Near surface superconductivity of niobium cavity cutouts probed by low energy muon spin rotation

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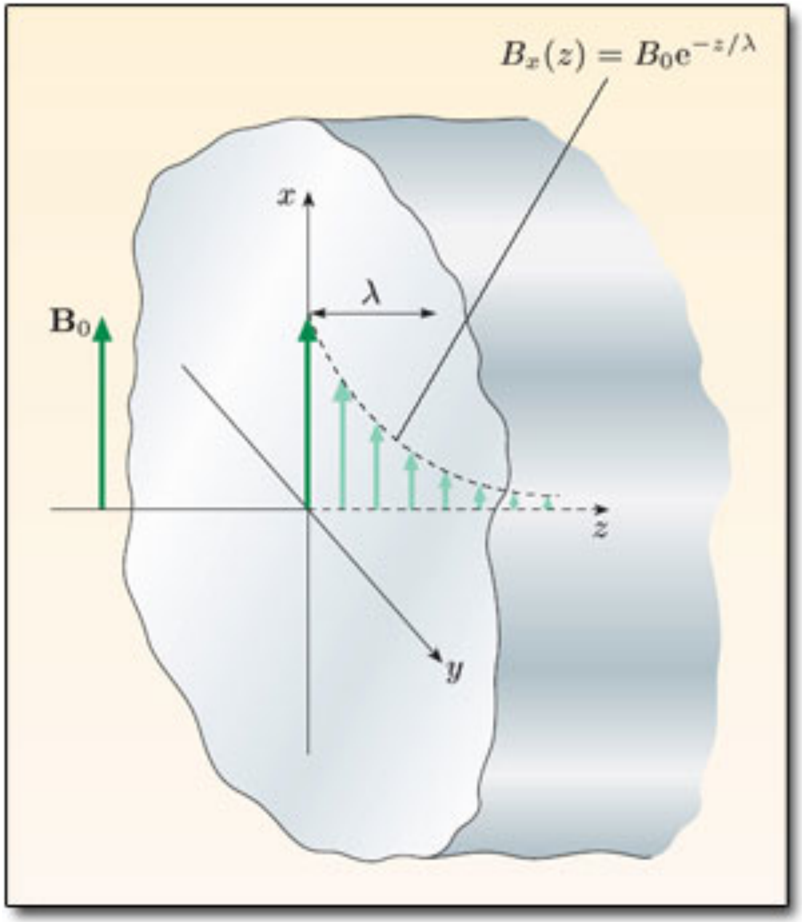
Goal of the experiment

- Mainly: obtain first DIRECT measurement of the magnetic field profile of niobium cutout samples in the Meissner state (applied field parallel to the sample ~5-25mT)

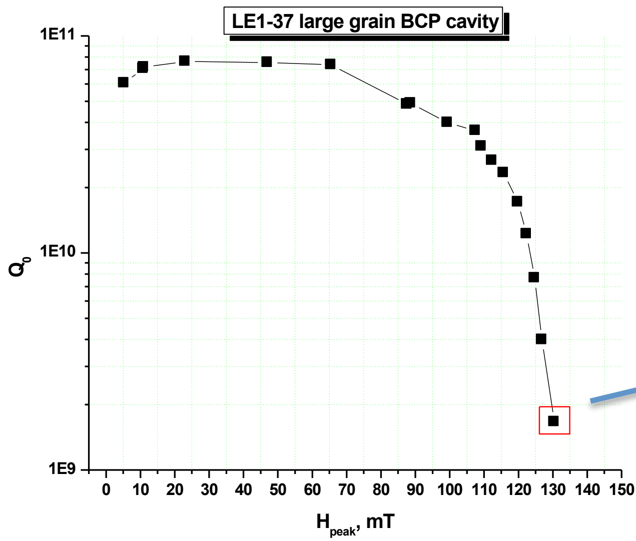
- → Extract the 'penetration depth' λ parameter and mean free path in the first 100 nm of the RF surface of our cavities

