



Hyperfine Structure Measurements on Hydrogen and Deuterium for CPT and Lorentz Invariance Tests

Martin C. Simon
Stefan Meyer Institute, Vienna, Austria
for the ASACUSA collaboration

PSI - Workshop
20th October 2022

Motivation

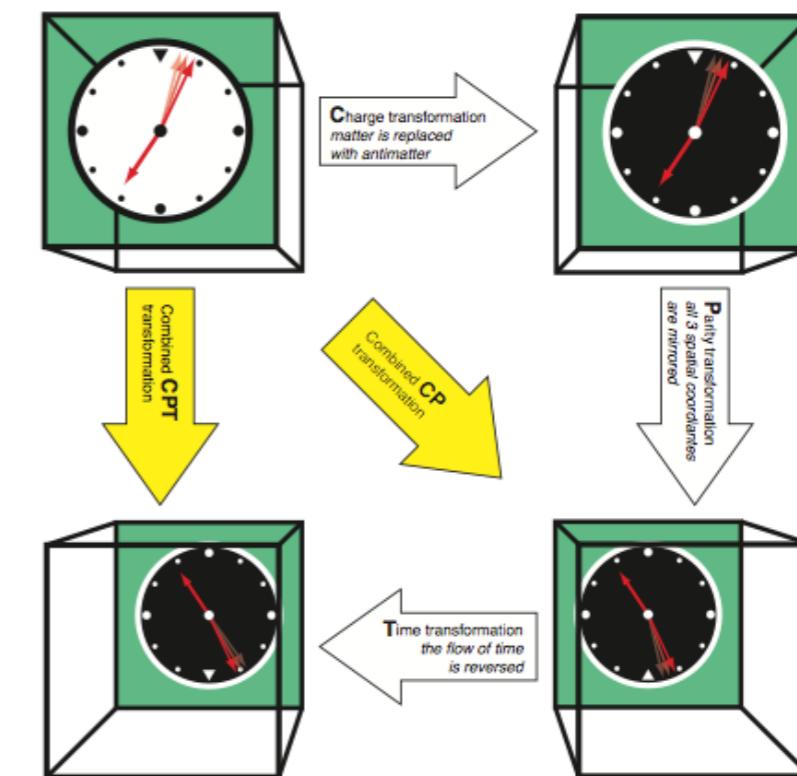
Fundamental Symmetries

- CPT Test by ASACUSA
at AD of CERN:



Compare Hyperfine Structure (HFS) of H & \bar{H}

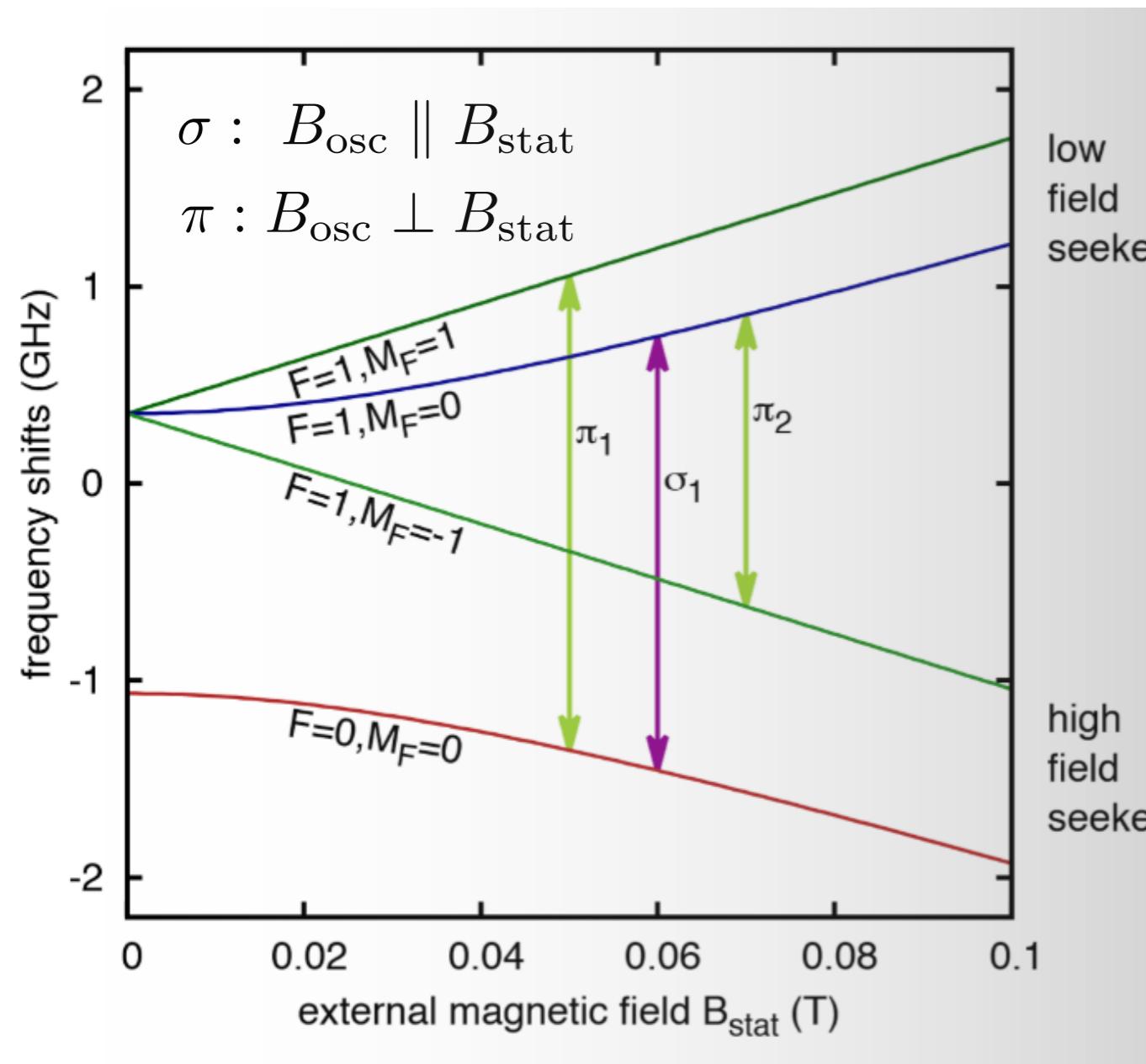
- Standard Model Extension (SME)
 - Hydrogen Beam
 - Test of spectroscopy equipment for \bar{H}
 - New SME constraints (no \bar{H} needed)
 - Deuterium Beam
 - Increased sensitivity due to proton mo



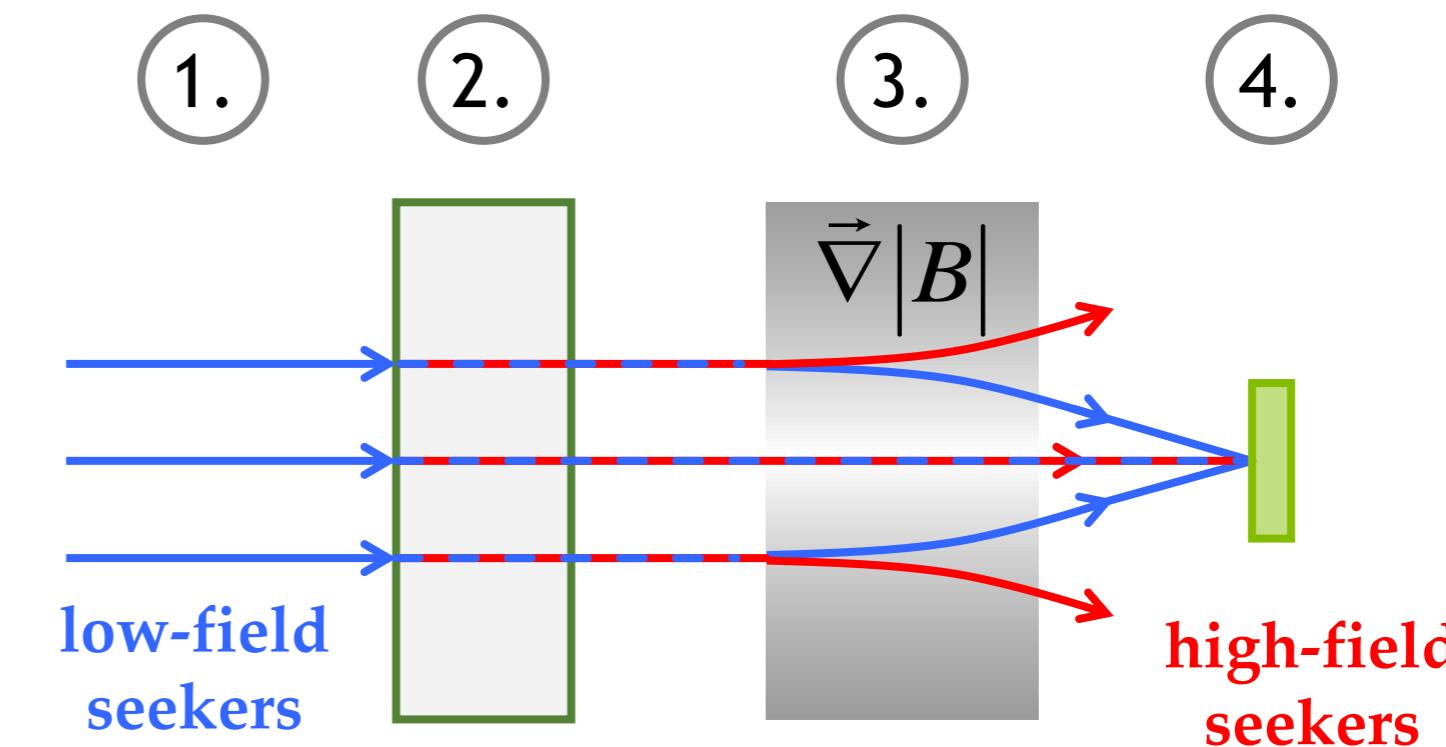
CPT & LORENTZ VIOLATION

$$\begin{aligned}
 & \text{SM Dirac eqn.} \\
 & \quad (i\gamma^\mu D_\mu - m_e) \psi + \boxed{a_\mu^e \gamma^\mu - b_\mu^e \gamma_5 \gamma^\mu} \\
 & \quad - \boxed{-\frac{1}{2} H_{\mu\nu}^e \sigma^{\mu\nu} + i c_{\mu\nu}^e \gamma^\mu D^\nu + i d_{\mu\nu}^e \gamma_5 \gamma^\mu D^\nu} \psi = 0. \\
 & \quad \text{LORENTZ VIOLATION}
 \end{aligned}$$

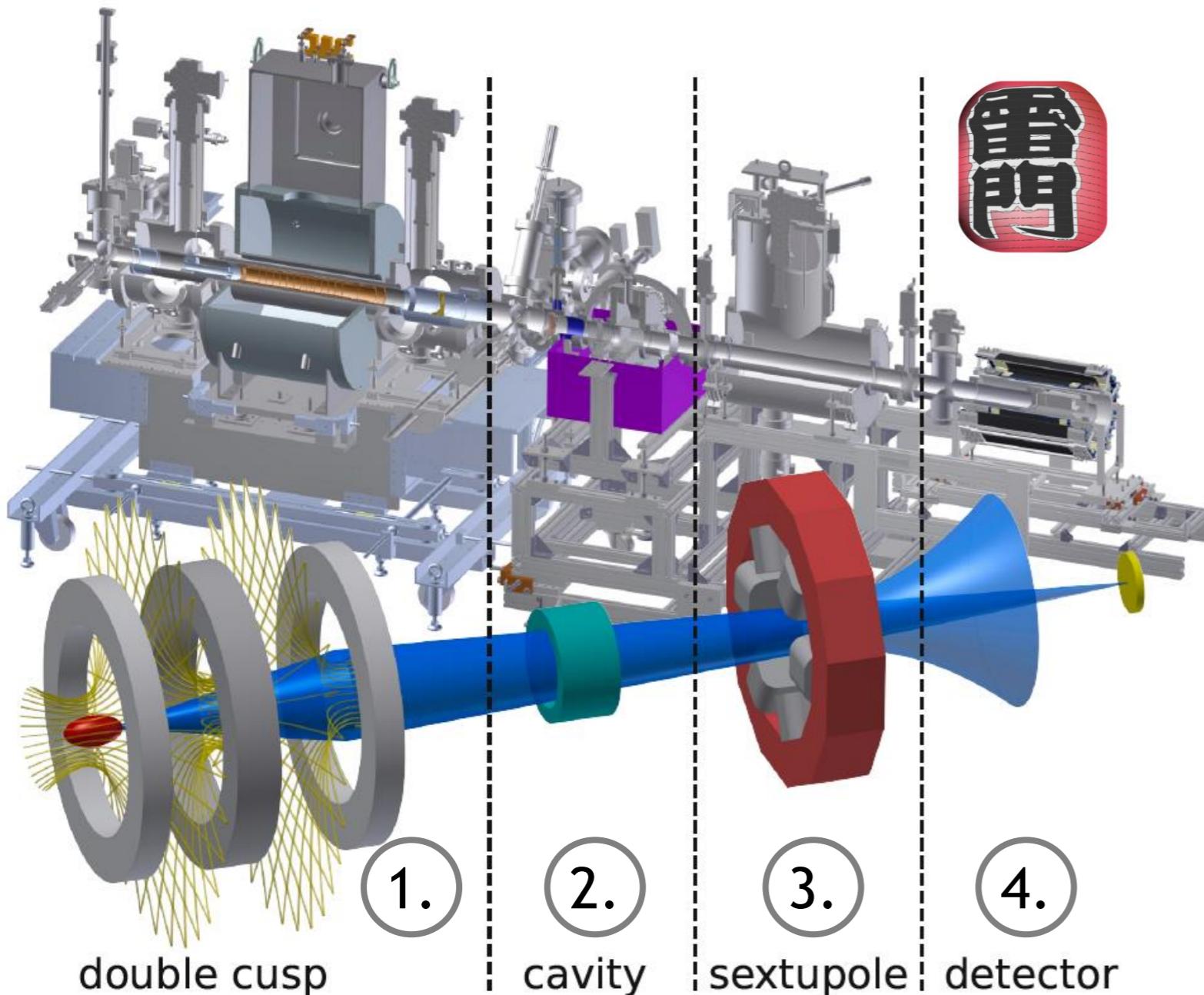
HFS and Rabi Spectroscopy



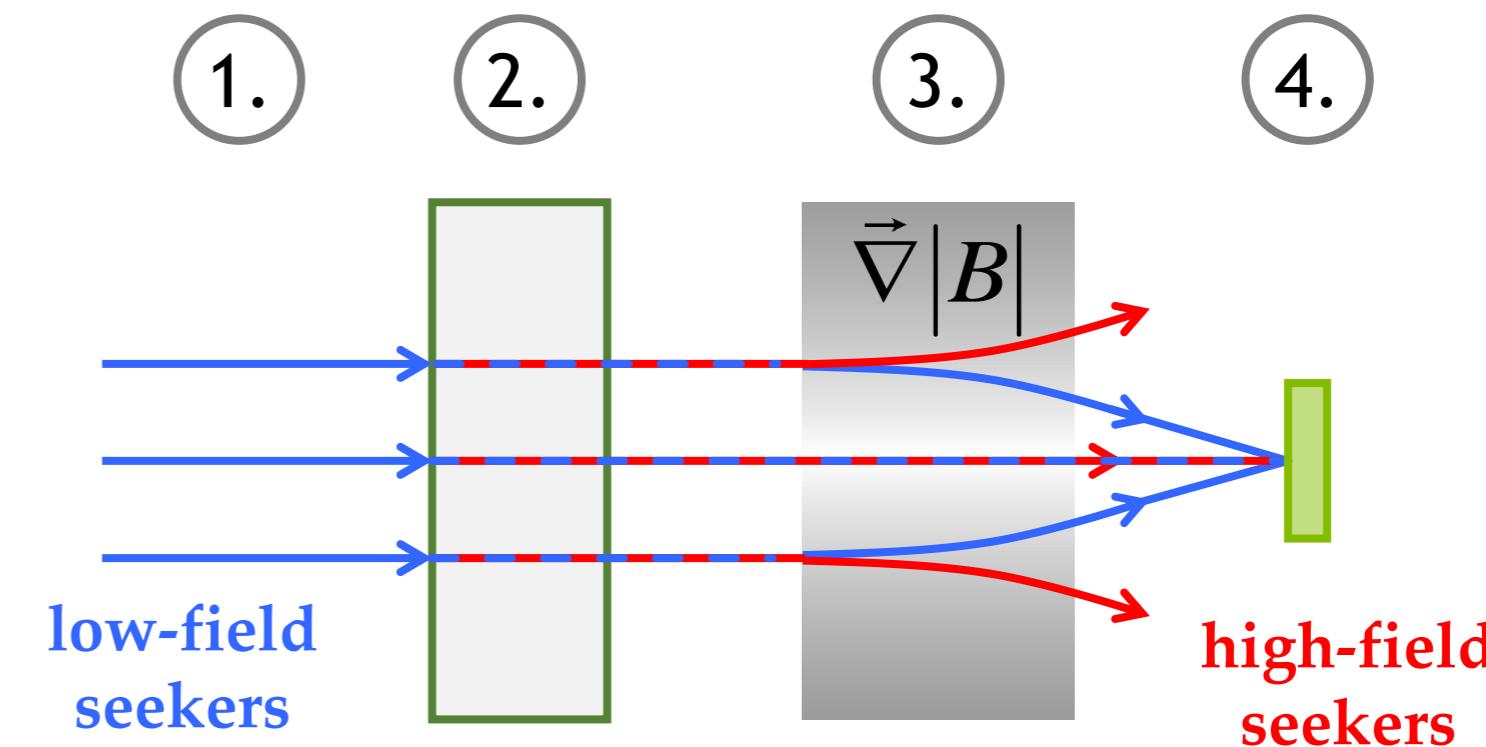
1. polarized beam (low-field seekers)
2. spin flip drive (osc. B-field: ~1.42 GHz)
3. spin state analysis (Stern-Gerlach effect)
4. detection (count rate drop → spin flip)



