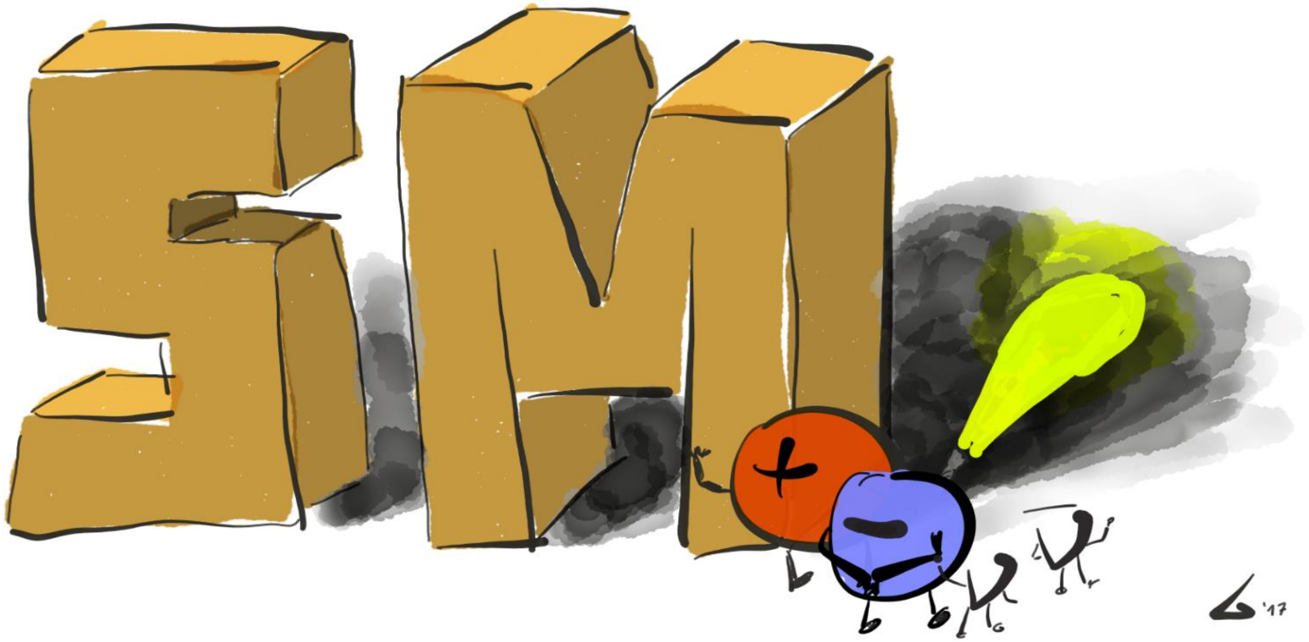


Michael W. Heiss

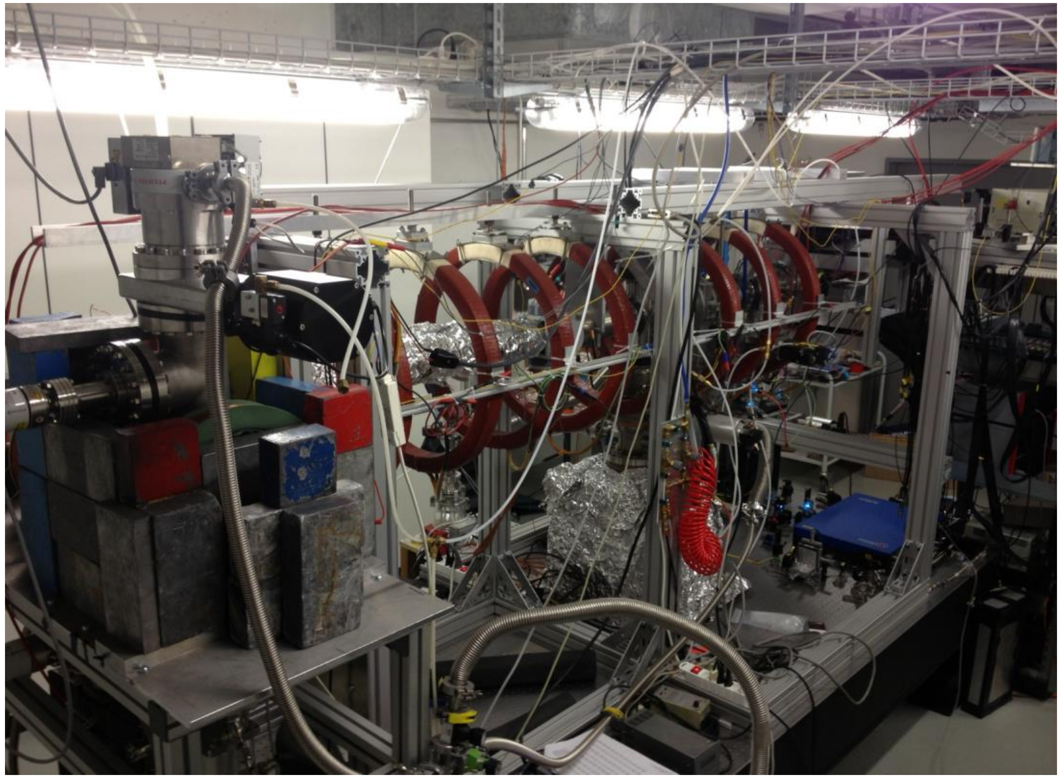
ETH Zürich – Institute for Particle Physics and Astrophysics – group of Prof. Rubbia

Positronium precision spectroscopy: Measuring the 1S-2S and excited state hyperfine transitions

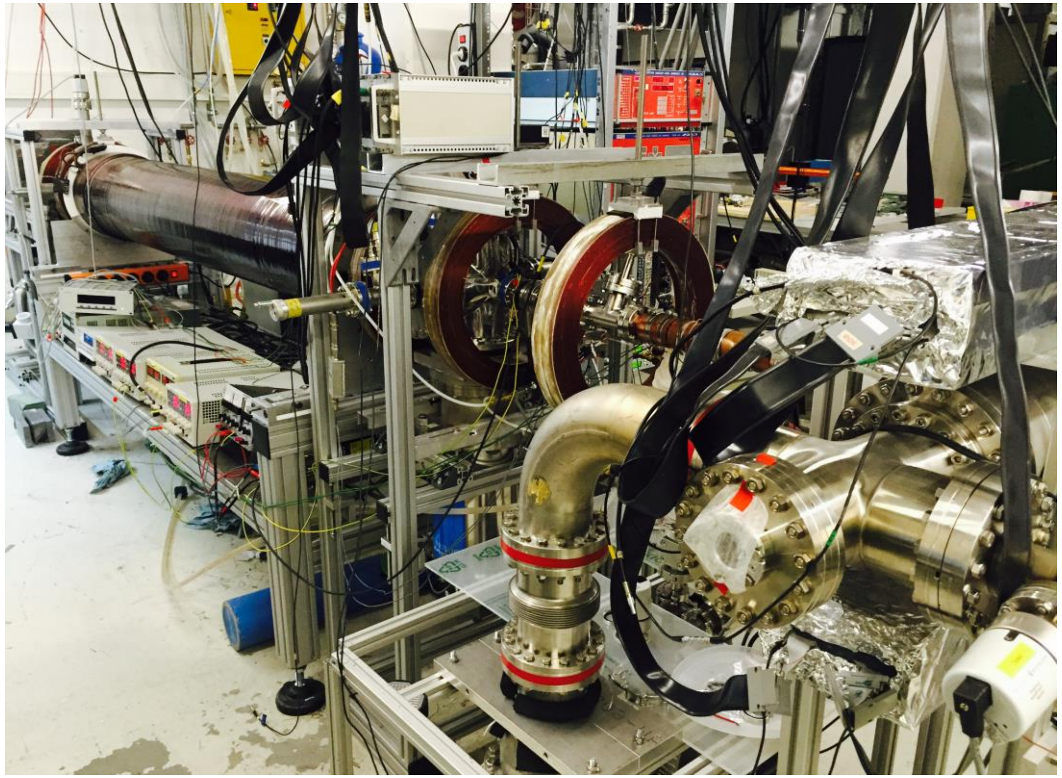
this work is supported by the SNF grant 166286 - PI: <u>Paolo Crivelli</u>

ETH slow positron beamlines

- Continuous beam (since 2012)



- Pulsed beam (since 2015)

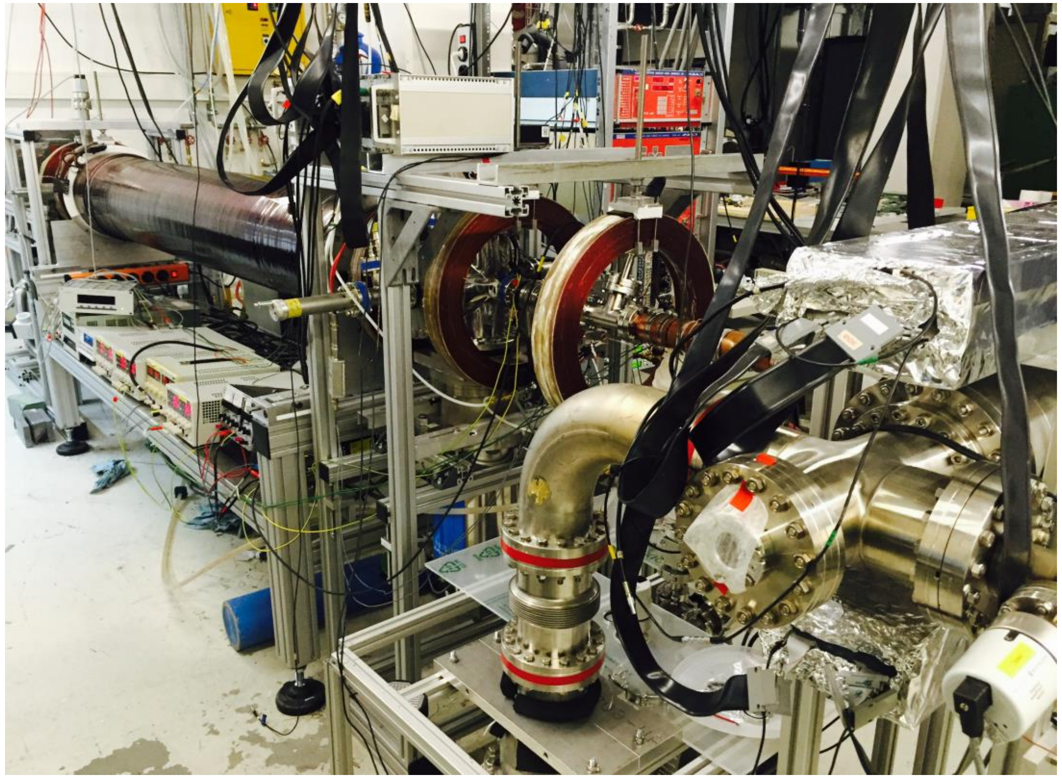


ETH slow positron beamlines

- Continuous beam (since 2012)

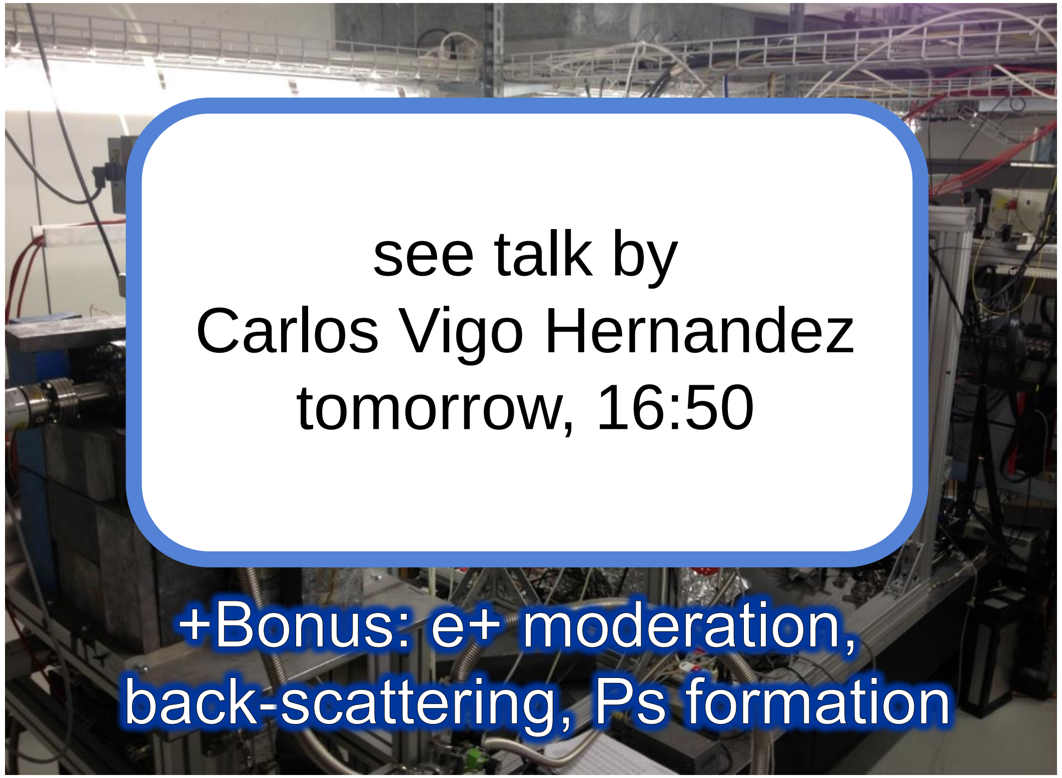
see talk by
Carlos Vigo Hernandez
tomorrow, 16:50

- Pulsed beam (since 2015)

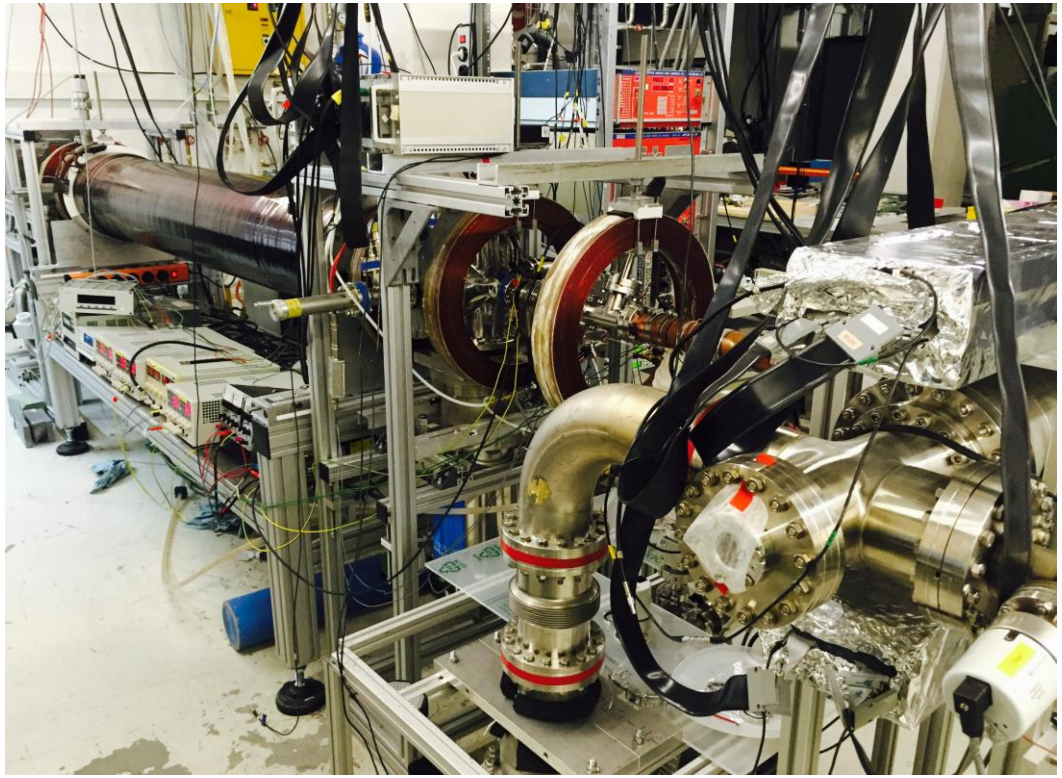


ETH slow positron beamlines

- Continuous beam (since 2012)



- Pulsed beam (since 2015)



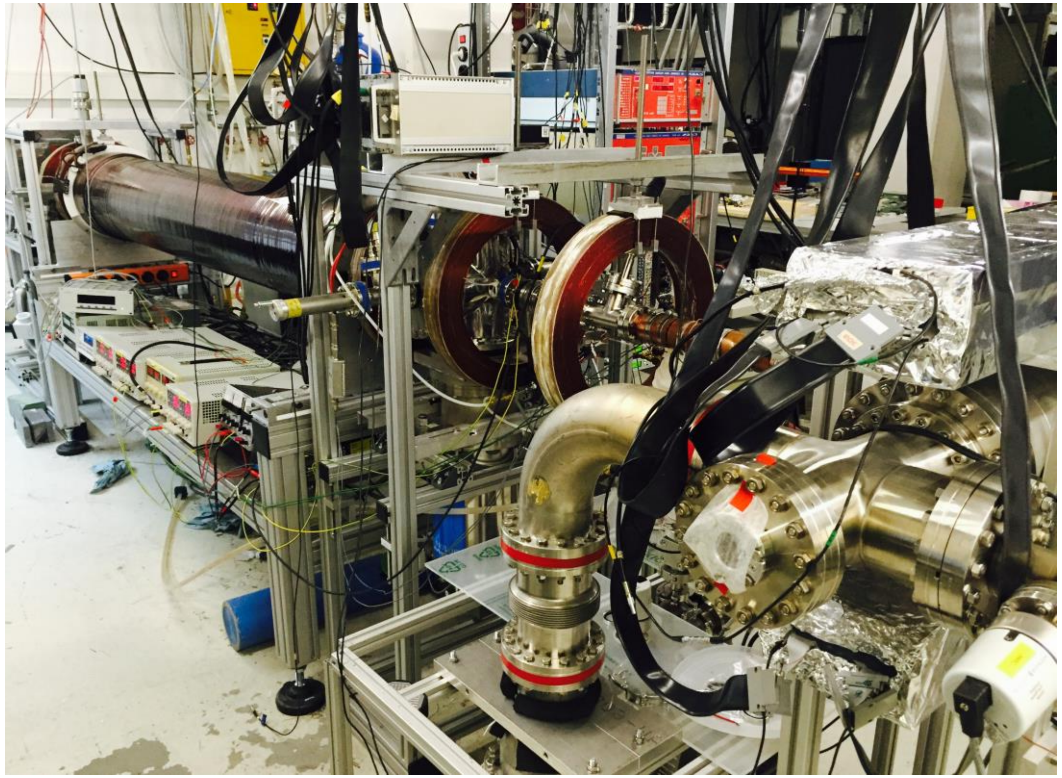
ETH slow positron beamlines

- Continuous beam (since 2012)

see talk by
Carlos Vigo Hernandez
tomorrow, 16:50

+Bonus: e+ moderation,
back-scattering, Ps formation

- Pulsed beam (since 2015)

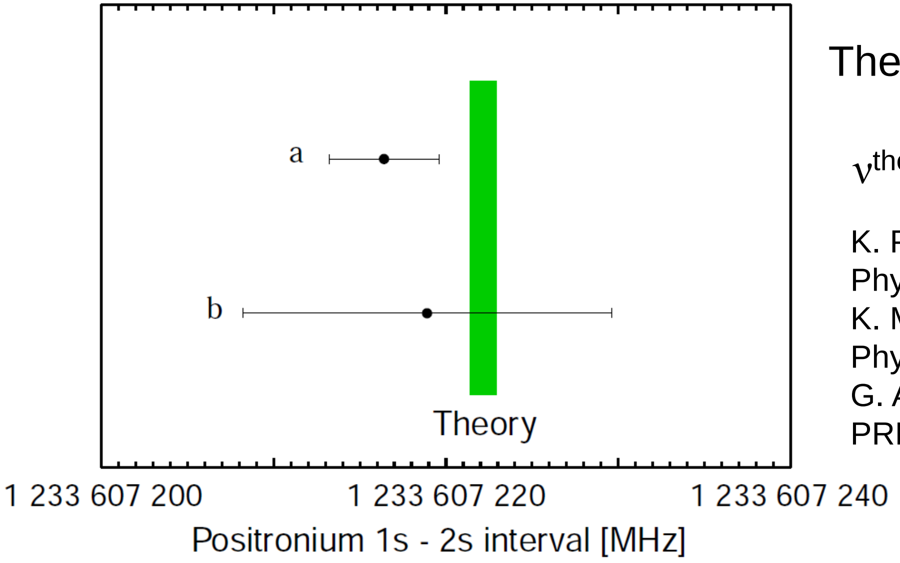


Motivation – Part 1 1S-2S HFS

- Ps is purely leptonic system
- (almost) free from
  - QCD effects
  - weak force effects
- Precision test bench for
  - bound state QED

