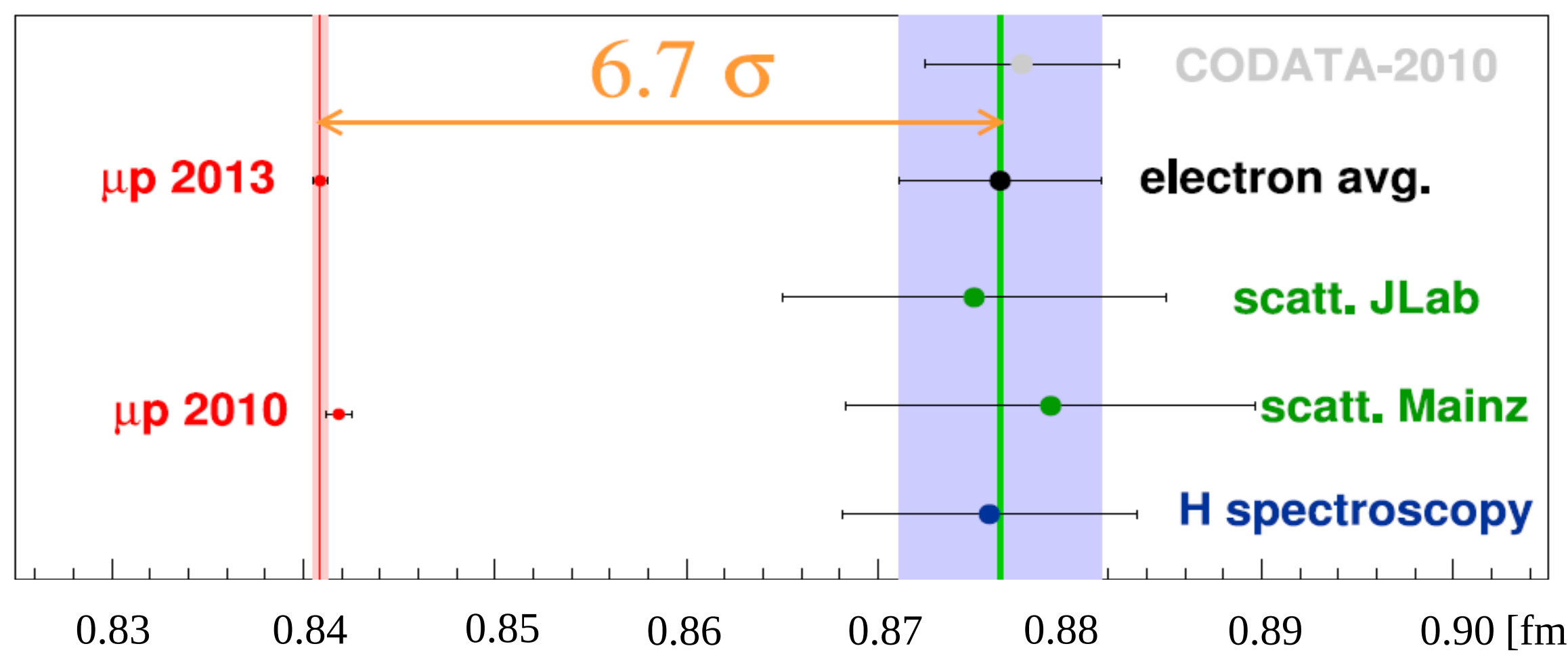
FAMU: high precision measurement of the muonic hydrogen hyperfine splitting