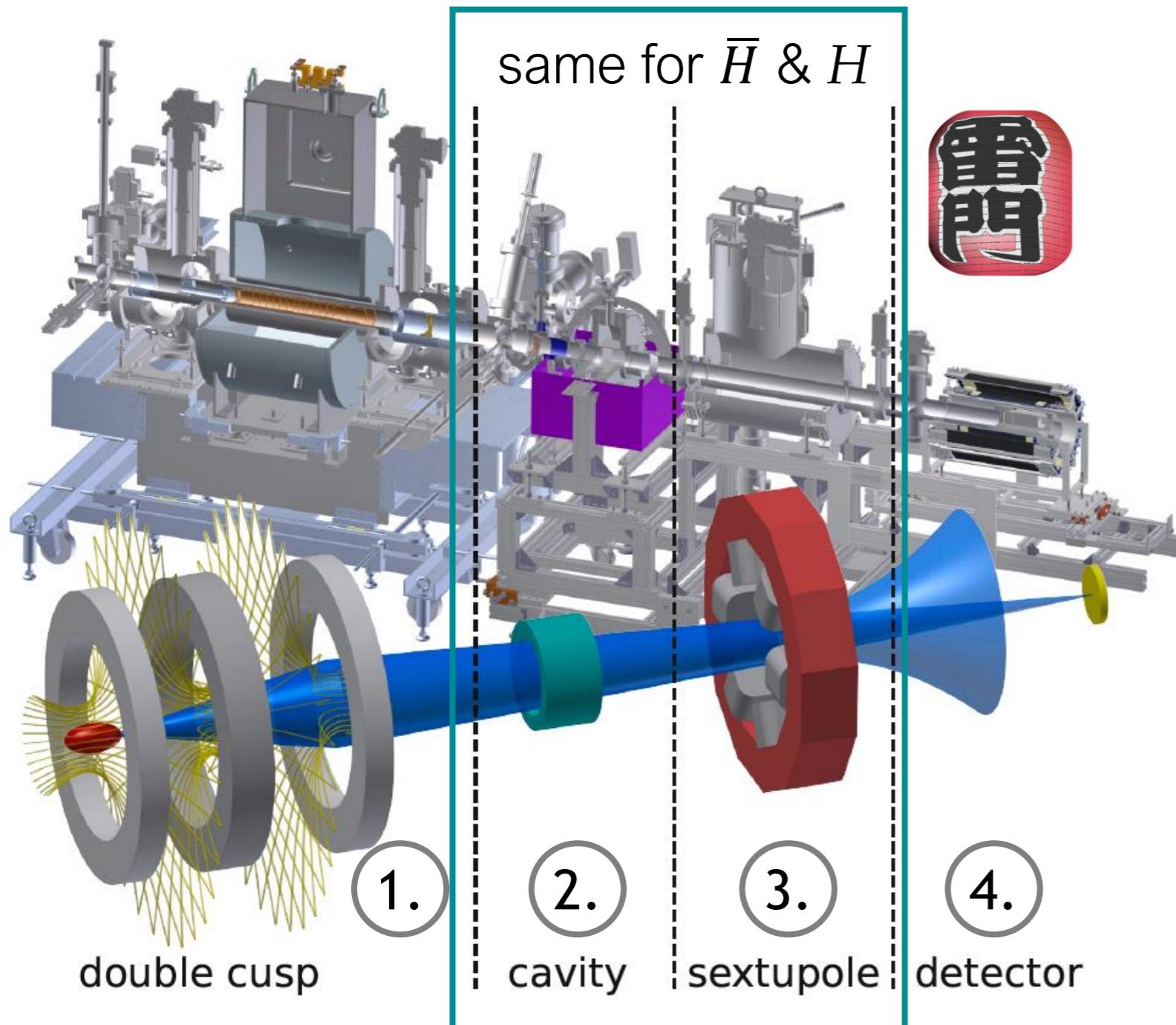
The Antihydrogen HFS spectrometer



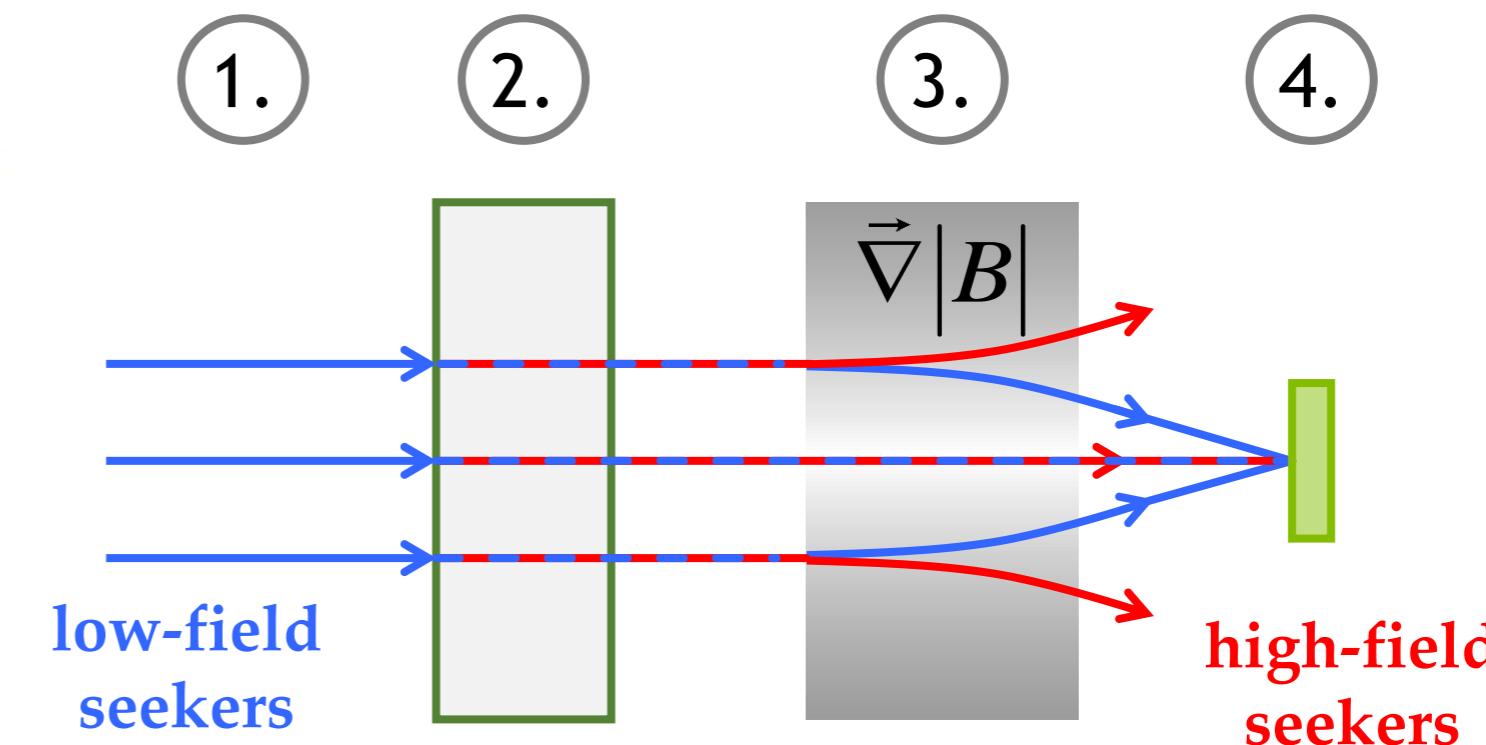
1. polarized beam (low-field seekers)
2. spin flip drive (osc. B-field: ~1.42 GHz)
3. spin state analysis (Stern-Gerlach effect)
4. detection (count rate drop → spin flip)



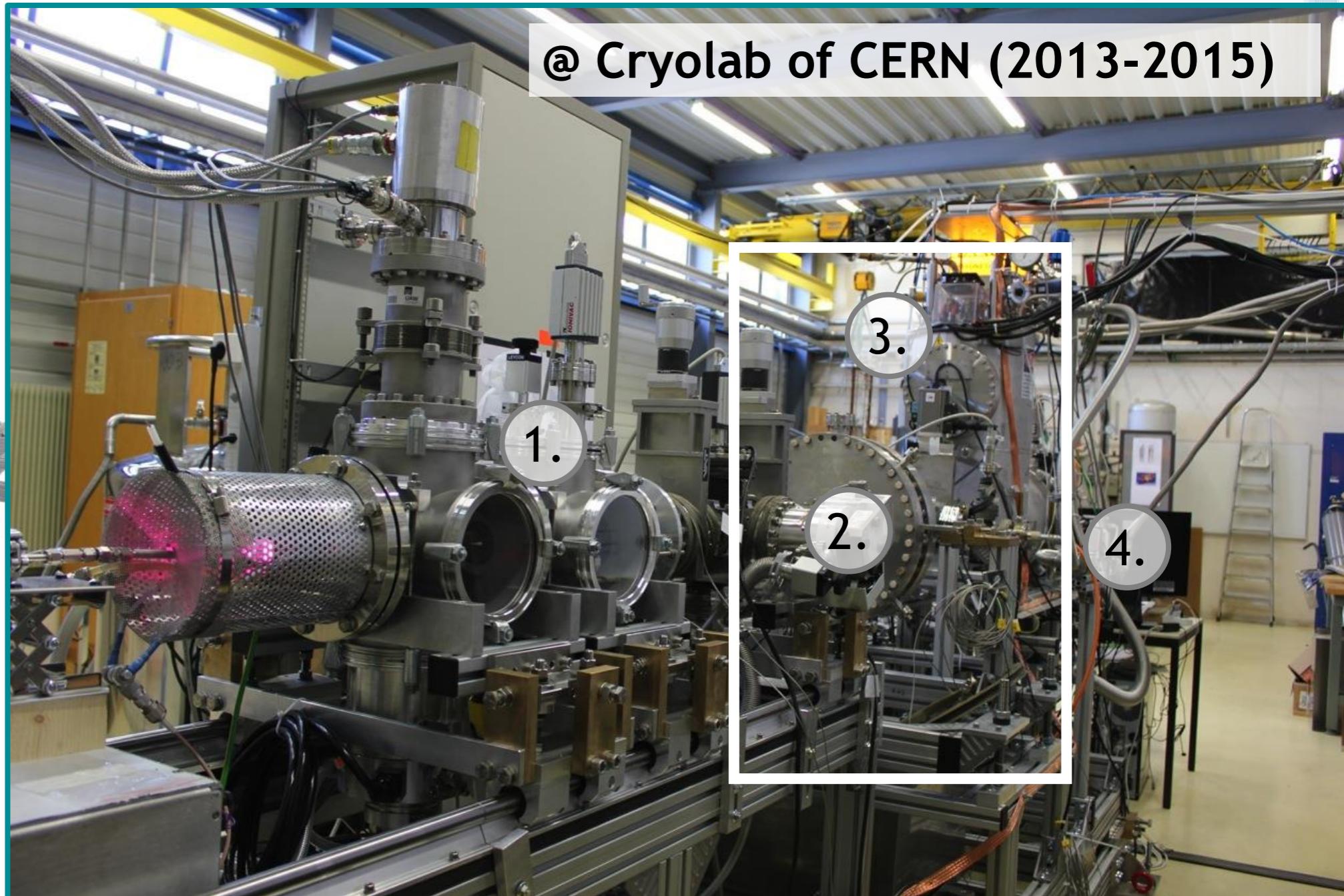
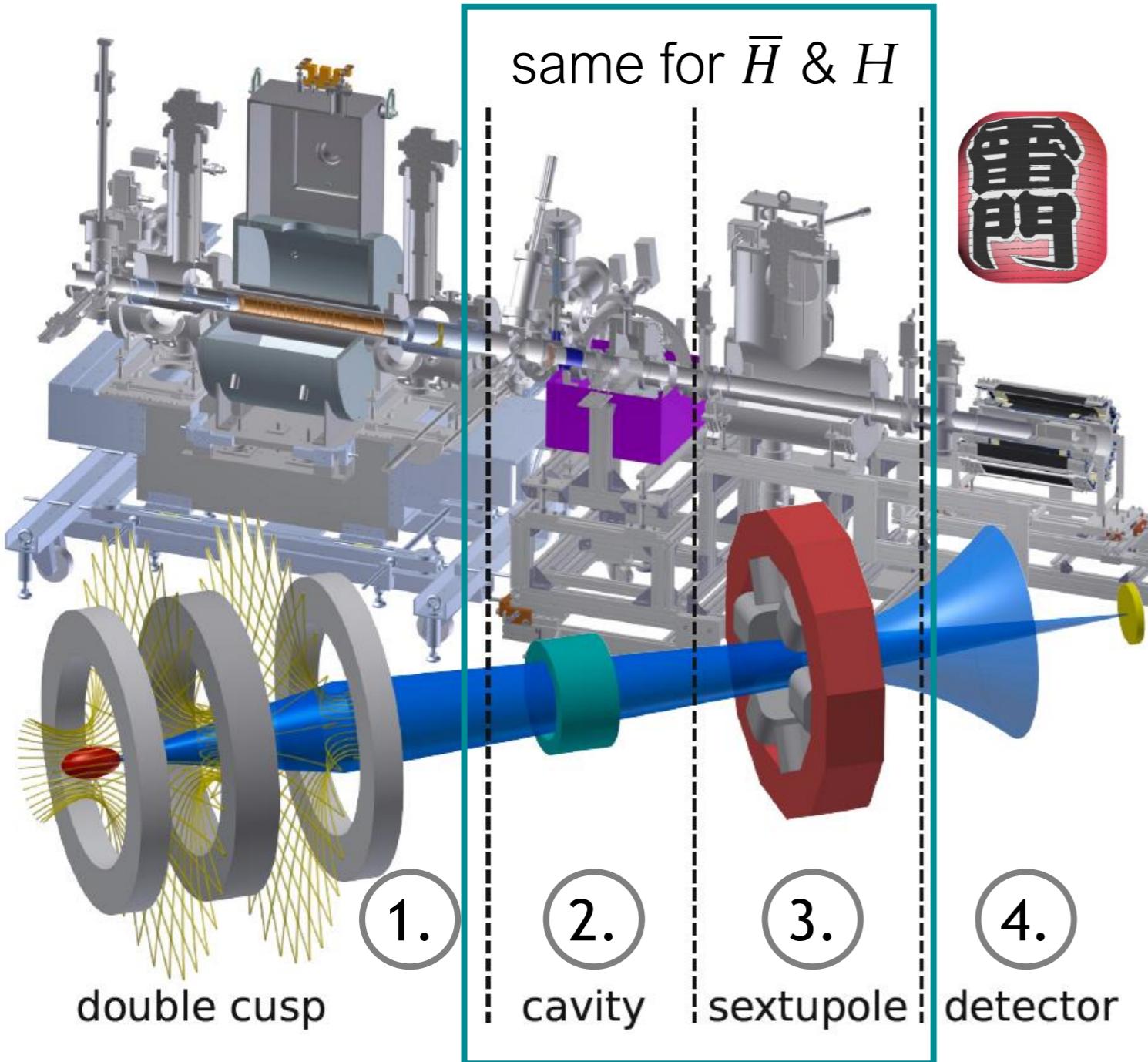
The Antihydrogen HFS spectrometer



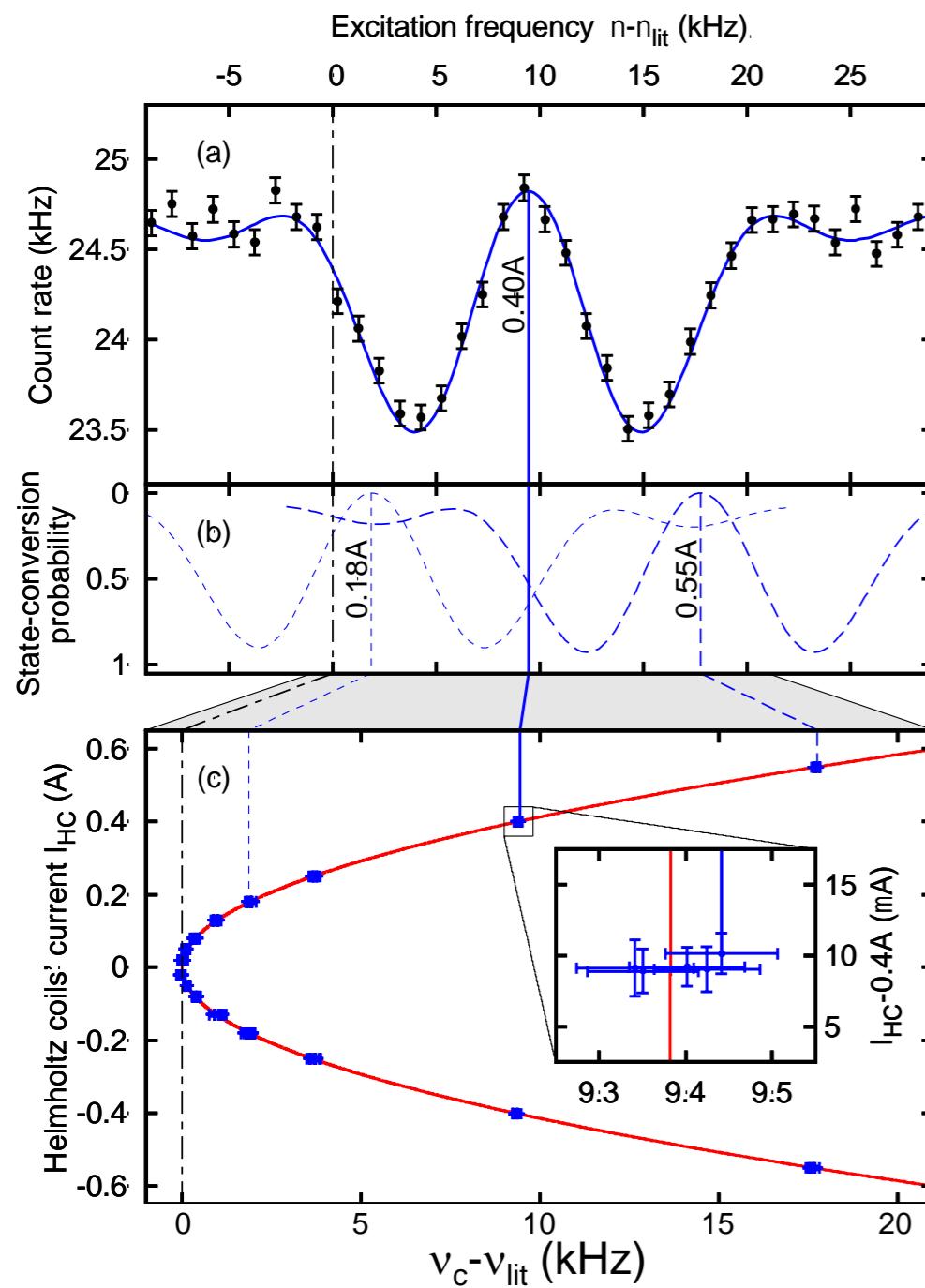
1. polarized beam (low-field seekers)
2. spin flip drive (osc. B-field: ~1.42 GHz)
3. spin state analysis (Stern-Gerlach effect)
4. detection (count rate drop → spin flip)



The Antihydrogen HFS spectrometer



Hydrogen results on the σ transition



ASACUSA *Nat. Commun.* 8, 15749 (2017).

