MeV scale photon quantum entanglement

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EPSRC

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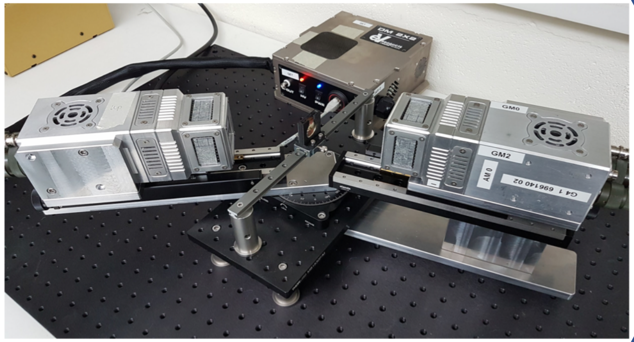
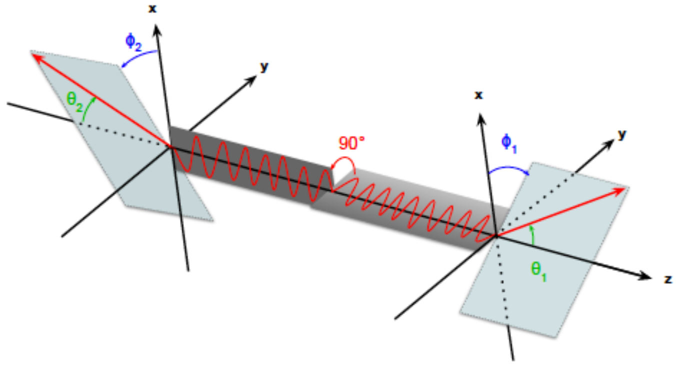
UNIVERSITY of York

