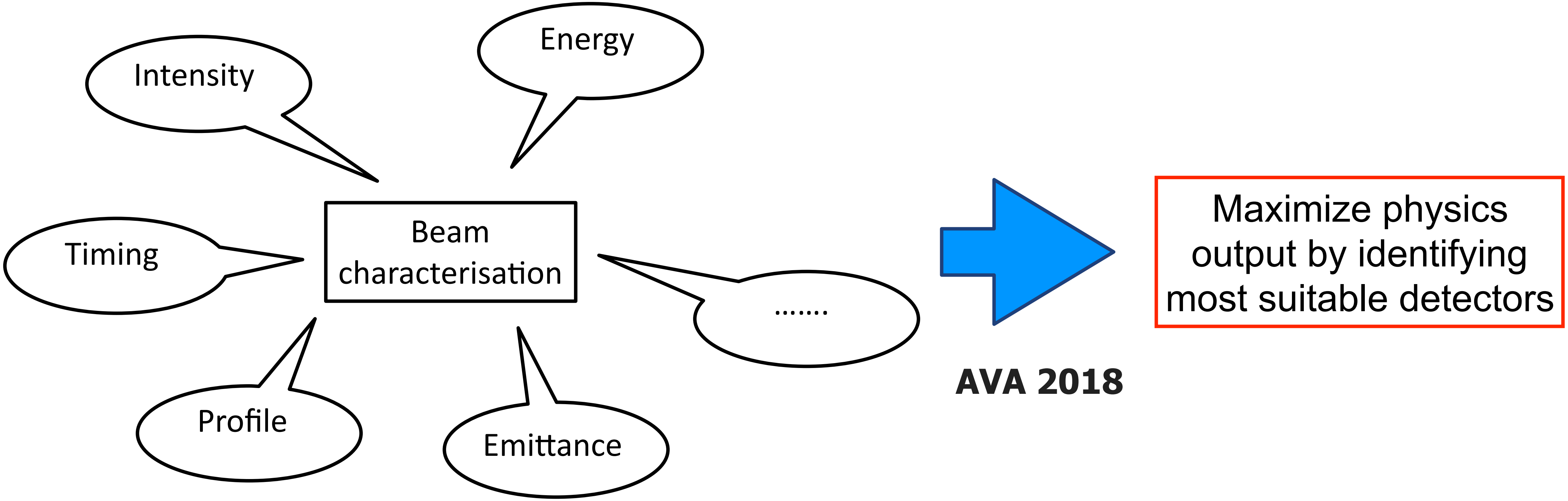
Instrumentation for Antimatter Beams

1st AVA Topical Workshop, 15th of October 2018

Paolo Crivelli, ETH Zurich, Institute for Particle Physics and Astrophysics, 8093 Zurich (Switzerland)

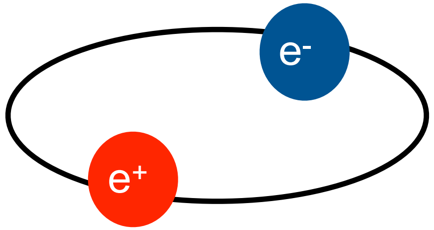
Antimatter Beams:
- Charged low energy (keV range) beams: positrons/positive muons and antiprotons
- Low energy neutral beams (meV-keV range): positronium, muonium, anti-hydrogen

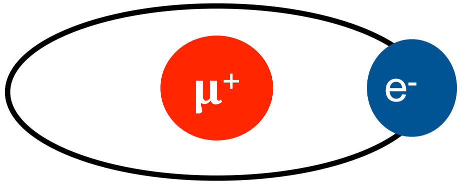


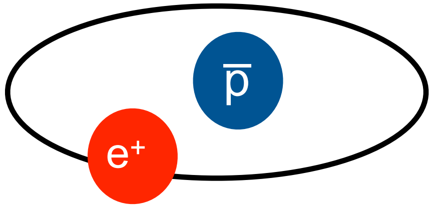
Physics with the simplest exotic atoms and their constituents

Precise bound state QED test free from finite size effects

Fundamental constants







Positronium (Ps)

Muonium (Mu)

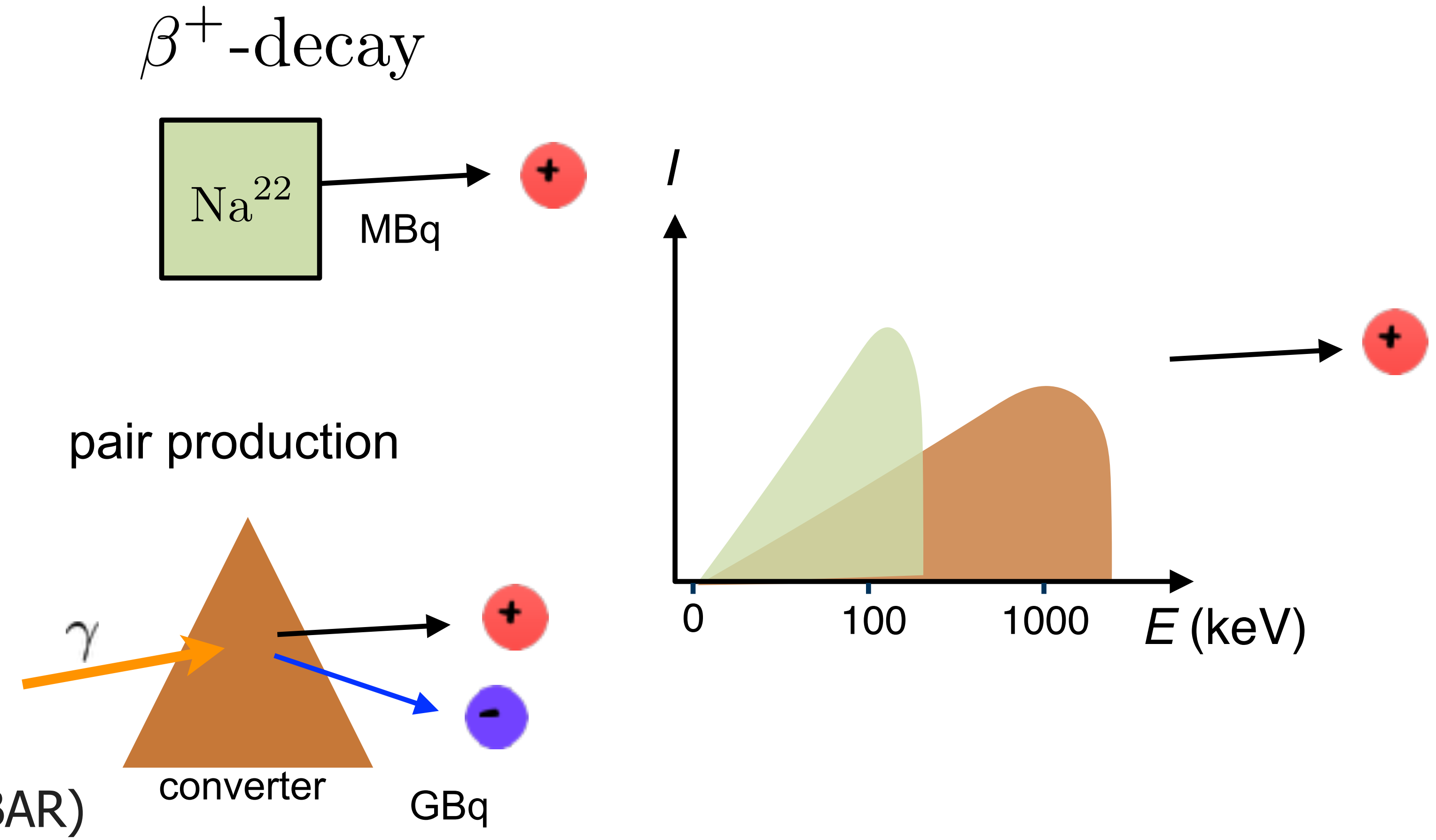
Anti-hydrogen (H̄)

Test fundamental symmetries and search for new physics

Test effect of gravity on anti-matter

Applications in material science

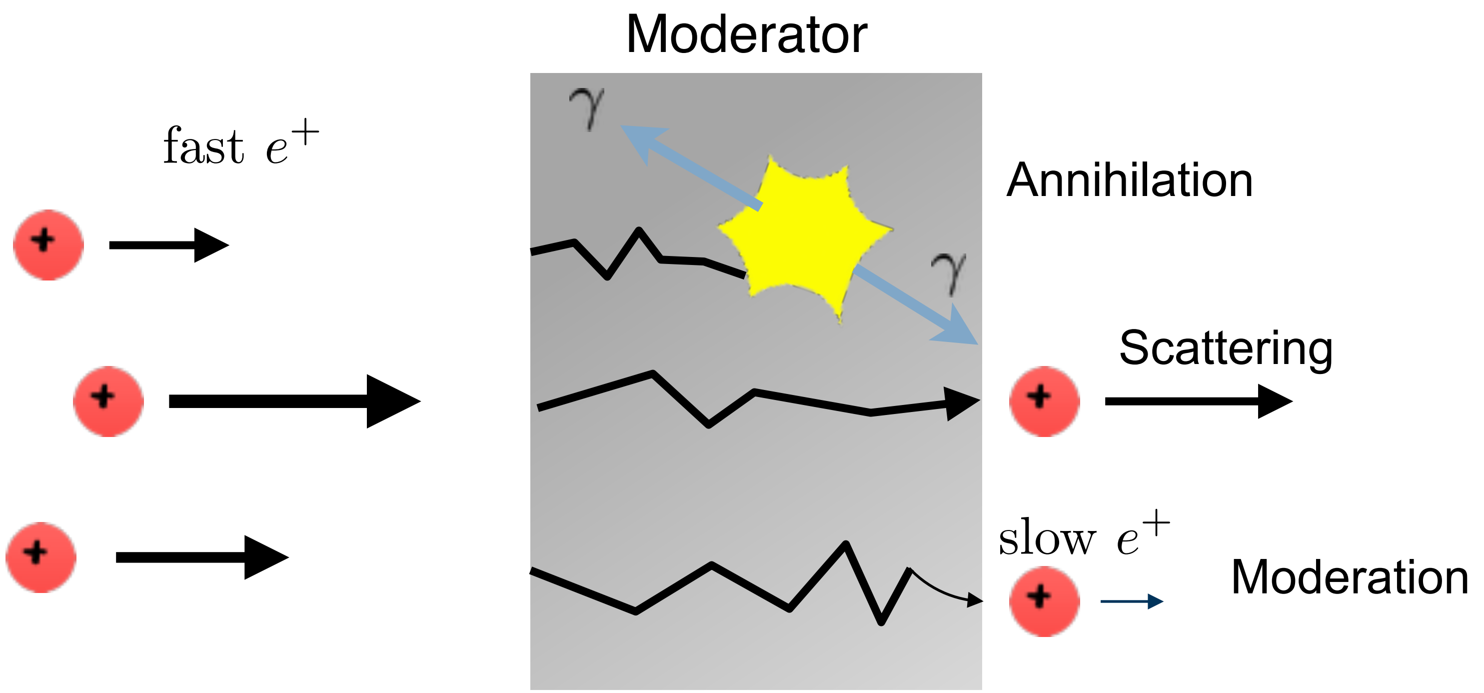
Positron sources



BEAM
mono energetic
e^+ necessary

LINAC (e.g. GBAR)
Nuclear reactors

Moderation



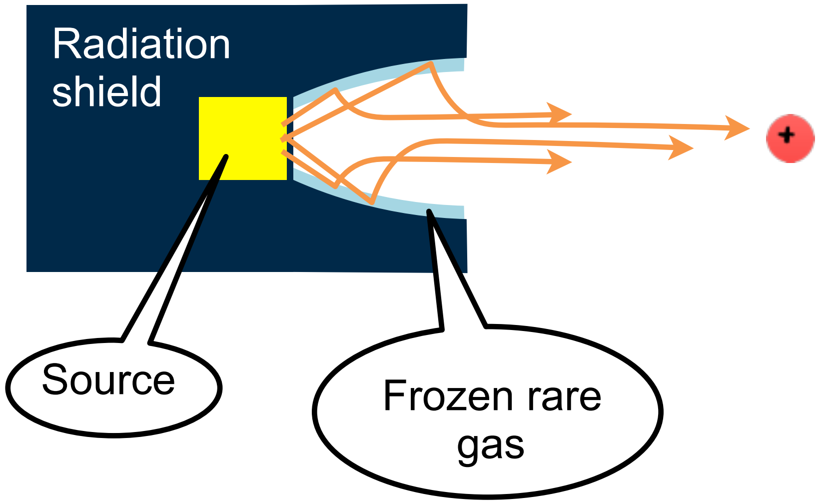
moderation efficiency

$$\epsilon = \frac{\text{slow } e^+}{\text{fast } e^+}$$

Moderators

Rare gas moderators
Ne, Ar, …

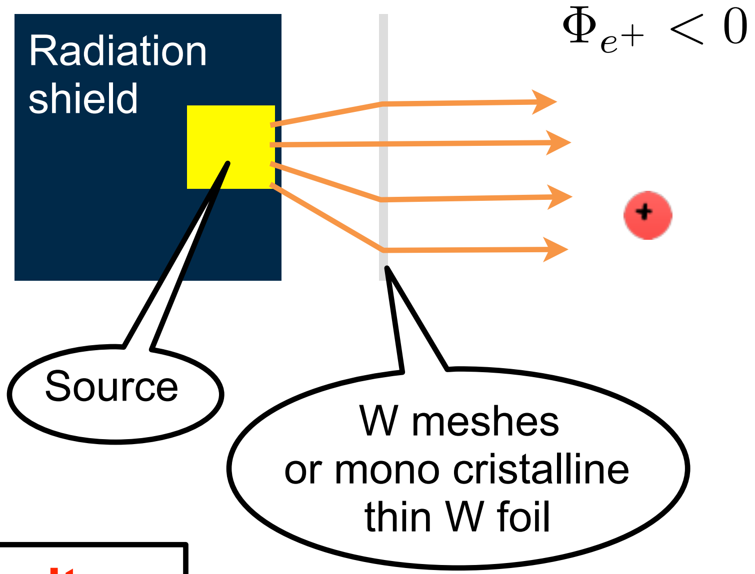
Long diffusion length



$\epsilon \approx 10^{-3}$

Metal moderators
W, Ni, …

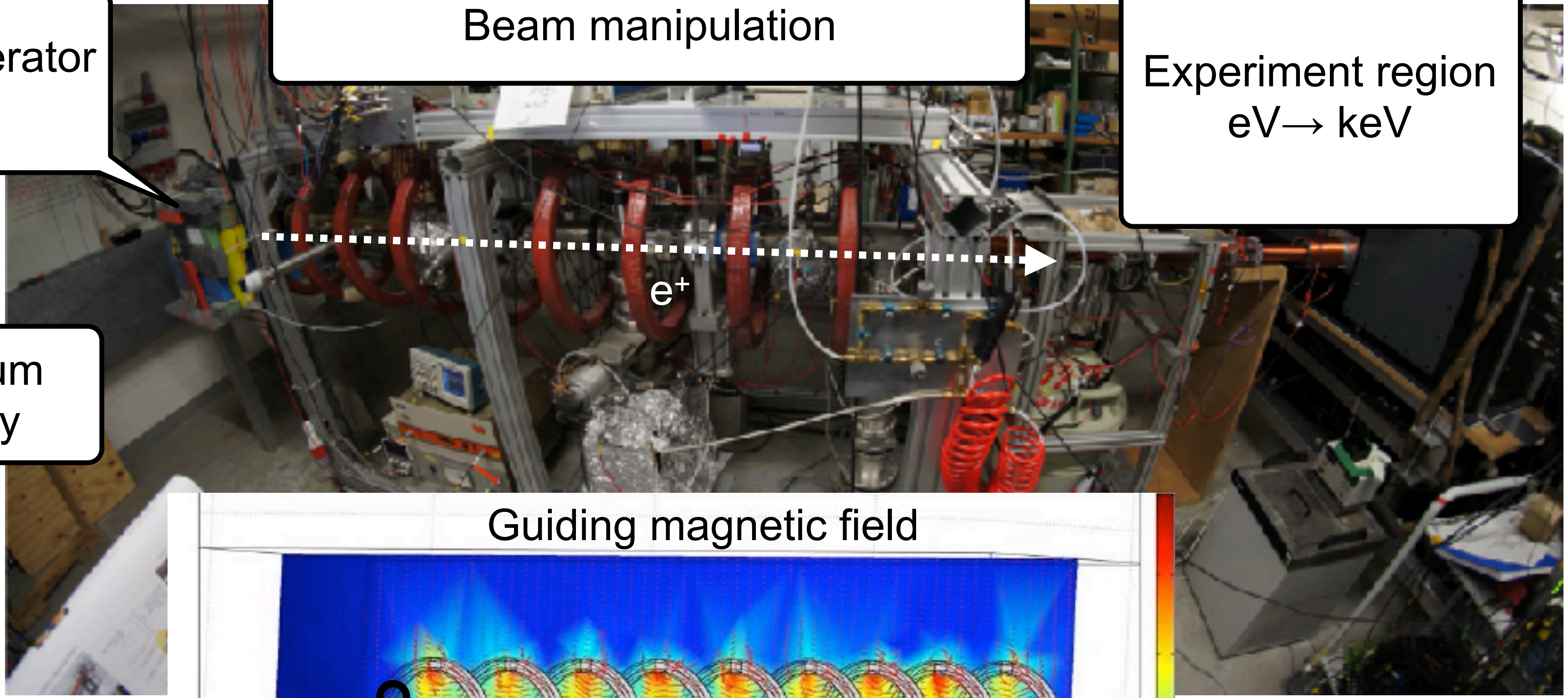
Negative workfunction

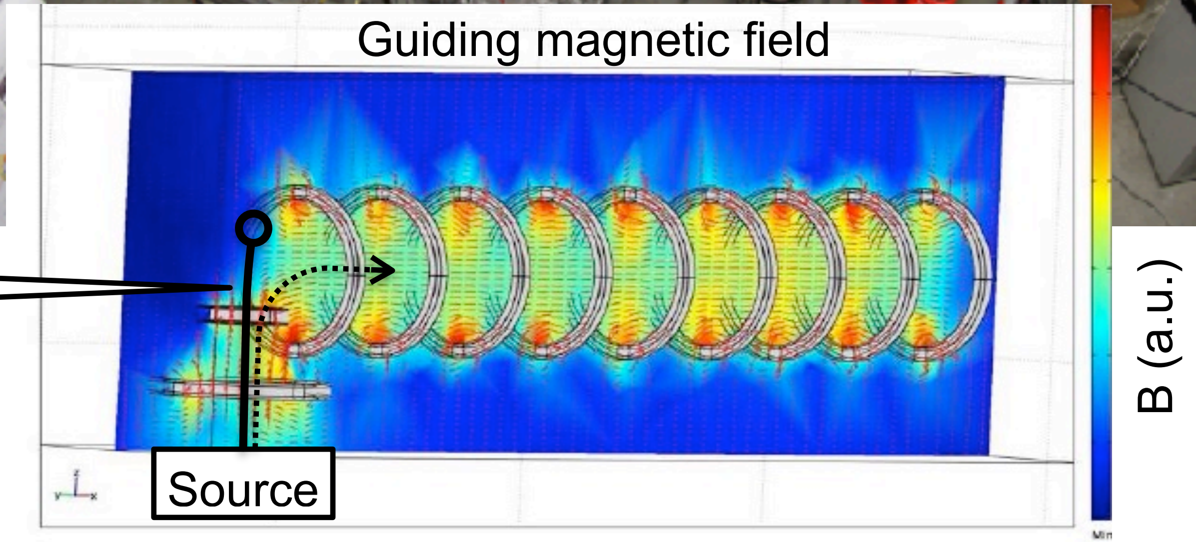


$\epsilon \approx 5 \cdot 10^{-5}$

Mono-energetic positron with few eV energies

CW Positron beam

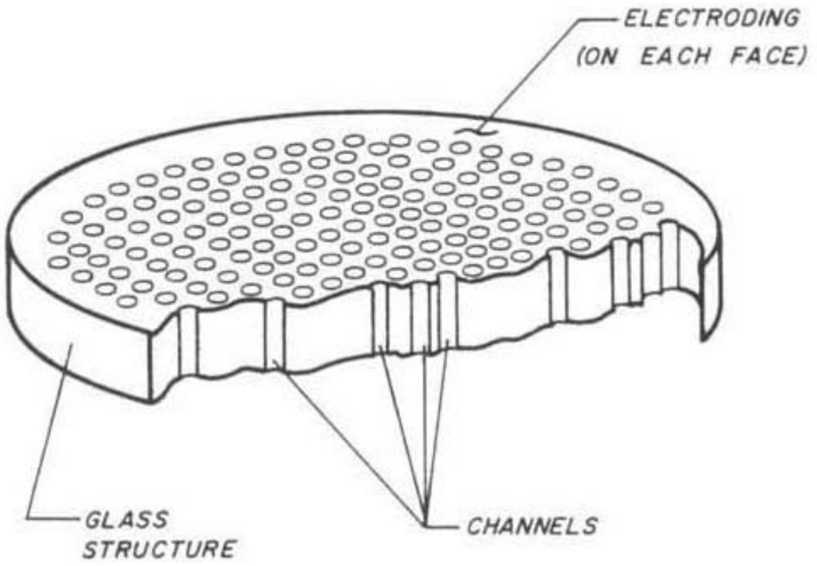


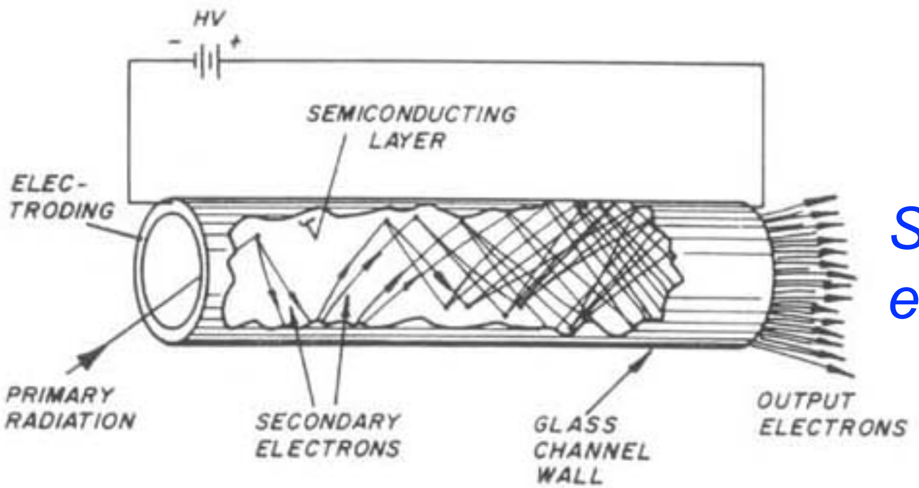


CW Positron beam - characterisation/tagging

Intensity →	Annihilation plate + Scintillator detecting gamma Micro-channel-plate (MCP)
Profile →	Movable aperture+ scintillator detecting gamma Position sensitive MCP
Positron Tagging →	Detection of secondary electrons emitted when the positron hit the target with MCP

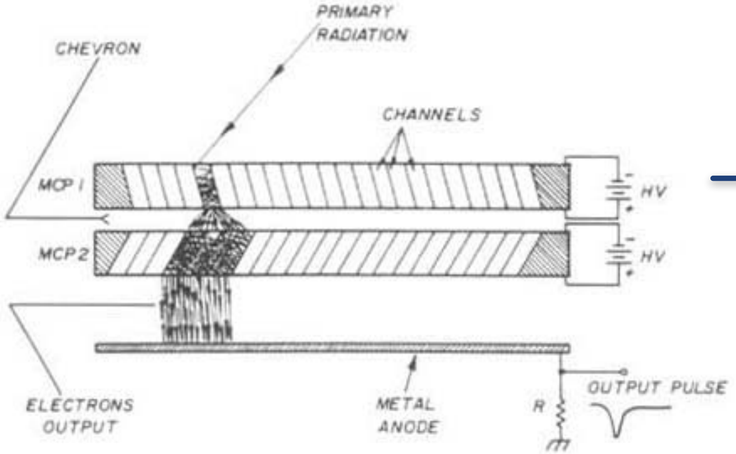
Micro Channel Plates (MCPs)

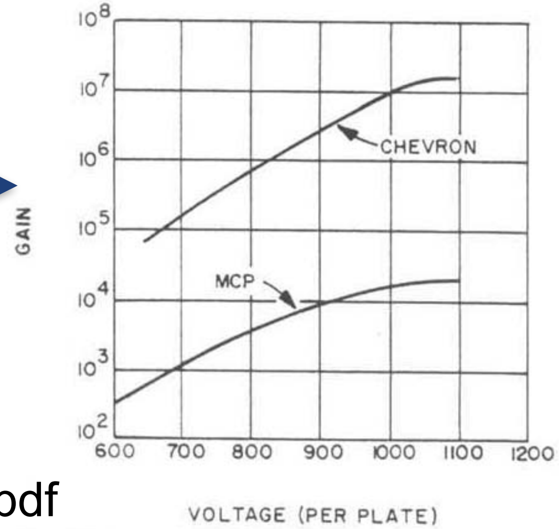




Straight channel electron multiplier

Chevron geometry





https://www.photonis.com/uploads/literature/library/TP209_MCP_Reprint.pdf
https://www.hamamatsu.com/resources/pdf/etd/MCP_TMCP0002E.pdf

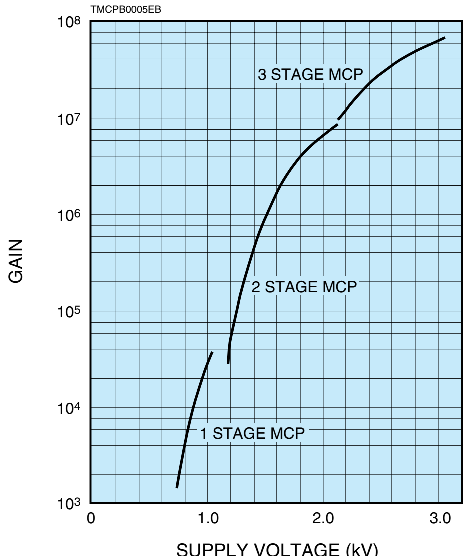
MCPs - typ. performances

Typical performances:
- High gains: typ. 10^6 (Chevron geometry)
- Fast rising time < 1 ns
  → excellent timing <100 ps
- low dark count rate: few 1/(s.cm²)
- work in high magnetic fields

TABLE I: Detection efficiency of channel multipliers[a].

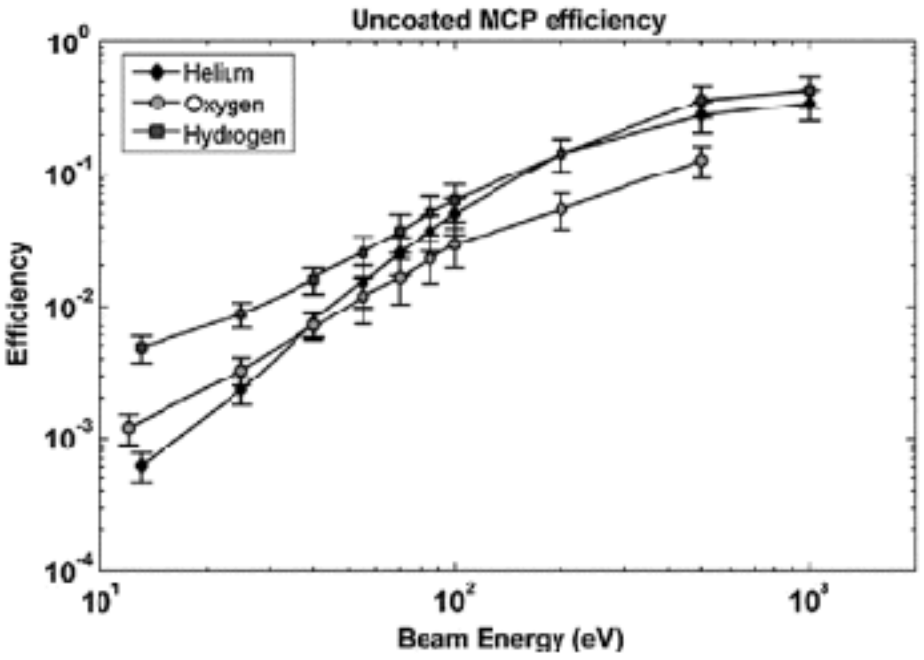
Type of radiation		Detection efficiency (%)
Electrons	0.2 - 2 keV	50-85
	2 - 50 keV	10-60
Positive ions	0.5 - 2 keV	5-85
(H+, He+, A+)	2 - 50 keV	60-85
	50 -200 keV	4-60
U.V. radiation	300 - 1100 Å	5-15
	1100-1500 Å	1-5
Soft X-rays	2 -.50 Å	5-15
Diagnostic X-rays	0.12 - 0.2 Å	~1

[a] From Schagen[17]).



