Cryogenic muonium beam for the LEMING experiment

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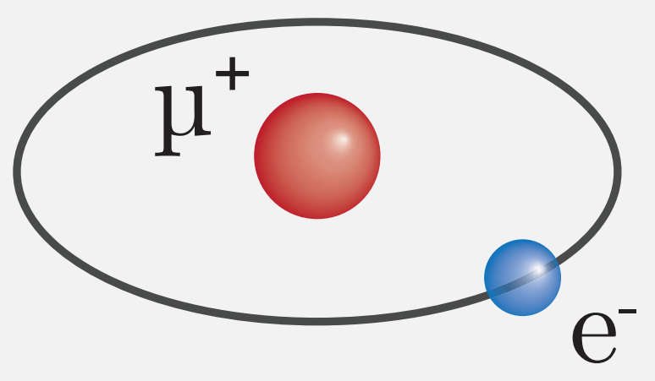
00 Motivation

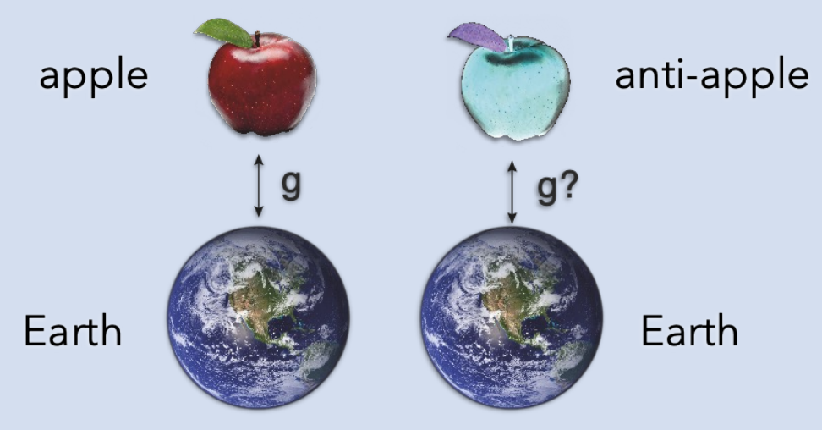


- Muonium atom (**Mu** = μ^+ + e^-)
- Purely leptonic, exotic atom
- Free of finite size and hadronic effects
- mass dominated by μ^+

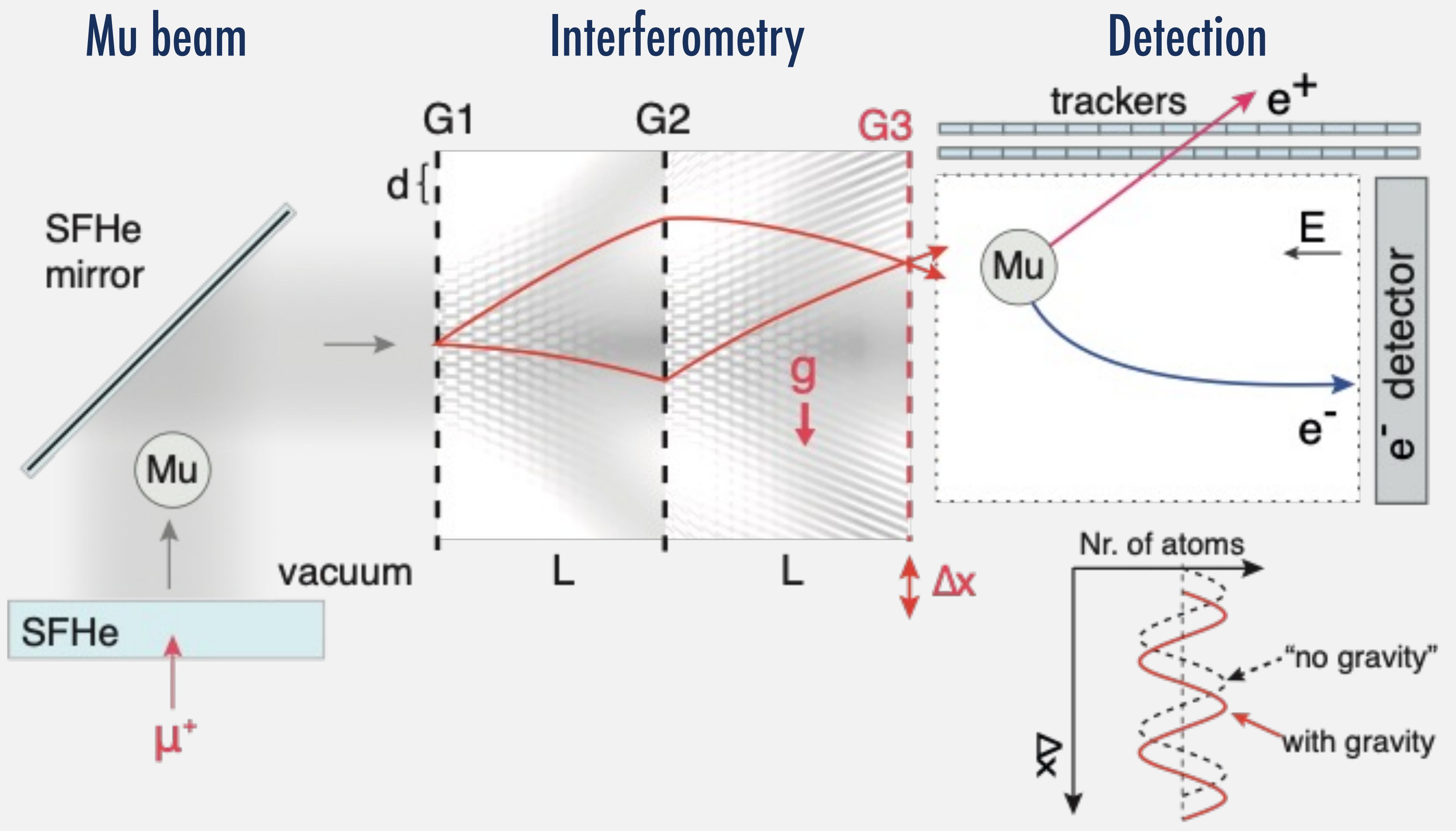
Precision spectroscopy [1]:

- test of bound-state QED
- determination of fundamental constants ($m_\mu, \mu_\mu, \dots$)

Test **weak equivalence principle** with purely leptonic, second generation (anti-)matter [2]



01 The LEMING experiment



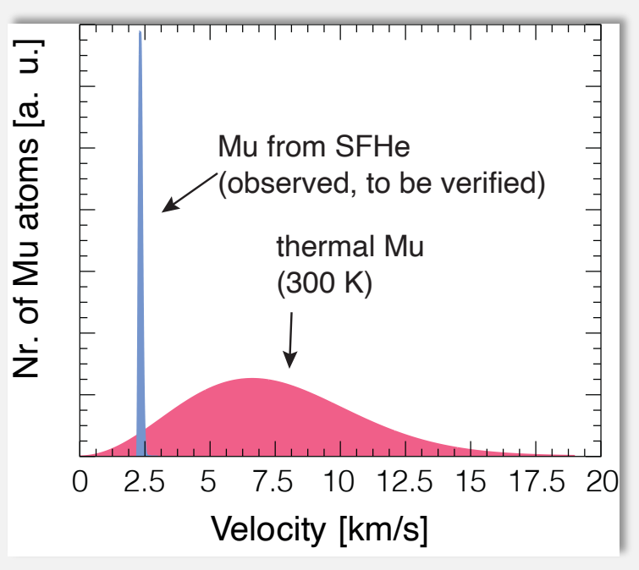
3 ingredients:

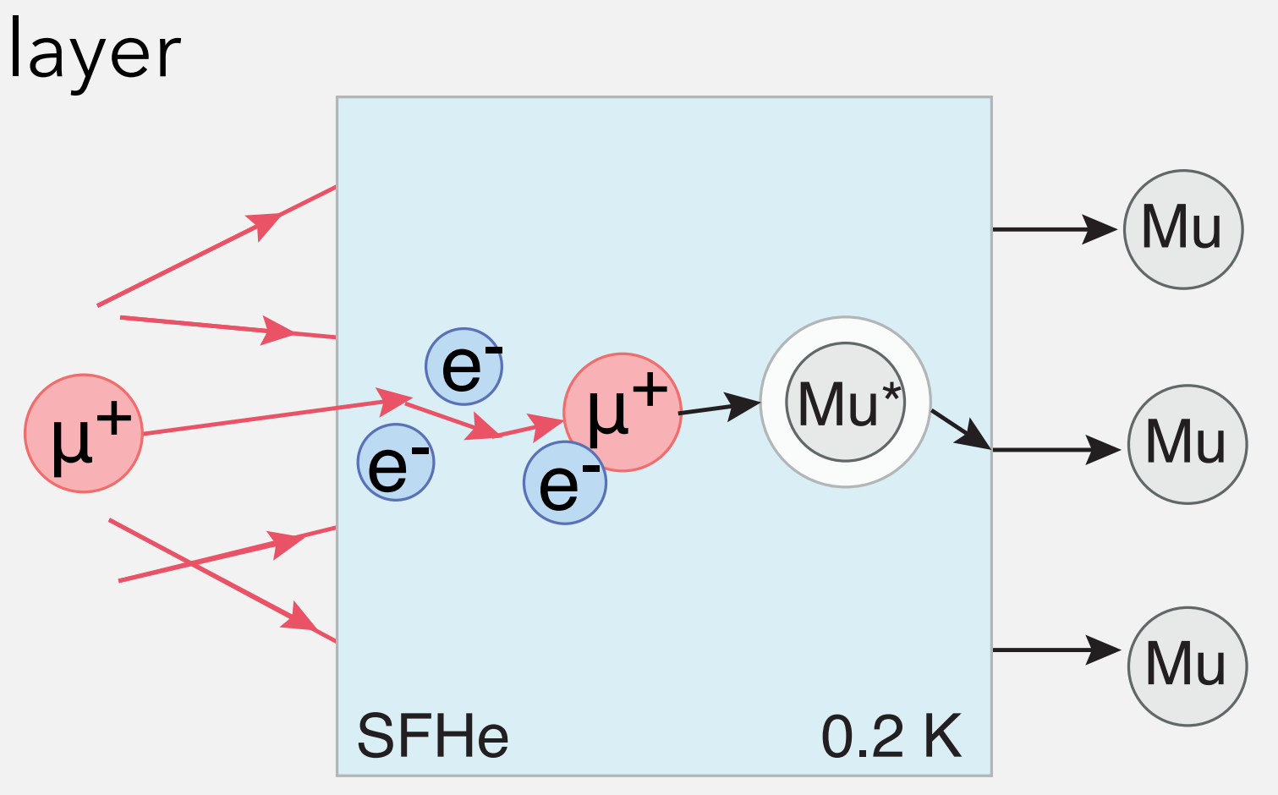
- Mu beam:
  - small angular spread
  - narrow momentum distribution
- Atom interferometer:
  - gravitational interaction shifts interference pattern
- Detection:
  - coincidence of μ^+ and e^-

