

# Diffusion in the hyperfine splitting experiment with muonic hydrogen

*PhD Seminar 26.01.2023*

**Jonas Nuber**

For the CREMA collaboration

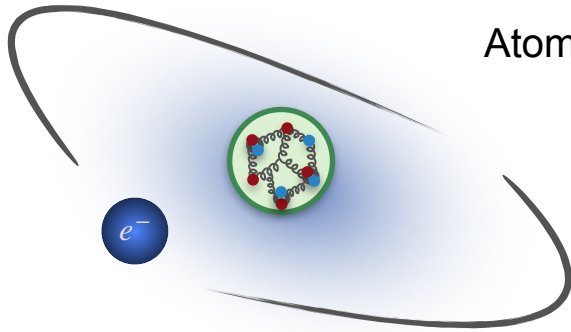
Supervised by

Aldo Antognini

Klaus Kirch

Andreas Knecht

# Muonic hydrogen and the proton structure

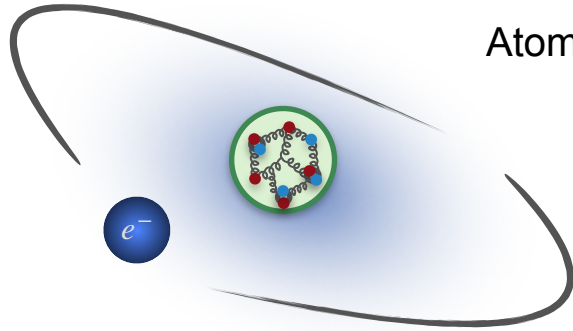


Hydrogen

Atomic levels of hydrogen are shifted by size and structure of the proton.

Effect of the finite size: 
$$\Delta E_{\text{size}} = \frac{2(Z\alpha)^4}{3n^3} \underline{m_r^3} r_p^2$$
  
reduced mass!

# Muonic hydrogen and the proton structure



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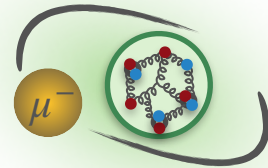
$$\Delta E_{\text{size}} = \frac{2(Z\alpha)^4}{3n^3} m_r^3 r_p^2$$

reduced mass!

$$m_\mu \approx 200 \cdot m_e$$

$$\Delta E_{\text{size}}(\mu p) \sim 10^7 \cdot \Delta E_{\text{size}}(\text{H})$$

CREMA collaboration:  
Laser spectroscopy with light muonic atoms

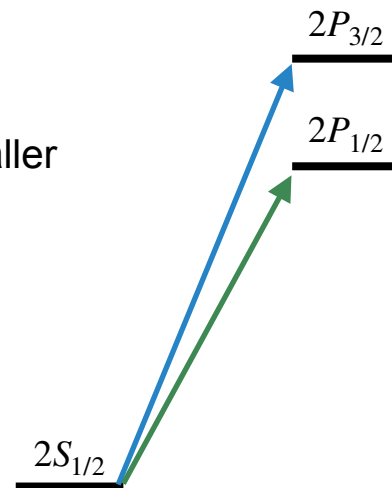
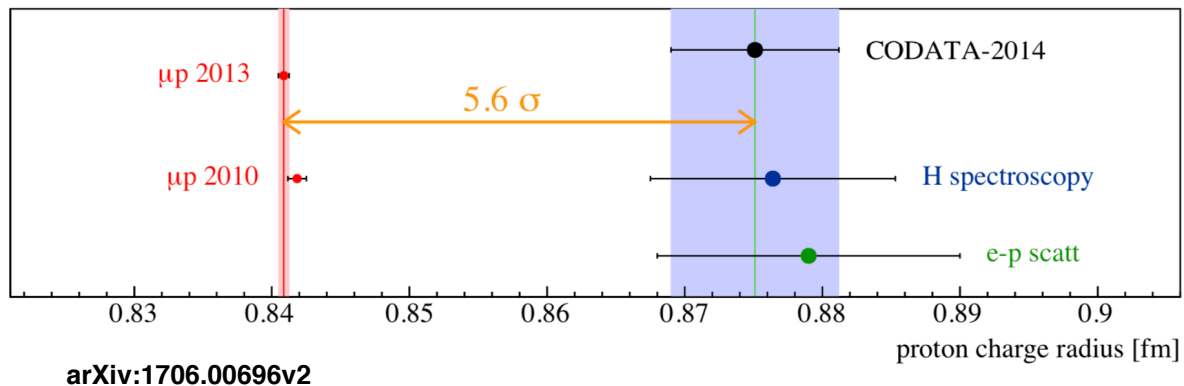


Muonic hydrogen

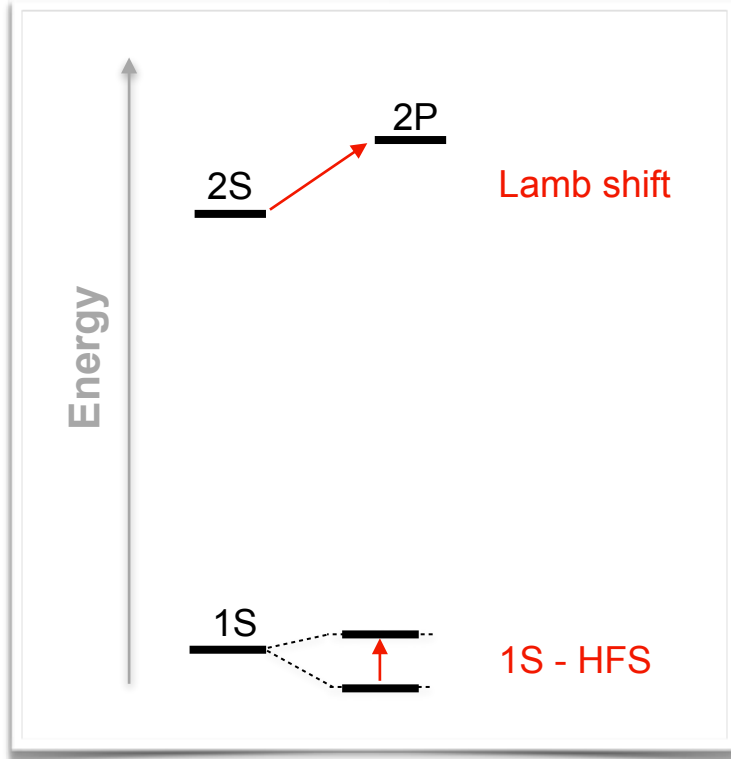
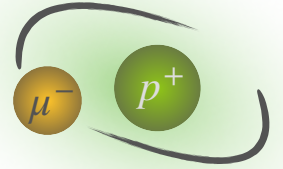
# History lesson: The proton radius puzzle

Measurements of the Lamb shift in  $\mu p$  implied a significantly smaller proton charge radius compared to previous measurements.

## The situation as of 2017



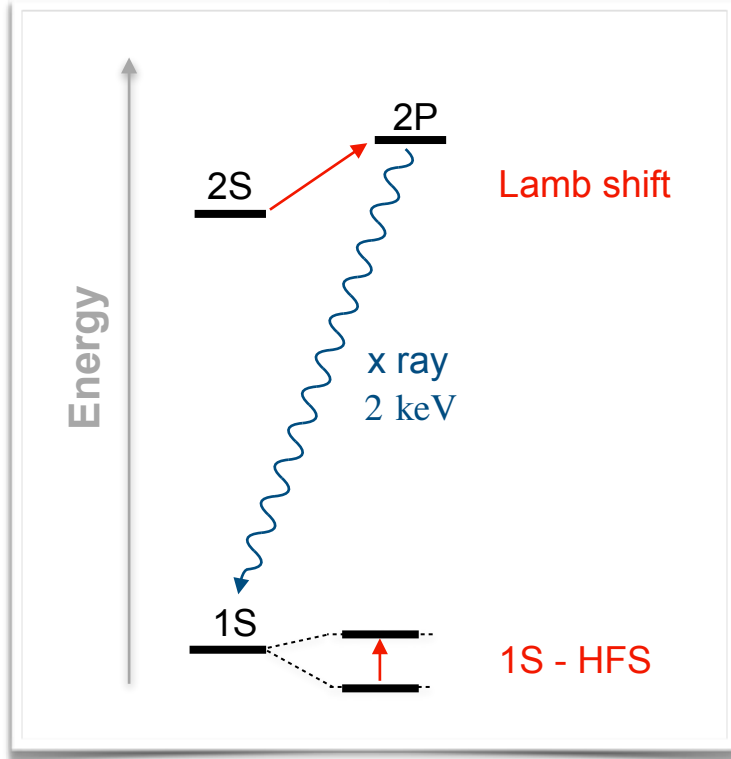
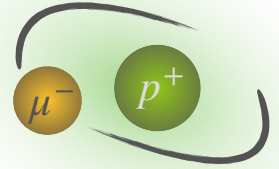
# Lamb shift and 1S hyperfine splitting (HFS) in $\mu p$