Martin Diermaier, PhD Thesis

final result

1 420 405 748.4 (3.4) (1.6) Hz

agrees with literature (maser)

1 420 405 751.768 (0.002) Hz

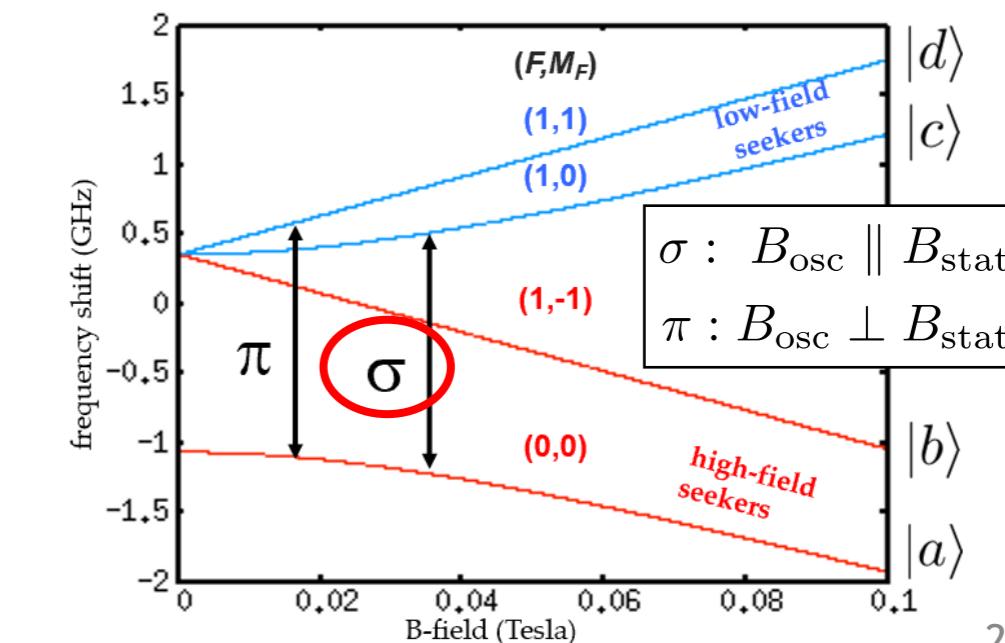
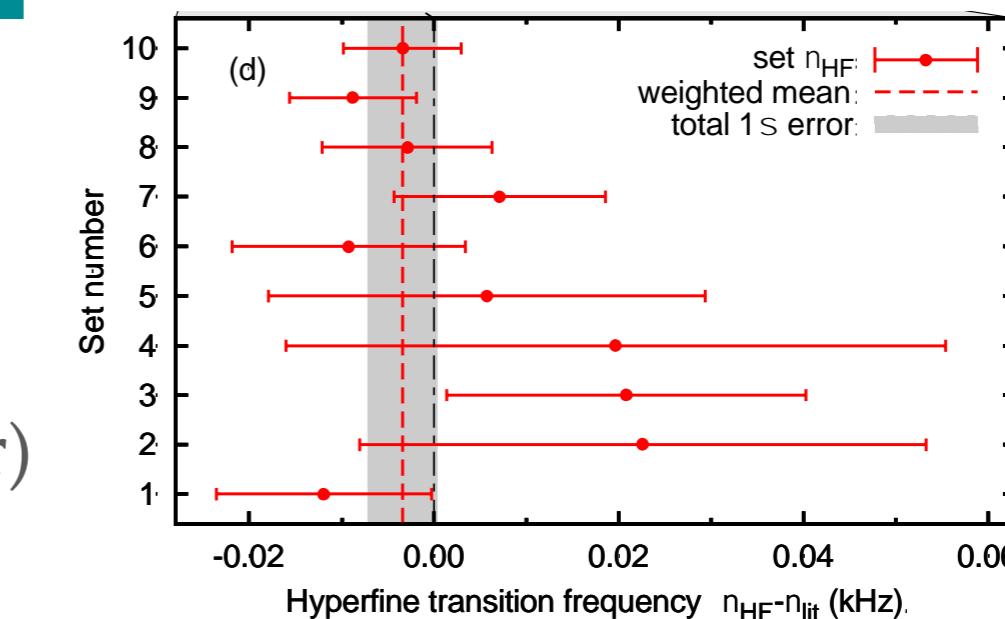
H. Hellwig *et al.*, *IEEE Trans. Instrum. Meas.* 19, 200 (1977).
S. G. Karschenboim, *Can. J. Phys.* 78, 639 (2000).

$$v_\sigma(B_{\text{stat}}) = \sqrt{v_{\text{HF}}^2 + \left(\frac{\mu_+}{h}\right)^2 B_{\text{stat}}^2}$$

$$\mu_+ = |g_e|\mu_B + g_p\mu_N$$

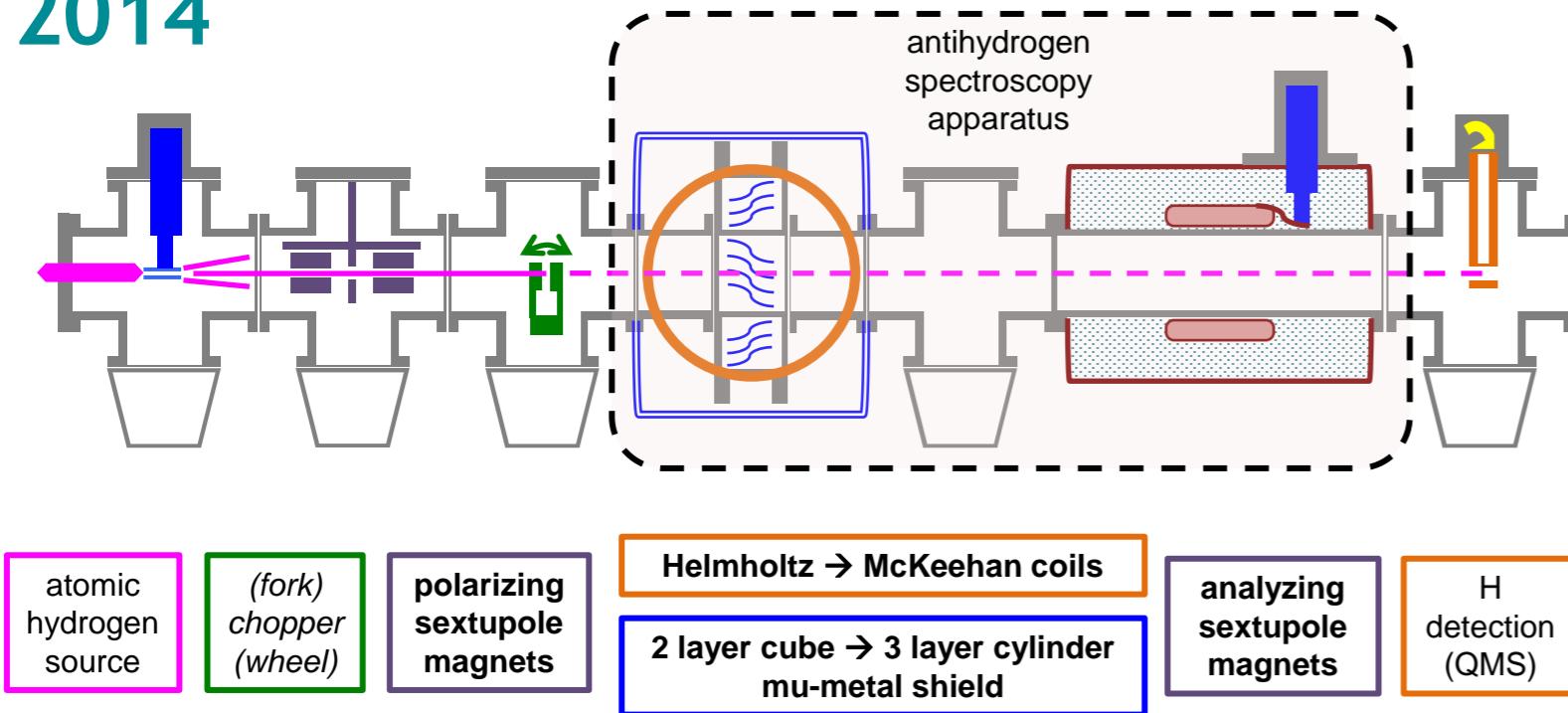
no systematic uncertainty
on few ppb level

anti-H 1st stage goal: ppm

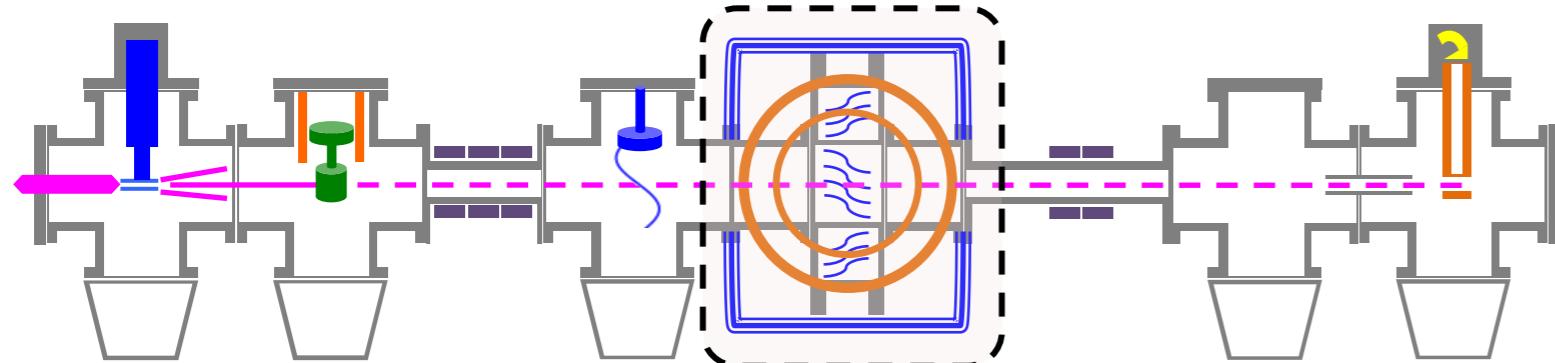


Access to the σ and π transition

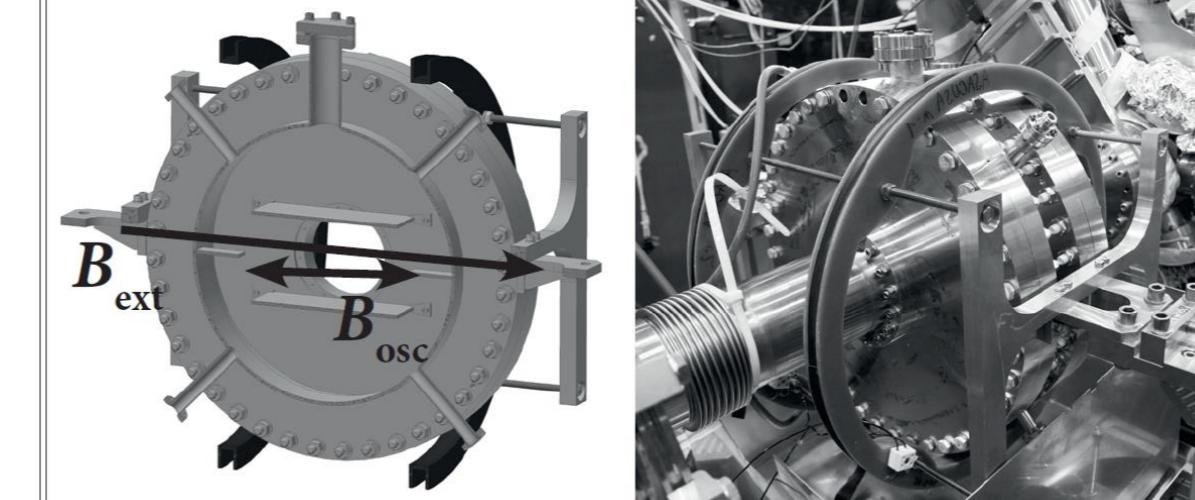
2014



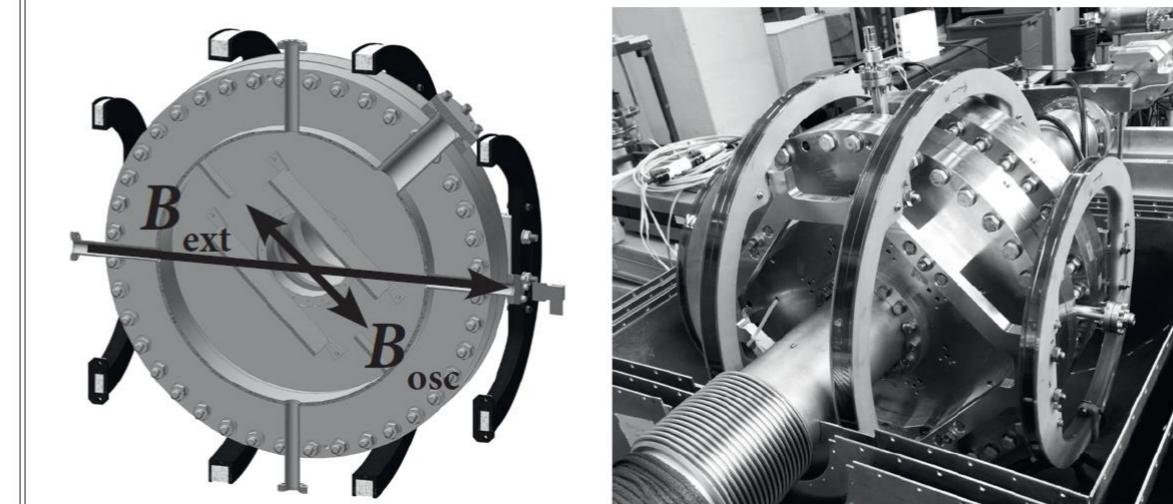
until 2022



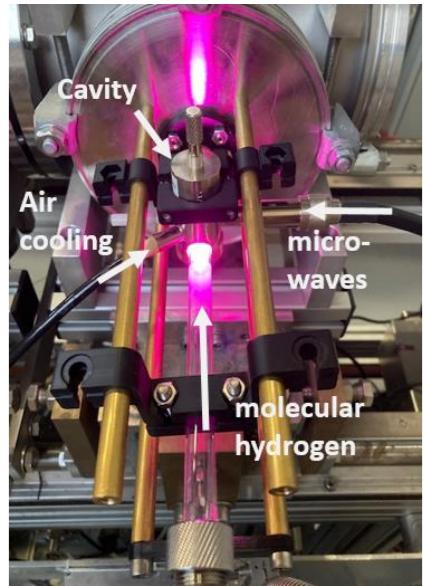
σ -cavity: Helmholtz coils, 2 layer cuboid shielding



σ/π -cavity: McKeehan-like coils, 3-layer cylindrical shielding



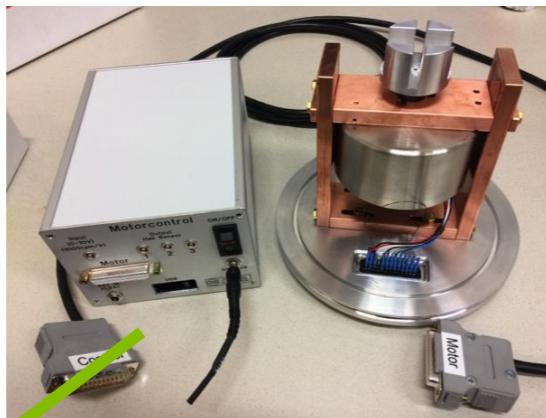
Access to the σ and π transition



source with
Evenson cavity



chopper wheel



helical
blocker



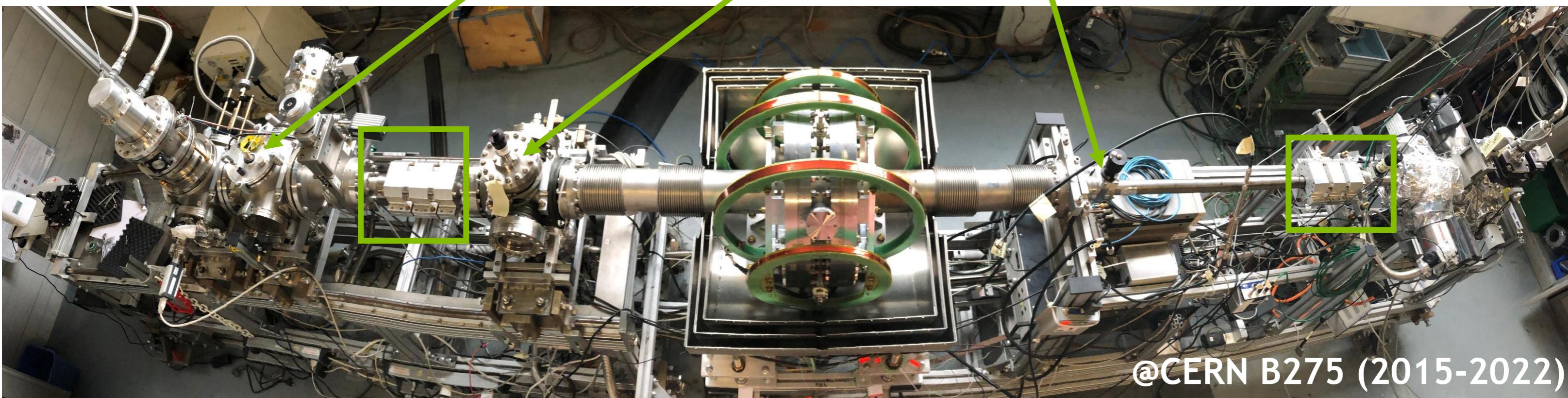
ring
apertures



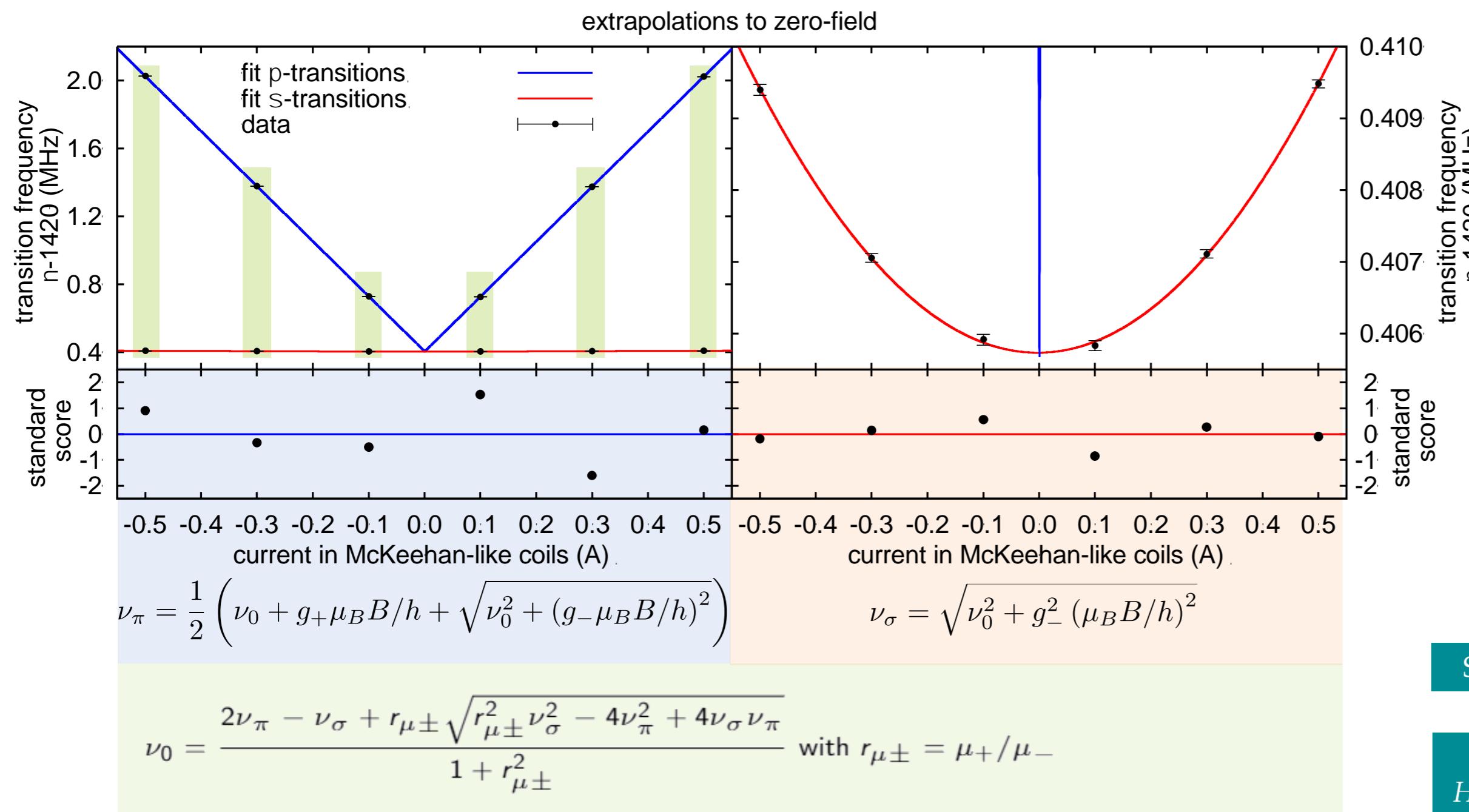
sextupoles



QMS



First π_1 -Transitions (2017)



$\nu_0 - \nu_{\text{lit}}$

extrapolation of σ :

$+15 \pm 15$ Hz
10 ppb

extrapolation of π :

$+8 \pm 34$ Hz
24 ppb

$\sigma-\pi$ pairs:
 $+1 \pm 8$ Hz
5.6 ppb

Sergio Arguedas, Master Thesis

E. Widmann/ASACUSA
Hyperfine Interactions 240:5 (2019).

Complementing sidereal variations

$$\mathcal{K}_{\mathcal{W}_{k10}}^{Lab} = \boxed{\mathcal{K}_{\mathcal{W}_{k10}}^{Sun} \cos(\theta)} - \sqrt{2} \Re e \left(\mathcal{K}_{\mathcal{W}_{k11}}^{Sun} \right) \sin(\theta) \cos(\omega_{\oplus} T_{\oplus}) + \sqrt{2} \Im m \left(\mathcal{K}_{\mathcal{W}_{k11}}^{Sun} \right) \sin(\theta) \sin(\omega_{\oplus} T_{\oplus})$$

V A Kostelecky and A J Vargas, *PRD* **92** 056002 (2015).

ASACUSA, *Phil. Trans. R. Soc. A* **376**:20170273, (2018).

