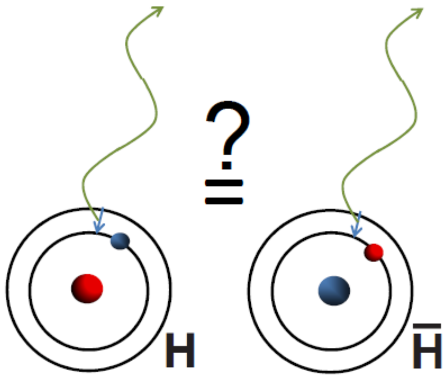
EXPERIMENTS AT CERN

AEgIS ALPHA ASACUSA

Why study antihydrogen?

1) Precise matter/antimatter comparison

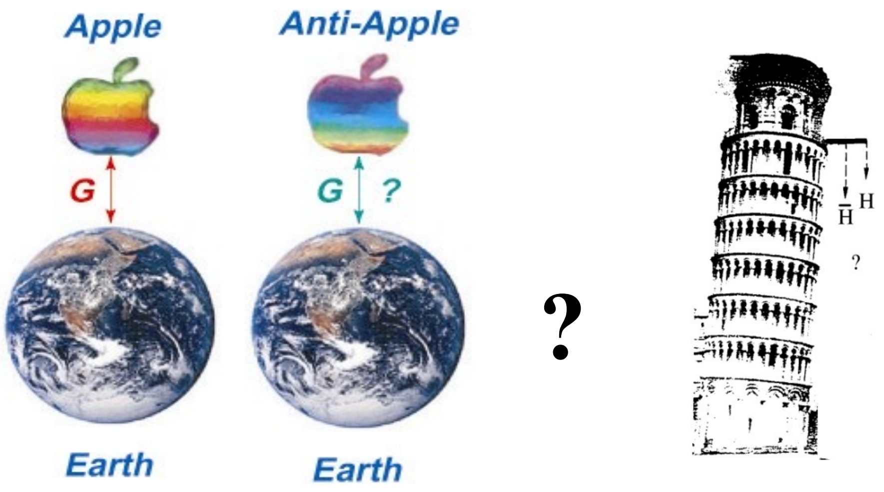
→ test of CPT symmetry



Spectroscopy of $\bar{H}$

2) Measurement of the gravitational behaviour of antimatter

→ test of WEP



Not possible with charged antiparticle

only with neutral system → $\bar{H}$ (or Ps)

AEgIS

Antihydrogen Experiment: Gravity, Interferometry and Spectroscopy

INFN contact person: Roberto Brusa (TN)

Main physics goals
Tests of the Weak Equivalence Principle
Spectroscopy and tests of CPT
Beyond the Standard Model searches

Systems
antihydrogen, positronium, antiprotonic atoms

Main tools
Laser-controlled charge-exchange reactions
Spectroscopy and laser cooling with pulsed lasers
Moiré deflectometry and atom interferometry

57 members from 15 institutes from 10 countries

Switzerland	France
Poland	Latvia
Italy	India
Germany	Czech Republic
Norway	UK

New groups (MoU signed in 2023)
- Jagiellonian University, Poland
  1 senior + 1 post.doc + 1 student

New groups (MoU in discussion for 2024)
- Siegen University, Germany
- Technical University of Munchen, Germany

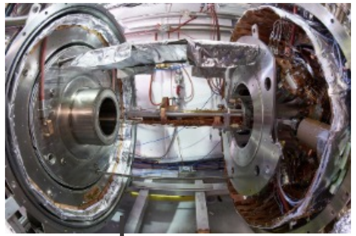
AEgIS past timeline and active research lines

Active research lines: Shared dev + H̄ + Ps + p̄ atoms + R&D

PROPOSAL

2008

Construction began

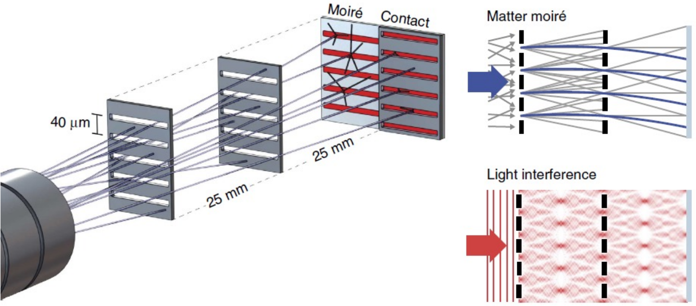


2012

2014

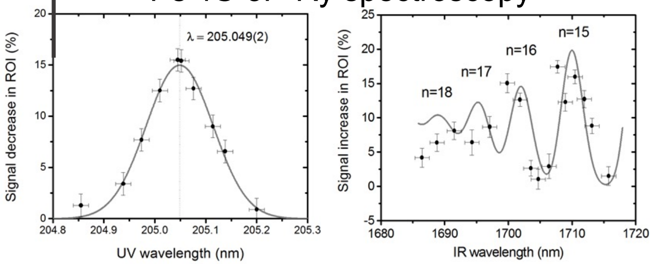
Received 5 Nov 2013 | Accepted 27 Jun 2014 | Published 28 Jul 2014 DOI: 10.1038/ncomms5538 OPEN

A moiré deflectometer for antimatter



2016

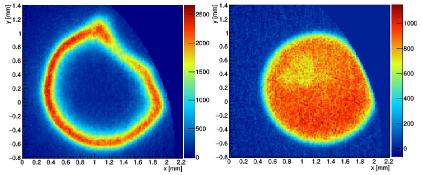
Ps 1S-3P-Ry spectroscopy



S. Aghion et al., PRA **94,** 012507 (2016)

2017

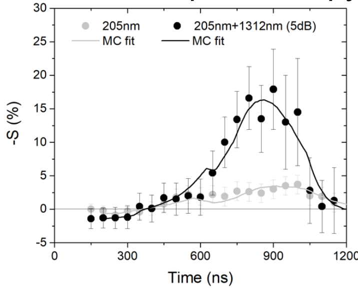
Pbar compression to mm radius



S. Aghion et al., Eur. Phys. J. D (2018) 72: 76

2018

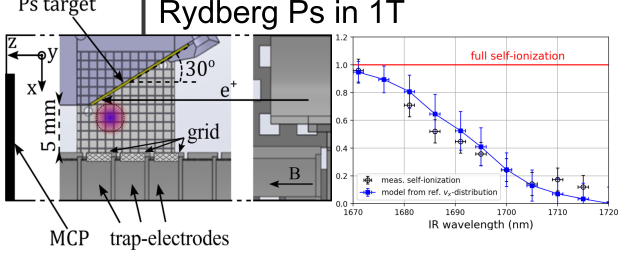
Ps 2S-3P spectroscopy



M. Antonello et al., PRA **100,** 063414 (2019)

2019

Rydberg Ps in 1T

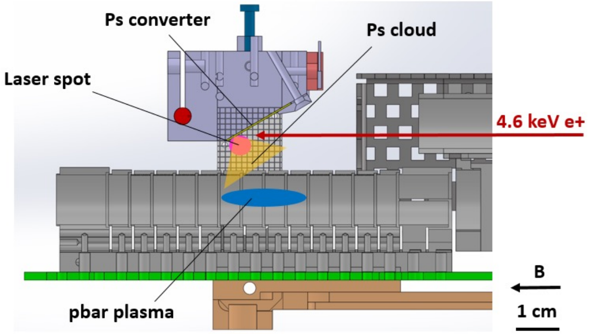


M. Antonello et al., PRA **102,** 013101 (2020)

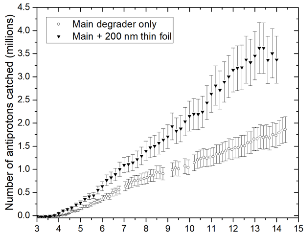
2020

https://doi.org/10.1038/s42005-020-00494-z OPEN

Pulsed production of antihydrogen



2023

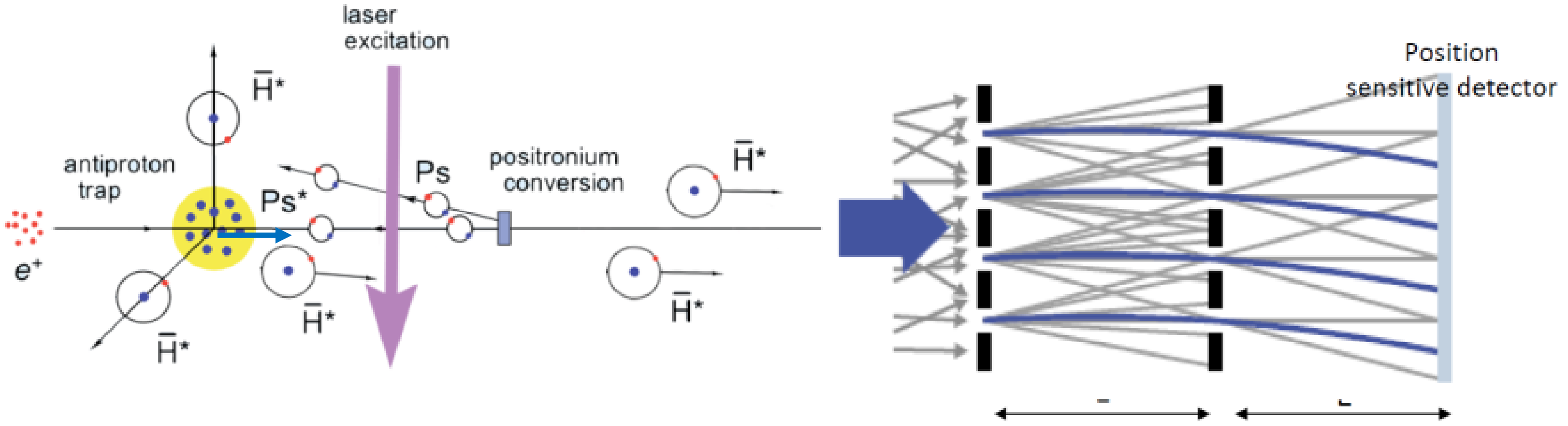


Efficient catching from ELENA

AEgIS : Overview of the experiment

Schematic

$$\overline{p}+(Ps)^{*}\rightarrow\overline{H}^{*}+e^{-}$$



New pulsed $\overline{H}$ production

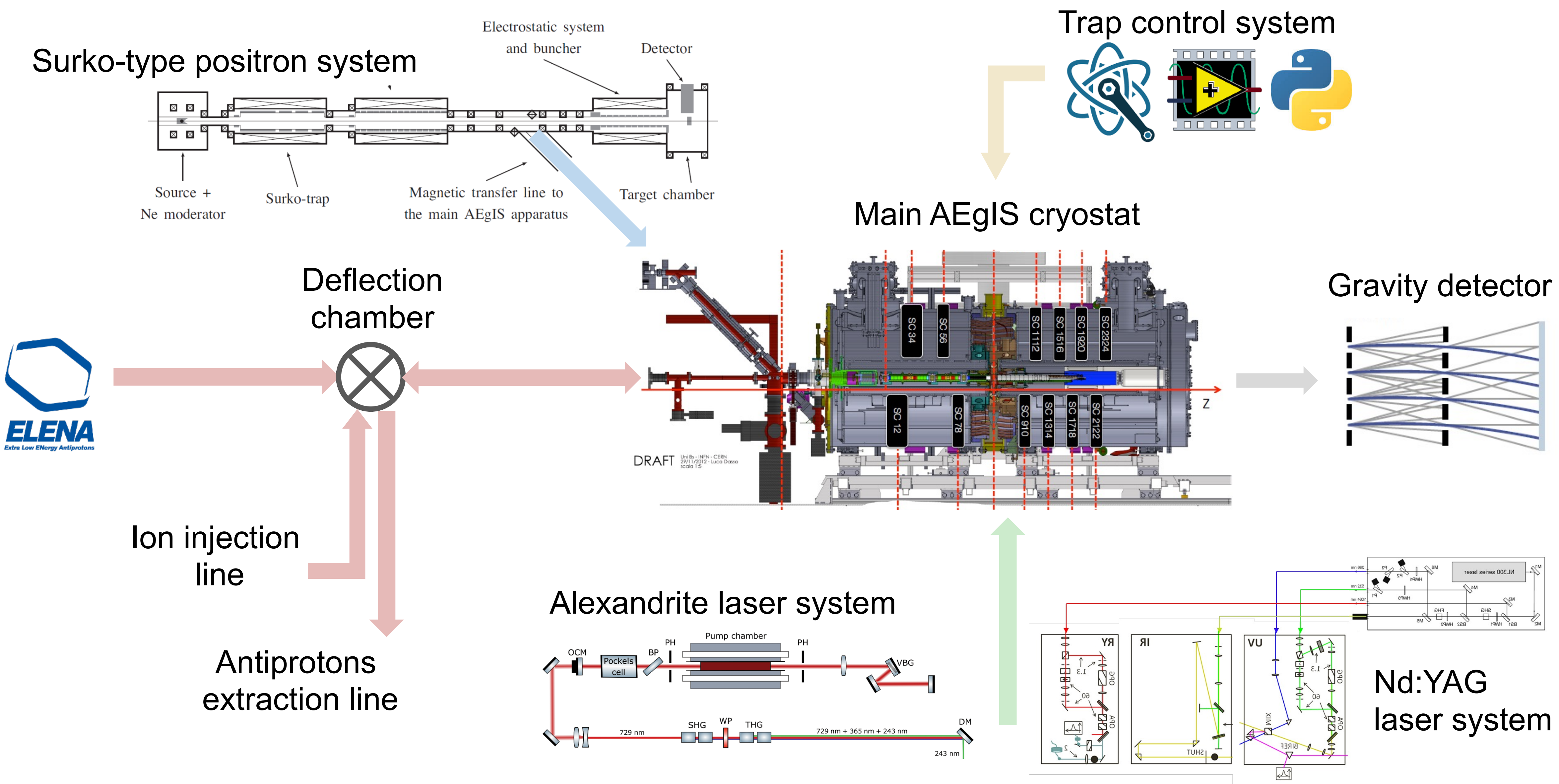
Beam formation

Gravity measurement

Physical goal: measurement of the gravitational interaction between matter and antimatter

Technical steps: cold $\bar{p}$; pulsed cold *Ps* and *Ps** formation; pulsed formation of $\overline{H}$; beam formation ; deflectometer

The main apparatus in 2023: an overlook

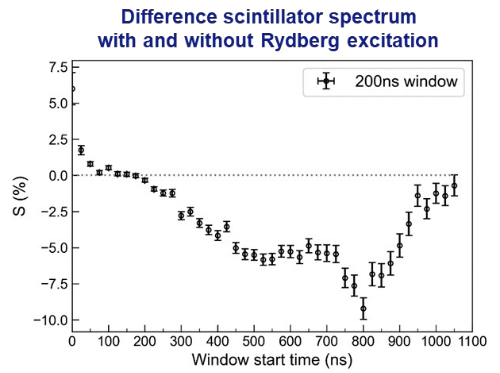


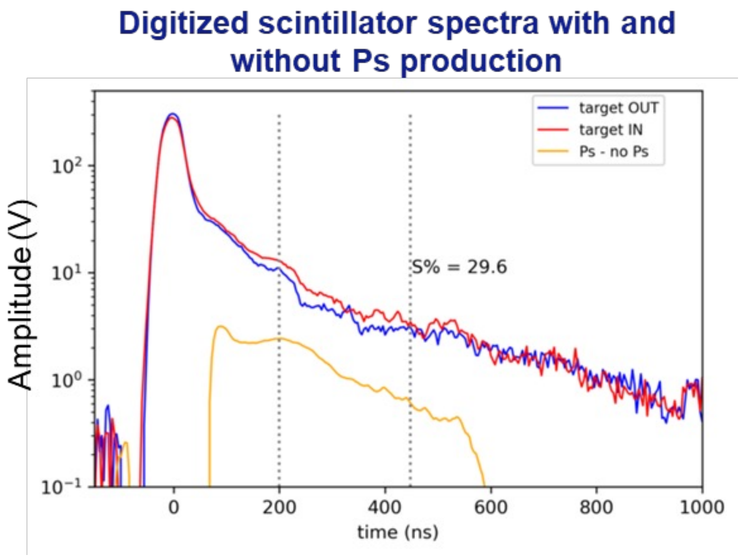
AEgIS Results 2023

Results of the main research line in 2023:

- **Formation and excitation of positronium in collinear geometry**. Alignment of positron and laser beams on the small-sized positron/positronium converter (5x5 mm).

Ps excited to the **Rydberg level n = 21** beyond the n = 17 limit of non-collinear geometry, allowing an increase in the anti-hydrogen formation cross-section.





- Plasma manipulations (antiprotons - electrons) were implemented with the new control system, including continuous and efficient capture in 5T traps and efficient transport in 1T traps of the formation region.

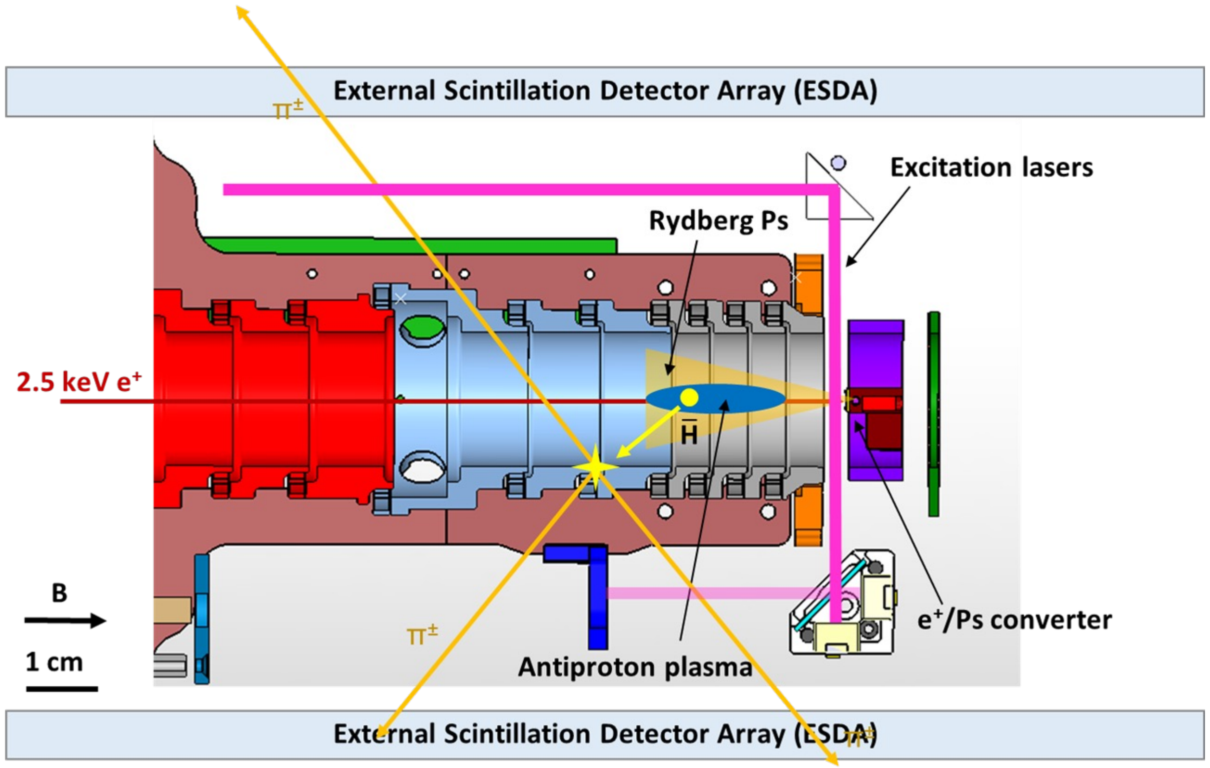
- A new absolute record of **cold antiprotons in trap**, about a **hundred million particles**, has been established.