Proton charge radius from Lamb shift

Magnetic properties from 1S HFS

# Lamb shift and 1S hyperfine splitting (HFS) in $\mu p$



## Proton charge radius from Lamb shift

- Excite 2S-2P with a  $6.0 \mu\text{m}$  laser
- Detect 2 keV x ray on resonance

## Magnetic properties from 1S HFS

- Excite HFS transition with a  $6.8 \mu\text{m}$  laser
- But what to detect?

# The 1S hyperfine splitting (HFS) in $\mu p$

Most important corrections:

$$E_{\text{HFS}}(1S) = E_F + \Delta_{\text{QED+weak}} + \Delta_{\text{hVP}} + \Delta_{2\gamma}$$

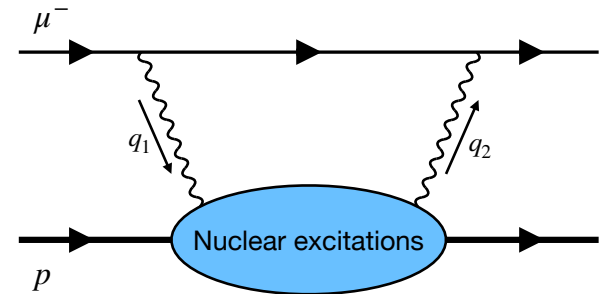
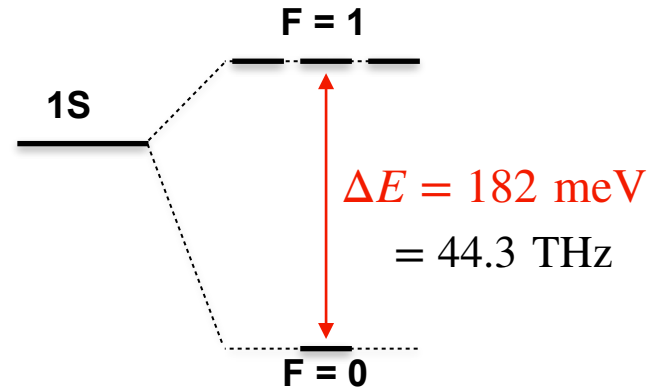


Most interesting for theorists: Two-photon exchange

**Experimental goal:**

Measure 1S-HFS with  $\sim 1\text{ppm}$  precision ( $\sim 40\text{ MHz}$ )

$\rightarrow$  extract  $\Delta_{2\gamma}$  with relative accuracy of  $10^{-4}$



# Where do we measure?

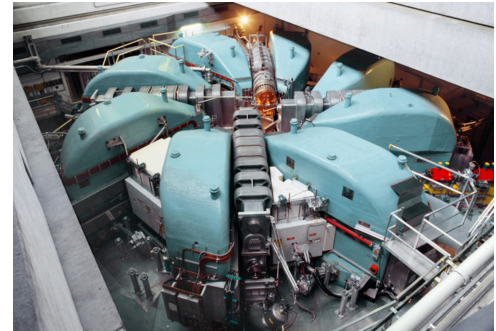


source: PSI

## Paul Scherrer Institute

Hosts the world's most intense continuous muon beam

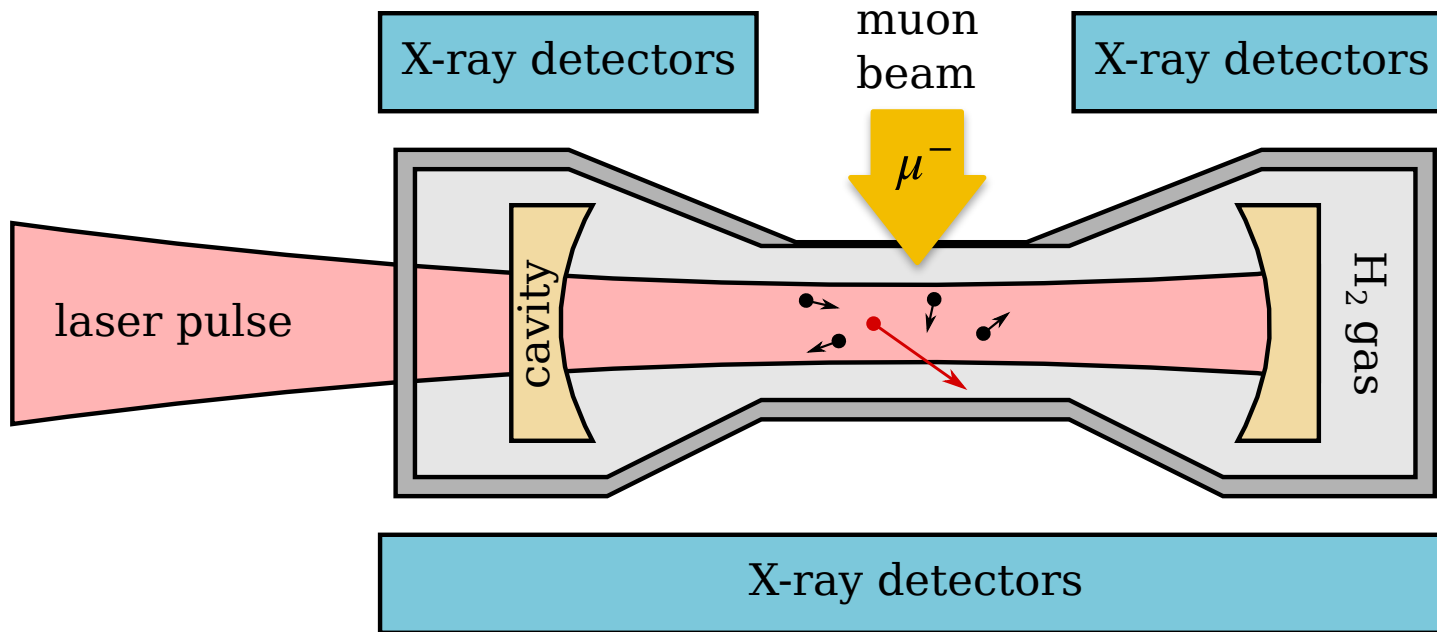
## Cyclotron for proton acceleration



source: PSI

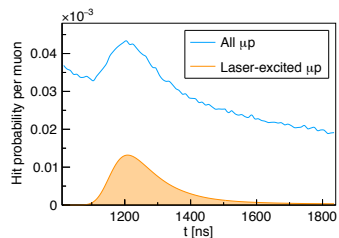


# Scheme of the HFS measurement



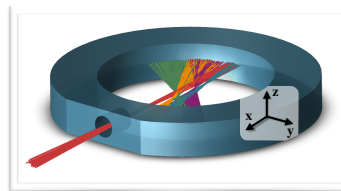
adapted from [arXiv:2211.08297](https://arxiv.org/abs/2211.08297)

### Diffusion simulations



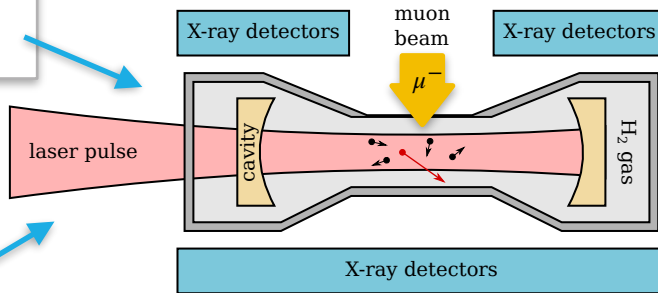
This work

### Laser fluence distribution



PhD thesis M. Marszalek

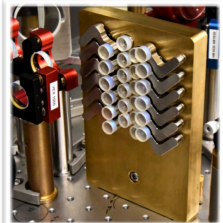
## This work: Predict event rates



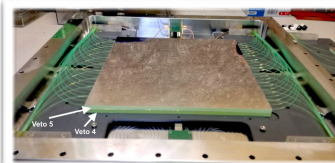
### Laser parameters

PhD thesis  
M. Zeyen

Lukas Affolter  
after lunch!