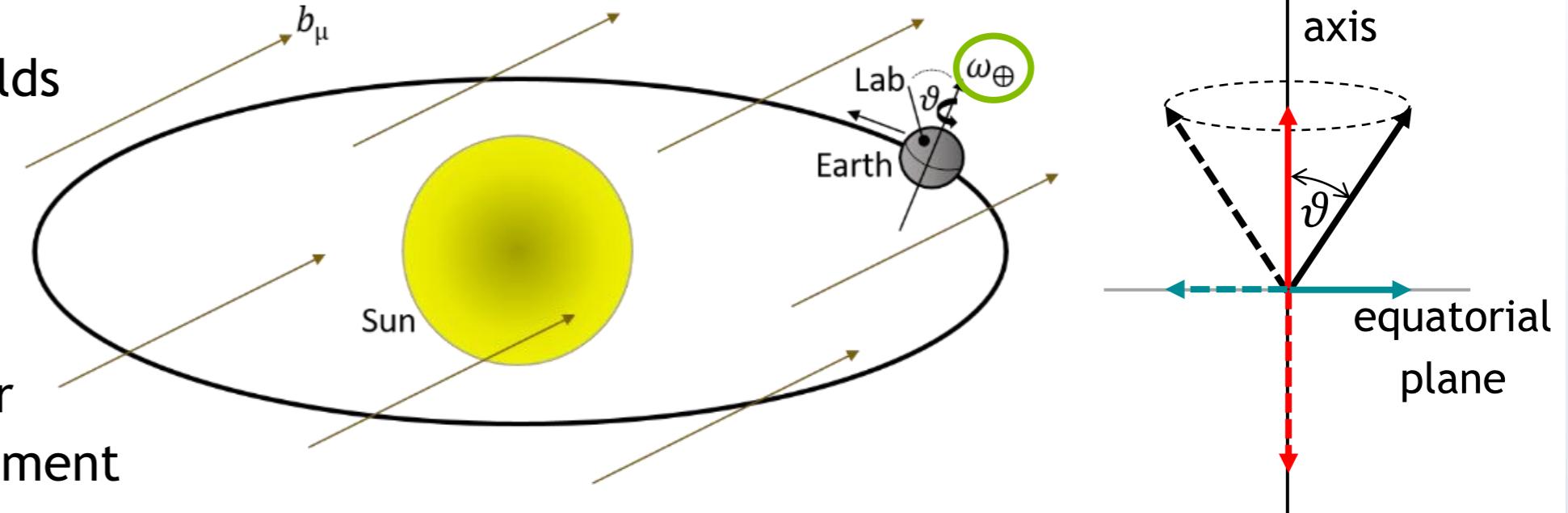
sidereal variation constraints by maser (~mHz, 10^{-27} GeV):

M A Humphrey et al., *PRA* **68** 063807 (2003).

Principle: compare π transition in B-fields of same strength,
but opposite polarity

Challenge: B-field determination

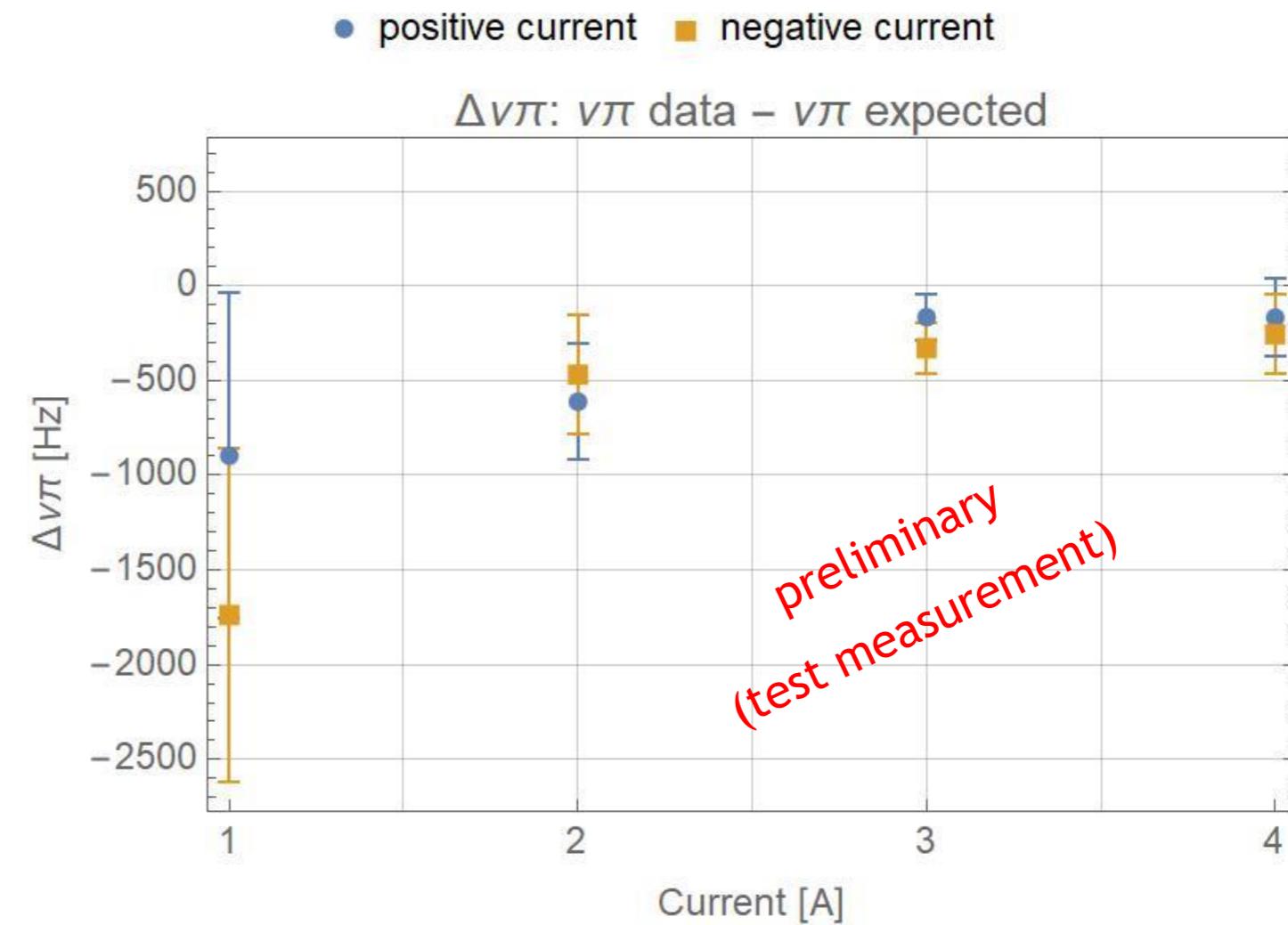
Approach: use σ transition ($\Delta M_F = 0$) for independent B-field measurement



$$2\pi\delta\nu(\Delta M_F) = \frac{\Delta M_F}{2\sqrt{3}\pi} \sum_{q=0}^2 \alpha m_r^{2q} (1 + 4\delta_{q2}) \times \sum_{\mathcal{W}} [-g_{\mathcal{W}(2q)10}^{0B} + H_{\mathcal{W}(2q)10}^{0B} - 2g_{\mathcal{W}(2q)10}^{1B} + H_{\mathcal{W}(2q)10}^{1B}]$$

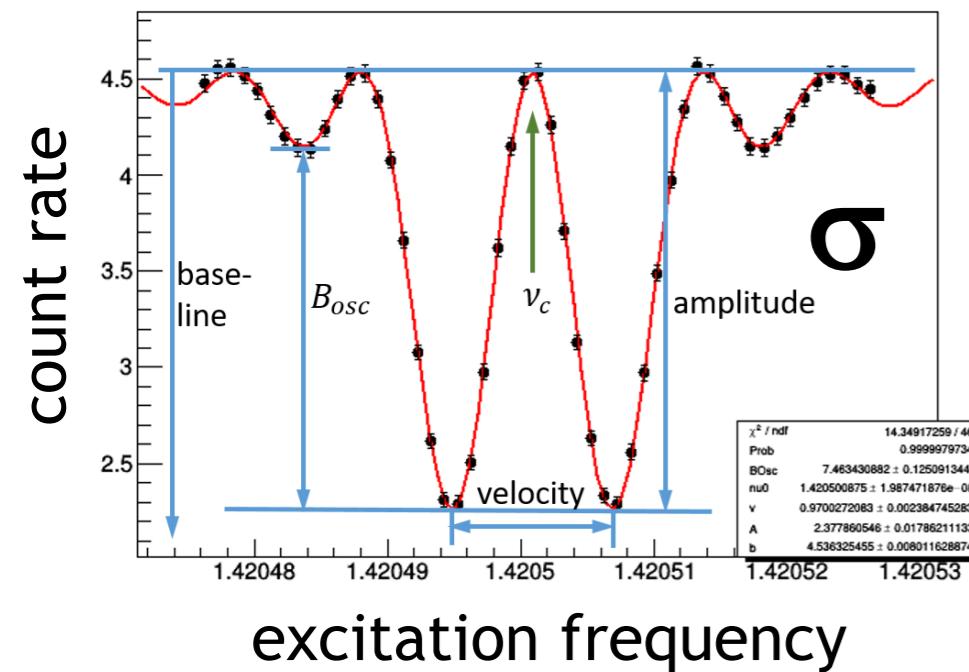
Result illustration

- σ transition measures B-field: $B(\sigma)$
→ more precise at high field
- test measurements at
 $+/- 1 \text{ A}, 2 \text{ A}, 3 \text{ A}, \text{ and } 4 \text{ A}$
($2.3 \text{ G}, 4.6 \text{ G}, 6.9 \text{ G}, \text{ and } 9.2 \text{ G}$)
- predict π transition from $B(\sigma)$: v_π expected
- compare with measured value: v_π measured
- compare for both polarities
→ double differential
- final measurements at $2.0 \text{ A}, 2.5 \text{ A}, \text{ and } 3 \text{ A} \rightarrow$ blind analysis
- expect: 100 Hz uncertainty, 10^{-22} GeV on $\mathcal{K}_{W_{k10}}^{Sun}$



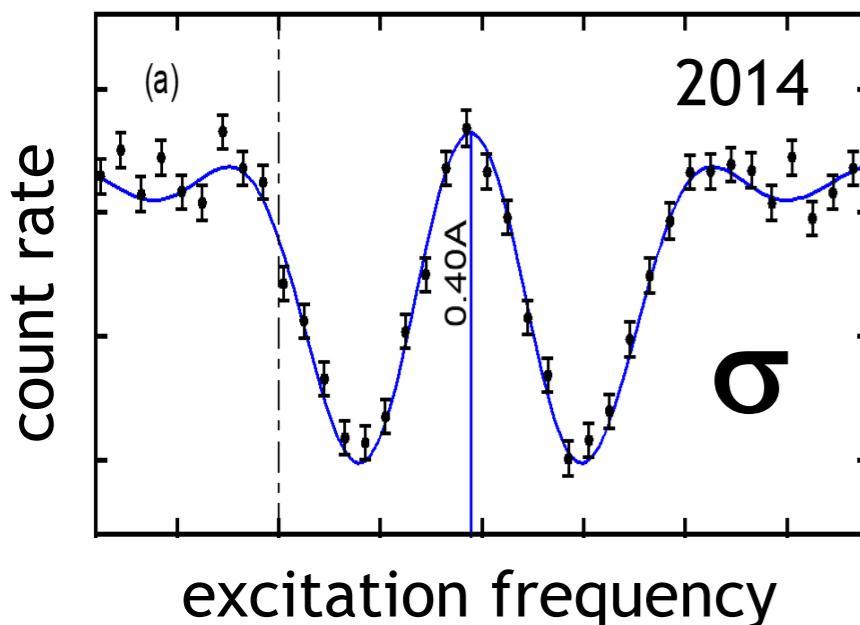
Lilian Novak

Lineshape & B-field uniformity

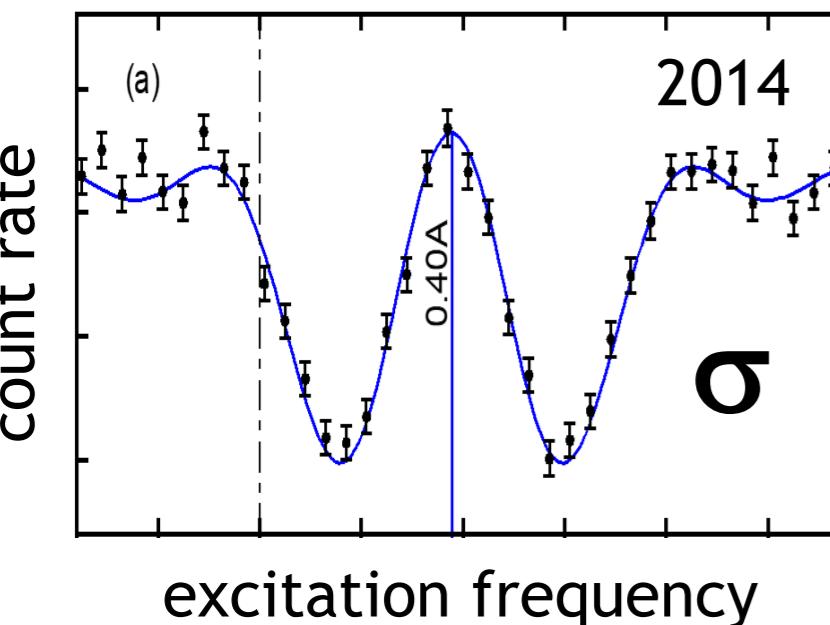
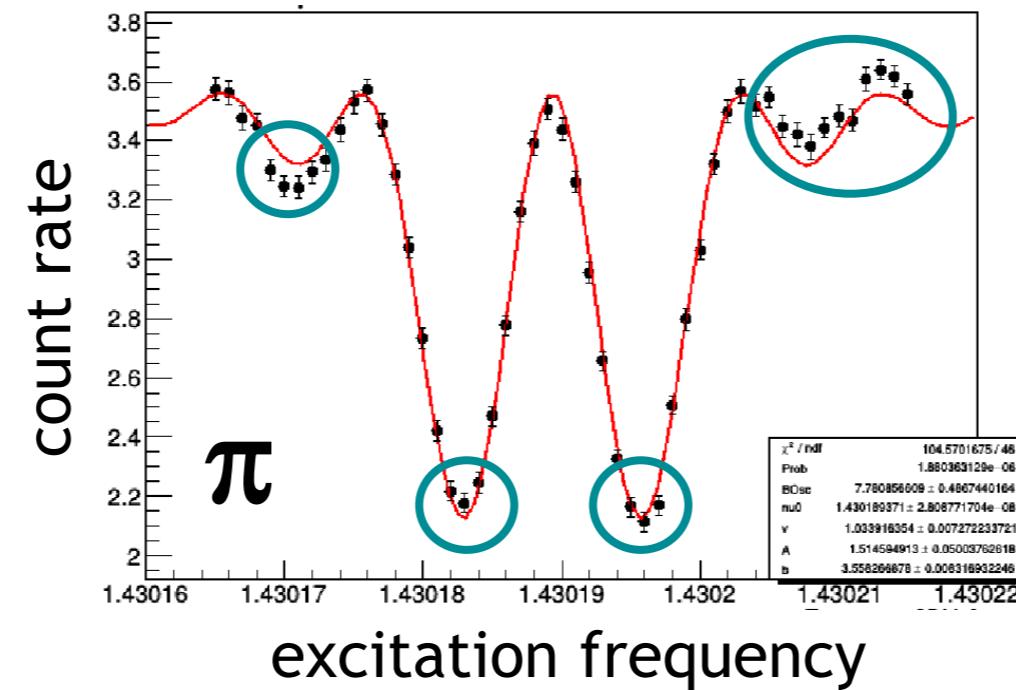
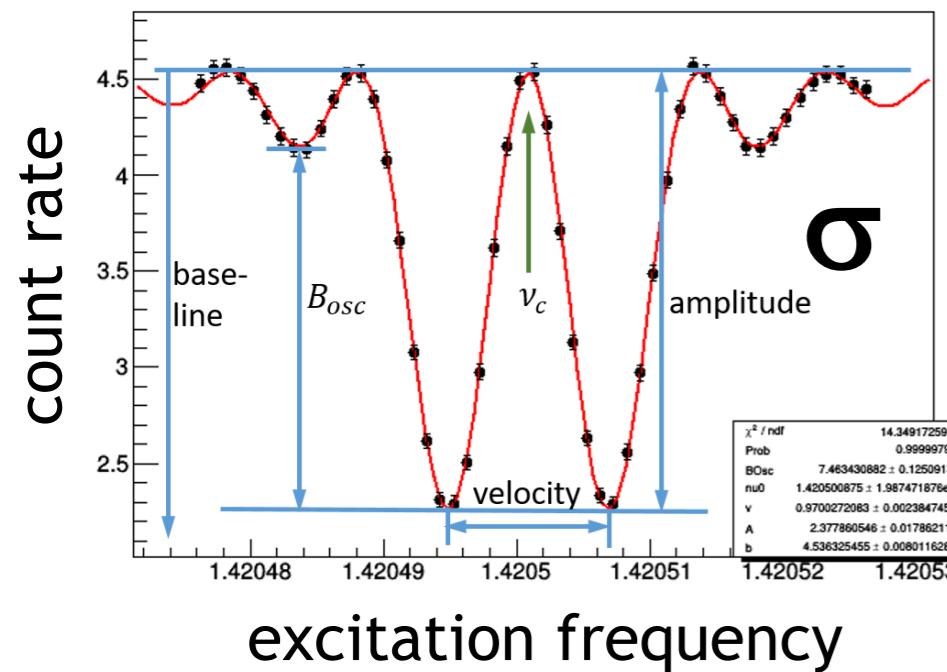


fit parameter:

- rate baseline and count rate drop (amplitude)
 - conversion $B_{osc} \rightarrow$ relative strength of main and side lobes
 - velocity \approx linewidth \rightarrow separation of two main lobes
 - velocity spread (2014)
- baseline not recovered between main and side lobes