E. Mocchiutti (Emiliano.Mocchiutti@ts.infn.it) on behalf of the FAMU Collaboration: A. Adamczak, G. Baccolo, D. Bakalov, G. Baldazzi, R. Bertoni, M. Bonesini, V. Bonvicini, G. Campana, R. Carbone, T. Cervi, F. Chignoli, M. Clemenza, L. Colace, A. Curioni, M. Danailov, P. Danev, I. D'Antone, A. De Bari, C. De Vecchi, M. De Vincenzi, M. Furini, F. Fuschino, K.S. Gadedjisso-Tossou, D. Guffanti, A. Iaciofano, K. Ishida, D. Iugovaz, C. Labanti, V. Maggi, A. Margotti, M. Marisaldi, R. Mazza, S. Meneghini, A. Menegolli, E. Mocchiutti, M. Moretti, G. Morgante, R. Nardò, M. Nastasi, J. Niemela, E. Previtali, R. Ramponi, A. Rachevski, L.P. Rignanese, M. Rossella, P.L. Rossi, F. Somma, M. Stoilov, L. Stoychev, A. Tomaselli, L. Tortora, A. Vacchi, E. Vallazza, G. Zampa and M. Zuffa.

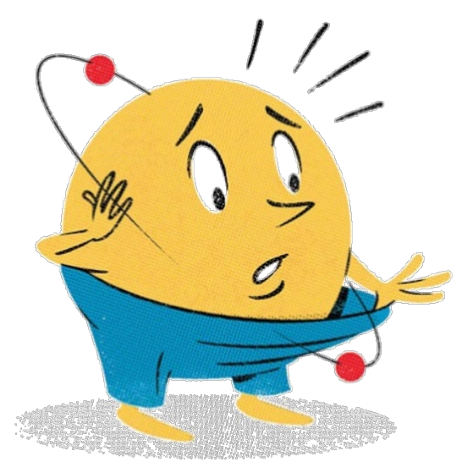
1. Experimental errors, new physics or misgauged Rydberg constant?

The proton radius is extremely hard to measure with high precision and with excellent control of systematics.



Proton radius measurements: discrepancy between electron measurements and muon spectroscopy at PSI [1].

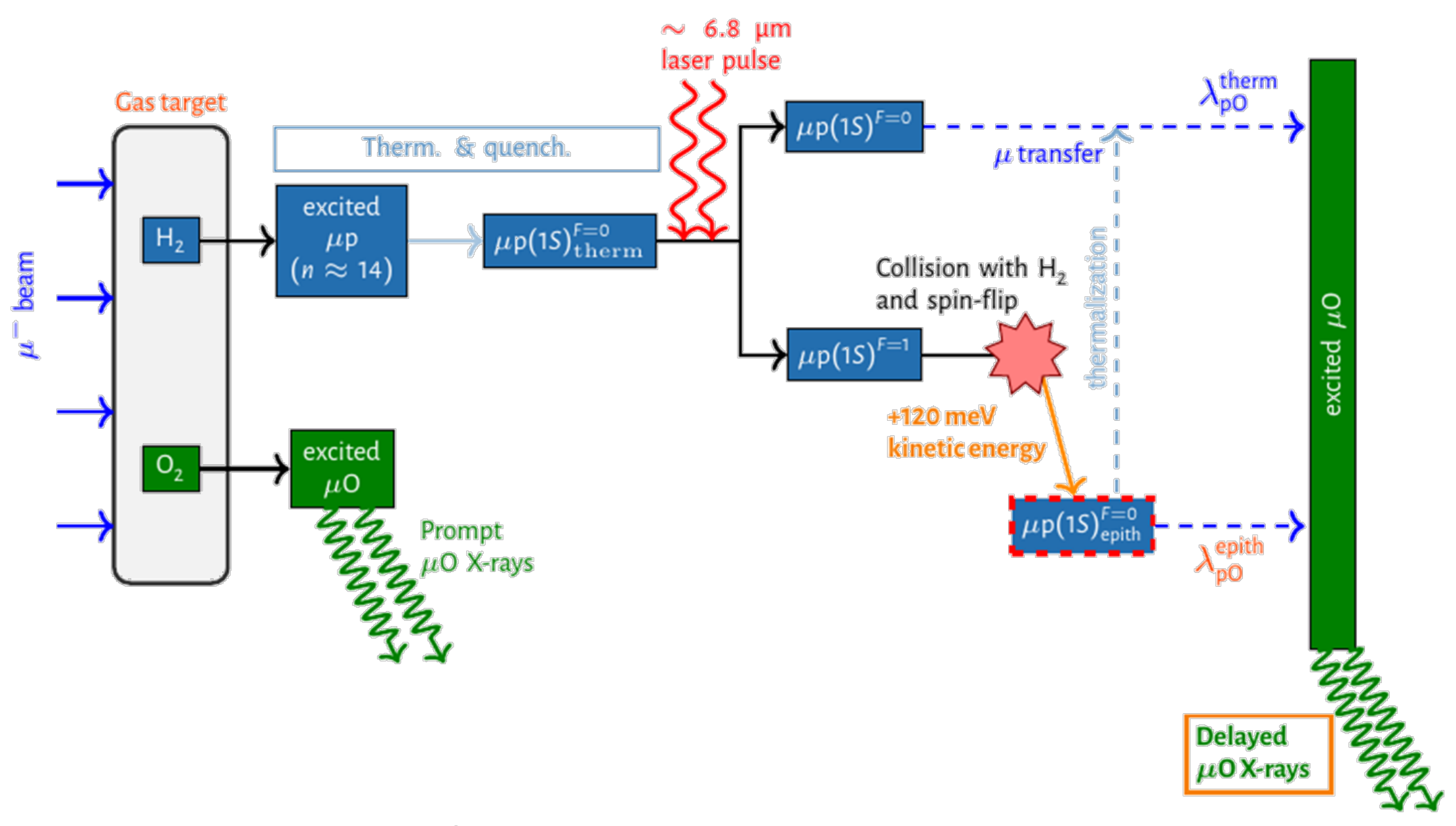
A shrinking of the proton in presence of a muon could signify the existence of a **previously unknown fundamental force** - one that acts between protons and muons but not between protons and electrons.