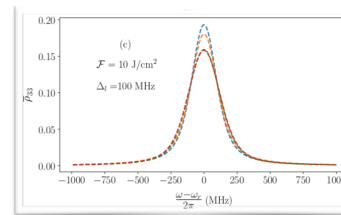


### Detection efficiencies



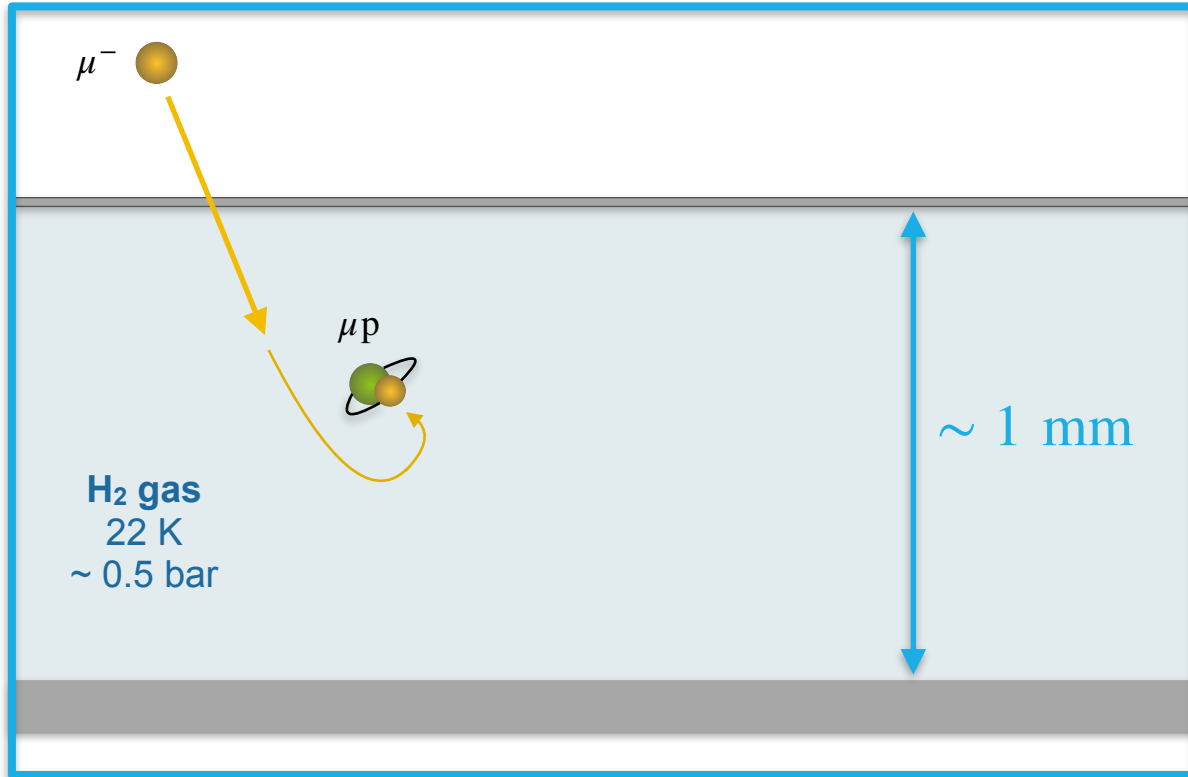
PhD thesis L. Sinkunaite

### Excitation probability

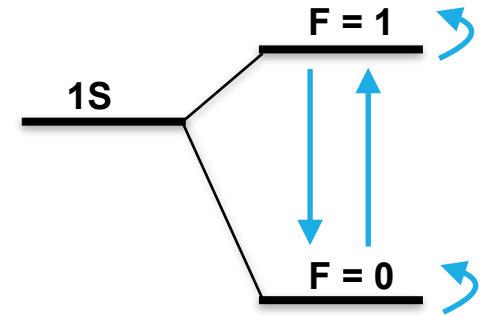
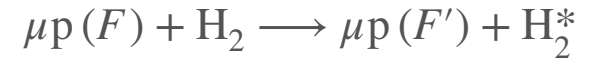
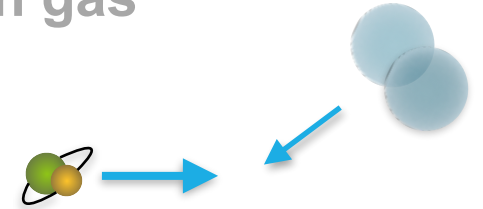
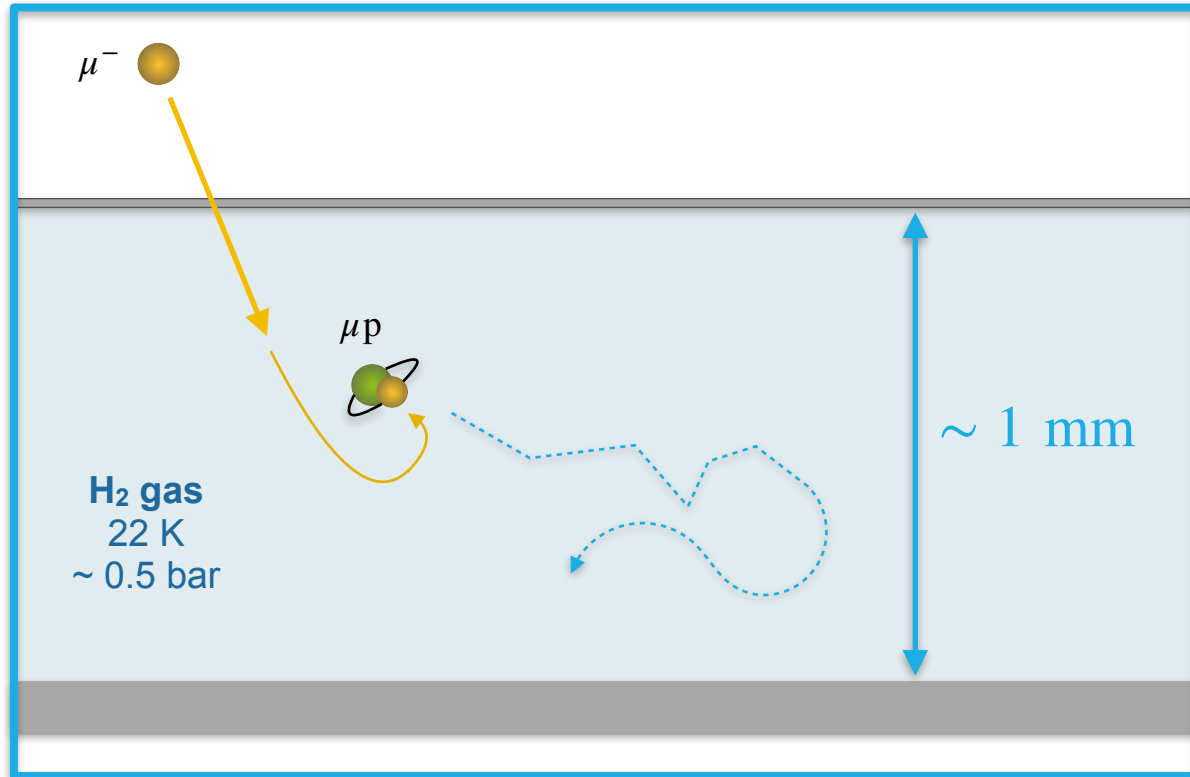


