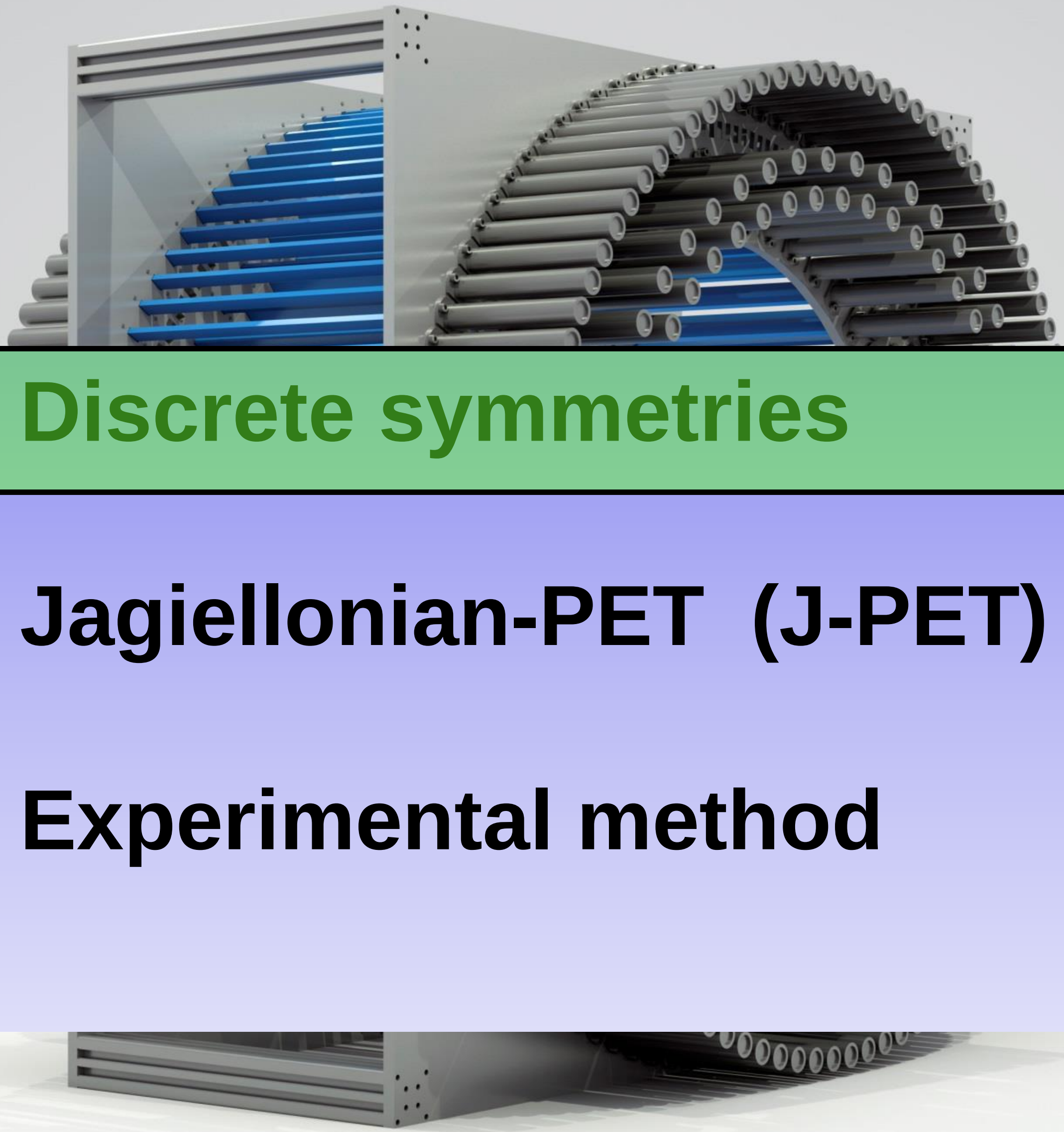
Tests of discrete symmetries in positronium decays with the J-PET detector

Low Energy Antiproton Physics Conference
Paris, 15 March 2018

Paweł Moskal on behalf and for the J-PET collaboration
Jagiellonian University, **http://koza.if.uj.edu.pl**

J-PET



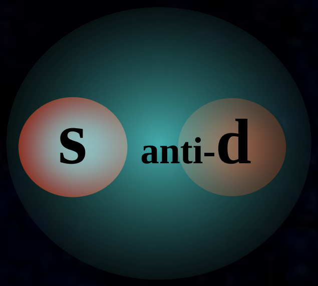
- **Discrete symmetries**
- **Jagiellonian-PET (J-PET)**
- **Experimental method**

Discrete symmetries

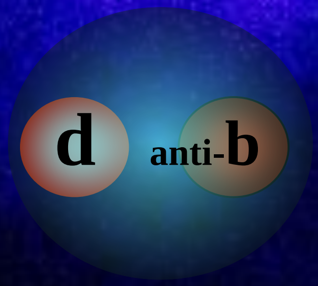
P	reflection in space	(x,y,z $\rightarrow$ -x,-y-z)
C	charge conjugation	(particles $\rightarrow$ anti-particle)
T	reversal in time	(A $\rightarrow$ B => B $\rightarrow$ A)
CP		
CPT		

[redacted]

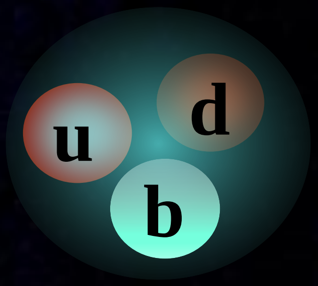
Violation of CP and T confirmed experimentally for hadrons only



meson K

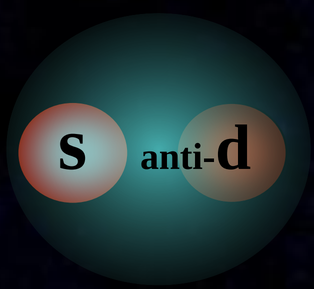


meson B



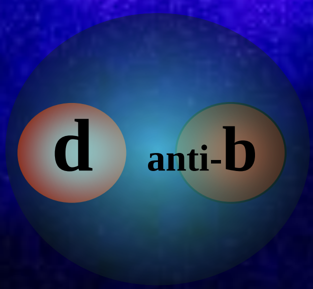
Baryon Λ_b^0

Violation of CP and T confirmed experimentally for hadrons only



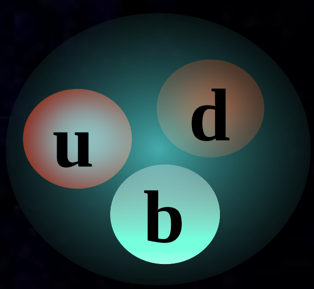
meson K

1964



meson B

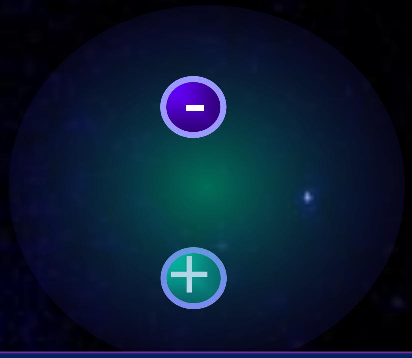
2012



Baryon Λ_b^0

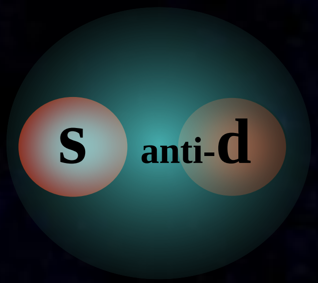
2017

Violation of CP and T confirmed experimentally for hadrons only



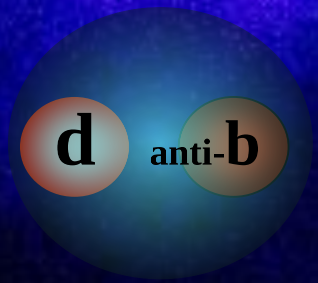
positronium

?



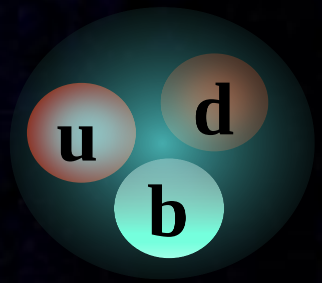
meson K

1964



meson B

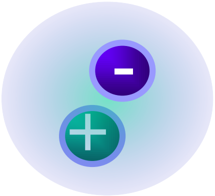
2012



Baryon Λ_b^0

2017

ODE TO POSITRONIUM



Eigen-state of Hamiltonian and P, C, CP operators

The lightest known atom and at the same time anti-atom which undergoes self-annihilation as flavor neutral mesons

The simplest atomic system with charge conjugation aigenstates.

Electrons and positron are the lightest leptons so they can not decay into lighter partilces via weak interactiom ...
effects due the weak interaction can lead to the violation at the order of 10^{-14}.
M. Sozzi, Discrete Symmetries and CP Violation, Oxford University Press (2008)

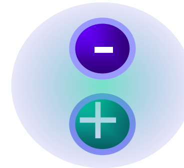
No charged particles in the final state (radiative corrections very small 2 * 10^{-10})
Light by light contributions to various correlations are small
B. K. Arbic et al., Phys. Rev. A 37, 3189 (1988).
W. Bernreuther et al., Z. Phys. C 41, 143 (1988).

Purely Leptonic state !

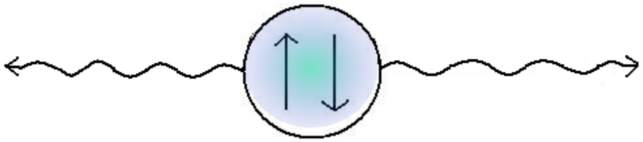
Breaking of T and CP was observed but only for processes involving quarks.
So far breaking of these symmetries was not observed for purely leptonic systems.

10^{-9} vs   upper limits of 3 10^{-3} for T, CP, CPT

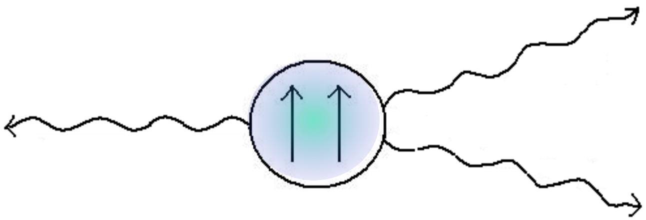
P.A. Vetter and S.J. Freedman, Phys. Rev. Lett. 91, 263401 (2003)
T. Yamazaki et al., Phys. Rev. Lett. 104 (2010) 083401



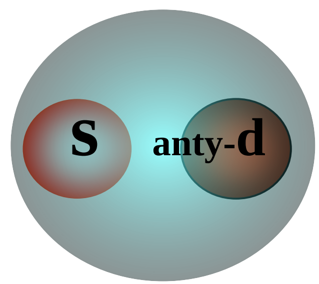
POSITRONIUM



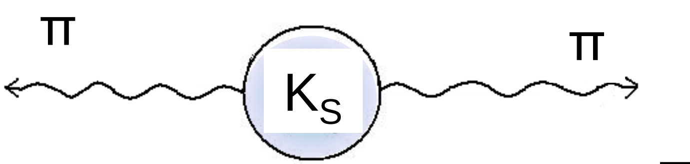
CP = + Para-positronium   tau(p-Ps) ≈ 125 ps



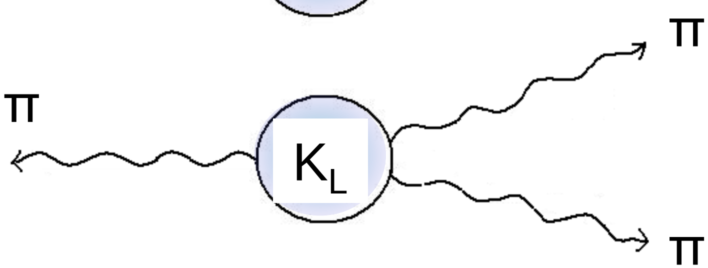
CP = - Ortho-positronium tau(o-Ps) ≈ 142 ns



MESON K

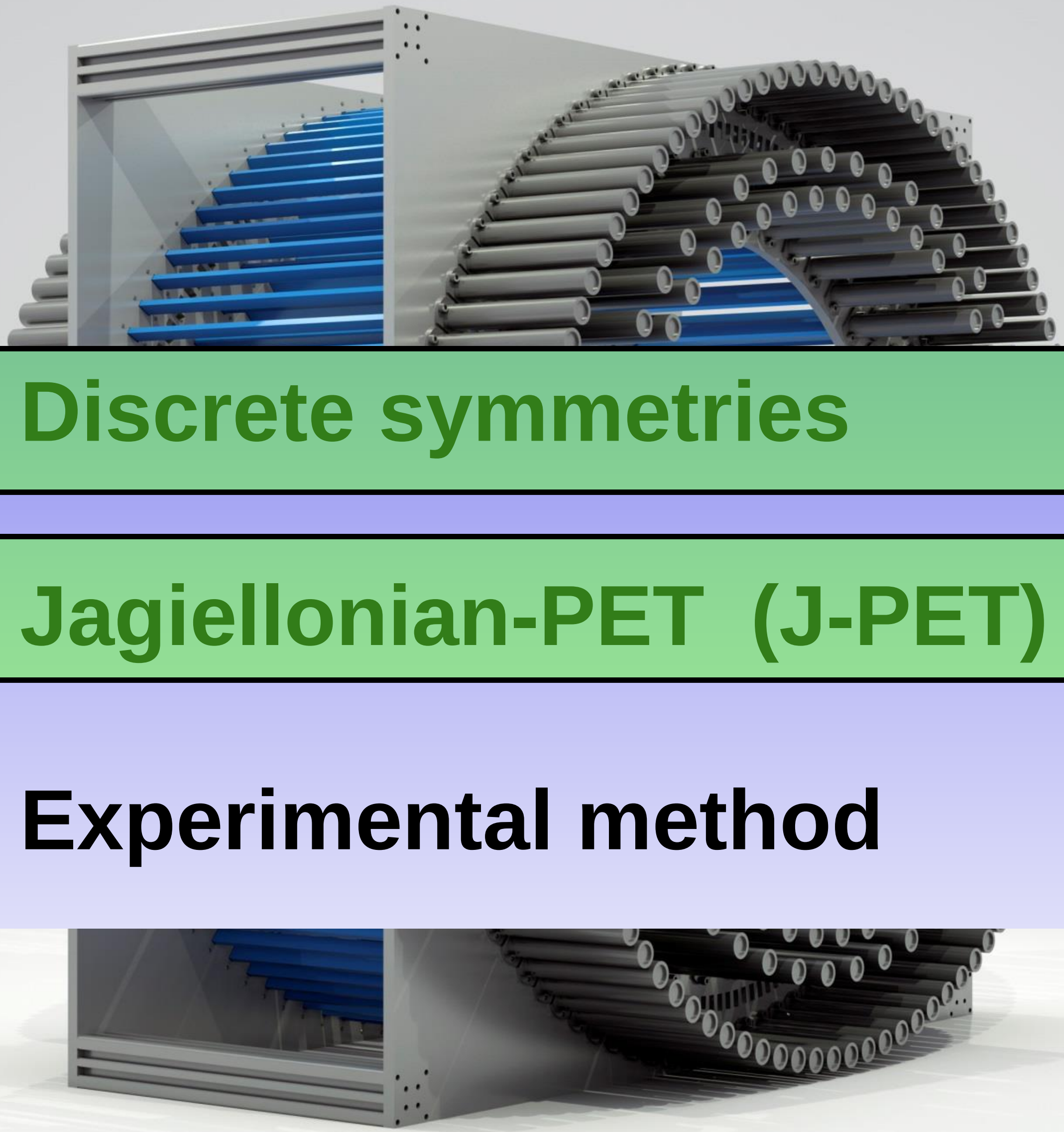


CP ~= +   tau(K_S) ≈ 90 ps



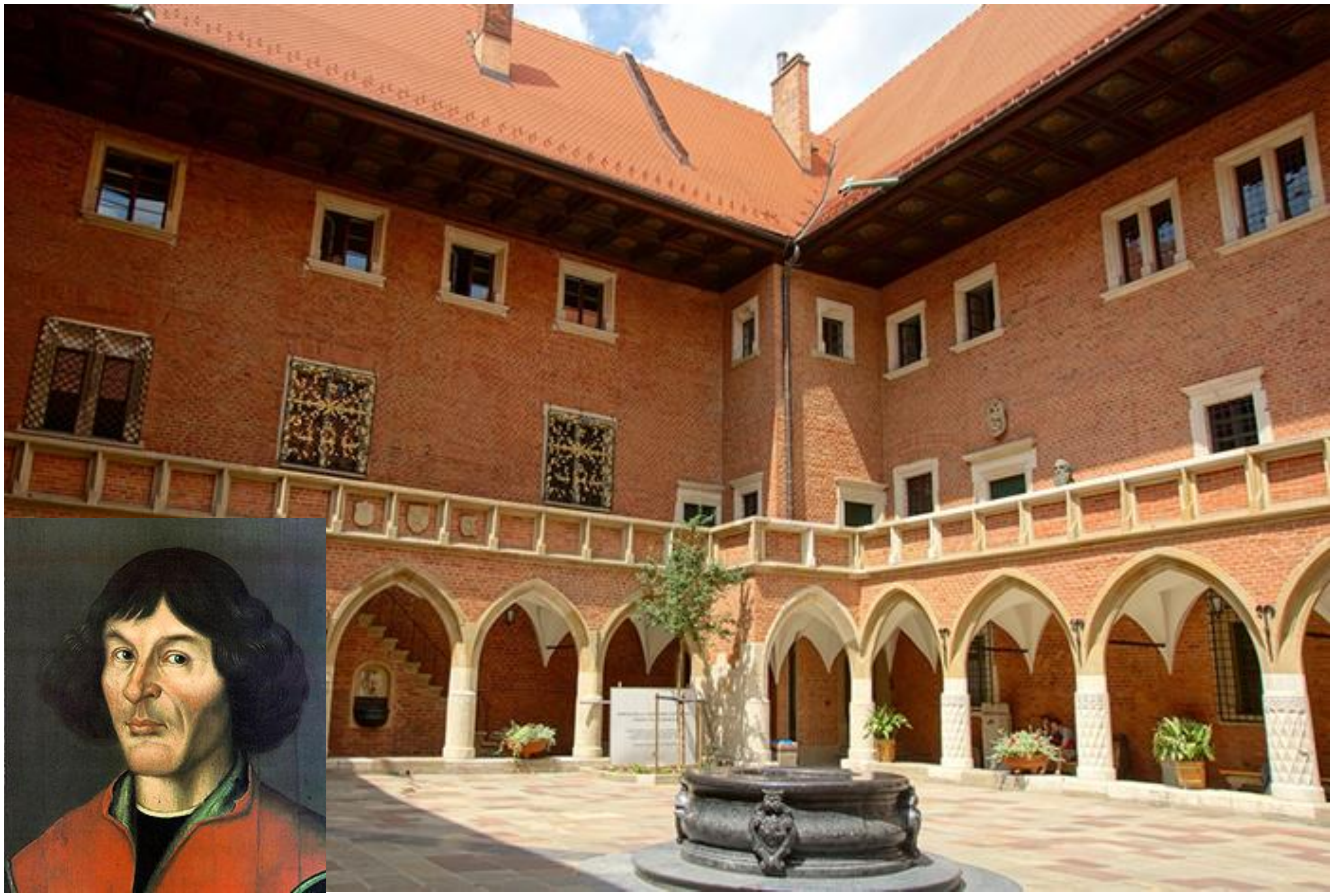
CP ~= -   tau(K_L) ≈ 52 ns

J-PET



- Discrete symmetries
- Jagiellonian-PET (J-PET)
- Experimental method

Jagiellonian University
1364



Collegium Maius at the University since **1400**

Jagiellonian PET

Collegium Maius 2015

J-PET: First PET based on plastic scintillators

Jagiellonian-PET Collaboration:

P. Moskal[1], C. Curceanu[2], E. Czerwiński[1], K. Dulski[1], A. Gajos[1], M. Gorgol[3], B. Hiesmayr[4], B. Jasińska[3], D. Kisielewska[1], G. Korcyl[1], P. Kowalski[5], T. Kozik[1], W. Krzemień[5], E. Kubicz[1], N. Krawczyk[1] M. Mohammed[1], M. Pawlik-Niedźwiecka[1], Sz. Niedźwiecki[1], M. Pałka[1], L. Raczyński[5], J. Raj[1], Z. Rudy[1], N. Sharma[1], S. Sharma[1], Shivani[1], M. Silarski[1], M. Skurzok[1], W. Wiślicki[5], B. Zgardzińska[3], M. Zieliński[1]

[1]Jagiellonian University, Poland; [2]LNF INFN, Italy; [3]Maria Curie-Skłodowska University, Poland; [4]University of Vienna, Austria; [5]National Centre for Nuclear Research, Poland;

Aim:

- Cost effective whole-body PET
- MR and CT compatible PET insert
- Configurable
- For large animals

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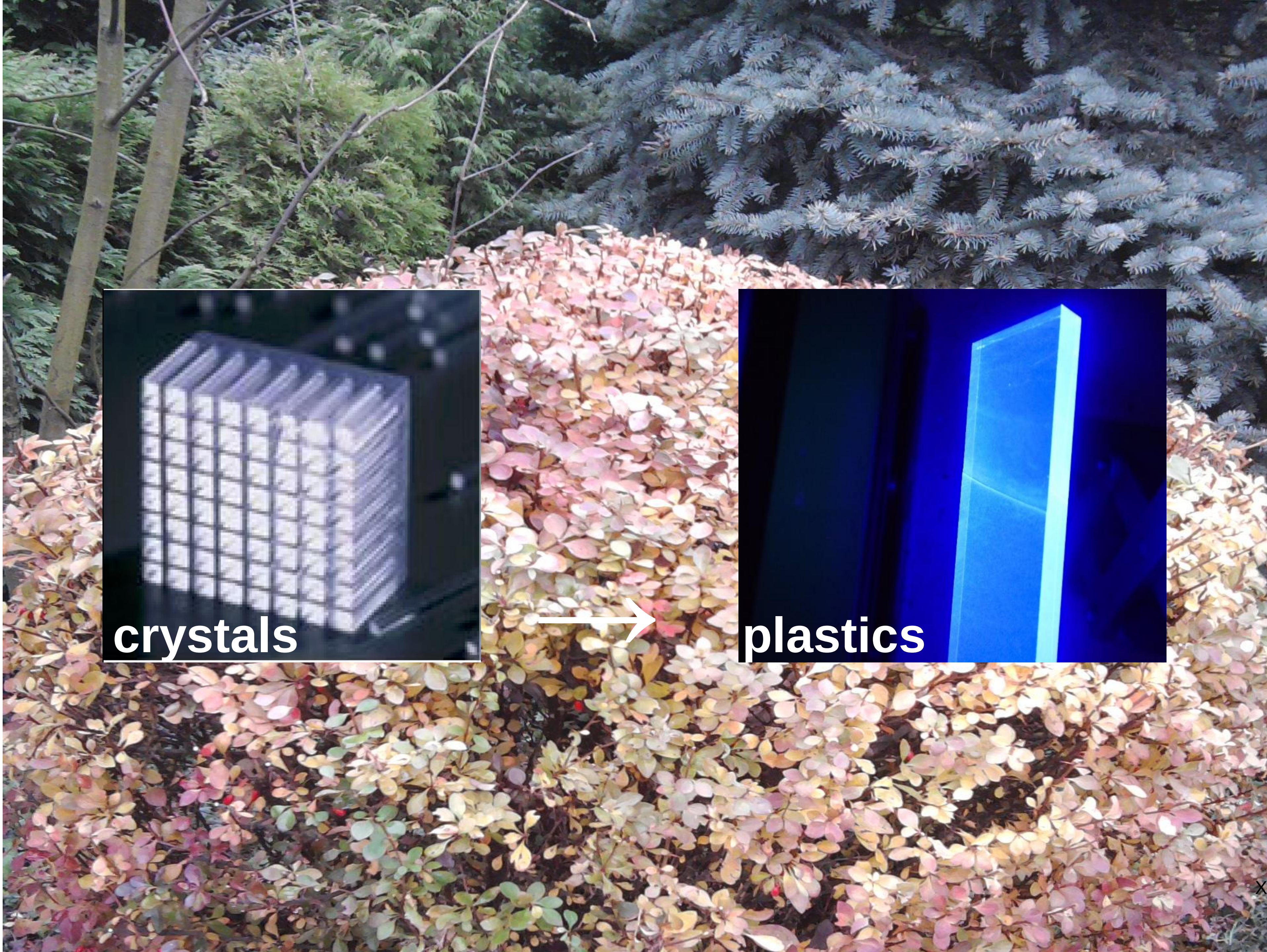
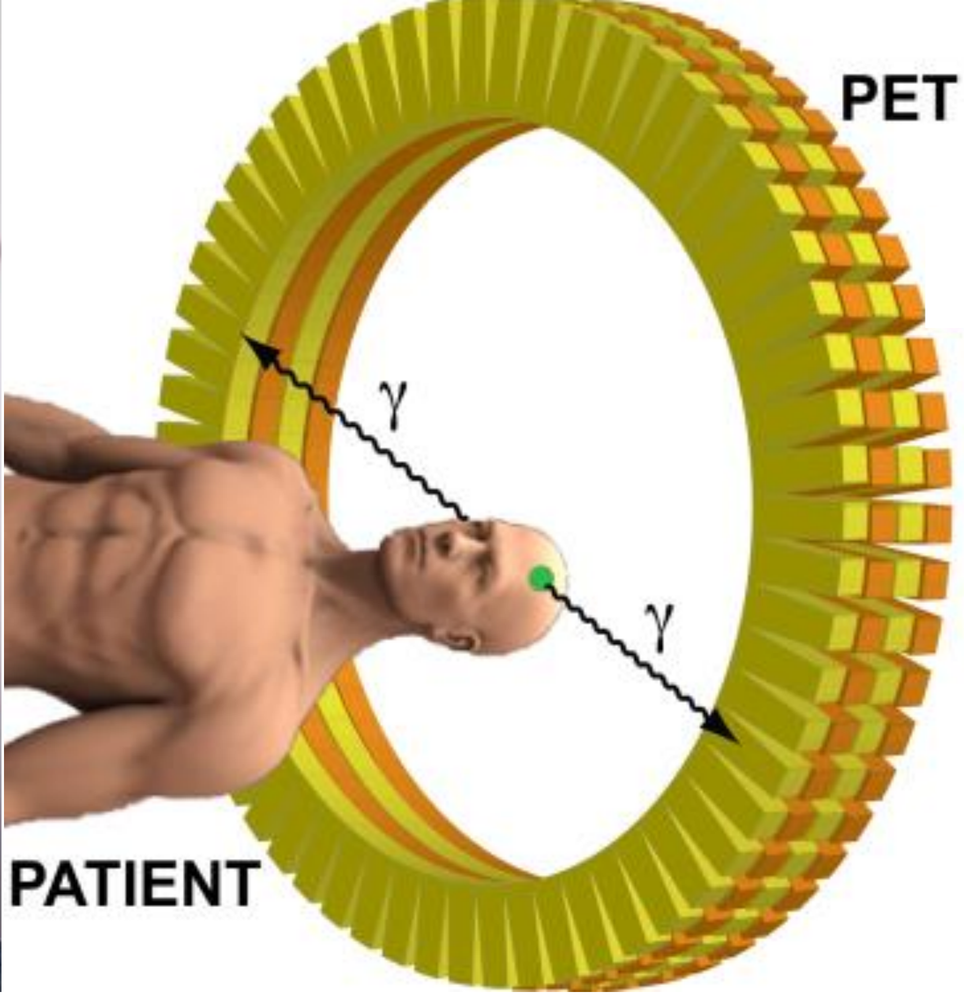
J-PET

Jagiellonian PET

J-PET

Cracow, July 2016

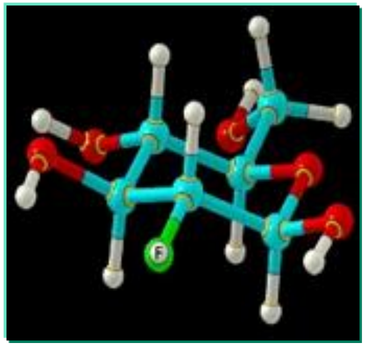

crystals
plastics



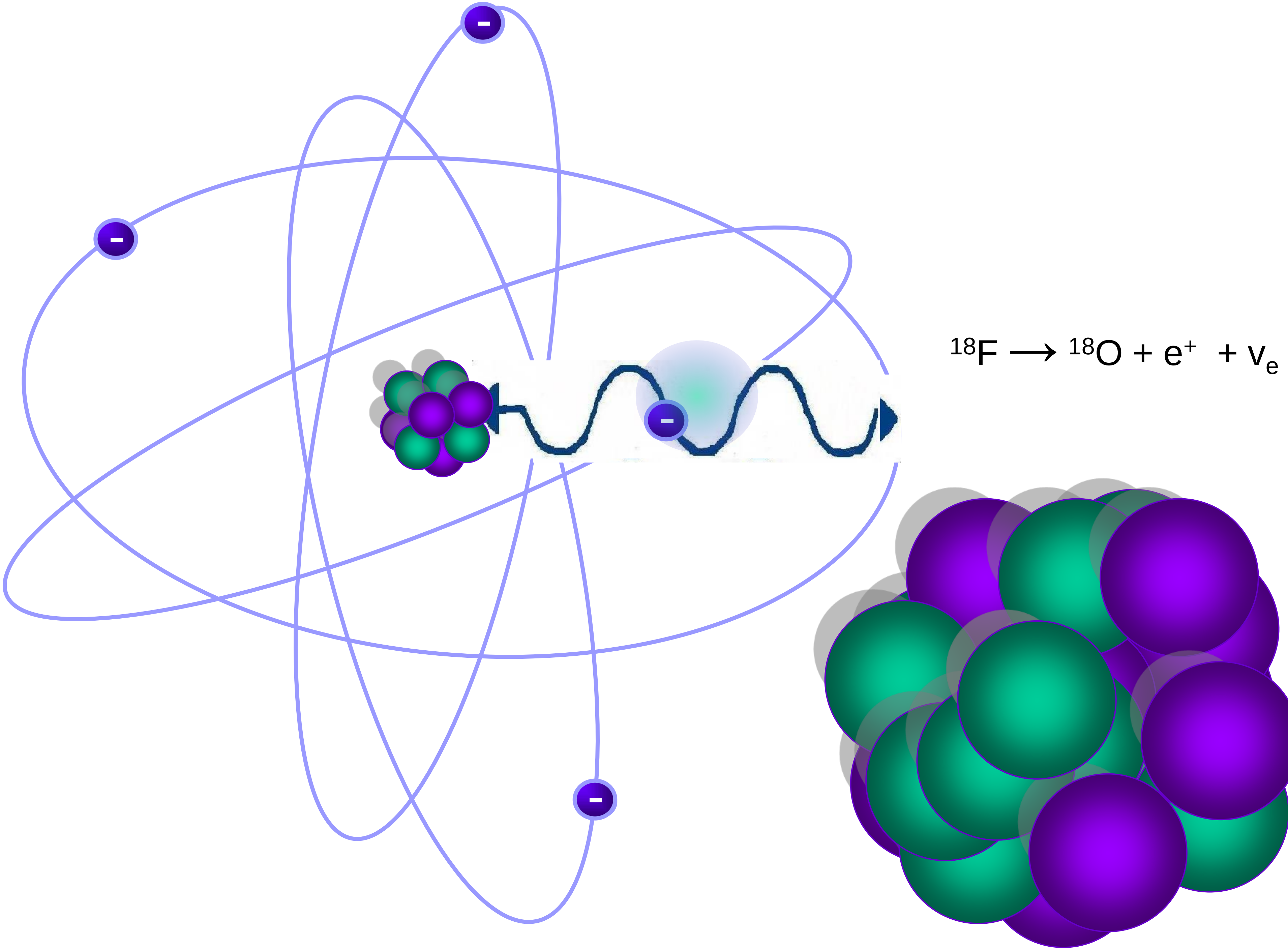
RADIOACTIVE SUGER

Fluoro–deoxy-glucose
(F-18 FDG)

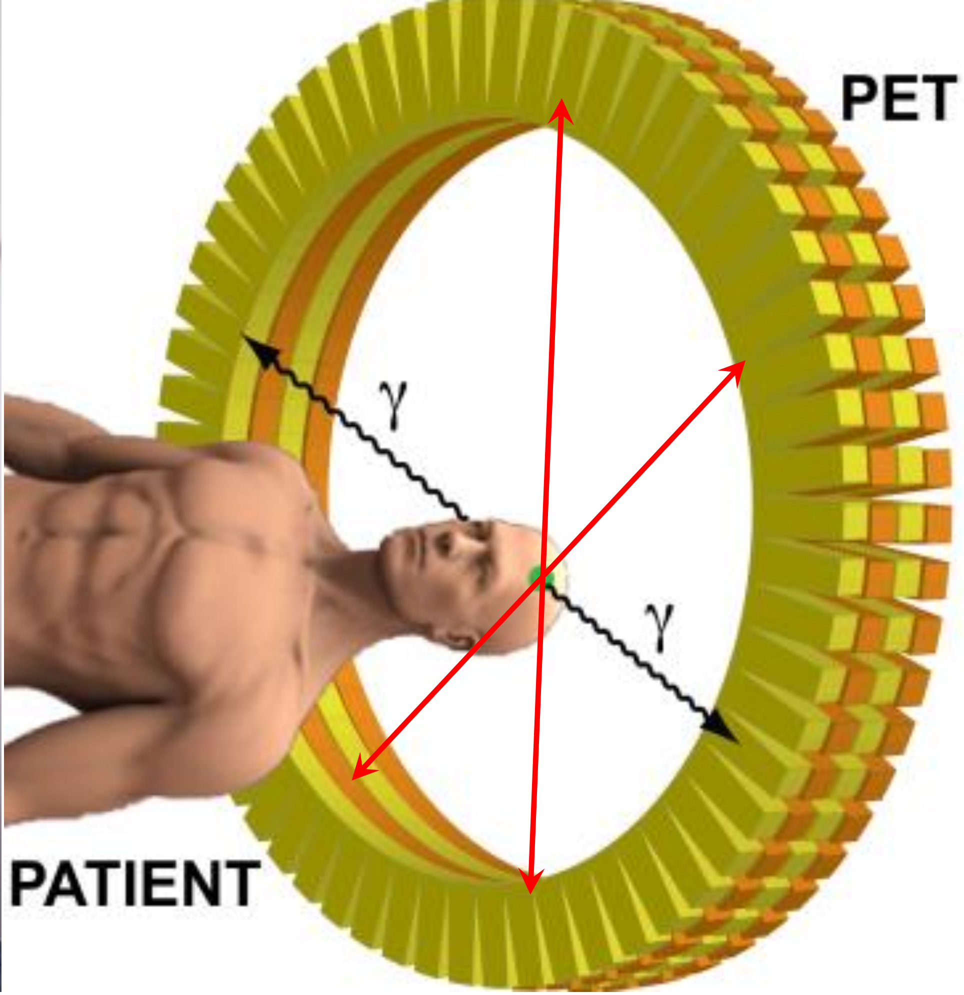
~200 000 000
gamma per second



7 mSv PET/CT
~ 2.5 mSv PET
~3 mSv natural background in Poland



$$^{18}F \longrightarrow {}^{18}O + e^{+} + \nu_e$$



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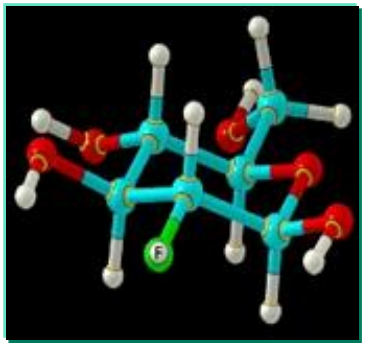

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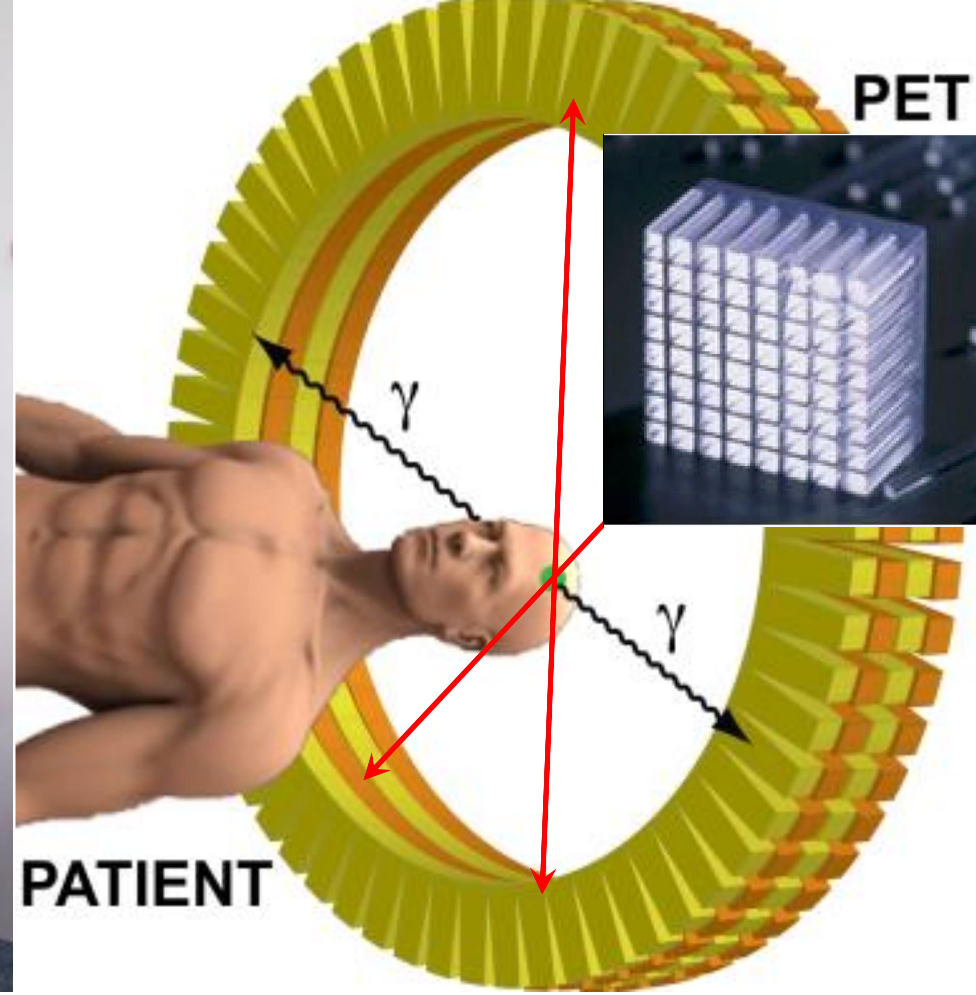

