Search for the exotic matter at low energies

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Abstract: We will review

- **the search for the hypothetical dark matter boson**
- **the search for the new kind of nuclear matter in the form of the mesic-nuclei and dibaryons**
- **the proposal for studies of the violations of discrete symmetries in the purely leptonic systems**

- **WASA at COSY, KLOE at DAFNE, J-PET at Cracow**

Seminar for Theory of Elementary Interactions
University of Warsaw, December 15th 2014

Search for the exotic matter at low energies

- dark photon
- mesic-nuclei ; dibaryons ...
- discrete symmetries

Princess Elisabeth of Bohemia writes on 10.vi.1643:

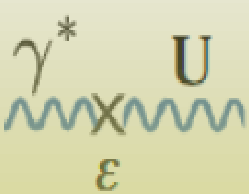
„…I don't see how the idea that you used to have about weight can guide us to the idea we need in order to judge **how the (nonextended and immaterial) soul can move the body"**

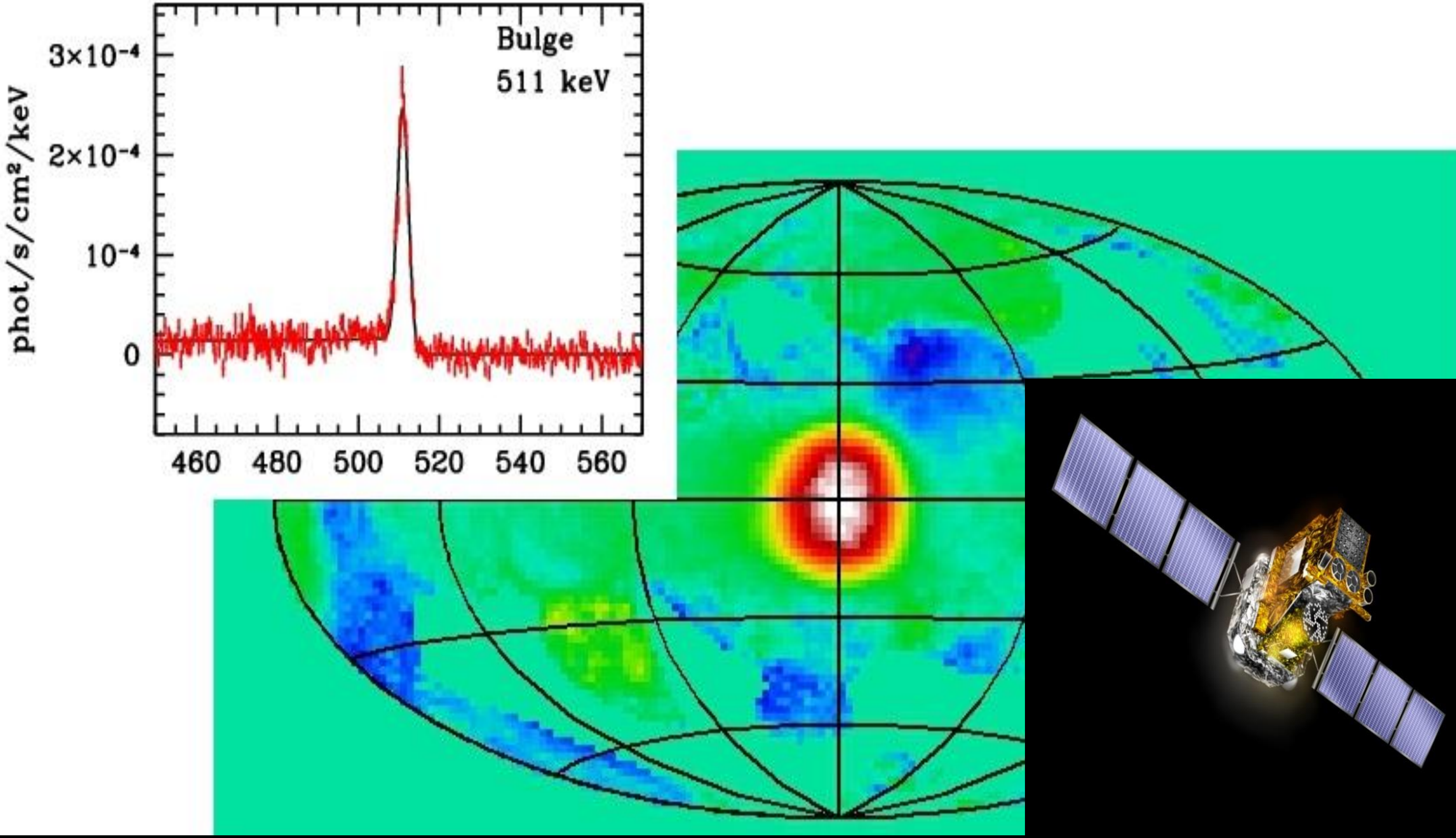
Descartes writes on 28.vi.1643:

„…I ought to have made clear that although one may wish to think of the soul as material (…), that wouldn't stop one from realizing that the soul is separable from the body. I think that those cover everything that you asked me to do in your letter."

Particle physics four centuries later:
How the „non-SM dark matter" can move the „SM matter" ?:

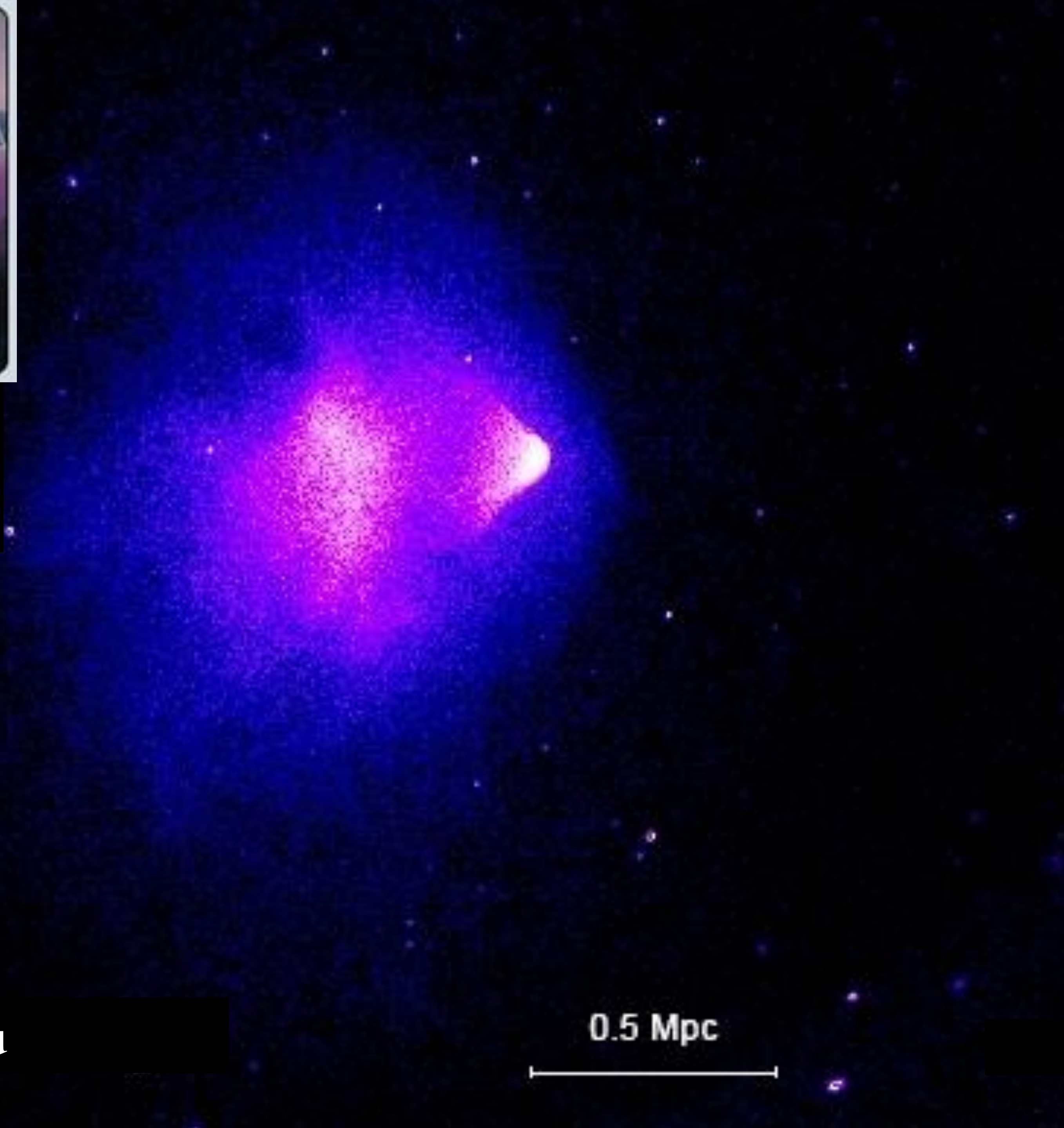
$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4}F_{\mu\nu}^{dark}F^{\mu\nu}_{dark} - \frac{\epsilon}{2}F_{\mu\nu}^{dark}F^{\mu\nu} + |D^{\mu}\phi|^2 - V(\phi)$$





INTEGRAL SATELLITE

CHANDRA
SATELLITE



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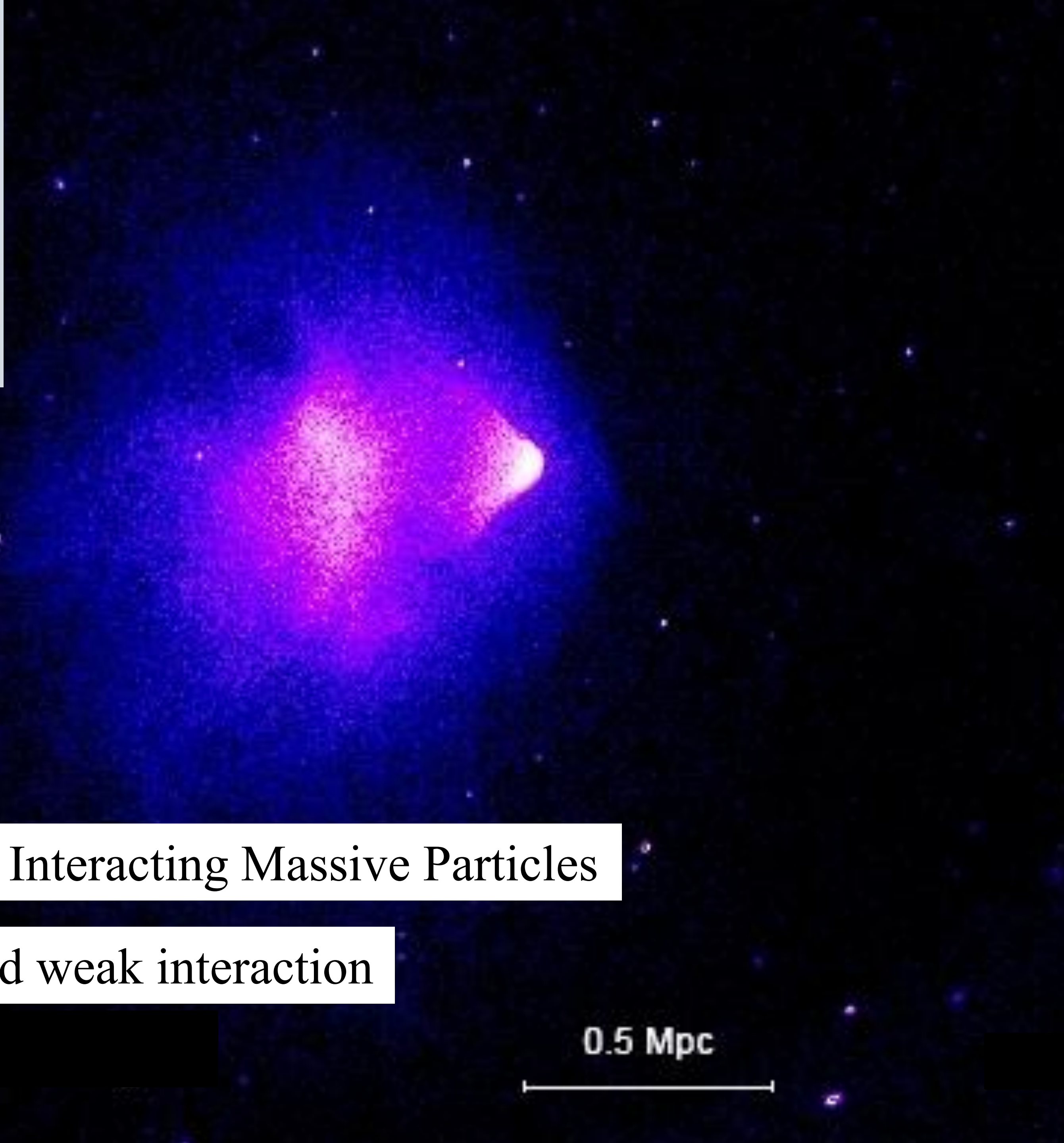

WIMP Weakly Interacting Massive Particles

gravitational and weak interaction

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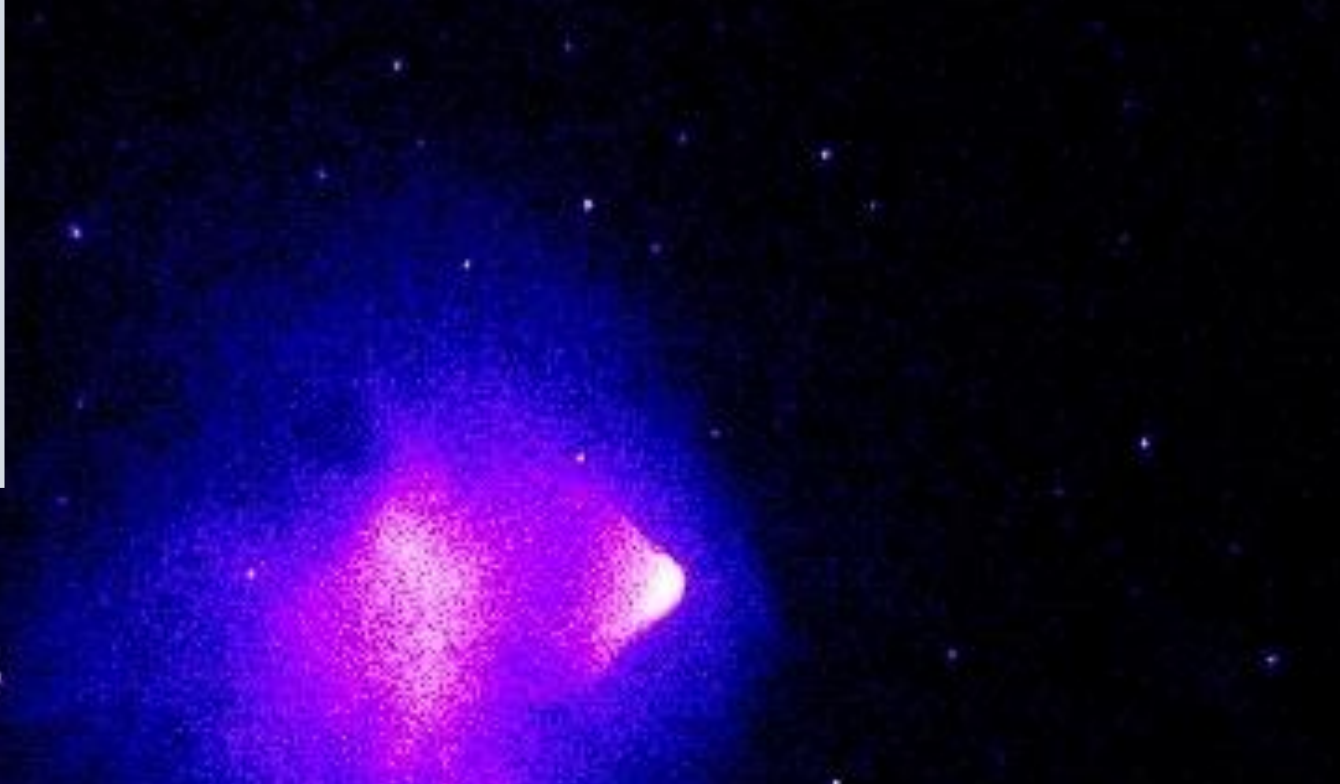
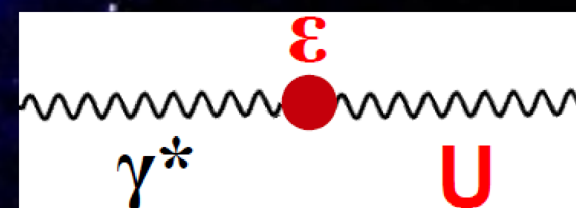


If the dark matter is utterly different from SM matter than from the known interactions it will feel only gravitation



$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4} F^{dark}_{\mu\nu} F^{\mu\nu}_{dark} - \frac{\epsilon}{2} F^{dark}_{\mu\nu} F^{\mu\nu} + |D^\mu \phi|^2 - V(\phi)$$

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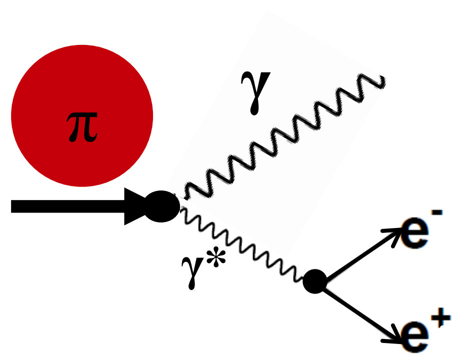
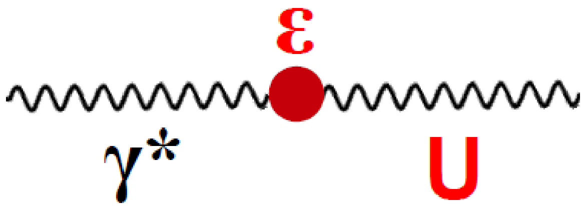
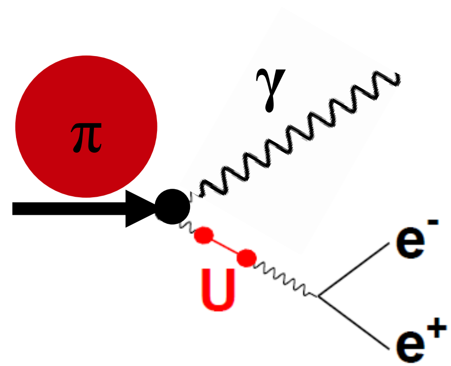
0.5 Mpc



π
γ
γ*
e-
e+


ε
γ*
U


π
γ
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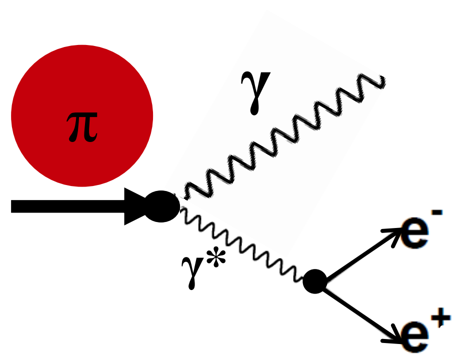
π
γ
γ*
e-
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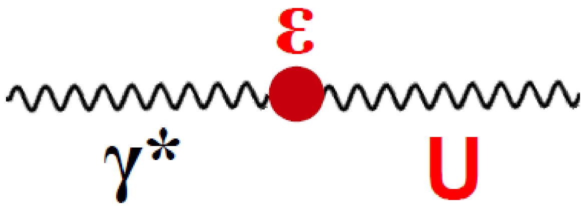
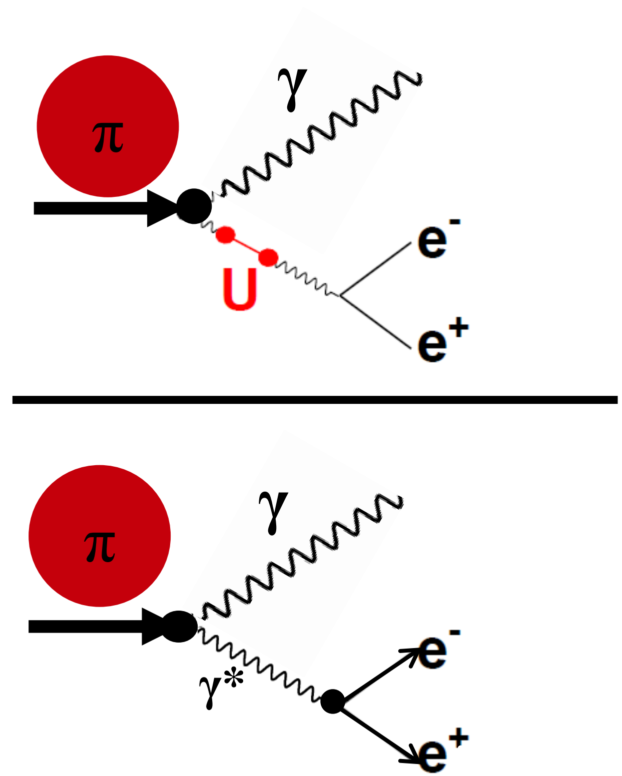




=~ ... ε^2 ...

WASA-at-COSY

$10^9\ \eta$ and $10^{11}\ \pi^0$

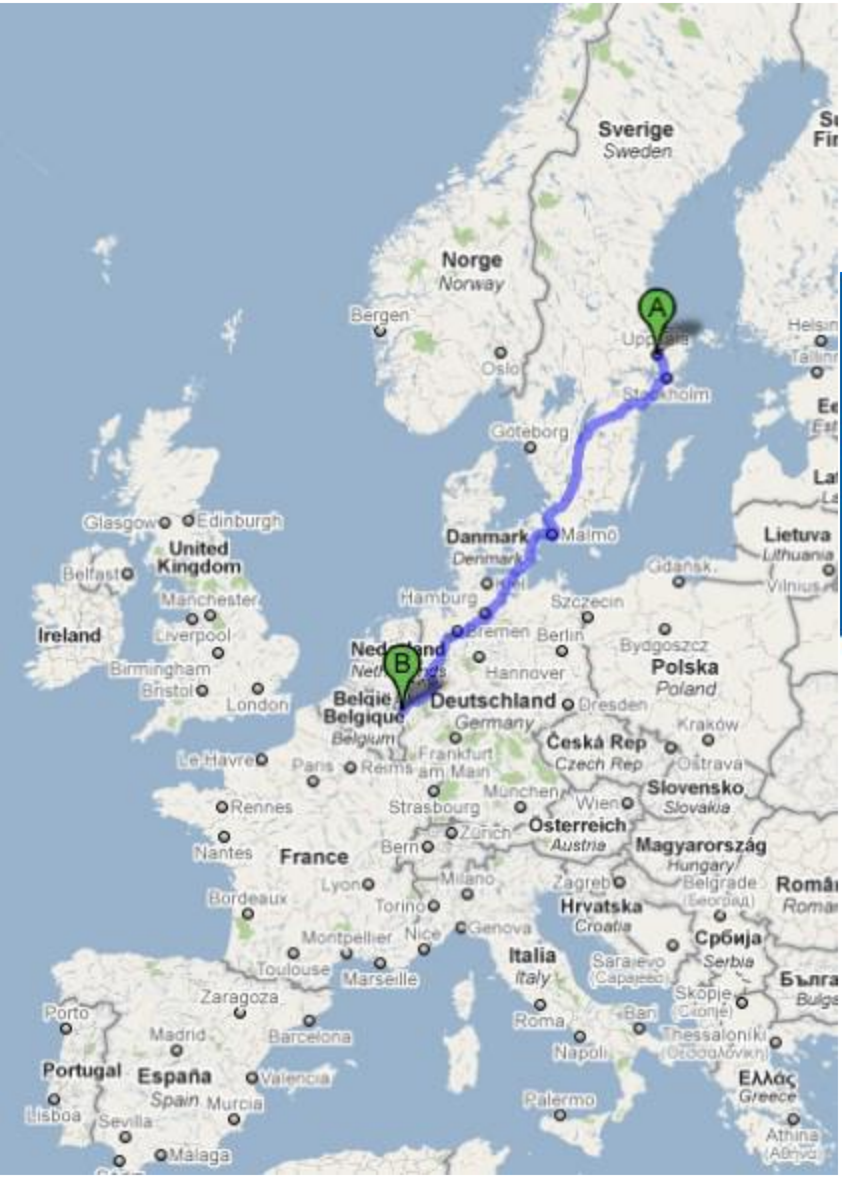
mesons on discs

this presentation is based on

$6 \cdot 10^7 \eta$ and $10^{10}\ \pi^0$

WASA

A WARSHIP built for the war with Poland
which sank in 1628 in the middle of Stockholm harbour
after sailing barely 1300 meters



Sverige
Sweden
Norge
Norway
Bergen
Oslo
Stockholm
Göteborg
Danmark
Denmark
Malmö
Glasgow
Edinburgh
United Kingdom
Belfast
Manchester
Liverpool
Ireland
Birmingham
Bristol
London
België
Belgique
Belgium
Hamburg
Bremen
Berlin
Szczecin
Gdańsk
Hannover
Deutschland
Germany
Dresden
Polska
Poland
Bydgoszcz
Lietuva
Lithuania
Vilnius
Kraków
Česká Rep
Czech Rep
Ostrava
Slovensko
Slovakia
Wien
Österreich
Austria
Magyarország
Hungary
Le Havre
Paris
Reims
Frankfurt am Main
München
Strasbourg
Zürich
Bern
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France
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Hrvatska
Croatia
Belgrade
Србија
Serbia
Italia
Italy
Sarajevo
Roma
Napoli
Bari
Skopje
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Zaragoza
Barcelona
Madrid
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Málaga
Palermo
Ελλάς
Greece
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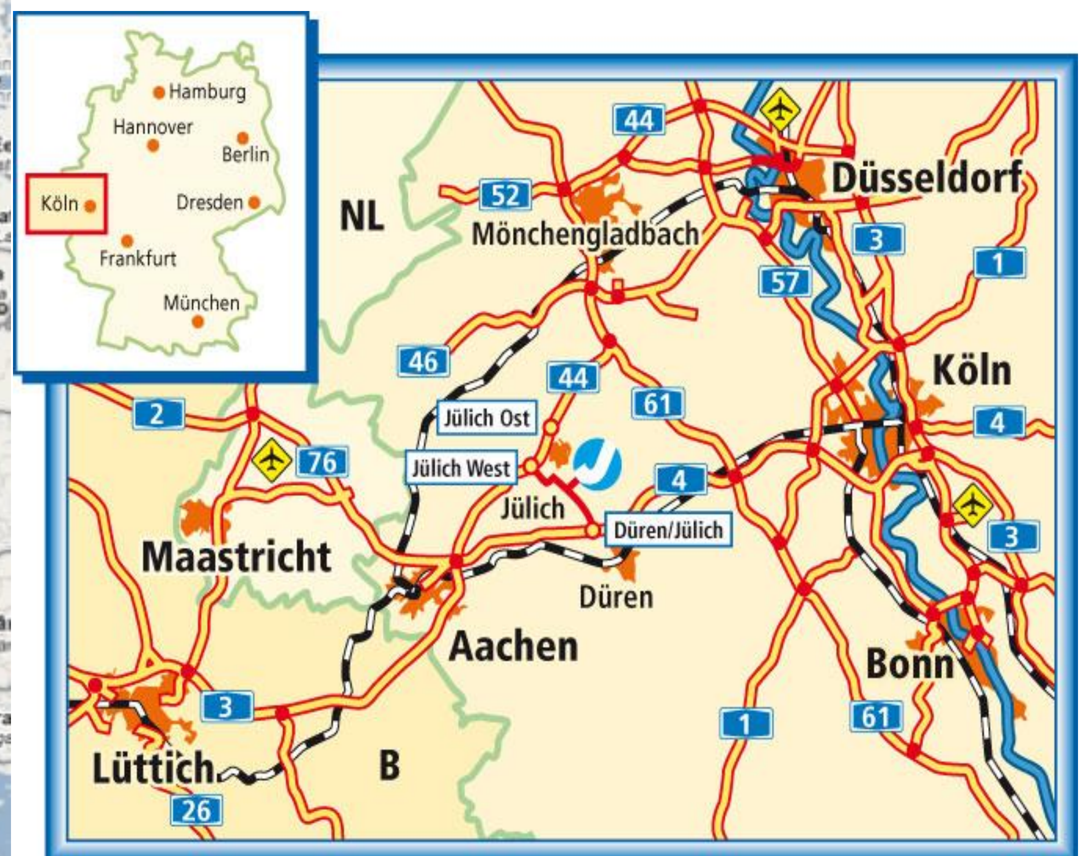

Hamburg
Hannover
Berlin
Köln
Dresden
Frankfurt
München
NL
Mönchengladbach
Düsseldorf
Köln
Jülich Ost
Jülich West
Jülich
Düren/Jülich
Düren
Maastricht
Aachen
Bonn
Lüttich
B
44
52
3
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57
46
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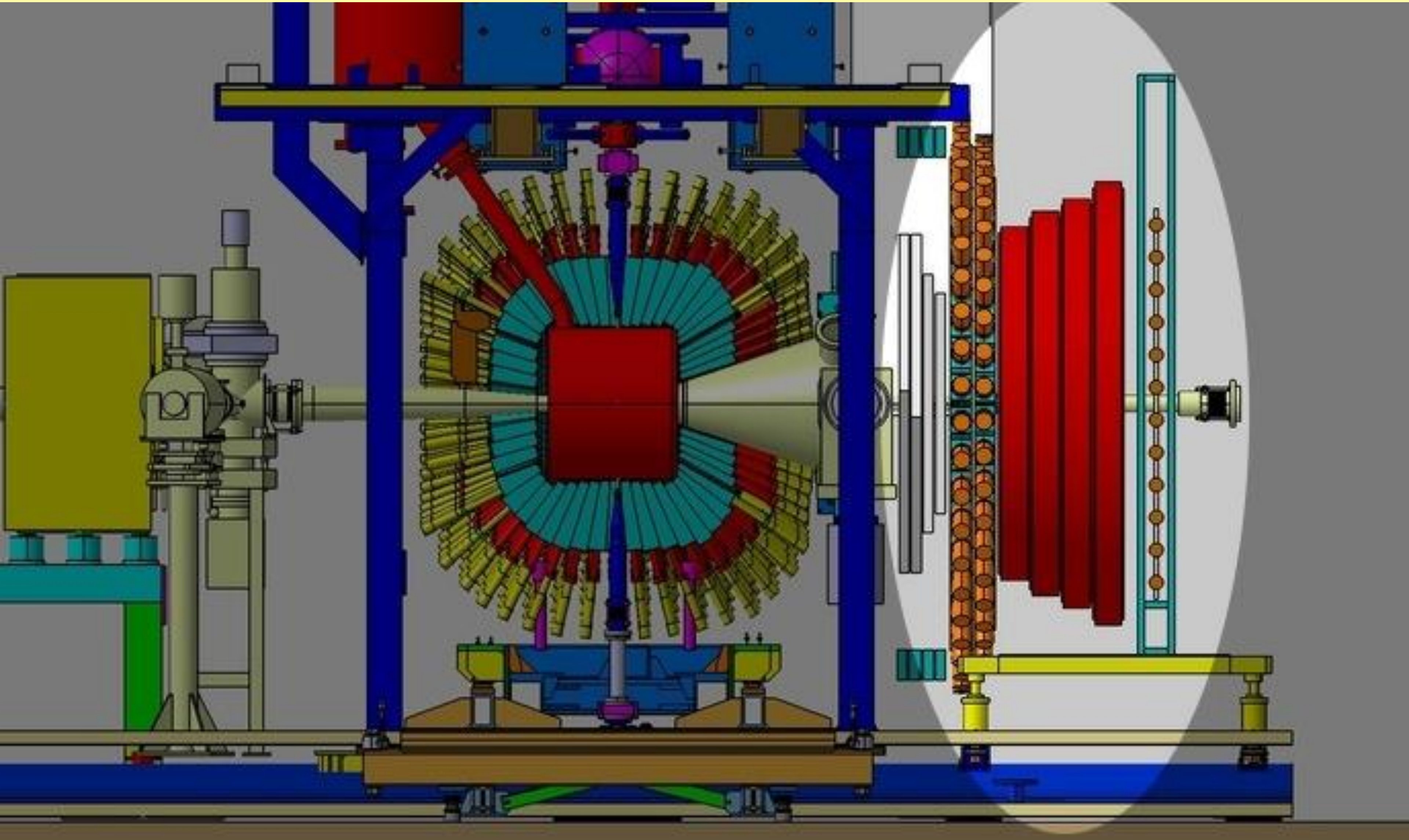
61
26

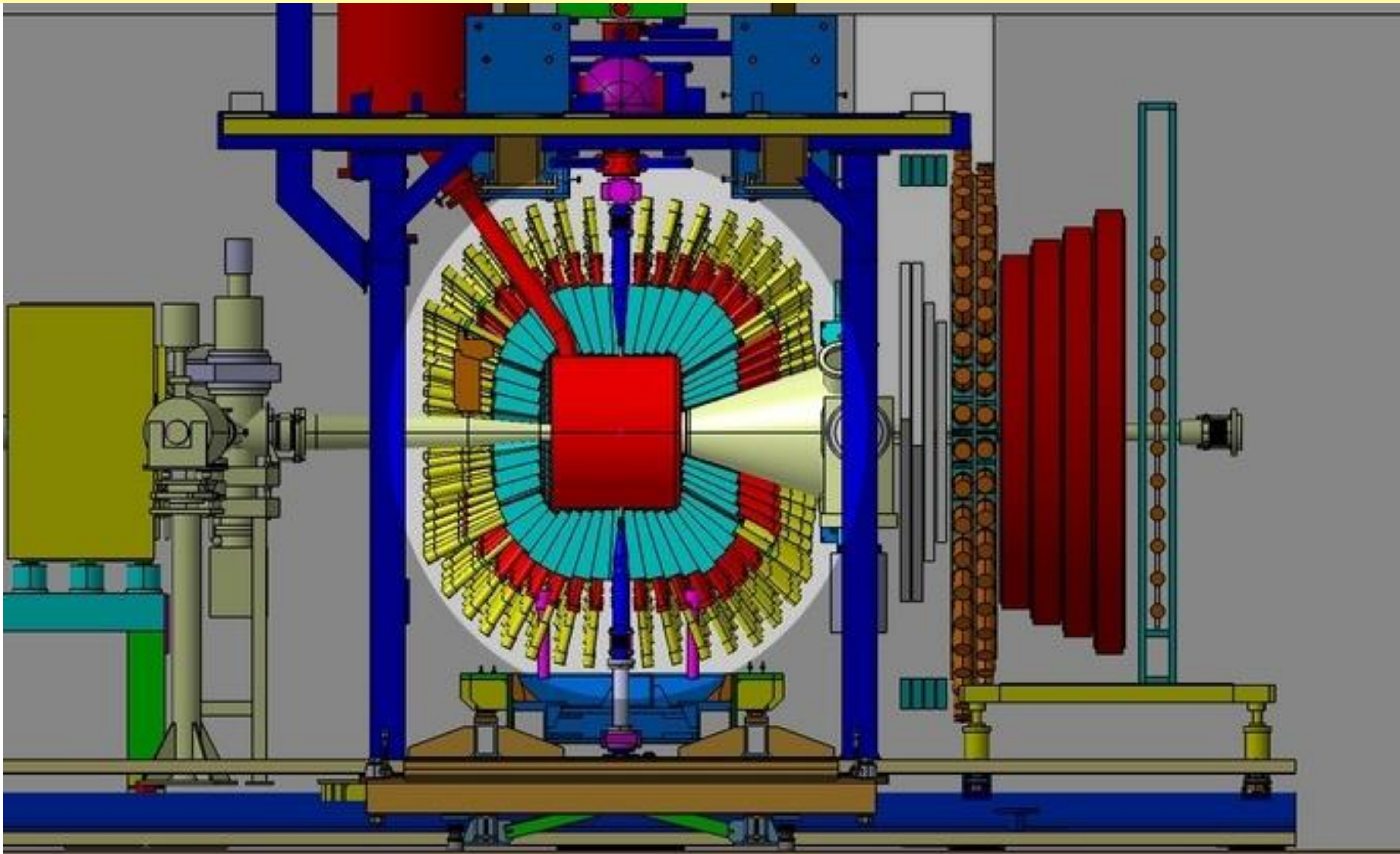
WASA-at-COSY

pp $\rightarrow$ pp η pd $\rightarrow$ ^{3}He η



WASA-at-COSY

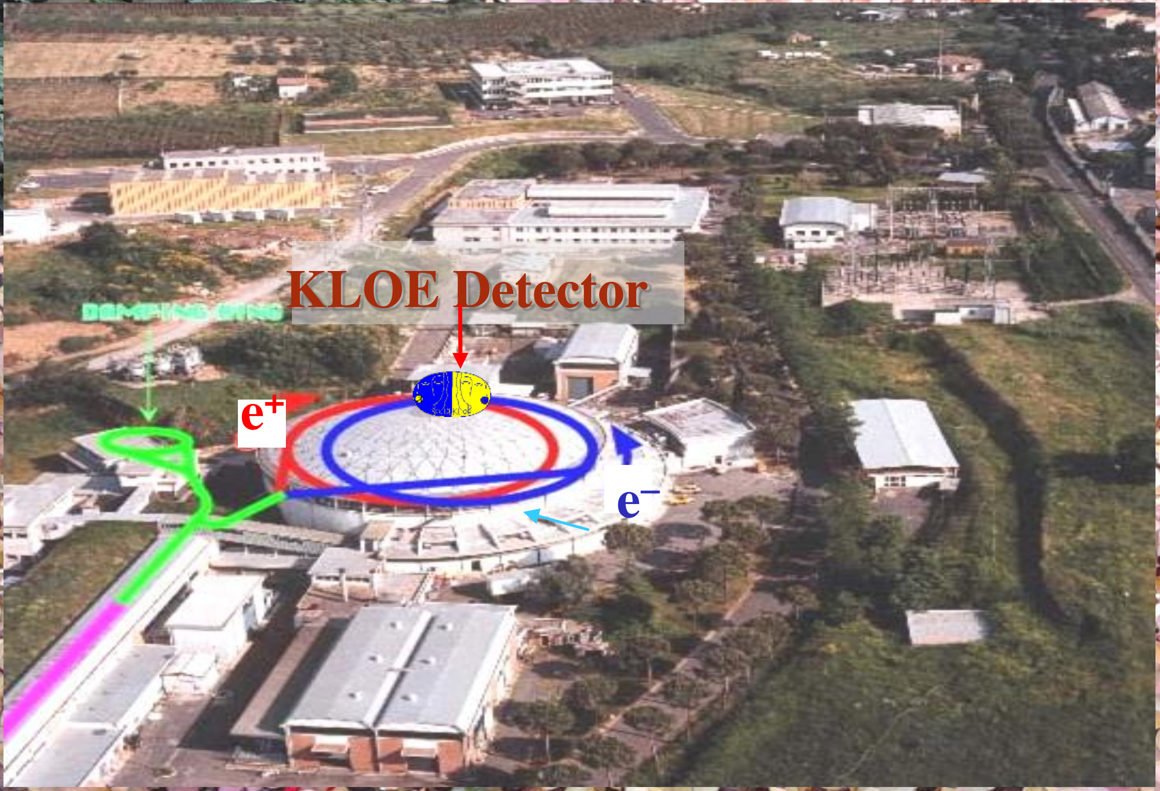
pp → pp η **pd → ^{3}He η**



WASA-at-COSY

pp → pp η **pd → ^{3}He η**

DAΦNE e^+e^- collider Frascati (Rome)

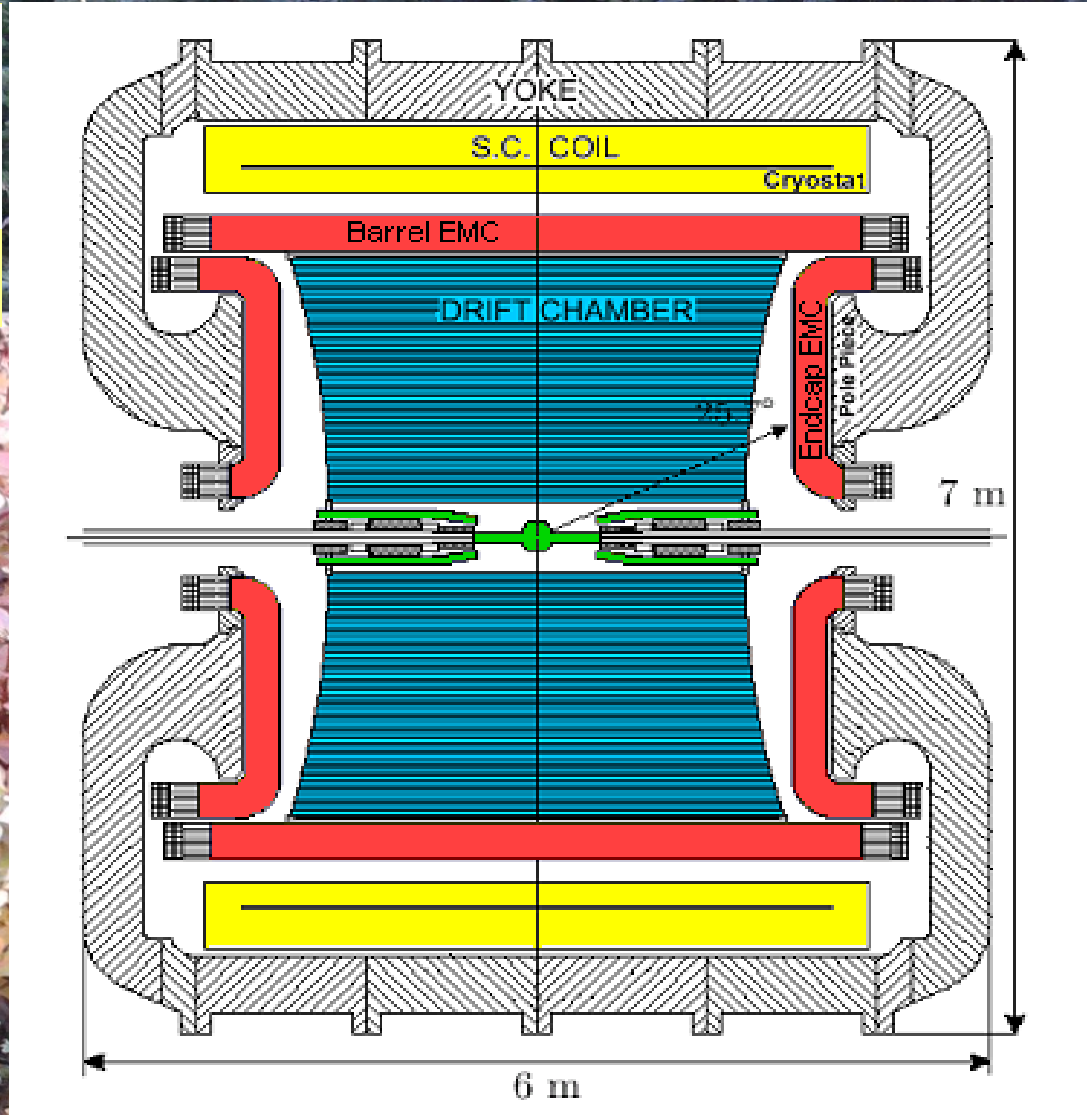


BR's for selected ϕ decays	
K^+K^-	49.1%
K_SK_L	34.1%
$\rho\pi + \pi^+\pi^-\pi^0$	15.5%
$\eta\,\gamma$	1.3 %
$\eta'\,\gamma$	0.006%

- $e^+e^- \to \phi \quad \sqrt{s} \sim m_\phi = 1019.4$ MeV

KLOE

K LOng Experiment



WASA-at-COSY

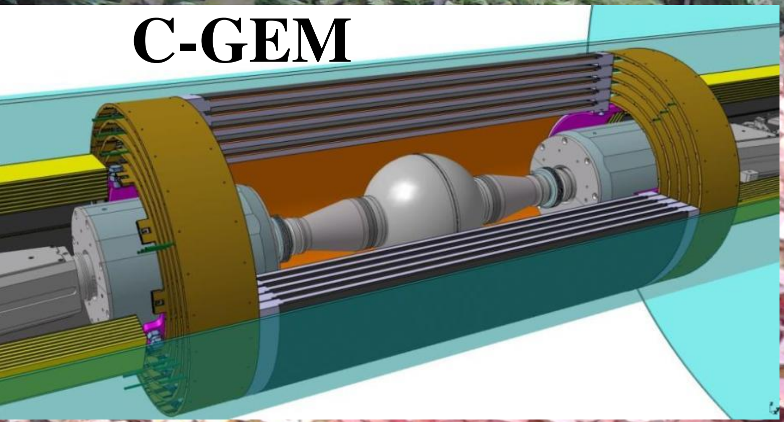
$10^9\ \eta$ and $10^{11}\ \pi^0$

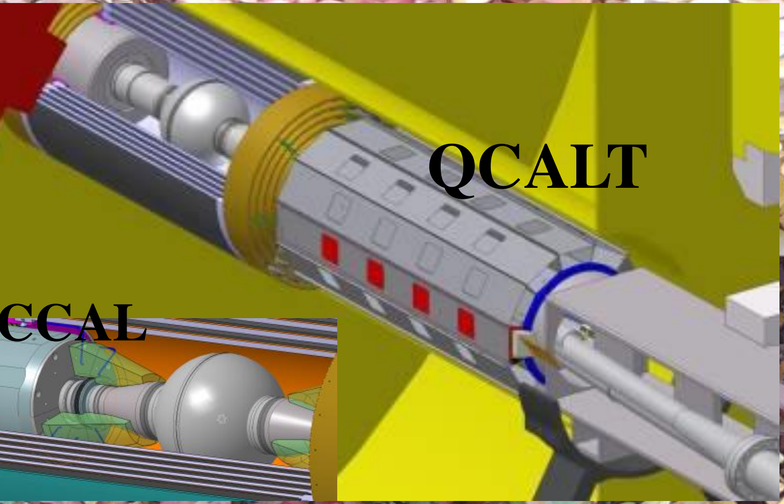
KLOE

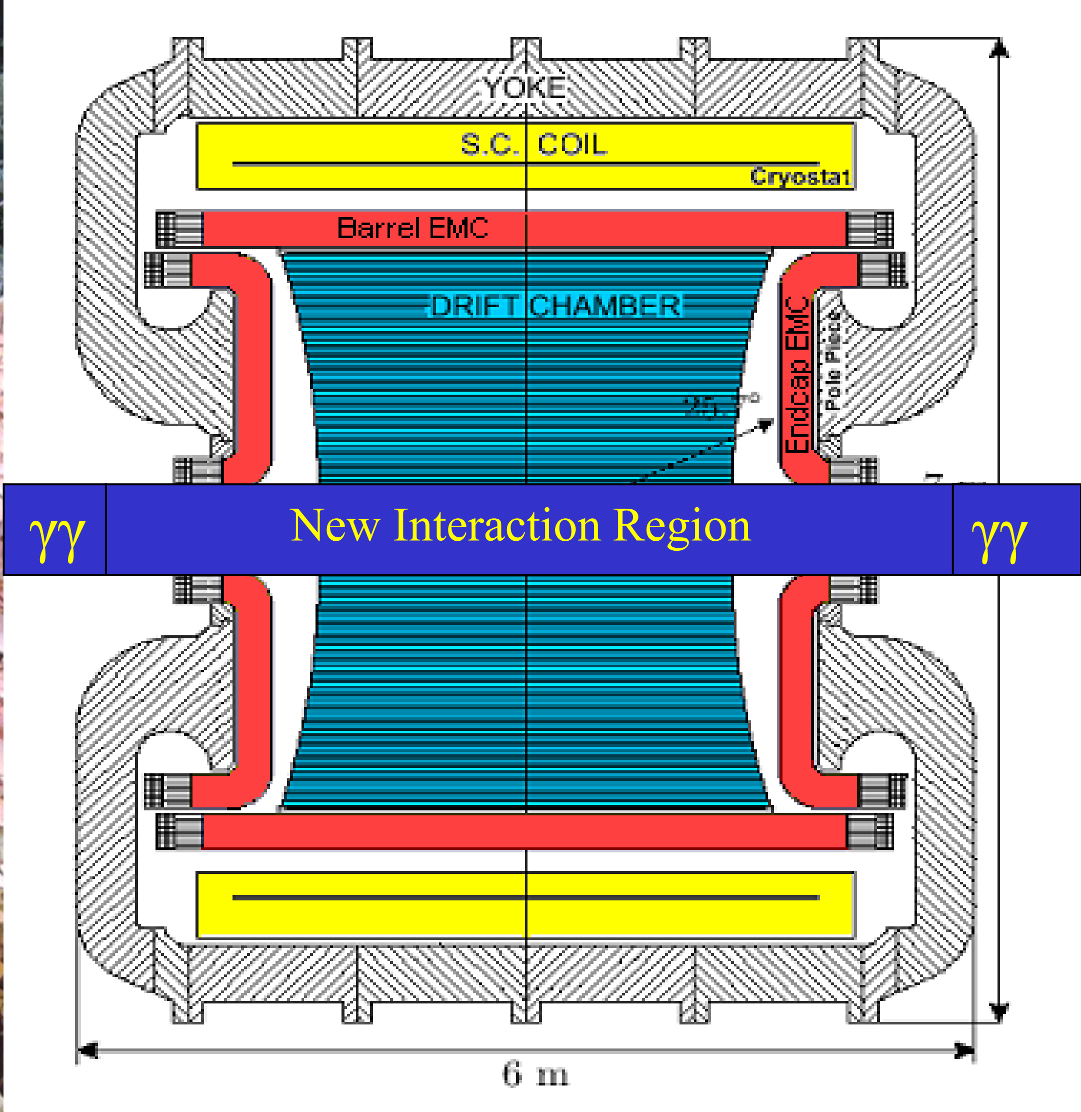
completed data taking with 2.5 fb^{-1}

$\sim 8 \cdot 10^9\ \phi\ ,\ \sim 10^8\ \eta\ ,\ \sim 5 \cdot 10^5\ \eta'$

KLOE-2







Magnetic field 0.52 Tesla

KLOE –> KLOE-2

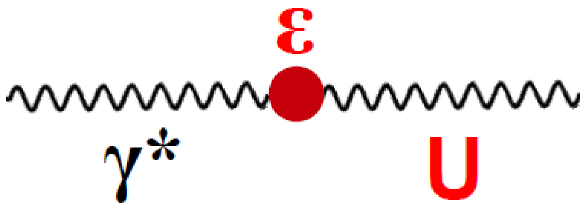
2.5 fb^{-1} –> ~10 fb^{-1} (expected)

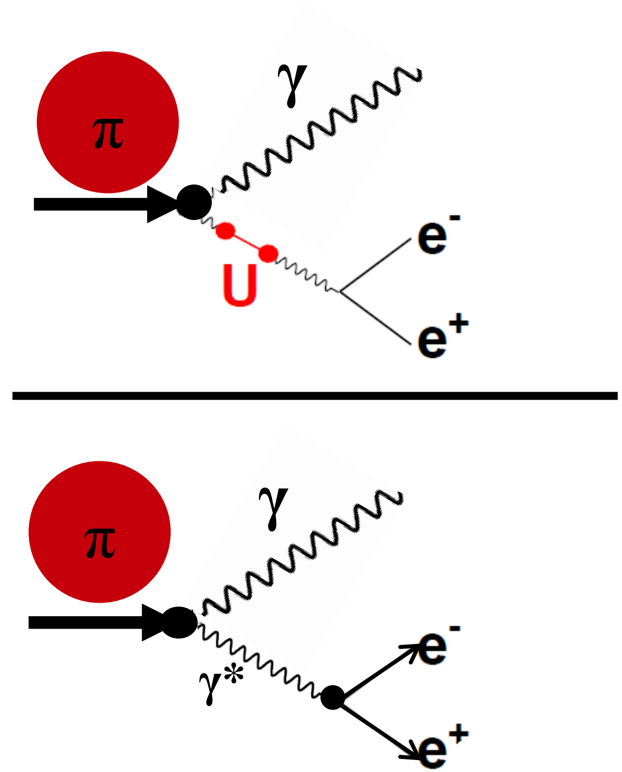
$$\sim 8 \cdot 10^{9}\ \phi \quad \text{–>} \quad \sim 3 \cdot 10^{10}\ \phi$$

…

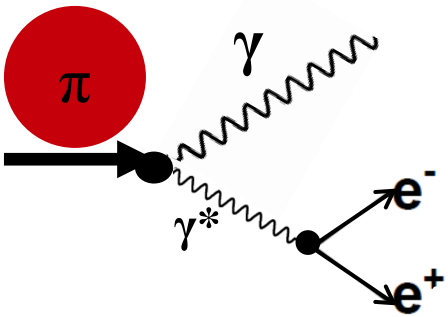
Detector upgrade completed

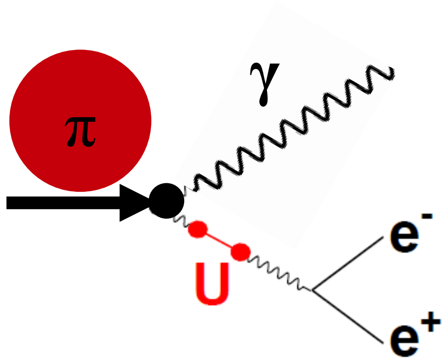
Experimental camaign in progress ...