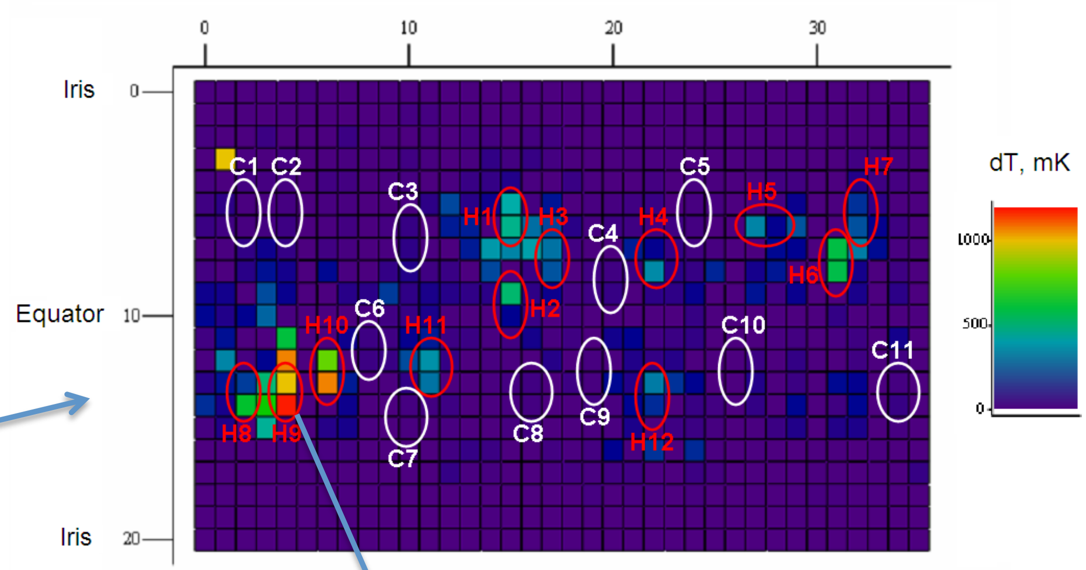
Goal of the experiment

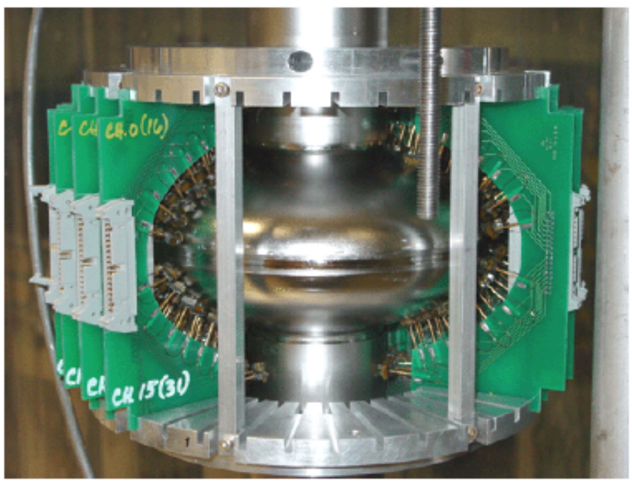


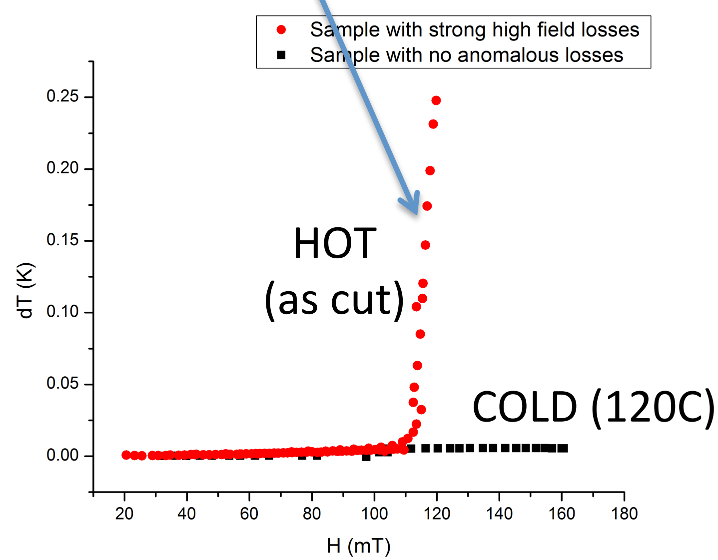
- How is the magnetic field in our cavities truly decaying? We assume exponentially, is this true? We assume a lambda of ~ 40 nm, is this true?
- By looking at how field is screened in the SC, we can make important conclusions on material properties of the surface

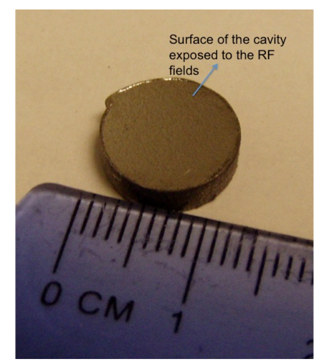
Samples used











The technique

	Conventional Methods		Nuclear Beam Methods	
	NMR	ESR	μSR	β-NMR
Probe:	host nuclei	host electrons	muons	radioactive nuclei
Lifetime:	infinite	infinite	2.2 μs	100 ms - hours
Polarization Method:	apply large field	apply large field	natural	optical pumping
Polarization (max.):	« 1 %	« 1 %	100 %	80 %
Detection:	absorbed RF radiation	absorbed microwave radiation	anisotropic decay of muon	anisotropic decay of nucleus
Sensitivity:	10^{17} spins	10^{17} spins	10^{7} spins	10^{7} spins

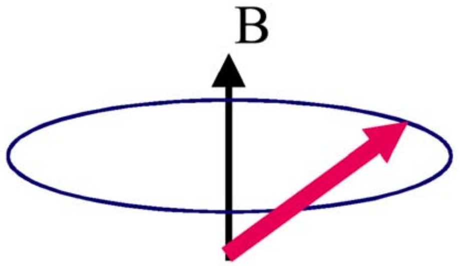
μSR: Muon Spin Rotation/Relaxation

Method:

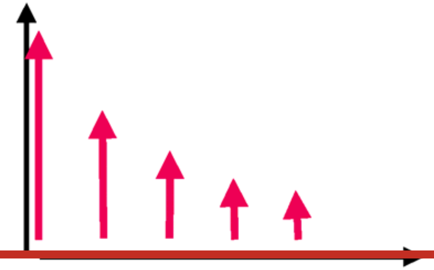
- Implant and thermalize ~100% polarized muons in matter (stopping time in solid ~ 10 ps, no initial loss of polarization, stop site: generally interstitial). $P(0) \cong 1$
- Magnetic moment of muon interacts with local magnetic fields (moments, currents, spins) → P(t)
- P(t) is characterized by precession and/or depolarization/relaxation.
- Observe time evolution of the polarization P(t) of the muon ensemble via asymmetric muon decay: (positrons preferentially emitted along muon spin).
- P(t) contains information about static and dynamic properties of local environment (fields, moments,..)

$$\frac{d\vec{\mu}_\mu}{dt} = \gamma_\mu \left(\vec{\mu}_\mu \times \vec{B}(t) \right) \qquad \vec{P} = \frac{<\vec{s}>}{\frac{1}{2}\hbar}$$

$$\frac{d\vec{P}}{dt} = \gamma_\mu \left(\vec{P} \times \vec{B}(t) \right)$$



$$\omega_L = \gamma_\mu B_{loc}$$



Measuring P(t): Muon Decay $\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$

- Muon decay (life time 2.2. μs) violates parity conservation

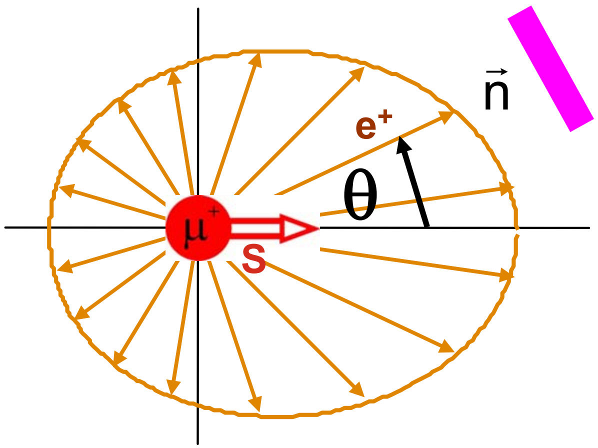
→ asymmetric decay

- Positrons preferentially emitted along muon spin (along polarization vector of muon ensemble)

$$\frac{dN_{e^+}(\theta)}{d\Omega} \propto \left(1+\frac{1}{3}P\cos\theta\right) = \left(1+\frac{1}{3}\vec{P}\cdot\vec{n}\right)$$

$\vec{n}$: direction of observation (detector position)

For $P=1$:



$$\frac{dN_{e^+}(\theta)}{d\Omega} \propto \left(1+\frac{1}{3}P\cos\theta\right)$$