Motivation – Part 1 **1S-2S** HFS

- Ps is purely leptonic system
- (almost) free from
  - QCD effects
  - weak force effects
- Precision test bench for
  - bound state QED
- 1S-2S transition
  - 0.5 ppb precision
  - check bound state QED up to order $\alpha^7 m$



Theory:

ν^{theory} = 1233607222.2(6) MHz

K. Pachucki and S.G. Karshenboim, Phys. Rev. A60, 2792 (1999).
K. Melnikov and A. Yelkhovsky, Phys. Lett. B458, 143 (1999).
G. Adkins, Parsons and Fell, PRL 115 233401 (2015)

Experiments: ν^{a} = 1233607216.4(3.2) MHz

M. S. Fee et al., Phys. Rev. Lett. 70, 1397 (1993)

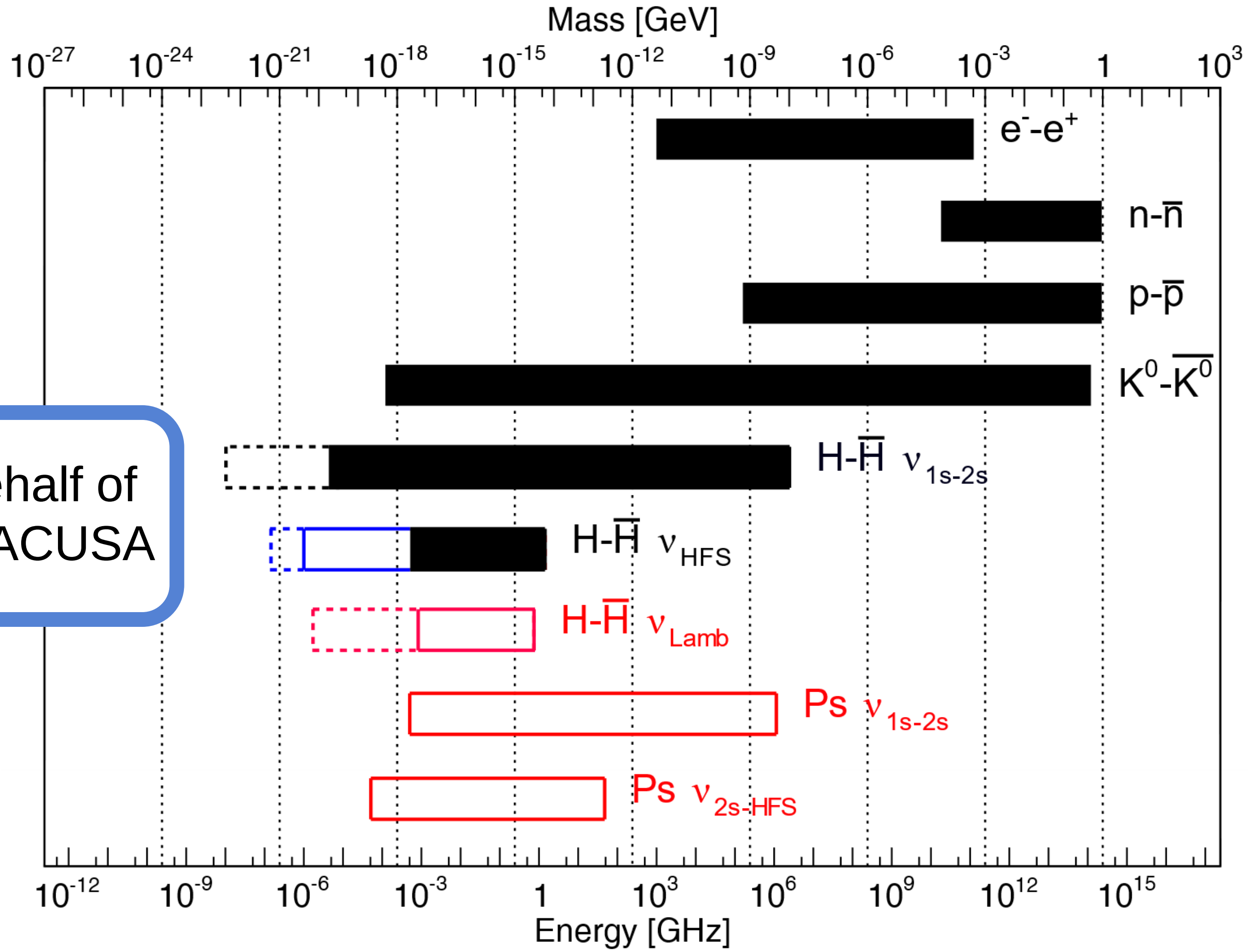
ν^{b} = 1233607218.9(10.7) MHz

S. Chu, A. P. Mills, Jr. and J. Hall, Phys. Rev. Lett. 52, 1689 (1984)

see next talk by Gregory Adkins

- S. G. Karshenboim, Phys. Rep. 422, 1 (2005)

Additional Motivation: CPT violation



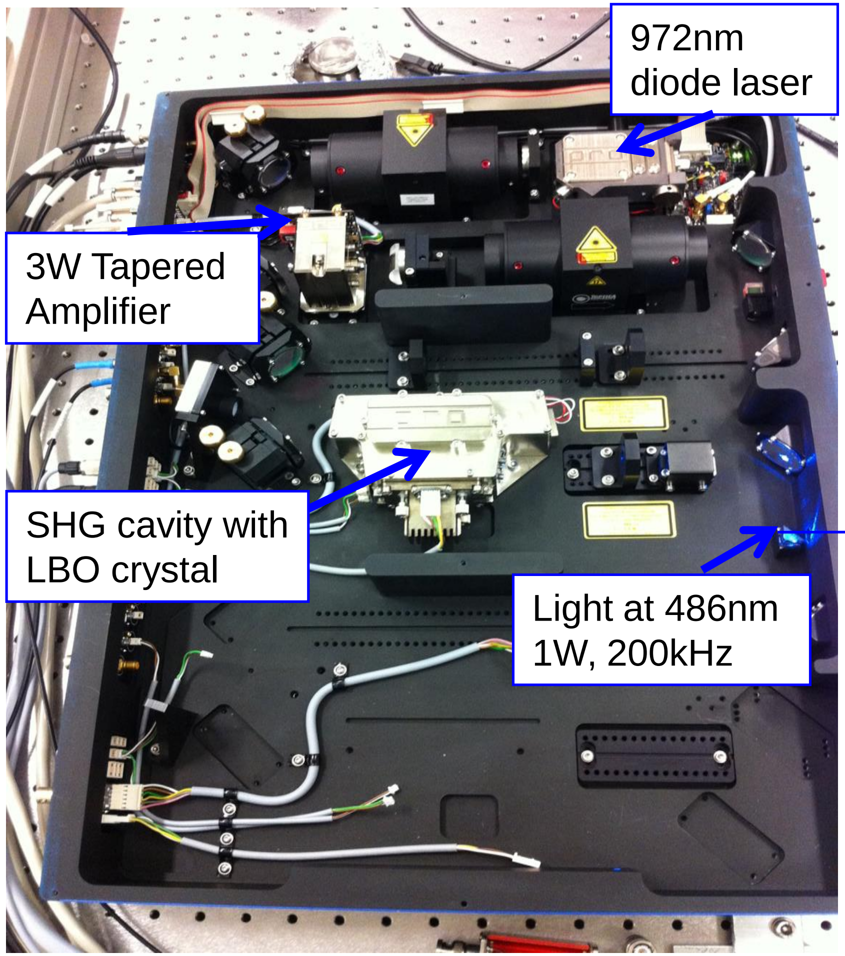
see talks on behalf of ALPHA and ASACUSA

- Adapted from: E. Widmann et al., Hyperfine Interact. 215, 1 (2013).

Ps 1S-2S: laser system

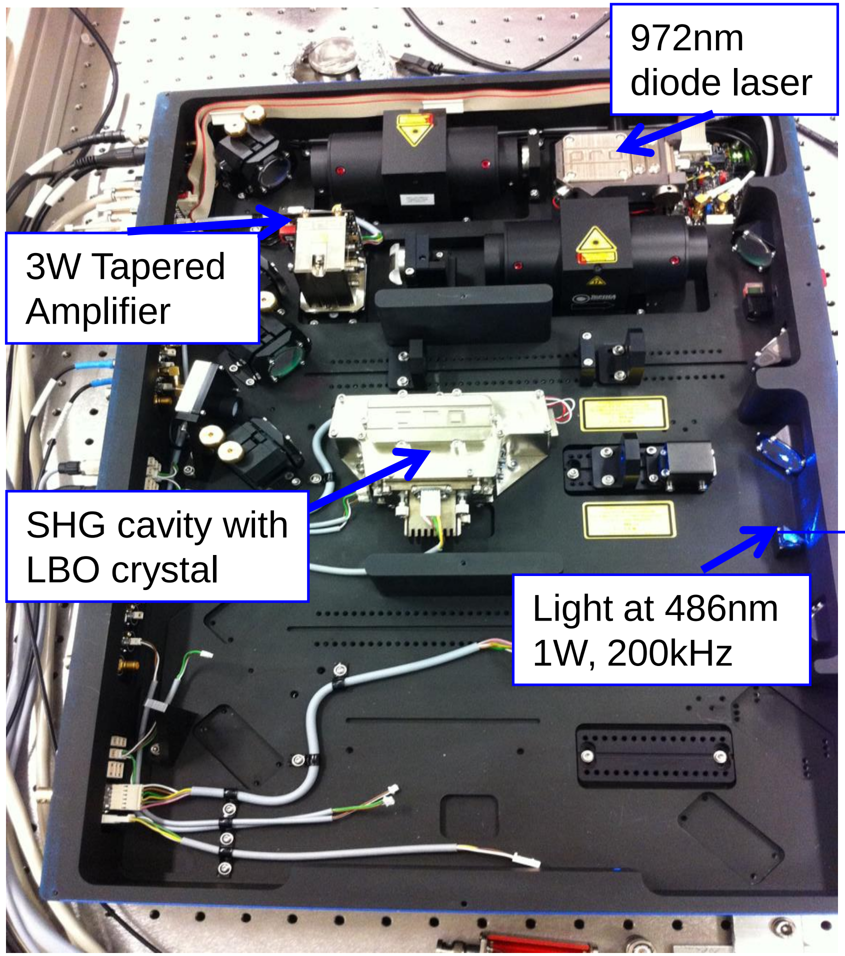
Requirements:
- High power (up to 1 kW) at 486 nm → detectable signal
- Long term stability (continuous data taking over days)
- Scanning of the laser ≈ 100 MHz

Ps 1S-2S: laser system

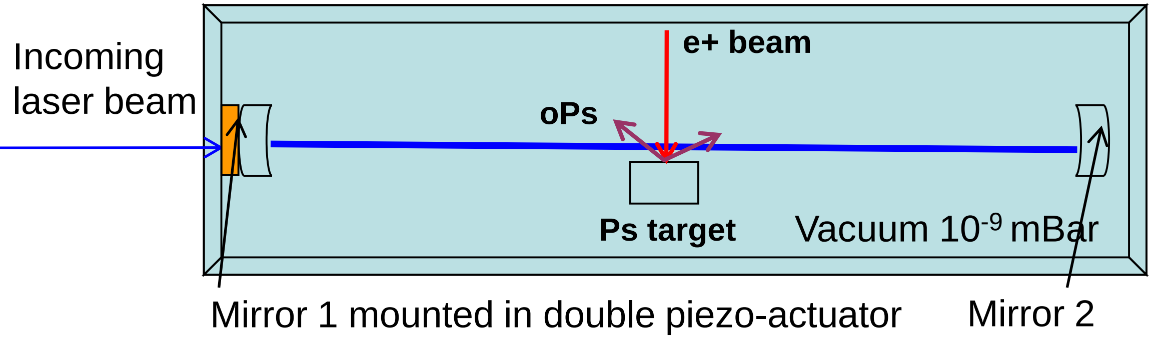


Requirements:
- High power (up to 1 kW) at 486 nm → detectable signal
- Long term stability (continuous data taking over days)
- Scanning of the laser ≈ 100 MHz

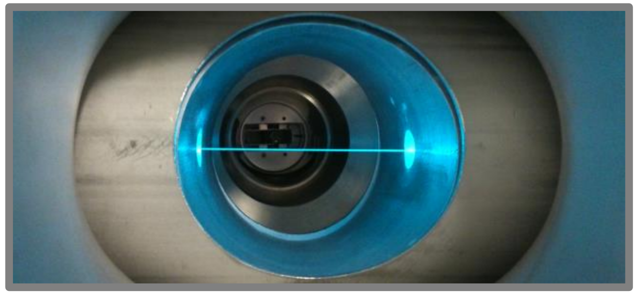
Ps 1S-2S: laser system



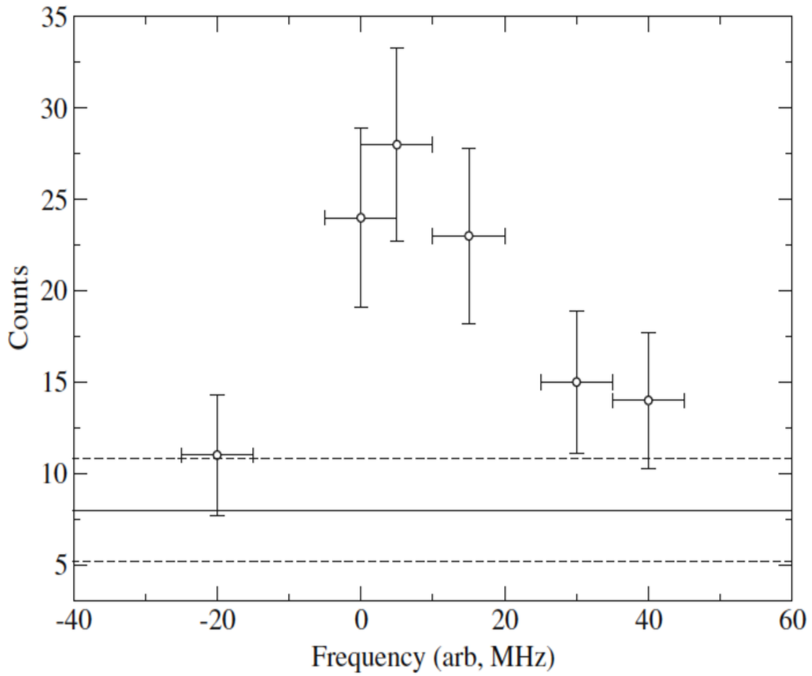
Requirements:
- High power (up to 1 kW) at 486 nm → detectable signal
- Long term stability (continuous data taking over days)
- Scanning of the laser ≈ 100 MHz



High finesse resonator
for power build up
500 mW ⇒ 1 kW



Ps 1S-2S: preliminary results (2014)

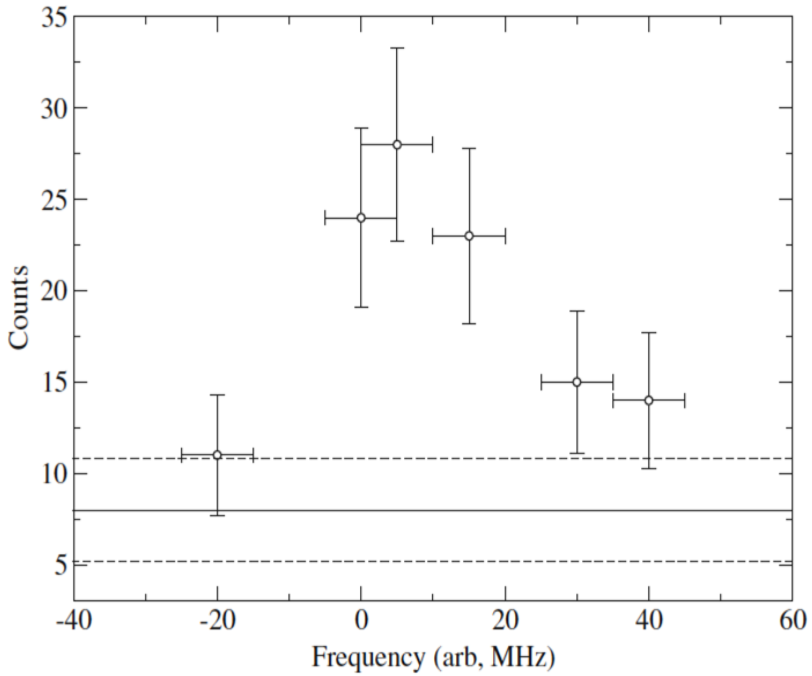


First successful scans
(about 3 hours data taking,
~ 10^6 positronium atoms/point)

S/N ratio should be improved.

- D.Cooke et al, Hyperfine Interact. 233 (2015) 1-3, 67.

Ps 1S-2S: preliminary results (2014)



First successful scans
(about 3 hours data taking,
~ 10^6 positronium atoms/point)

→ S/N ratio should be improved.

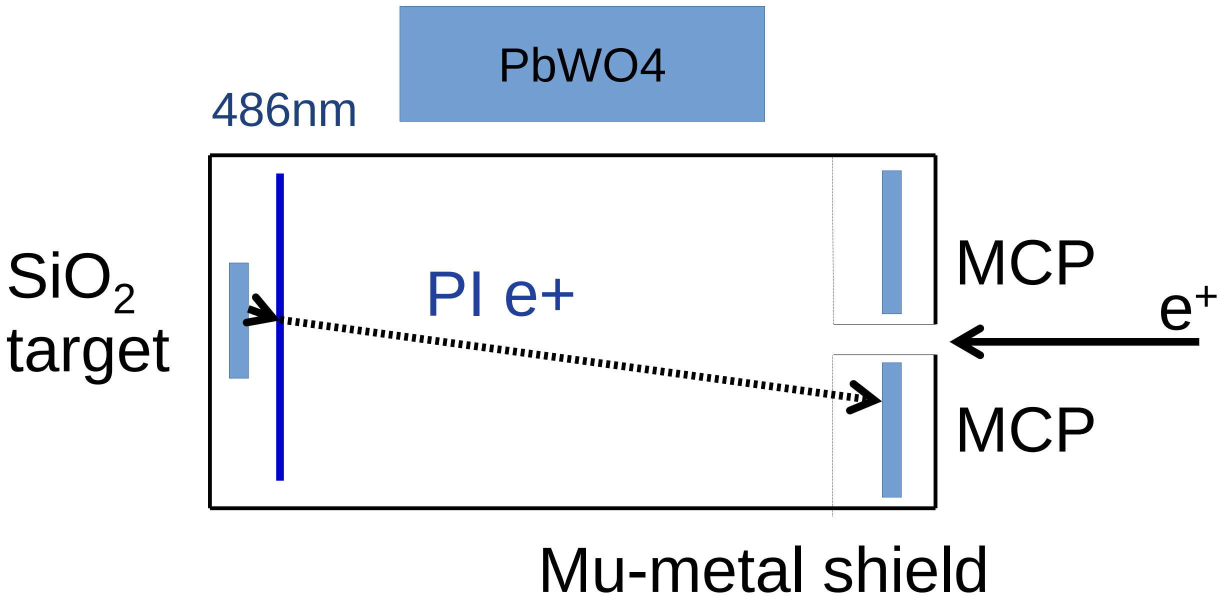
Need for a bunched beam → use buffer gas trap

→ noise from accidentals reduced by 2 orders of magnitude

→ In addition to lifetime method possibility to use pulsed lasers for systematic studies and increased signal rate

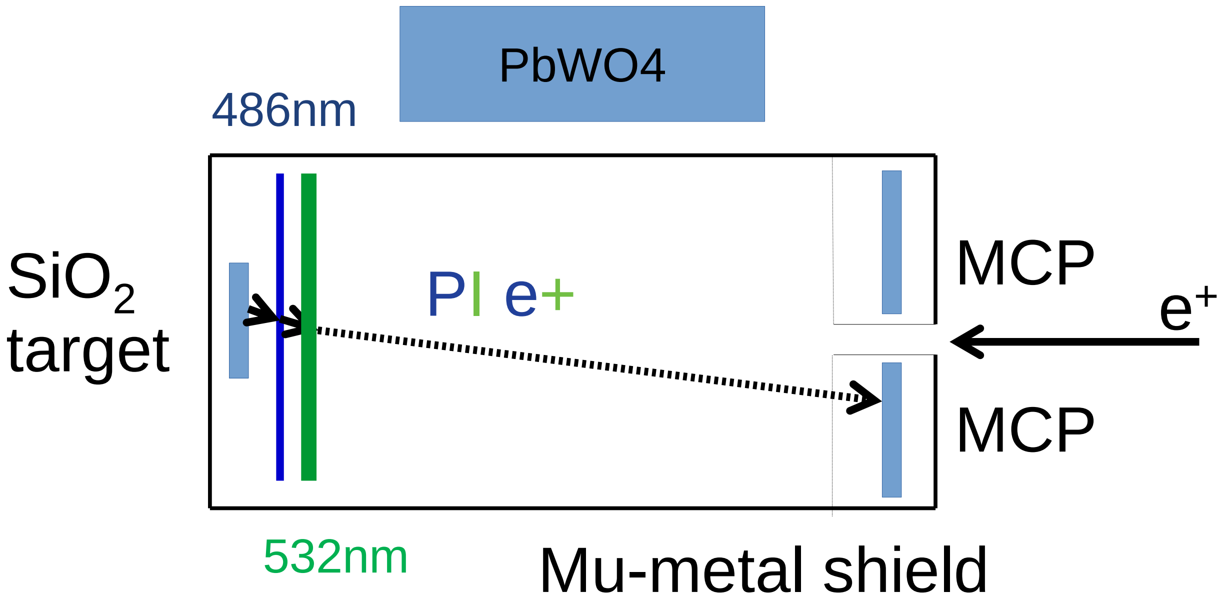
- D.Cooke et al, Hyperfine Interact. 233 (2015) 1-3, 67.