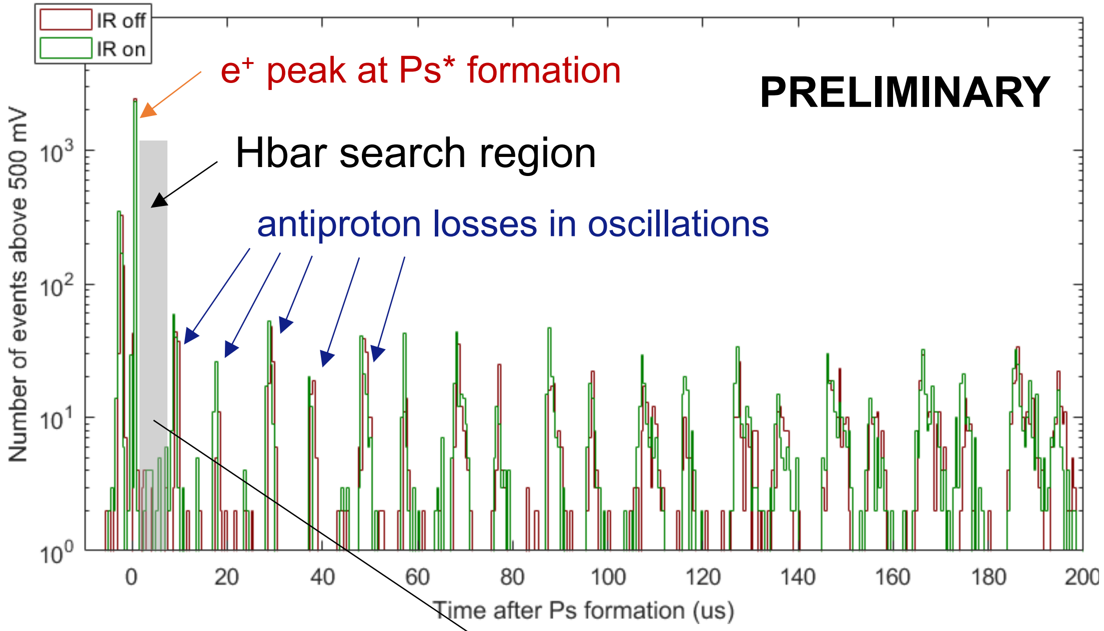
- Experimentally verified that the **positron bunch passes through the antiproton plasma** to reach the e+/Ps converter **without disturbing it**. Thus, the correct choice of collinear geometry is confirmed.

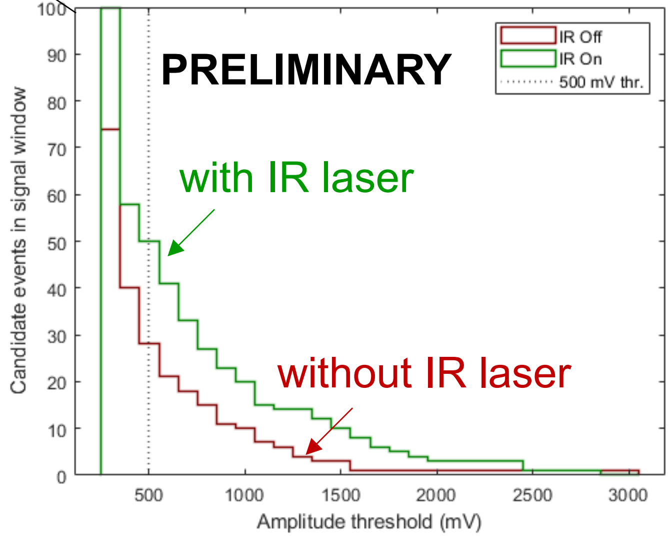
AEgIS Results 2023

Results of the main research line in 2023:

- The first **evidence of antihydrogen formation in collinear configuration** has been obtained. The data are still preliminary and under analysis.







AEgIS Results 2023

Scientific results from other research lines in 2023:

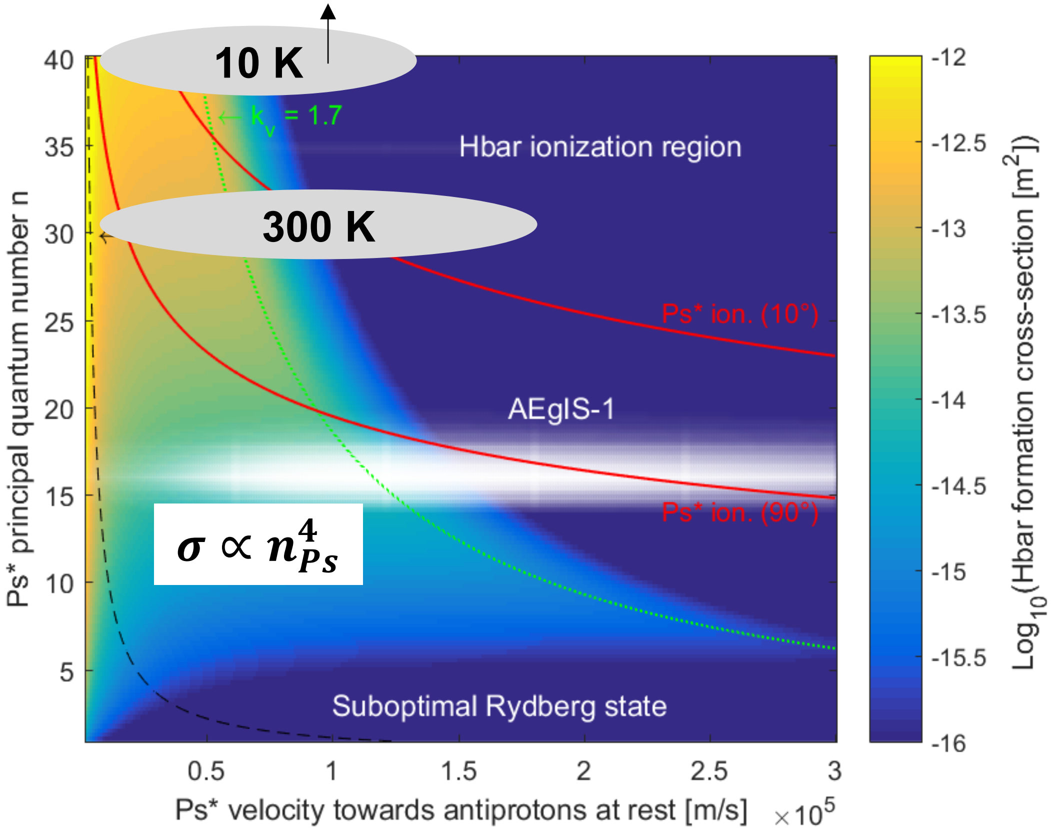
- **Laser cooling of positronium** for the first time: Data acquisition campaign concluded in the experimental chamber dedicated to positronium physics. It was cooled in 1D using lasers, bringing its temperature from 380 to 170 K. The result is under publication in Physical Review Letters (expected by late February) and has been selected as Editors' Highlight and for a press release by APS, CERN, and INFN.

- **Development of a high-resolution detector** (less than 2 µm) **for anti-hydrogen/antiprotons** annihilation vertices, based on CMOS sensors, surpassing previously tested nuclear emulsions. An article on tests with antiprotons is being prepared.

- **Development of a technique to form antiprotonic atoms** by mixing antiprotons with a gaseous target, trapping the products, and analyzing them with Time of Flight spectroscopy for identification. It opens new avenues for precision measurements of antiproton fragmentation on different elements, for forming exotic nuclei and highly charged ions in Penning trap. An article is in preparation.

Highlight: Positronium Laser Cooling

The interaction cross-section between pbar and Ps* can be enhanced by targeting higher Rydberg levels, only by first **lowering the temperature/improving the collimation** of the Ps beam.



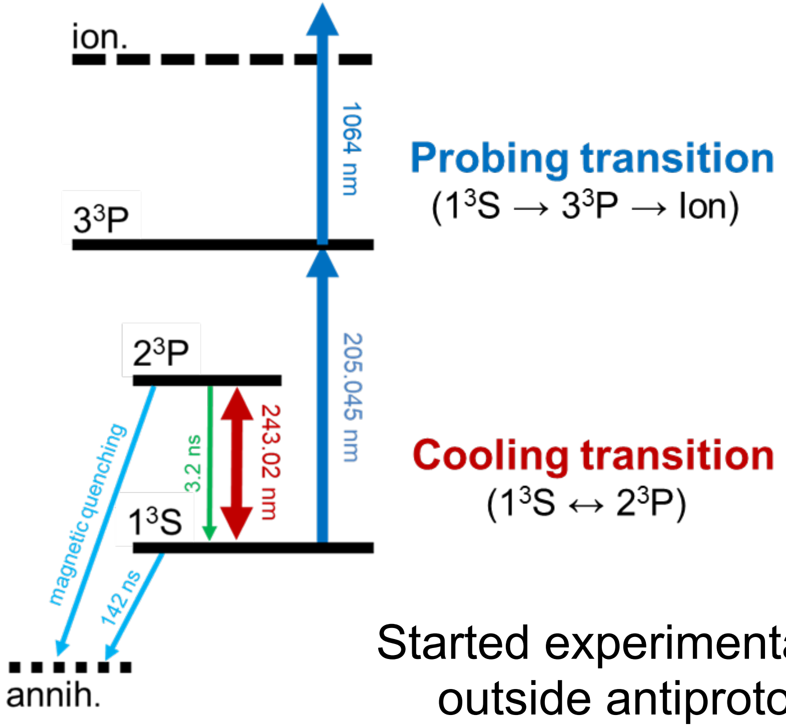
collinear + 300 K → cross-section ×10

collinear + 100 K + Ps cooling to 10 K → cross-section ×70

PHYSICAL REVIEW A **104**, 023106 (2021)

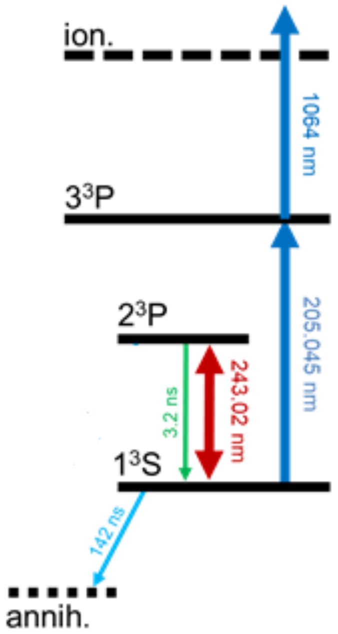
Positronium laser cooling in a magnetic field

Christian Zimmer,[1,2,3,4,*] Pauline Yzombard,[5,*] Antoine Camper,[4] and Daniel Comparat[6]



Started experimentation in 2020
outside antiproton beam time

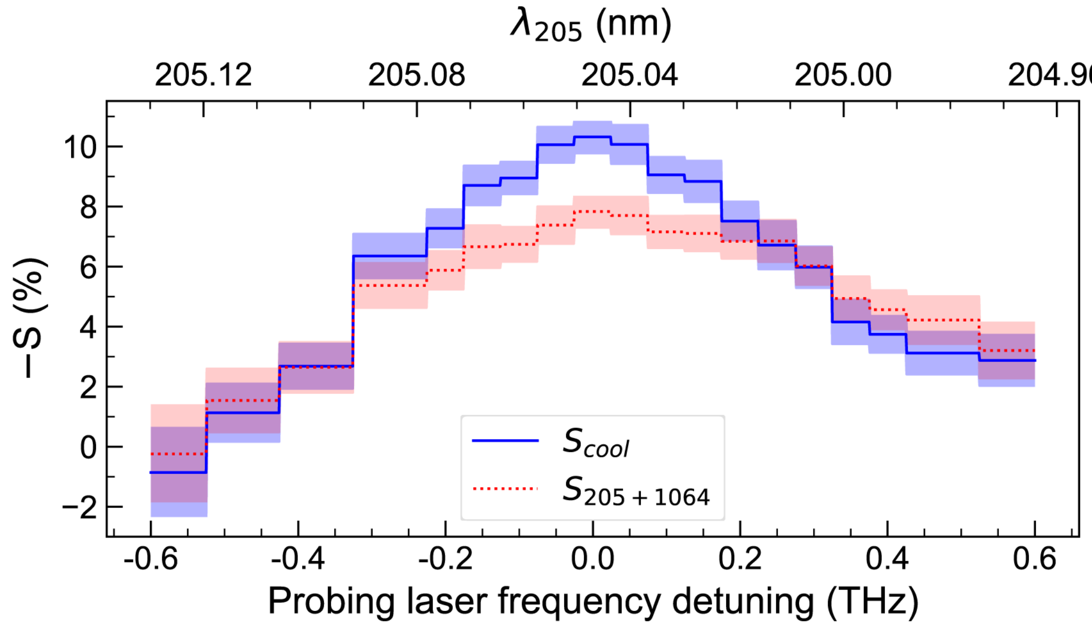
Highlight: Positronium Laser Cooling



Probing transition
($1^3S \rightarrow 3^3P \rightarrow$ Ion)

Cooling transition
($1^3S \leftrightarrow 2^3P$)

Narrowing and increase of the probing line with laser cooling



> The Ps cloud was cooled from 380(20) K to 170(20) K <

> Maximum cooling efficiency allowed by Doppler laser cooling reached <

The impact of this result goes beyond enhancing the antihydrogen production cross-section:
opens the way for precision spectroscopy, clock tests of the WEP with Ps, and Bose-Einstein condensation

Per tutti I dettagli si rimanda a: L. Gloggler et al. (AEgIS collaboration), PHYSICAL REVIEW LETTERS 132, 083402 (2024)

Progresso AEgIS 2023 – tabella milestones, pubblicazioni e conferenze

Milestones 2023	Data completamento	Percentuale
Trasporto laser in zona Hbar e formazione Ps	31/12/23	100 %
Manipolazione antiprotoni nelle nuove trappole	31/12/23	100 %

Pubblicazioni

- **"Positronium laser cooling via the 1^3S-2^3P transition with a broadband laser pulse"**, L. Gloggler et al. (AEgIS Collaboration), accettato su Physical Review Letters with Editors' Highlights
- **"CIRCUS: an autonomous control system for antimatter, atomic and quantum physics experiments"**, M. Volponi et al. (AEgIS Collaboration), accettato su EPJ Quantum Technologies
- **"TALOS: a framework for autonomous control systems for complex experiments"**, Volponi, M. et al. (AEgIS Collaboration), *sottomesso a Review of Scientific Instruments*
- **"Pulsed Production of Antihydrogen in AEgIS"**, Zurlo, N. et al. (AEgIS Collaboration), EPJ Web of Conferences 290, 07001 (2023)
- **"Weighing antimatter: AEgIS Phase 2, upgrades and first data"**, Volponi, M., Il Nuovo Cimento C, 2023, issue 4, article 106
- **"Toward a pulsed antihydrogen beam for WEP tests in AEgIS"**, Huck, S. et al. (AEgIS Collaboration), EPJ Web of Conferences 282, 01005 (2023)

Conferenze

- **Marco Volponi**, *Progress towards measuring the gravitational coupling of antimatter,* Rencontres de Moriond – Gravitation, La Thuile (IT), 20-25 Marzo 2023 (**Invited Talk**)
- **Marco Volponi,** *Measuring the fall of antimatter in Earth's gravitational field* - ECT* PhD Seminar, Trento (IT), 14 Aprile 2023 (**Invited seminar**)
- **Ruggero Caravita,** *Pulsed beams of cold antihydrogen and positronium for inertial experiments at the AEgIS experiment,* XXI International Workshop on Low-Energy Positron and Positronium Physics and XXIII International Symposium on Electron-Molecule Collisions and Swarm (POSMOL 2023)- Notre Dame (USA), 3-6 August, (**Invited Talk**)

LEA_ALPHA – ALPHA COLLABORATION

INFN contact person: Germano Bonomi (Bs-Pv)