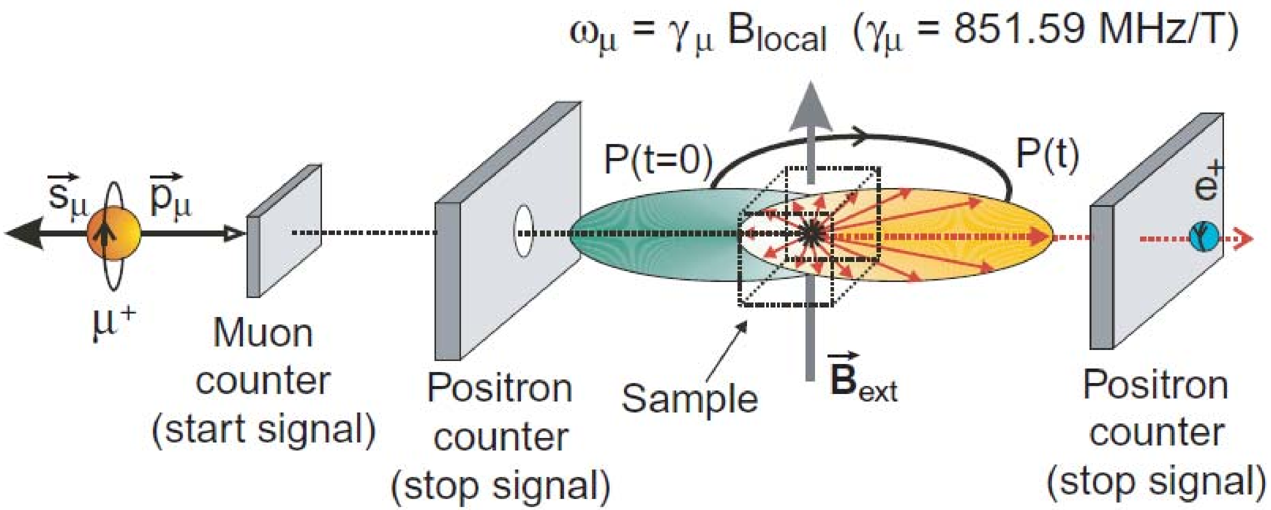
θ : angle between spin (polarization) and positron direction

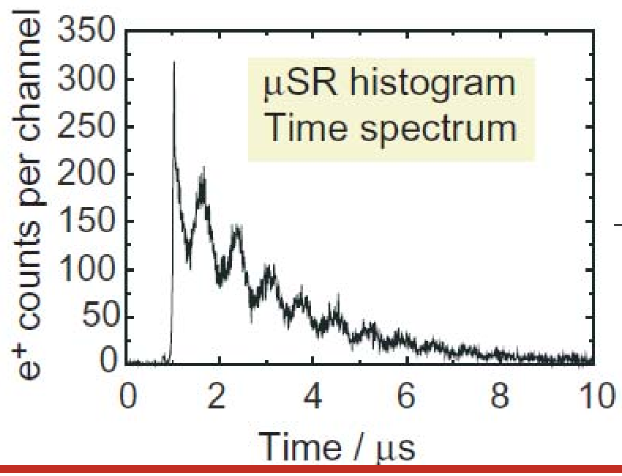
- Measuring positrons allows to observe time evolution of the polarization P(t) of the muon ensemble
- Positron intensity as a function of time after implantation:

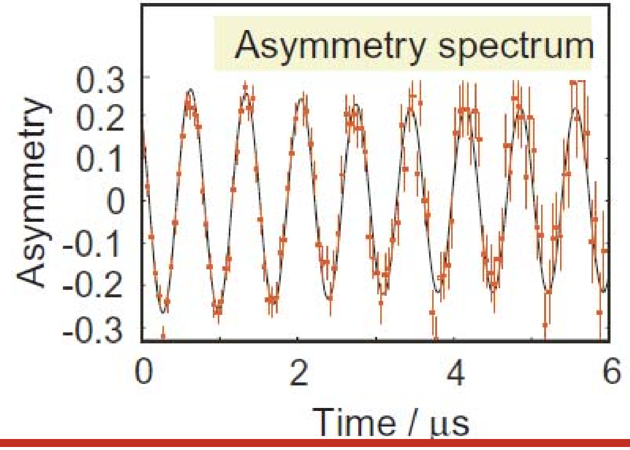
$$N_{e^+}(t) = N_0\left[1+A_0P(t)\right]e^{-\frac{t}{\tau_\mu}} \qquad P(t)=\vec{P}(t)\cdot\vec{n}$$

- A_0: Maximum observable asymmetry
  theoretically: A_0=1/3
  practically it depends on setup (average over solid angle, absorption in materials): A_0 = 0.25 - 0.30
- $A_0P(t)$ is called asymmetry: A(t)