Ps 1S-2S: Updated detection techniques



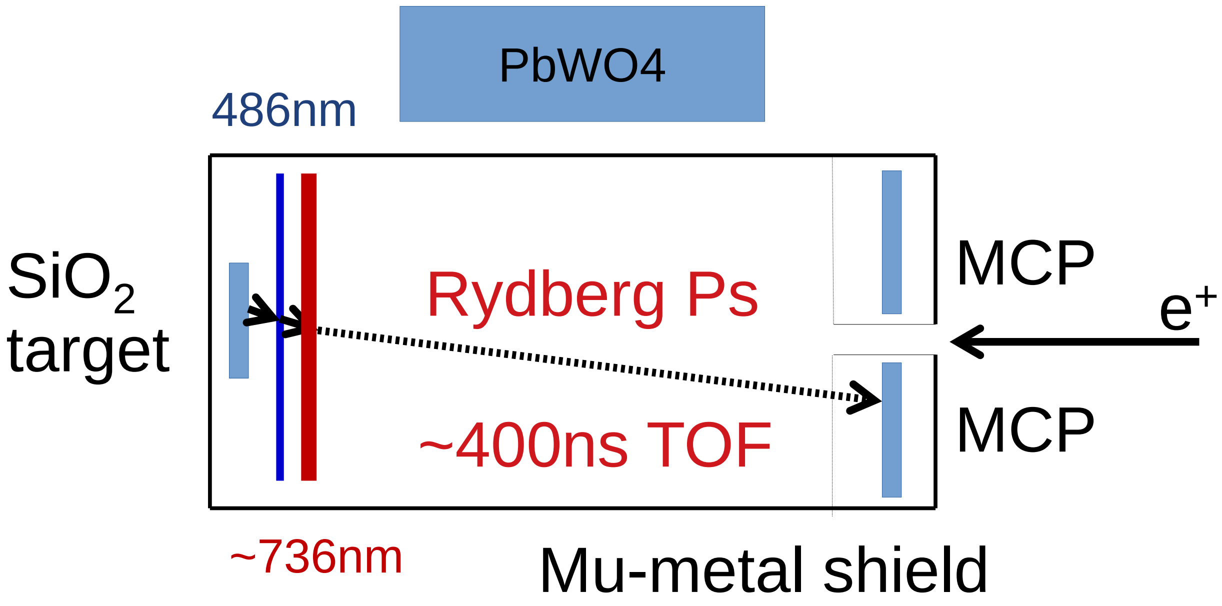
- Direct photo-ionization in the exciting laser

Ps 1S-2S: Updated detection techniques



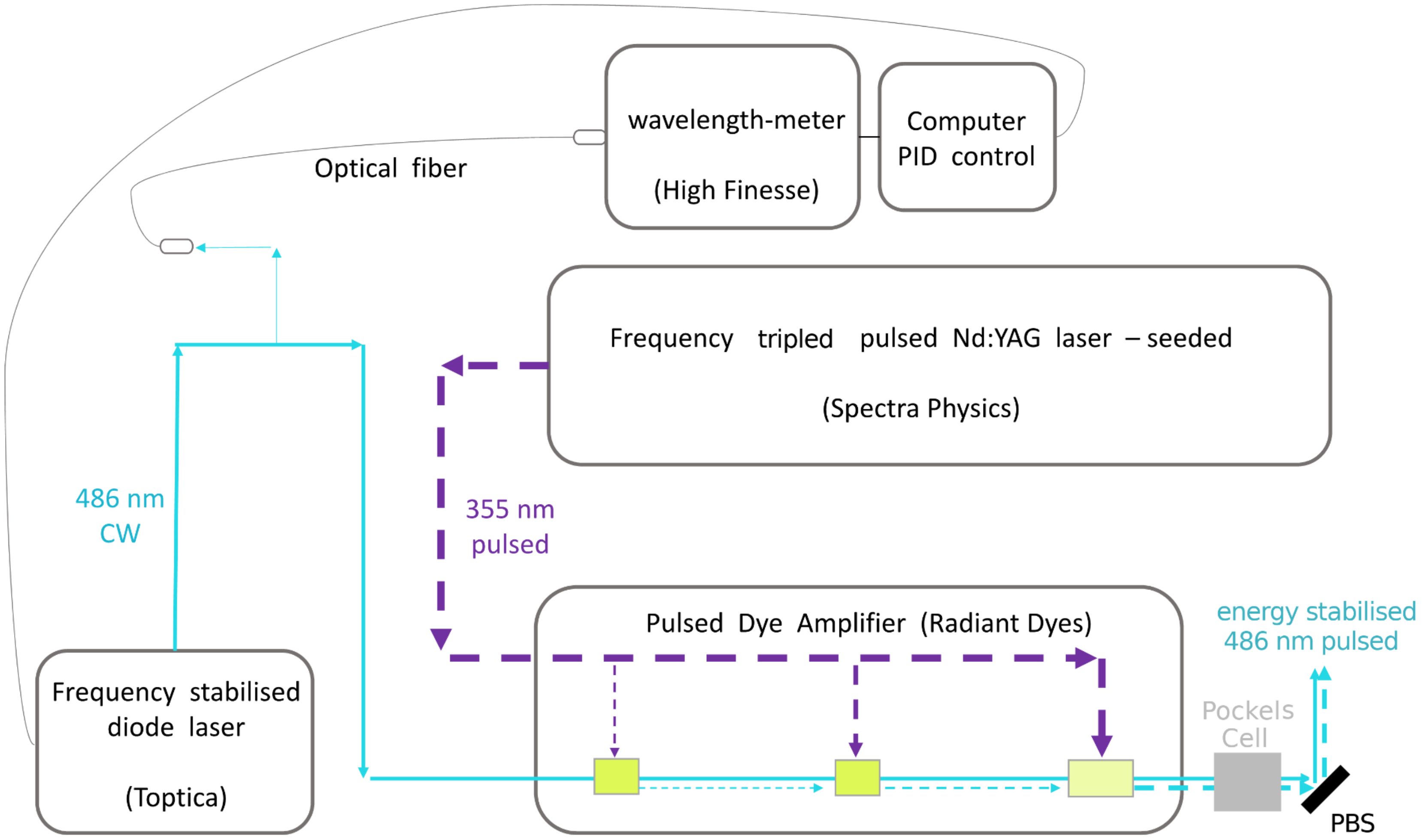
- Direct photo-ionization in the exciting laser
- 2S photo-ionization in separate laser

Ps 1S-2S: Updated detection techniques

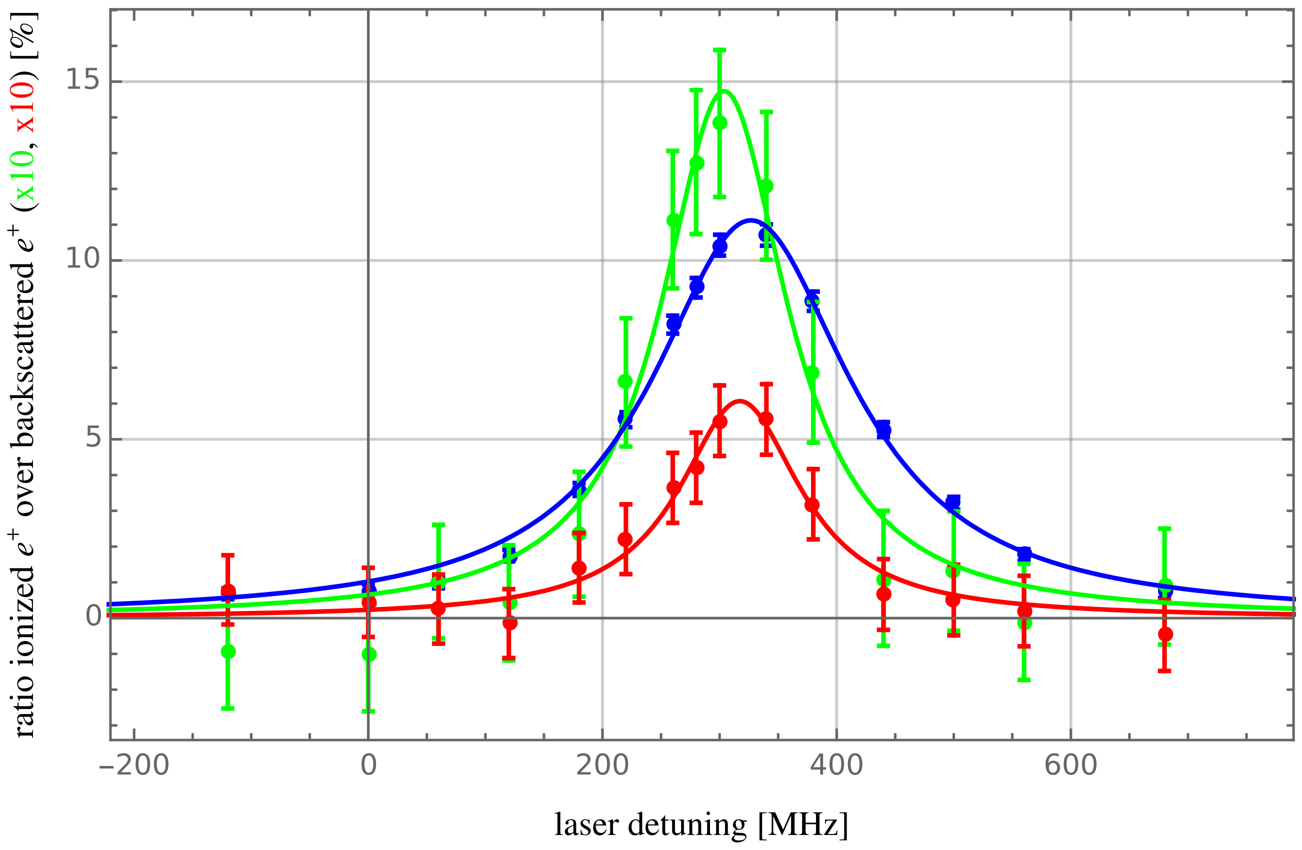


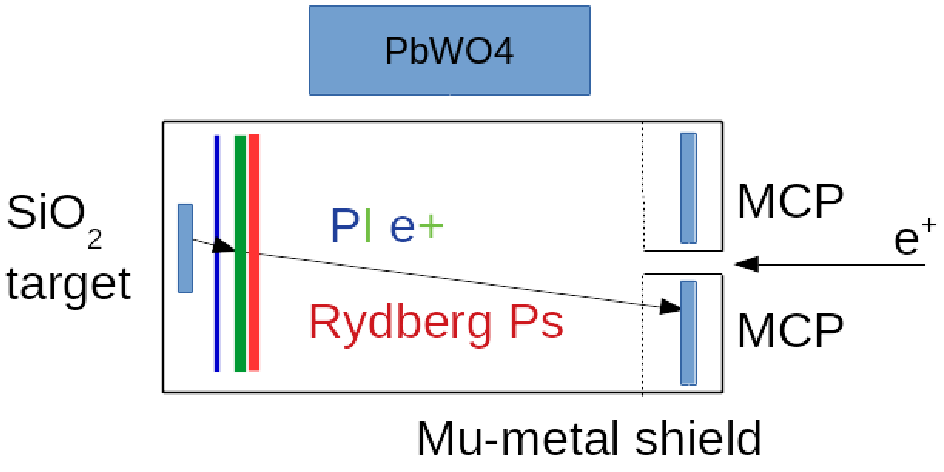
- Direct photo-ionization in the exciting laser
- 2S → Rydberg (e.g. 20P) and field ionization on MCP
  - allows for correction of second order doppler shift (main systematic!)

