MeV scale quantum entanglement

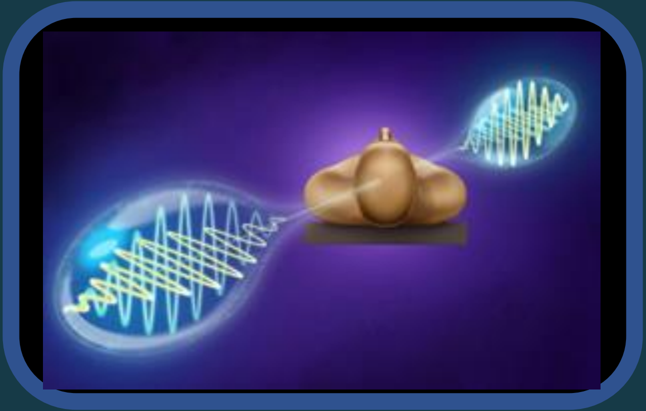
Applications in imaging and fundamental tests

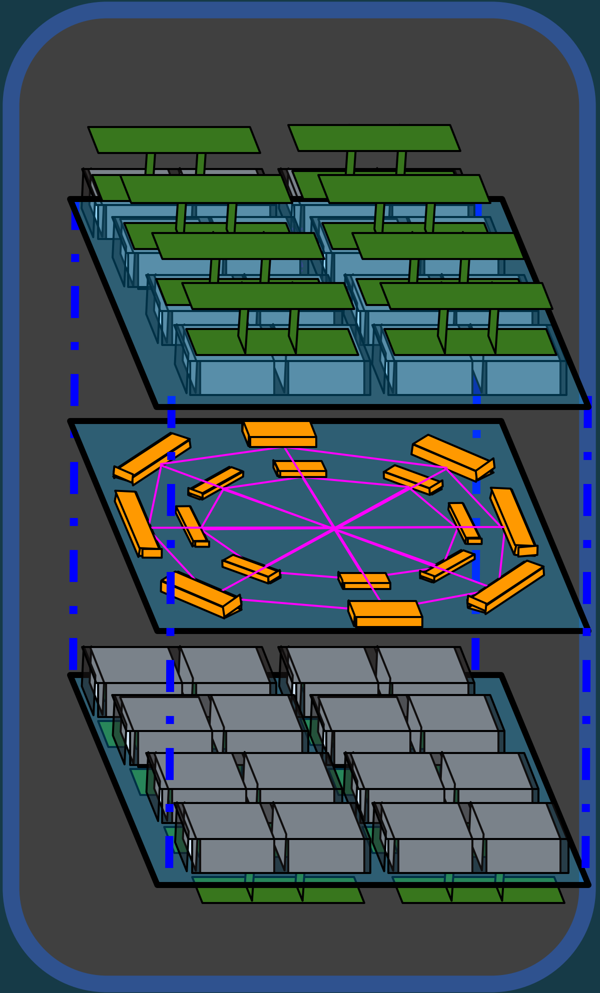
Prof Dan Watts
(University of York)

Dr Nick Zachariou, Dr Jamie Brown, Dr Julien Bordes, Dr Mikhail Bashkanov, Dr Ruth Newton, Dawid Grabowski, Laura Stephenson
Prof Karla Evans, Cameron Kyle-Davidson (AI imaging group, Psychology)
Prof Kenji Shimazoe, Mizuki Uenomachi (University of Tokyo)
Prof Steve Archibald, John Wright (King's College London)
Prof Harry Tsoumpas (Groningen PET research centre)

Talk outline

- Photonic QE at the MeV scale (positron annihilation γ)
- MeVQE decoherence – a paradigm shift in understanding
- York/Tokyo large acceptance AI-QEPET & AI-QESPECT prototype
- Measurements plans at York and KCL





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Entanglement in positron annihilation

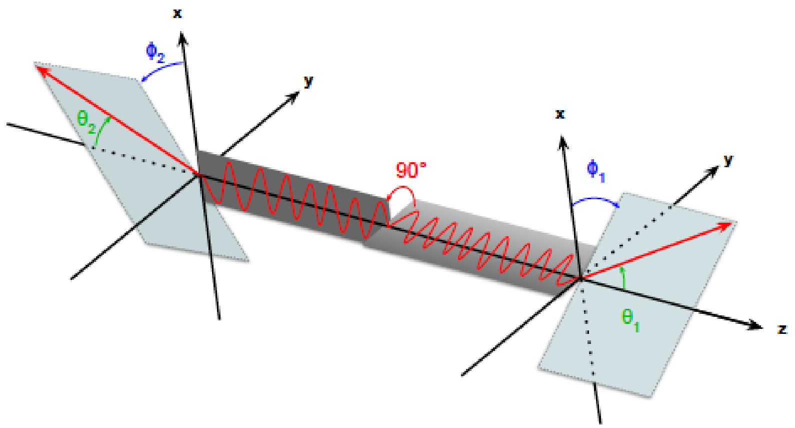
Positron annihilation $e^{-} + e^{+} \rightarrow 2\gamma$

Annihilation at rest (L=0)

γ polarisations perpendicular (conservation of momentum)

1 entangled combination of directions (-,+) and polns. ***(H,V)*** also conserves parity. A Bell state

$$|\psi> = \frac{1}{\sqrt{2}}(|H>_{-}|V>_{+} - |H>_{+}|V>_{-})$$



e.g. Yang, Amer Phys Soc 77 242 (1950)
Bohm and Aharonov, PRC 108 1070 (1957))

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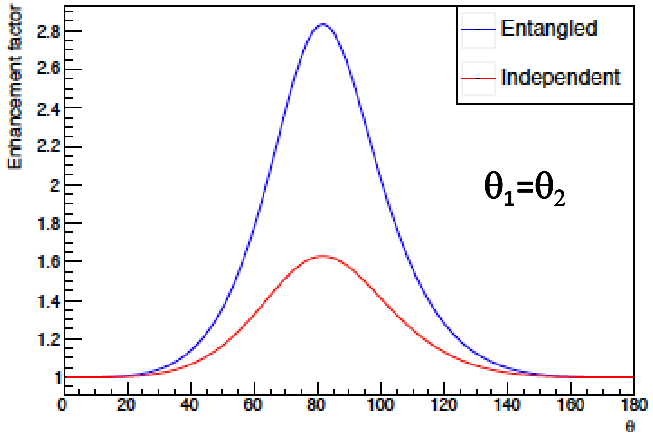
Entanglement in double Compton scattering

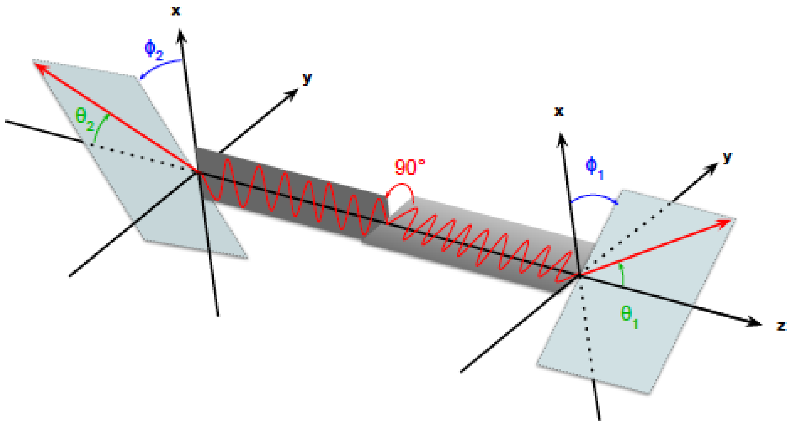
CS depends on γ polarization (pol. Klein Nishina prop $\sin^2\Phi$)



$$|\psi> = \frac{1}{\sqrt{2}}(|H>_{-}|V>_{+} - |V>_{+}|H>_{-})$$

Incorporate polarised KN

$$\frac{d^2\sigma}{d\Omega_1 d\Omega_2} = \frac{r_0^4}{16}(K_a(\theta_1\ \theta_2) - K_b(\theta_1\ \theta_2)\cos(2\Delta\phi))$$



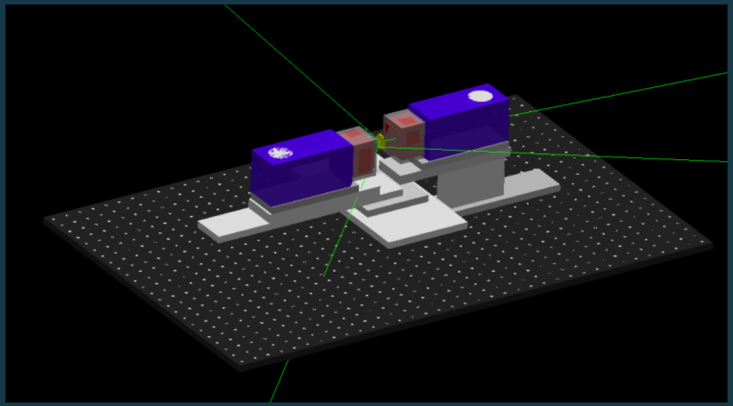
Entanglement -> ***magnitude*** of $\cos(2\Delta\phi)$ modulation

-> Implemented into GEANT4 simulation

e.g. Snyder et. al. , Phys Rev 73 440 (1947)
Pryce and Ward, Nature 160 435 (1947)
Bohm and Aharonov, PRC 108 1070 (1957)
Hiesmayr et al, Sci Rep 2019 9(1):8166
Caradonna et. al., JPC 3, 105005 (2019)
Duarte EPJ H 37 311 (2012) - historical overview