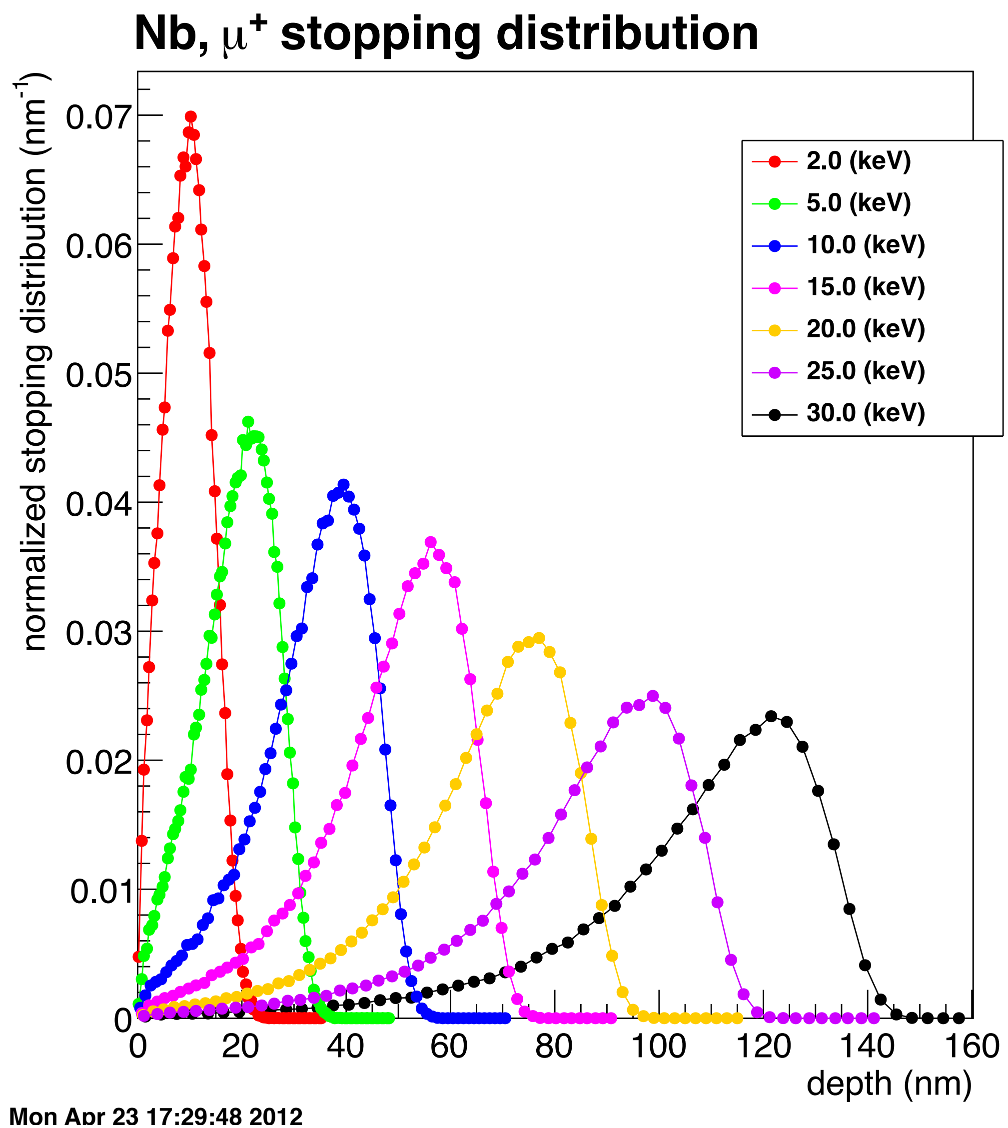
Principle of a μSR experiment



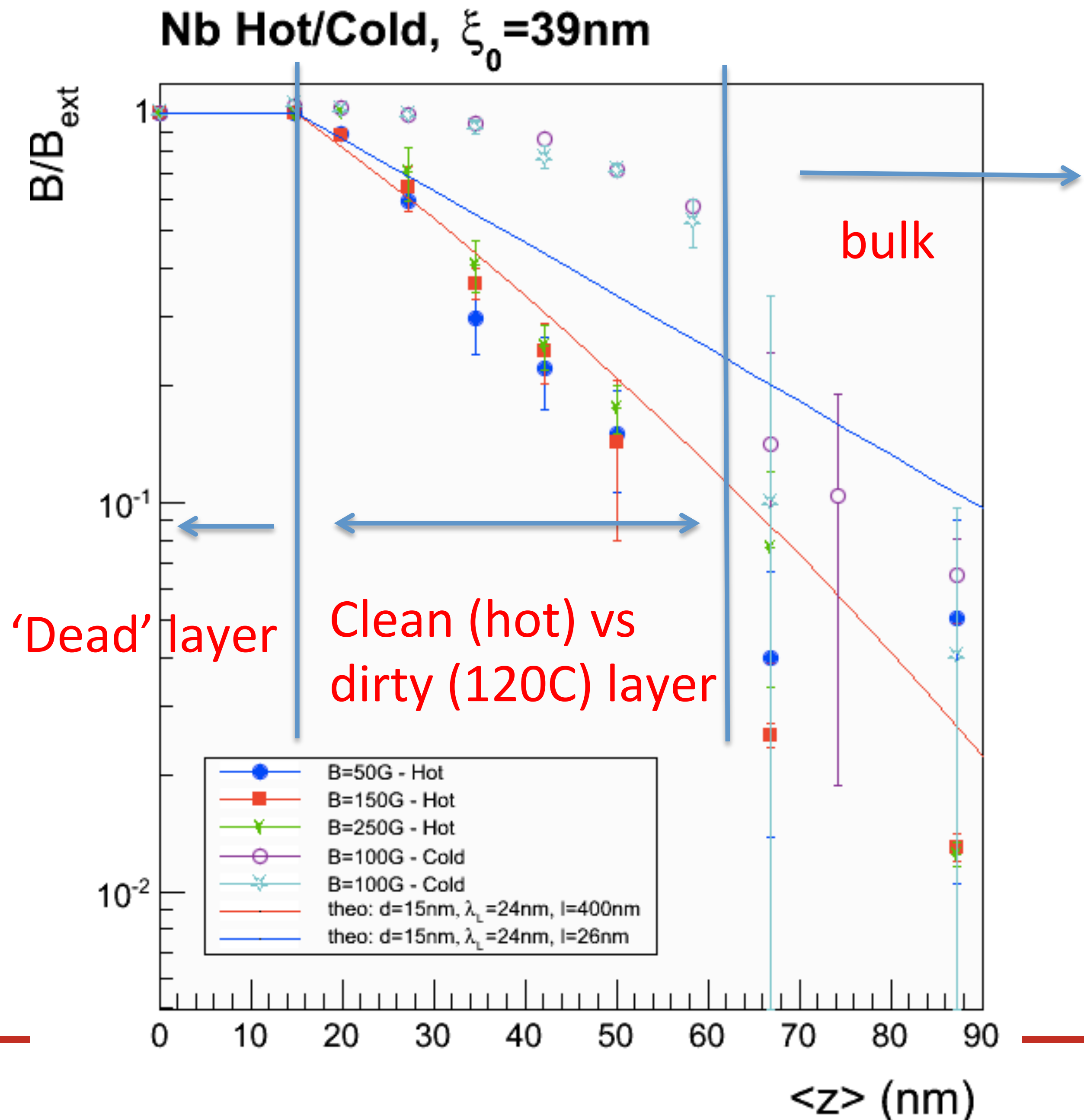




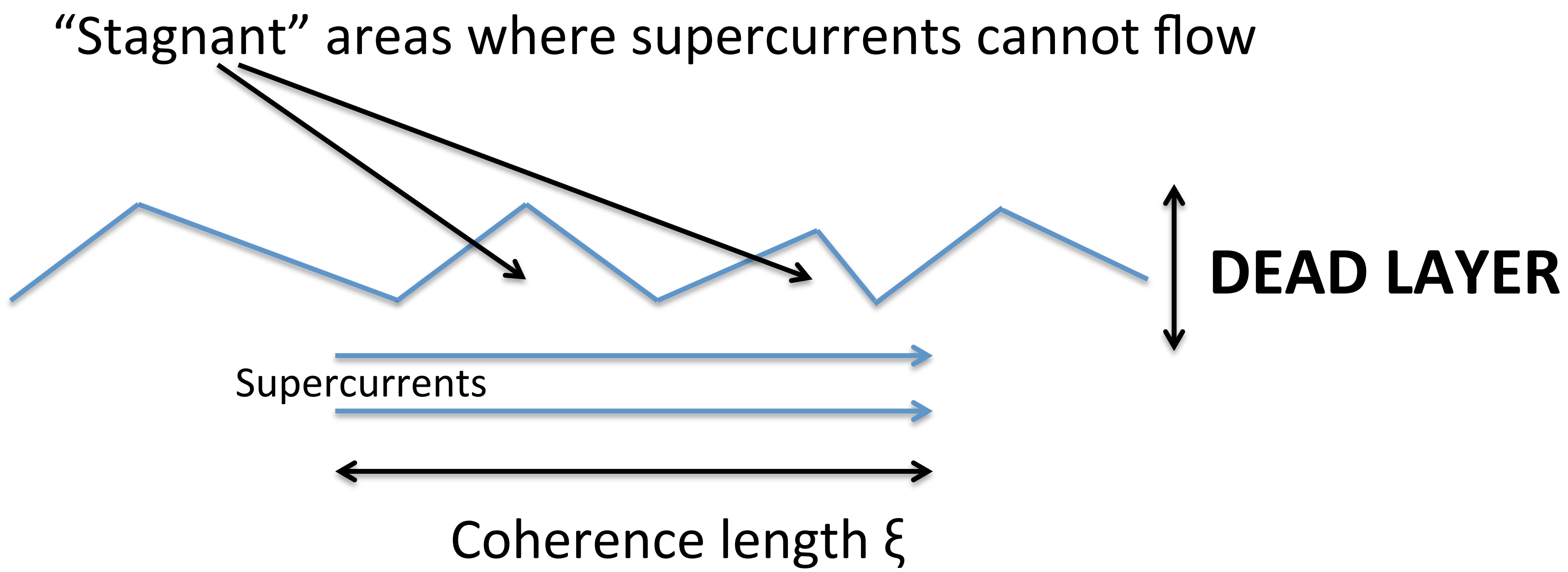
Low energy muons @ PSI



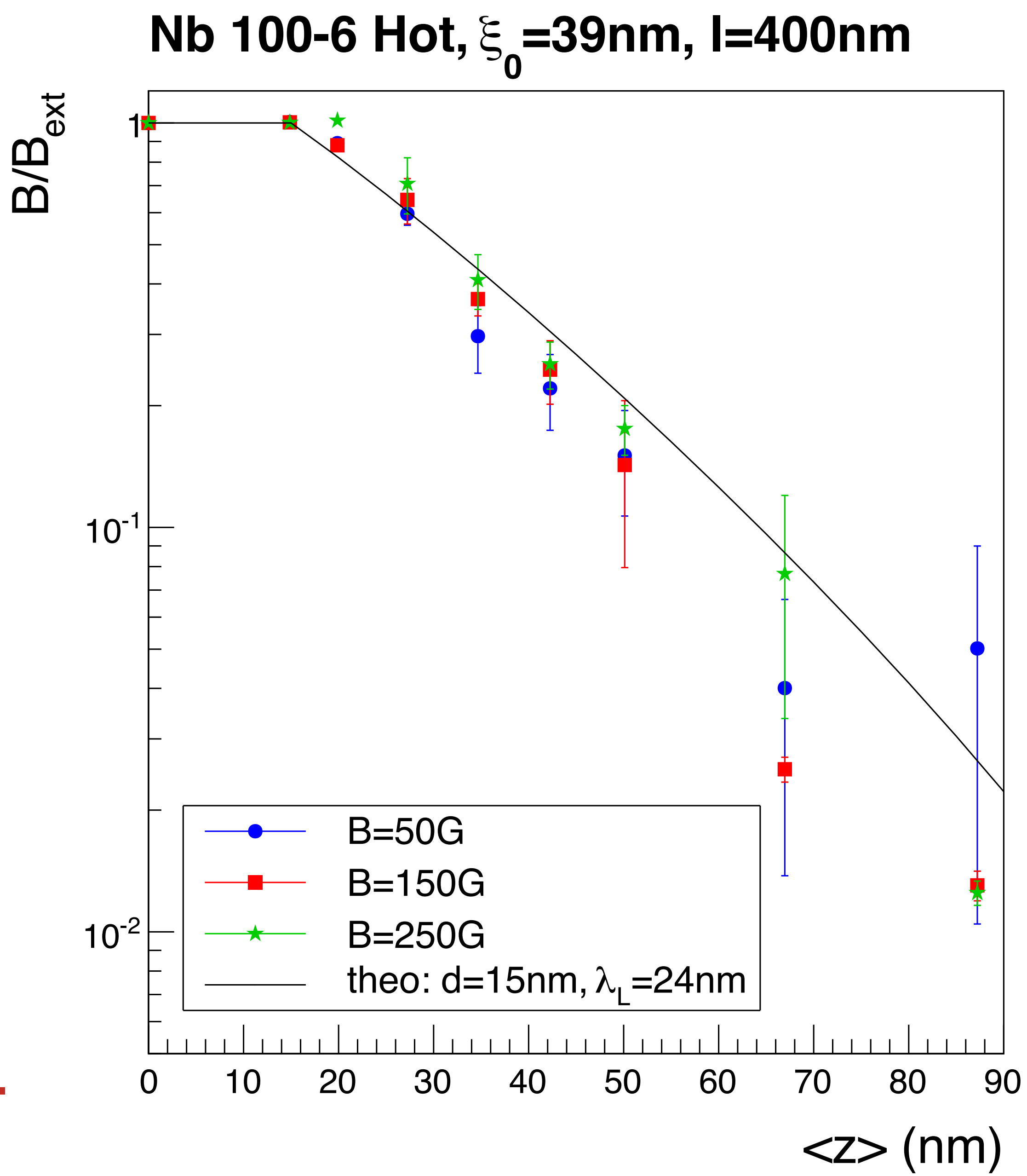
Results: field profile hot/cold



NANOROUGHNESS: roughness of the order or smaller than the coherence length

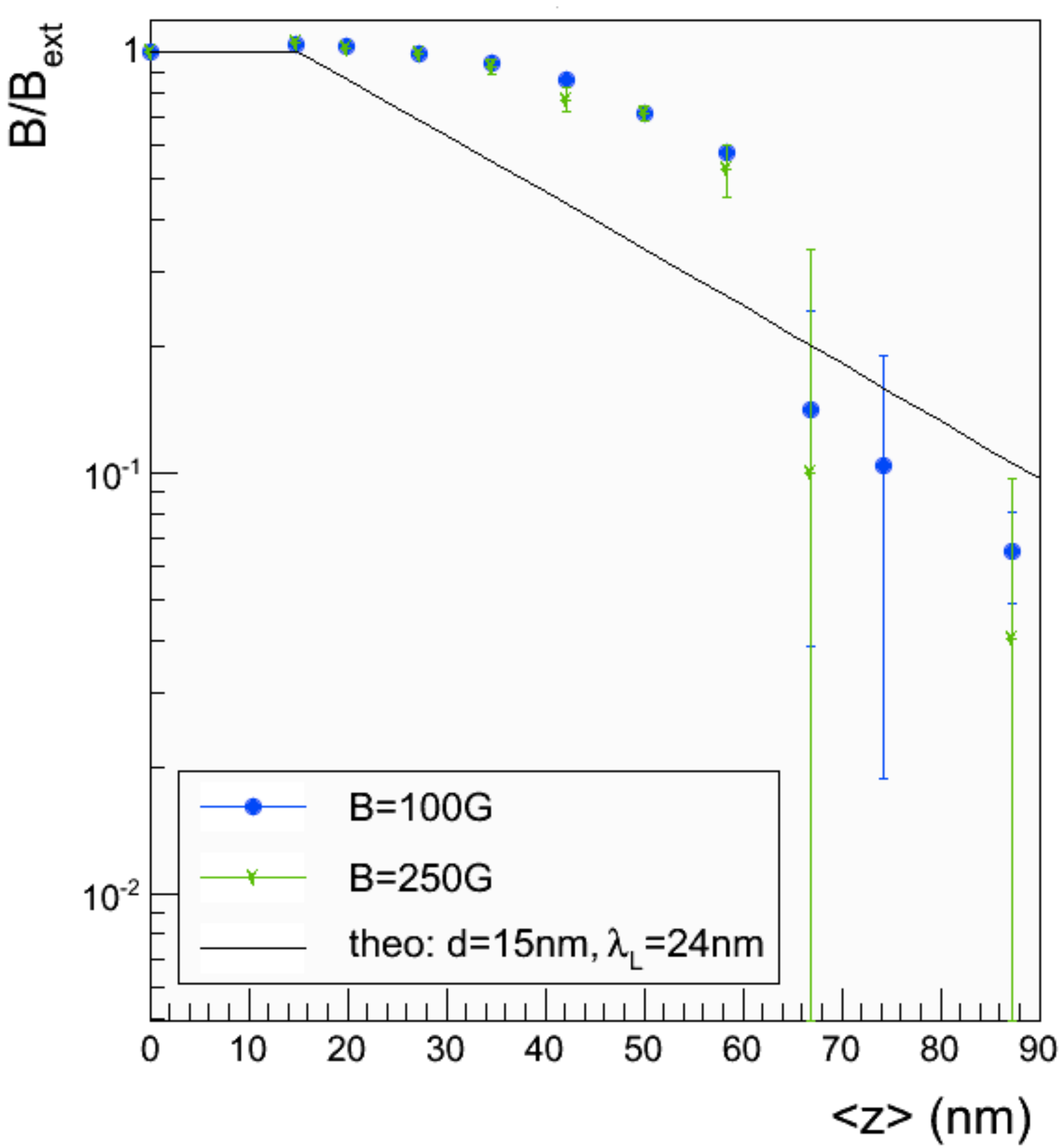


Results: field profile hot



1. **15 nm +-3nm of 'dead layer'**
2. NON LOCAL: <u>not an exponential decay!</u>
3. Non local fit (obtained from Gaussian fitting model as in Phys. Rev. B **72**, 024506 2005): **λ = 24 +-2 nm**
4. Magnetic penetration depth in quantitative agreement with high quality Nb films, measured previously with LEM
5. Different lambda in the first 50 nm from below?