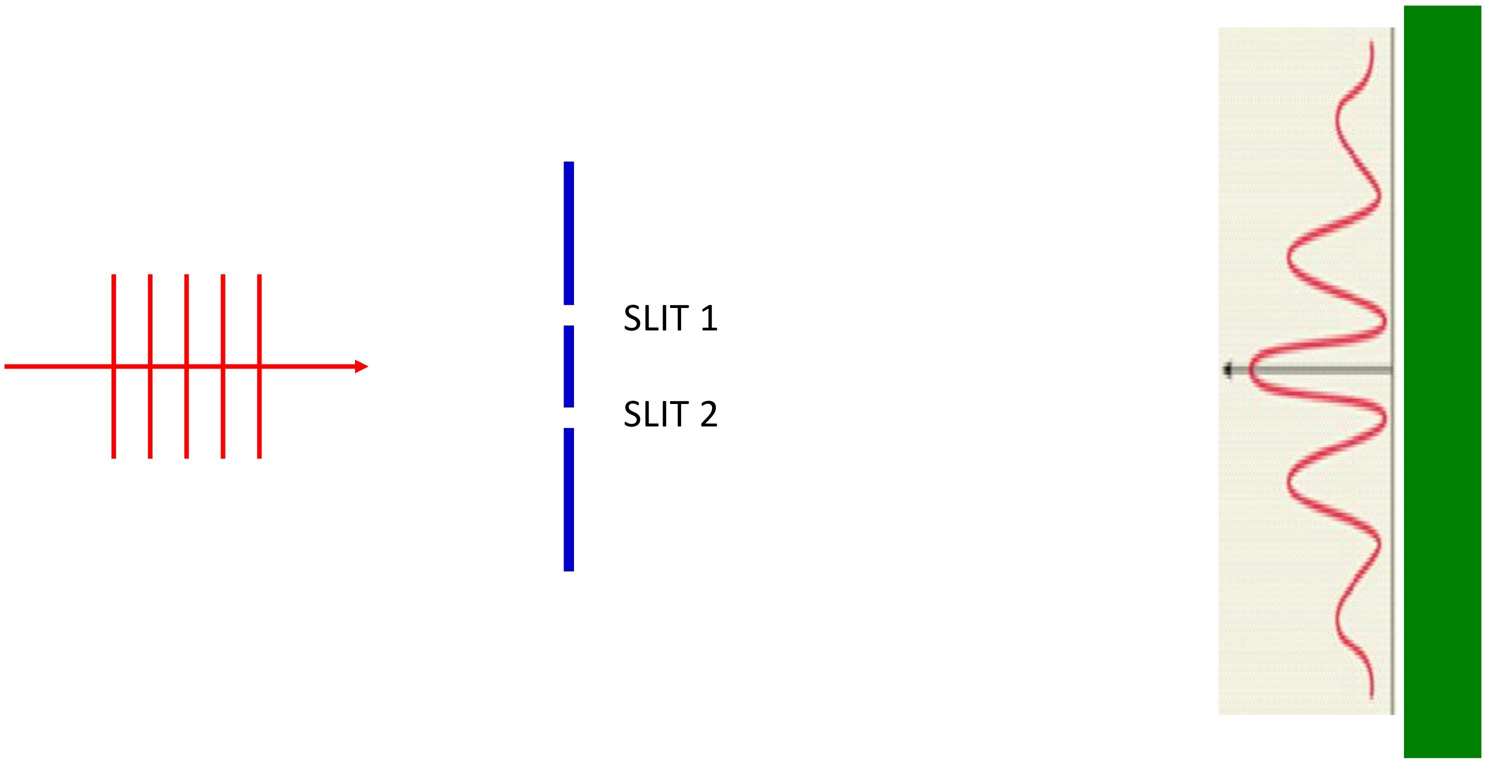
Talk outline

- Quantum entanglement primer
- Entanglement in positron annihilation gamma
- New entangled GEANT-4 simulation
- CZT demonstrator system
- Results from demonstrator and benchmarking of simulation
- Future plans