Aarhus University, Denmark

University of Brescia, Italy

University of British Columbia, Canada

University of California Berkeley, USA

University of Calgary, Canada

University of Liverpool, UK

University of Manchester, UK

NRCN - Nuclear Res. Center Negev, Israel

Purdue University, USA

Federal University of Rio de Janeiro, Brazil

INFN (Pavia, Pisa) Italy

Stockholm University, Sweden

Simon Fraser University, Canada `

TRIUMF, Canada

University of Wales Swansea, UK

Cockcroft Institute, UK

York University, Canada

INFN in ALPHA since 2022

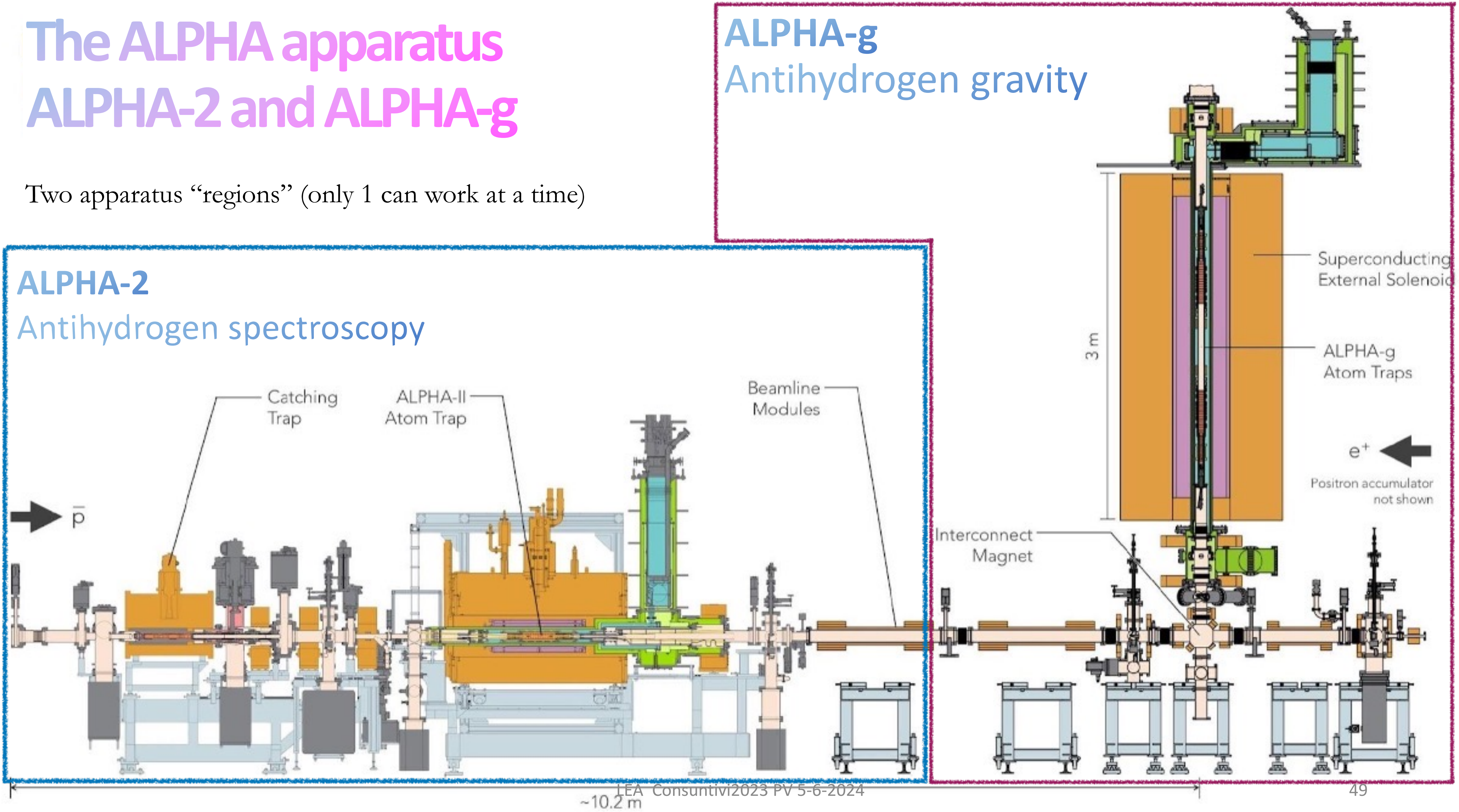
INFN 2023: G. Bonomi, S. Stracka, M. Urioni
INFN 2024: G. Bonomi, A. Del Vecchio, S. Stracka

The ALPHA apparatus
ALPHA-2 and ALPHA-g

Two apparatus "regions" (only 1 can work at a time)

ALPHA-g
Antihydrogen gravity

ALPHA-2
Antihydrogen spectroscopy

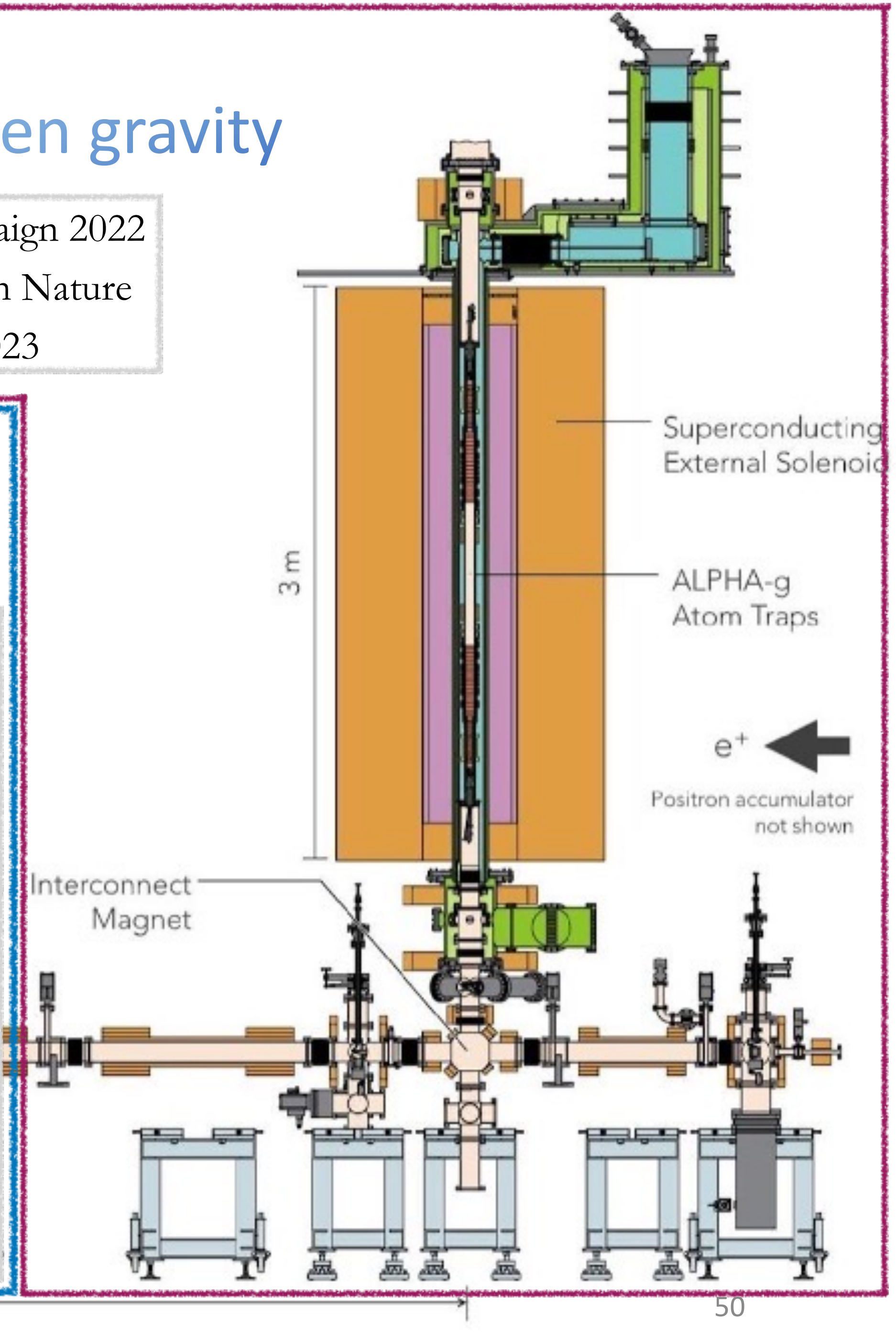


The ALPHA apparatus ALPHA-2 and ALPHA-g

relevant publications

ALPHA-g
Antihydrogen gravity

Measurement campaign 2022
Results published on Nature
on 28 September 2023



ALPHA-2
Antihydrogen spectroscopy

o) "*Trapped antihydrogen*" - Nature 468.7324 (2010)

o) "*Confinement of antihydrogen for 1,000 seconds*" - Nature Physics 7.7 (2011)

o) "*Resonant quantum transitions in trapped antihydrogen atoms*" - Nature 483.7390 (2012)

o) "*Observation of the hyperfine spectrum of antihydrogen*" - Nature 548.7665 (2017)

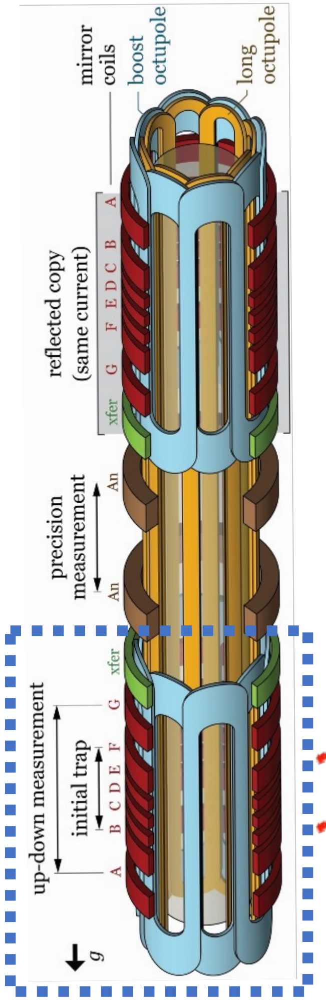
o) "*Observation of the 1S-2S transition in trapped antihydrogen*" - Nature 541.7638 (2017)

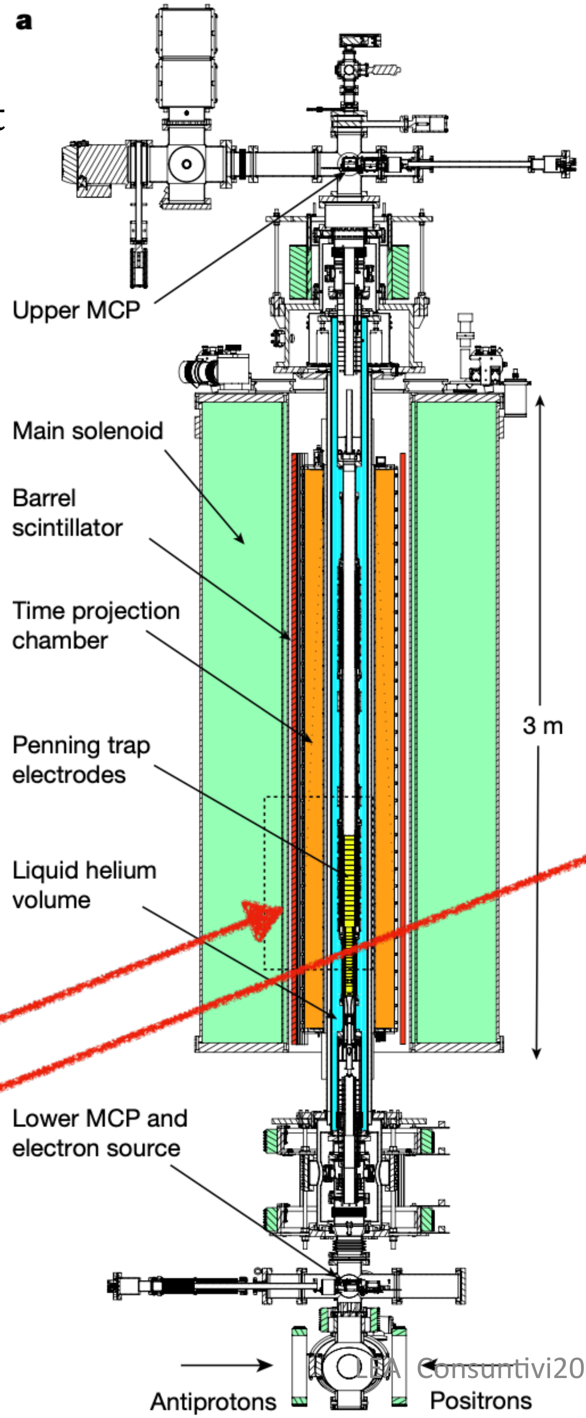
o) "*Observation of the 1S–2P Lyman-a transition in antihydrogen*" - Nature 561.7722 (2018)

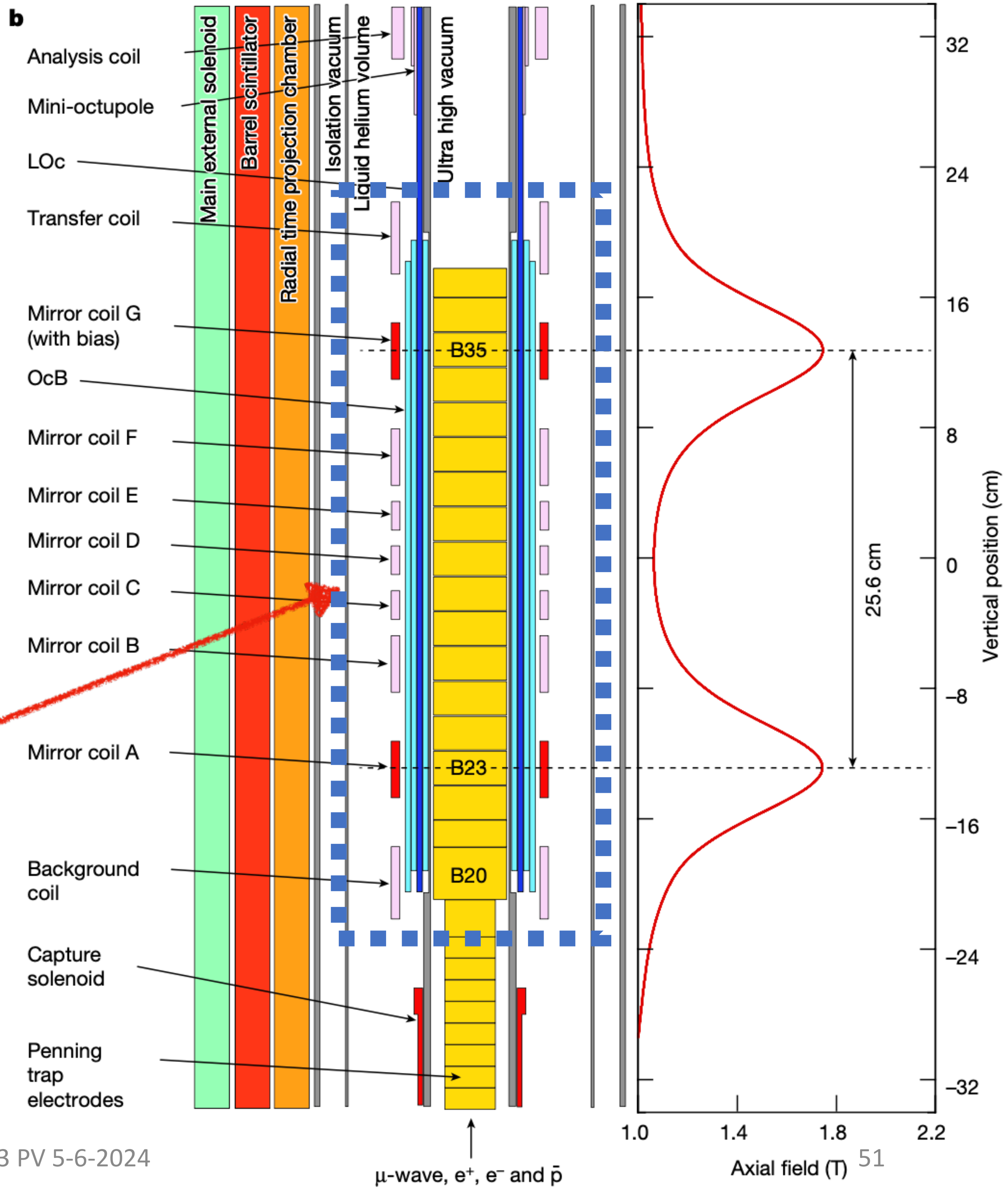
o) "*Investigation of the fine structure of antihydrogen*" - Nature 578.375 (2020)

o) "*Laser cooling of antihydrogen atoms*" - Nature 592.7852 (2021)

LEA_ALPHA
Gravity measurement





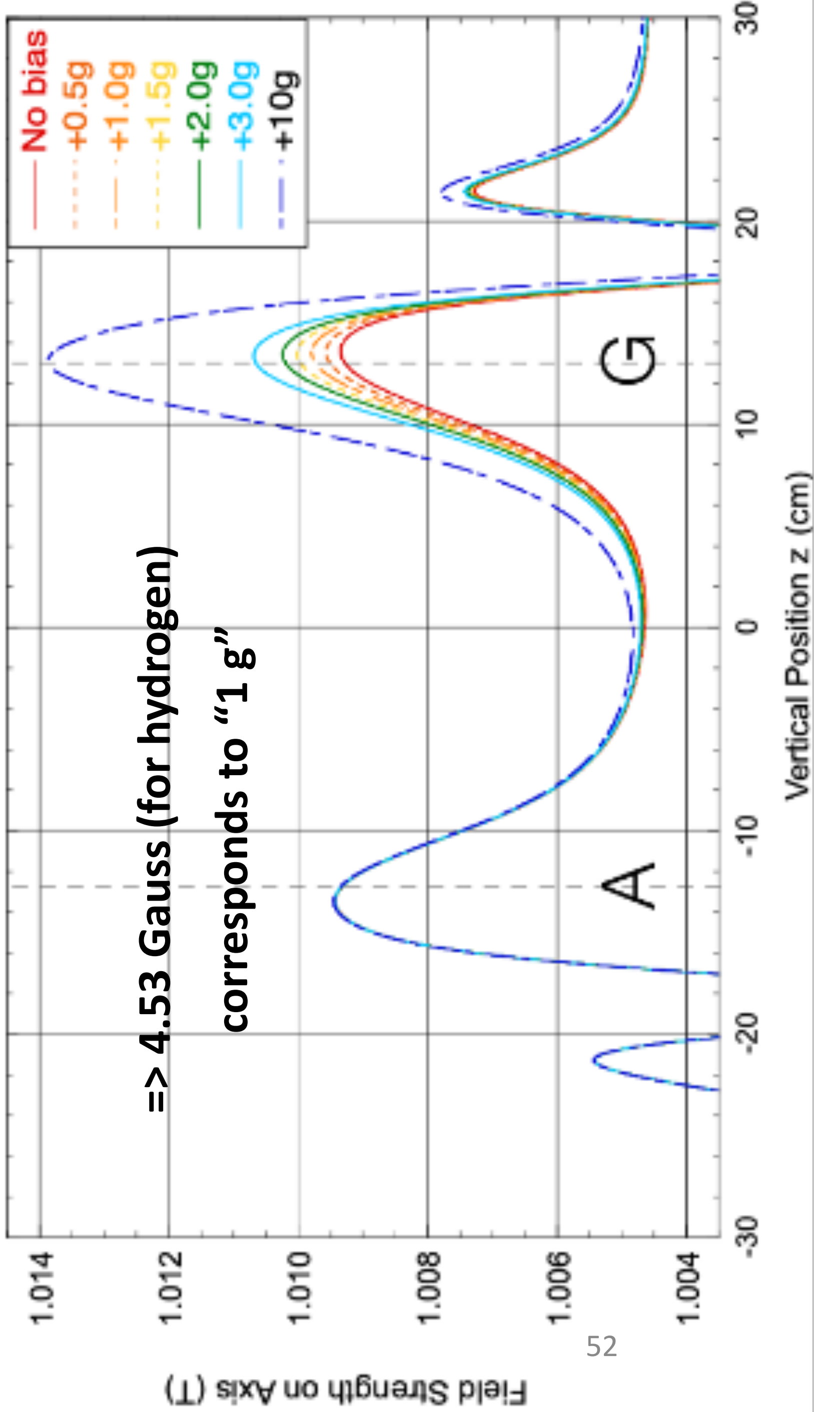


LEA_ALPHA – Gravity measurement

Nominal bias (*g*)	Number of trials	N_{up} (events)	N_{dn} (events)	Events during LOc ramp-down
−3.0	7	151.7	16.5	199.2
−2.0	7	128.7	33.5	168.2
−1.5	6	128.9	57.7	192.0
−1.0	7	69.7	62.5	183.2
−0.5	7	55.7	67.5	201.2
0	7	36.7	94.5	144.2
0.5	7	36.7	124.5	177.2
1.0	7	17.7	119.5	185.2
1.5	6	13.9	180.7	234.0
2.0	7	6.7	163.5	228.2
3.0	7	7.7	147.5	199.2
−10.0	6	142.9	0.7	169.0
10.0	6	−0.1	185.7	213.0

