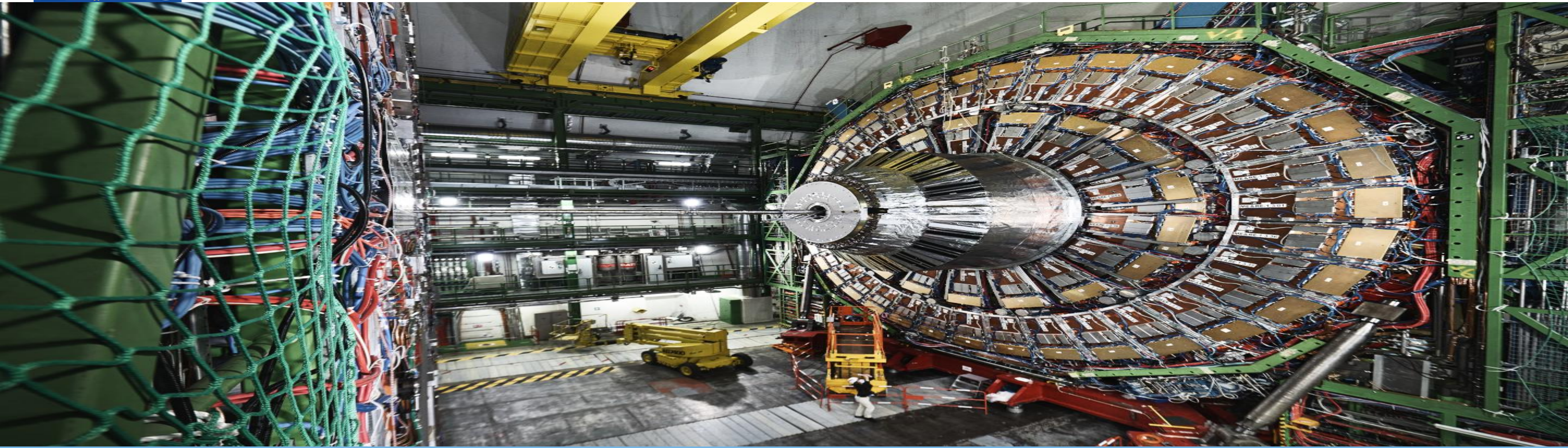


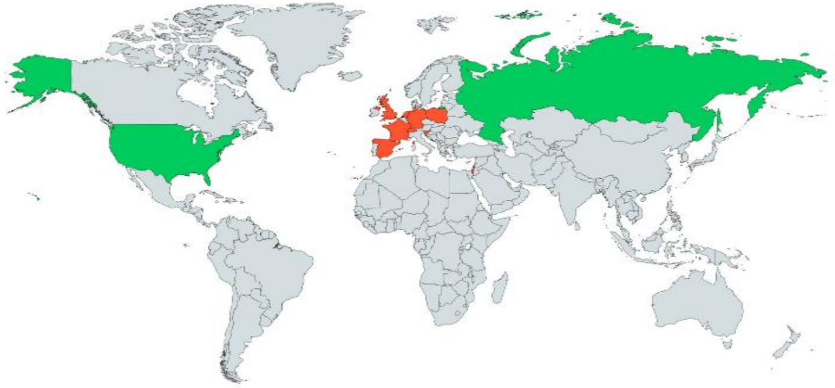
NA4 - Proton Radius European Network (PREN)

Dominique Marchand, IJCLab, CNRS/IN2P3 - Université Paris-Saclay, Orsay, France
on behalf of PREN collaborators

STRONG-2020 Annual meeting, Nov. 8th - 10th, 2021

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824093

Proton charge Radius European Network



Experimental determination:

- ➢ Lepton scattering off protons, nuclear physics
- ➢ Atomic spectroscopy, atomic physics
  - Hydrogen atoms, hydrogen molecular ions
  - Muonic hydrogen, muonic ions

To **stimulate** and support a real **synergy** between all the physicists involved in the world-wide **experimental** and **theoretical** effort from **atomic spectroscopy** and **lepton scattering** in order to fully understand the persistent discrepancies and to come to a statement on the **value of the proton charge radius**.