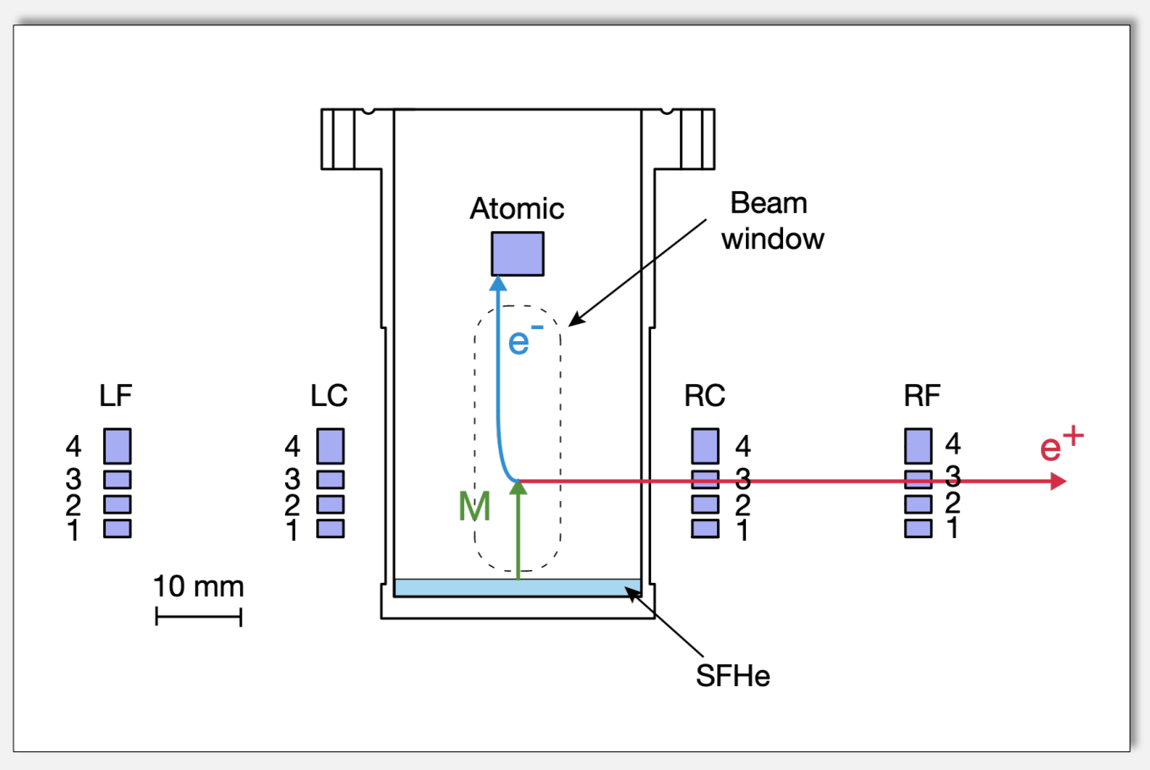
02 Vacuum muonium from superfluid helium

Superfluid helium (SFHe) target [3]:

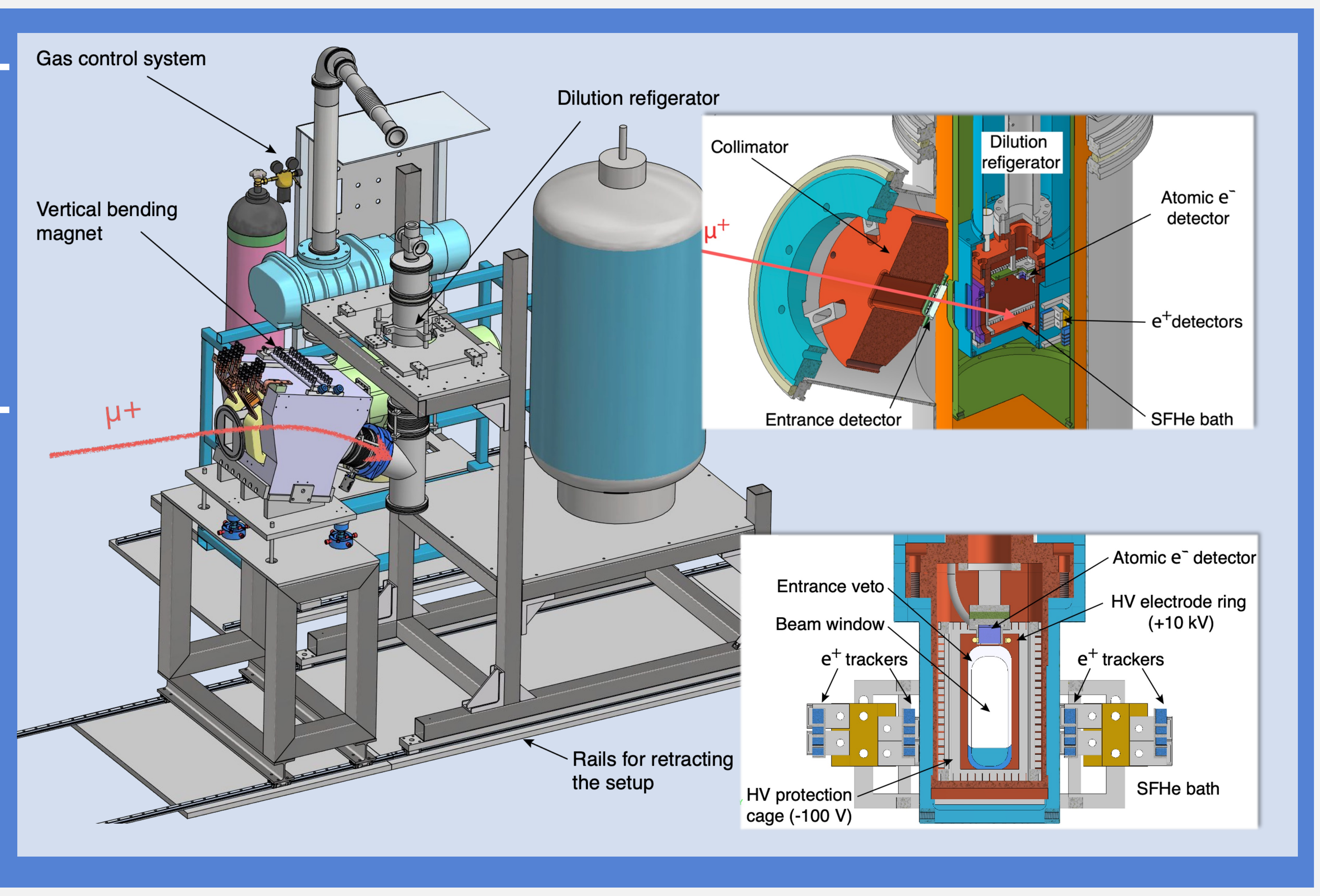
- stop accelerator μ^+ in thin layer of SFHe
- Mu **formation** and **diffusion**
  - Mu behaves as small impurity in SFHe: $m_{Mu^*} \approx 2.5\, m_{He}$
  - unlikely to scatter at phonons: $\frac{1}{\tau_c} \propto T^7 \sim 5/s$
  - collision-free propagation in SFHe observed previously for antiprotonic Helium [4]
- Mu surface ejection
  - large **chemical potential** if Mu considered as a light hydrogen isotope: $\frac{E}{k_B} \sim 270$ K
  - Mu ejected from bulk with low thermal energy spread -> small angular distribution
- Detection [5] of ejected Mu via decay e⁺ and atomic e⁻ at various heights above SFHe layer