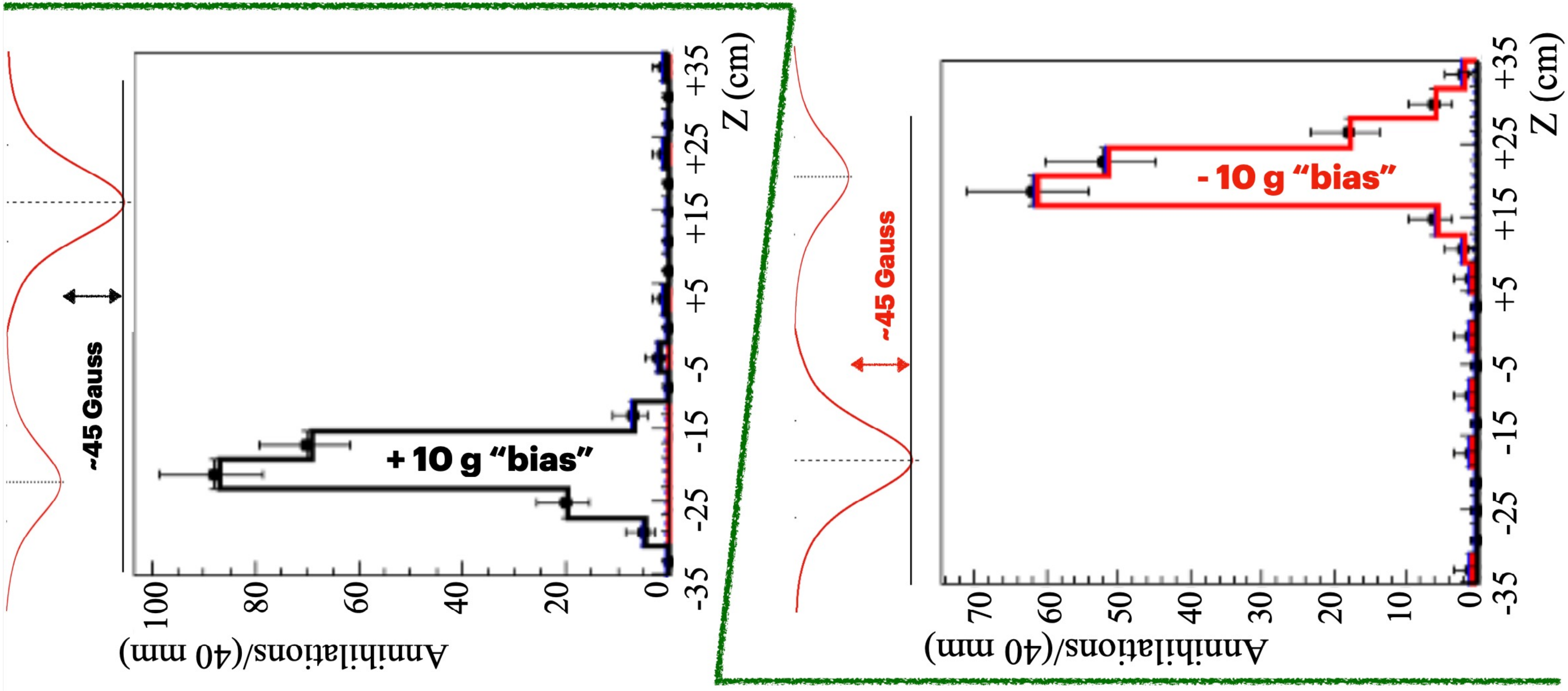
Some parameters:

- ramp time of 20 s (also 130 s were tested) from B ~ 1 T to ~ 0
- **antihydrogen temperature** of less than **0.55 K** => velocity <= 65 m/s
  (real temperature/energy distribution is unknown)



LEA_ALPHA – Gravity measurement

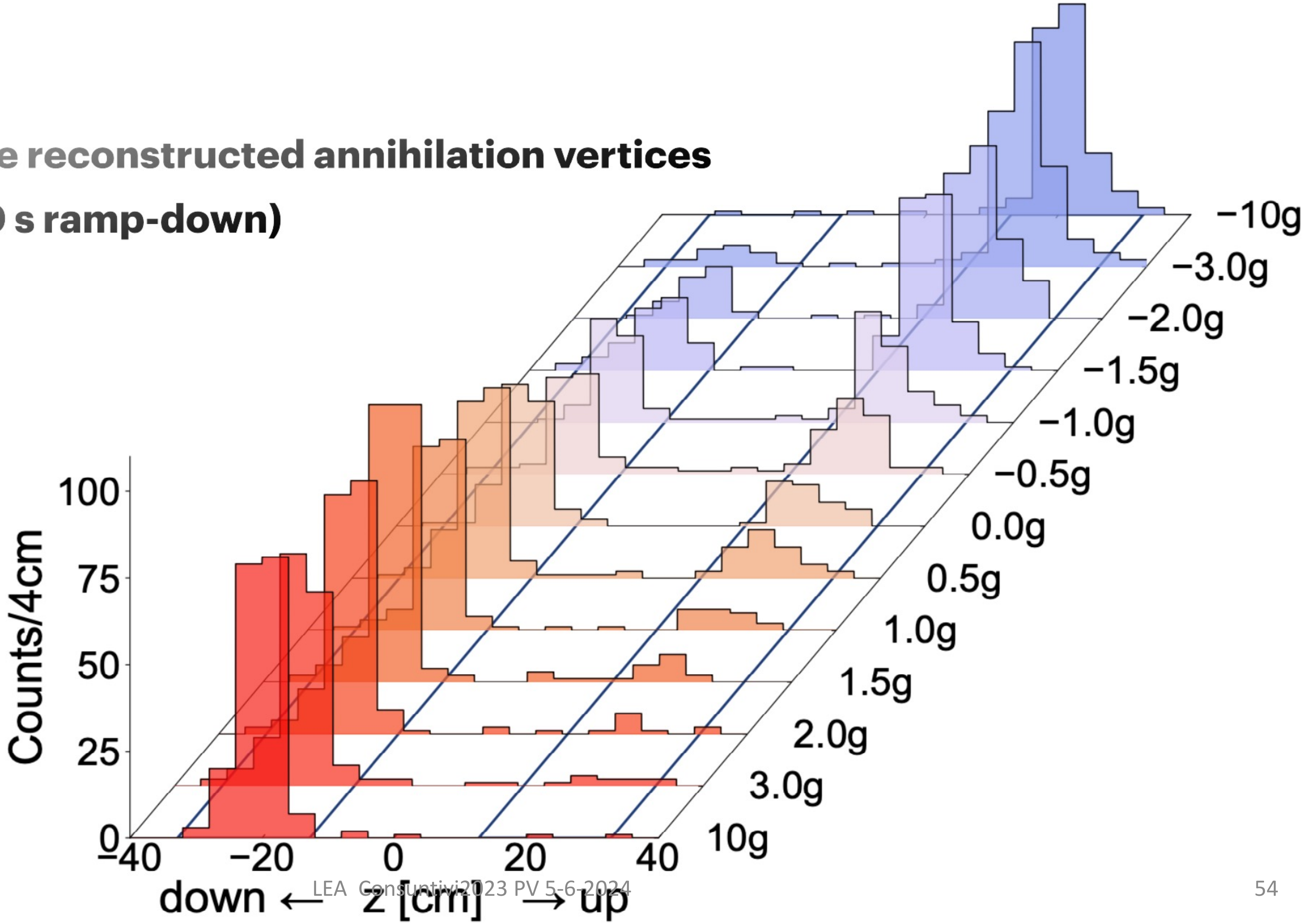
Distributions of the vertical coordinate reconstructed annihilation vertices



LEA_ALPHA – Gravity measurement

Distributions of the reconstructed annihilation vertices

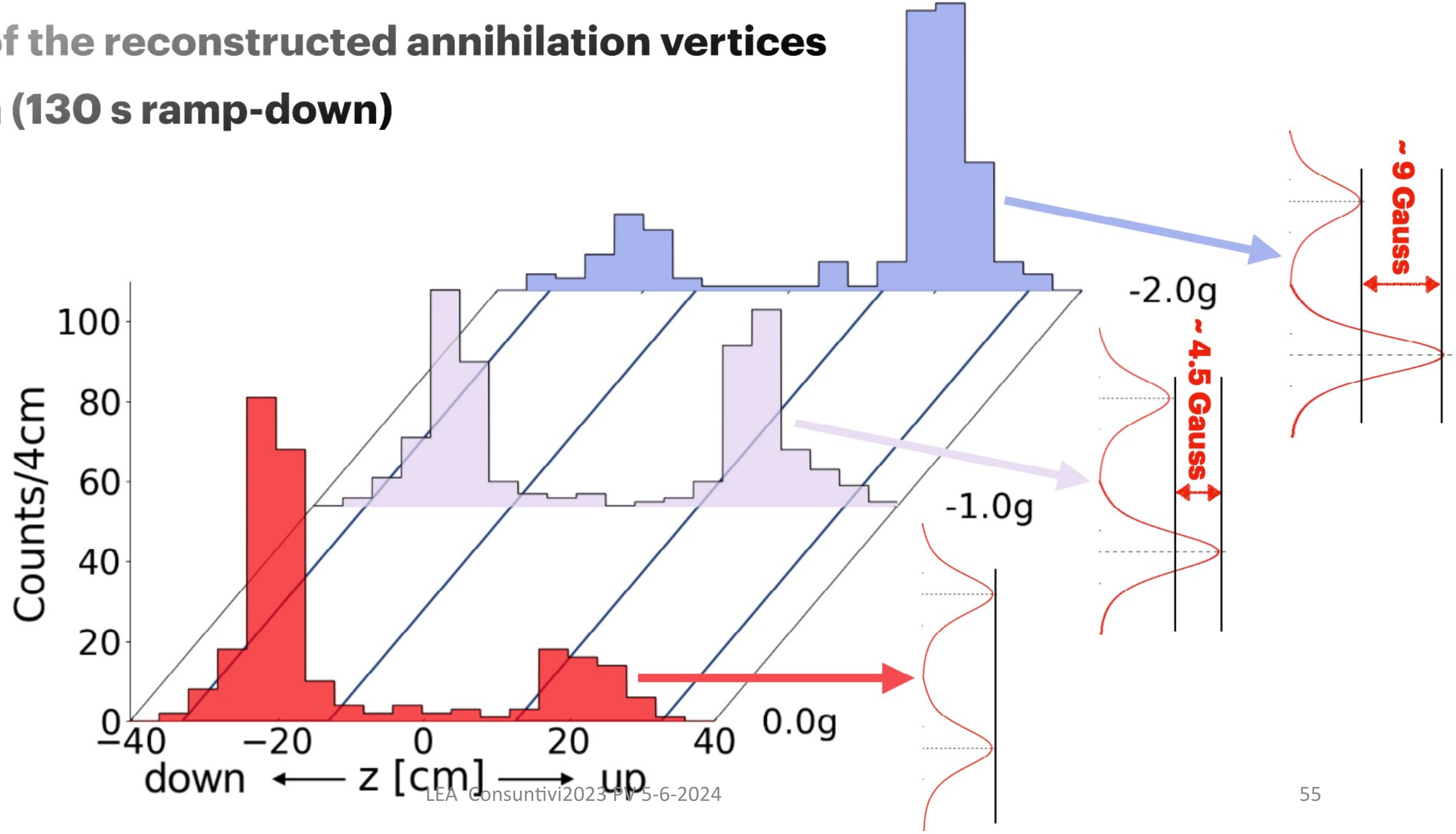
"Physics" data (20 s ramp-down)



LEA_ALPHA – Gravity measurement

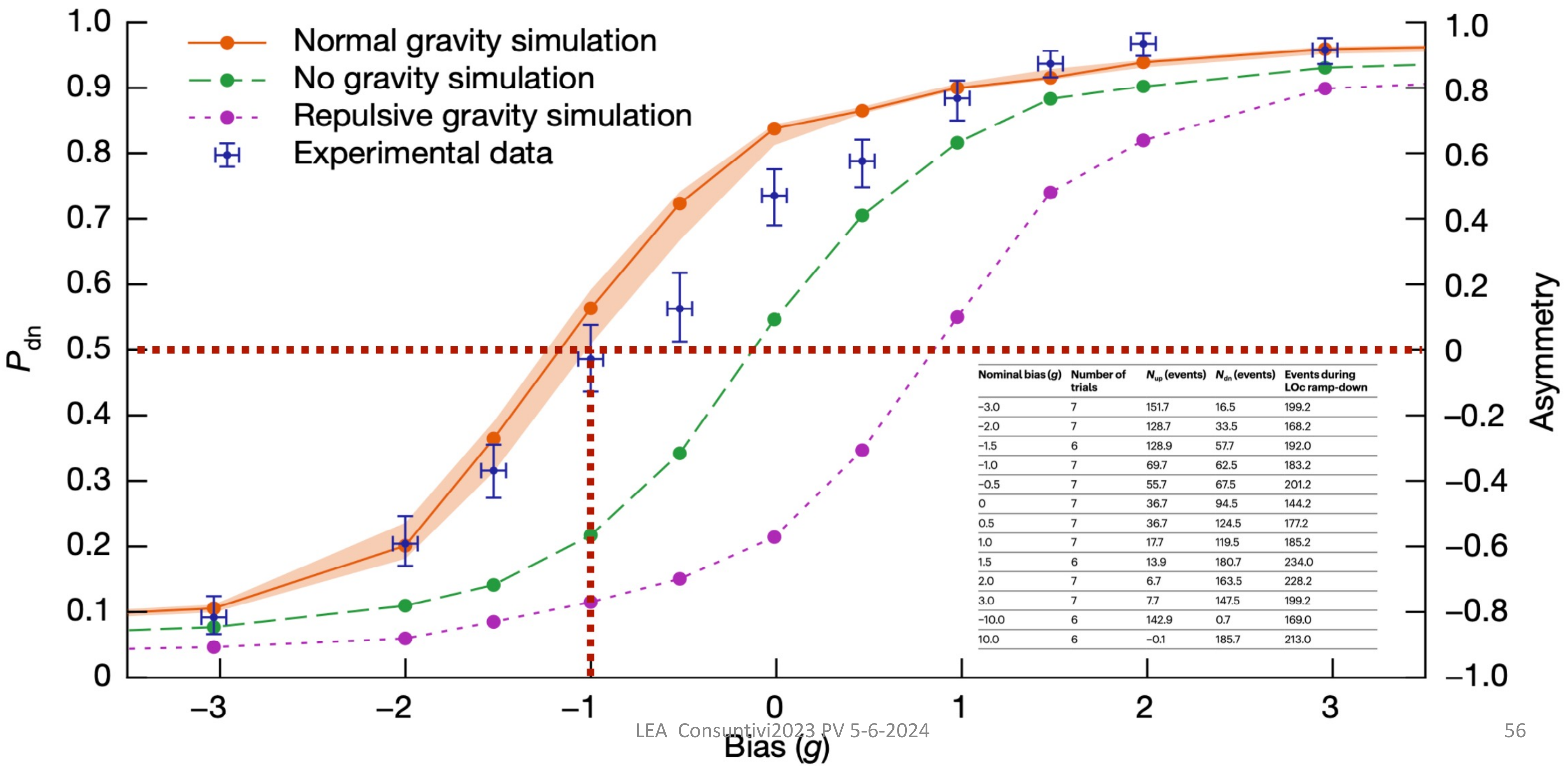
Distributions of the reconstructed annihilation vertices

"Physics" data (130 s ramp-down)



LEA_ALPHA – Gravity measurement

Asymmetry = $(N_{dn}-N_{up})/(N_{dn}+N_{up})$



Nominal bias (g)	Number of trials	N_{up} (events)	N_{dn} (events)	Events during LOc ramp-down
−3.0	7	151.7	16.5	199.2
−2.0	7	128.7	33.5	168.2
−1.5	6	128.9	57.7	192.0
−1.0	7	69.7	62.5	183.2
−0.5	7	55.7	67.5	201.2
0	7	36.7	94.5	144.2
0.5	7	36.7	124.5	177.2
1.0	7	17.7	119.5	185.2
1.5	6	13.9	180.7	234.0
2.0	7	6.7	163.5	228.2
3.0	7	7.7	147.5	199.2
−10.0	6	142.9	0.7	169.0
10.0	6	−0.1	185.7	213.0

LEA_ALPHA – Gravity measurement

$a_g = [0.75 \pm 0.13$ (statistical + systematic)

± 0.16 (simulation)] g

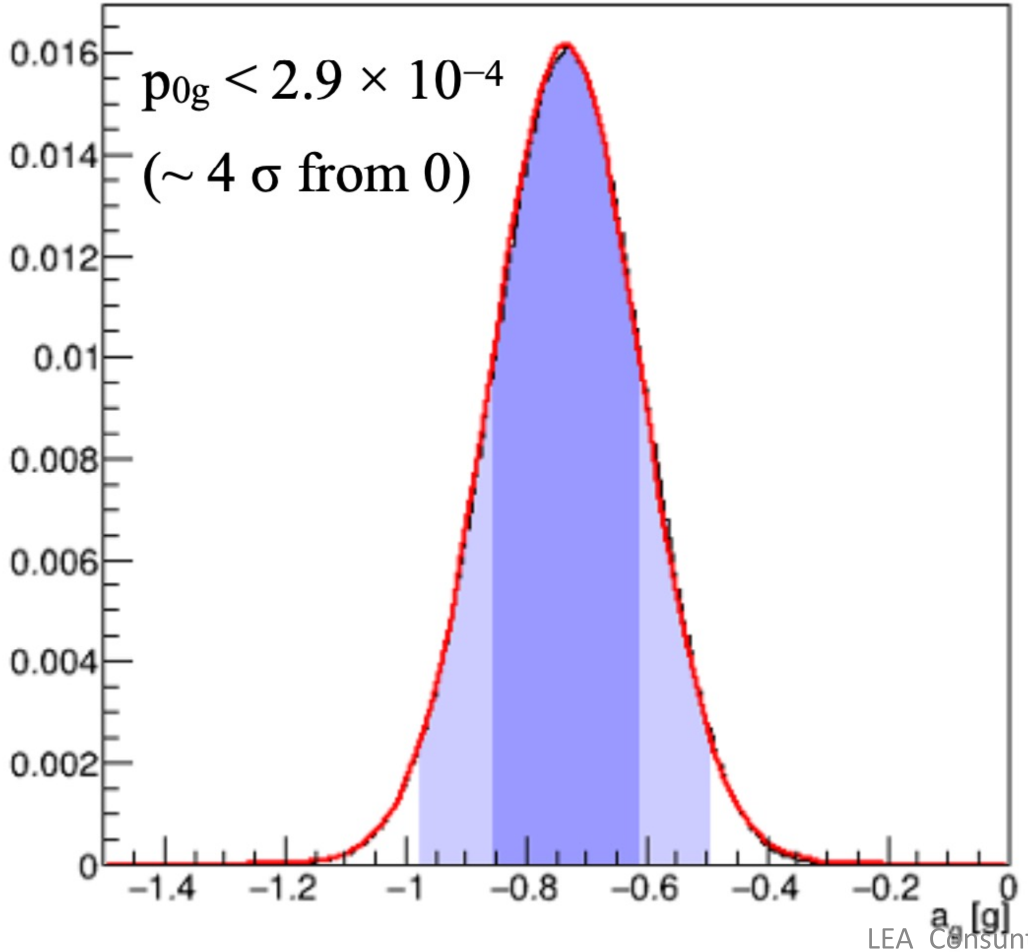


Table 2 | Uncertainties in the bias determination

Uncertainty	Magnitude (g)	
ECR spectrum width	0.07	
Repeatability of ($B_G - B_A$)	0.014	
Peak field size and z-location fit	0.009	
Field decay asymmetry (A to G) after ramp	0.02	correlated
Bias variation in time	0.02	
Field modelling	0.05	correlated

Summary of the uncertainties in the derived bias values, expressed in units of the local acceleration of gravity for matter (9.81 m s^{-2}). See Methods for definitions and details.