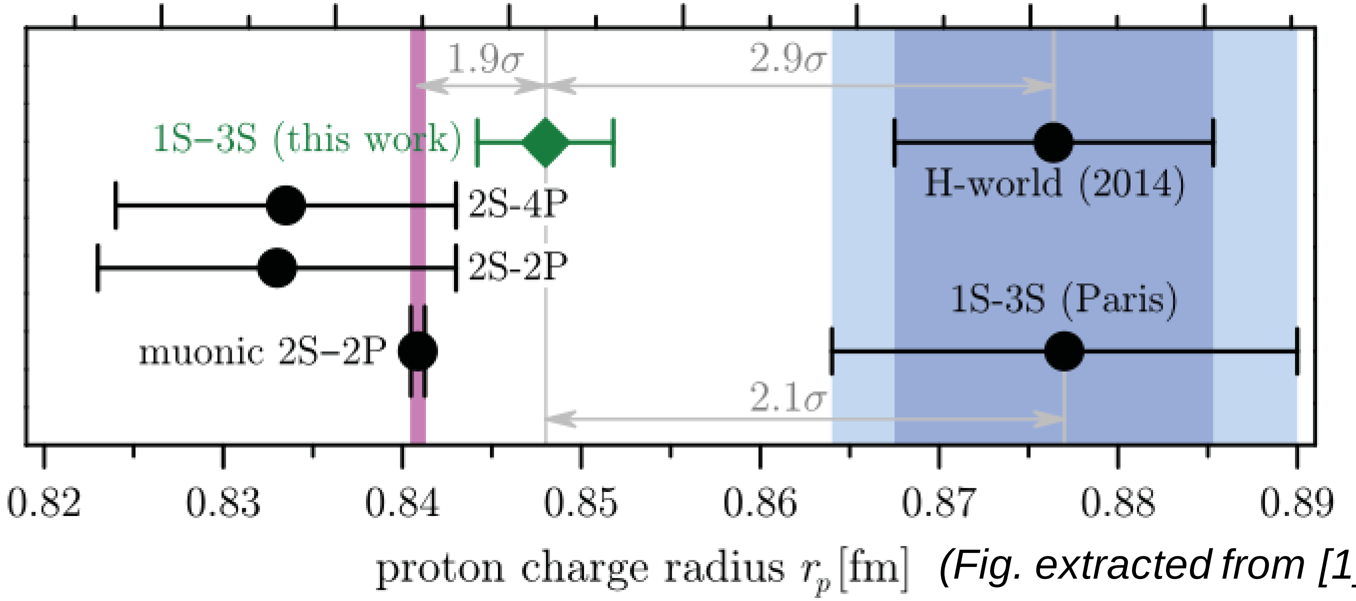
Activities

- Two-photon UV direct frequency comb spectroscopy on the 1S-3S transition in atomic hydrogen (MPQ, Garching, Germany)

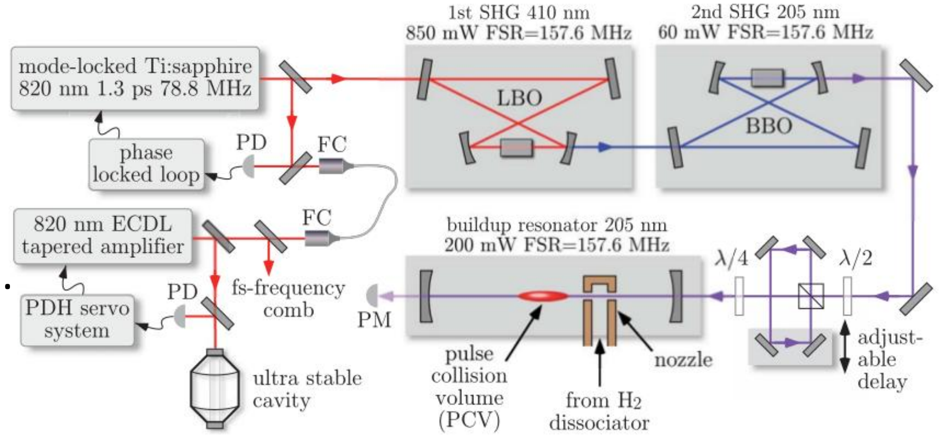
[1] Grinin *et al.*, *Science* **370**, 1061–1066 (2020) 27 November 2020

1S-2S transition frequency from A. Matveev et al.,Phys. Rev. Lett. 110, 230801 (2013).

R_∞ = 10 973 731.568226(38) m^{-1} ⟷ r_p = 0,8482(38) fm



(Fig. extracted from [1])



Experimental setup *(Fig. from [1])*

- Direct Frequency Comb Spectroscopy
- cryogenic H beam (6 K)
- 740 Hz (total), 110 Hz (stat.)

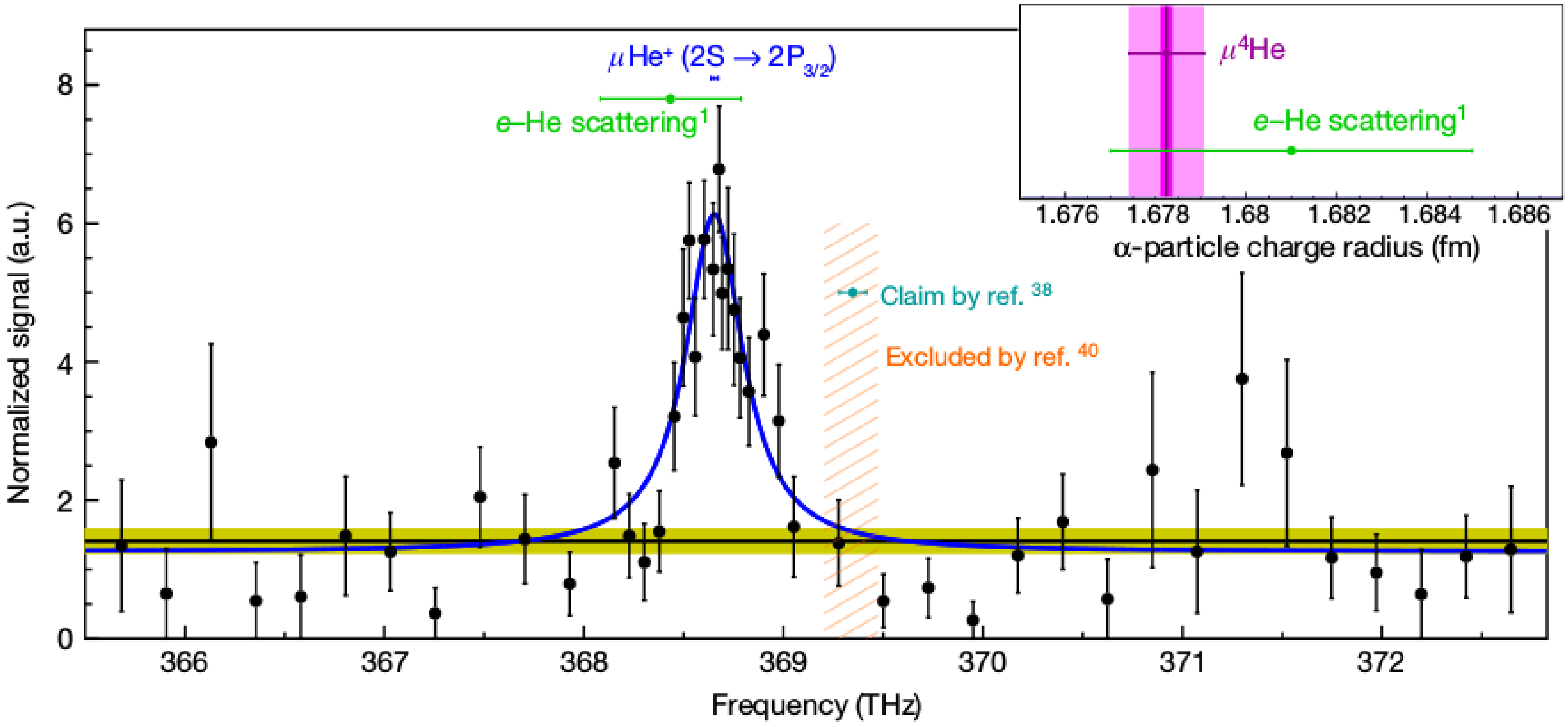
- Demonstrated the potential of this method
- R_∞ in agreement with the latest CODATA value '18
- r_p more precise compared to Paris 1S-3S
- r_p in better agreement with 2S-2P, 2S-4P (missing systematic in 2-photon transitions?)