=~ … ε^2 …


π
γ
γ*
e-
e+


π
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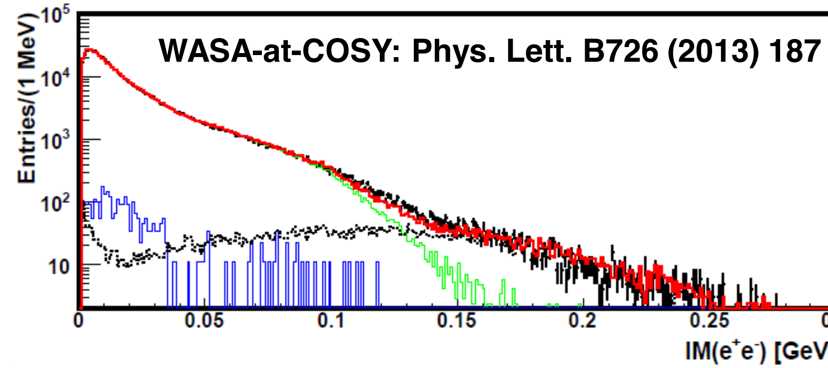
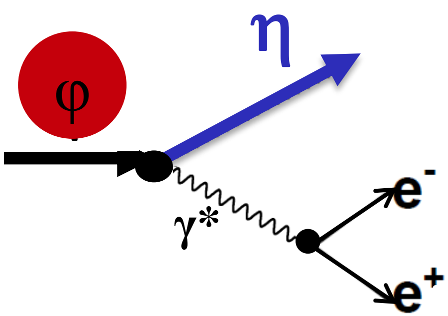

WASA-at-COSY: Phys. Lett. B726 (2013) 187
Entries/(1 MeV)
IM(e+e-) [GeV]


φ
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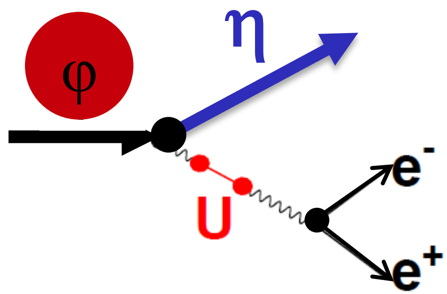
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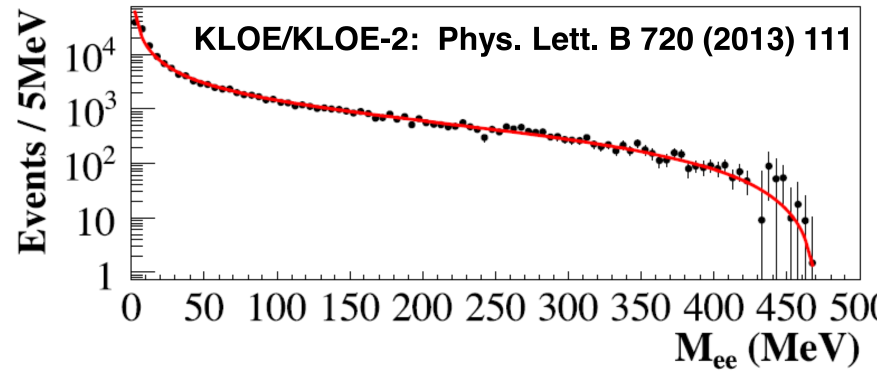
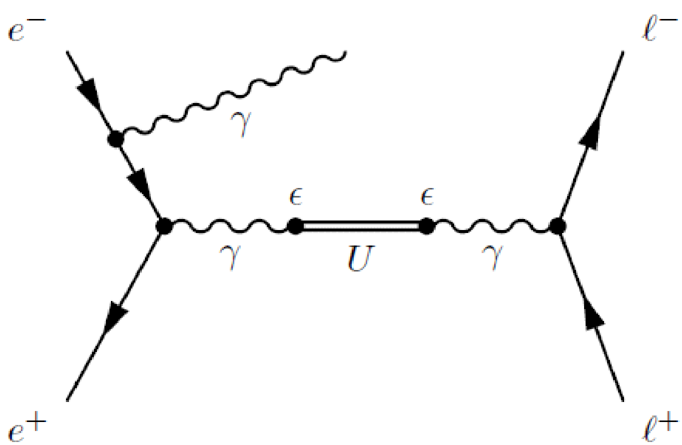

KLOE/KLOE-2: Phys. Lett. B 720 (2013) 111
Events / 5MeV
M_ee (MeV)


e−
e+
γ
ϵ
ϵ
γ
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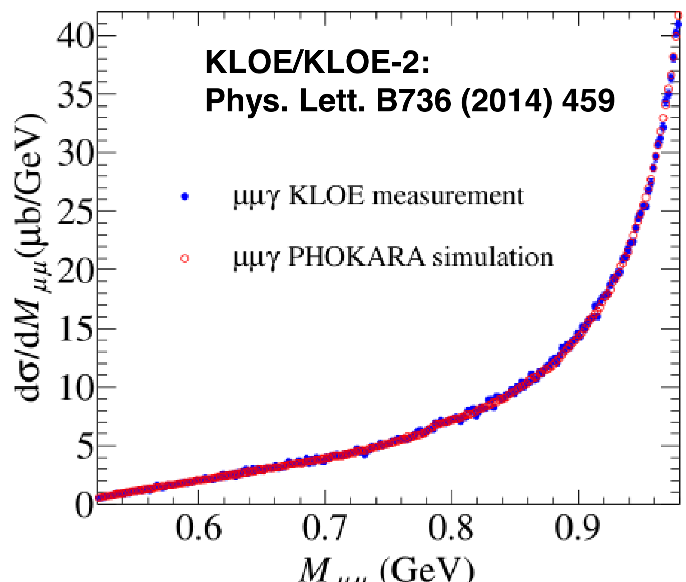
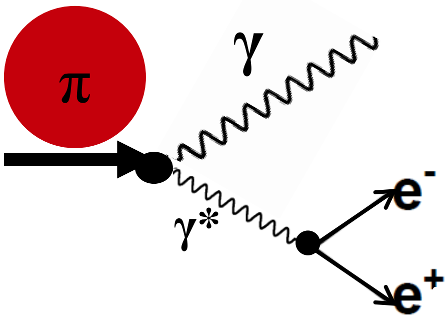
γ
ℓ−
ℓ+


KLOE/KLOE-2:
Phys. Lett. B736 (2014) 459
μμγ KLOE measurement
μμγ PHOKARA simulation
dσ/dM_μμ(μb/GeV)
M_μμ (GeV)

The size of the hadron

R. Pohl et al., The size of the proton, Nature 466 (2010) 213
A. Liesenfeld et al., Phys. Lett. B468 (1999) 20

Transition Form-Factors: J. Zdebik PhD JU (2013); M.Hodana PhD JU (2012)


π
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e-
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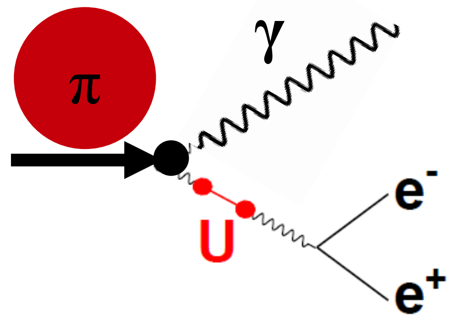
π
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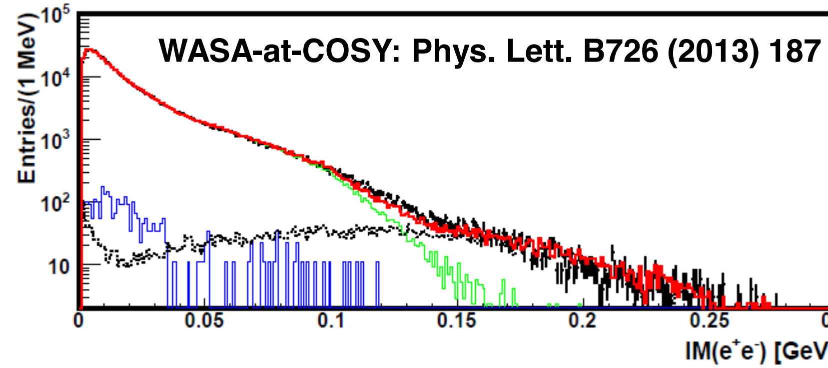
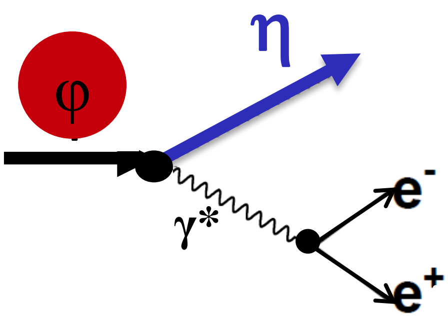

WASA-at-COSY: Phys. Lett. B726 (2013) 187
Entries/(1 MeV)
IM(e+e-) [GeV]


φ
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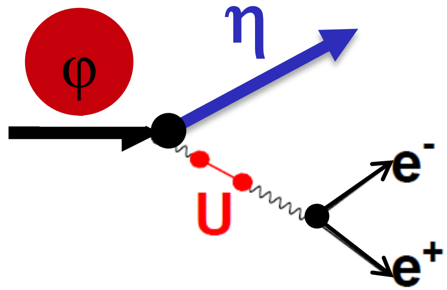
φ
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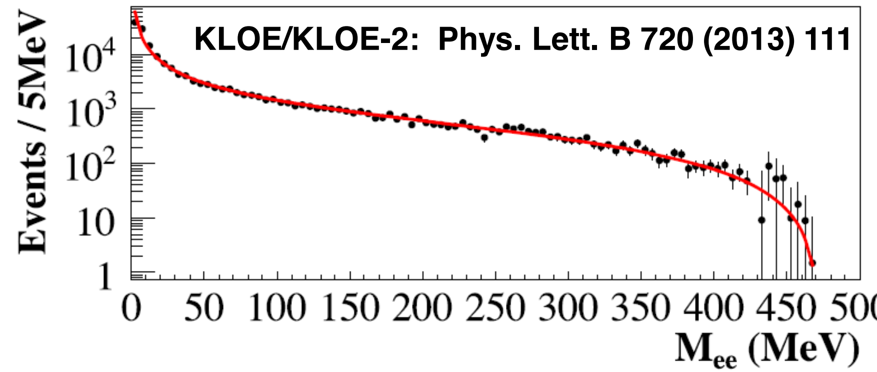
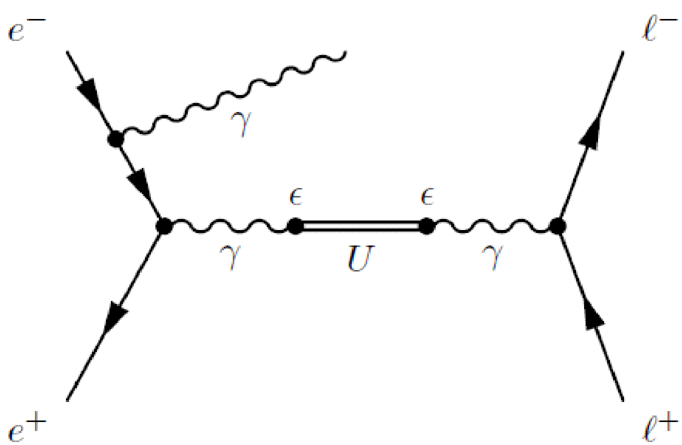

KLOE/KLOE-2: Phys. Lett. B 720 (2013) 111
Events / 5MeV
Mee (MeV)


e−
e+
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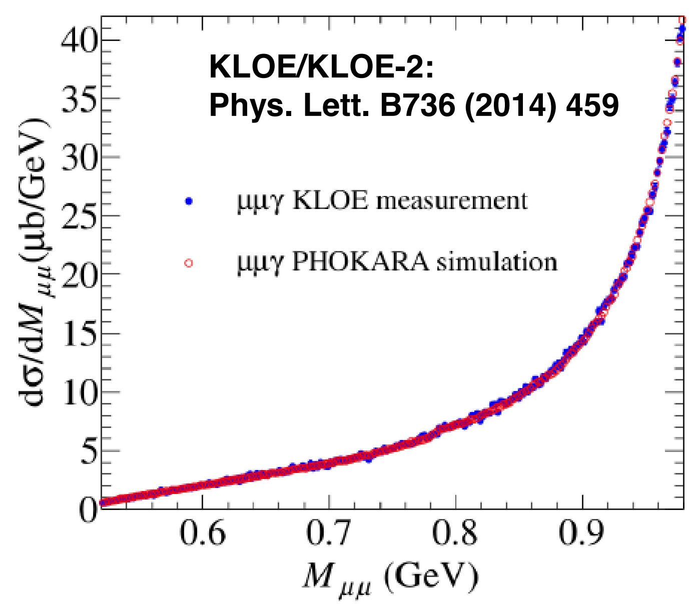
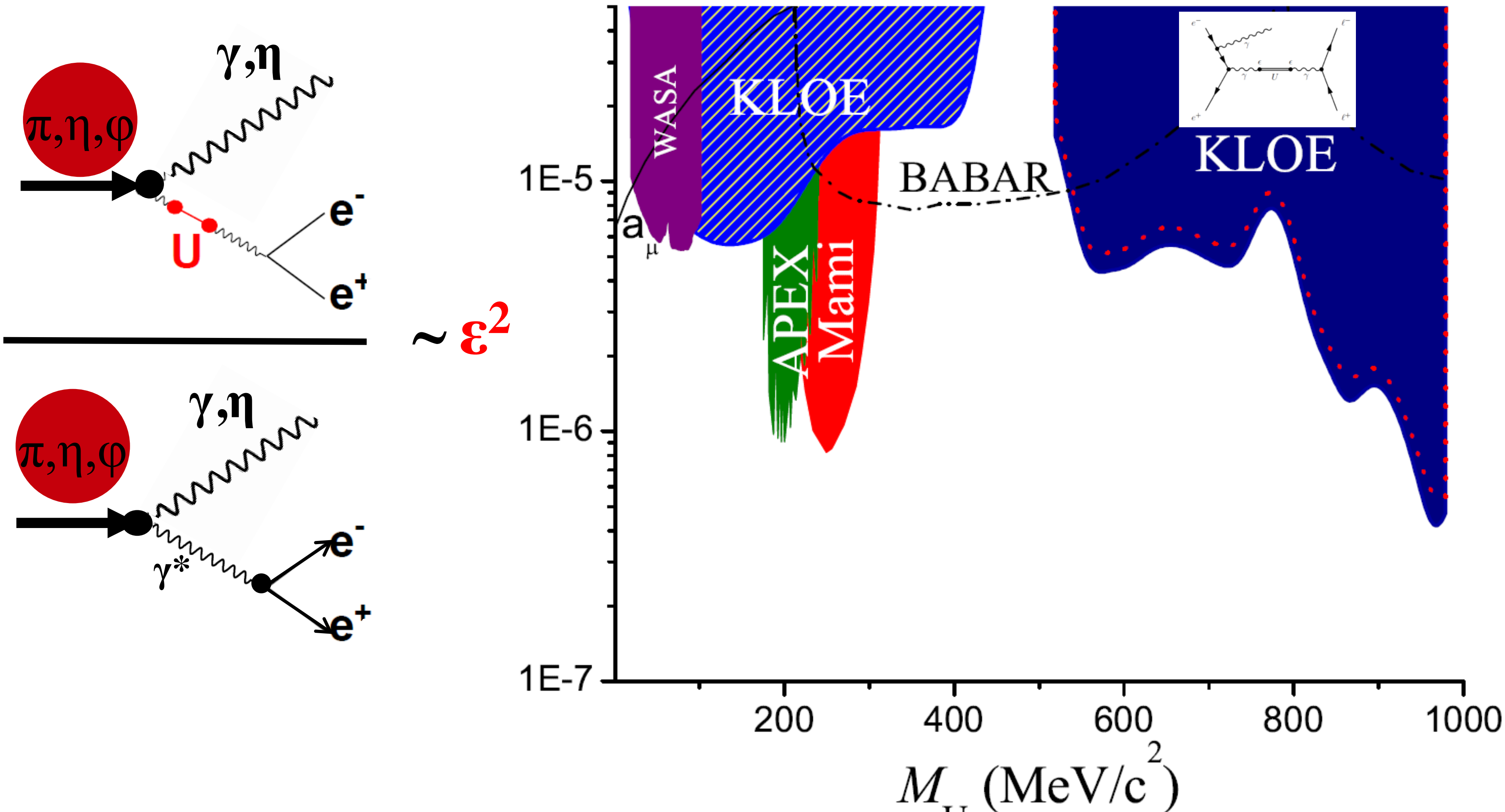

KLOE/KLOE-2:
Phys. Lett. B736 (2014) 459
μμγ KLOE measurement
μμγ PHOKARA simulation
dσ/dMμμ(μb/GeV)
Mμμ (GeV)



APEX: S. Abrahamyan et al., Phys. Rev. Lett. 107 (2011) 191804

BABAR: B. Aubert et al., Phys. Rev. Lett. 103 (2009) 081803

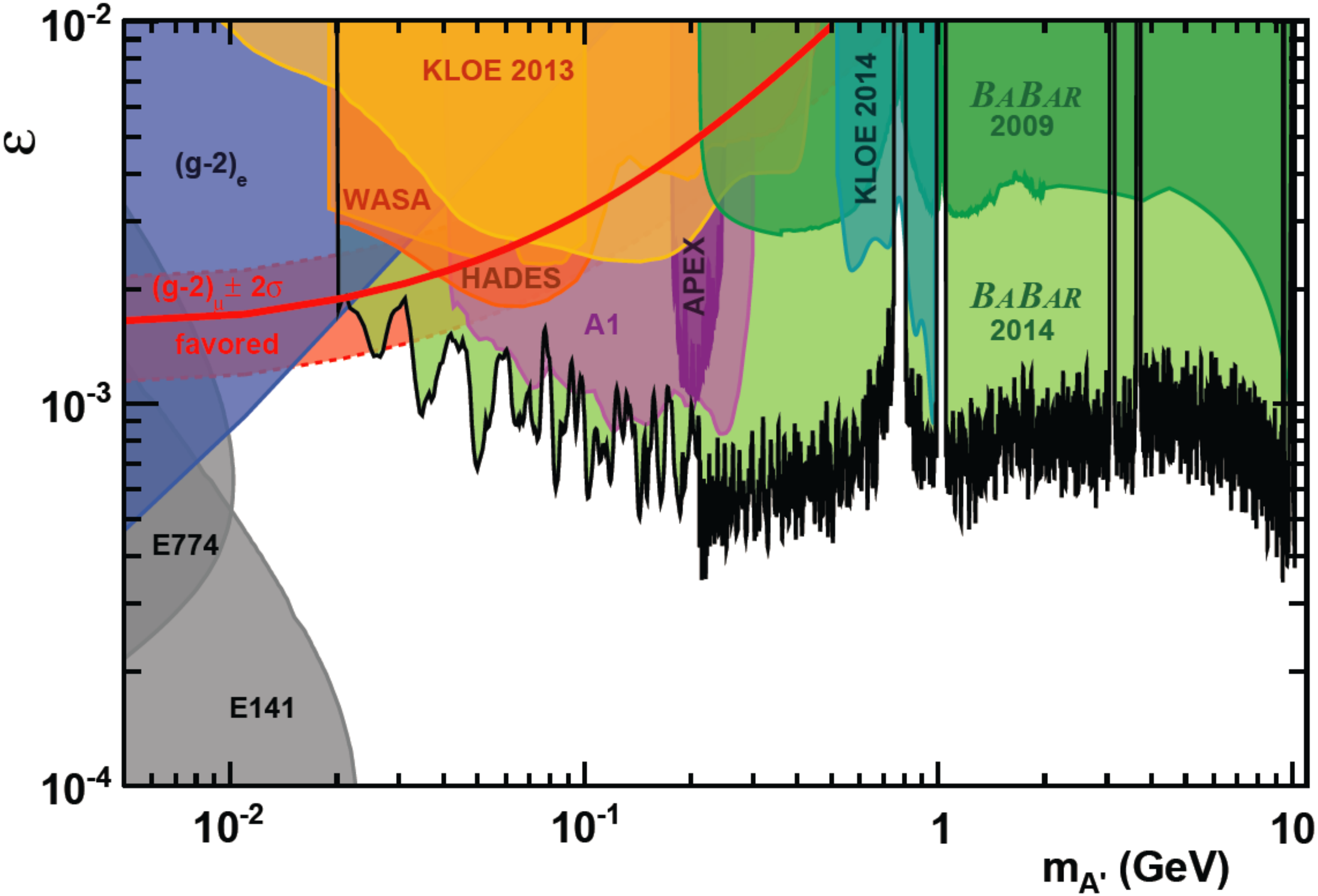
KLOE/KLOE-2: F. Archilli et al., Phys. Lett. B 720 (2013) 111

KLOE/KLOE-2: D. Babusci et al., Phys.Lett B 706 (2012) 251

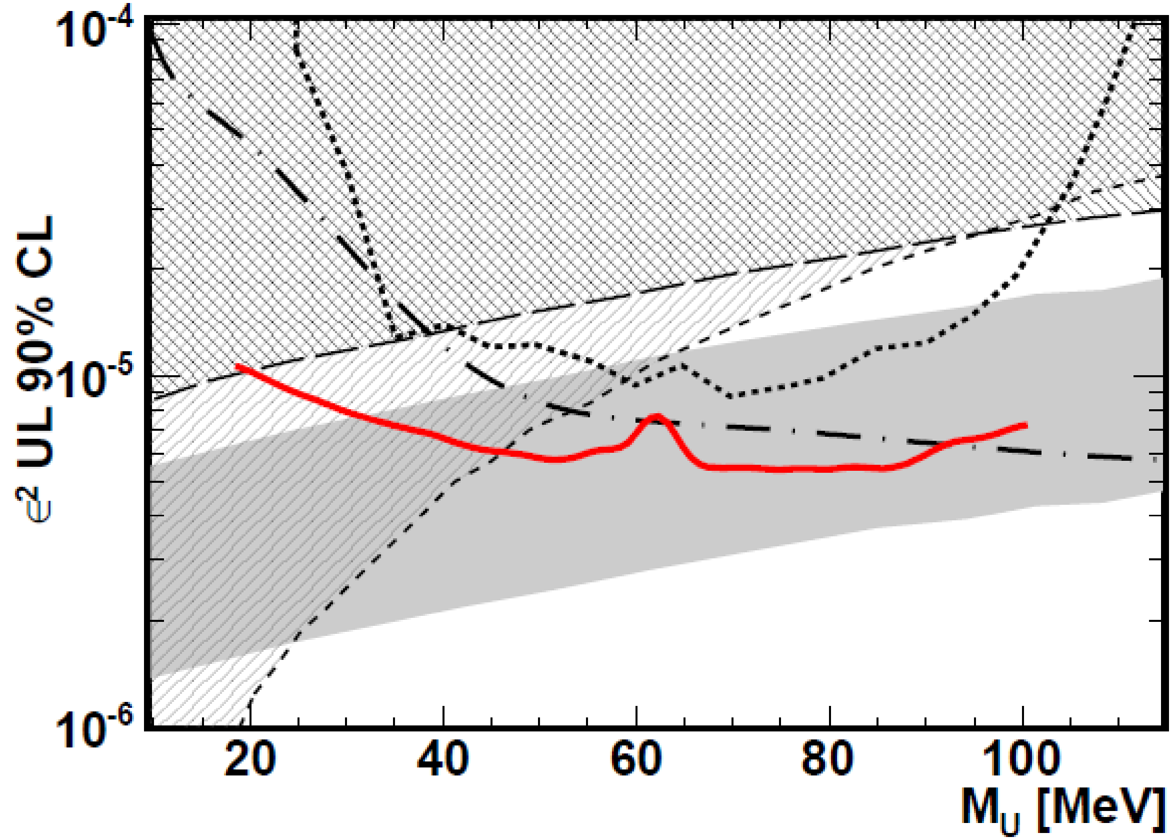
MAMI: M. Merkel et al., Phys. Rev. Lett. 106 (2011) 251802

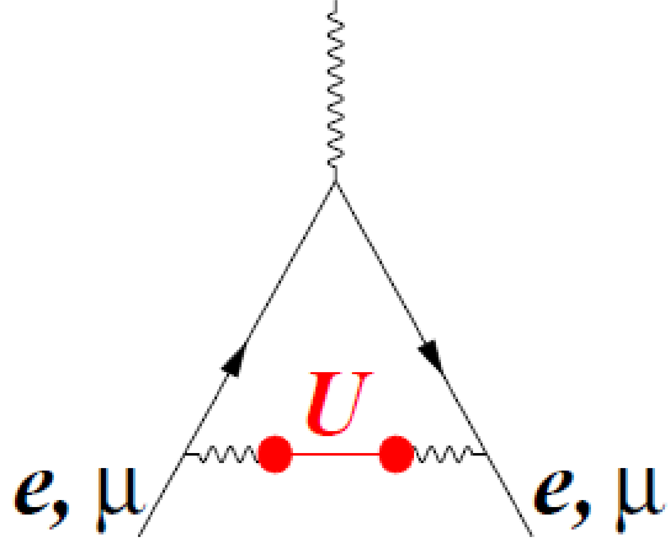
WASA-at-COSY: P. Adlarson et al., Phys. Lett. B 726 (2013) 187

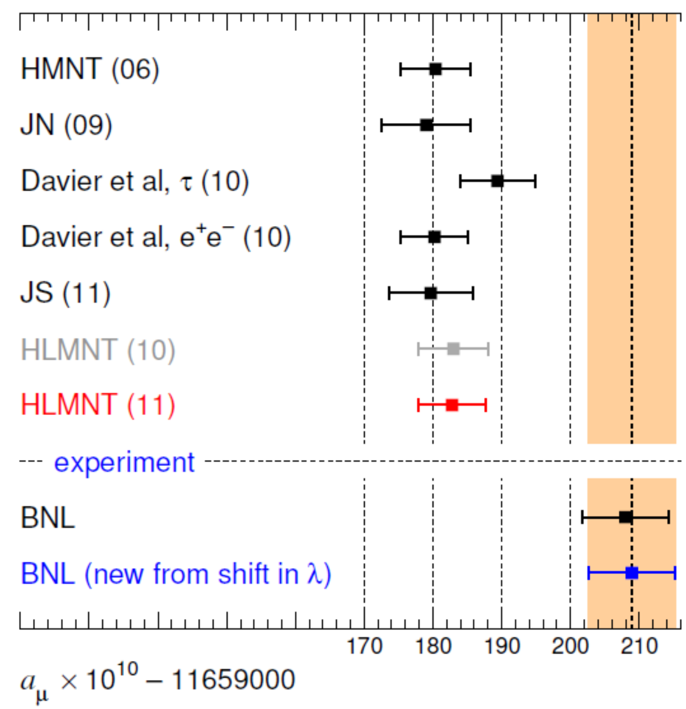
KLOE/KLOE-2: D. Babusci et al., Phys.Lett. B736 (2014) 459-464



BABAR: J.P. Lees et al., Phys.Rev.Lett. 113 (2014) 20, 201801
HADES: G. Agakishiev et al., Phys.Lett. B731 (2014) 265-271







WASA-at-COSY:
P. Adlarson et al., Phys. Lett. B726 (2013) 187

factor of 10 more π^0 mesons collected by WASA-at-COSY

$\pi^0 \to e^+e^-$

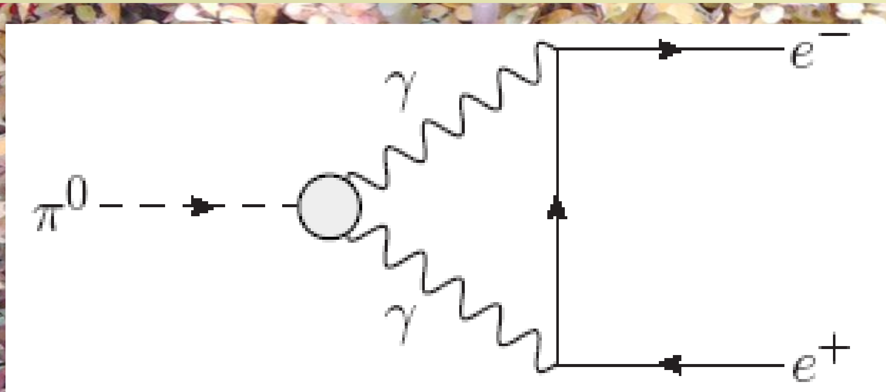
BR ($\pi^0 \to e^+e^-$) = (6.44 ± 0.25 ± 0.22) 10^{-8}

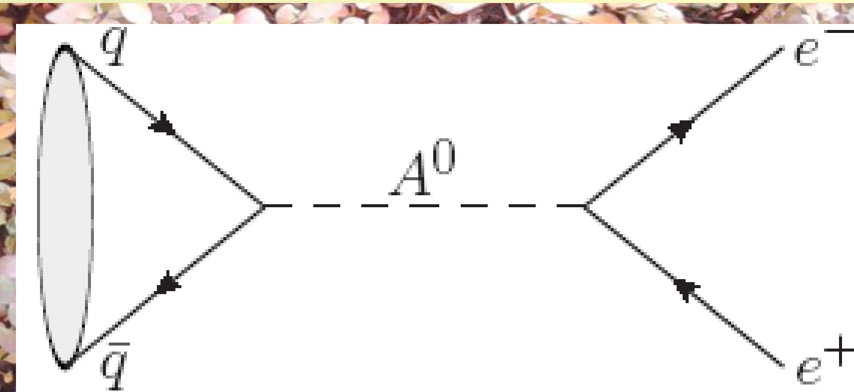
KTEV: E. Abouzaid et al. Phys. Rev. D75 (2007) 012004

SM: A. E. Dorokhov, Nucl. Phys. Proc. Suppl. 181-182 (2008) 37

SM ≠ EXP by 3.3σ

Nothing is more pleasurable than to falsify the theory !!



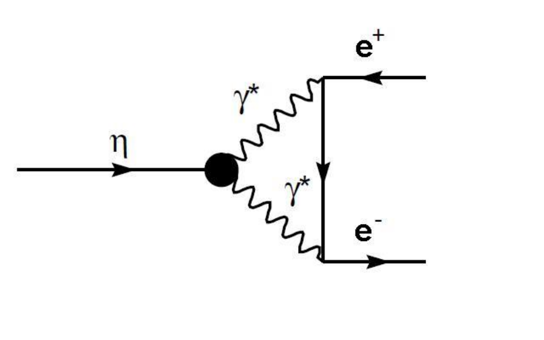


$\eta \to e^+e^-$

Neutral modes

Γ_1	neutral modes	(71.90 ± 0.34) %	S=1.2
Γ_2	2γ	(39.31 ± 0.20) %	S=1.1

Suppressed by α^2 and by $(m_e/m_\eta)^2$



10^{-9}

Sensitive to hypothetical interactions from beyond the Standard Model

Γ_{13}	e^+e^-	$<$ 2.7	$\times 10^{-5}$	CL=90%
Γ_{14}	$\mu^+\mu^-$	(5.8 ± 0.8)	$\times 10^{-6}$	
Γ_{15}	$2e^+2e^-$	$<$ 6.9	$\times 10^{-5}$	CL=90%
Γ_{16}	$\pi^+\pi^-e^+e^-(\gamma)$	(2.68 ± 0.11)	$\times 10^{-4}$	
Γ_{17}	$e^+e^-\mu^+\mu^-$	$<$ 1.6	$\times 10^{-4}$	CL=90%
Γ_{18}	$2\mu^+2\mu^-$	$<$ 3.6	$\times 10^{-4}$	CL=90%

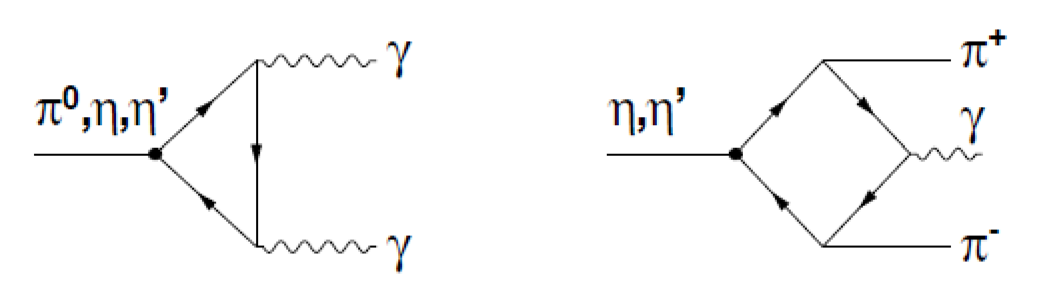
$C(\eta) = +1$, $P(\eta) = -1$; $C(\pi^0) = +1$, $P(\pi^0) = -1$

$\eta \to \pi\pi$ violates P and CP

$\eta \to \pi\pi\pi$ violates G and (I or C)

$\eta \to \pi^0\gamma$, $\eta \to \pi^0\pi^0\gamma$ violates C

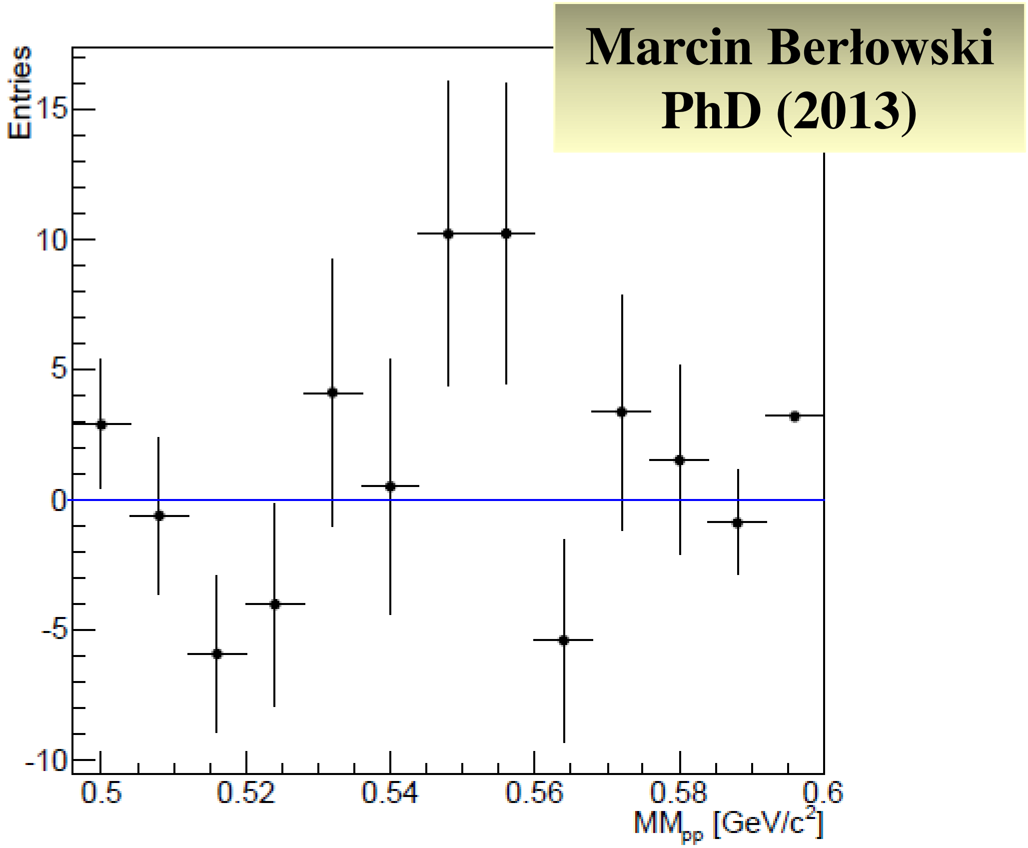
Second order EM $\eta \to \gamma\gamma$
is forbidden in a massless quarks limits



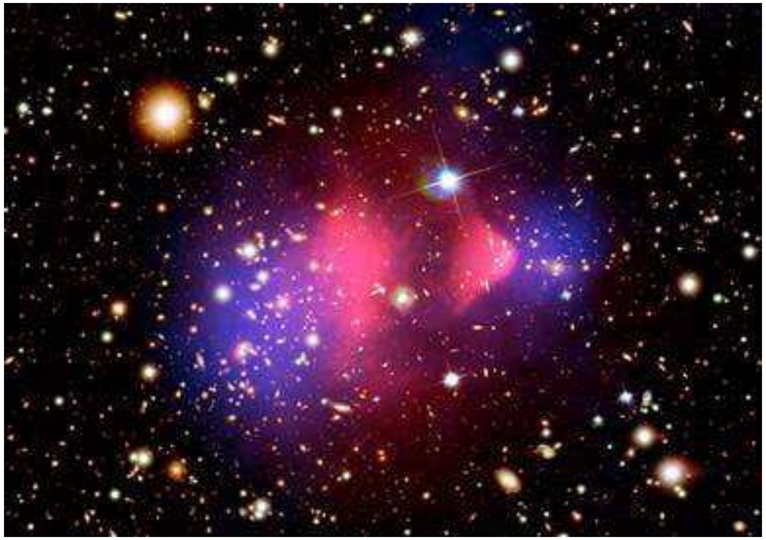
$\eta \to \gamma\gamma\gamma$ violates C etc…

$\eta \to e^+e^-$

HADES Collaboration: $< 5.6 \cdot 10^{-6}$ at CL=90% Eur. J. Phys. A48 (2012) 64



MM_{pp} for $\eta \to e^+e^-$ event candidates after background subtraction



Background: $pp \to pp\pi^+\pi^-$, $\eta \to e^+e^-\gamma$, $pp \to p\Delta(1232) \to pp[\gamma^* \to e^+e^-]$

based on 5.9 10^7 η mesons

BR_{limit} = **3.9 × 10^{-6}** at CL 90%

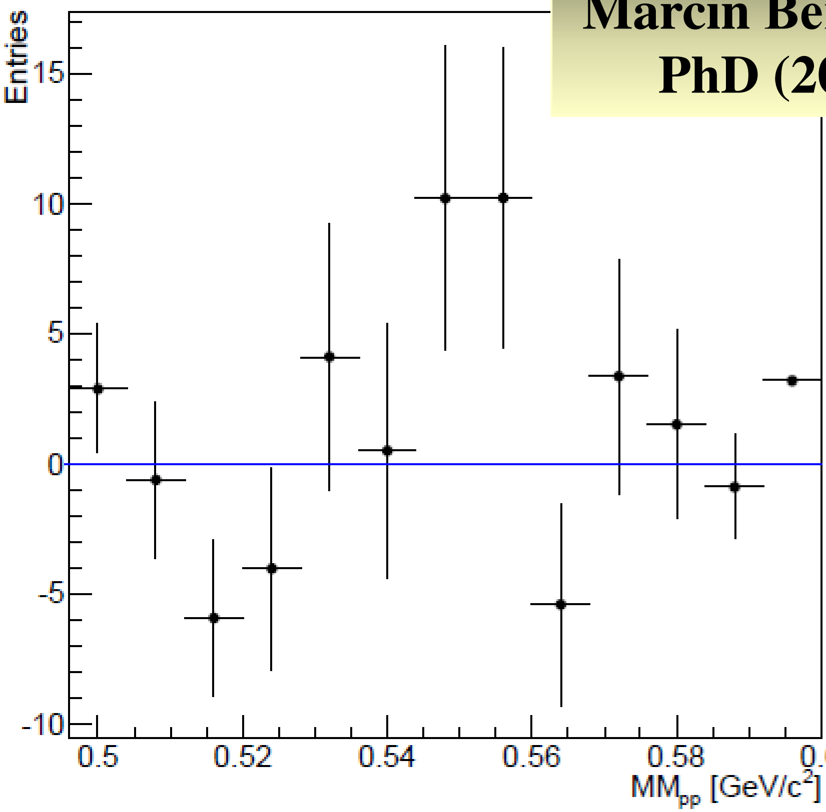
(preliminary)

M.Berłowski PhD (2013)

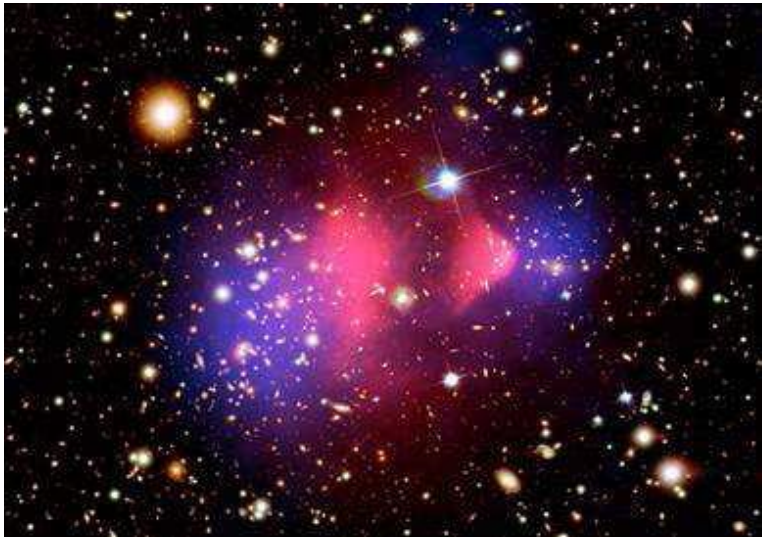
$\eta \to e^+e^-$

HADES Collaboration: < $5.6 \cdot 10^{-6}$ at CL=90% Eur. J. Phys. A48 (2012) 64

Marcin Berłowski PhD (2013)



MM_{pp} for $\eta \to e^+e^-$ event candidates after background subtraction



Background: $pp \to pp\pi^+\pi^-$, $\eta \to e^+e^-\gamma$, $pp \to p\Delta(1232) \to pp[\gamma^* \to e^+e^-]$

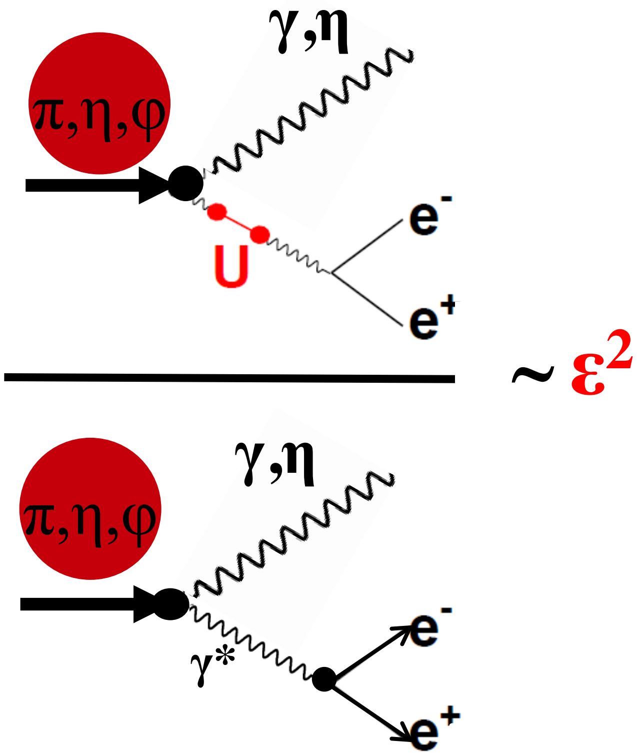
based on 5.9 10^7 η mesons

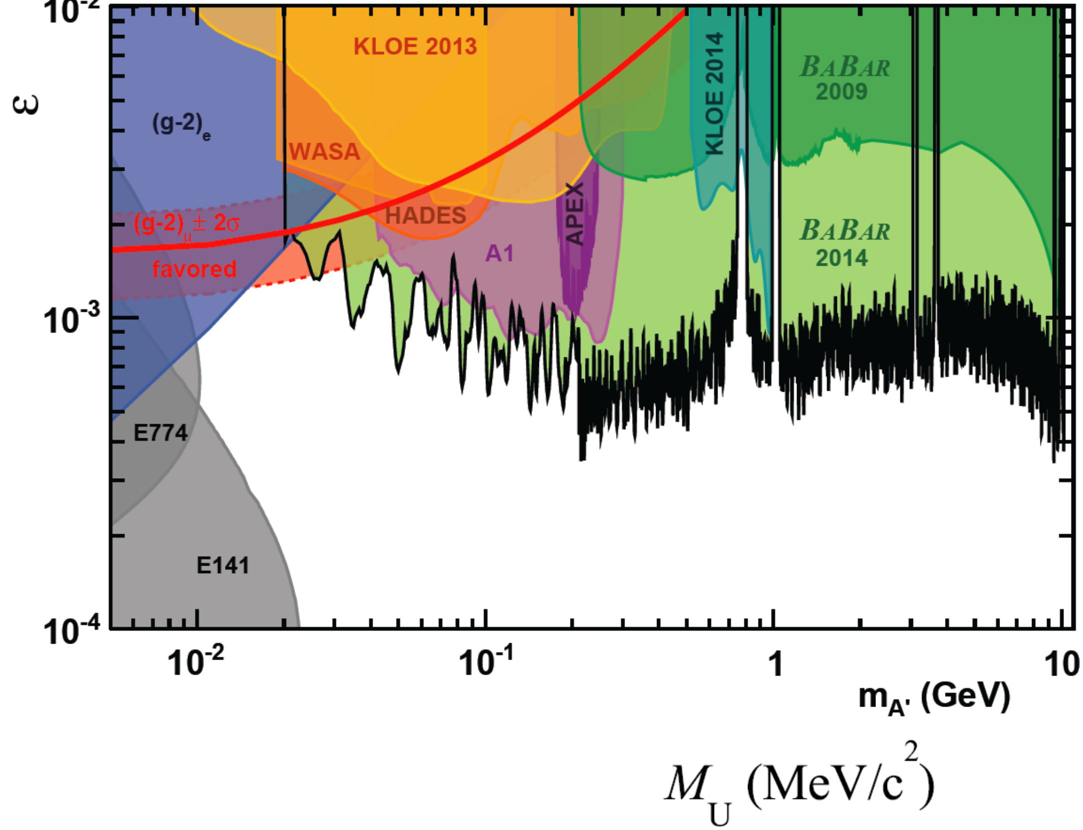
BR_{limit} = **3.9×10^{-6}** at CL 90%

(preliminary)