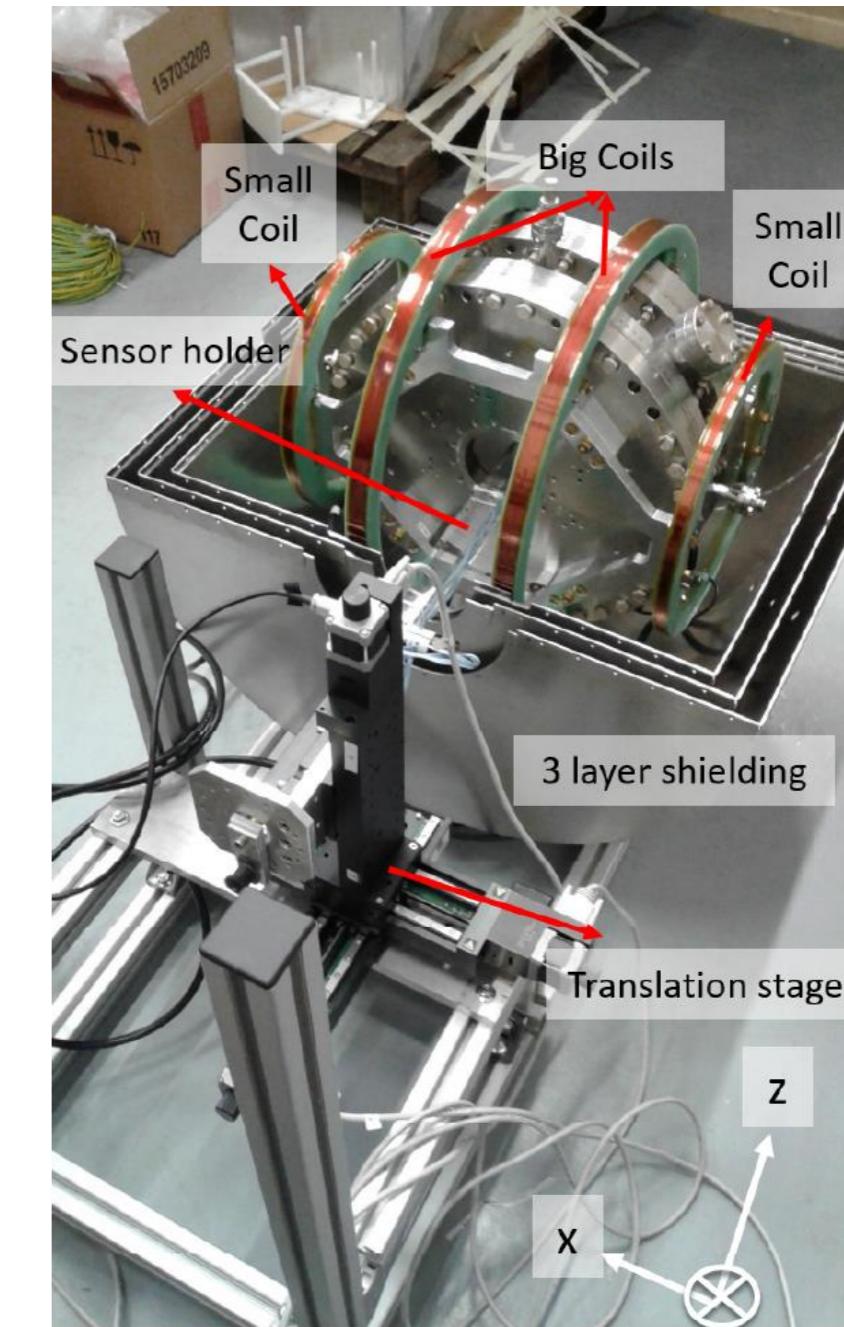
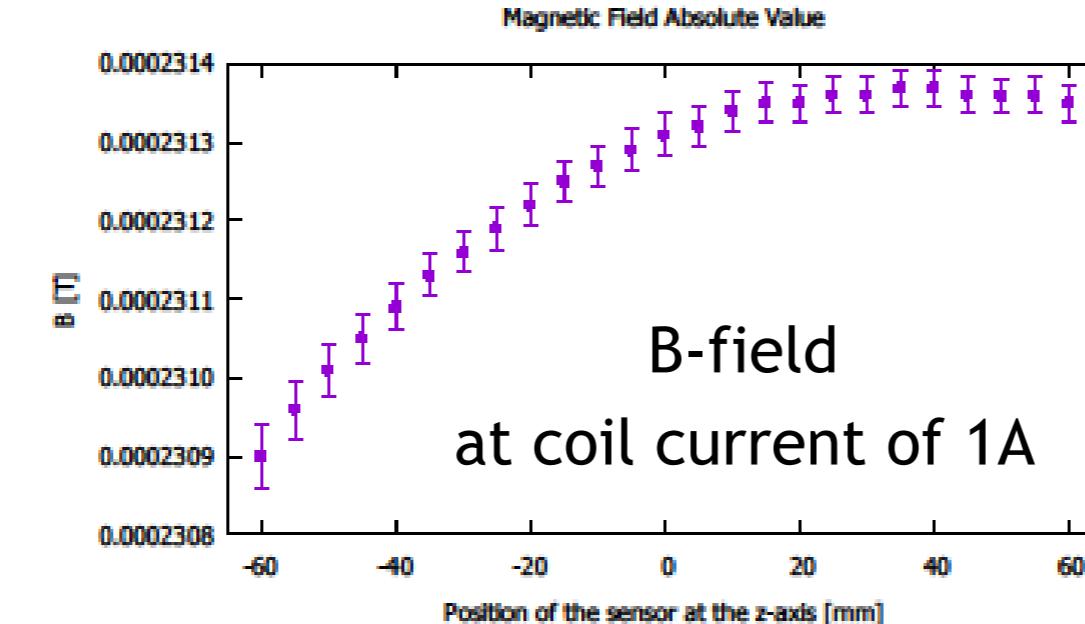
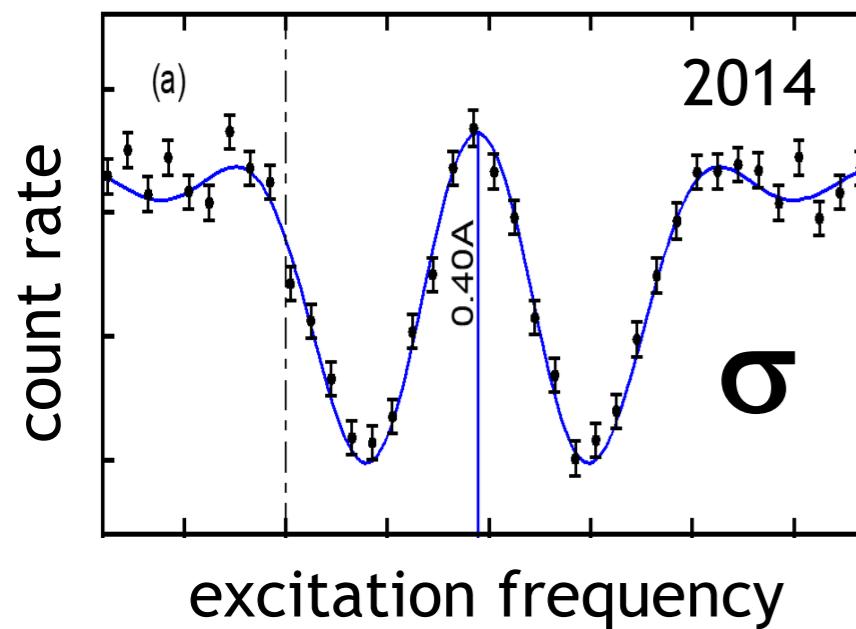
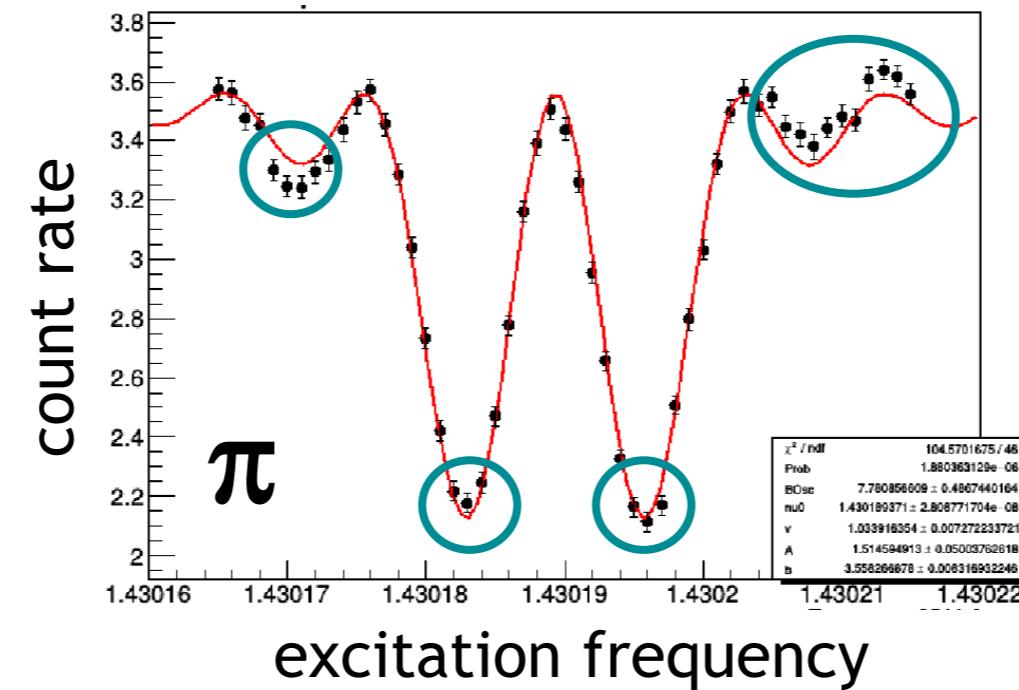
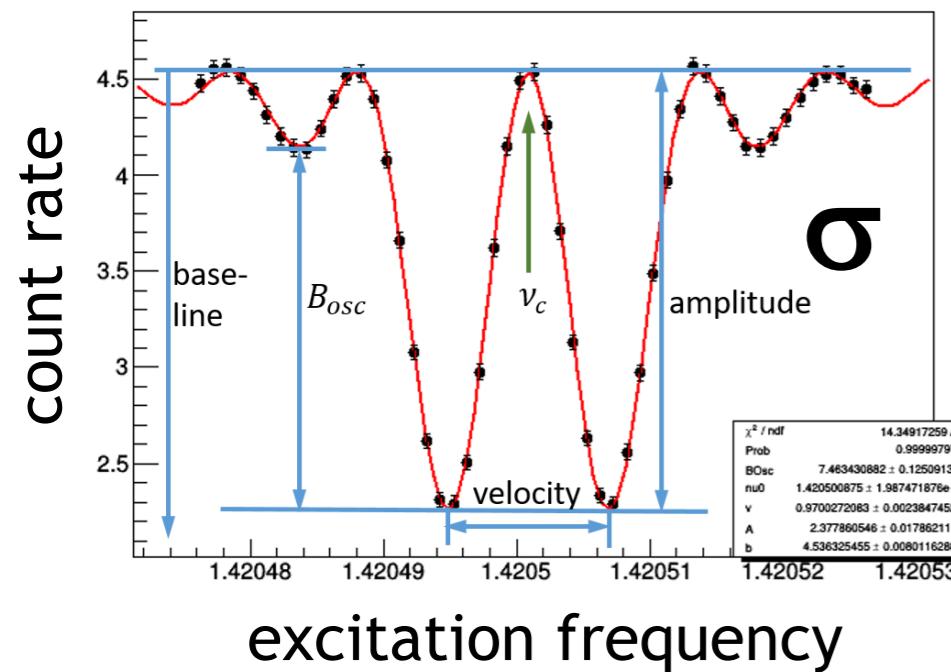


Lineshape & B-field uniformity



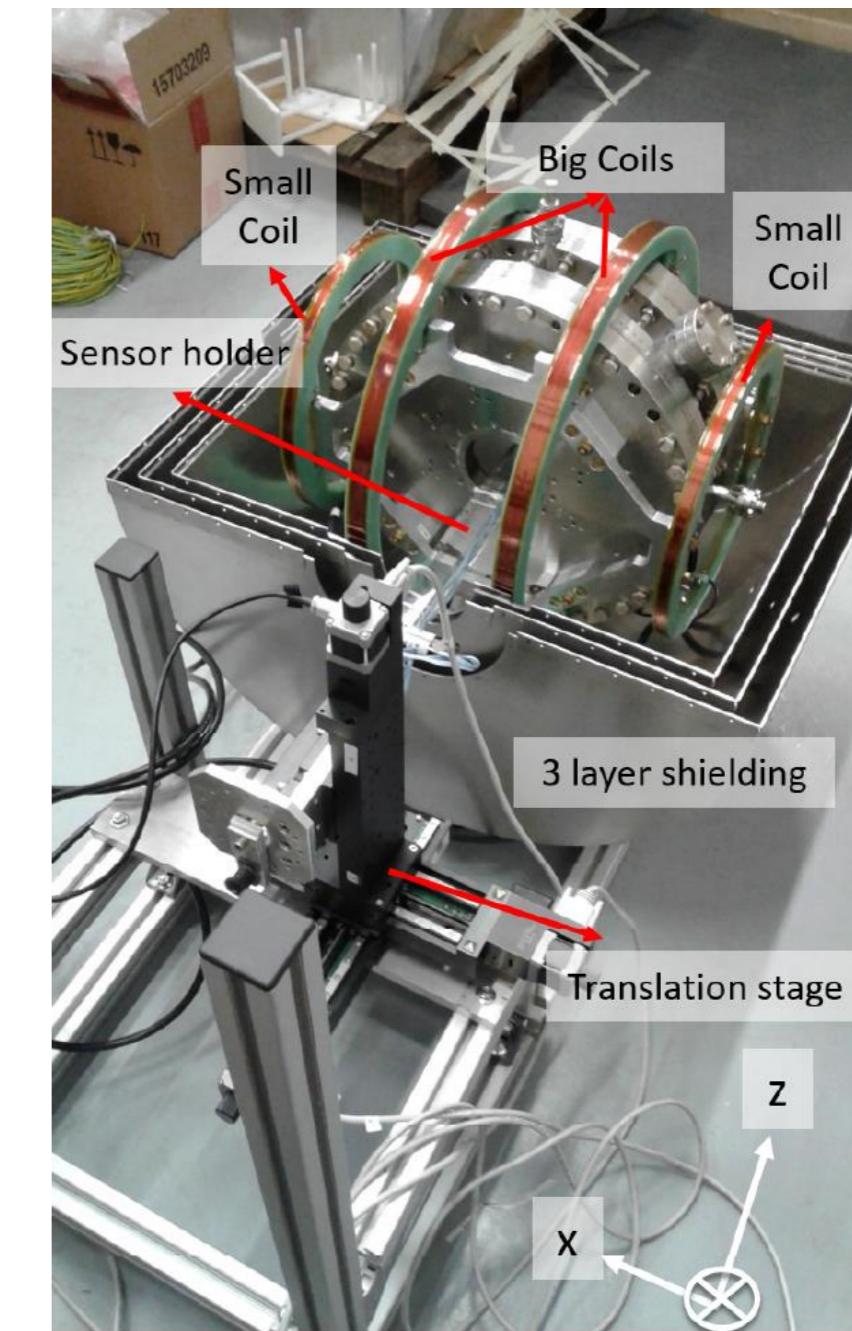
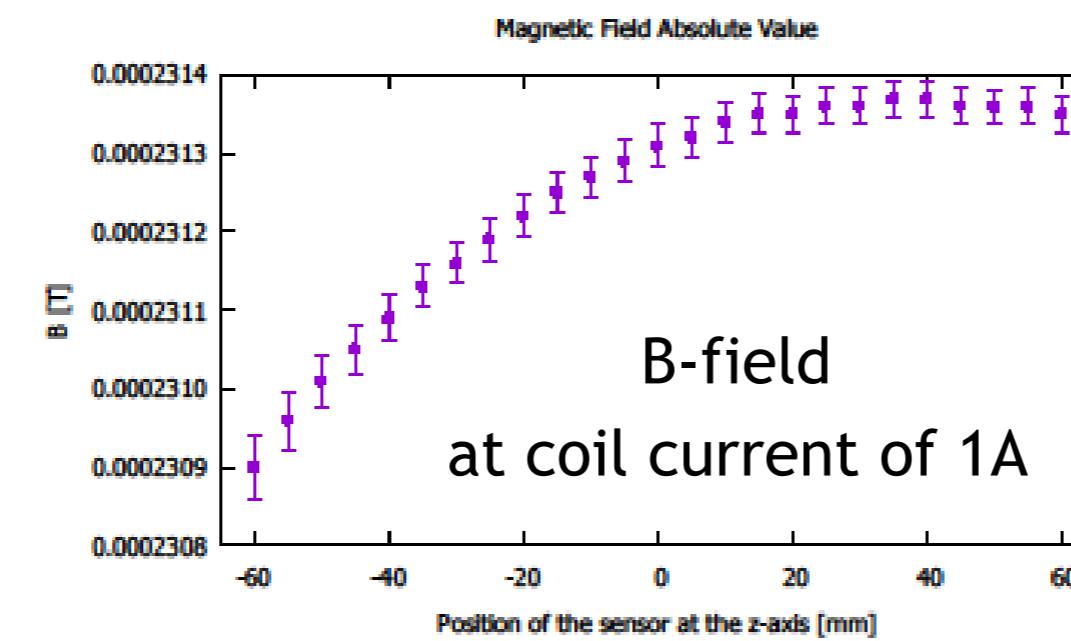
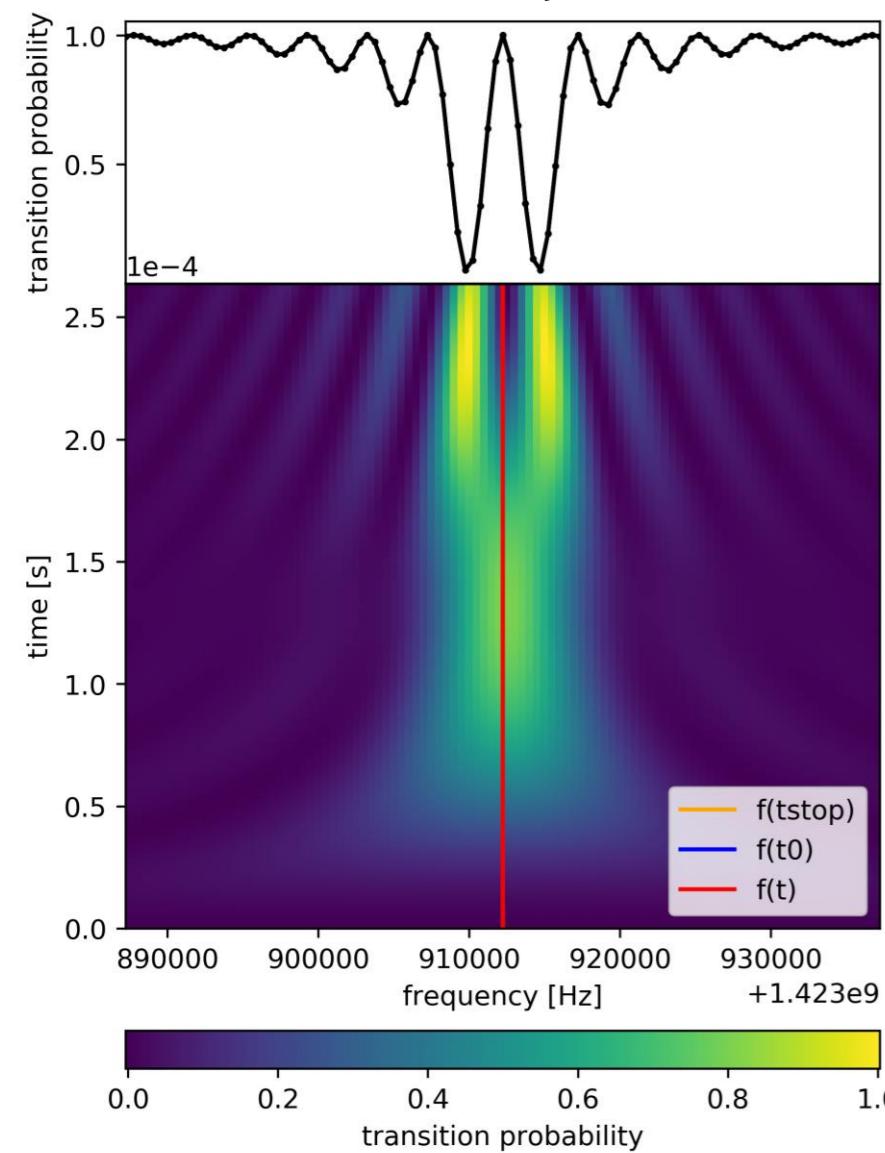
asymmetries for p transitions
at higher B-fields!!!