Ps 1S-2S: Pulsed laser scheme



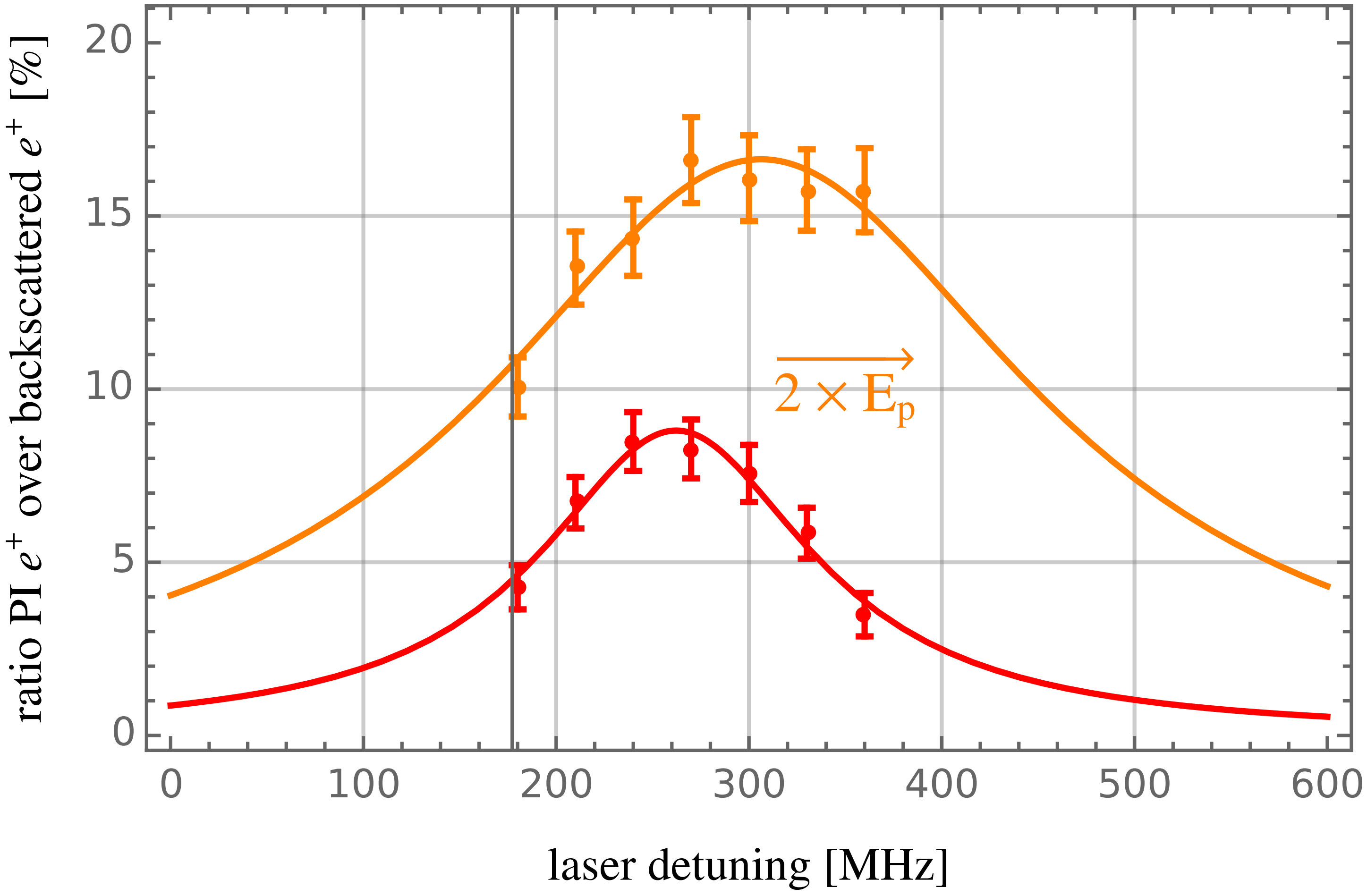
Ps 1S-2S: Pulsed laser scheme





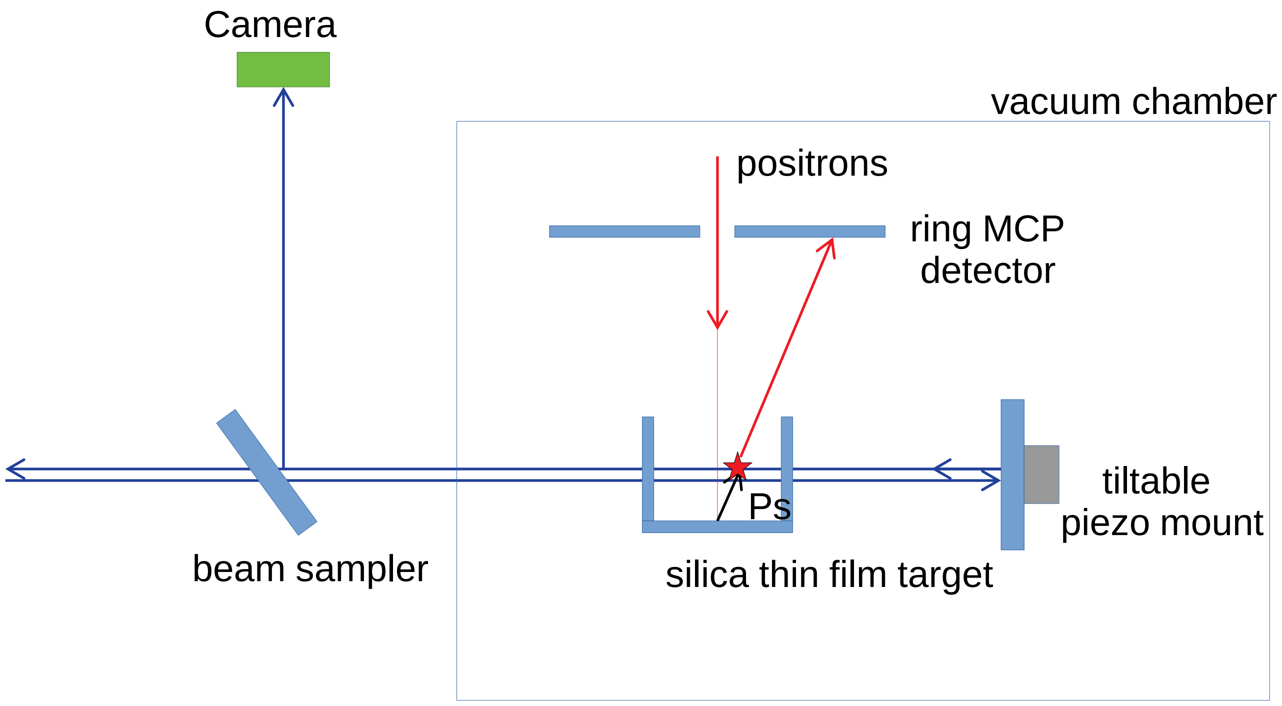
Ps 1S-2S: Studies of systematics

- AC stark shift
  - correct via extrapolation



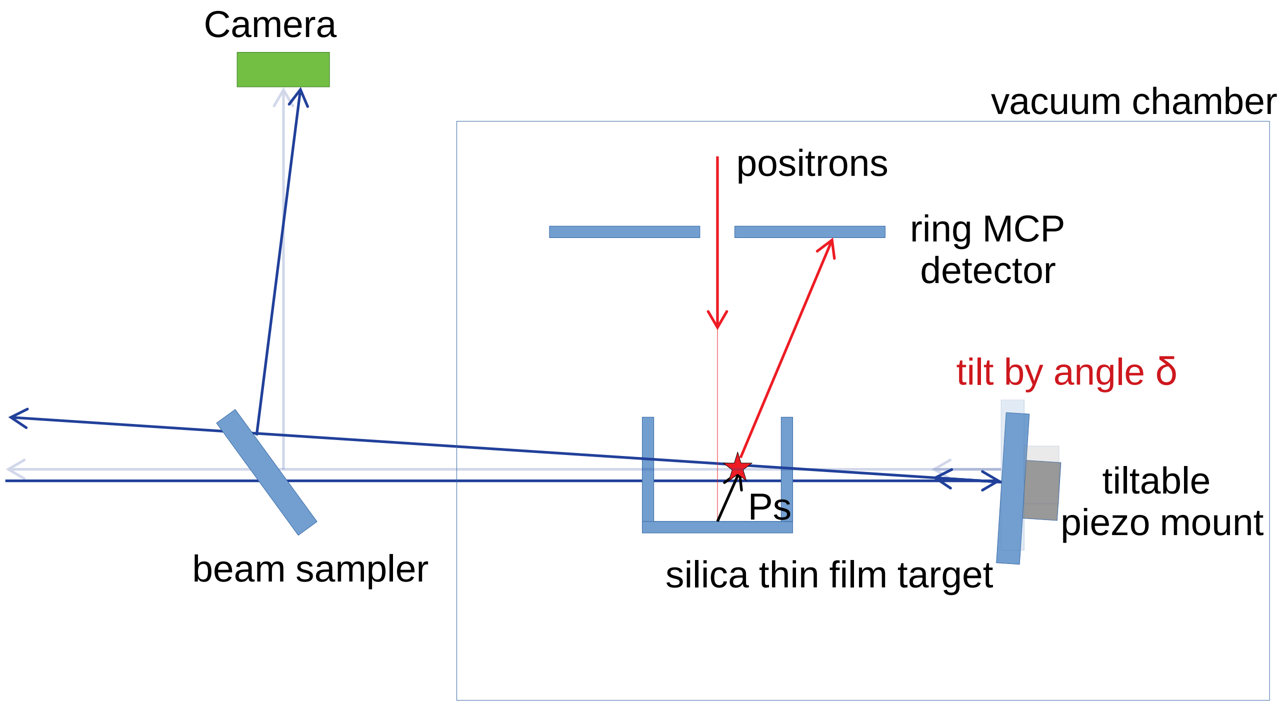
Ps 1S-2S: Studies of systematics

- Residual first order doppler shift



Ps 1S-2S: Studies of systematics

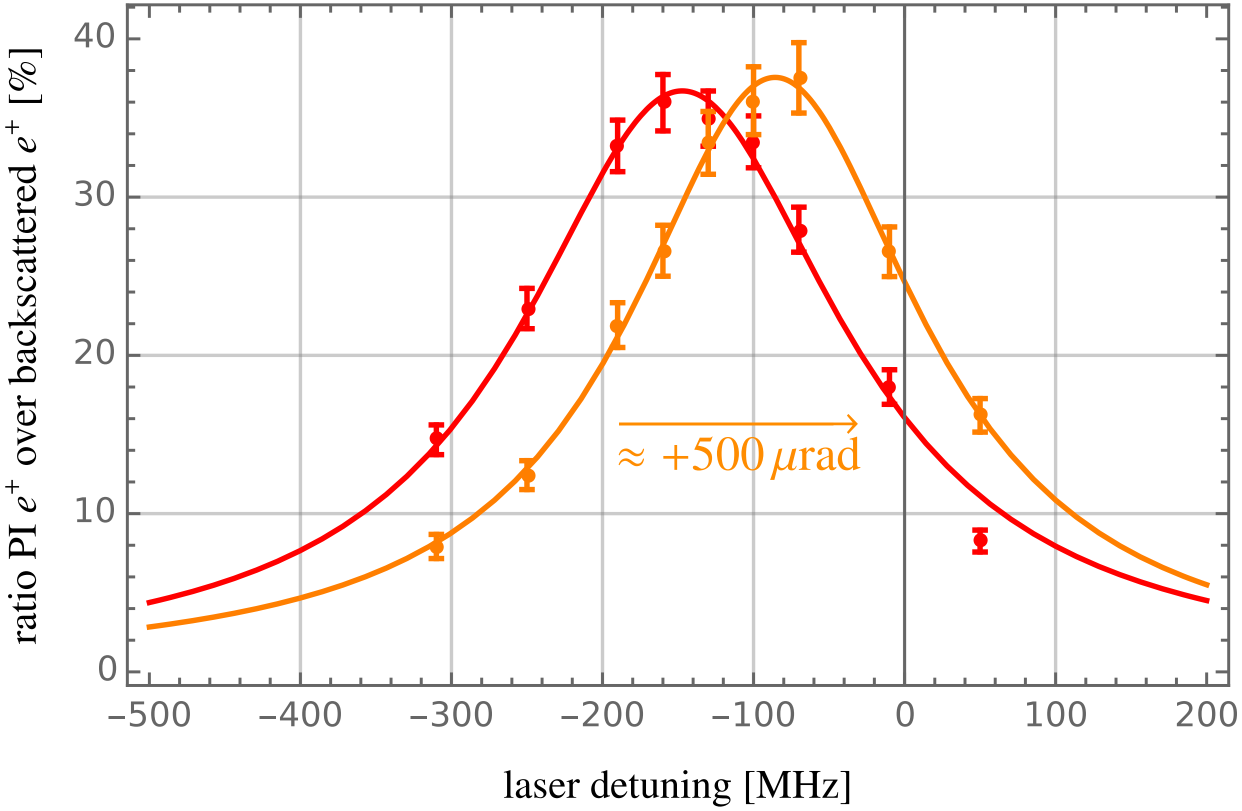
- Residual first order doppler shift



$$\Delta\nu \propto v_{Ps} \cdot \delta$$

Ps 1S-2S: Studies of systematics

- Residual first order doppler shift



Ps 1S-2S: Status and outlook

- Status
  - pulsed beam operational
  - enhancement cavity installed and locked
  - new detection schemes tested with pulsed dye amplifier and additional dye laser
  - systematic studies with pulsed laser underway

Ps 1S-2S: Status and outlook

- Status
  - pulsed beam operational
  - enhancement cavity installed and locked
  - new detection schemes tested with pulsed dye amplifier and additional dye laser
  - systematic studies with pulsed laser underway
- Outlook
  - next step: switch to CW excitation
  - precision of 0.5 ppb feasible
    - stringent test of current QED calculations
    - constrain SME coefficients (measure sidereal shifts)
  - further improvements require cold positronium (e.g. via Rydberg deceleration)

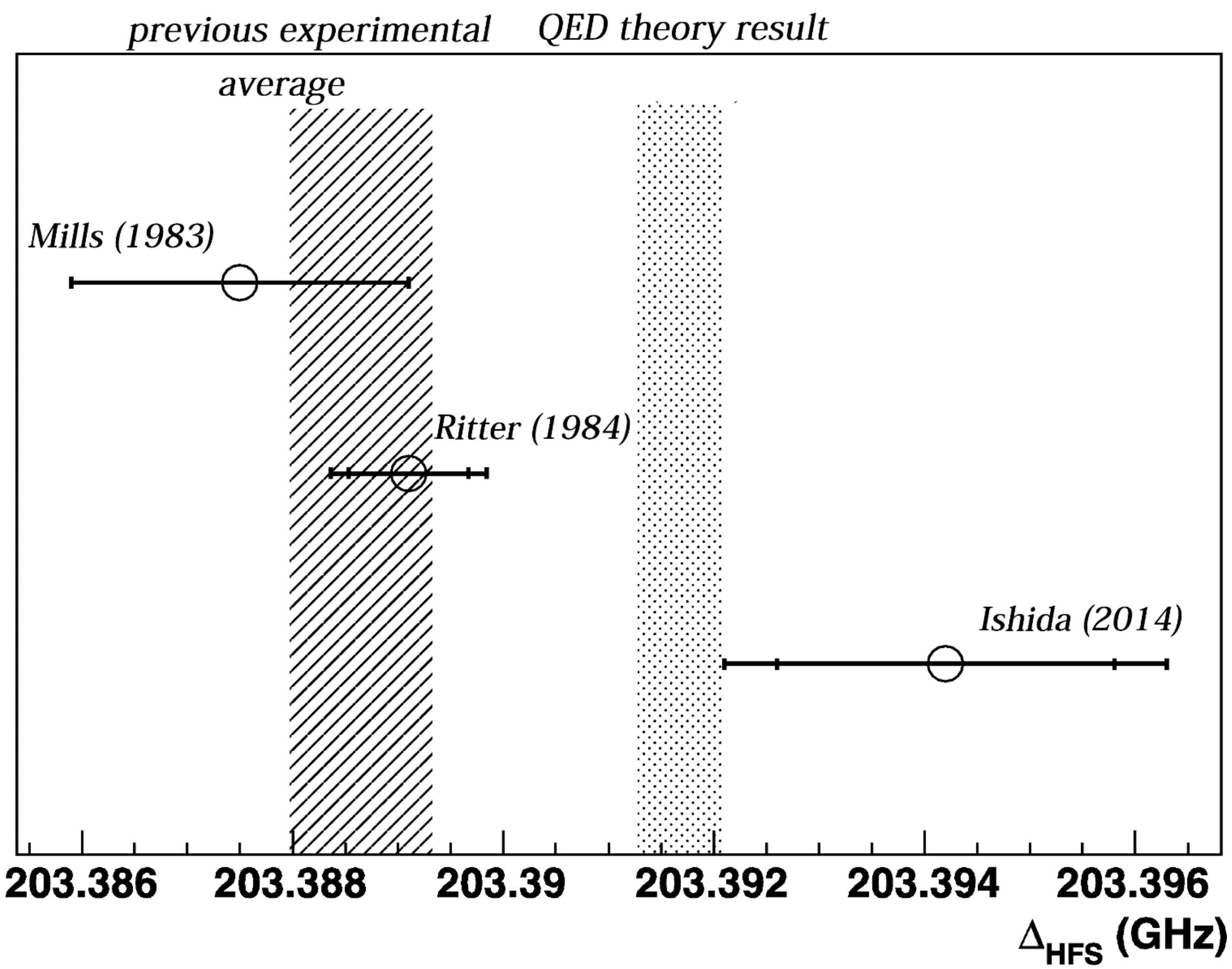
Motivation – Part 2 1S-2S **HFS**

- Ps is purely leptonic system
- (almost) free from
  - QCD effects
  - weak force effects
- Precision test bench for
  - bound state QED

Motivation – Part 2

1S-2S **HFS**

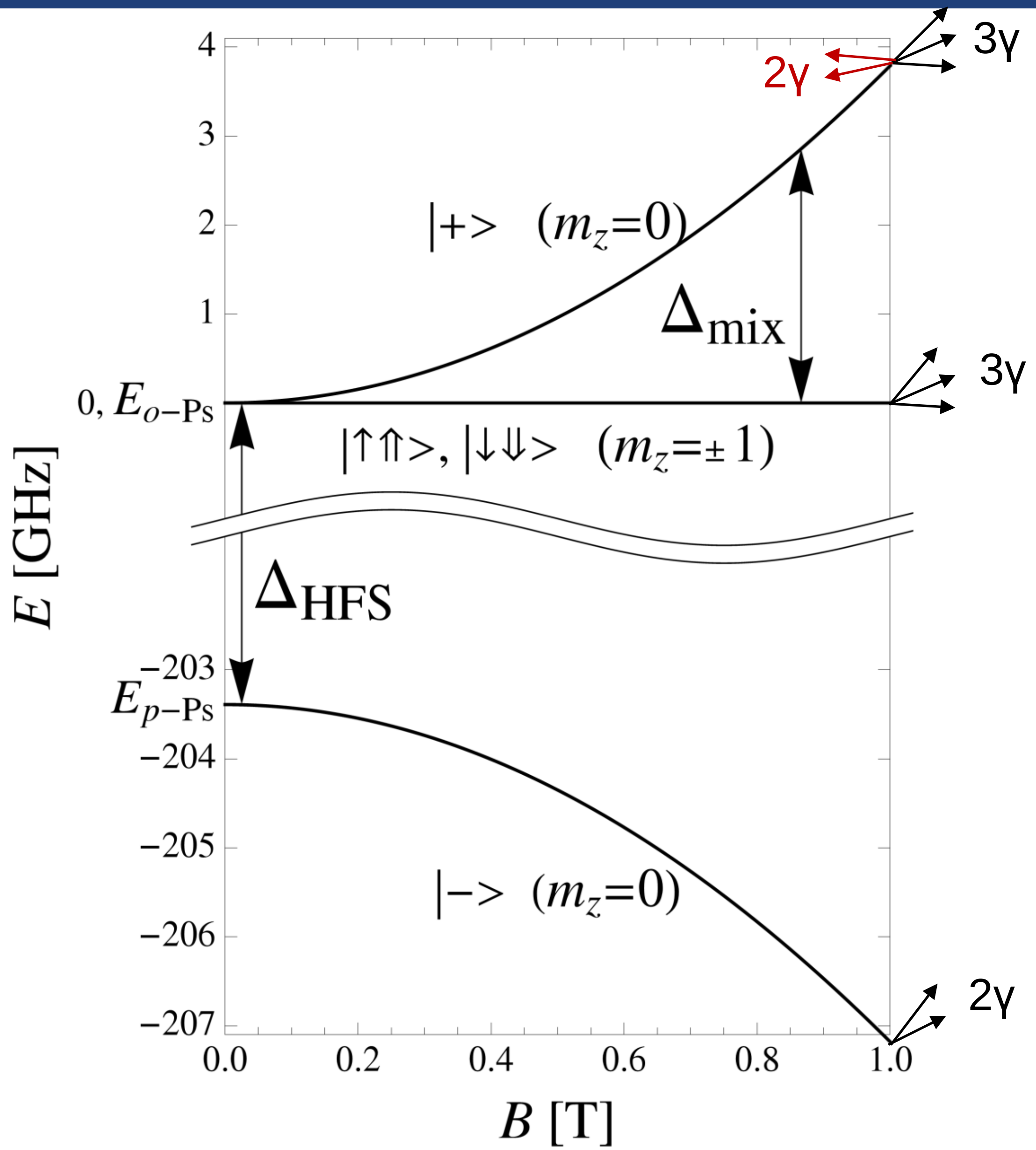
- Ps is purely leptonic system
- (almost) free from
  - QCD effects
  - weak force effects
- Precision test bench for
  - bound state QED
- Hyperfine structure
  - Very precise measurements in 1970s and 1980s
  - Almost 4 sigma discrepancy with most recent QED result



- A. Ishida et al. New Precision Measurement of Hyperfine Splitting of Positronium. *Phys. Rev. Lett. B*, 734:338–344, June 2014.

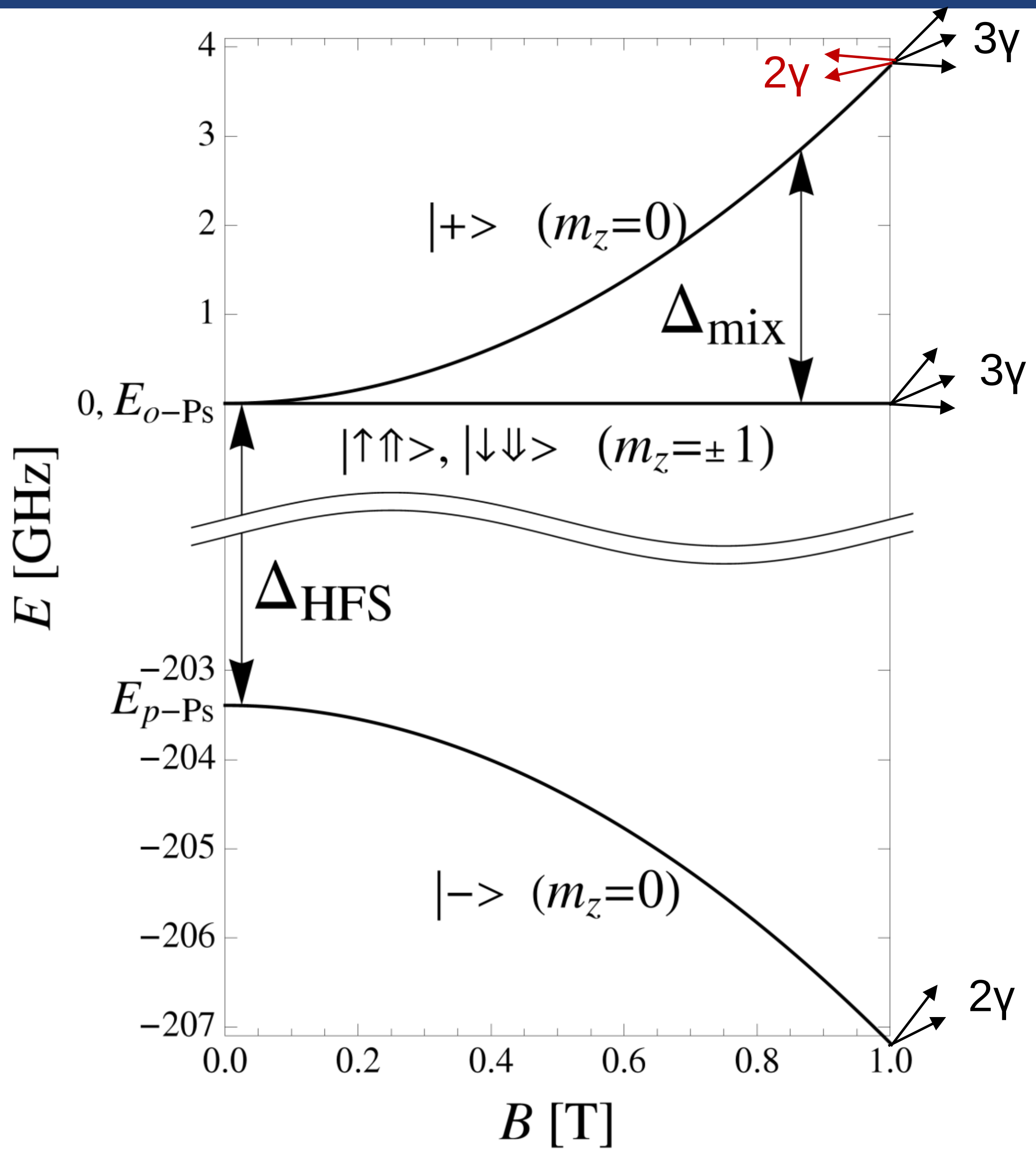
Ps HFS: Indirect measurements

- In a static magnetic field:
  - antiparallel spin states pick up ΔE
  - magnetic quenching



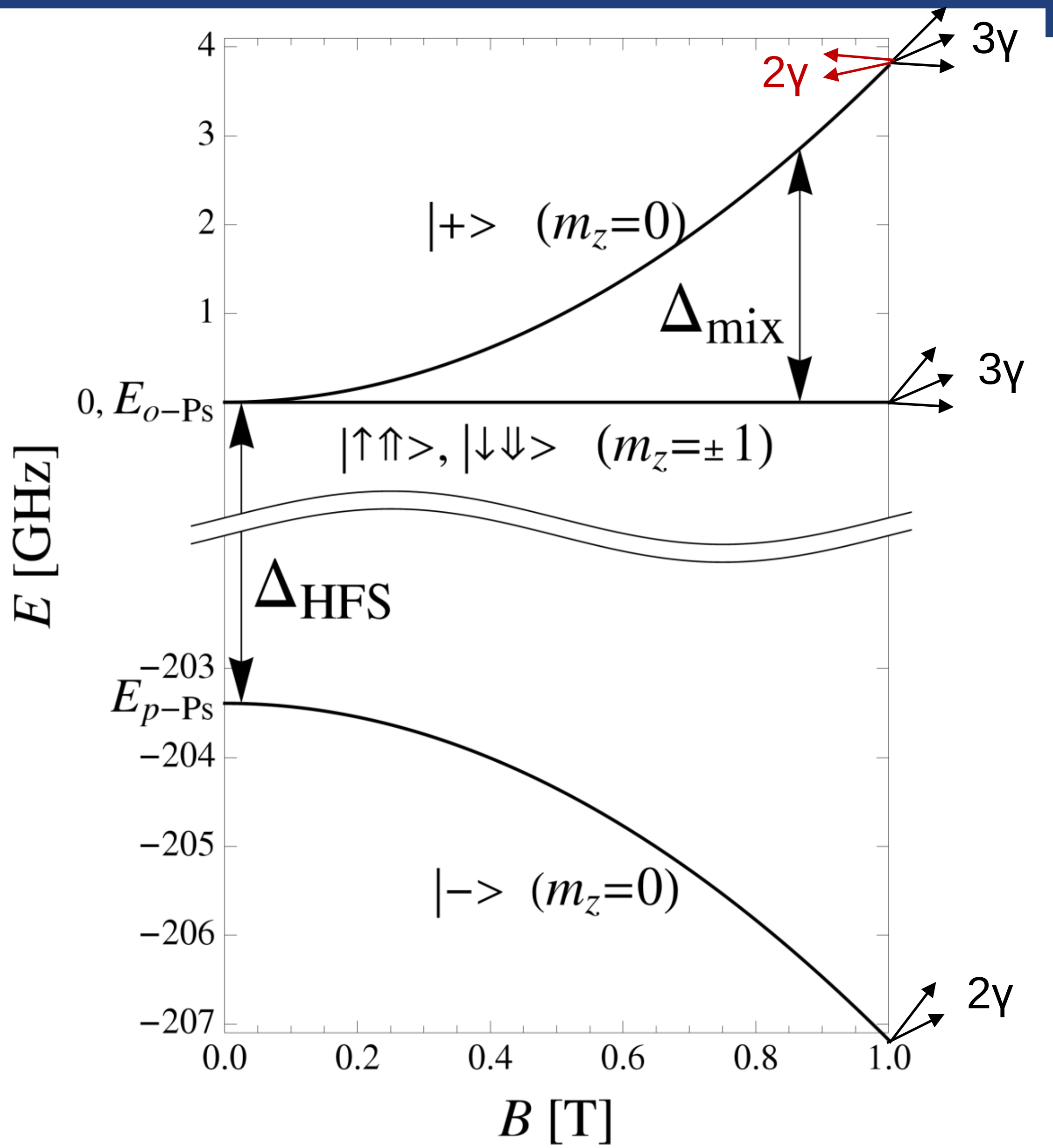
Ps HFS: Indirect measurements

- In a static magnetic field:
  - antiparallel spin states pick up ΔE
  - magnetic quenching
- one calculates Δ_{HFS} from:
  - $\Delta_{\text{mix}} \approx 0.5 \cdot \Delta_{\text{HFS}}\left(\sqrt{1+q^2}-1\right)$
  - where: $q \propto \frac{B}{\Delta_{\text{HFS}}}$