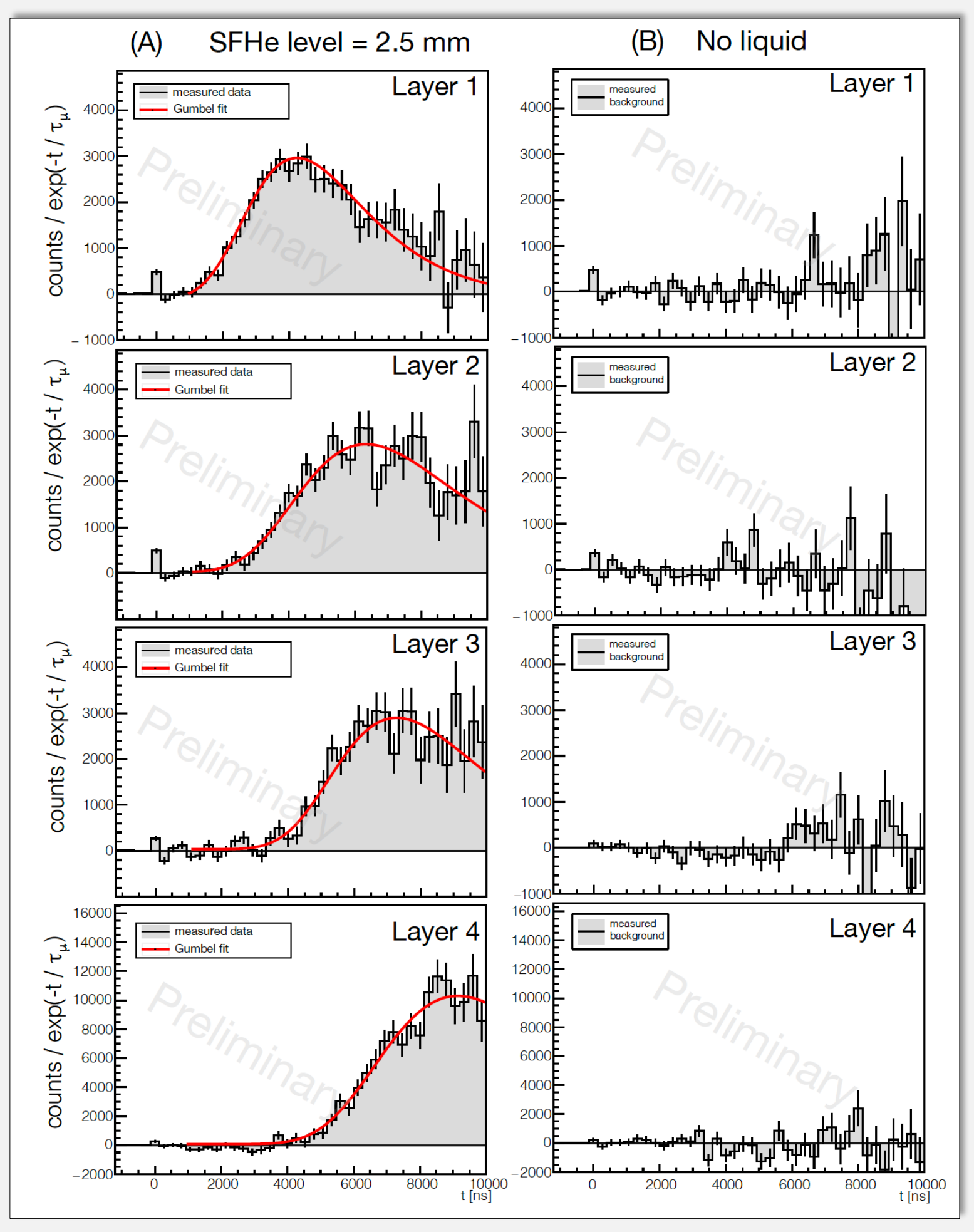


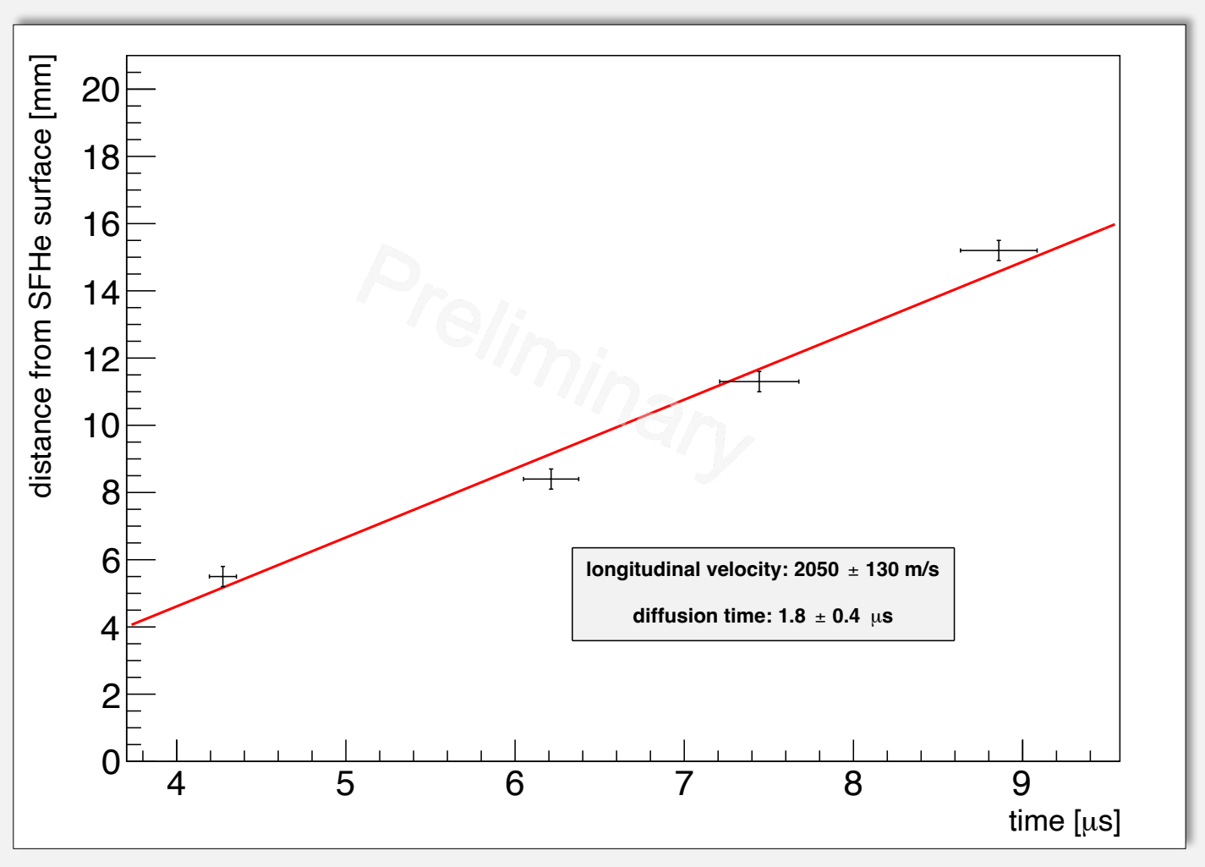


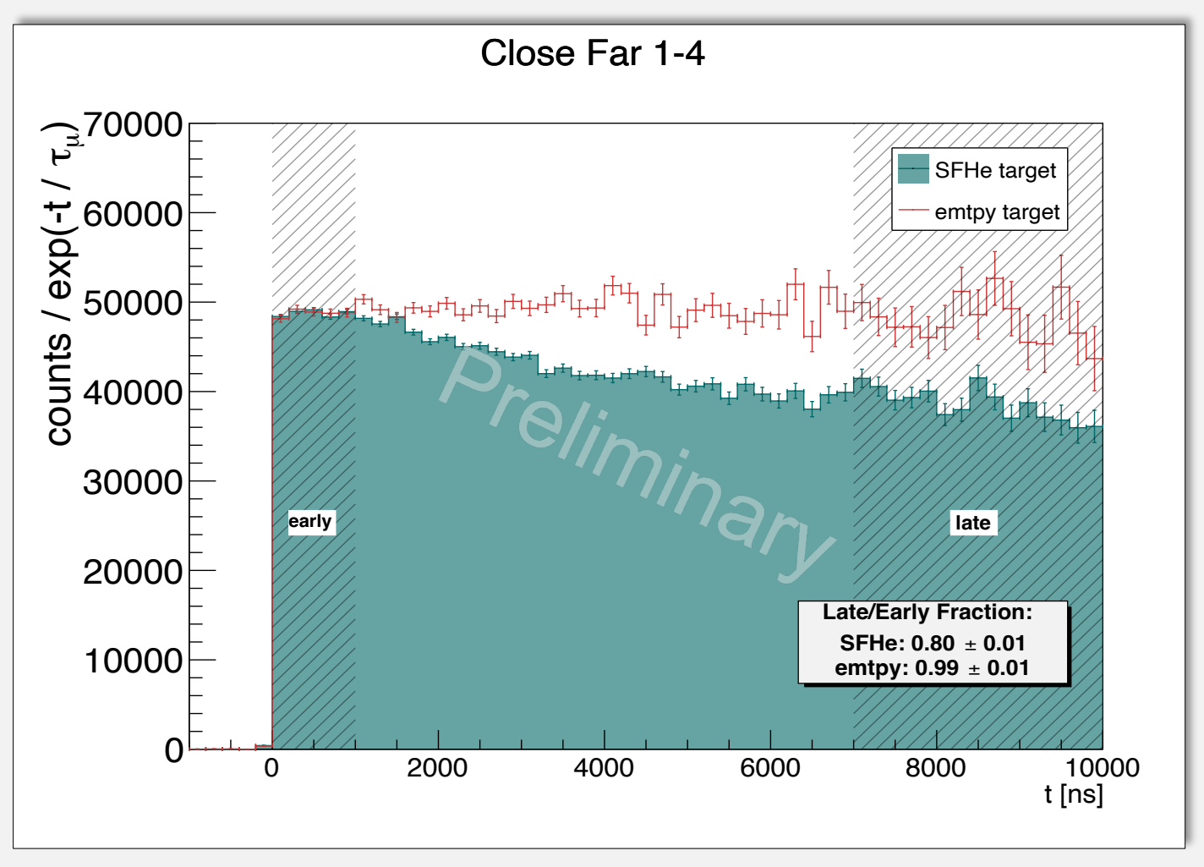
Experimental Setup