Lineshape & B-field uniformity



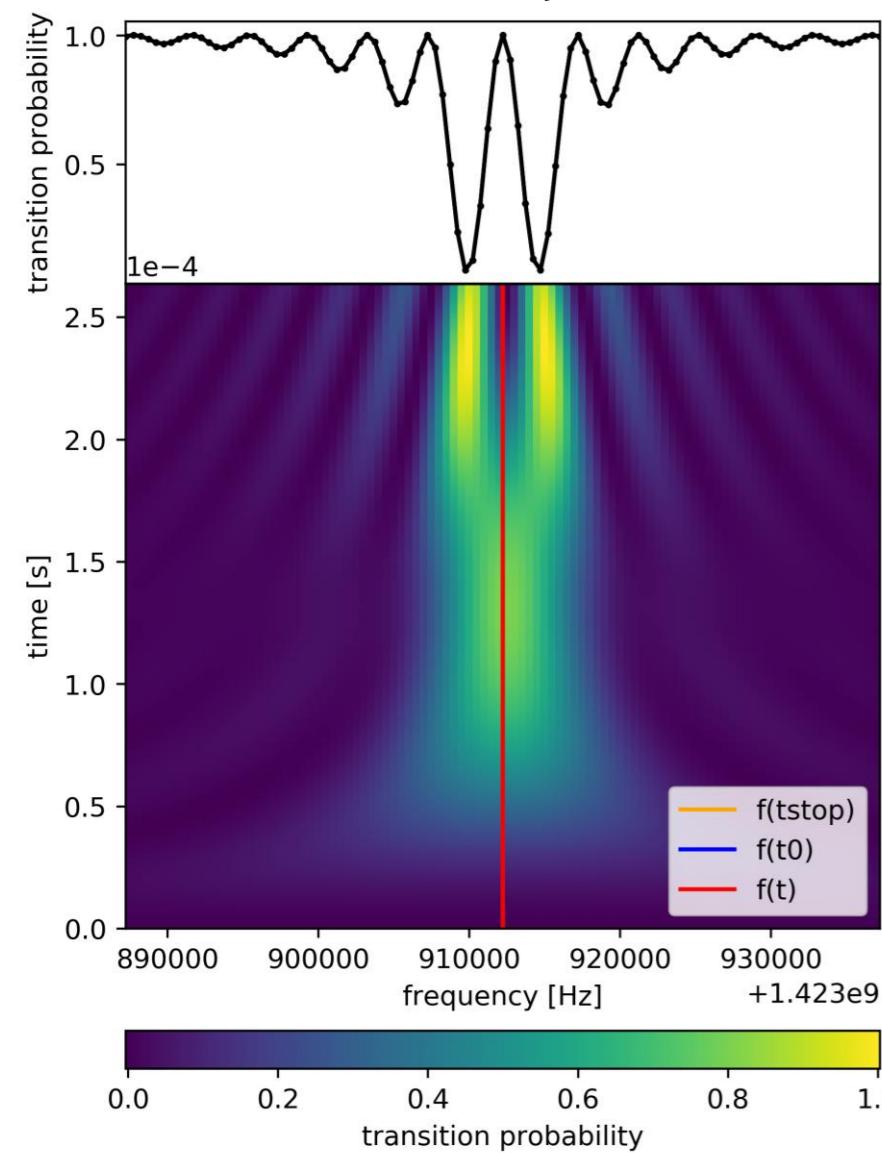
Lineshape & B-field uniformity

Numerical solution of
4-level system

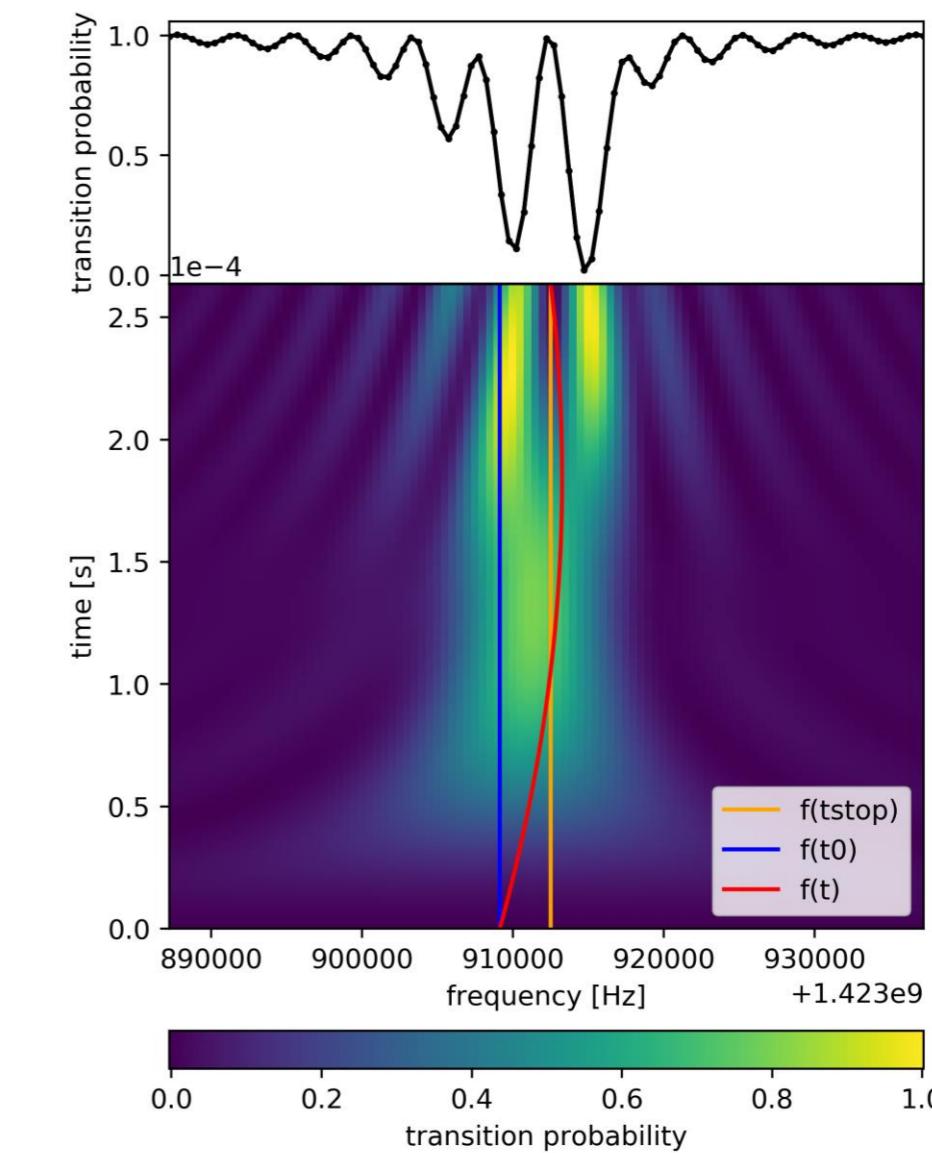
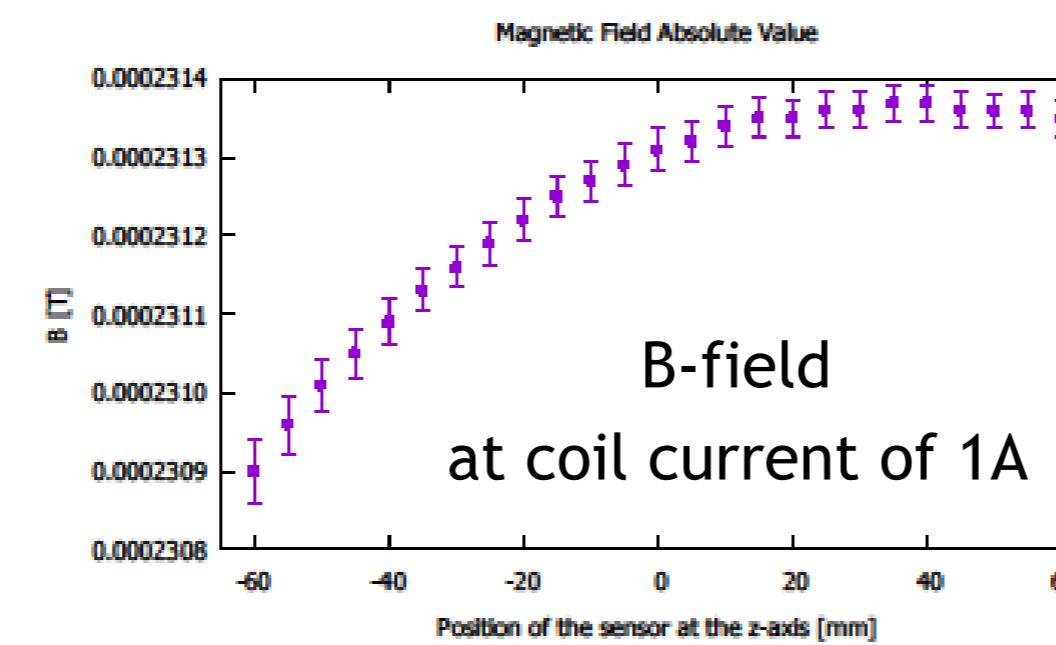


Lineshape & B-field uniformity

Numerical solution of
4-level system

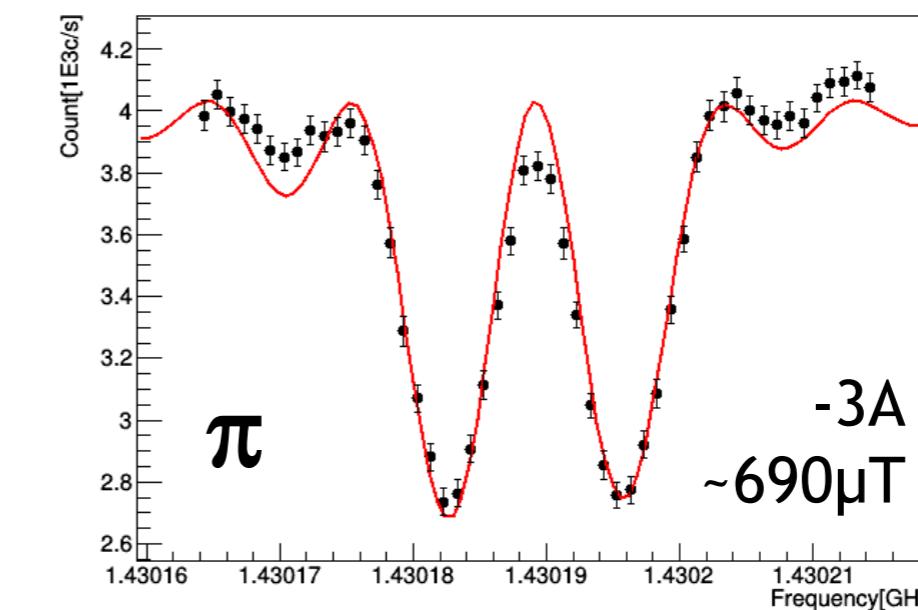
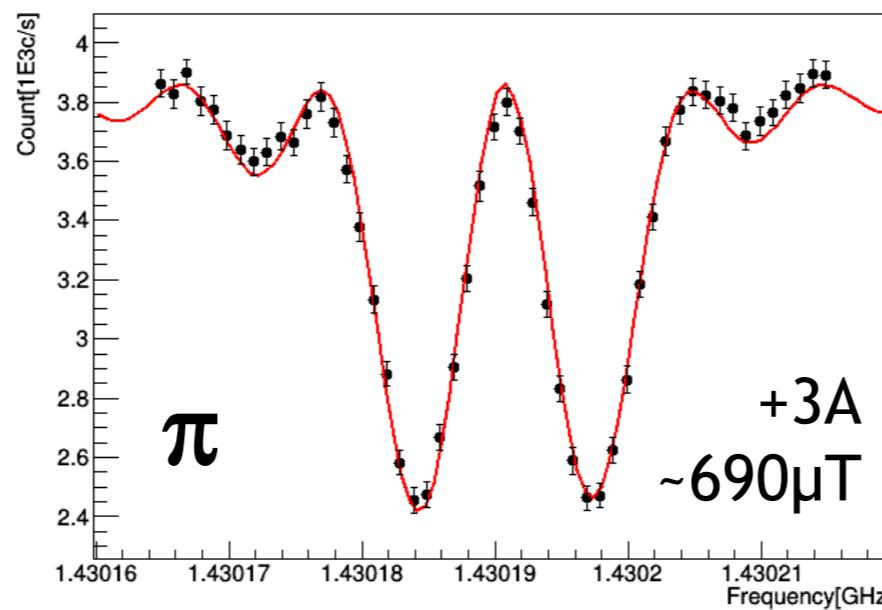


Systematic parabolic change
of B-field can explain asymmetries
(linear change could not)



Lineshape & B-field uniformity

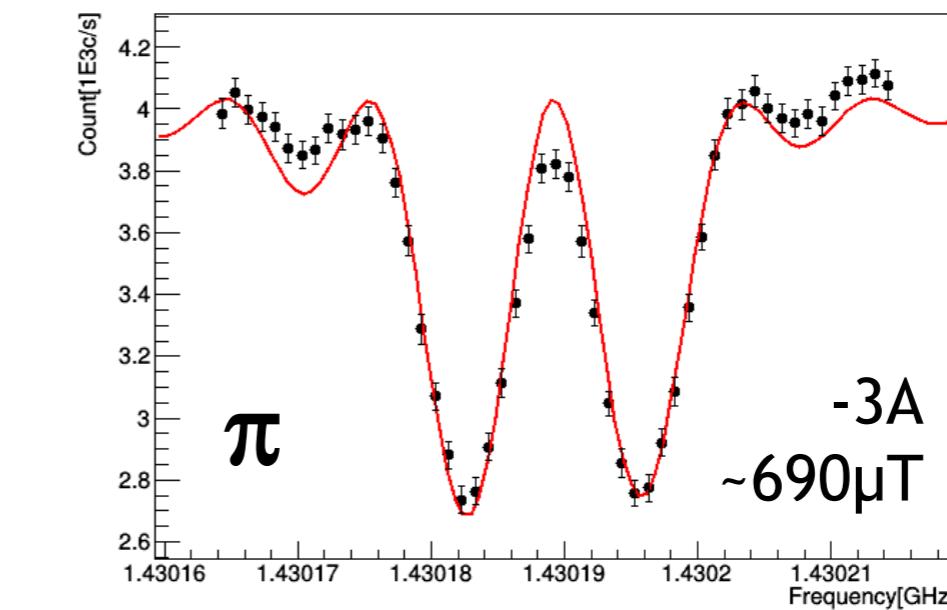
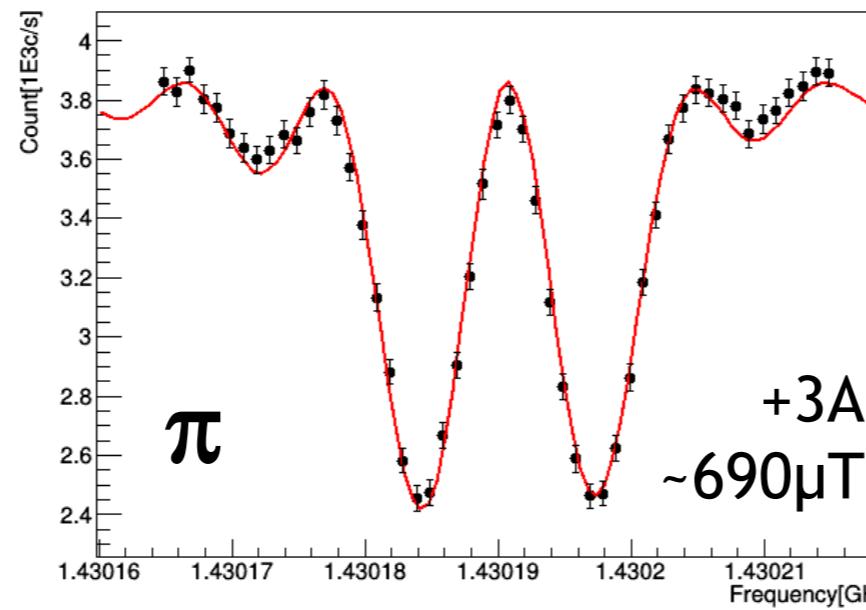
only small improvement
by asymmetry originating
from systematic B-field change
along beam axis



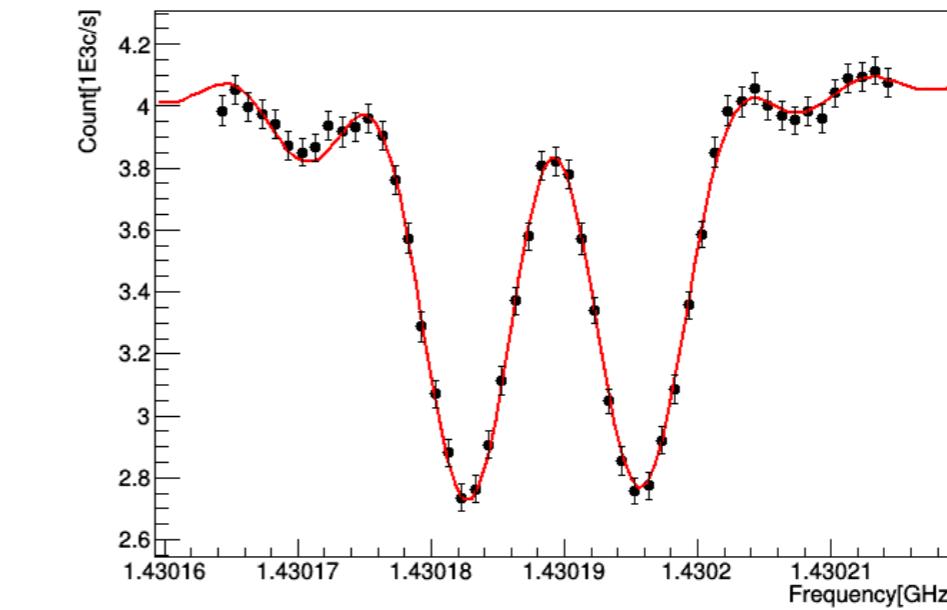
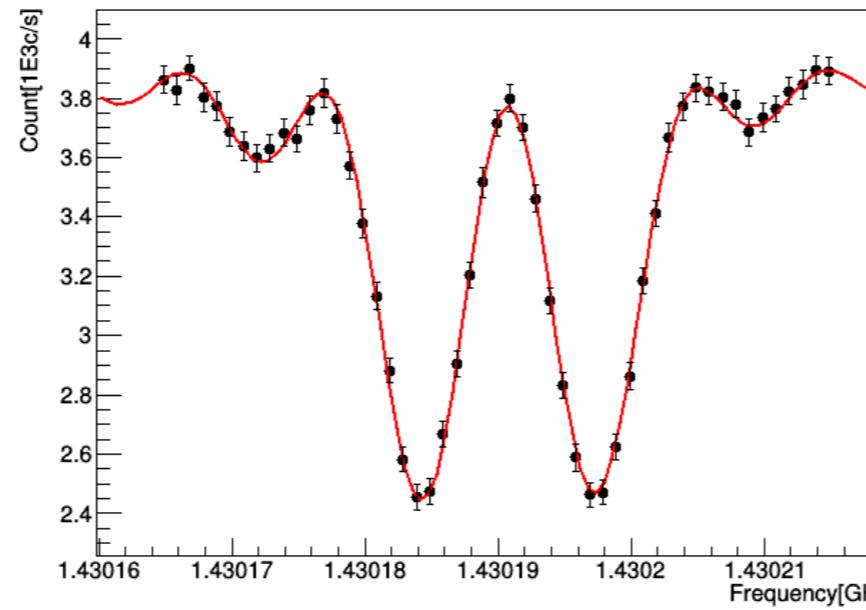
→ include “smear out”
due to random B-field changes
within plane perpendicular
to beam axis

Lineshape & B-field uniformity

only small improvement
by asymmetry originating
from systematic B-field change
along beam axis