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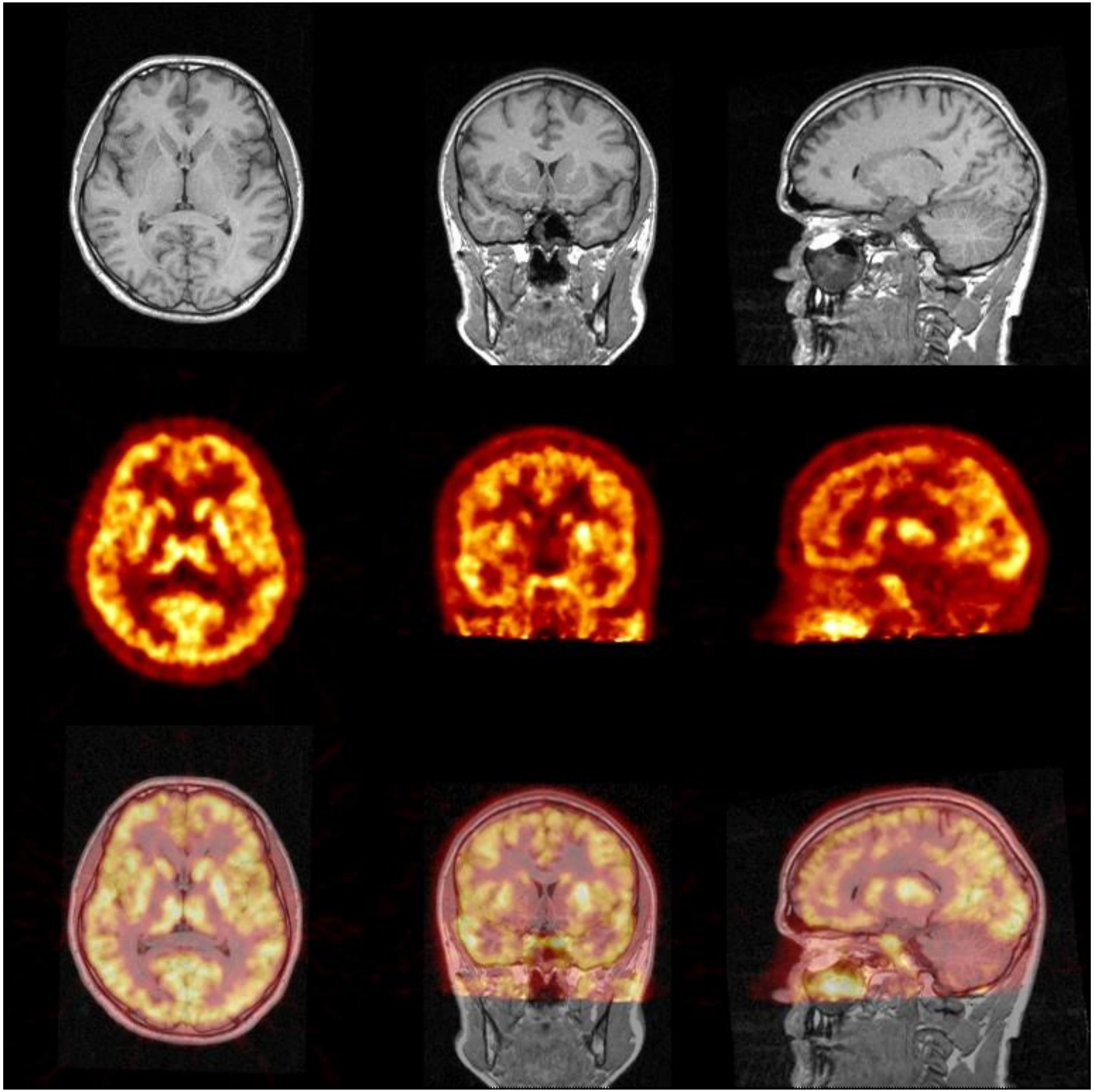
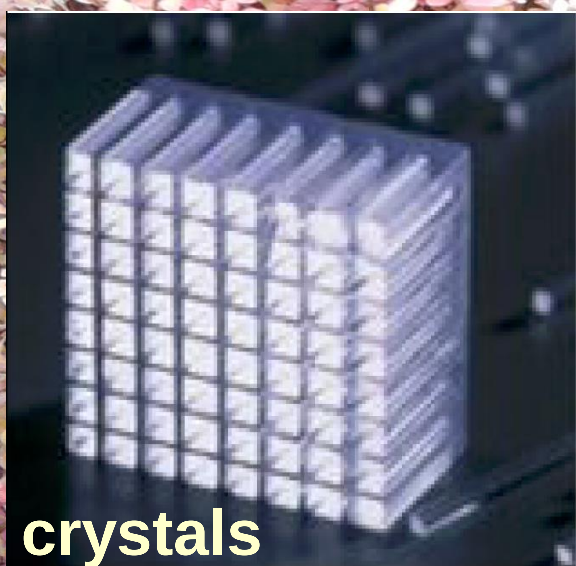
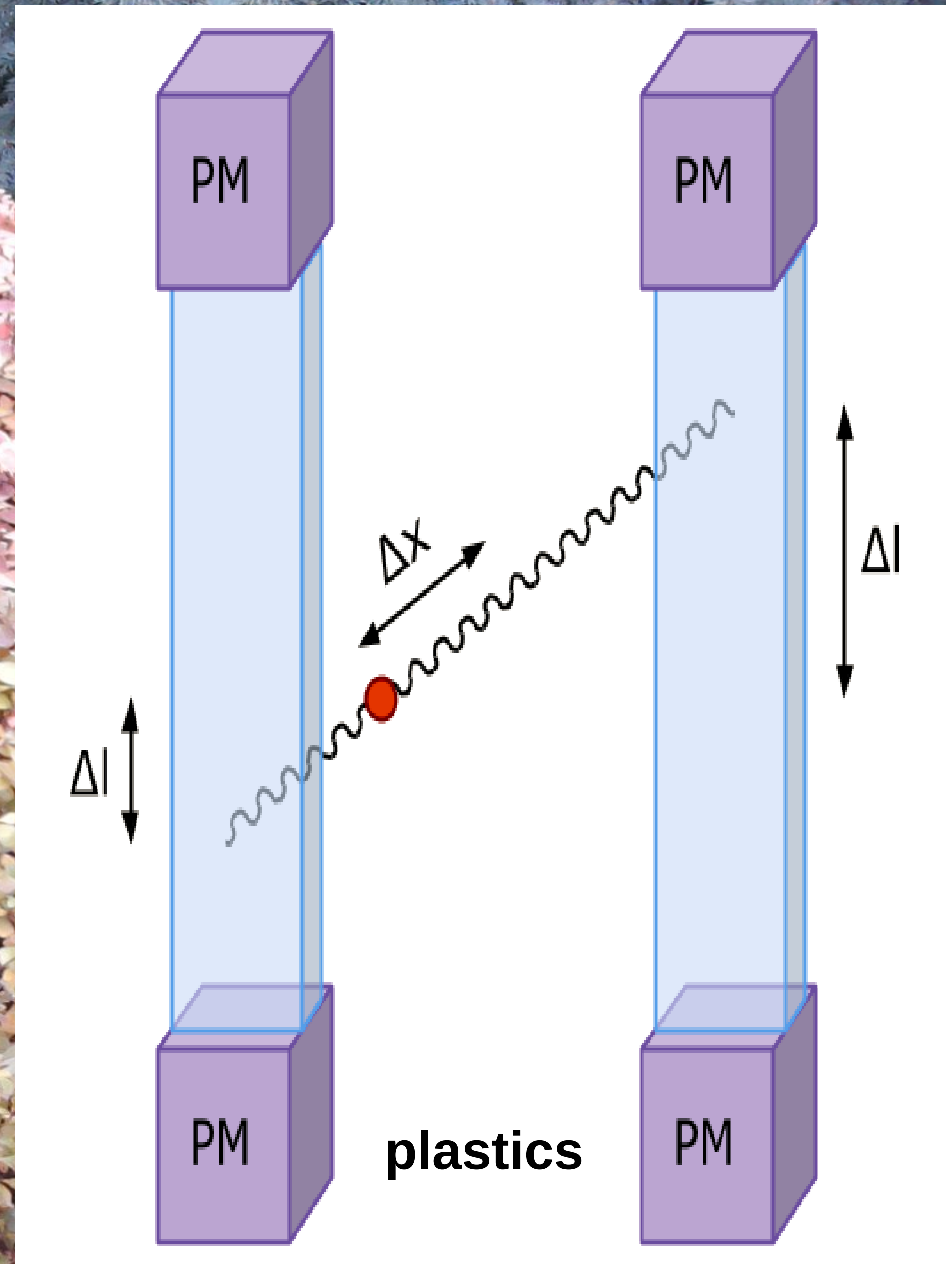
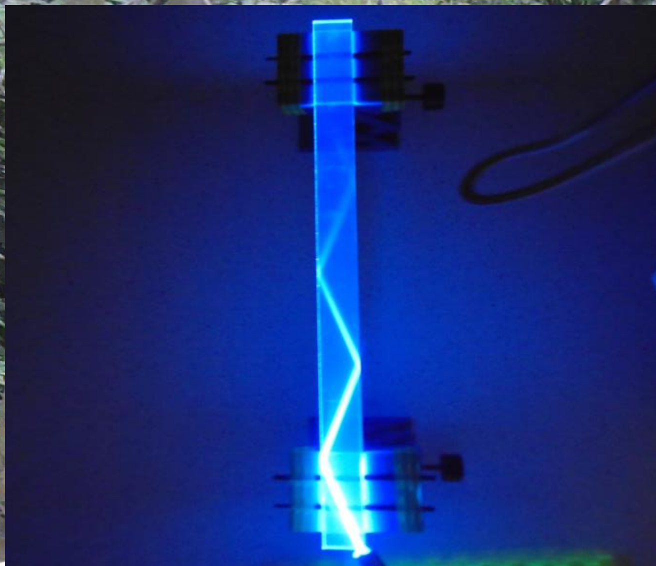
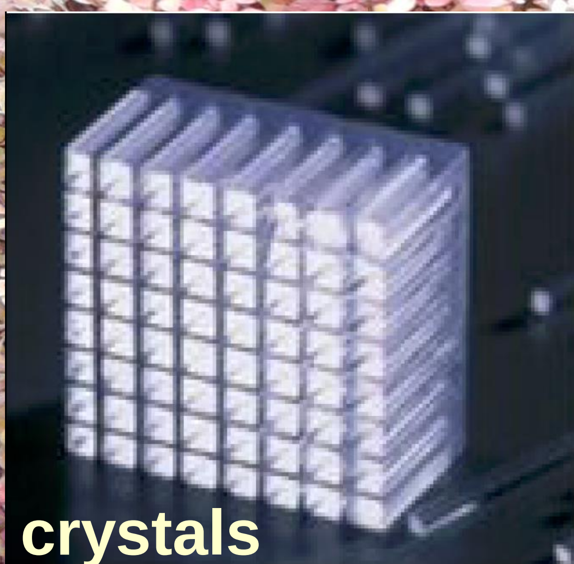



crystals


PM
PM
Δx
Δl
Δl
PM
plastics
PM

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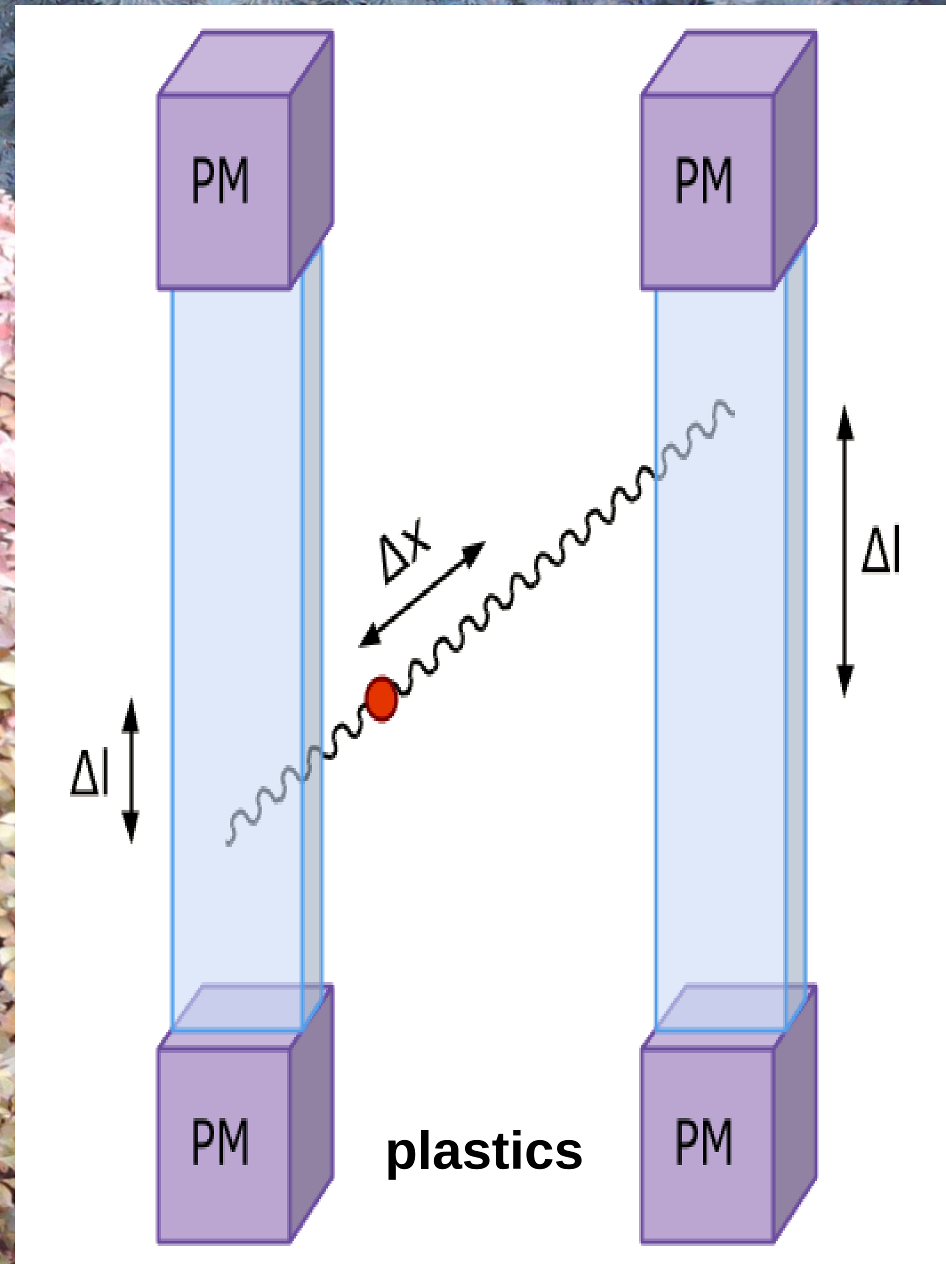
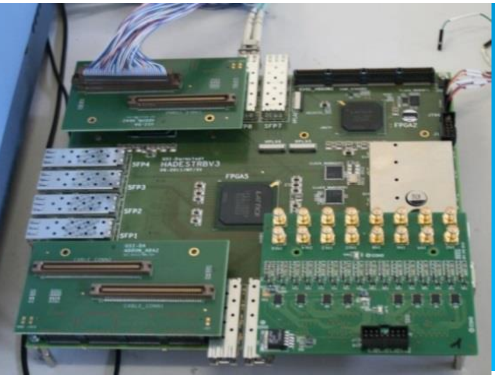

PM
PM
Δx
Δl
Δl
PM
plastics
PM



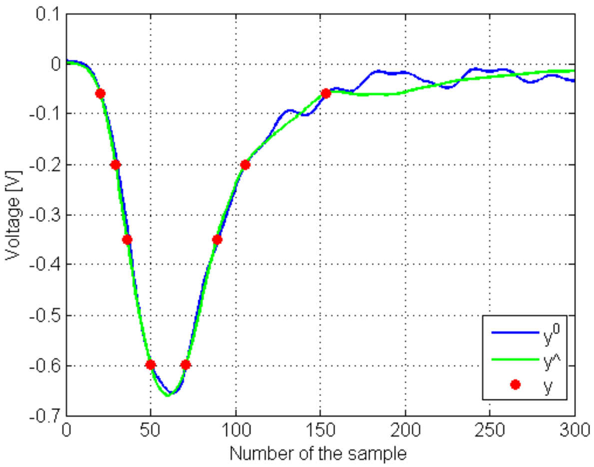
ONLY DIGITAL in triggerless mode

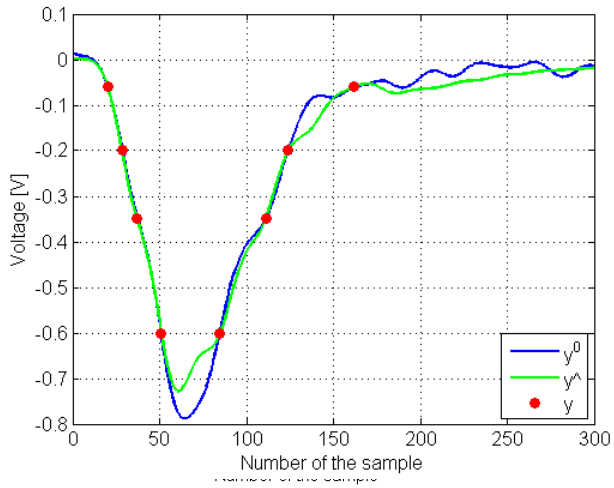
FFE sampling & Readout electronics

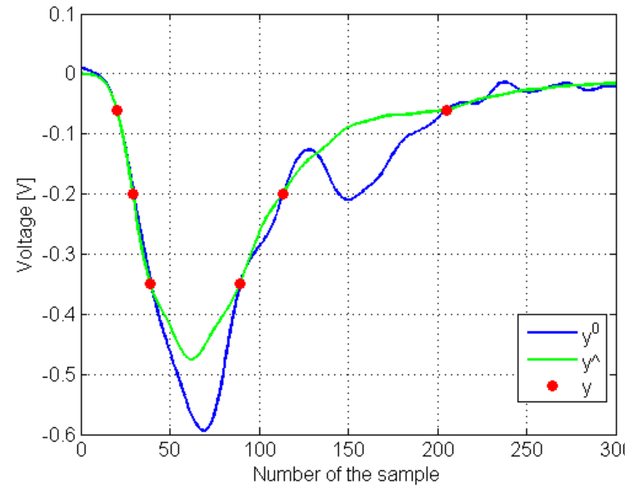
precision of 21ps (sigma) for 10 Euro per sample

M.Pałka, P.M., **PCT/EP2014/068367**

G. Korcyl, P. M., M. Kajetanowicz, M. Pałka, **PCT/EP2014/068352**





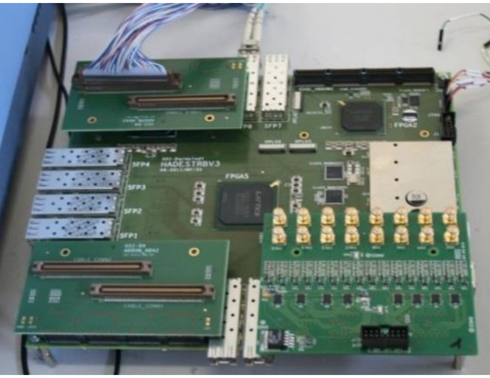


Library of signals; Principal Component Analysis; Compressive Sensing;
J-PET: L. Raczyński et al., Nucl. Instr. Meth. A786 (2015) 105
J-PET: P. M. et al., Nucl. Instrum. Meth. A775 (2015) 54

Reconstruction

Detector	FrontEnd electronics	Electronics controller	Hit along strip	Annihilation point	Image

J-PET: W. Krzemień et al., Acta Phys. Pol. B47 (2016) 561



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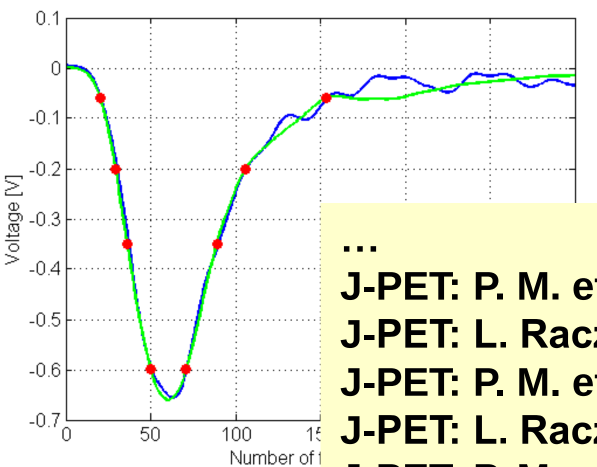
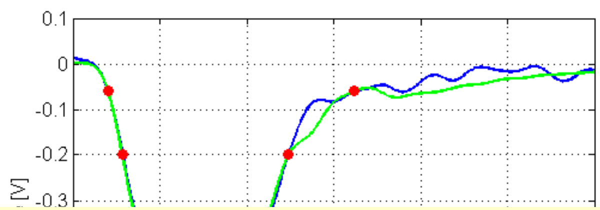
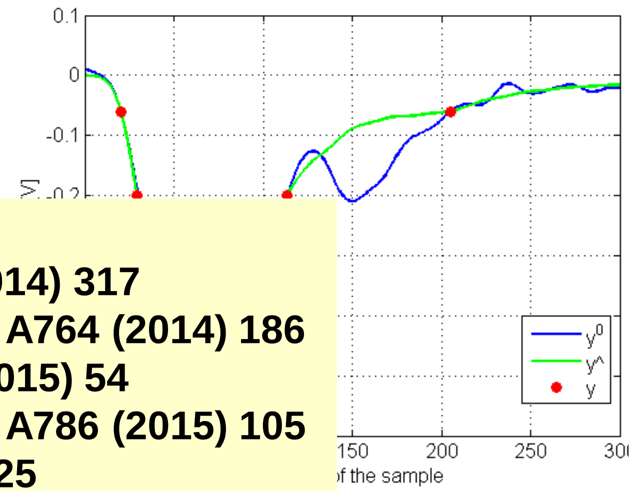






…

J-PET: P. M. et al., Nucl. Instrum. Meth. A764 (2014) 317
J-PET: L. Raczyński et al., Nucl. Instrum. Meth. A764 (2014) 186
J-PET: P. M. et al., Nucl. Instrum. Meth. A775 (2015) 54
J-PET: L. Raczyński et al., Nucl. Instrum. Meth. A786 (2015) 105
J-PET: P. M. et al., Phys. Med. Biol. 61 (2016) 2025
J-PET: A. Gajos et al., Nucl. Instrum. Meth. B 819 (2016) 54
J-PET: P. M. et al., Acta Phys. Pol. B 47 (2016) 509
J-PET: D. Kamińska et al., Eur. Phys. J. C76 (2016) 445
J-PET: J. Smyrski et al., Nucl. Instrum. Meth. A851 (2017) 39
J-PET: L. Raczyński et al., Phys. Med. Biol. 62 (2017) 5076
J-PET: M. Pałka et al., JINST 12 (2017) P08001

~60 articles and 17 patent applications

Library of signals
J-PET: L. Raczyń
J-PET: P. M. et al.

on

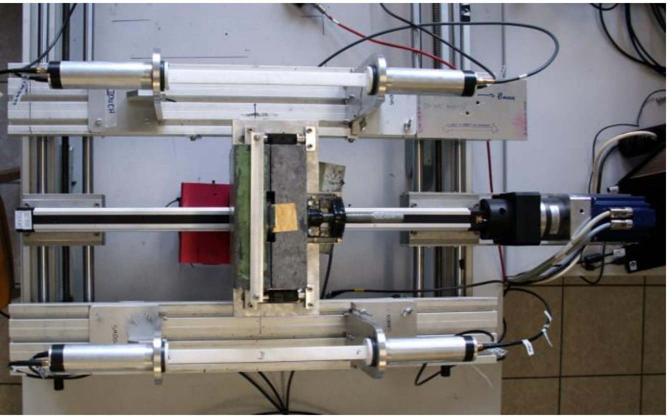
Detector

Image

J-PET: W. Krzemień et al., Acta Phys. Pol. B47 (2016) 561

2012

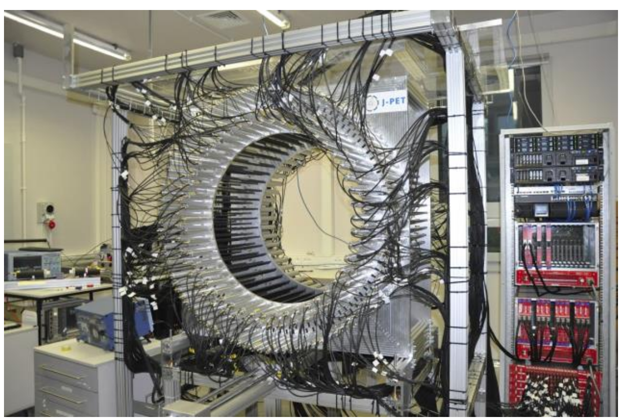
2 modules



2014

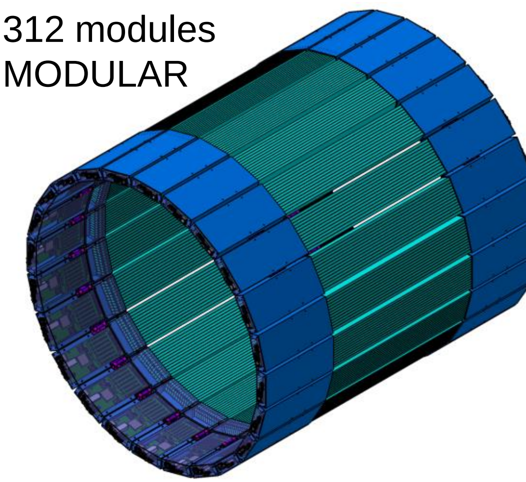
48 modules

192 modules



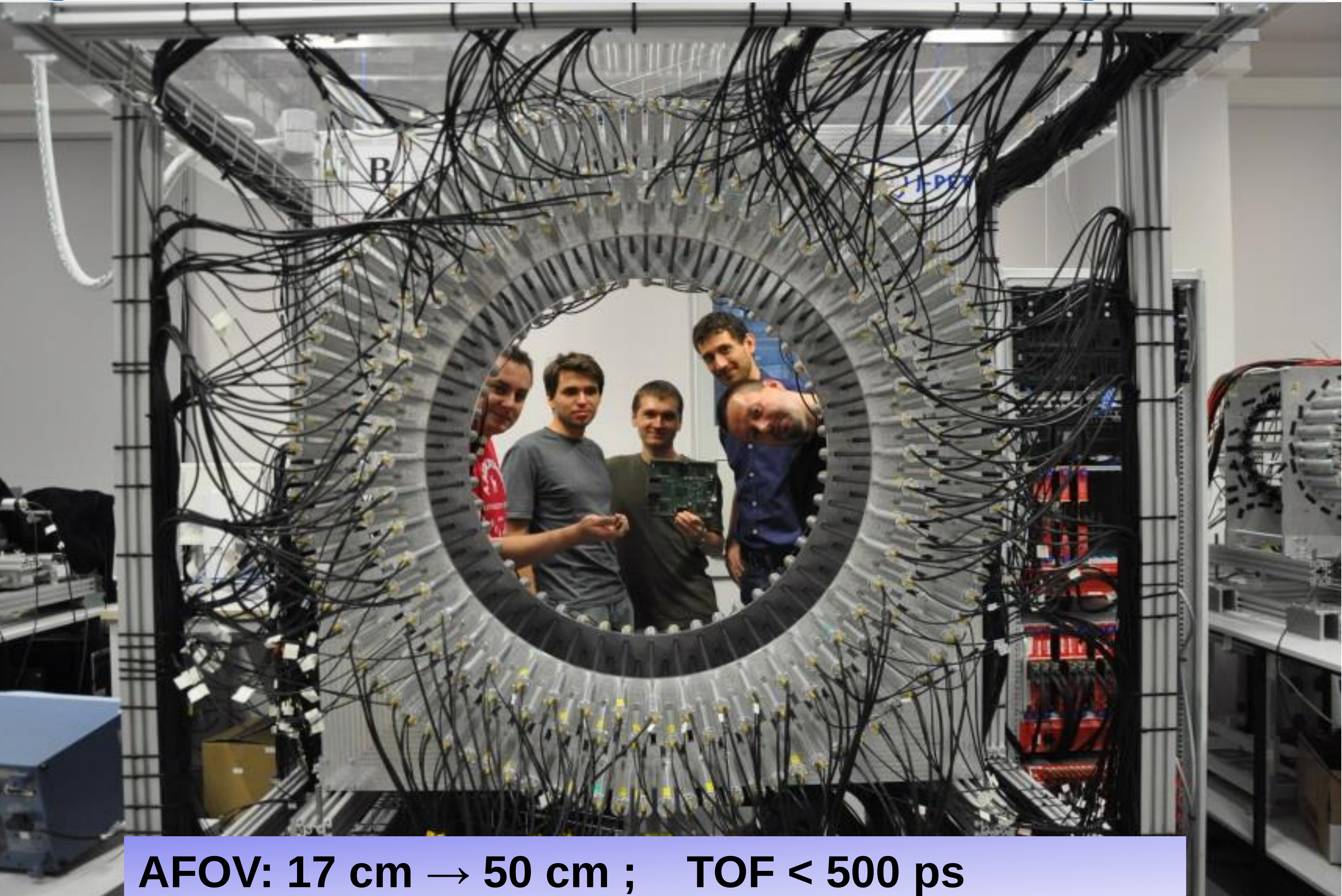
2016

312 modules
MODULAR



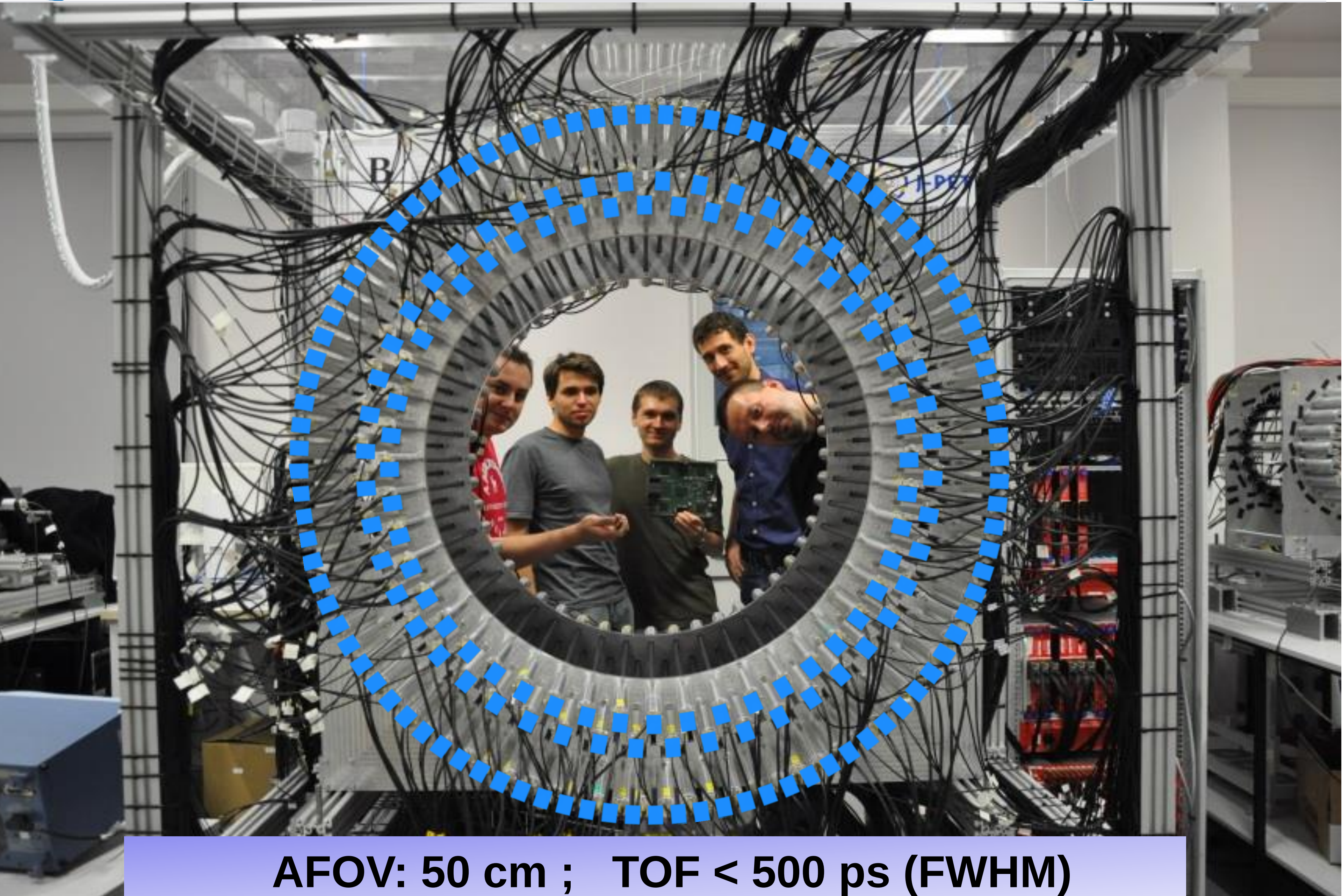
2018

Jagiellonian PET



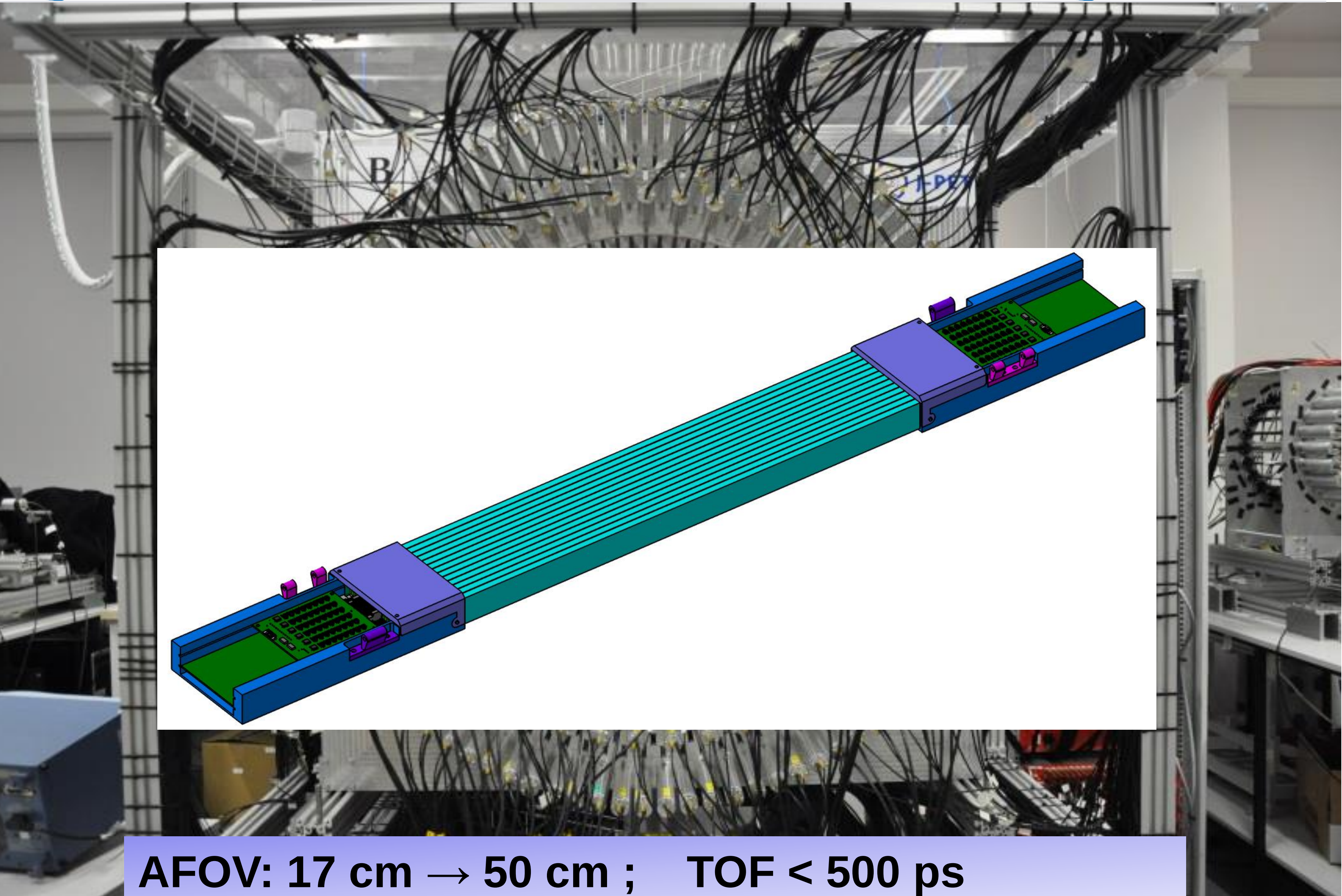
AFOV: 17 cm → 50 cm ; TOF < 500 ps

Jagiellonian PET



AFOV: 50 cm ; TOF < 500 ps (FWHM)