Comparison of entangled GEANT4 and experimental data

G4 simulation of detector apparatus



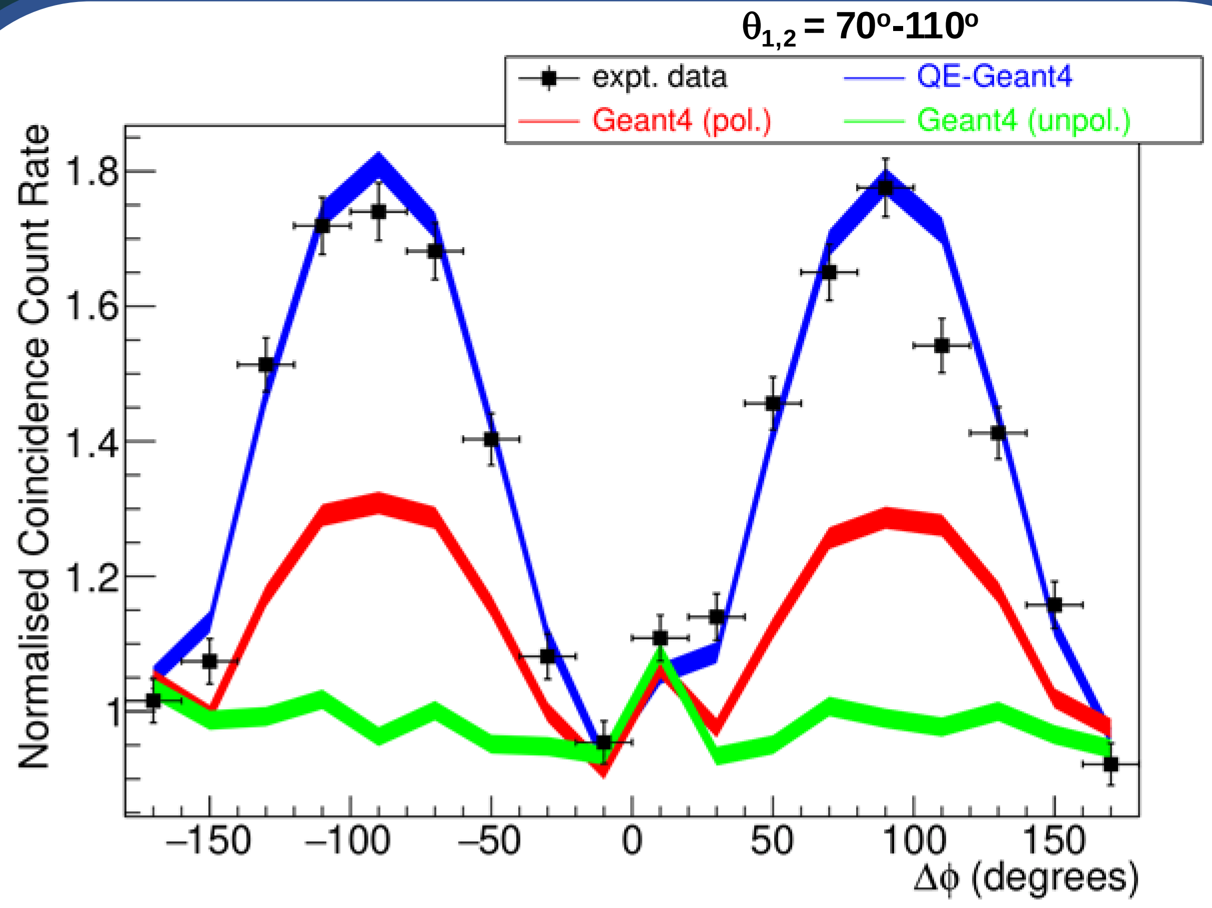
Analysed with same code and cuts as the experimental data

Agreement with **entangled prediction**

Clear disagreement with **standard G4**

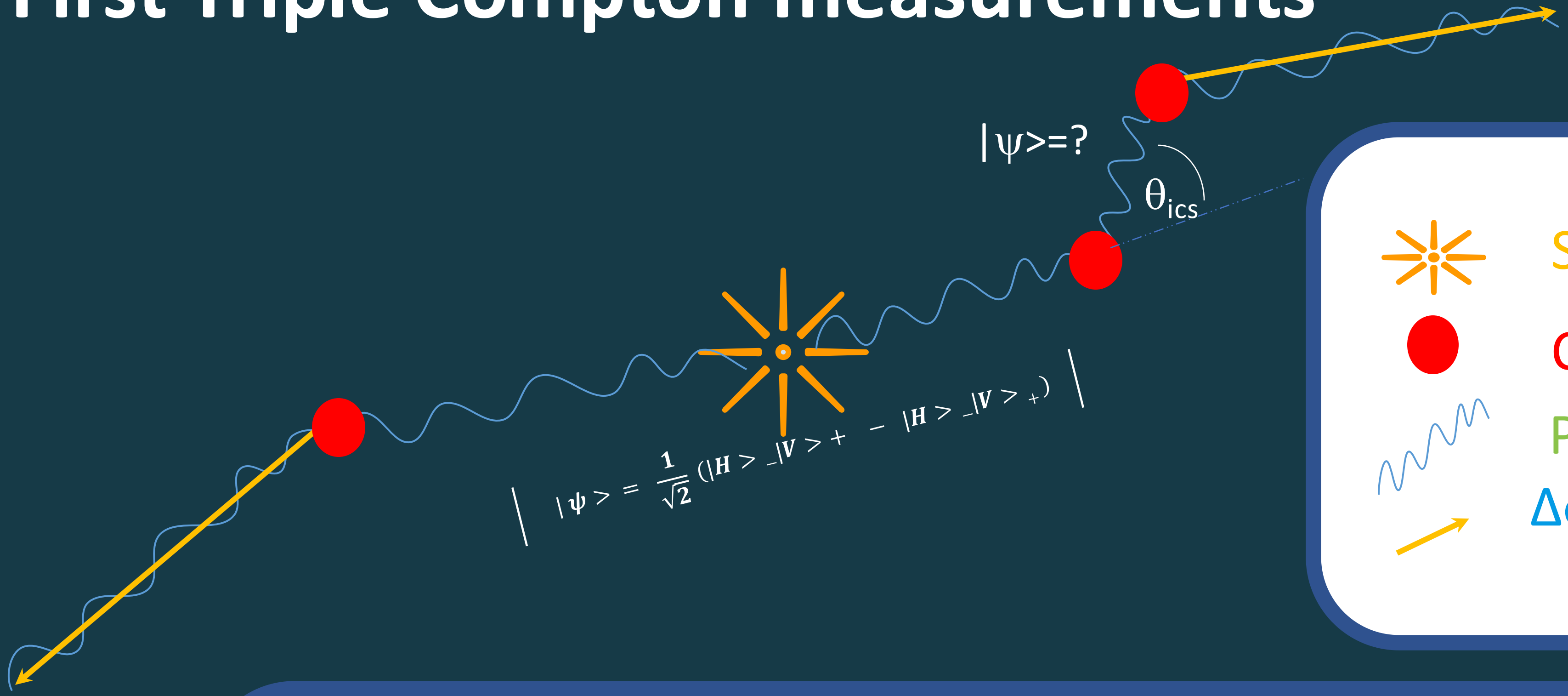
Unpolarised ~flat -> uniform acceptance

Watts, Bordes, Brown, Cherlin, Newton *et al.* 2021 Nat. Comms. 12 : 2646

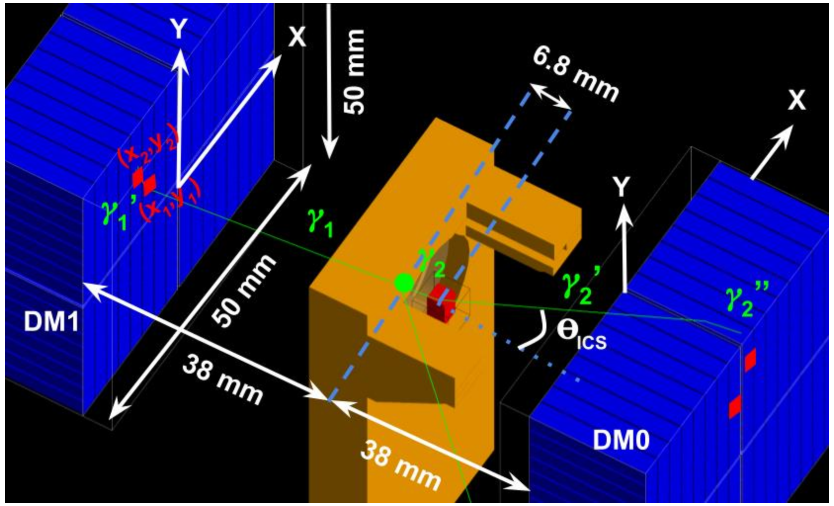


Also see previous tests in more limited kinematics – summarized In
Caradonna et. al., JPC 3, 105005 (2019)

First Triple Compton measurements



Source
Compton scatter location
Photon
$\Delta\phi = \phi_2 - \phi_1$



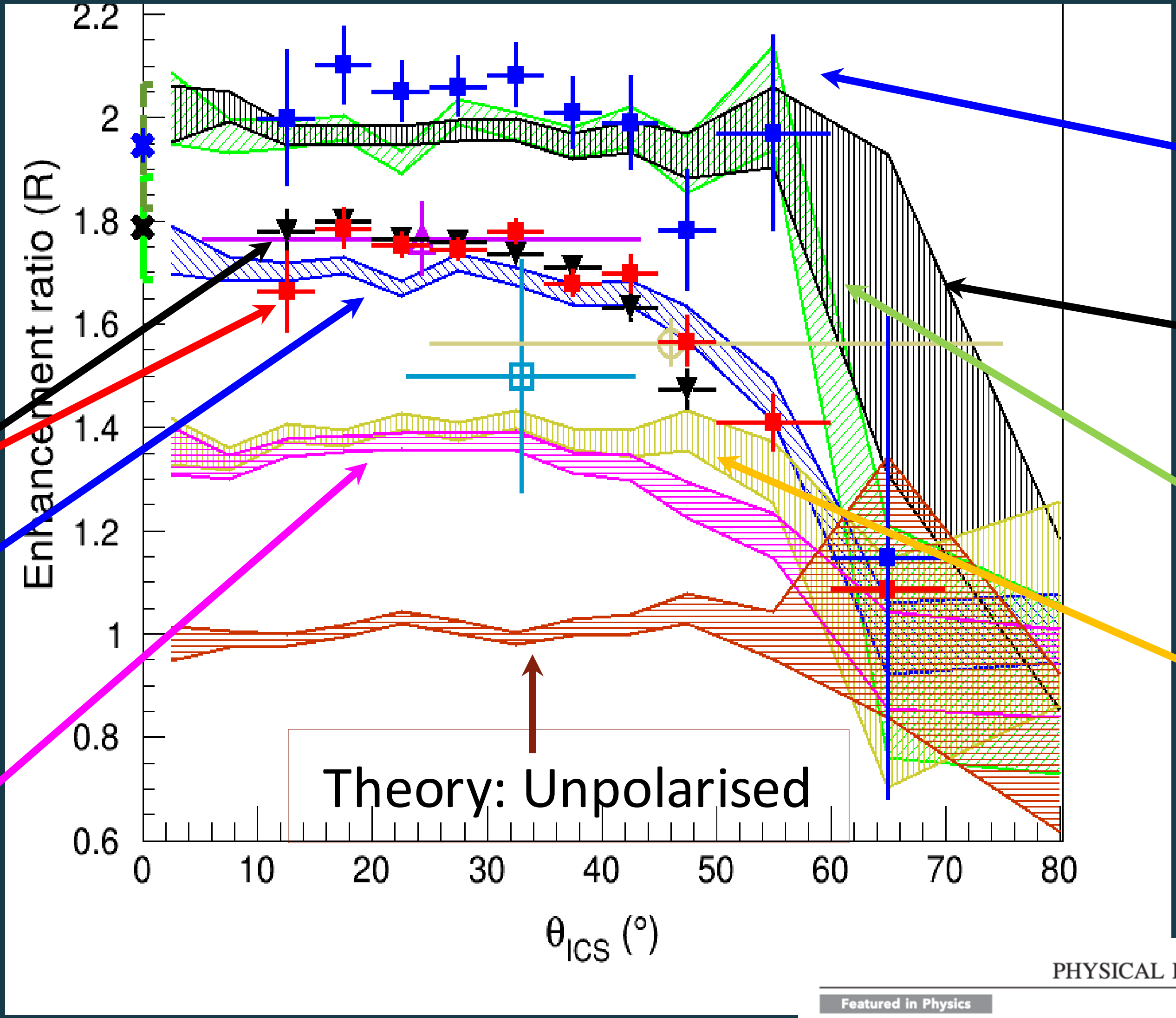
Measure intermediate scatter in single LYSO crystal

$\Delta\phi$ from inter-crystal Compton scatter

Arrays 512 3x3x20mm LYSO crystals

PETSYS ASIC DAQ system

First Triple Compton Measurements



Without Multiple Scatting deconvolution

Experimental

Theory

Classical limit

With multiple scattering deconvolution

Experimental

Theory: QE TCS (QFT)

Theory: QE maintained

Classical limit

QE robust in measured range

Agrees with QFT calcs (York) (and no QE loss calcs..)