Ps HFS: Indirect measurements

- In a static magnetic field:
  - antiparallel spin states pick up ΔE
  - magnetic quenching
- one calculates Δ_{HFS} from:
  - $\Delta_{\text{mix}} \approx 0.5 \cdot \Delta_{\text{HFS}}\left(\sqrt{1+q^2}-1\right)$
  - where: $q \propto \frac{B}{\Delta_{\text{HFS}}}$
- Disadvantages
  - needs very high B-Fields ($\sim 1\ T$)
  - inhomogeneities in the fields contribute directly to systematic errors



Ps HFS: Measurements in dense gases

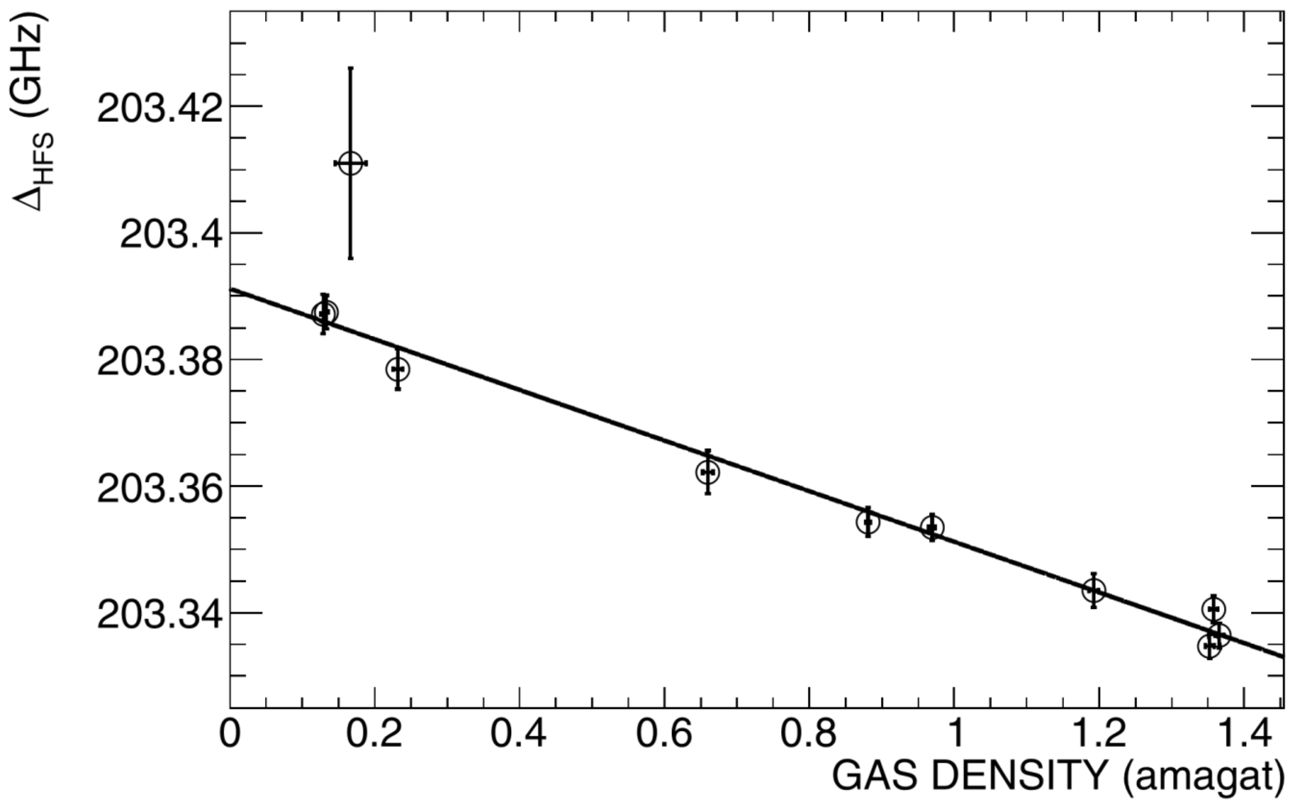
- In dense gases
  - gas acts as e^+ target
  - e^+ can ionize a gas atom
  - e^+ picks up the e^- and forms Ps

Ps HFS: Measurements in dense gases

- In dense gases
  - gas acts as e^+ target
  - e^+ can ionize a gas atom
  - e^+ picks up the e^- and forms Ps
- Advantage: no need for a beam

Ps HFS: Measurements in dense gases

- In dense gases
  - gas acts as e^+ target
  - e^+ can ionize a gas atom
  - e^+ picks up the e^- and forms Ps
- Advantage: no need for a beam
- Disadvantages:
  - E field of gas atoms → Stark effect
  - Needs extrapolation to vacuum
  - High MW powers can strongly interfere with Ps production in gases



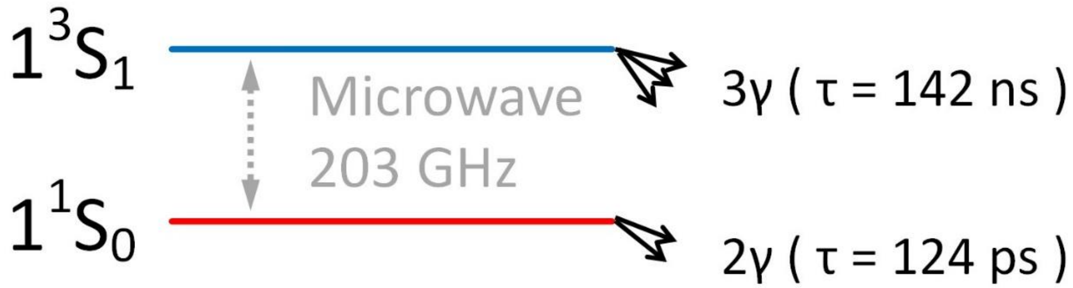
- A. Ishida et al. New Precision Measurement of Hyperfine Splitting of Positronium. *Phys. Rev. Lett. B*, 734:338–344, June 2014.

Ps HFS: New technique avoiding systematic sources

- Transition in vacuum
  - no extrapolation necessary
  - need a beam
  - need different converter

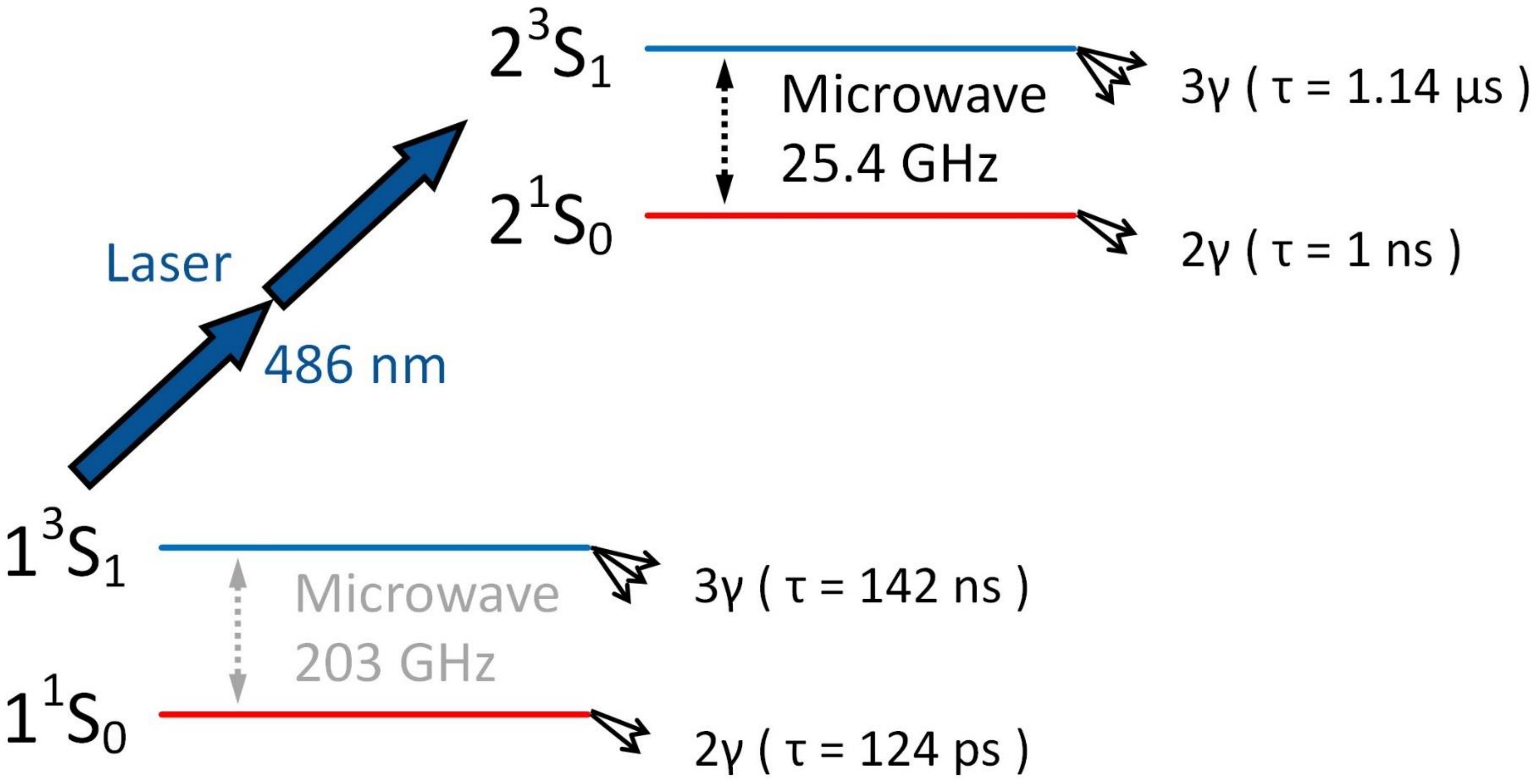
Ps HFS: New technique avoiding systematic sources

- Transition in vacuum
  - no extrapolation necessary
  - need a beam
  - need different converter
- Direct transition
  - doesn't need strong B field
  - no homogeneity concerns



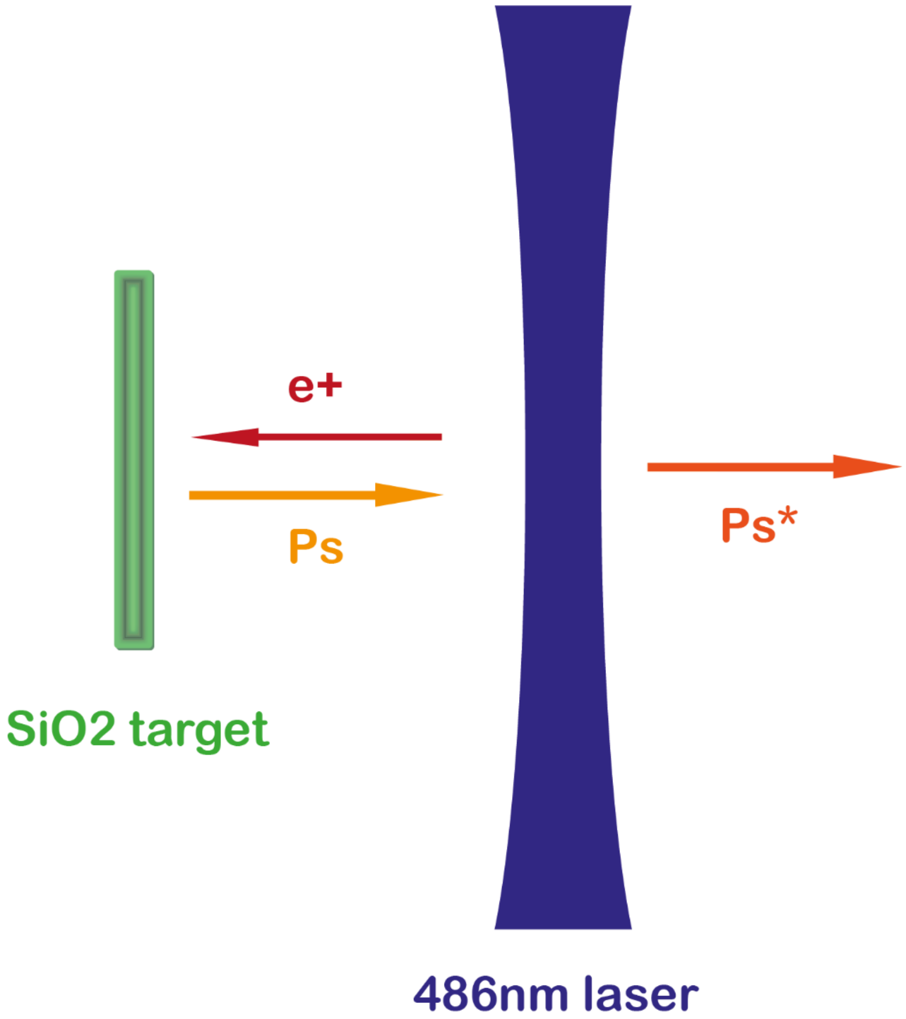
Ps HFS: New technique avoiding systematic sources

- Transition in vacuum
  - no extrapolation necessary
  - need a beam
  - need different converter
- Direct transition
  - doesn't need strong B field
  - no homogeneity concerns
- use 486nm laser
- Microwave sources
  - 100's mW (w/o Amp.)
  - 100's W (with Amp.)

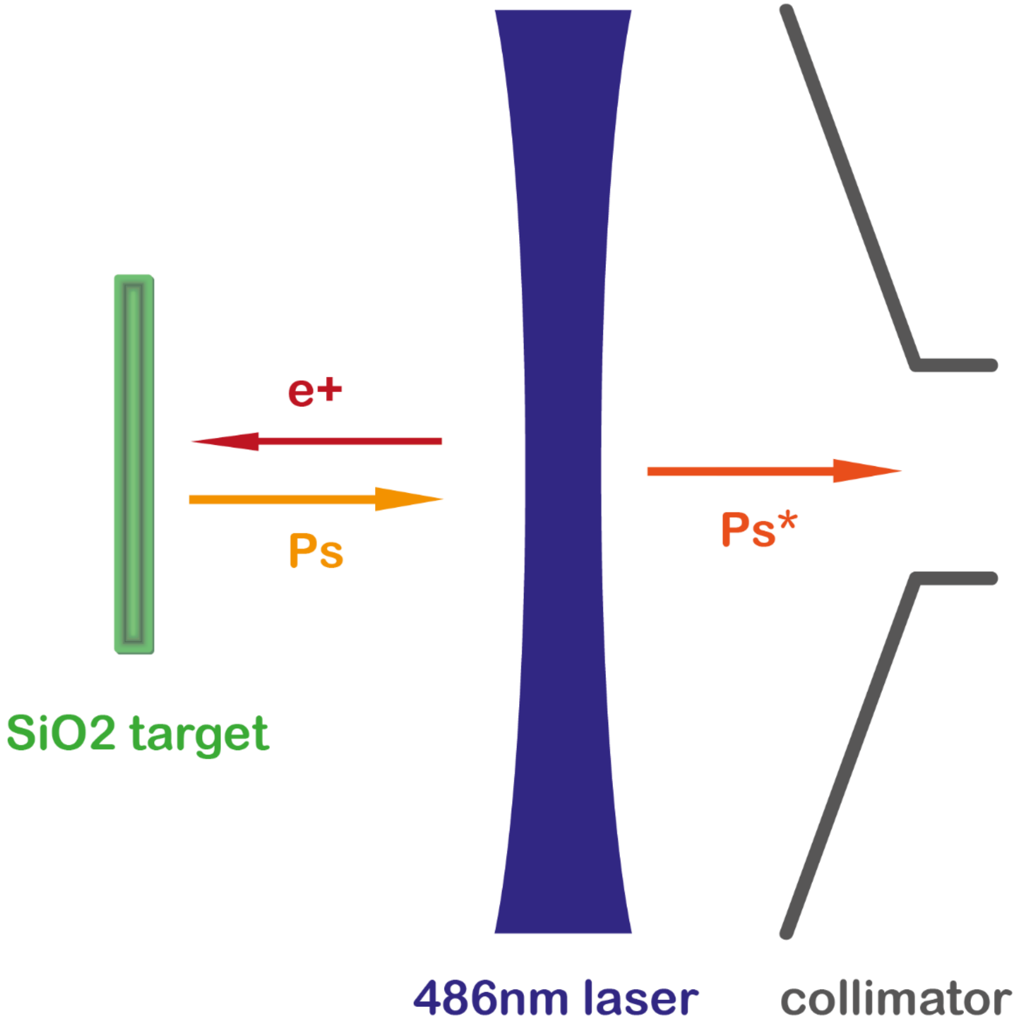


Ps HFS: Schematic overview of the experiment

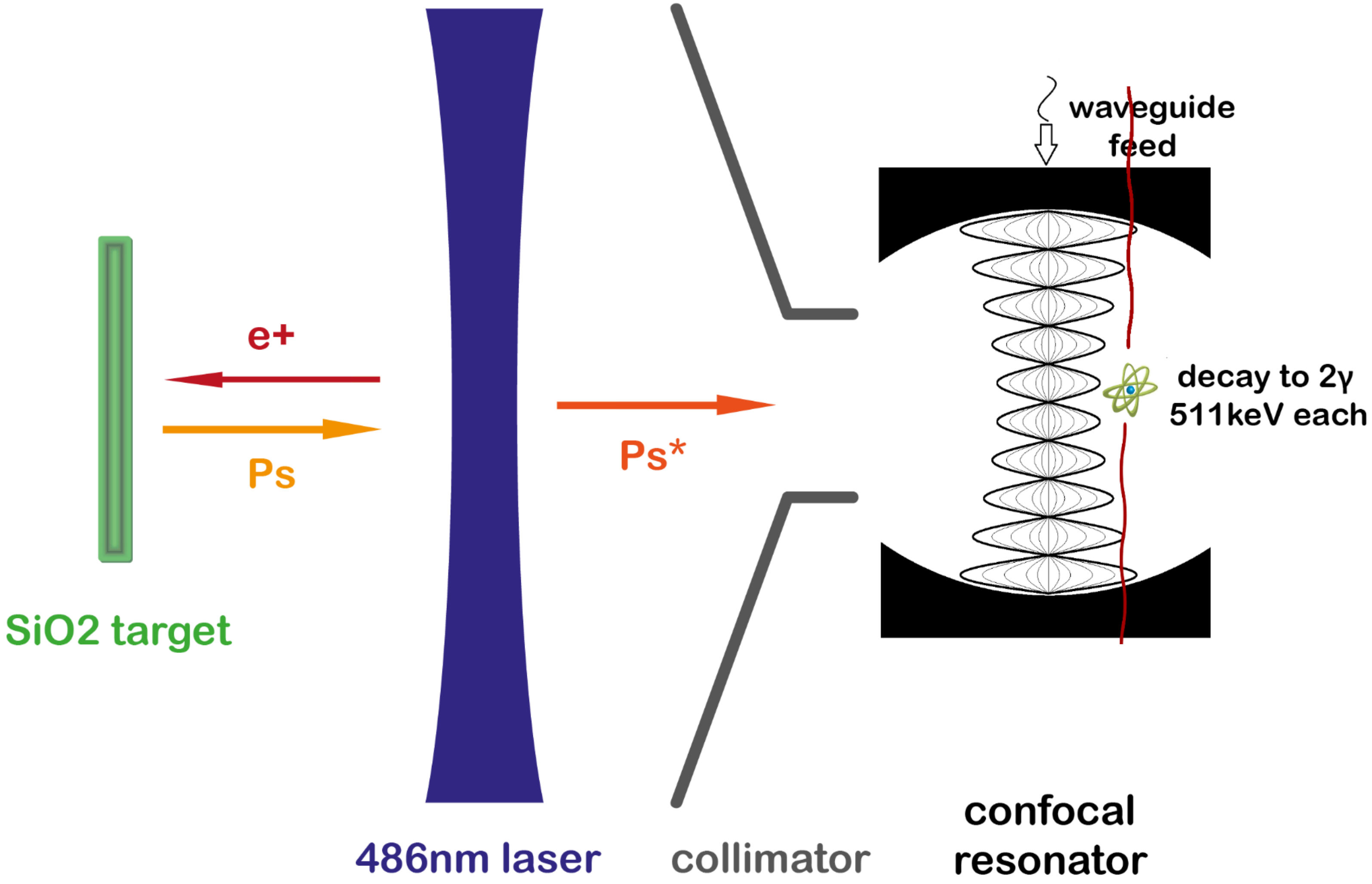
Ps HFS: Schematic overview of the experiment