Jagiellonian PET



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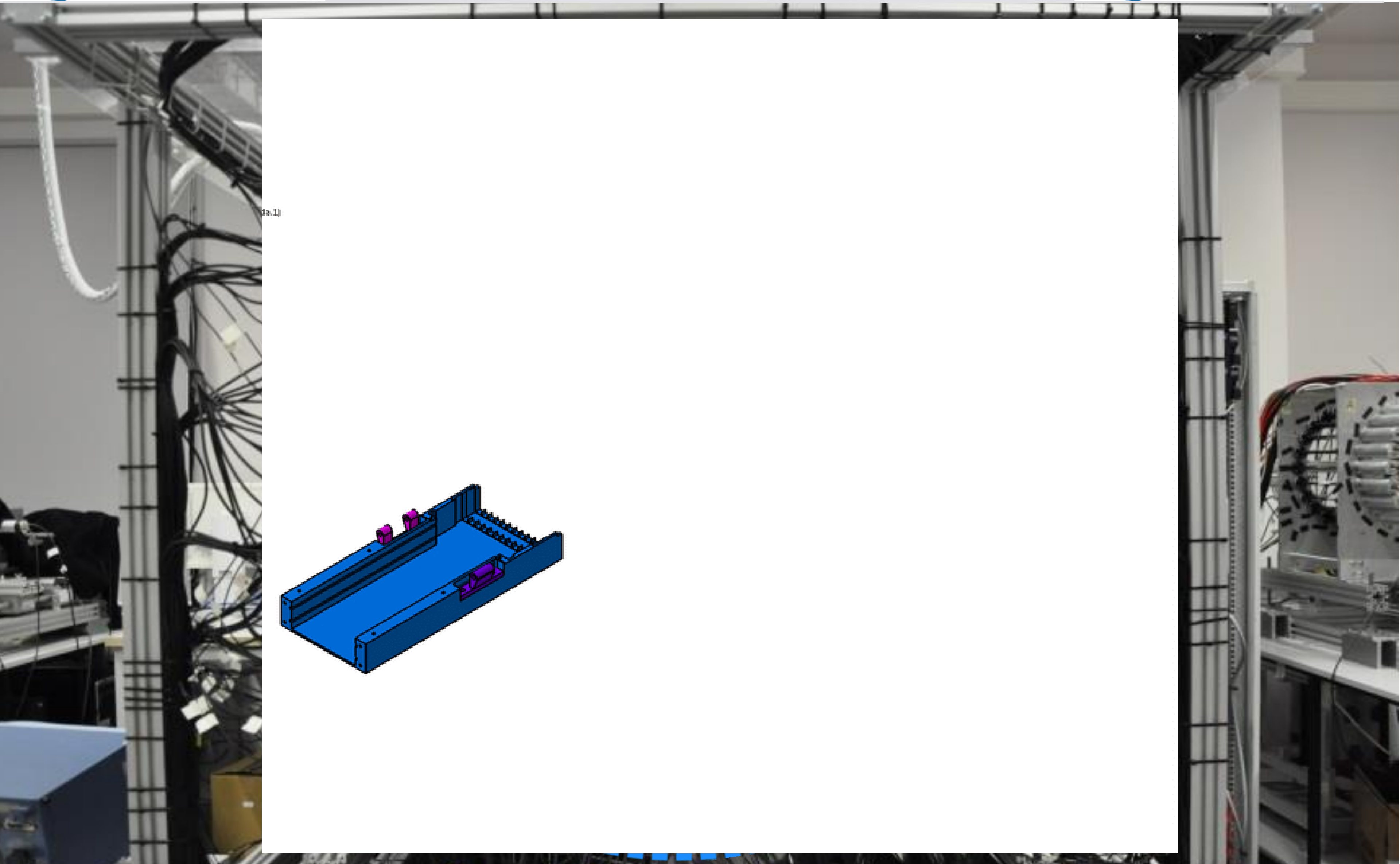

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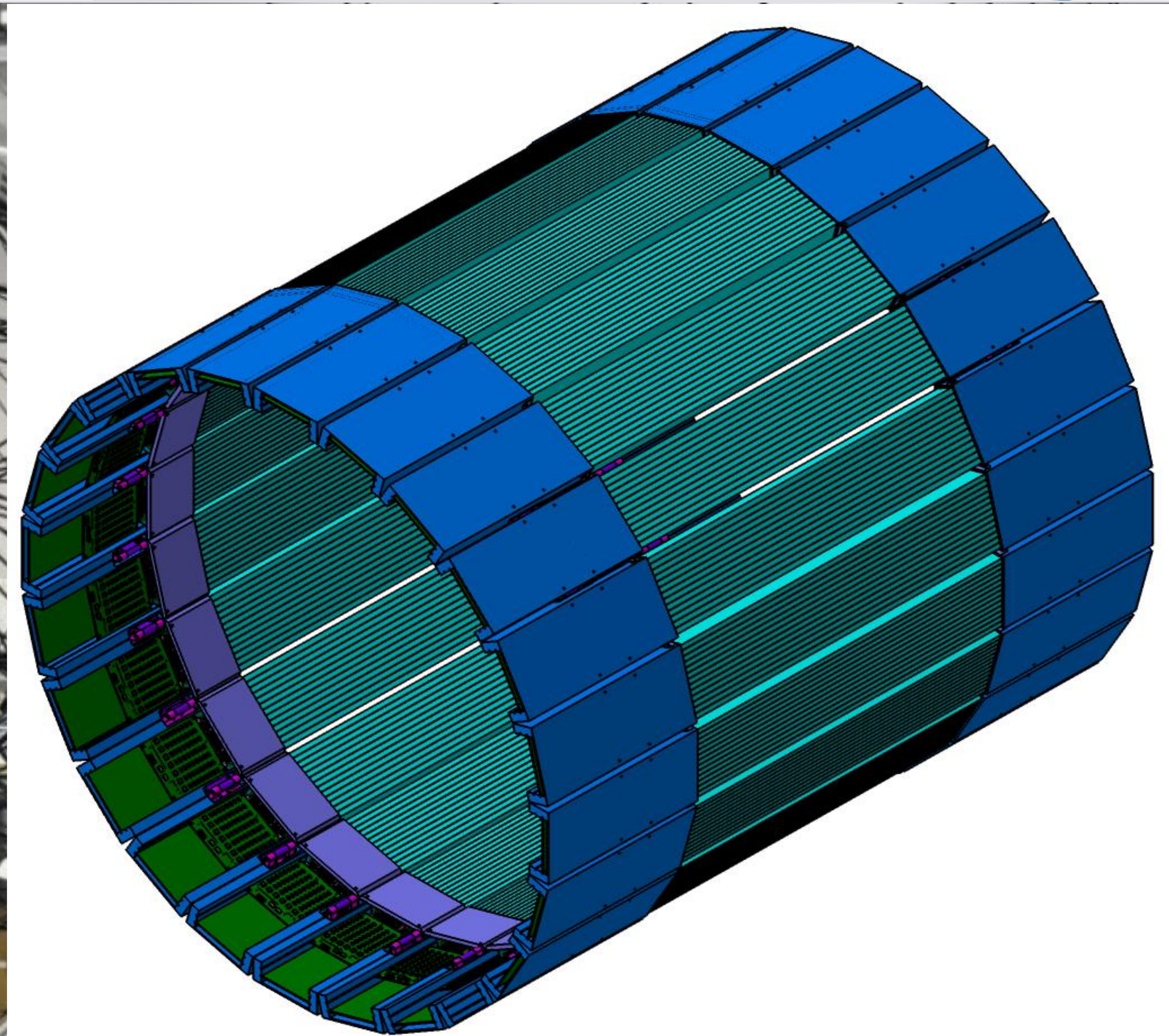

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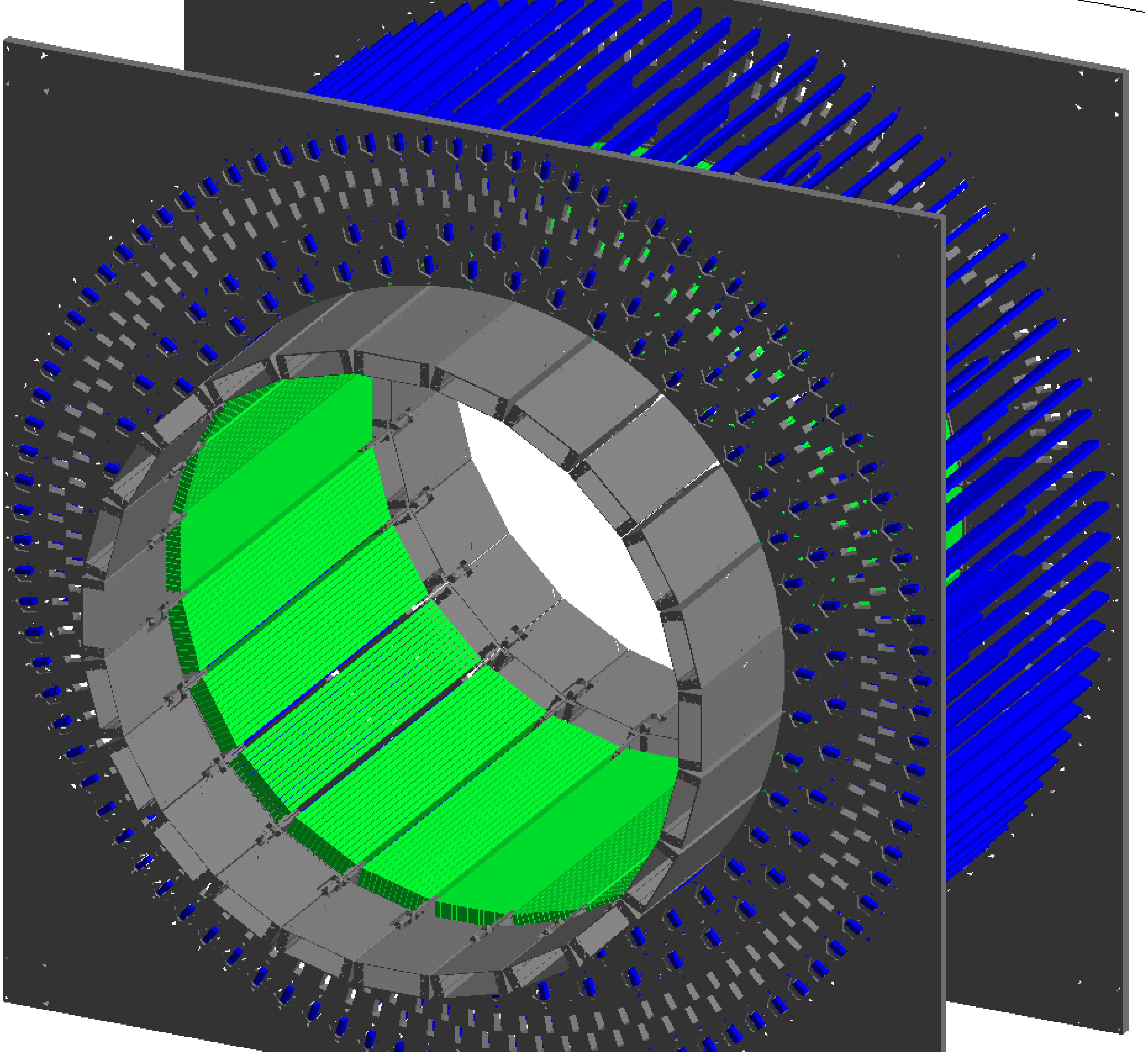
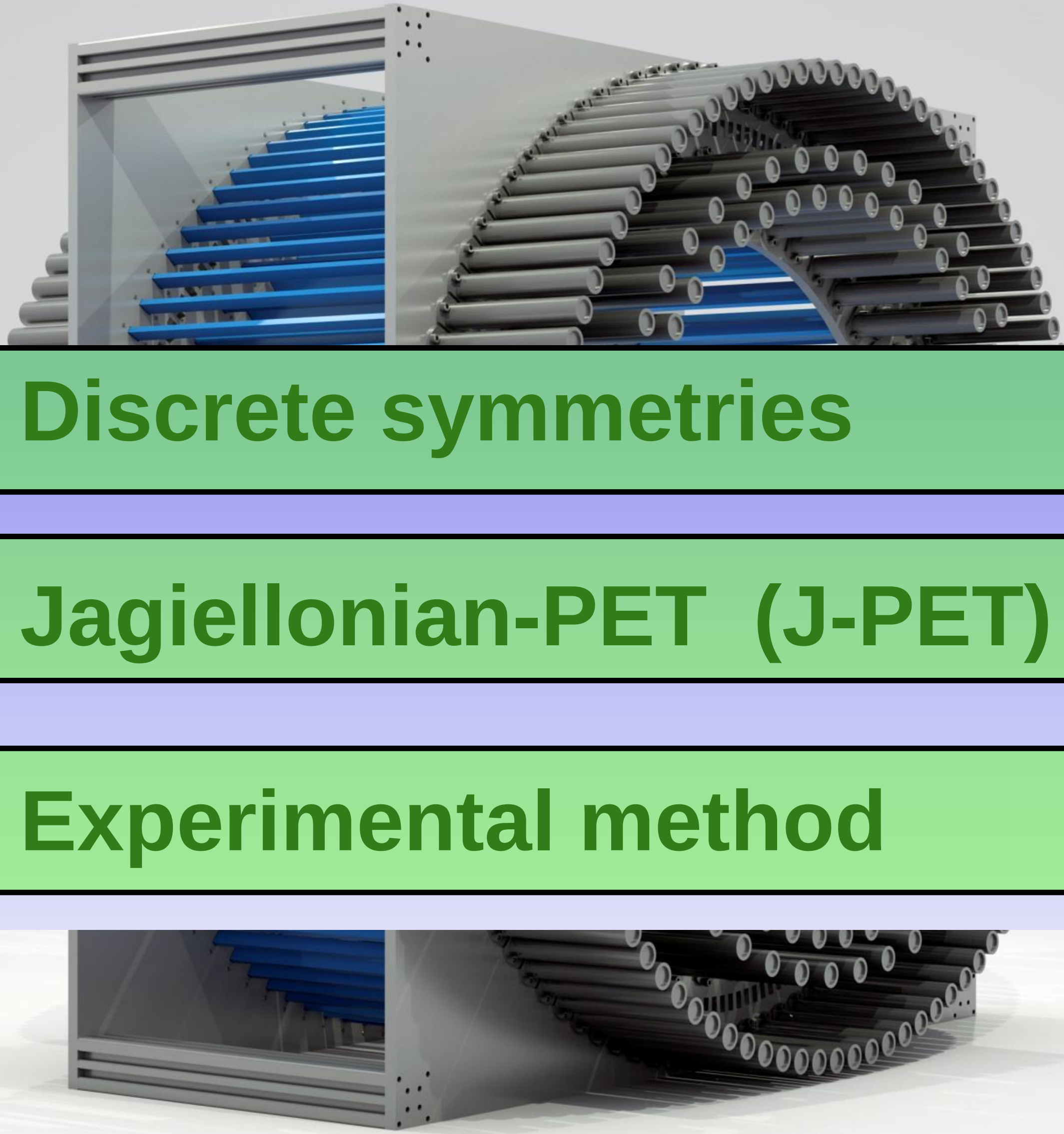


First experiments with upgraded J-PET shall start in winter 2018

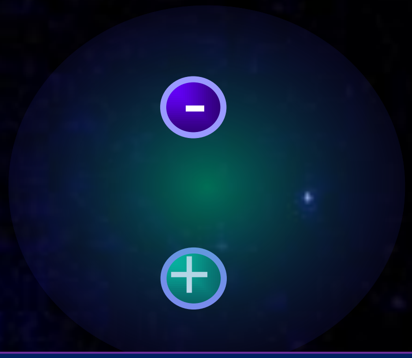
J-PET



- Discrete symmetries
- Jagiellonian-PET (J-PET)
- Experimental method

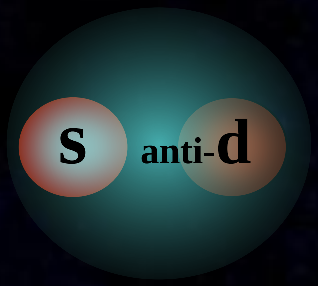
T symmetry violation

- $A \longrightarrow B$ $\qquad$ $B \longrightarrow A$
- T symmetry odd operators
- Particle mixing



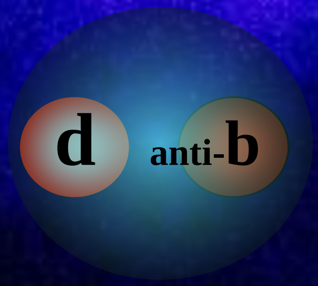
positronium

?



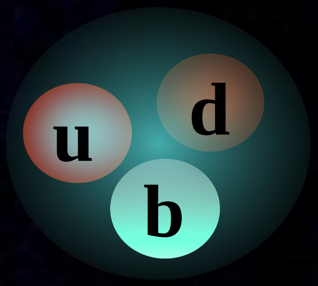
meson K

1964



meson B

2012



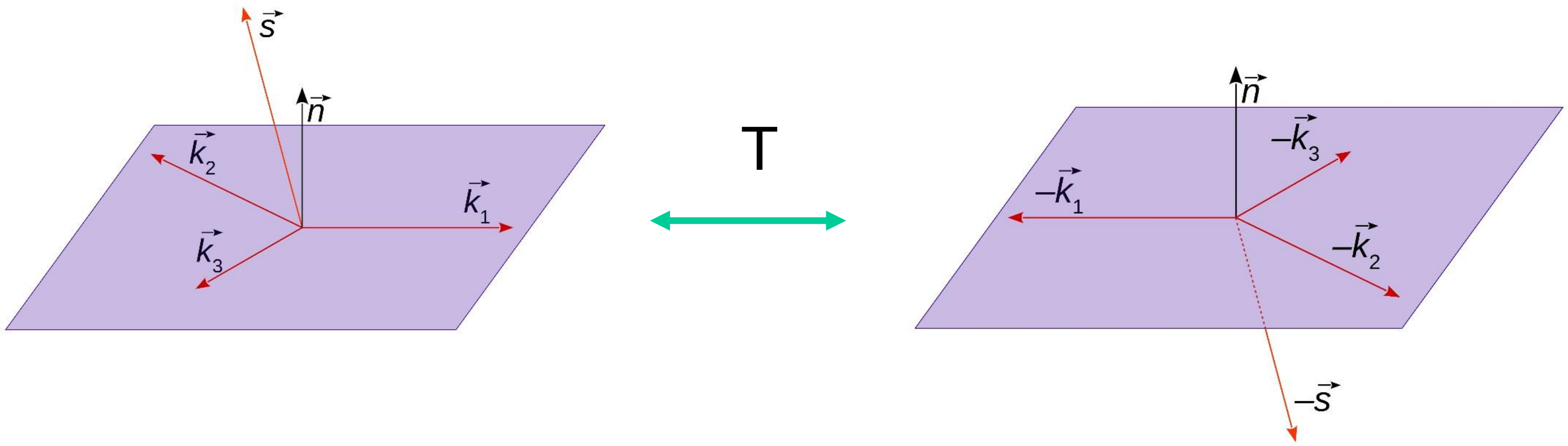
Baryon Λ_b^0

2017

Operator	C	P	T	CP	CPT
$\vec{S} \cdot \vec{k}_1$	+	–	+	–	–
$\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2)$	+	+	–	+	–
$(\vec{S} \cdot \vec{k}_1)(\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2))$	+	–	–	–	+

Operators for the o-Ps→3γ process, and their properties with respect to the C, P, T, CP and CPT symmetries.

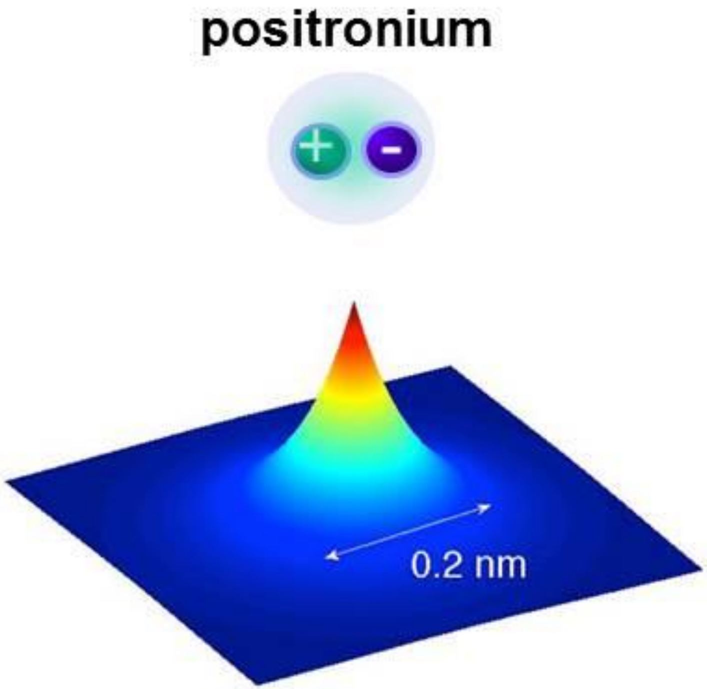
$$|k_1| > |k_2| > |k_3|$$



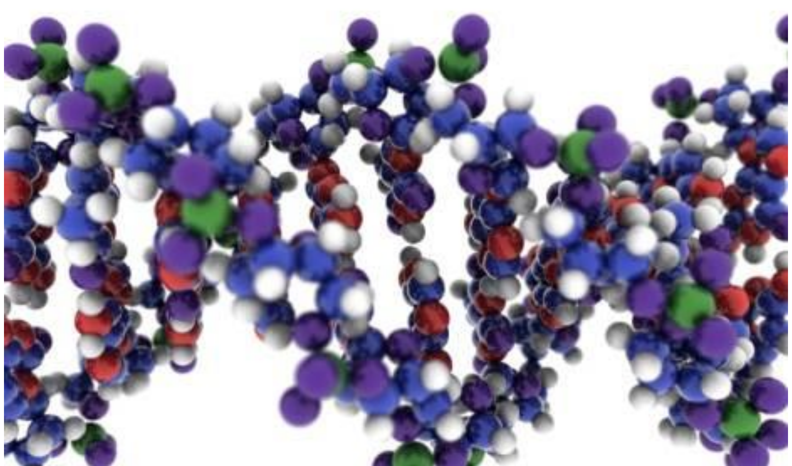
So far best accuracy for tests of **CP and CPT violation** was reported by

-0.0023 < CP < 0.0049 at 90% CL T. Yamazaki et al., Phys. Rev. Lett. 104 (2010) 083401

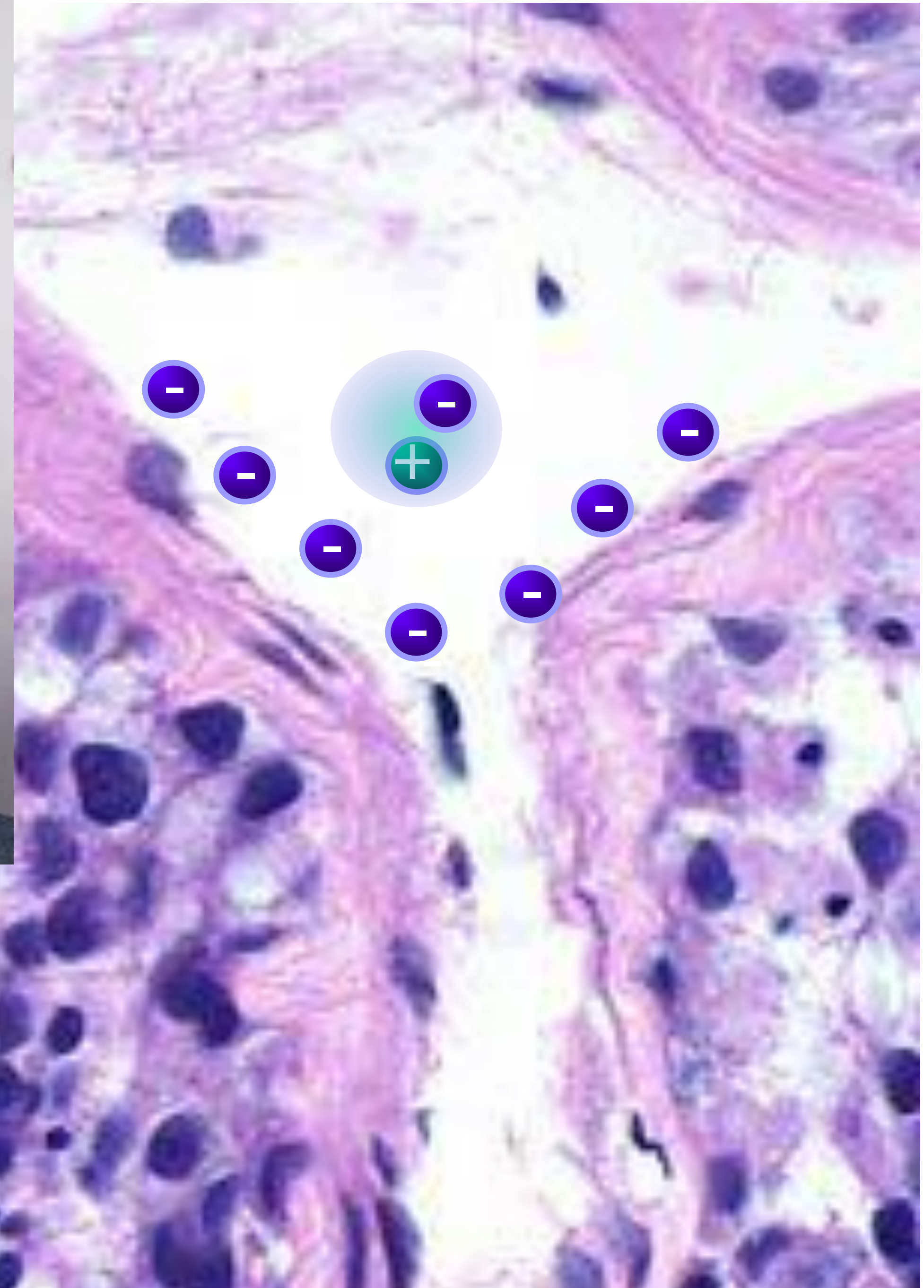
CPT = 0.0071 ± 0.0062 P.A. Vetter and S.J. Freedman, Phys. Rev. Lett. 91, 263401 (2003).

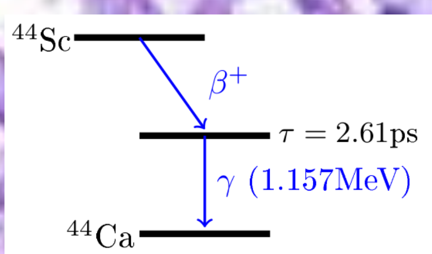


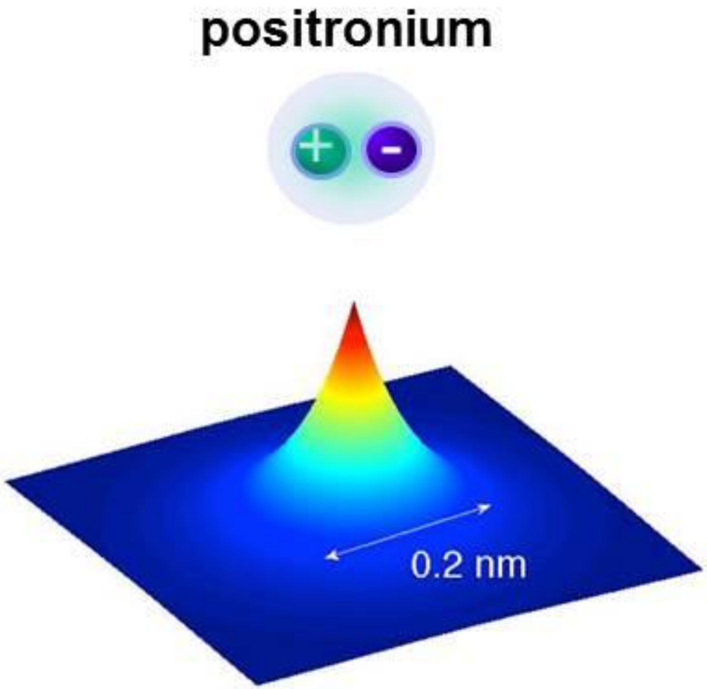
Y.H. Wang et al., Phys. Rev. A 89 (2014) 043624,
http://www.chem-eng.kyushu-u.ac.jp/e/research.html

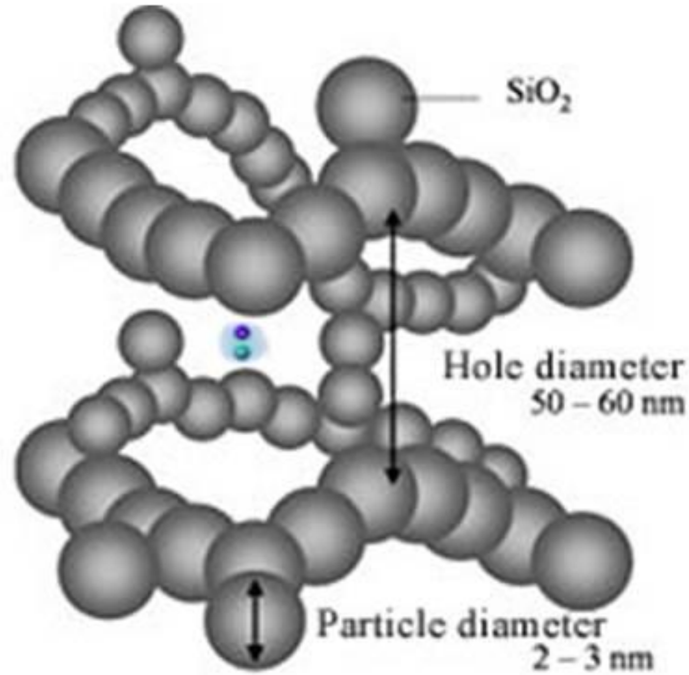


Patent P. M., P 405185, PCT/EP2014/068374

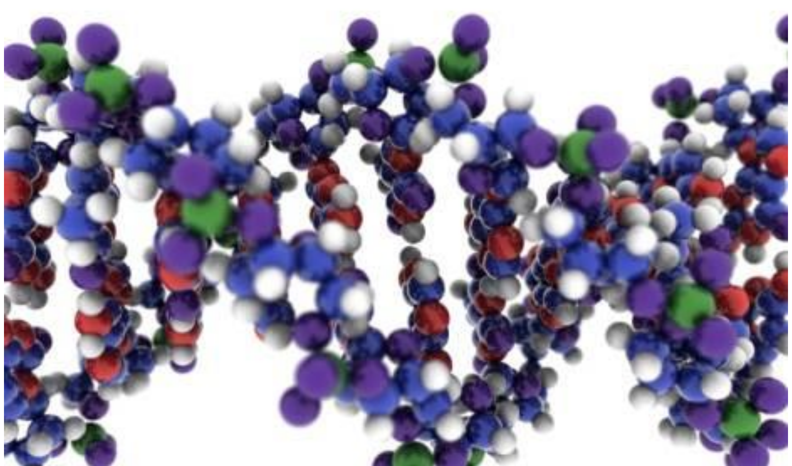




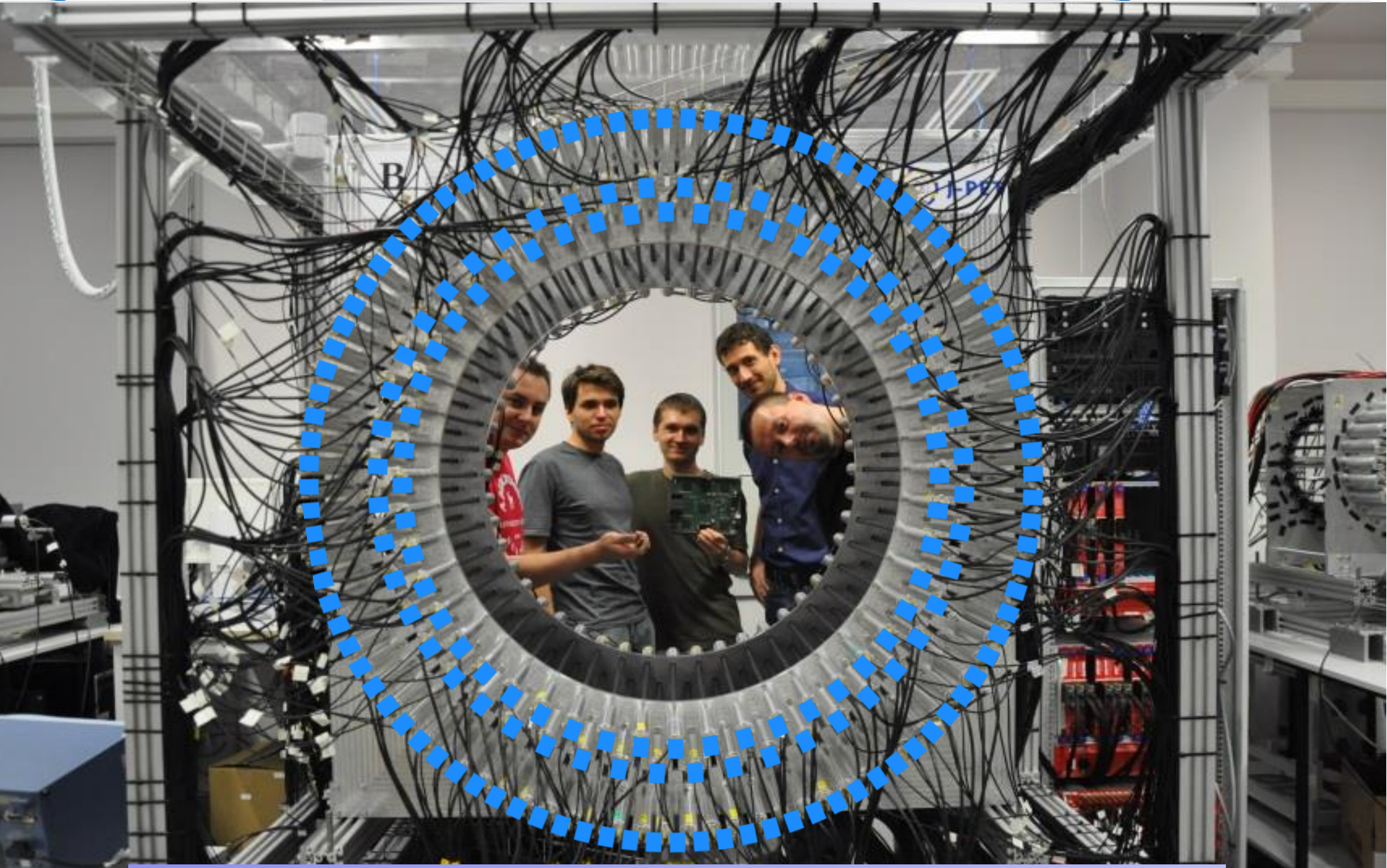




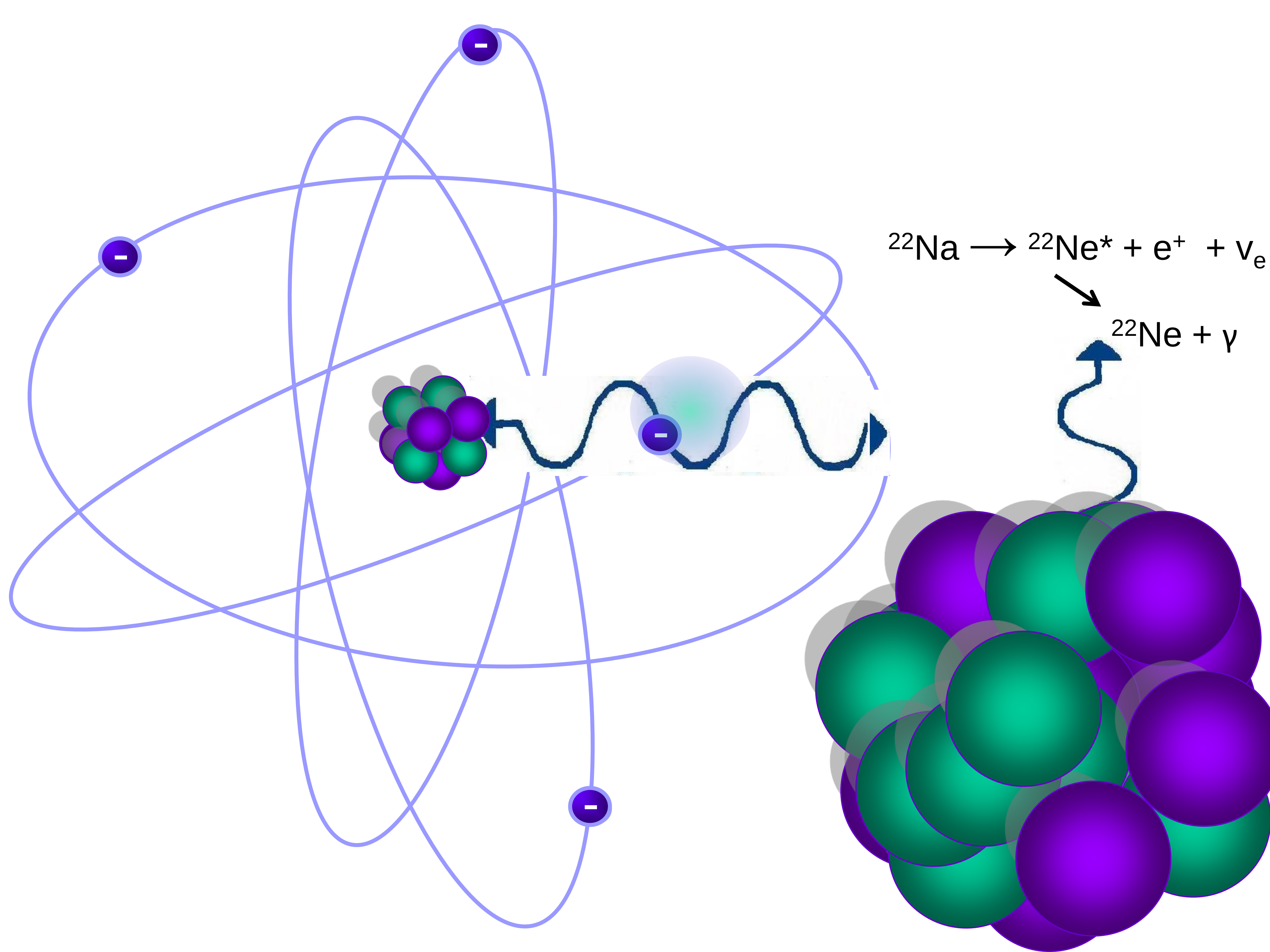
Y.H. Wang et al., Phys. Rev. A 89 (2014) 043624,
http://www.chem-eng.kyushu-u.ac.jp/e/research.html