MCP detection efficiency for neutral atoms

For keV neutrals high detection efficiency, around 100 eV in the % level and below 10 eV basically < 10^{-4})



ELENA microchannel plate detector: absolute detection efficiency for low energy neutral atoms, Optical Engineering 52(5):051206-051206, DOI: 10.1117/1.OE.52.5.051206

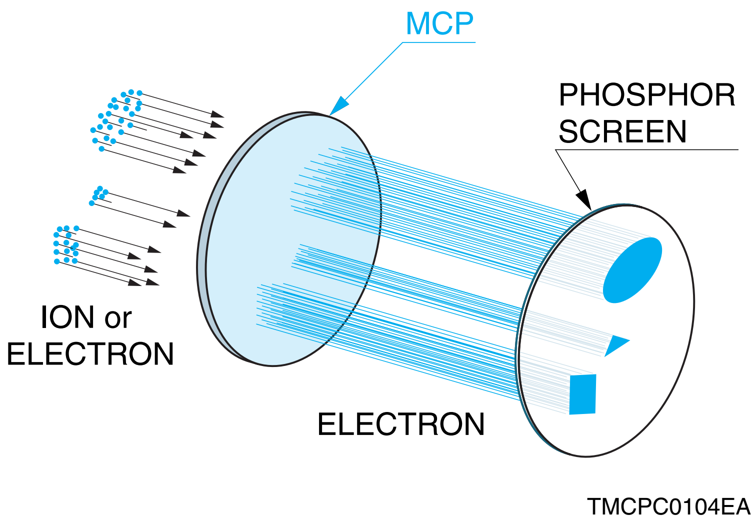
CW Positron beam - characterisation/tagging

Intensity → Annihilation plate + Scintillator detecting gamma
Micro-channel-plate (MCP)

Profile → Movable aperture+ scintillator detecting gamma
Position sensitive MCP

Positron Tagging → Detection of secondary electrons emitted when the positron hit the target with MCP

MCP - position sensitivity, phosphor screen

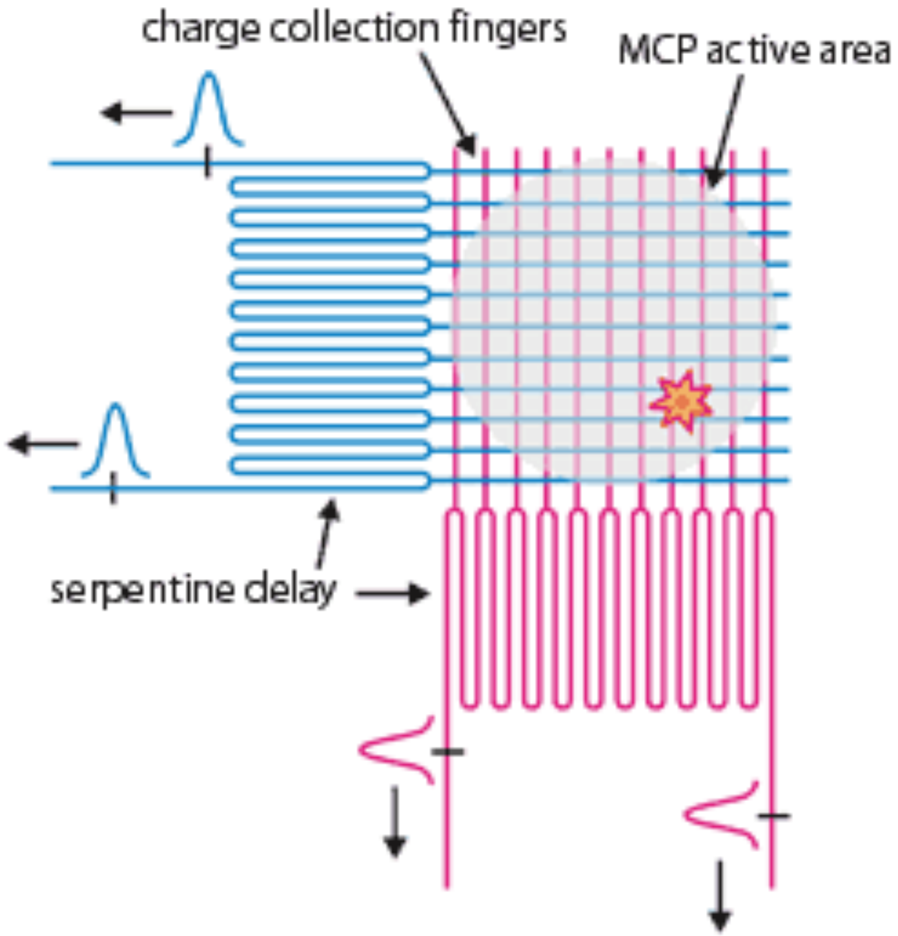


Readout with CCD camera

Phosphor screen type	Peak emission wavelength (nm)	Emission color	Relative energy efficiency ①	10 % decay time	Remarks
P43	545	Yellowish green	1	1 ms	Standard type
P46	510	Yellowish green	0.3	0.2 µs to 0.4 µs ②	Short decay
P47	430	Purplish blue	0.3	0.11 µs	Very short decay

https://www.hamamatsu.com/resources/pdf/etd/MCP_TMCP0002E.pdf

MCP - delay line



Signals to TDC:
time difference used to reconstruct position

$$X = (x_1 - x_2) \cdot v_\perp$$
$$Y = (y_1 - y_2) \cdot v_\perp$$

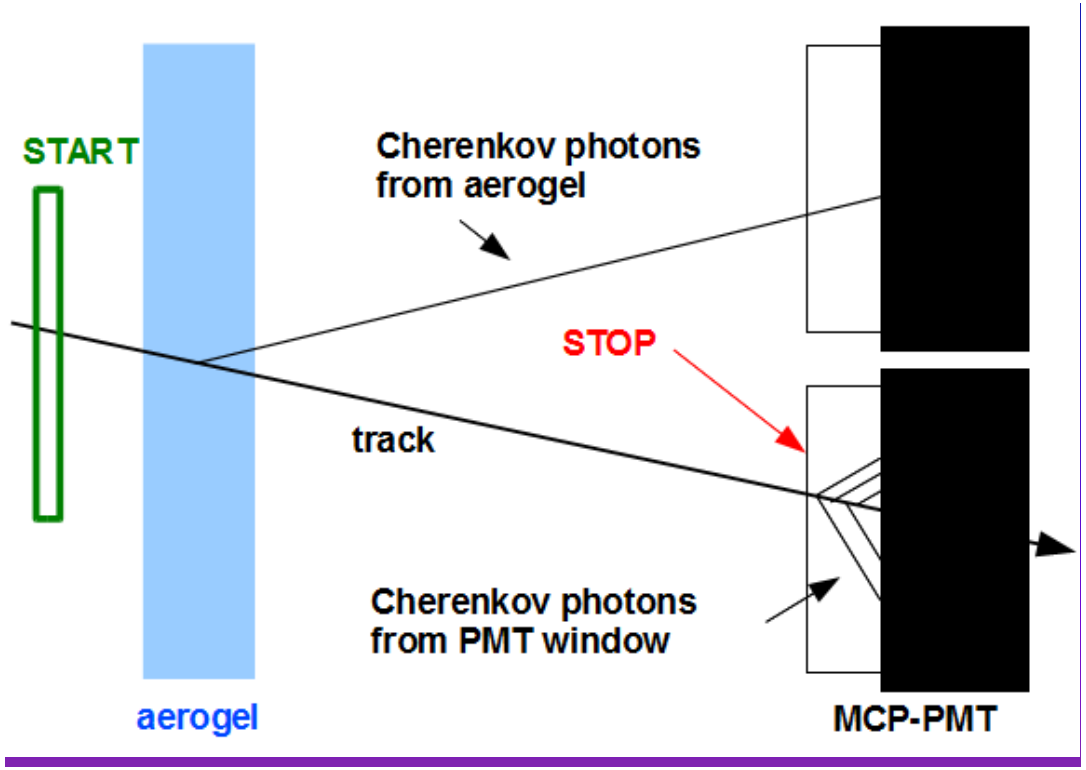
typical perp. propagation velocity in delay line 1 mm/ns

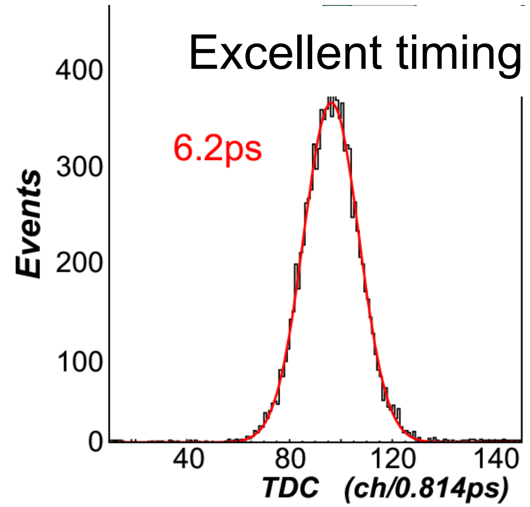
Typical spatial resolution of 50 microns

$$\sigma_X = \sigma_{\mathrm{dx}} \cdot v_\perp$$

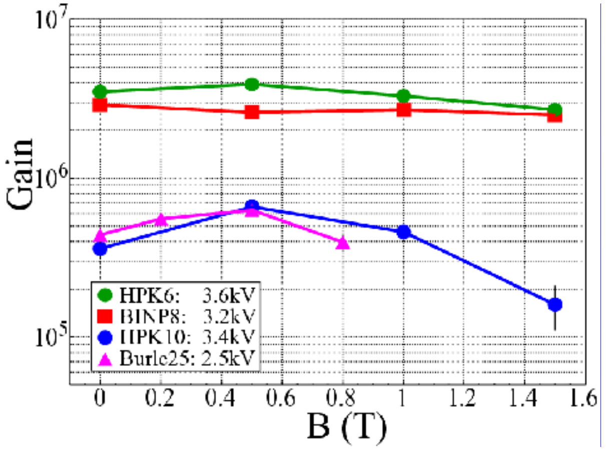
O. H. W. Siegmund, P. Jelinsky, S. Jelinskyk, J. Stock, J. Hull, D. Doliber, J. Zaninovich, A. S. Tremsin, and K. Kromer, “High resolution cross delay line detectors for the GALEX mission,” in *Proc. SPIE*, vol. 3765, 1999, pp. 429–440.

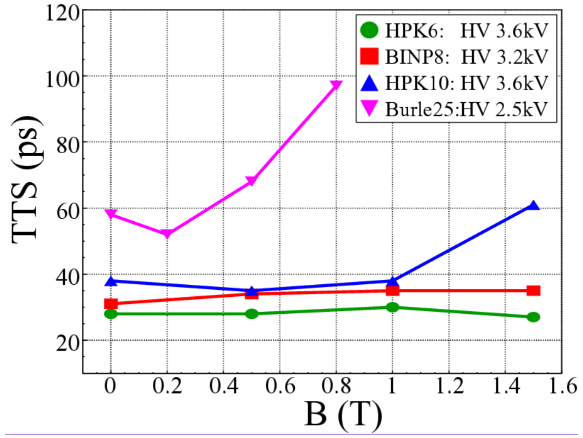
MCP-PMT





Operation in axial magnetic field vs pore diameter





N. Dinu, T. Gys, C. Joram, S. Korpar, Y. Musienko, V. Puill, D. Renker
https://indico.cern.ch/event/111710/attachments/37211/53776/mcppmt.pdf

MCP- Summary

Other techniques
- Timepix readout: +very good position sensitivity (tens of μm), - 1 μs time resolution
- Sensing wires: + cheap, - limited (100 microns) spatial resolution https://doi.org/10.1016/j.nima.2010.08.009
- Resistive anodes https://doi.org/10.1016/j.nima.2017.08.032

https://arxiv.org/ftp/arxiv/papers/1806/1806.07133.pdf

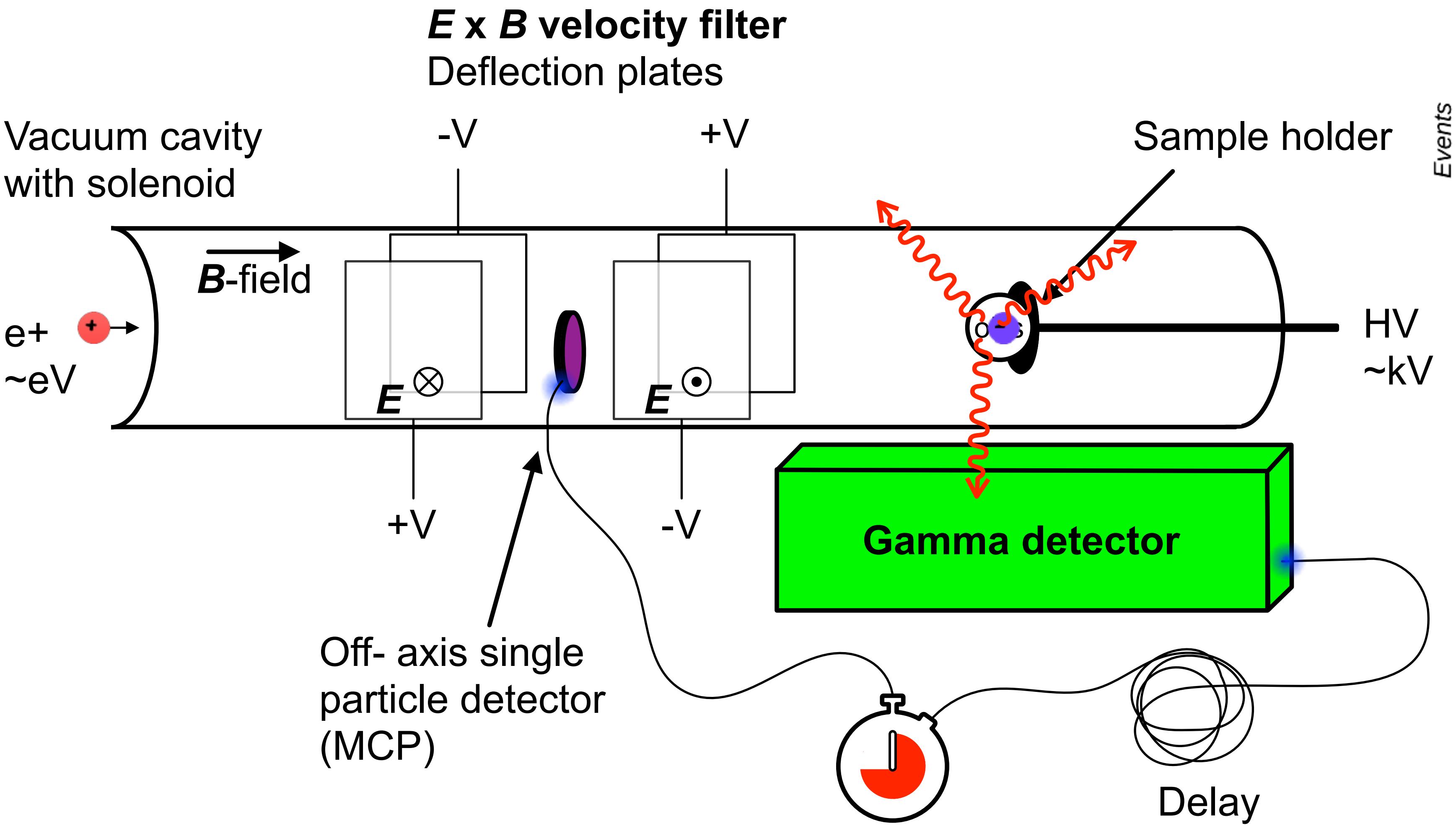
MCP are a great tool for detection of charged particles
- Very good spatial resolution
- Excellent time resolution
- High rate capability
- Operation if high magnetic field

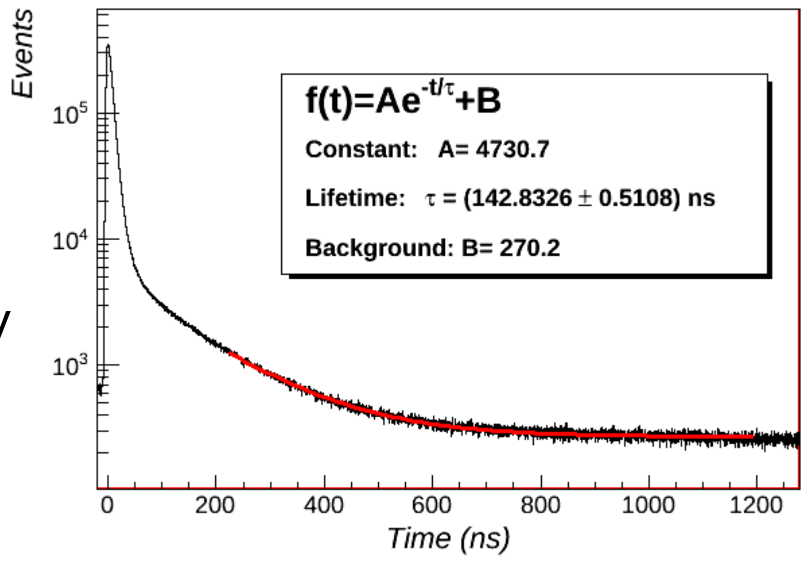
Drawbacks:
- destructive technique
- very inefficient for low (<100 eV) energy neutral antimatter beams

CW Positron beam - characterisation/tagging

Intensity	Annihilation plate + Scintillator detecting gamma Micro-channel-plate (MCP)
Profile	Movable aperture+ scintillator detecting gamma Position sensitive MCP
Positron Tagging	Detection of secondary electrons emitted when the positron hit the target with MCP

Positron tagging and annihilation's photon detection





Positron tagging with SE- perfomances & limitations

- Time resolution limited to about 1 ns (good enough for oPs studies)
- Efficiency dependent on positron implantation energy
  (few 10%@ 1kV to few % at 10 kV)

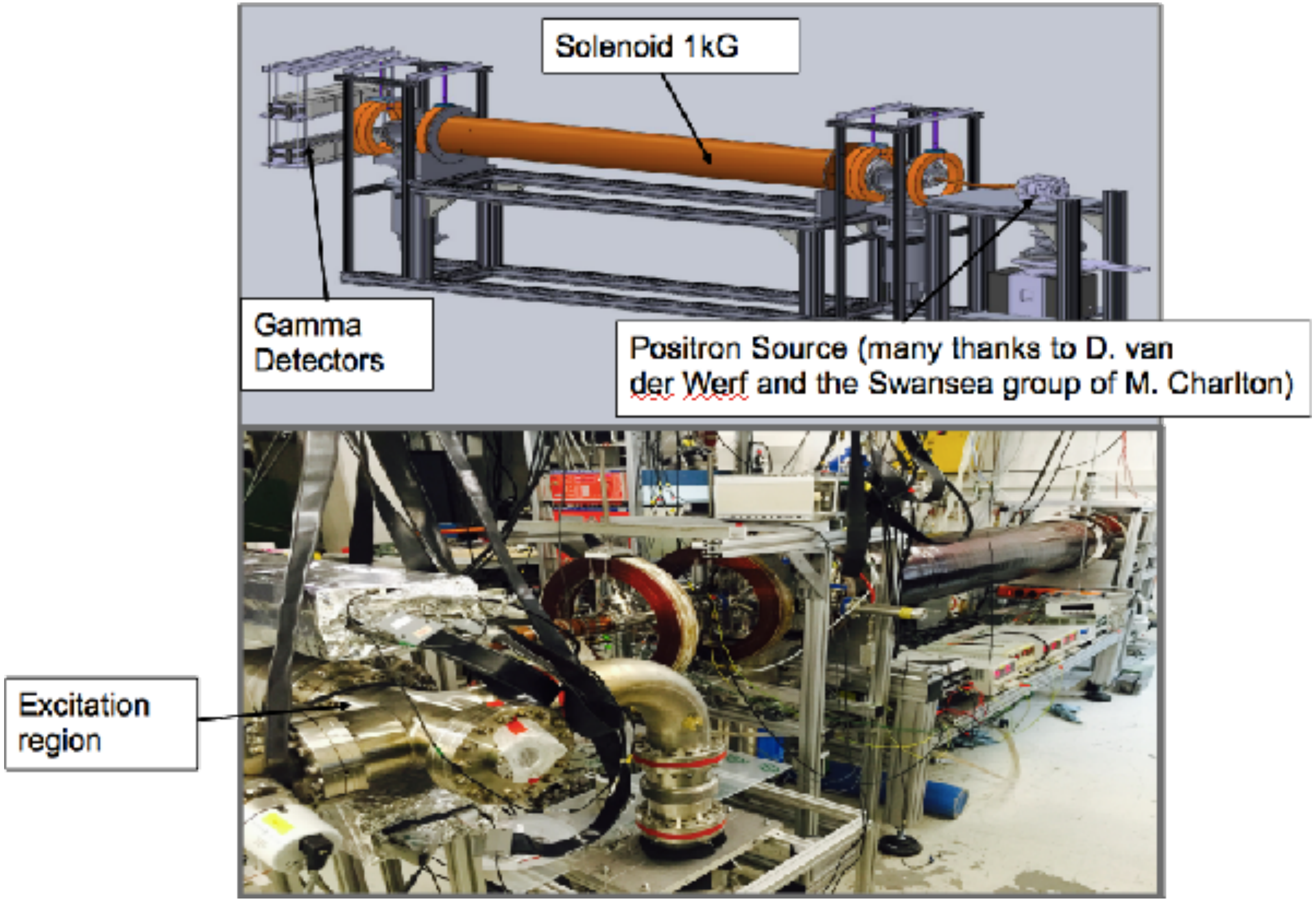
Could those performances be improved with alternative detection scheme?

Great potential for material characterisation with positrons

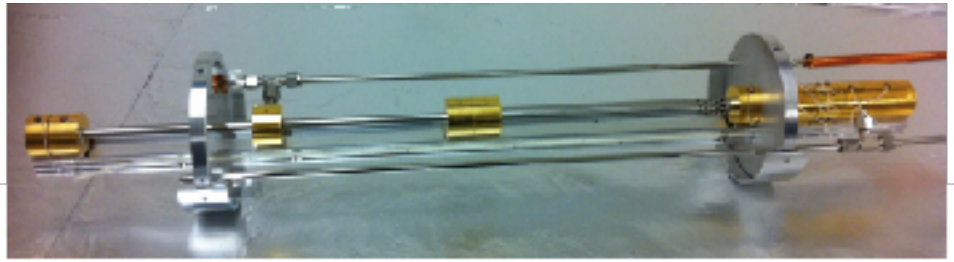
see e.g "Shedding New Light on Nanostructured Catalysts with Positron Annihilation Spectroscopy"

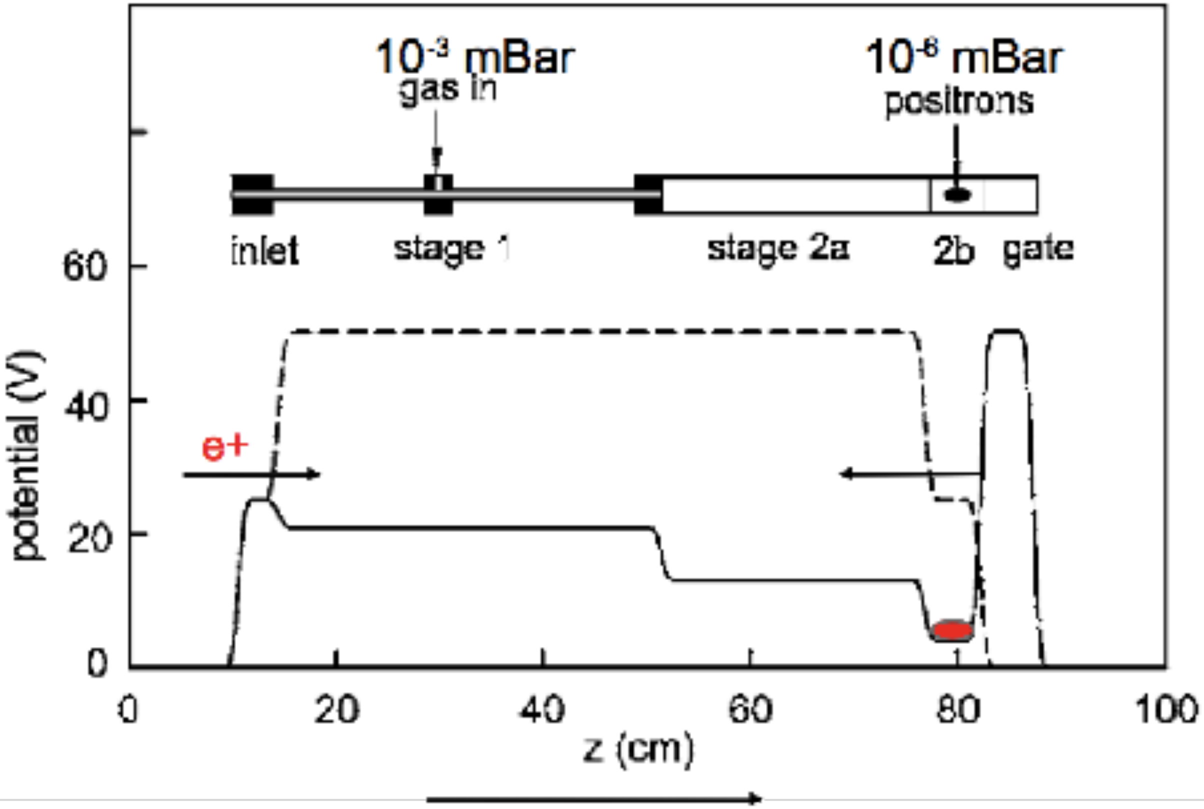
https://doi.org/10.1002/smtd.201800268

Pulsed Positron beam (buffer gas trap)



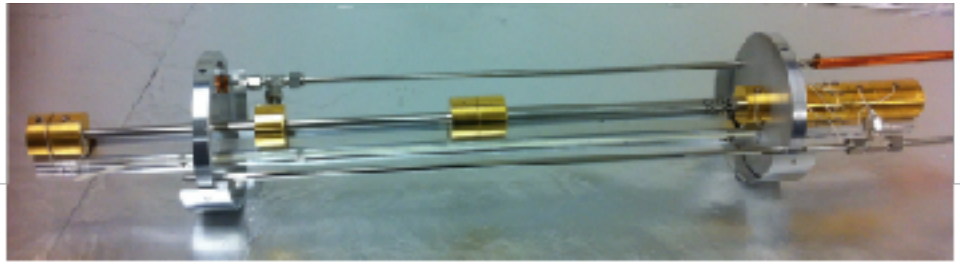
Principle of a buffer gas trap

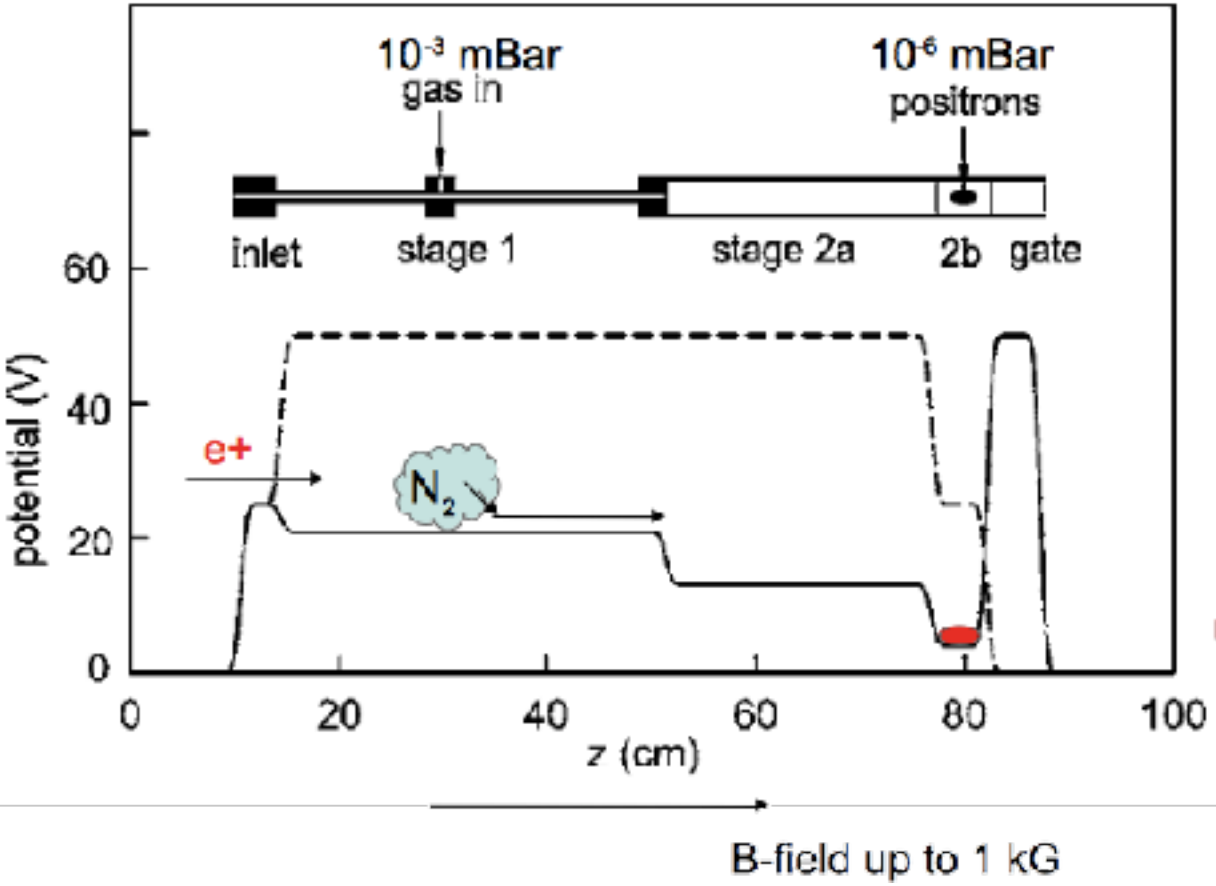




B-field up to 1 kG

Principle of a buffer gas trap





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

Pulsed Positron beam - characterisation/tagging

Intensity	Annihilation plate + Scintillator detecting gamma ~~Micro-channel-plate (MCP)~~ saturation
Profile	Movable annihilation plate + scintillator detecting gamma Position sensitive MCP
Time structure	Annihilation plate + Scintillator detecting gamma Micro-channel-plate (MCP)