Activities

Alpha particle charge radius from muonic ^{4}He

Measurement of 2S-2P transitions in $(\mu^4He)^+$ ions

$R(^4He) = 1.67824\ (13)_{exp}\ (82)_{theo}$ fm



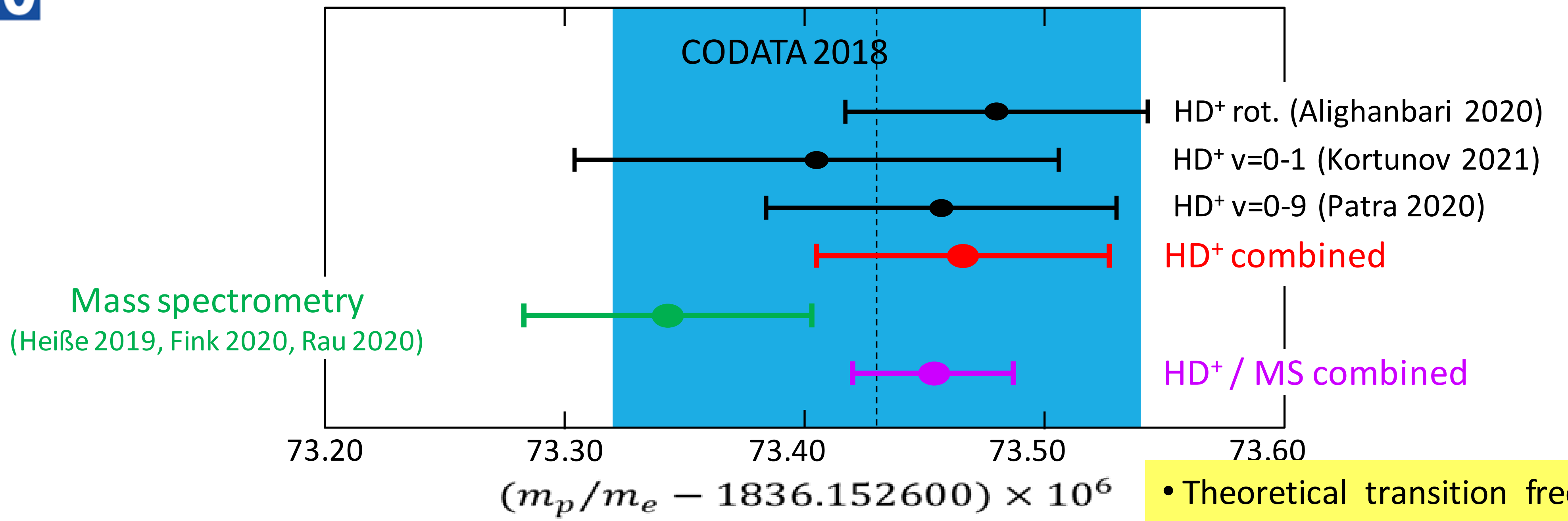
- In agreement with electron scattering result, I. Sick, 2008, but **4.8 times** more precise determination.
- Excludes most BSM scenarios and set upper limits for some others invoked to adress Proton Radius Puzzle
- Benchmark for few-nucleon theories, Lattice QCD and electron scattering.
- in agreement with a recent r_α extracted from χEFT framework
- can be used to fix low-energy constants of the nuclear potential.

« Measuring the α-particle charge radius with muonic helium-4 ions »
Krauth *et al.*, Nature, vol. 589 (January 2021) 527.

Theory: Diepold *et al.*, Ann. Phys. (2018)
incl. 3-photon nuclear polarizability (K. Pachucki, 2018)

Activities

Determination of fundamental constants from HD^+ spectroscopy



- From HD^+ data alone:

  $$m_p/m_e = 1836.152\,673\,466(61) \quad [3.3\times10^{-11}]$$

  Good agreement with CODATA 2018 and recent mass spectrometry results.