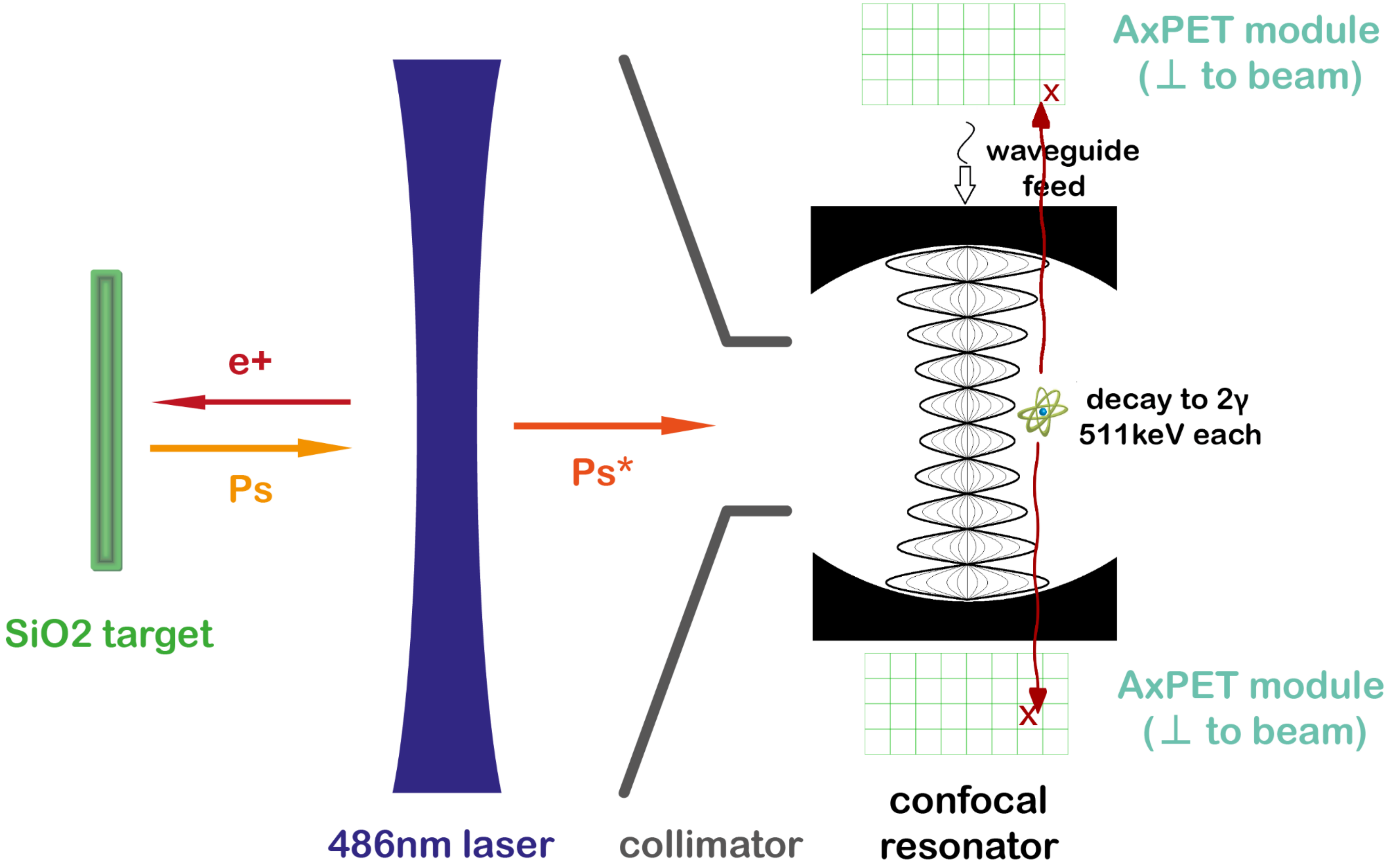
Ps HFS: Schematic overview of the experiment



Ps HFS: Schematic overview of the experiment

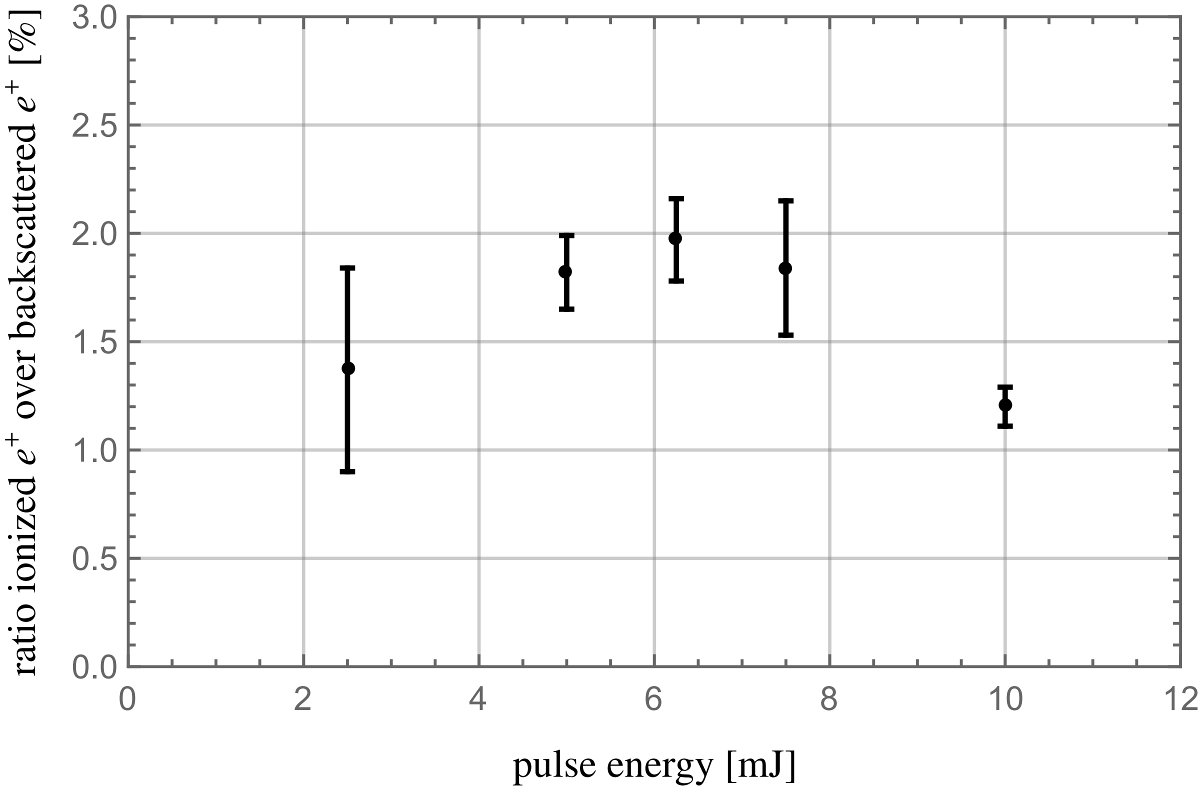


Ps HFS: Schematic overview of the experiment



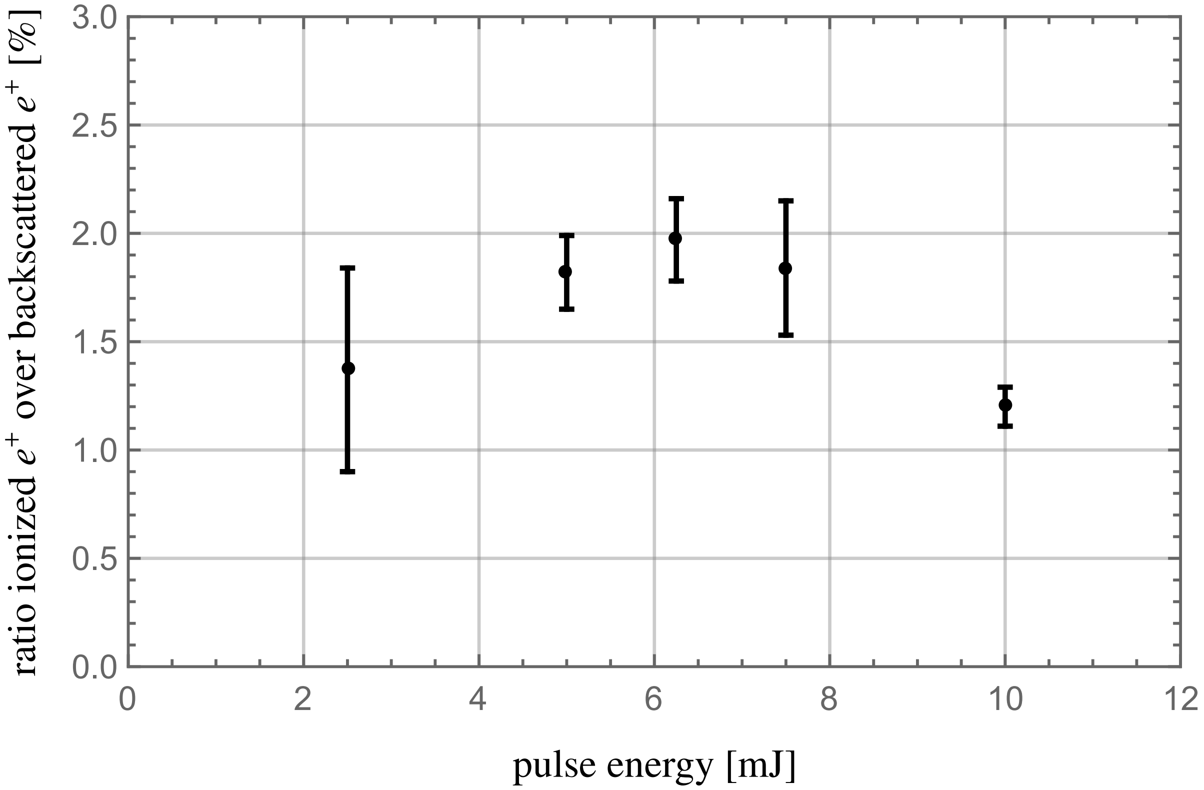
Ps HFS: Optimization of 2S surviving fraction

- scan laser parameters
- optimize for 2S fraction
  - PI signal due to 532nm laser



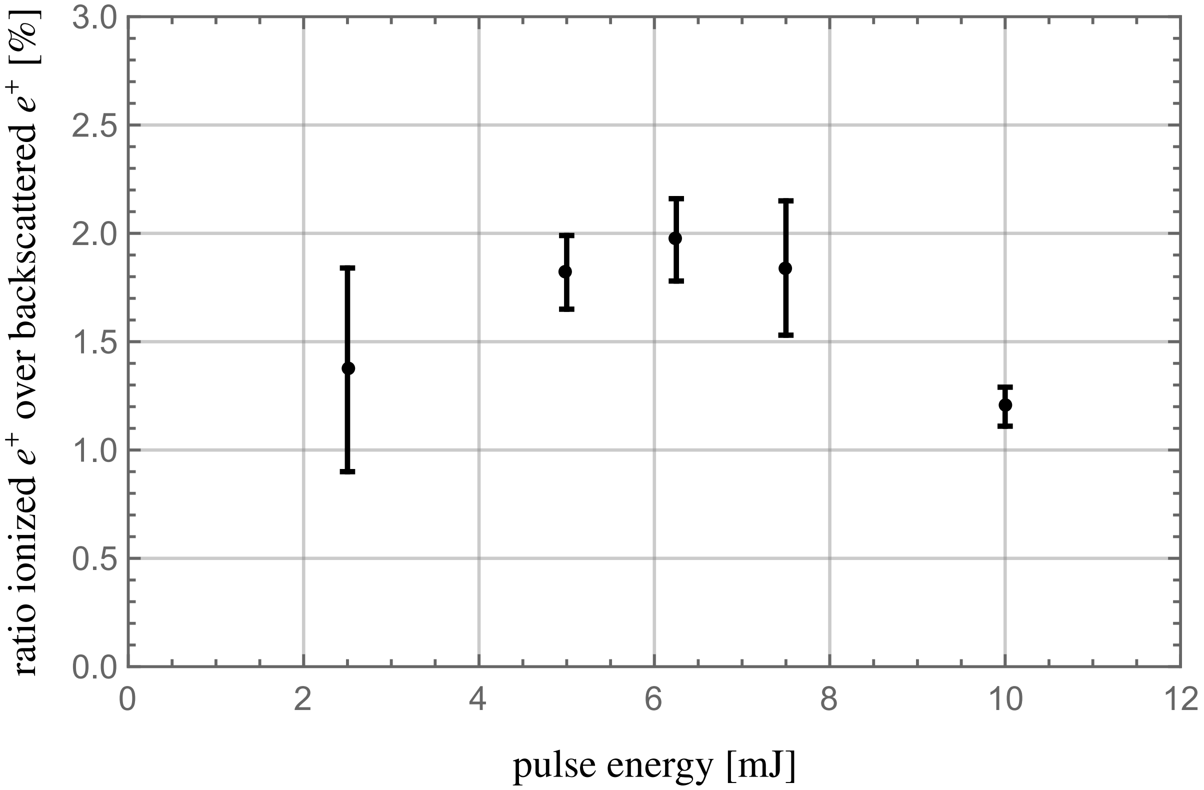
Ps HFS: Optimization of 2S surviving fraction

- scan laser parameters
- optimize for 2S fraction
  - PI signal due to 532nm laser
- include normalization:
  - $N = \frac{P_{bs}}{\varepsilon_c(1-P_{bs})} \approx 0.26$



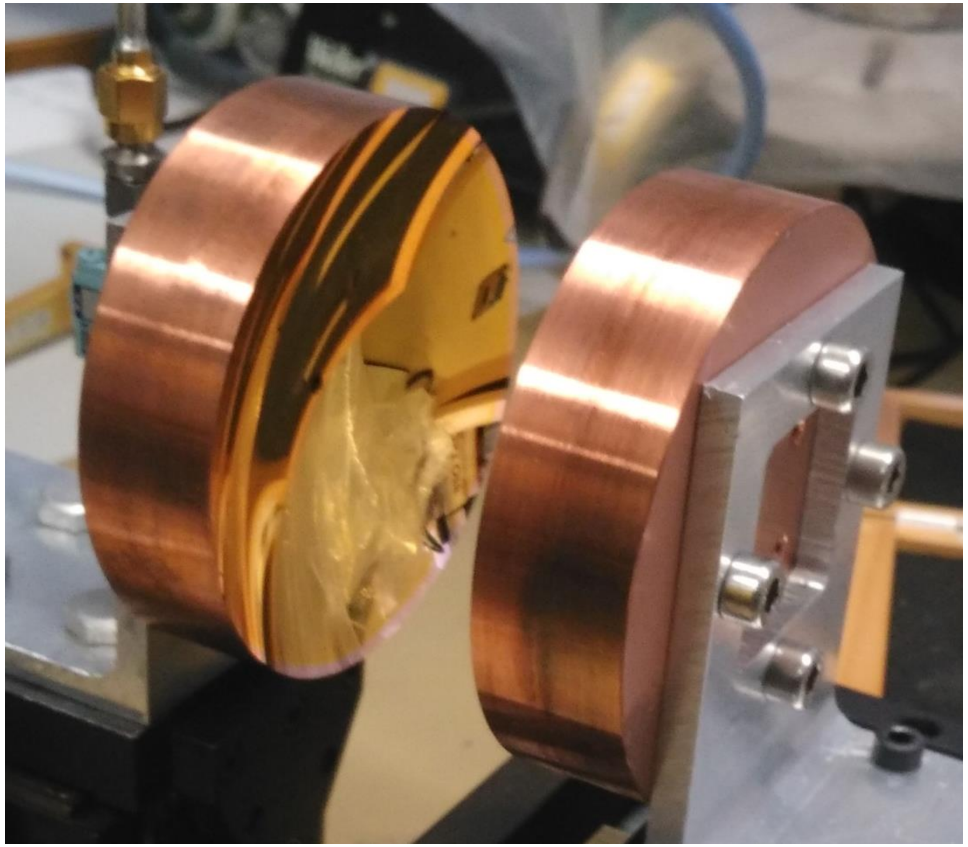
Ps HFS: Optimization of 2S surviving fraction

- scan laser parameters
- optimize for 2S fraction
  - PI signal due to 532nm laser
- include normalization:
  - $N = \frac{P_{bs}}{\varepsilon_c(1-P_{bs})} \approx 0.26$
- Surviving 2S fraction:
  - $P_{2S} \cong 0.5\%$
- Simulation: % level



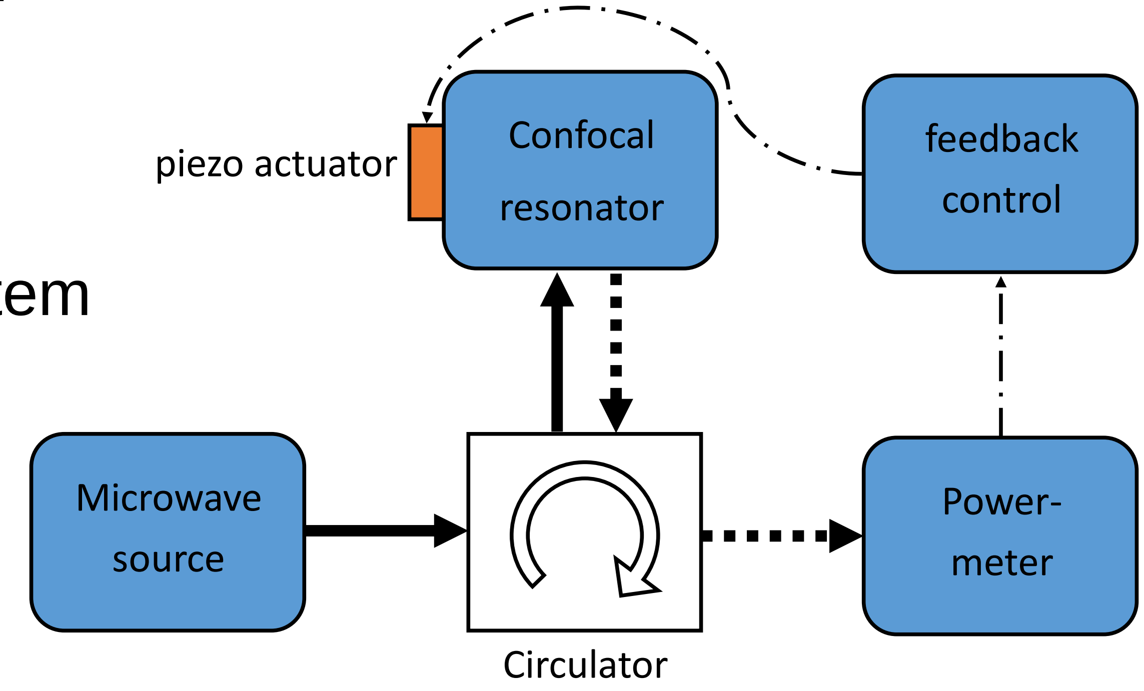
Ps HFS: Microwave system

- Confocal resonator @ 25.4 GHz
  - two spherical mirrors
  - impedence matched coupling hole
  - waveguide signal feed



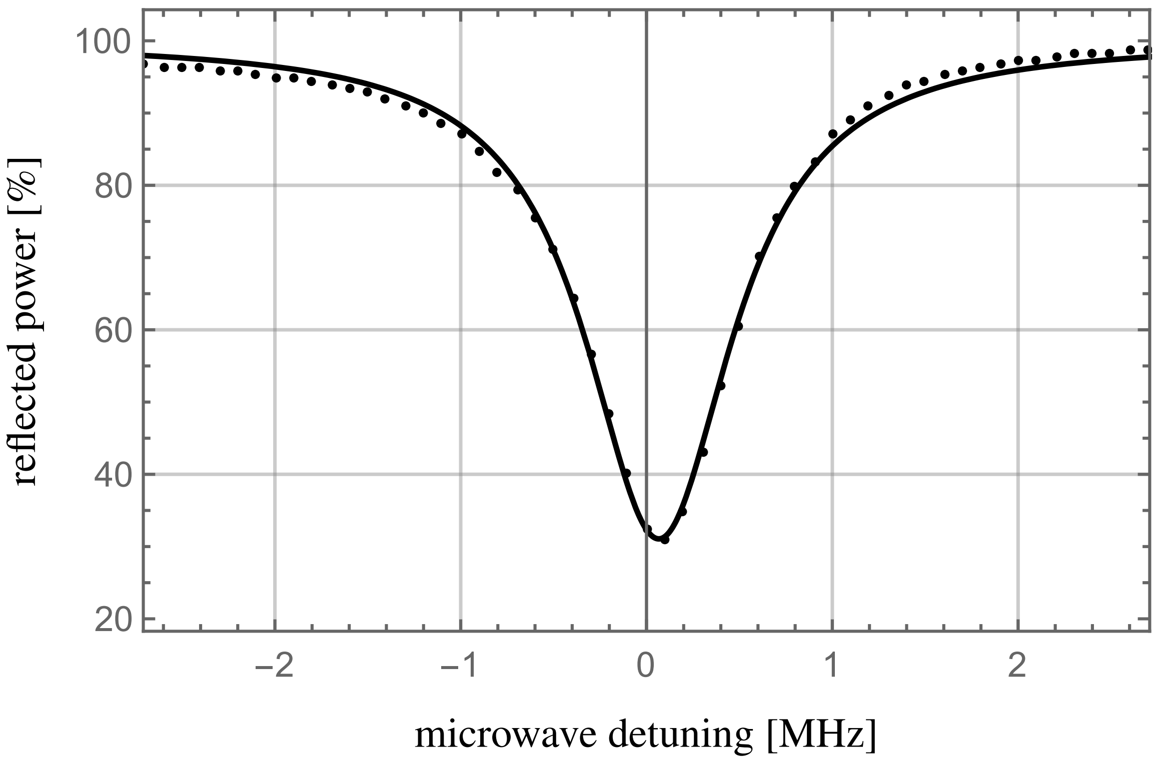
Ps HFS: Microwave system

- Confocal resonator @ 25.4 GHz
  - two spherical mirrors
  - impedence matched coupling hole
  - waveguide signal feed
- Monitoring and stabilization system