Another possibility is a **misgauged Rydberg constant**, a factor that goes in the QED calculations of differences between atomic energy levels.

2. FAMU experimental method

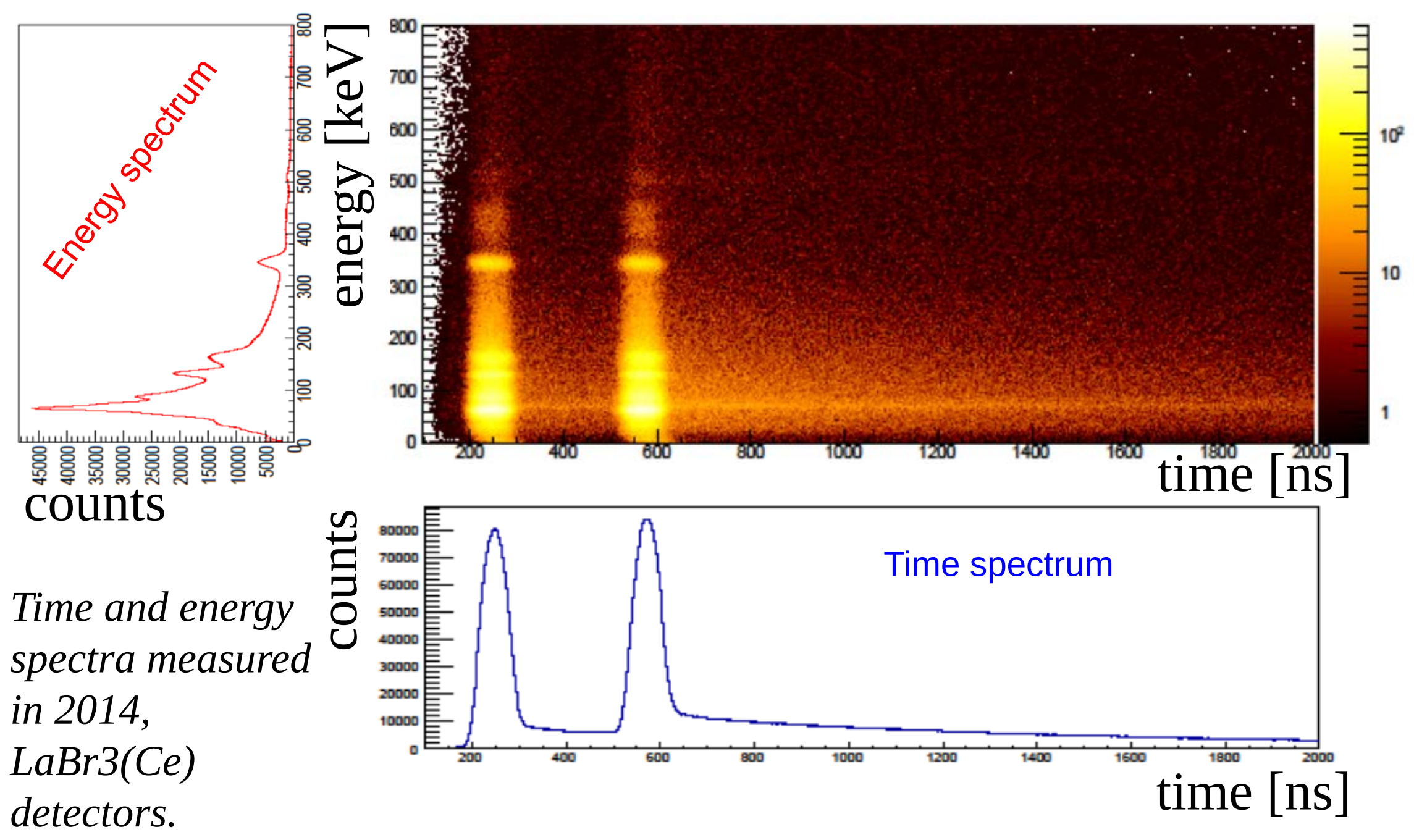
FAMU will realize a spectroscopic measurement of the hyperfine splitting (hfs) in the 1S state of muonic hydrogen $\Delta E^{hfs}(\mu^- p)_{1S}$ with **unprecedented precision** – $d\lambda/\lambda < 10^{-5}$ – providing crucial information on proton structure and muon- nucleon interaction [2]. The method is the following: muonic hydrogen atoms (μp) form in an appropriate mixture of hydrogen and a higher-Z gas. A μp in the ground state, after absorbing a photon of energy equal to the hfs resonance-energy, is very quickly de-excited in subsequent collision with other molecules. At the exit of the collision the **μp is accelerated** by ~2/3 of the excitation energy, taken away as kinetic energy. The observable is the time distribution of the characteristic X-rays emitted from the muonic atoms formed by μ transfer (which is kinetic energy dependent [3]) from hydrogen to the atom of the admixture gas $(\mu p) + Z \rightarrow (\mu Z)^* + p$ and its response to variations of the laser radiation wavelength [4].