- From HD^+ and mass spectrometry combined:

  $$m_p/m_e = 1836.152\,673\,454(33) \quad [1.8\times10^{-11}]$$

- Theoretical transition frequencies in HD^+ revised taking into account recent progress in QED correction calculations and CODATA '18 recommended values of fundamental constants
- Excellent agreement with high-precision '20. '21 measurements
- Indication that HD^+ spectroscopy supports the small Rp value

"Rovibrational spin-averaged transitions in the hydrogen molecular ions"
V.I. Korobov (BLTP, JINR, Dubna, Russia) and J.-Ph. Karr (LKB, Paris), Phys. Rev. A **104**, 032806 (2021)

Activities: reviews

- (Invited) Review

Progress in Particle and Nuclear Physics
Volume 121, November 2021, 103901

The proton radius (puzzle?) and its relatives

Clara Peset [a], Antonio Pineda [b,c,*], Oleksandr Tomalak [d,e]

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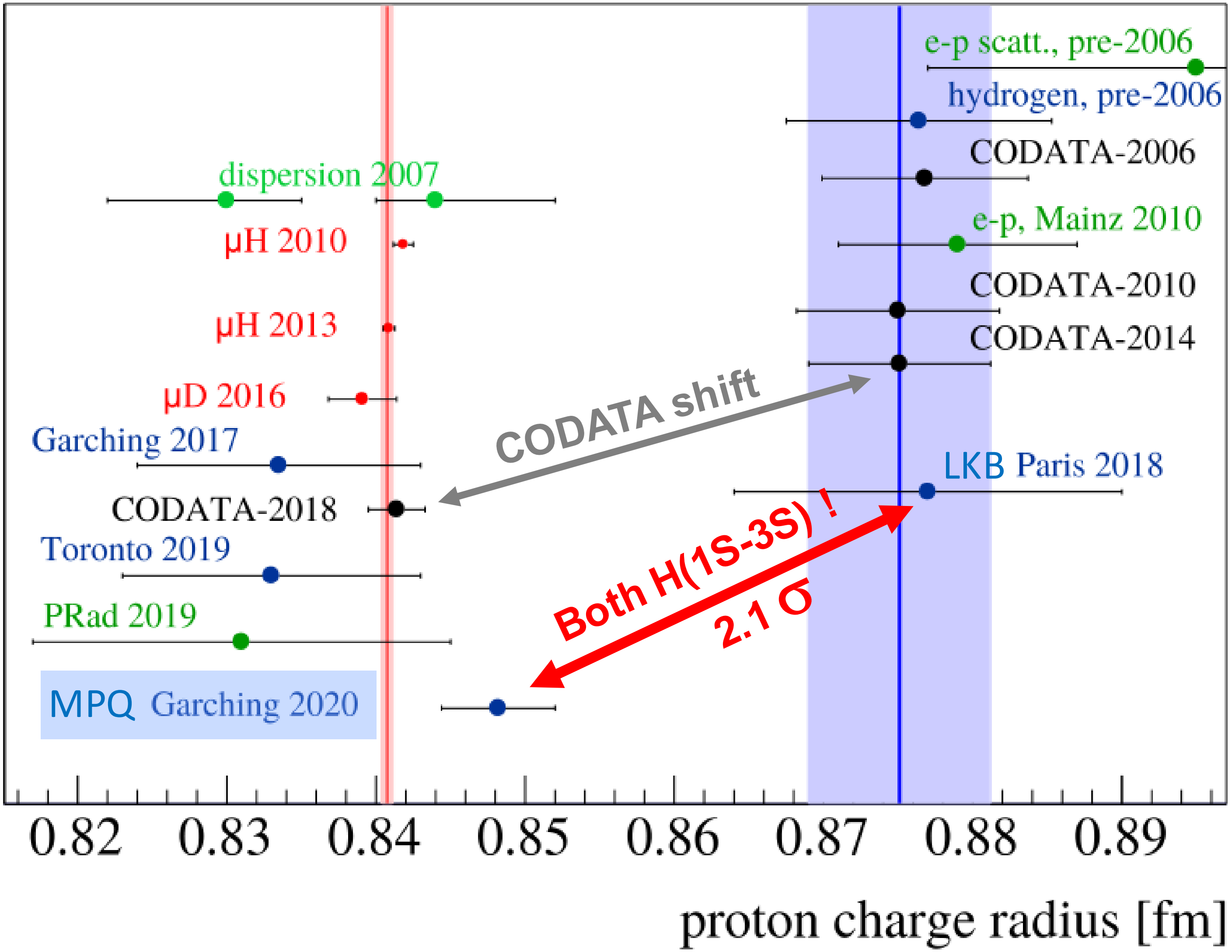
[b] Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Campus UAB, 08193 Bellaterra (Barcelona), Spain
[c] Grup de Física Teòrica, Dept. Física, Universitat Autònoma de Barcelona, E-08193 Bellaterra, Barcelona, Spain
[d] Department of Physics and Astronomy, University of Kentucky, Lexington, KY 40506, USA
[e] Theoretical Physics Department, Fermilab, Batavia, IL 60510, USA

- **« The proton charge radius »**
  H. Gao and M. Vanderhaeghen, Rev. Mod. Phys. (accepted Sept. 2021)
  arXiv:2105.00571v [hep-ph] (May 2021)