PHYSICAL REVIEW LETTERS **133**, 132502 (2024)

Featured in Physics

First Detailed Study of the Quantum Decoherence of Entangled Gamma Photons

Julien Bordes, James R. Brown, Daniel P. Watts,* Mikhail Bashkanov, Kieran Gibson, Ruth Newton, and Nicholas Zachariou

School of Physics, Engineering and Technology, University of York, York, YO10 5DD, United Kingdom

(Received 8 December 2023; revised 21 March 2024; accepted 27 June 2024; published 25 September 2024)

AI-QEPET : Doing better with the scatter

Early results training AI on simulated QE-PET data

Multilayer Perceptron with 10 layers and ReLU Activations throughout.

Use of QE-PET significantly improves reconstruction of both the annihilation site and the scatter site 😀

Uses the ~80% of “scatter“ events discarded in current PET

Enhanced contrast, lower dose – screening PET?

Next steps

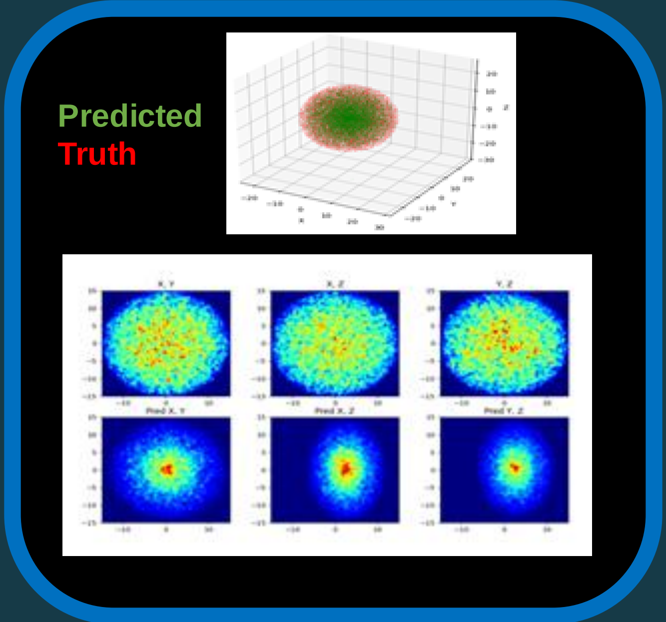
-> Expand training data – Stats, phantoms

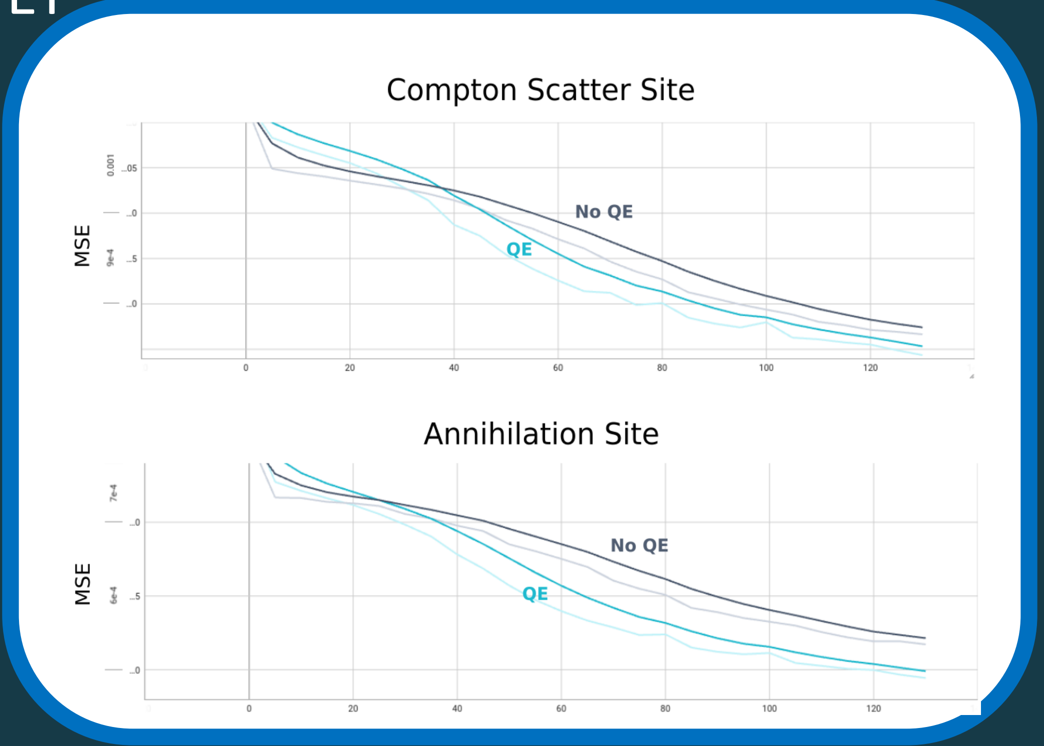
-> Optimise algorithm/network

-> Anatomical information for free?

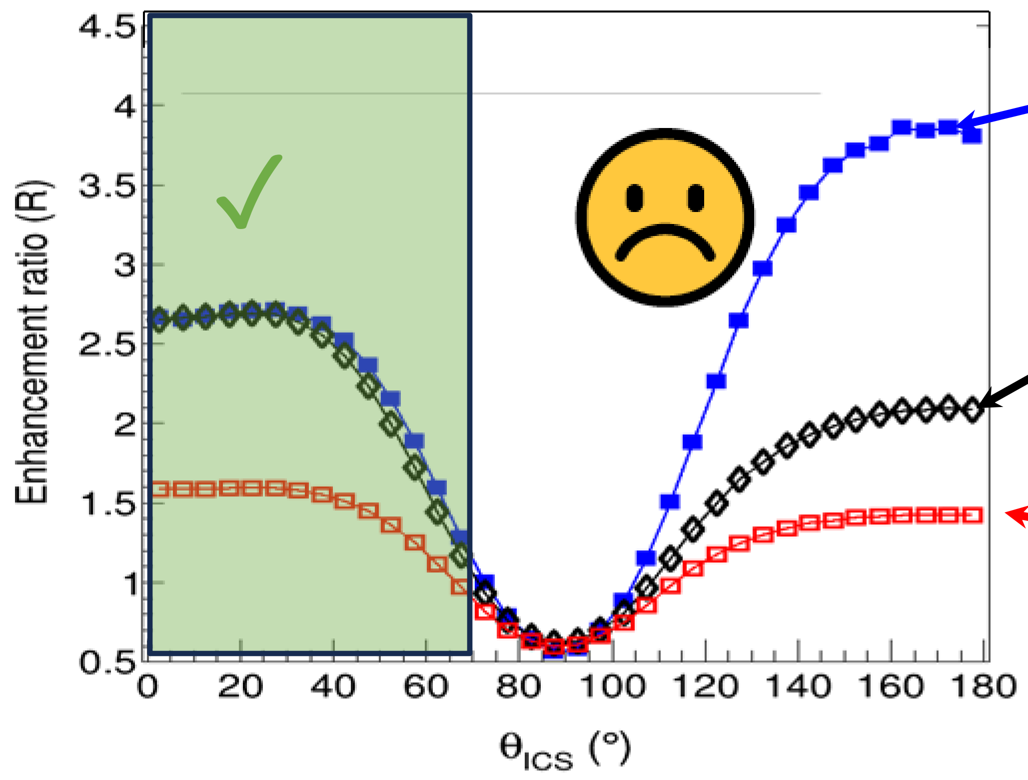
-> Attenuation correction for free – no CT?

-> Movement corrections?





”Missing” acceptance leaves uncertainties …



Theory QE fully maintained

Theory QE TCS using QFT

Classical Limit

Need a larger acceptance apparatus ..

Larger acceptance -> Environment sensing in PET/SPECT, tests

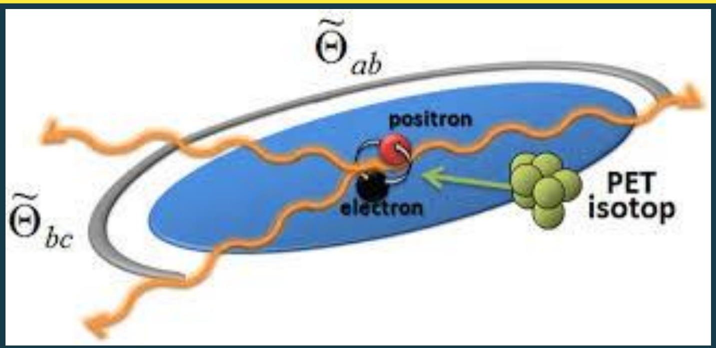
3γ PET – relative yield sensitive to oxygen concentrations.

e.g. Radiation Physics and Chemistry 203 (2023) 110610

Hypoxic (low oxygen) tumours less sensitive to radiotherapy – influence treatment pathways?