Amaro et al., arXiv:2112.00138

# Formation and thermalization of $\mu p$ in hydrogen gas

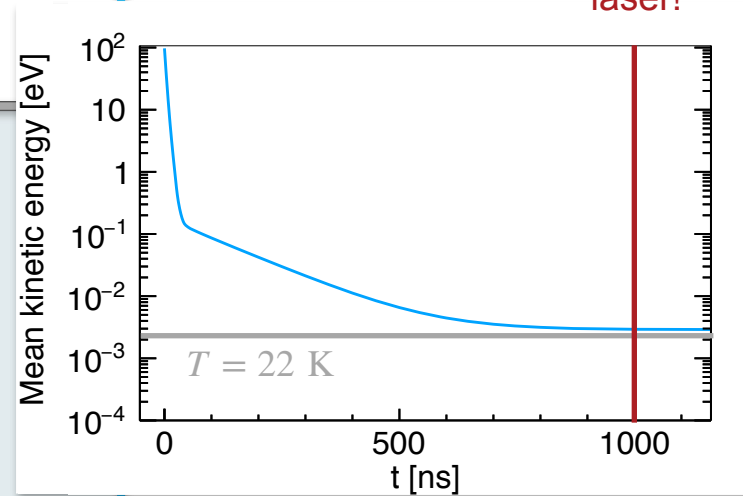
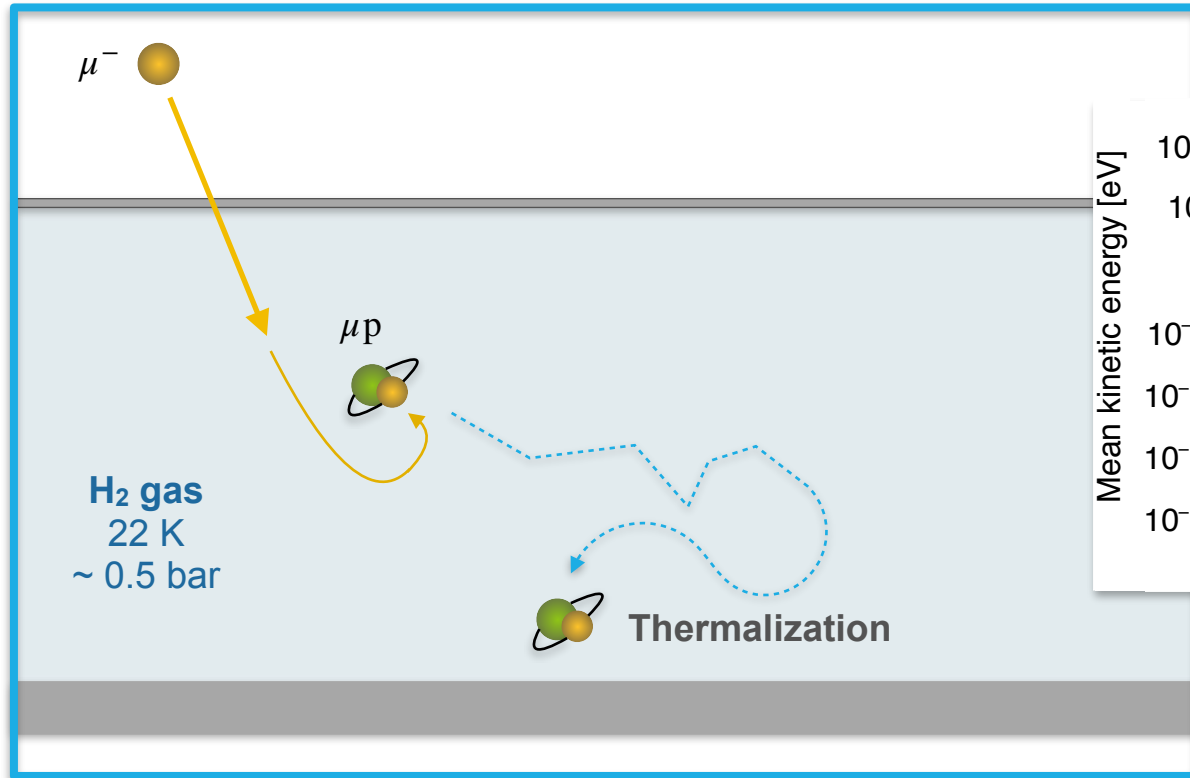


# Formation and thermalization of $\mu p$ in hydrogen gas



Implementation in  
Geant4 / G4beamline

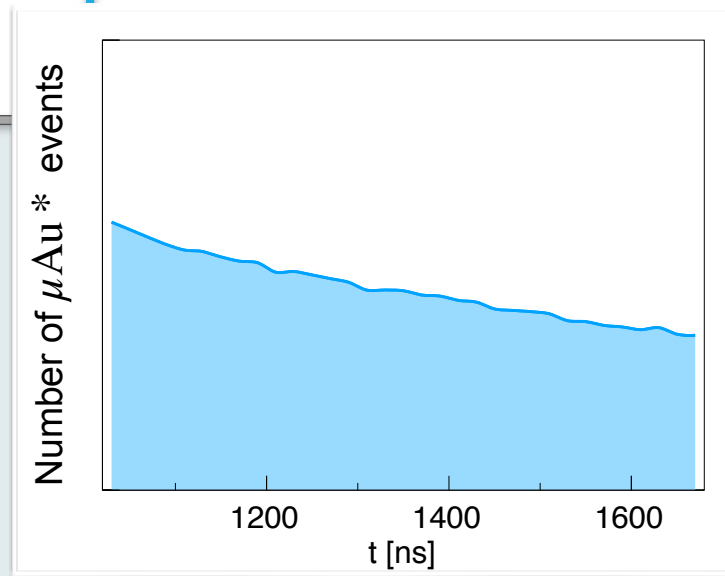
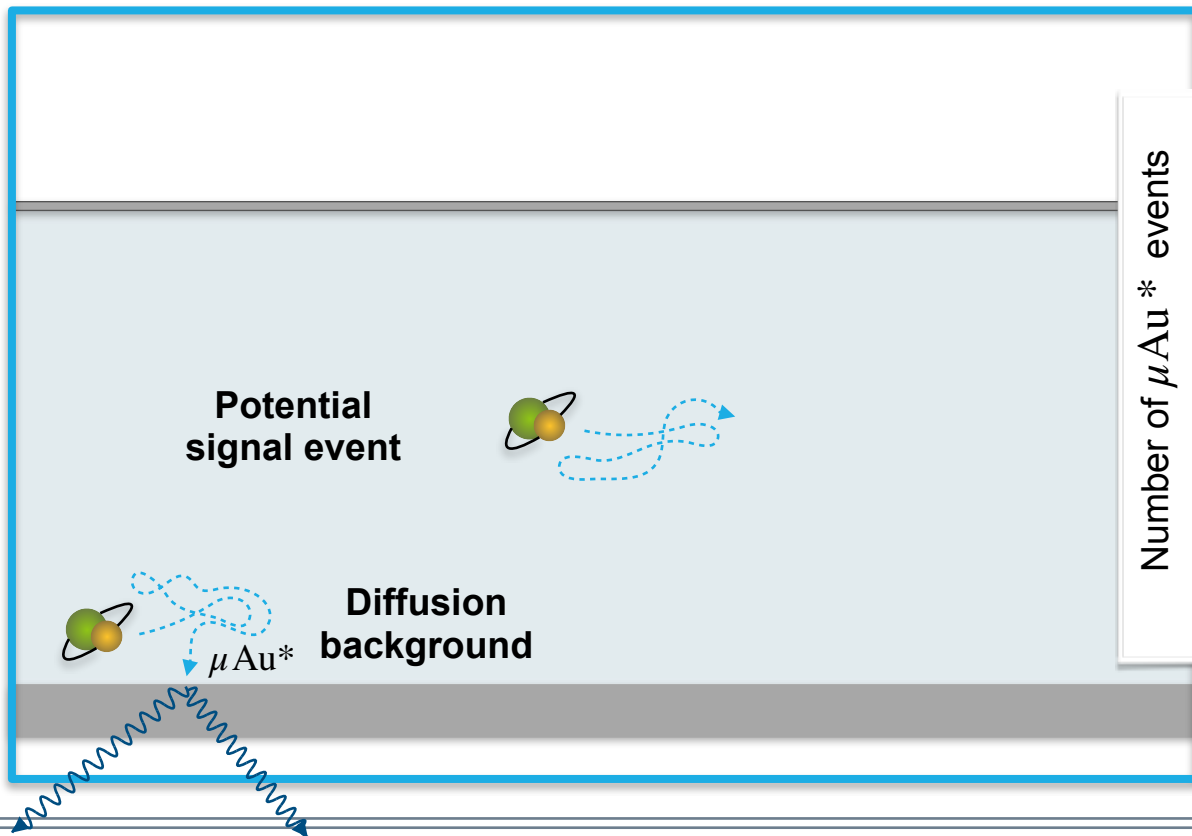
# Formation and thermalization of $\mu p$ in hydrogen gas