M.Berłowski PhD (2013)

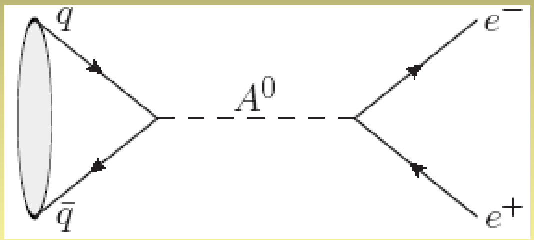
factor of 17 more η mesons collected by WASA-at-COSY





$\pi^0 \rightarrow e^+e^-$

SM ≠ EXP by 3.3σ



$\eta \rightarrow e^+e^-$

SM ~ 10^{-9}

3.9×10^{-6} CL90%

M.Berłowski PhD

more than factor of 10 η and π^0 mesons collected by WASA-at-COSY

Search for the dark photon at KLOE

$\phi \to \eta\, \gamma^* \to \eta\, e^+e^-$

$\phi \to \eta\, \gamma^* \to \eta U \to \eta\, \gamma^* \to \eta\, e^+e^-$

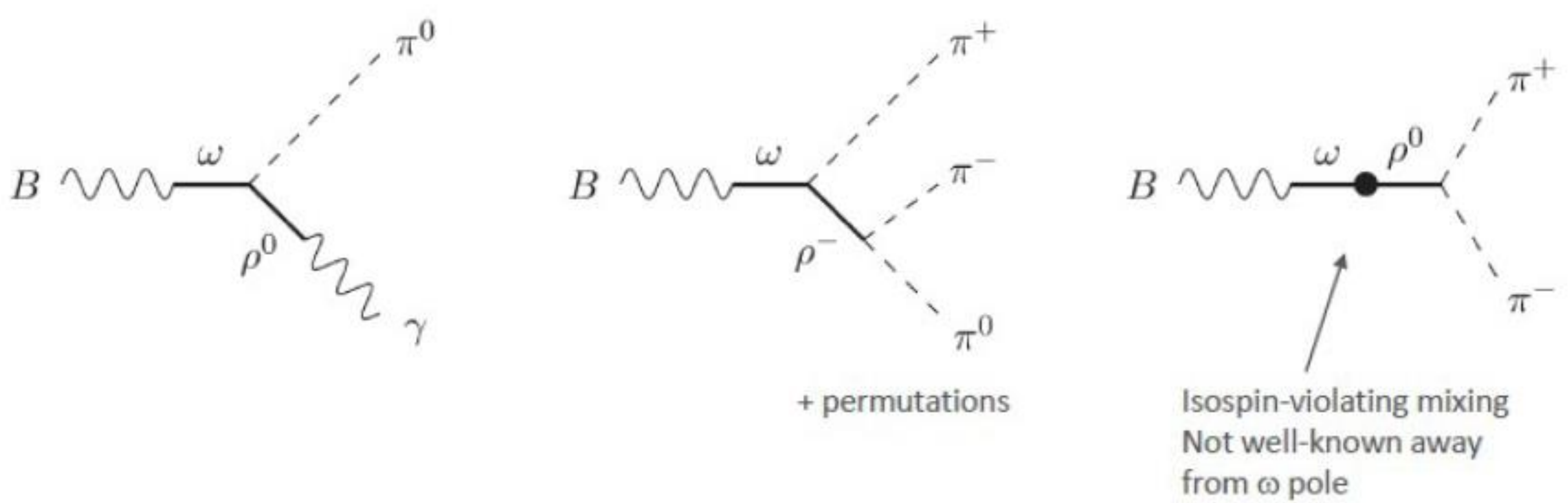
$e^+e^- \to \gamma^*\, \gamma \to \mu^+\mu^-\gamma$ (ISR)

$e^+e^- \to \gamma^*\, \gamma \to U\gamma \to \gamma^*\gamma \to \mu^+\mu^-\gamma$

higgsstrahlung: $e^+e^- \to \gamma^* \to U \to U\, h \to \gamma^*\, h \to \mu^+\mu^-$ + missing energy

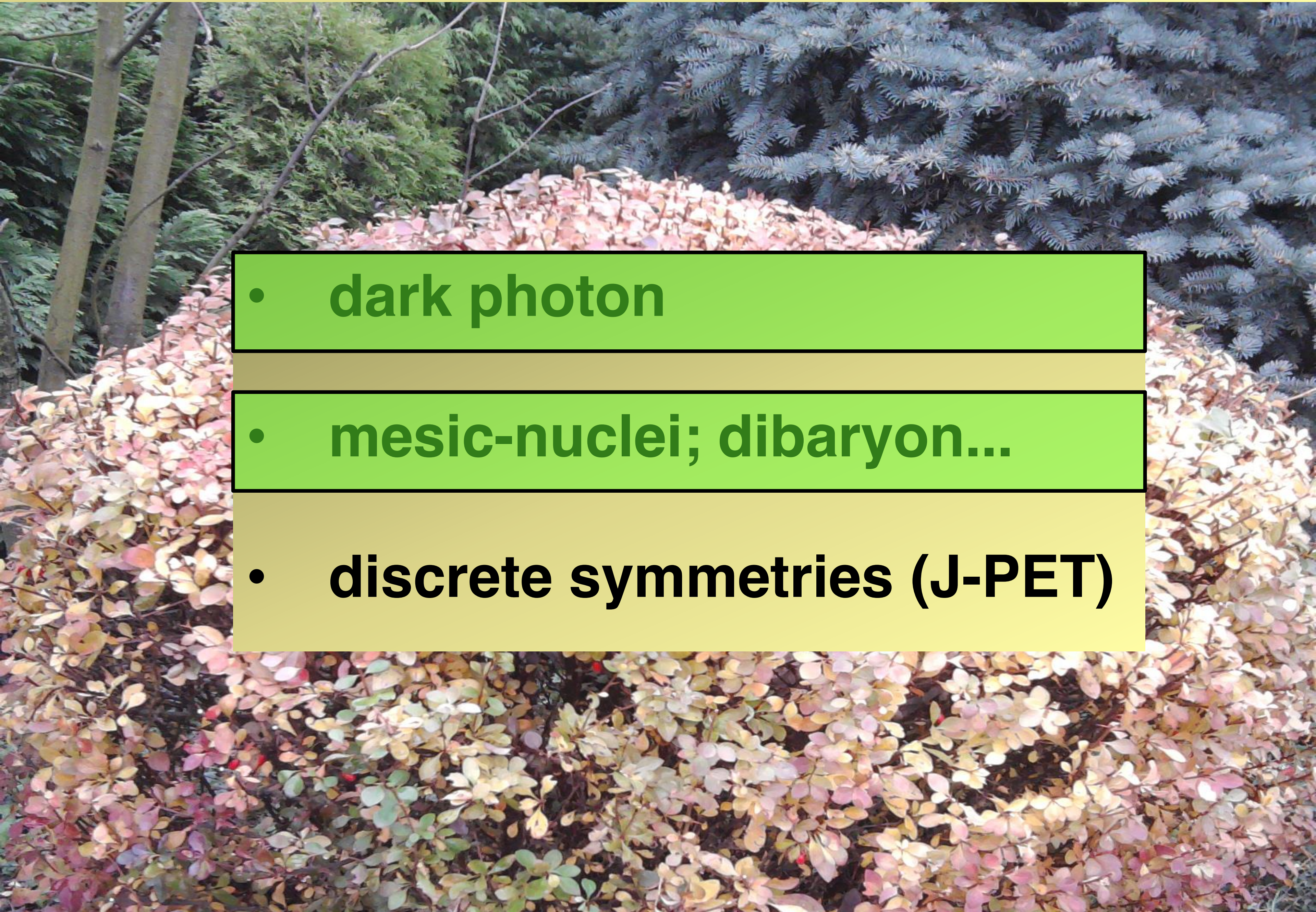
...

dark boson coupling to baryons....



S. Tulin, Phys.Rev. D89 (2014) 114008

Search for the exotic matter at low energies



- dark photon
- mesic-nuclei; dibaryon...
- discrete symmetries (J-PET)

Attractive interaction between η and N

(*R. Bhalerao and L. C. Liu, Phys. Lett. B54 (1985) 685*)

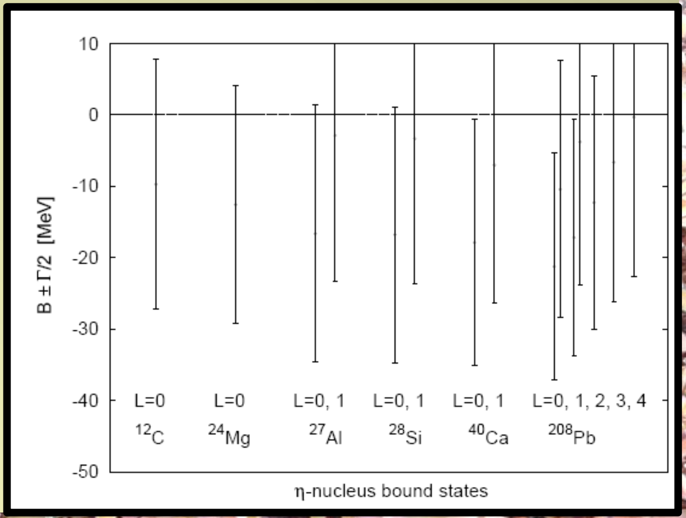
↓

possible existence of bound states of the η meson with nuclei for A>10

(*Q. Haider and L. C. Liu, Phys. Lett. B172 (1986) 257*)

↓

(C.Garcia-Recio, T. Inoue, J.Nieves, E. Oset, Phys. Lett. B550 (2002) 47).



η bound state possible with the light nuclei
C. Wilkin, Phys. Rev. C47 (1993) 938

^{3}He-η ^{3}H-η ^{4}He-η

Supported by model calculations of:

- S. Wycech et al., Phys. Rev. C52(1995)544

(the multiple scattering theory)

…

…

η-nuclear bound states revisited

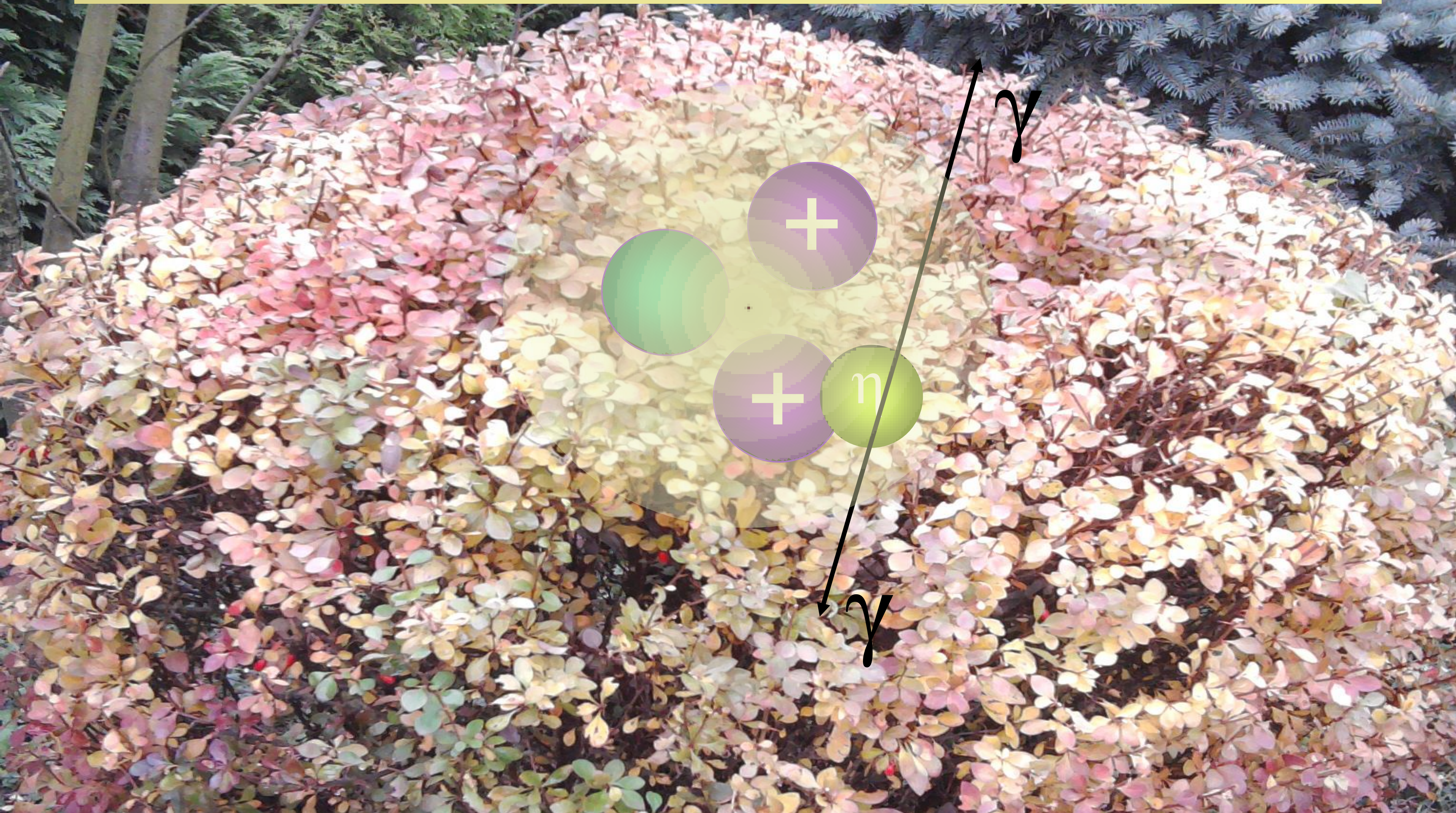
E. Friedman, A. Gal, J. Mares, Phys. Lett. B725 (2013) 334

THE ETA-MESIC NUCLEUS

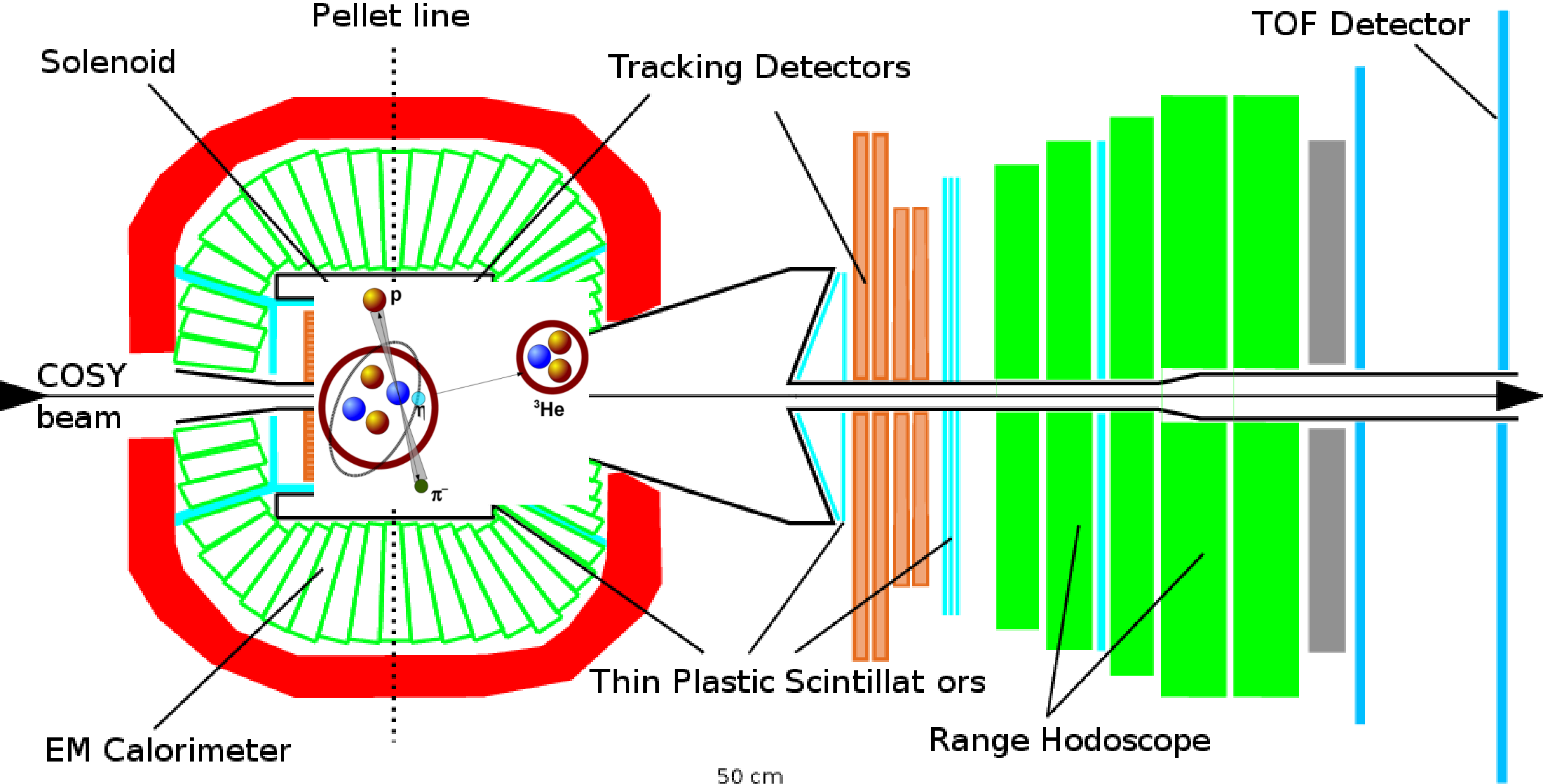
η meson bound with nucleus via
STRONG INTERACTION

THE ETA-MESIC NUCLEUS

η meson bound with nucleus via
STRONG INTERACTION

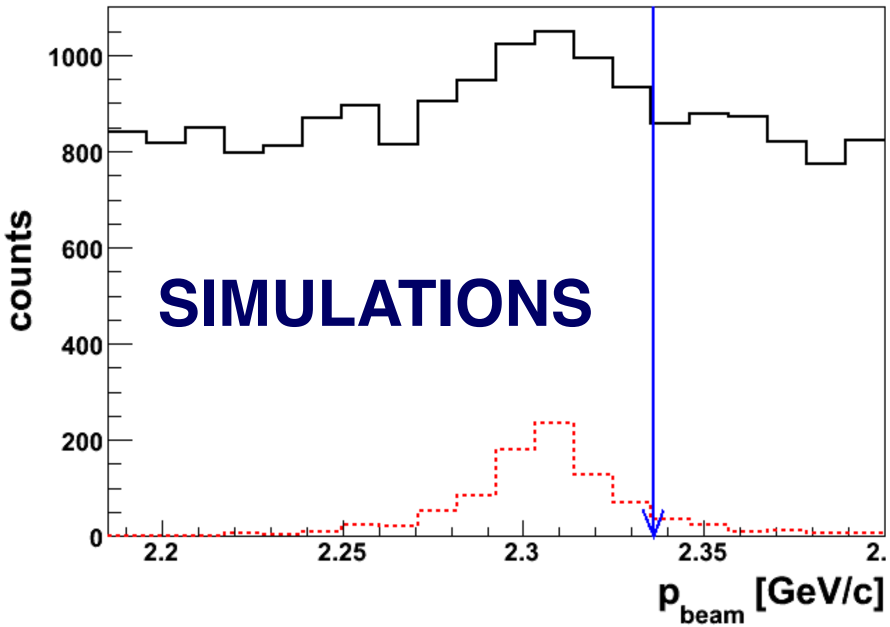


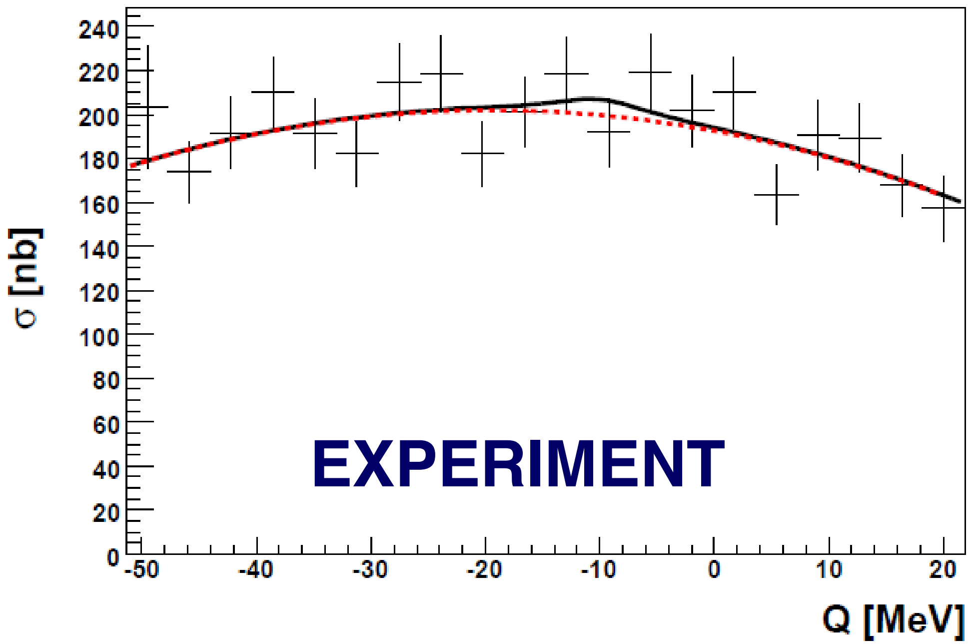
WASA-at-COSY


Pellet line
Solenoid
Tracking Detectors
TOF Detector
p
COSY
beam
^{3}He
η
π⁻
Thin Plastic Scintillat ors
Range Hodoscope
EM Calorimeter
50 cm

$$d+d \rightarrow ({}^4He\text{-}n)_{bound} \rightarrow {}^3He + p + \pi^-$$

$$d+d \rightarrow {}^3He + p + \pi^-$$





Upper limit of about 25 nb

WASA-at-COSY: Phys. Rev. C87(2013) 035204

η - ^{4}He

~25nb -- Present experimental upper limit

WASA-at-COSY: Phys. Rev. C87(2013) 035204

~ 4 nb -- Theoretical estimation

S. Wycech, W. Krzemien , Acta. Phys. Pol. B45 (2014) 745

~ few nb -- WASA-at-COSY data collected in 2010

η - ^{3}He

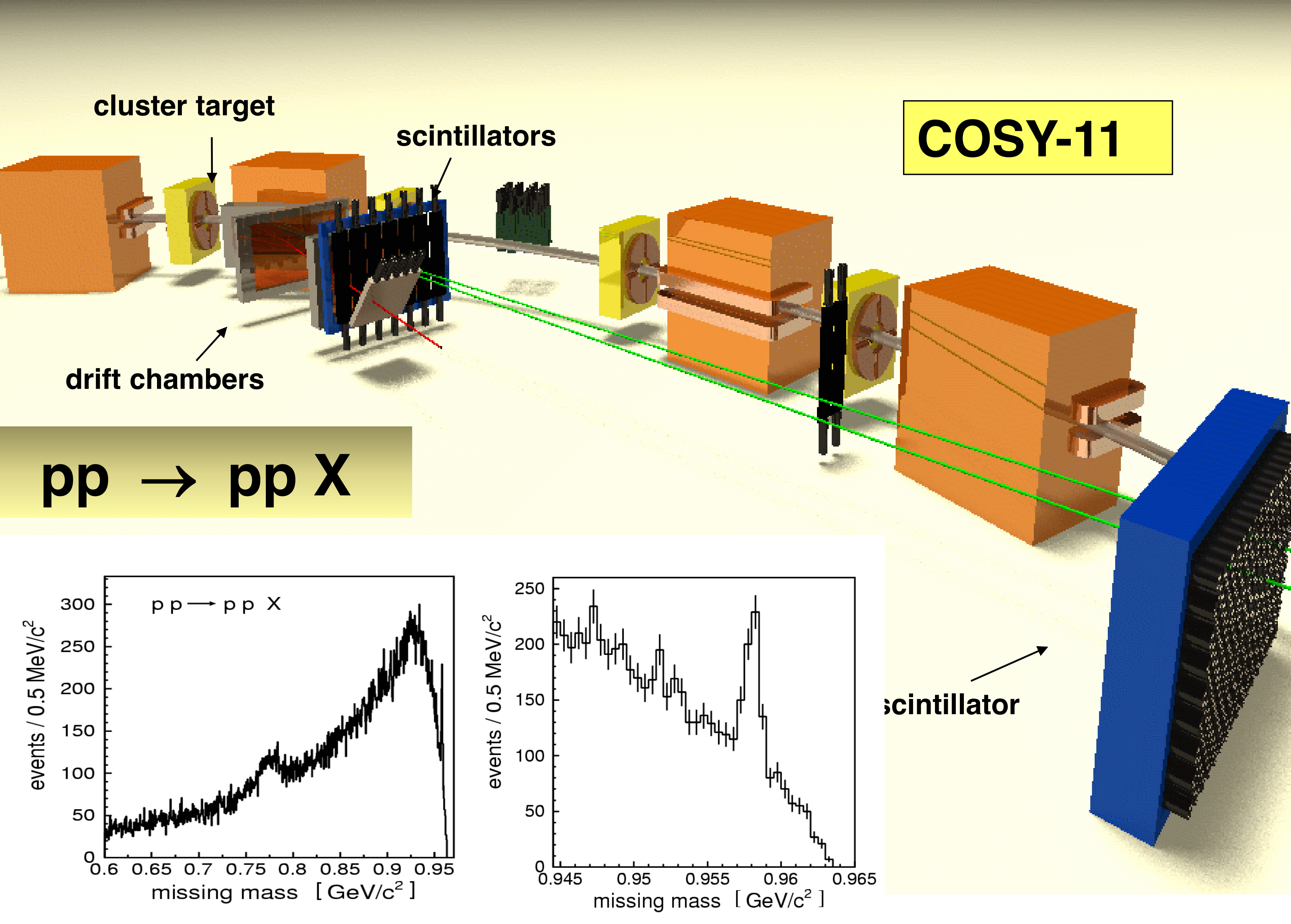
~270 nb -- Present experimental upper limit pppπ^-

COSY-11: Acta Phys. Pol B41 (2010) 21

~80 nb -- Theoretical estimation

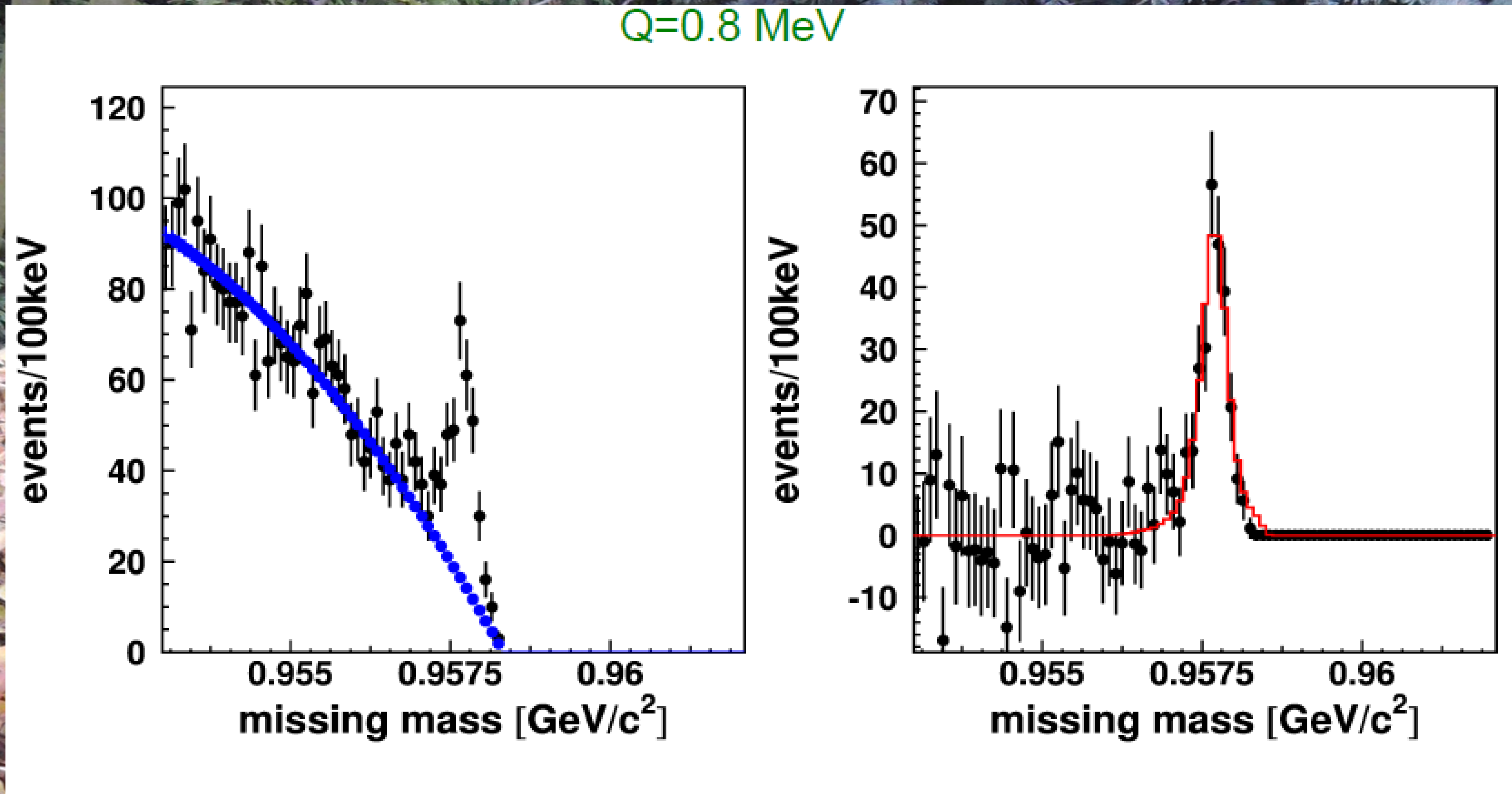
C. Wilkin, Acta. Phys. Pol. B45 (2014) 603

~ 10 nb -- expected from New WASA-at-COSY data collected in May 2014



COSY-11
cluster target
scintillators
drift chambers
pp → pp X
scintillator
p p ⟶ p p X
events / 0.5 MeV/c²
missing mass [GeV/c²]
events / 0.5 MeV/c²
missing mass [GeV/c²]

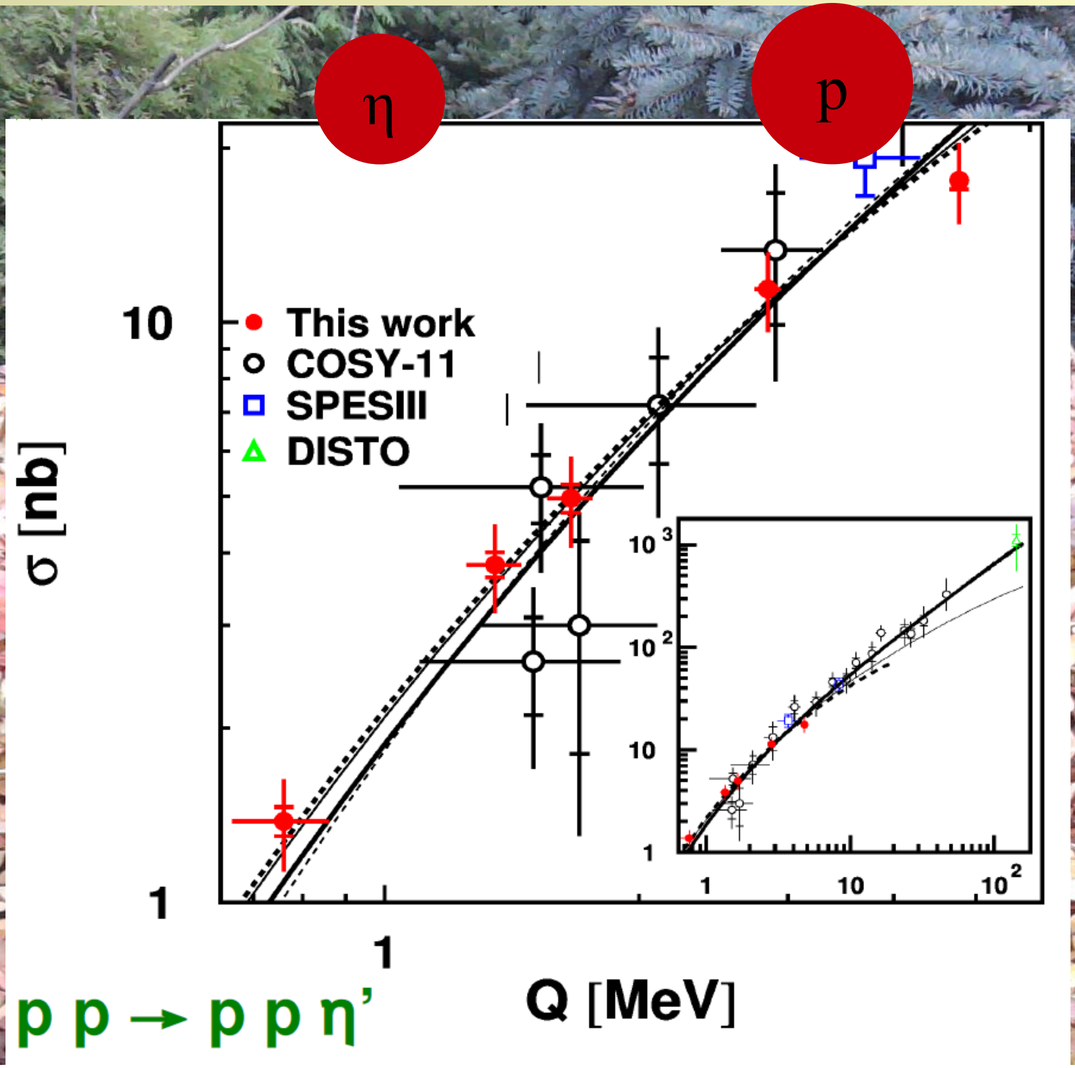
COSY-11



$$\Gamma_{\eta'} = 0.226 \pm 0.017(\text{stat.}) \pm 0.014(\text{syst.})\ \text{MeV}/\text{c}^2$$

E. Czerwiński, P.M. et al., Phys. Rev. Lett. 105 (2010) 122001

The η′ - proton hadronic interaction



$$\mathrm{Re}(a_{p\eta'}) = 0 \pm 0.43\ \mathrm{fm}\ \text{and}\ \mathrm{Im}(a_{p\eta'}) = 0.37\ ^{+0.40}_{-0.16}\ \mathrm{fm}.$$

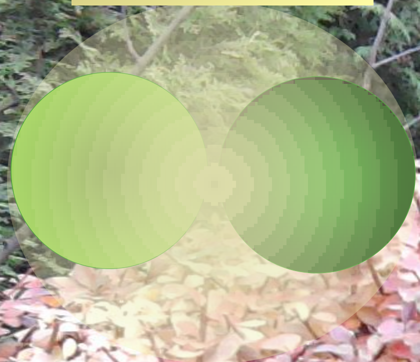
E. Czerwiński, P.M. et al., Phys. Rev. Lett. 113 (2014) 062004

Search for the exotic matter at low energies

- dark photon
- mesic-nuclei; dibaryon...
- discrete symmetries (J-PET)

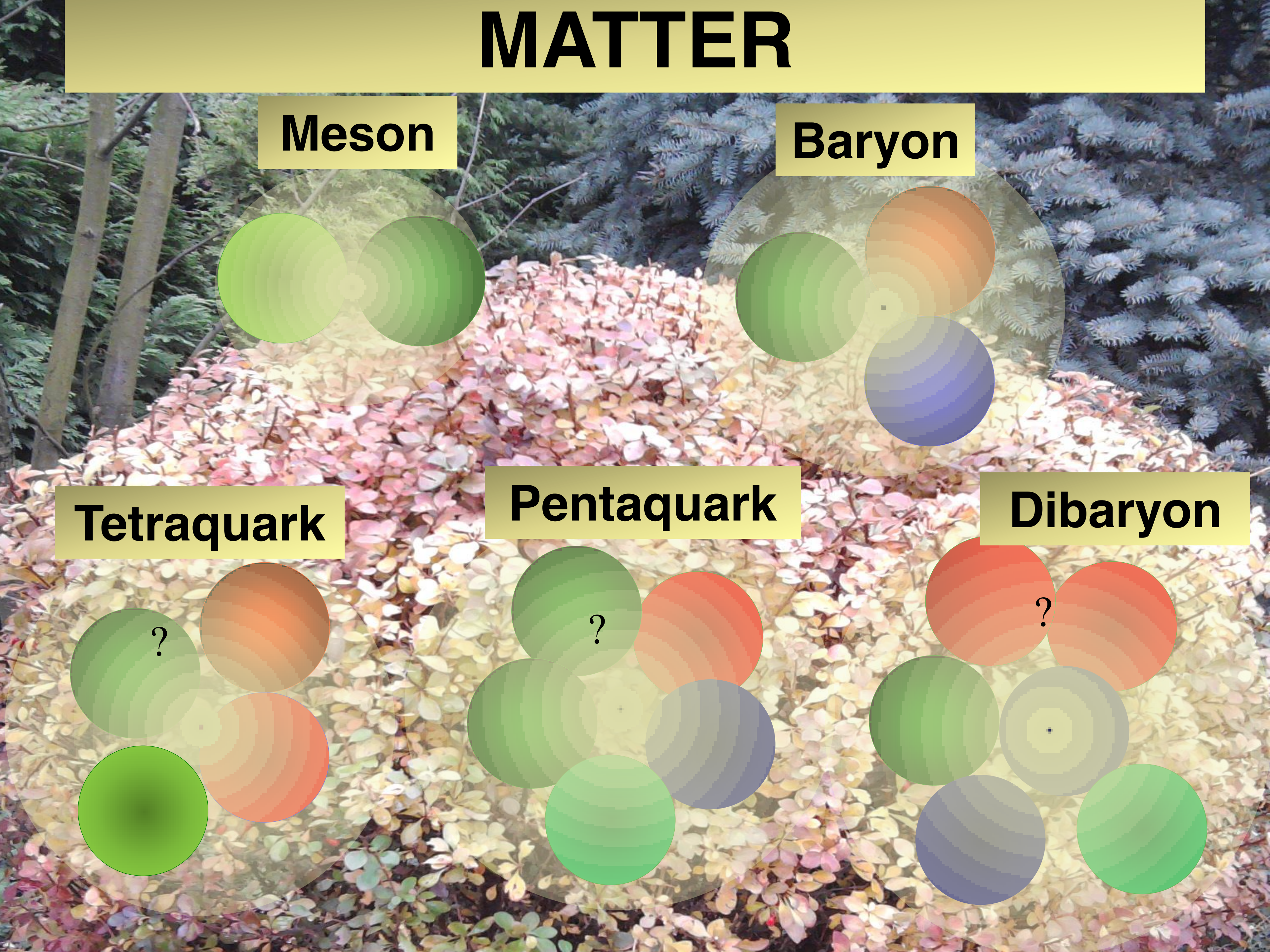
MATTER

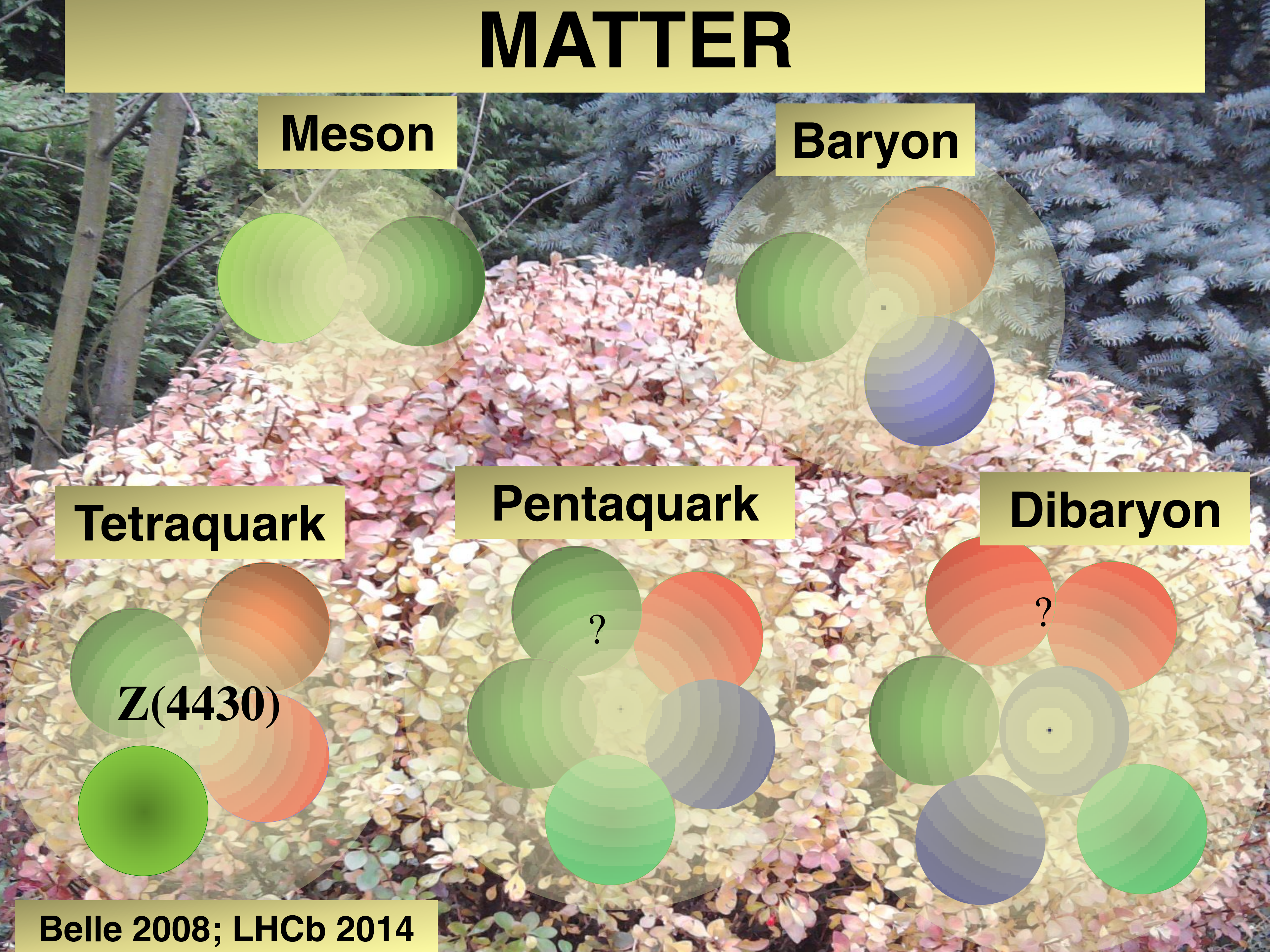
Meson



Baryon

1947 Powell in Cracow
1950 Powell <-- Nobel Prize
1960 Quark Model

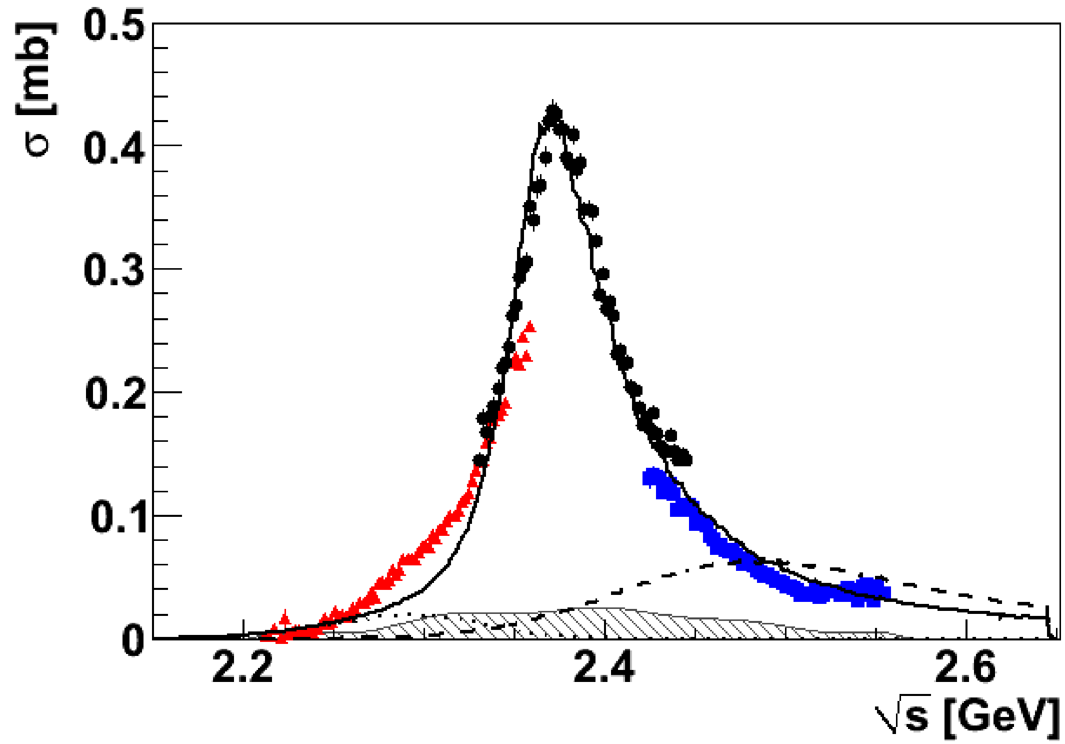

MATTER
Meson
Baryon
Tetraquark
?
Pentaquark
?
Dibaryon
?



MATTER
Meson
Baryon
Tetraquark
Pentaquark
Dibaryon
?
?
Z(4430)
Belle 2008; LHCb 2014

Double pionic fusion - a new resonance?