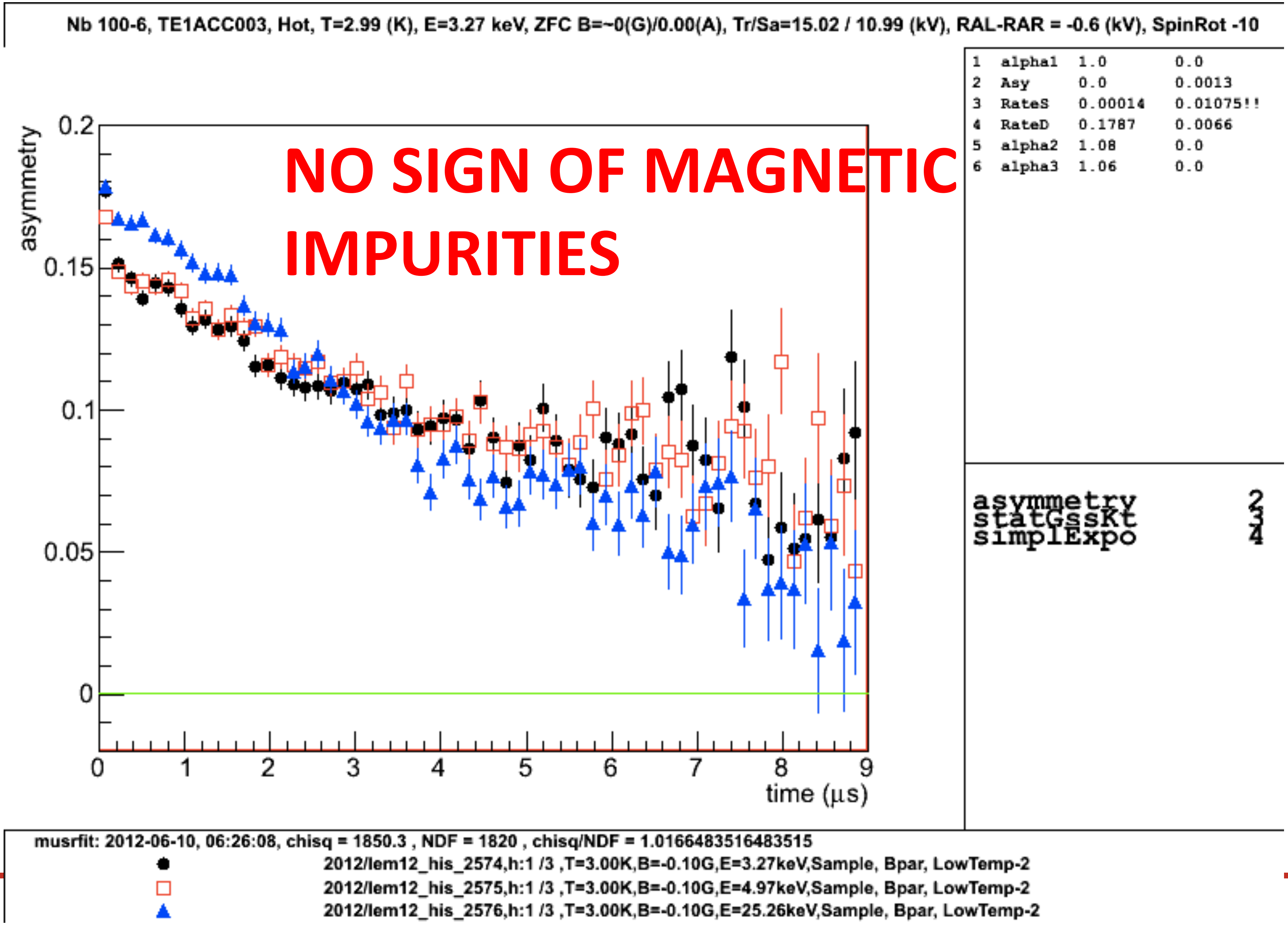
Results: field profile cold



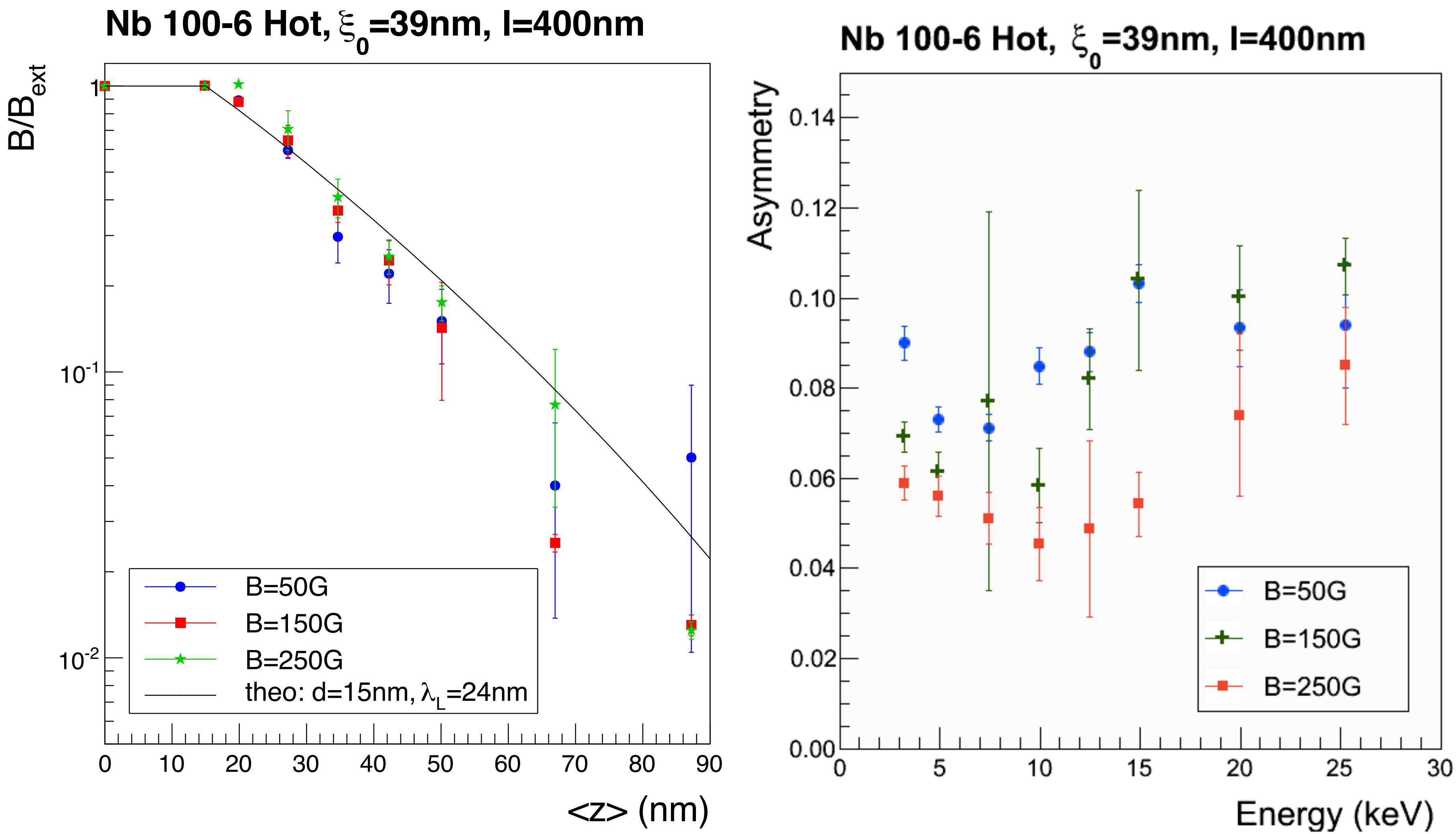
1. **~15 nm of 'dead layer'**
2. NOT an exponential decay! But also non local fit does not work! Lambda much larger:
   - Estimate in the first 50 nm:

   λ~ 100nm, below ~ 40 nm