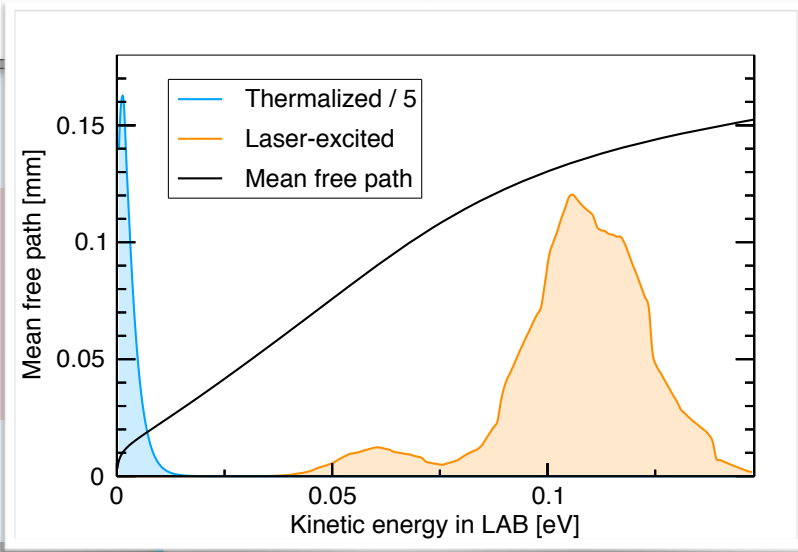
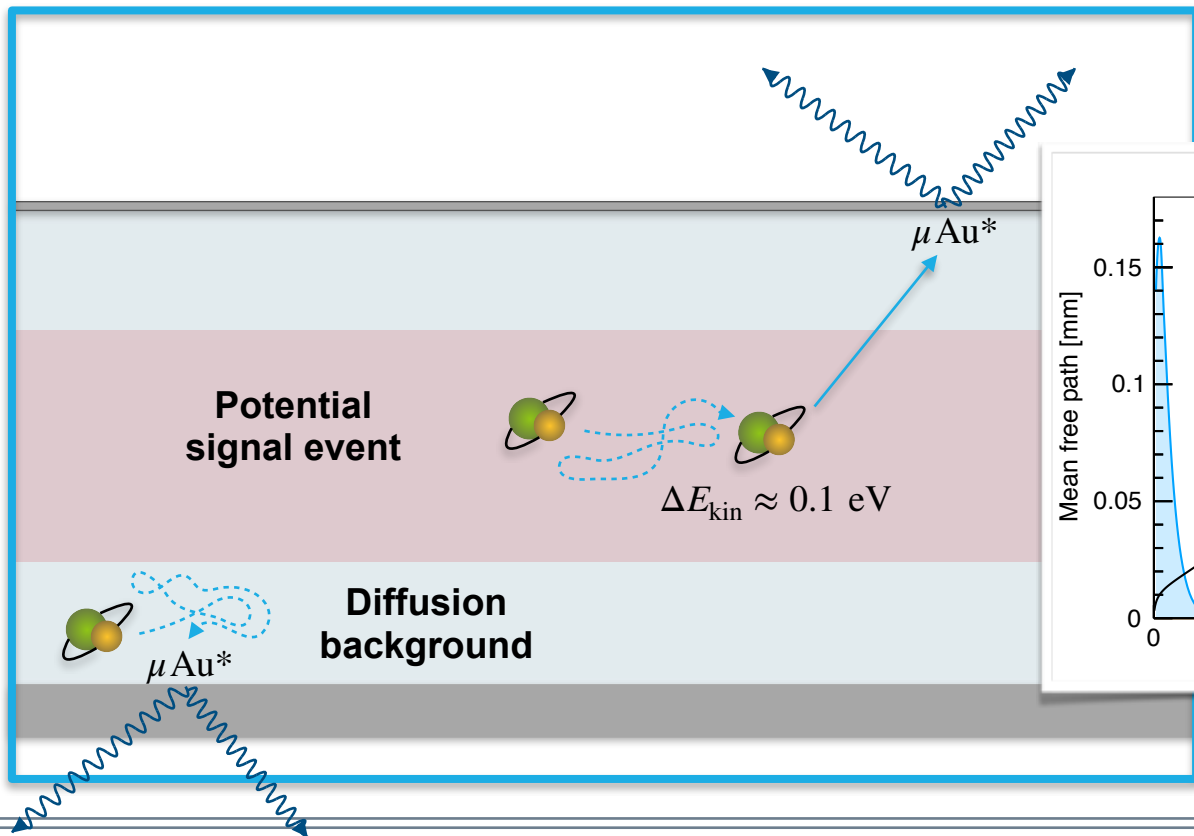
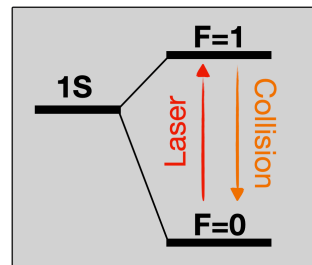
All  $\mu p$  in  $F=0$

ready for  
laser!