Cross section for pn → $d\pi^0\pi^0$



WASA-at-COSY: Phys. Rev. Lett. 106 (2011) 242302

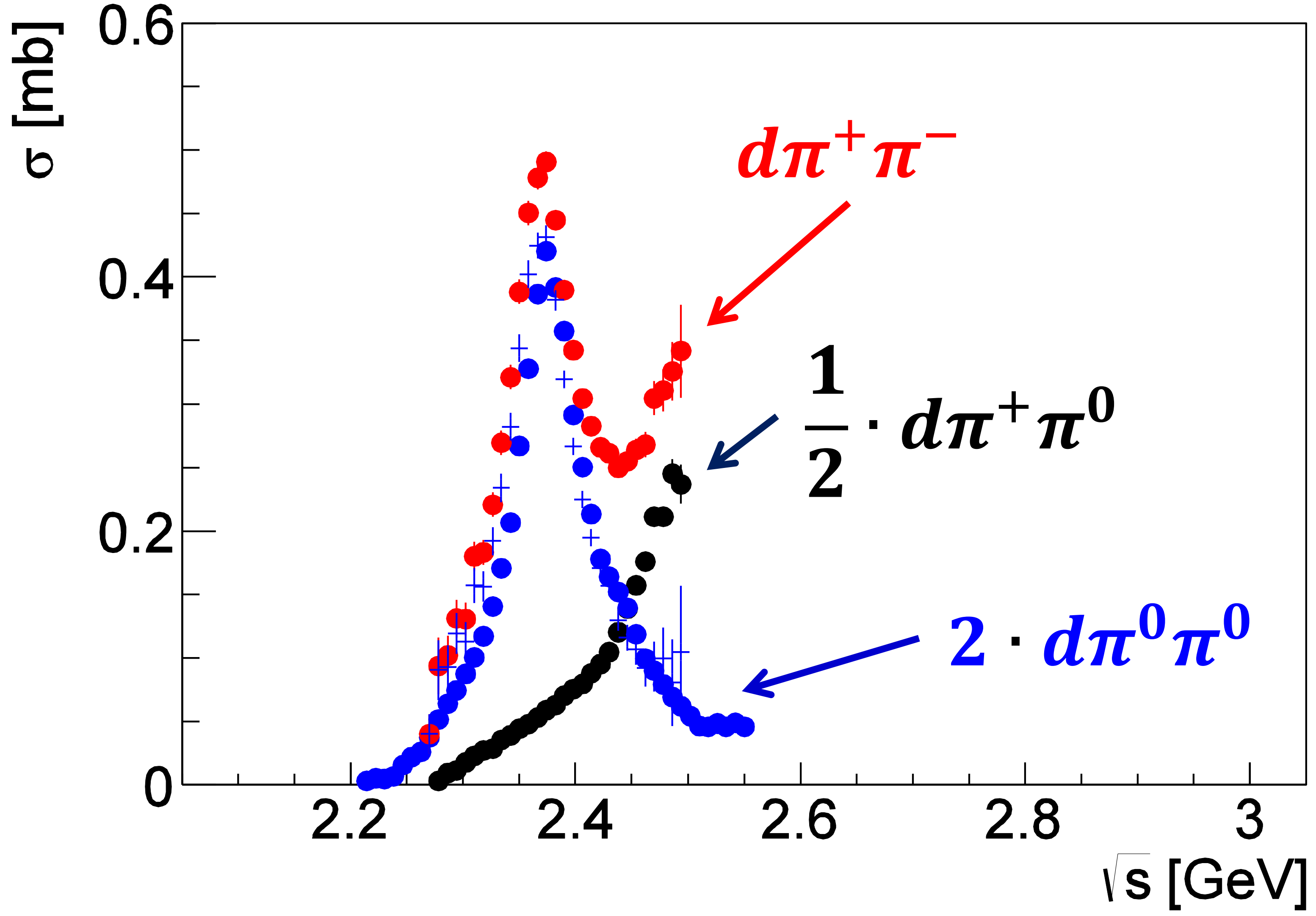
$I = 0$; $J^P = 3^+$

F. J. Dyson, N.-H. Xuong, Phys. Rev. Lett. **13**, 815 (1964).

The decay modes of the dibaryon

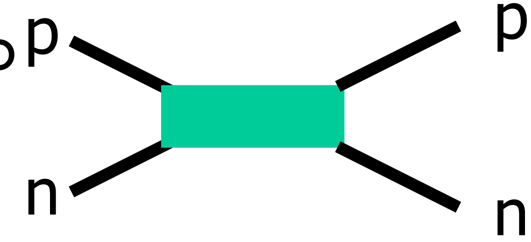
Channel	Publications
d $\pi^0\pi^0$	**P. Adlarson et. al Phys. Rev. Lett. 106 (2011) 242302** P. Adlarson et. al Phys. Lett. B721 (2013) 229-236
d $\pi^+\pi^-$	P. Adlarson et. al Phys. Lett. B721 (2013) 229-236
pp$\pi^0\pi^-$	P. Adlarson et. al Phys. Rev. C 88, 055208
np$\pi^0\pi^0$	arXiv:1409.2659
np	**P. Adlarson et al. Phys. Rev. Lett. 112, 202301, (2014)** P. Adlarson et al. Phys. Rev. C **90**, 035204 , (2014)
^{3}He $\pi\pi$	M. Bashkanov et. al Phys.Lett. B637 (2006) 223-228 arXiv:1408.5744
^{4}He $\pi\pi$	P. Adlarson et. al. Phys.Rev. C86 (2012) 032201

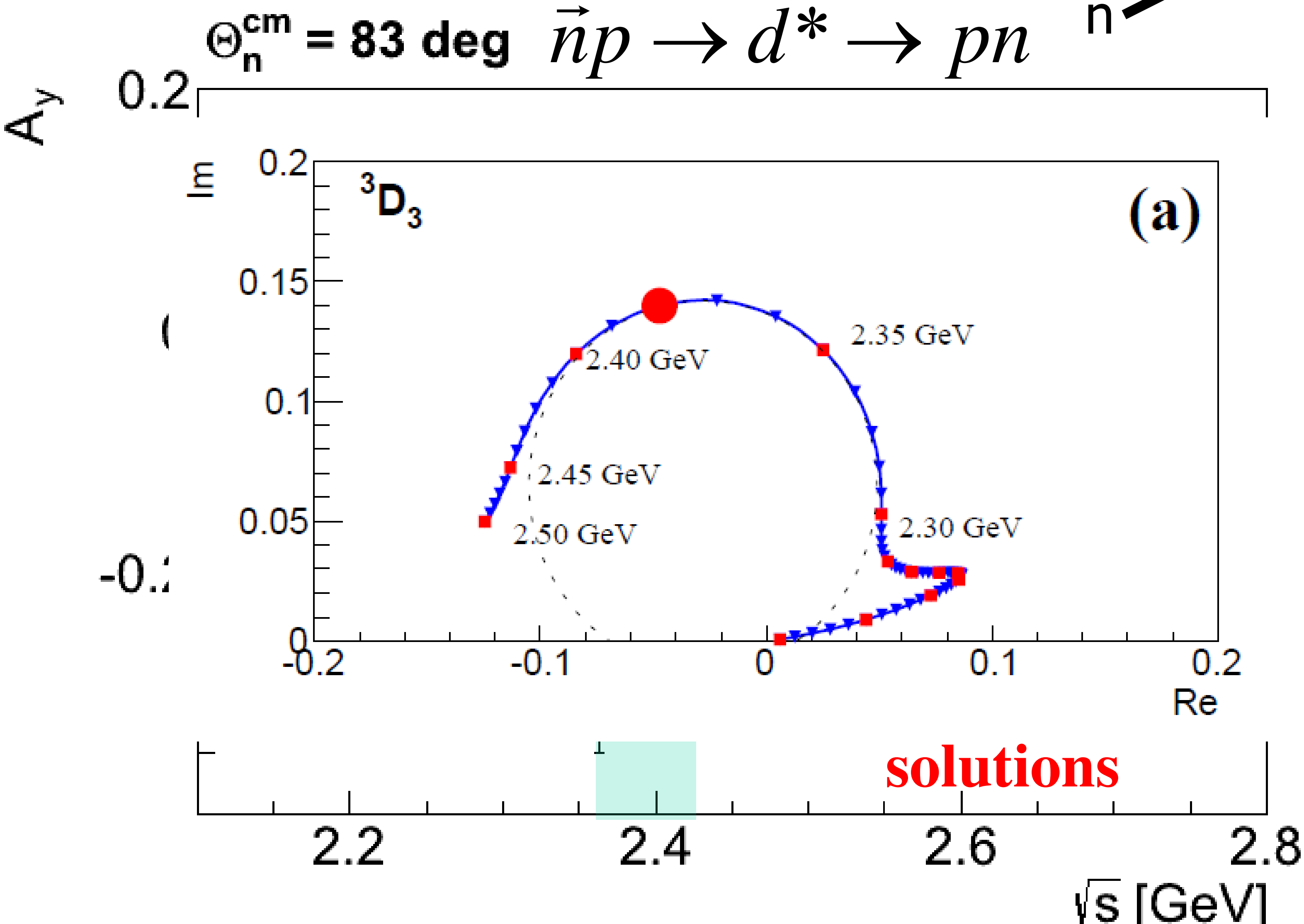
Total cross section pN → dππ



WASA-at-COSY: Phys. Lett. B721 (2013) 229

A_y energy dependence at 83°

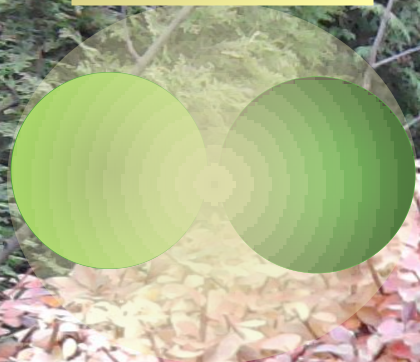




WASA-at-COSY: Phys. Rev. Lett. 112 (2014) 202301

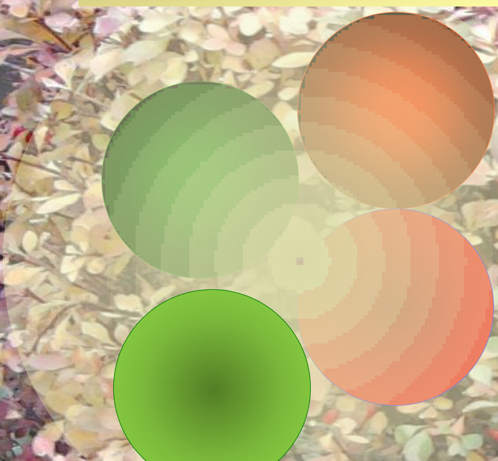
MATTER

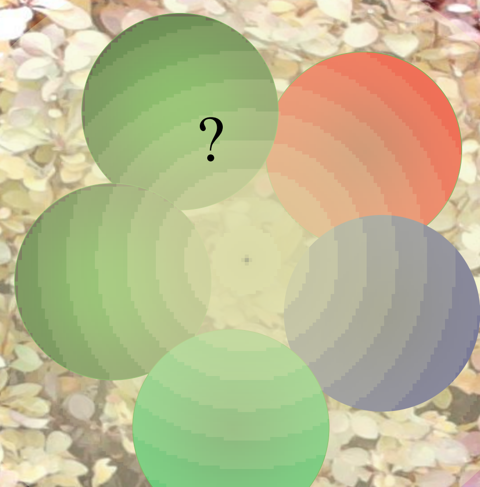
Meson



Baryon

Tetraquark





Dibaryon

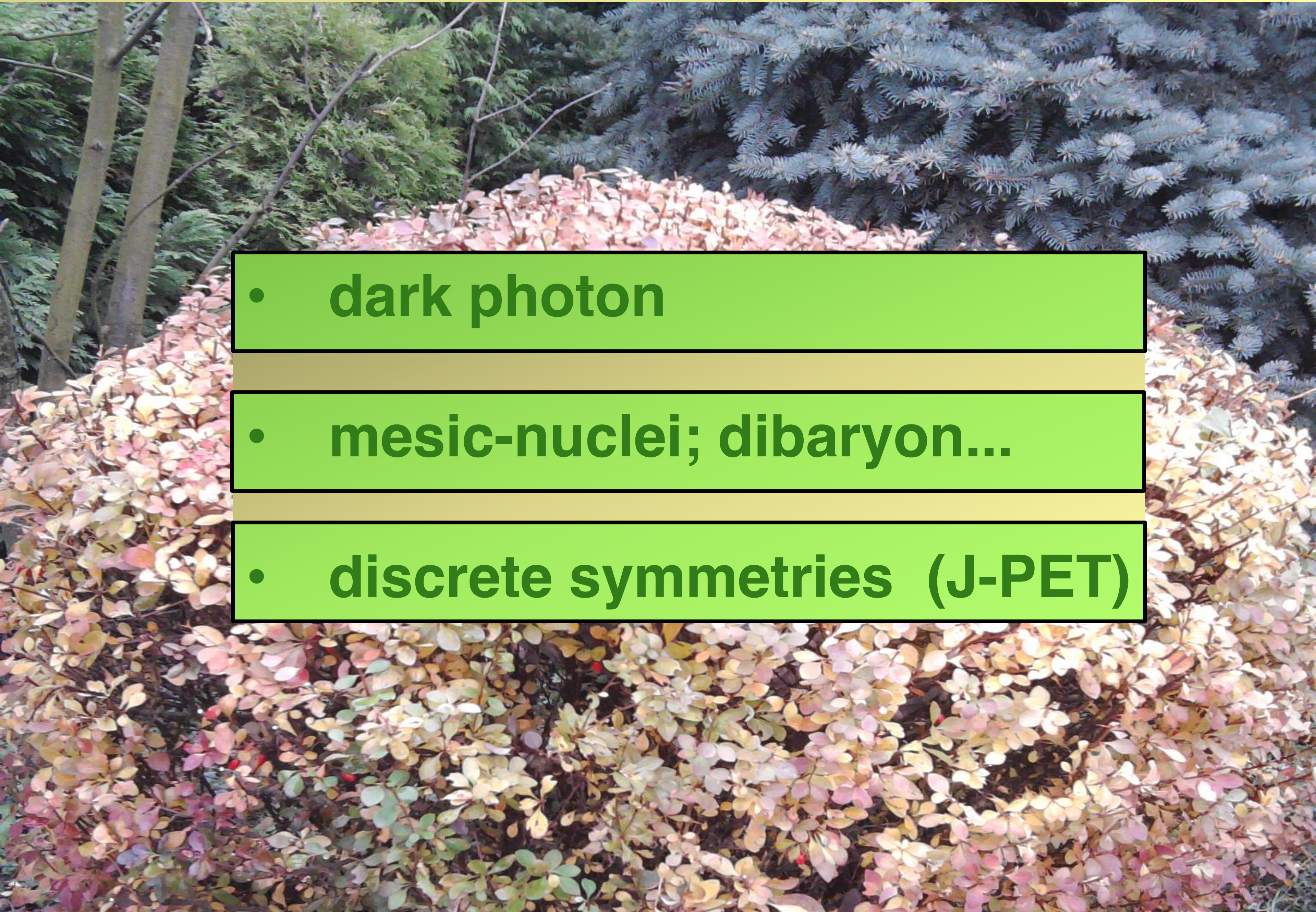
Belle 2008: Phys. Rev. Lett. 100 (2008) 142001
LHCb 2014: Phys. Rev. Lett. 112 (2014) 222002

WASA-at-COSY
Phys. Rev. Lett. 112 (2014) 202311

2014

EXCITING YEAR FOR THE HADRON PHYSICS

Search for the exotic matter at low energies



- dark photon
- mesic-nuclei; dibaryon...
- discrete symmetries (J-PET)

Radiological Laboratory in Warsaw (1934)

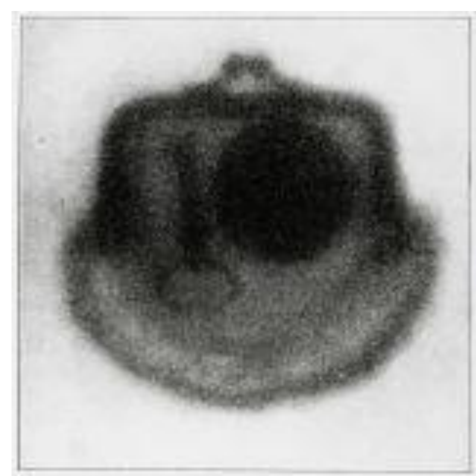
Marian Danysz

$$^{4}He + {}^{14}N \rightarrow {}^{17}F + n$$

$$^{17}F \rightarrow {}^{18}O + e^{+} + \nu$$

Formal leader of the Radiological Laboratory in Warsaw

A girl from Warsaw

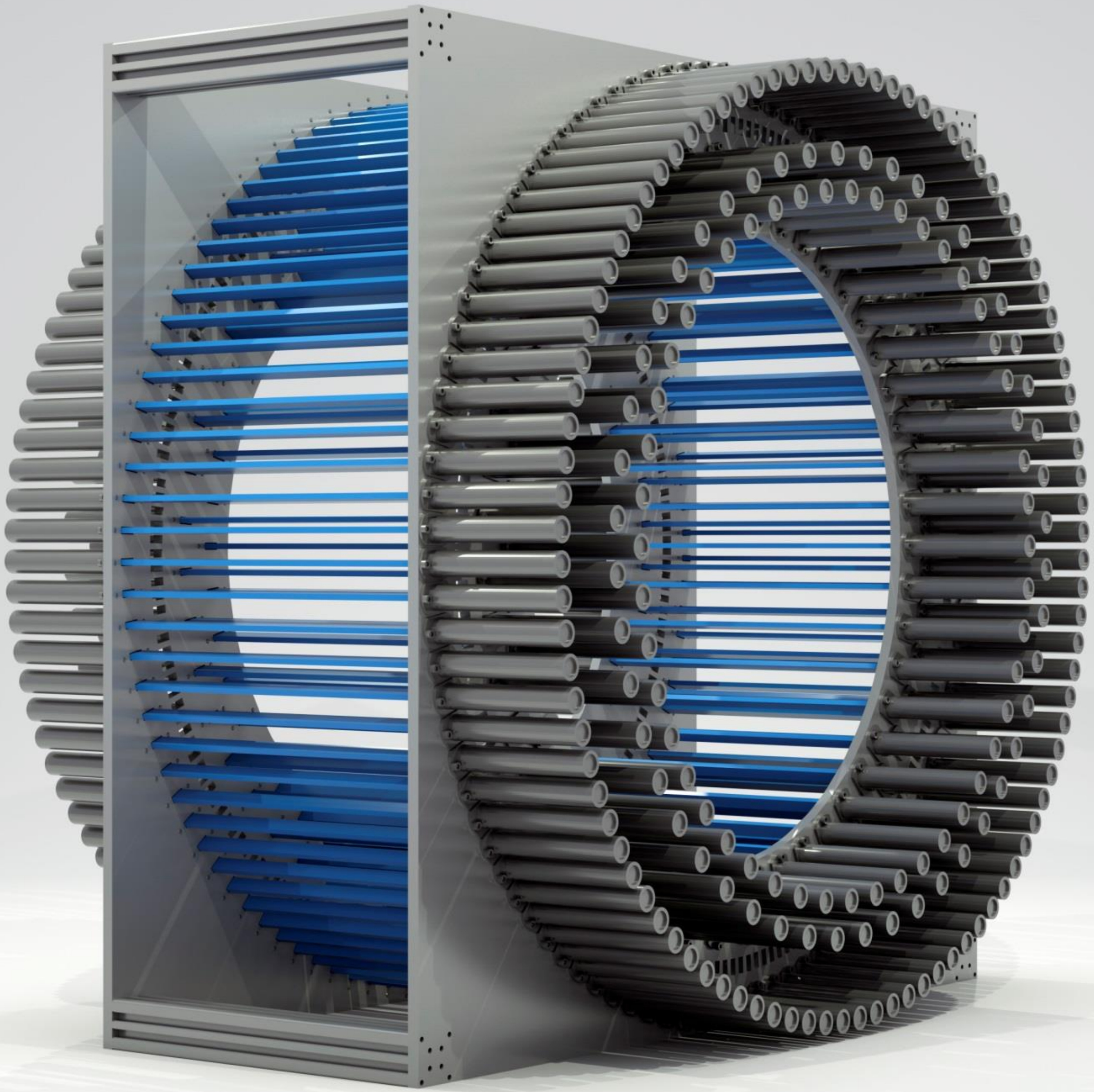


„Radiograph" taken by Maria Curie by exposing a purse to radium.

http://www.galloimages.co.za/

R.F. Mould, The British Journal of Radiology, **71**, 1229 (1998)

J-PET (Jagiellonian PET)



crystals → plastics

Utterly new concept
Experts do not accept it !

KAPITAŁ LUDZKI
NARODOWA STRATEGIA SPÓJNOŚCI

Projekt współfinansowany przez Unię Europejską
w ramach Programu Operacyjnego Kapitał Ludzki

UNIA EUROPEJSKA
EUROPEJSKI
FUNDUSZ SPOŁECZNY

numer umowy: Umowa nr CITTRU/061023/01/10/2009
płatne ze środków: budżetu projektu Kompas innowacji (PSP:S/FS0/0023)
jednostka organizacyjna: CITTRU

Warszawa, dnia 17 listopada 2009 roku.

P. M., Patent (2014) No. EP2454612B1, WO2011008119.

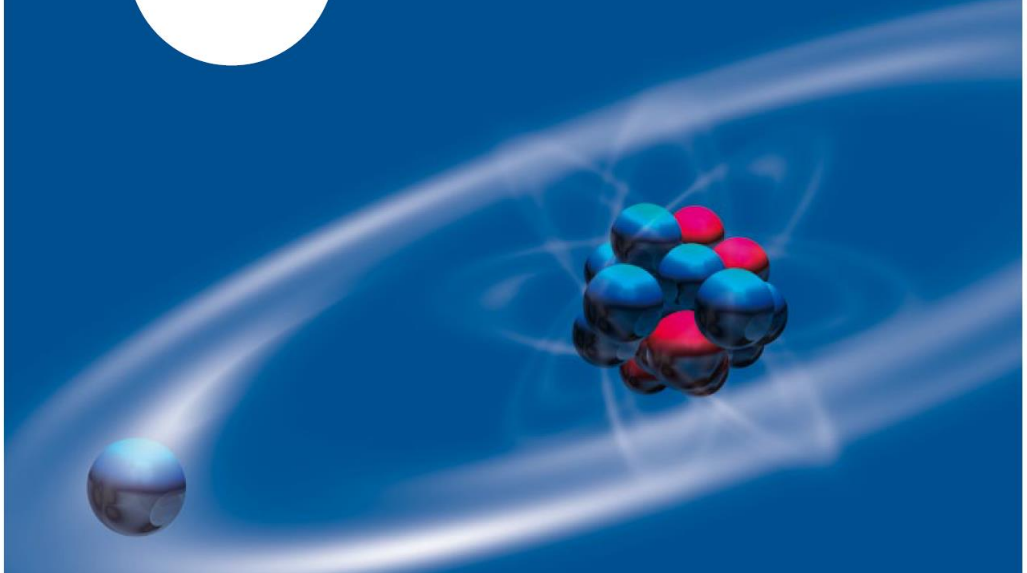
Recenzja wniosku patentowego nr 9534/09

„Urządzenie matrycowe i sposób do wyznaczania miejsca i czasu reakcji kwantów gamma oraz zastosowanie urządzenia do wyznaczania miejsca i czasu reakcji kwantów gamma w emisyjnej tomografii pozytonowej"

Kierując się obecnym stanem wiedzy, zarówno z zakresu dostępnych technologii, jaki i podstaw fizyki uważam, że proponowane rozwiązanie nie nadaje się do zastosowania w praktyce. Przedłożony wniosek przedstawia ogólną definicję tomografii pozytonowo emisyjnej, natomiast w dalszym jego części proponuje rozwiązania, które świadczą o niezrozumieniu zasady działania układu detekcyjnego będącego fizyczną podstawą dyskutowanej metody obrazowania, czyli detekcji kwantów anihilacji gamma o energii 511 keV.

EUROPEAN SCIENCE FOUNDATION

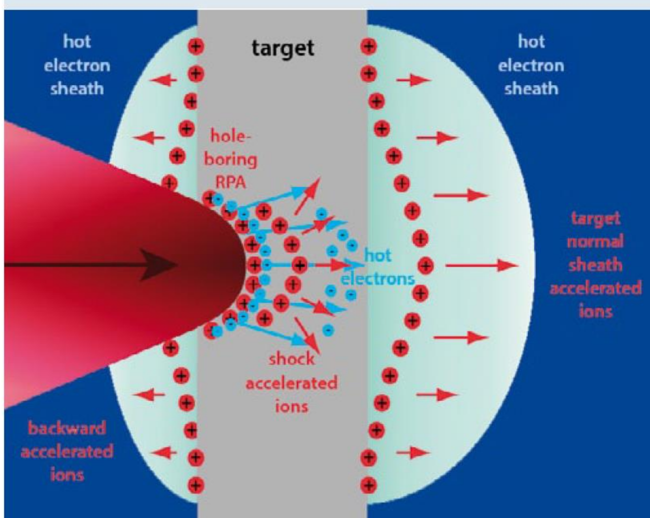
NuPECC

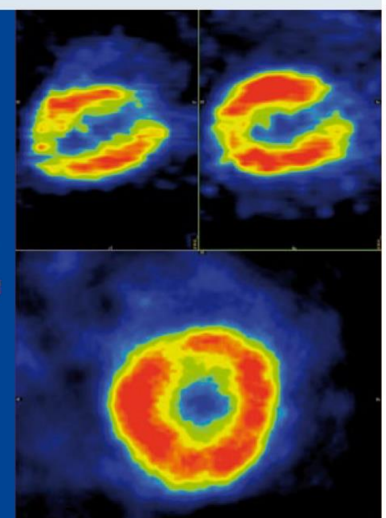


Printed April 2014

Nuclear Physics European Collaboration Committee (NuPECC)

Nuclear Physics for Medicine





J-PET (Jagiellonian PET)

crystals
→ plastics

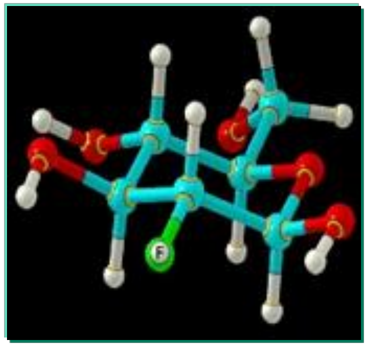
P. M. et al., Radioteraphy and Oncology 110 (2014) S69
L. Raczyński et al., Nucl. Instrum. Meth. A764 (2014) 186
P. M. et al., Nucl. Instrum. Meth. A764 (2014) 317
12 International patent applications

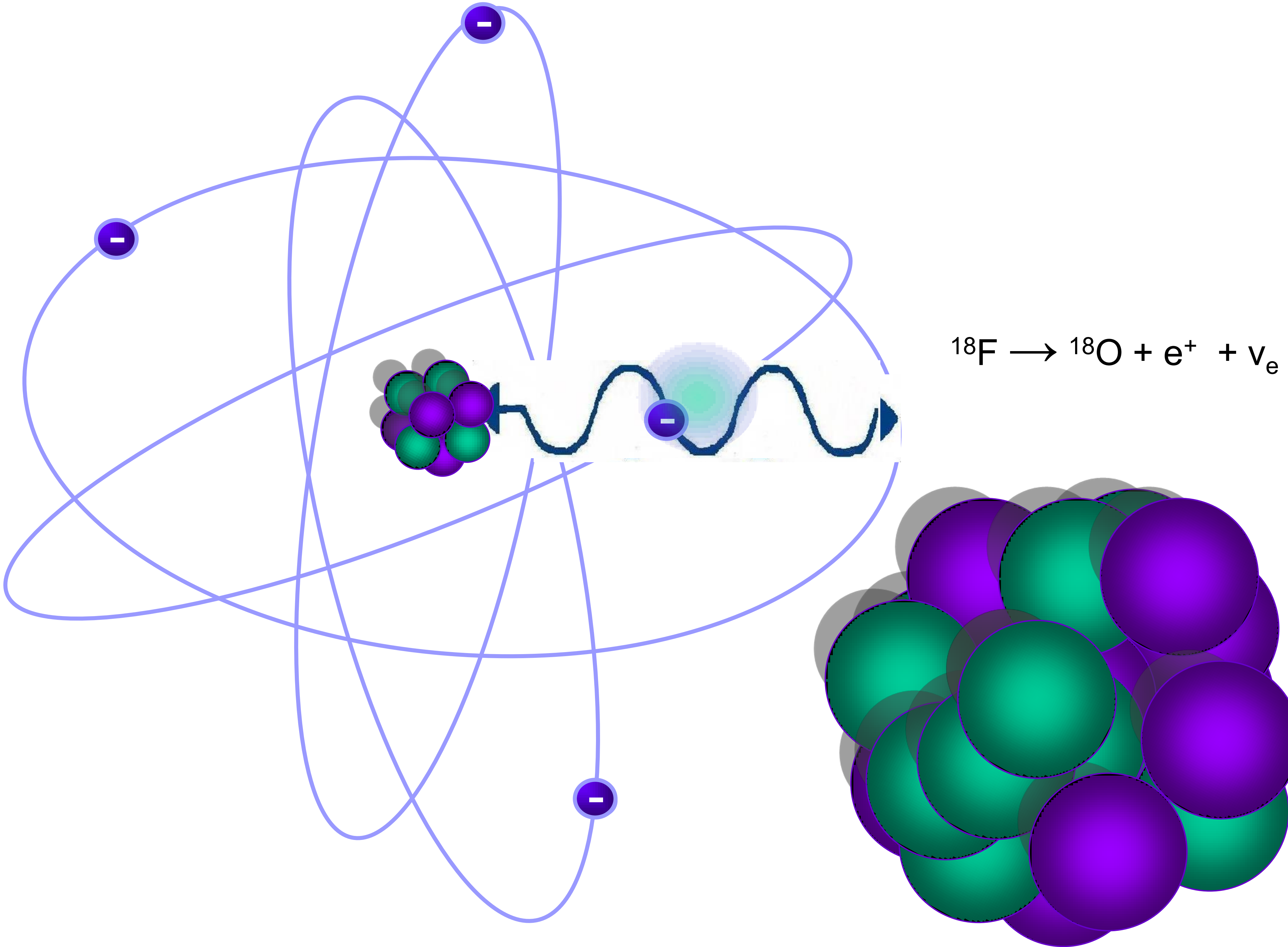
Increased glycolysis in tumor cells
-Warburg phenomenon-
20-30 time higher glucose metabolism

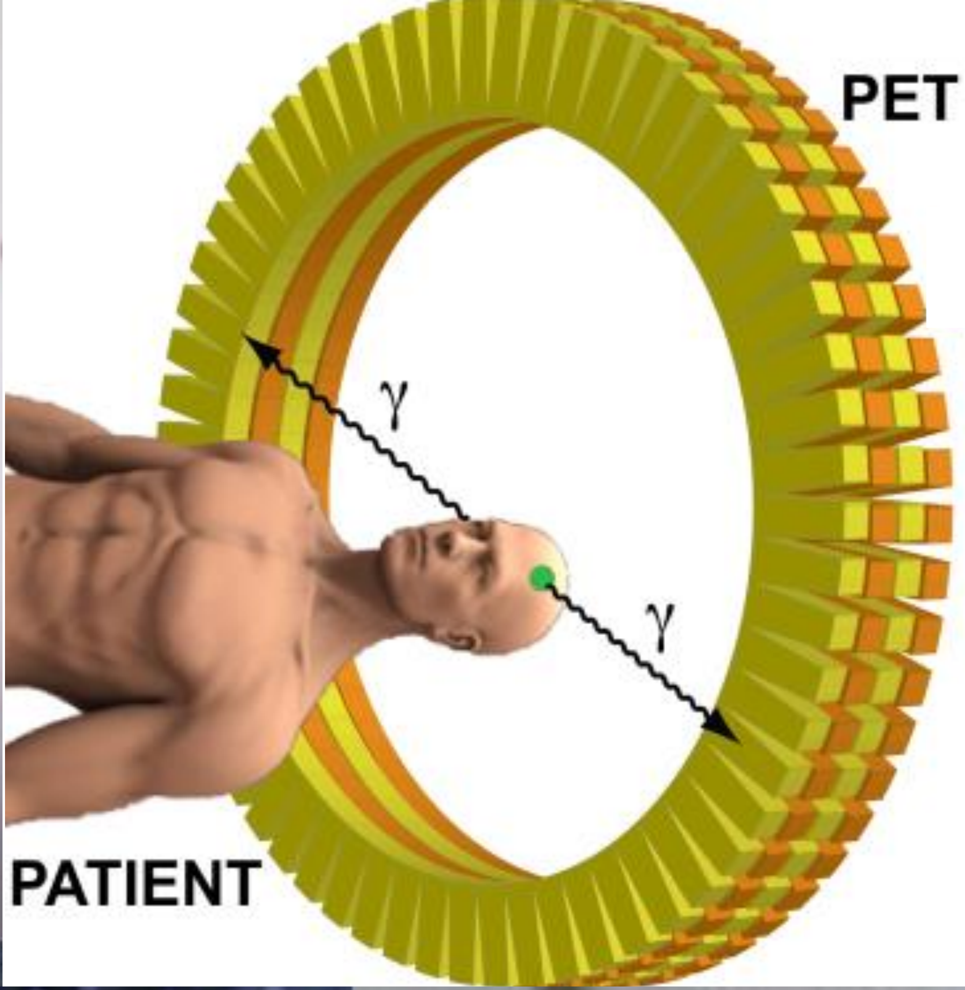
Due to the structure differences between glucose and FDG, FDG is trapped
In malignant cells.

RADIOACTIVE SUGER

Fluoro–deoxy-glucose
(F-18 FDG)



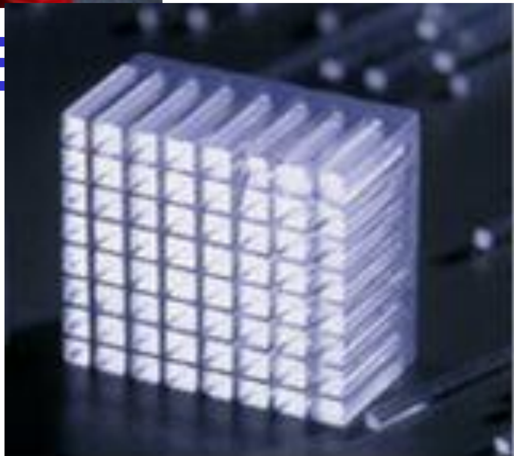

$^{18}F \longrightarrow {}^{18}O + e^{+} + v_e$



RADIOACTIVE SUGE

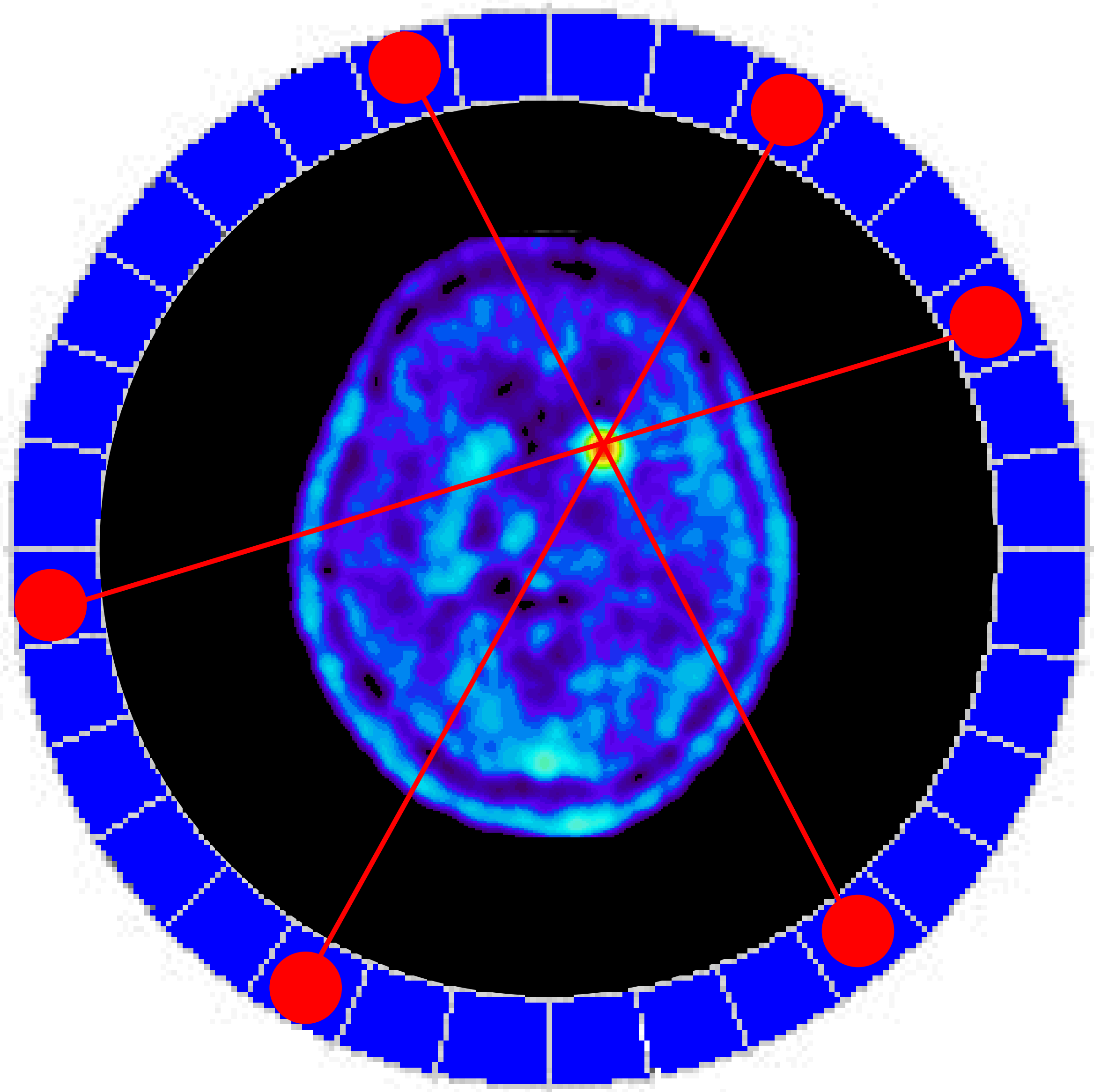
Fluoro–deoxy-glucose (F-18 FDG)

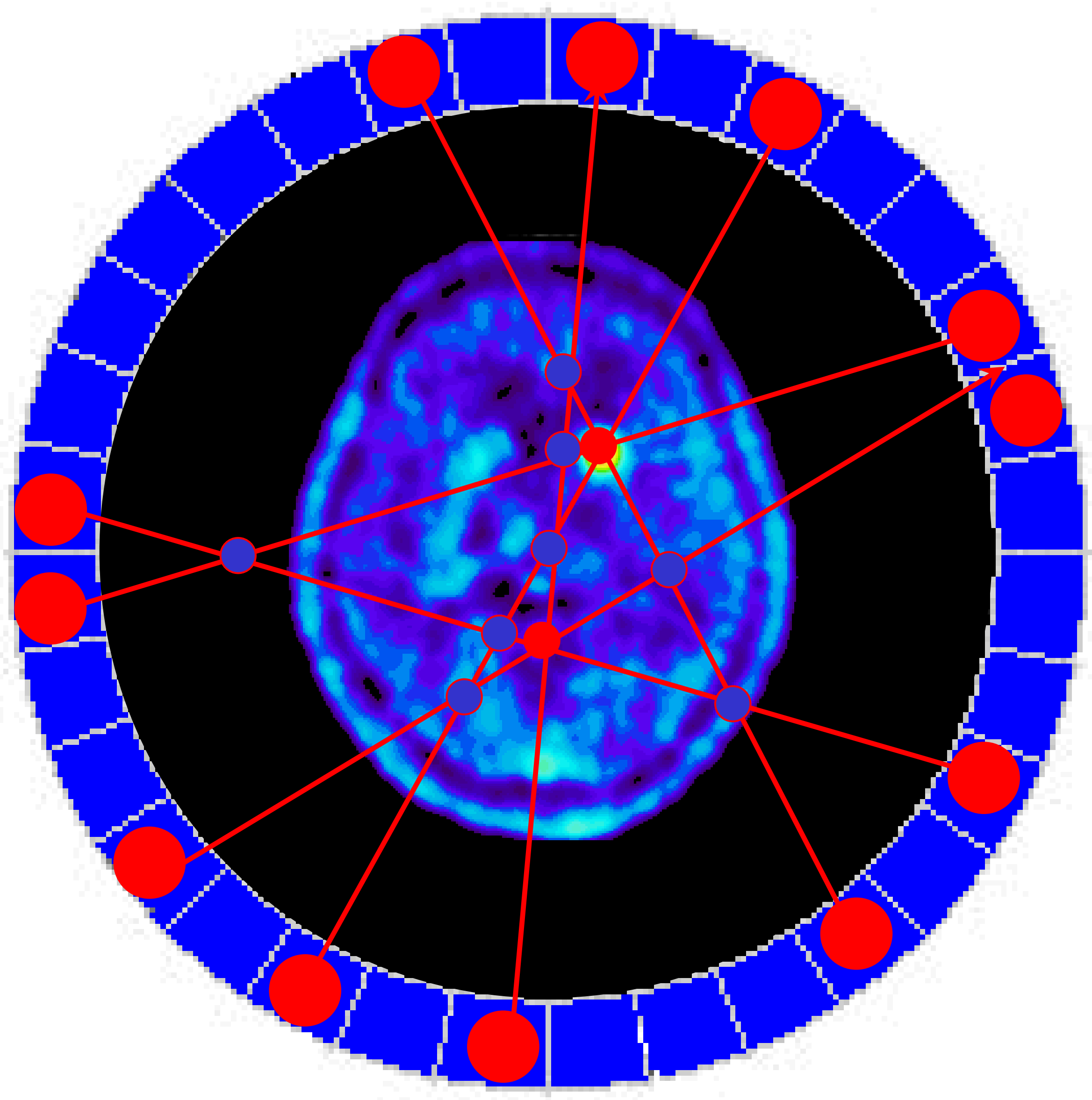
~200 000 000 gamma per second

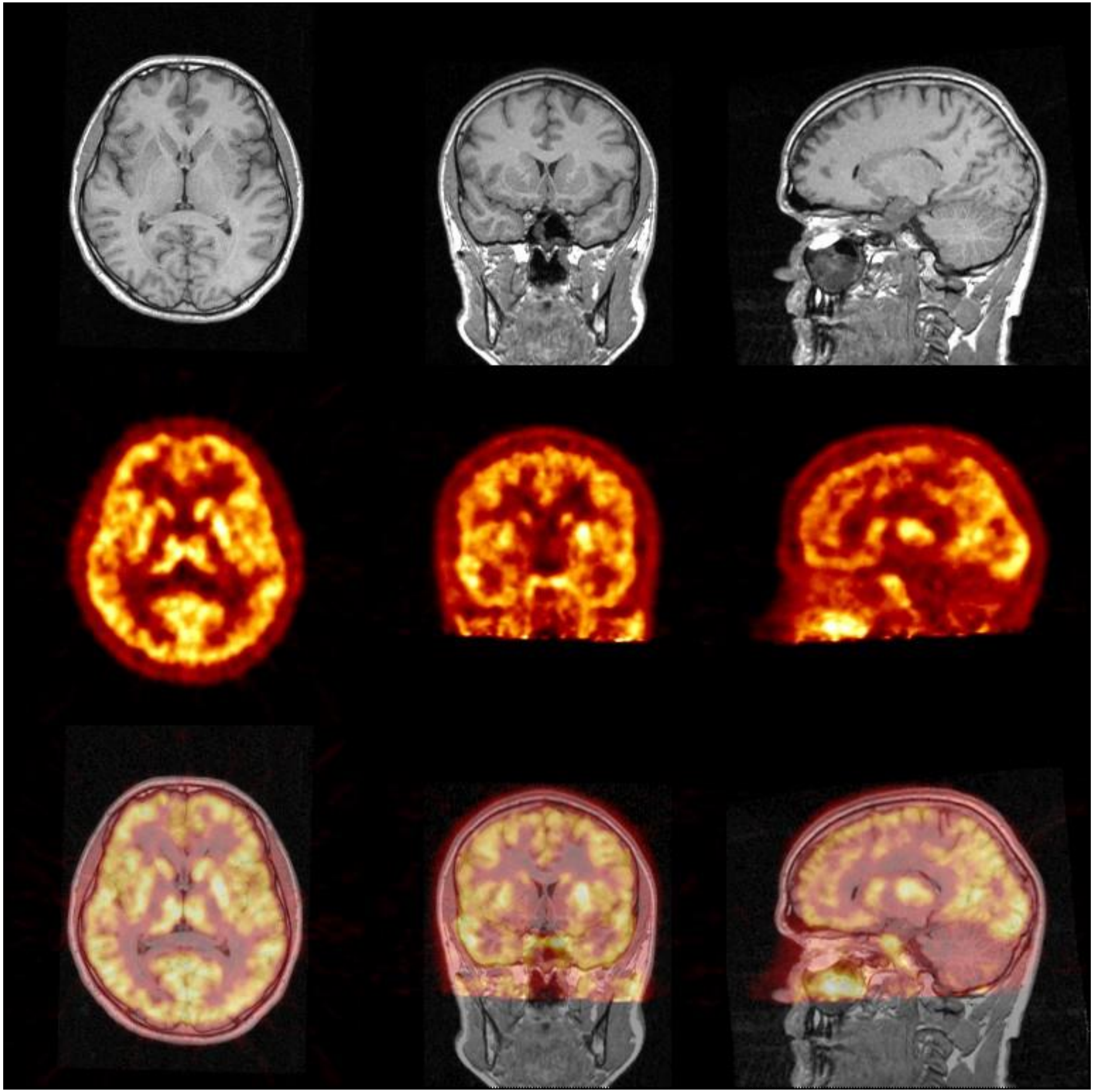


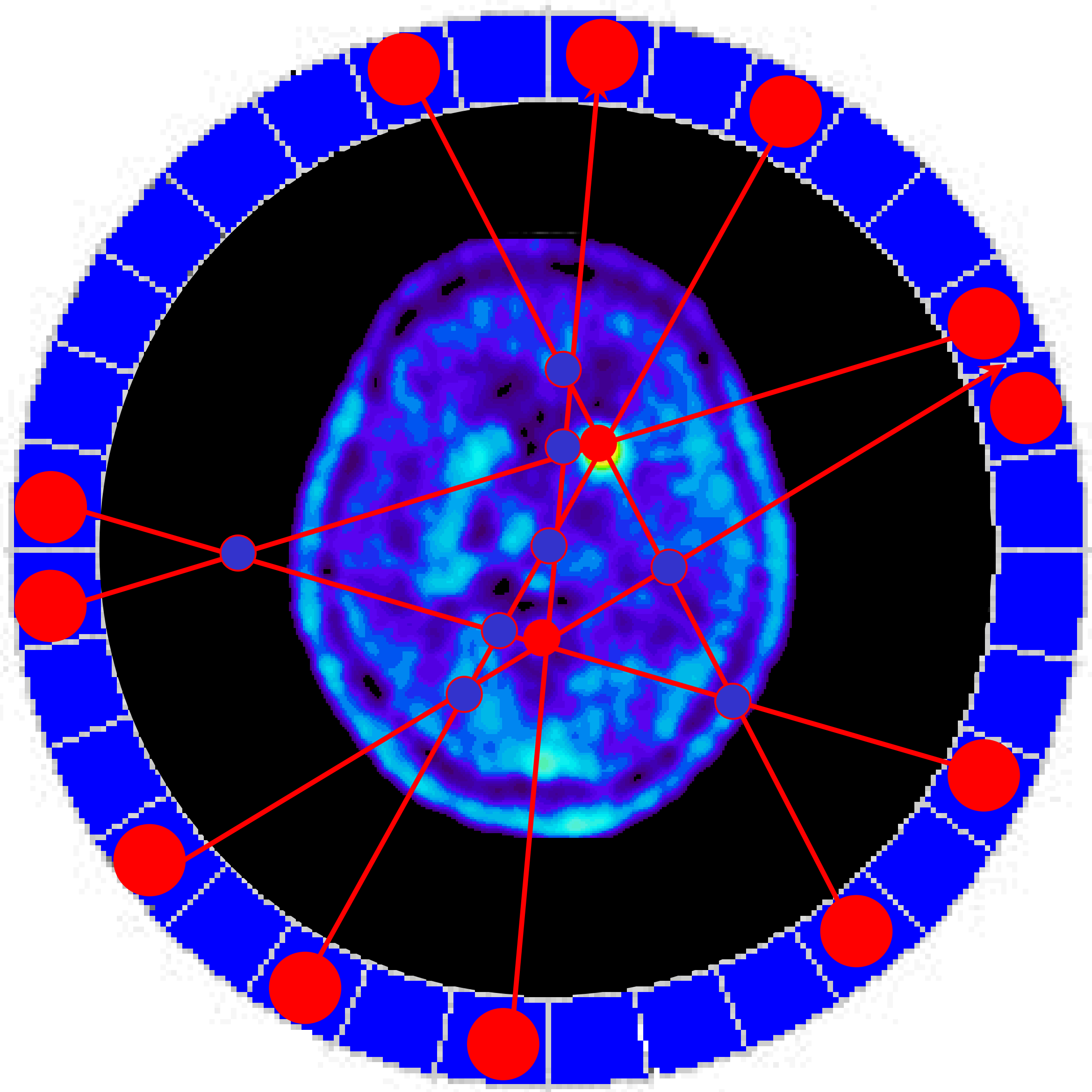
LIGHT SIGNALS FROM POLYMERS ARE MUCH „FASTER” !!!