- **« The proton size »** *(invited review)*
  J.-P. Karr, DM, E. Voutier, Nature Reviews Physics 2 (2020) 601-14.
  https://rdcu.be/cyFp5 (open access -read only- shared link)

LKB
IJCLab Irène Joliot-Curie

Proton charge radius: the situation in 2021



CODATA 2018 recommended value*:

r_p = 0,8414(19) fm

"… and the puzzle appears to be resolved"

CODATA '18* Average (Toronto'19, PRad, μH'13):

r_p = 0,8409(4) fm

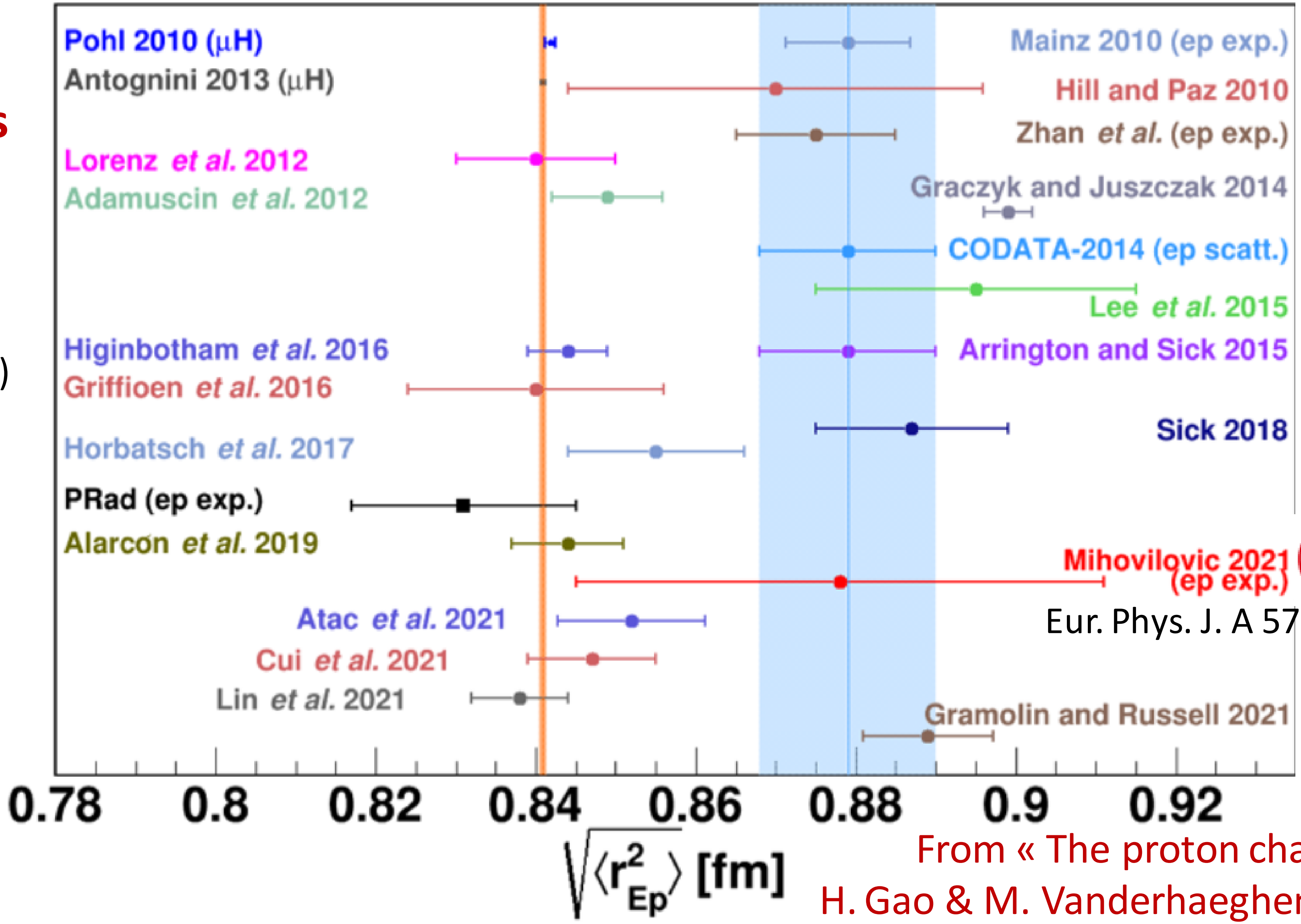
Reasons why most H spectroscopy and e-p scattering experiments obtained a « Large » radius have still to be fully understood as well as discrepancies in atomic hydrogen results

* P.A. Zyla et al. (Partcile Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2020)

Proton charge radius: the situation in 2021

(Re)anlayses of e-p scattering data

(not exhaustive)