Schematic view of the FAMU experimental method

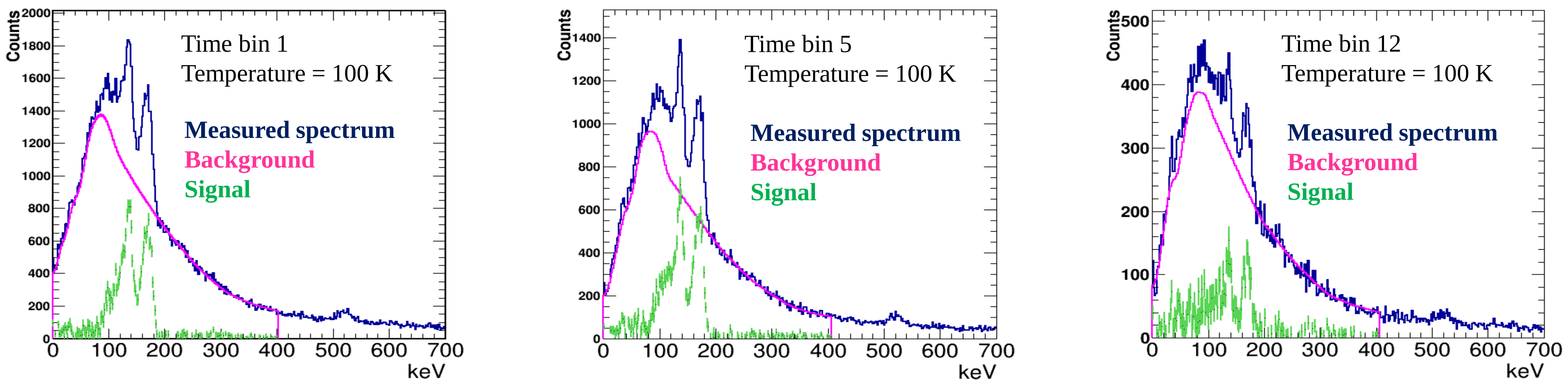
An intense muon beam, like the RIKEN-RAL one (UK), is needed to achieve the needed statistics and precision. The planning is to: 1) optimize the gas filling of the target and it operating conditions (2014 run) 2) measure the transfer rate from μp to Oxygen (2016 run) 3) measure $\Delta E^{hfs}(\mu^- p)_{1S}$ and derive the proton Zemach radius, run with the laser to drive the hfs transition (expected in 2018).