name	type	density [g/cm³]	decay time [ns]	photons/ MeV	mean free path [cm]
BGO	crystal	7.13	300	6000	1.04
GSO	crystal	6.71	50	10000	1.49
LSO	crystal	7.40	40	29000	1.15
NE102A	polymer	1.032	2.4	10000	10.2
BC404	polymer	1.032	1.8	10000	10.2
RP422	polymer	1.032	1.6	10000	10.2



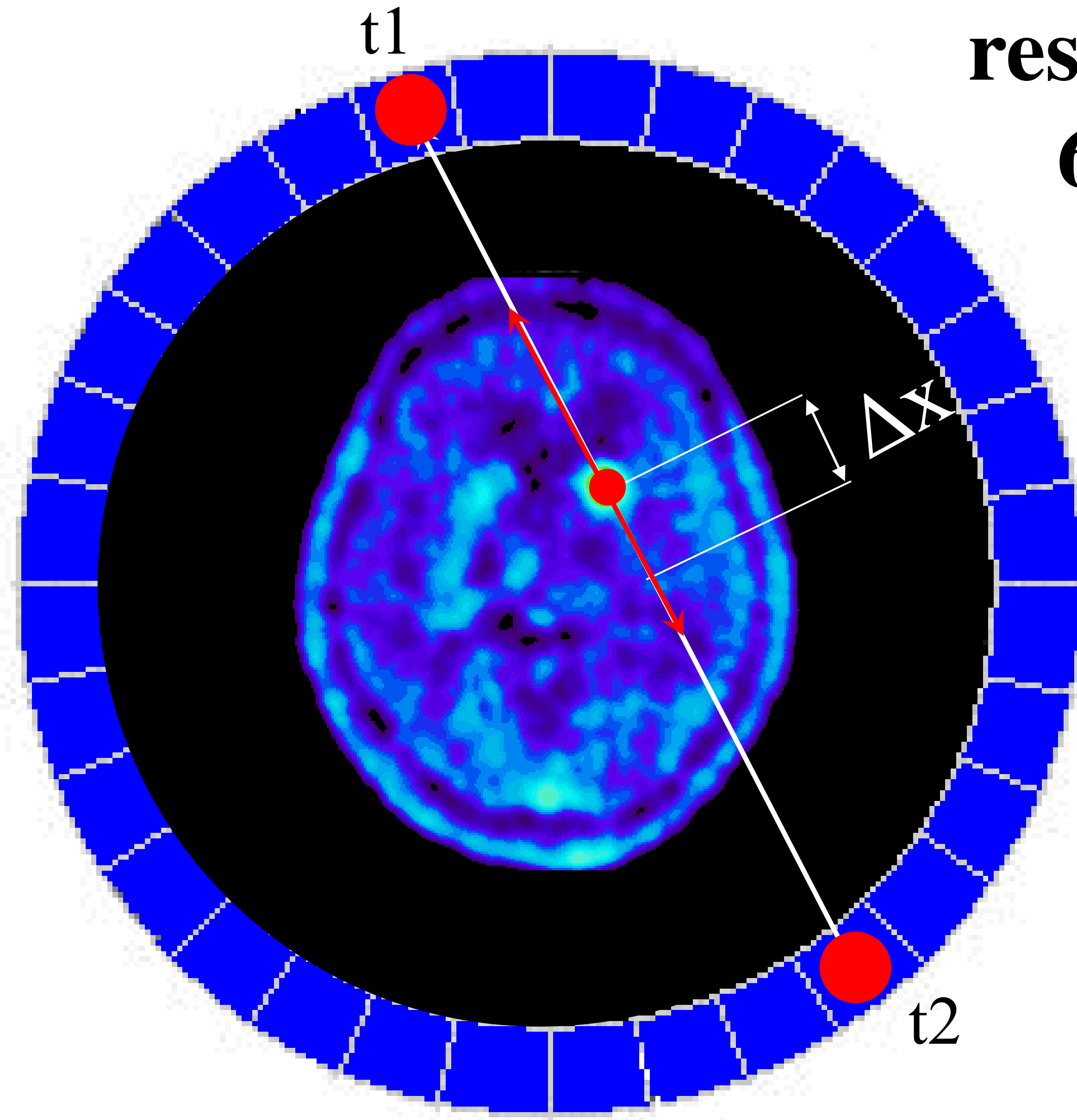




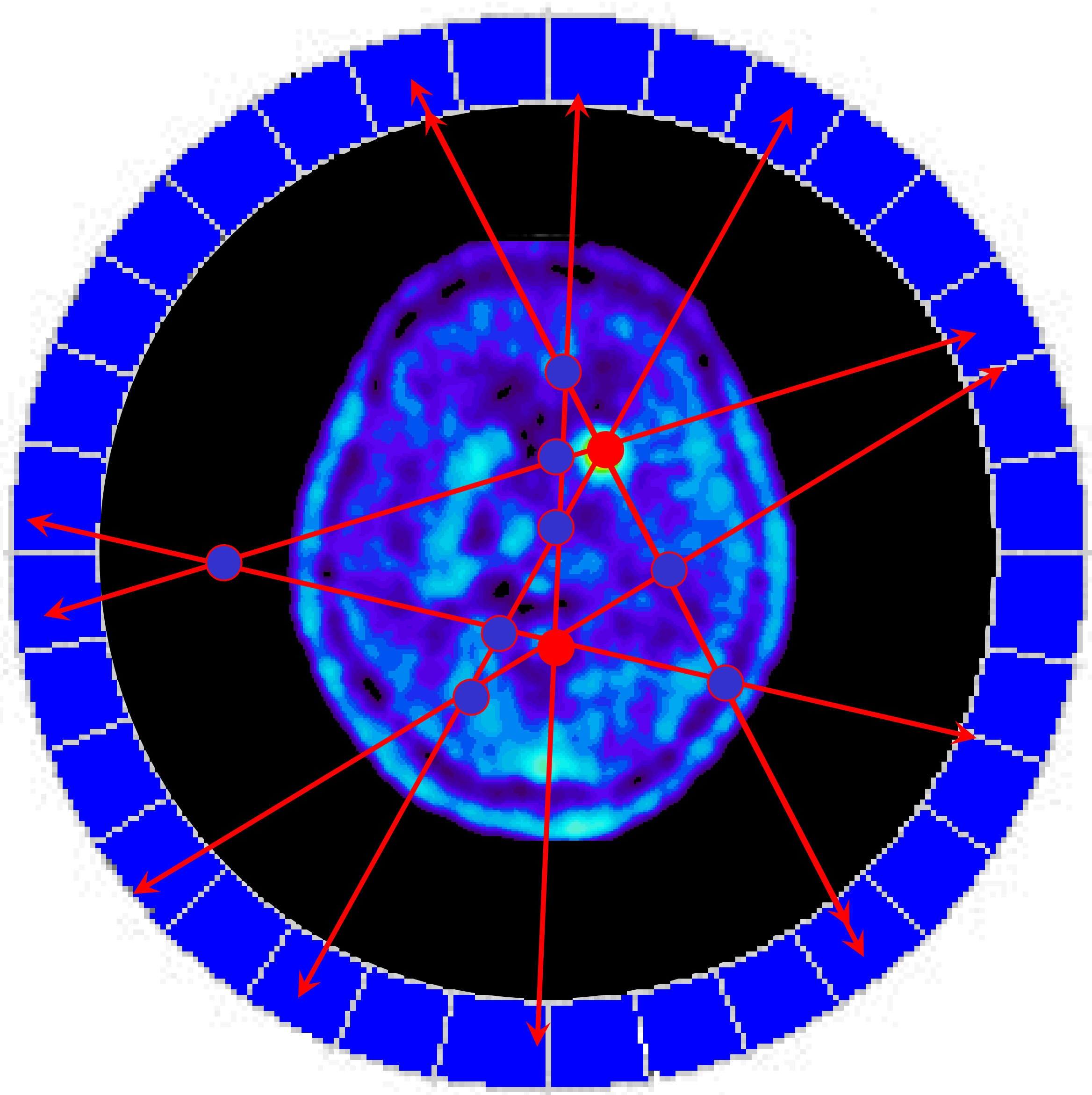


PET-TOF

$$\Delta x = (t2 - t1)\, c / 2$$



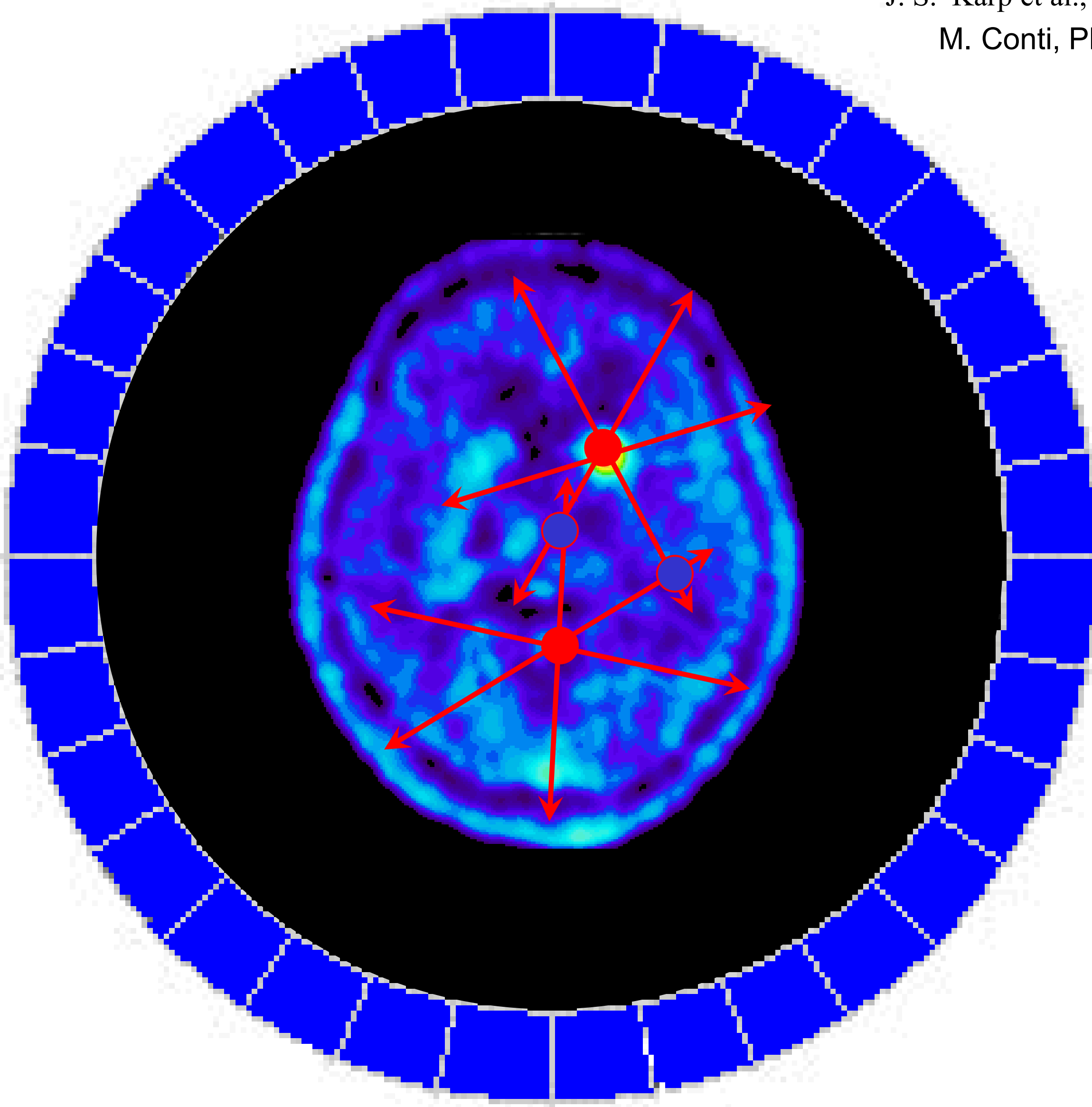
resolution 600ps



signal/background ~ D / Δt

40cm/600ps improvement by factor of 4

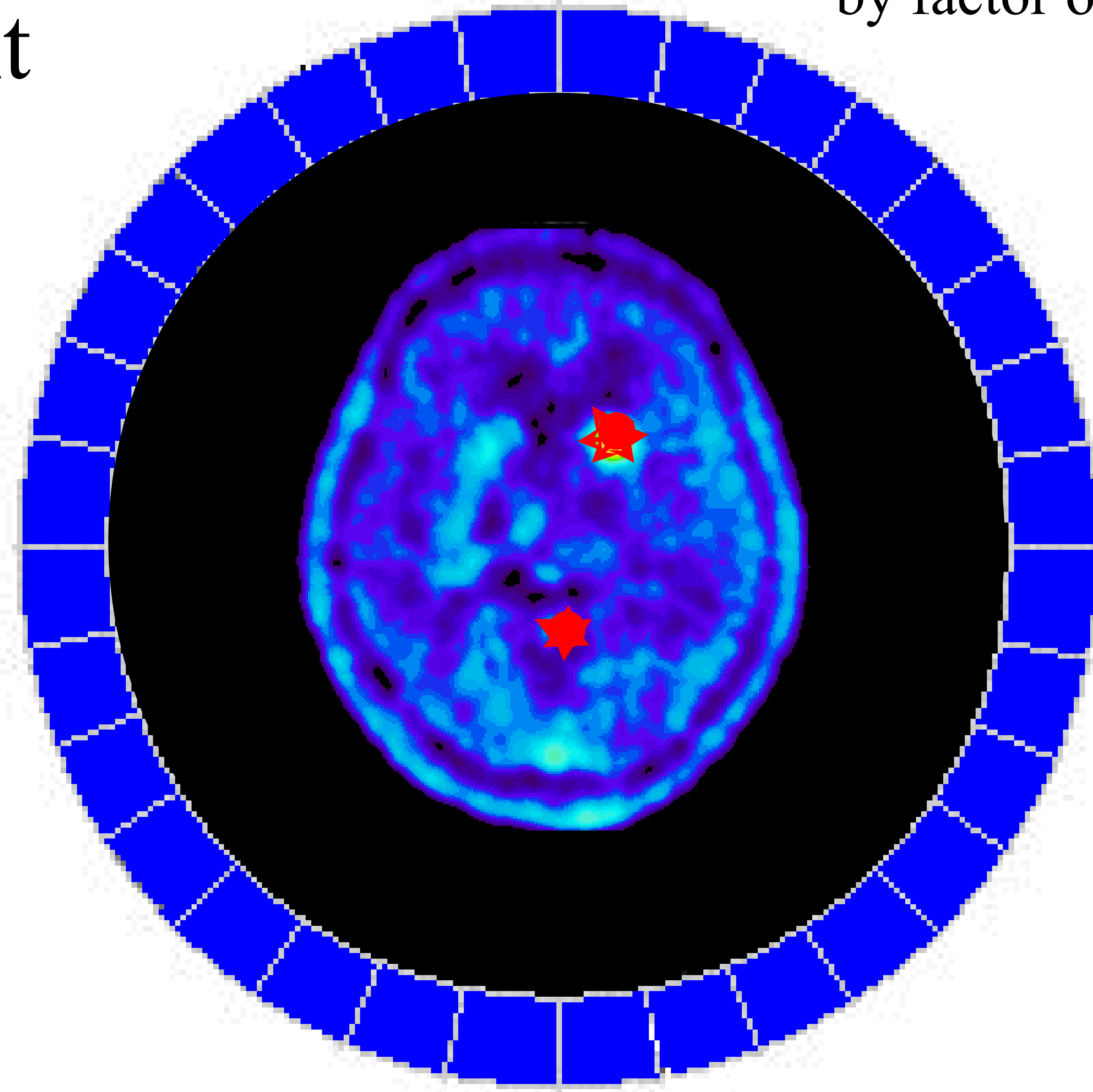
J. S. Karp et al., J Nucl Med 2008; 49: 462
M. Conti, Physica Medica 2009; 25: 1.



signal / background

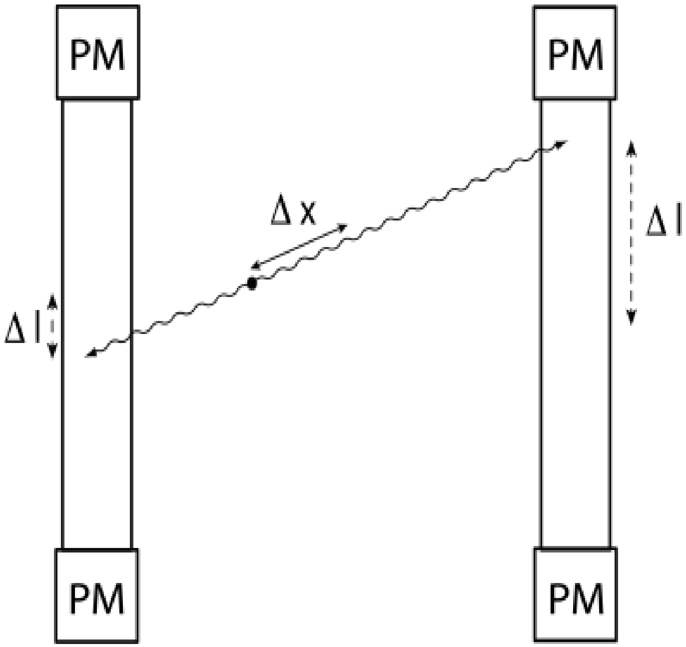
~ D / Δt

40cm/70ps improvement by factor of 30

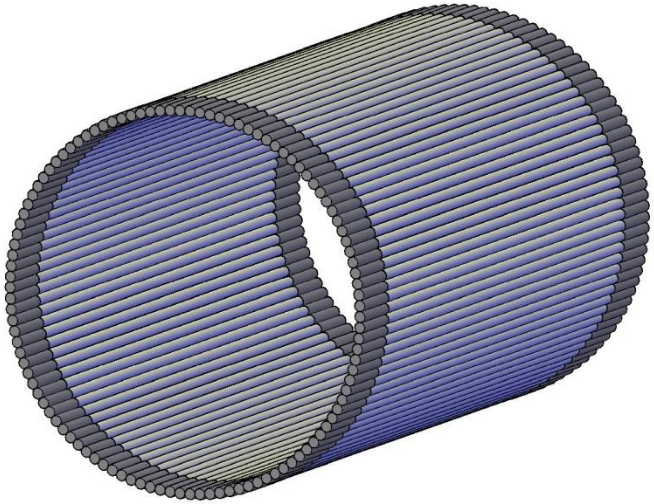


J-PET (**J**agiellonian **PET**)

$\Delta l = (t2 - t1)\, v / 2$



$\Delta x = (t\_l - t\_r)\, c / 2$



$\mathrm{FWHM}(\Delta l) \approx \mathrm{FWHM}(\Delta t) * c/4$
$\mathrm{FWHM}(\Delta x) \approx \mathrm{FWHM}(\Delta t) * c / 2\sqrt{2}$

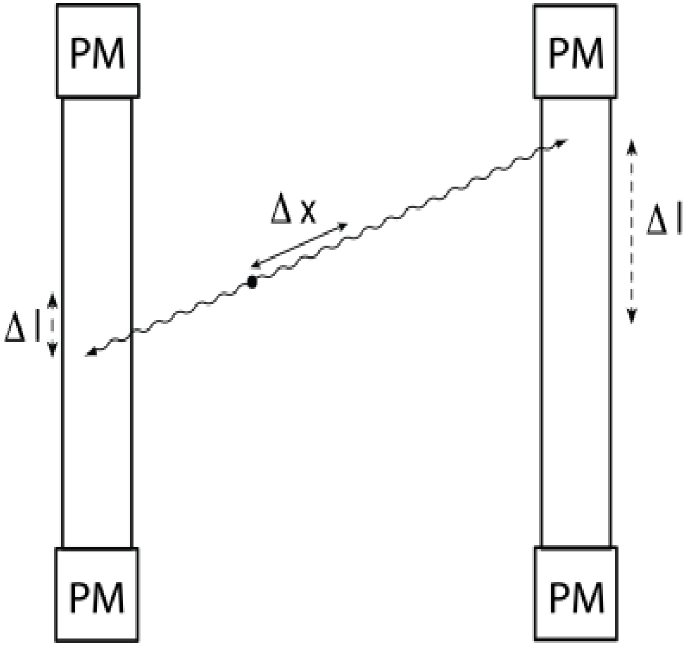
Lets take advantage of TIME resolution not only for TOF but also for the determination of hit positions

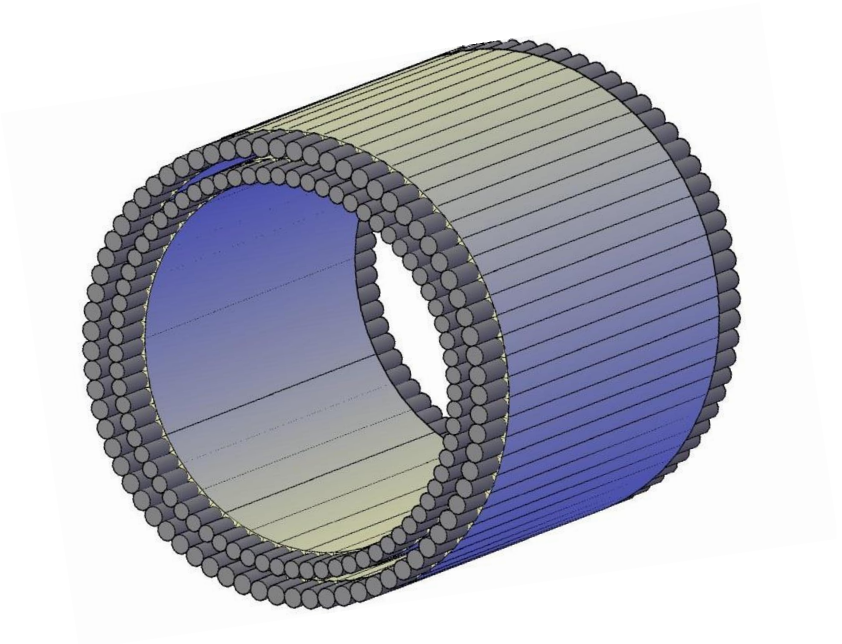
Thus for example:

$\mathrm{FWHM}(\Delta t) = 100\mathrm{ps} \rightarrow \mathrm{FWHM}(\Delta l) = 0.7\mathrm{cm} \rightarrow \mathrm{FWHM}(\Delta x) = 1\ \mathrm{cm}$

J-PET (**J**agiellonian **PET**)

$\Delta l = (t2 - t1)\, v / 2$

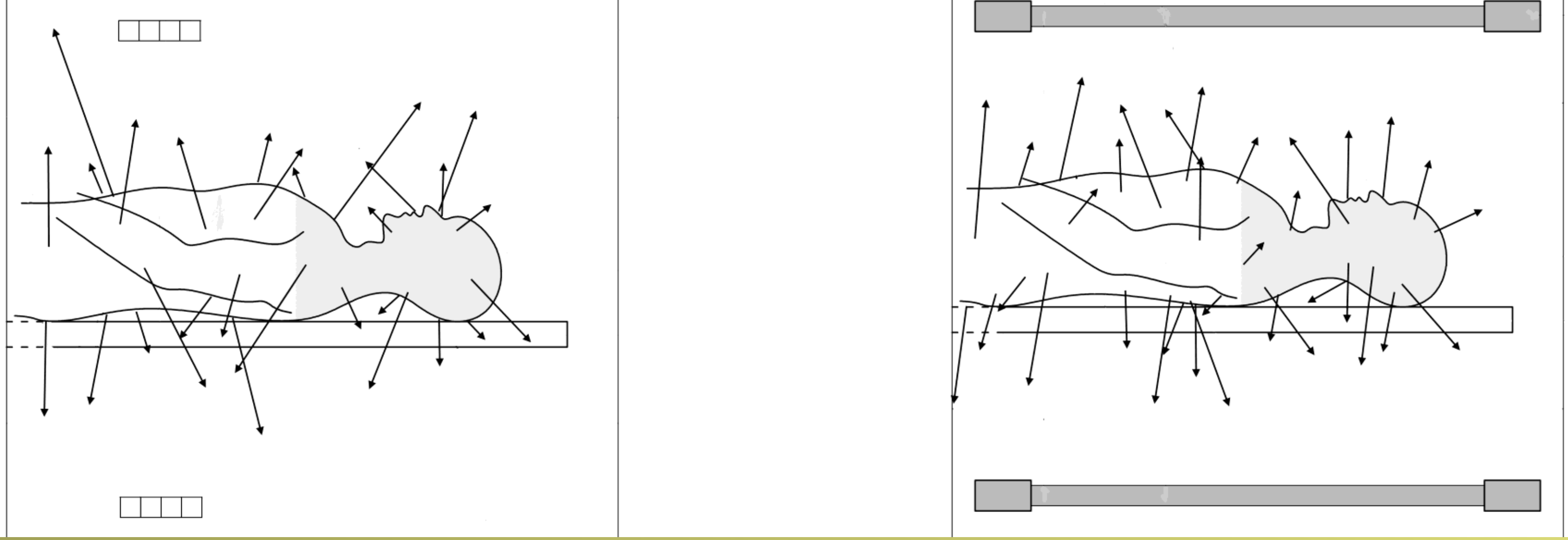




$\Delta x = (t\_l - t\_r)\, c / 2$

FWHM(Δl) ≈ FWHM(Δt) * c/4
FWHM(Δx) ≈ FWHM(Δt) * c / 2√2

Thus for example:
FWHM(Δt) = 100ps → FWHM(Δl) = 0.7cm → FWHM(Δx) = 1 cm



It is important to note that the cost of J-PET does not increase with the increas of the FOV

epsilon^2 = 20 to 40 smaller efficiency

But

2D --> 3D -------------------- > factor of ~5

600ps --> 100ps – 200ps --> factor of 6 -- 3

1m instead of 20cm ---------> factor of 9

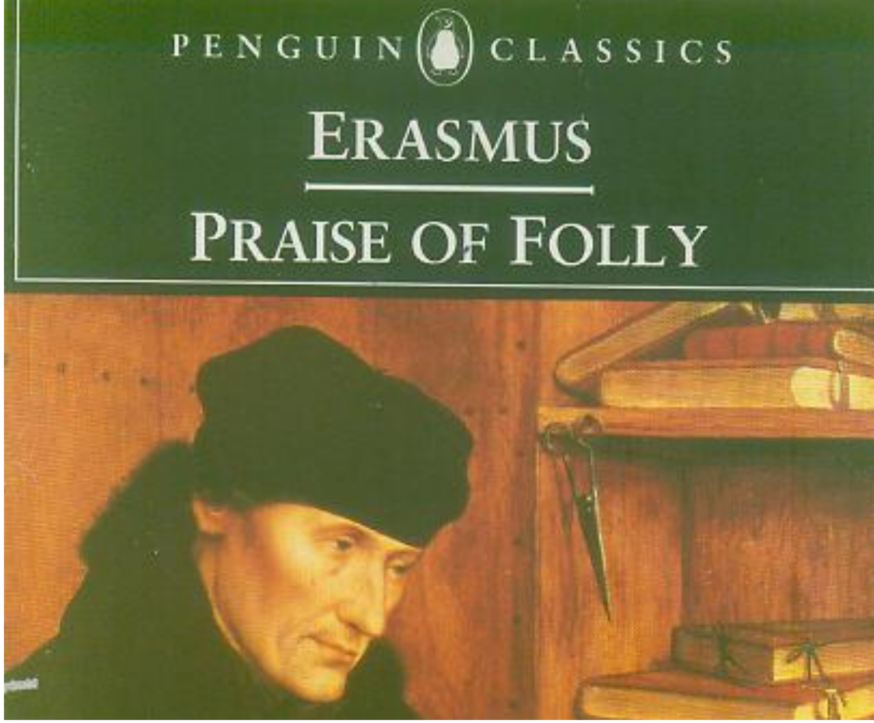
N layers in the strip-PET --> factor **N^2**

For N=1 --- -> total factor of ~ 200

Lower dose by factor of 7 (200 better / 30 worse)

Accidental coincidences less by factor of about 1000

(epsilon * 7)^2



eulogies in praise of gods and heroes, so it's a eulogy you are going to hear now, though not one of Hercules or Solon. It's in praise of myself, namely, Folly.

Now, I don't think much of those wiseacres who maintain it's the height of folly and conceit if anyone speaks in his own praise; or rather, it can be as foolish as they like, as long as they admit it's in character. What could be more fitting than for Folly to trumpet her own merits abroad and 'sing her own praises'.[6] Who could portray me better than I can myself? Unless, of course, someone knows me better than I know myself. Yet in general I think I show a good deal more discretion than the general run of gentry and scholars, whose distorted sense of modesty leads them to make a practice of bribing some sycophantic speaker or babbling poet hired for a fee so that they can listen to him praising their merits, purely fictitious though these are. The bashful listener spreads his tail-feathers like a peacock and carries his head high, while the brazen flatterer rates this worthless individual with the gods and sets him up as the perfect model of

Finally, I follow the well-worn popular proverb

which says that

a man does right to prise himself

if he can't find anyone else to prise him

dialectic and rhetoric).

6. Folly here quotes a Greek proverb in Greek, as she does three times more in the following lines. Most of the proverbs are commented on in the *Adages*.

Solon, the law-giver who reformed the Athenian constitution, is famous for the introduction of humane and liberal legal, social and political systems.

7. The Greek phrase for 'infinity doubled', actually 'through two octaves' indicates, says Lijster, the greatest interval in musical harmony, known popularly, he says, as 'the double octave'.

on behalf and for the J-PET collaboration

Jagiellonian - PET

particle and nuclear physics, electronics, IT, chemistry

Supported by Polish National Center for Development and Research

since June 2012 for two years

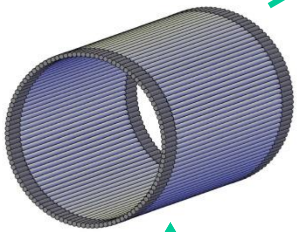
INSTYTUT FOTONOWY COMPANY

ELECTRONICS

P. Salabura, T. Kozik,
M. Pałka, P. Strzempek

Nowoczesna Elektronika COMPANY

DAQ TRIGGERLESS
G. Korcyl, M. Kajetanowicz



SIMULATIONS
P. Kowalski, W. Wiślicki
(Świerk Computing Centre)
D. Kamińska, O. Rundel

EXPERIMENTS, CALIBRATIONS
D. Alfs, T. Bednarski, E. Czerwinski,
J. Smyrski, E. Kubicz,
Sz. Niedźwiecki, M. Silarski,
M. Zieliński

Analysis framework
W.Krzemień, T. Gruntowski,
A.Gruntowski

SYNTHESIS OF SCINTILLATORS
Ł. Kapłon,
A. Wieczorek,
A. Kochanowski,
M. Molenda,
A. Danel (AU)

TIME and HIT-POSITION
RECONSRUCTION
L. Raczyński, N. Sharma, N.Zoń

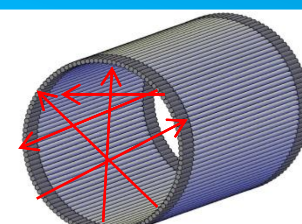
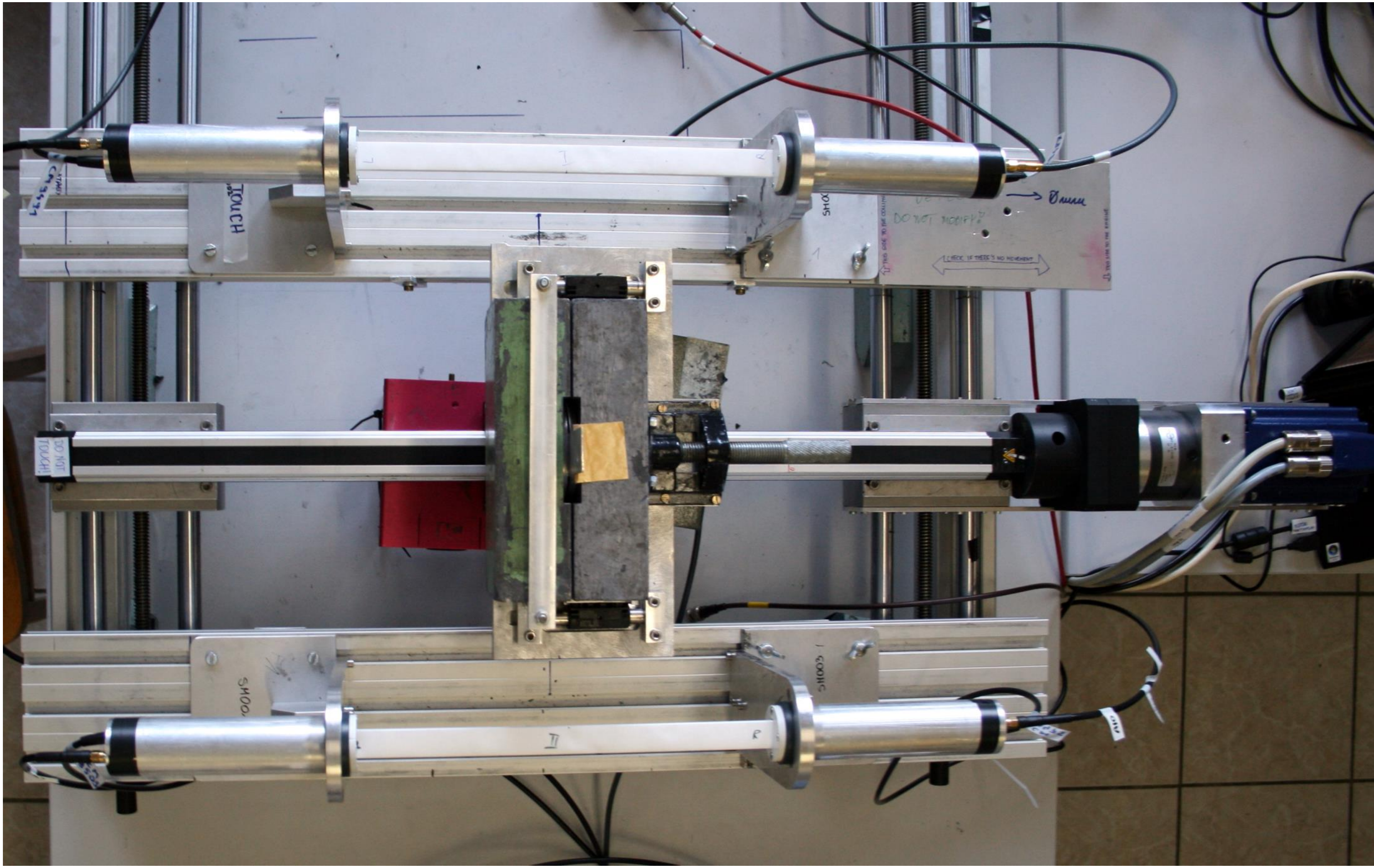
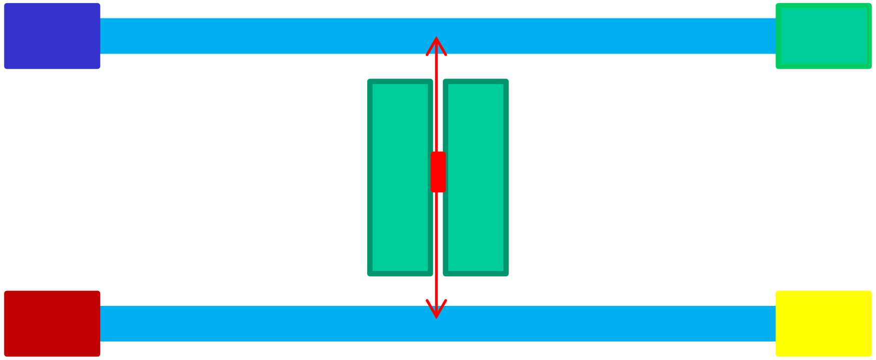


IMAGE RECONSTRUCTION
P. Białas, J. Kowal, Z. Rudy,
A. Słomski, A. Strzelecki

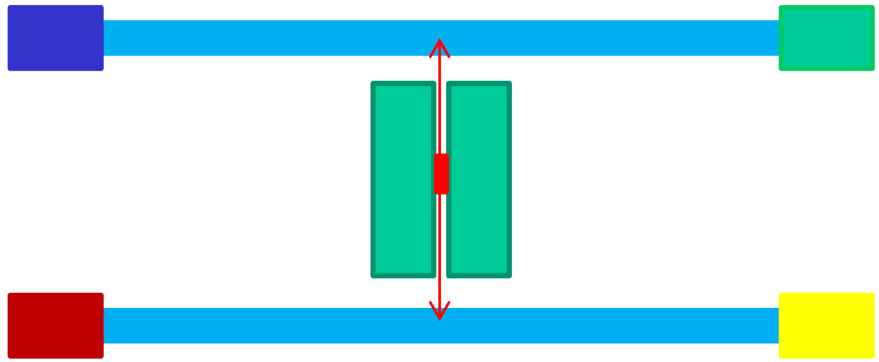
IMAGE
VISUALISATION

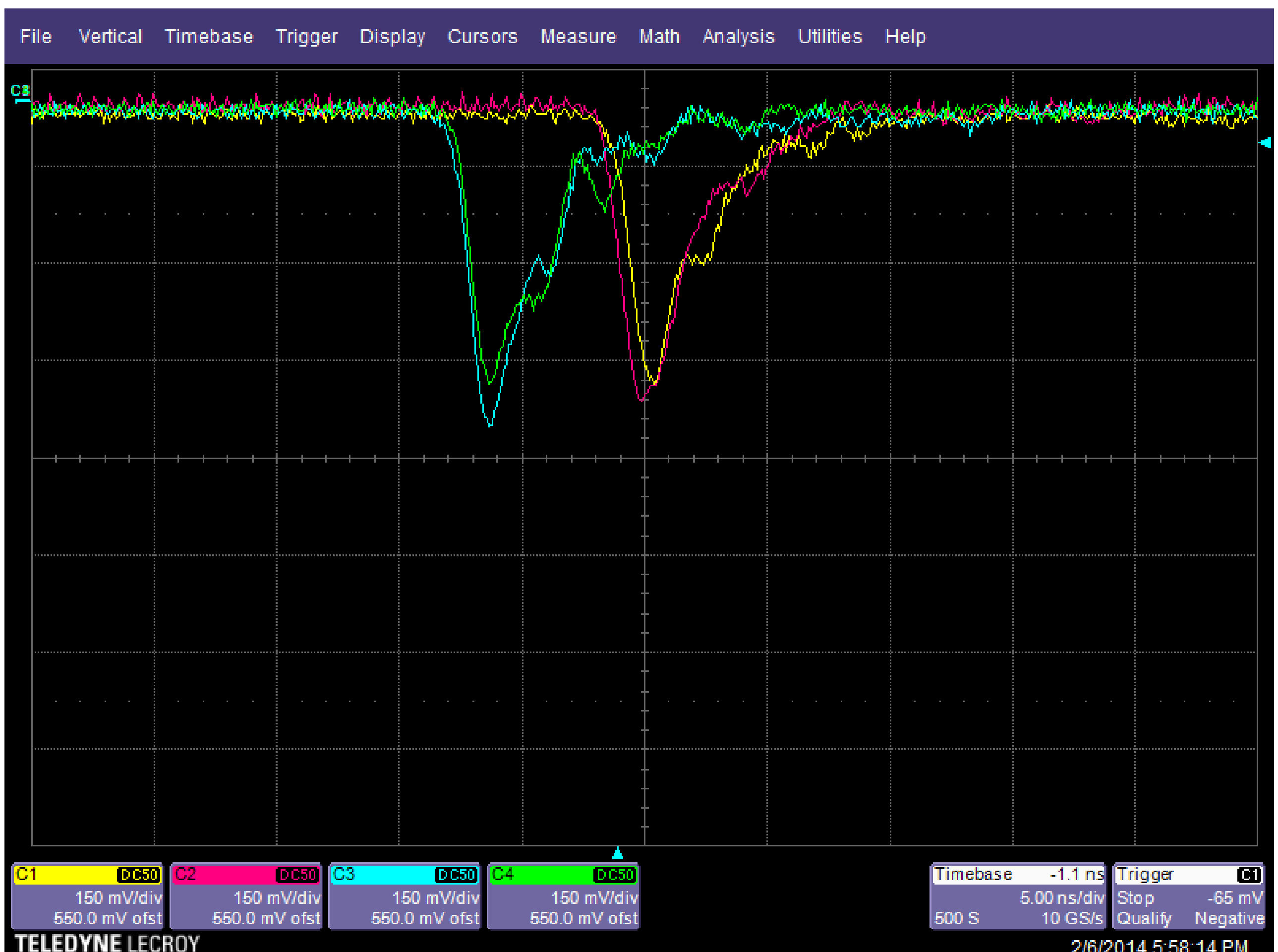
SILVERMEDIA IT COMPANY


DO NOT TOUCH
DO NOT MODIFY
CHECK IF THERE'S NO MOVEMENT




File Vertical Timebase Trigger Display Cursors Measure Math Analysis Utilities Help
C1 DC50 150 mV/div 550.0 mV ofst
C2 DC50 150 mV/div 550.0 mV ofst
C3 DC50 150 mV/div 550.0 mV ofst
C4 DC50 150 mV/div 550.0 mV ofst
Timebase -1.1 ns 5.00 ns/div 500 S 10 GS/s
Trigger C1 Stop -65 mV Qualify Negative
TELEDYNE LECROY
2/6/2014 5:55:32 PM




File Vertical Timebase Trigger Display Cursors Measure Math Analysis Utilities Help
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C3 DC50 150 mV/div 550.0 mV ofst
C4 DC50 150 mV/div 550.0 mV ofst
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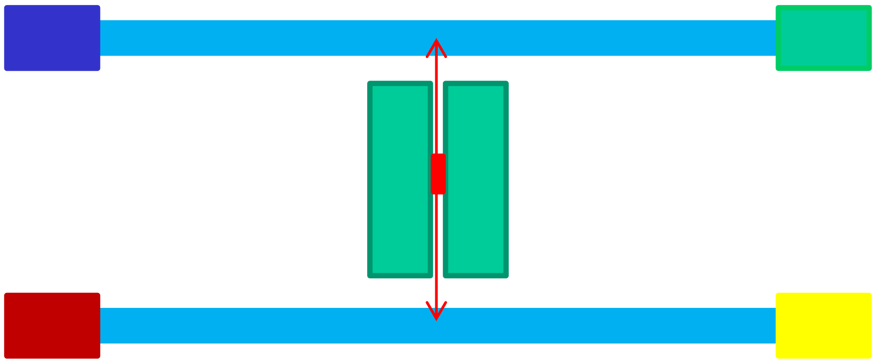
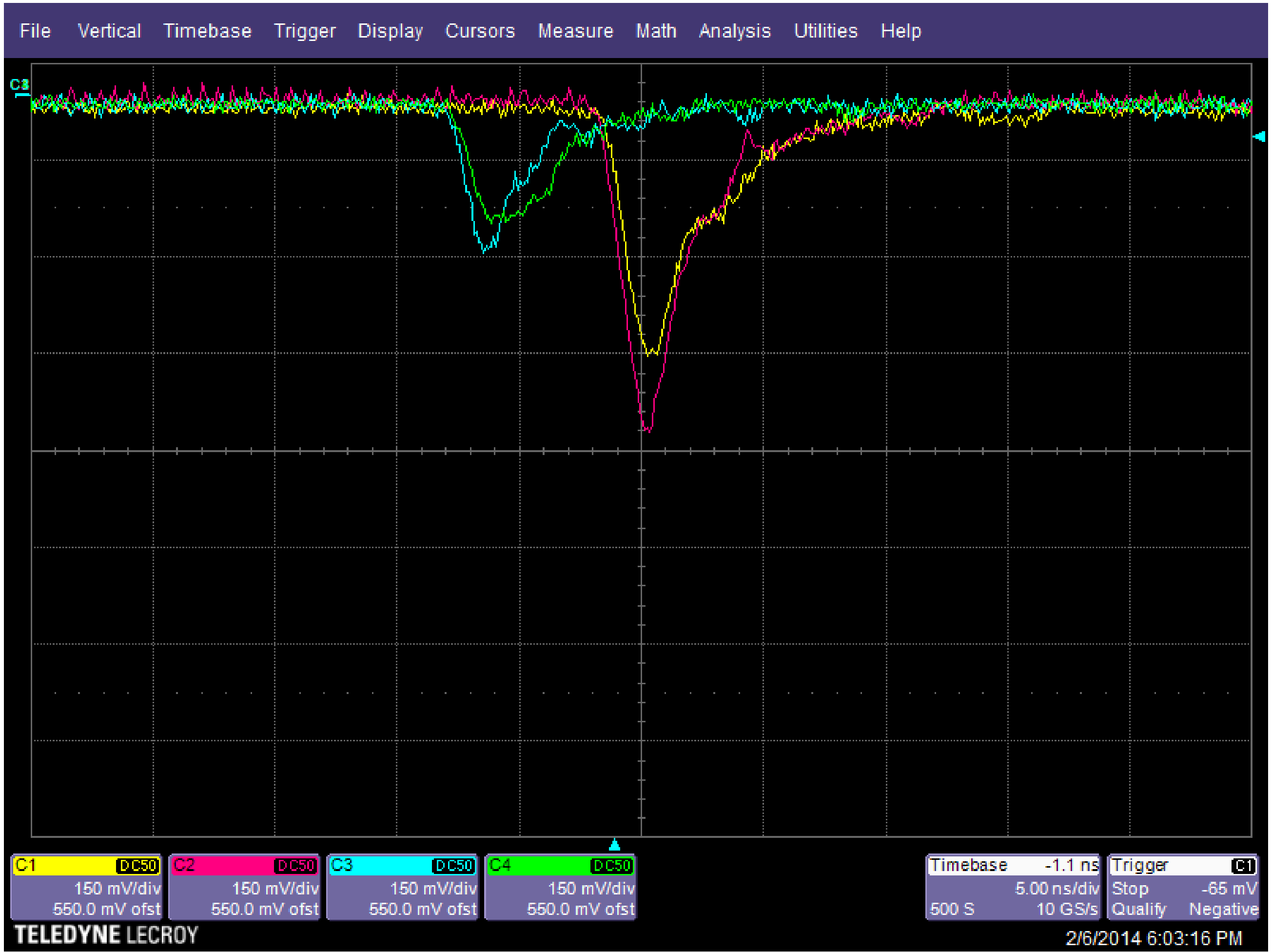


- 
File Vertical Timebase Trigger Display Cursors Measure Math Analysis Utilities Help
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C2 DC50 150 mV/div 550.0 mV ofst
C3 DC50 150 mV/div 550.0 mV ofst
C4 DC50 150 mV/div 550.0 mV ofst
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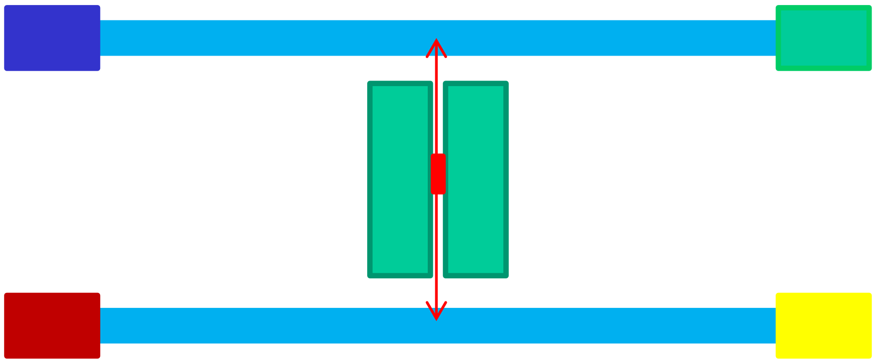