Table 3 | Uncertainties in the determination of $a_{\bar{g}}$

	Uncertainty	Magnitude (g)
Statistical and systematic	Finite data size	0.06
	Calibration of the detector efficiencies in the up and down regions	0.12
	Other minor sources	0.01
Simulation model	Modelling of the magnetic fields (on-axis and off-axis)	0.16
	Antihydrogen initial energy distribution	0.03

Summary of the uncertainties involved in the determination of the gravitational acceleration $a_{\bar{g}}$. The uncertainties are one standard deviation and are expressed in units of the local acceleration of gravity for matter (9.81 m s^{-2}). See Methods for the details.

LEA_ALPHA – 2023 RESULTS

Article

Observation of the effect of gravity on the motion of antimatter

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E. K. Anderson[1], C. J. Baker[2], W. Bertsche[3,4✉], N. M. Bhatt[2], G. Bonomi[5], A. Capra[6], I. Carli[8], C. L. Cesar[7], M. Charlton[2], A. Christensen[8], R. Collister[6,9], A. Cridland Mathad[2], D. Duque Quiceno[6,9], S. Eriksson[2], A. Evans[6,9], N. Evetts[9], S. Fabbri[3,10], J. Fajans[8✉], A. Ferwerda[11], T. Friesen[12], M. C. Fujiwara[6], D. R. Gill[6], L. M. Golino[2], M. B. Gomes Gonçalves[2], P. Grandemange[6], P. Granum[1], J. S. Hangst[1✉], M. E. Hayden[13], D. Hodgkinson[3,8], E. D. Hunter[8], C. A. Isaac[2], A. J. U. Jimenez[6], M. A. Johnson[3,4], J. M. Jones[2], S. A. Jones[14], S. Jonsell[15], A. Khramov[6,9,16], N. Madsen[2], L. Martin[6], N. Massacret[6], D. Maxwell[2], J. T. K. McKenna[1,3], S. Menary[11], T. Momose[6,9,17], M. Mostamand[6,17], P. S. Mullan[2,18], J. Nauta[2], K. Olchanski[6], A. N. Oliveira[1], J. Peszka[2,18], A. Powell[12], C. Ø. Rasmussen[19], F. Robicheaux[20], R. L. Sacramento[7], M. Sameed[3,21], E. Sarid[22,23], J. Schoonwater[2], D. M. Silveira[7], J. Singh[3], G. Smith[6,9], C. So[6], S. Stracka[24], G. Stutter[1,25], T. D. Tharp[26], K. A. Thompson[2], R. I. Thompson[6,12], E. Thorpe-Woods[2], C. Torkzaban[8], M. Urioni[5], P. Woosaree[12] & J. S. Wurtele[8]

Einstein's general theory of relativity from 1915[1] remains the most successful description of gravitation. From the 1919 solar eclipse[2] to the observation of gravitational waves[3], the theory h… the evolving concepts of dark ma… be learned about the gravitating… theory of relativity and the lack o… picture is incomplete. It is thus pr… Antimatter was unknown to Einst… positron was observed[5] in 1932. T… and antimatter. The theoretical c… attracted[6] by the Earth, although… consequences if antimatter shou… of relativity, the weak equivalenc… identically to gravity, independe… antihydrogen atoms, released fro… behave in a way consistent with g… 'antigravity' is ruled out in this ca… studies of the magnitude of the g… the Earth to test the WEP.

The weak equivalence principle (WEP) has recently been tested for matter in Earth's orbit[11] with a precision of order 10^{-15}. Antimatter has hitherto resisted direct ballistic tests of the WEP due to the lack of a stable, electrically neutral, test particle. Electromagnetic forces on charged antiparticles make direct measurements in the Earth's gravitational field extremely challenging[12]. The gravitational force on a proton at the Earth's surface is equivalent to that from an electric field of … about 10^{-7} V… a cryogenic… in a magneti… to unmask g… confined, o… when consi… produce[17] a…

[1]Department of Physics and Astronomy, Aarhus University, Aarhus, Denmark. [2]Department of Physics, Faculty of Sc… and Astronomy, University of Manchester, Manchester, UK. [4]Cockcroft Institute, Sci-Tech Daresbury, Warrington, UK. … British Columbia, Canada. [7]Instituto de Física, Universidade Federal do Rio de Janeiro, Rio de Janeiro, Brazil. [8]Depar… [9]Department of Physics and Astronomy, University of British Columbia, Vancouver, British Columbia, Canada. [10]Acc… of Physics and Astronomy, York University, Toronto, Ontario, Canada. [12]Department of Physics and Astronomy, Univ… Fraser University, Burnaby, British Columbia, Canada. [14]Van Swinderen Institute for Particle Physics and Gravity, Uni… Stockholm University, Stockholm, Sweden. [16]Department of Physics, British Columbia Institute of Technology, Burn… British Columbia, Vancouver, British Columbia, Canada. [18]Institute for Particle Physics and Astrophysics, ETH, Zurich, … [20]Department of Physics and Astronomy, Purdue University, West Lafayette, IN, USA. [21]Accelerator Systems Depart… Physics, Ben Gurion University, Beer Sheva, Israel. [24]INFN Pisa, Pisa, Italy. [25]School of Mathematical and Physical Sc… University, Milwaukee, WI, USA. [✉]e-mail: william.bertsche@cern.ch; joel@physics.berkeley.edu; jeffrey.hangst@ce…

17:06 4G

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Published: 27 September 2023

Observation of the effect of gravity on the motion of antimatter

… Baker, … J. S. Wurtele

…2 (2023) | Cite this article

…heory of relativity from 1915 … uccessful description of … he 1919 solar eclipse[2] to the … vitational waves[3], the theory…

THE TIMES

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Ryder Cup preview 12-page pullout

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No 10 backs threat to leave rights convention

Antimatter falls in line with theory of gravity

Schoolgirl stab horror

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CERN

ALPHA experiment at CERN observes the influence of gravity on antimatter

The result is a milestone in the study of the properties and behaviour of antimatter

Nothing's the Matter With Antimatter, a New Experiment by Physicists Confirms

By DENNIS OVERBYE

Installing a magnetic apparatus as part of the Antihydrogen Laser Physics Apparatus collaboration at CERN in Switzerland.

"All the News That's Fit to Print"

The New York Times

LATE EDITION

VOL. CLXXIII … No. 59,925 NEW YORK, THURSDAY, SEPTEMBER 28, 2023 $4.00

BBC NEWS

Menu

Science

Scientists get closer to solving mystery of antimatter

18 minutes ago

…TERKE/SCIENCE PHOTO LIBRARY

…: shortly after the Big Bang which created the …, matter and antimatter existed in equal amounts

physicsworld
TOP 10 BREAKTHROUGH 2023

LEA_ALPHA – 2023 data taking

ALPHA used only the ALPHA-2 apparatus

Main activities:

o) Cooling of positrons with Be+ for antihydrogen production

o) Anti-hydrogen spectroscopy:
- 1S-2S spectroscopy
- hyperfine ground state splitting (GSHFS)
- 2S-2P spectroscopy (Lamb shift)

o) Other studies
- Anti-hydrogen laser cooling
- Anti-hydrogen temperature measurements (using fast ramp dumps)

o) Refurbishment of the (ALPHA-g) vertical magnets

Analyses are underway – target for publications end 2024/start of 2025

LEA_ALPHA – 2023 INFN activities

INFN: G. Bonomi, S. Stracka, M. Urioni

Le attività in cui siamo stati coinvolti sono le seguenti:

Hardware

- Contributo all'acquisto del nuovo sistema di stabilizzazione del laser 243 nm (ordinato in maggio 2023, arrivato a fine anno) – Installazione nel 2024

Analisi

- Analisi dei dati raccolti per la misura della «caduta dell'anti-idrogeno» (*)
- Sviluppo di Toy MC per l'analisi dell'HFS
- Simulazioni MC (sia per ALPHA-g che per ALPHA-2)
- S*ervice work di mantenimento e sviluppo del software «online» e «offline» dell'esperimento*

Funzionamento generale dell'esperimento

- Partecipazione ai turni di presa dati (senior ~*4 settimane*, junior >*10 settimane*)

(*) Il gruppo di analisi era composto da 6 persone di cui 3 ricercatori di Berkeley e dal nostro gruppo INFN
L'analisi è oggetto della tesi di dottorato di Marta Urioni dal titolo:
"Measurement of Earth's gravitational acceleration on anti-hydrogen with the ALPHA experiment at CERN"

LEA_ALPHA – Milestones/Pubblicazioni

Milestones 2023

31/12/2023

misura dell'interazione gravitazionale dell'anti-idrogeno (**100%**)

Pubblicazione

Observation of the effect of gravity on the motion of antimatter, Nature 621 (2023)
https://doi.org/10.1038/s41586-023-06527-1

ASACUSA

Atomic Spectroscopy And Collisions Using Slow Antiprotons

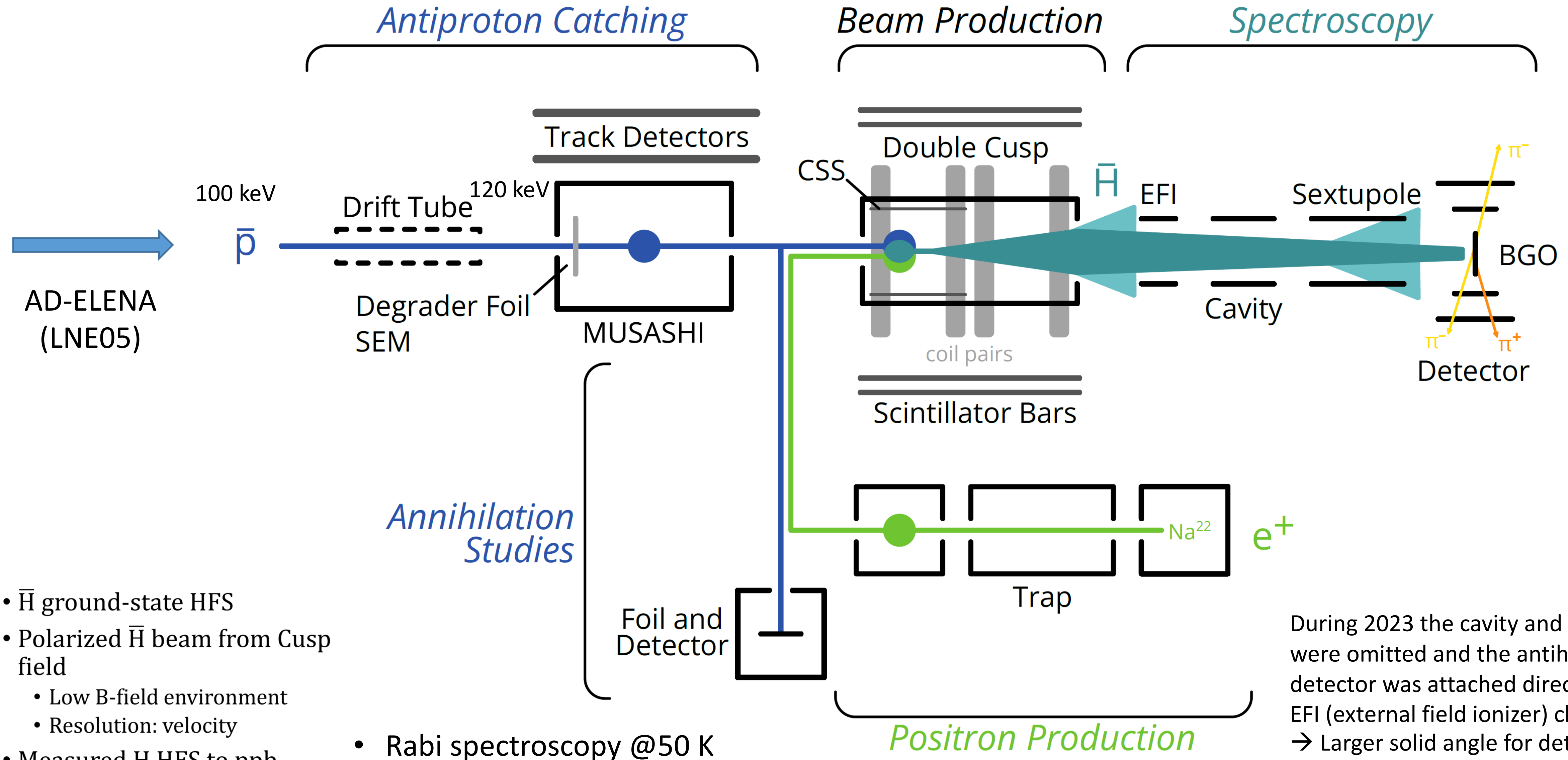
INFN contact person: Luca Venturelli (Bs-Pv)

17 Institutions 39 Researchers (11 INFN)

- antiprotonic helium atoms with laser spectroscopy to test CPT
- antihydrogen ground-state hyperfine structure to test CPT.
- atomic and nuclear collision cross sections of antiprotons at low energies.

Spokespersons:
M.Hori, E.Widmann

ASACUSA-Cusp experiment



- H̄ ground-state HFS
- Polarized H̄ beam from Cusp field
  - Low B-field environment
  - Resolution: velocity
- Measured H HFS to ppb precision

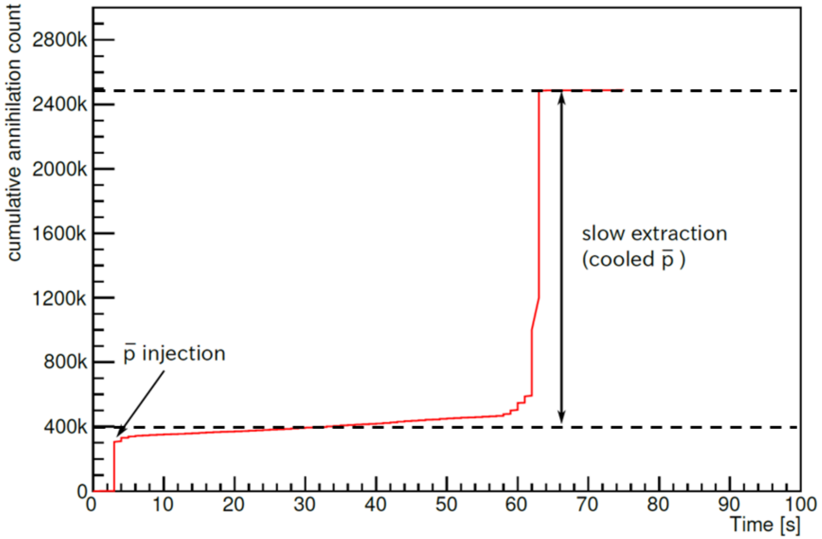
- Rabi spectroscopy @50 K
- Line width ~10 kHz: precision ~ppm

During 2023 the cavity and sextupole were omitted and the antihydrogen detector was attached directly to the EFI (external field ionizer) chamber.
→ Larger solid angle for detecting Hbar

ANTIPROTONS

From ELENA

- in 2023, **8 x 10^6 antiprotons** / one ELENA shot.
  Stable beam throughout the run



Counts of pbar annihilation during one cycle of capture, cool, and release

Trapping in MUSASHI

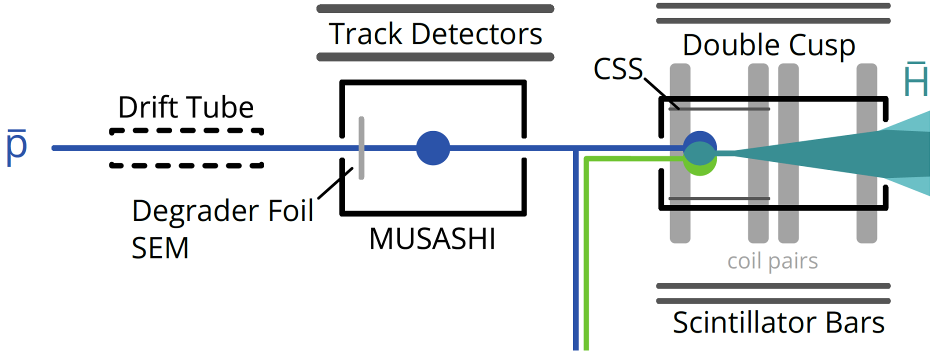
- The trapped and cooled pbars: 2 x 10^6 / (one ELENA shot)

  In 2022 Cycle time shortened to ~110s (one ELENA cycle)
  (We can use 1 cycle instead of 3-5 in the past)

Trapping in the Double CUSP trap

- pbars transferred into the Cusp: 1 x 10^6 / cycle (x 2.5 wrt 2022)

  electrostatic deflectors for slow pbar extraction were installed between MUSASHI and the Cusp and used to improve transport



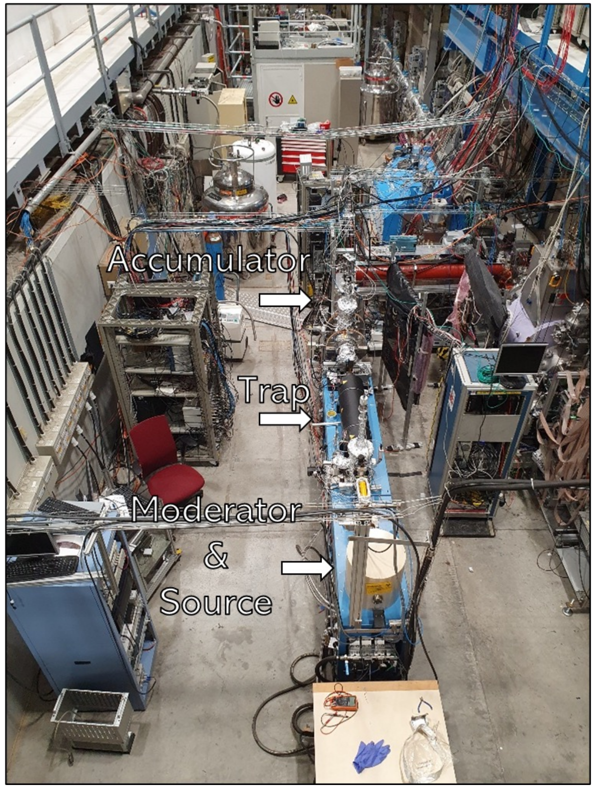
- pbars cooled (evaporation) into the Cusp: **0.5 x 10^6** / cycle (x 2.5 wrt 2022)

  for mixing

POSITRONS 1/2

In 2022

- replaced the previous e+ trap having a SC magnet (1000l/week of LHe) with a room temperature model (FPS)
- many damages due to the transport from Aarhus to CERN
- low efficiencies achieved, but all new techniques and methods were demonstrated.
- new 1.85 GBq e+ source non (yet) delivered. Ordered in Jan2022, originally expected in July 2022.