Single Shot Positron Annihilation Lifetime spectroscopy (SSPALS)

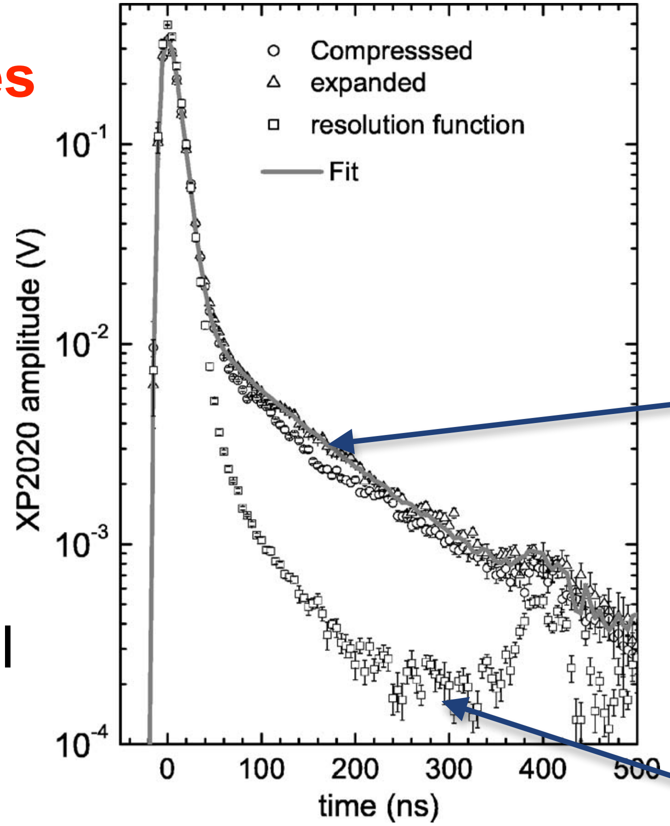
Measurement of positronium lifetimes from single intense bursts

Lead tungstate PbWO4:
fast decay time <15 ns
low afterglow

Output split and recorded with scope:
to reduce digitisation noise two channel with high and low gain

Alternative:
Cherenkov radiator such as PbF2 (time resolution 20→ 4 ns)

D. Cassidy and A. Mills, NIMA 580 (2007) 1338–1343



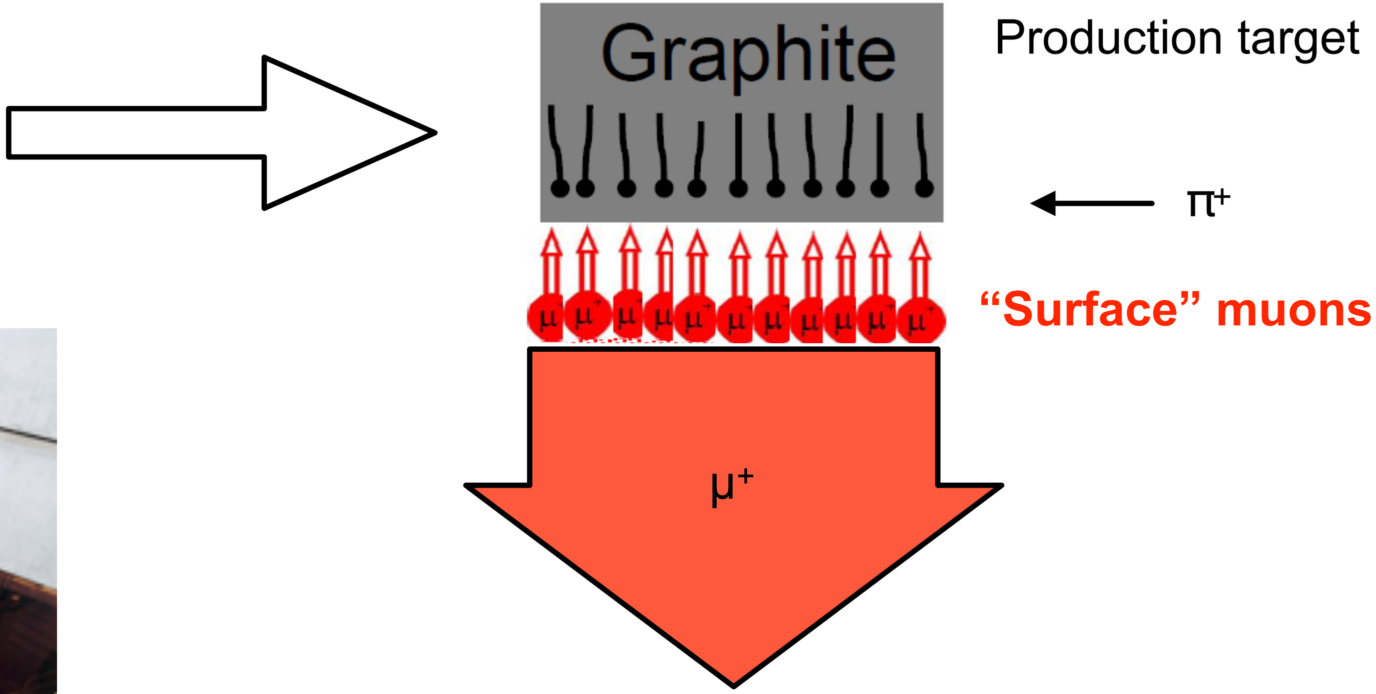
D. Cassidy et al.
Appl. Phys. Lett. **88**, 194105 (2006);

positronium formation,
porous target (long lifetime)

no positronium formation,
e.g. Al target

Muon beam generation

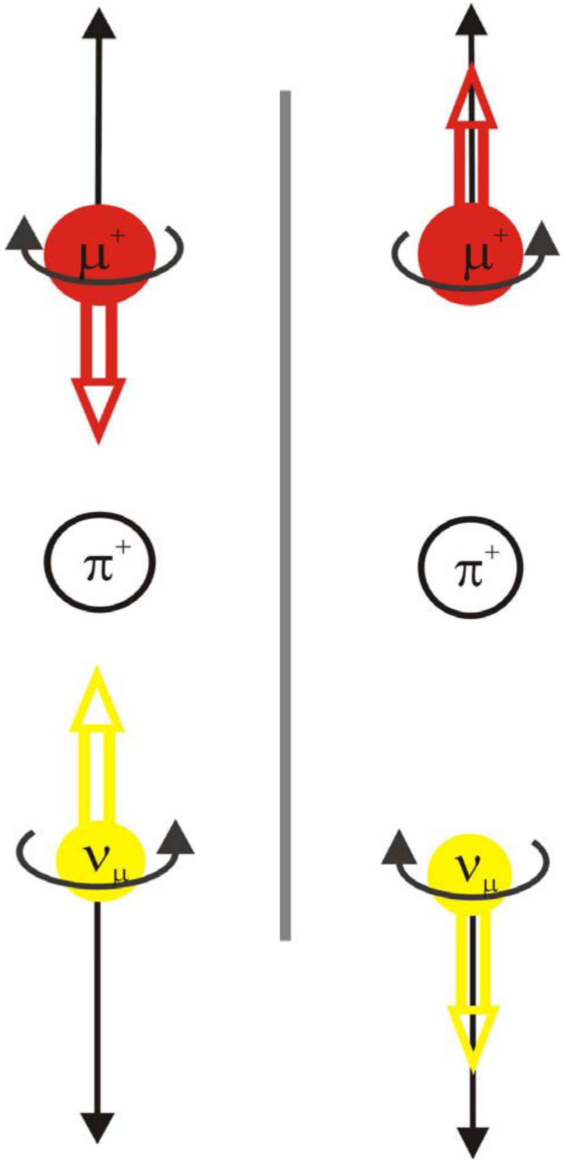
- 2.2 mA ~ 1.4 x 10^{16} Protons/s
- ~600 MeV
- p+C → $\pi^+ + \pi^- +$ p + n + …



- 10^7-10^8 μ^+/s
- 100% polarized
- 4 MeV
  - generally used for "bulk" condensed matter studies
  - For thin film studies E = eV-30 keV

Polarized positive muons

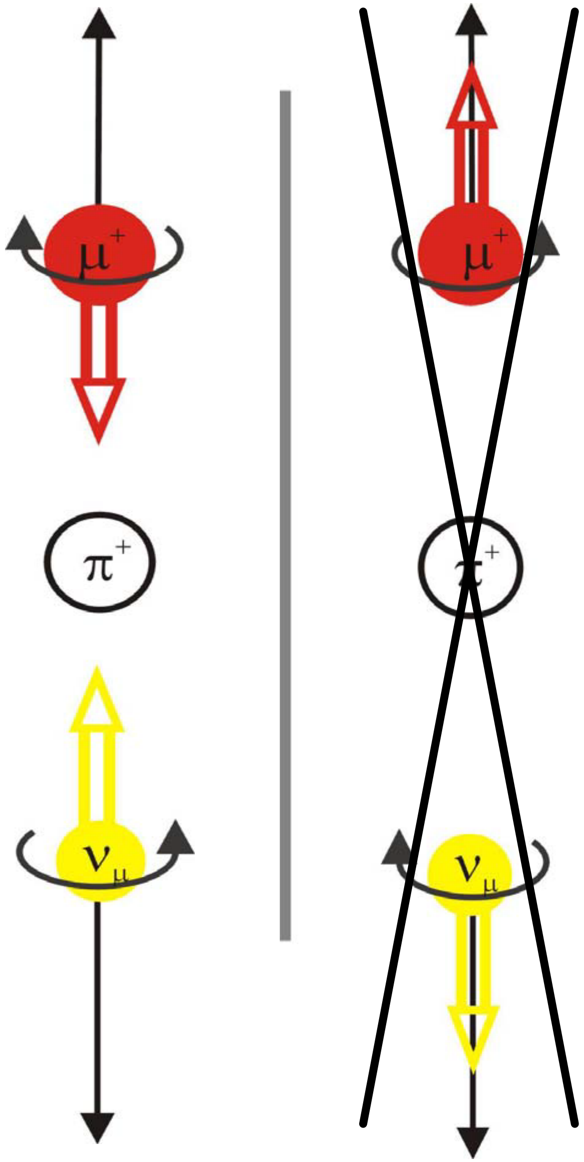
- Kinematics of pion decay at rest;
  - From energy and momentum conservation:
    - Momentum: p = 29.79 MeV/c
    - Kinetic energy: E = 4.12 MeV



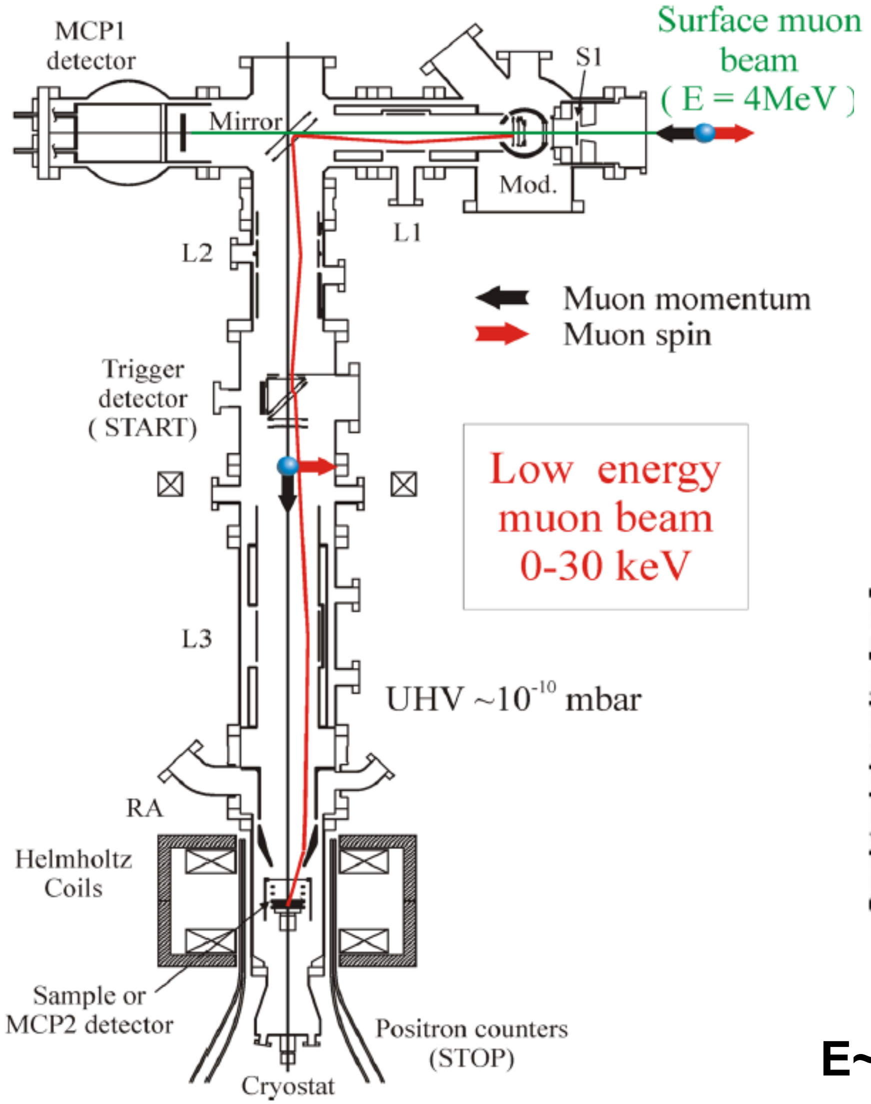
Polarized positive muons

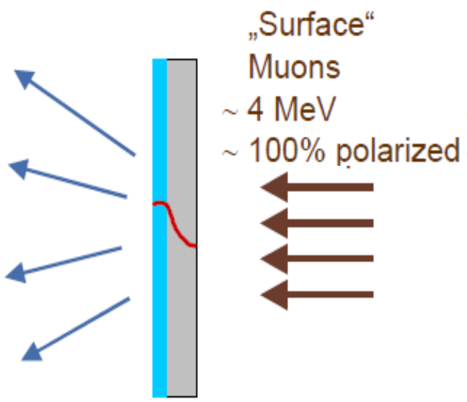
- Kinematics of pion decay at rest;
  - From energy and momentum conservation:
    - Momentum: p = 29.79 MeV/c
    - Kinetic energy: E = 4.12 MeV

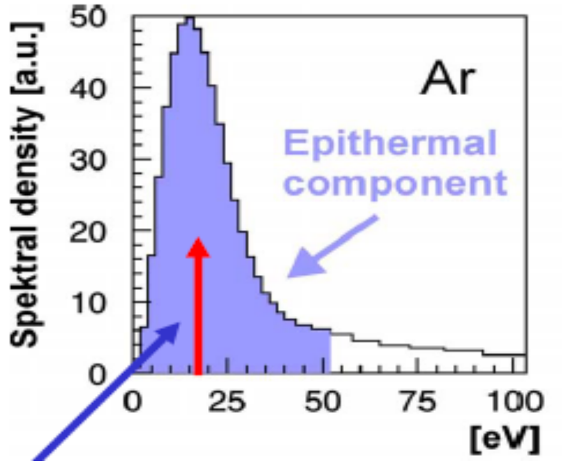
- Parity violation in weak interaction
  - Neutrinos are left handed
  - Polarized muon beam with spin anti-parallel to their momentum



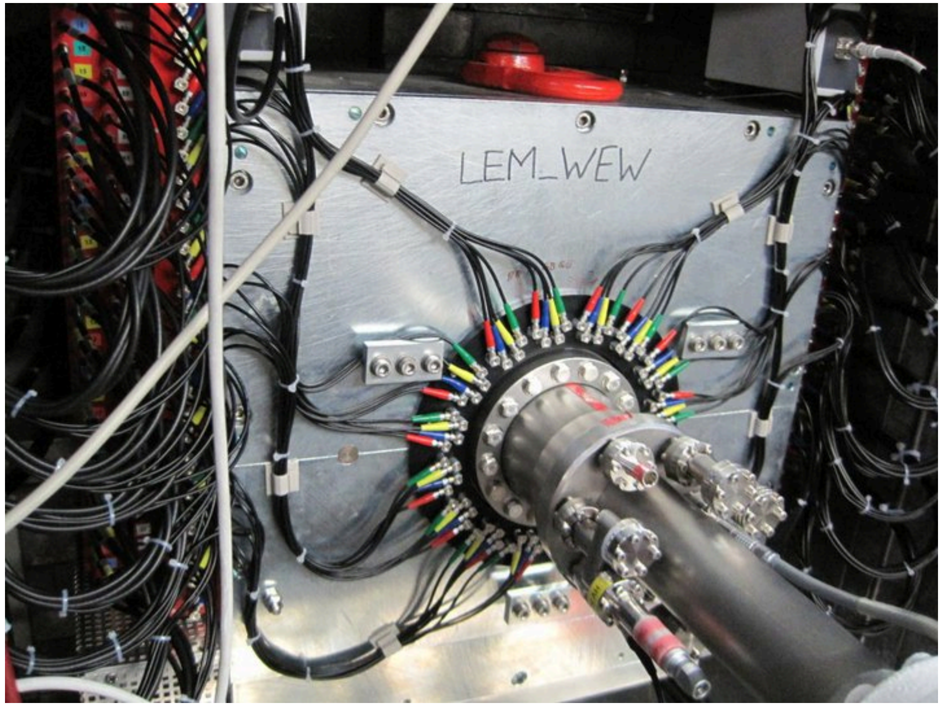
Low energy muon (LEM) beam @PSI



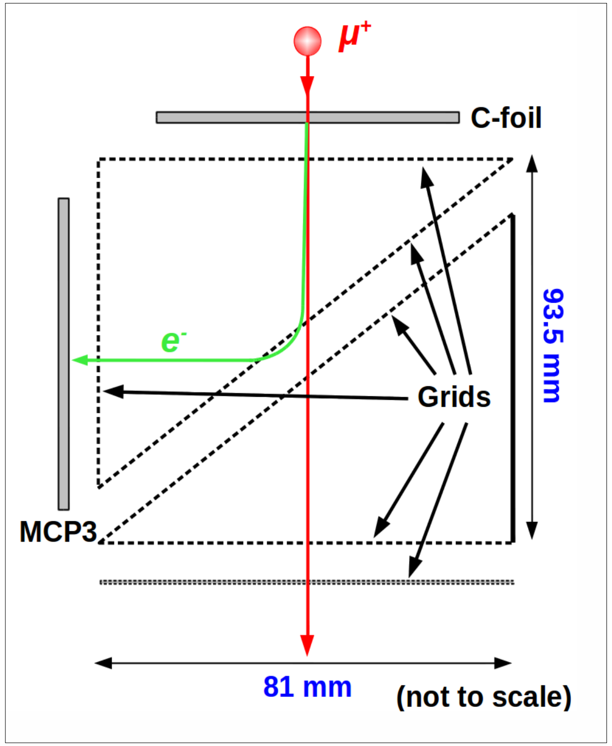




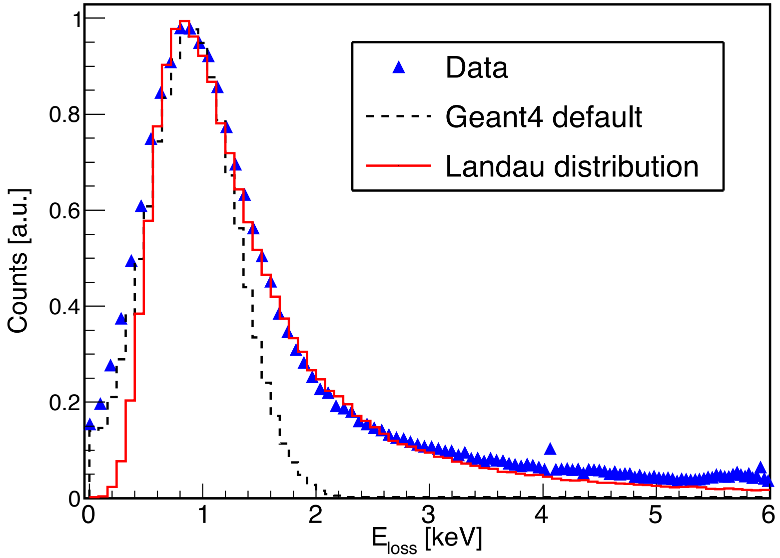
E~15eV



Muon Tagging



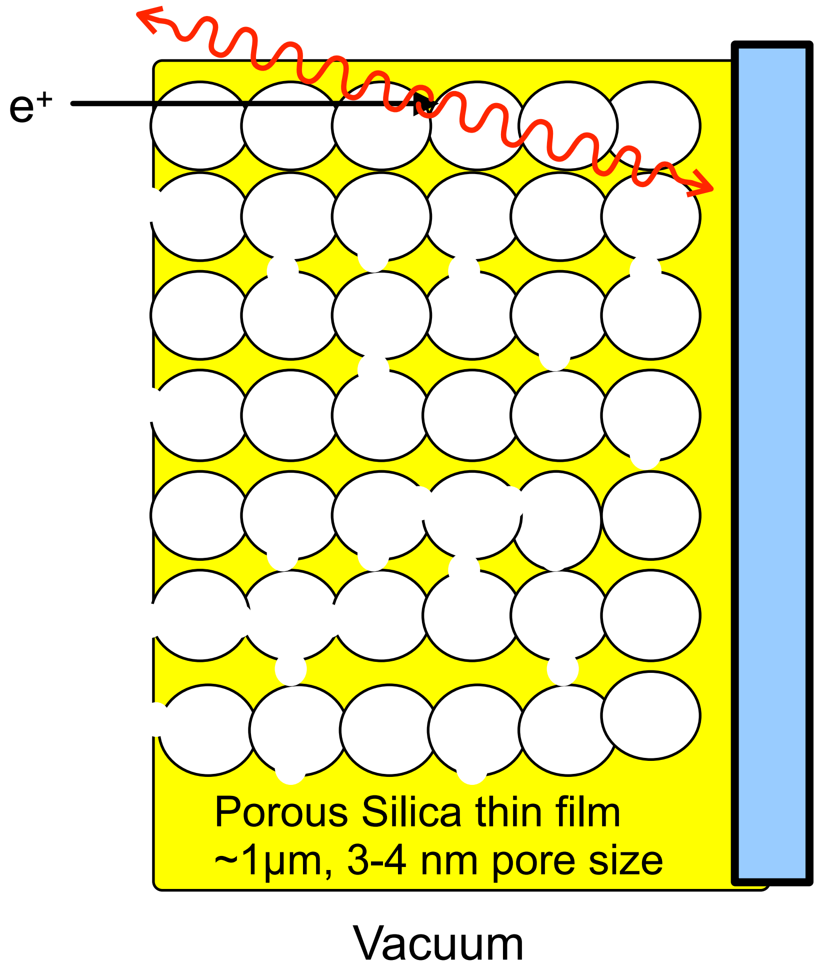
- Tagging via detection of SE from 10 nm carbon foil
- Timing of about 1 ns, efficiency around 40%
- Main drawback: beam degradation via scattering in the foil



http://iopscience.iop.org/article/10.1088/1748-0221/10/10/P10025

Positronium (Muonium) formation

- Positron implanted with keV energies
- Rapidly thermalizes in the bulk (~ps)
- **Positron diffusion and annihilation**



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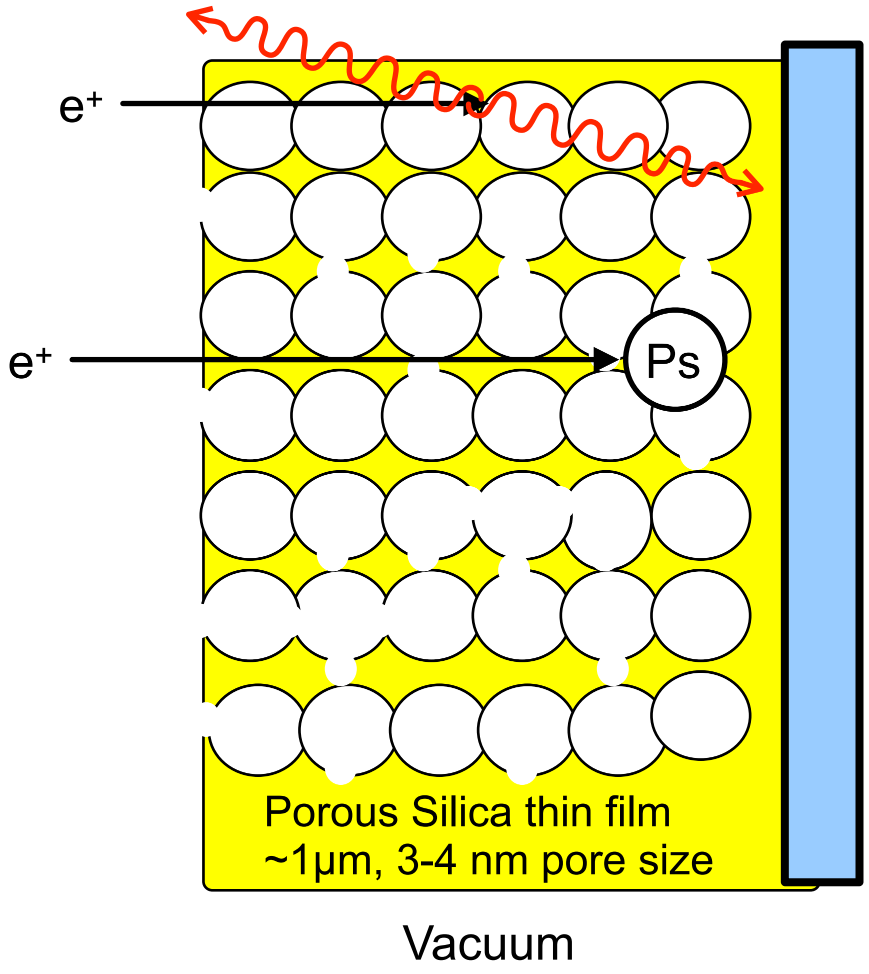
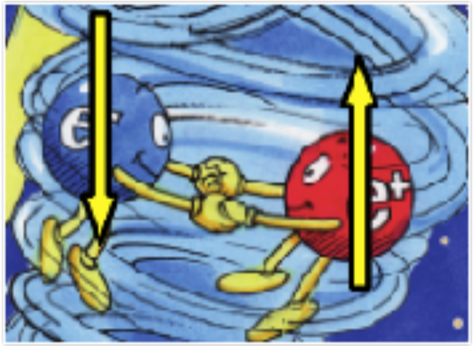


Reminder: Ps

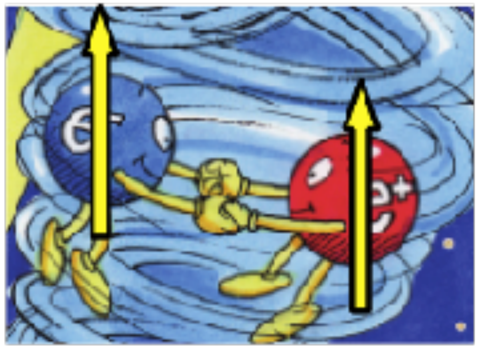
Two ground states:

Parapositronium (p-Ps) singlet spin state $^{1}S_{0}$



$$|0,0\rangle = (\uparrow\downarrow \quad \downarrow\uparrow)/\sqrt{2} \Big\} \quad s=0 \quad \text{(singlet)}$$

Orthopositronium (o-Ps) triplet spin state $^{3}S_{1}$

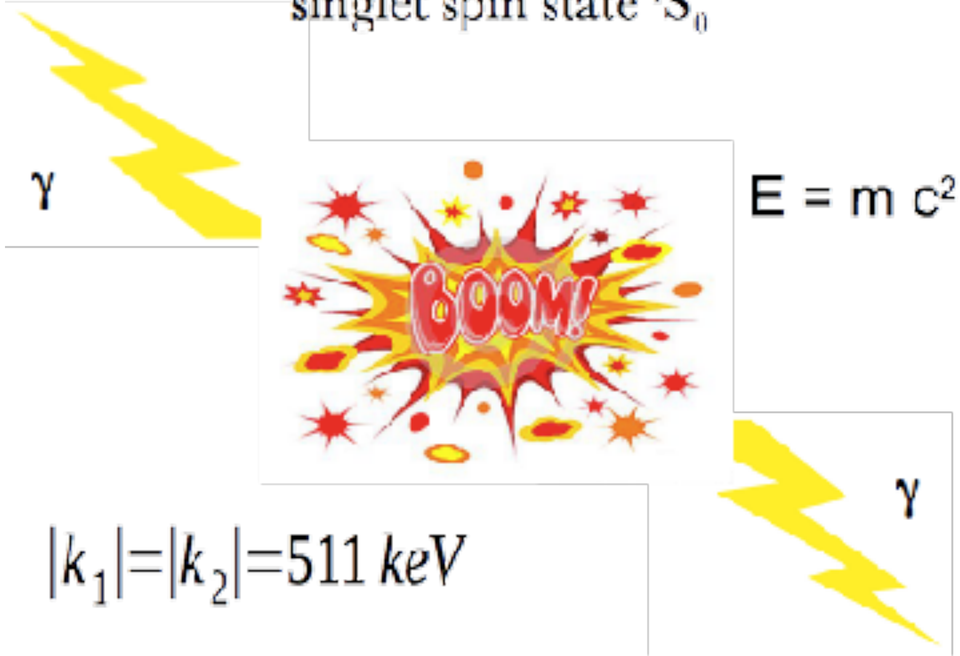


$$\left.\begin{array}{l} |1,1\rangle = \uparrow\uparrow \\ |1,0\rangle = (\uparrow\downarrow + \downarrow\uparrow)/\sqrt{2} \\ |1,-1\rangle = \downarrow\downarrow \end{array}\right\} \quad s=1 \quad \text{(triplet)}$$