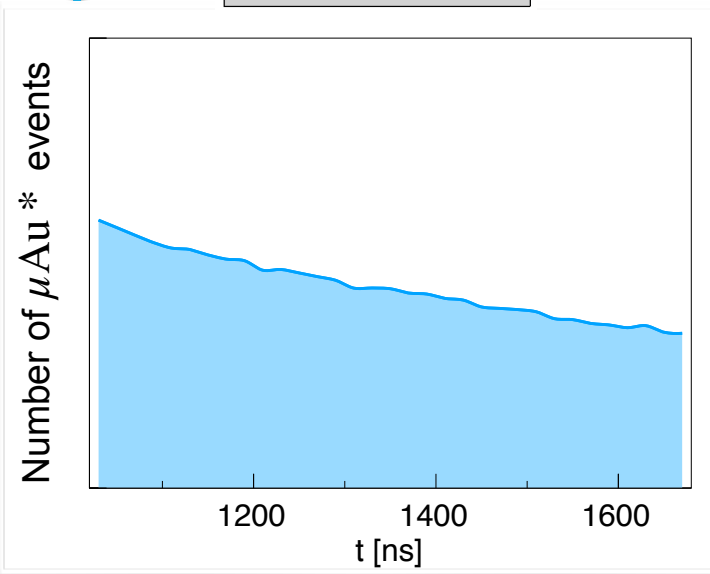
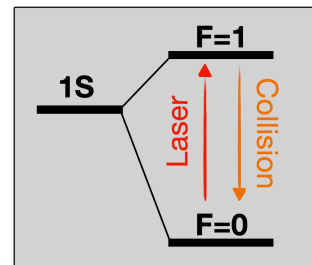
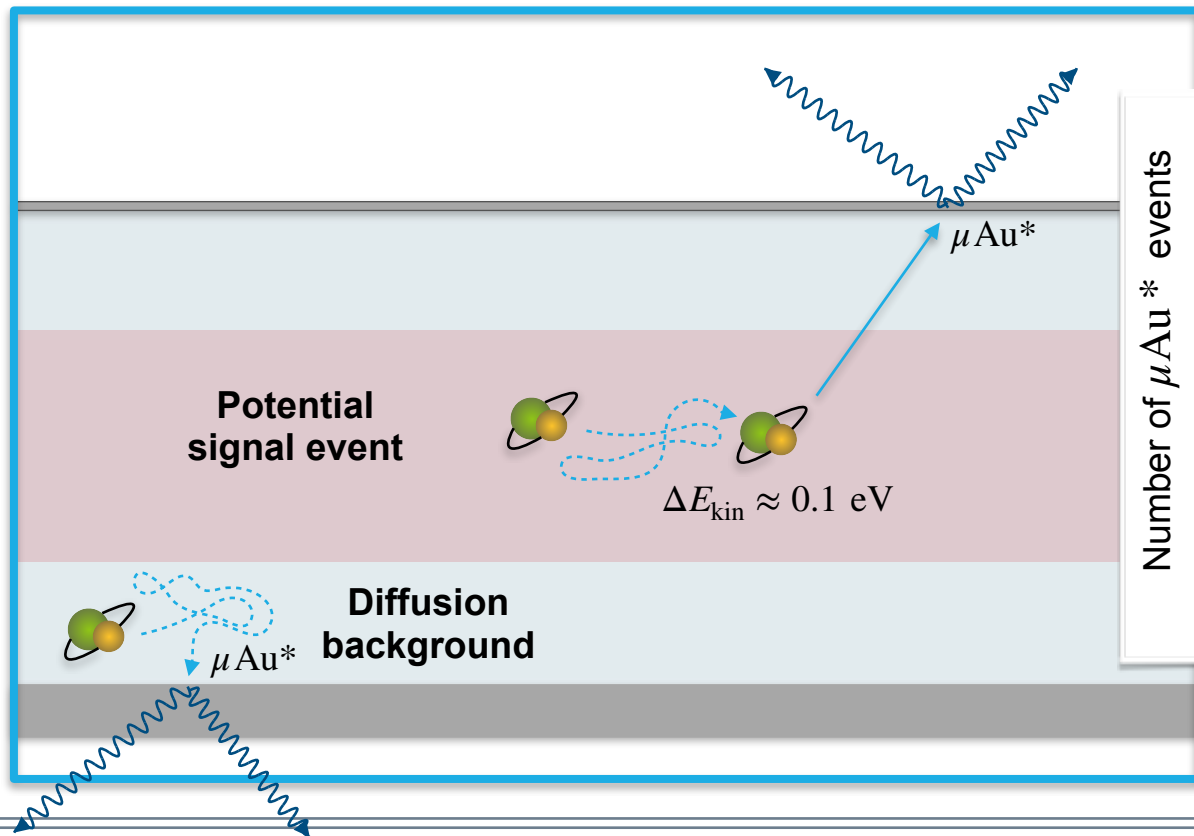
# Diffusion for $t > 1000$ ns and laser excitation



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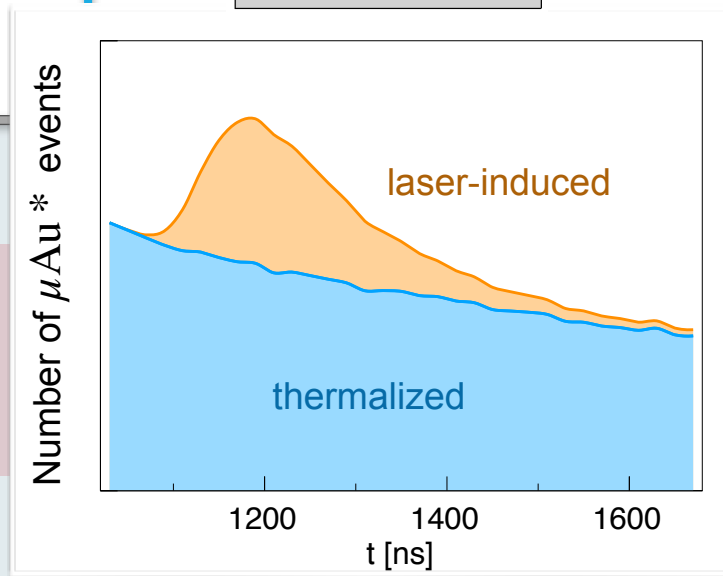
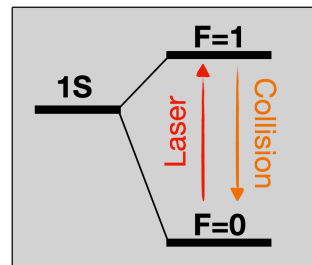
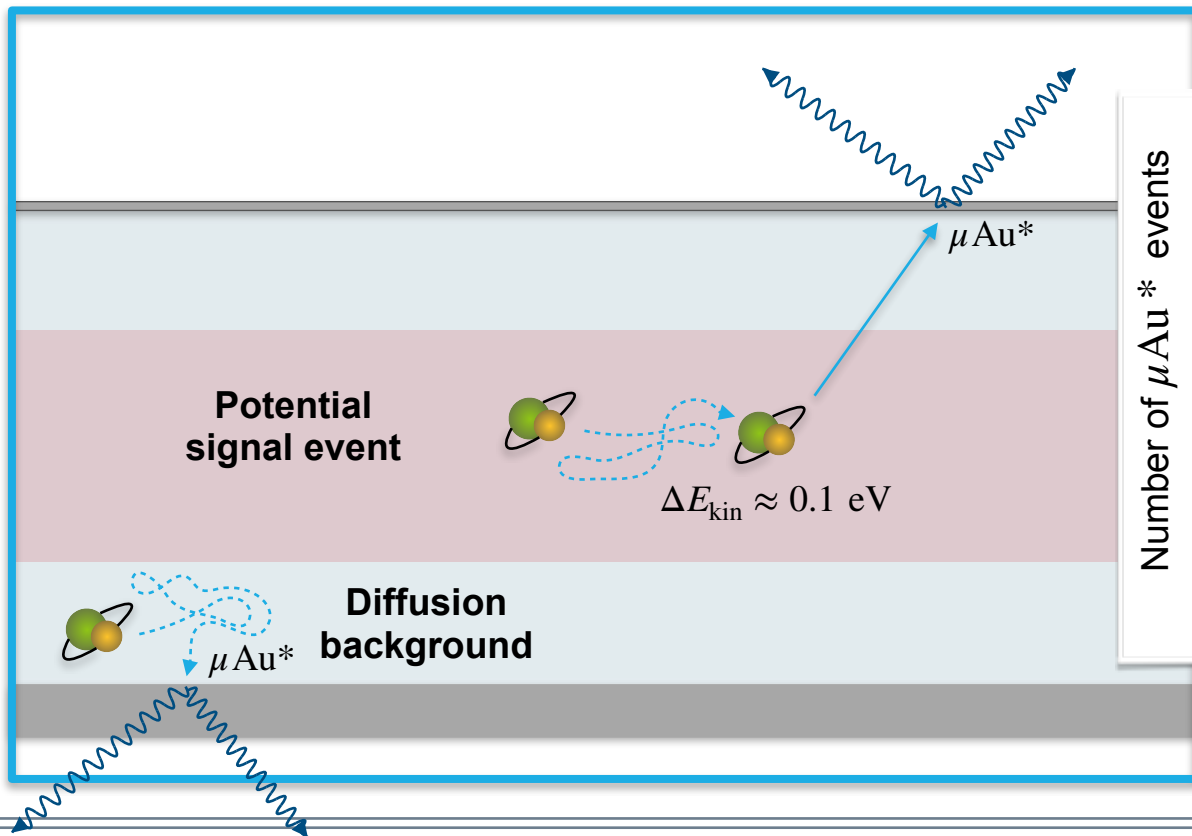