ISR@Mainz

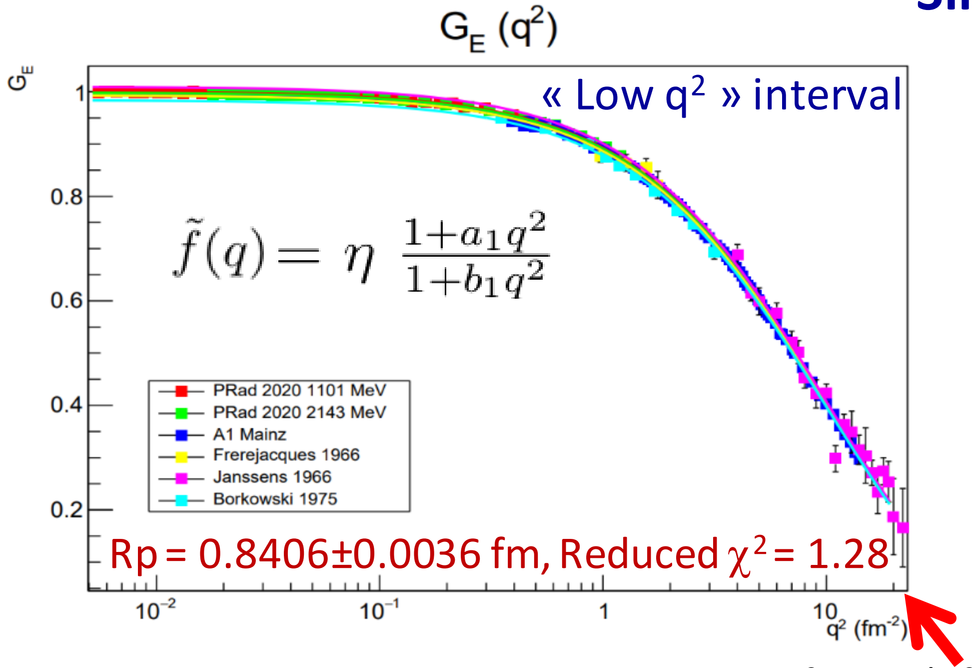
Eur. Phys. J. A 57 (2021)107

From « The proton charge radius »
H. Gao & M. Vanderhaeghen, Rev. Mod. Phys.
(accepted Sept. 2021), arXiv

Activities

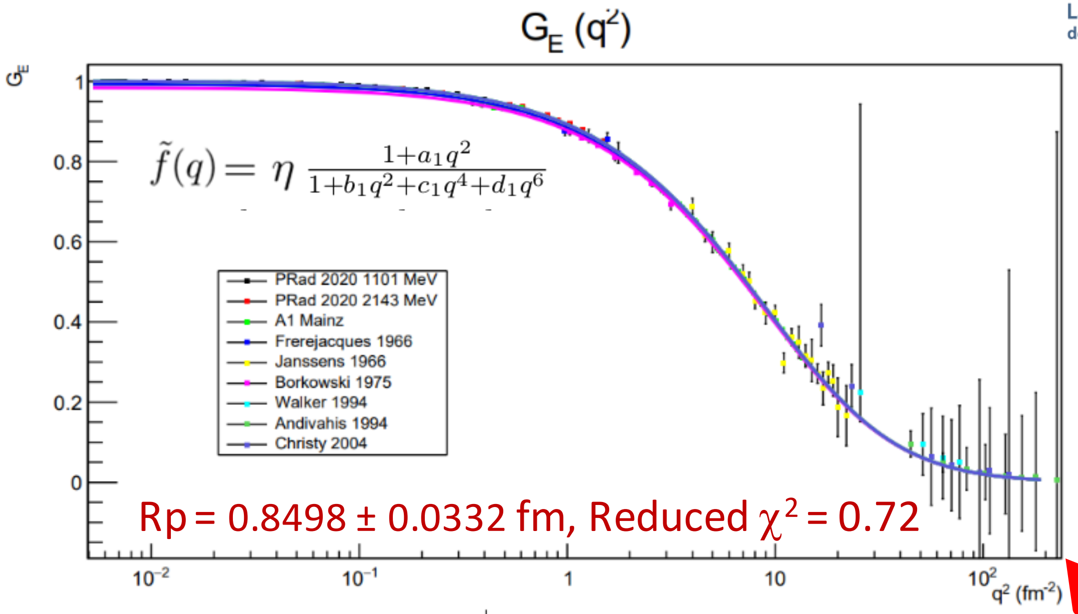
Carelle Keyrouz (Master thesis, 2021)

Simultaneous fit of available ep scattering data



Q^2 [$(GeV/c)^2$] ~ 0.8

Experiment	Normalization values
Frerejacques [12]	0.9938±0.0006
Janssens [14]	1.0097±0.0108
Borkowski [16]	0.9836±0.0023
Bernauer [21]	0.9986±0.001
Xiong 1.1 GeV [8]	1.0003±0.0004
Xiong 2.1 GeV [8]	0.9986±0.0001



Q^2 [$(GeV/c)^2$] ~ 8

Experiment	Normalization values
Frerejacques	0.9941 ± 0.0097
Janssens	1.0012 ± 0.0069
Borkowski	0.9845 ± 0.0027
Bernauer	0.9942 ± 0.0019
Xiong 1.1 GeV	1.0004 ± 0.0004
Xiong 2.1 GeV	0.9988 ± 0.0003
Walker	1.0012 ± 0.1878
Andivahis	1.0011 ± 0.1526
Christy	1.0012 ± 0.0298

Activities

Carelle Keyrouz (Master thesis, 2021)

Determination of spatial moments of the charge density

Integral method* relying on integral forms of the inverse Fourier transform of the charge distribution
⇒ determination of both **odd** and **even**, **positive** and **negative**, spatial moments of the distribution.
⇒ method not limited to low Q^2, overcomes the limitations of the derivative method.

p	r^p $(Q_C^2 = 52 fm^{-2})$	r^p
-2	6.4334	8.4480
-1	1.4206	2.0672
0	1.0000	1.0000
1	0.6838	0.7267
2	0.7224	0.7224
3	0.9461	0.9560
4	1.6915	1.6915
5	4.0316	4.0029
6	12.2974	12.2974
7	46.7539	46.5429