   - → **Mfp ~ 2 nm**
3. Possible interpretation:
   - a distribution of mean free paths with extremely short values
   - the surface is only superconducting due to proximity effects

Results: magnetic impurities?



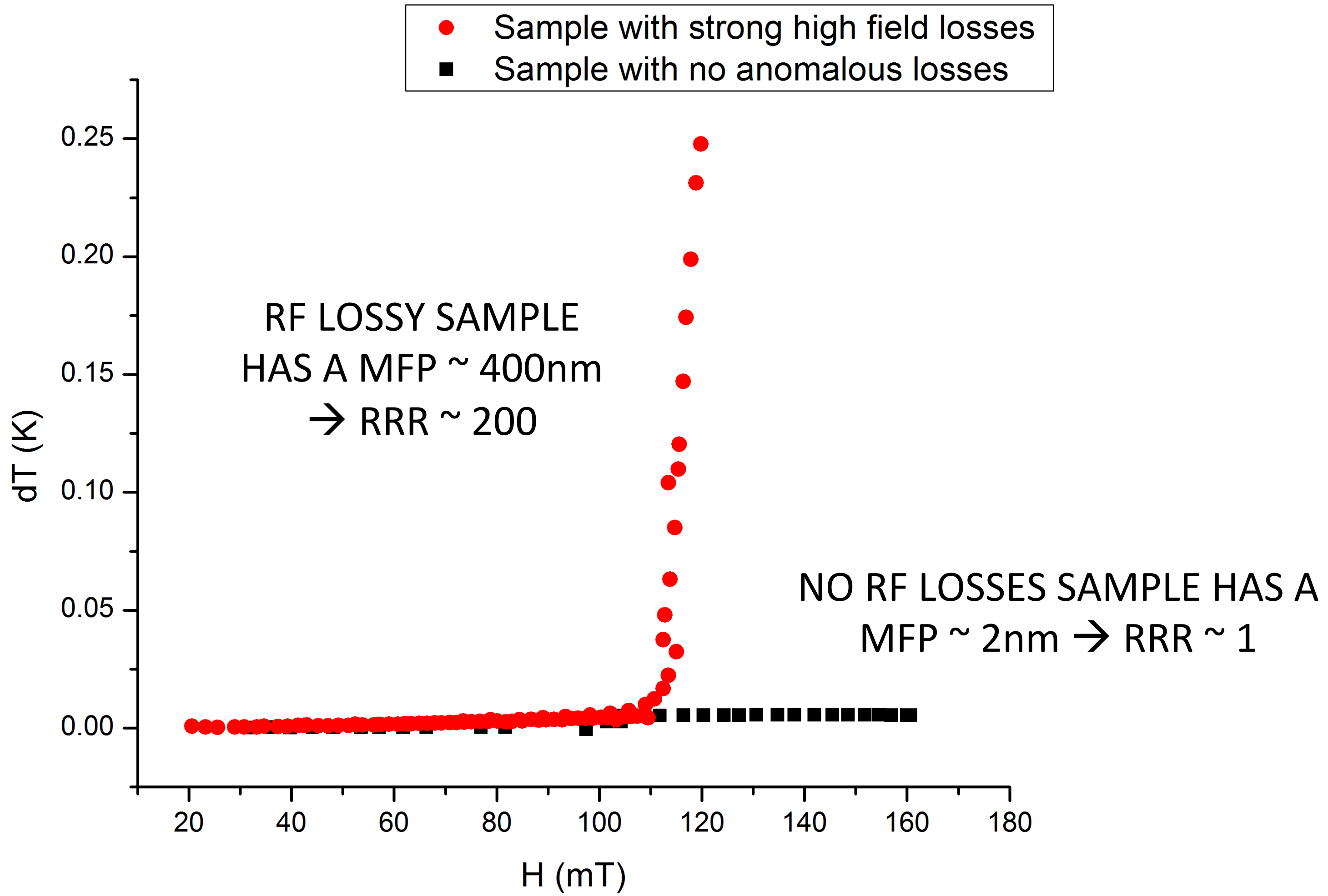
Results: field dependence of λ?