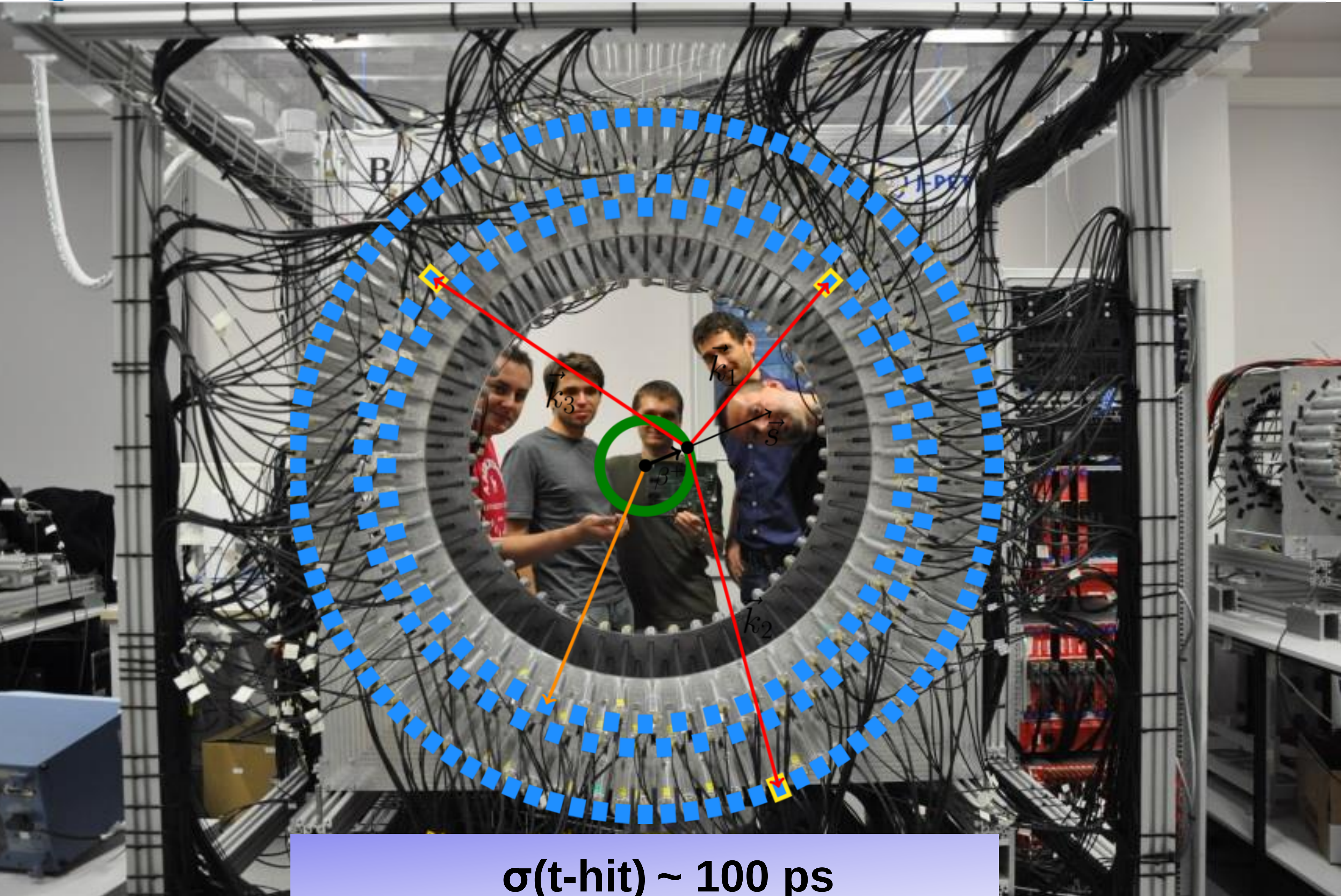
Jagiellonian PET



AFOV: 50 cm ; TOF < 500 ps (FWHM)

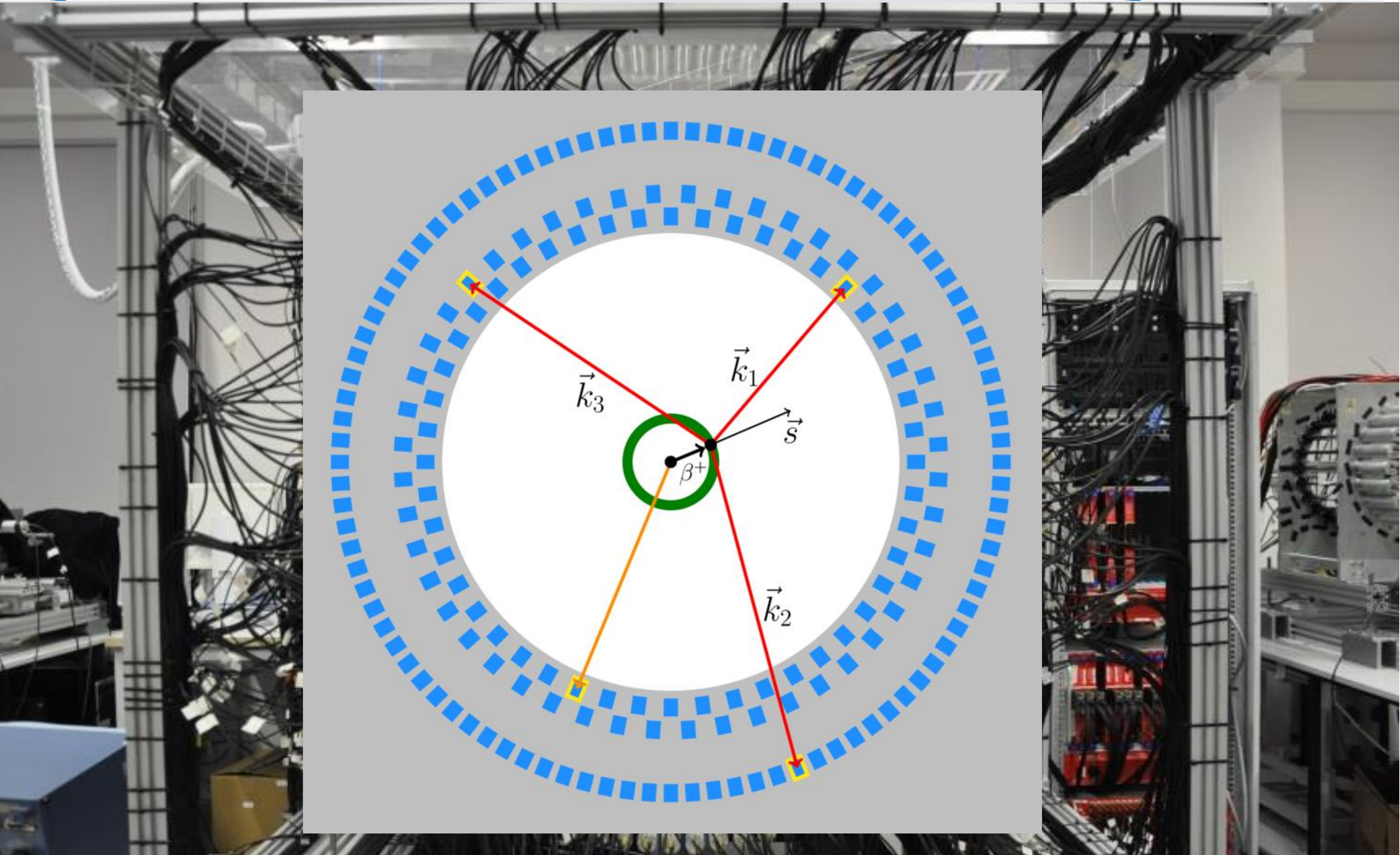

$^{22}Na \longrightarrow {}^{22}Ne^{*} + e^{+} + \nu_e$
$^{22}Ne + \gamma$

Jagiellonian PET



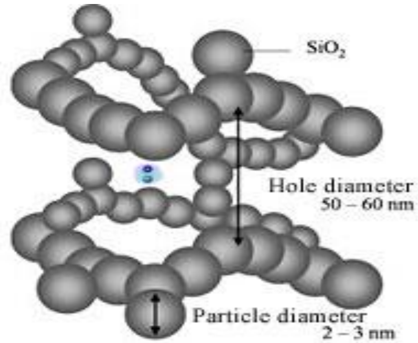
σ(t-hit) ~ 100 ps

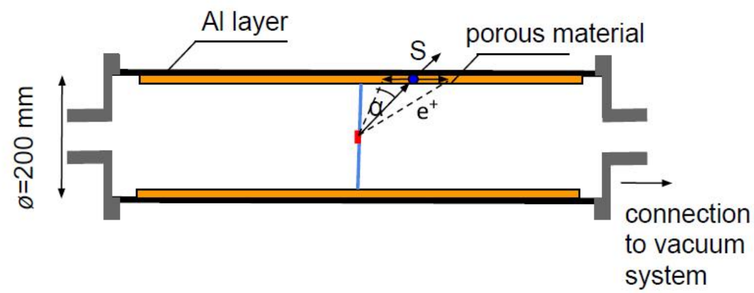
Jagiellonian PET



σ(t-hit) ~ 100 ps

Jagiellonian PET





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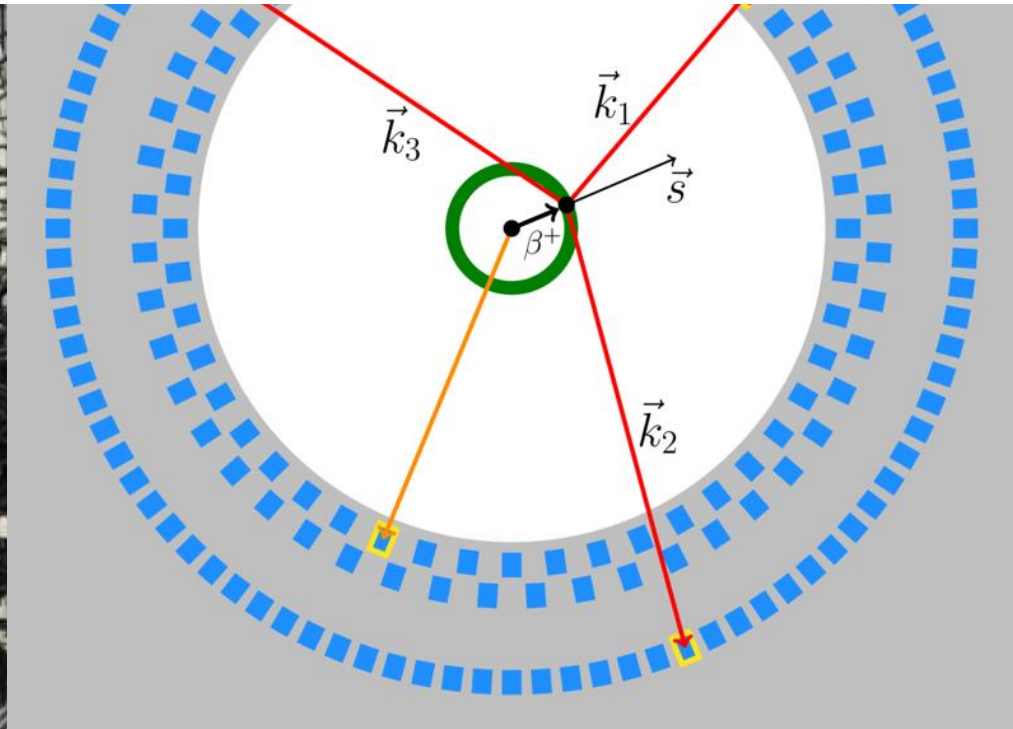
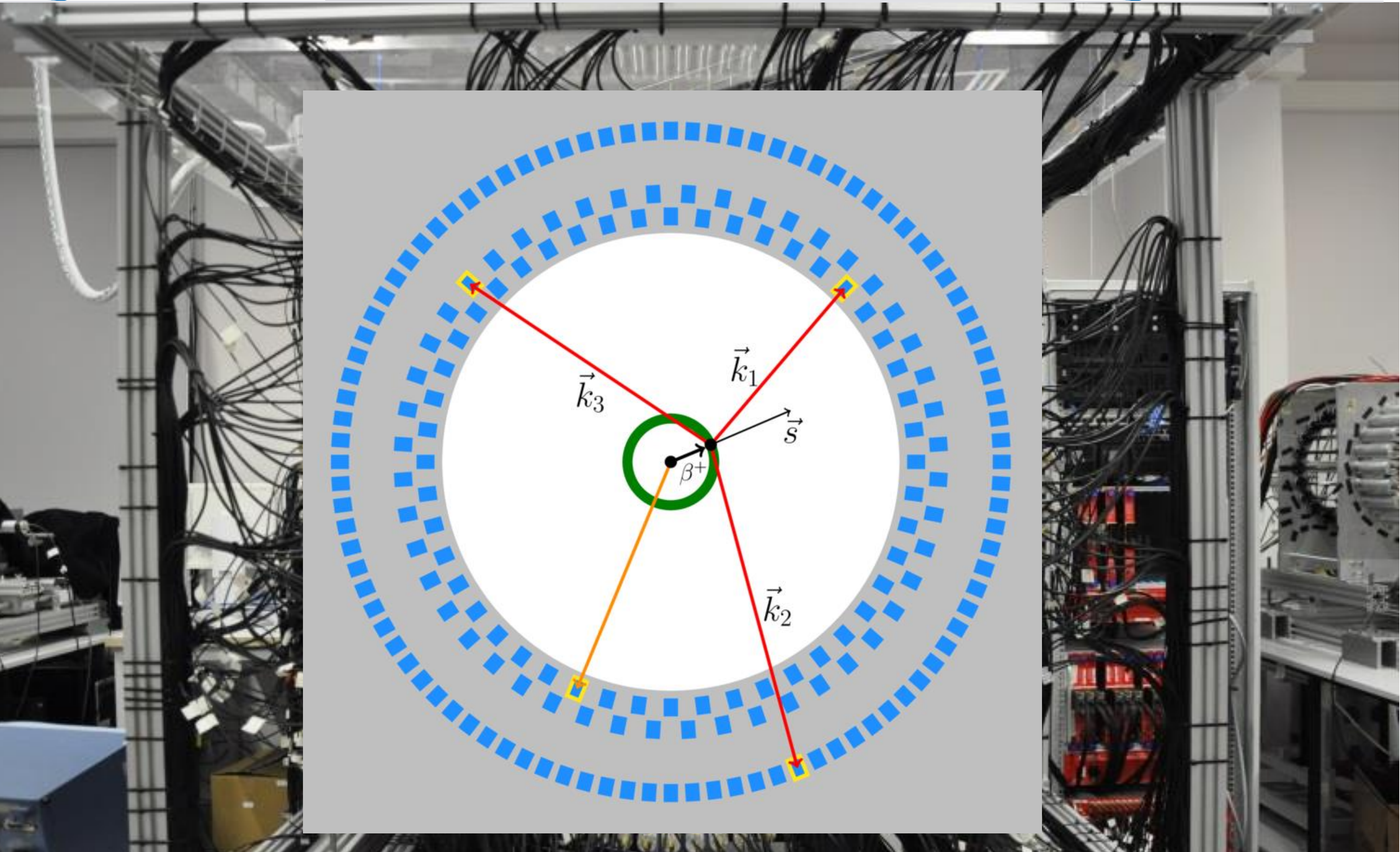


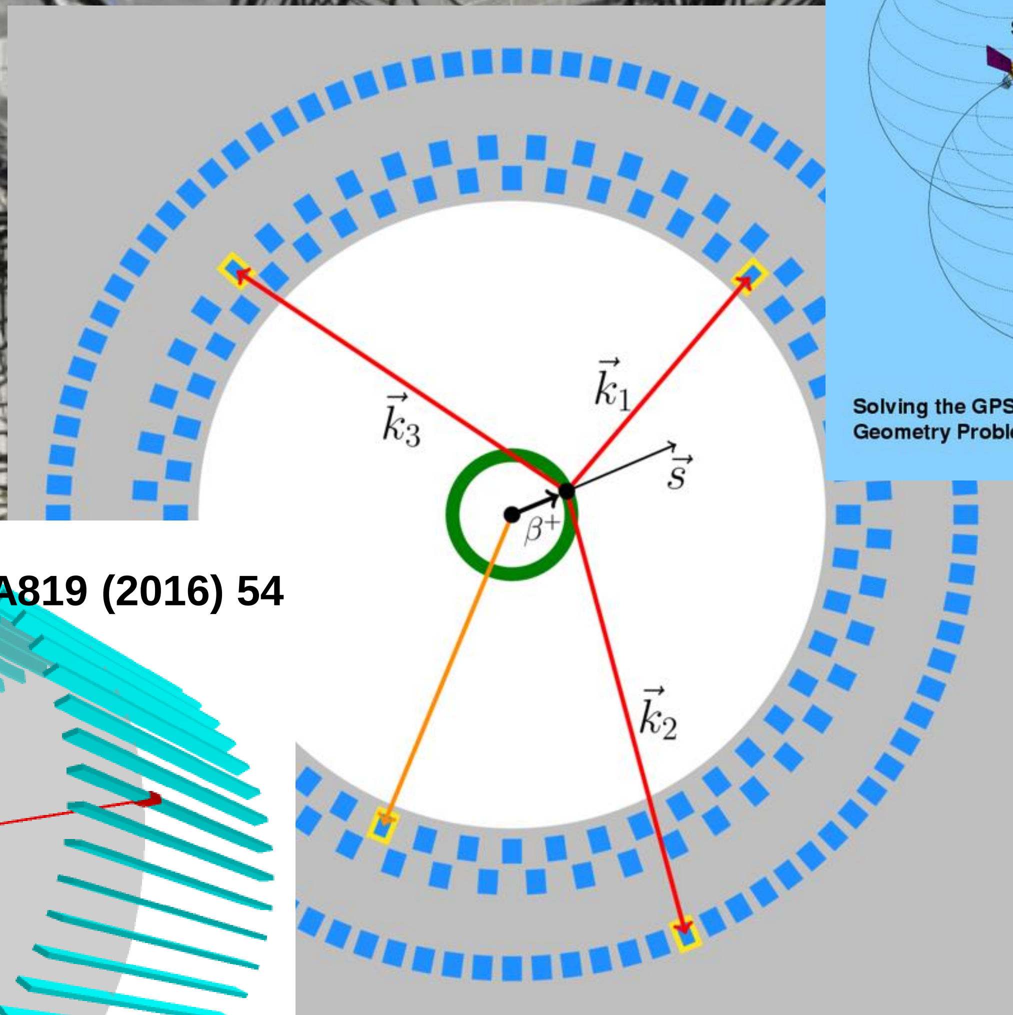
σ(t-hit) ~ 100 ps

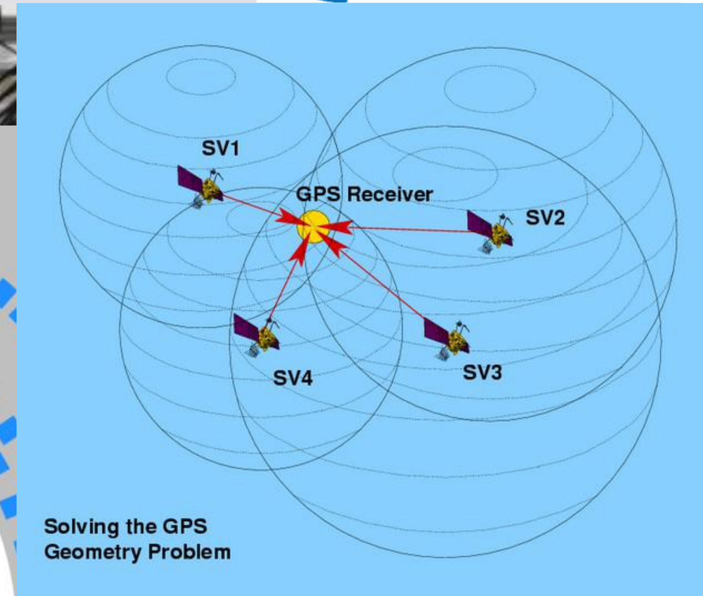
Jagiellonian PET



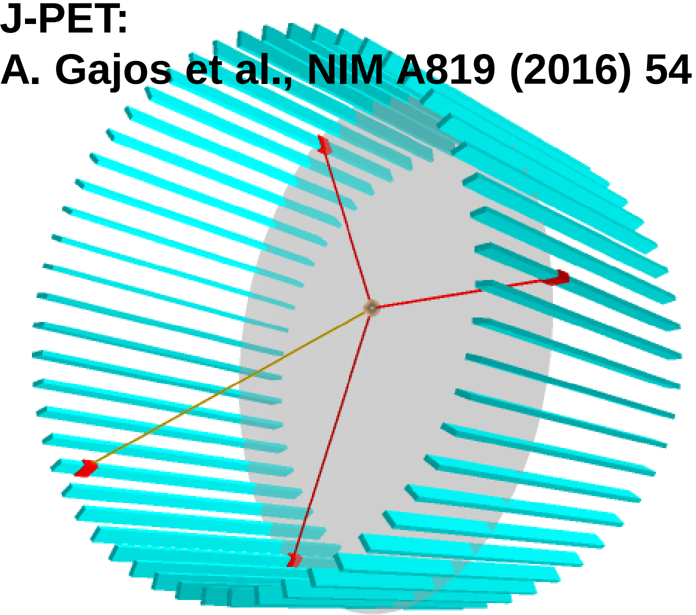
σ(t-hit) ~ 100 ps

Jagiellonian PET

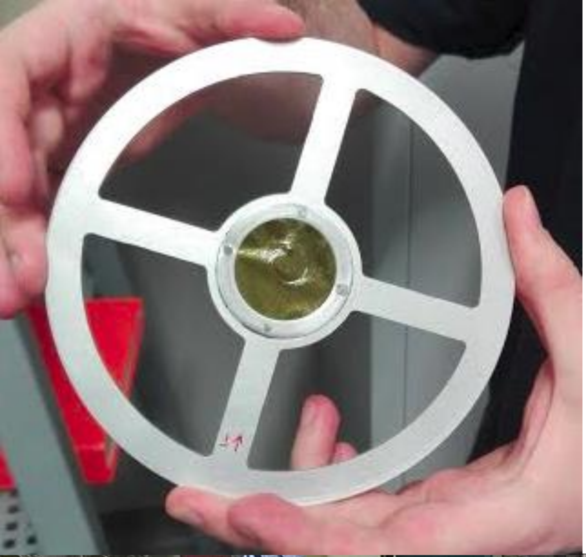


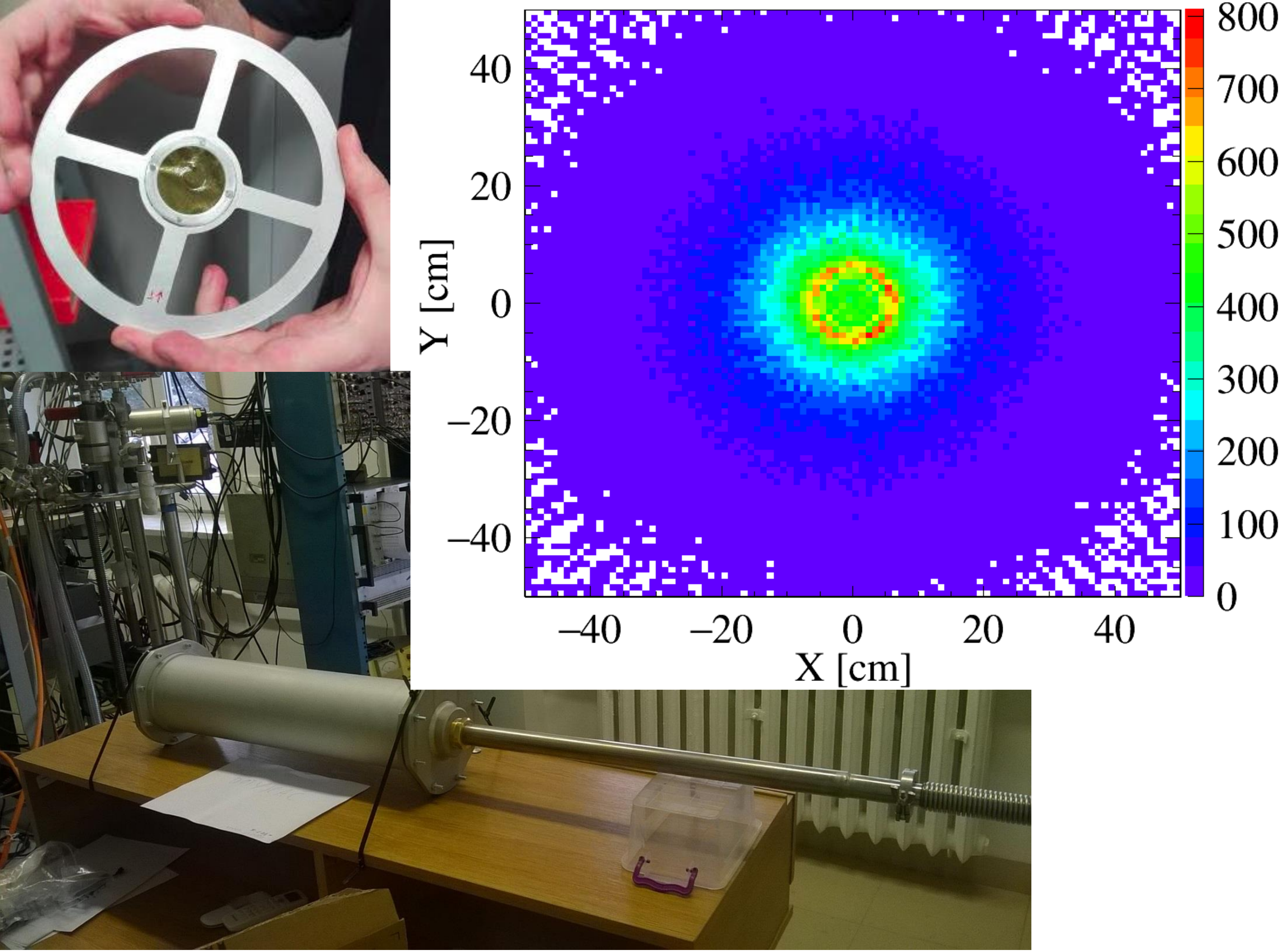


J-PET:
A. Gajos et al., NIM A819 (2016) 54



σ(t-hit) ~ 100 ps



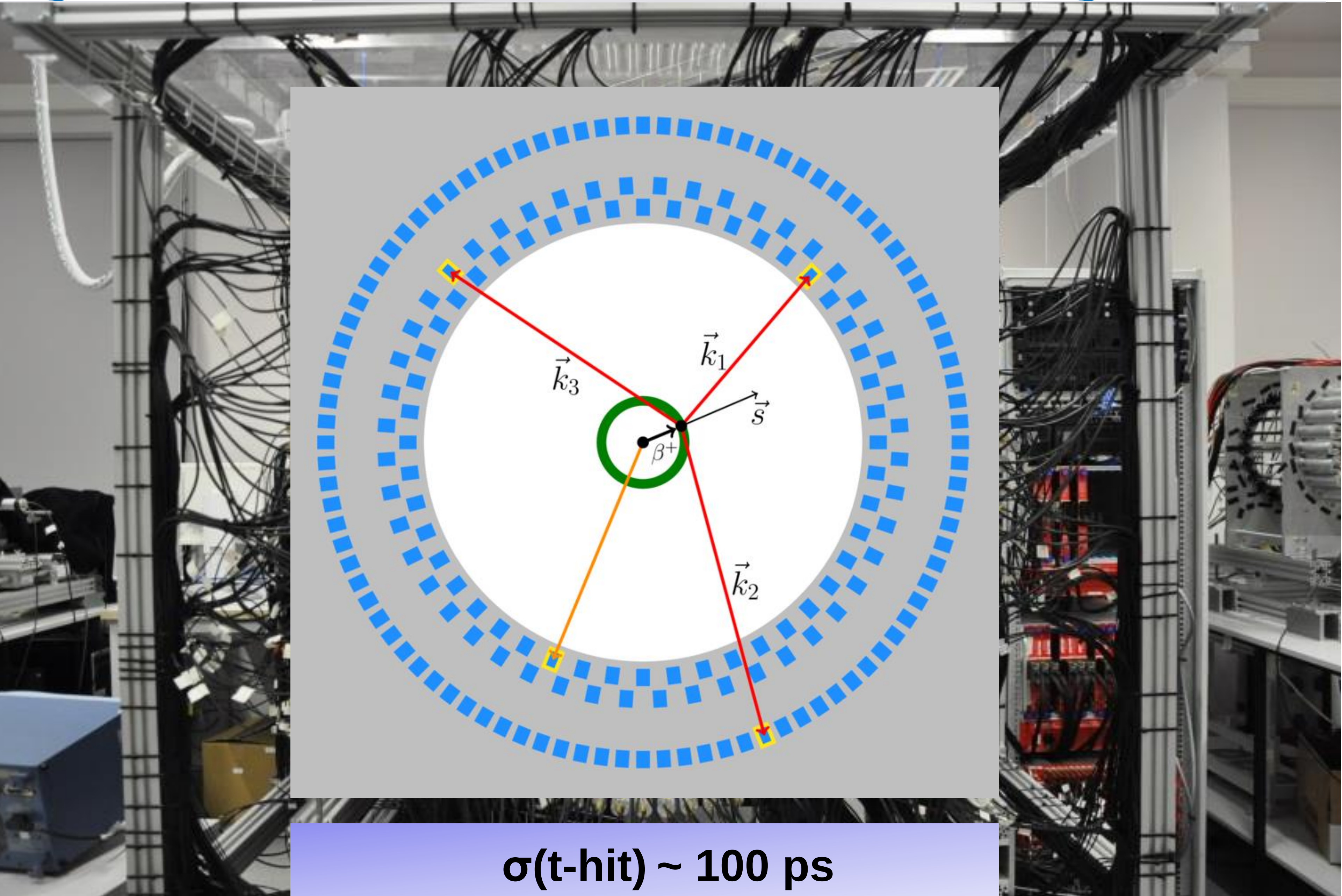

Y [cm]
X [cm]
40
20
0
−20
−40
−40
−20
0
20
40
800
700
600
500
400
300
200
100
0

J-PET

First cylindrical porous target by Prof. J. Goworek from UMCS in Lublin

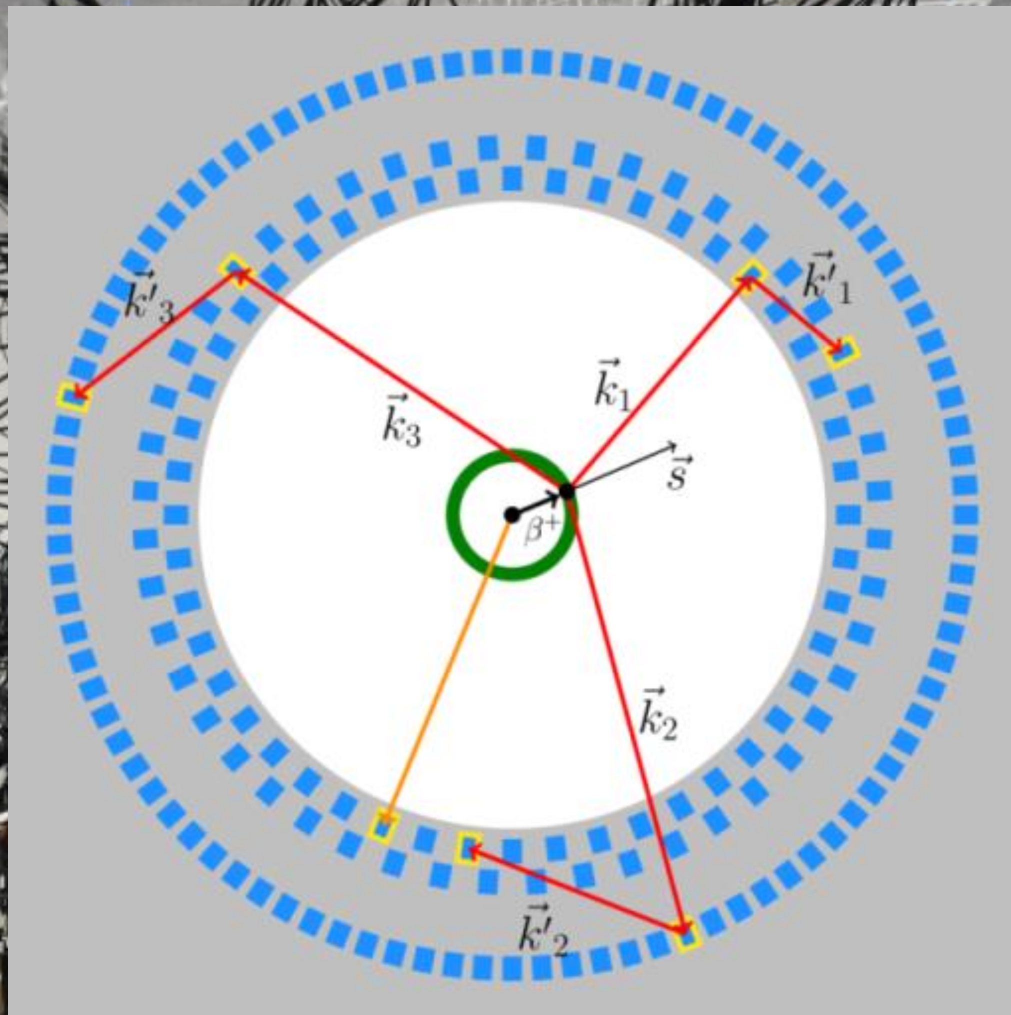

Mikrokapsułki

Jagiellonian PET



σ(t-hit) ~ 100 ps

Jagiellonian PET



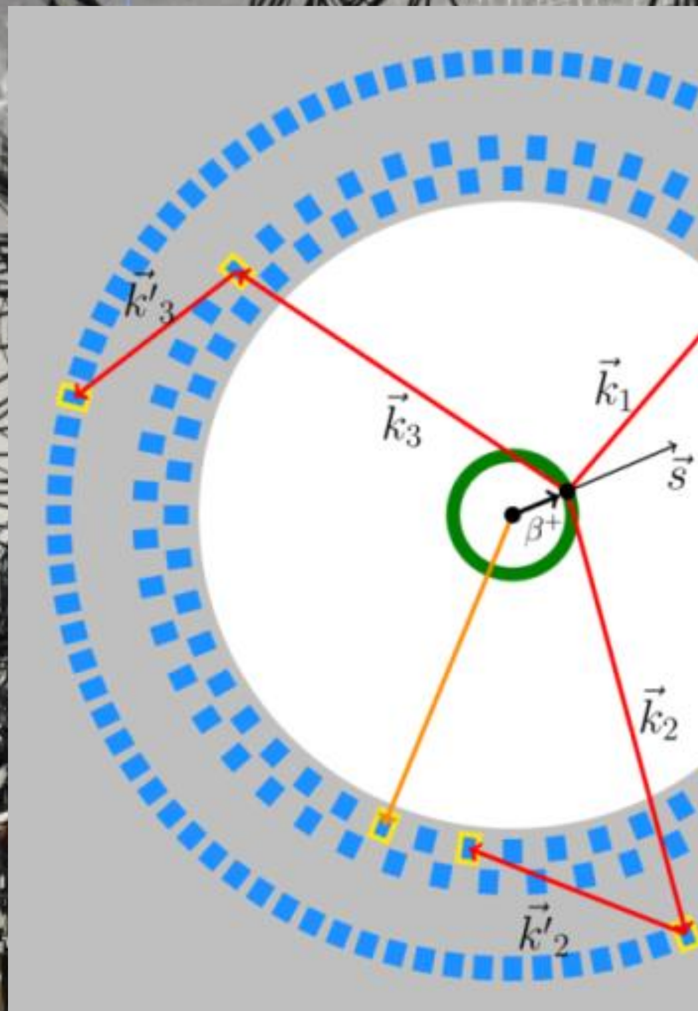
N. Krawczyk
Poster

J. Raj
Talk

$\vec{\varepsilon}_i = \vec{k}_i \times \vec{k'}_i$

σ(t-hit) ~100 ps

Jagiellonian PET



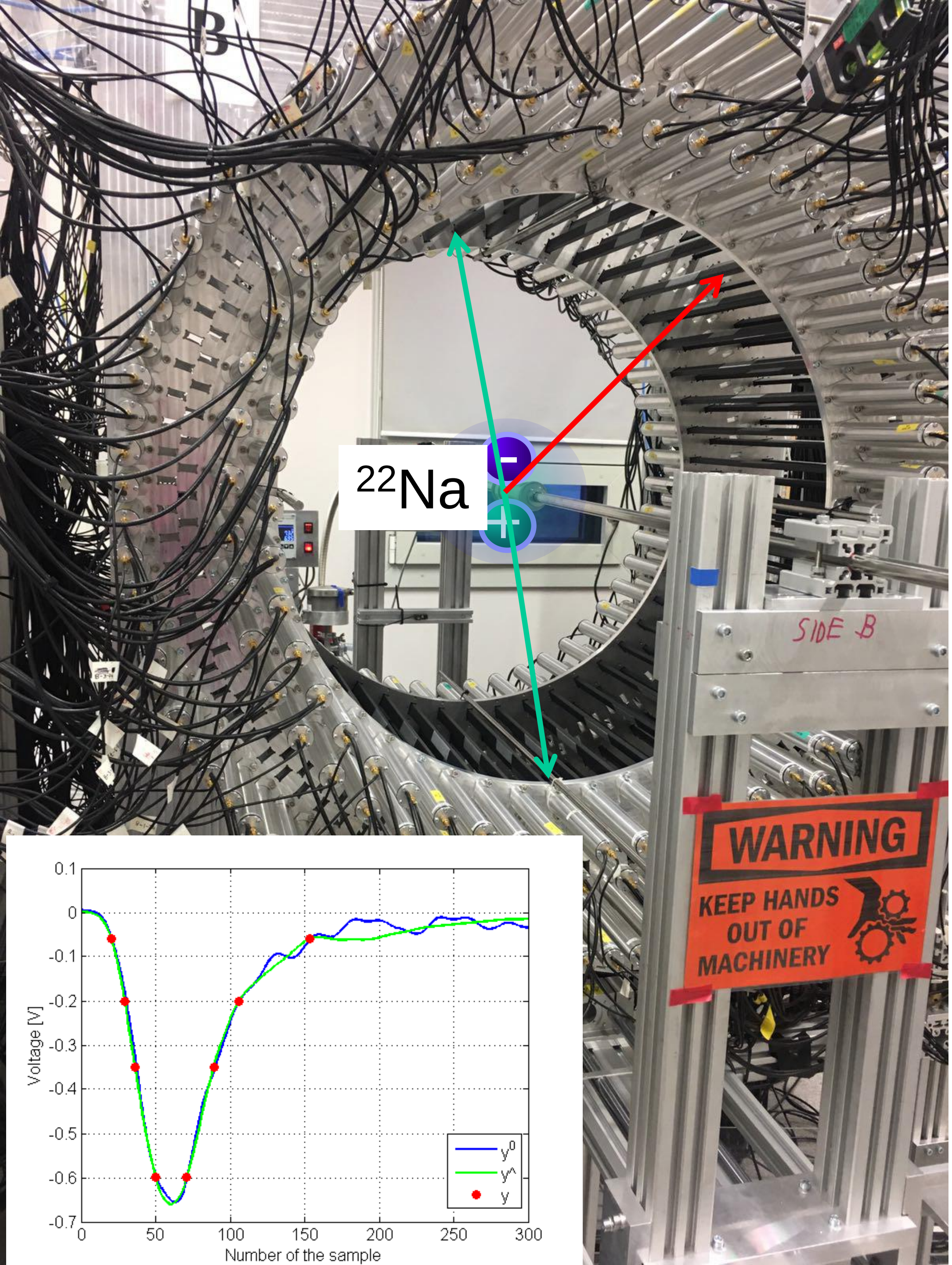
Operator	C	P	T	CP	CPT
$\vec{S} \cdot \vec{k}_1$	+	–	+	–	–
$\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2)$	+	+	–	+	–
$(\vec{S} \cdot \vec{k}_1)(\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2))$	+	–	–	–	+
$\vec{k}_1 \cdot \vec{\varepsilon}_2$	+	–	–	–	+
$\vec{S} \cdot \vec{\varepsilon}_1$	+	+	–	+	–
$\vec{S} \cdot (\vec{k}_2 \times \vec{\varepsilon}_1)$	+	–	+	–	–