# Diffusion for $t > 1000$ ns and laser excitation

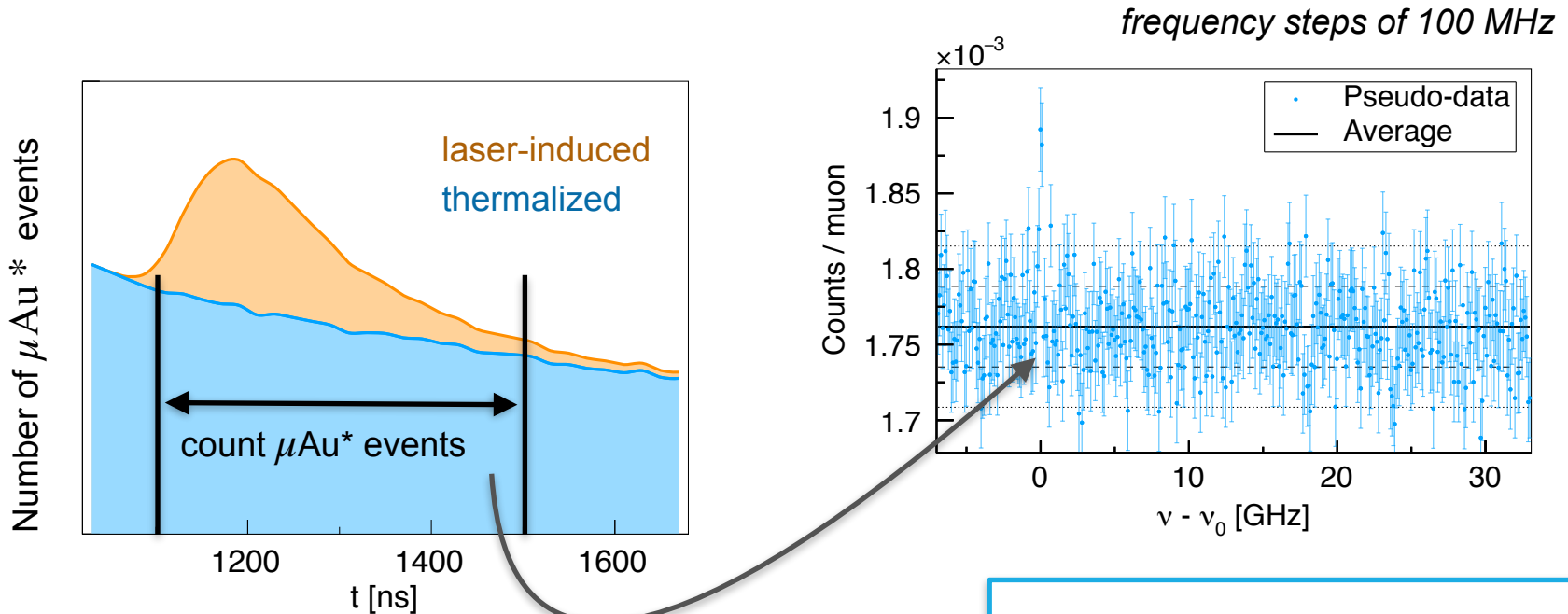




# Diffusion for $t > 1000$ ns and laser excitation



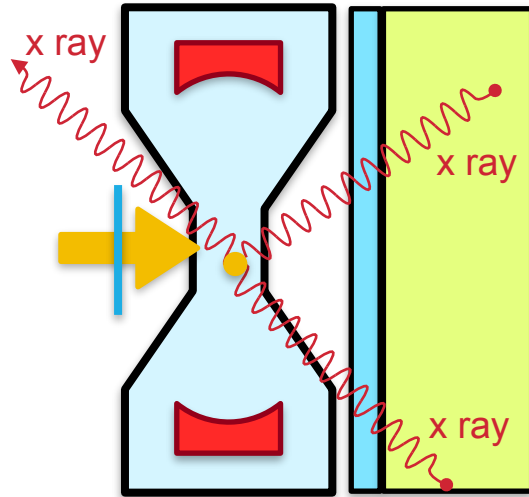
# Frequency scan to search for the resonance



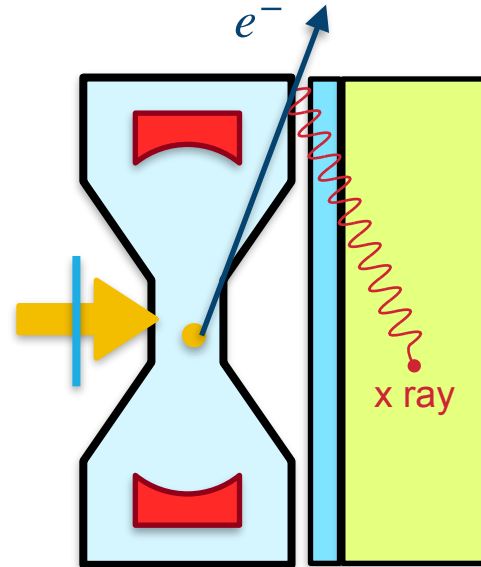
*include further background  
(muon decay, uncorrelated bg)*

**Expect to find the resonance  
within  $\sim 8$  weeks!**

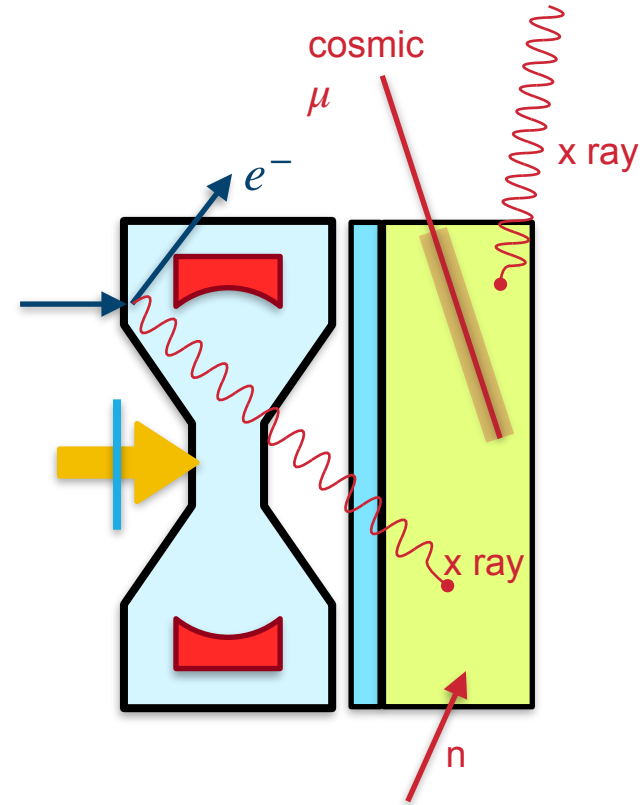
# Background in the HFS experiment



Diffusion background



Bremsstrahlung background

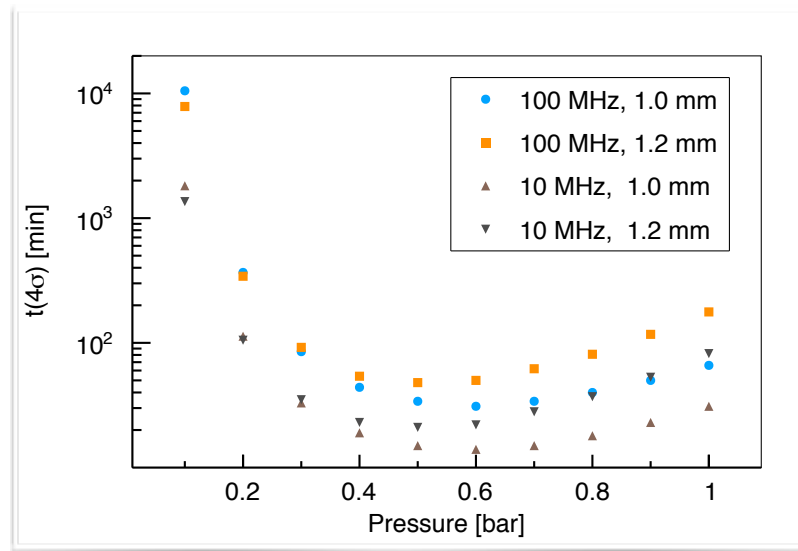
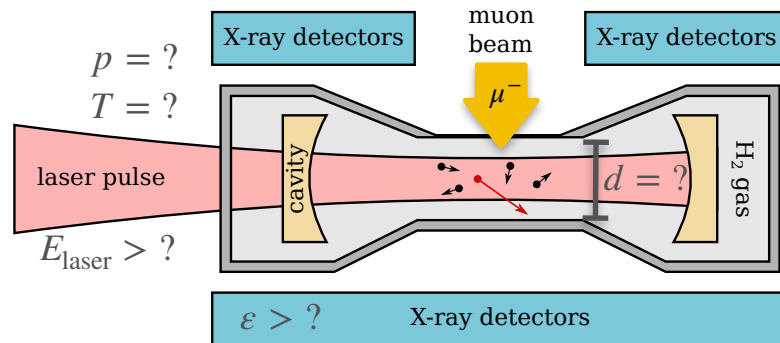
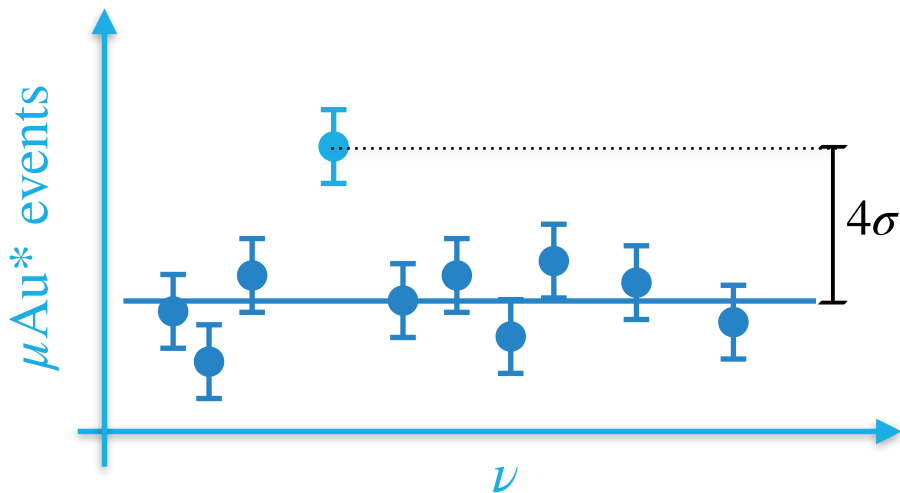