(Cut-off Q_C^2 [(GeV/c)^2] ~ 2)

→ r_p = 0.8499 fm

Evaluation of errors requires a dedicated pseudo data study to be performed

* Based on « Connecting spatial moments and momentum densities », M. Hoballah et al, Phys. Lett. B 808 (2020) 135669

Lepton scattering: on-going and future activities

Experiment	Beam	Laboratory	Q^2 $(\mathrm{GeV}/c)^2$	δr_p (fm)	Status	Data taking
MUSE	$e^\pm, \mu^\pm$	PSI	0.0015 - 0.08	0.01	Ongoing	End 2021-2022
PRM Compass++/AMBER	$\mu^\pm$	CERN	0.001 - 0.04	0.01	Future	2022 - 2023
PRad-II	e^-	Jefferson Lab	4×10^{-5} - 6×10^{-2}	0.0036	Future	2024 -
PRES @ A2	e^-	Mainz	0.001 - 0.04	0.6% (rel.)	Future	2022 -
A1@MAMI (jet target)	e^-	Mainz	0.004 - 0.085		Ongoing	Done
MAGIX@MESA	e^-	Mainz	$\geq 10^{-4} - 0.085$		Future	2024 -
ULQ^2	e^-	Tohoku University	3×10^{-4} - 8×10^{-3}	$\sim 1\%$ (rel.)	Future	2022 -

A1@MaMi (gas jet target): results from prototype measurements released by end 2021. Additional beamtime might be scheduled. Alternative ML approach (Y. Wang)

MUSE: commisioning run on-going, data taking end 2021-2022

PRM (Proton Radius Measurement with Muons) featuring a high pressure active TPC target (detection of recoil proton). 1st pilot run in 2021

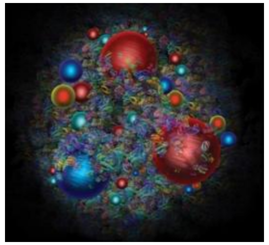
PRES@A2 (Proton Radius from Electron Scattering) high pressure active TPC target (detection of recoil proton + scattered electron)

PRad-II: engineering drawings finalized. Pre-proposal of PRad full upgrade setup submitted to NSF RI-I (Jan. '21). HyCal calorimeter upgrade proposal to be submitted Jan. '22 (NSF MRI). Looking to borrow used $PbWO_4$ crystals from other collaborations. Work in progress to find a collaboration to implement a new hydrogen droplet target in the experiment.

(Table from H. Gao, PANIC 2021)

PREN: outreach & dissemination

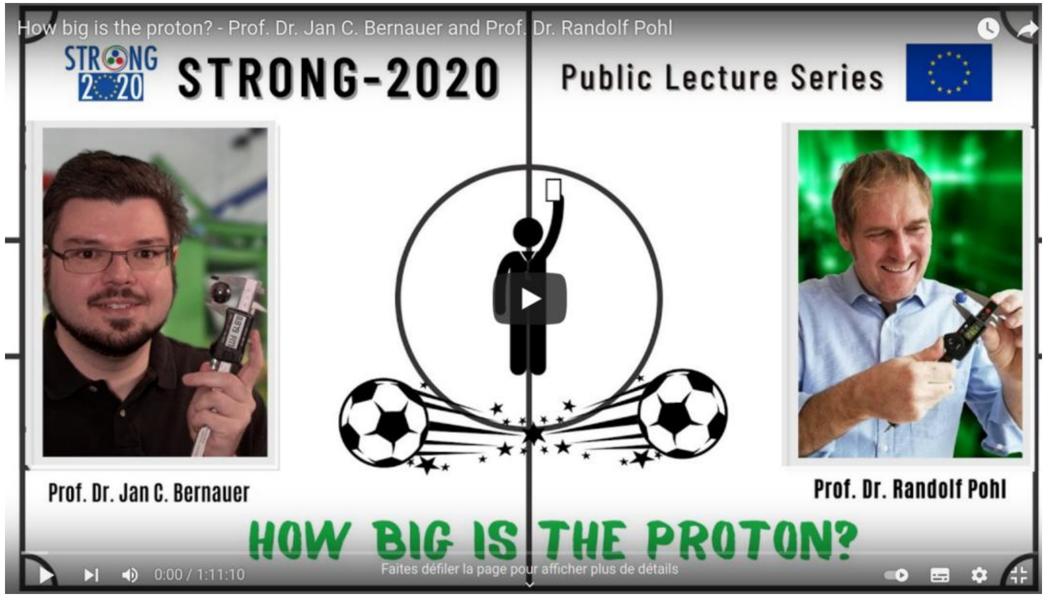
- **STRONG-2020 Newsletter #2**, Nov. 2020



Shrinking the proton (a featured article)

Jan C. Bernauer (Stony Brook University), Ashot Gasparian (North Carolina A&T University), Dominique Marchand (IJCLab Orsay), Randolf Pohl (J-G Mainz University)

- **STRONG-2020 1st Public Lecture**, December 16th, 2020



https://www.youtube.com/watch?v=C5B_ZfGy4d0

2 275 views

PREN: Milestones deviation

TASKS/Subtasks	Year 1				Year 2				Year 3				Year 4			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
1. PREN-COLLABORATION																
1.1 Development of a dedicated website																
2. PREN-MEETINGS																
2.1- Conventions																
2.2- Targeted workshops																

Dec. 2021

Schedule of relevant Milestones

Milestone number[18]	Milestone title	Lead beneficiary	Due Date (in months)	Means of verification
MS17	Development of a dedicated website	1 - CNRS	6	Access availability
MS18	Conventions	1 - CNRS	45	Convention, due dates (in months): 3, 24, 45
MS19	Meetings	1 - CNRS	33	Targeted workshop organization, due dates (in months) : 15, 33

In order to fulfill our objectives to stimulate a synergy between the 2 communities involved what we NEED is in-person meetings in order to meet each other and have thorough discussions to draw collaborative work.