$$\vec{\varepsilon}_i = \vec{k}_i \times \vec{k}'_i$$

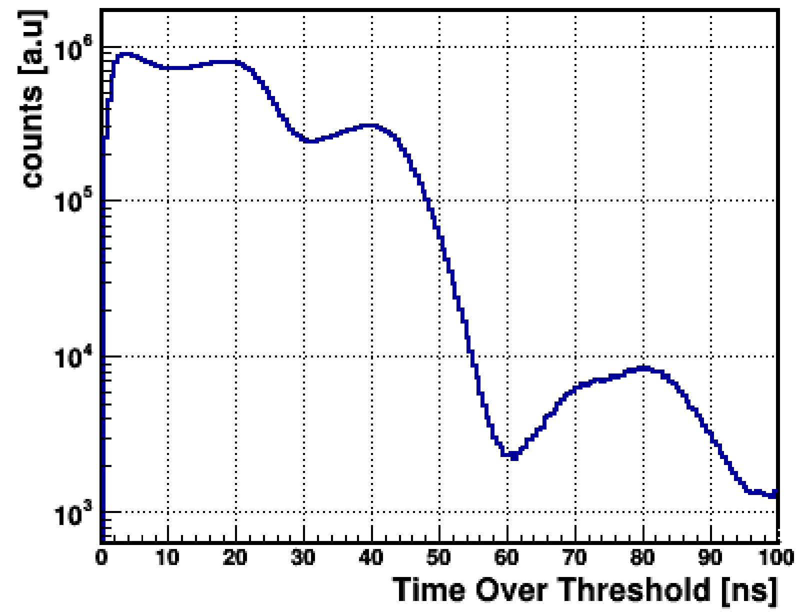
σ(t-hit) ~ 100 ps

SM 10^{-9} vs upper limits of 3 10^{-3} for T, CP, CPT

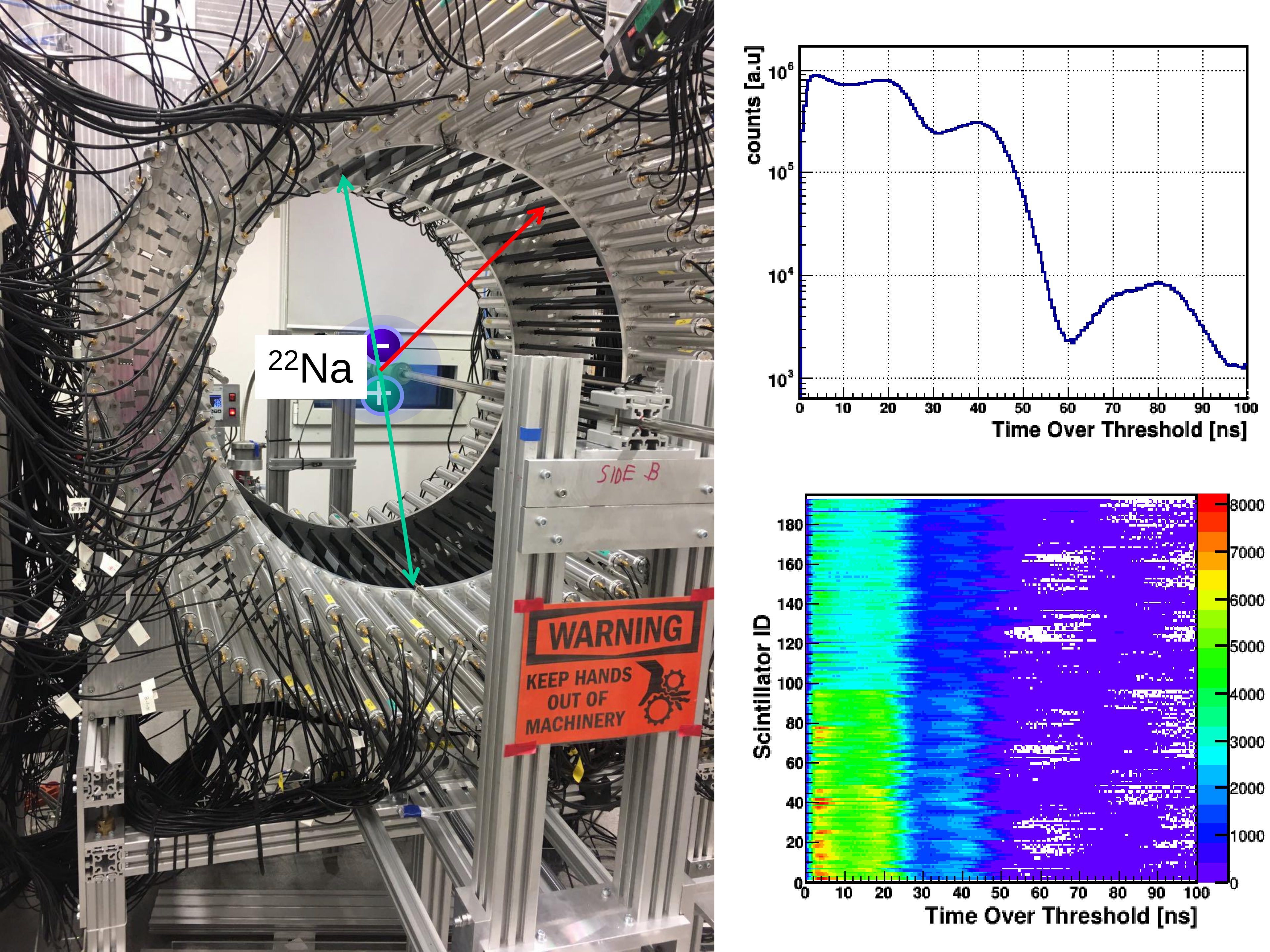

B
SIDE B
WARNING
KEEP HANDS
OUT OF
MACHINERY



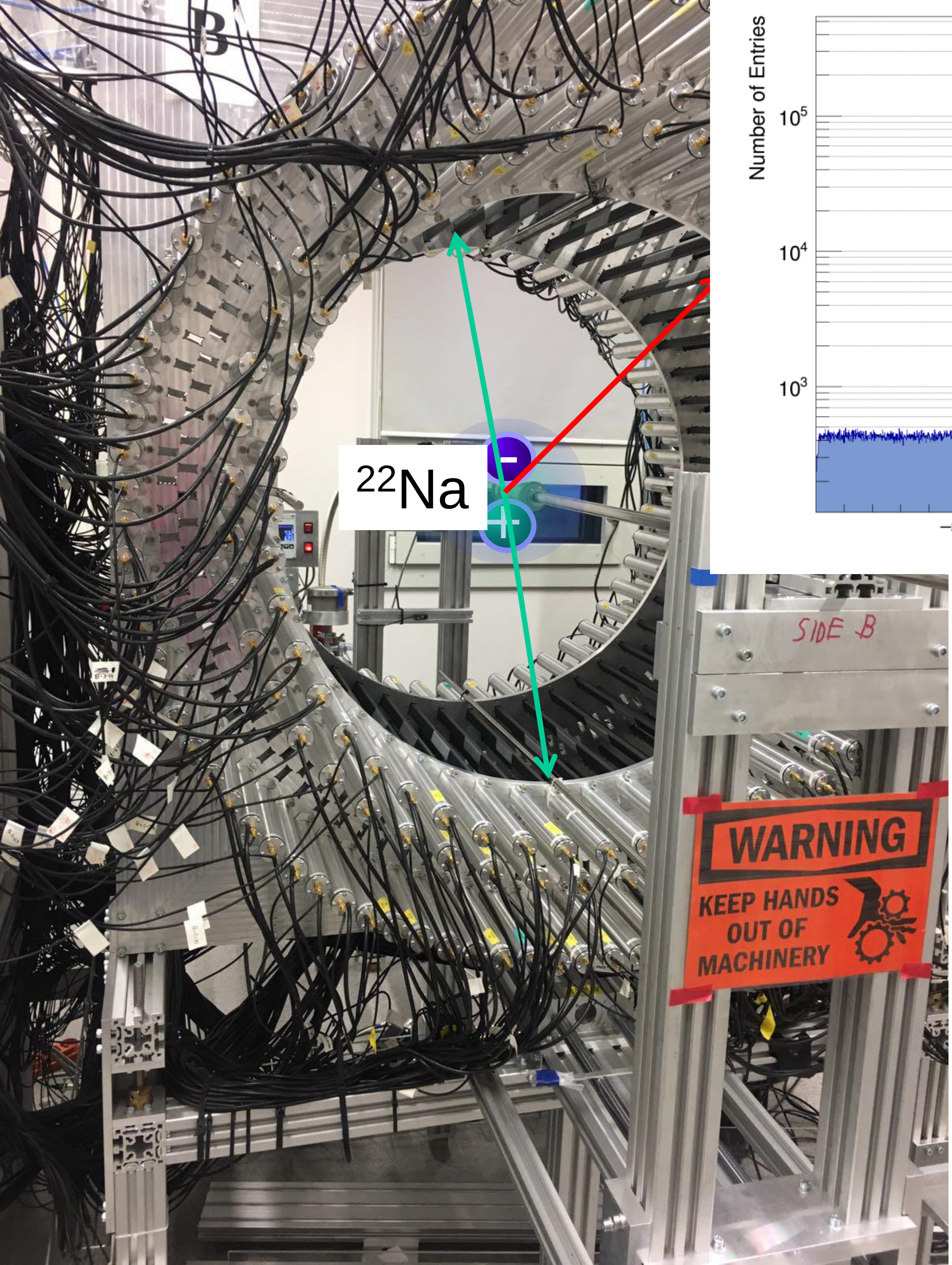
B
^{22}Na
SIDE B
WARNING
KEEP HANDS OUT OF MACHINERY
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
Voltage [V]
0 50 100 150 200 250 300
Number of the sample
y^0
$y^\wedge$
y

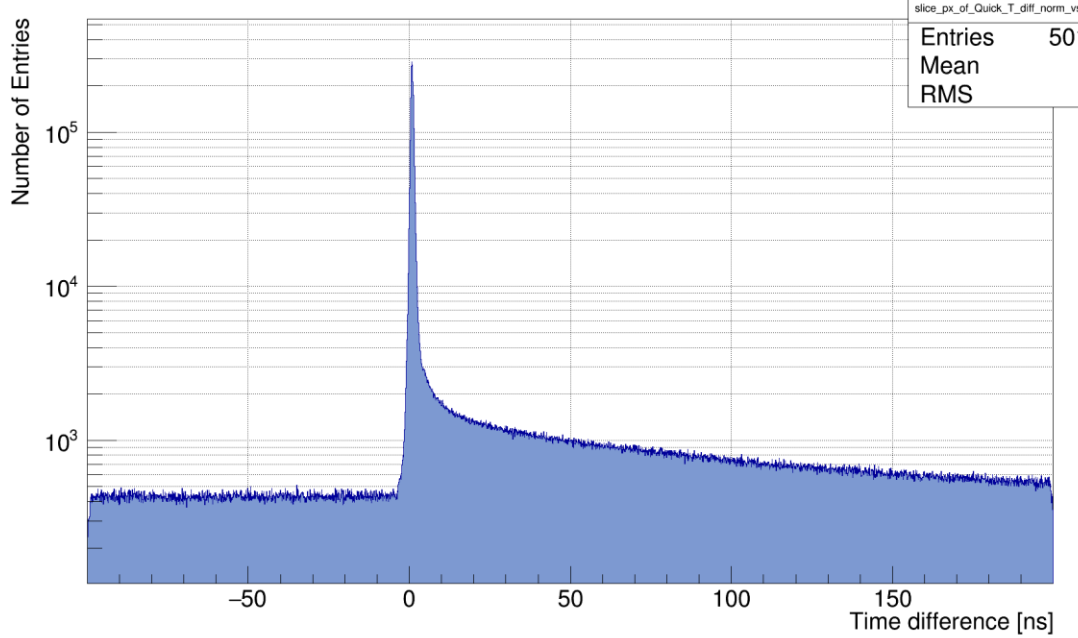


counts [a.u]
10^6
10^5
10^4
10^3
0 10 20 30 40 50 60 70 80 90 100
Time Over Threshold [ns]

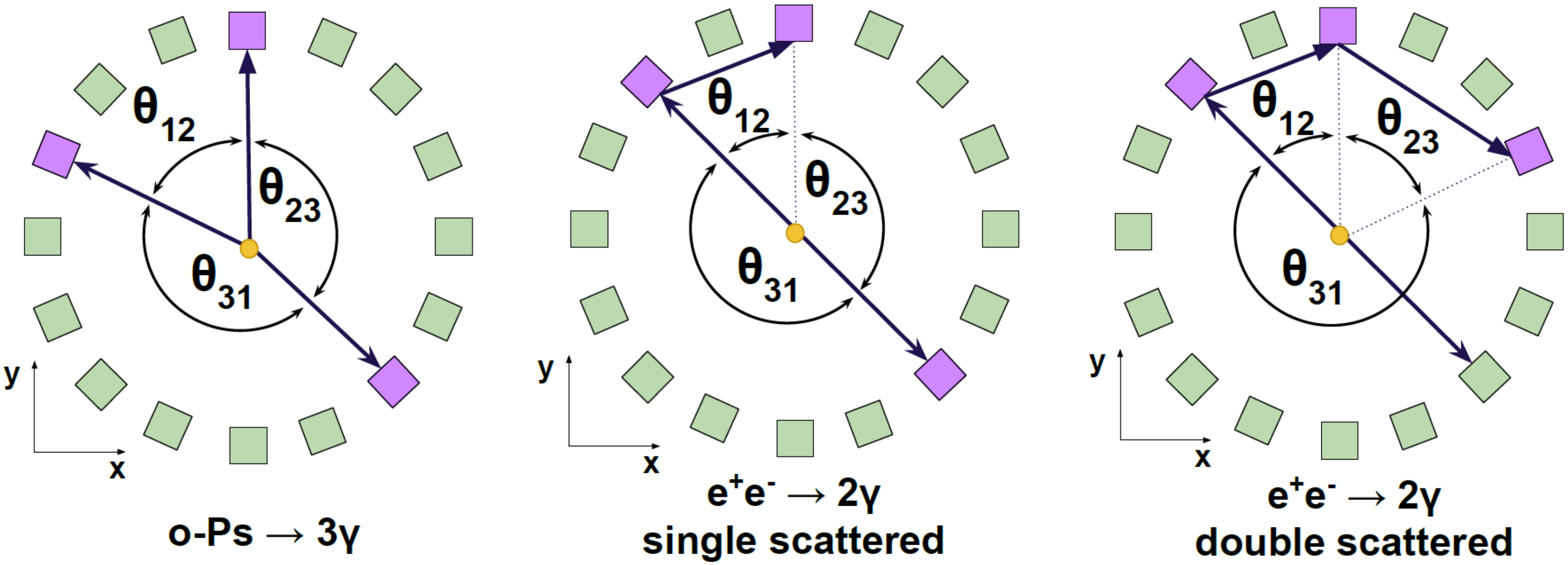


B
22Na
SIDE B
WARNING
KEEP HANDS
OUT OF
MACHINERY
counts [a.u]
10^6
10^5
10^4
10^3
0 10 20 30 40 50 60 70 80 90 100
Time Over Threshold [ns]
Scintillator ID
0 20 40 60 80 100 120 140 160 180
0 10 20 30 40 50 60 70 80 90 100
Time Over Threshold [ns]
0 1000 2000 3000 4000 5000 6000 7000 8000

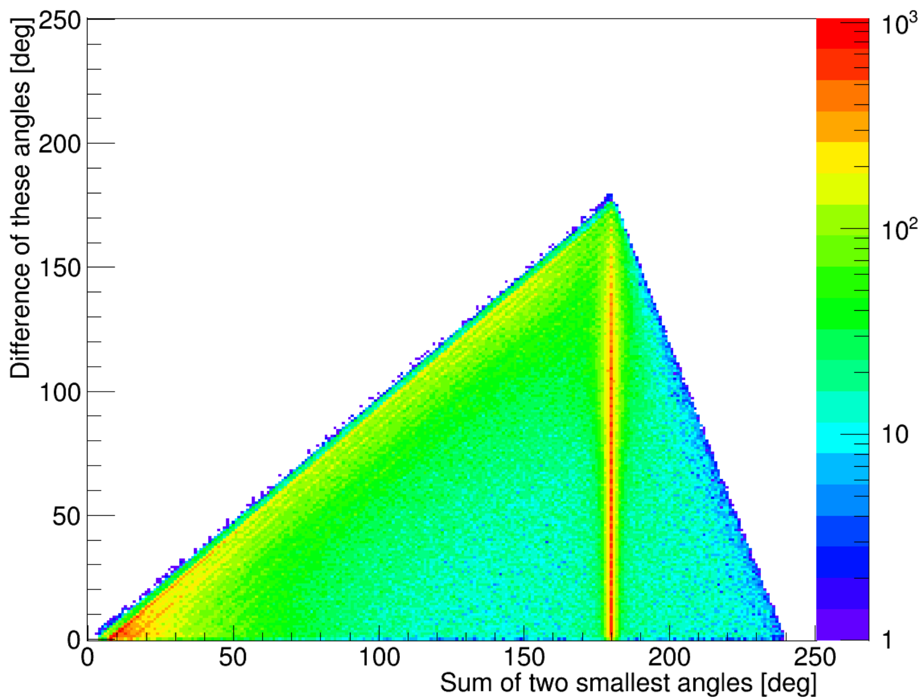


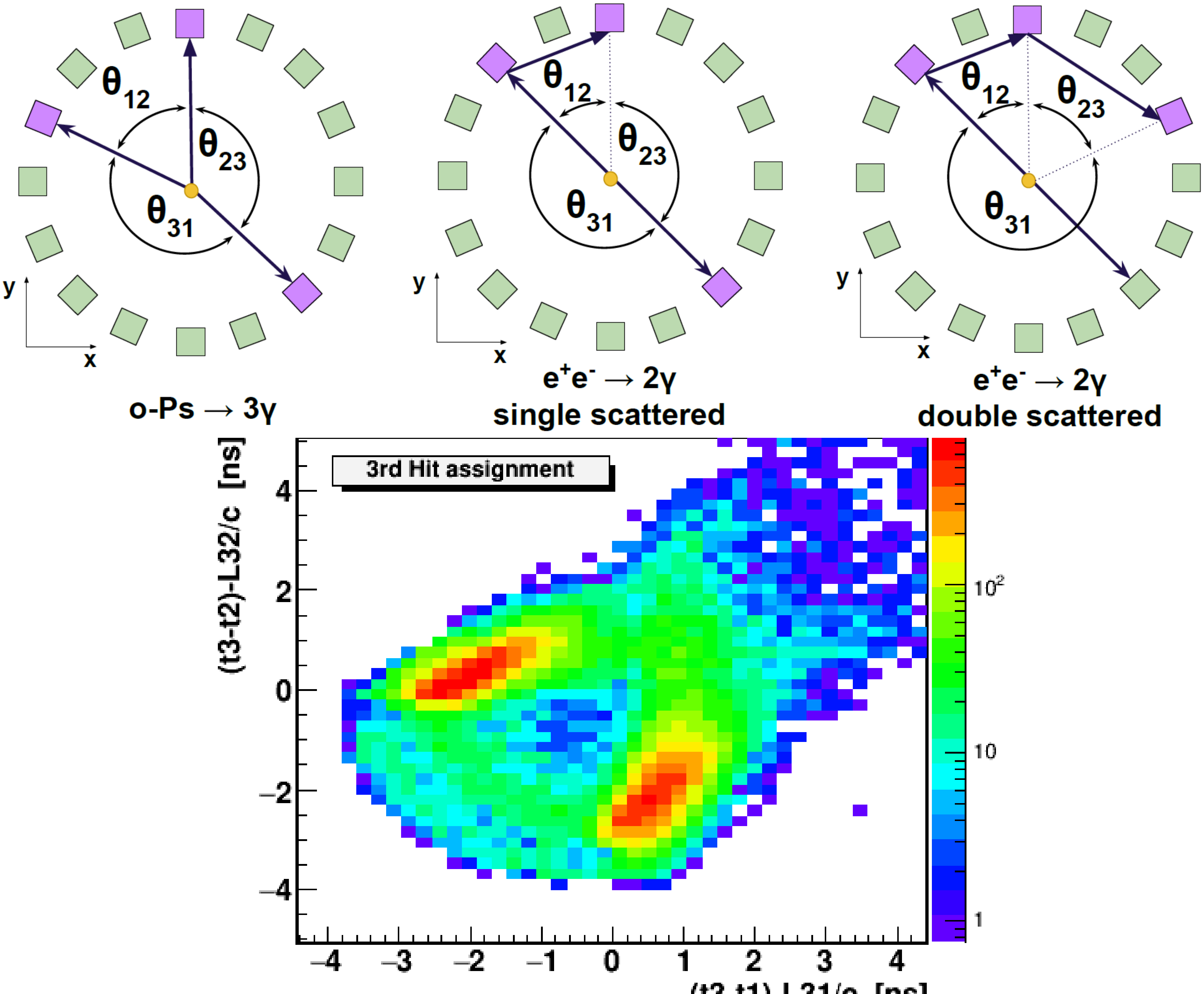


K. Dulski
Poster



$\theta_{23} + \theta_{12} > 180$ $\theta_{23} + \theta_{12} = 180$ $\theta_{23} + \theta_{12} < 180$

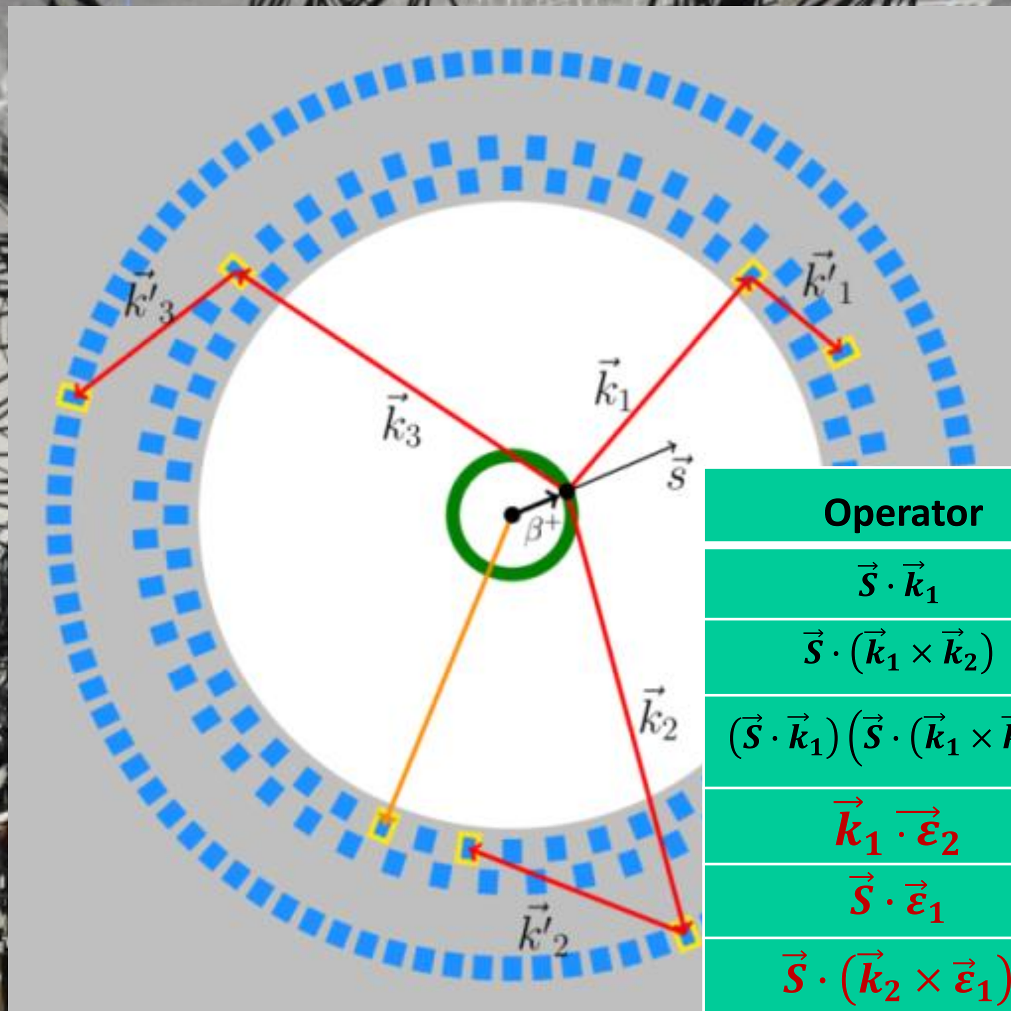




θ12
θ23
θ31
y
x
o-Ps → 3γ
e+e- → 2γ
single scattered
e+e- → 2γ
double scattered
3rd Hit assignment
(t3-t2)-L32/c [ns]
(t3-t1)-L31/c [ns]
4
2
0
−2
−4
−4
−3
−2
−1
0
1
2
3
4
10^2
10
1

Jagiellonian PET

J. Raj Talk



Operator	C	P	T	CP	CPT
$\vec{S}\cdot\vec{k}_1$	+	–	+	–	–
$\vec{S}\cdot(\vec{k}_1\times\vec{k}_2)$	+	+	–	+	–
$(\vec{S}\cdot\vec{k}_1)(\vec{S}\cdot(\vec{k}_1\times\vec{k}_2))$	+	–	–	–	+
$\vec{k}_1\cdot\vec{\varepsilon}_2$	+	–	–	–	+
$\vec{S}\cdot\vec{\varepsilon}_1$	+	+	–	+	–
$\vec{S}\cdot(\vec{k}_2\times\vec{\varepsilon}_1)$	+	–	+	–	–

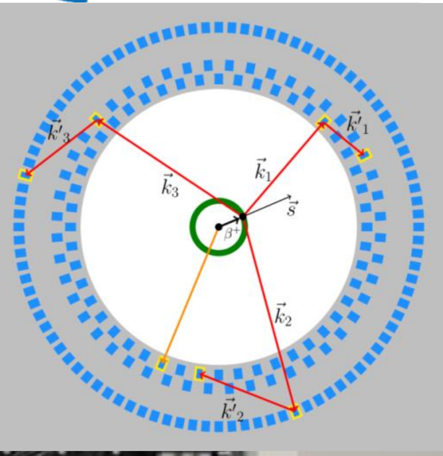
$$\vec{\varepsilon}_i = \vec{k}_i \times \vec{k}'_i$$

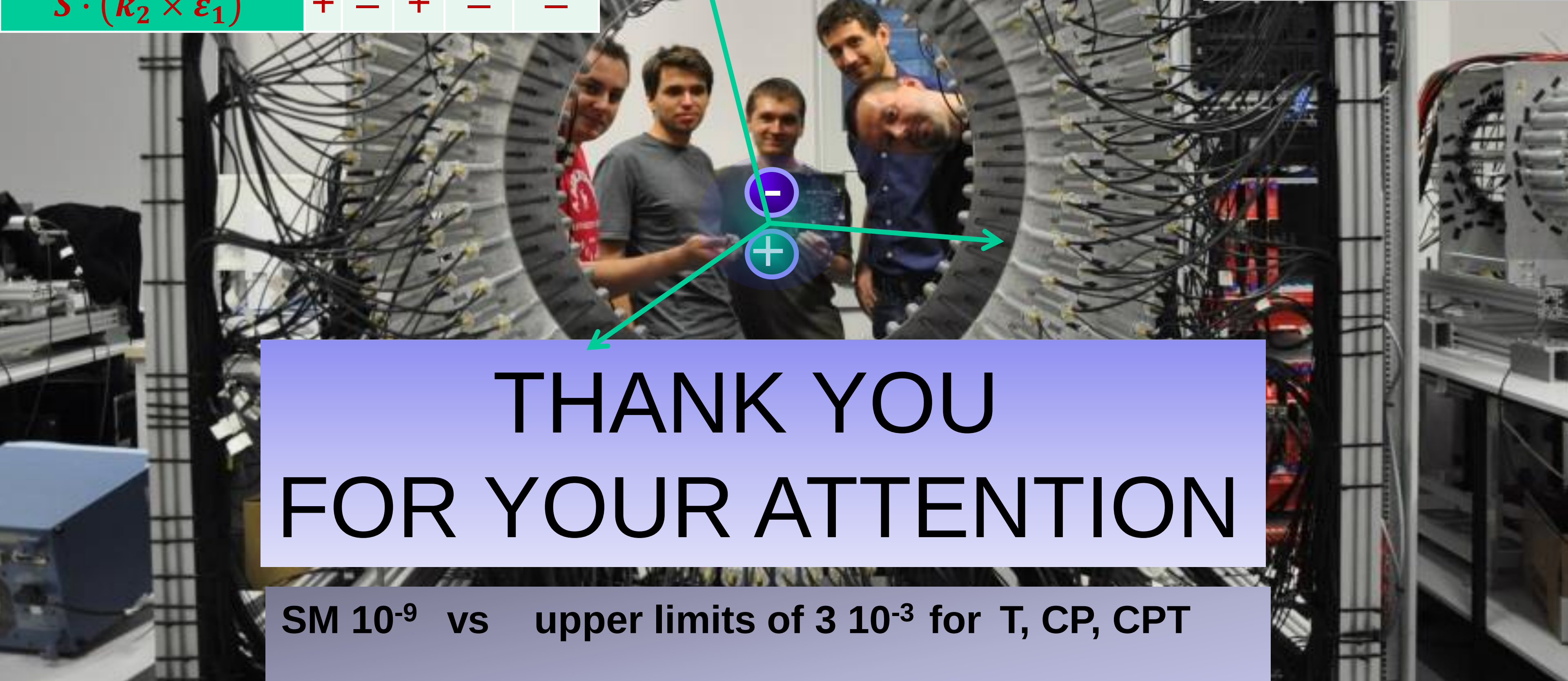
σ(t-hit) ~ 100 ps

SM 10^{-9} vs upper limits of 3 10^{-3} for T, CP, CPT

Jagiellonian PET

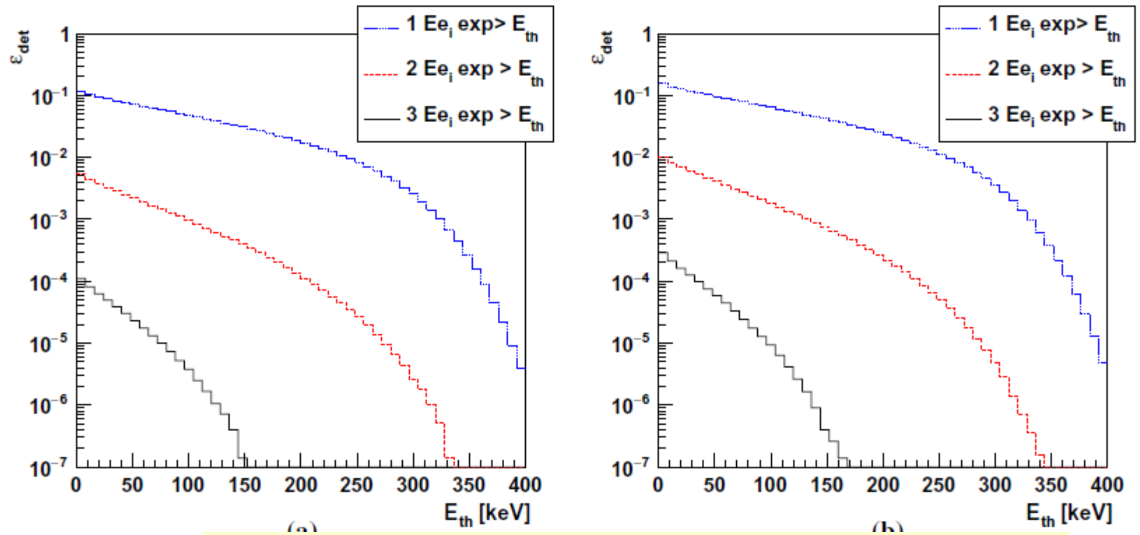
Operator	C	P	T	CP	CPT
$\vec{S}\cdot\vec{k}_1$	+	–	+	–	–
$\vec{S}\cdot(\vec{k}_1\times\vec{k}_2)$	+	+	–	+	–
$(\vec{S}\cdot\vec{k}_1)(\vec{S}\cdot(\vec{k}_1\times\vec{k}_2))$	+	–	–	–	+
$\vec{k}_1\cdot\vec{\varepsilon}_2$	+	–	–	–	+
$\vec{S}\cdot\vec{\varepsilon}_1$	+	+	–	+	–
$\vec{S}\cdot(\vec{k}_2\times\vec{\varepsilon}_1)$	+	–	+	–	–



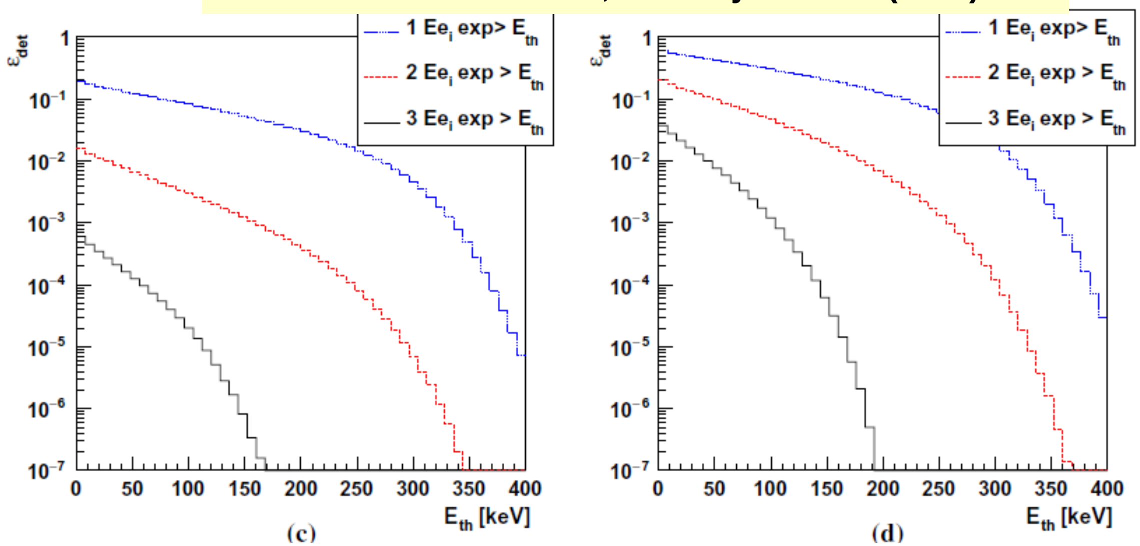


THANK YOU
FOR YOUR ATTENTION

SM 10^{-9} vs upper limits of $3\ 10^{-3}$ for T, CP, CPT



J-PET: D. Kamińska et al., Eur. Phys. J. C76 (2016) 445



Target material	Rate of registered o-Ps $\rightarrow 3\gamma$ events (s^{-1})			
	J-PET	J-PET+1	J-PET+2	J-PET-full
IC3100	15	70	130	10600
XAD-4	25	115	230	18300

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SCIENTIFIC REPORTS

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Genuine Multipartite Entanglement in the 3-Photon Decay of Positronium

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Published online: 10 November 2017

Beatrix C. Hiesmayr[1] & Pawel Moskal[2]

The electron-positron annihilation into two photons is a standard technology in medicine to observe e.g. metabolic processes in human bodies. A new tomograph will provide the possibility to observe not only direct e^+e^- annihilations but also the 3 photons from the decay of ortho-positronium atoms formed in the body. We show in this contribution that the three-photon state with respect to polarisation degrees of freedom depends on the angles between the photons and exhibits various specific entanglement features. In particular genuine multipartite entanglement, a type of entanglement involving all degrees of freedom, is subsistent if the positronium was in a definite spin eigenstate. Remarkably, when all spin eigenstates are mixed equally, entanglement –and even stronger genuine multipartite entanglement– survives. Due to a "*symmetrization*" process, however, *Dicke*-type or W-type entanglement remains whereas *GHZ*-type entanglement vanishes. The survival of particular entanglement properties in the mixing scenario may make it possible to extract quantum information in the form of distinct entanglement features, e.g., from metabolic processes in human bodies.