3. Detectors characterization and transfer rate to Oxygen

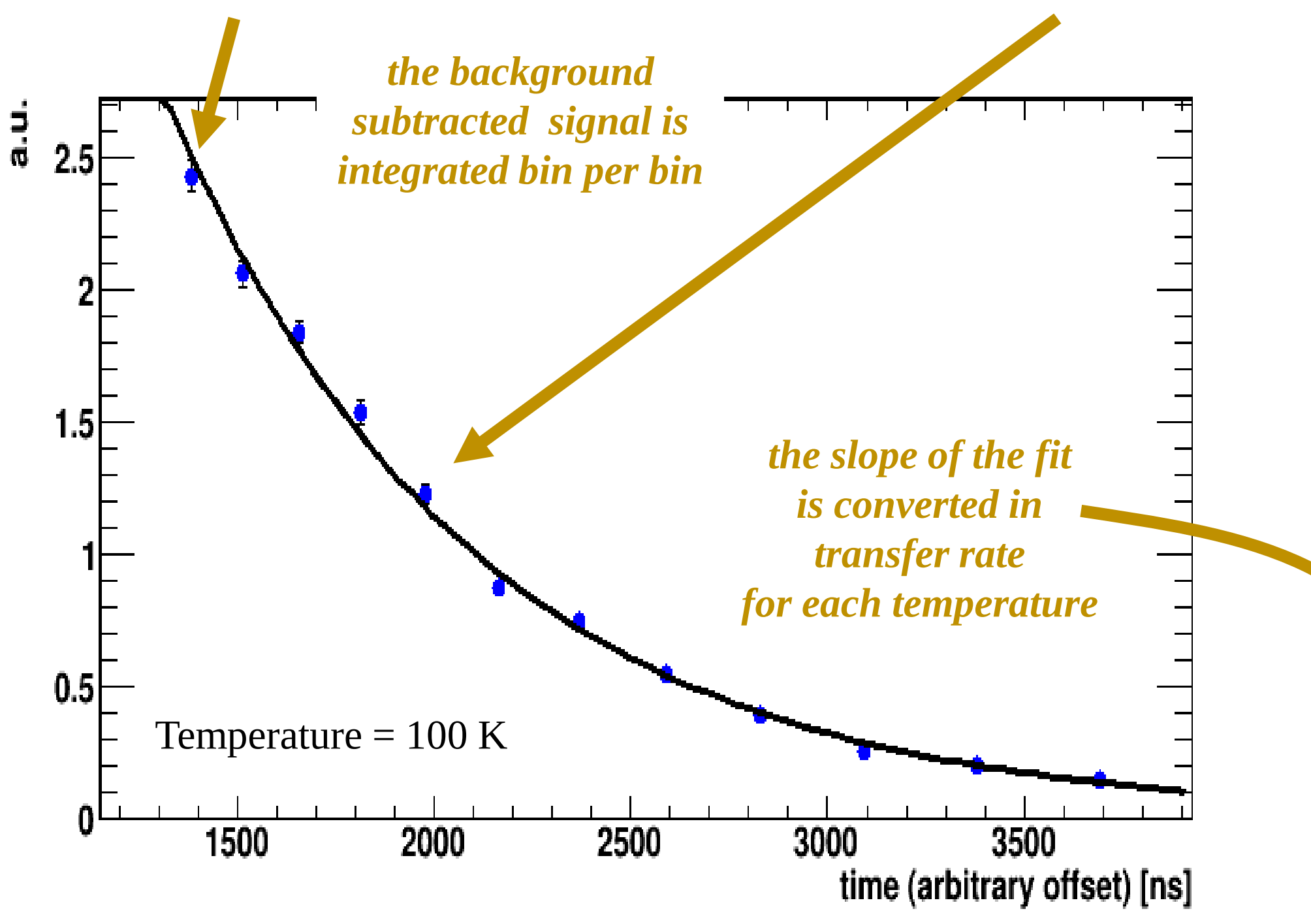


Time and energy spectra measured in 2014, LaBr3(Ce) detectors.

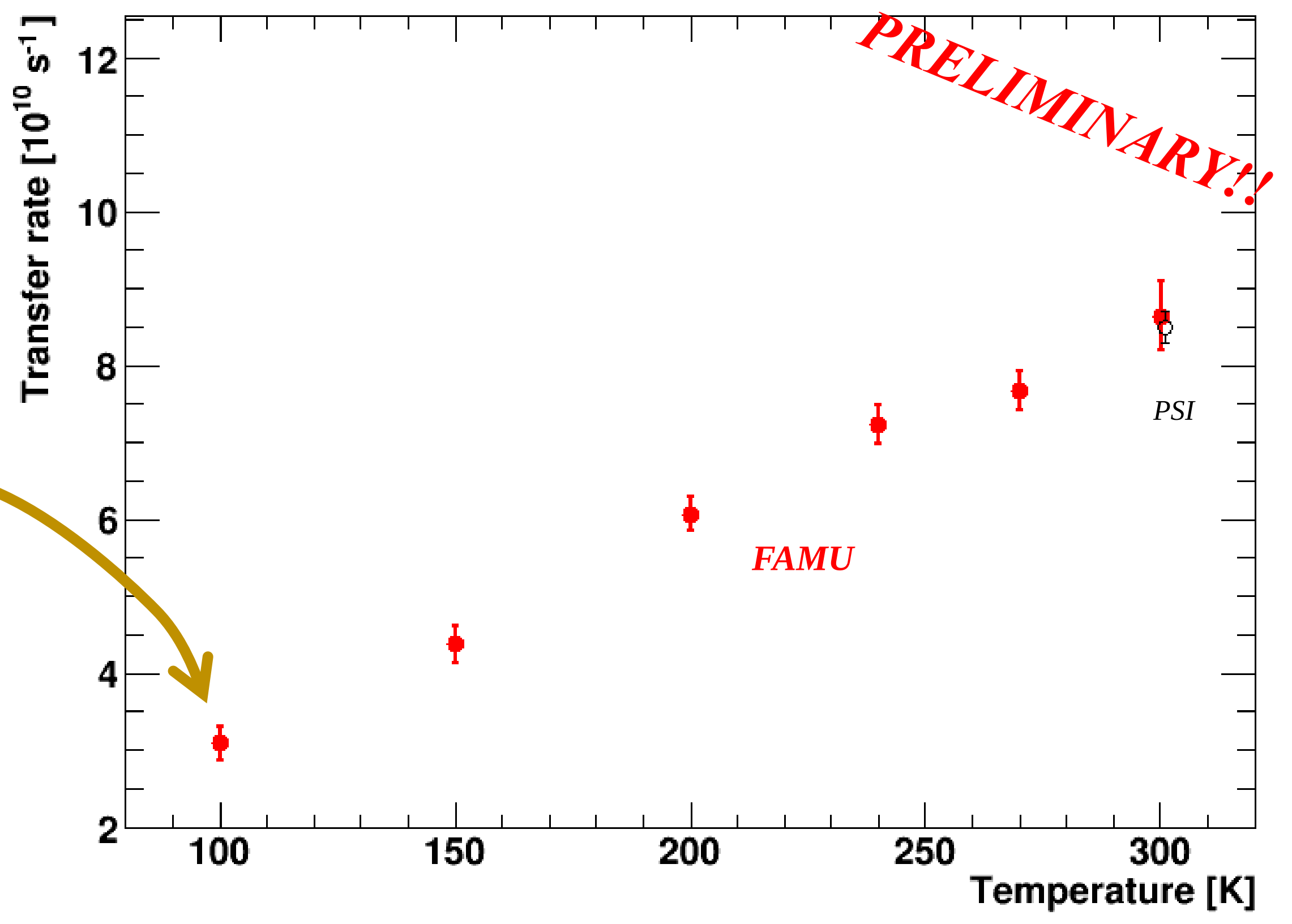
The experimental apparatus includes a precise **fiber-SiPMT** beam **hodoscope**, a crown of **eight LaBr3 crystals** and **four HPGe** detectors for detection of emitted characteristic X-rays. FAMU target is kept at 40 bars, permitting about $3\cdot10^4$ μ/s stop in the target forming muonic hydrogen, as compared to the $4\cdot10^2$ μ/s flux from the continuous muon source of PSI, a gain of nearly two orders of magnitude. During first validation tests at the beam delivery Port 4 of the RIKEN-RAL facility, the detection system and the beam condition allowed a perfectly satisfactory background situation [2] and an excellent time and energy X-rays reconstruction. Measurements taken in 2016 confirm the **energy dependent muon transfer rate to Oxygen**.