Due to the pandemic situation, no possibility to meet in person in 2020 nor in 2021…

The PREN collaborators expressed clearly that we do not need virtual meetings (succession of progress reports).

PREN: Milestones deviation deviation

SORBONNE UNIVERSITÉ
Campus
Pierre et Marie Curie

Laboratoire Kastler Brossel
Physique quantique et applications

In person meeting in central Paris, Spring 2022

3-4 days format

Leaving time slots for discussions

Organized by IJCLab and LKB PREN collaborators

Contacts to book rooms is underway

International / Local organizing committees in discussion to start inviting participants

Estimation of the budget enveloppe by next month

+ 1 targetted workshop foreseen in Fall 2022, Germany

Conclusions

Summary

- New R_p result from 1S-3S trasition frequency measurement (MPQ, Garching)
- Updated precision calculations of fundamental constants (LKB and collaborators)
- Constraints/limits on BSM physics invoked to adress the proton radius puzzle
- Many re-analyses of available lepton scattering data including TMVA techniques
- Recent exhaustive reviews published

Small value of proton charge radius is favored
----> the proton radius puzzle seems to be resolved (less tension)

Discrepancies

- between lepton scattering Rp large value and PRad and hydrogen (ordinary/muonic) spectroscopy
- between values from ordinary hydrogen spectroscopy (LKB Paris – Toronto – MPQ Garching)
- between values from ordinary hydrogen (LKB Paris) and muonic hydrogen like atoms/molecules

have to be fully understood

Waiting for results from:

- « New » Mainz A1 (gas jet target) e-p scattering
- MUSE ($e^{+/-}$ / $\mu^{+/-}$ - p scattering)
- H_2^+ , μ^3He

Conclusions

Perspectives

Perspectives in lepton-p scattering:

- PRES@A2 (MaMi, Mainz), 2022-
- PRM,COMPASS++/AMBER-CERN, 2022-
- ULQ2 (Japan), 2022-
- MAGIX@MESA, Mainz, 2024-
- PRad II (JLab), 2024-

Perspectives in atomic physics:

- μD
- hydrogen molecular ions
- muonium

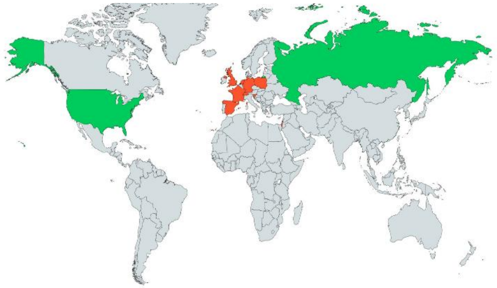
Theoretical / analytical developements

Our network activity suffered dramatically from the pandemic situation delaying experiments and preventing us to meet in person.

- PREN meeting in person in Paris in Spring 2022
- Investigating the opportunity to propose a subject concerning an objective analysis of past lepton ep scattering data (6-8 months postdocral position)

PREN: 22 institutions / 11 countries

Eligible EU countries
Other countries



Theorists and **Experimentalists**
from
Atomic and **Lepton Scattering Physics**

Thank you!

- **CEA** Saclay/DRF/Irfu/Département de Physique Nucléaire, France;N. D'Hose,
- **CNRS**: France; D. Marchand (IPN Orsay) and J.-Ph. Karr (LKB, Paris),
  G. Quéméner (LPC Caen), H. Fonvielle (LPC Clermont-Ferrand),
- **ETH Zurich**, Switzerland; P. Crivelli,
- **Hebrew University**, Jerusalem, Israel; G. Ron,
- ***JG University Mainz***, Germany; M. Ostrick, R. Pohl, M. Vanderhaeghen,
- **JWG University** Frankfürt, Germany; R. Grisenti,
- **Jožef Stefan Institute**, Ljubljana, Slovenia; M. Mihovilovič, S. Sirca,
- **LaserLaB**, Vrije Universiteit, Amsterdam, Netherlands; W. Vassen, K. Eikema,
- **MPQ Garching**, Germany; T.W. Hänsch, Th. Udem, S. Karshenboim,
- **Paul-Scherrer-Institut (PSI)**, Villigen, Switzerland; A. Antognini,
- **Technische University** München, Garching, Germany; S. Paul,
- **Universitat Autonoma de Barcelona** / IFAE, Spain; A. Pineda,
- **University College of London**, London, UK; D. Cassidy,
- **University of Warsaw**, Warszawa, Polska; Krzysztof Pachucki.

- **Bogoliubov Laboratory of Theoretical Physics**, JINR Dubna, Russia; V. Korobov,
- **George Washington University**, Washington DC, USA; A. Afanasev,
- **CFNS, Stony Brook University & RIKEN BNL Research Center**; J. Bernauer,
- **North Carolina A&T State University**, Greensboro, NC, USA; A. Gasparian,
- **Rutgers**, The State University of New Jersey, Piscataway, NJ, USA; R. Gilman,
- **Petersburg Nuclear Physics Institute** (PNPI), Gatchina, Russia; A. Vorobyov