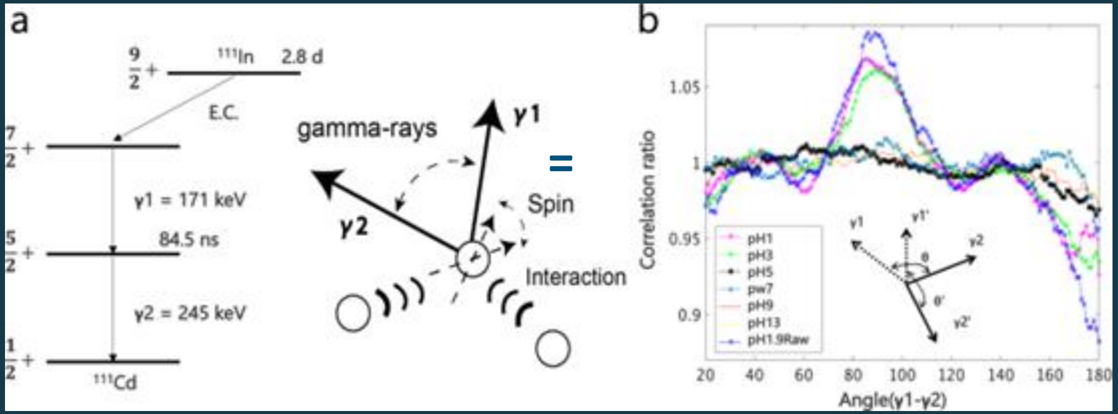
Fundamental tests – QE in genuine tripartite system, CP/CPT violation

e.g Hiesmayer, Sci. Reports 15349 (2017)



Cascade gamma – sensitive to pH of environment

Nat Comms vol5, Article number: 24 (2022)



Main clinical aims:

Measure the "missing piece" for understanding QE decoherence in PET

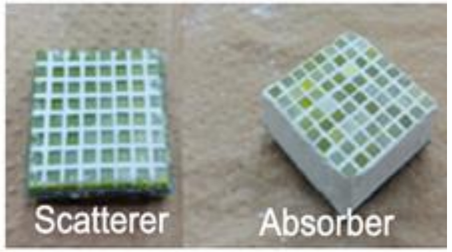
Polarisation correlations and QE unexplored for both 3γ and cascade-γ – crucial to deeper understanding

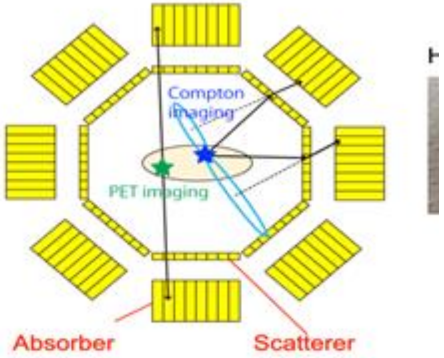
Analyse large acceptance PET and SPECT data for clinical images using AI-QE trained algorithms

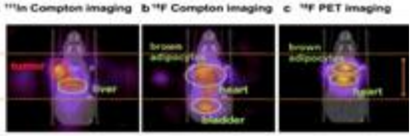
York/Tokyo: Large acceptance 2γ, 3γ PET/SPECT system

M. Uenomachi et al 2022 JINST 17 P04001

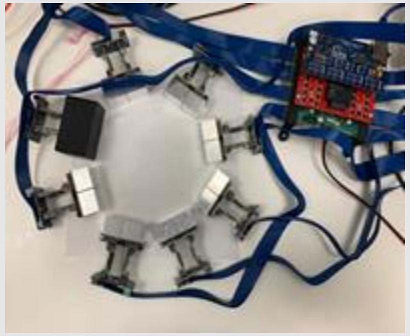
High resolution GAGG



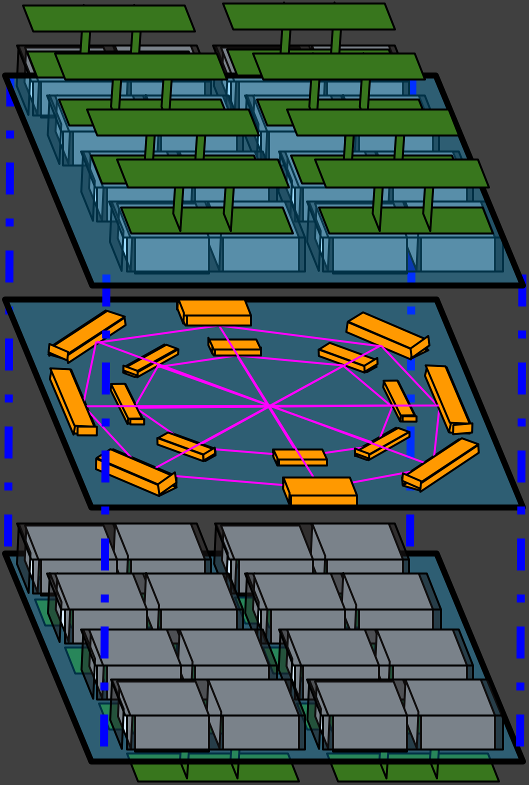




1024 2.5x2.5x1.5(or 9) mm GAAG



2046 3x3x20 mm LYSO



York – 0.2 GBq ^{22}Na source

KCL PET centre – ^{18}F and ^{111}I with controlled pH, p(O_2)

Summary

Photonic QE at the MeV scale – we are learning new things !

AI-QEPET shows promise in early studies

Next generation large acceptance data to be obtained soon

UK leadership in MeVQE (seeded by QTFP) -> new collaborations
e.g. Japan, UK, Netherlands

And a whole host of new competitors…

Other ongoing/completed work:
QE of decay photons from decay of neutral pi meson
Measurement of entanglement witness in rotating frames up to 100g and gravitational fields
Distance tests
Consistency of entanglement witness in different positron annihilating media

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Backup slides

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TCS data – Δϕ distributions

Δϕ distributions for different intermediate CS angles

Event mixing to remove detector acceptance

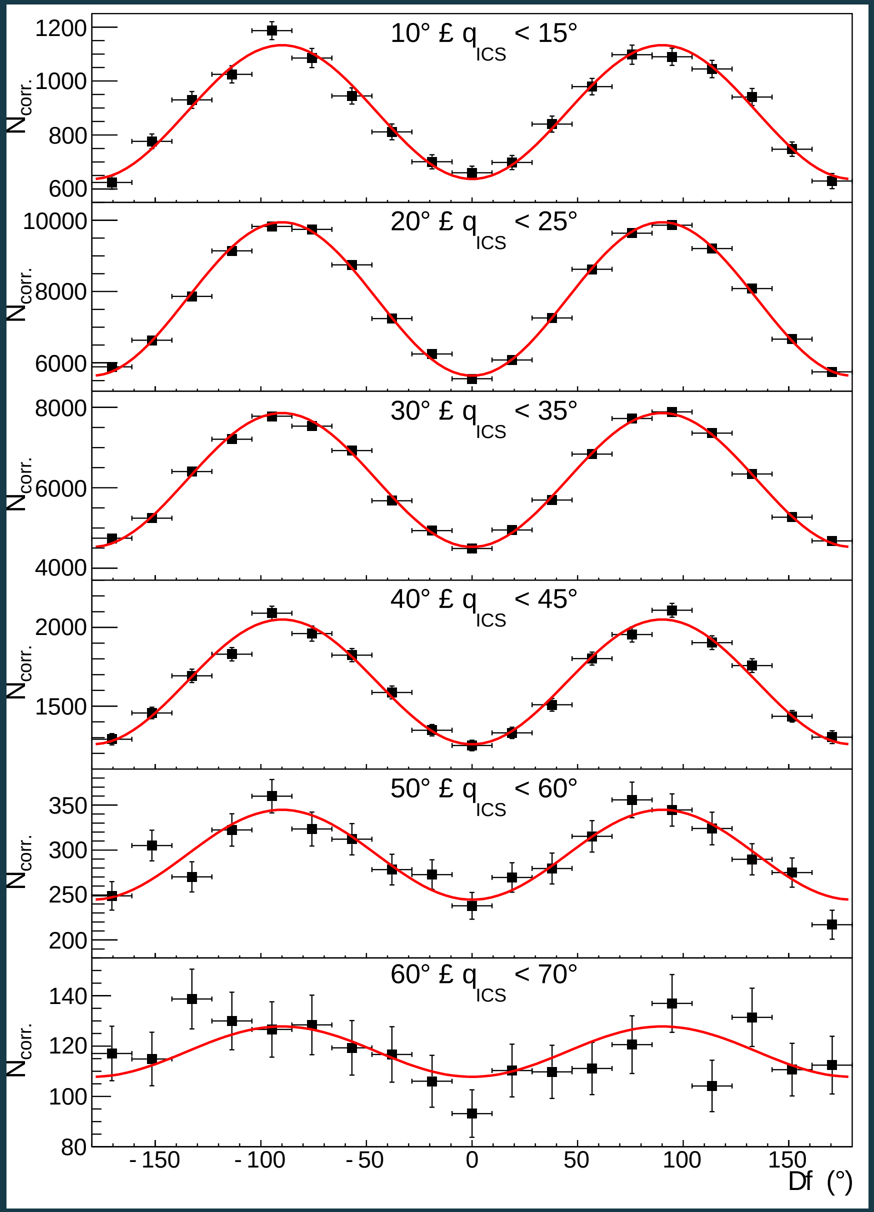
Fit with:

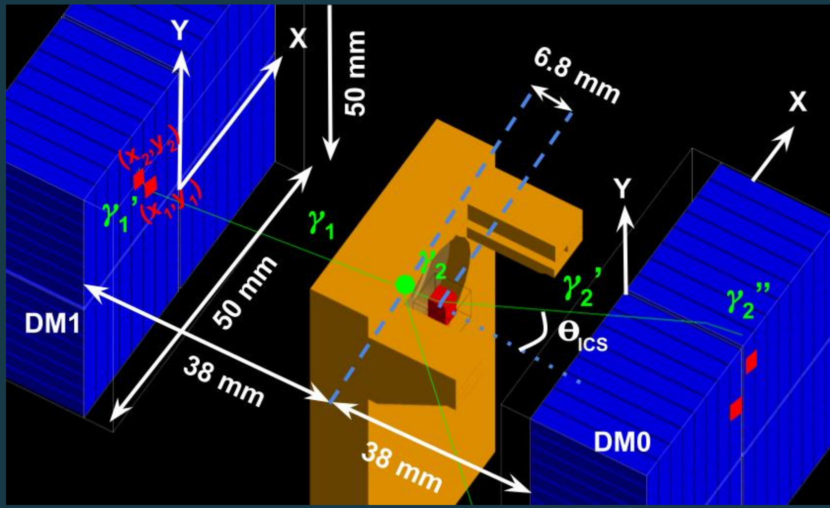
$A\cos(2\Delta\phi) + B$

"Enhancement" (R) is:

$R = (B-A) / (B+A)$

Measure of correlation between the γ





MeVQE

Precision EW
σQE unmeasured
Organic media

Distance tests
Push limit to 15m
Equivalent to $6 \times 10^{12}\ \lambda$
Also in B-field