a. Oxygen lines (~133 keV and ~150 keV) reconstruction in different time bins (2016 run).



b. Fitting of the oxygen signal time evolution.



c. For the **first time** ever the transfer rate is measured as function of the temperature.

A cryogenic temperature controlled target was used to study the time evolution of Oxygen X-ray lines. At each of the six chosen temperatures the delayed Oxygen signal is measured after a background estimation and subtraction. This procedure is performed in several time bins delayed respect the muon arrival (panel a). The time evolution is then fitted with an exponential function (panel b) and the transfer rate is finally evaluated (panel c).

4. Outlook and future measurements

While finalizing the preliminary measurements, the laser measurements is prepared by:

- finishing the realization of the **tunable mid-infrared laser source** with the needed characteristics - wavelength 6785 nm (44.22 THz), line width 0.07 nm (450 MHz), tunability ±10 nm (120 GHz), operating at repetition rate 50Hz with 20-30 ns long pulse, pulse energy >2 mJ. The laser is based on non-linear optics using direct difference frequency generation in non-oxide nonlinear crystals and using a Q-switched single longitudinal mode Nd:YAG laser (1064 nm) and a tunable narrowband Cr:forsterite laser operating at 1260 nm, pumped by another YAG laser [5].
- realizing an **optical multi-pass reflecting cavity** meeting strict geometrical and optical constraints to maximize the spin-flip transition probability. Our specifically-designed mirrors will have reflectivity better than 99.95%.
- modifying the 2016 **cryogenic target** to include optical path and cavity.

A set of preliminary measurements with the laser will be carried out in 2017, aiming at 2018 for the measurement of the Zemach radius.

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