Reminder: Ps

Two ground states:

Parapositronium (p-Ps) singlet spin state $^1S_0$

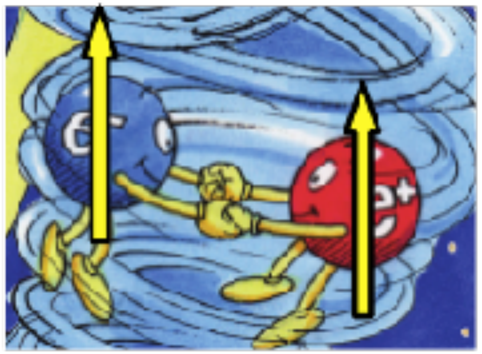


$E = m c^2$

$|k_1| = |k_2| = 511\ keV$

$\Gamma^{-1} = \tau \approx 0.000000000125\ s$

Orthopositronium (o-Ps) triplet spin state $^3S_1$



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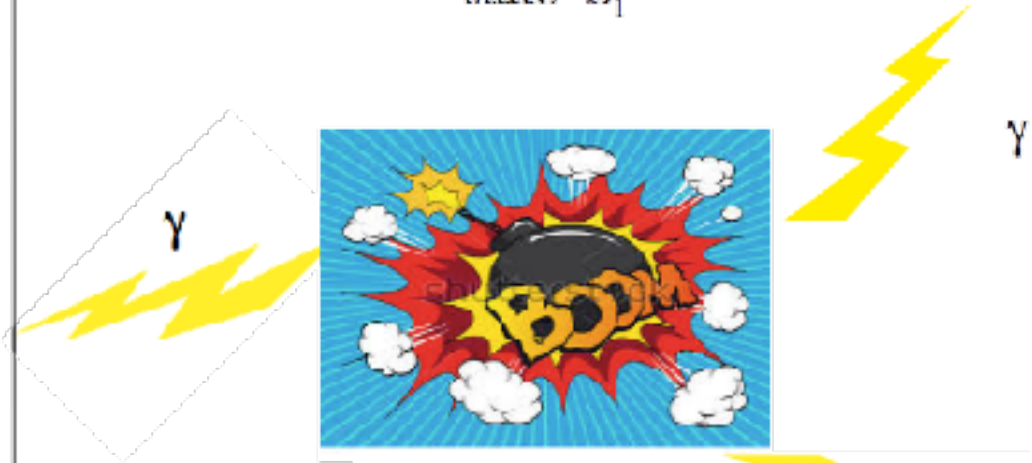


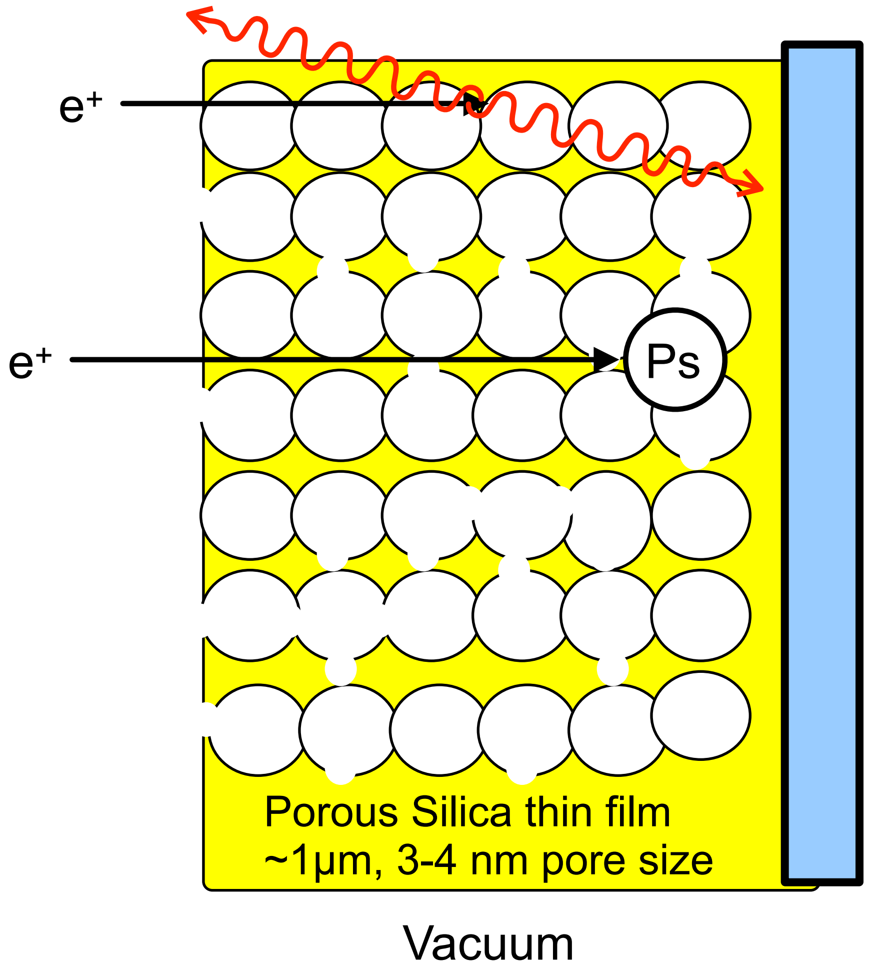
$$0 \le |k_i| \le 511\,keV$$

$$\Gamma^{(0)}_{3\gamma}(n^3S_1) = \frac{2}{9\pi}(\pi^2 - 9)\frac{m_e c^2}{\hbar}\frac{\alpha^6}{n^3}$$

$$\boxed{\Gamma^{-1} = \tau \approx 0.000000142\ \mathrm{s}}$$

Positronium (Muonium) formation

- Positron implanted with keV energies
- Rapidly thermalizes in the bulk (~ps)
- **Positron diffusion and annihilation**
- Positronium formation (1/4 pPs, 3/4 oPs) in SiO_2 by capturing 1 ionized electron



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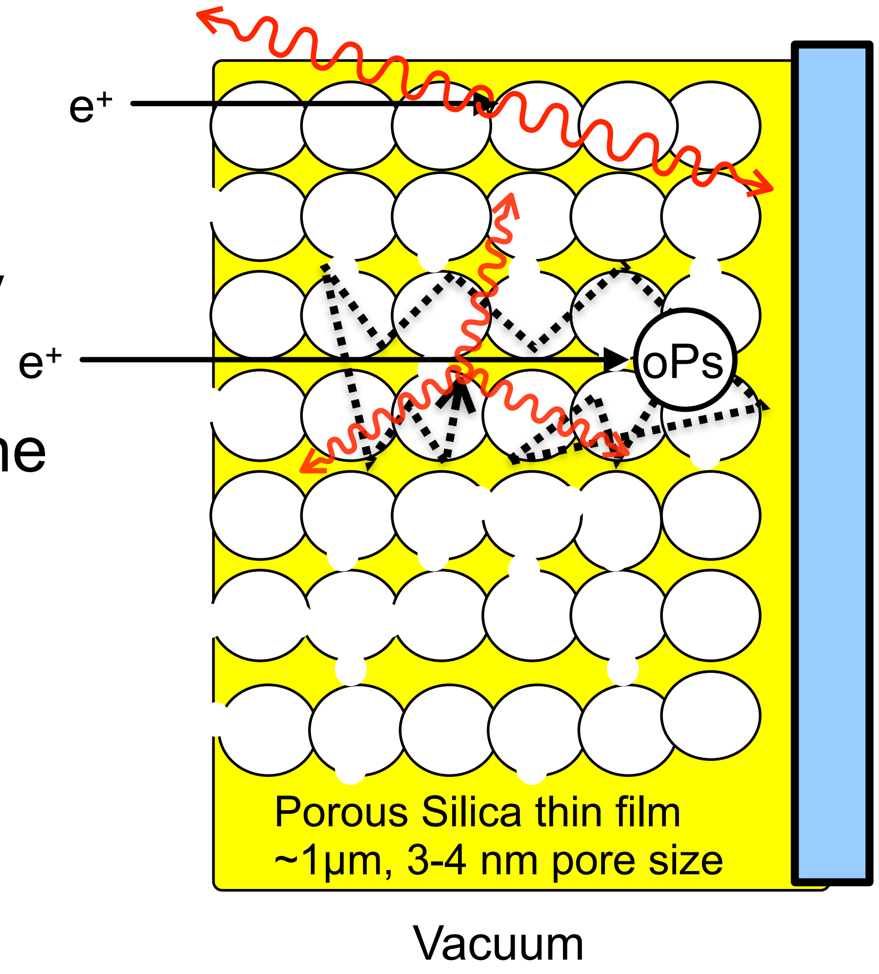
- Rapidly thermalizes in the bulk (~ps)

Positron diffusion and annihilation

- Positronium formation (1/4 pPs, 3/4 oPs) in SiO_2 by capturing 1 ionized electron
  - Diffusion to the pore surface and emission into the pores: $W_{Ps}=\mu_{Ps} + E_B - 6.8\ \text{eV} = -1\ \text{eV}$
  - Thermalization via collisions and diffusion in interconnected pore network

oPs annihilating in pore network

$$\tau_{\text{oPs, pore}} \begin{cases} \sim \phi_{\text{pore}} \\ \leq 142\ \text{ns} \end{cases}$$



Positronium (Muonium) formation

- Positron implanted with keV energies
- Rapidly thermalizes in the bulk (~ps)

Positron diffusion and annihilation

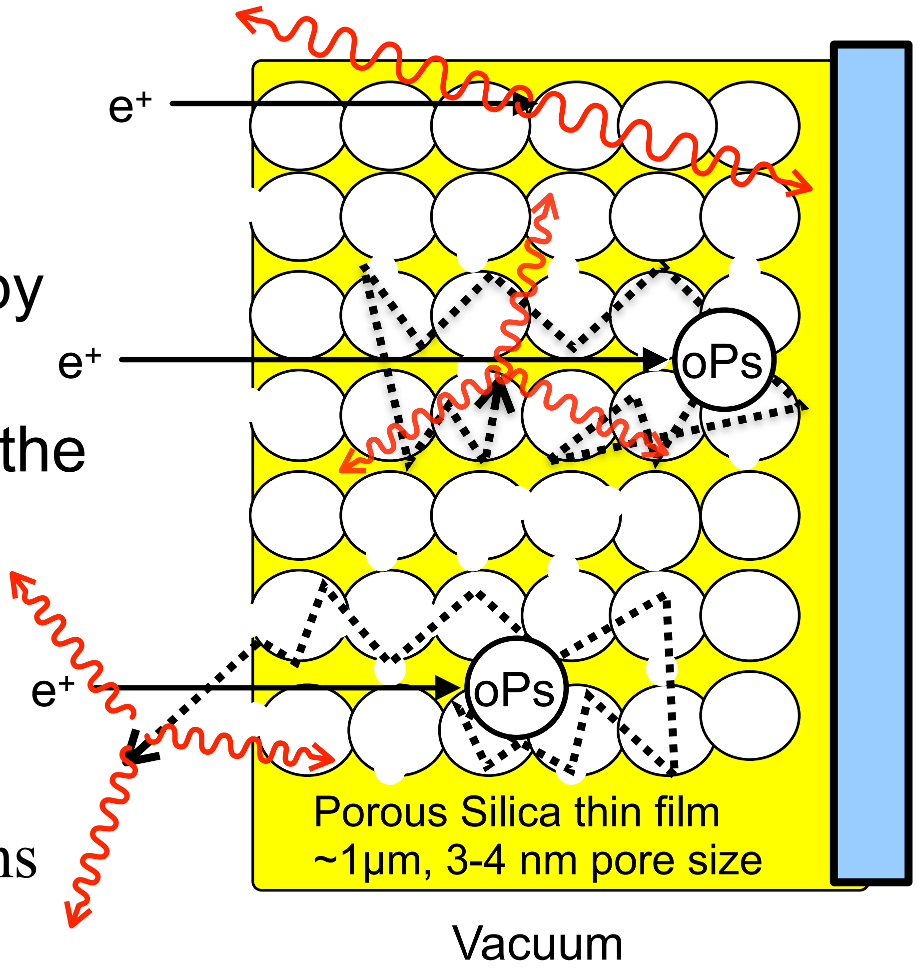
- Positronium formation (1/4 pPs, 3/4 oPs) in SiO_2 by capturing 1 ionized electron
  - Diffusion to the pore surface and emission into the pores: $W_{Ps} = \mu_{Ps} + E_B$ - 6.8 eV= -1 eV
  - Thermalization via collisions and diffusion in interconnected pore network

oPs annihilating in pore network

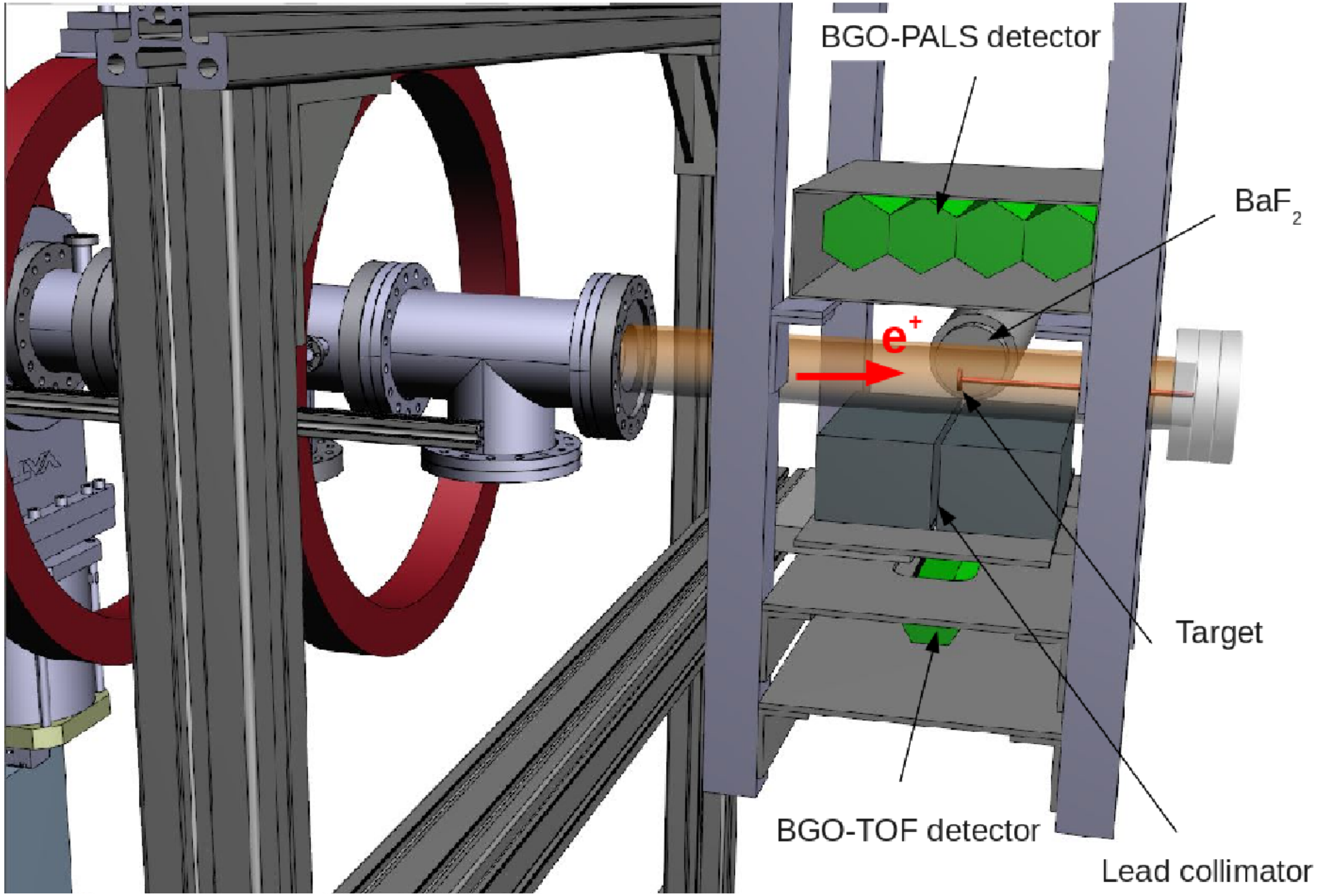
$$\tau_{\text{oPs, pore}} \begin{cases} \sim \phi_{\text{pore}} \\ \leq 142 \text{ ns} \end{cases}$$

Emission into vacuum (30%)

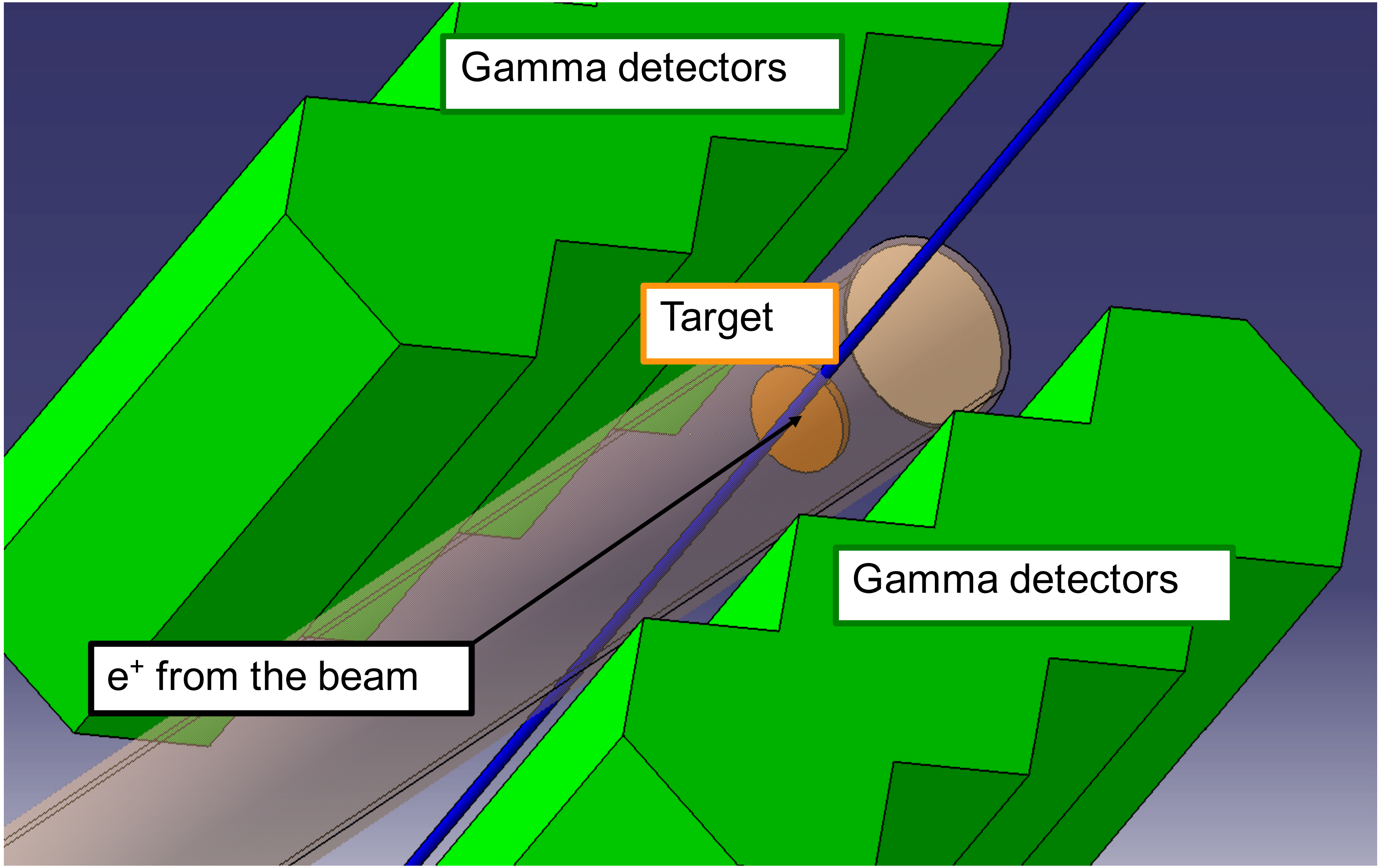
- At 40 meV ~ 10^5 m/s, $\tau_{\text{oPs, vac}} = 142 \text{ ns}$