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150 mV/div
550.0 mV ofst
C3 DC50
150 mV/div
550.0 mV ofst
C4 DC50
150 mV/div
550.0 mV ofst
Timebase -1.1 ns
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500 S 10 GS/s
Trigger C1
Stop -65 mV
Qualify Negative
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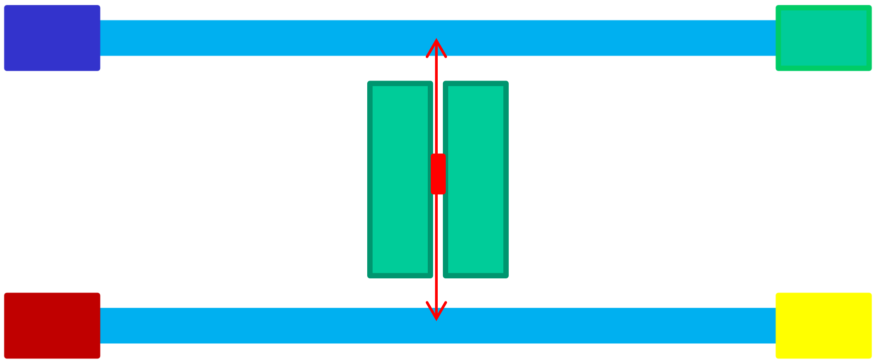
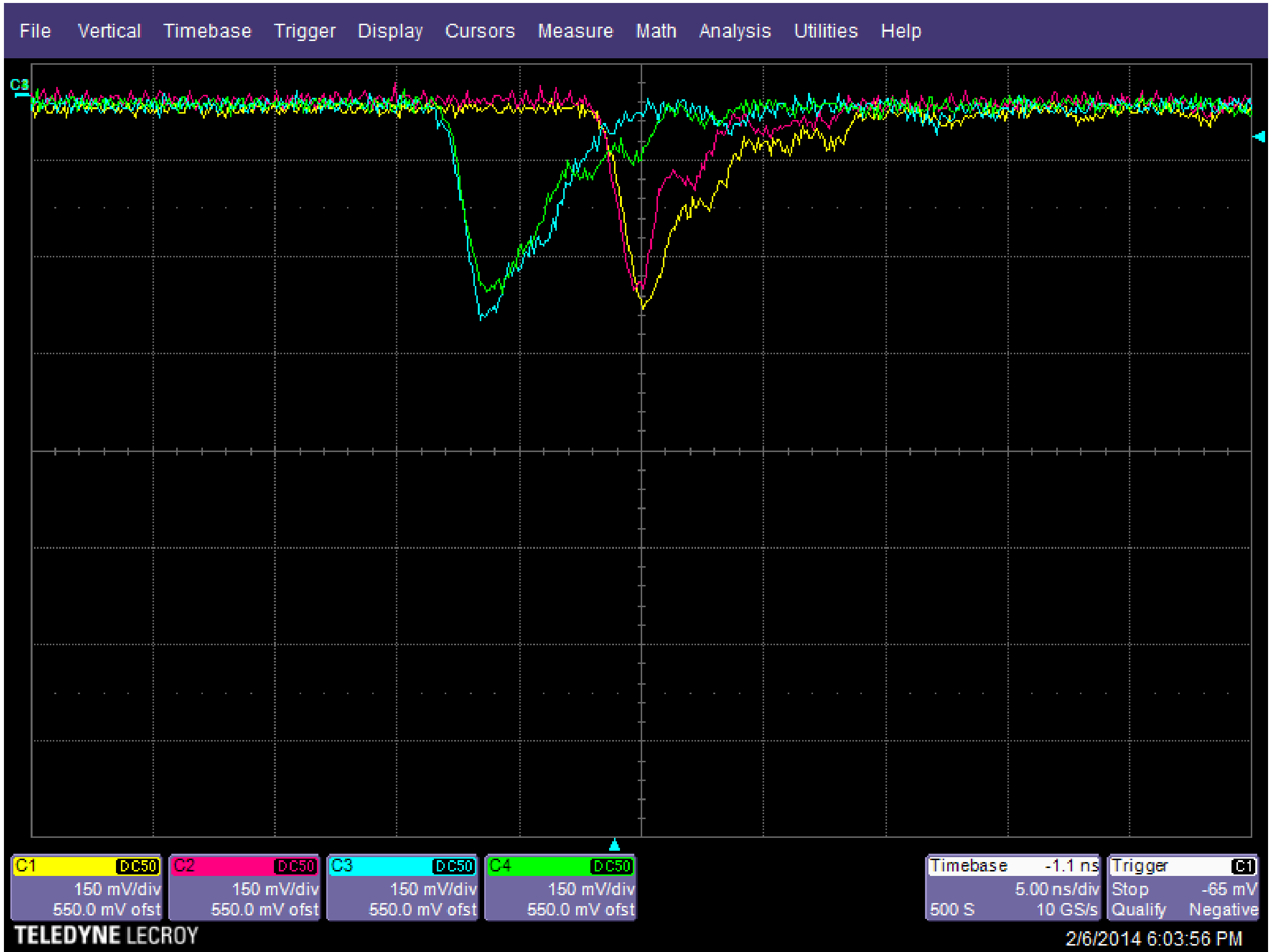
2/6/2014 5:56:15 PM





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C1 DC50
150 mV/div
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C4 DC50
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550.0 mV ofst
Timebase -1.1 ns
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Stop -65 mV
Qualify Negative
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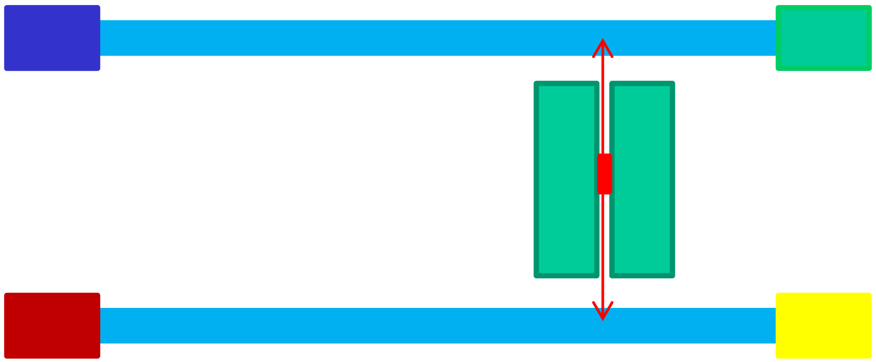

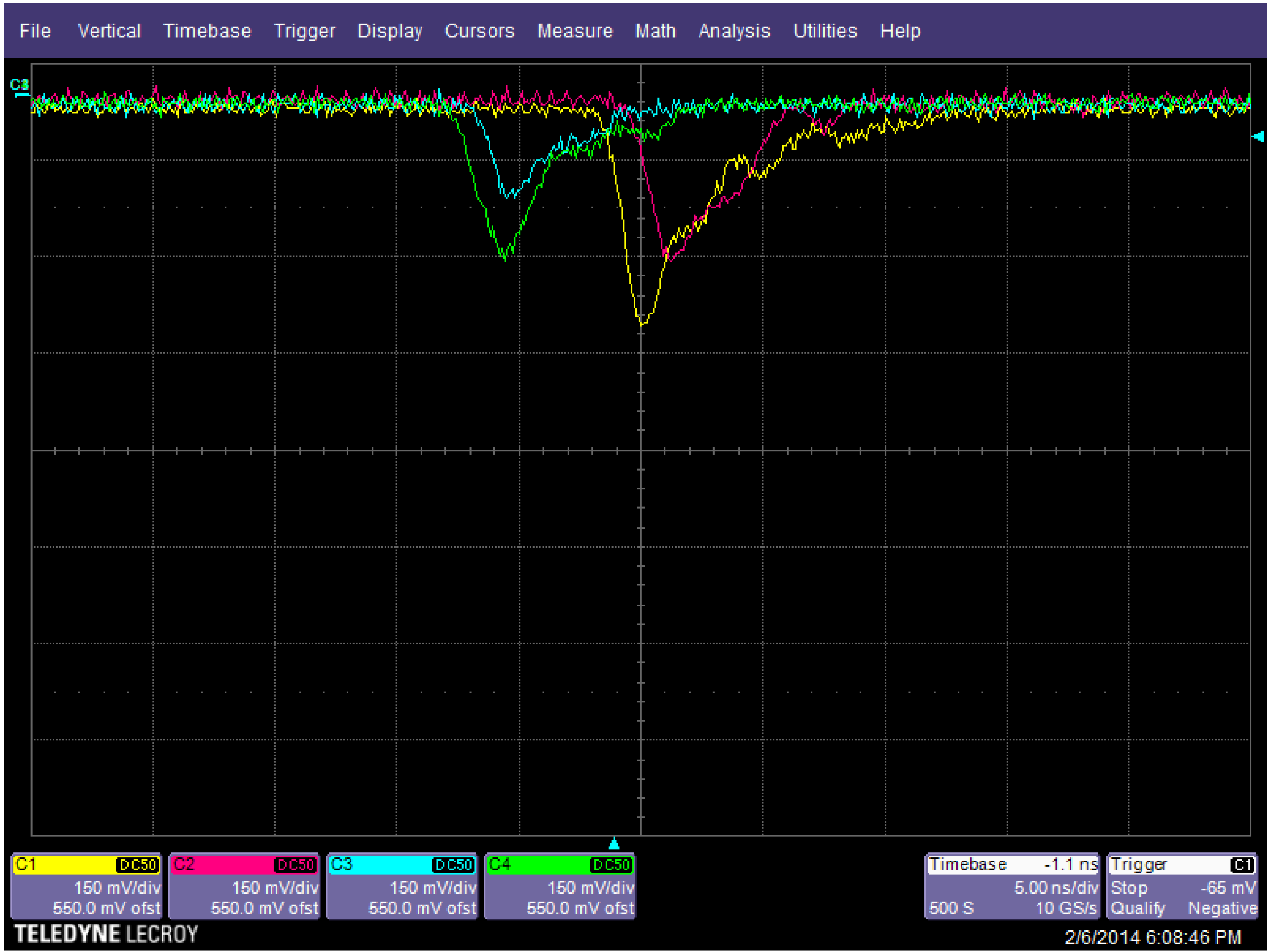
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C1 DC50 150 mV/div 550.0 mV ofst
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C3 DC50 150 mV/div 550.0 mV ofst
C4 DC50 150 mV/div 550.0 mV ofst
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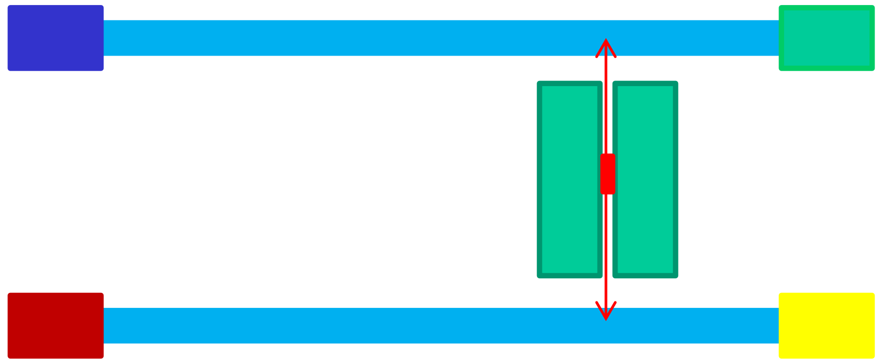

File
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Utilities
Help
C1 DC50
150 mV/div
550.0 mV ofst
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550.0 mV ofst
C4 DC50
150 mV/div
550.0 mV ofst
Timebase -1.1 ns
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500 S 10 GS/s
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Stop -65 mV
Qualify Negative
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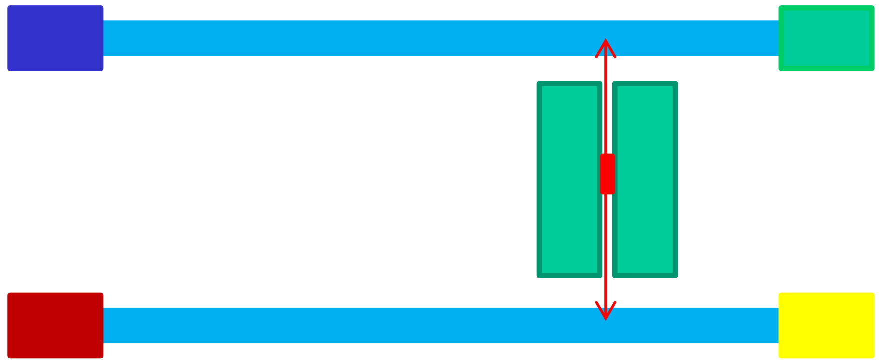

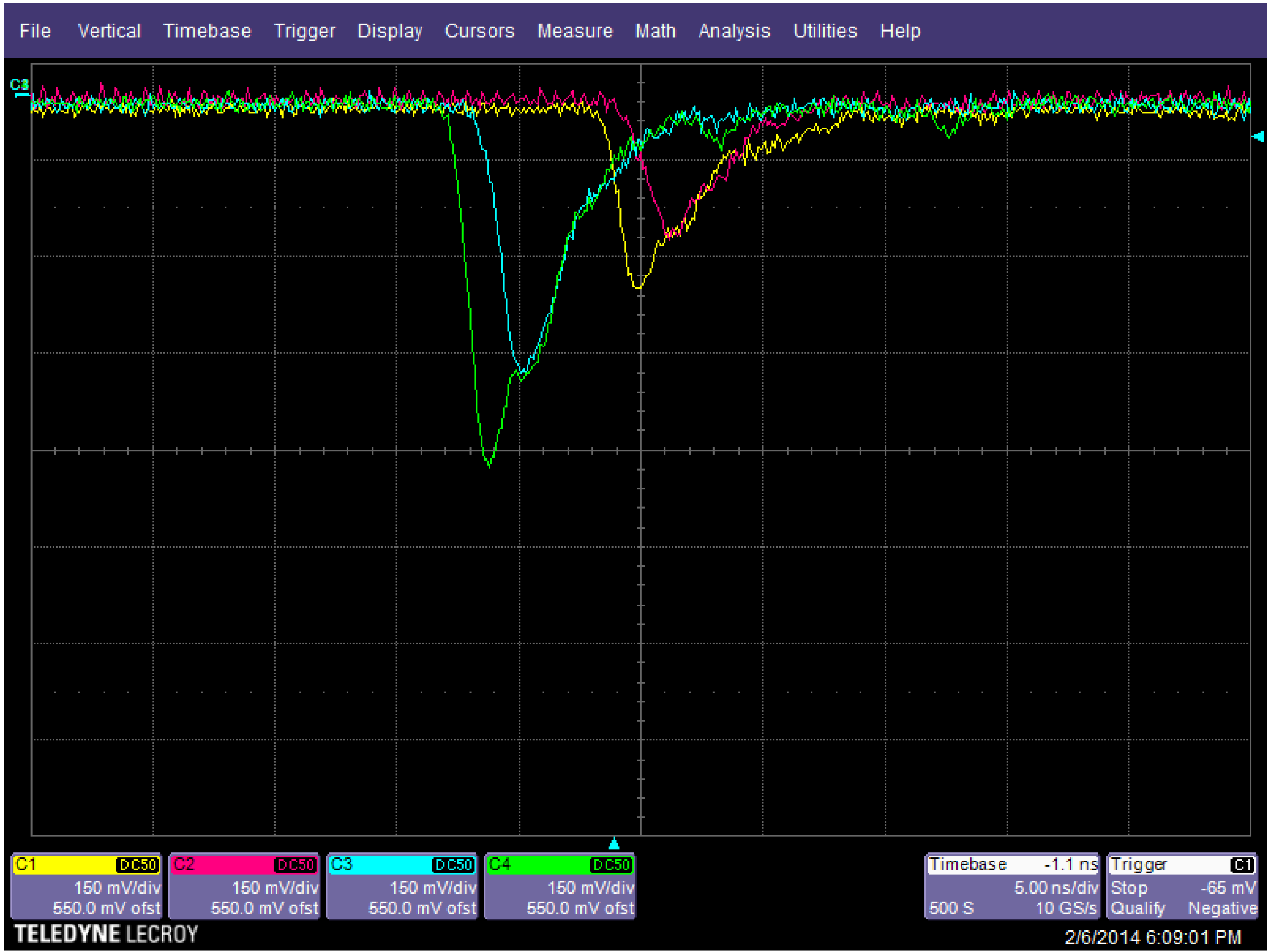
File
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Timebase
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Cursors
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Math
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Utilities
Help
C1 DC50
150 mV/div
550.0 mV ofst
C2 DC50
150 mV/div
550.0 mV ofst
C3 DC50
150 mV/div
550.0 mV ofst
C4 DC50
150 mV/div
550.0 mV ofst
Timebase -1.1 ns
5.00 ns/div
500 S 10 GS/s
Trigger C1
Stop -65 mV
Qualify Negative
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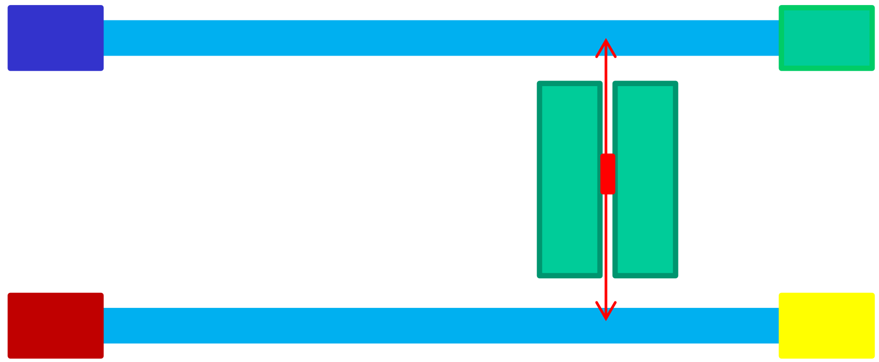

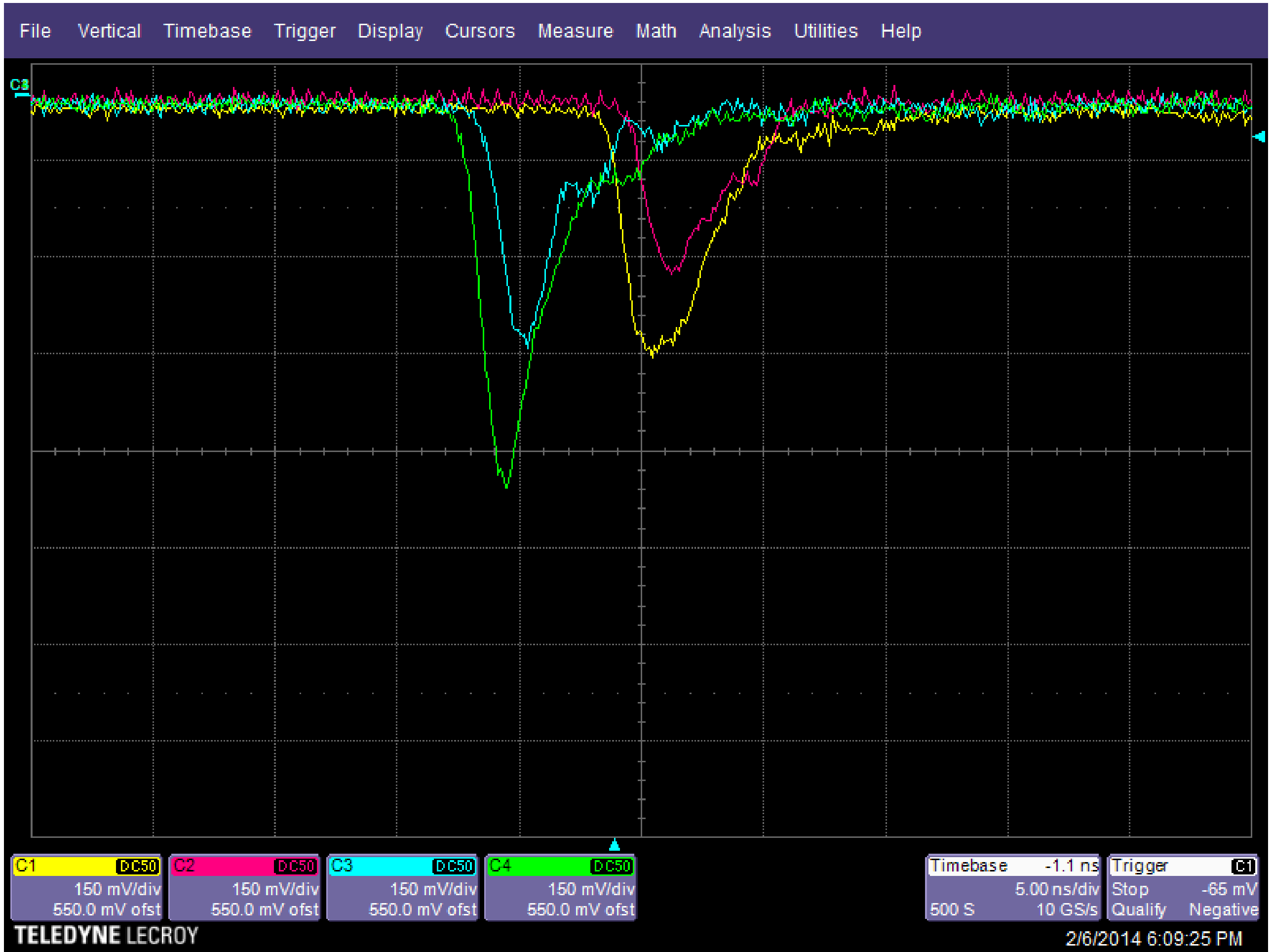
File Vertical Timebase Trigger Display Cursors Measure Math Analysis Utilities Help
C3
C1 DC50 150 mV/div 550.0 mV ofst
C2 DC50 150 mV/div 550.0 mV ofst
C3 DC50 150 mV/div 550.0 mV ofst
C4 DC50 150 mV/div 550.0 mV ofst
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Trigger C1 Stop -65 mV Qualify Negative
TELEDYNE LECROY
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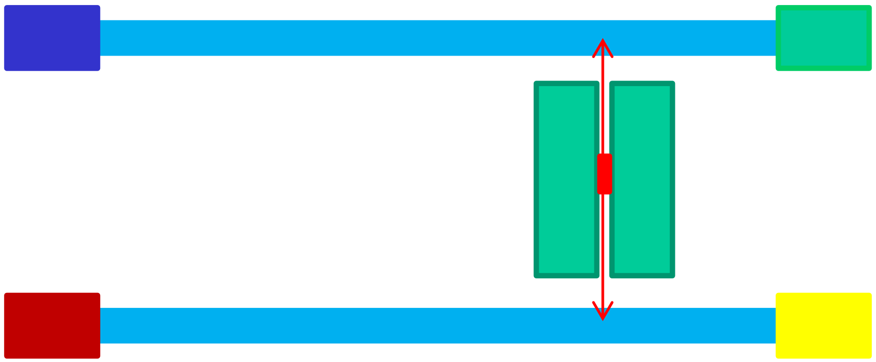

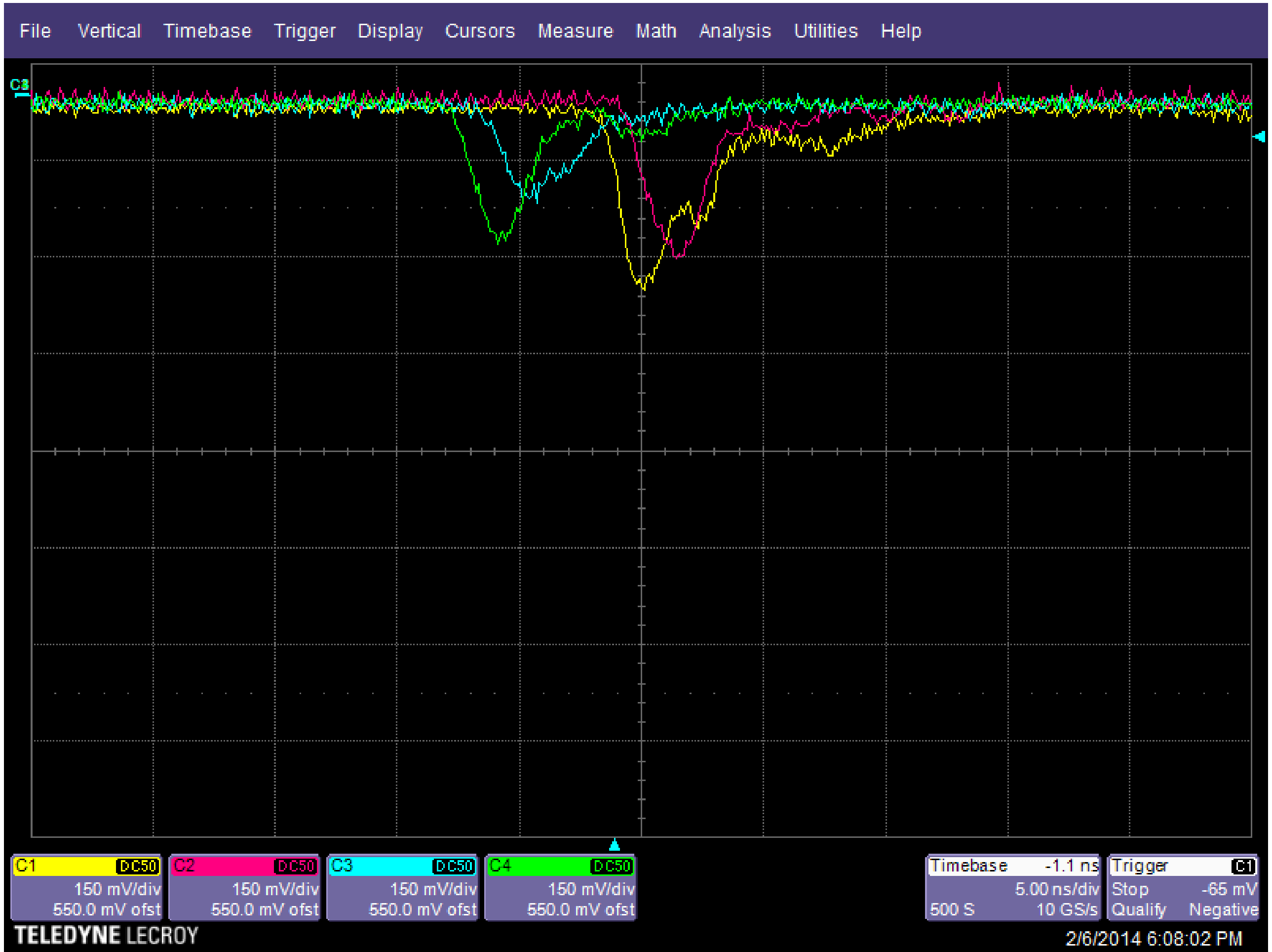

File
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Utilities
Help
C1 DC50
150 mV/div
550.0 mV ofst
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150 mV/div
550.0 mV ofst
C3 DC50
150 mV/div
550.0 mV ofst
C4 DC50
150 mV/div
550.0 mV ofst
Timebase -1.1 ns
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500 S 10 GS/s
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Stop -65 mV
Qualify Negative
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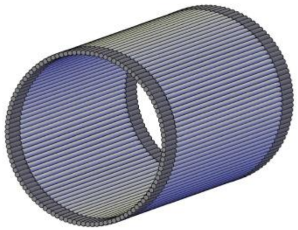
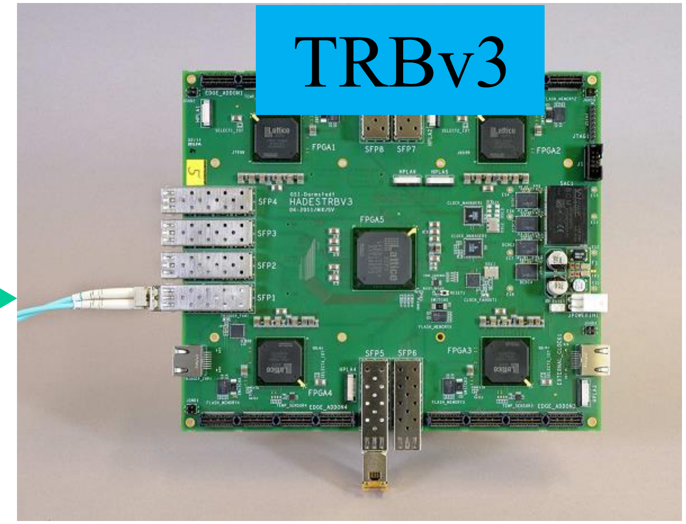
2/6/2014 6:08:02 PM

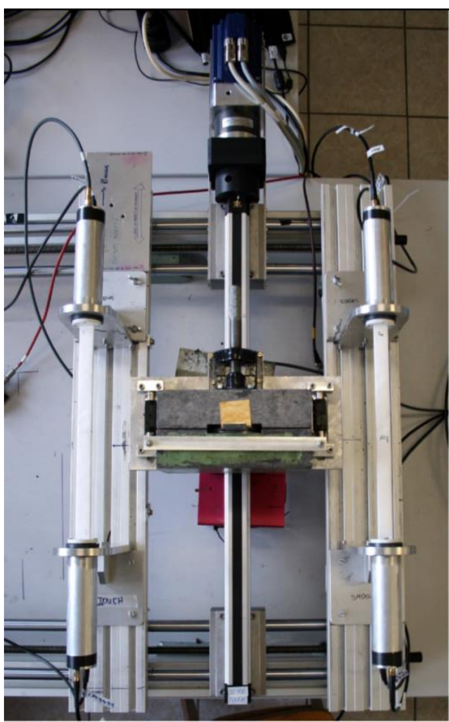


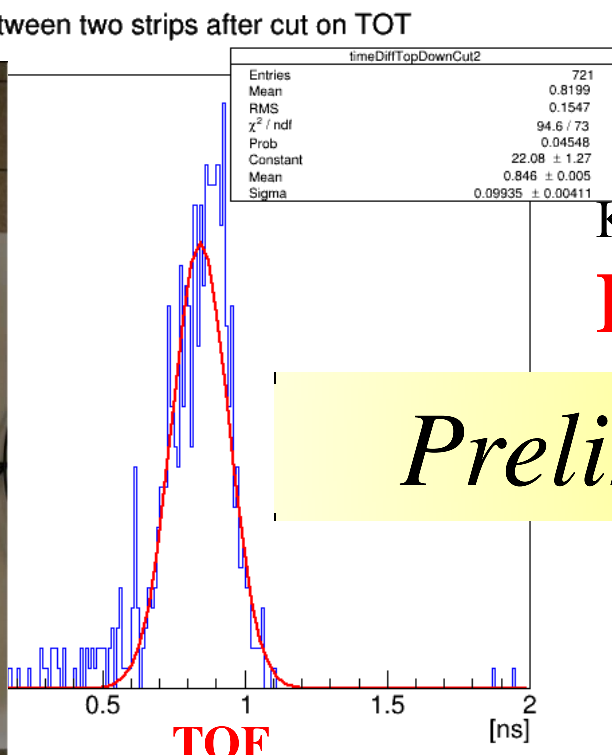


Triggerless mode !

PCT/EP2014/068352

Si-Ge and As-Ge
sigma(t) = 25 ps



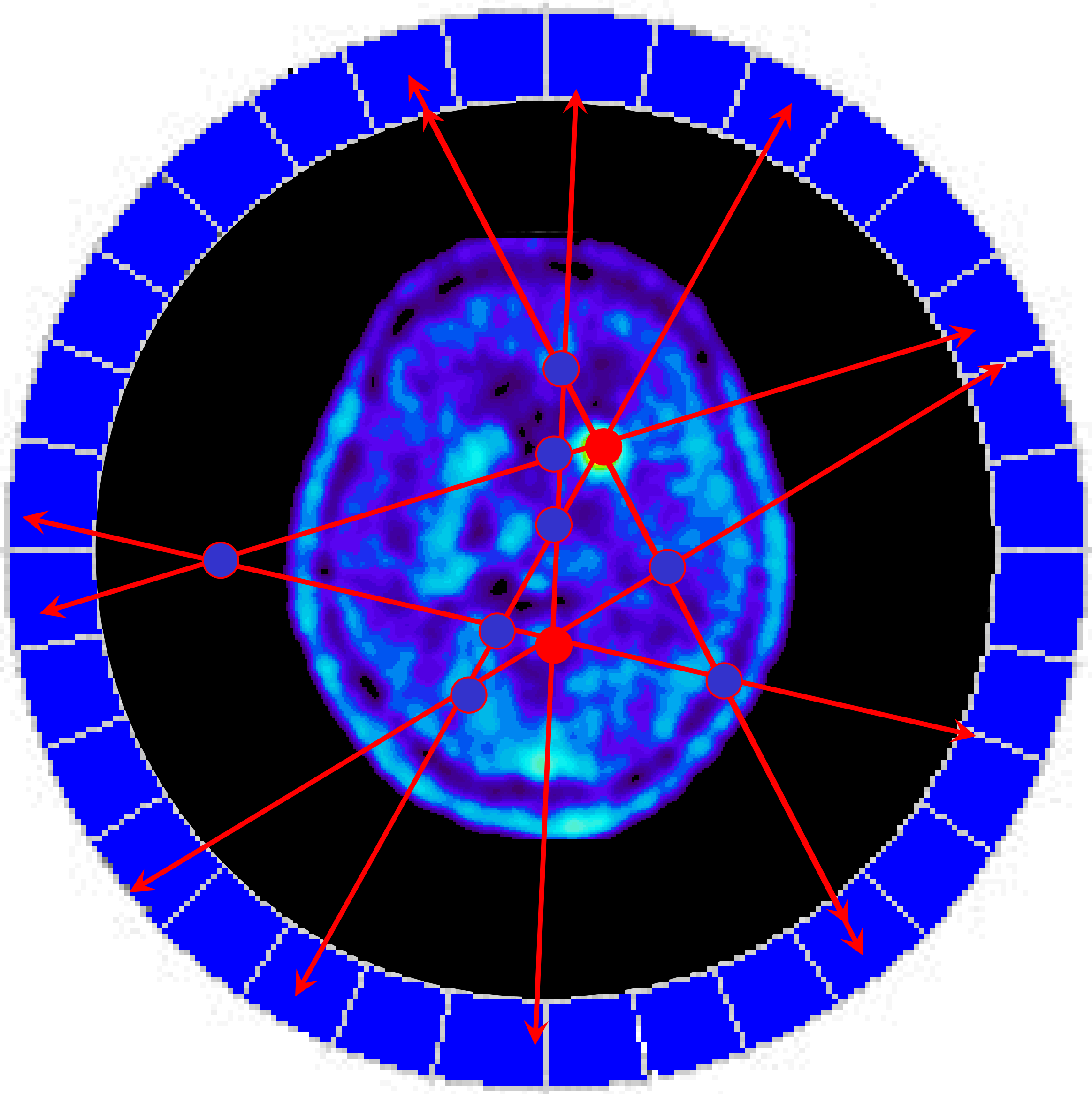


KB7 + TRBv3 with single threshold

FWHM(TOF) < 220 ps

Preliminary

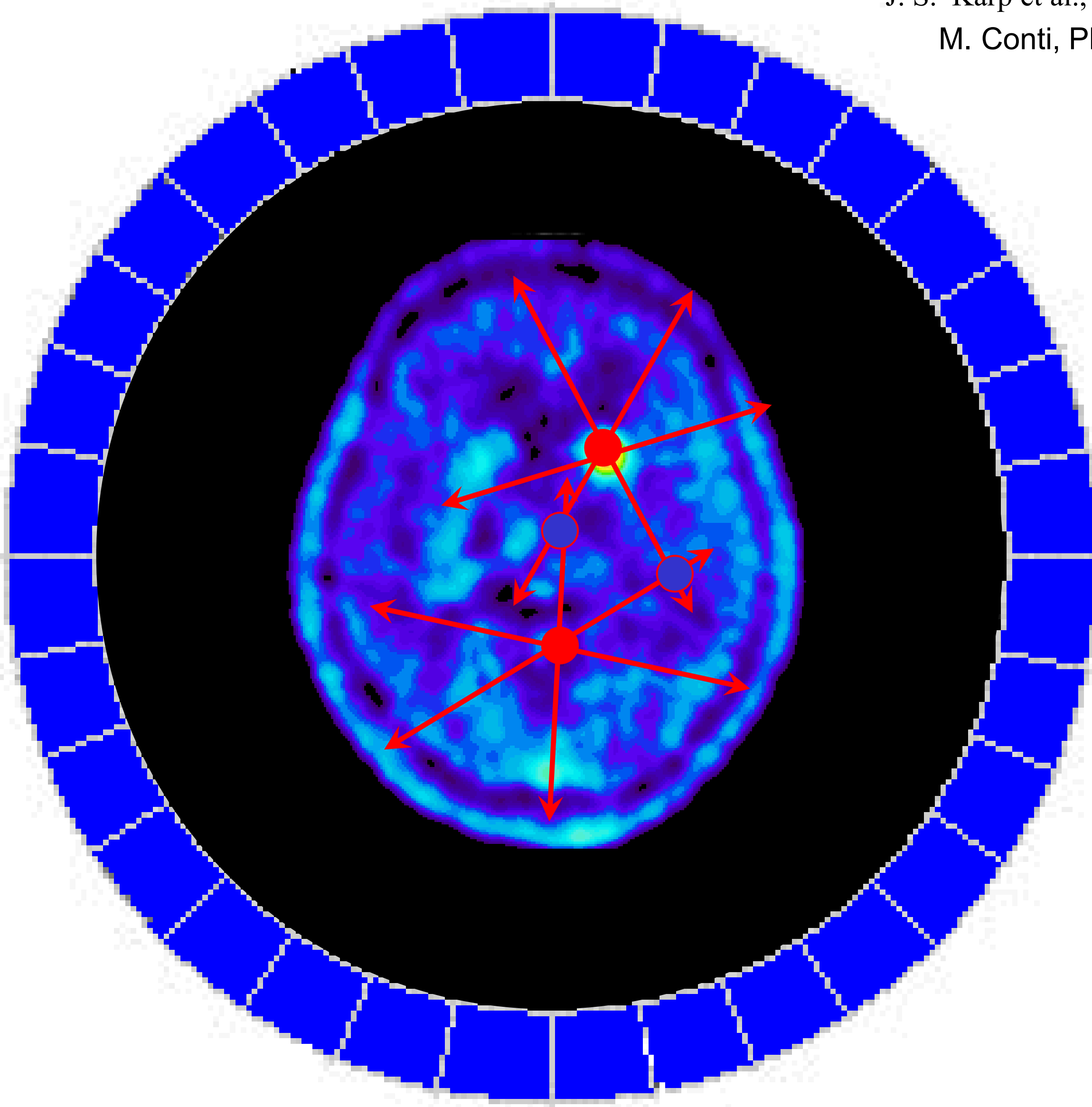
Comapred to ~ 600 ps
of current TOF-PET



signal/background ~ D / Δt

40cm/600ps improvement by factor of 4

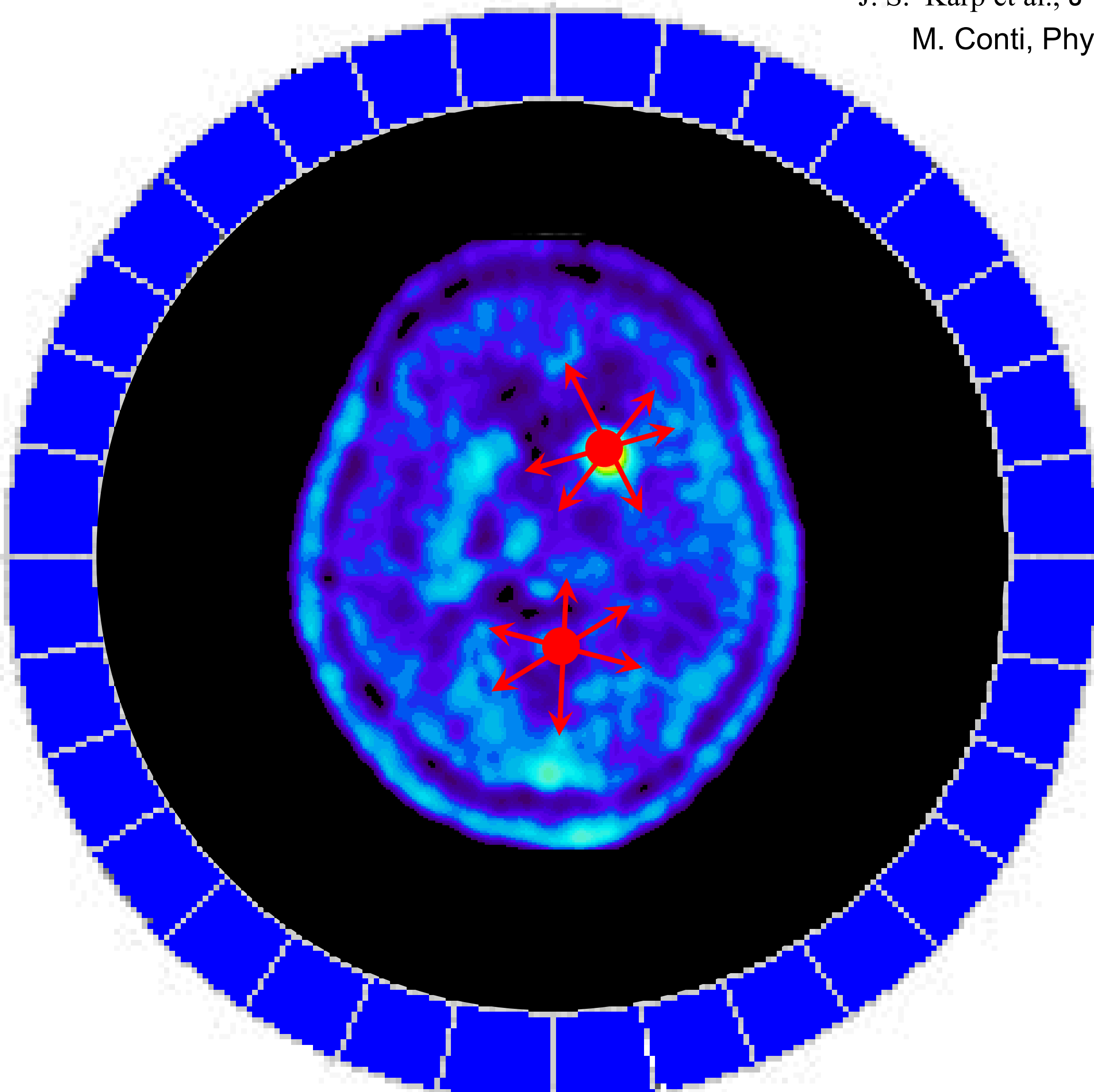
J. S. Karp et al., J Nucl Med 2008; 49: 462
M. Conti, Physica Medica 2009; 25: 1.