POSITRON TRAP

In 2023

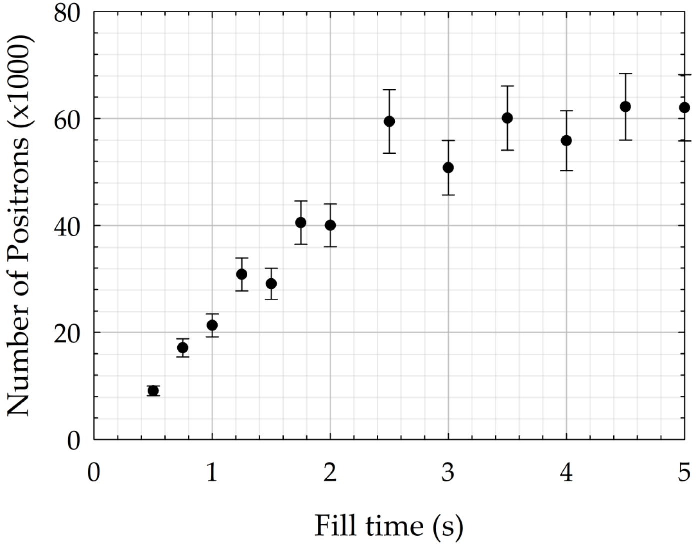
- installation of a new detector in the beam line (to measure beam intensity).
- Leaks in moderator gas lines repaired, hydrocarbon contaminated parts were removed
- Source + Moderator baked (2 weeks at low T, preserve cold head)

Moderator efficiency (%)	**0.2+-0.1 (x 2 wrt 2022)**	0.35 (FPS specification) (difference due to absorption by excess decayed material in old source?)

- Trap baked
- Cryopump reinstalled (with new compressor)

Trapping efficiency (%)	**15+-4 (x 10 wrt 2022)**	17 (FPS specification)

Pulses from the trap were transferred to the accumulator after 1 s



Number of positrons trapped vs accumulation time

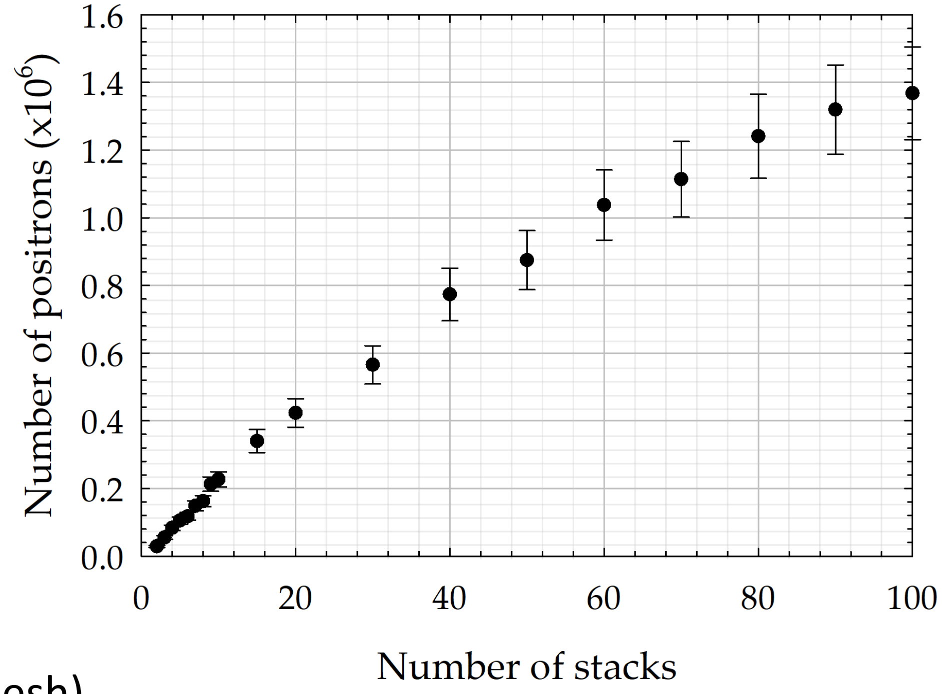
POSITRONS 2/2

POSITRON ACCUMULATOR

Built by MI group and installed in 2021

In 2022
- High pressure (10^{-7}-10^{-8} mbar) and a floating electrode prevented full operation

In 2023
- Reinstalled after modifications:
  - gas conductance towards the FPS trap was further reduced (by the implementation of thinner cables)
  - faulty flange replaced
  - magnet re-aligned
- **pressure** after baking = **10^{-9}-10^{-10} mbar** (as desired)
- **opening time** of the gate valve between FPS and accumulator was **minimized** to reduce the gas in-flow towards accumulator and Cusp
- **lifetime** increased (s): **104+-22 (x 10 wrt 2022)**
- **trapping efficiency** (%) = **95+-4**
- after compression: **radius (mm) < 1.85 +- 0.06**
- **1×10^6 trapped e+**/(60 stacks=60s) <--> 2 x 10^4 e+/stacks (with new Na-22 source: expected x 20)
- **transfer efficiency to cusp (%)= 55** (limit value =62 due to the MW-shield mesh)



Number of positrons trapped in the accumulator versus the number of stacks from the FPS trap

MIXING 1/3

PREPARATION OF ANTIPROTON AND POSITRON PLASMA IN THE CUSP

- antiprotons and e+ incrementally cooled, compressed, and purified from contaminants (e- for antiprotons and positive ions for e+)

- rotating wall is used to tune densities: **1×10^7 cm^{-3} for antiprotons** and **2×10^8 cm^{-3} for e+**.
This antiproton density is among the highest so far reported (partly due to the large number of antiprotons, 10^6)

- **e+ temperature = 25 K** (maintained throughout the 60 s mixing cycle).

- **Up to 3×10^7 e- have been cooled to 25 K** in the Cusp. However, only 4×10^6 e+ were used for mixing in 2023 because the stronger Na-22 source not yet arrived. (With the old source, it takes over an hour to accumulate 3×10^7 e+ in the Cusp.)

- antiprotons and e+ are then merged by slowly ramping the trapping voltages

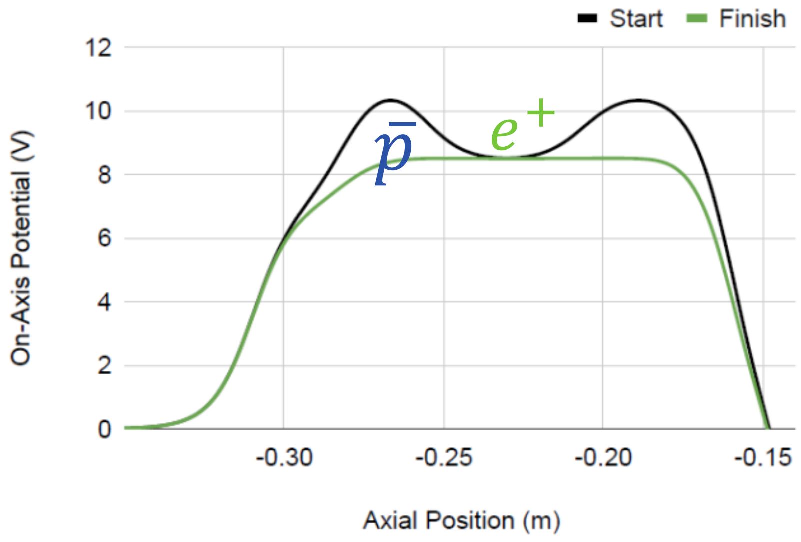
MIXING 2/3

ANTIHYDROGEN PRODUCTION 1/2

- e+ stay in the 2T maximum of the Cusp magnetic field --> cyclotron cooling rate 0.9 s^{-1}
- In ASACUSA developed new methods **to reduce the e+ temperature** (2 times better than ALPHA-2)

ALPHA-like "slow merge" scheme employed in 2023 for antihydrogen production. Antiprotons begin in the left well and are gradually pushed into the positrons at −0.23m

$$\bar{\mathrm{p}} + e^+ + e^+ \rightarrow \bar{\mathrm{H}} + e^+$$



- possible to study of antihydrogen formation over times ranging from 100 ms to 60 s
- **antihydrogen yield** monotonically increases with mixing time, from **50% for 500 ms** mixing to **80% for 60 s** mixing (**250 - 400 k** antihydrogen atoms)
- **total antihydrogen yield is at least 5 times greater than has been reported elsewhere** (due to the number of antiprotons is higher than before, 4 × 10^5 after evaporative cooling)

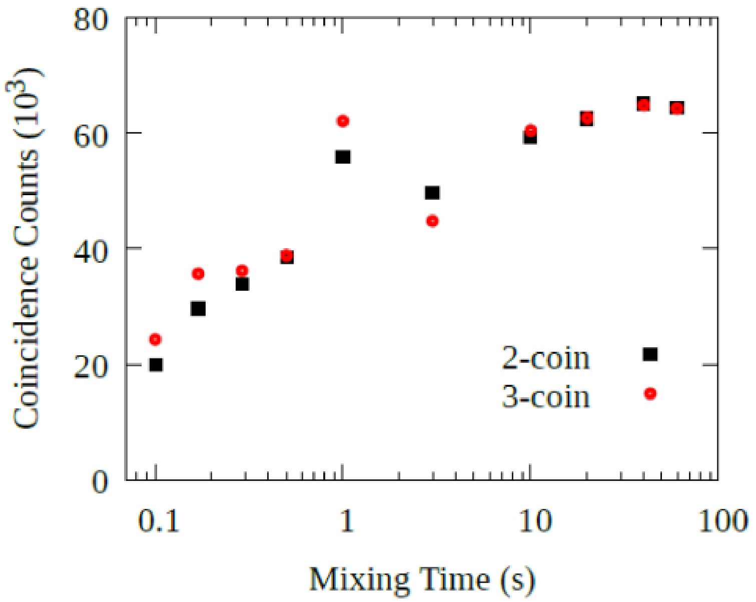
MIXING 3/3

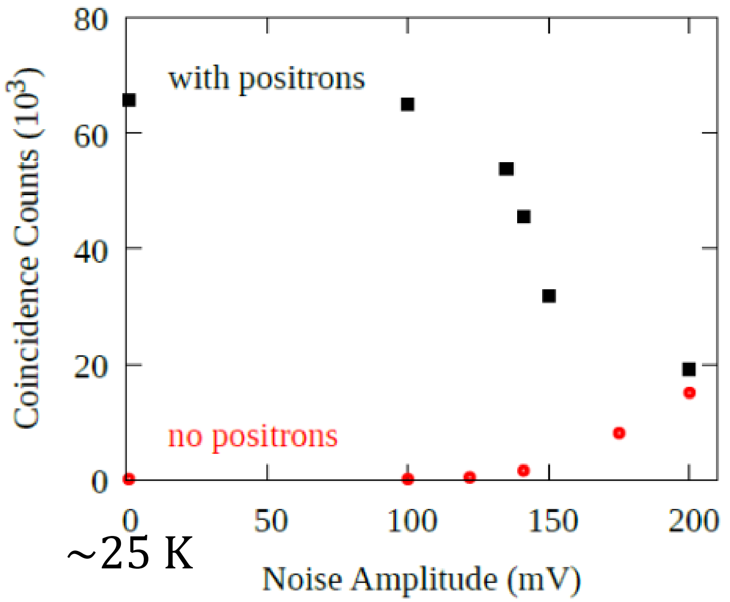
ANTIHYDROGEN PRODUCTION 2/2

different measurements were performed in 2023.
Some preliminary results (final results will be published):

1. The plasma (antiproton and e+) remains close to the axis until > 50% of the antihydrogen has been formed
2. The space charge of the antiprotons falls linearly with time. The space charge of e+ is relatively stable until the antiprotons are nearly depleted
3. The antiproton temperature seems to rise as the cloud expands, while the e+ temperature is stable at 25K for the entire mixing ramp
4. The antihydrogen yield is zero with no positrons
5. A small amount of noise causes the antihydrogen yield to fall sharply. This is visible around 150mV in Fig. 8.

Antihydrogen production vs mixing time. Measured by AMT scintillators. (3-coincidence ev. scaled by 5.4 for easy comparison)



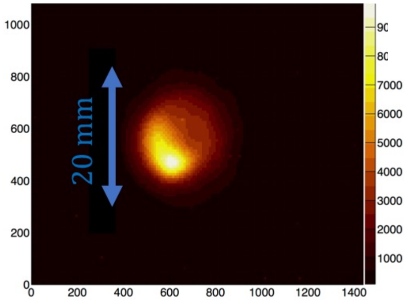


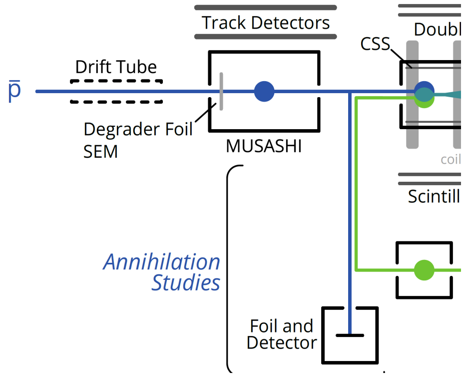
Antihydrogen production vs noise voltage

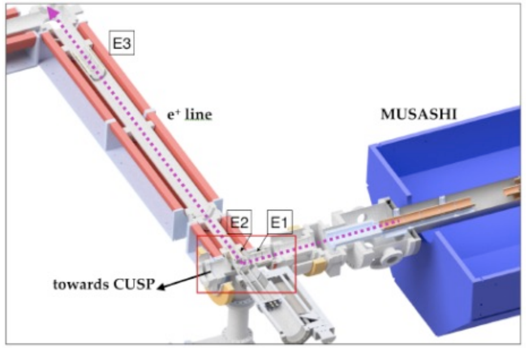
STUDY OF ANNIHILATIONS WITH SLOW EXTRACTED ANTIPROTONS

SLOW EXTRACTION BEAM LINE IN ASACUSA

- Experiments to **transport a slow extracted beam of $\overline{p}$ out of MUSASHI** along the existing e^+ transfer line using electrostatic beam elements
- ~ **25,000 $\overline{p}$ detected** and imaged on MCP detector
  - Transport efficiency ~ 10%
  - Beamspot < 1cm







Einzel lens E1 is used to steer and focus the beam before bending. The quadrupole deflector and E2 can be inserted and retracted in the six-way cross between MUSASHI and Cusp

Timepix4 ASICs coupled to 500 µm thick silicon sensors

2023 MILESTONES - ASACUSA

31dic2023	ASACUSA: Ottimizzazione dell'interazione del fascio di anti-idrogeno con microonde	50%
	La milestone era stata formulata prima dei notevoli problemi di danneggiamento del sistema di positroni che ha provocato ritardi in tutta l’attività con anti-idrogeno nel 2022 e di conseguenza anche nel 2023	
31dic2023	ASACUSA: Commissioning nuova linea secondaria di antiprotoni	100%

Pubblicazioni - ASACUSA

- Murtagh D. J. et al., *Slow positron production and storage for the ASACUSA-Cusp experiment*, Journal of Plasma Physics 89 6
- Hunter E. D. et al., *SDR, EVC, and SDREVC: Limitations and Extensions*, Journal of Plasma Physics 89 5
- Costantini G. et al., *The upgrade of the ASACUSA scintillating bar detector for antiproton annihilation measurements*, JINST 18 4
- Bianconi A. et al., *Optical Channeling of Low Energy Antiprotons in Thin Crystal Targets*, Symmetry 15 3
- Kraxberger V. et al., Upgrade of ASACUSA's antihydrogen detector, NIMA 1045 167568
- Amsler, C. et al., *Injection and capture of antiprotons in a Penning-Malmberg trap using a drift tube accelerator and degrader foil*, to be submitted
- Lanz, A. et al., *Upgrade of the positron system of the ASACUSA-Cusp experiment*, arXiv
- Hunter E. D. et al., *[results from 2023 run]*, in preparation
- Amsler, C. et al. Study of annihilations with slow extracted antiprotons, in preparation

Proceedings

- Costantini G. et al., *Upgrade of the scintillator detector for particle tracking in experiments with antiprotons*, IJMPA 38 18-19
- Bianconi A. et al., *Annihilation and nuclear elastic scattering of low-energy antiprotons*, IJMPA Conference Series 51 2361009

Conferences, Seminars

- Venturelli L., *Design of an experiment for the measurement of Pontecorvo reactions*, SMI - Seminar on fundamental interactions and symmetries SMI Vienna, Nov. 8, 2023
- Venturelli L., *Pontecorvo reactions study at the AD-ELENA, talk at the ADUC Meeting, CERN, Feb.6 2024*

Thesis

- [PhD] Costantini G. - *Simulations and reconstruction of antiproton-matter annihilation events in antimatter experiments 2023 -* *Università degli Studi di Brescia*
- [PhD] Migliorati S. - *Modeling Antinucleon-Nucleus Interactions at Low Energy: Analysis of Experimental Data Using an Optical Potential Approach* - Università degli Studi di Brescia - 2024 - submitted

LEA SUMMARY

- In 2023 much progress achieved

AEgIS:
- antihydrogen produced with the new collinear configuration
- laser cooling of positronium
- development of techniques for antiproton/antihydrogen detection and antiprotonic atom formation