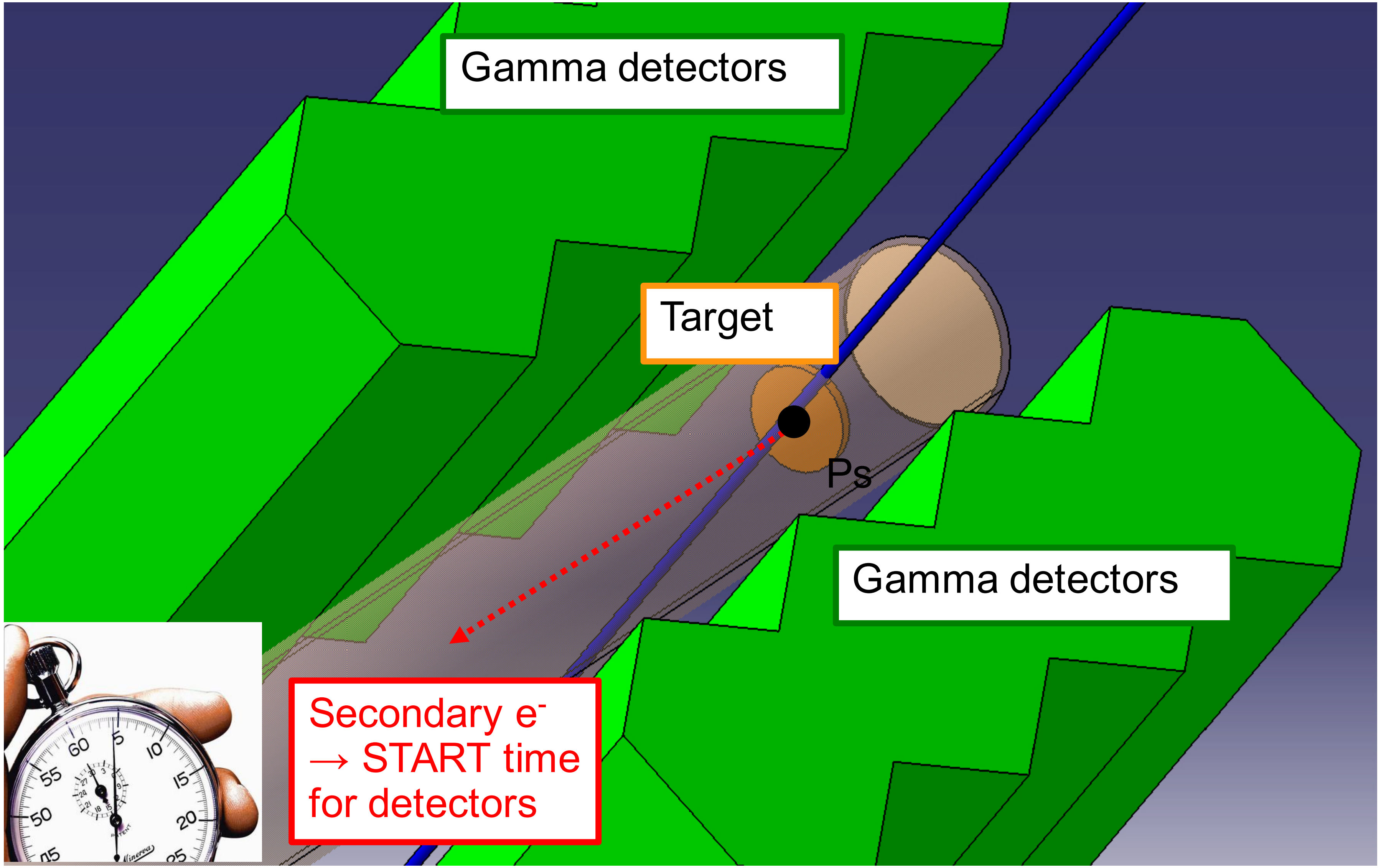
Detection of annihilation photons



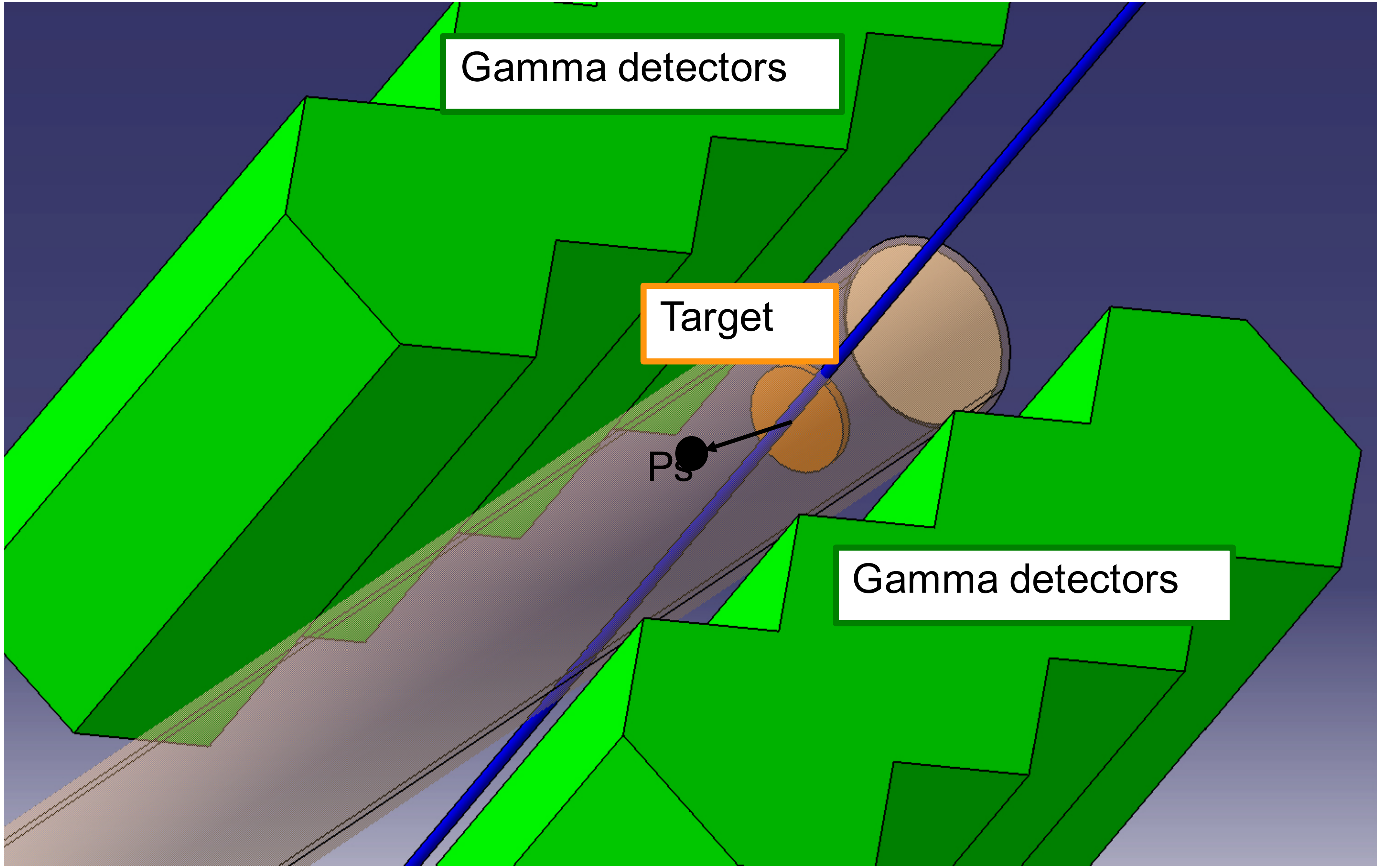
Ps lifetime acquisition



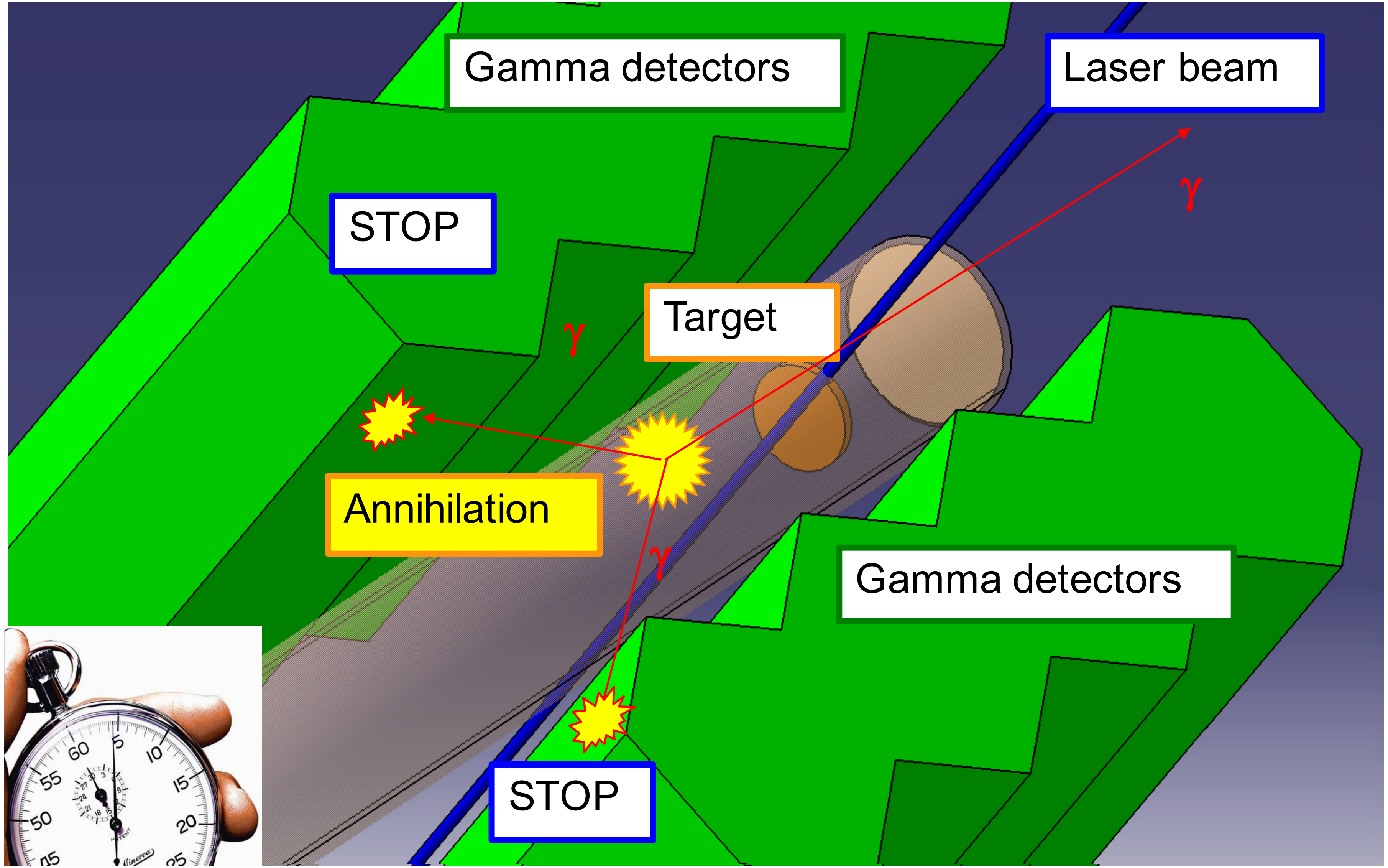
Ps lifetime acquisition



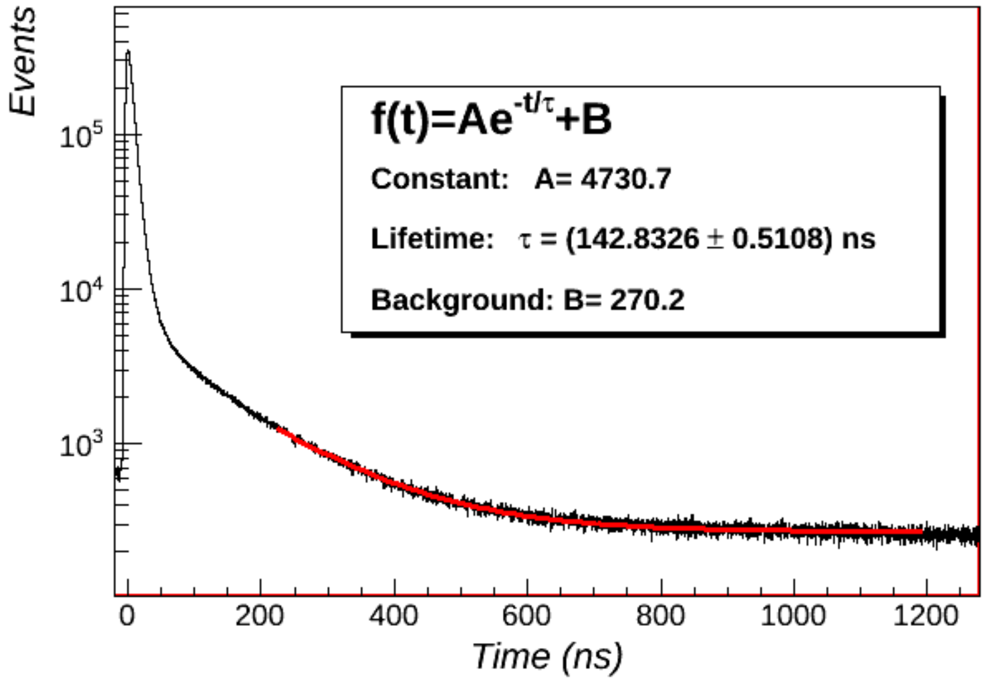
Ps lifetime acquisition



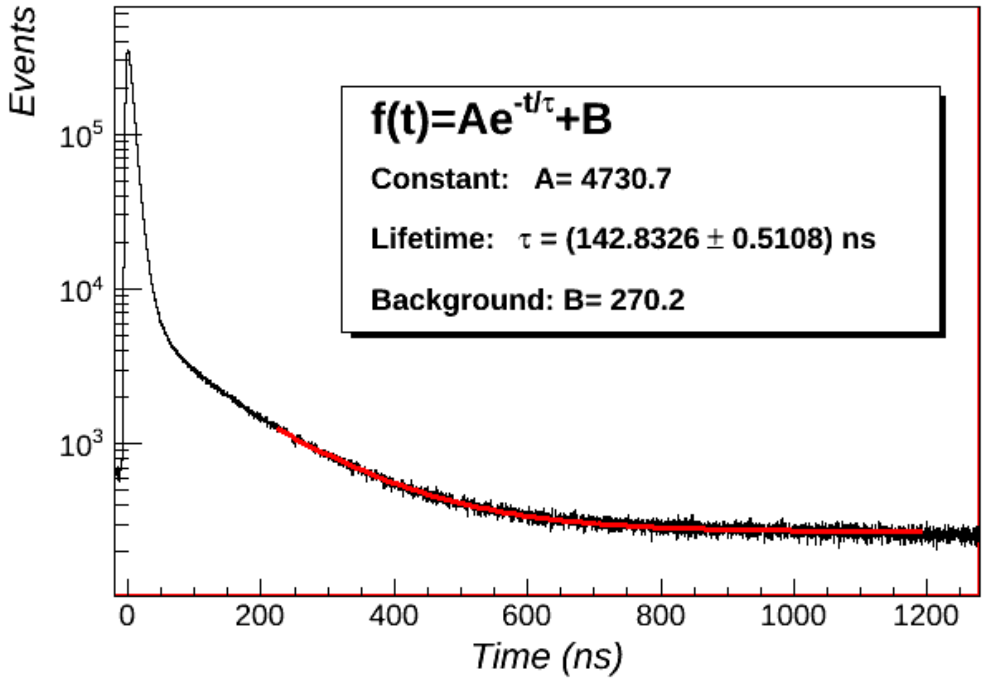
Ps lifetime acquisition

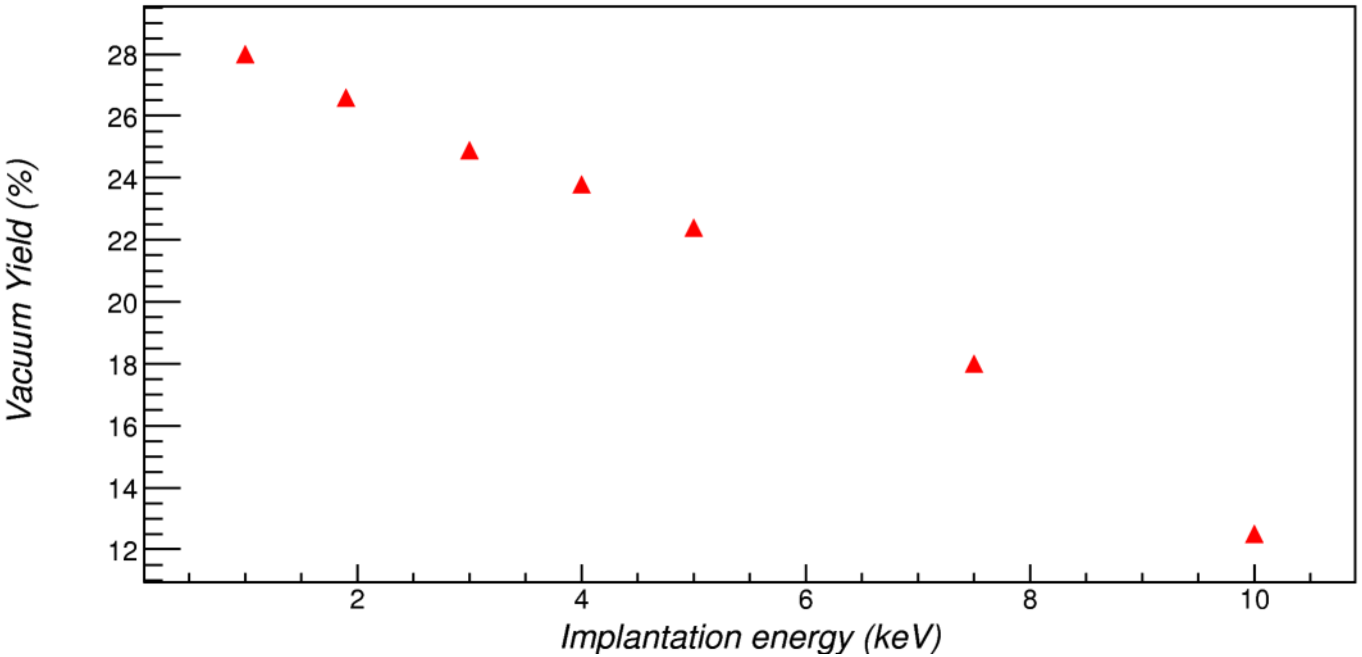


Positron Annihilation Lifetime Spectra PALS



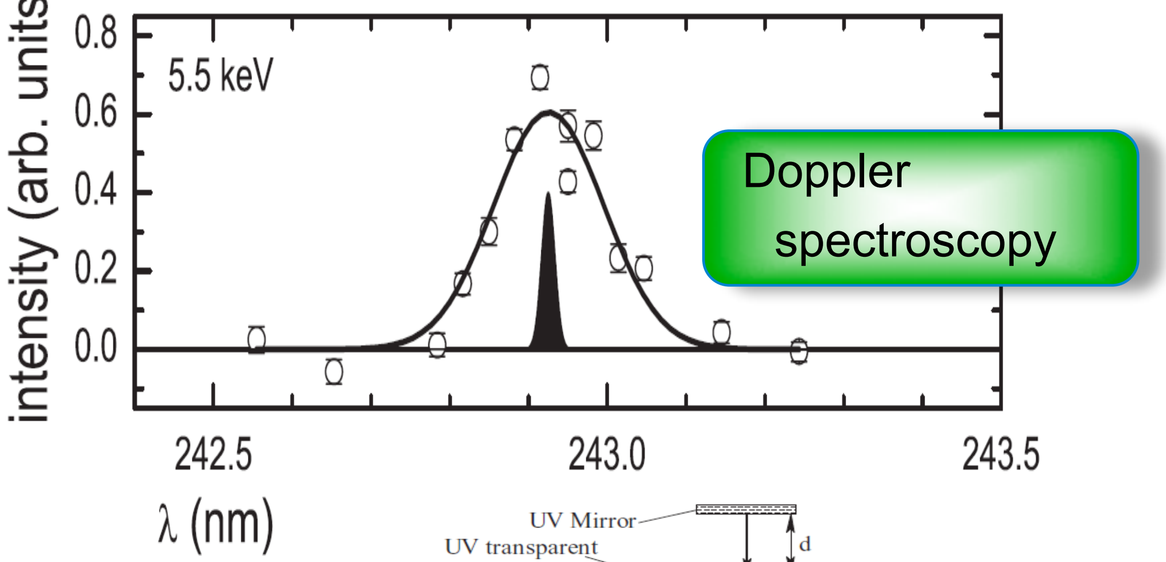
Positron Annihilation Lifetime Spectra PALS

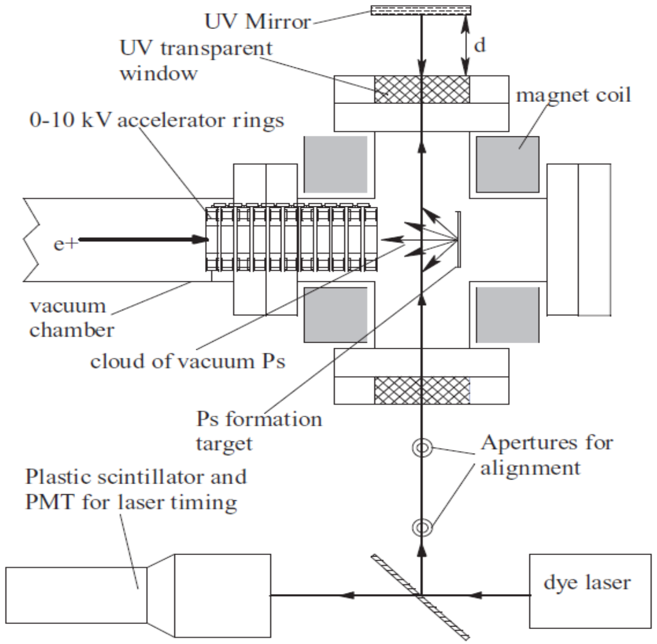




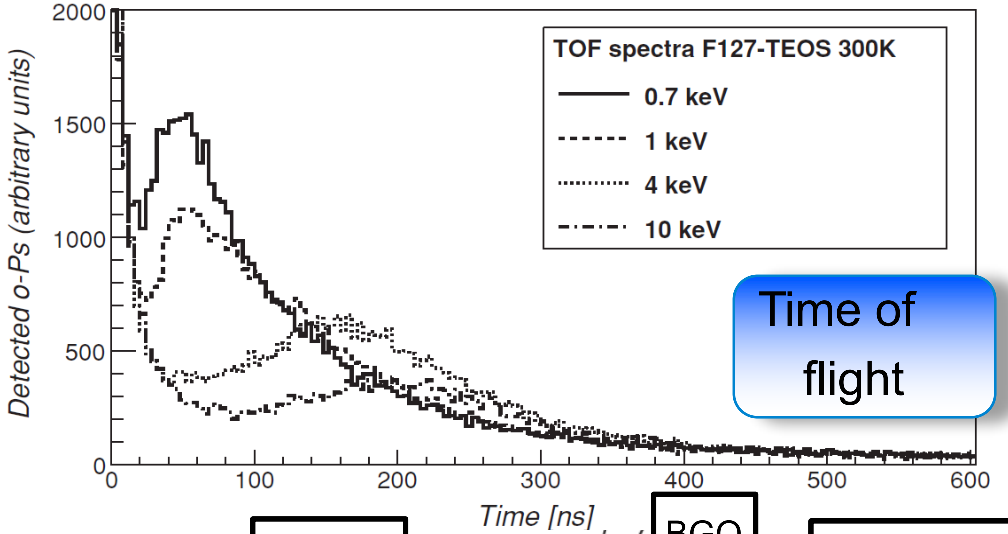
Measurement of Ps energy

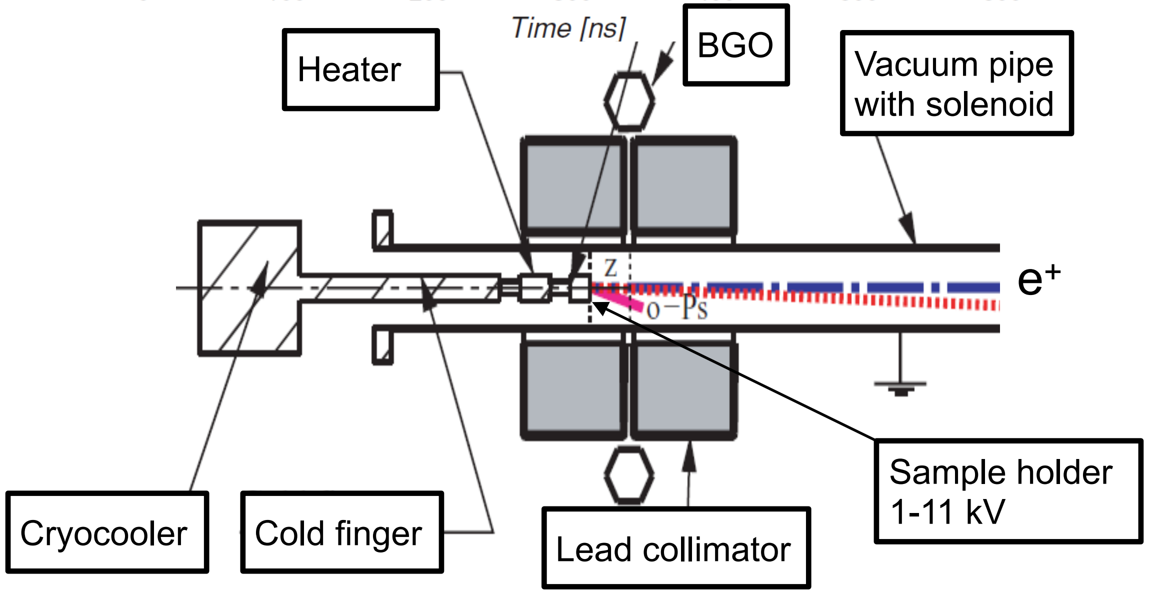
D. Cassidy, P. Crivelli et al., Phys. Rev. A 81, 012715 (2010)