Uncorrelated background

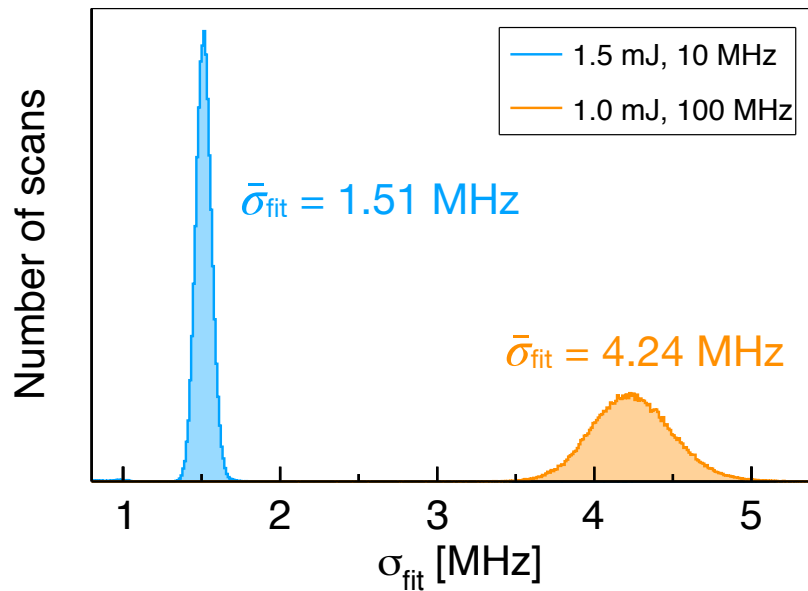
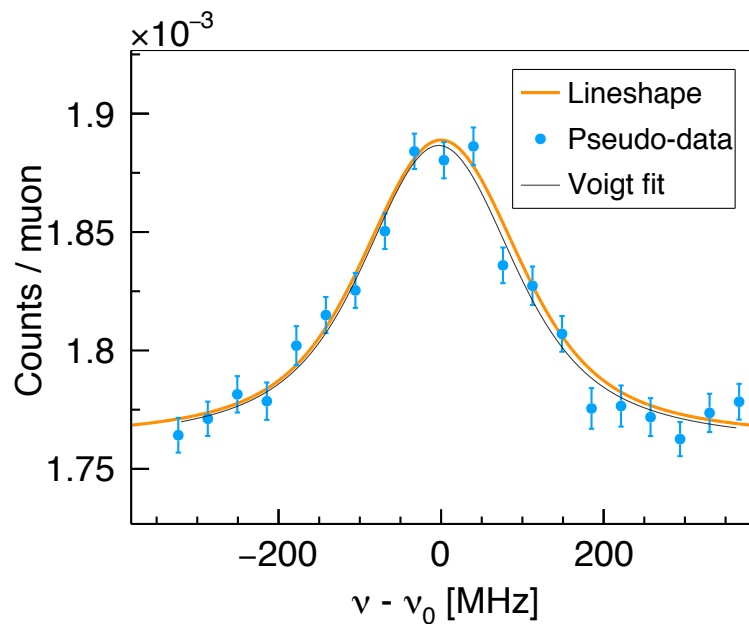
# Optimization of the experiment

$t(4\sigma)$

Measurement time to expose a  $4\sigma$  effect over background on resonance.



# Two weeks of measurement to reach 0.1 ppm



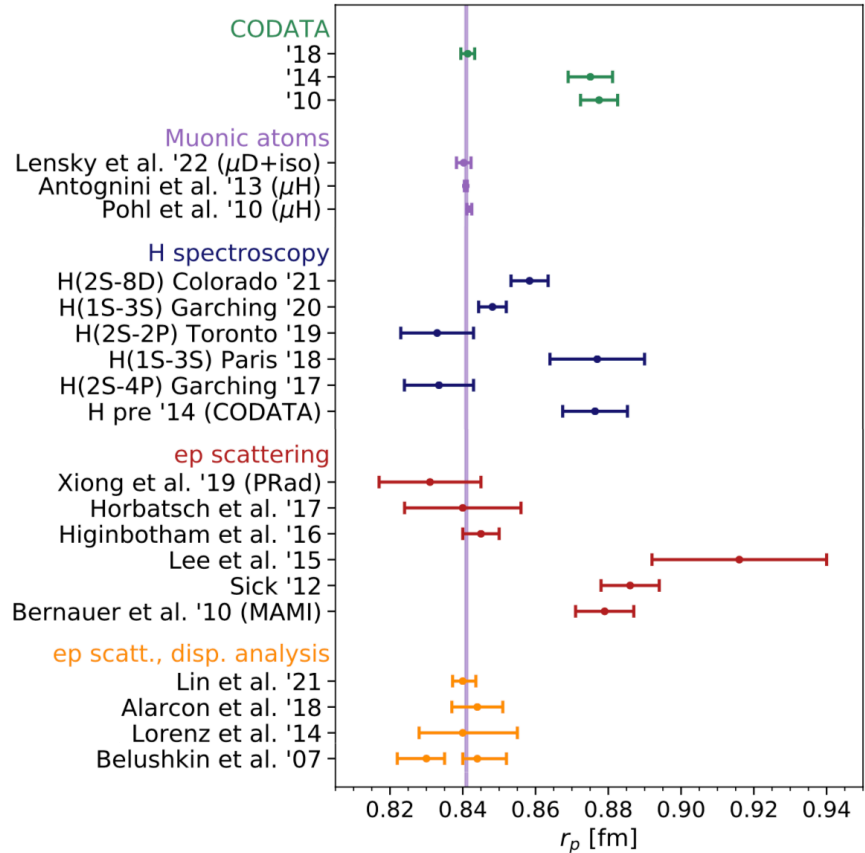
# Summary

- ▶ Laser spectroscopy of light muonic atoms helps to learn more about the nucleon structure.
- ▶ At PSI, we are aiming at measuring the 1S hyperfine splitting of muonic hydrogen.
- ▶ This talk addressed the diffusion of  $\mu p$  atoms through the H<sub>2</sub> gas target.
- ▶ Simulations of the diffusion allow to estimate event rates and to plan the measurement.

For further information: [arXiv:2211.08297](https://arxiv.org/abs/2211.08297)

**Thank you for your attention!**

# The aftermath of the Lamb shift experiments



doi: [10.1146/annurev-nucl-101920-024709](https://doi.org/10.1146/annurev-nucl-101920-024709)



# Scattering rates in the laboratory frame