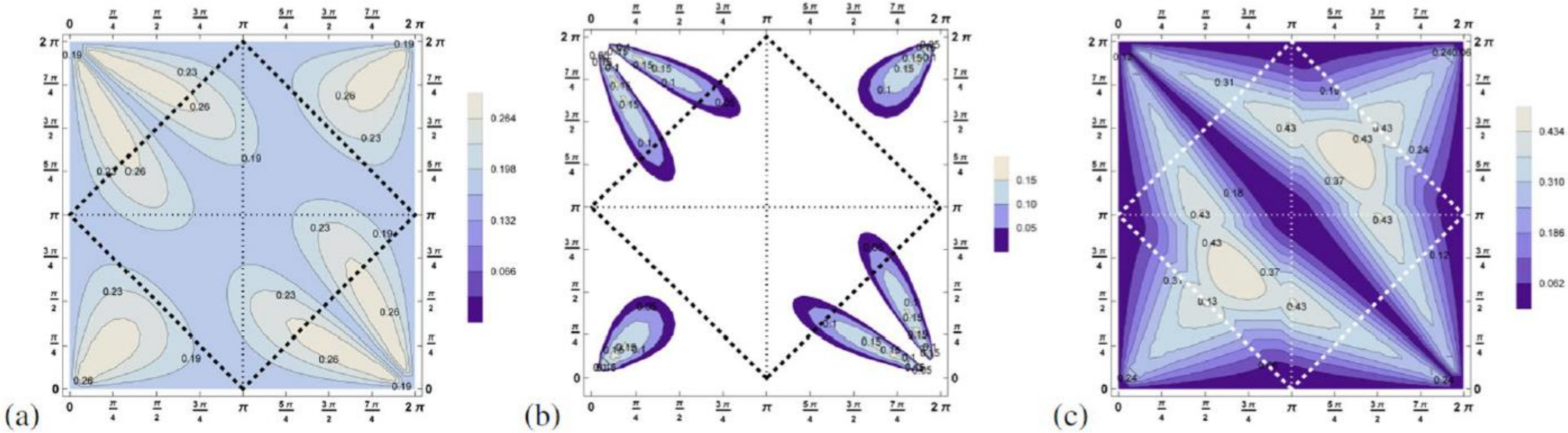
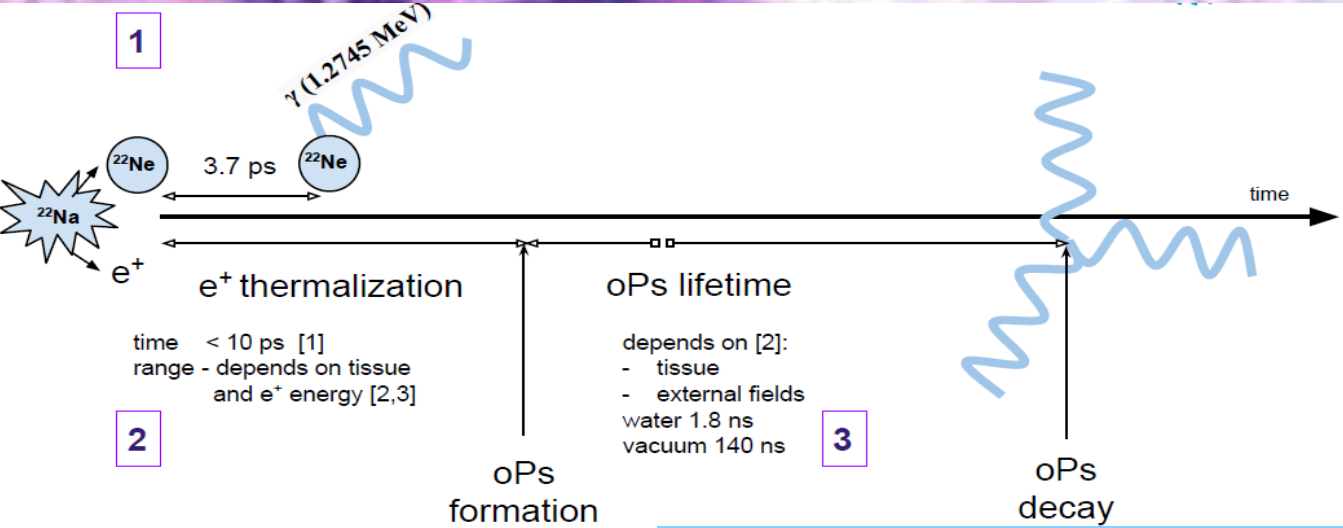
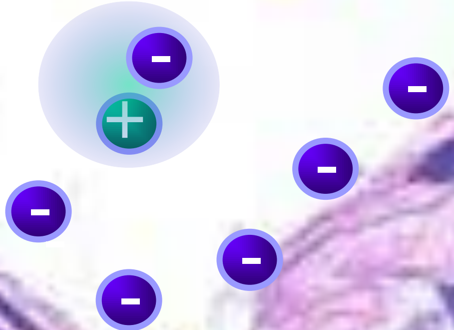


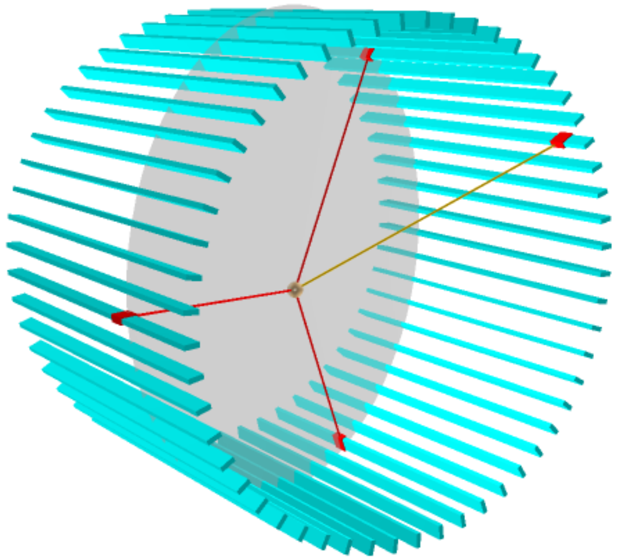
Figure 5. These three contour plots show (**a**) Q_{SEP}, (**b**) Q_{GHZ} and (**c**) Q_W for the state mixed equally between all three possible quantum states $s_{\hat{\vec{n}}} = 0, \ +1, \ -1$, equation 17. Still genuine multipartite entanglement is revealed for some scenarios ($\widetilde{\Theta}_{ab}, \ \widetilde{\Theta}_{bc}$). The criterion Q_W detecting *W*-type of genuine multipartite entanglement is by far more sensitive to reveal genuine multipartite entanglement.

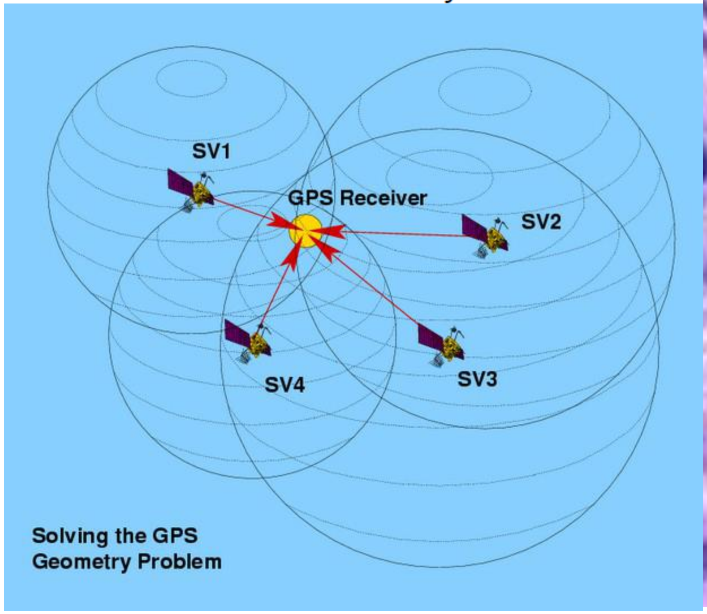
B. Hiesmayr P.M., Scientific Reports 7 (2017) 15349

Ortho-positronium life-time tomography









Patent applications: P. M., **PCT/EP2014/068374**; A. Gajos, E. Czerwiński, D. Kamińska, P. M., **PCT/PL2015/050038**

3g/2g tomography

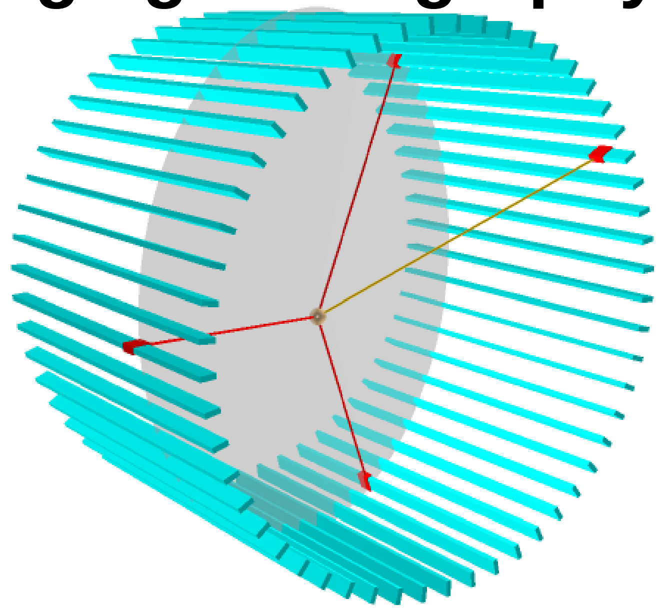


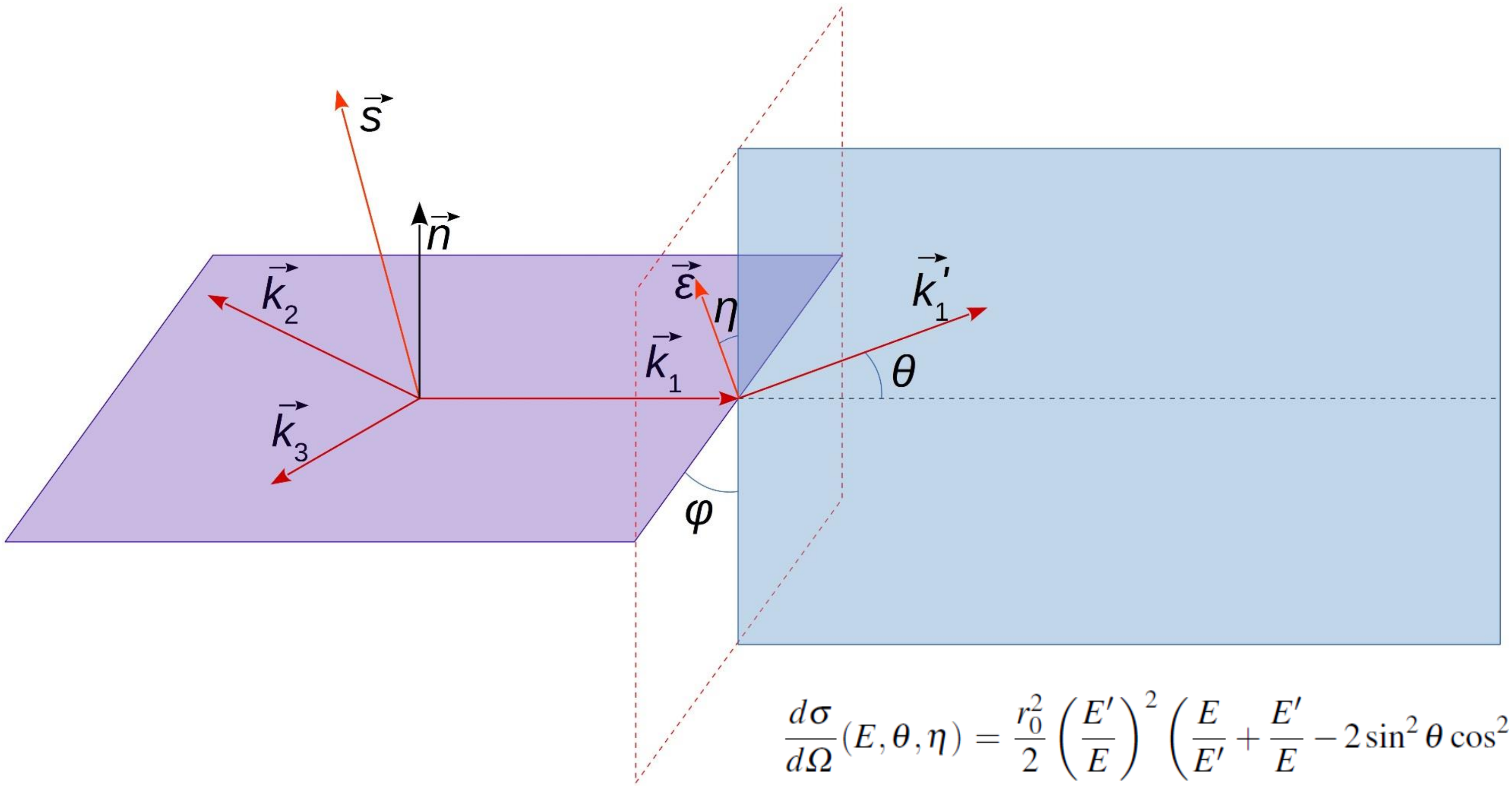
Table 1 Summary of major physical characteristics of beta-plus isotopes useful for PET imaging and positron annihilation lifetime spectroscopy (PALS) investigations. For isotopes that decay into excited states the properties of emitted gamma quanta are denoted. Data were adapted from [27]

Isotope	Half-life	β^+ decay	E_γ (MeV)	$E_{e^+}^{max}$ (MeV)	Excited nuclei lifetime
Isotopes for PALS and PET imaging					
^{22}Na	2.6 (years)	$^{22}\text{Na} \rightarrow ^{22}\text{Ne} + e^+ + \nu_e + \gamma$	1.27	0.546	3.63 (ps)
^{68}Ga	67.8 (min)	$^{68}\text{Ga} \rightarrow ^{68}\text{Zn} + e^+ + \nu_e + \gamma$	1.08	0.822	1.57 (ps)
^{44}Sc	4.0 (h)	$^{44}\text{Sc} \rightarrow ^{44}\text{Ca} + e^+ + \nu_e + \gamma$	1.16	1.474	2.61 (ps)
Isotopes for PET imaging					
^{68}Ga	67.8 (min)	$^{68}\text{Ga} \rightarrow ^{68}\text{Zn} + e^+ + \nu_e$	–	1.899	–
^{11}C	20.4 (min)	$^{11}\text{C} \rightarrow ^{11}\text{B} + e^+ + \nu_e$	–	0.961	–
^{13}N	10.0 (min)	$^{13}\text{N} \rightarrow ^{13}\text{C} + e^+ + \nu_e$	–	1.198	–
^{15}O	2.0 (min)	$^{15}\text{O} \rightarrow ^{15}\text{N} + e^+ + \nu_e$	–	1.735	–
^{18}F	1.8 (h)	$^{18}\text{F} \rightarrow ^{18}\text{O} + e^+ + \nu_e$	–	0.634	–

B. Jasińska, P. M., Patent application P 418689

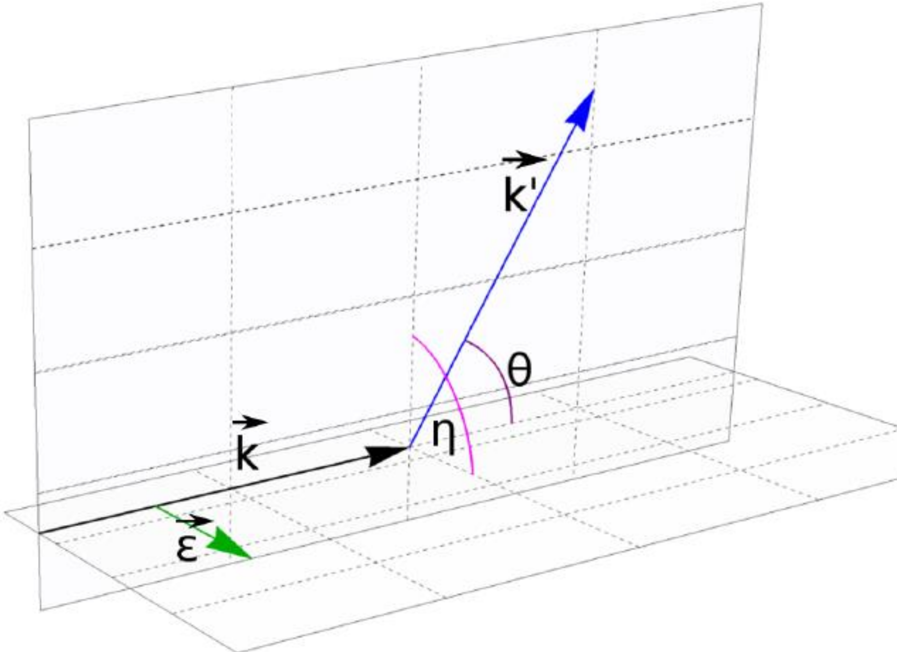
B. Jasińska, P. M., Acta Physica Polonica B 48 (2017) 1577

Jagiellonian PET

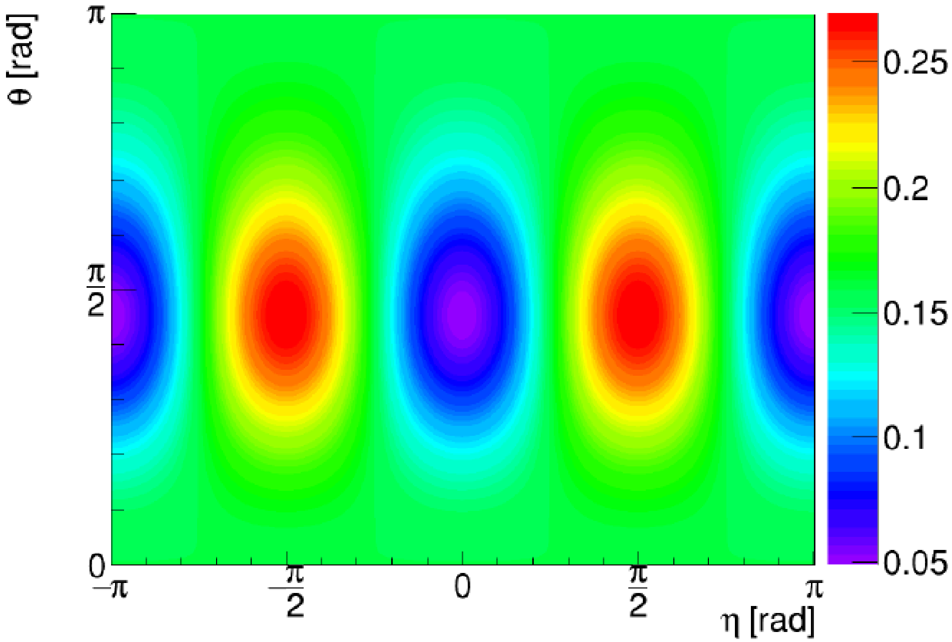


$$\frac{d\sigma}{d\Omega}(E,\theta,\eta) = \frac{r_0^2}{2}\left(\frac{E'}{E}\right)^2\left(\frac{E}{E'} + \frac{E'}{E} - 2\sin^2\theta\cos^2\eta\right)$$

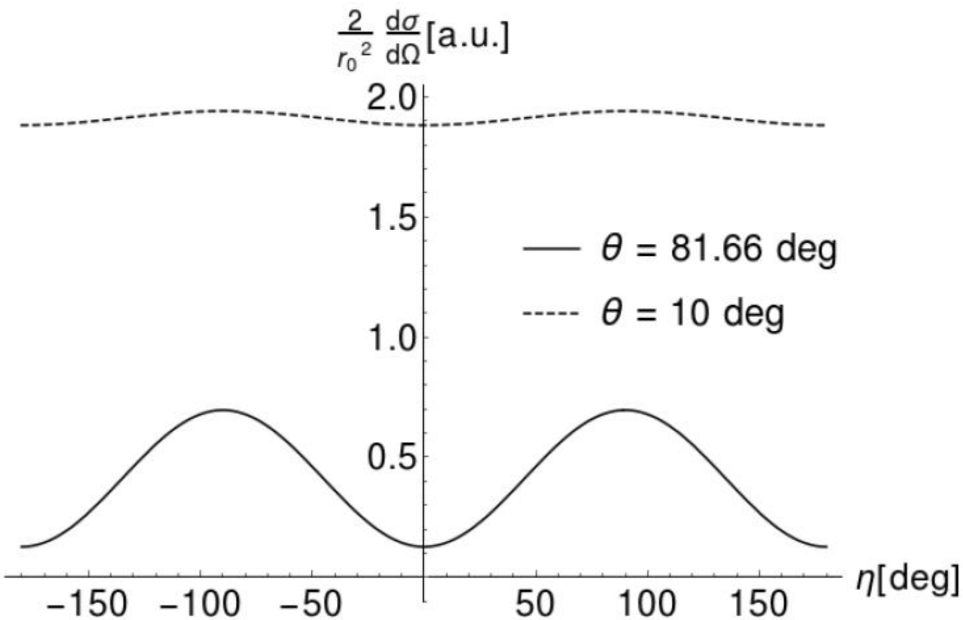
$$E'(E,\theta) = \frac{E}{1+\frac{E}{m_e c^2}(1-cos\theta)},$$



k'
θ
k
η
ε



θ [rad]
π
π/2
0
−π
−π/2
0
π/2
π
η [rad]
0.25
0.2
0.15
0.1
0.05



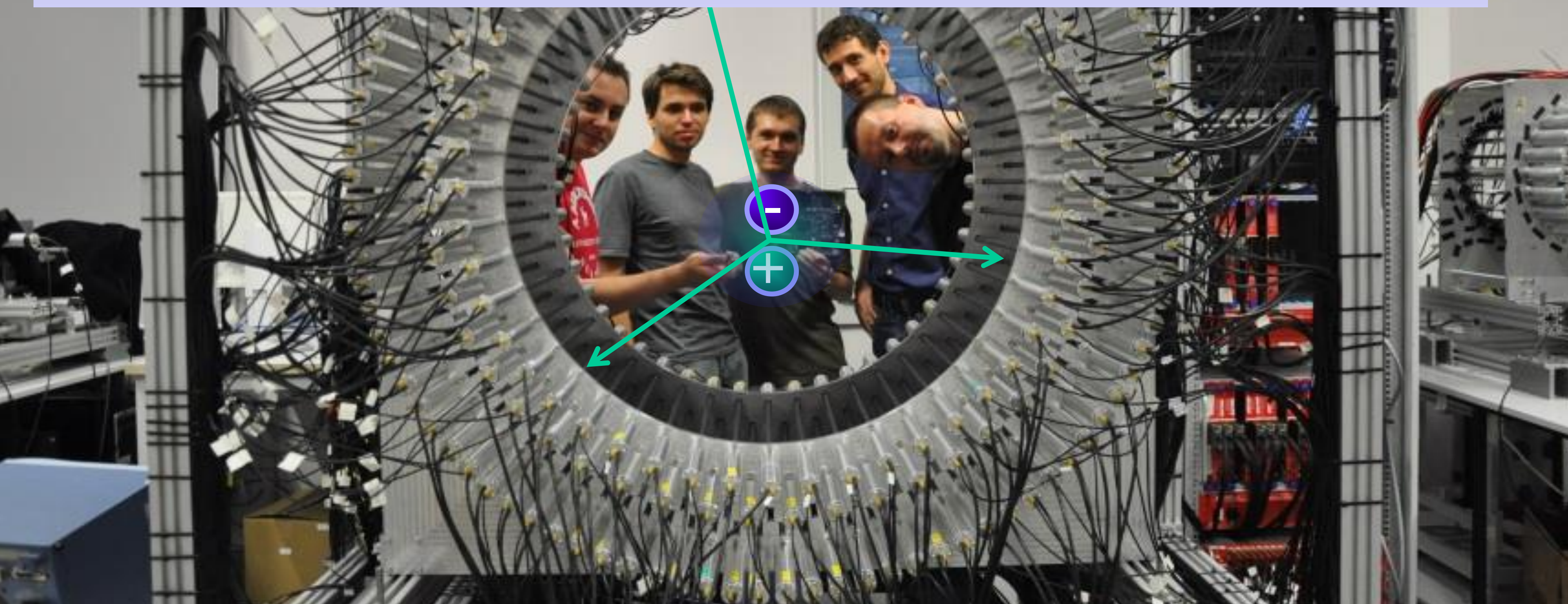
$\frac{2}{r_0^2}\frac{d\sigma}{d\Omega}$[a.u.]
2.0
1.5
1.0
0.5
θ = 81.66 deg
θ = 10 deg
−150
−100
−50
50
100
150
η[deg]

Jagiellonian PET

It is an open question whether or not the three-photon entanglement can be reduced to the two-photon entanglement and decoherence of the two-photon states does imply decoherence in photon triplets. This hypothesis can be tested by comparison of measured two- and three-photon correlation functions. There exist three-photon states maximizing the Greenberger-Horn-Zeilinger (GHZ) entanglement and they can be used to test quantum local realism versus quantum mechanics.

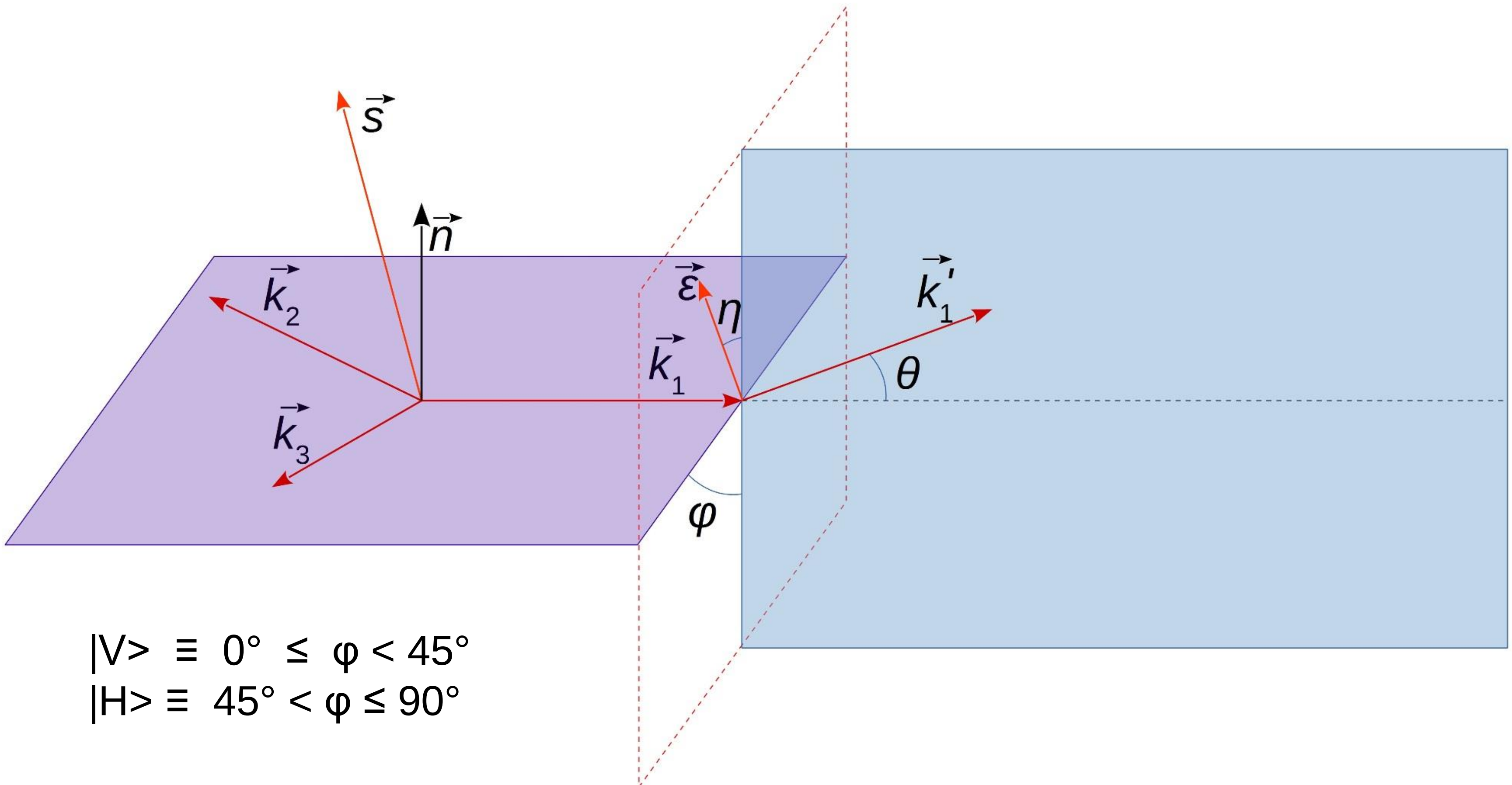
D.M. Greenberger et al., Am. J. Phys. 58(1990)1131

A. Acin et al., Phys. Rev. A63(2001) 042107; N.D. Mermin, Phys. Rev. Lett. 65 (1990)1838



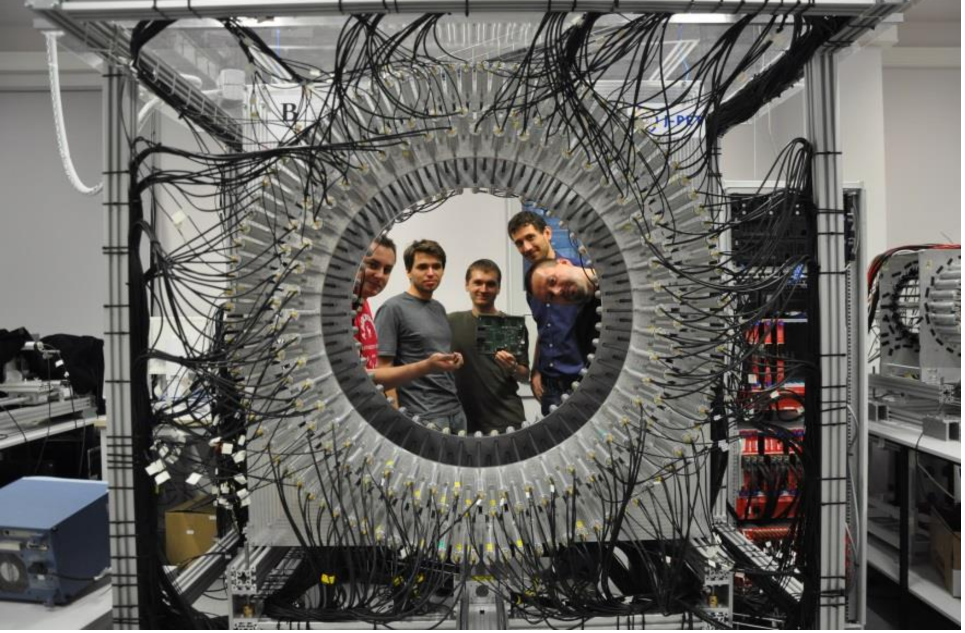
$$\vec{\varepsilon}_i = \vec{k}_i \times \vec{k'}_i$$

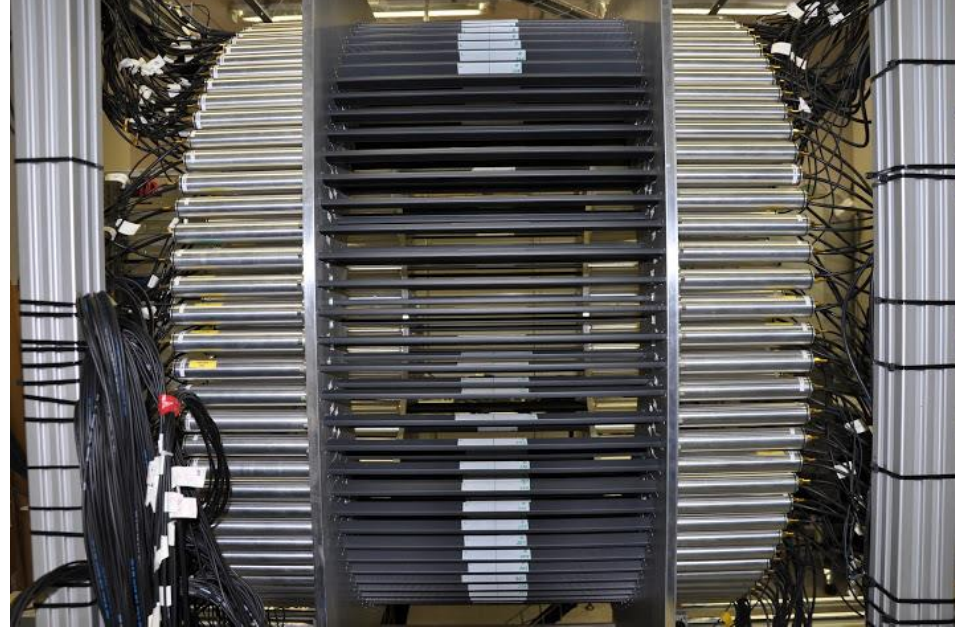
σ(t-hit) ~ 100 ps

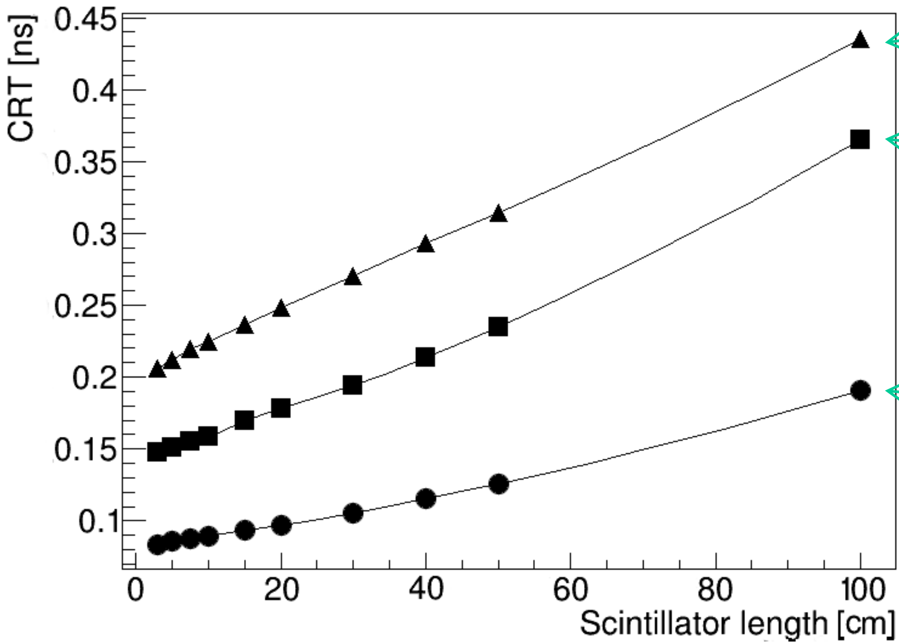


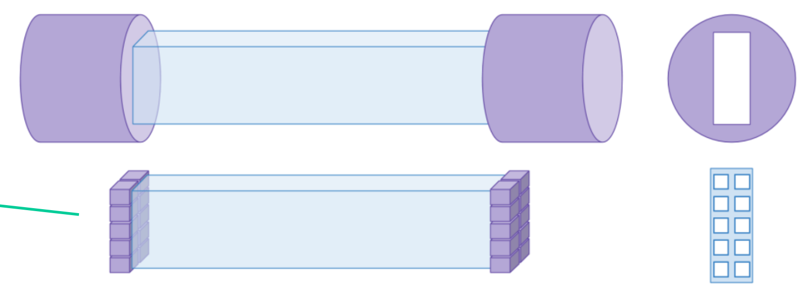
|V> ≡ 0° ≤ φ < 45°
|H> ≡ 45° < φ ≤ 90°

|GHZ > = 1/sqrt(2) (|H H H> + |V V V>)
| W > = 1/sqrt(3) (|H H V> + |H V H> + |V H H >)