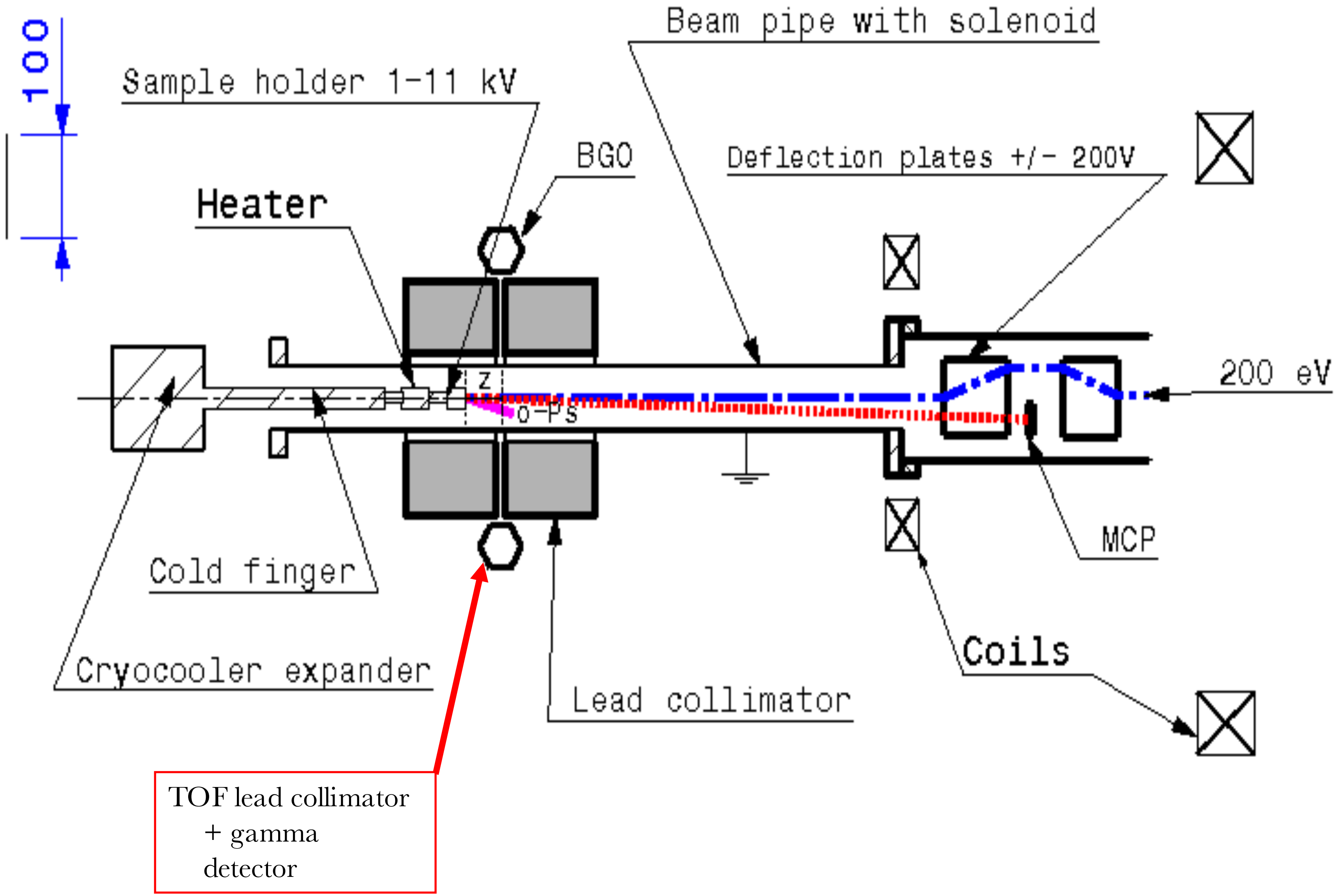


P. Crivelli et al. , Phys. Rev. A81, 052703 (2010)

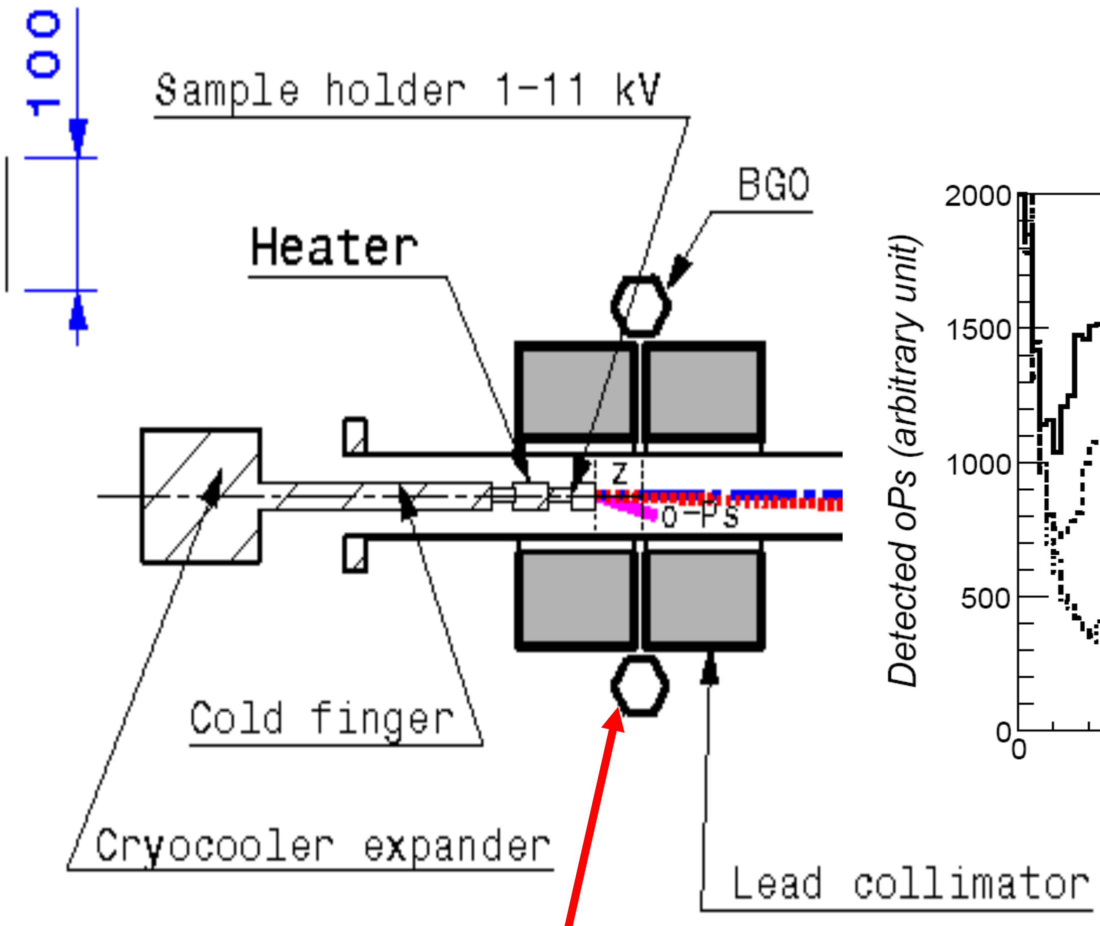




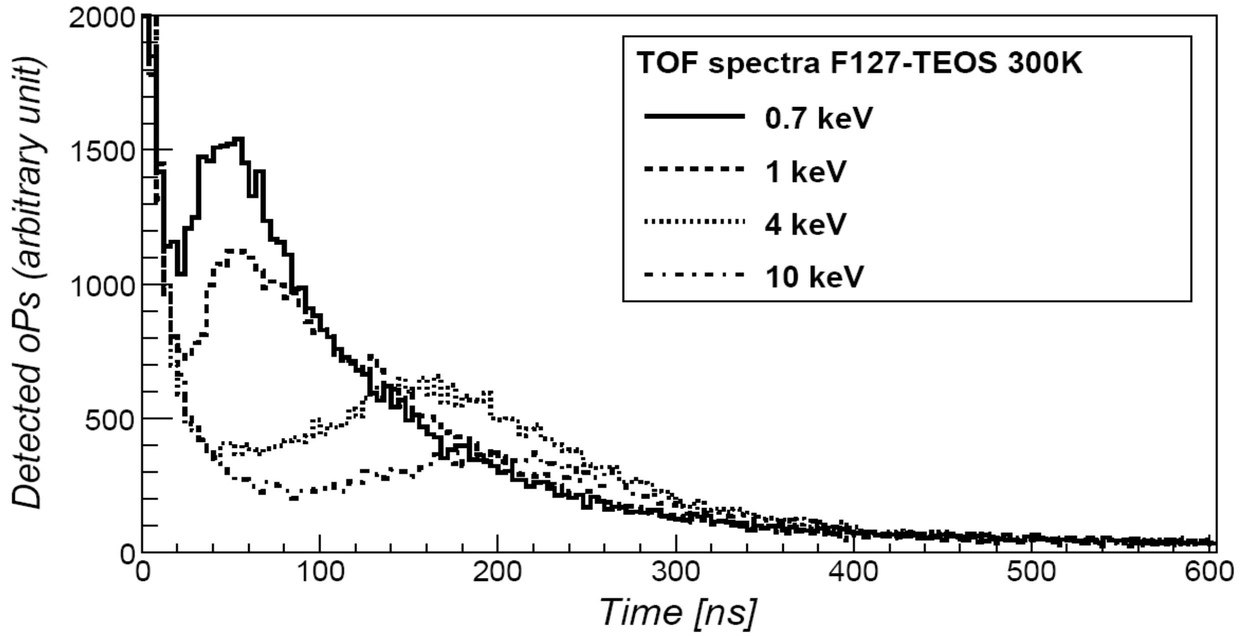
Measurement of Ps energy



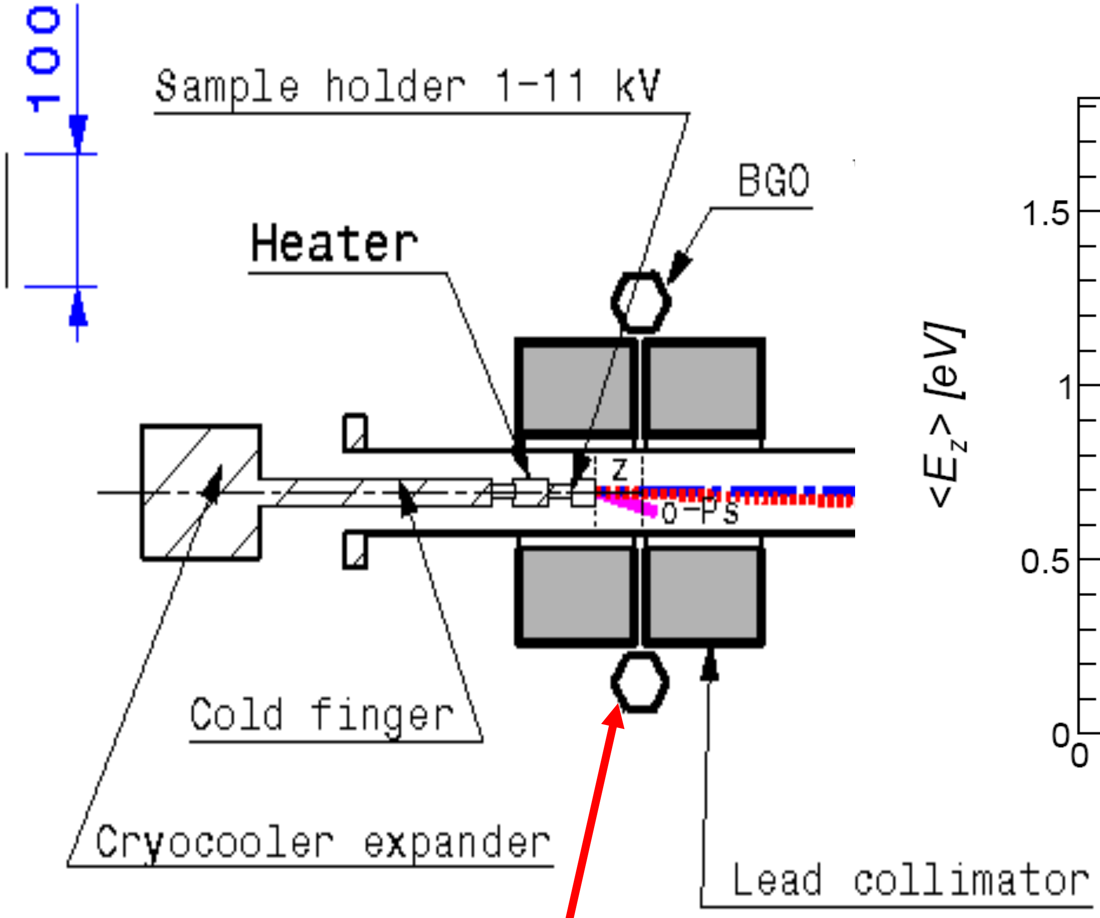
Measurement of Ps energy



TOF lead collimator
+ gamma
detector



Measurement of Ps energy



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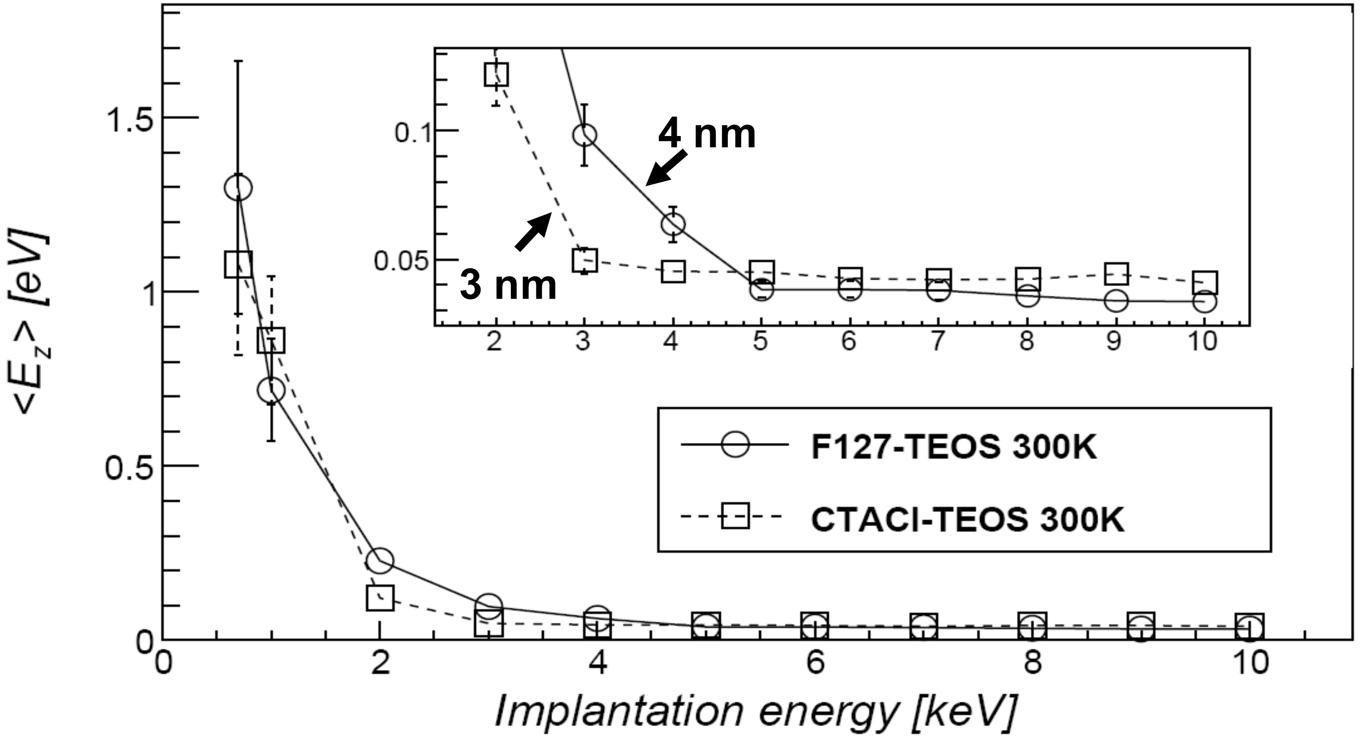
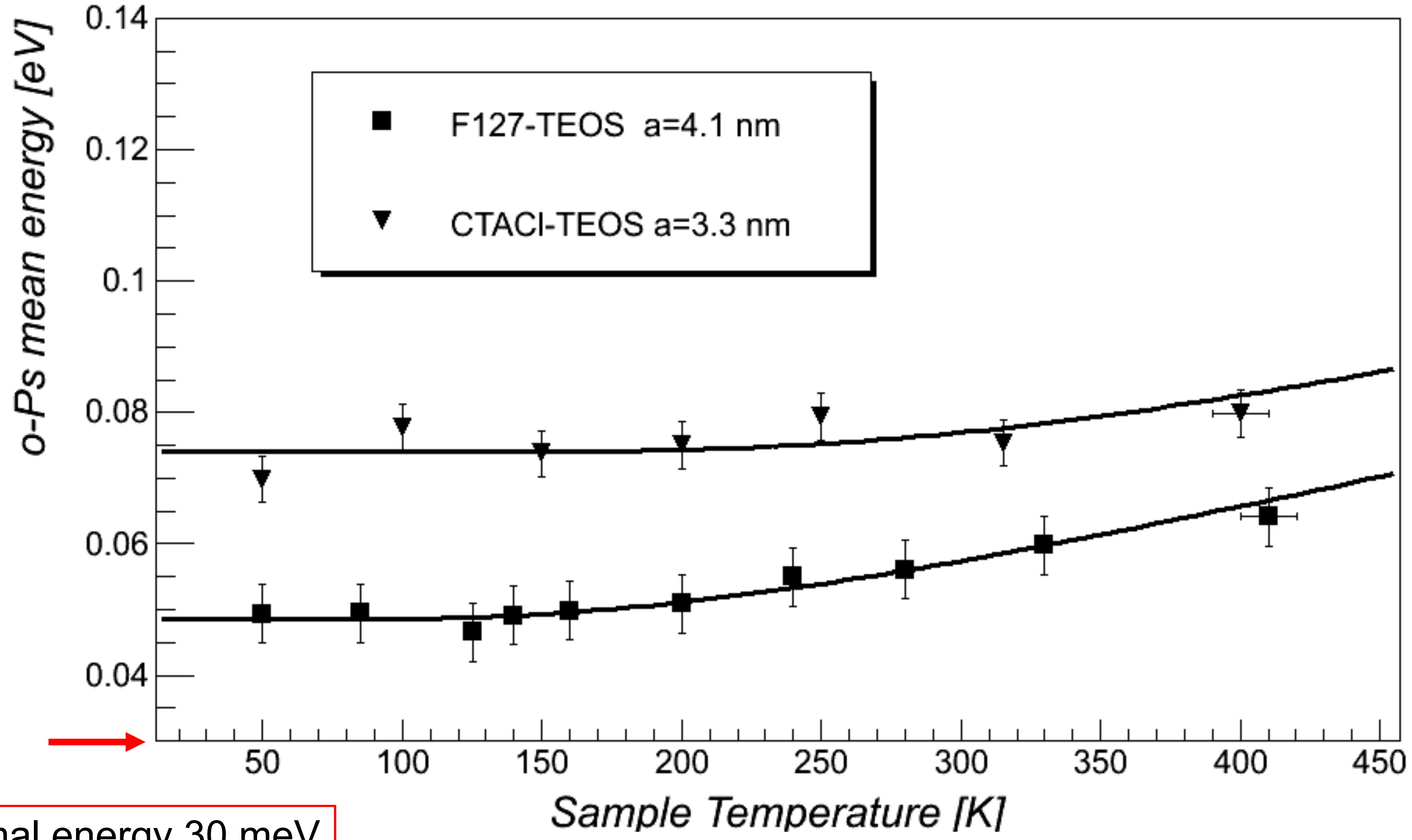


Measurement of Ps energy vs T



Thermal energy 30 meV

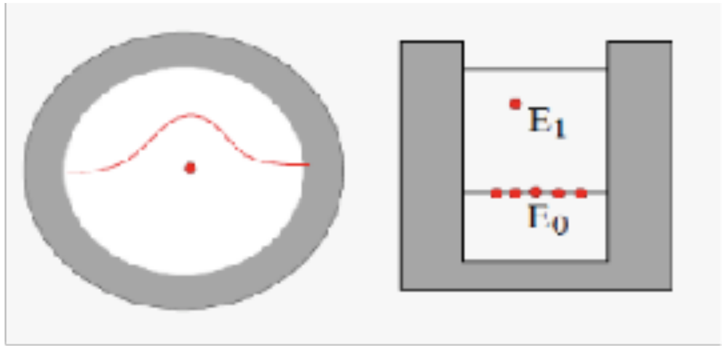
Ps confinement energy

Ps de Broglie wavelength at kinetic energy E_{Ps},

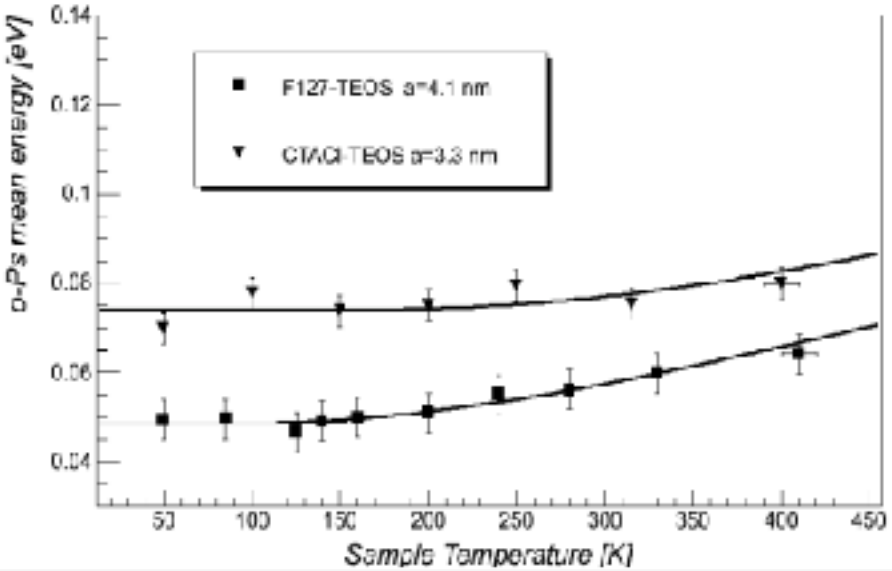
$$\lambda_{Ps} = h(2m_{Ps}E_{Ps})^{-1/2} \sim 0.9\,\text{nm}(1\,\text{eV}/E_{Ps})^{1/2},$$

For Ps with 100 meV, λ_{Ps} is comparable with the pore size.

QM effects!



$$E_{Ps} = \frac{h^2}{2m\,d^2} \approx 0.8\,\text{eV}(1\,\text{nm}/d)^2$$



$$\langle H\rangle = kT^2\left(\frac{1}{Z(a)}\frac{dZ(a)}{dT} + \frac{1}{Z(b)}\frac{dZ(b)}{dT} + \frac{1}{Z(c)}\frac{dZ(c)}{dT}\right)$$

Z is the partition function defined as

$$Z(a) = \sum_{n=1}^{\infty} e^{-\frac{h^2 n^2}{8ma^2}/kT},$$

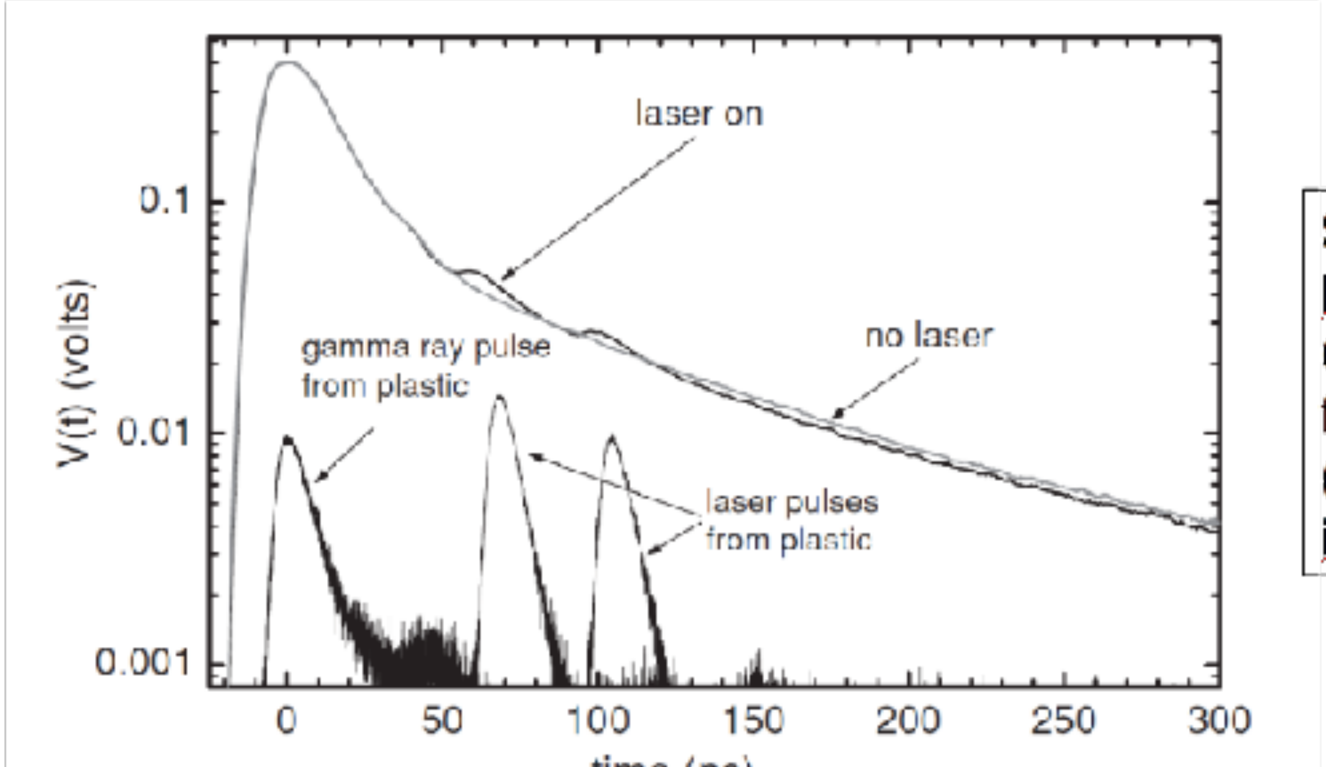
P. Crivelli et al. , Phys. Rev. A81, 052703 (2010)

Doppler spectroscopy

In collaboration with University of Riverside California, *D. Cassidy, P. Crivelli et al., Phys. Rev. A 81, 012715 (2010)*

Detection of Ps excited in the 2P state exploting triplet-singlet mixing in magnetic field -> increase of annihilation rate for excited atoms (about 10% of Ps decay as a singlet).

$$1^3S_1[142\,\mathrm{ns}] + h\nu_0 \rightarrow$$
$$\rightarrow \langle 2^3P_j + 2^1P_0 \rangle\,[3.2\,\mathrm{ns}]$$
$$\rightarrow 1^1S_0[125\,\mathrm{ps}] + h\nu_0 \rightarrow 2\gamma$$

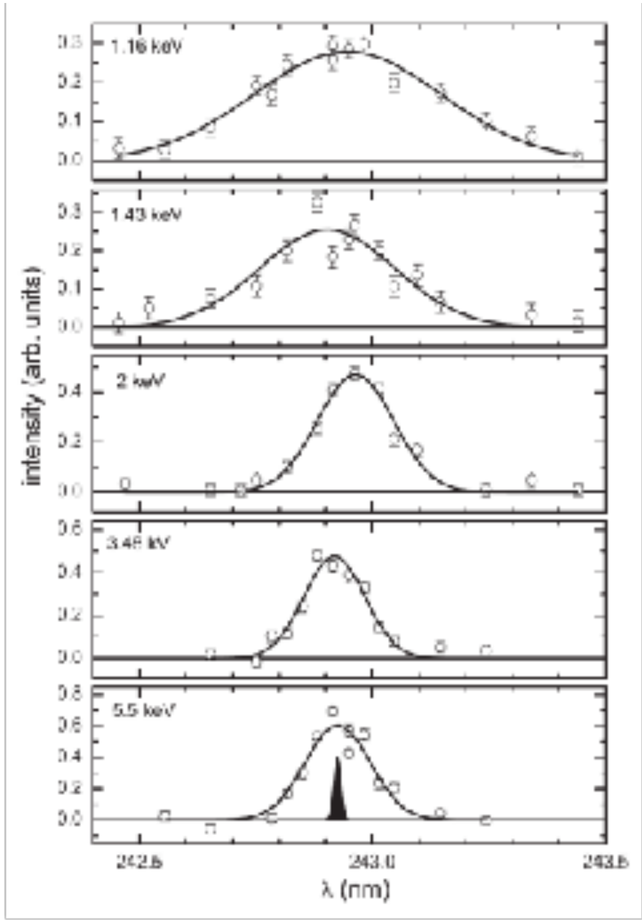


Single shot lifetime spectra. Output from scintillator (PbWO) directly into scope.

Doppler spectroscopy

In collaboration with University of Riverside California, *D. Cassidy, P. Crivelli et al., Phys. Rev. A 81, 012715 (2010)*

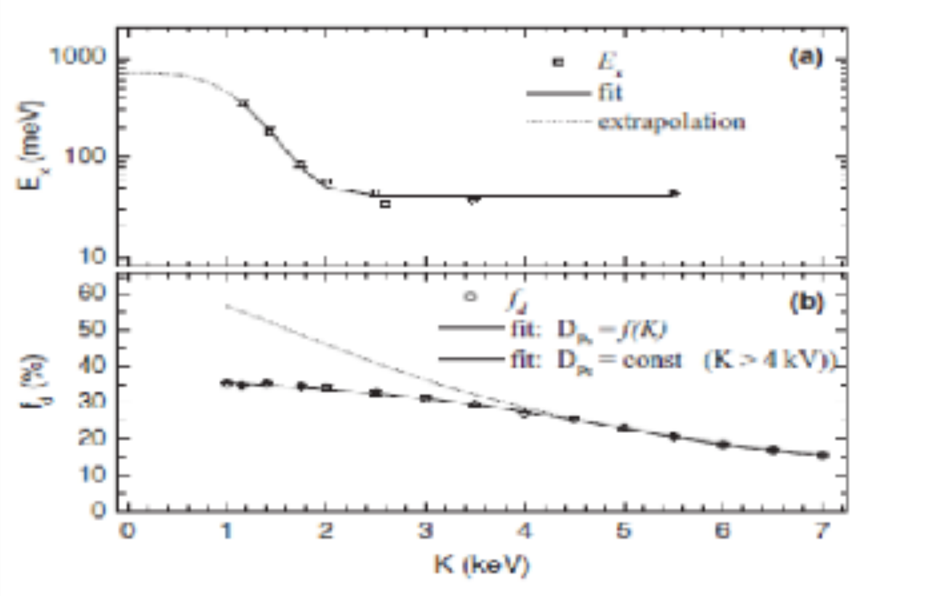
From the measured Doppler profiles one can extract v_x



Probe laser with bandwidth of 100 GHz

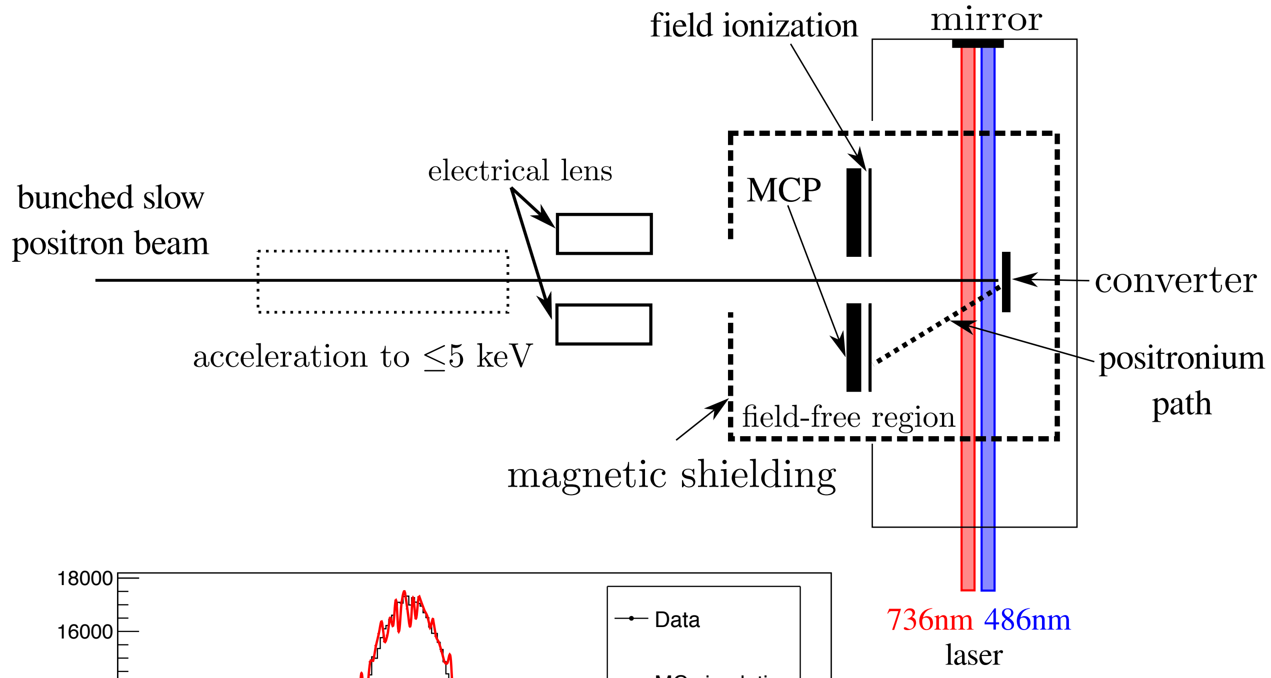
$$P(\lambda) \propto \exp\{-(\lambda-\lambda_0)^2 c^2 / 2\lambda_0^2 \langle v_x^2 \rangle\}$$

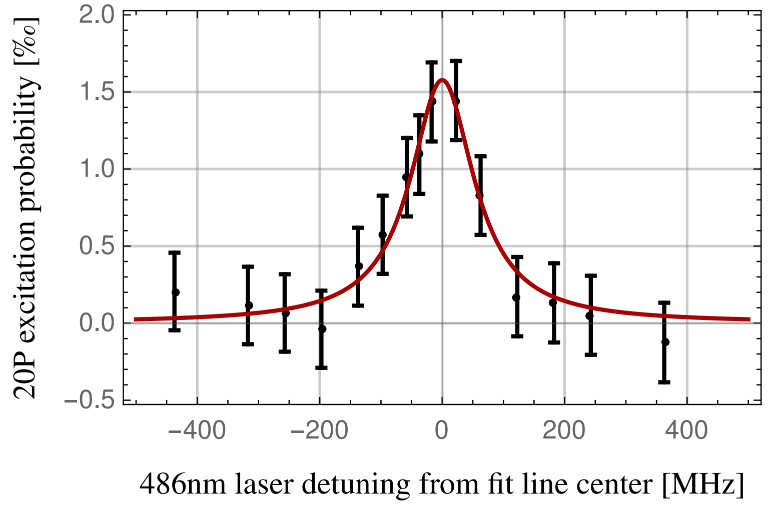
$$\frac{\Delta\lambda}{\lambda_0} \approx 2\sqrt{2\ln 2}\sqrt{\frac{\langle v_x^2 \rangle}{c^2}}$$

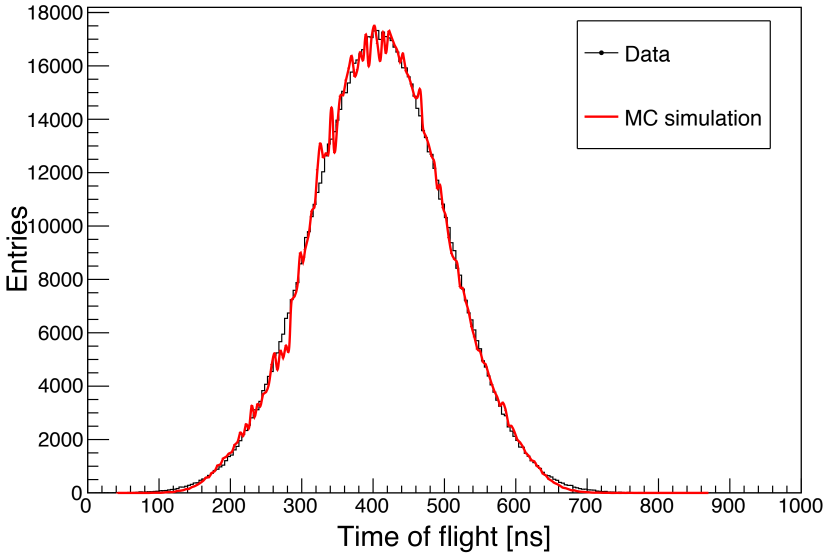


Results in agreement with TOF results

Excitation in Rydberg states and detection with an MCP







Time of flight spectra 20P Ps atoms → Atoms velocity

arXiv:1809.07854

Summary and outlook - detection of Positronium “beams”

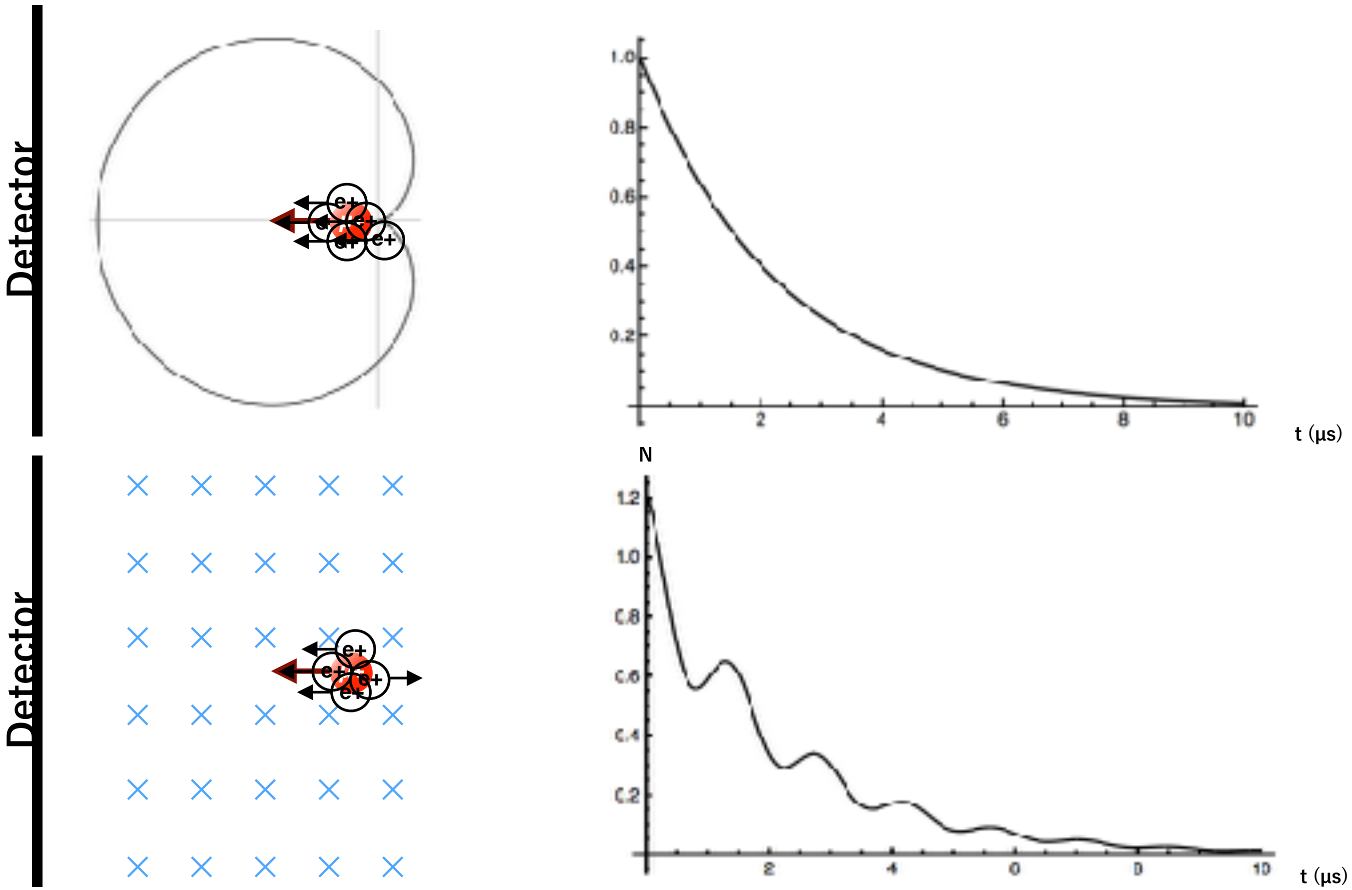
- TOF with collimation slit and scintillator → velocity perpendicular to collimation slit
- Doppler spectroscopy → velocity parallel to laser beam
- Rydberg excitation + TOF measurement → total velocity

- Detection of Rydberg Ps with position sensitive MCP → angular distribution

★ Drawback: excitation via laser in Rydberg states + detection
→ low efficiency <0.1% level.
Alternatives?