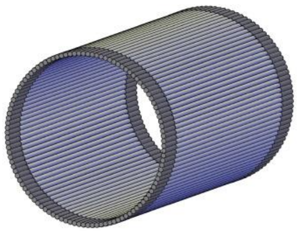
signal/background
~ D / Δt

40cm/200ps improvement by factor of 12

J. S. Karp et al., J Nucl Med 2008; 49: 462
M. Conti, Physica Medica 2009; 25: 1.



ANALOG DIGITAL

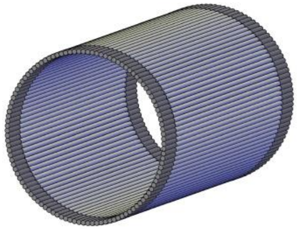


FFE
Sampling
in voltage domain

FFE
Sampling in domain
of fraction of amplitude

Readout electronics

New idea… BREAK THROUGH

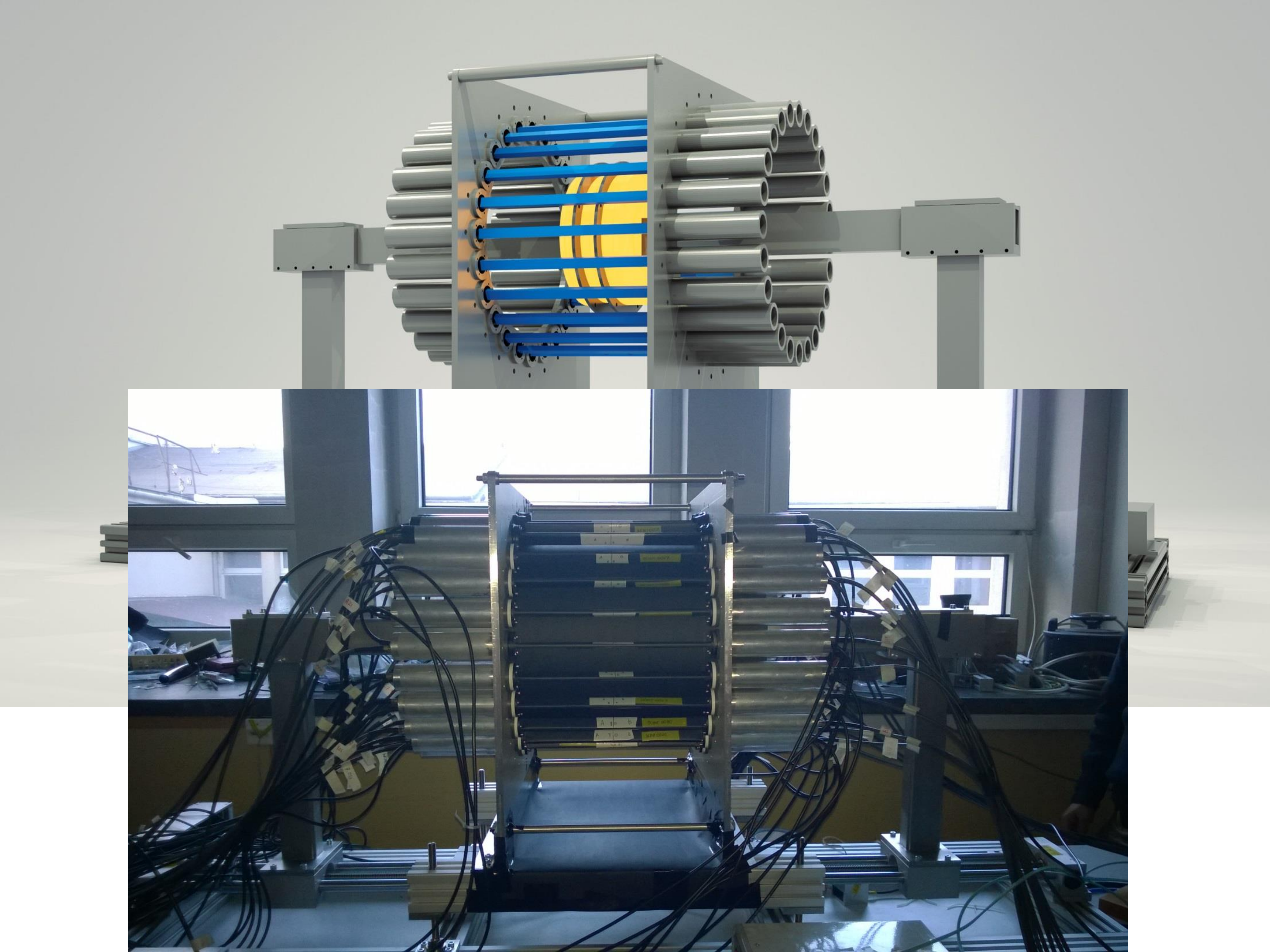


ONLY DIGITAL

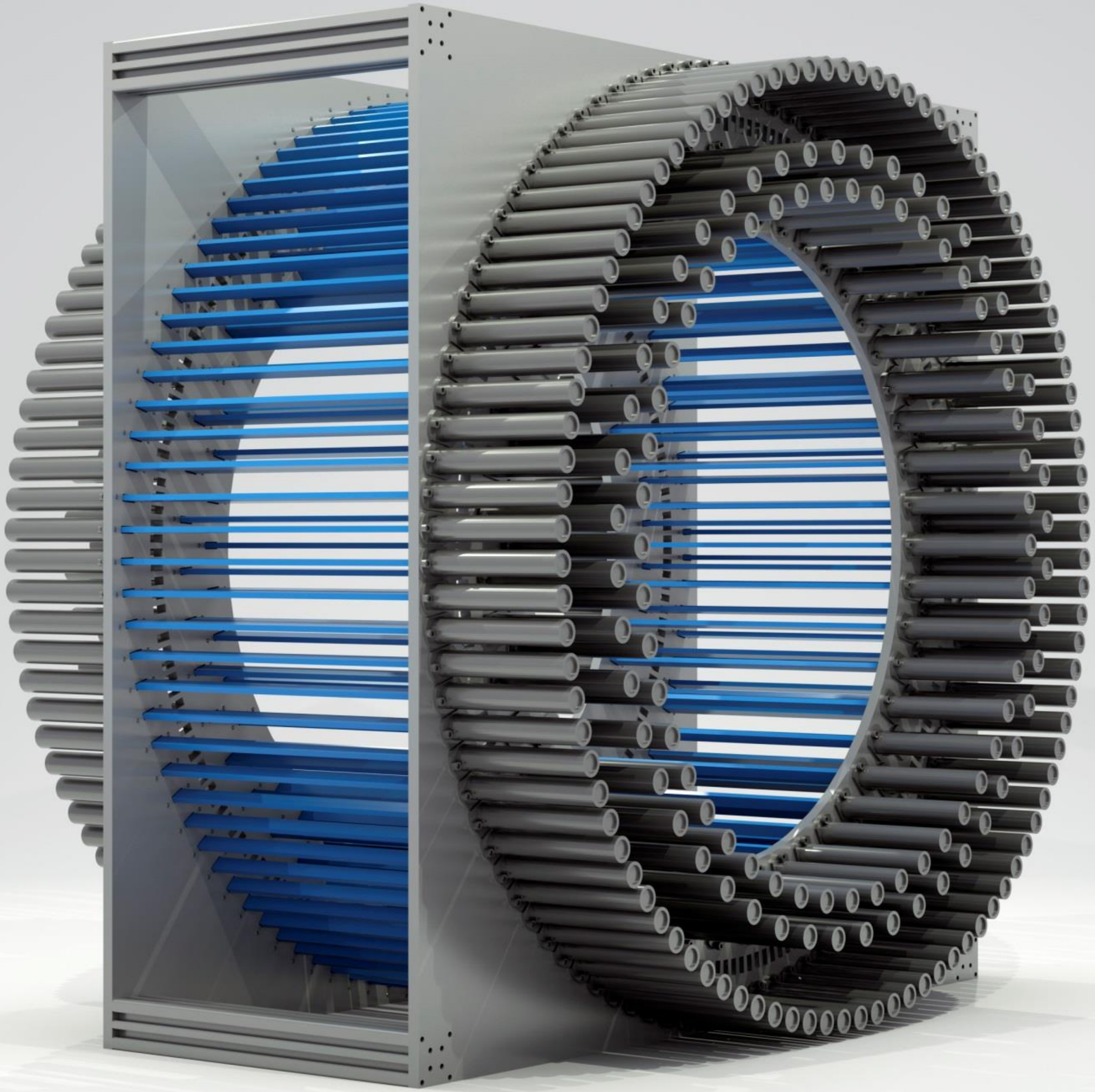
FFE sampling & Readout electronics

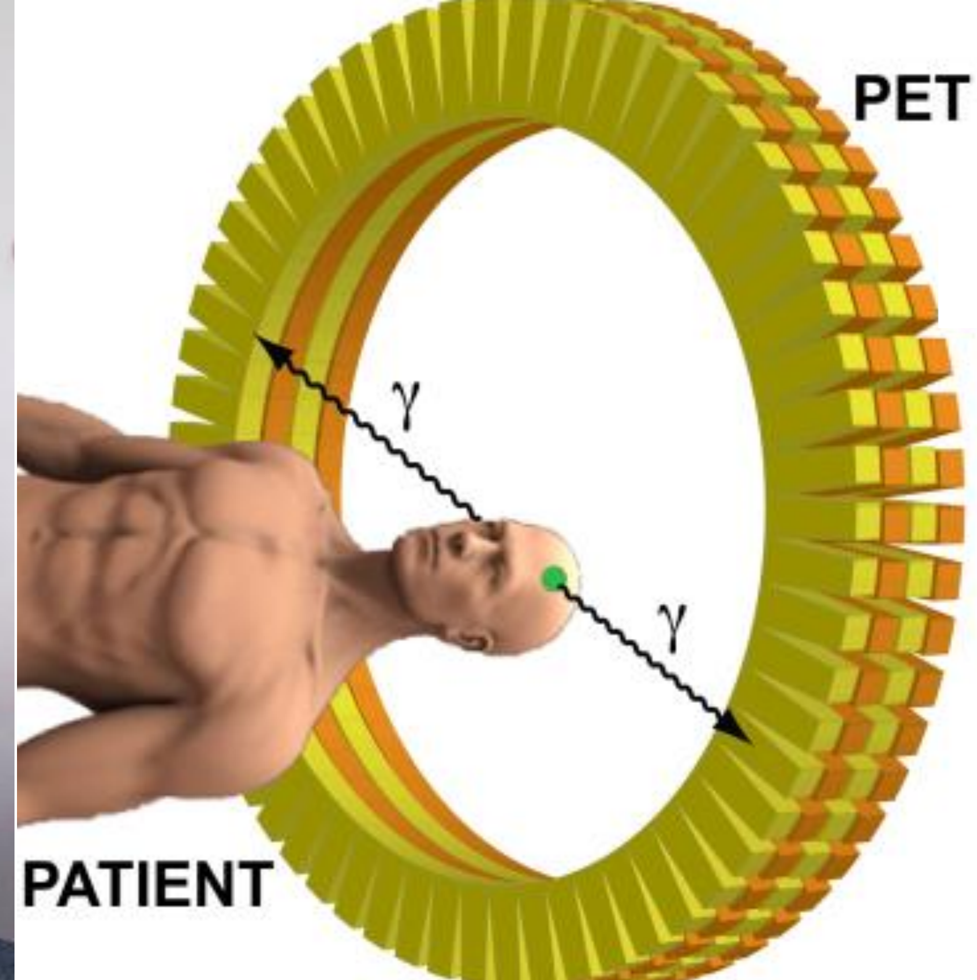
PCT/EP2014/068367

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



J-PET

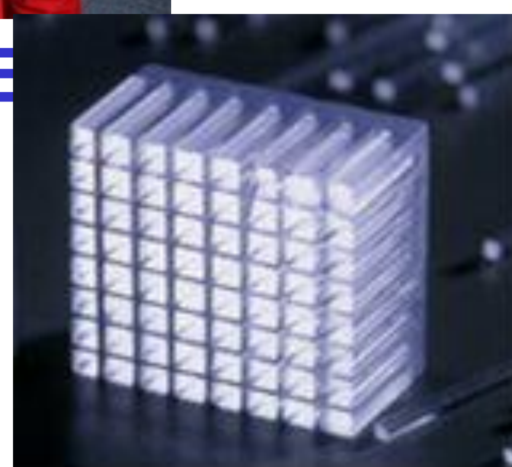


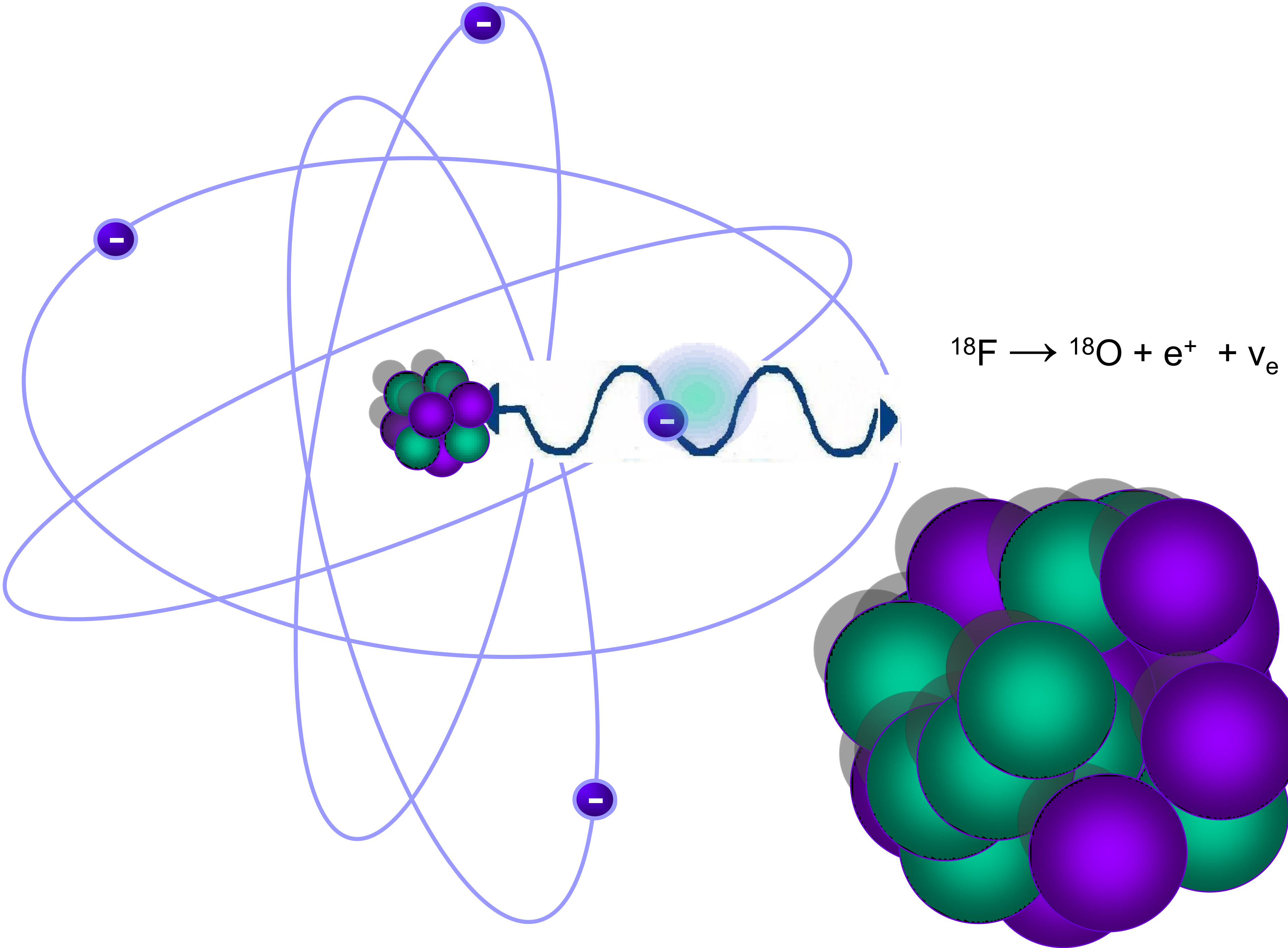


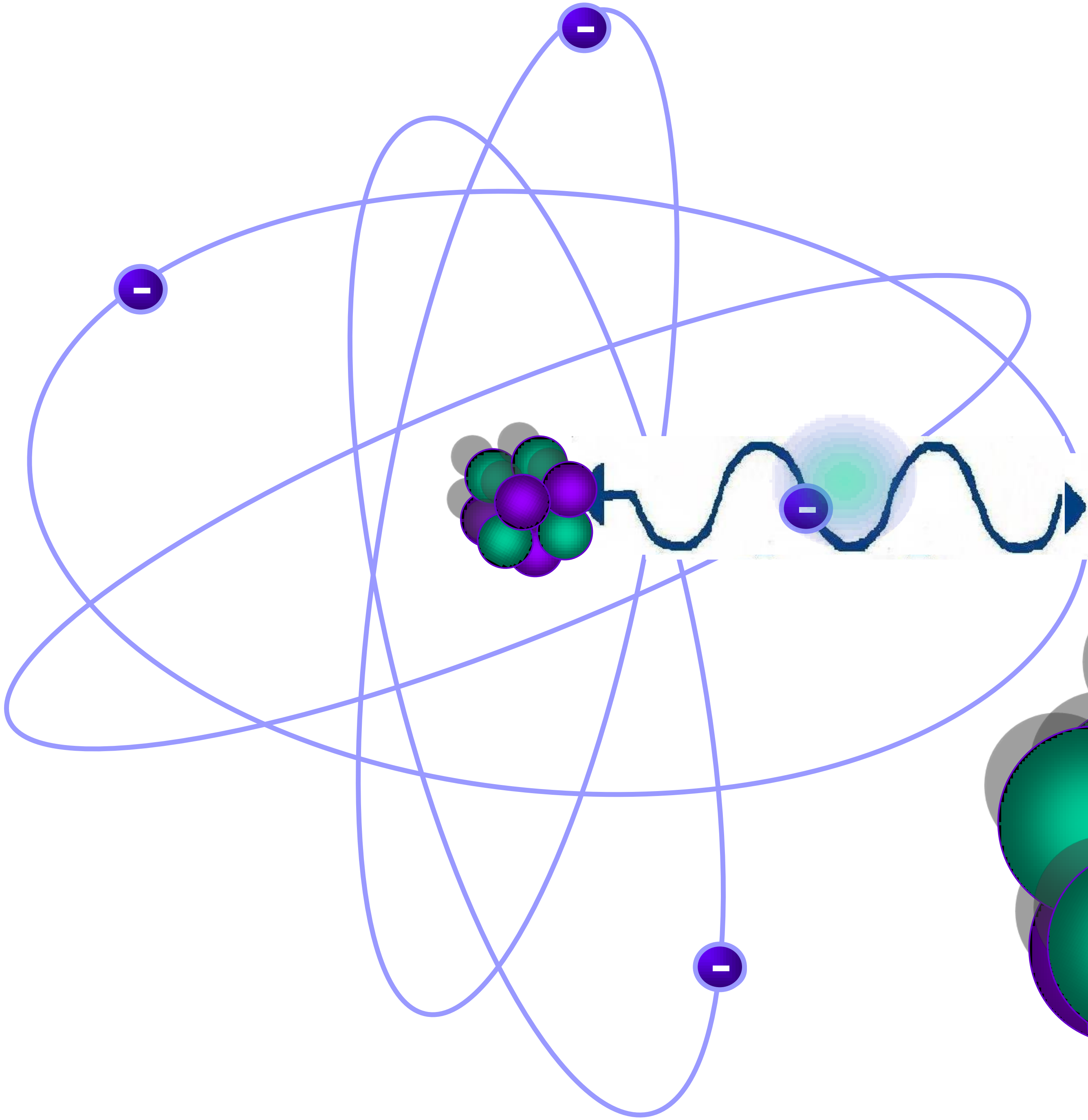
RADIOACTIVE SUGE

Fluoro–deoxy-glucose (F-18 FDG)

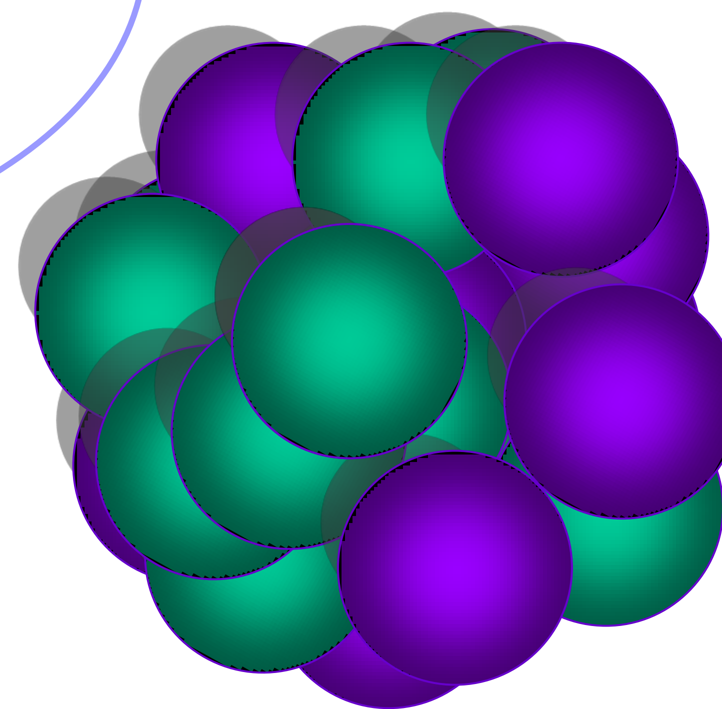
~200 000 000 gamma per second

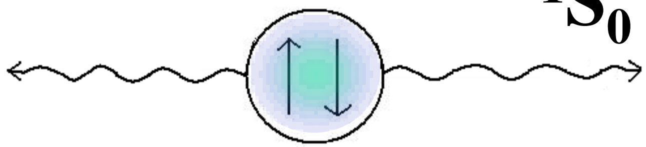



¹⁸F ⟶ ¹⁸O + e⁺ + νₑ

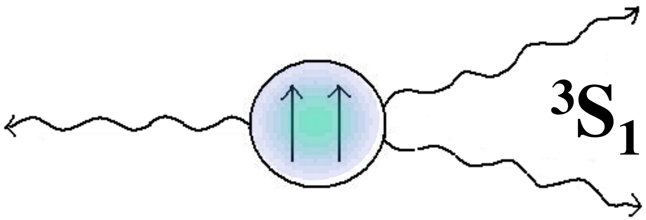


$^{18}F \longrightarrow {}^{18}O + e^{+} + \nu_e$





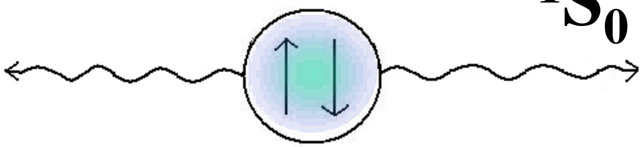
$^1S_0$ **Para-positronium tau(p-Ps) ≈ 125 ps**



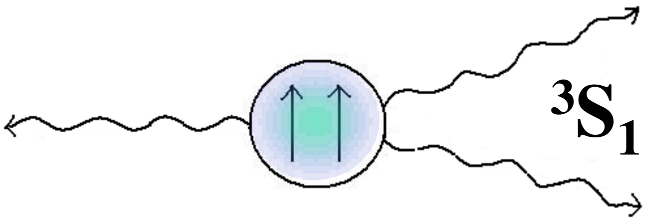
$^3S_1$ **Ortho-positronium tau(o-Ps) ≈ 142 ns**

	$^1S_0$	$^3S_1$
L	0	0
L=0 -> P	-	-

$P = (-1)^L \bullet$ internal parity



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



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

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

S = 0 $\downarrow\uparrow - \uparrow\downarrow$

S = 1 $\uparrow\uparrow + \downarrow\downarrow$

$$C\,|Ps> = (-1)^{L+S}\,|Ps>$$

$$C\,|n\gamma> = (-1)^{n}\,|n\gamma>$$

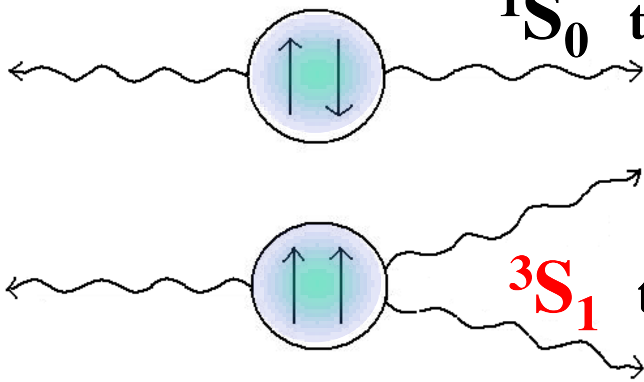
Production rate

$\frac{1}{4}$ m = 0

m = +1

$\frac{3}{4}$ m = 0

m = -1



$^1S_0$ tau(p-Ps) ≈ 125 ps

$^3S_1$ tau(o-Ps) ≈ 142 ns

But

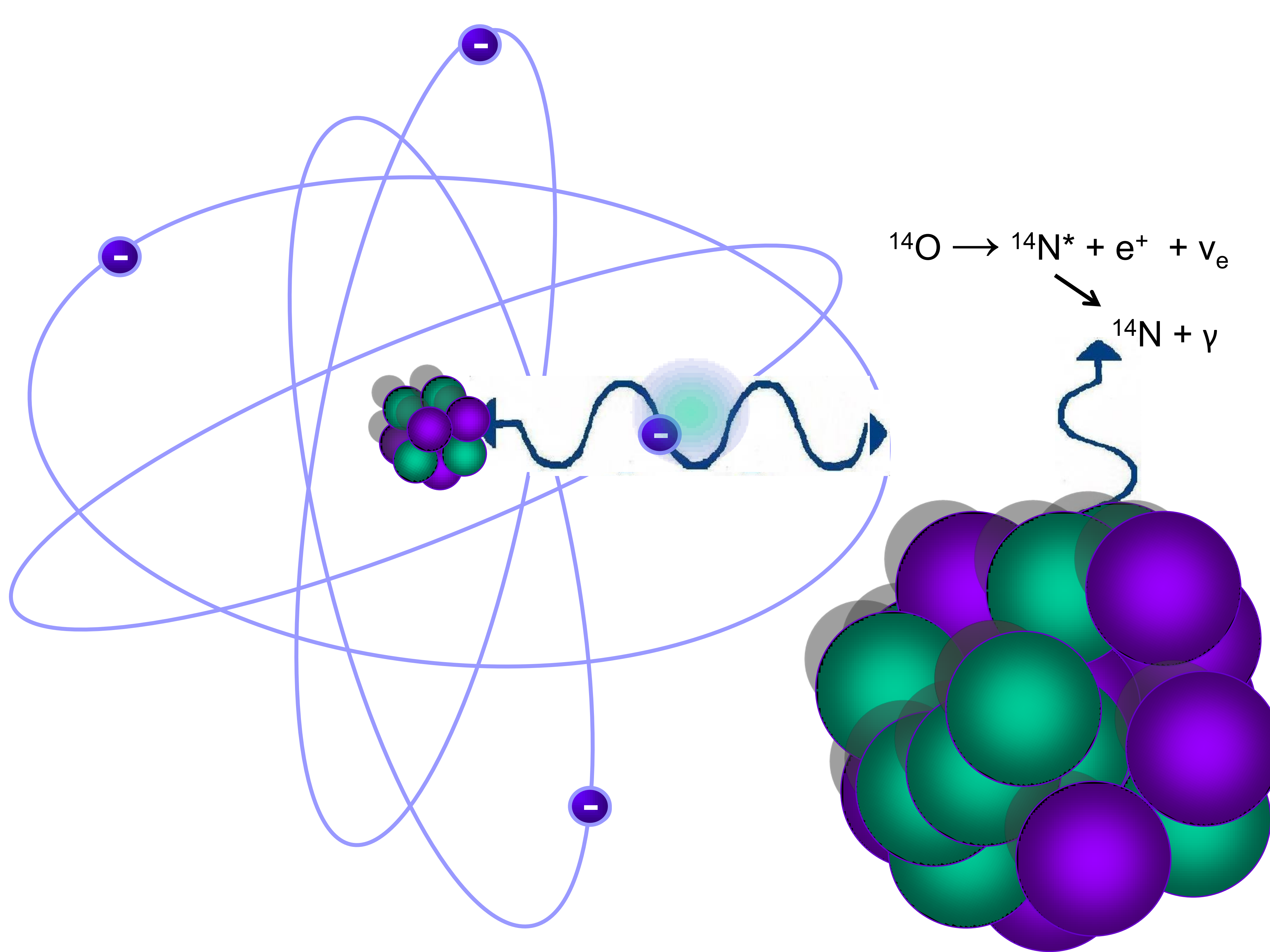
e+e- may undergo a direct annihilation:

e+ e- --> γ γ / e+ e- --> γ γ γ / e+e- --> γ γ γ γ ≈ 1 / 370 / 1000000

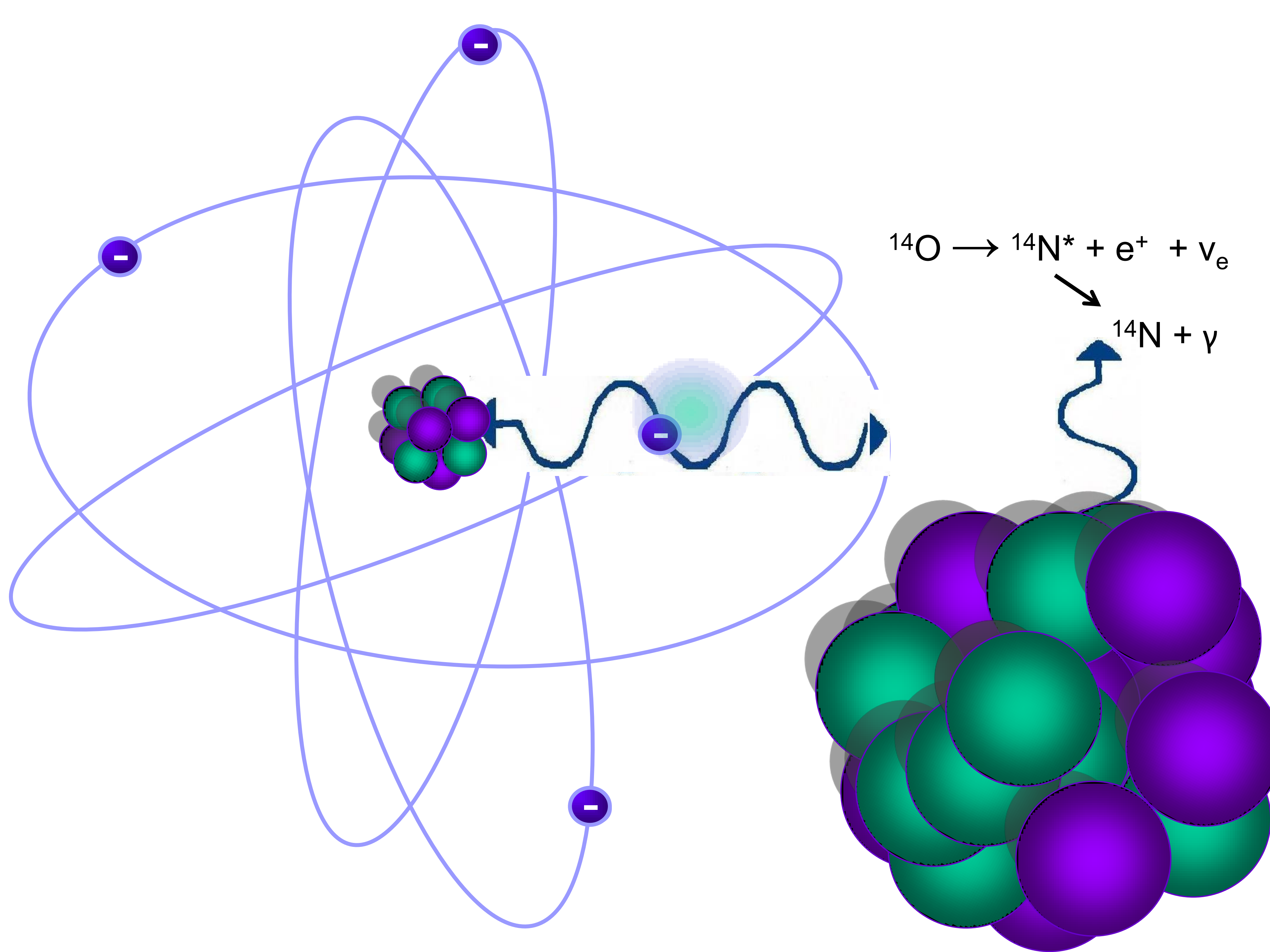
positron „life time" in matter depends on the material properties ≈ **300-400 ps**

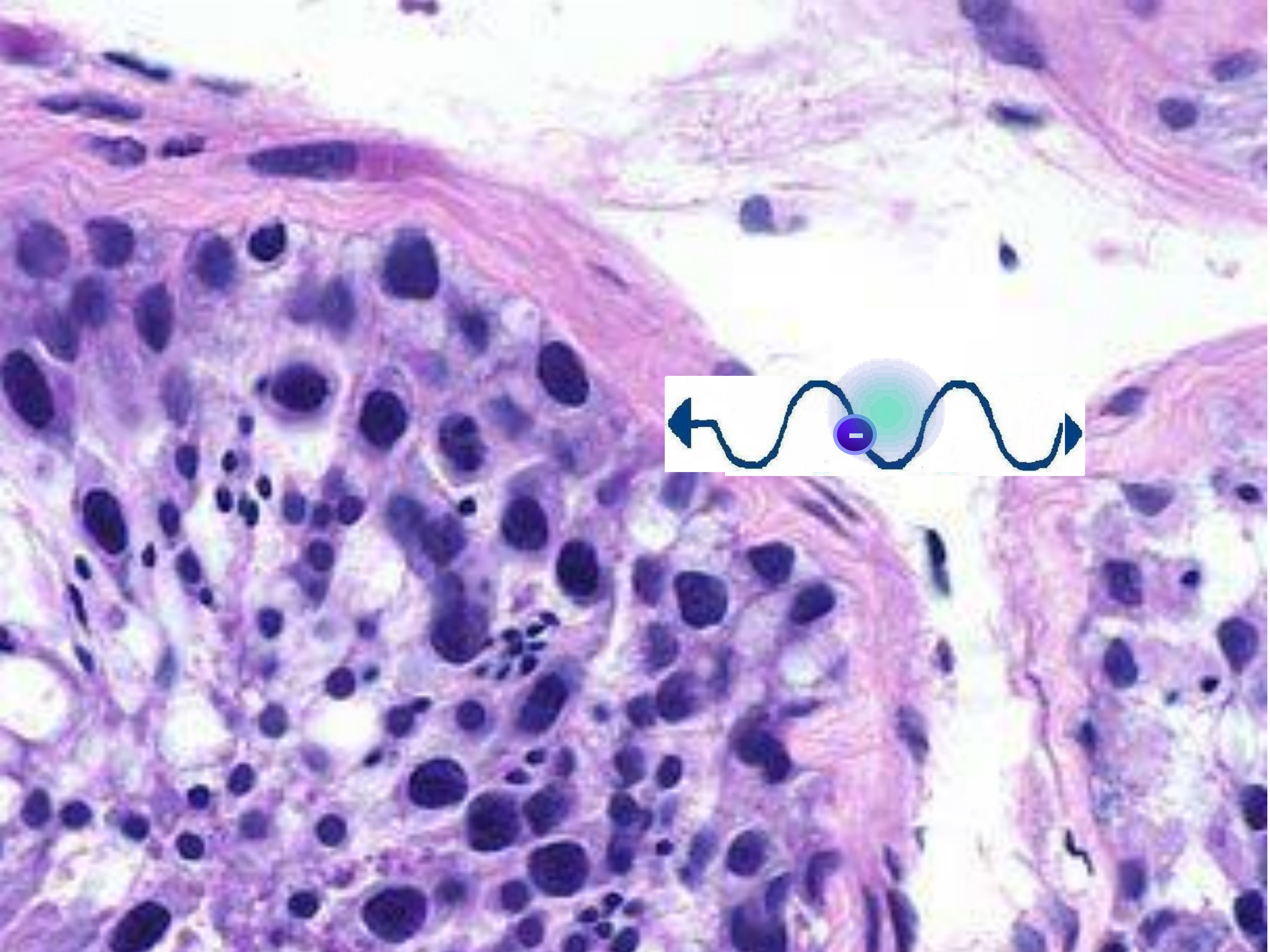
tau(o-Ps) strongly depends on the size of the free volumes between molecules…

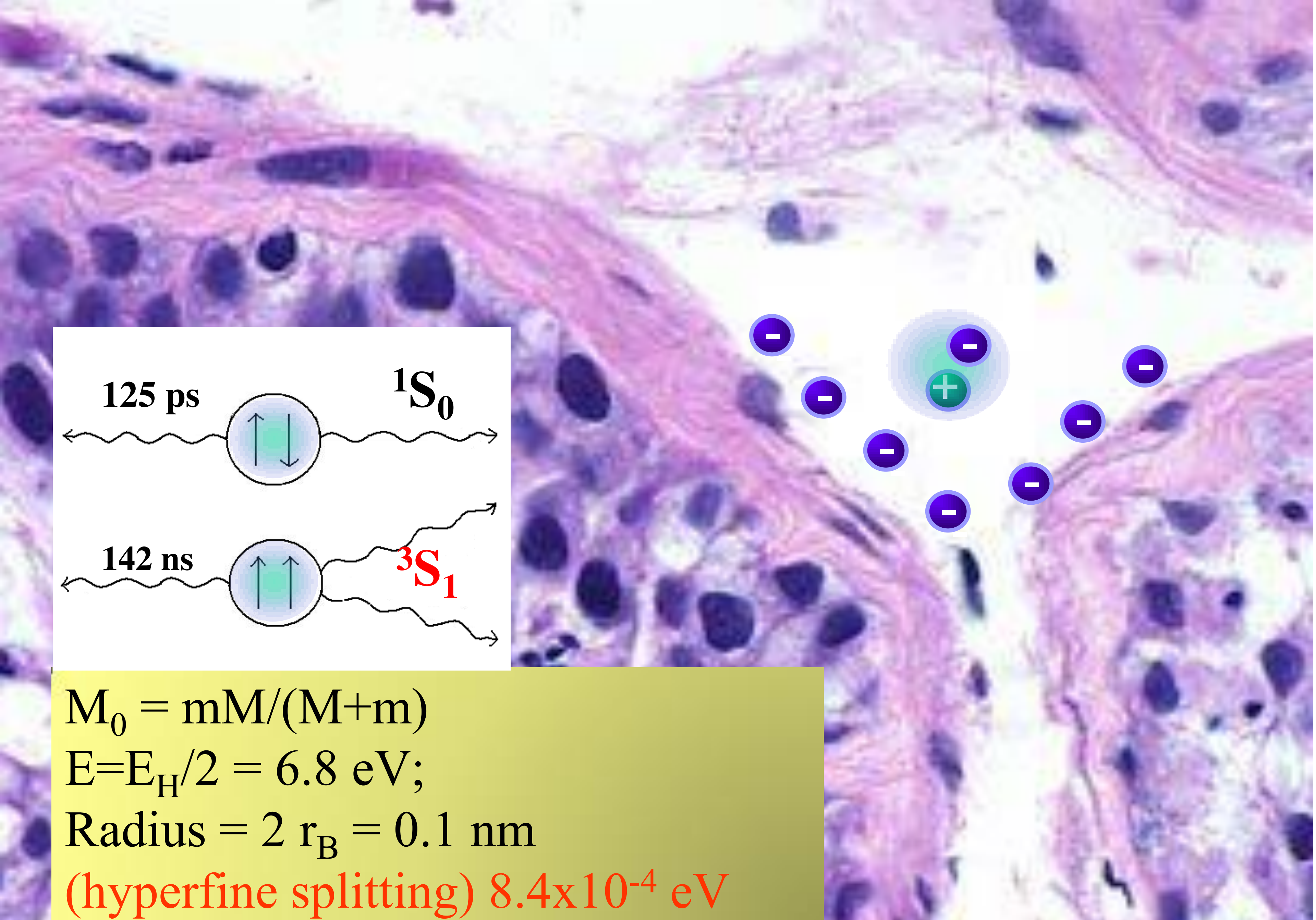
$$N(\Delta t) = N_o P_{ps} \tfrac{3}{4} e^{-\Delta t/\tau o\text{-}Ps} + N_0 \tfrac{1}{4} P_{ps} e^{-\Delta t/\tau p\text{-}Ps} + N_0 (1-P_{ps}) e^{-\Delta t/\tau b}$$



$^{14}O \longrightarrow {}^{14}N^{*} + e^{+} + \nu_e$
$^{14}N + \gamma$


$^{14}O \longrightarrow {}^{14}N^{*} + e^{+} + \nu_e$
$^{14}N + \gamma$





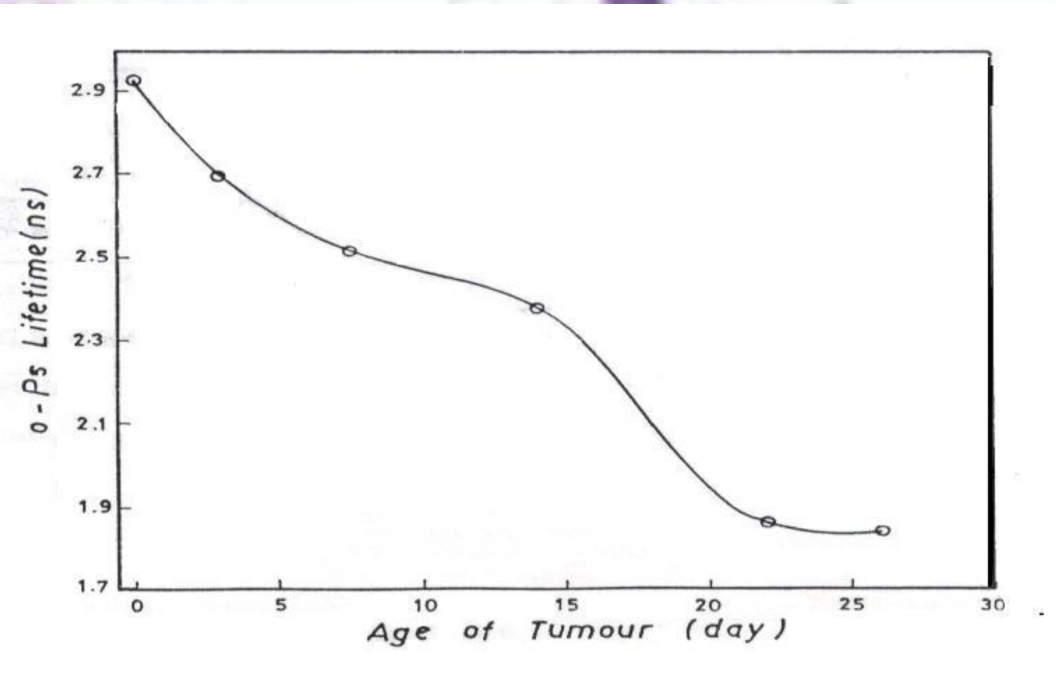
$M_0 = mM/(M+m)$

$E=E_H/2 = 6.8$ eV;

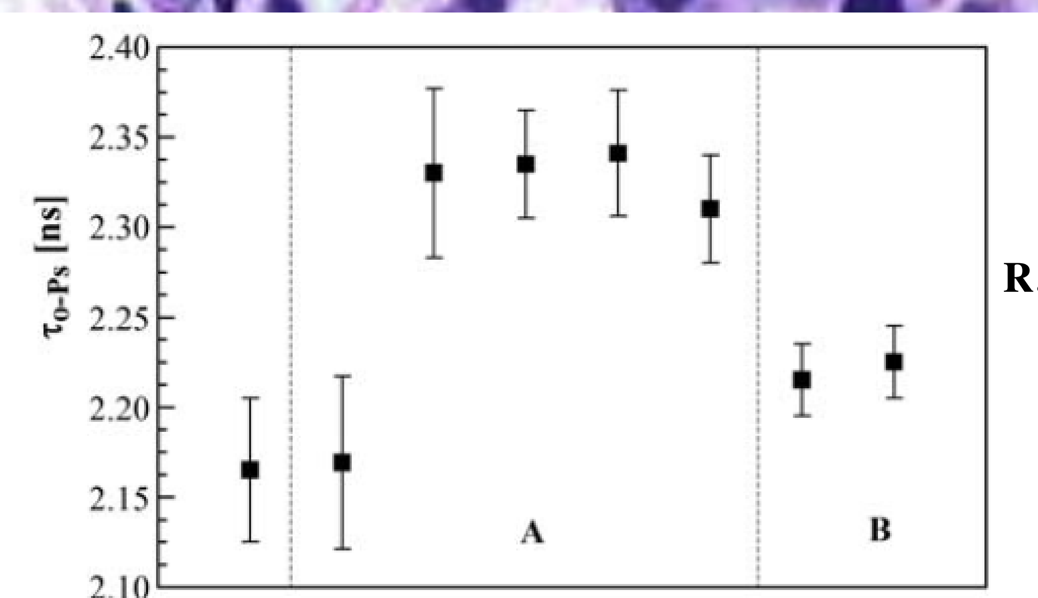
Radius = $2\ r_B = 0.1$ nm

(hyperfine splitting) 8.4×10^{-4} eV

Patent application: **Morphometric imaging PCT/EP2014/068374 (2014)**



The age of mice's tumour
with o-Ps lifetime
A.H. Al-Mashhadani et al.,
Iraqi J. Sci. 42C, 60 (2001) 3.



R. Pietrzak et al., NUKLEONIKA 58 (2013) 199

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

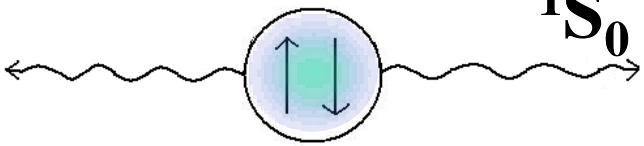
The simplest atomic system with charge conjugation aigenstates.

Electrons and positron are the lightest leptons so they can not decay into lighter partilces via weak interactiom ..

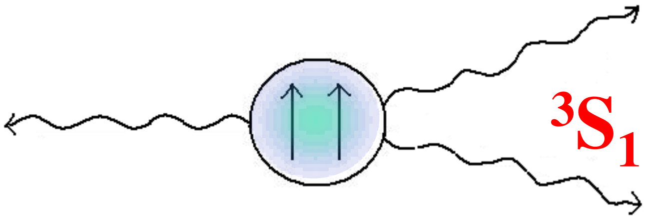
No charged particles in the final state (radiative corrections very small $2 * 10^{-10}$)
Light by light contributions to various correlations are small
B. K. Arbic et al., Phys. Rev. A 37, 3189 (1988).
W. Bernreuther et al., Z. Phys. C 41, 143 (1988).

Purely Leptonic state !

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



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



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

	$^1S_0$	$^3S_1$	2γ	3γ	4γ	5γ	…
C	+	-	+	-	+	-	

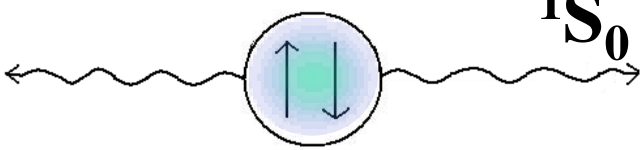
bound state mixing is not possible because there are no positronium states with opposite *C*-parity and the same J^P.

$$\mathrm{BR}\ ({}^3S_1 \dashrightarrow 4\gamma\ /\ {}^3S_1 \dashrightarrow 3\gamma) < 2.6\ 10^{-6} \text{ at } 90\%\mathrm{CL}$$

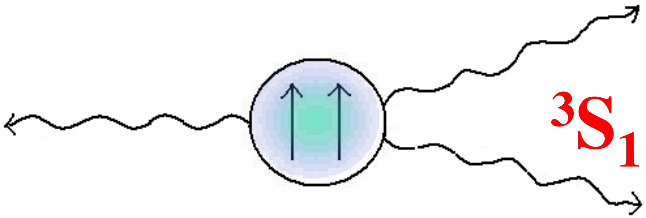
J. Yang et al., Phys. Rev. A54 (1996) 1952

$$\mathrm{BR}\ ({}^1S_0 \dashrightarrow 3\gamma\ /\ {}^1S_0 \dashrightarrow 2\gamma) < 2.8\ 10^{-6} \text{ at } 68\%\mathrm{CL}$$

A. P. Mills and S. Berko, Phys. Rev. Lett. 18 (1967) 420



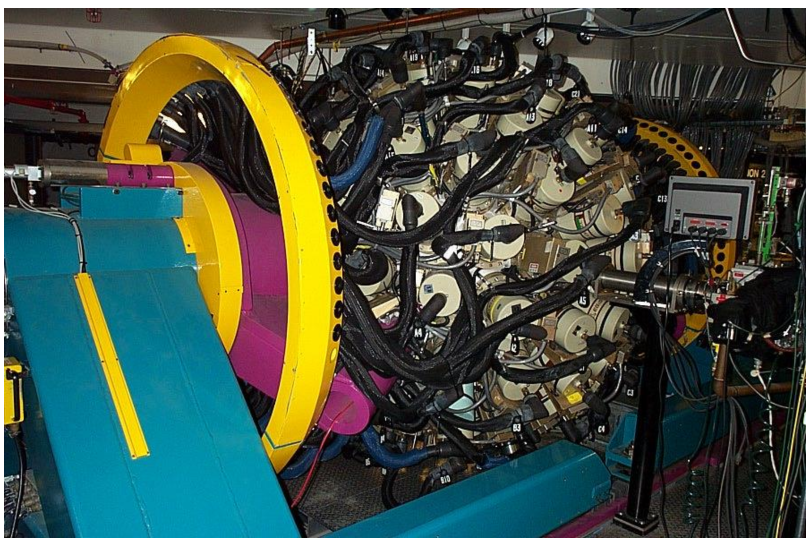
$^1S_0$ **Para-positronium tau(p-Ps) ≈ 125 ps**

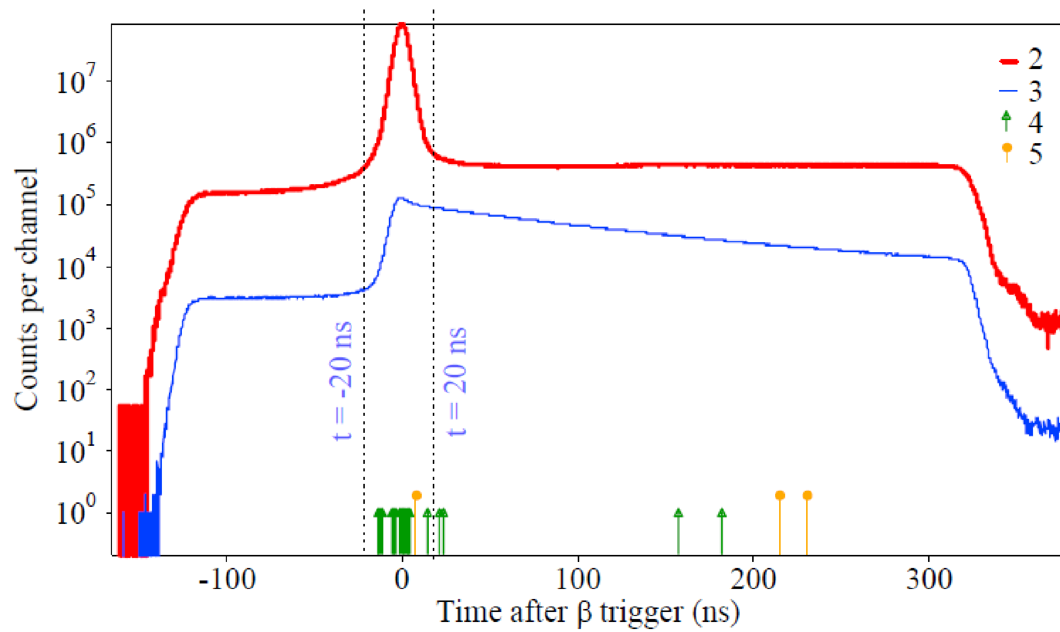


$^3S_1$ **Ortho-positronium tau(o-Ps) ≈ 142 ns**

BR ($^1S_0$ --> 5γ / $^1S_0$ --> 2γ) < 2.7 10^{-7} at 90%CL

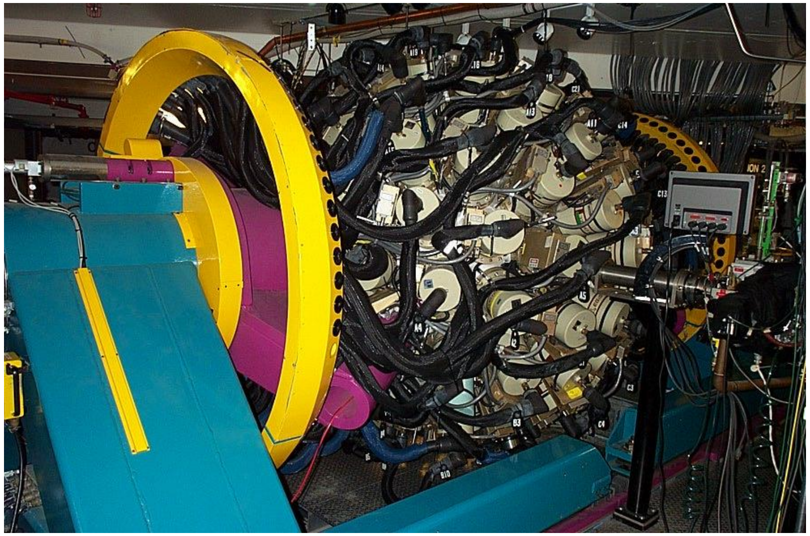
P. A. Vetter and S. J. Freedman Phys. Rev. A 66 (2002) 052505

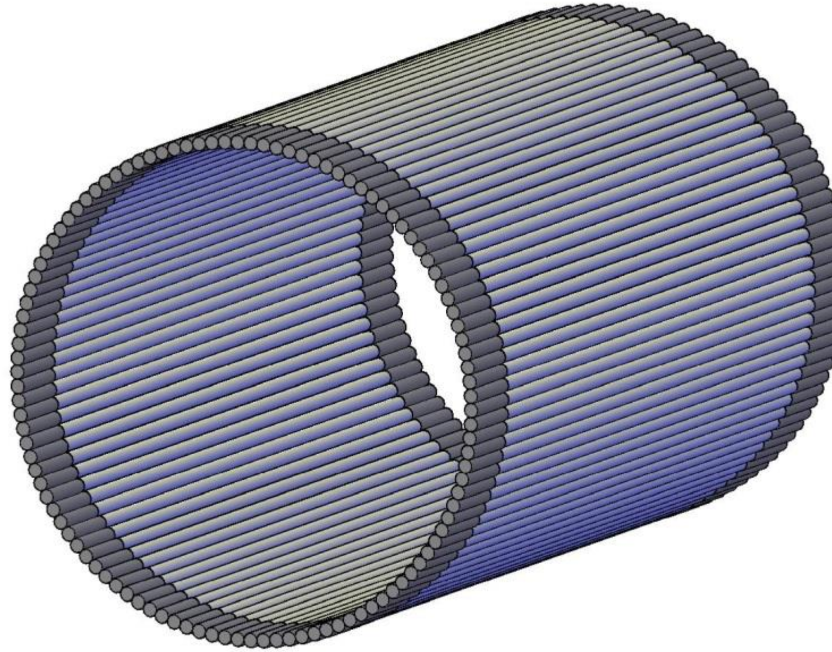




Result from: P. A. Vetter and S. J. Freedman Phys. Rev. A 66 (2002) 052505

Figure taken form the presentation of A. O. Macchiavelli, Nuclear Structure, Oak Ridge, 2006