03 First observation of Mu beam from SFHe



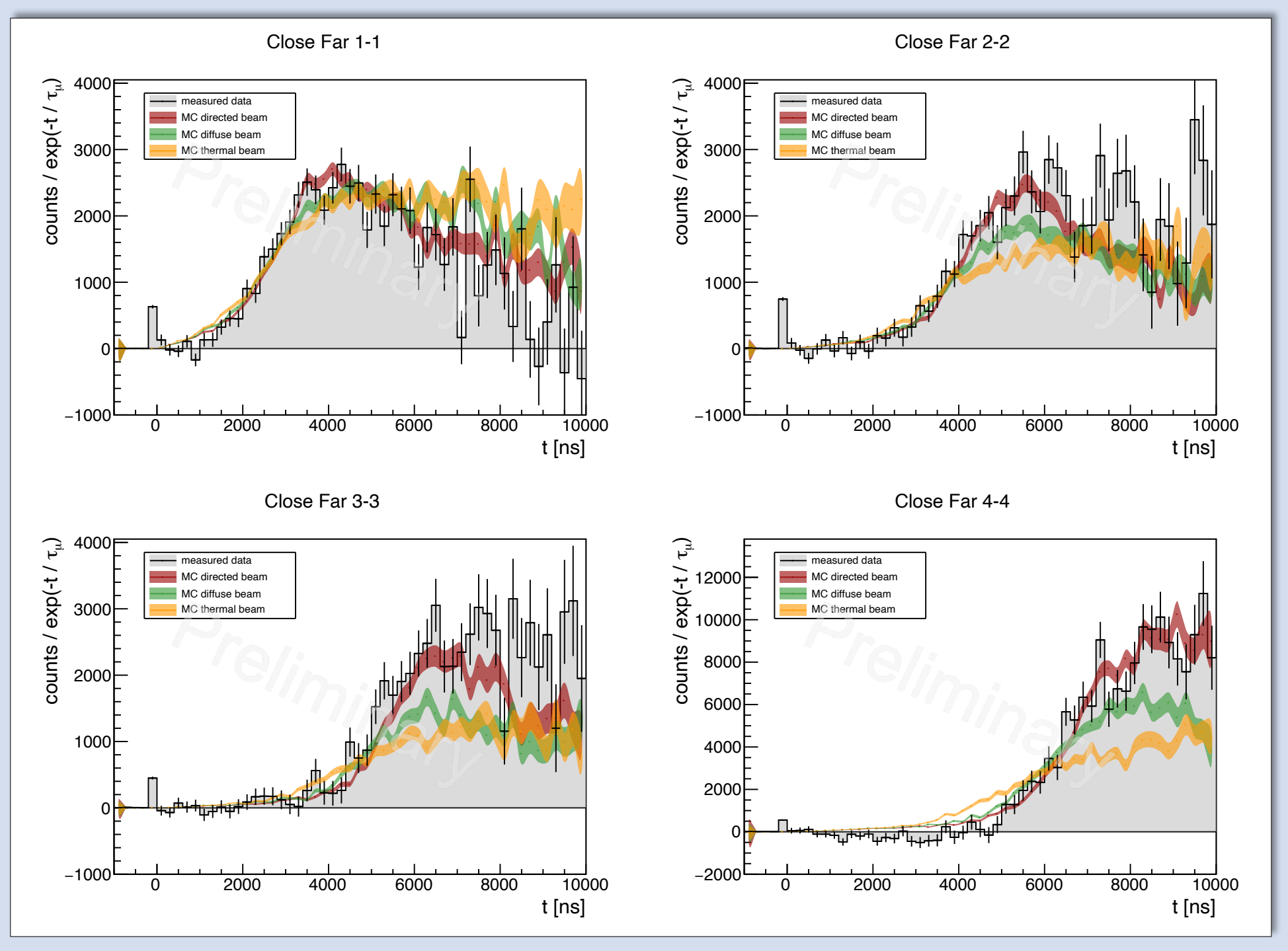




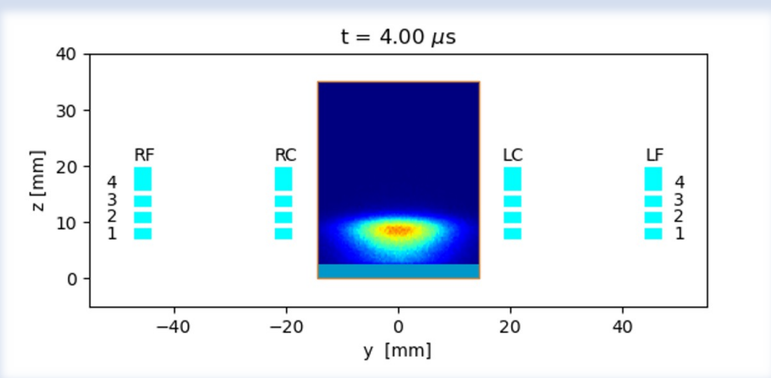
- Propagation of **dynamic Mu** cloud across detection planes
- Estimated longitudinal velocity: $v \approx 2100$ m/s
- **Fast diffusion** of Mu to surface
- Conversion efficiency: $\epsilon \approx 20$ %