Entanglement loss
(Was!) unknown how a prior interaction affects entanglement

Theory
Entanglement loss
Circular pol
Cascade gamma
Fission

Non inertial frames
Centrifuge aiming for ~ 100g under construction

QE in Boosted frames
$\pi^0 \rightarrow 2\gamma$
Map EW from $\beta = 0$ to 0.5
New methods for γ poln measurement

QE in circular polarisation
Magnetised scatterer

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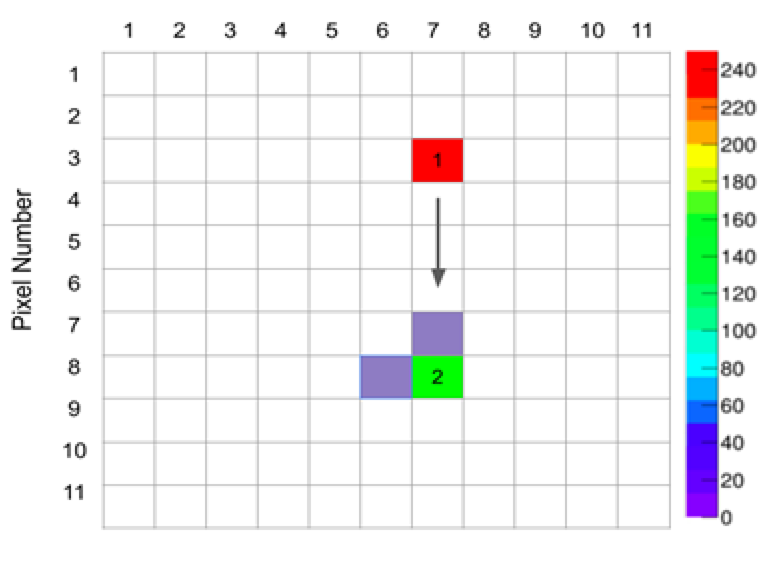
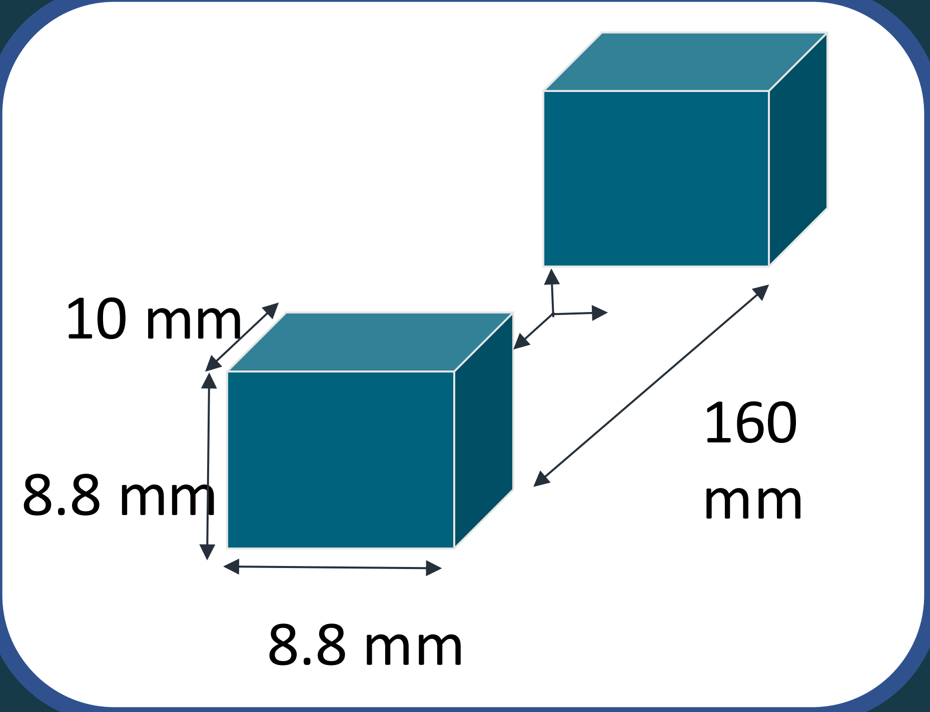
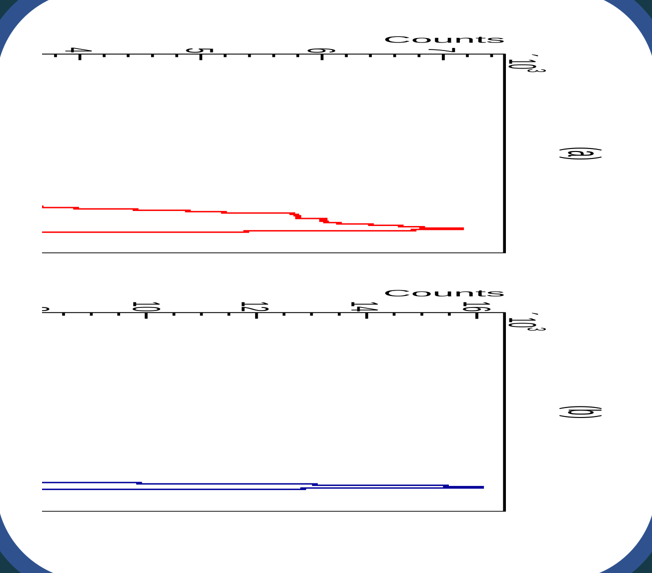
Scatter reconstruction in pixelated arrays







DMatrix ASIC - reads out energy of triggered pixel, and energy deposited in nearest neighbours
Neighbours added if anode timing matches

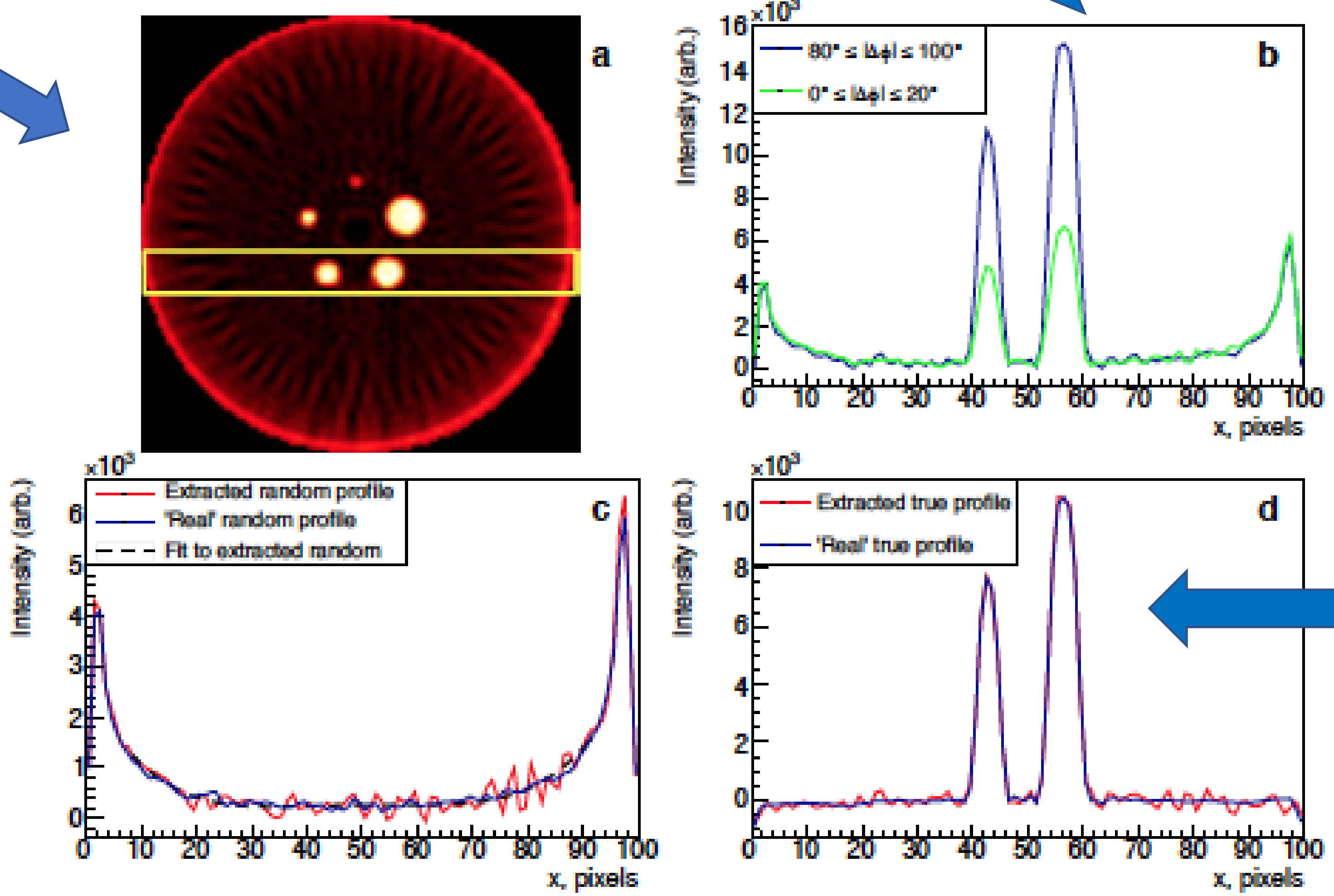
2.97% FWHM at 511 keV (for double hits)