ALPHA:
- analysis and publication of the effect of gravity on the motion of antimatter
- antihydrogen spectroscopy measurements (1S-2S, GSHFS, 2S-2P - Lamb shift): to be analyzed
- technological developments

ASACUSA:
- large production of antihydrogen (thanks to very low temperature of e+ and large # of antiprotons)
- identified a new method for producing many beam-like antihydrogens (to be implemented n 2024)
- commissioning of the slow extraction antiproton line

MAMBO

MAMBO

MAMiBOnn

Studio di fotoreazioni indotte su nucleoni e nuclei utilizzando gli acceleratori

- **MAMI $E_\gamma \leq$ 1.6 GeV (Mainz)**
  A2 Collaboration (spokepersons : A. Thomas Mainz
  (circa 60 persone) P. Pedroni INFN-PV)
- **ELSA $E_\gamma \leq$ 3.0 GeV (Bonn)**
  BGO-OD collaboration (spokepersons : H. Schmieden Bonn
  (circa 50 persone) P. LeviSandri INFN-LNF)

Sezioni INFN Partecipanti: RM1, LNF, PV, RM2, TO

COLLABORAZIONE MAMBO -2023

Responsabile Nazionale: **PAOLO LEVI SANDRI**

Sezioni INFN partecipanti:

ROMA TOV	**Responsabile Locale**	**ALESSIA FANTINI**
LNF	**Responsabile Locale**	**PAOLO LEVI SANDRI**
PAVIA	**Responsabile Locale**	**PAOLO PEDRONI**
ISS-RM	**Responsabile Locale**	**FRANCESCO GHIO**

10 ricercatori; 6.3 FTE

Pavia

Costanza Susanna	**10 %**	
Montagna Paolo	**30 %**	
Pedroni Paolo	**90 %**	**(10% EU-STRONG2020)**

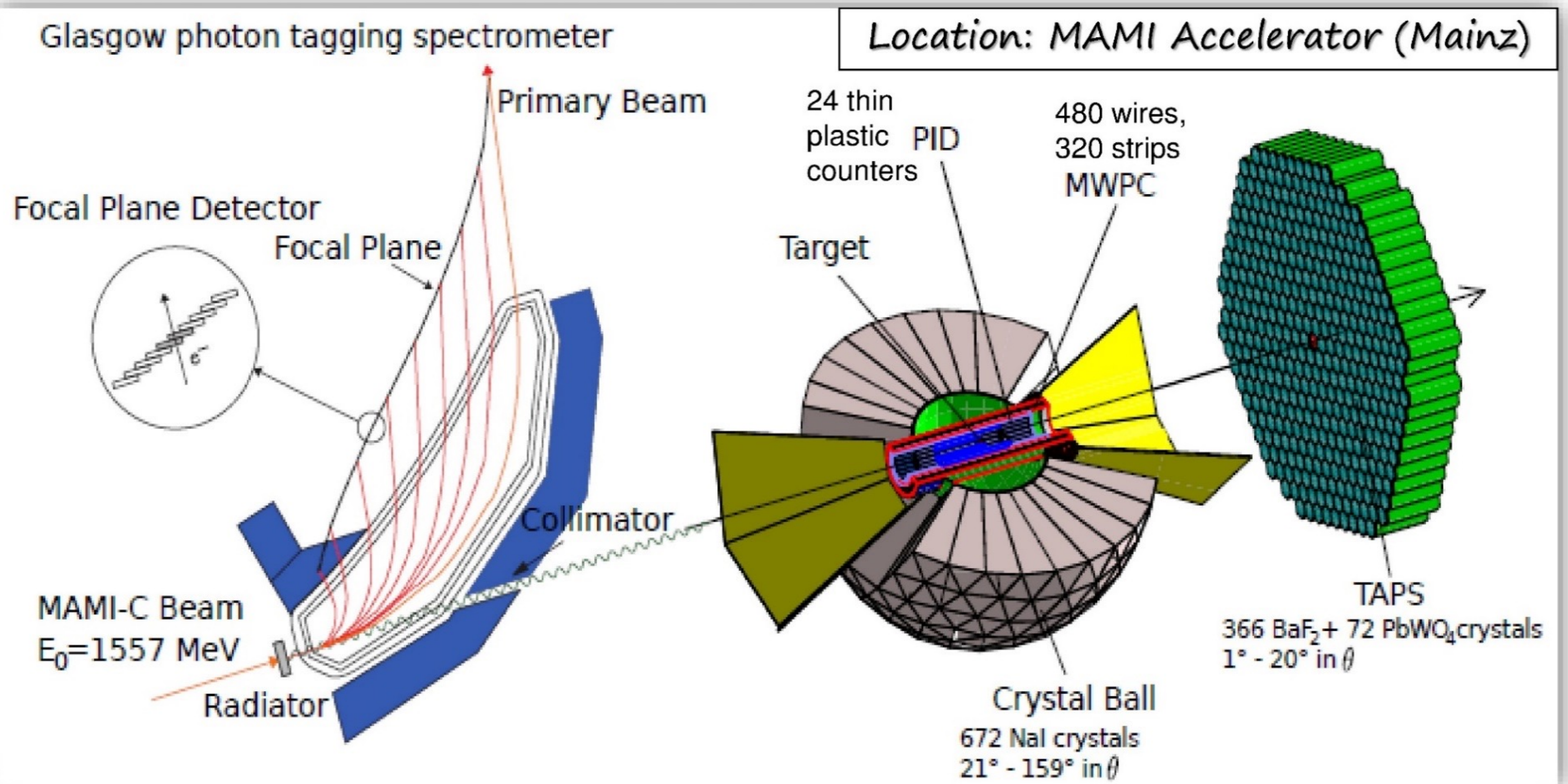
MAMBO- Physics Topics

(mainly involving low cross sections and/or precision measurements)

- **Threshold meson production:** (test of LET/ ChPT):
  Strangeness (γ N $\rightarrow \Lambda$K)
  π^0 meson photoproduction at threshold
- **Ambiguity free amplitude analysis of meson photoproduction**
  Requires Double polarization measurements:
  $\gamma N \rightarrow N\pi(\pi)$; N$\eta$ (ρ,...) channels
- **Tests of fundamental symmetries (C,CP,CPT...)**
  (Rare) η, η' decays
- **In medium properties of hadrons & nuclear physics:**
  Meson photo production on nuclei
- **Search for "missing" baryon resonances**
  Vector meson (ϕ, ω) photo production

Use of state-the-art technology (circularly and linearly polarised photon beams; longitudinally and transverse polrised proton/deuteron/3He targets) is required

A2@MAMI: detector overview

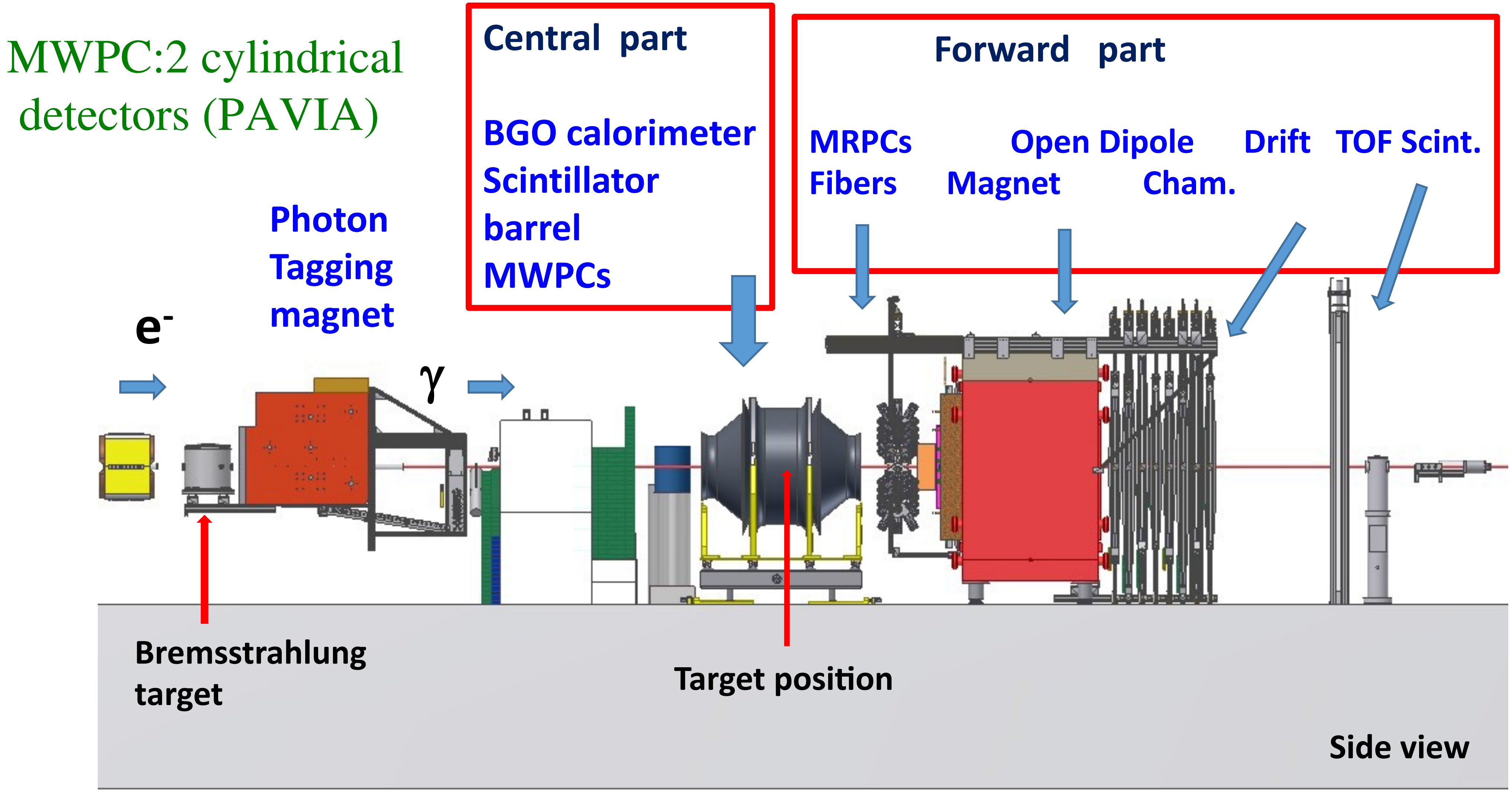


MWPC:2 cylindrical detectors (PAVIA)

Beam:

- *photon beam produced by bremsstrahlung process and tagged by the magnetic spectrometer*
- $E_\gamma < 1.5$ GeV, $\Delta E_\gamma = 2 - 4$ MeV
- *Linear and circular polarisations available*

MAMBO – Bonn- Apparato



Attività svolta 2023-2024

- **Mainz:**

Prese dati su scattering Compton su deuterio. Queste misure serviranno per l'estrazione delle polarizzabilità elettrica (α) e magnetica (β) del neutrone, attualmente note con una notevole incertezza (circa 20-30%) (polarizzabilità sono costanti fondamentali, al pari di carica e massa che descrivono la distribuzione di carica e magnetismo all'interno del nucleone)

- **Bonn** :

Sono stati raccolti dati solo in una dei 3 previsti periodi di fascio (fotoproduzione coerente di pioni e di $K\Lambda$ su deuterio per lo studio di stati esotici) a causa di problemi dell'acceleratore ELSA

Mainz – risultati principali

- **Migliore stima del momento di quadrupolo elettrico del protone / risonanza Δ (1232)**

HIGHLIGHTED ARTICLES **E. Mornacchi et al. PRC 109, 055201 (2024)**

Editors' Suggestion

Evaluation of the $E2/M1$ ratio in the $N \to \Delta(1232)$ transition from the $\vec{\gamma}\vec{p} \to p\pi^0$ reaction

E. Mornacchi *et al.* (A2 Collaboration at MAMI)

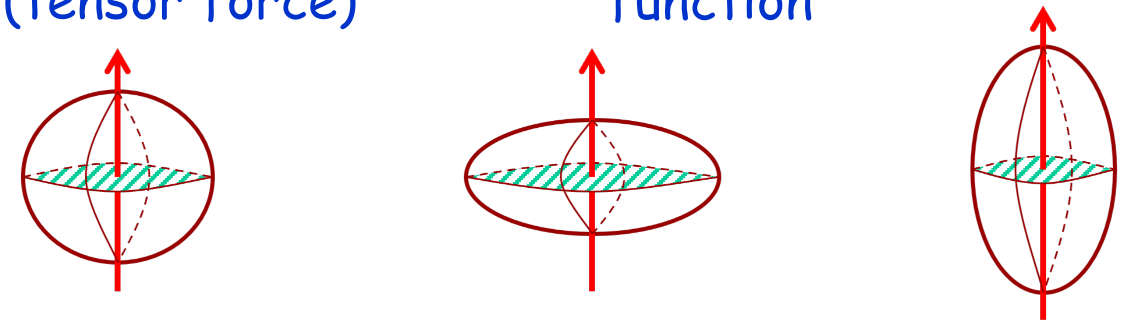
Phys. Rev. C **109**, 055201 (2024) – Published 6 May 2024

Lavoro selezionato come «Editor's suggestion» su Phys.Rev.C di maggio

E2/M1 ratio

p-n interaction is spin dependent (tensor force) → d- state admixture in the deuteron wave function → non-spherical charge distribution (quadrupole moment for the deuteron)

(E2 absorption)



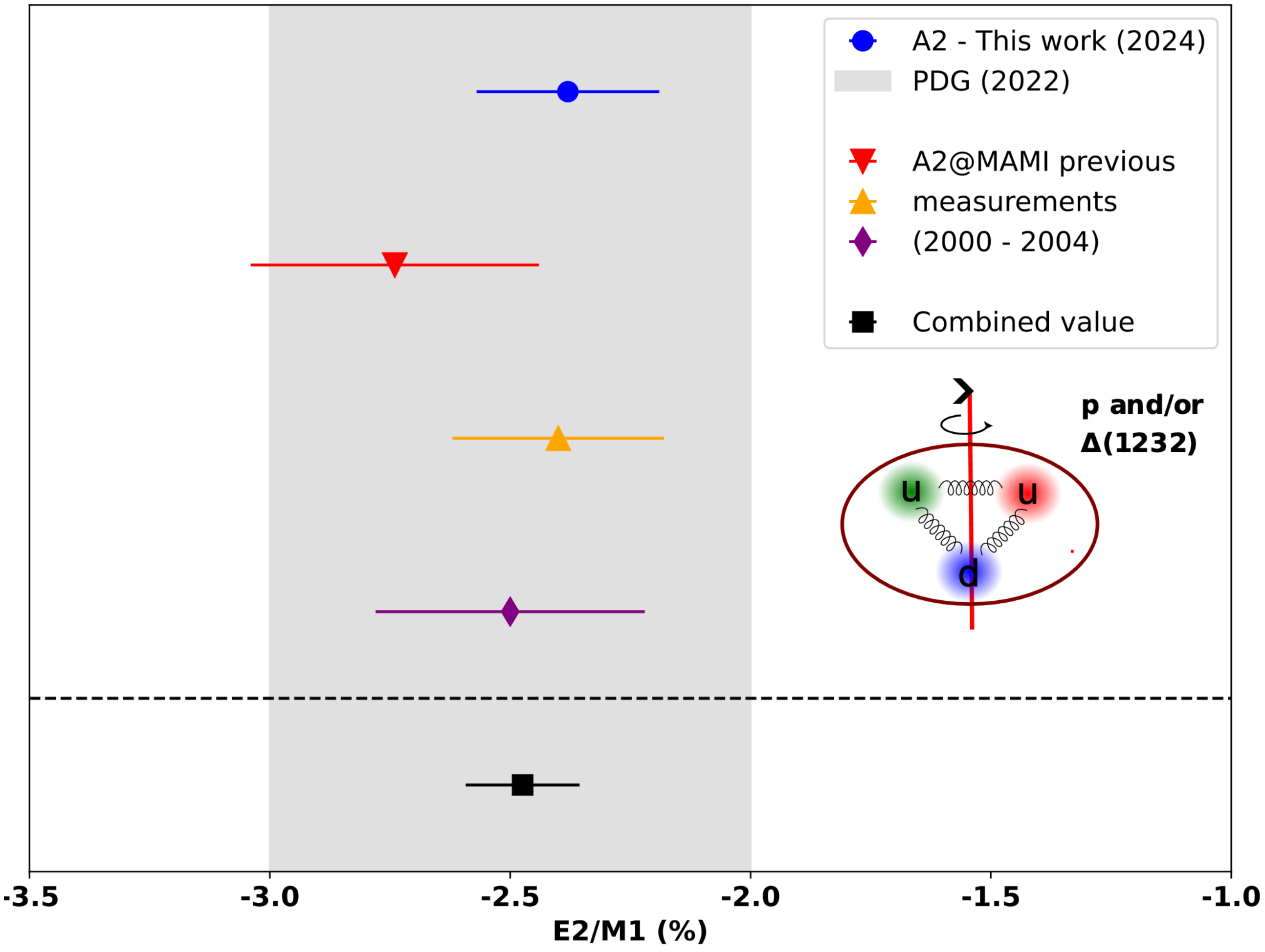
Sphere: $Q_{20}=0$ Oblate: $Q_{20}/R^2 < 0$ Prolate: $Q_{20}/R^2 > 0$

Tensor correlation between the quark core and the pion cloud /gluon exchange current between quarks

quark-quark interaction is spin dependent (gluon exchange) (color tensor force) → d- state admixture in the proton wave function (modification of the quark core) → (E2 absorption)

Proton electron quadrupole moment can not be directly measured (spin=1/2 particle). The only indirect way is to measure the E2/M1 ratio between the electric quadrupole (E2) and the dominant spin-flip (M1) amplitude in the $\gamma N \rightarrow \Delta(1232)$ transition

Oblate shape deformation due to the color tensor force



Questo progresso è stato reso possibile da:

- precisi dati raccolti da A2-Mainz sulla dipendenza dall'elicità della transizione protone → $\Delta(1232)$ (fascio di fotoni circolarmente polarizzato su protoni linearmente polarizzati)

- Un innovativo metodo di fit basato sulla tecnica di bootstrap che consente di includere in maniera semplice e consistente errori sistematici e di ricavare in maniera esatta gli intervalli di confidenza sui parametri di fit con qualunque tipo di errori statistici e sistematici

(P.Pedroni, S.Sconfietti, JPG 47, 054001(2020))

N-ToF

n_TOF
Neutron time of flight

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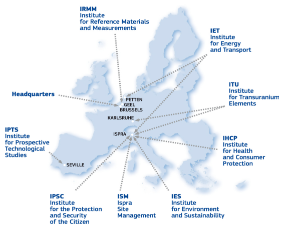