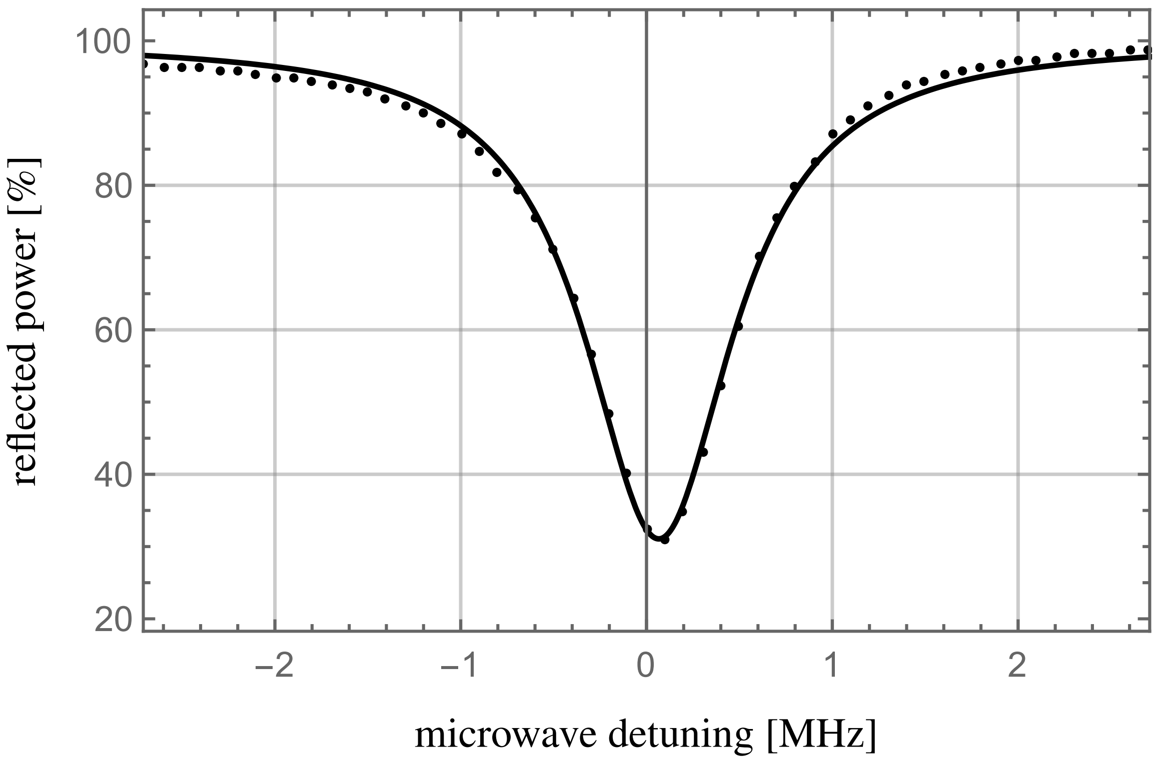
Ps HFS: Microwave system

- Confocal resonator @ 25.4 GHz
  - two spherical mirrors
  - impedence matched coupling hole
  - waveguide signal feed
- Monitoring and stabilization system
- Performance close to design values
  - $Q \approx 26300$ or equivalently $\Gamma_{\text{FWHM}} \approx 1\ MHz$
  - Coupling efficiency $\approx 70\%$



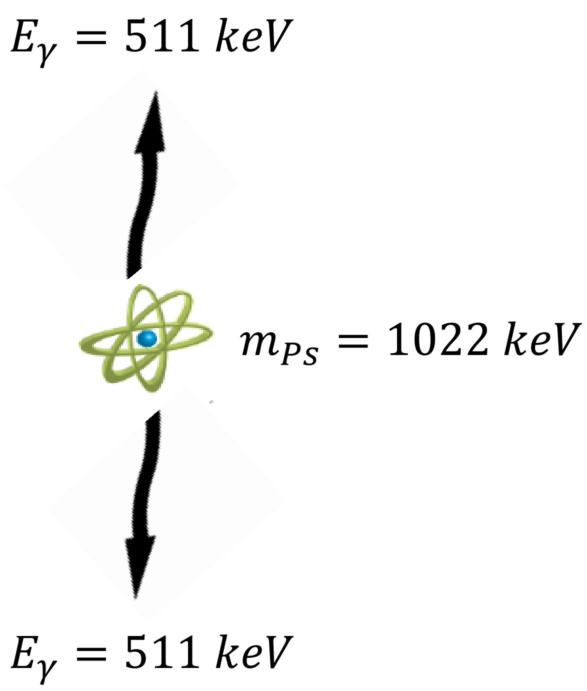
Ps HFS: Microwave system

- Confocal resonator @ 25.4 GHz
  - two spherical mirrors
  - impedence matched coupling hole
  - waveguide signal feed
- Monitoring and stabilization system
- Performance close to design values
  - $Q \approx 26300$ or equivalently $\Gamma_{\mathrm{FWHM}} \approx 1\ MHz$
  - Coupling efficiency $\approx 70\%$
- Simulation: HFS transition probability
  - $\approx$ 0.5% (signal generator)
  - $\approx$ 15% (additional 10W amplifier)



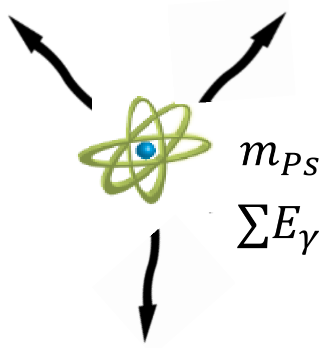
Ps HFS: Event signature

- Experimental signature (pPs decay)
  - 2 matching back-to-back 511 keV photons
    - temporal coincidence
    - vertex reconstruction
    - energy cut



Ps HFS: Event signature

- Experimental signature (pPs decay)
  - 2 matching back-to-back 511 keV photons
    - temporal coincidence
    - vertex reconstruction
    - energy cut
- Dominant background (oPs decay)

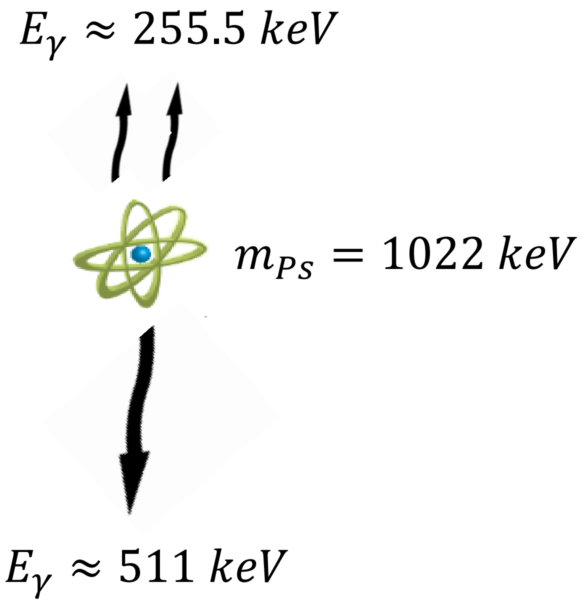


$$m_{Ps} = 1022\ keV$$

$$\sum E_{\gamma} = 1022\ keV$$

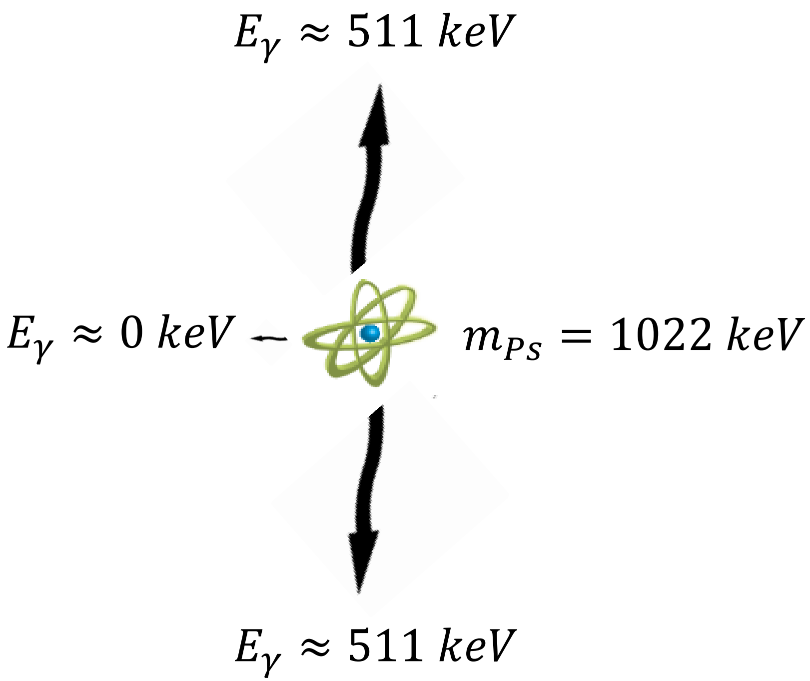
Ps HFS: Event signature

- Experimental signature (pPs decay)
  - 2 matching back-to-back 511 keV photons
    - temporal coincidence
    - vertex reconstruction
    - energy cut
- Dominant background (oPs decay)
  - misidentification of 3 photon decays as 2 photon decays
    - 2 of the 3 photons almost colinear



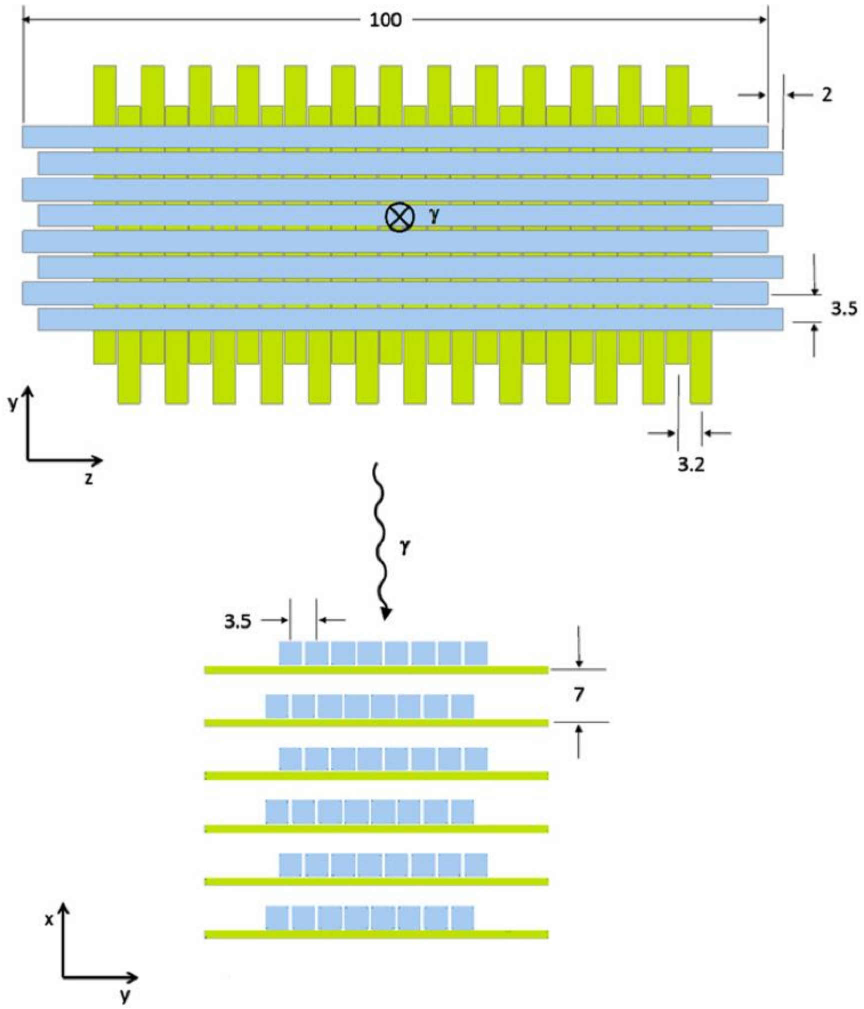
Ps HFS: Event signature

- Experimental signature (pPs decay)
  - 2 matching back-to-back 511 keV photons
    - temporal coincidence
    - vertex reconstruction
    - energy cut
- Dominant background (oPs decay)
  - misidentification of 3 photon decays as 2 photon decays
    - 2 of the 3 photons almost colinear
    - one photon very soft



Ps HFS: Event signature

- Experimental signature (pPs decay)
  - 2 matching back-to-back 511 keV photons
    - temporal coincidence
    - vertex reconstruction
    - energy cut
- Dominant background (oPs decay)
  - misidentification of 3 photon decays as 2 photon decays
    - 2 of the 3 photons almost colinear
    - one photon very soft
- Granular detector
  - good spatial, temporal, and energy resolution



- Beltrame et al., The AX-PET demonstrator – Design, construction and characterization. 2011.

Ps HFS: Simulation results

- Simulation
  - rate on the order of 10^5 e^+/s
  - 25% Ps conversion efficiency
- optimization for S/N
  - % level detection efficiency
  - S/N ≈ 10
- projected sensitivity
  - ± 10 ppm (stat.)

Ps HFS: Simulation results

- Simulation
  - rate on the order of 10^5 e^+/s
  - 25% Ps conversion efficiency
- optimization for S/N
  - % level detection efficiency
  - S/N ≈ 10
- projected sensitivity
  - ± 10 ppm (stat.)
  - ± 4 ppm (syst.)

Summary of systematic errors.

Source	Errors in Δ_{HFS} (ppm)
Material Effect:	
o-Ps pick-off	3.5
Gas density measurement	1.0
Temperature measurement	0.1
Spatial distribution of density and temperature in the RF cavity	2.5
Thermalization of Ps:	
Initial kinetic energy E_0	0.2
DBS result σ_m	0.5
pick-off result σ_m	[illegible]
Magnetic Field:	
Non-uniformity	3.0
Offset and reproducibility	1.0
NMR measurement	1.0
RF System:	
RF power	1.2
Q_L value of RF cavity	1.2
RF frequency	1.0
Power distribution in the cavity	< 0.1
Others:	
Choice of timing window	1.8
Choice of energy window	0.6
Polarization of e^+	< 0.2
Phase of microwaves	< 0.1
o-Ps lifetime	< 0.1
p-Ps lifetime	< 0.1
Quadrature sum	6.4

- A. Ishida et al. New Precision Measurement of Hyperfine Splitting of Positronium. *Phys. Rev. Lett. B*, 734:338–344, June 2014.

Ps HFS: Current status and outlook

- Status
  - 2s excitation optimization working well
  - microwave system successfully tested and up to spec
  - microwave chamber being commissioned
  - new detector DAQ tested and being commissioned

Ps HFS: Current status and outlook

- Status
  - 2s excitation optimization working well
  - microwave system successfully tested and up to spec
  - microwave chamber being commissioned
  - new detector DAQ tested and being commissioned
- Outlook
  - precision of a few ppm should be achievable → probe discrepancy with bound state QED
  - more precise measurements feasible
    - LN2 cooling of resonator (increase Q factor significantly)
    - increase MW power (TWT amplifier)
    - improved event analysis (pattern recognition, e.g. neural net)
    - limited by systematic uncertainties

more information:
arXiv:1805.05886

PI: Paolo Crivelli

Additional Credits: G. Wichmann, D. Cooke, A. Antognini, K. Kirch, A. Rubbia

BACKUP SLIDES

CPT – Violation

- CPT can be naturally broken (e.g. in string theory)
- Breaks Lorentz symmetry
- Can be well described at low energy scales as effective field theory:
  Standard Model Extension (SME)
  - built from General Relativity and the Standard Model
  - includes Lorentz- and CPT violating operators
  - up to mass dimension 4 (minimal SME) and above
  - coefficients have to be determined experimentally

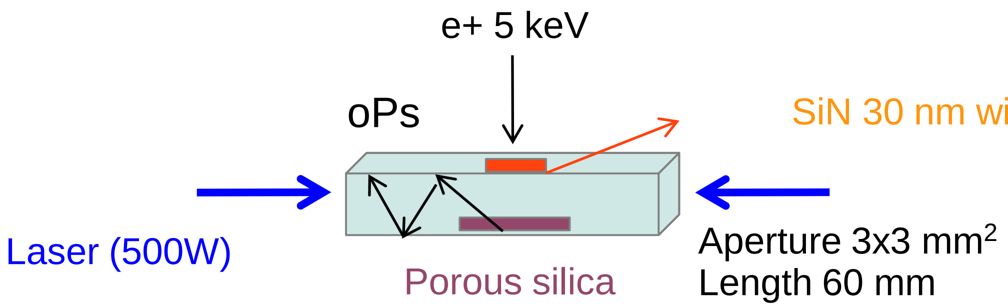
- Colladay, D., & Kostelecký, V. A. (1997). CPT violation and the standard model. Phys. Rev. D, 55(11), 6760-6774.

Spectroscopy and the minimal SME

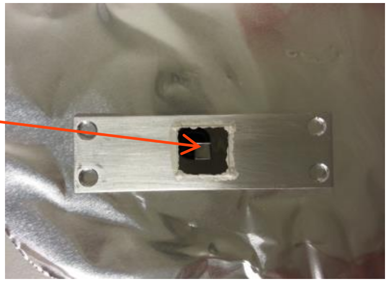
- Minimal SME terms can produce striking effects, e.g.
  - Hydrogen sector
    - time dependent shifts in hydrogen spectra (e.g. annual shifts)
    - different hydrogen and anti-hydrogen spectra
  - Positronium sector
    - SM forbidden momentum-polarization correlations in Positronium decay
    - shifts in Positronium spectrum from Lorentz-invariant values
      - 1s-2s transition
      - hyperfine splitting

- Kostelecký, V. A.; Vargas, A. J. (2015). Lorentz and CPT tests with hydrogen, antihydrogen, and related systems. Phys. Rev. D 92, 056002.
- Adkins, G.S., arXiv:1007.3909.