Assume highest energy site of first CS – improvements possible

Random backgrounds

FBP PET image

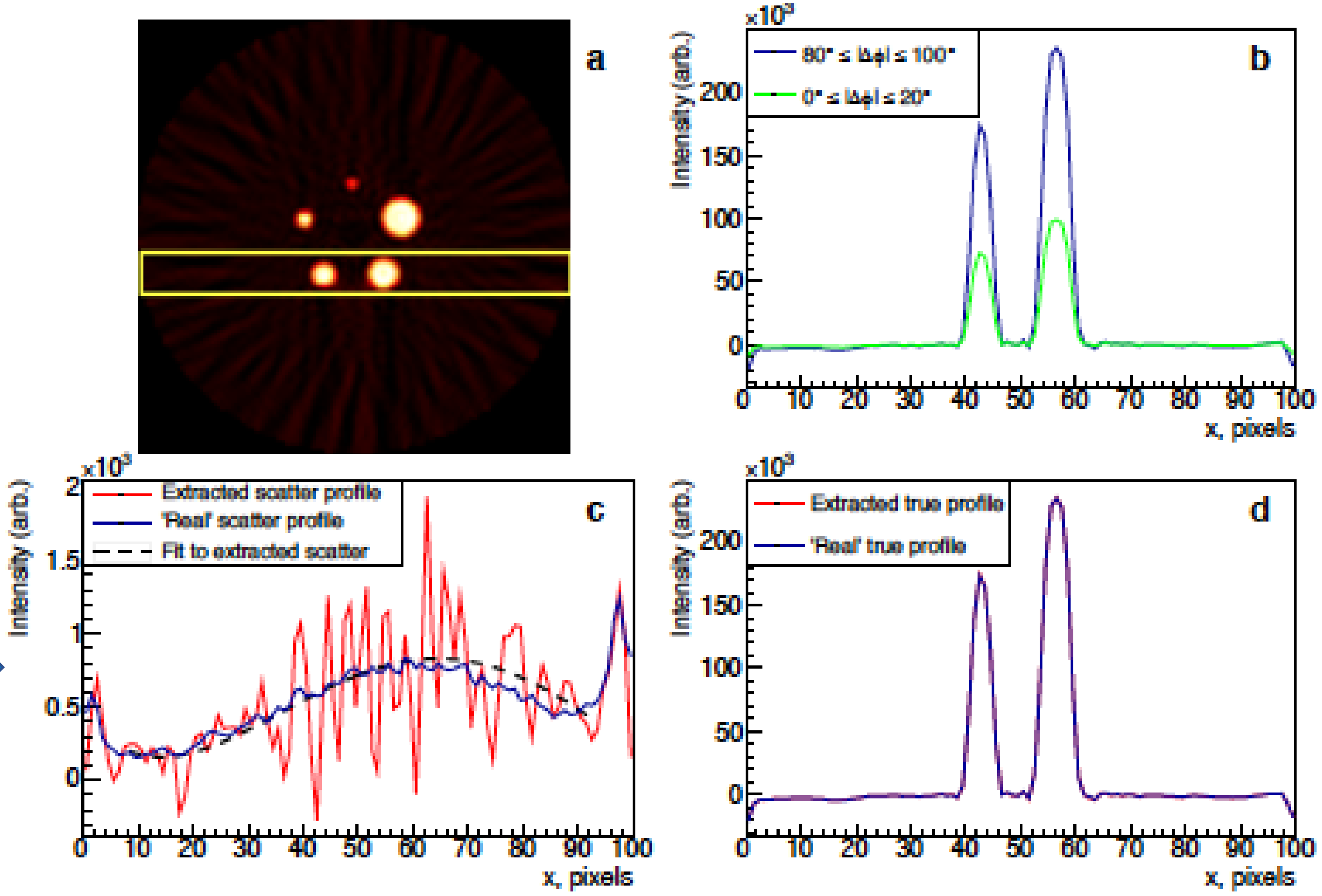
Image slice from ΔΦ around max (min) amplitude



Different weighting:
Spatially resolved determination of random profile

Subtract slices using weight derived from G4 simulation
Isolate true events!

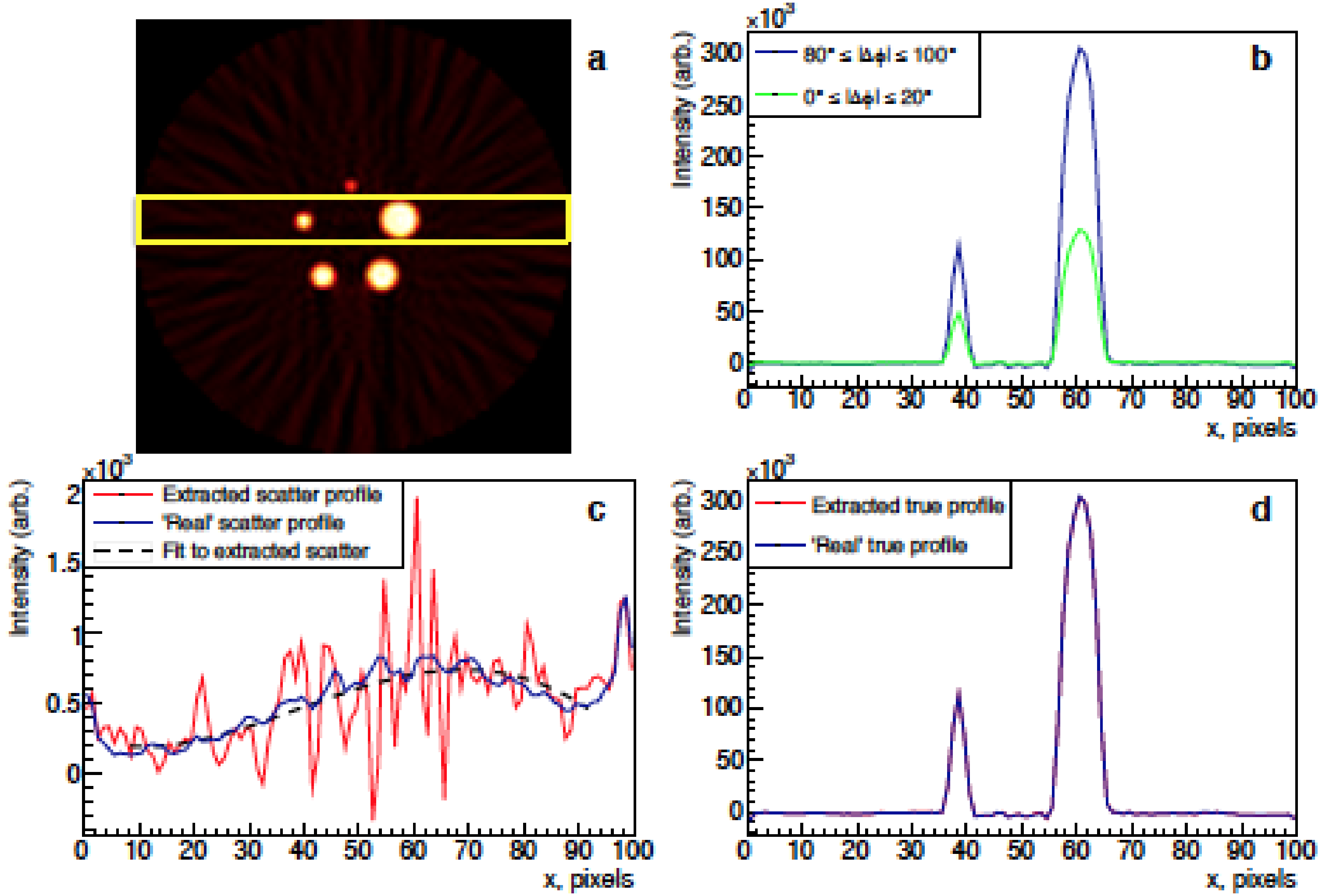
Scatter backgrounds



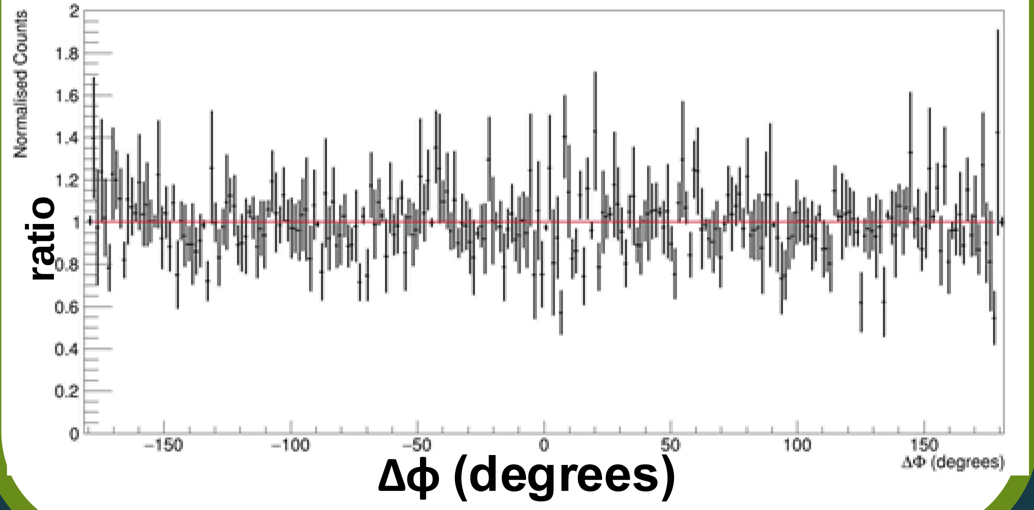
Different weighting:
Spatially resolved determination of scatter profile

But
Assumes QE lost after first DCS ->TCS stated as a clear next step

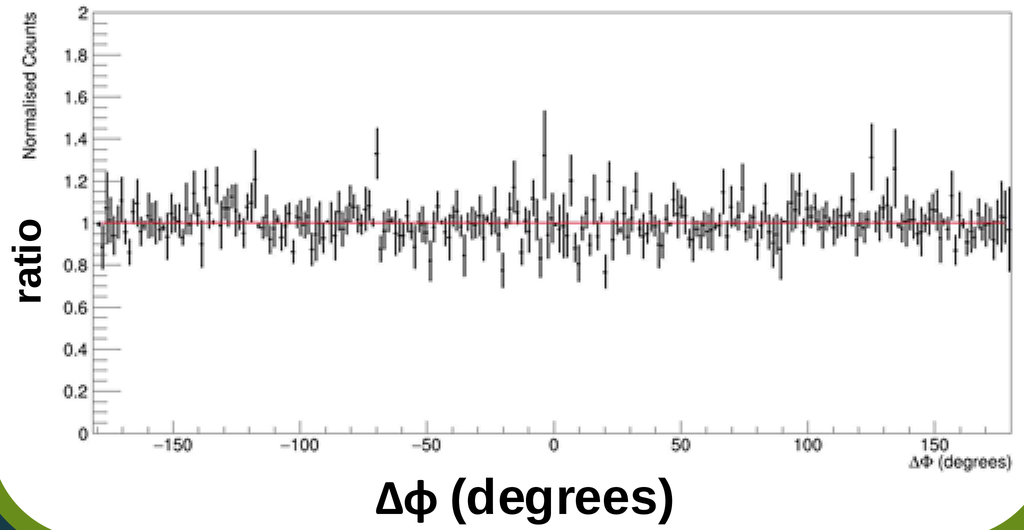
A different slice ..