How to detect Muonium?

- Muon spin rotation (muSR) technique: $\mu^+ \longrightarrow e^+ + \nu_e + \bar{\nu}_\mu$
- Due to parity violation of weak decay, the direction of emitted positron is distributed asymmetrically with respect to the spin of muon



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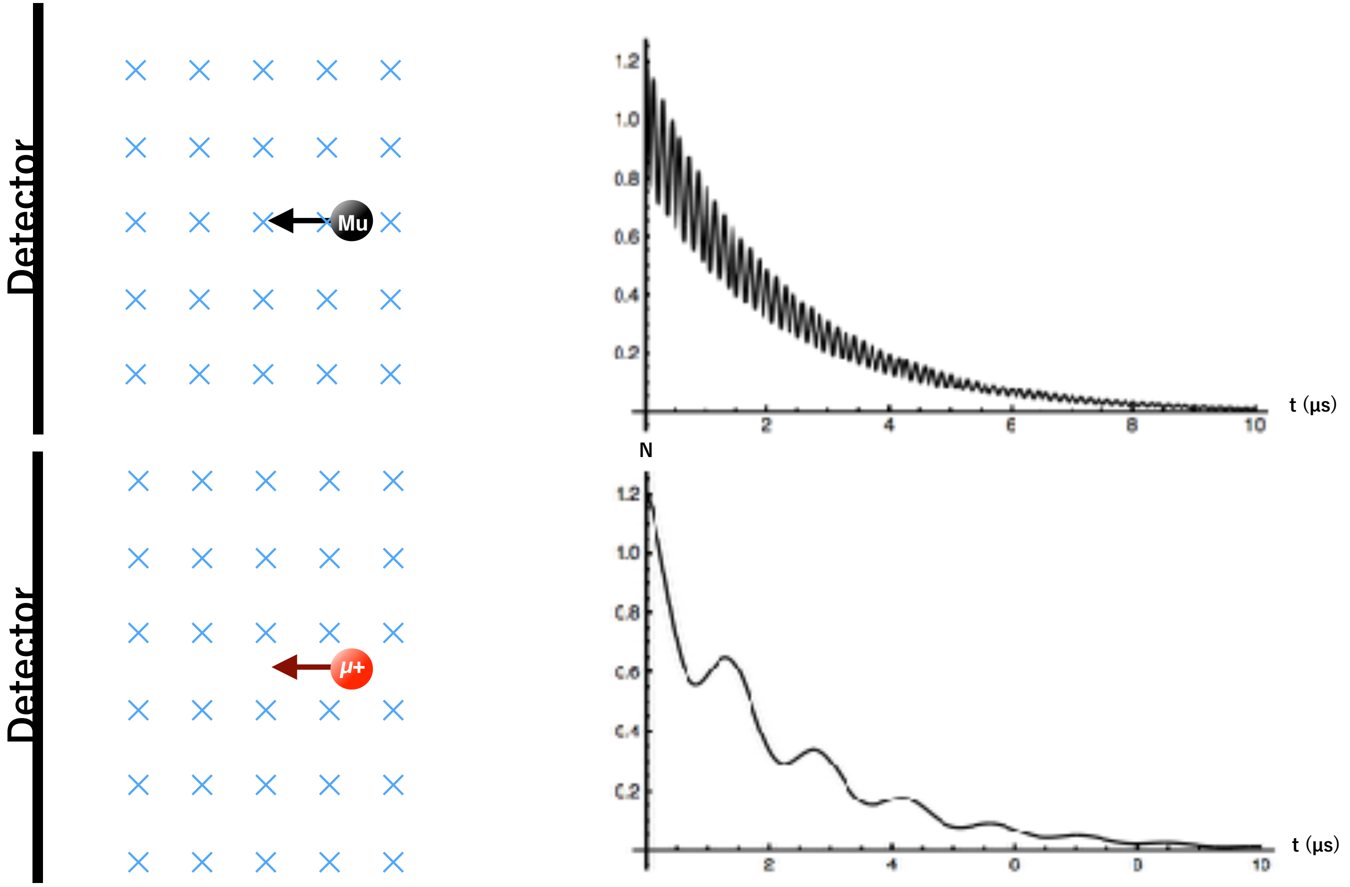
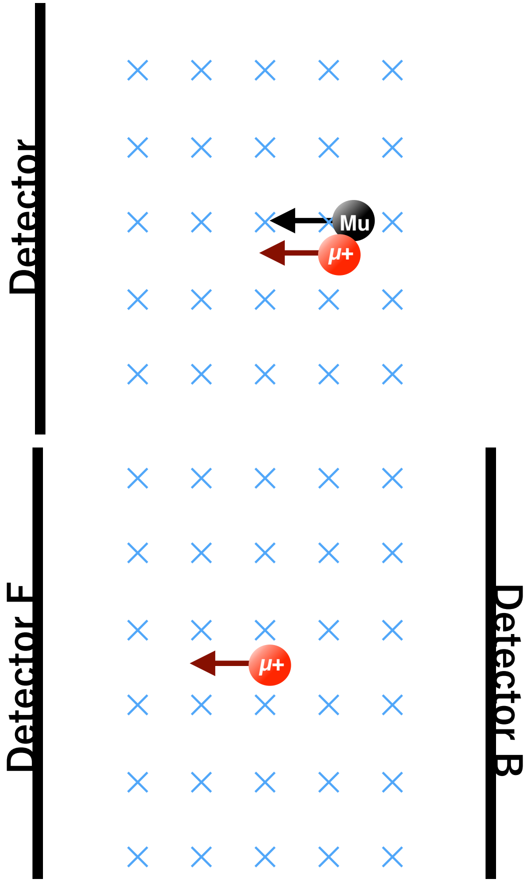


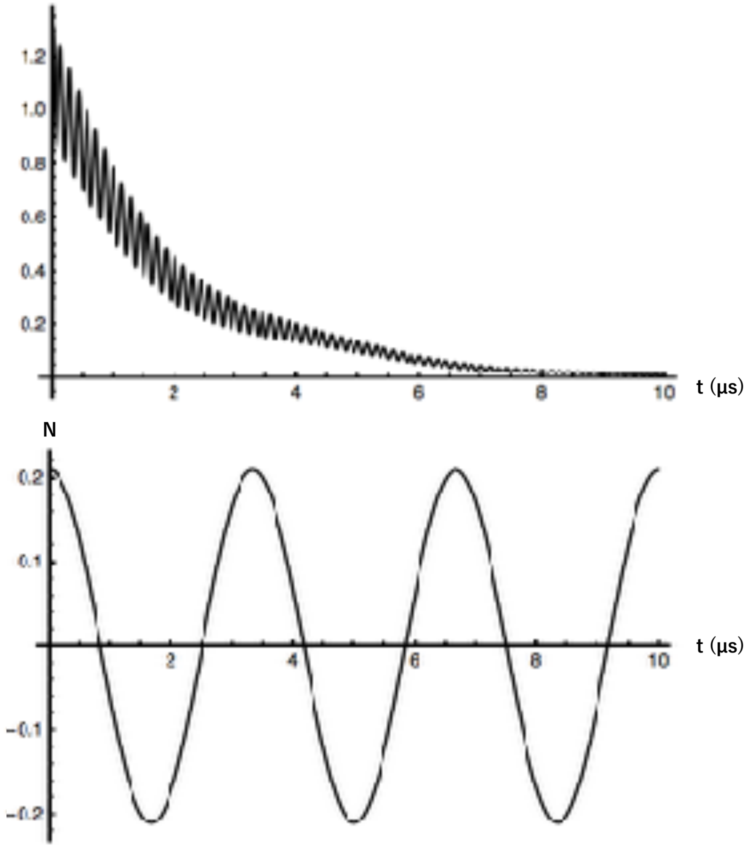
- Gyromagnetic ratio
- $\omega = \gamma \cdot B$
- $\gamma_{Mu} = 103 \cdot \gamma_{\mu}$

How to detect Muonium?

- Muon spin rotation (muSR) technique: $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$
- Due to parity violation of weak decay, the direction of emitted positron is distributed asymmetrically with respect to the spin of muon

Decay asymmetry
$A = (N_F - N_B)/(N_F + N_B)$



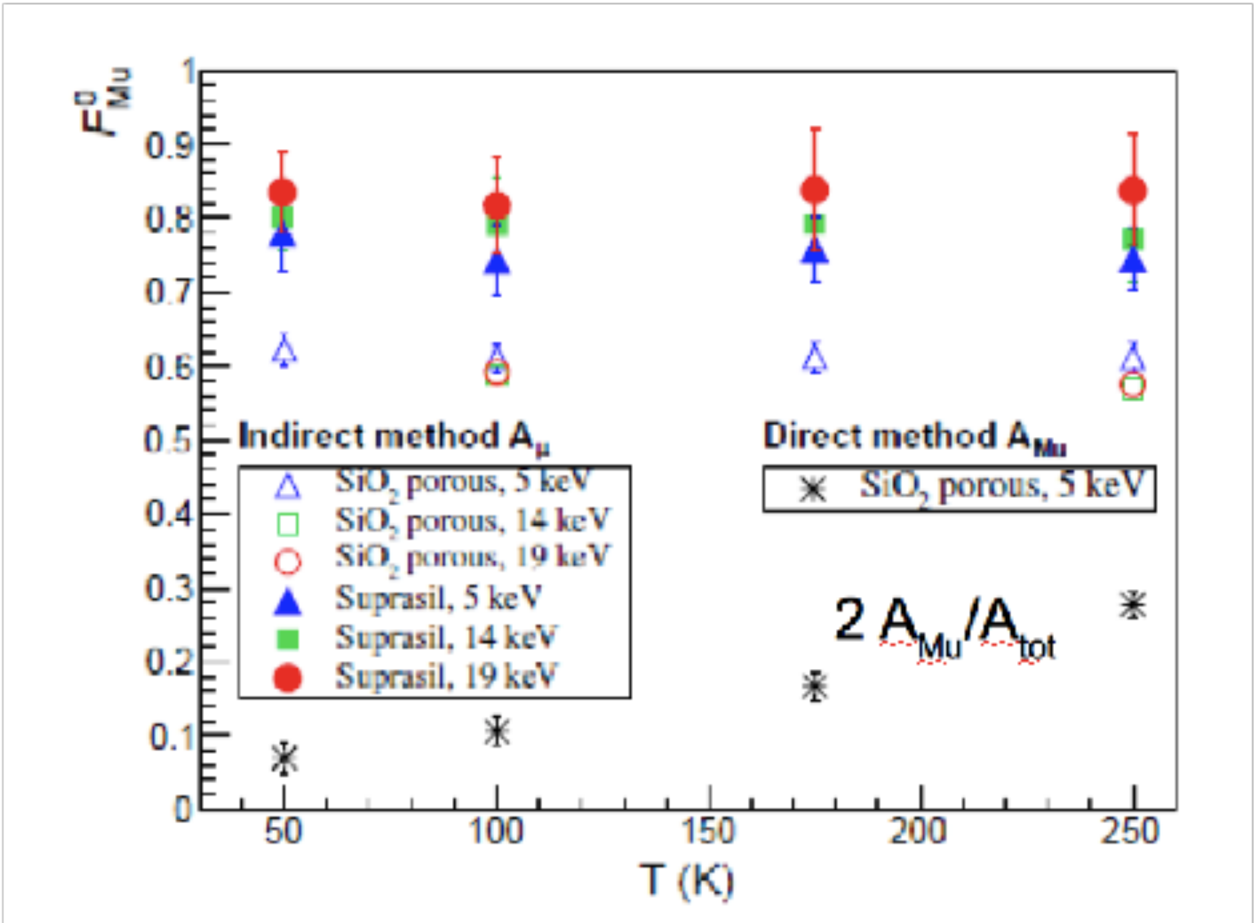


Muonium formation in SiO2 porous films -muSR

Initial fraction of Mu formed in SiO2 bulk (Suprasil) and SiO2 porous films

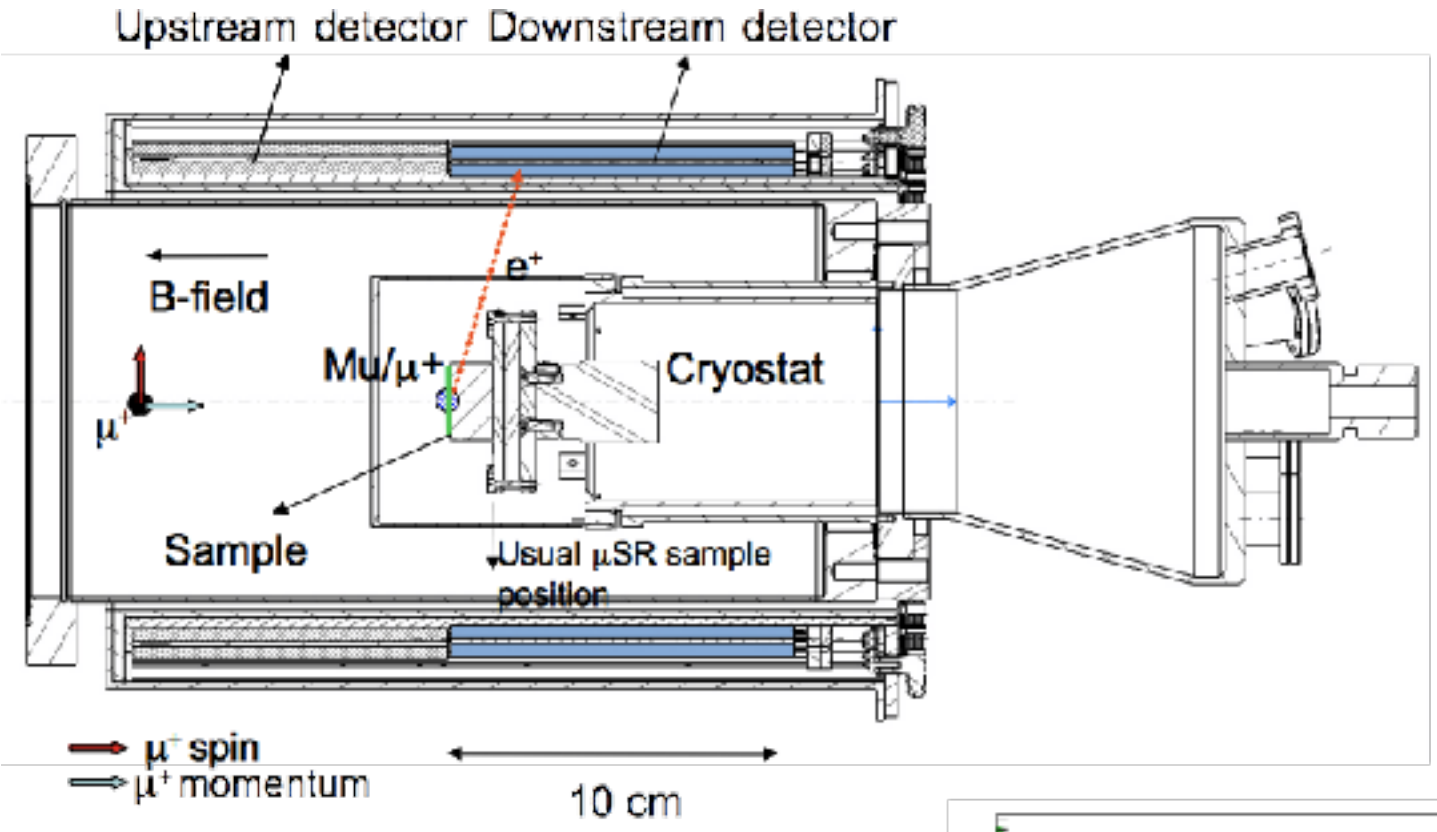
$$F^{()}_{\mathrm{Mu}} = 1 - A_{\mu^+} / A_{tot}$$

N

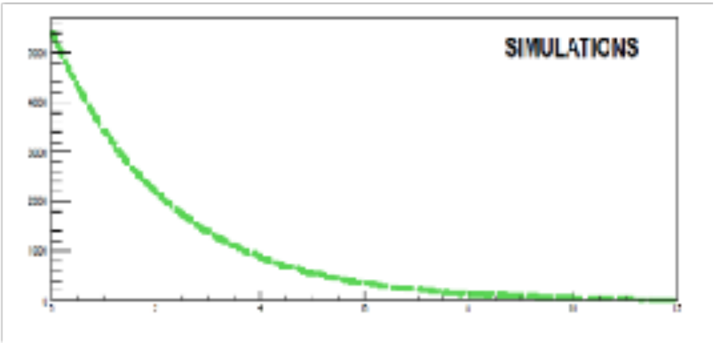


How do we know if Muonium is emitted in vacuum?

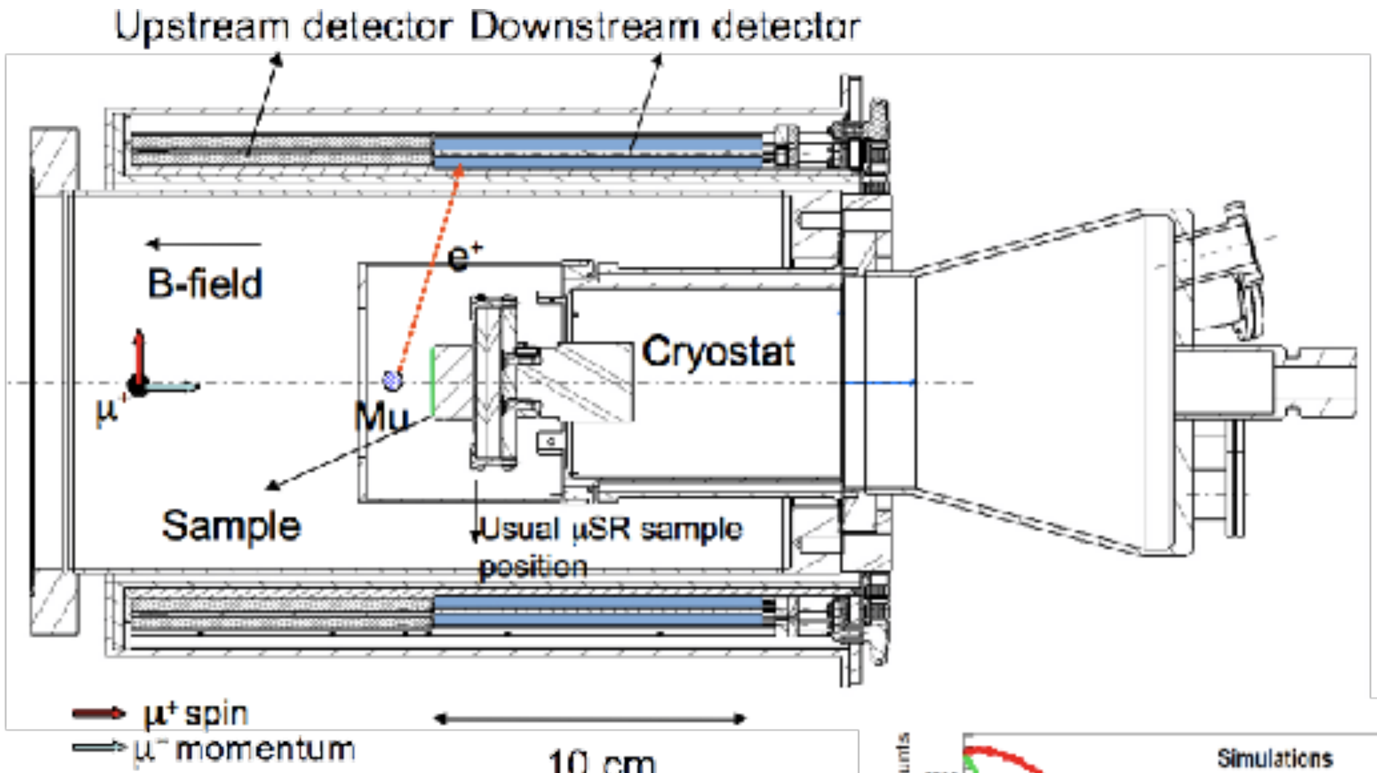
Positron shielding technique



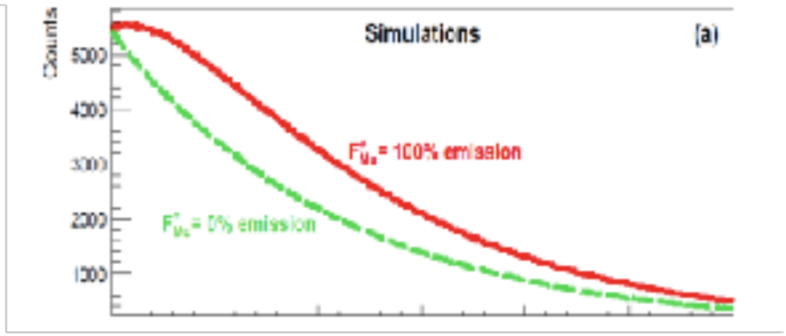
No emission in vacuum
Exponential decay distribution
From mu and μ+ decays



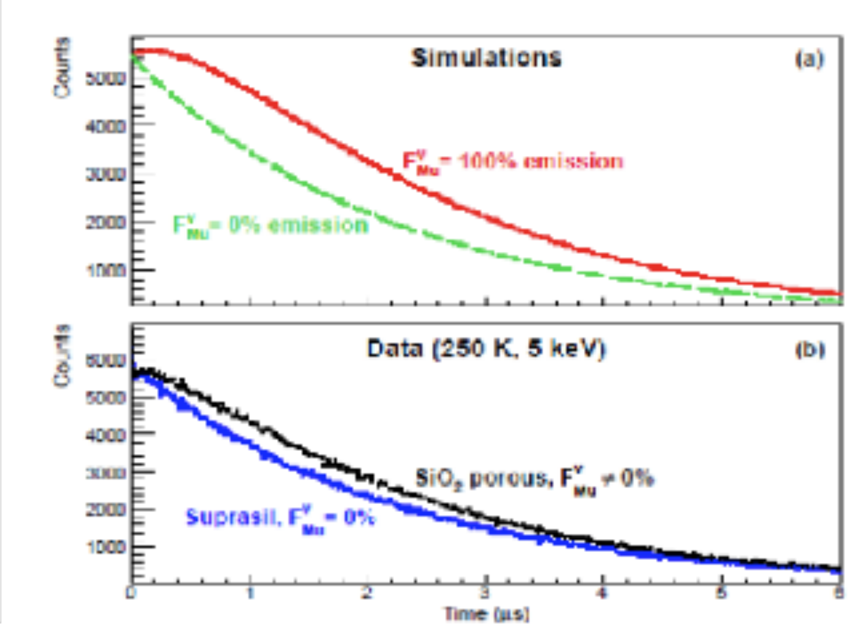
Positron shielding technique

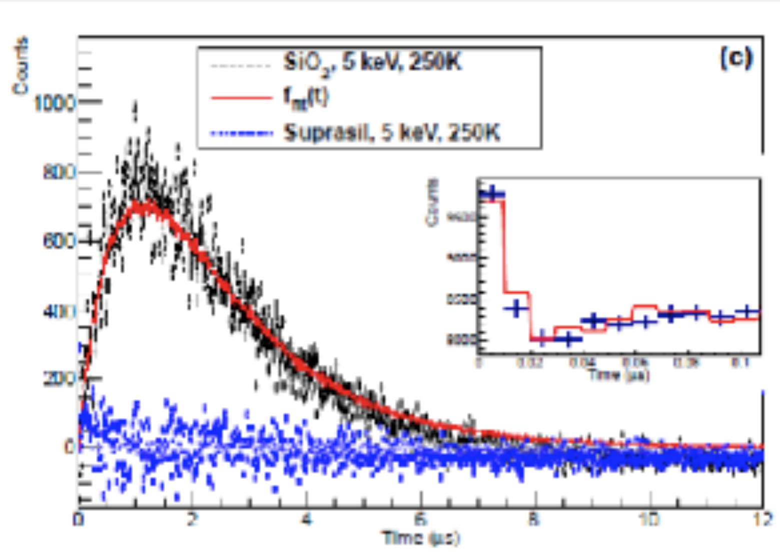


Mu emission in vacuum
detection efficiency in downstream
detector is time dependent,
deviation from exponential decay



Results



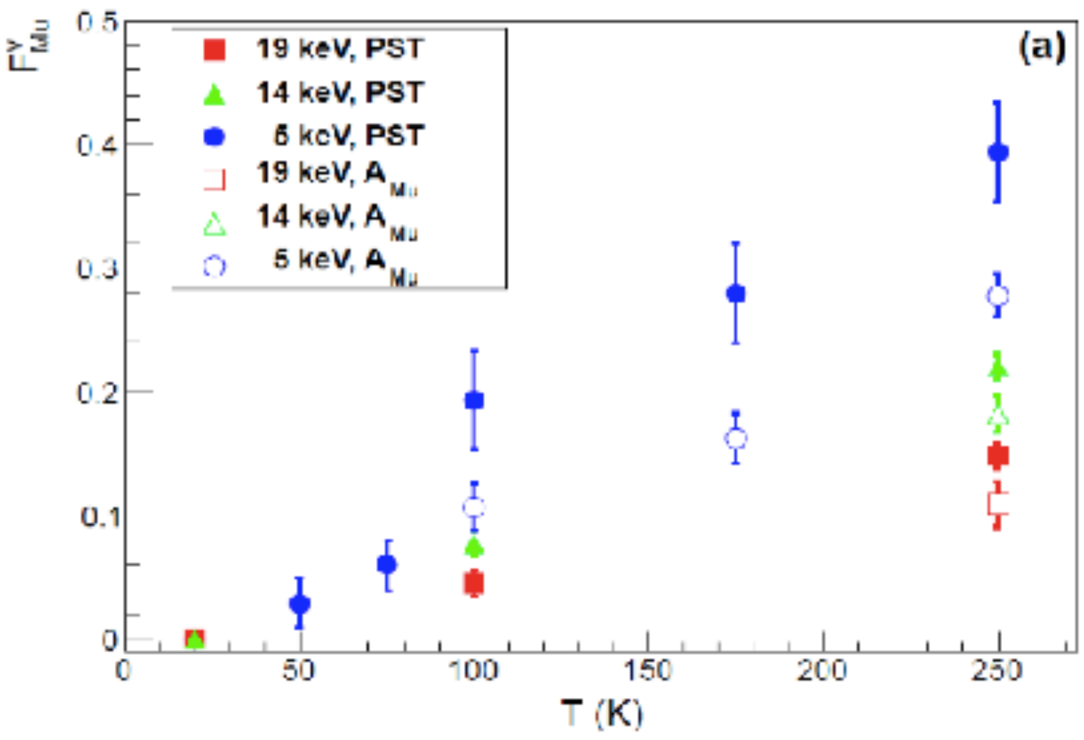


$$f_{\rm fit}(t) = n[(1 - F^{v}_{Mu}) f_0(t) + F^{v}_{Mu} f_{100}(t)] + n_{pp} f_{pp}(t)$$

$\Rightarrow$ Vacuum yield $F^{\rm v}_{\rm Mu}$

Results

A. Antognini, P. Crivelli et al., PRL 108, 143401(2012)



(38±4)% at 250 K and (20±4)% at 100 K for 5 keV

Prior to this study few % at 300K from SiO_2 powders, emission at lower T has never been reported.

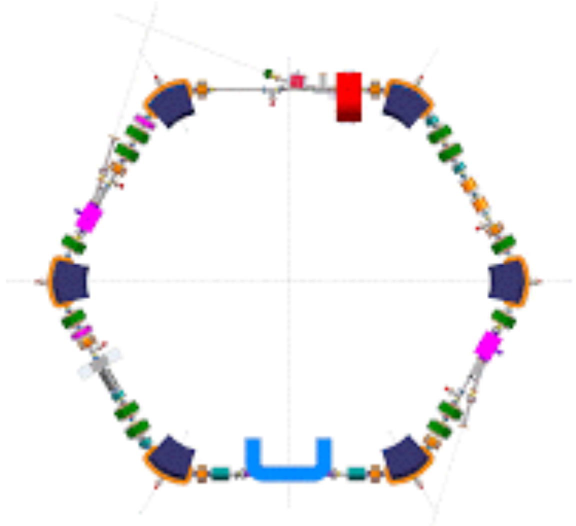
Muonium detection summary and outlook

- Measurement of angular distribution + improved energy study: excitation via laser in Rydberg states + detection very low efficiency (muons cannot be accumulate)

- Tracking back the decaying positron? Single track no vertex 😕

★ Ideally efficient detector for Mu atoms with meV energies.