Monte Carlo comparison

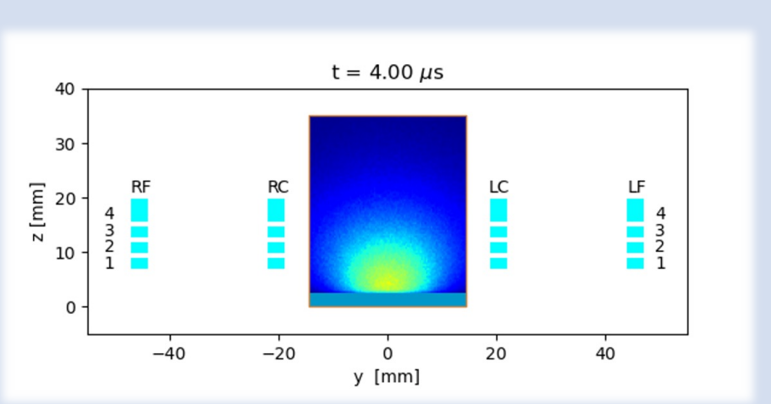
- Implemented various simplified models of Mu in SFHe
- Measurement more compatible with **non-thermal beam**
- small angular divergence ~30 mrad
- Further cryogenic Mu beam characterization planned



directed beam



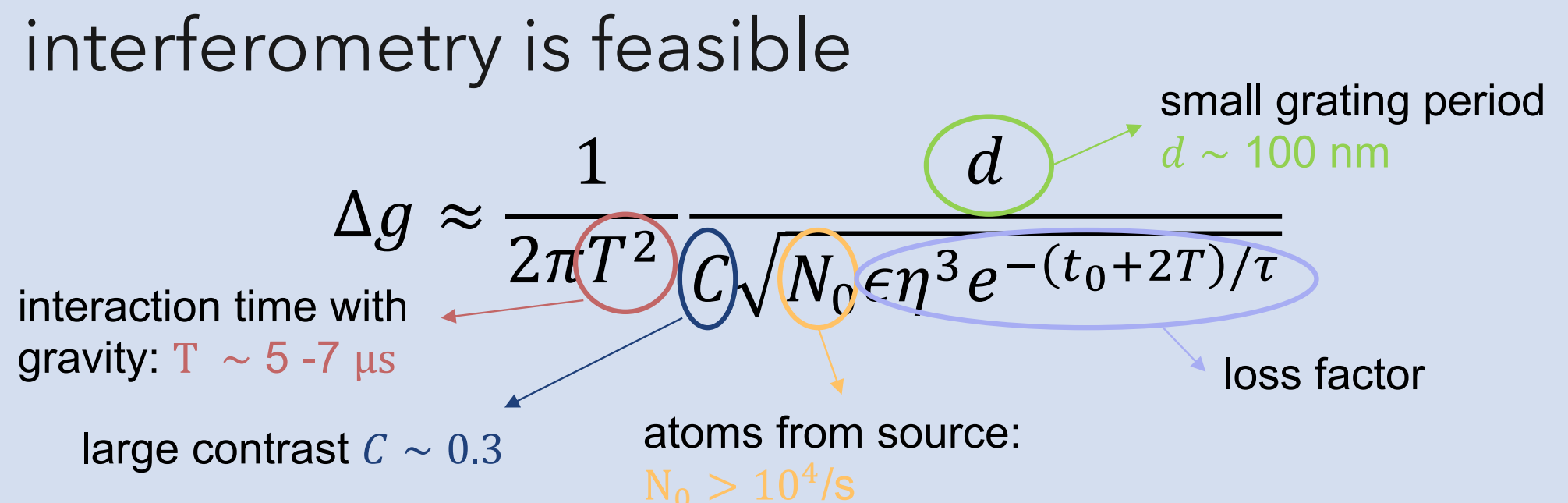
thermal beam



04 Outlook

Atom interferometry:

- With the high quality Mu beam atom interferometry is feasible



$$\Delta g \approx \frac{1}{2\pi T^2}\frac{d}{C\sqrt{N_0 \epsilon \eta^3 e^{-(t_0+2T)/\tau}}}$$

- Sensitivity $\frac{\Delta g}{g} = 1\,\%$ is possible

Precision spectroscopy:

- 1S-2S Mu spectroscopy can benefit from small spot size and slow atoms
- Cryogenic source could reduce
  - Statistical uncertainty
  - Transit-time broadening
  - Second order Doppler shift

05 References

[1] P.Crivelli, *Hyperfine Interact.* **239**, 1-9 (2018)
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[5] J.Zhang et al., *JINST* **17**, P06024 (2022)