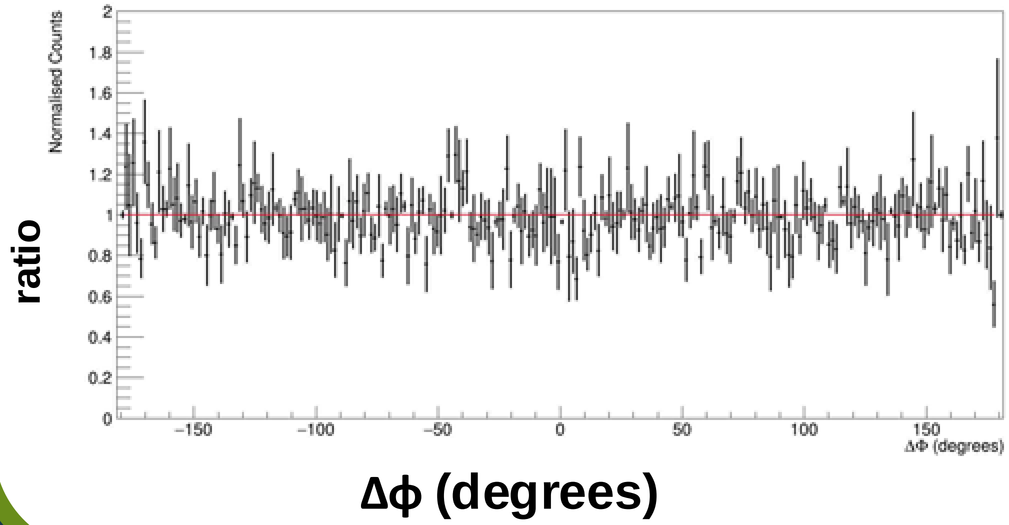
^{22}Na(Plastic)/^{18}F(Parafilm)



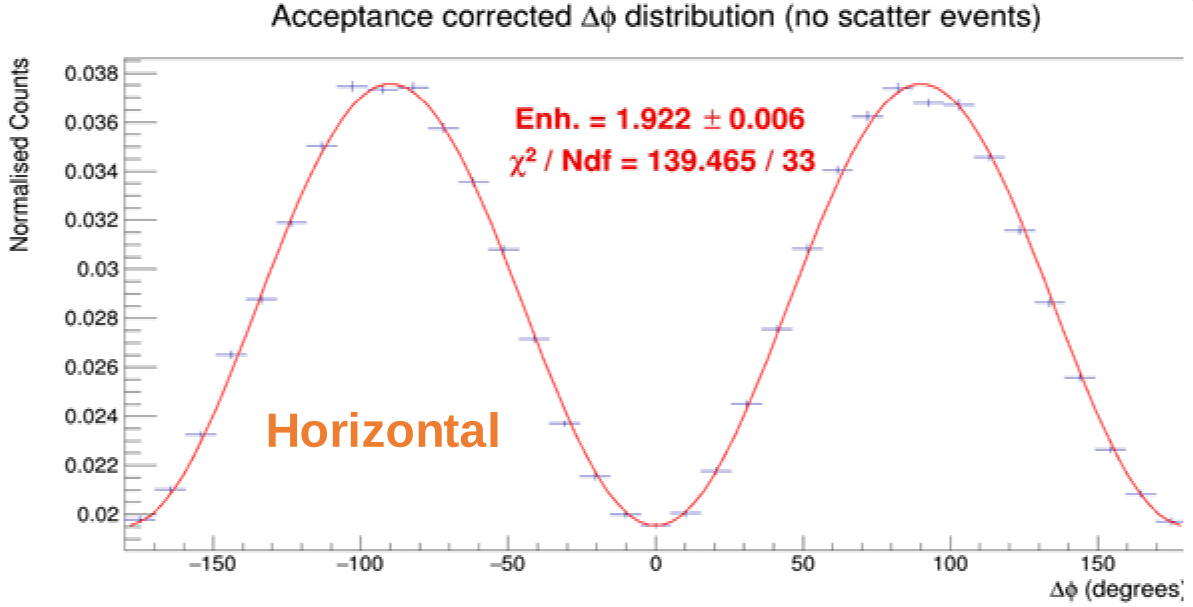
^{18}F(Parafilm)/^{18}F(Tissue)

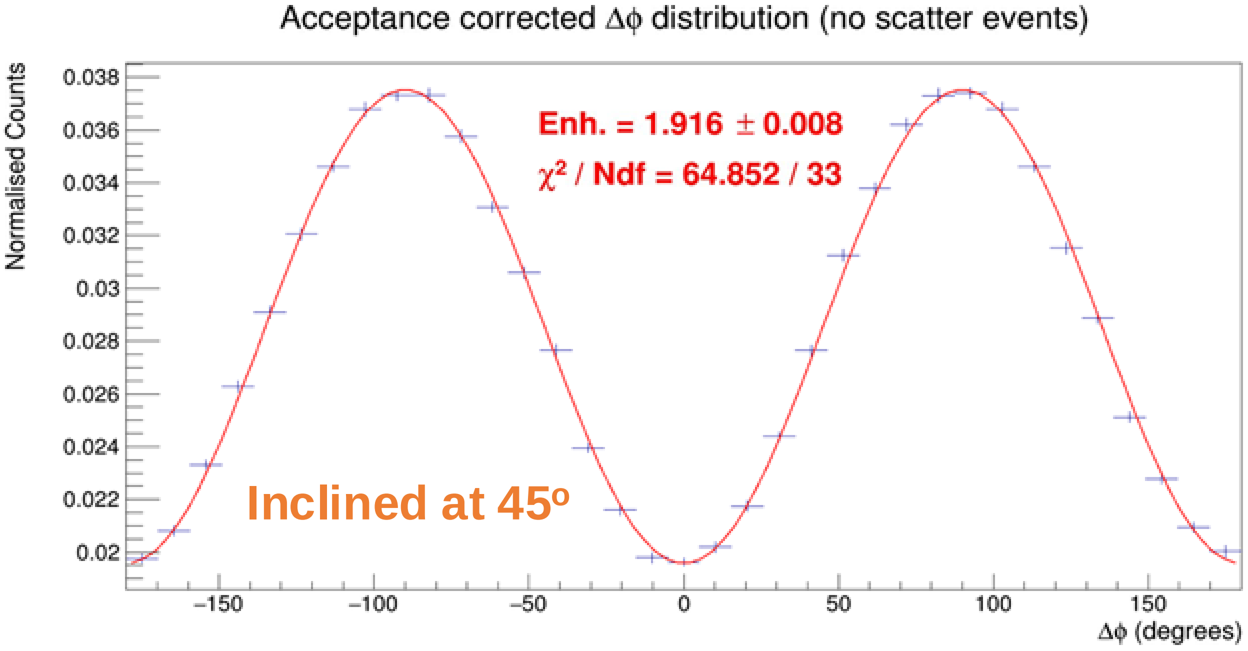


^{22}Na(Plastic)/^{18}F(Tissue)

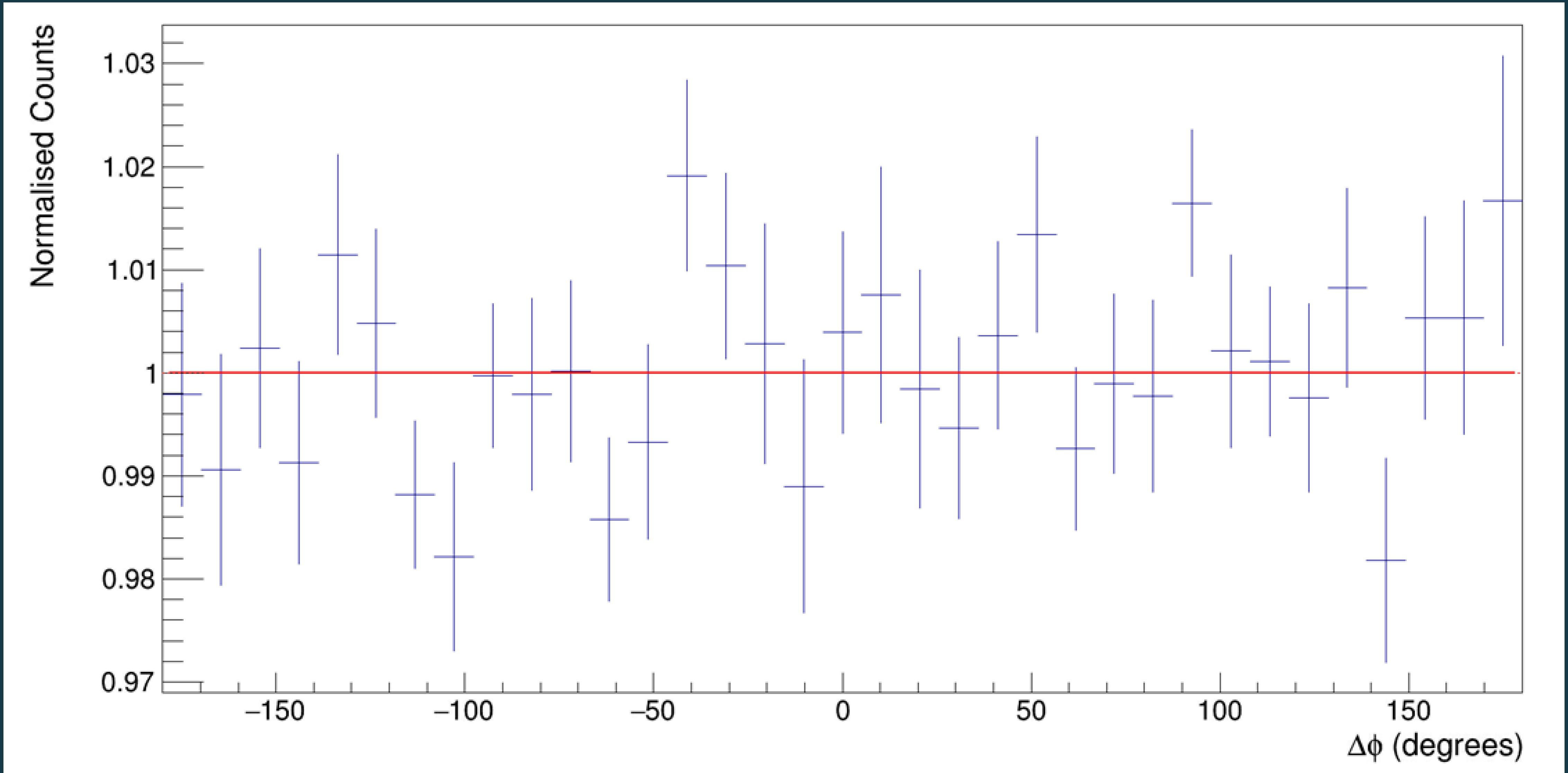


First measurements of EW in a gravitational field (and distance tests)