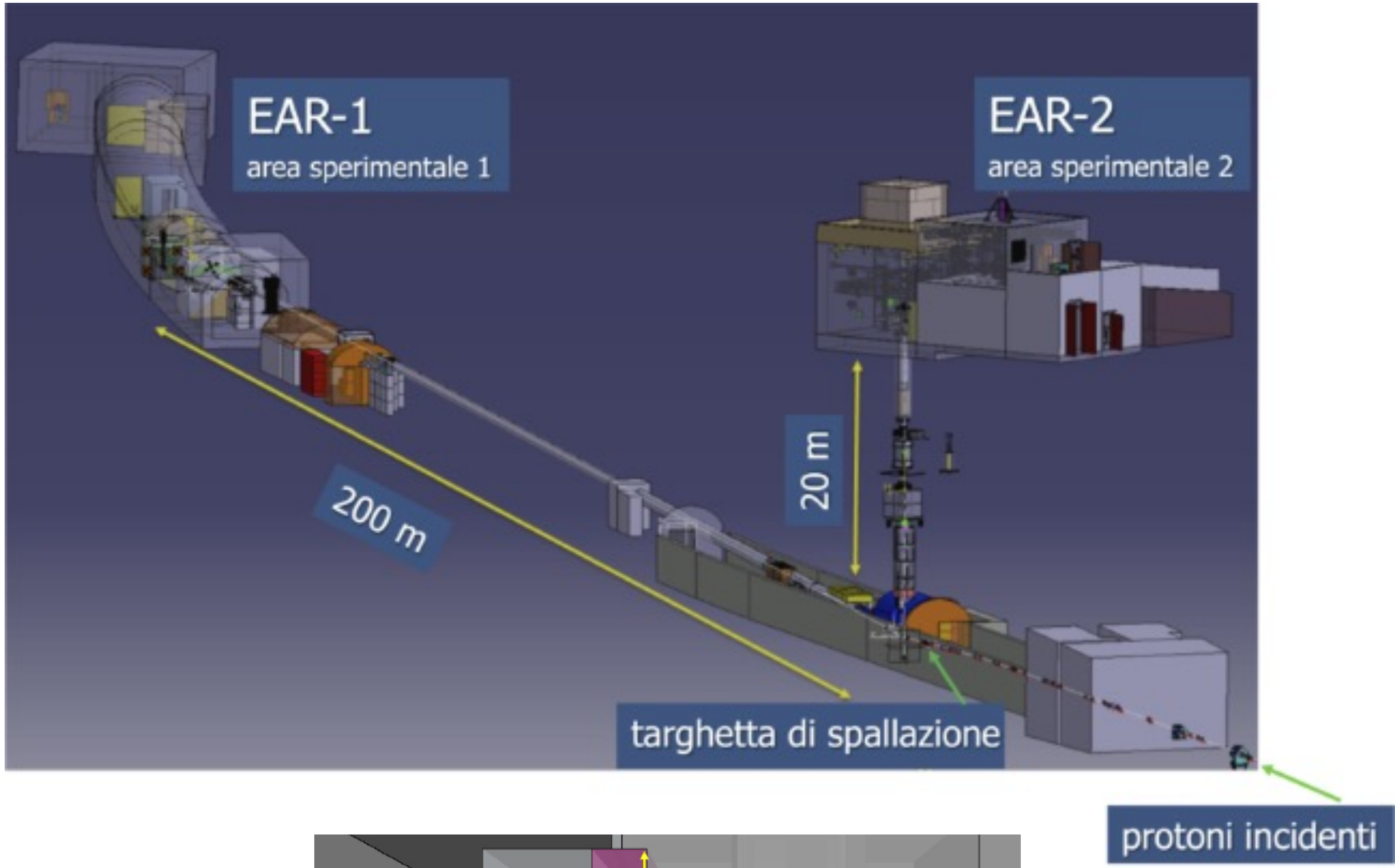
GELINA @EC-JRC-GEEL

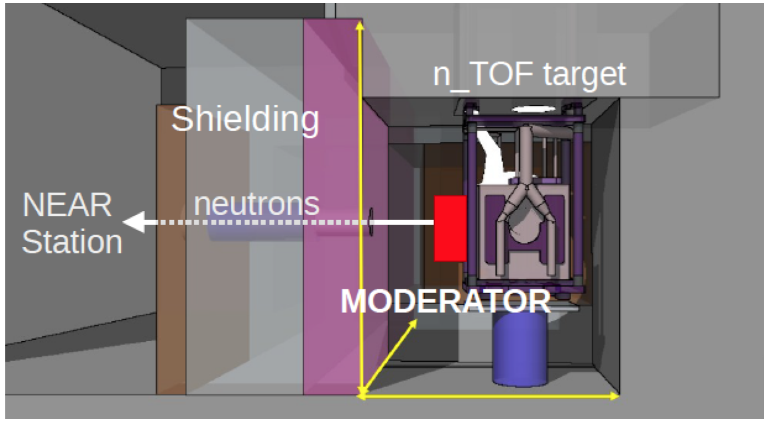
nTOF

Nicoletta Protti (RL)

Consuntivi 2023

CDS 05/06/2023





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Informazioni generali

Sezioni coinvolte:

BA, BO, CT, LNF, LNL, LNS,

PG, **PV**, RM1, TO, TS

Anagrafica Pavia, 2023:

De Bari A. (30%)

Pascali V. (PhD) (100%)

Protti N. (RL) (50%)

Zelaschi F. (30%)

FTE 2023:

2.2

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Goal del progetto

Obiettivi generali:

L'esperimento n_TOF e' finalizzato alla misura con elevata accuratezza di sezioni d'urto di reazioni indotte da neutroni.

Gli ambiti disciplinari spaziano dalla ricerca in Fisica Nucleare e in Astrofisica Nucleare, alle applicazioni inerenti le Tecnologie Nucleari emergenti e la Medicina Nucleare.

Le misure vengono effettuate (principalmente) presso la facility n_TOF al CERN.

Obiettivi di Pavia:

Sin dal suo ingresso nella collaborazione N_TOF, INFN-PV ha svolto un ruolo di supporto alle attività svolte presso il CERN grazie alla presenza del laboratorio LENA di UNIPV. Sfruttando le diverse posizioni di irraggiamento (canale centrale, colonna termica, canale B, …) INFN-PV ha realizzato misure preliminari quali:

- attivazione di polvere di fluoruro di Al (moderatore stazione NEAR)
- attivazione neutronica di multi-target per unfolding di spettri neutronici (nuova NEAR station)
- rivelatore TimePix (monitor di fascio n)

Di specifico interesse per le attività BNCT di INFN-PV, i test sul TimePix sono poi passati ad un adattamento del rivelatore stesso per la misura e l’imaging in tempo reale del B10. Le principali attività del 2023 si sono focalizzate proprio su quest’ultimo aspetto.

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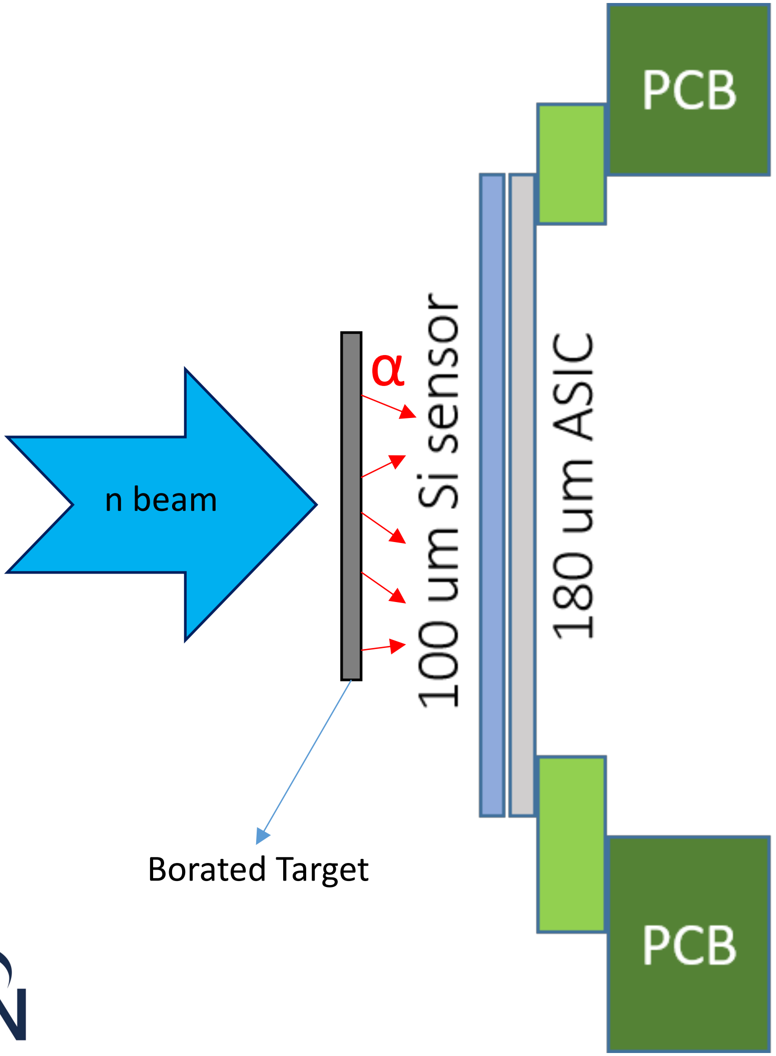
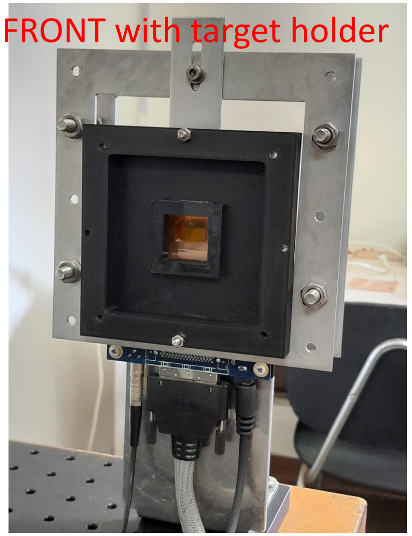
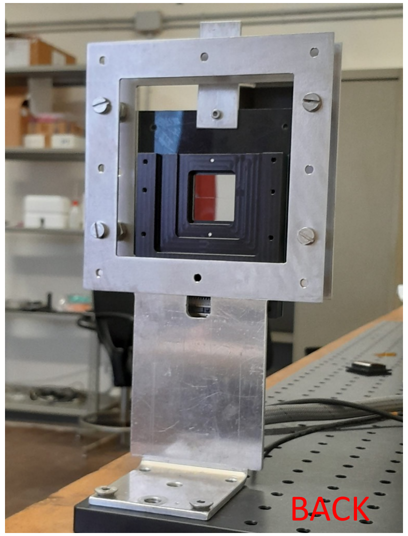
Risultati 2023

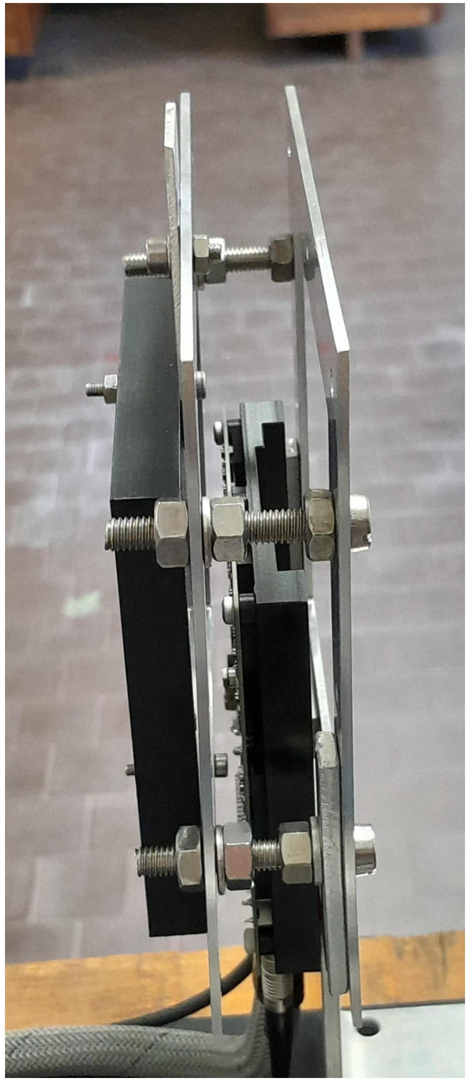
- Nei primi mesi del 2023, campioni di polvere di fluoruro di Al sono stati analizzati mediante attivazione neutronica nel canale centrale del LENA, come test preliminare per valutare l'adeguatezza del materiale come componente principale del moderator della NEAR station.
- A dicembre 2023, sono stati invece eseguiti esperimenti presso il canale B usando il rivelatore TimePix3 (TP3) quad caratterizzato da un design specific e che prevede l'assenza di PCB dietro il rivelatore di Si; questa modifica al layout originale rende possible una drastica diminuzione del background durante la lettura sotto fascio e un eccessivo overlapping delle tracce, consentendo così l'imaging del B10 contenuto nel campione tramite la rivelazione delle particelle alfa secondarie. I campioni misurati rappresentano degli standard, con elevate concentrazioni di B10 (rispettivamente 10^{18} atomi $B10/m^2$ e 10^{15} atomi $B10/cm^2$). In seguito ad una adeguata analisi della topologia delle tracce e dell'energia residua delle alfa ($E<0.8$ MeV), è stato possible ricostruire una imagine del campione. Sebbene le concentrazioni di B10 di questi standard siano di molto superiori a quelle attese in campioni biologici, I dati preliminary sin qui raccolti sono molto promettenti e suggeriscono l'effettiva possibilità di adattare definitivamente la tecnologia del TP3 per le specifiche richieste di misura di BNCT.

Experimental set-up of channel B irradiations









INFN
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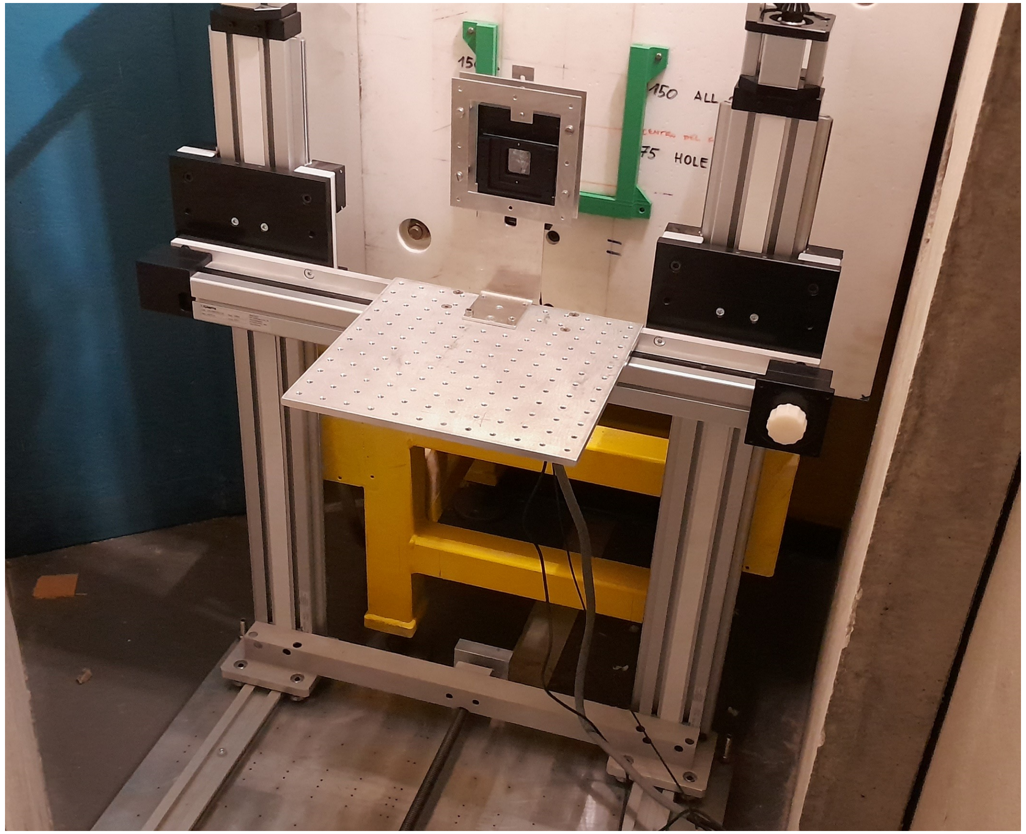
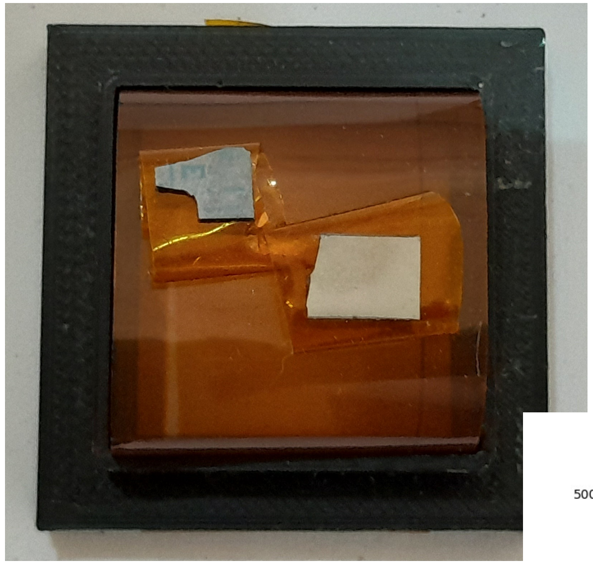
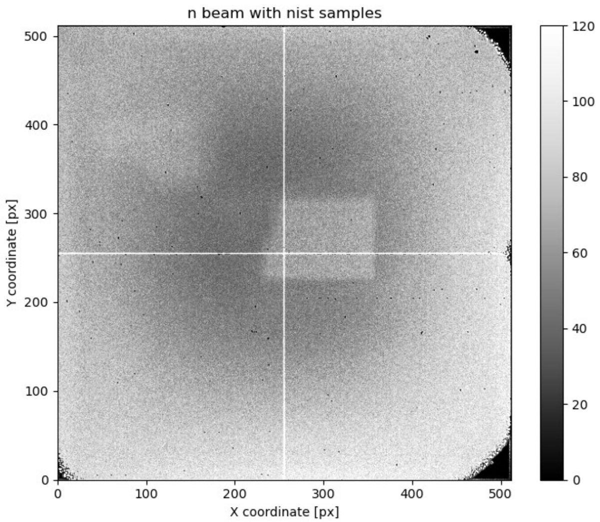
nTOF

Experimental set-up of channel B irradiations & preliminary results





Superficial B10 implant and BC4 sample



GRAZIE
PER L’ATTENZIONE