Antiprotons



ELENA
Extra Low ENergy Antiprotons

⇒ few 10^6 100 keV anti-protons

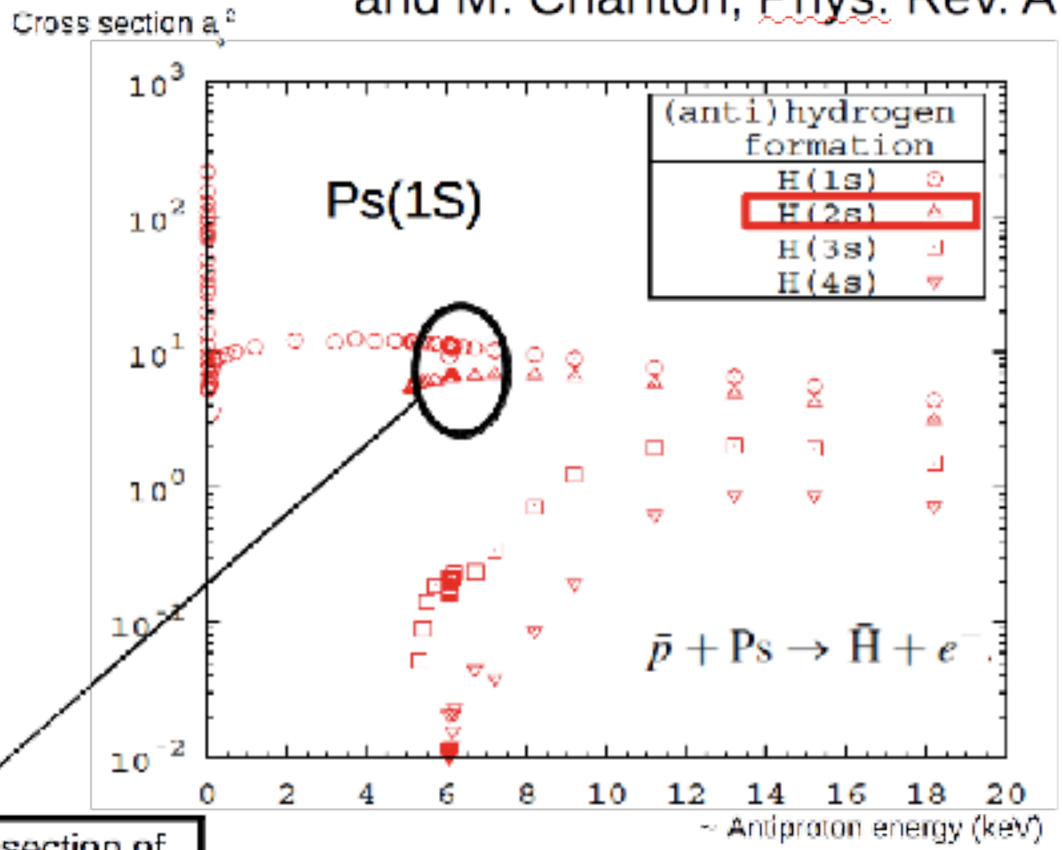
in 100 ns bunches

★ New era for antiproton/anti-hydrogen physics

$\bar{\mathrm{H}}$ production cross sections via charge exchange: $\bar{\mathrm{p}}$ +Ps → $\bar{\mathrm{H}}$ + e$^-$

C. M. Rawlins, A. S. Kadyrov, A. T. Stelbovics, I. Bray, and M. Charlton, Phys. Rev. A 93, 012709 (2016).

- ★Demonstrated for H
- ★Demonstrated for $\bar{\mathrm{H}}$ (ATRAP)
- ★Implemented by AEgIS and GBAR



For 6 keV cross section of H(2S) around 2.2x10^{-15} cm^2

$\bar{H}$ production cross sections via charge exchange: $\bar{p}$ +Ps → $\bar{H}$ + e^-

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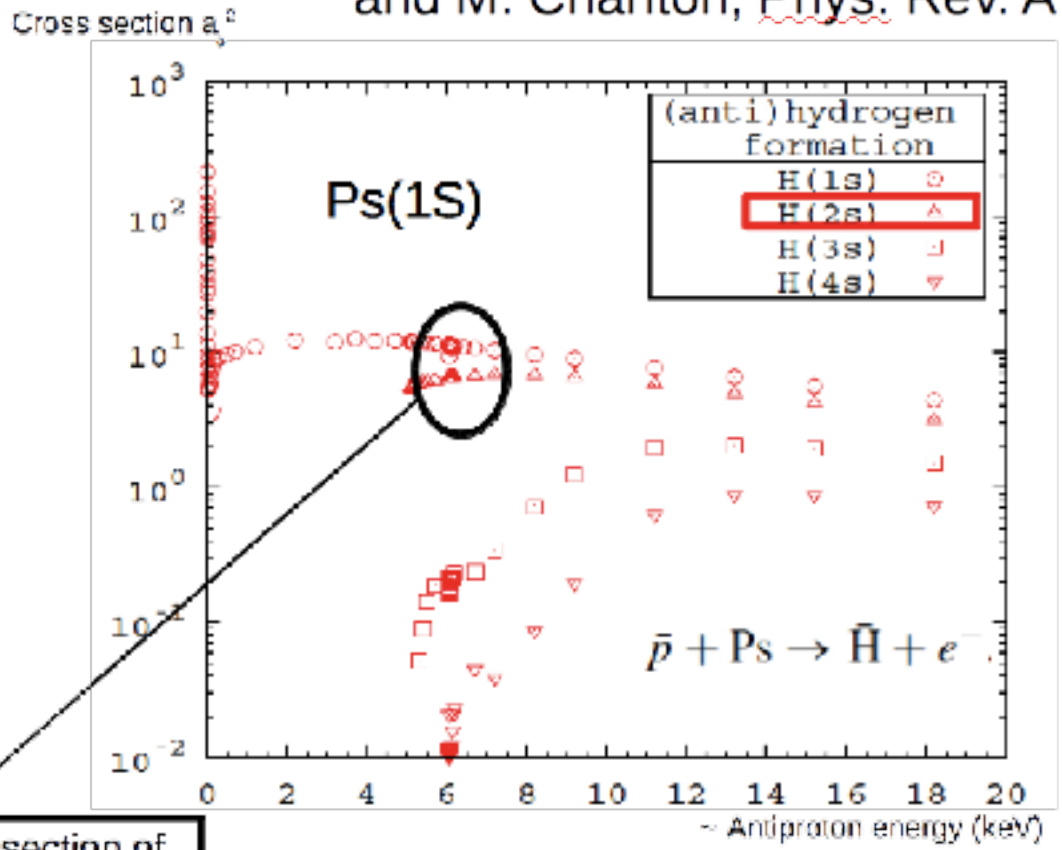
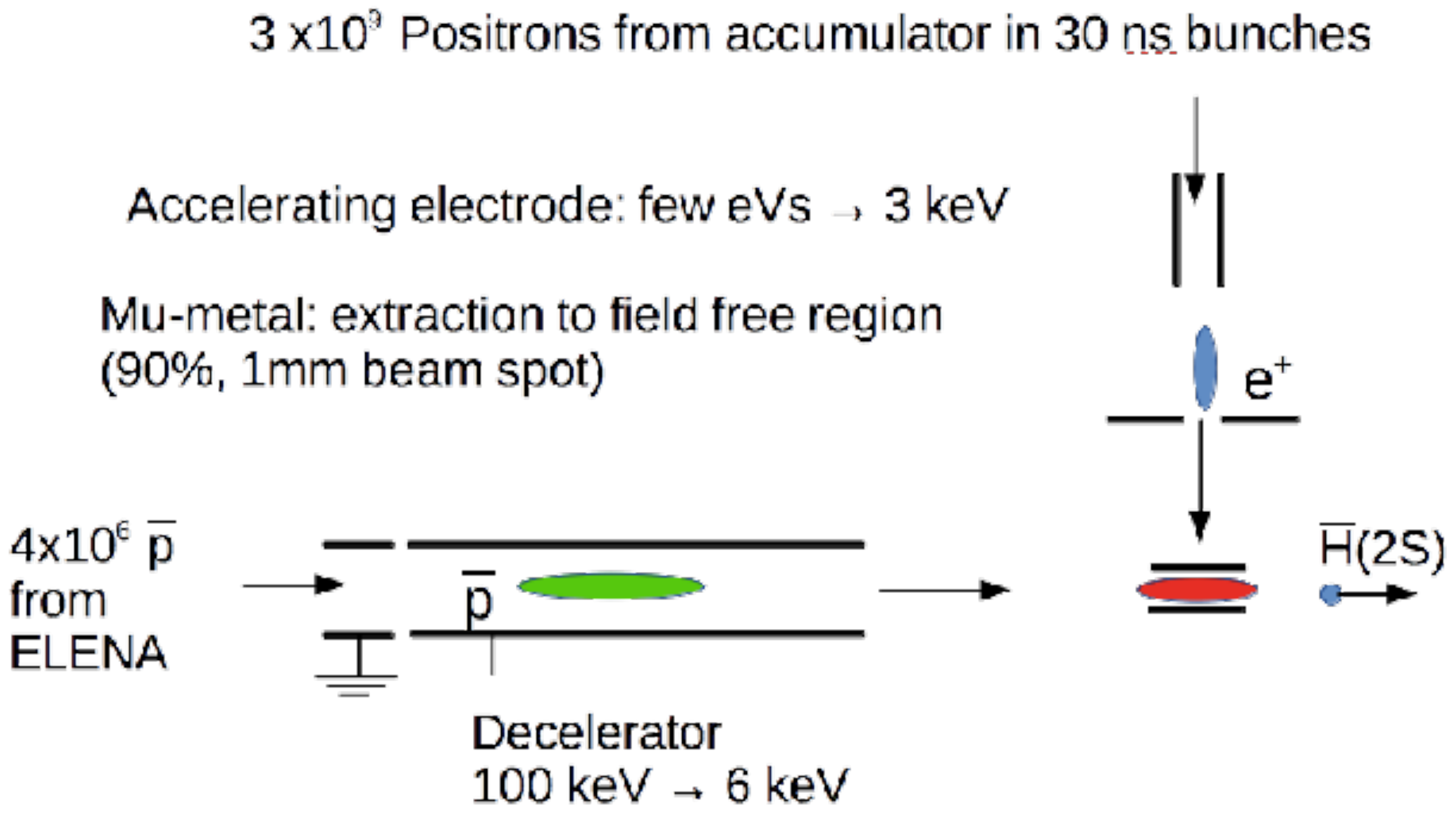


For 6 keV cross section of H(2S) around 2.2×10^{-15} cm^2

$$N_{\overline{\mathrm{H}}(2S)} = \sigma_{\overline{\mathrm{H}}} \cdot N_{\overline{\mathrm{p}}} \cdot n_{Ps} \cdot L \simeq 50$$

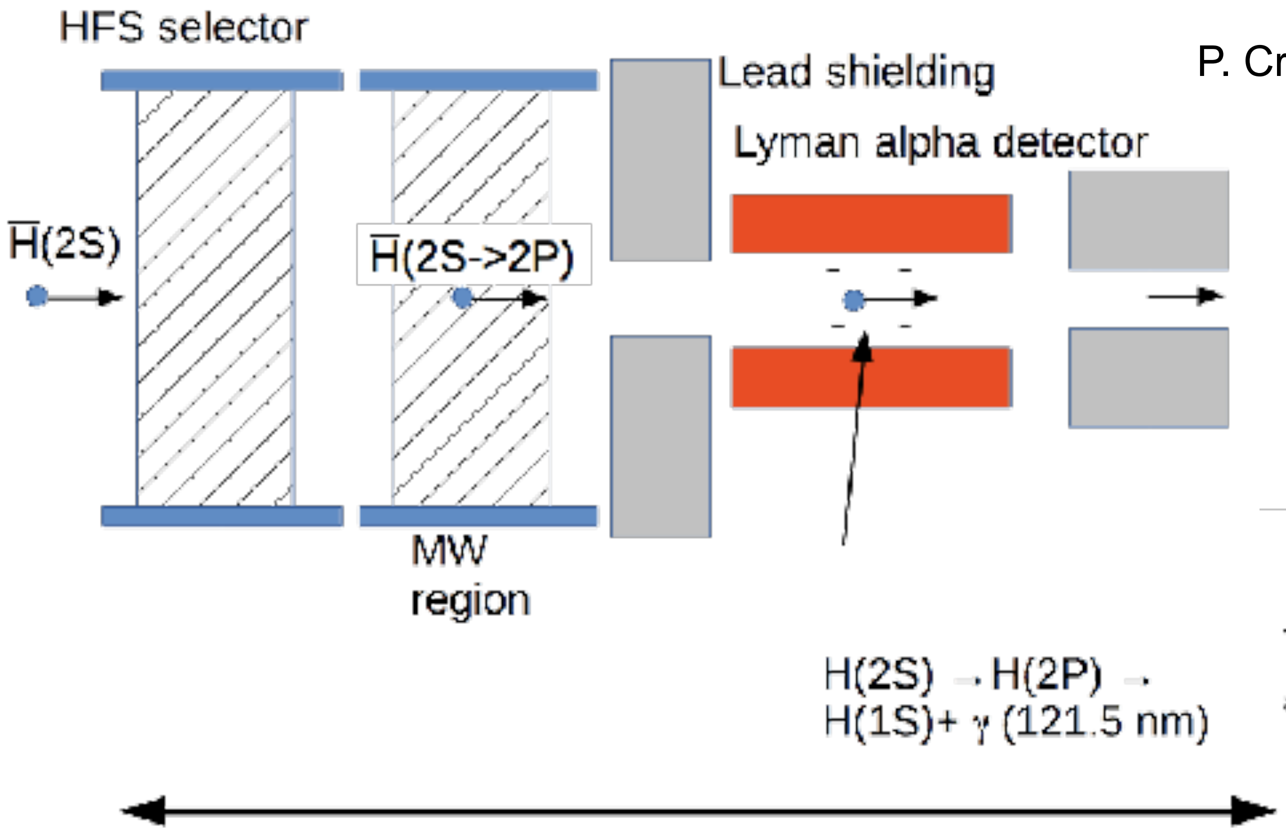
Anti-hydrogen $\bar{H}$(2S) beam → Lamb shift measurement

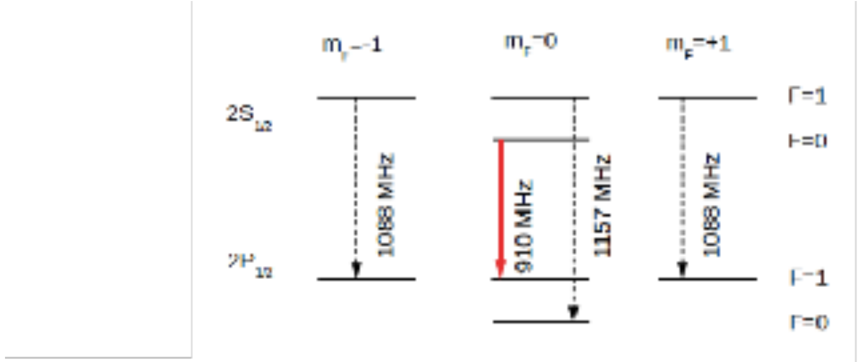


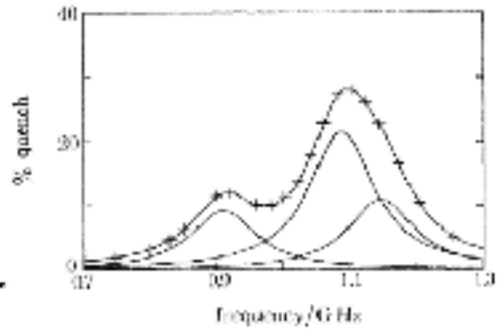
P. Crivelli et al. PRA, 81, 052703 (2010)
D. Cooke, P. Crivelli et al. Hyp. Int. 233, 67 (2015)

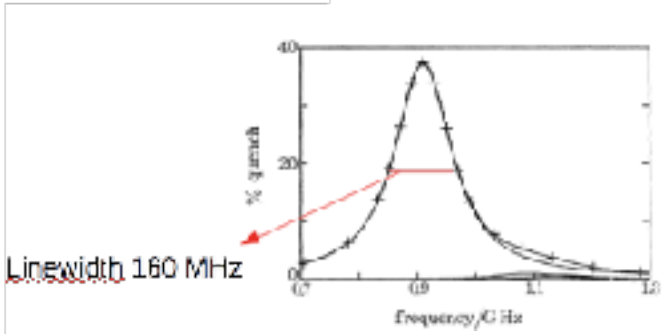
Principle of the measurement

P. Crivelli, D. Cooke, M. Heiss, Phys. Rev. D 94, 052008 (2016)



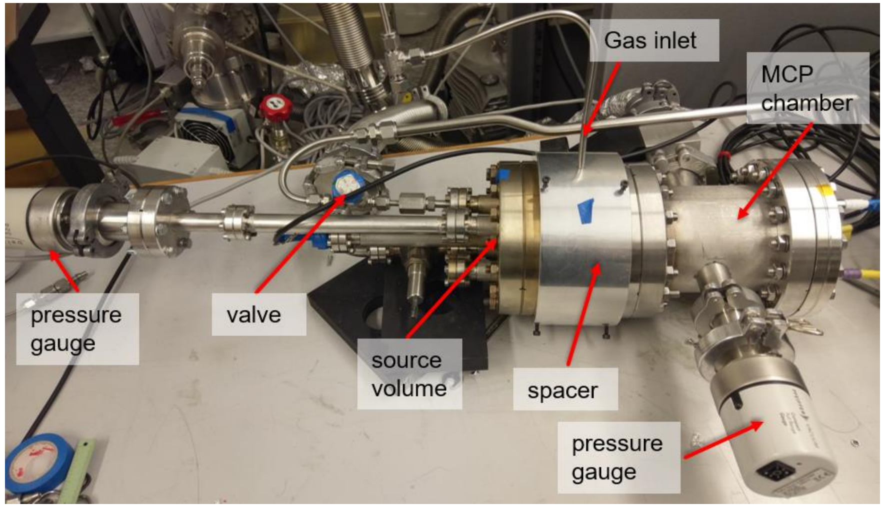






G. Newton; D. A. Andrews; P. J. Unsworth, Phil. Trans. of the Royal Soc. of London. Series A, Math. and Phys. Sciences 290, 373, (1979).

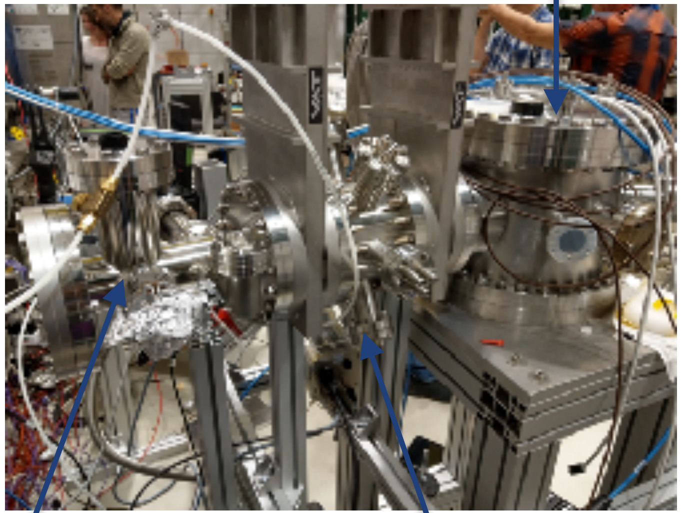
Lyman alpha detector



Detector based on CsI coated MCP
→ 40% efficiency tested
→ including solid angle
18% efficiency expected

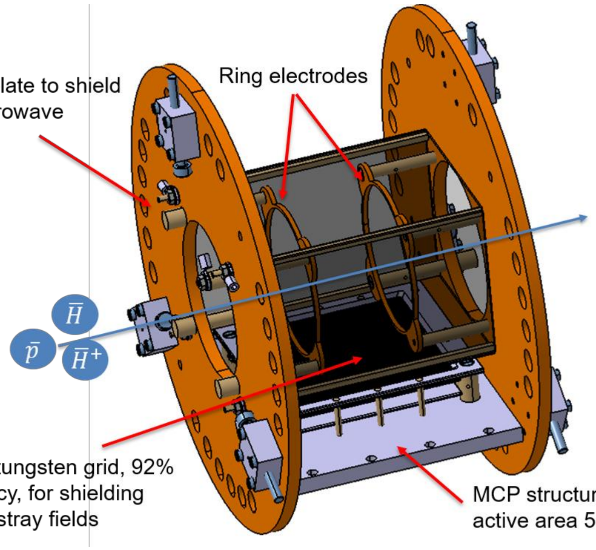
Detector in the AD

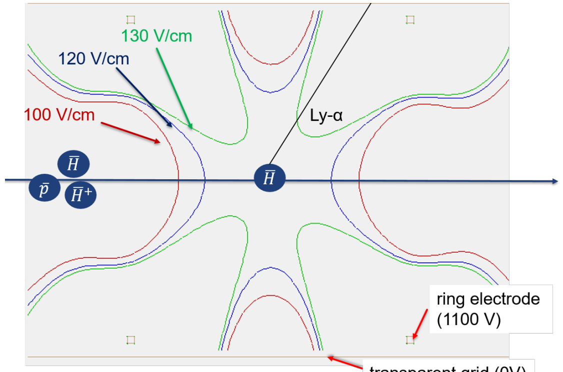
Switchyard



MW section

Lyman alpha detector





Simion simulation of quenching region

Micromegas detectors for anti-hydrogen annihilation

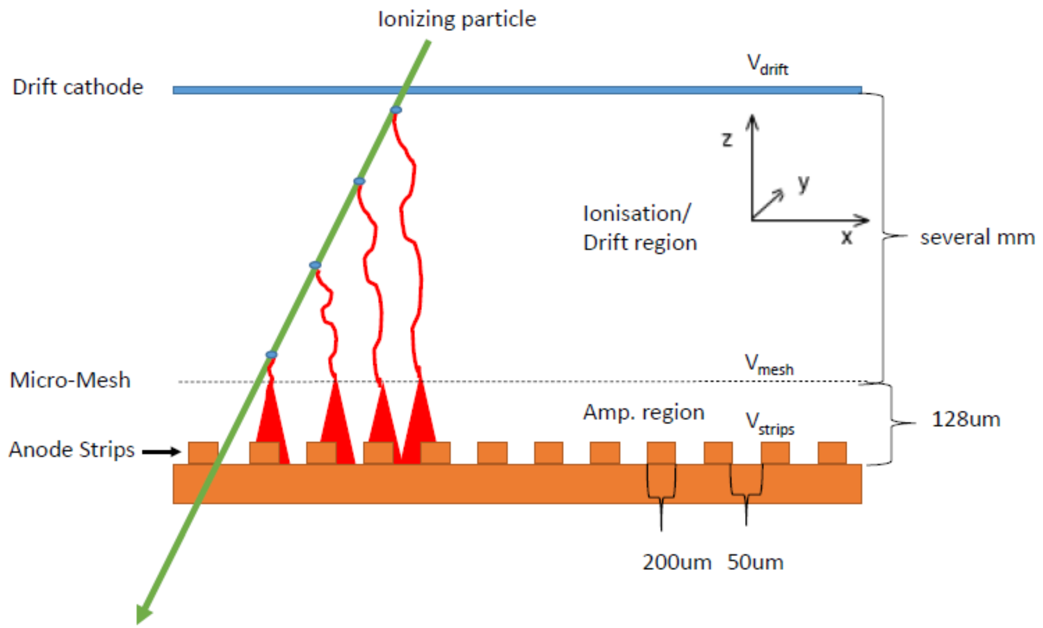
Detection of anti-hydrogen with micromegas by ASACUSA

Rev Sci Instrum. 2015 Aug;86(8):083304. doi: 10.1063/1.4927685.

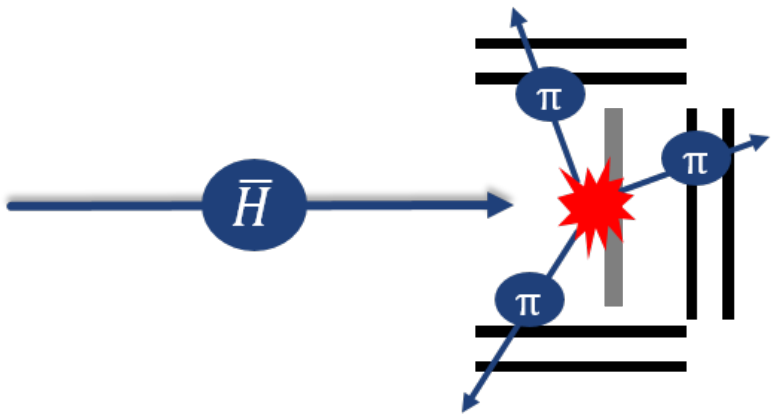
GBAR -prototypes

Filling gas: Ar93/$CO_2$7%
Drift: 6 mm long, ~ 600 V/cm
Amplification: 128 um, ~ 45 kV/cm
Detection: X&Y layers, 320 strips each
Active area: 8x8 cm^2
Readout: APV, 128 channels
Multiplexing: Factor 5
DAQ: SRS mmDAQ of RD51

https://doi.org/10.1016/j.nima.2017.10.067

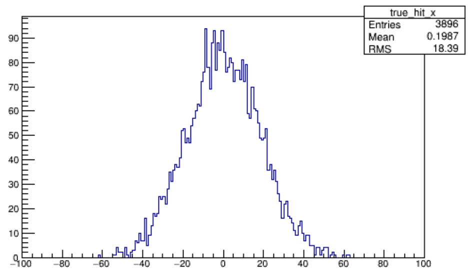


Micromegas detectors - beam profiling of low energy (<100 eV) $\bar{\mathrm{H}}$?

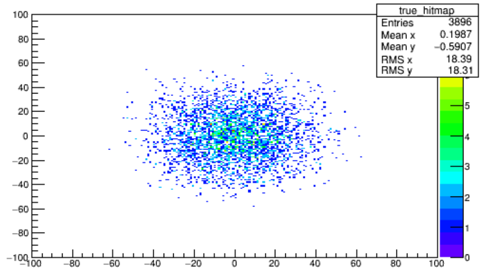


- H annihilating on the flange of a tube
- 8x8 Micromega doublets placed around the tube to measure pions coming from annihilation

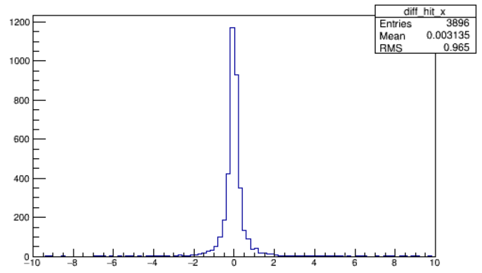
- 20’000 events simulated
- True hit position on flange recorded
- Beam spot reconstructed by fitting a line through hits of Micromega doublet close to the flange



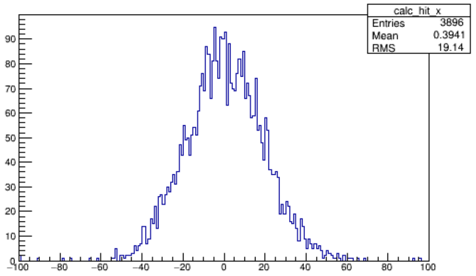
True hits on MM, X layer



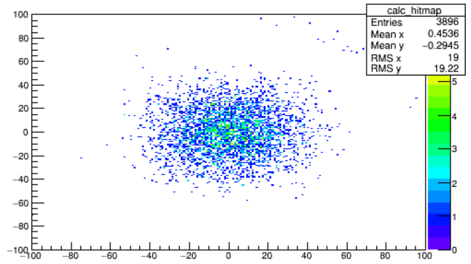
True beam spot

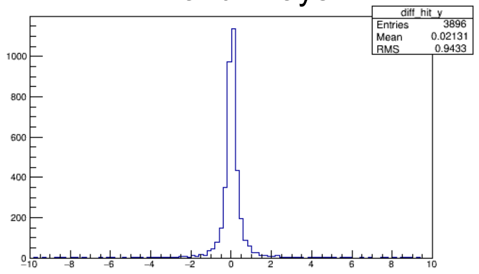


Differences between reconstructed and true hit In X and Y layer



Reconstructed beam spot





Simulation: promising results but limited spatial resolution + annihilation on end flange, alternatives?

Summary and outlook

- MCP workhorse for antimatter beams characterisation

✦ Main limitations:
- destructive technique
- bulky (e.g. phosphor screen requires optical access) and costly (MCP delay line commercially available but 20kEuros)
- low efficiency to detect neutrals with energies below 100 eV

★ Are there alternative new detector technologies could help in maximising the physics output?

Exciting times are ahead!