J-PET: P.M. et al., Phys. Med. Biol. 61 (2016) 2025

Limit of the J-PET

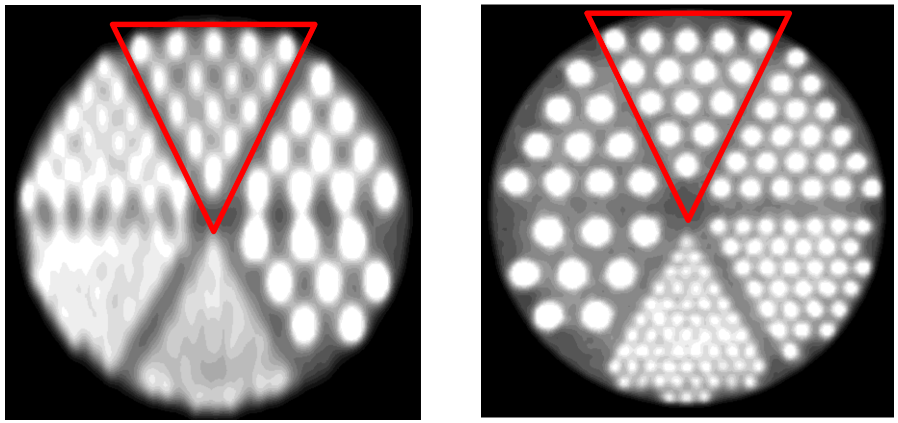
J-PET: P. Bialas, J. Kowal, A. Strzelecki et al. Acta Phys. Pol. A127 (2015) 1500

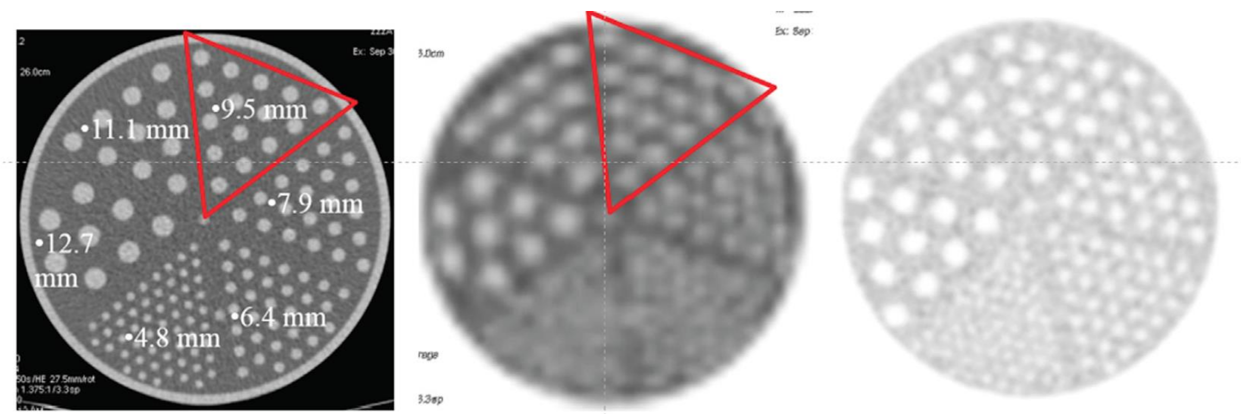
Adam Strzelecki, PhD thesis, 2016

384 strips, diameter 85 cm, 50 cm AFOV, 10^8 events, 50 iterations,

J-PET: image reconstracted from simulated data

rotated (coronal) axially arranged

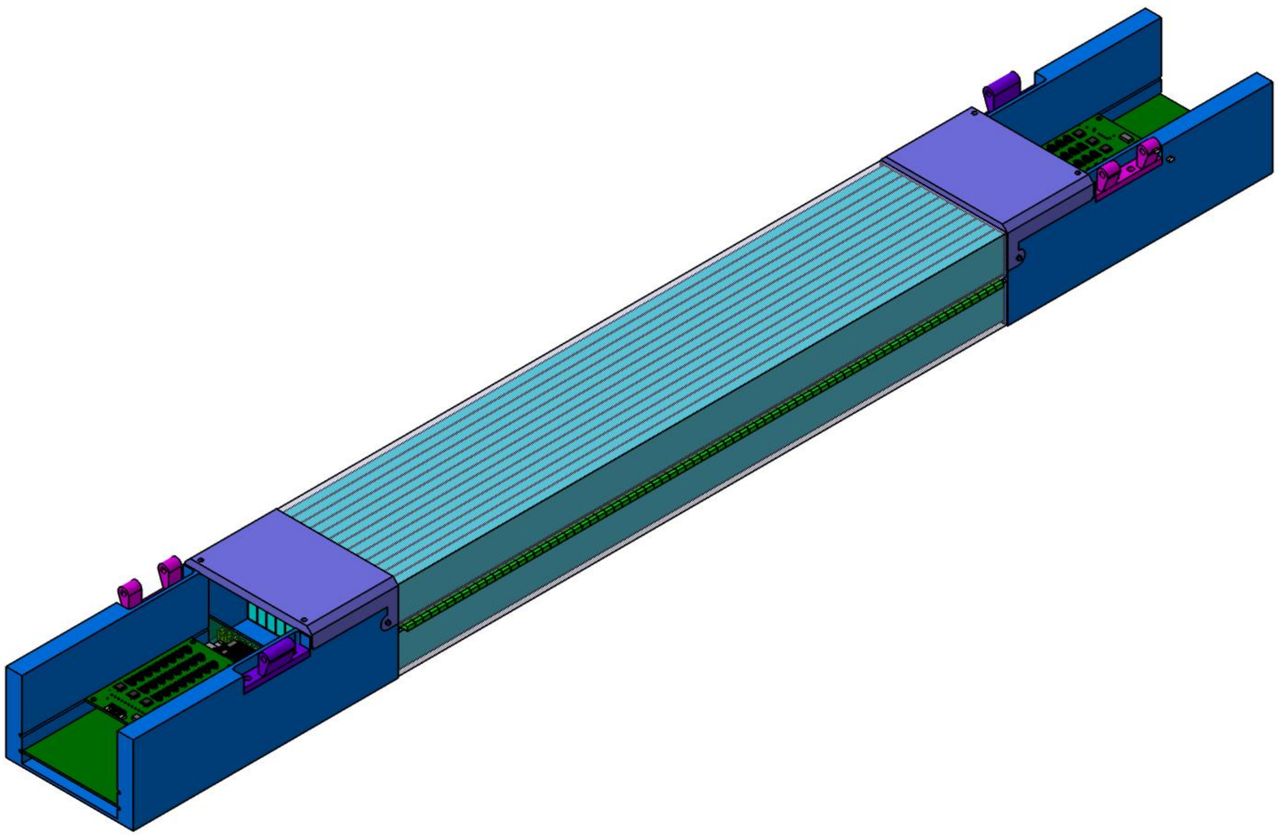




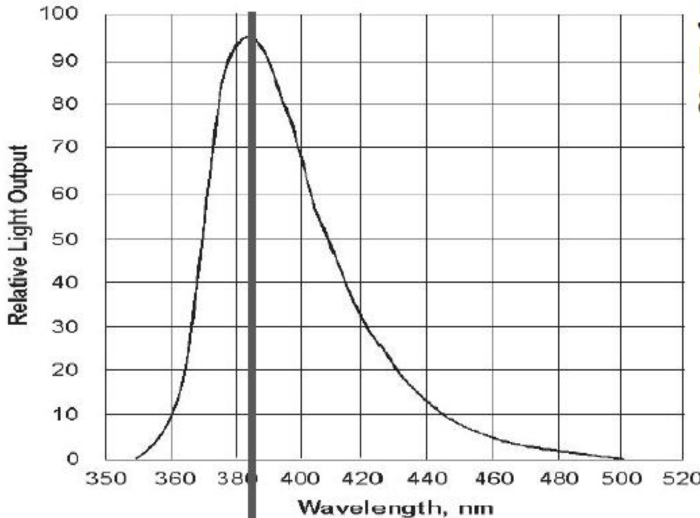
CT Conventional PET Digital PET

Figure from P. Slomka, T. Pan, G. Germano, Semin. Nucl. Med. 46 (2016) 46

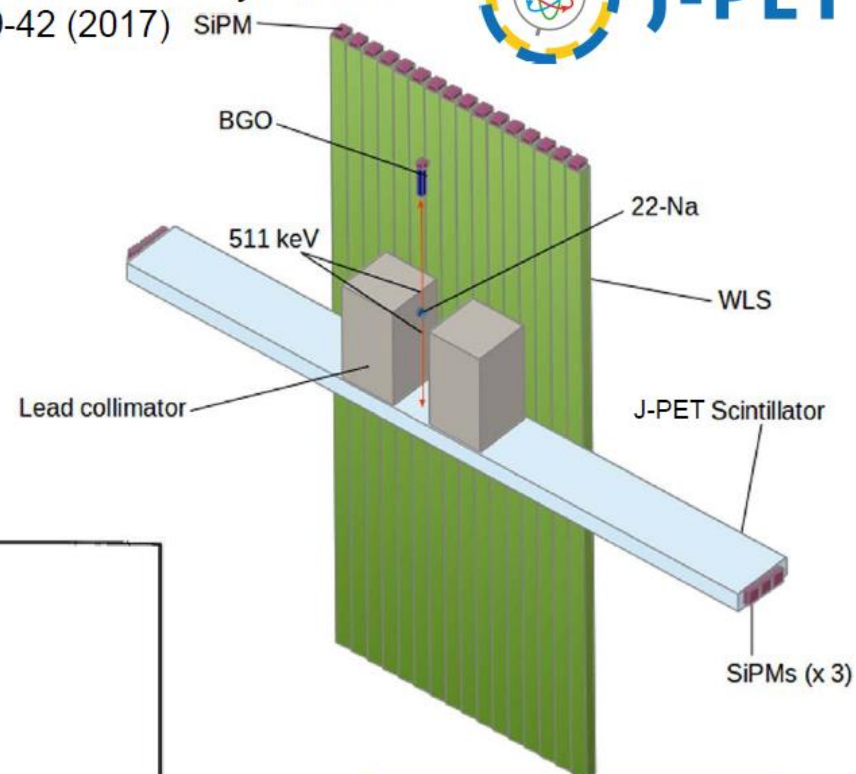
Digital PET, courtesy of Jun Zhang (PhD), Michael V. Knopp (MD, PhD), The Ohio State University



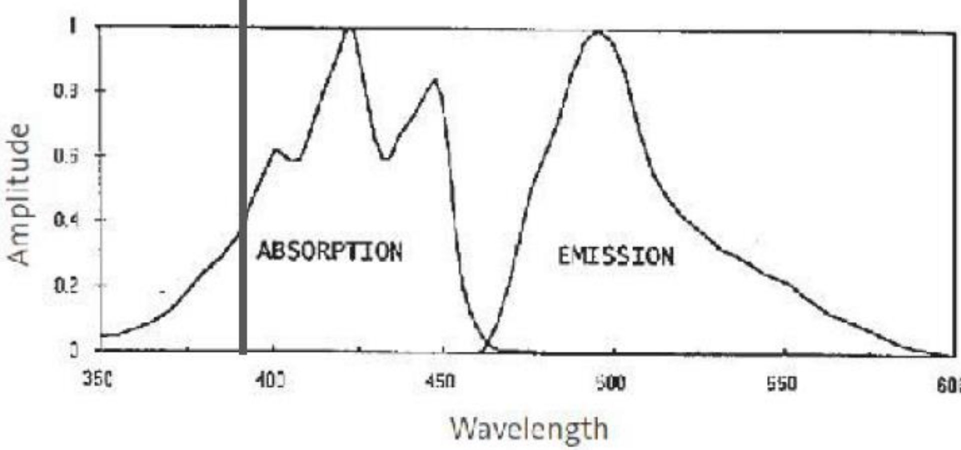
BC-420



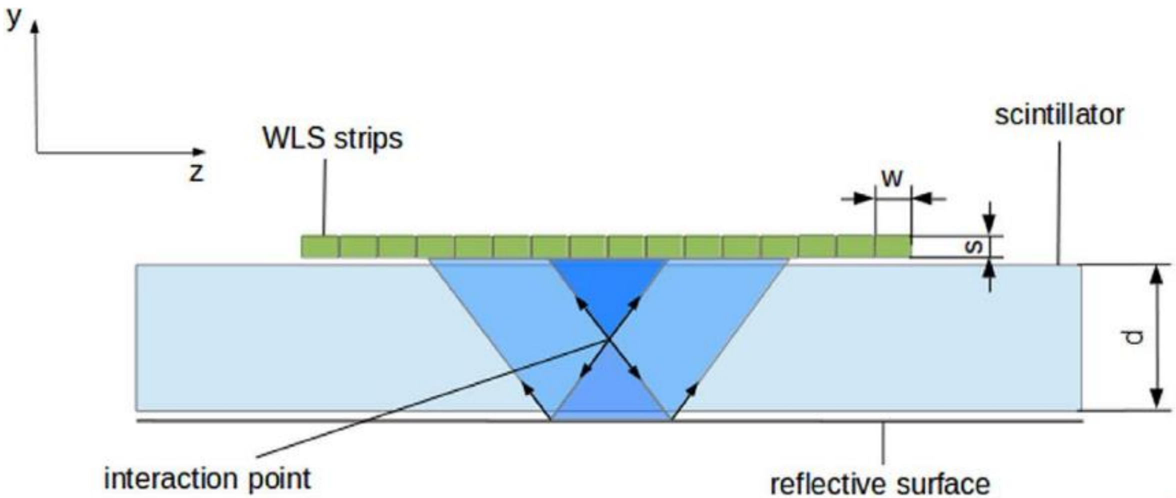
J. Smyrski, J-PET group, Nucl. Instr. and Meth. in Phys. Res. A 851:39-42 (2017)



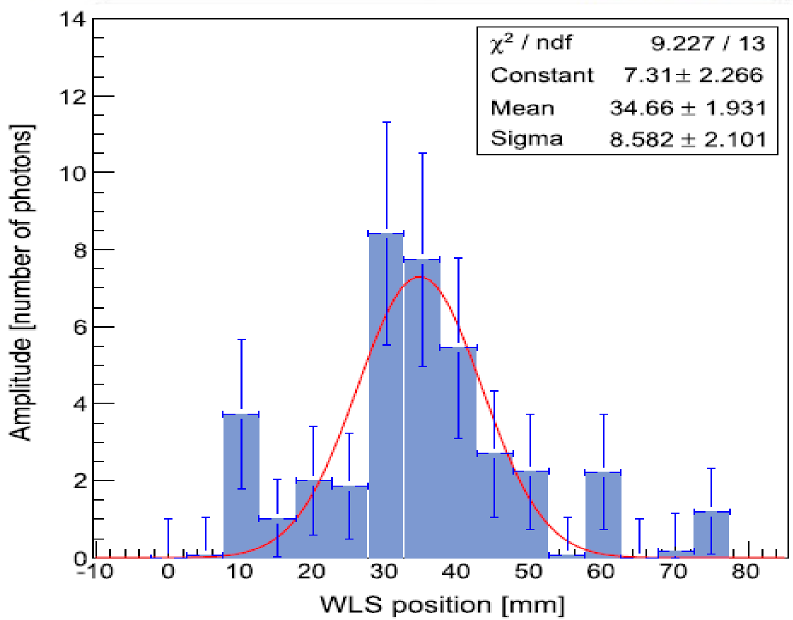
BC-482A



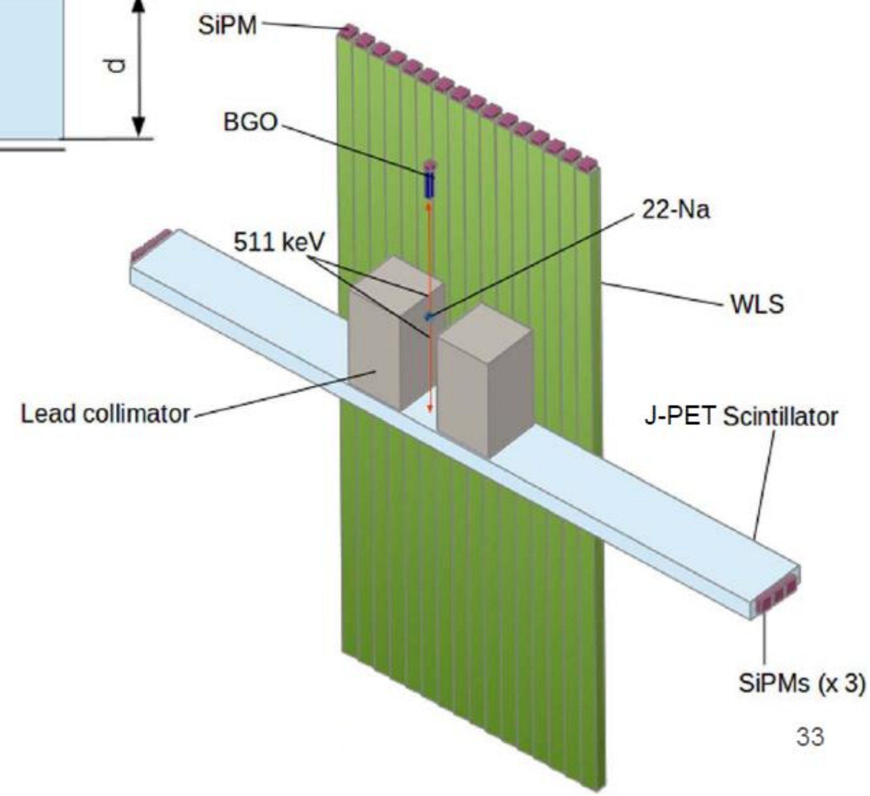
More details in
S. Choudhary and
J. Smyrski poster



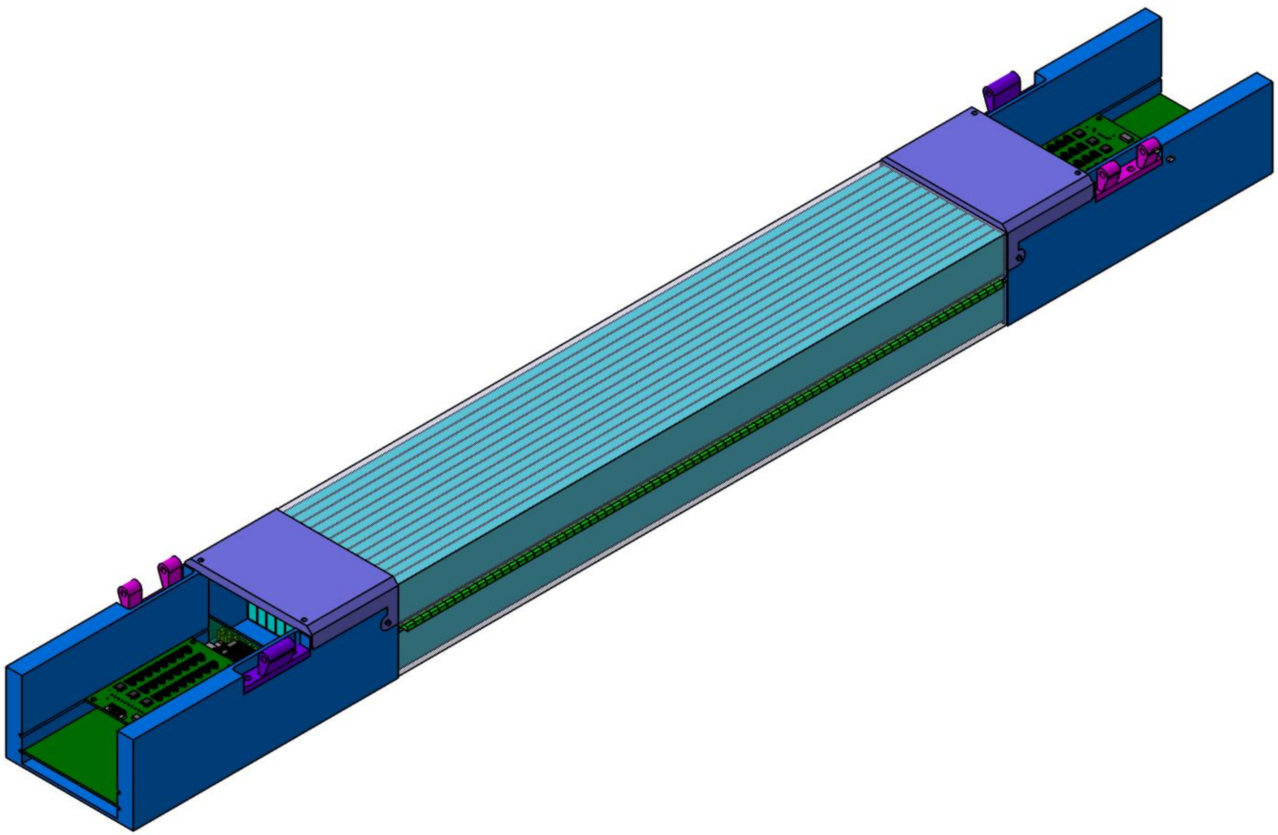
y
z
WLS strips
w
s
scintillator
d
interaction point
reflective surface

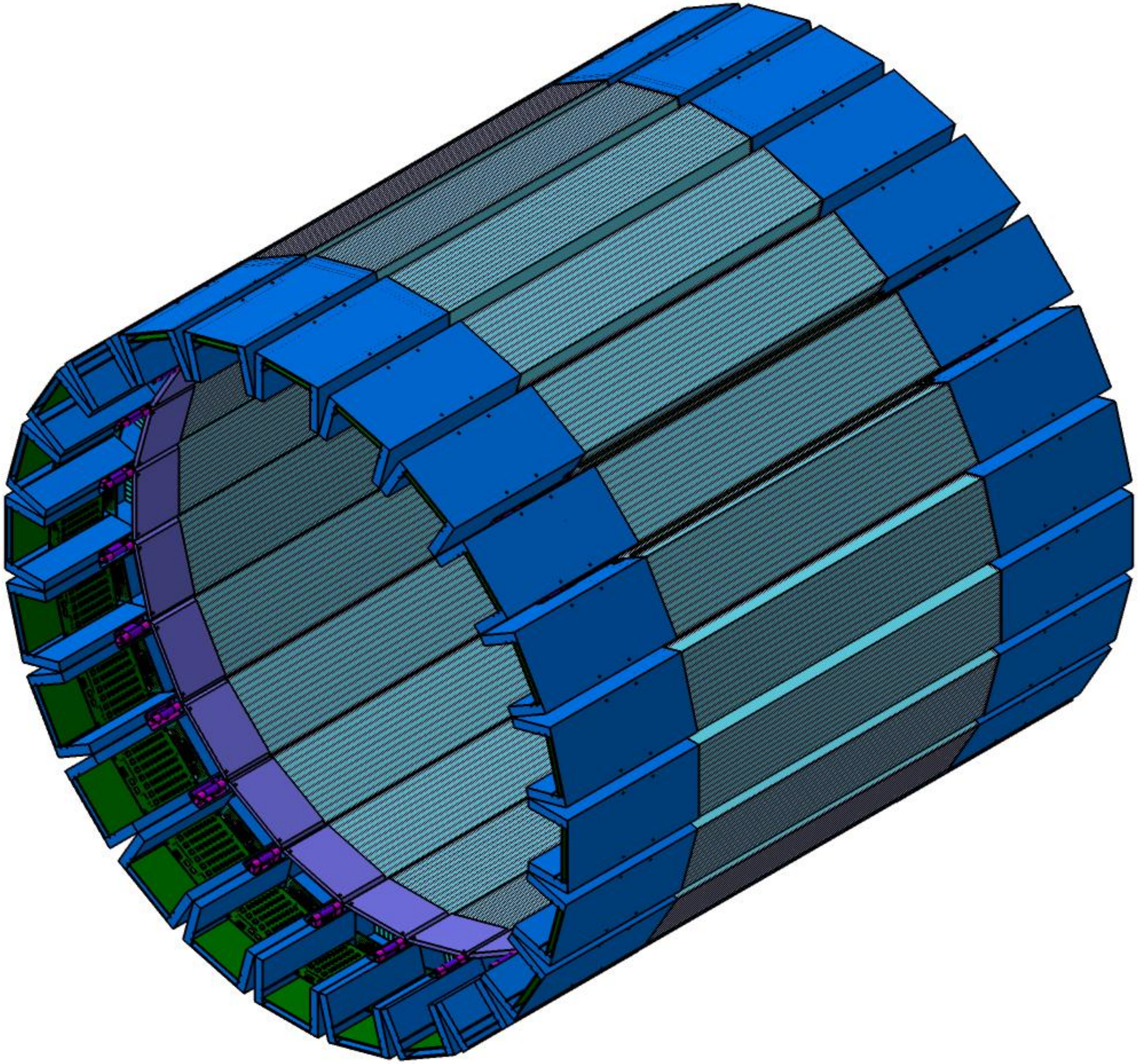


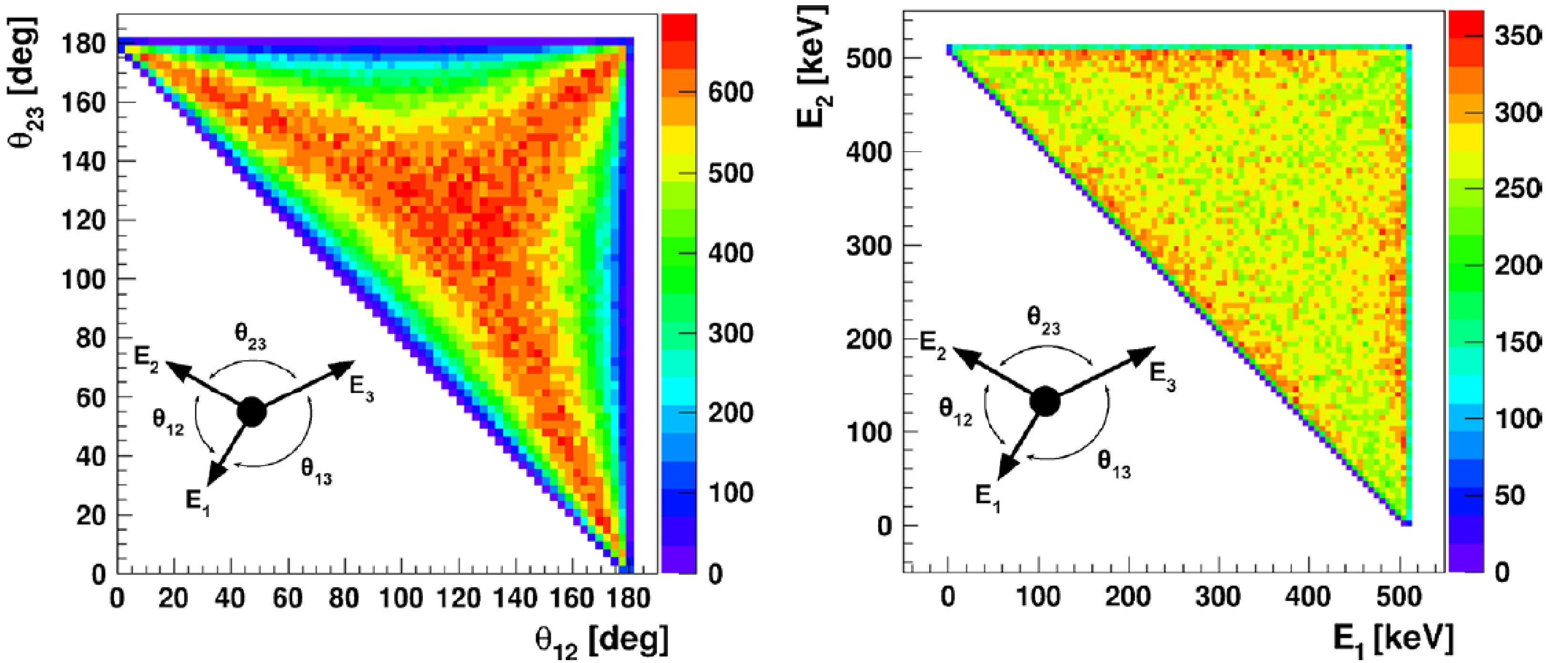
χ^2 / ndf 9.227 / 13
Constant 7.31± 2.266
Mean 34.66 ± 1.931
Sigma 8.582 ± 2.101
Amplitude [number of photons]
WLS position [mm]

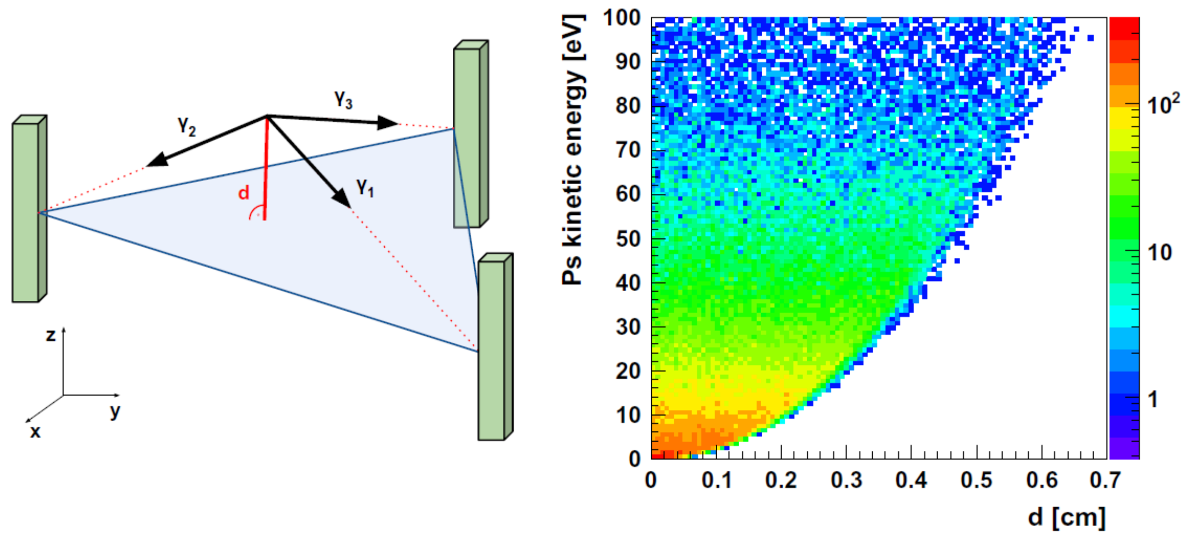


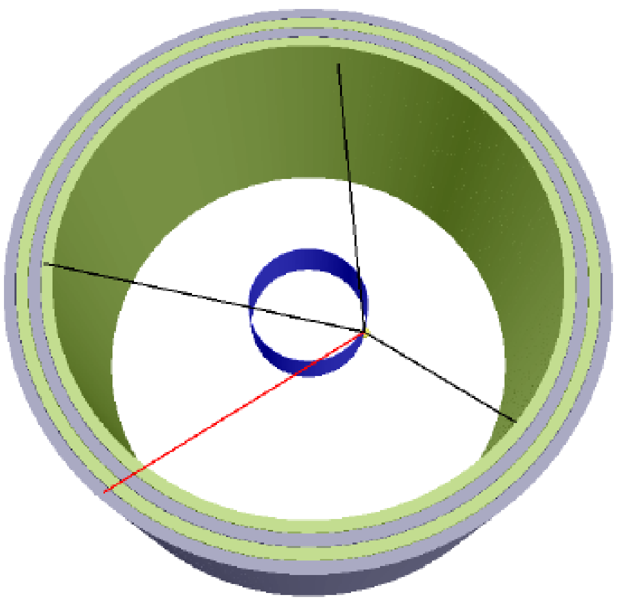
SiPM
BGO
22-Na
511 keV
WLS
Lead collimator
J-PET Scintillator
SiPMs (x 3)

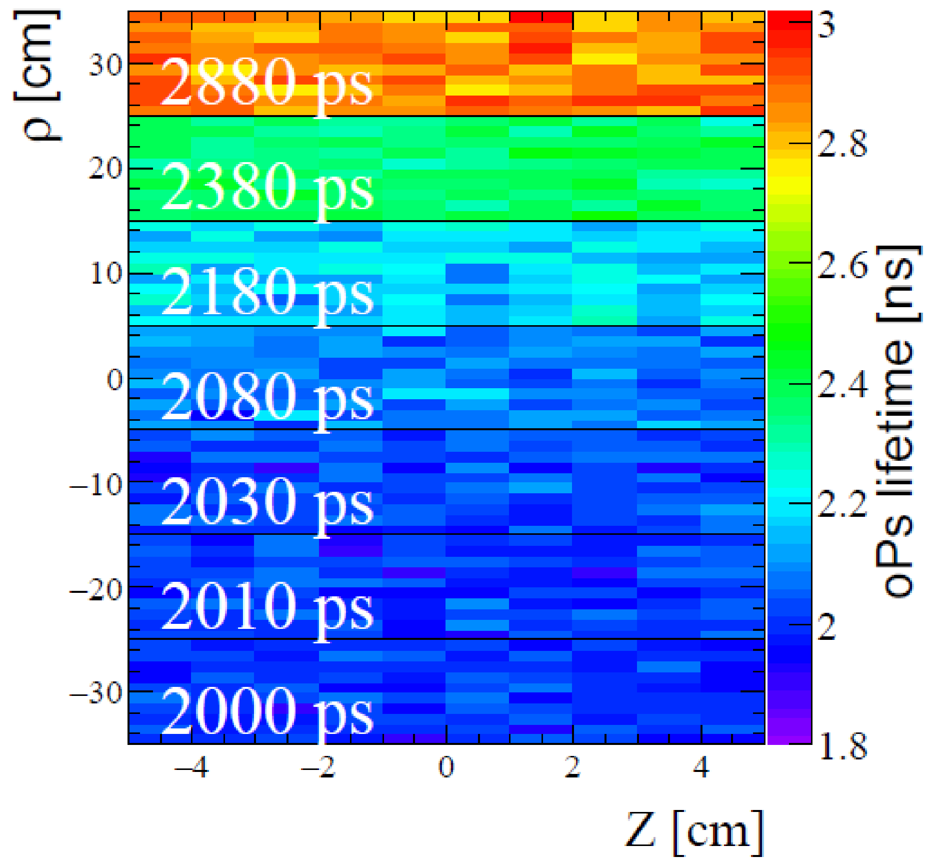





θ23 [deg]
θ12 [deg]
E1
E2
E3
θ12
θ13
θ23
E2 [keV]
E1 [keV]

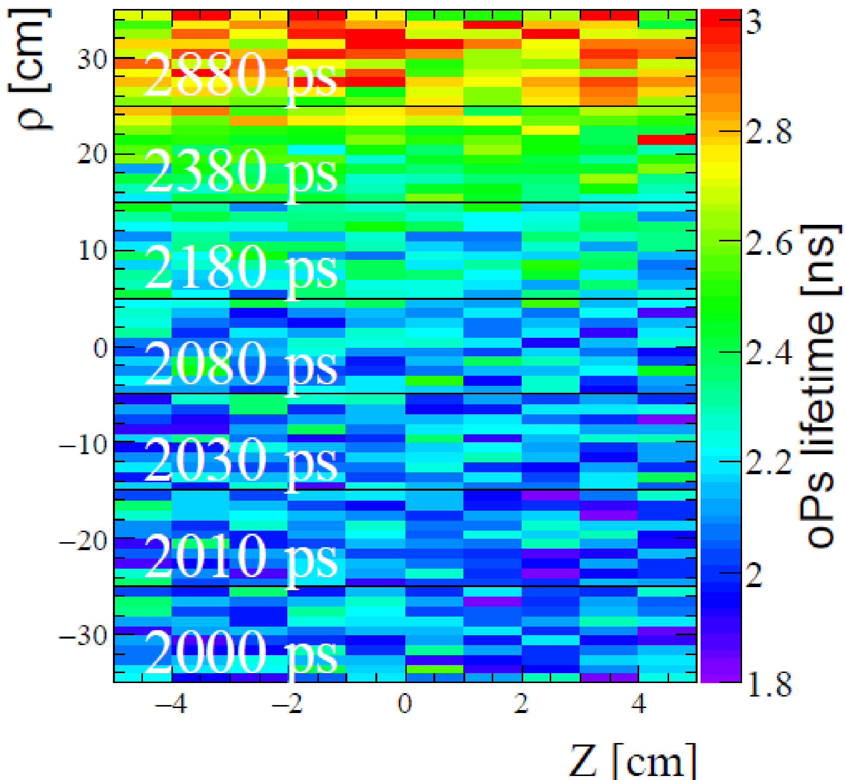

γ1
γ2
γ3
d
z
y
x
Ps kinetic energy [eV]
d [cm]

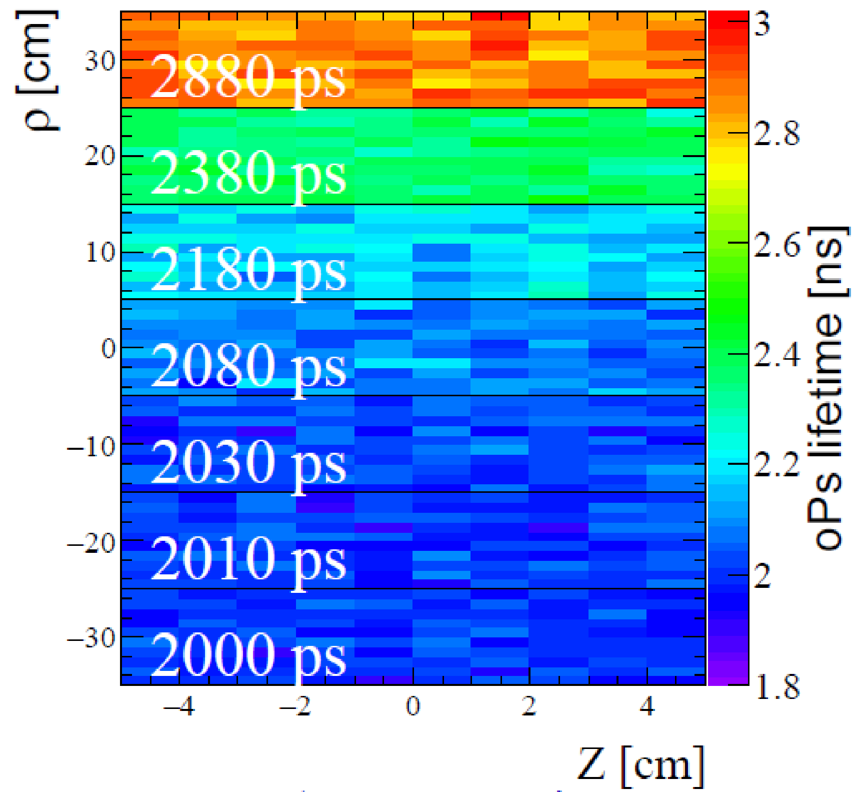




ρ [cm]
30
20
10
0
−10
−20
−30
2880 ps
2380 ps
2180 ps
2080 ps
2030 ps
2010 ps
2000 ps
−4
−2
0
2
4
Z [cm]
3
2.8
2.6
2.4
2.2
2
1.8
oPs lifetime [ns]