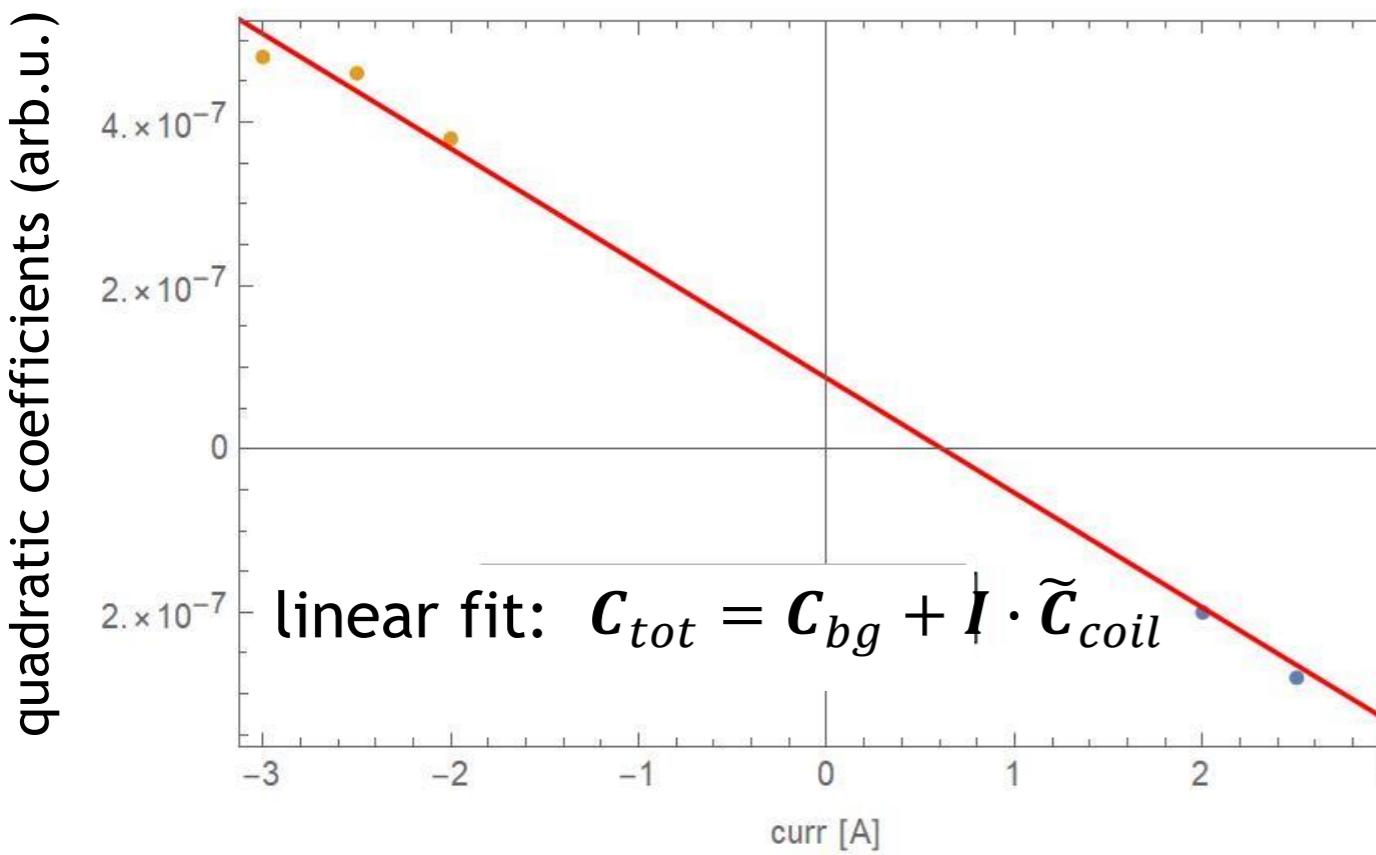


→ include “smear out”
due to random B-field changes
within plane perpendicular
to beam axis



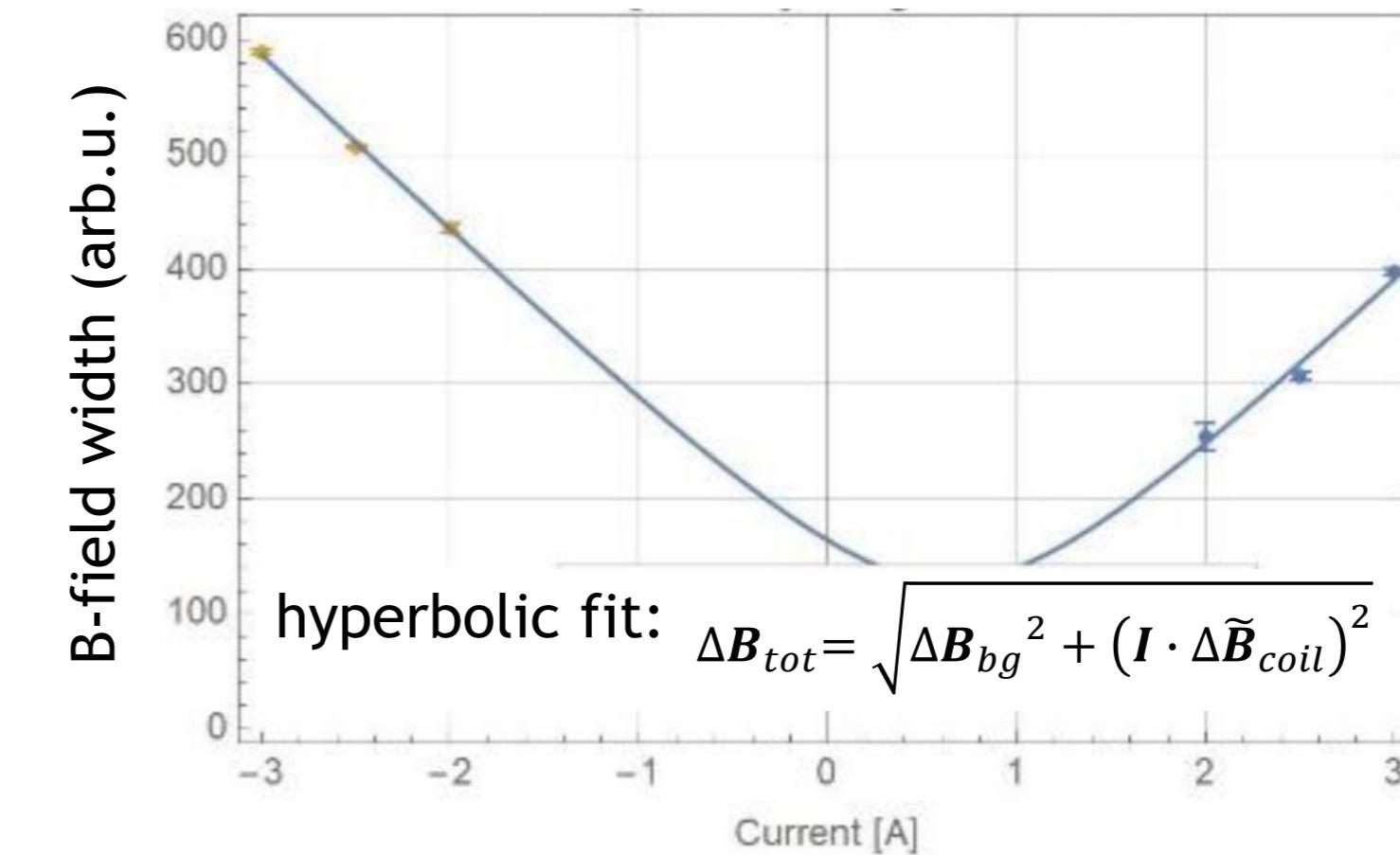
Common B-field

optimized quadratic coefficients
of parabola-shaped field change
→ B-field along beam directions

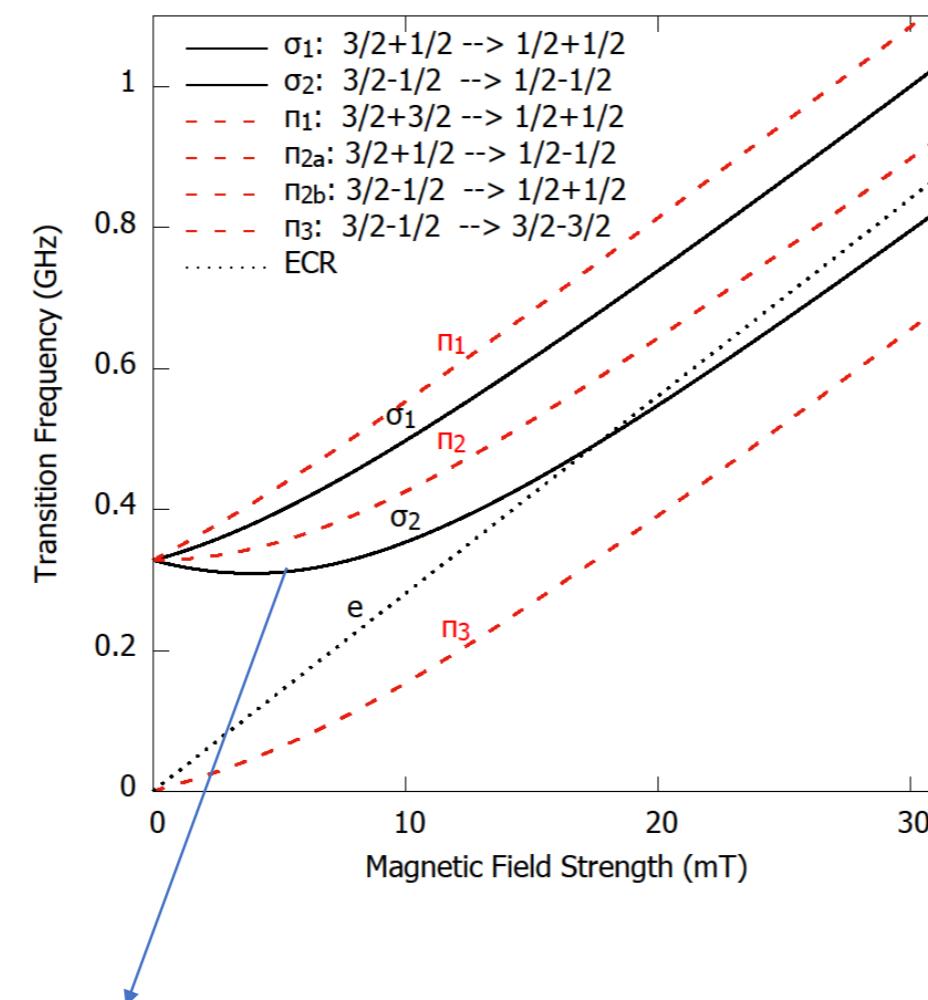
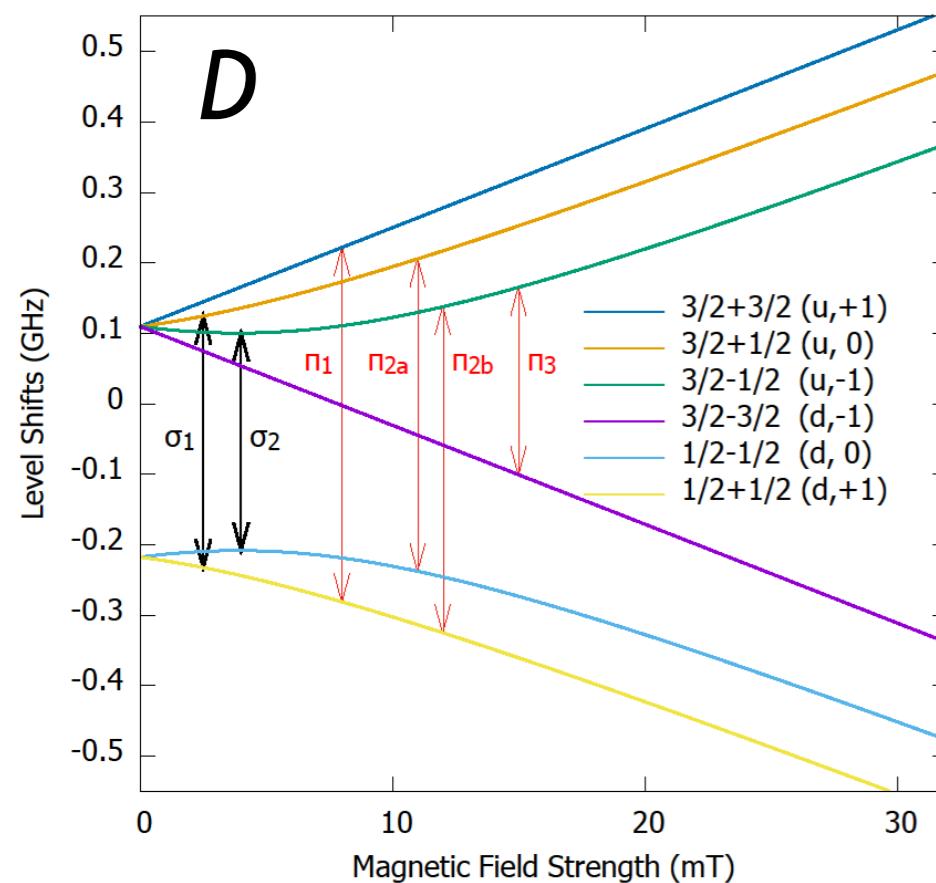


$$B_{tot} = B_{bg} + \underbrace{B_{coil}}_{I \cdot k_{coil}}$$

width of B-field distribution
within a plane perpendicular
to beam direction



Deuterium HFS



minima at 3.89 mT
at 308.7 MHz

Amit Nanda

$$\delta\epsilon(F, M_F) = \frac{1}{\sqrt{5\pi}} \frac{2F-1}{(8m_F^2 - 10)} \sum_{q=0}^2 \langle \mathbf{p}_{pd}^{2q} \rangle' \sum_{\mathcal{W}} \mathcal{V}_{\mathcal{W}(2q)20}^{NR} -$$

$$\frac{1}{3\sqrt{6\pi}} \frac{m_F}{2^{F-2}} \sum_{q=0}^2 \langle \mathbf{p}_{pd}^{2q} \rangle \times \sum_{\mathcal{W}} (\mathcal{T}_{\mathcal{W}(2q)10}^{NR(0B)} + \mathcal{T}_{\mathcal{W}(2q)10}^{NR(1B)})$$

$$- \frac{m_F}{3\sqrt{3\pi}} \sum_{q=0}^2 \frac{(\alpha m_r)^{2q}}{(2F-1)} (1 + 4\delta_q^2) \times (\mathcal{T}_{e(2q)10}^{NR(0B)} + \mathcal{T}_{e(2q)10}^{NR(1B)})$$

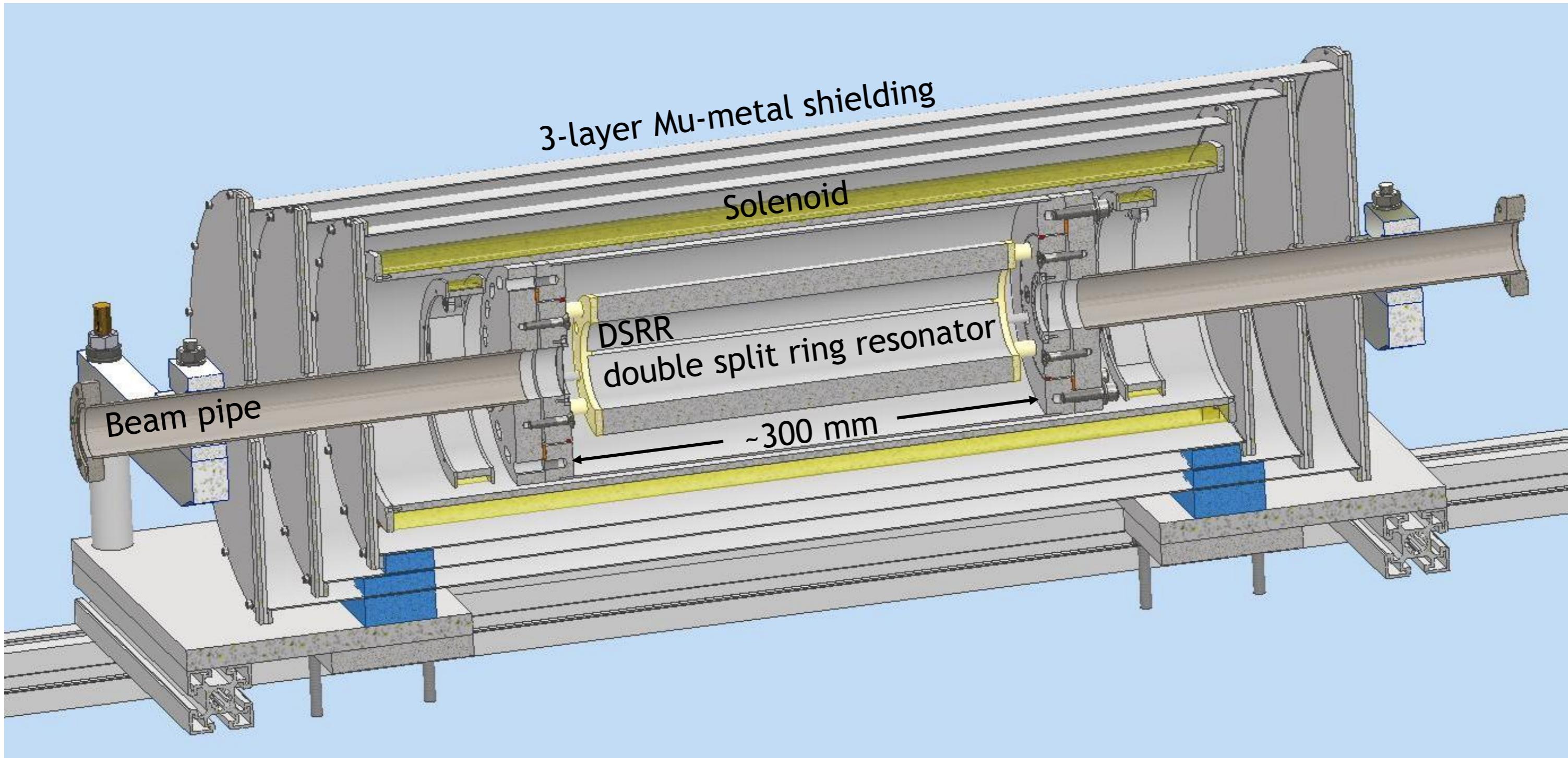
momentum of p in $H \sim$ a few keV/c

momentum of p in $D \sim$ 100 MeV/c

V A Kostelecky and A J Vargas
PRD 92 056002 (2015).