Ratio inclined/horizontal



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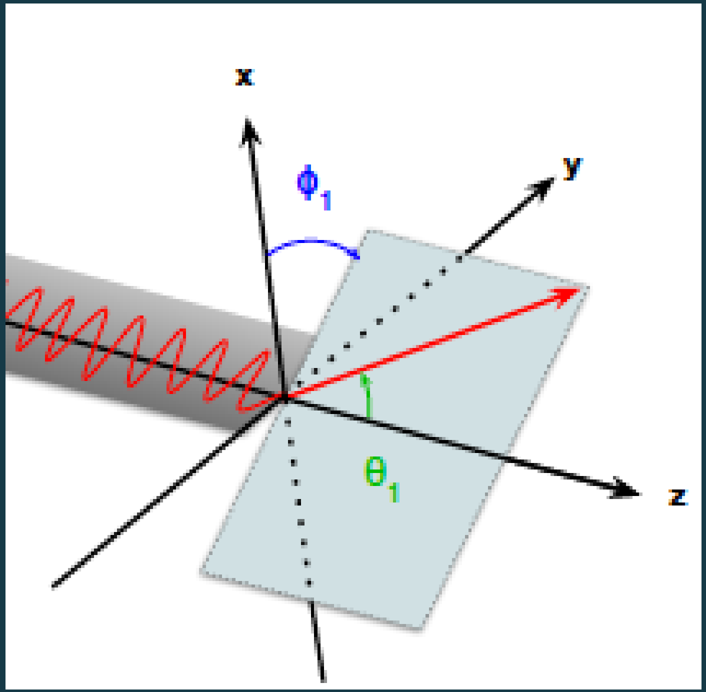
Measuring linear polarization at the MeV scale

Uses the process of Compton scattering. **$\gamma + e \rightarrow \gamma' + e'$**

Single polarized γ -> polarized Klein-Nishina formula

$$I = \frac{e^4}{r^2 m^2 c^4} I_0 \frac{\sin^2 \phi}{[1 + \alpha(1 - \cos\theta)]^3}$$



MeVQE – entanglement in accelerating frame

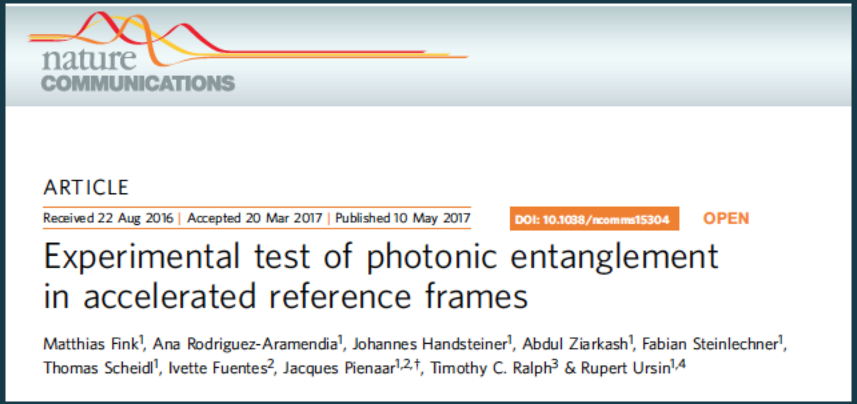
Single measurement of consistency of entanglement in (uniformally) accelerated frame obtained for optical photons (in 2017)

Entanglement witness measured from 30mg up to 30g

Centrifuge constructed at York to achieve measurement up to 100g

New energy range (6 orders of magnitude higher)

No theory of quantum gravity -> sets limits


nature COMMUNICATIONS

ARTICLE

Received 22 Aug 2016 | Accepted 20 Mar 2017 | Published 10 May 2017 DOI: 10.1038/ncomms15304 OPEN

Experimental test of photonic entanglement in accelerated reference frames

Matthias Fink[1], Ana Rodriguez-Aramendia[1], Johannes Handsteiner[1], Abdul Ziarkash[1], Fabian Steinlechner[1], Thomas Scheidl[1], Ivette Fuentes[2], Jacques Pienaar[1,2,†], Timothy C. Ralph[3] & Rupert Ursin[1,4]

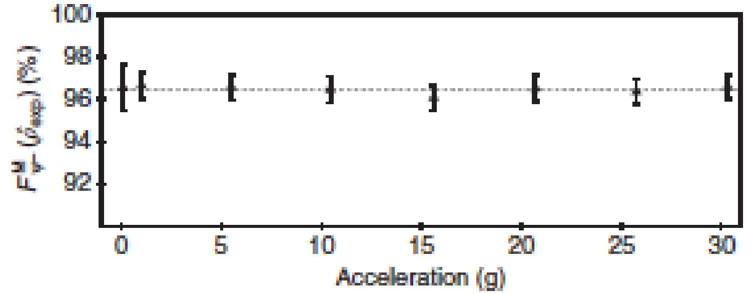
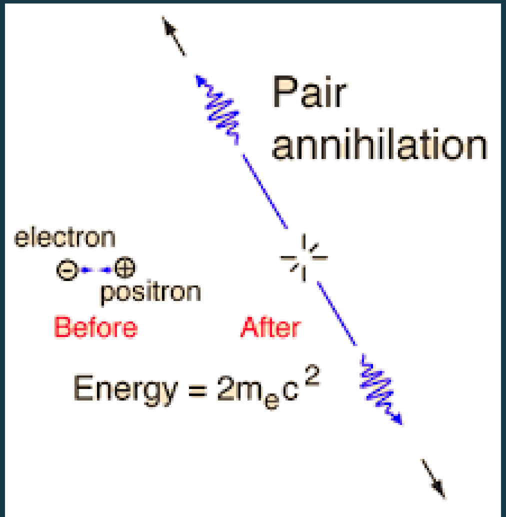


Figure 5 | Summary of experimental data. All data acquired during the experiments shown as the g-value versus lower bound on Bell-state fidelity ($F_{\Phi^-}^{LB}(\hat{\rho}_{exp})$), for g-values ranging from 3 mg to up to 30 g. The error bars shown in the graphs are calculated considering Poissonian statistics, as well as systematical errors for DA measurements due to temperature fluctuations. No deviation from the total average (96.45% represented as horizontal dashed line) for more than the estimated errors is visible.

Aside: Modes of positron annihilation



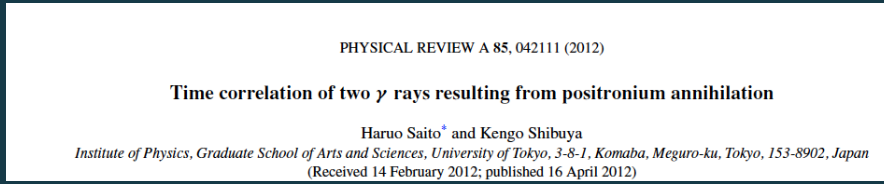
Positrons quickly thermalise (~1ps) -> annihilation dominantly at rest

$^1S_0$ (S=0, m_s=0) "para-positronium" dominant. τ =0.125 ns
-> 2γ decay dominates, each 0.511 MeV (4γ suppressed by 10^{-6})

$^3S_1$ "ortho-positronium" state (τ=142ns in free space) decays to 3γ
– its relative contribution, lifetime shows medium dependence, sensitivity to environment e.g. oxygen concentration.
(Ortho can annihilate with another electron in pickup reaction -> 2γ)

We plan study of 3γ Ortho decays in future work

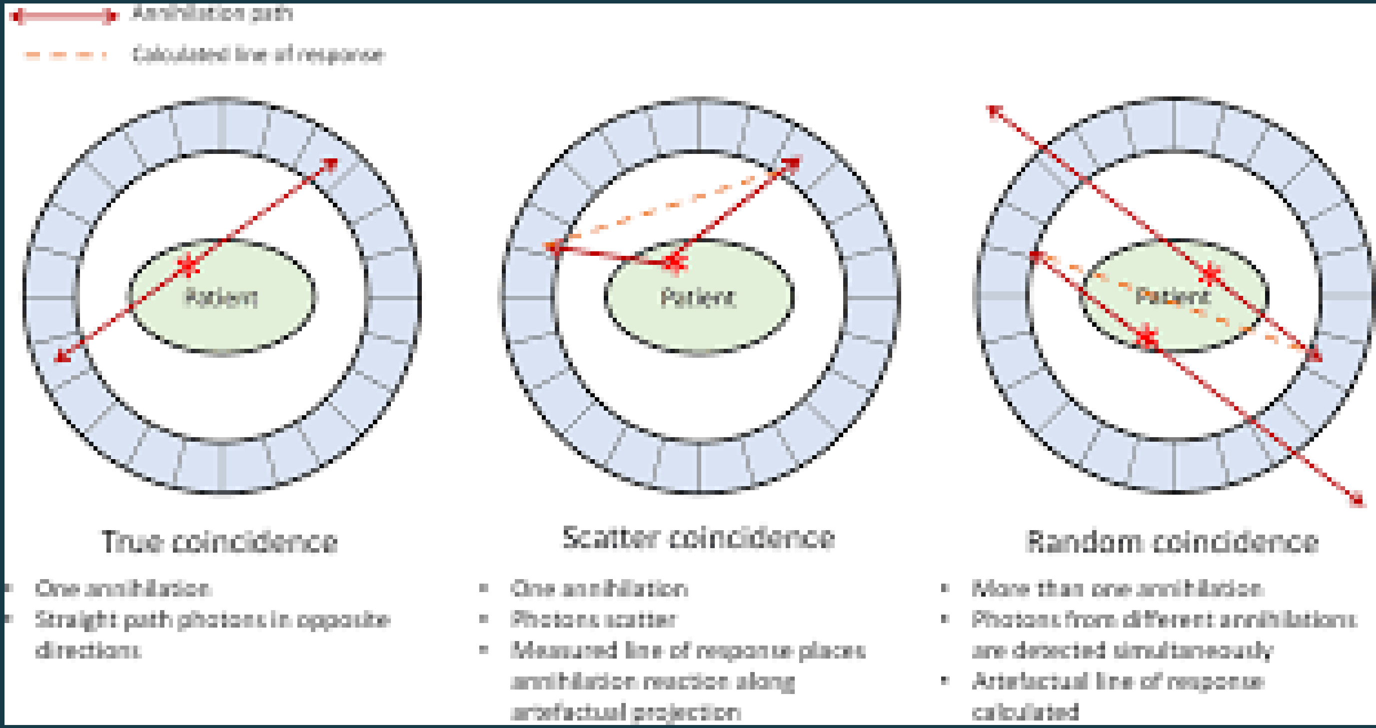
QE between all 3, 2 of 3 ,..-> additional info?


PHYSICAL REVIEW A 85, 042111 (2012)

Time correlation of two γ rays resulting from positronium annihilation

Haruo Saito* and Kengo Shibuya
Institute of Physics, Graduate School of Arts and Sciences, University of Tokyo, 3-8-1, Komaba, Meguro-ku, Tokyo, 153-8902, Japan
(Received 14 February 2012; published 16 April 2012)

MeVQE: Applications in PET medical imaging ?



Widely used imaging tool to study cellular and molecular processes in vivo

Biologically active molecule labelled with positron emitter (e.g. glucose)

-> Functional info about disease/ therapy response

Usually complemented by anatomical information from other modalities (CT/ MRI)

Scatter/True = 0.2 to 2 (brain/abdomen imaging respectively)
Random/true = 0.2 to 1

Images have to be processed to remove scatter – involves full MC simulation of the patient

The implicit quantum entanglement of the photons has been overlooked !!