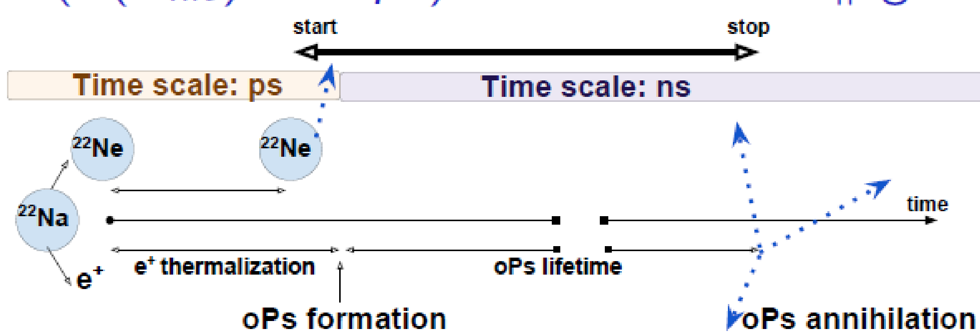
Morphological imaging

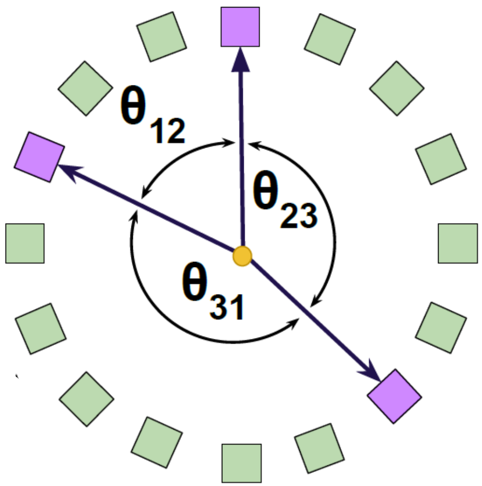




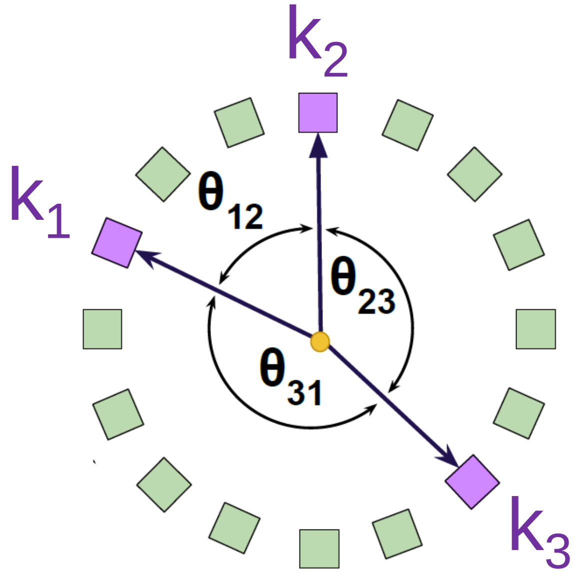
⇑ reconstructed $(\sigma(T_{hit}) = 60ps)$

⇑ generated



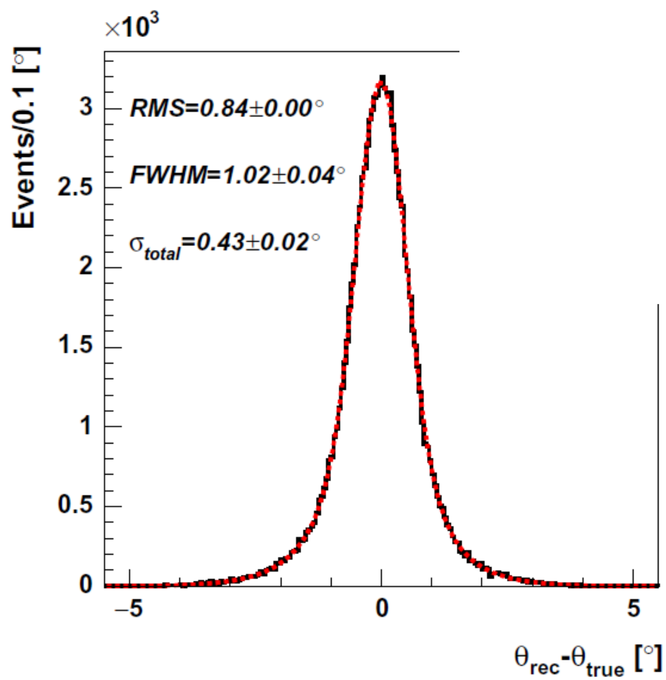


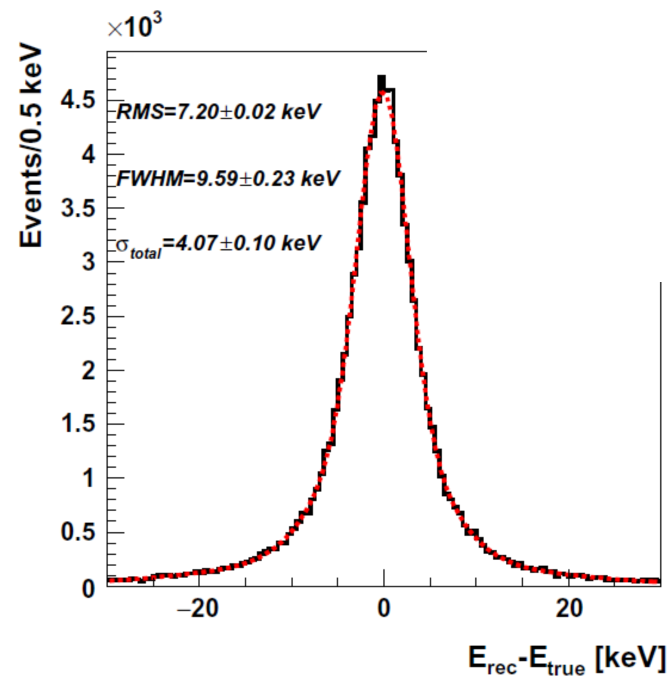
o-Ps → 3γ

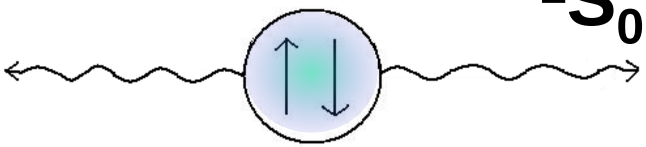


o-Ps → 3γ

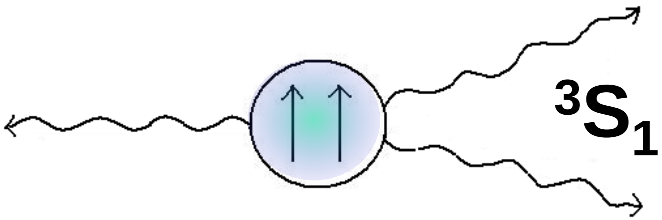
J-PET: D. Kamińska et al., Eur. Phys. J. C76 (2016) 445





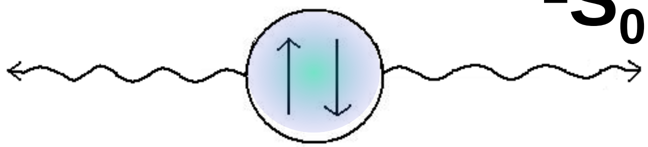


$^1S_0$ **Para-positronium tau(p-Ps) ≈ 125 ps**

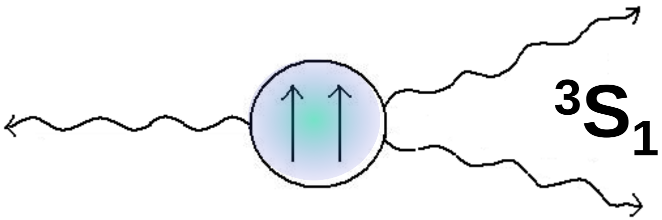


$^3S_1$ **Ortho-positronium tau(o-Ps) ≈ 142 ns**

	$^1S_0$	$^3S_1$
L	0	0



$^1S_0$ Para-positronium tau(p-Ps) ≈ 125 ps



$^3S_1$ Ortho-positronium tau(o-Ps) ≈ 142 ns

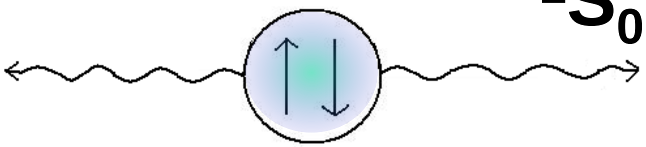
	$^1S_0$	$^3S_1$
L	0	0
S	0	1

S = 0   ↓↑ − ↑↓

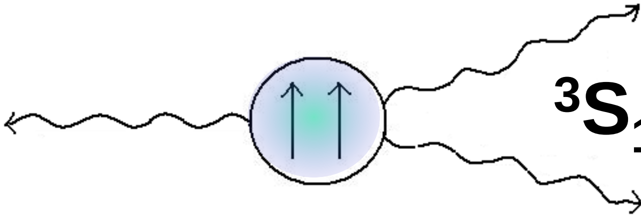
↑↑

S = 1   ↑↑ + ↓↓

↓↓



$^{1}S_{0}$ **Para-positronium tau(p-Ps) ≈ 125 ps**



$^{3}S_{1}$ **Ortho-positronium tau(o-Ps) ≈ 142 ns**

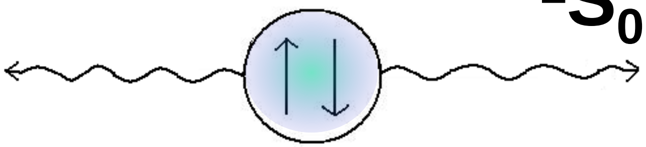
	$^{1}S_{0}$	$^{3}S_{1}$
L	0	0
S	0	1
C	+	-

S = 0 ↓↑ − ↑↓

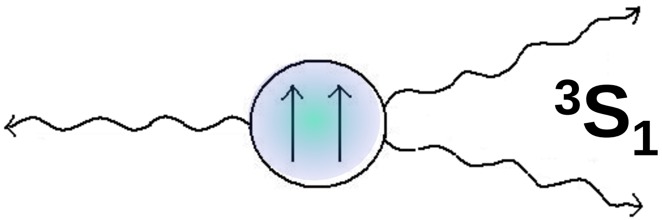
↑↑

S = 1 ↑↑ + ↓↓

↓↓



$^1S_0$ **Para-positronium tau(p-Ps) ≈ 125 ps**



$^3S_1$ **Ortho-positronium tau(o-Ps) ≈ 142 ns**

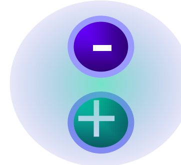
	$^1S_0$	$^3S_1$
L	0	0
S	0	1
C	+	-
L=0 -> P	-	-
CP	-	+

S = 0   ↓↑ − ↑↓

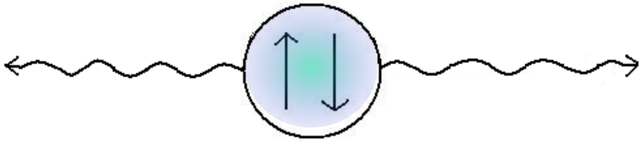
↑↑

S = 1   ↑↑ + ↓↓

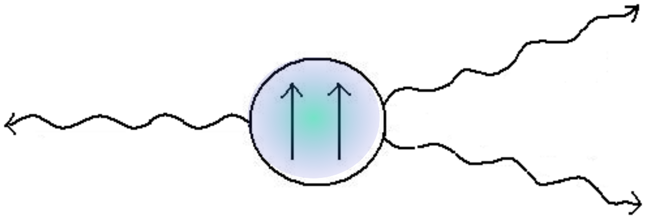
↓↓



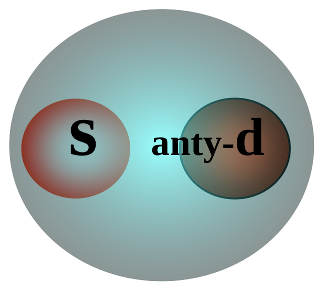
POSITRONIUM



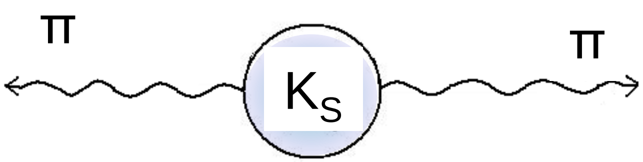
CP = + Para-positronium tau(p-Ps) ≈ 125 ps



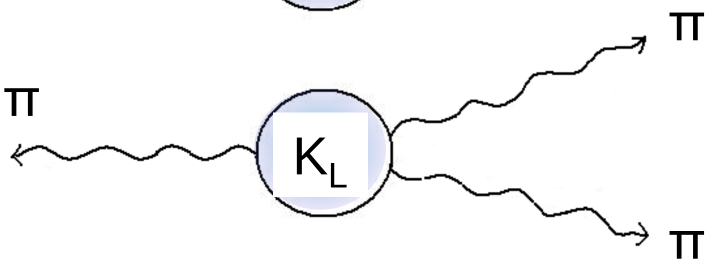
CP = - Ortho-positronium tau(o-Ps) ≈ 142 ns



MESON K



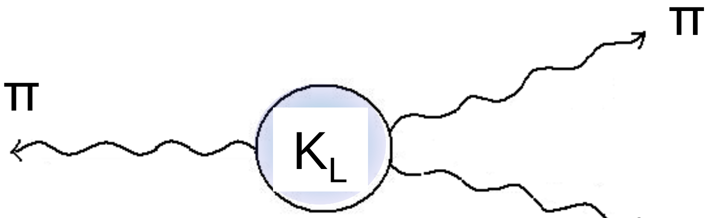
CP ~= + tau(K_S) ≈ 90 ps

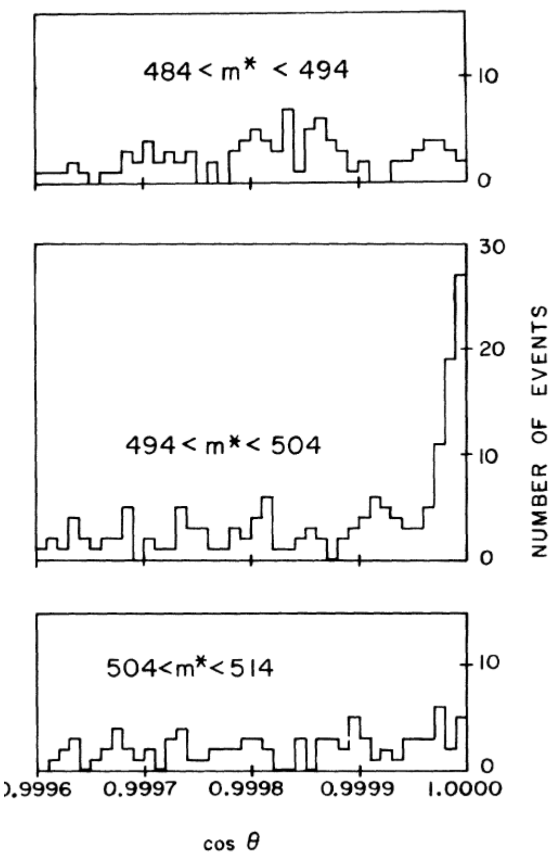


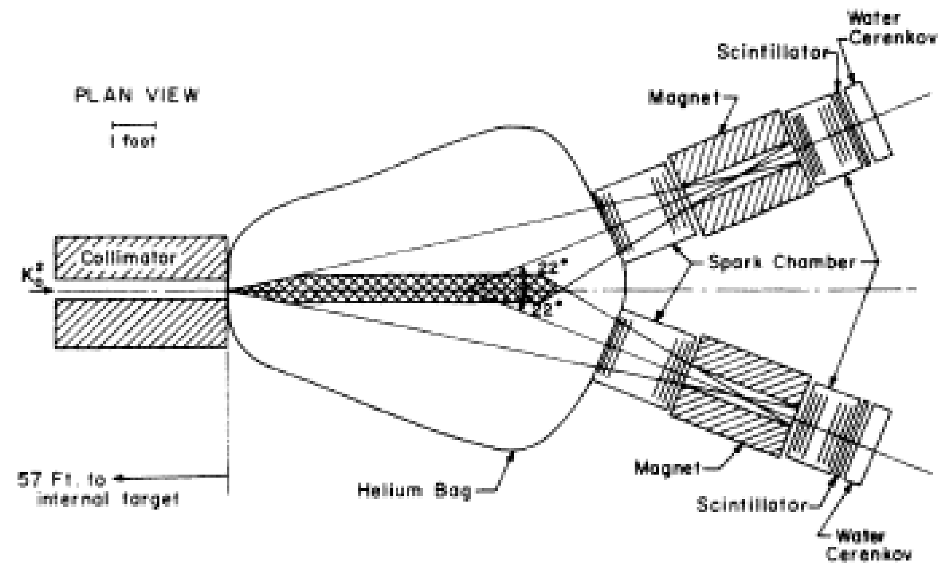
CP ~= - tau(K_L) ≈ 52 ns

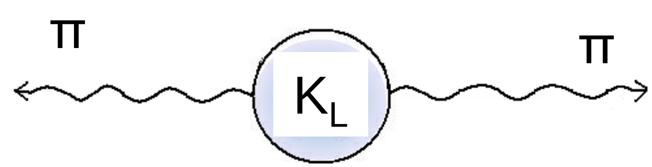
V.L.Fitch, R.Turlay, J.W.Cronin , J.H.Christenson

Phys. Rev. Lett. 13 (1964) 138.









V.L.Fitch, R.Turlay, J.W.Cronin , J.H.Christenson

Phys. Rev. Lett. 13 (1964) 138.

53 years later ....

Breaking of T and CP observed but only for processes involving quarks
So far breaking of these symmetries was not observed for purely leptonic systems.

V.L.Fitch, R.Turlay, J.W.Cronin , J.H.Christenson

Phys. Rev. Lett. 13 (1964) 138.

53 years later ....

Breaking of T and CP observed but only for processes involving quarks
So far breaking of these symmetries was not observed for purely leptonic systems.

$$\nu_\mu \to \nu_e \qquad \bar{\nu}_\mu \to \bar{\nu}_e$$

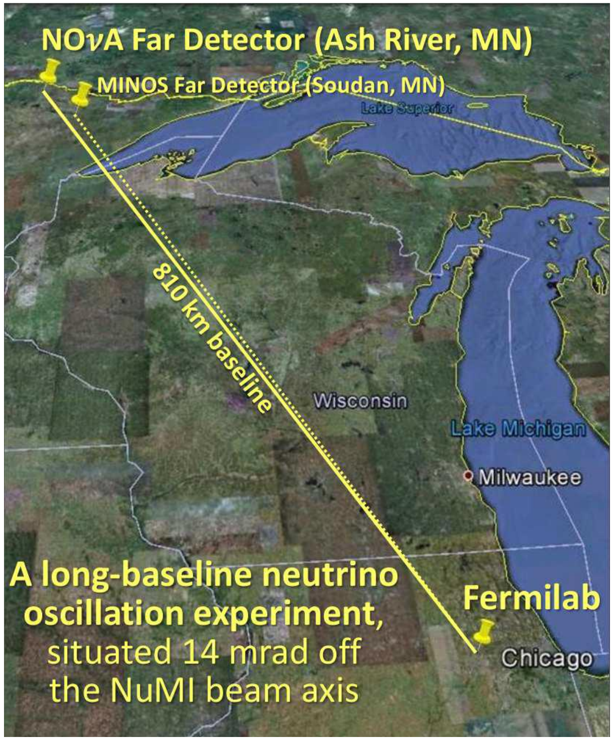
V.L.Fitch, R.Turlay, J.W.Cronin , J.H.Christenson

Phys. Rev. Lett. 13 (1964) 138.

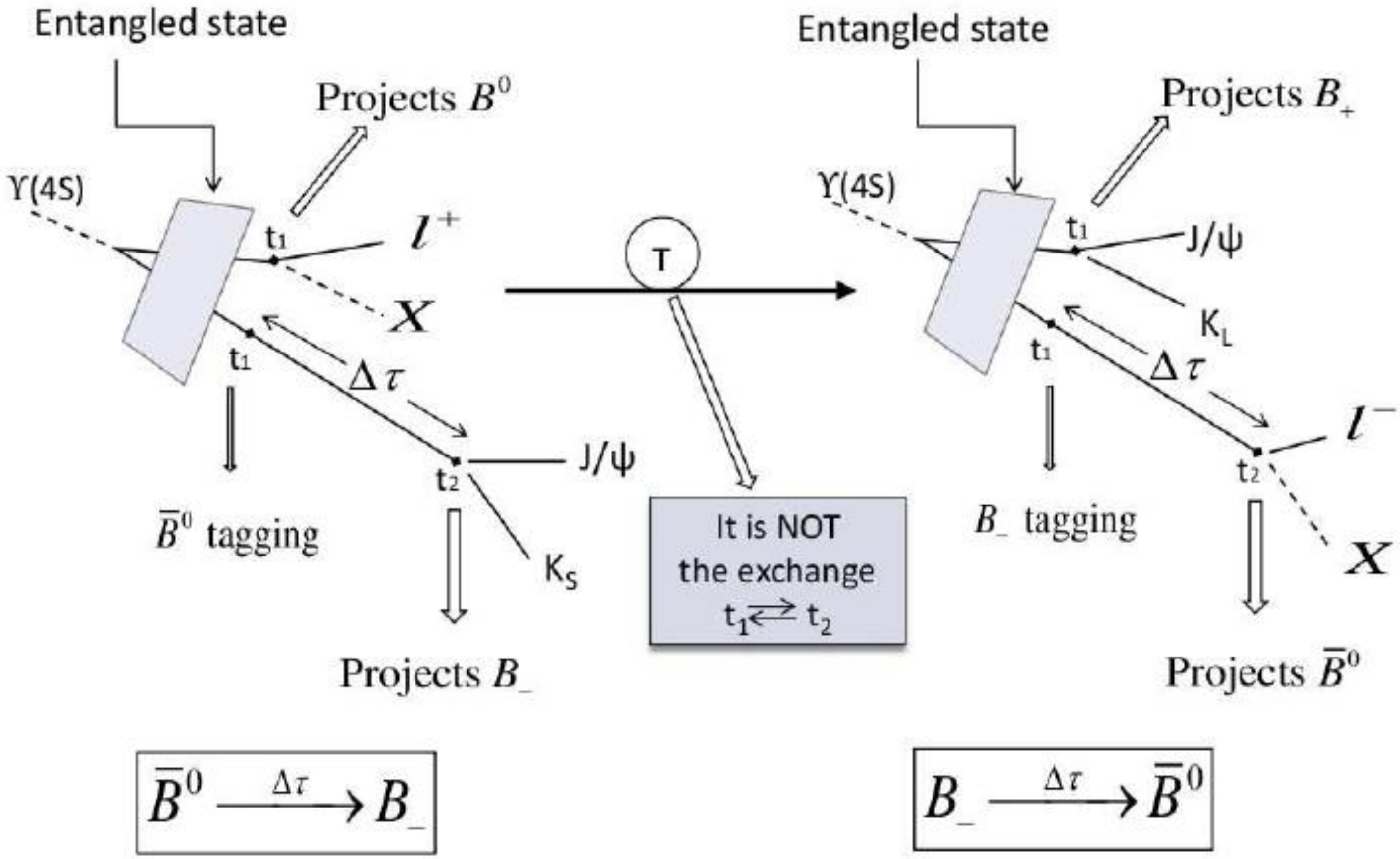
53 years later ....

Breaking of T and CP observed but only for processes involving quarks
So far breaking of these symmetries was not observed for purely leptonic systems.

$$\nu_\mu \rightarrow \nu_e \qquad \bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

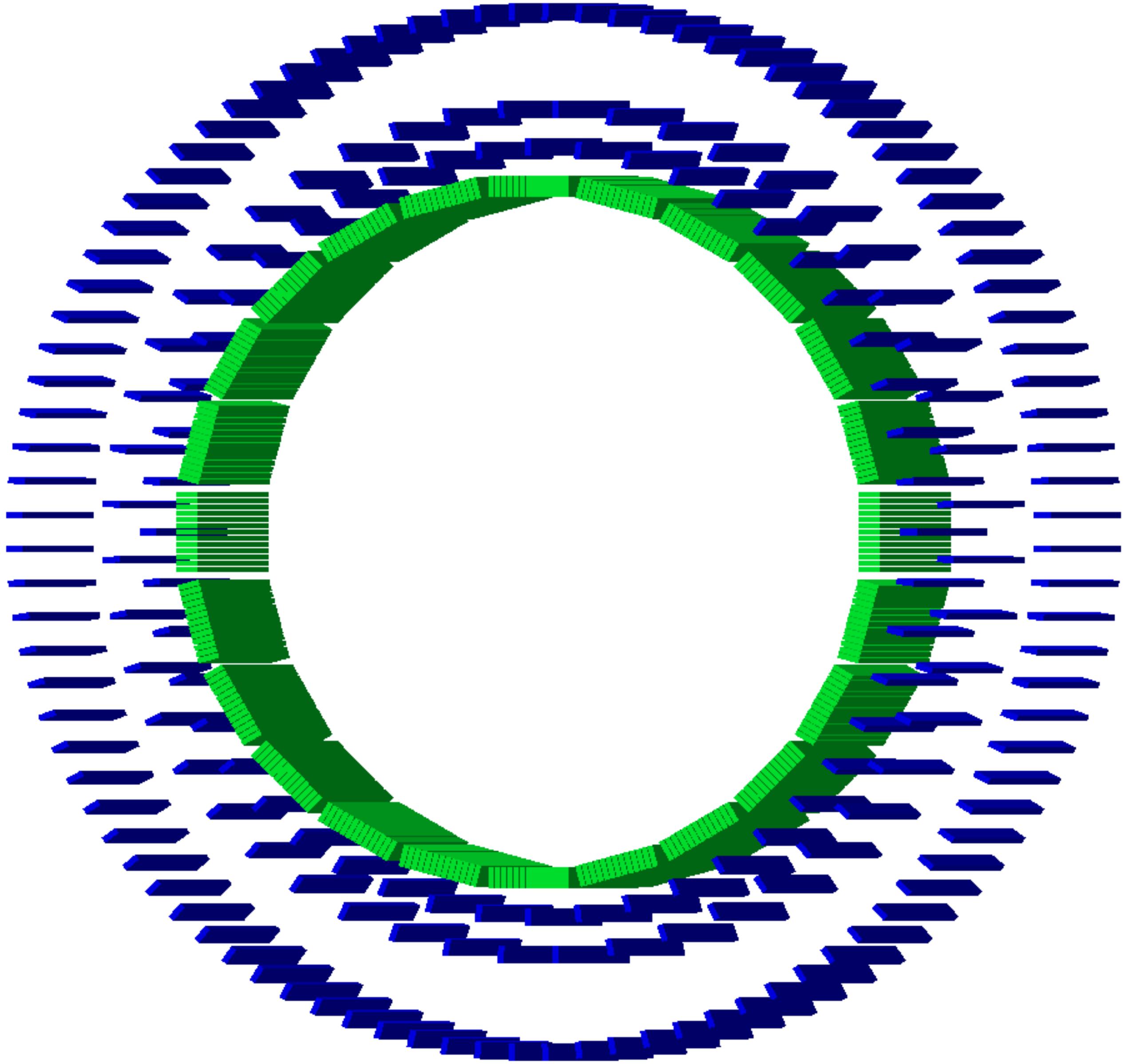


eksperyment BABAR



To nie są procesy powiązane symetrią CP !

J. Barnabeu et al., JHEP08 (2012) 064



Discrete symmetries

P reflection in space (x,y,z $\rightarrow$ -x,-y-z)

C charge conjugation (particles $\rightarrow$ anti-particle)

T reversal in time (A $\rightarrow$ B => B $\rightarrow$ A)

CP

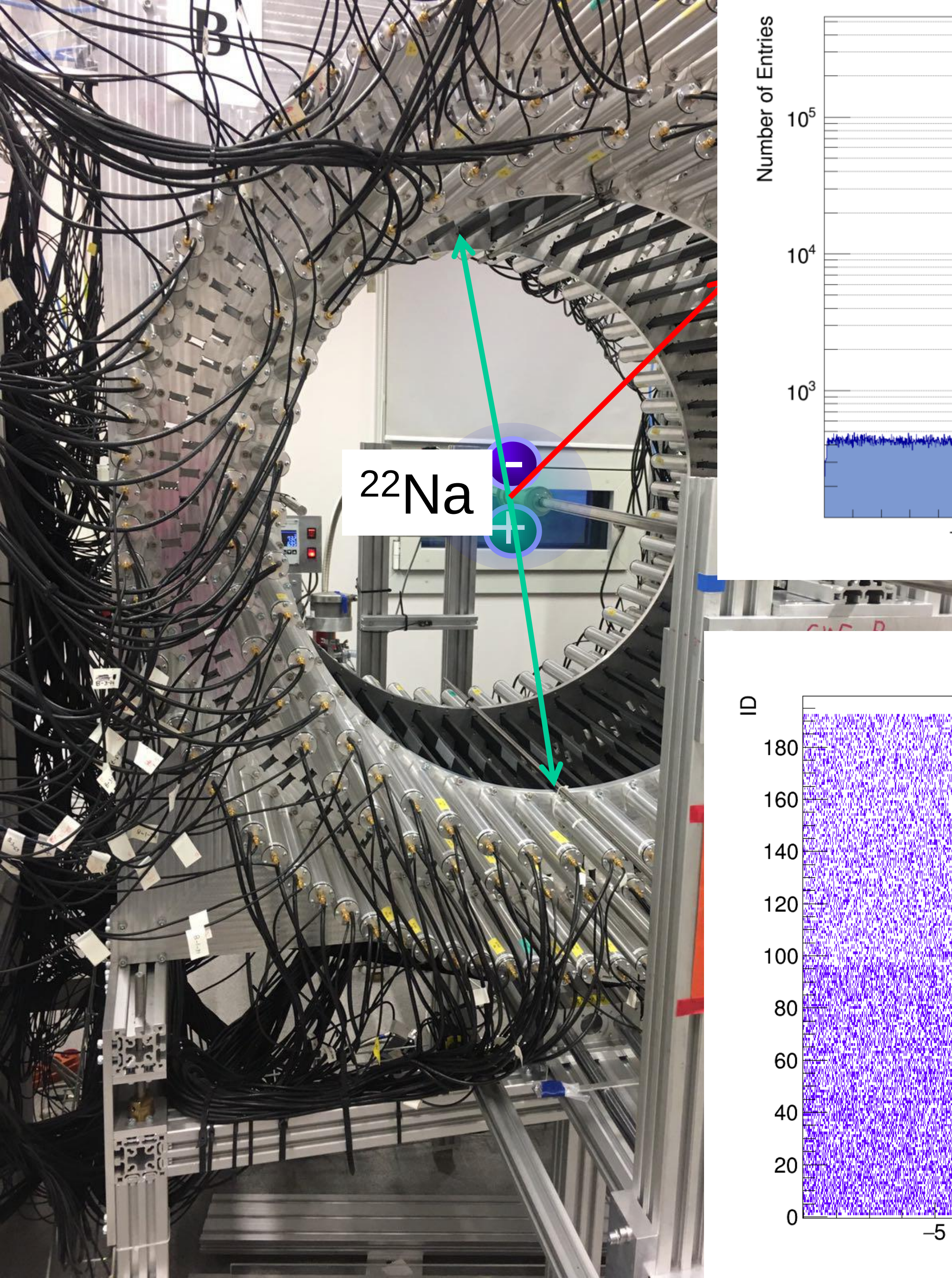
CPT

Lorentz and unitarity and locality => CPT

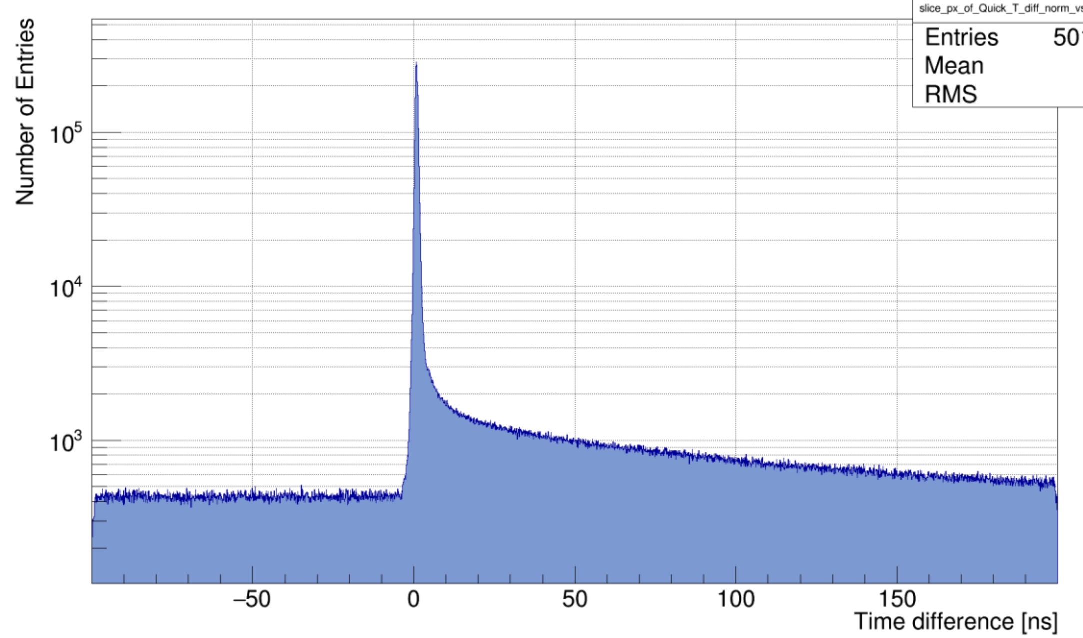
G. Lüders, Ann. Phys. 2 (1957) 1.; Ann. Phys. 281 (2000) 1004 „Proof of the TCP theorem"

~CPT => ~Lorentz

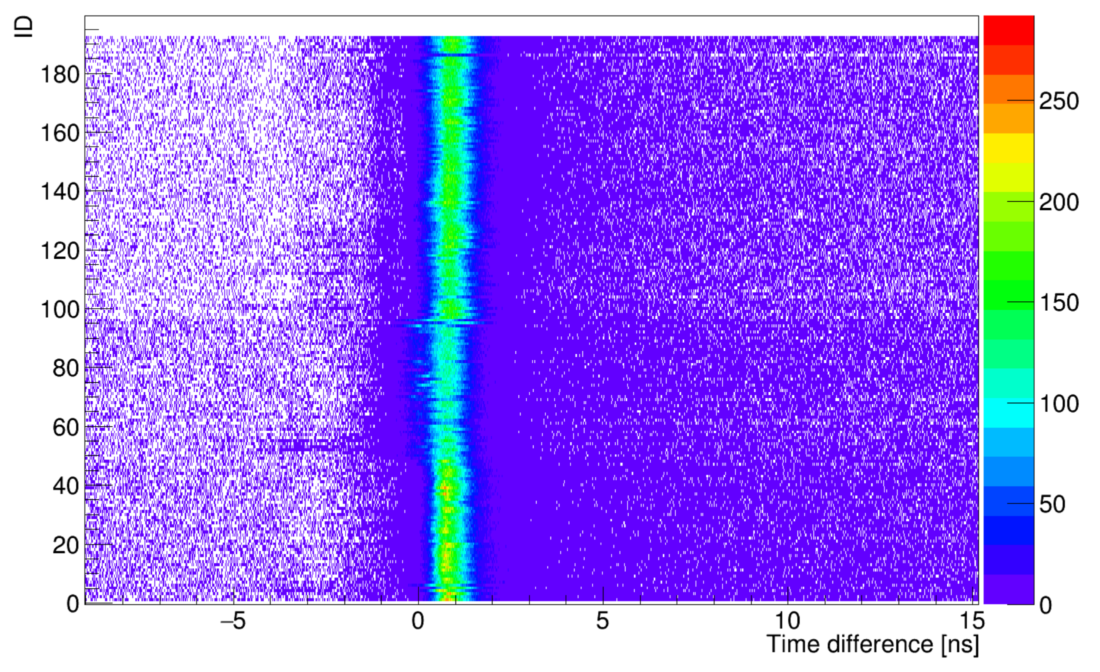
O. W. Greenberg Phys. Rev. Lett. 89 (2002) 231602.



22Na



slice_px_of_Quick_T_diff_norm_v
Entries 50
Mean
RMS
Number of Entries
10^5
10^4
10^3
−50
0
50
100
150
Time difference [ns]



ID
180
160
140
120
100
80
60
40
20
0
−5
0
5
10
15
Time difference [ns]
250
200
150
100
50
0