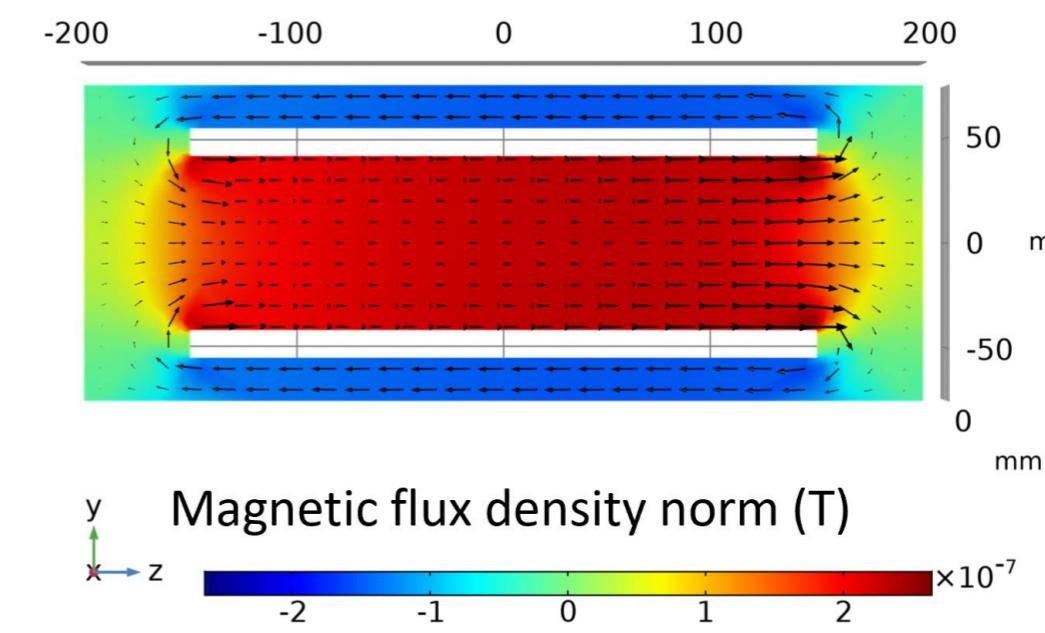
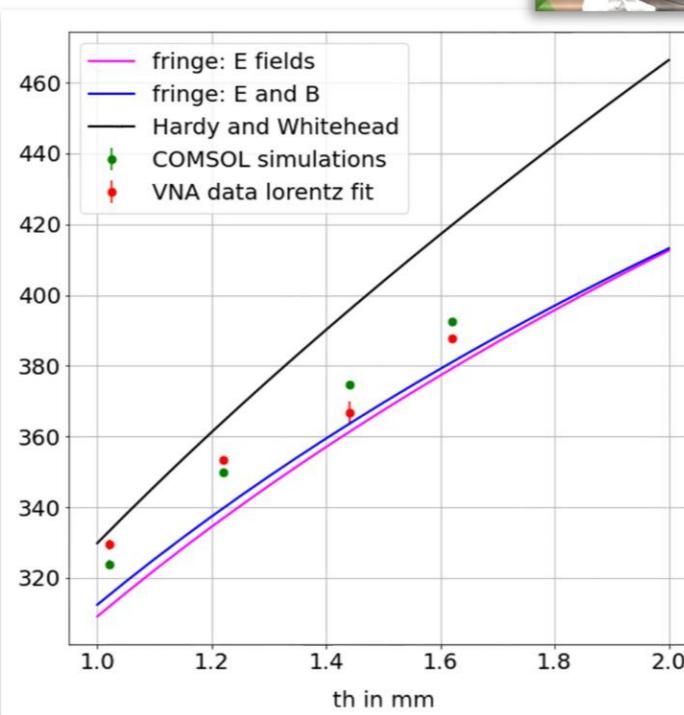
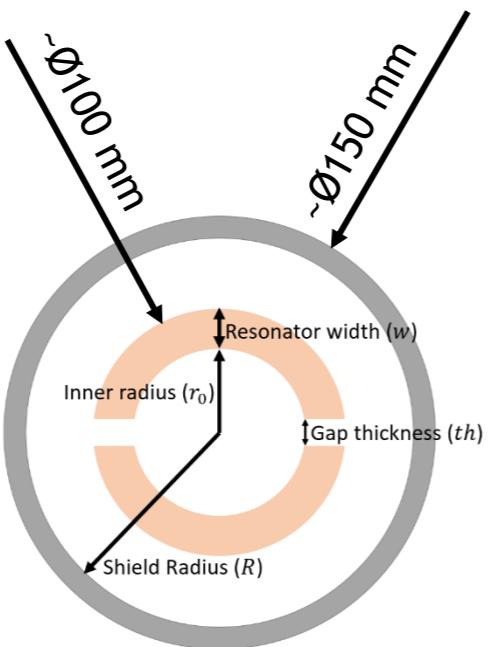
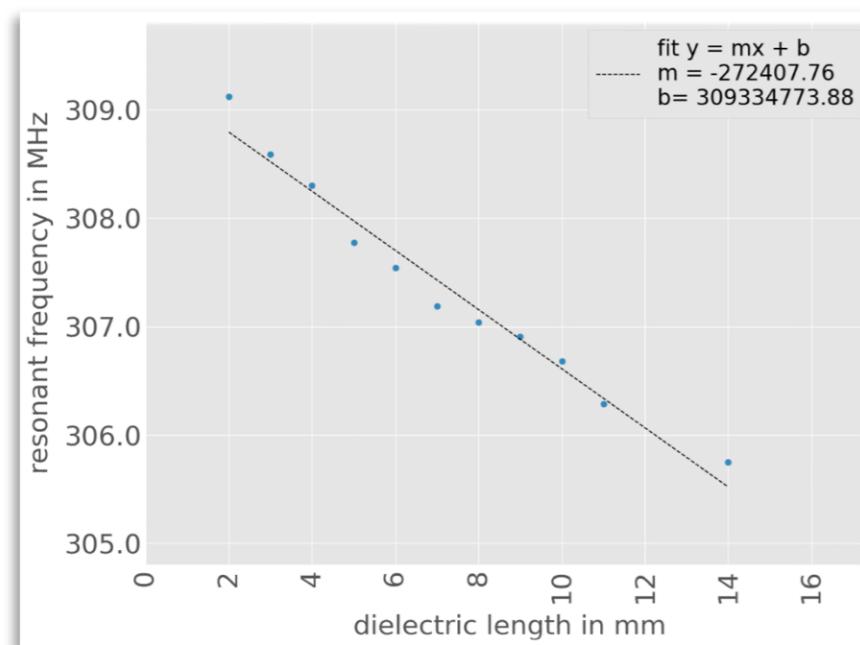
$\Delta F \neq 0$. Moreover, the dependence on the expectation values $\langle \mathbf{p}_{pd}^{2q} \rangle$ acts to enhance the sensitivity to the coefficients for Lorentz and *CPT* violation by factors of a billionfold for coefficients with $k = 2$ and by 10¹⁸-fold for

Interaction region for deuterium

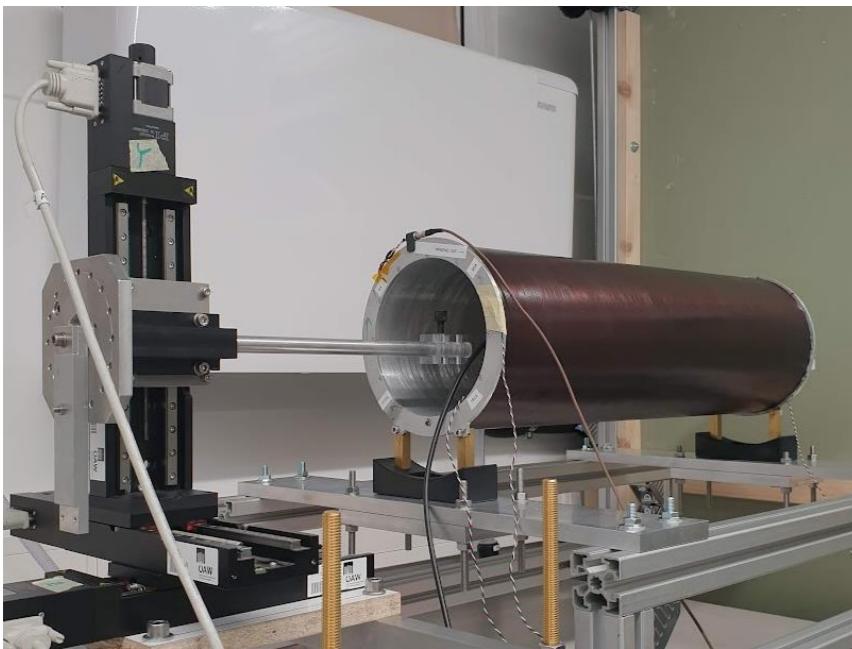


Resonator

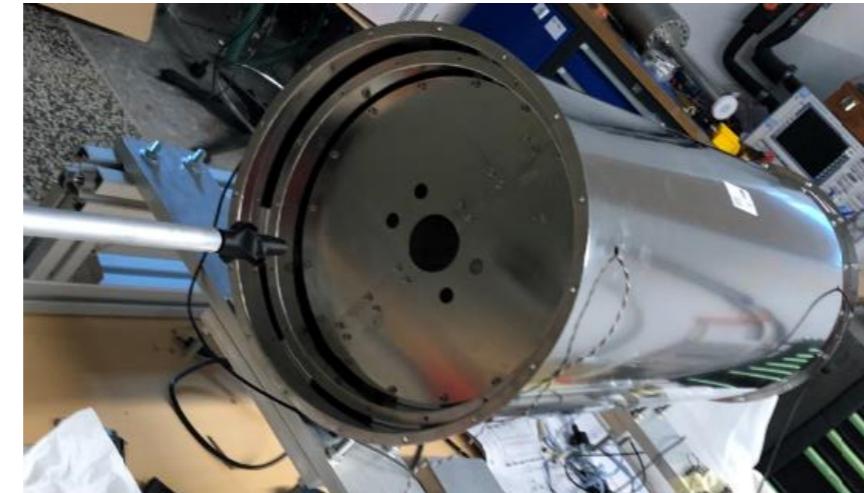
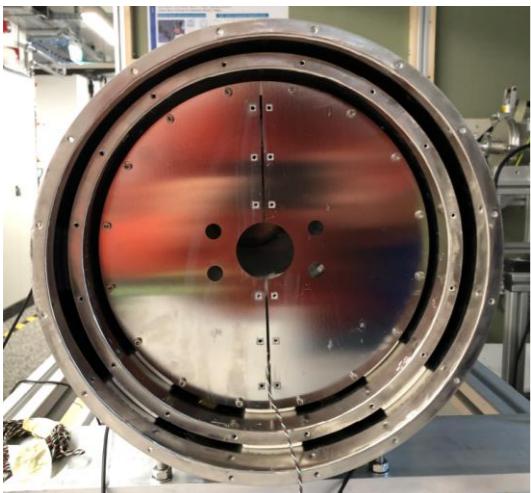
- Double split ring
 - Large tuning by gap size change
 - E-field excitations for calibrations
- Capacitive fine tuning in external boxes



Solenoid and Shielding



- 63 cm long coil, 6 layers ~2068 turns, 8.8Ω
- 2 correction coils, 2 layers, 0.17Ω
- total weight ~25 kg

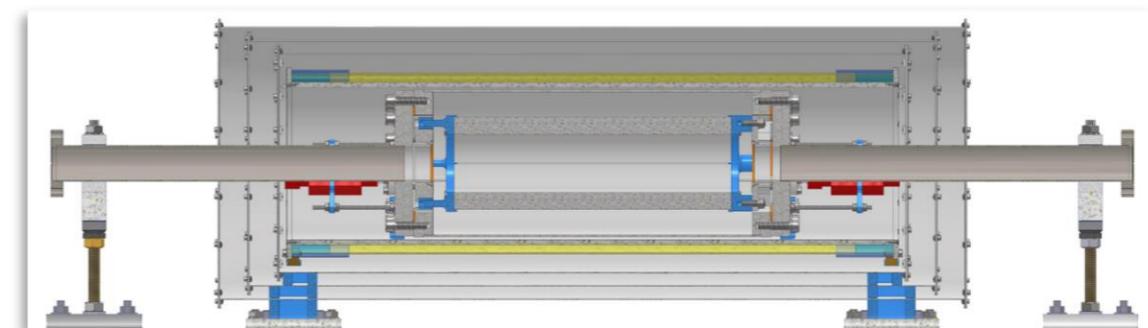
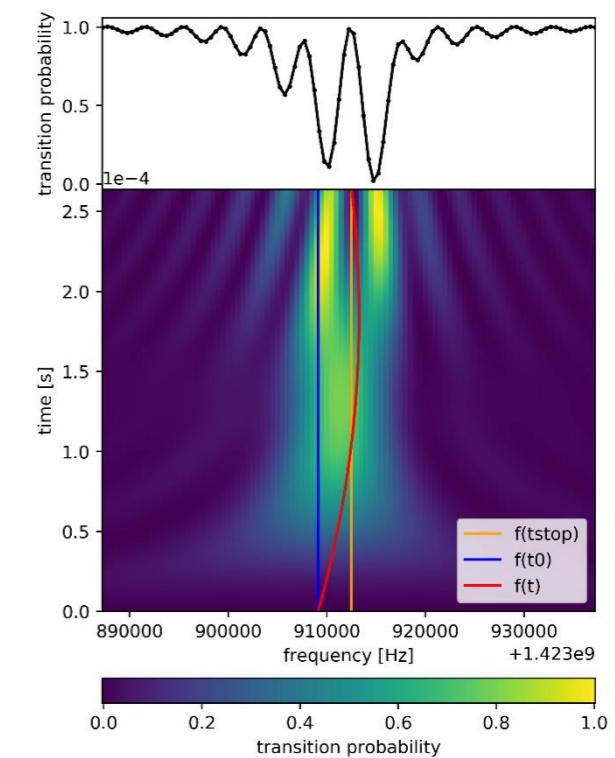


- 3 layer MuMetall shielding
- cylinders
- large axial air gaps



Summary

- Hyperfine spectrometer for \bar{H} thoroughly characterized
- Line-shapes well understood
effects from higher B-fields combined with sensitive π transition
- Analysis of H measurement almost completed
will yield new constraint on a SME coefficient $\mathcal{K}_{W_{k10}}^{Sun}$
- First measurements with deuterium coming soon
characterization of new device currently ongoing



Acknowledgements

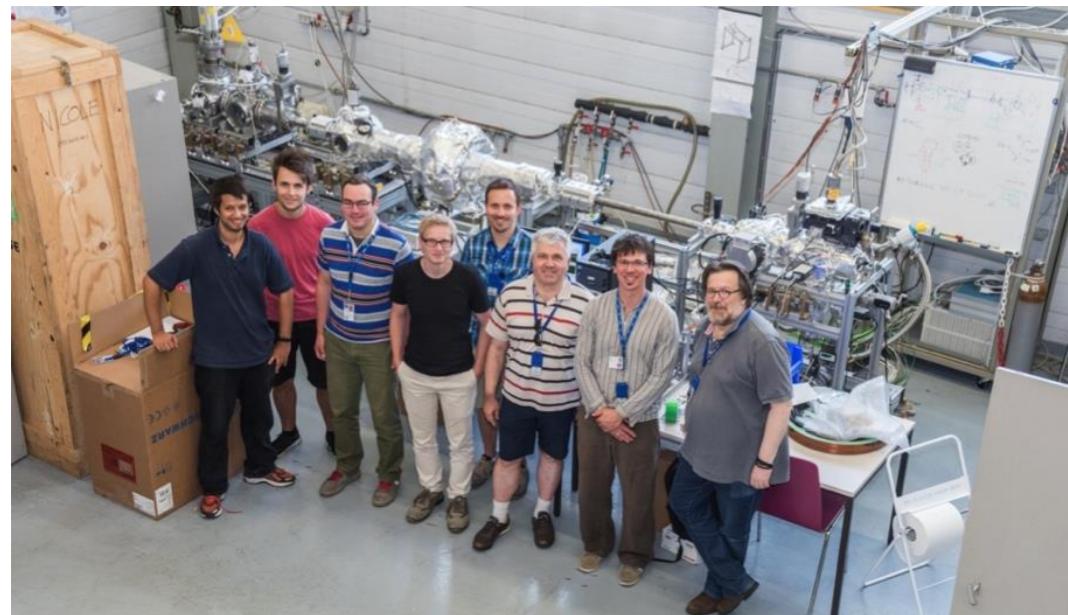
Sergio Arguedas
Tobias Becker
Fritz Caspers
Dmitry Chechenev
Martin Diermaier
Markus Fleck
Luke Von Freeden
Manuel Friedrich

Johannes Hansen
Marlene Hudler
Markus Hummer
Myron Huzan
Christian Jepsen
Gerhard Kaiser
Mikko Karppinen
Carina Killian

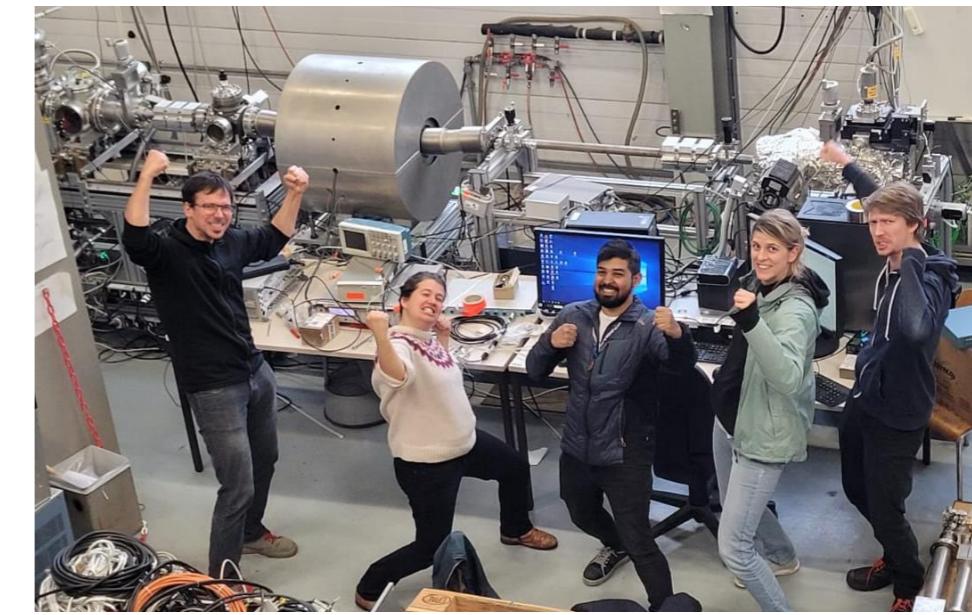
Bernadette Kolbinger
Sebastian Lahs
Andreas Lanz
Dennis Loggen
Carlos Lopez
Roberto Lopez
Anni Liu
Chloe Malbrunot

Oswald Massiczek
Attilio Milanese
Amit Nanda
Marco Nikolic
Lilian Novak
Lukasz Paszkowski
Doris Pristauz
Mark Pruckner

Simon Rheinfrank
Martin Roelfs
Leopold Stowasser
Duc Phan Thanh
Manfred Wendt
Markus Wiesinger
Eberhard Widmann
Johannes Zmeskal

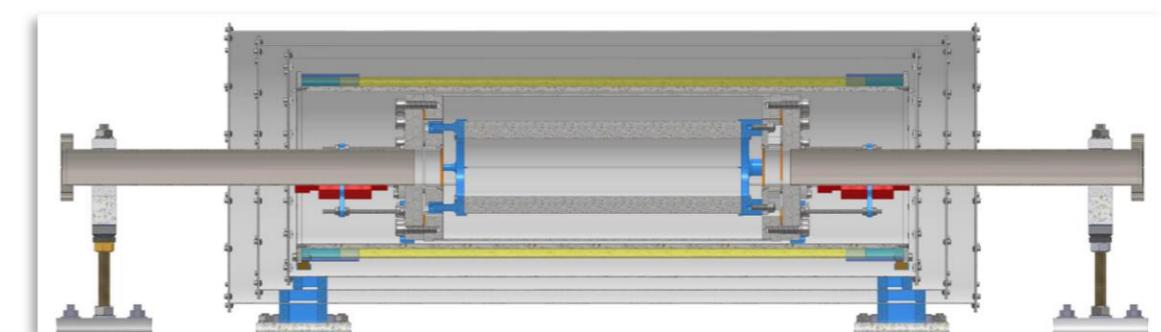
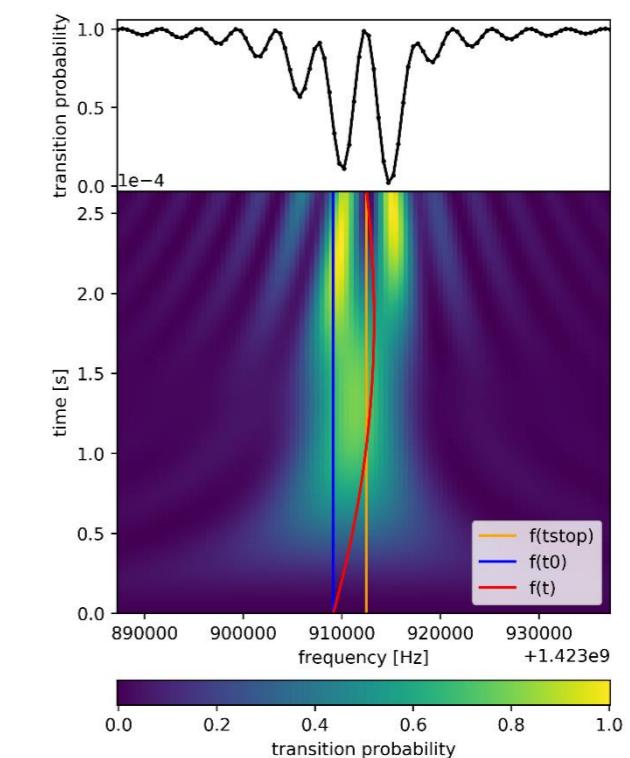


291242-HBAR-HFS

**FWF**
Der Wissenschaftsfonds.ÖAW Investment
Initiative 2020Marie Skłodowska-Curie
grant agreement No
721559 $\int dk \Pi$ 

Summary

- Hyperfine spectrometer for \bar{H} thoroughly characterized
- Line-shapes well understood
effects from higher B-fields combined with sensitive π transition
- Analysis of H measurement almost completed
will yield new constraint on a SME coefficient $\mathcal{K}_{W_{k10}}^{Sun}$
- First measurements with deuterium coming soon
characterization of new device currently ongoing



Thank you for listening