Sigma(Delta_T) > 4.6 ns

Sigma(Delta_T) < 0.1ns

$$N(\Delta t) = N_o^0 (1+C\ldots)\, e^{-\Delta t/\tau o\text{-}Ps} \quad + \quad N_{direct}\, e^{-\Delta t/\tau b} + N_p^0 (1+C\ldots)\, e^{-\Delta t/\tau p\text{-}Ps}$$

Efficiency + cuts 0.15 per gamma

Source activity 0.04 MBq

Acceptance x efficiency: 0.1 per gamma

Activity > 20 MBq

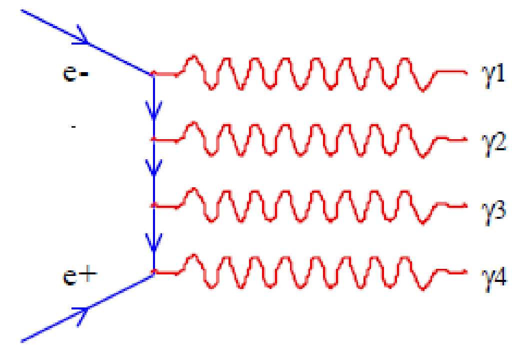
pile-ups t_crystal / t_plastic_scintillator ~= 100

Angular resolution

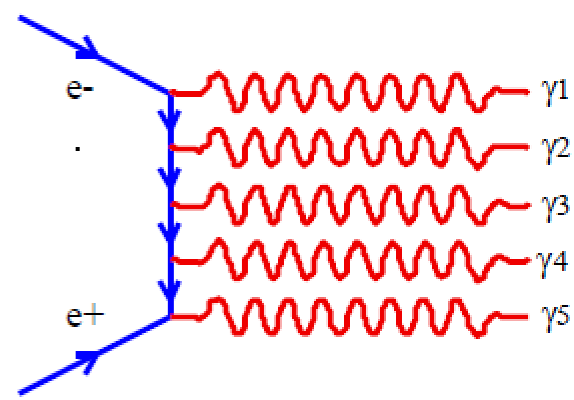
detector 7cm(dia) / 25cm (radius)

1cm / 40cm (radius)

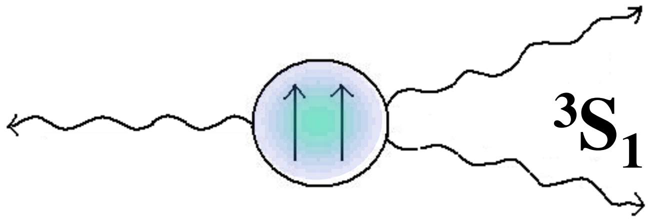
Tests of QED



$$\Gamma(Ps \rightarrow 4\gamma) \approx \alpha^7 = 1.43\ 10^{-6}$$

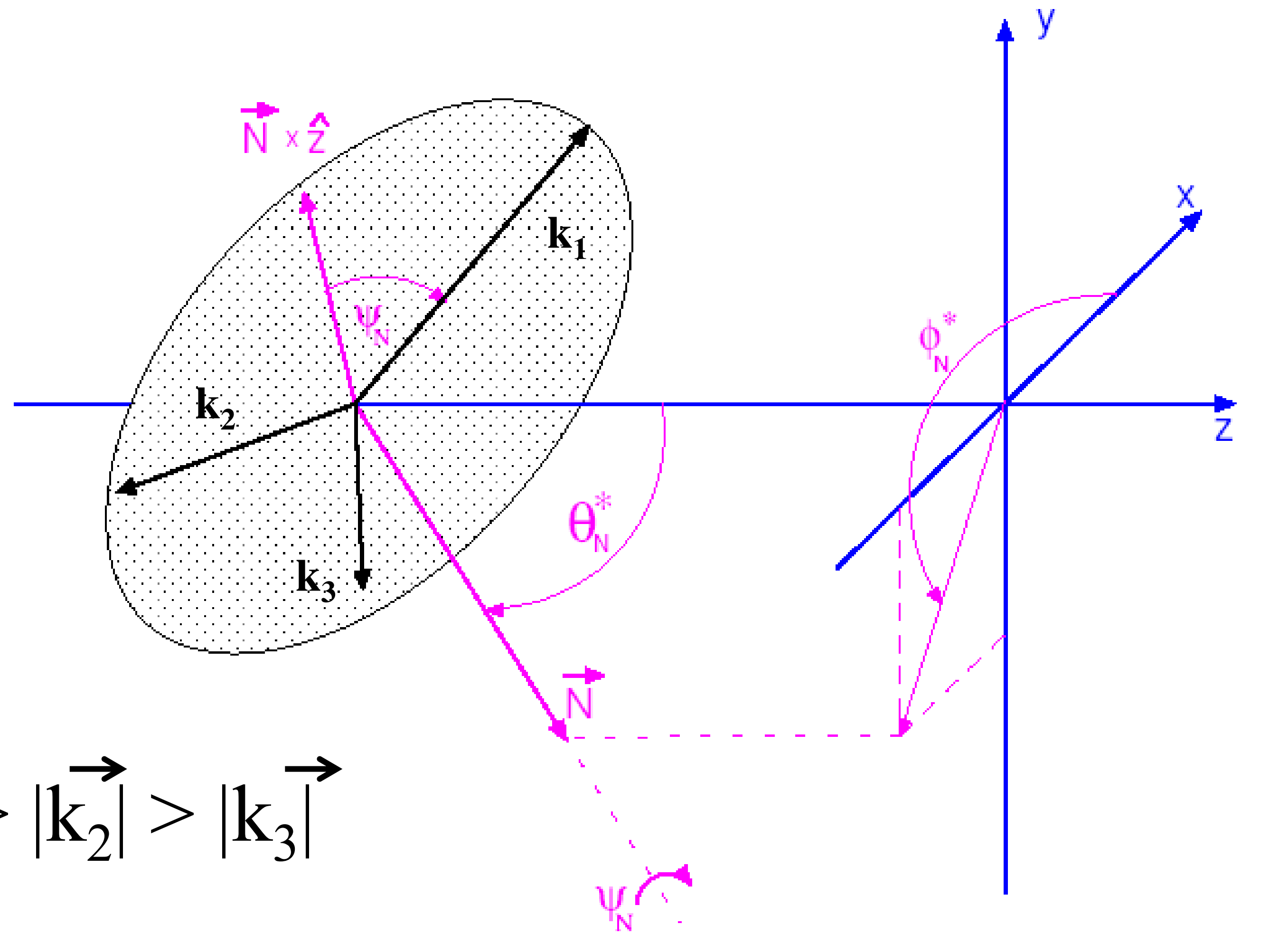


$$\Gamma(Ps \rightarrow 5\gamma) \approx \alpha^8 = 0.959\ 10^{-6}$$

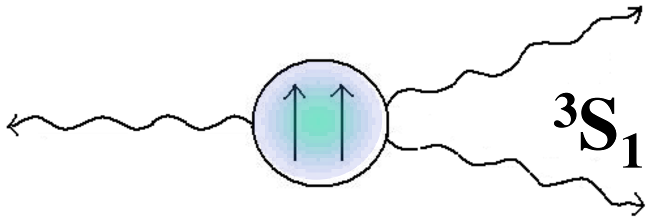


$^3S_1$ **Ortho-positronium tau(o-Ps) ≈ 142 ns**

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



$$|\vec{k}_1| > |\vec{k}_2| > |\vec{k}_3|$$



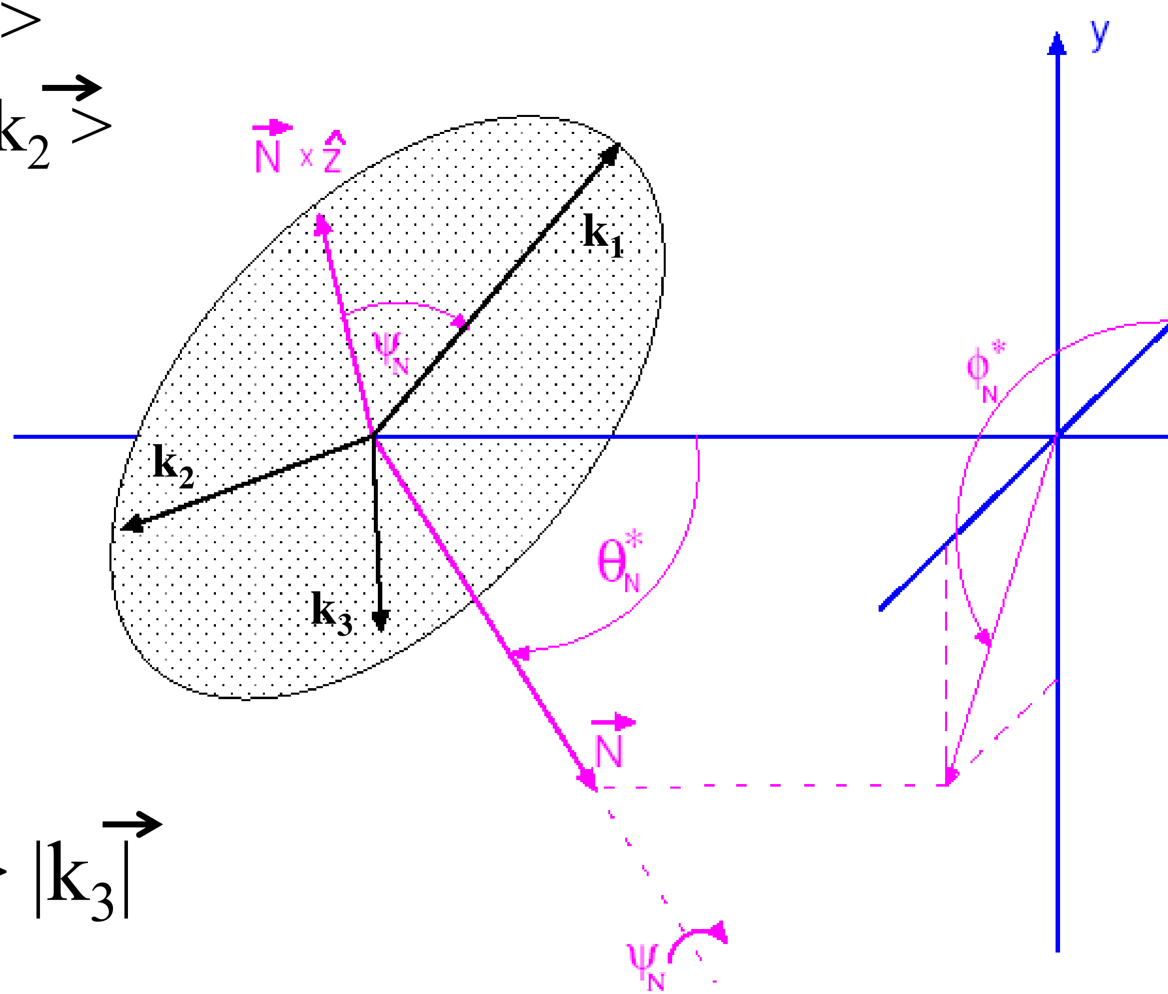
$^3S_1$ **Ortho-positronium tau(o-Ps) ≈ 142 ns**

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

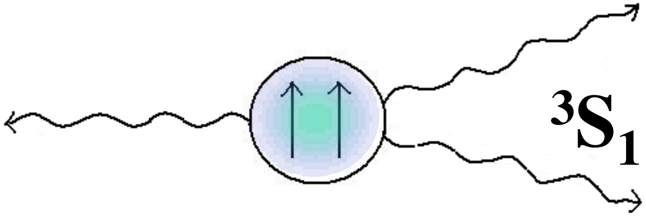
$$T\,|\vec{S},\vec{k}_1,\vec{k}_2> \; = |-\vec{S},-\vec{k}_1,-\vec{k}_2>$$

$$O|\vec{S},\vec{k}_1,\vec{k}_2> = -\,O|-\vec{S},-\vec{k}_1,-\vec{k}_2>$$

$$\sum O\,|\vec{S},\vec{k}_1,\vec{k}_2> \; = 0$$



$$|\vec{k}_1| > |\vec{k}_2| > |\vec{k}_3|$$



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

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

P.A. Vetter and S.J. Freedman,
Phys. Rev. Lett. 91, 263401 (2003).

C_CPT = 0.0071 ± 0.0062

SM $10^{-10} - 10^{-9}$

photon-photon interactions

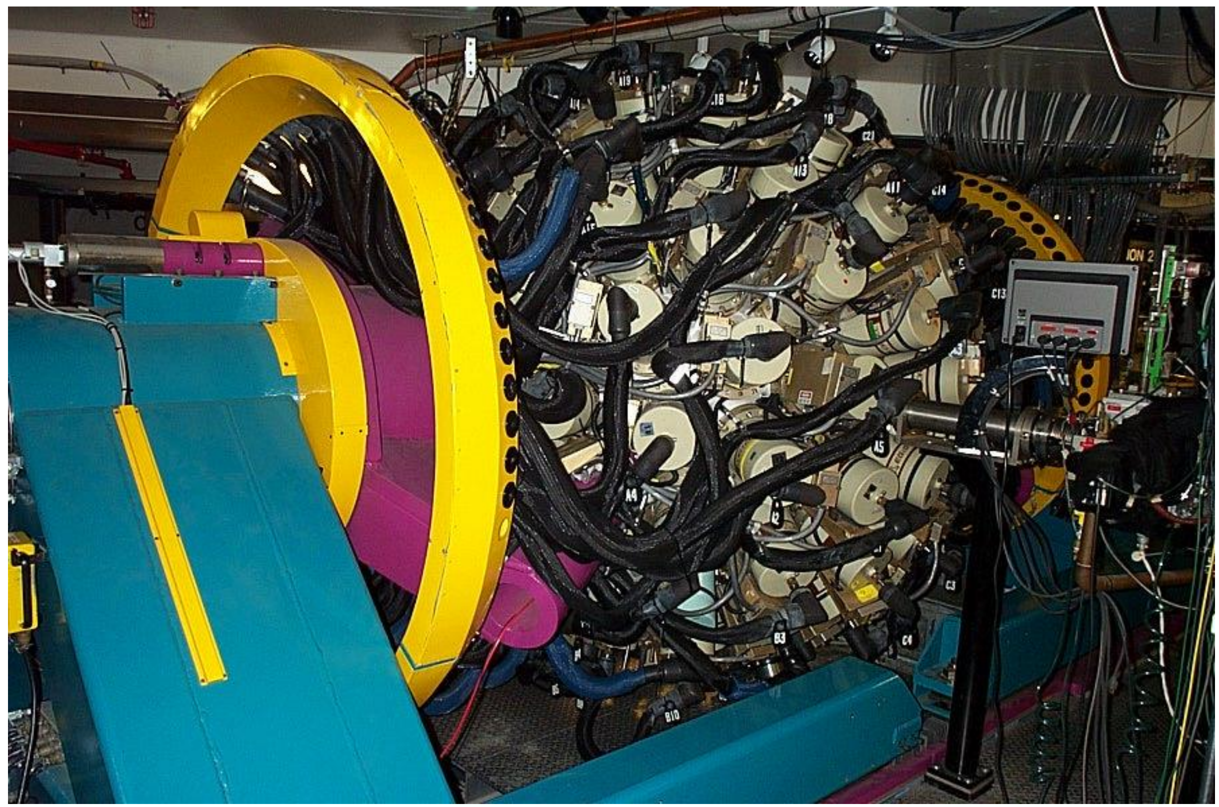
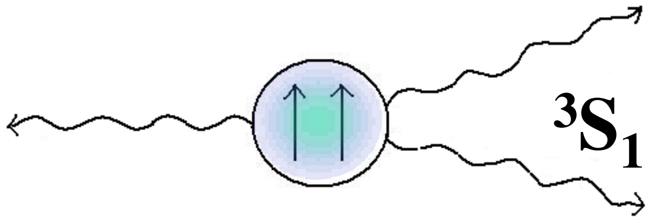
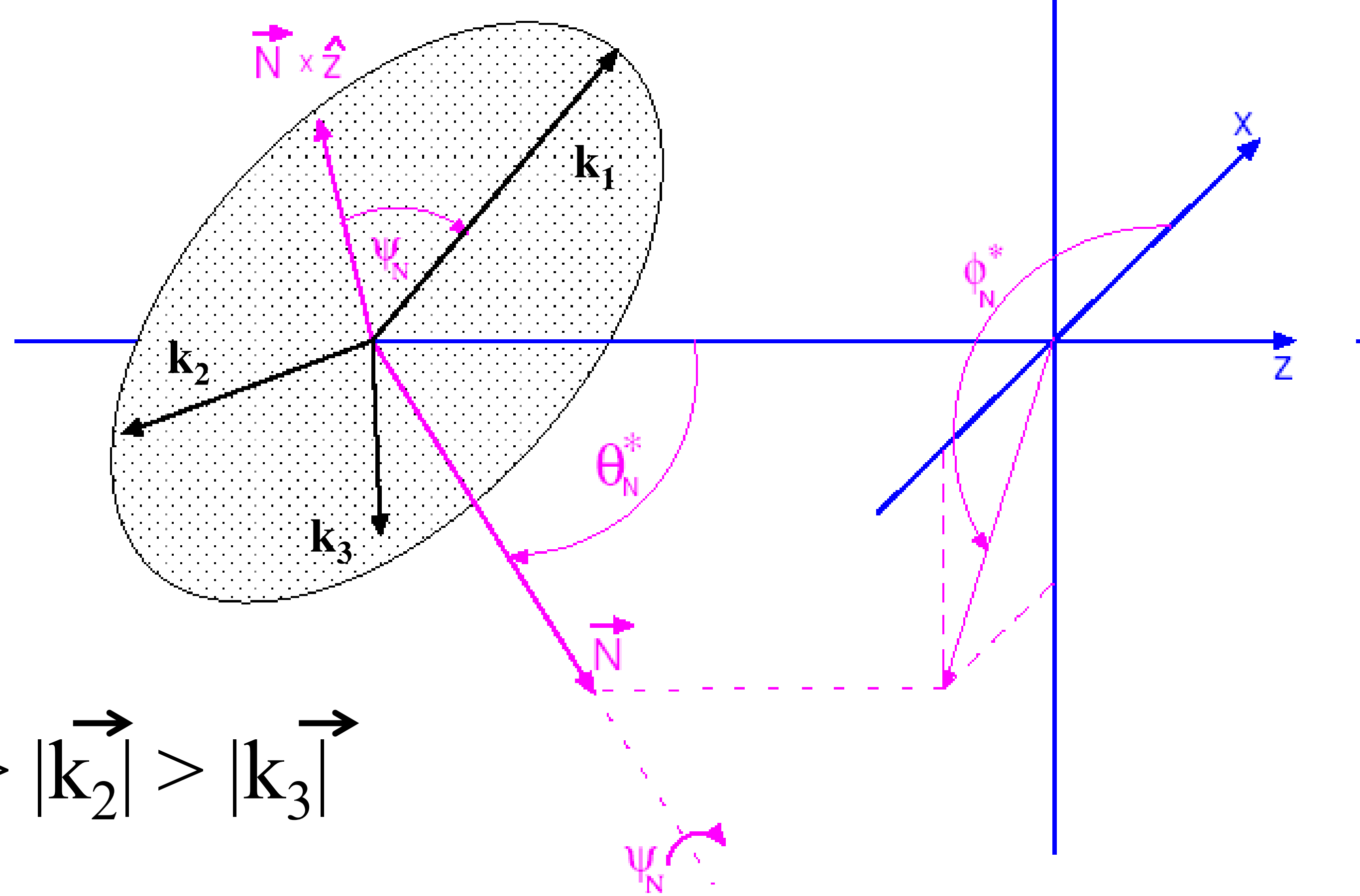


Figure taken form the presentation of P. Vetter, INT UW Seattle, November, 2002

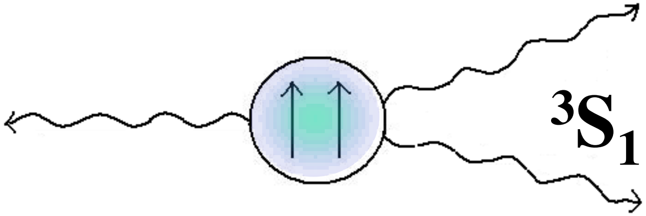


$^3S_1$ Ortho-positronium tau(o-Ps) ≈ 142 ns

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

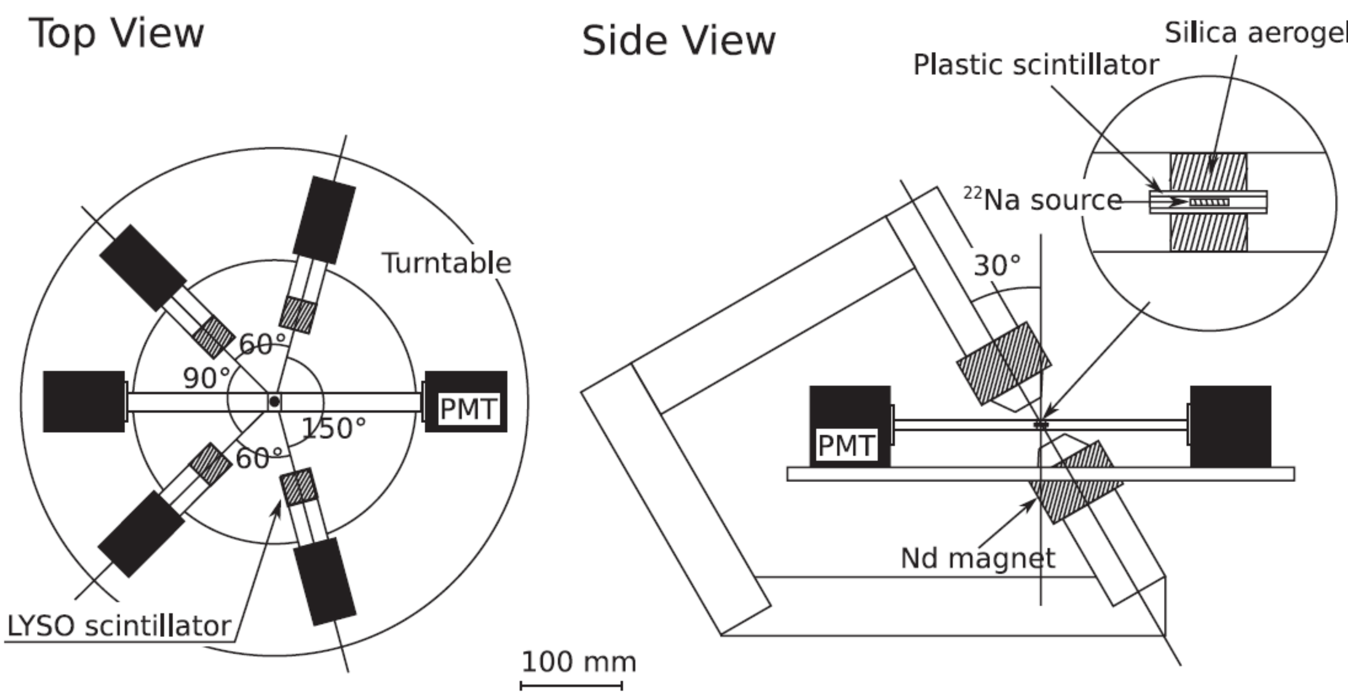


$$|\vec{k}_1| > |\vec{k}_2| > |\vec{k}_3|$$



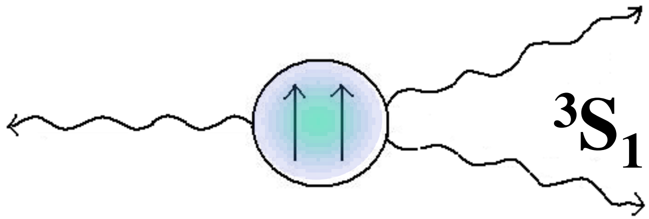
$^3S_1$ Ortho-positronium tau(o-Ps) ≈ 142 ns

So far best accuracy for **CP violation** was reported by
T. Yamazaki et al., Phys. Rev. Lett. 104 (2010) 083401



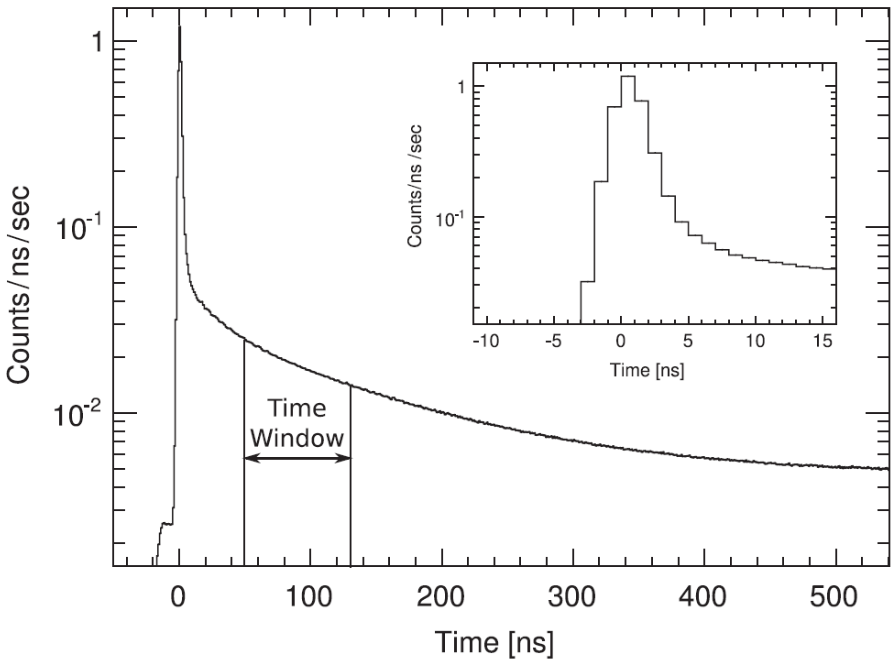
$$N = N_0[1 + C_{CP}(\vec{S} \cdot \vec{k}_1)(\vec{S} \cdot \vec{k}_1 \times \vec{k}_2)]\exp(-t/\tau)$$

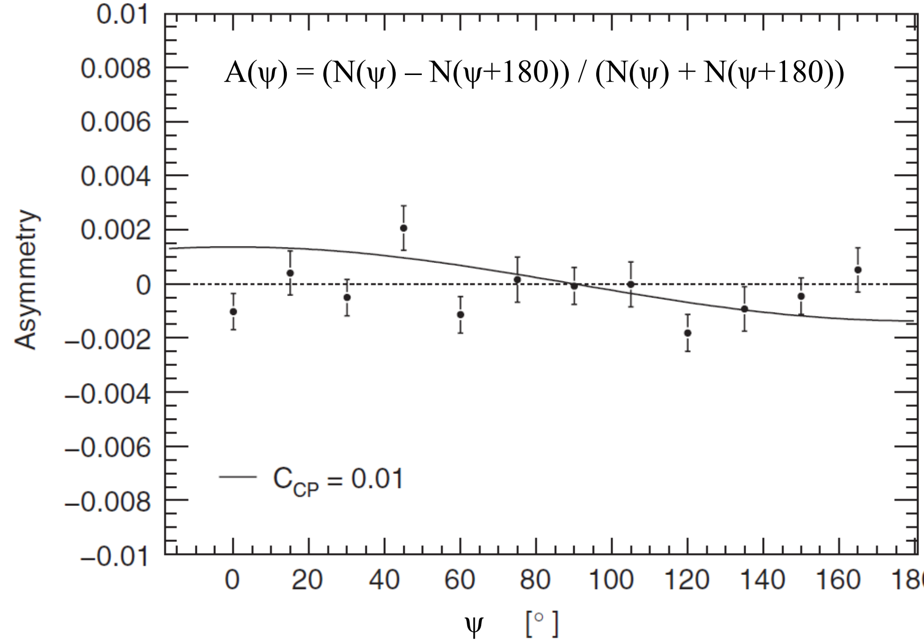
$$Q = (\vec{S} \cdot \vec{k}_1)(\vec{S} \cdot \vec{k}_1 \times \vec{k}_2) = P_2 \sin 2\theta \sin\psi \cos\phi$$



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

T. Yamazaki et al., Phys. Rev. Lett. 104 (2010) 083401





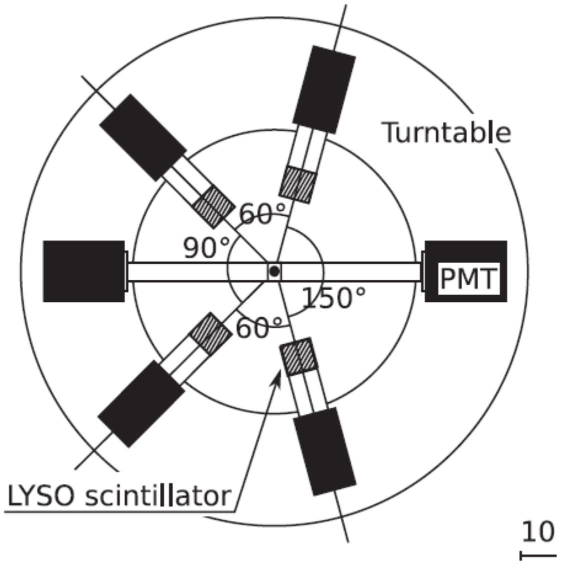
-0.0023 < C_CP < 0.0049 at 90% CL

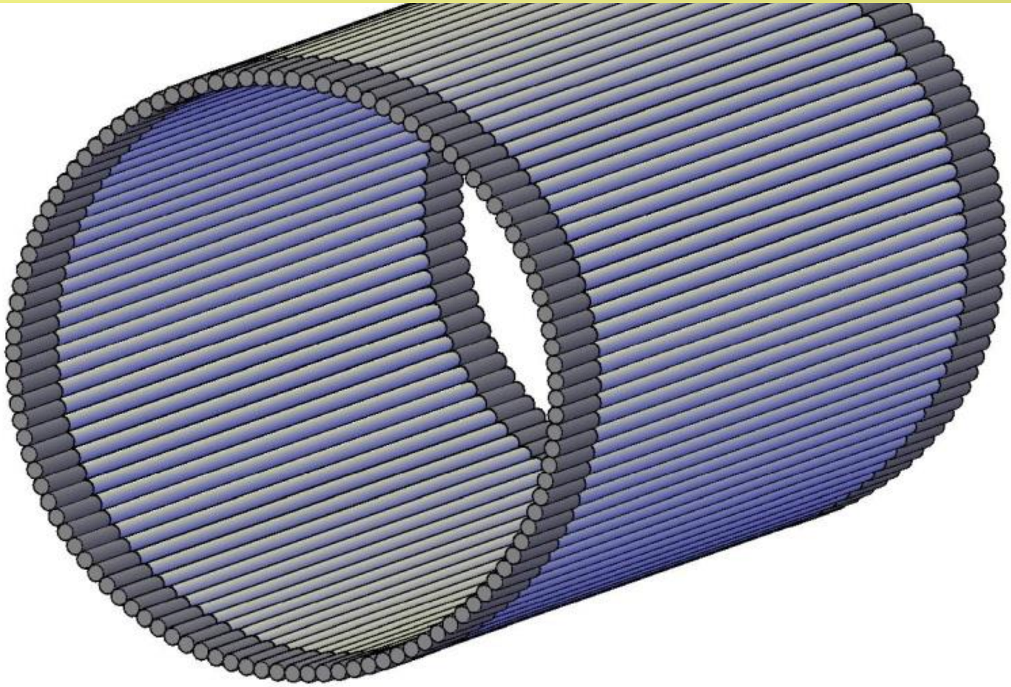
SM $10^{-10} - 10^{-9}$

W. Bernreuther et al., Z. Phys. C 41, 143 (1988)
This is due to photon-photon interactions in the final state caused by the creation of virtual charged particle pairs)

$$P_2 = \frac{N_{+1} - 2N_0 + N_{-1}}{N_{+1} + N_0 + N_{-1}}$$

J-PET (**J**agiellonian **PET**)





Sigma(Delta_T) ≈ 0.9ns

N(psi)

Magnet inside

Sigma(Delta_T) < 0.1ns

N(theta, psi, phi)

simultaneously,
psi and psi+180

Electromagnet outside

pile-ups t_crystal/t_plastic_scintillator ~= 100

Source activity 1 MBq — Activity > 20 MBq

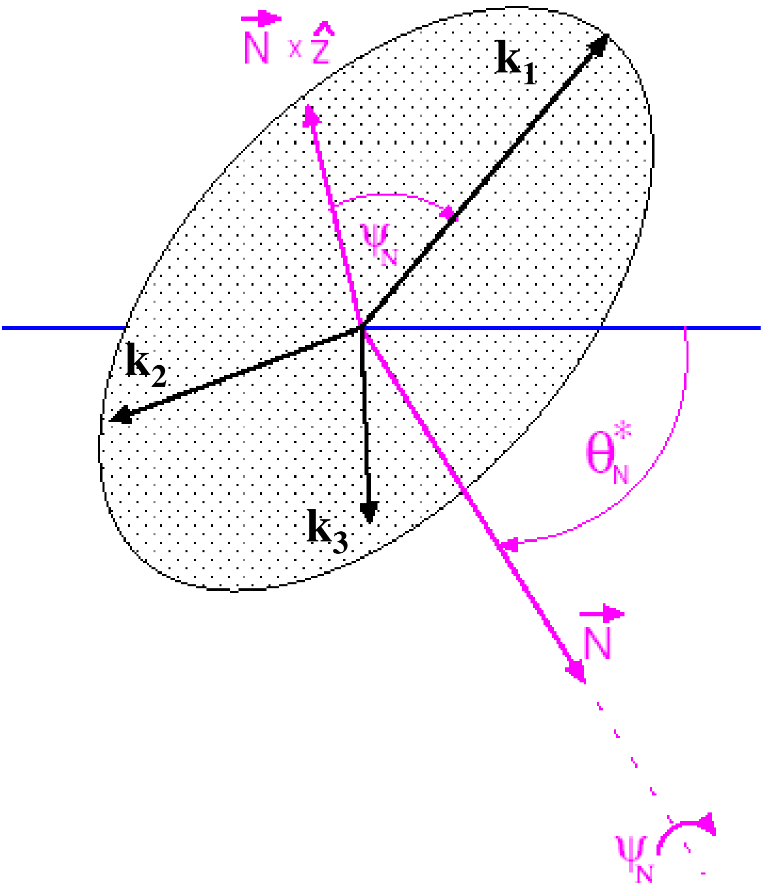
Coincidence gate: 700ns — none (1ns … offline)

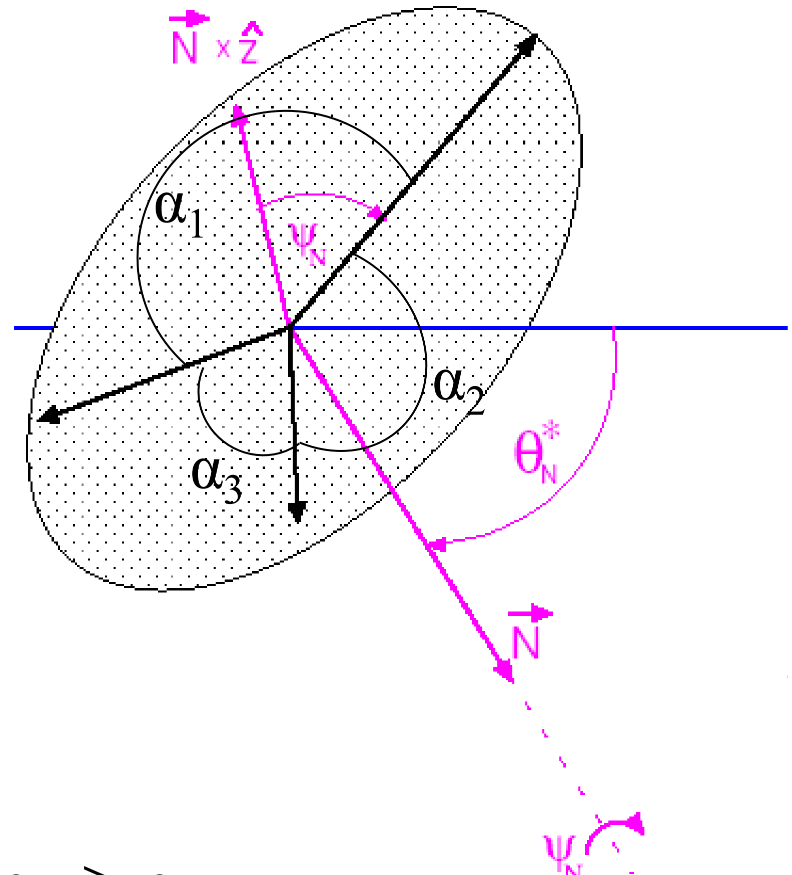
2gamma — 3gamma

Acceptance $3 * 10^{-5}$ for 2γ — Acceptance x efficiency: 10^{-4} for 4γ

Angualar resolution

detector 3cm / 10cm (radius) — 1cm / 40cm (radius)

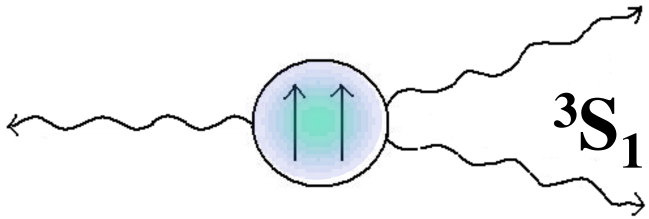




$|k_1| > |k_2| > |k_3|$

$\alpha_1 > \alpha_2 > \alpha_3$

$\alpha_1, \alpha_2, \alpha_3, 2m_e \;\text{-->}\; \vec{k}_1, \vec{k}_2, \vec{k}_3$



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

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

T. Yamazaki et al., Phys. Rev. Lett. 104 (2010) 083401

-0.0023 < C_CP < 0.0049 at 90% CL

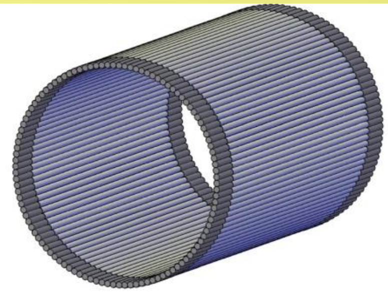
P.A. Vetter and S.J. Freedman, Phys. Rev. Lett. 91, 263401 (2003).

C_CPT = 0.0071 ± 0.0062

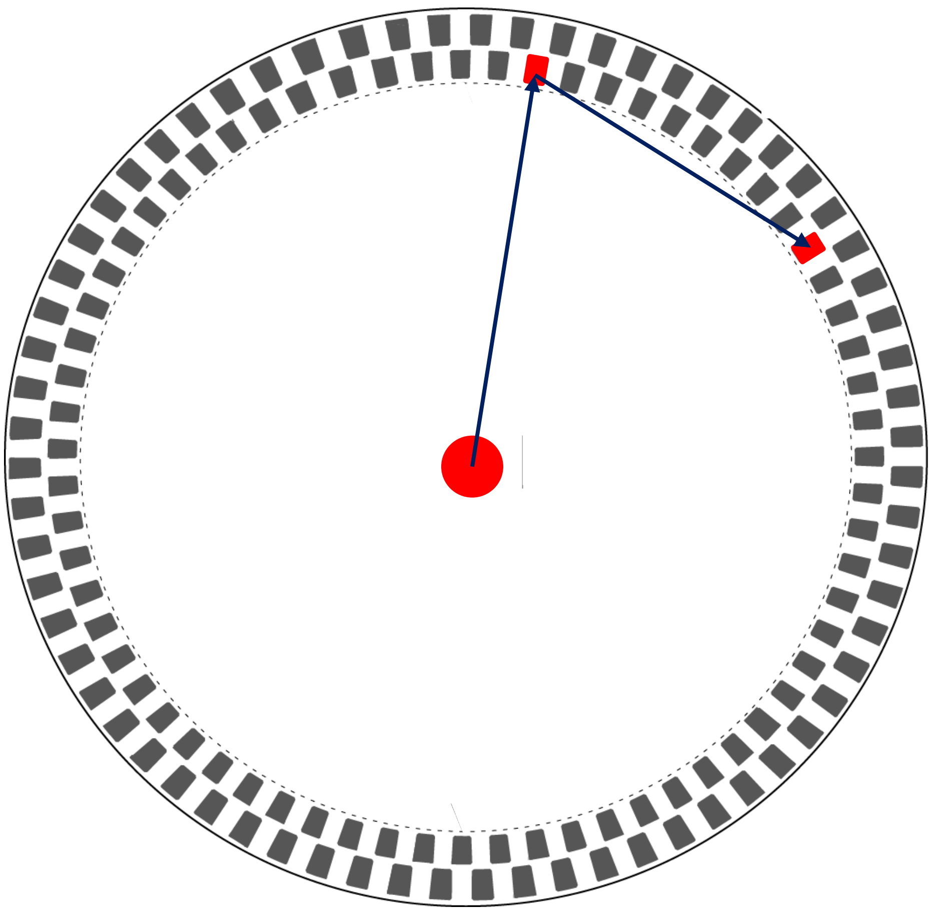
SM $10^{-10} - 10^{-9}$ W. Bernreuther et al., Z. Phys. C 41, 143 (1988)

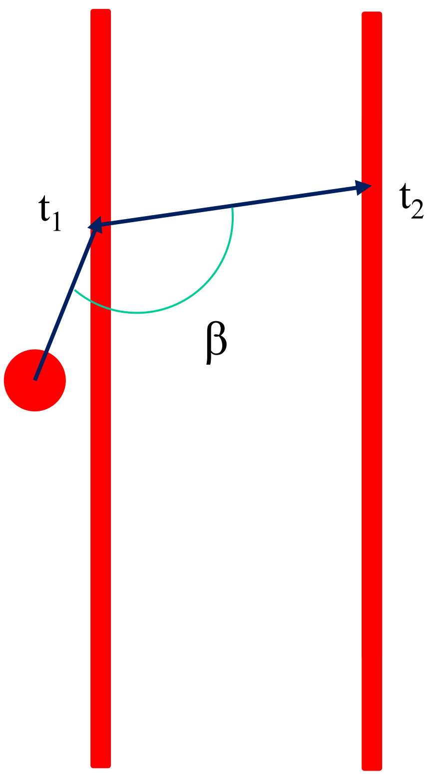
This is due to photon-photon interactions in the final state caused by the creation of virtual charged particle pairs.

J-PET --> polarization of γ



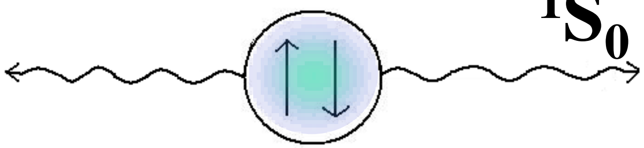
$\sigma(t_1 - t_2) < 100ps$



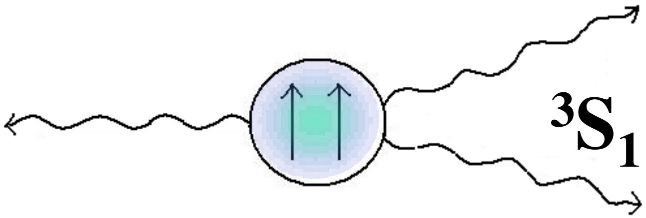


Compton scattering:

β correlated with $\vec{E}$

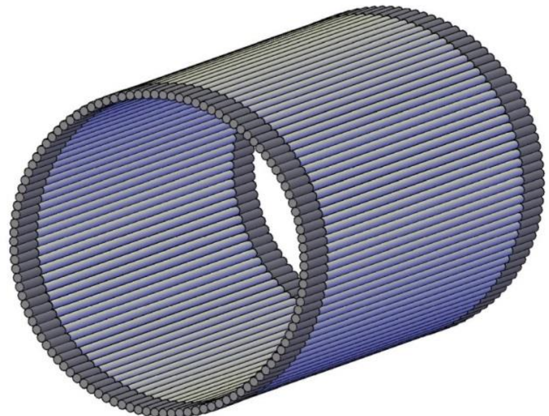


$^{1}S_{0}$ **Para-positronium tau(p-Ps) ≈ 125 ps**



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

	T	P
$\vec{S}$	-	+
$\vec{k}$	-	-
$\vec{E}$	+	-

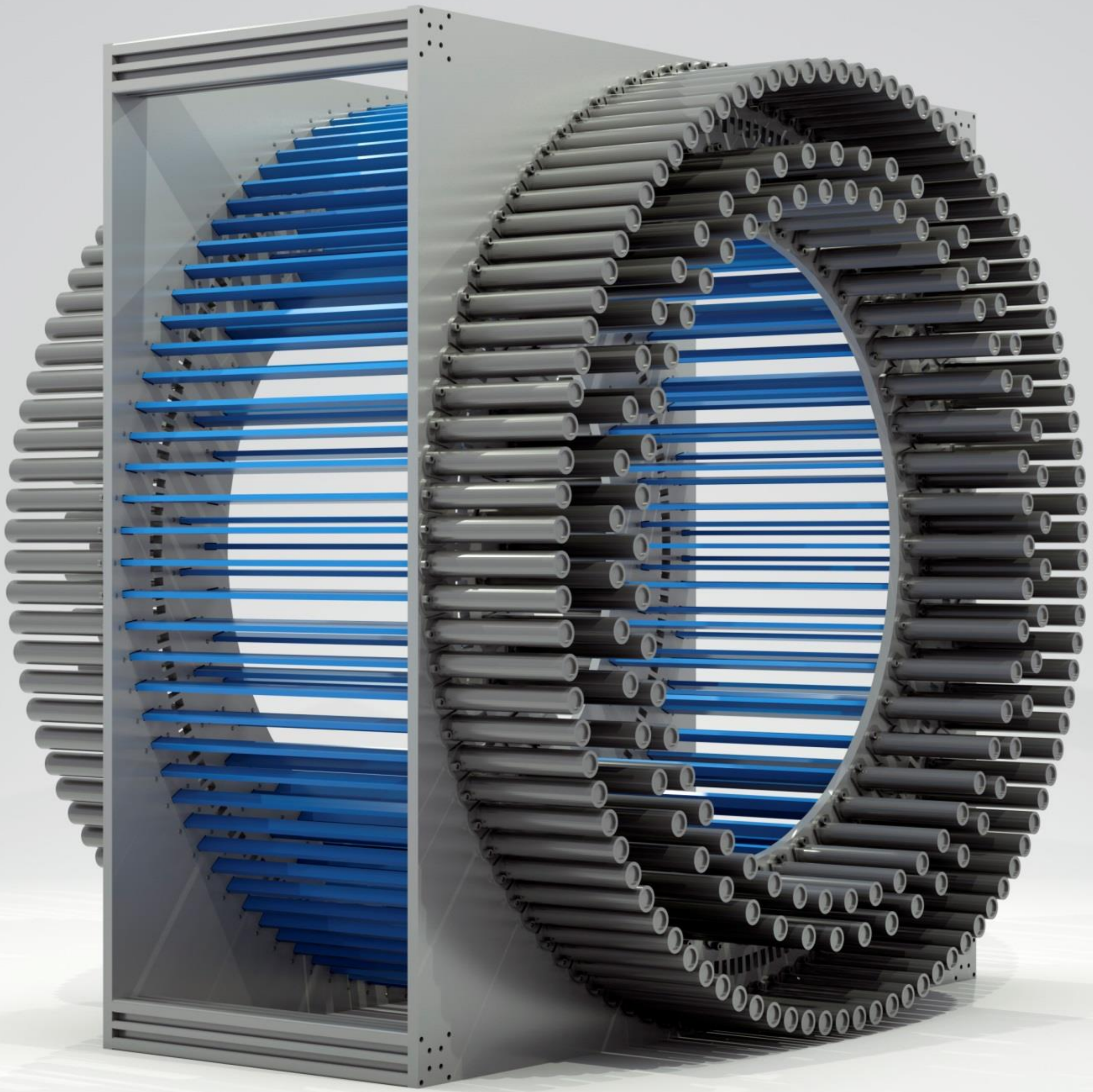


$^{3}S_{1}$ --> 3γ -->

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

$^{1}S_{0}$ --> 2γ -->

Operator	C	P	T	CP	CPT
$\vec{S} \cdot \vec{E}_1 \times \vec{E}_2$	+	+	-	+	-
$\vec{S} \cdot \vec{E}_1$	+	-	-	-	+



Jagiellonian **PET**


THANK YOU
FOR YOUR ATTENTION