Ps 1S-2S: original detection scheme

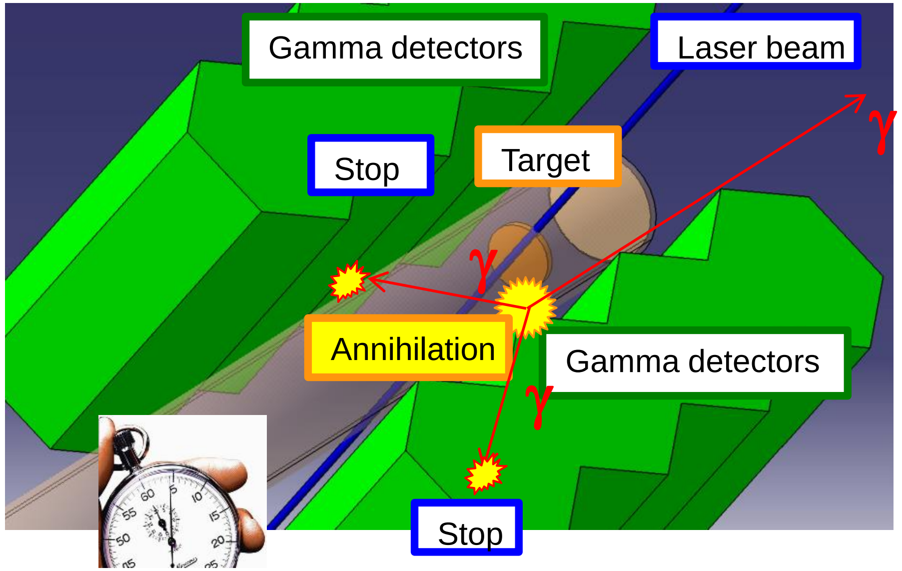


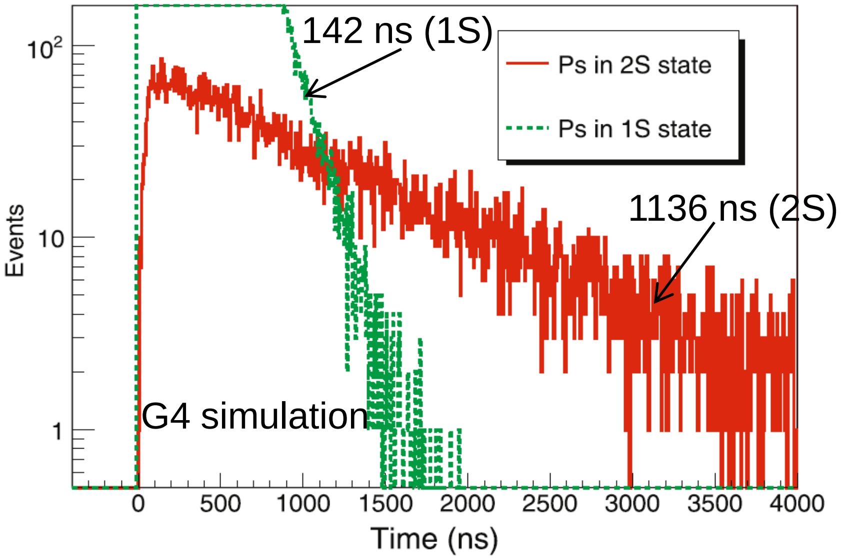
SiN 30 nm window 3x3 mm^2



Detection of annihilation photons. Lifetime of excited S states ~ n^3

$\tau_{2S} / \tau_{1S} = 8$





Ps HFS: Review - First direct measurement

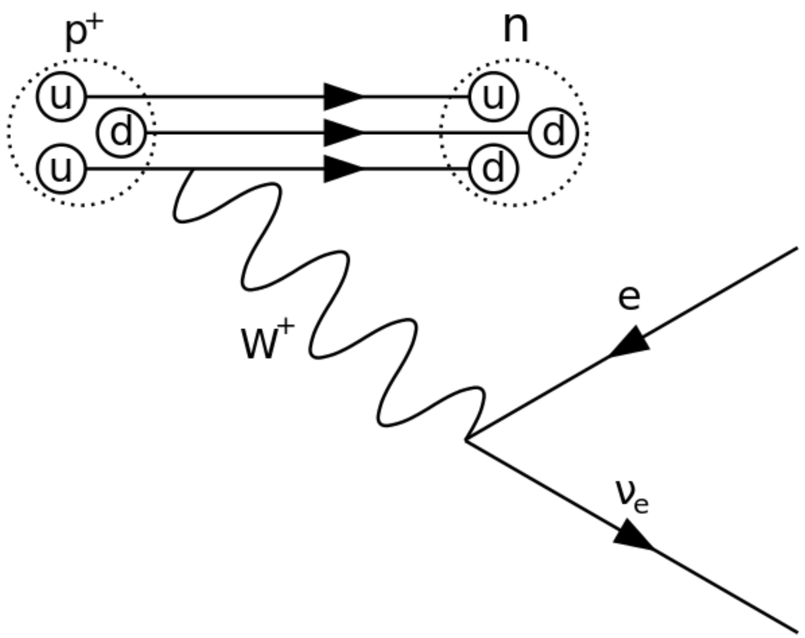
- Notoriously difficult ($\Delta\nu = 203\ GHz$)
  - no off-the-shelf sources
  - no off-the-shelf resonators
  - behavior somewhat between microwave and light
- Multiple resonators required
  - need to be changed for every frequency point
- Needs very high MW power
  - very rudimentary power estimation
    - measured the heat absorbed by water

Parameter
$\Delta^{\mathrm{Ps}}_{\mathrm{HFS}}$ [GHz]
Theory
203.391 69(16)
Direct Measurement
$203.39^{+0.15}_{-0.14} \pm 0.11$

- A. Miyazaki et al. First millimeter-wave spectroscopy of ground-state positronium. *Progress of Theoretical and Experimental Physics*, 2015(1), 2015.

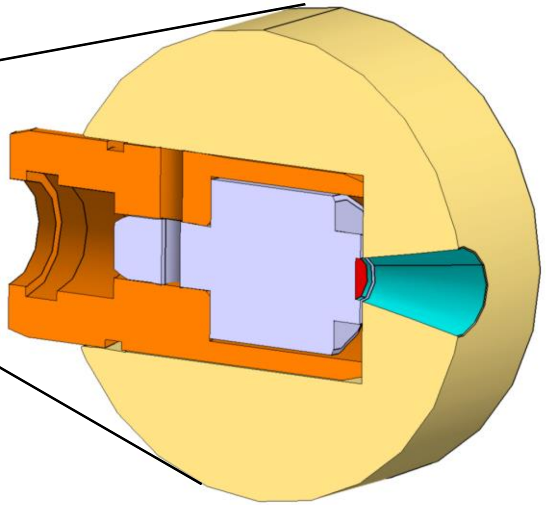
Positron production

- Positrons produced in β^+ decay of ^{22}Na
  - $^{22}Na \rightarrow \, ^{22}Ne^* + \nu_e + e^+$
    - continous spectrum: 0 – 543 keV
    - moderate half-life: $\tau_{1/2}$ = 2.6a
  - $^{22}Ne^* \rightarrow \, ^{22}Ne + \gamma$
    - discrete energy: 1.27 MeV
    - almost immediate process: 3.7 ps delay
    - can be used to tag β^+ decay of ^{22}Na
- Need for moderate rate sources
  - CW beam: 300 MBq
  - Pulsed beam: 350 MBq

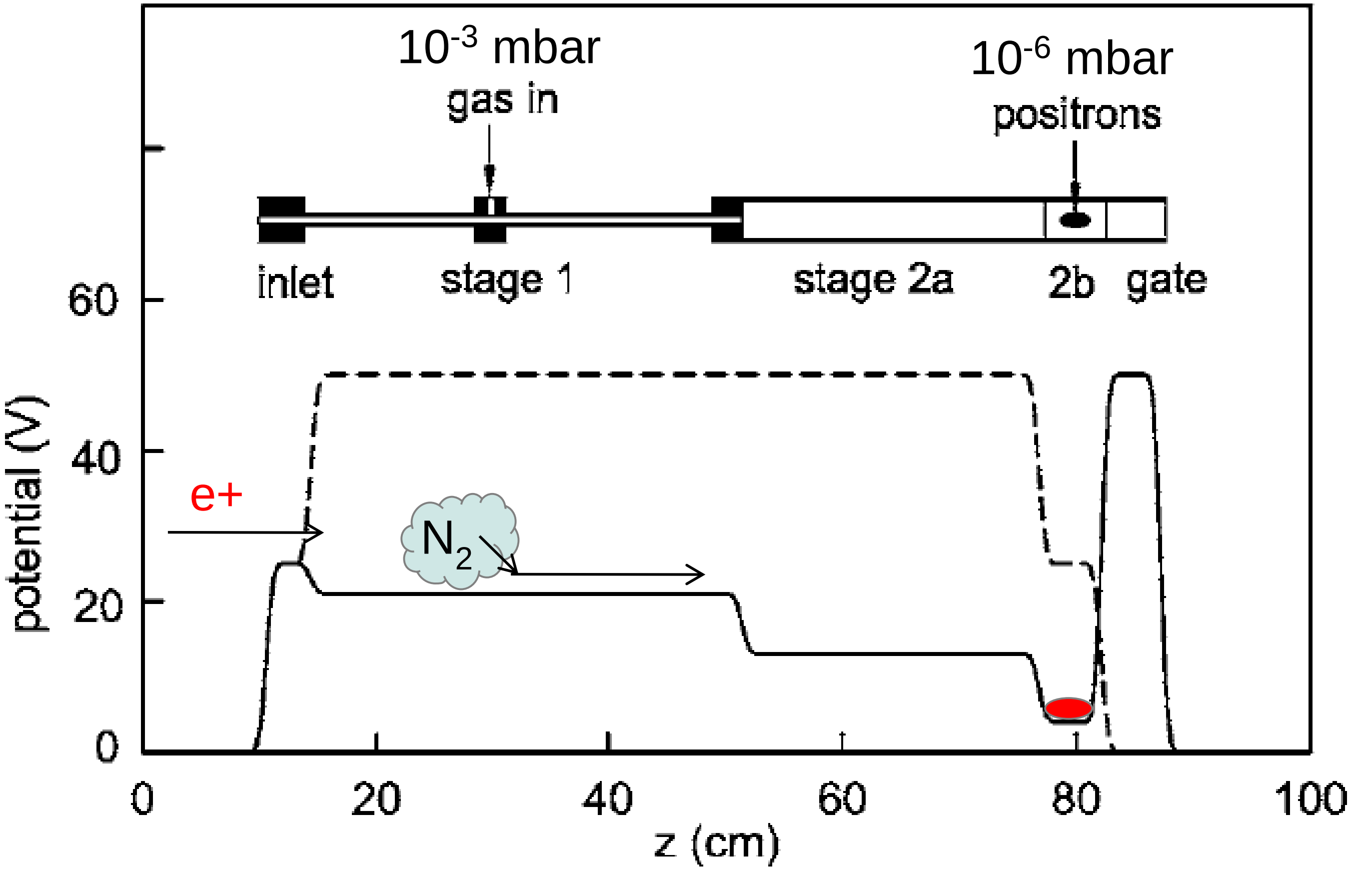


Positron moderation

- Large energy spread: use moderation
- Solid rare gas moderation
  - 4K cold head
  - tungsten allow shield
  - ^{22}Na in capsule with
    5µm titanium window
  - solid neon film is grown
    - e^{+} loses energy only inefficiently
      below band gap (≈20eV)
    - large fraction of e^{+} is emitted
      into vacuum with epithermal energies



Buffer gas trap

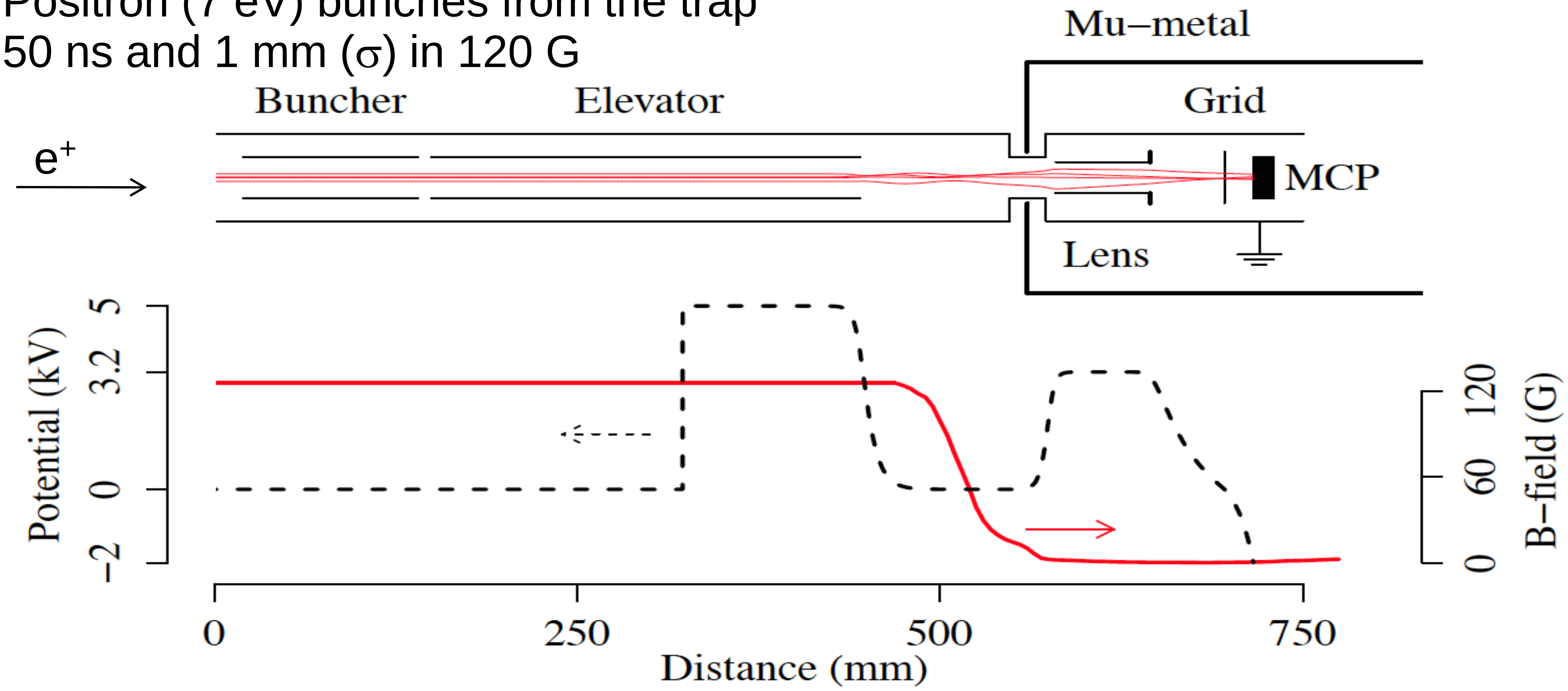


B-field up to 1 kG

Positrons in few eVs bunches (50 ns)
At 10 Hz rep rate

Positron bunching and extraction

Positron (7 eV) bunches from the trap
50 ns and 1 mm (σ) in 120 G

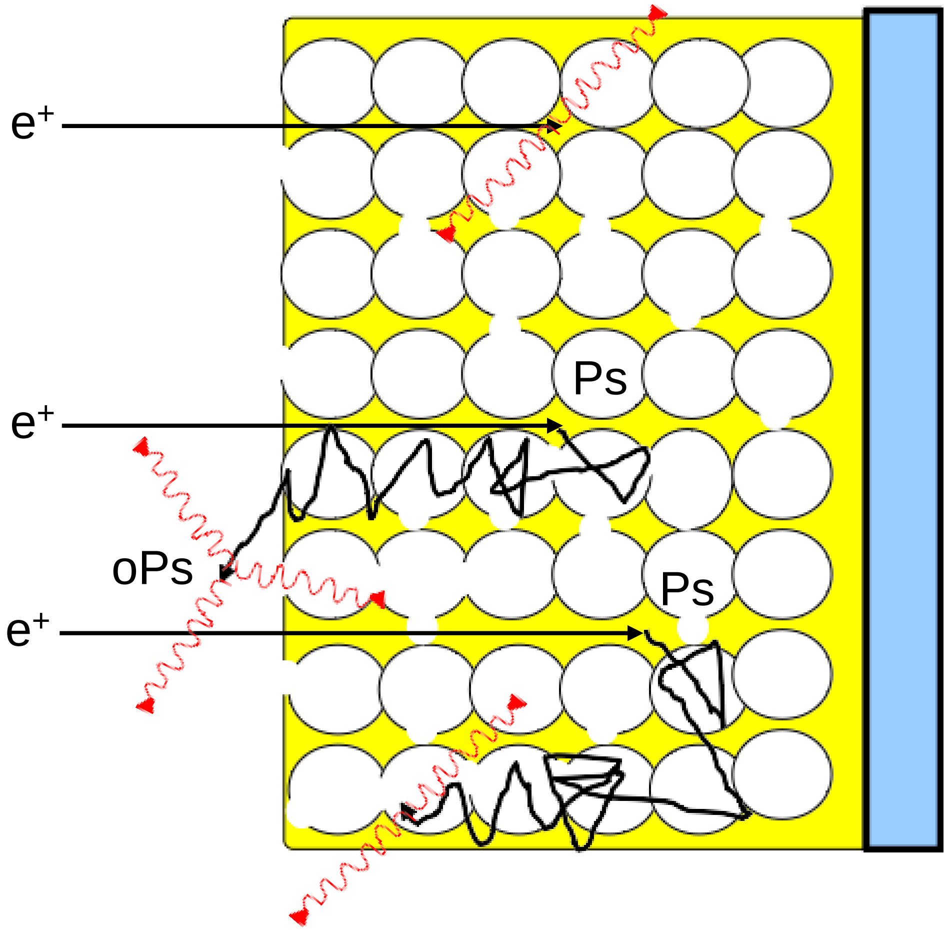


On target (kept at ground): positron bunches of 1 ns with a beam spot of 1 mm extracted to the field free e-m region with 90 % efficiency.

- D. A. Cooke G., Barandun, S Vergani,, B Brown, A Rubbia and P Crivelli, J. Phys. B: At. Mol. Opt. Phys. 49 014001 (2016).

Positronium formation

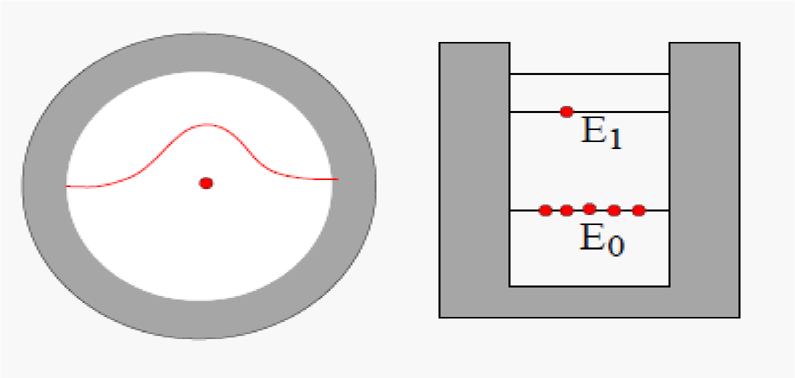
- Implantation in porous silica thin film
  - approx. 1 µm thick, 3-4 nm pore size
  - e^+ energy of a few keV
  - rapid thermalization
- Diffuse and annihilate
- Form Positronium by capturing e^-
  - 25% pPs and 75% oPs
  - diffusion to surface
  - emission into vacuum
    - $W_{Ps} = \mu_{Ps} + E_B - 6.8\text{ eV} < 0\text{ eV}$

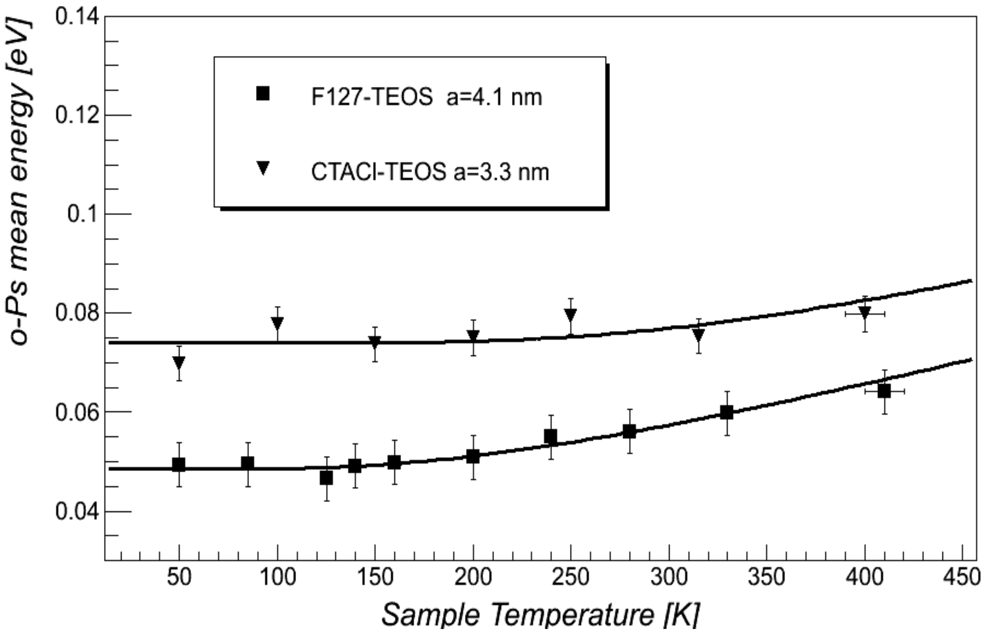


- P. Crivelli et al., Phys. Rev. A. 81, 052703 (2010).

Positronium emission into vacuum

- Very efficient
  - ≈ 30% of incident e^+ produce oPs into vacuum
- Almost monoenergetic
  - ≈ 40 meV (≈ 10^5 m/s!)
  - deBroglie wavelength of Ps:
    - $\lambda_{Ps} = \frac{h}{\sqrt{2\, m_{Ps}\, E_{Ps}}} \approx 0.9nm\, \sqrt{\frac{1eV}{E_{Ps}}}$
    - for ≈100 meV this becomes comparable to pore size!
  - particle in a box
    - $E_{Ps} = \frac{h^2}{2\, m\, d^2} \approx 0.8eV\, \left(\frac{1nm}{d}\right)^2$





- P. Crivelli et al., Phys. Rev. A. 81, 052703 (2010).