Conclusions

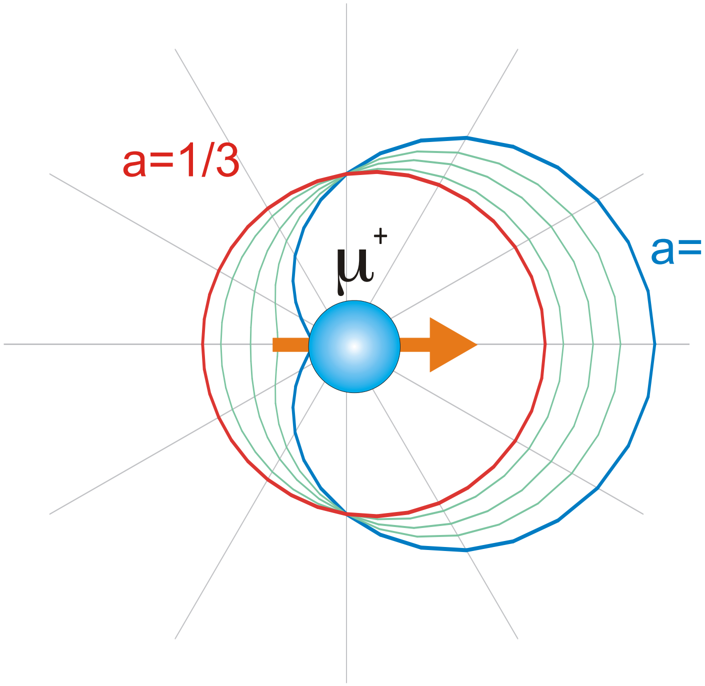
- Magnetic field profile inside SRF cavity cutouts has been measured for the first time via low energy muon spin rotation
- Results show that screening is NOT following the simple 'exponential falloff' model that we have always used
- **λ = 24 +-2 nm** for hot sample, significantly longer (5 times) for cold sample
- Existence of **15 nm** of '**dead layer**'
- Hot sample very 'clean', cold sample very 'dirty': **mfp ~ 400 nm** for the hot sample, **mfp ~ 2nm** for the cold
- NO MAGNETIC IMPURITIES detected in the niobium surface
- Niobium cavity surface ='Three layer' structure?

Lesson learned?



Optimizing sample parameters 'blindly' can be dangerous

Thanks for your attention!



Gaussian field distribution

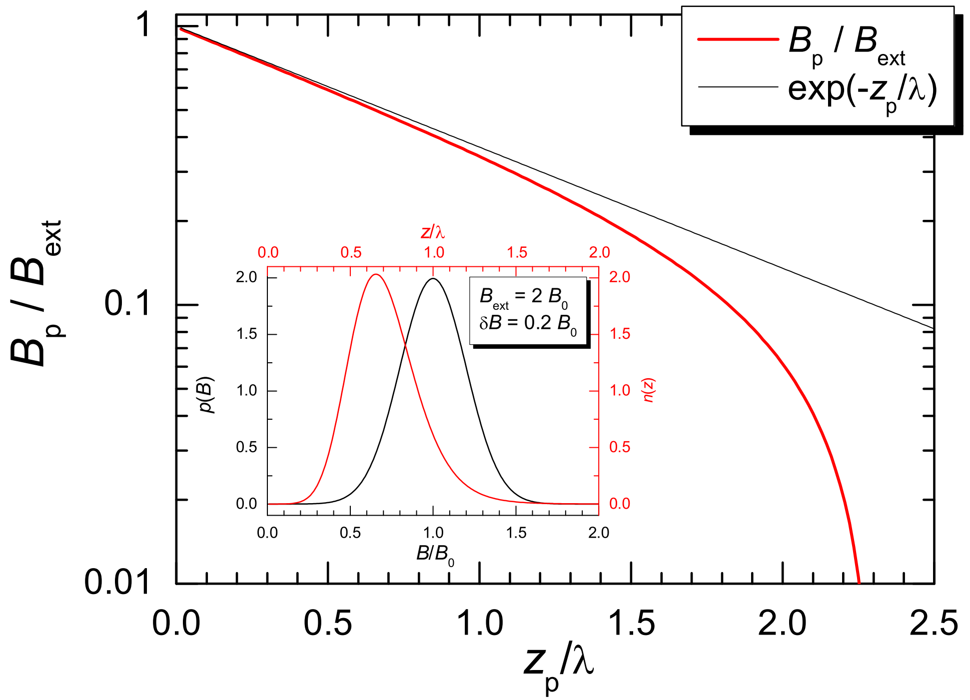


Figure 4: B_p vs. z_p reconstruction for a Gaussian $p(B)$ and an exponential $B(z)$.

4 Peak Value Reconstruction assuming Gaussian p(B)

The last case which can be calculated analytically and is perhaps closest to the online-analysis is that we assume a Gaussian field distribution

$$p(B) = \frac{1}{\sqrt{2\pi}\delta B} \exp\left[-\frac{1}{2}\left(\frac{B - B_0}{\delta B}\right)^2\right]. \tag{5}$$

According to Eq.(1), $n(z)$ can be calculated if an exponential $B(z)$ (Eq.(3)) is assumed, it takes the form

$$n(z) = \frac{1}{\sqrt{2\pi}\lambda} \frac{B_0}{\delta B} \exp\left[-\frac{1}{2}\left(\frac{B_{\mathrm{ext}} e^{-z/\lambda} - B_0}{\delta B}\right)^2 - \frac{z}{\lambda}\right] \tag{6}$$

The peak values are than given by

$$\begin{aligned} B_p &= B_0 \\ n_p &= \lambda \ln\left[\frac{B_{\mathrm{ext}}}{2\delta B^2}\left(\sqrt{B_0^2 + 4\delta B} - B_0\right)\right], \end{aligned}$$

which leads to

$$B_p(z_p) = B_{\mathrm{ext}}\, e^{-z/\lambda}\left[1 - \left(\frac{\delta B}{B_{\mathrm{ext}}}\right)^2 e^{+2z_p/\lambda}\right]. \tag{7}$$

This results are collected in Fig.4. As one can see, it shows the same trend as the peak value reconstruction described in Sec.3. The $n(z)$ profile seems the be a little less realistic compared to the one used above.