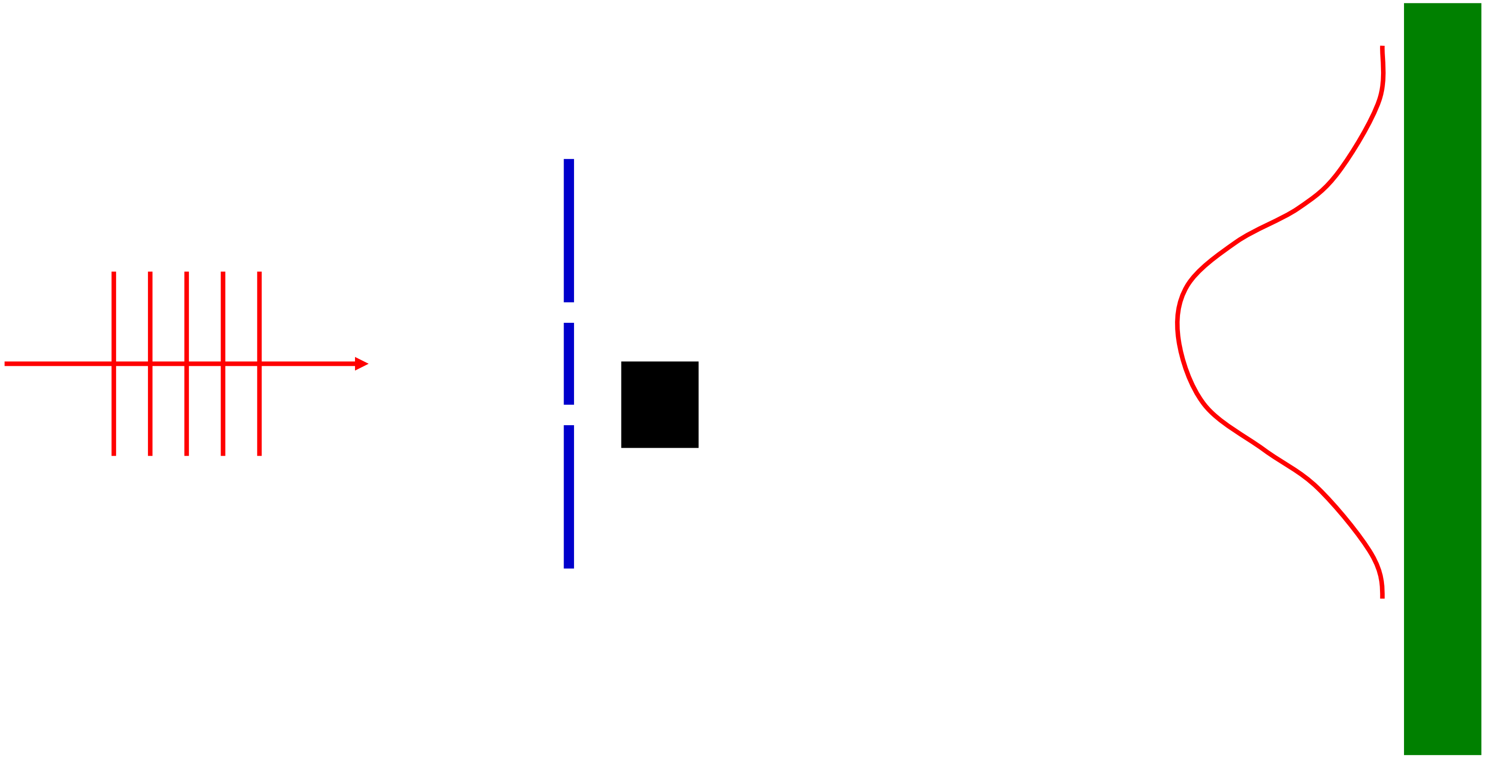


Entanglement - a primer



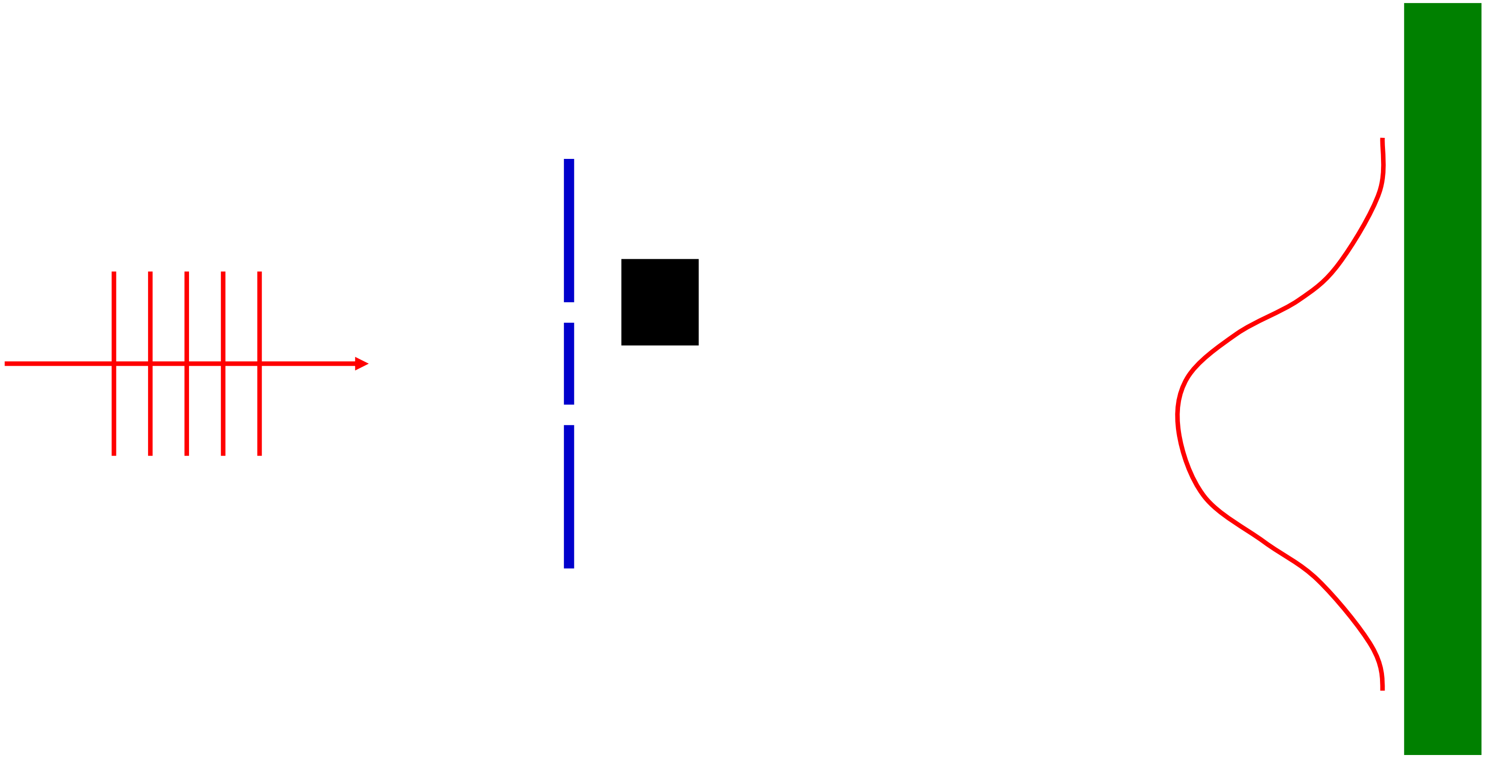
Observe interference pattern - P_{12}

Entanglement - a primer



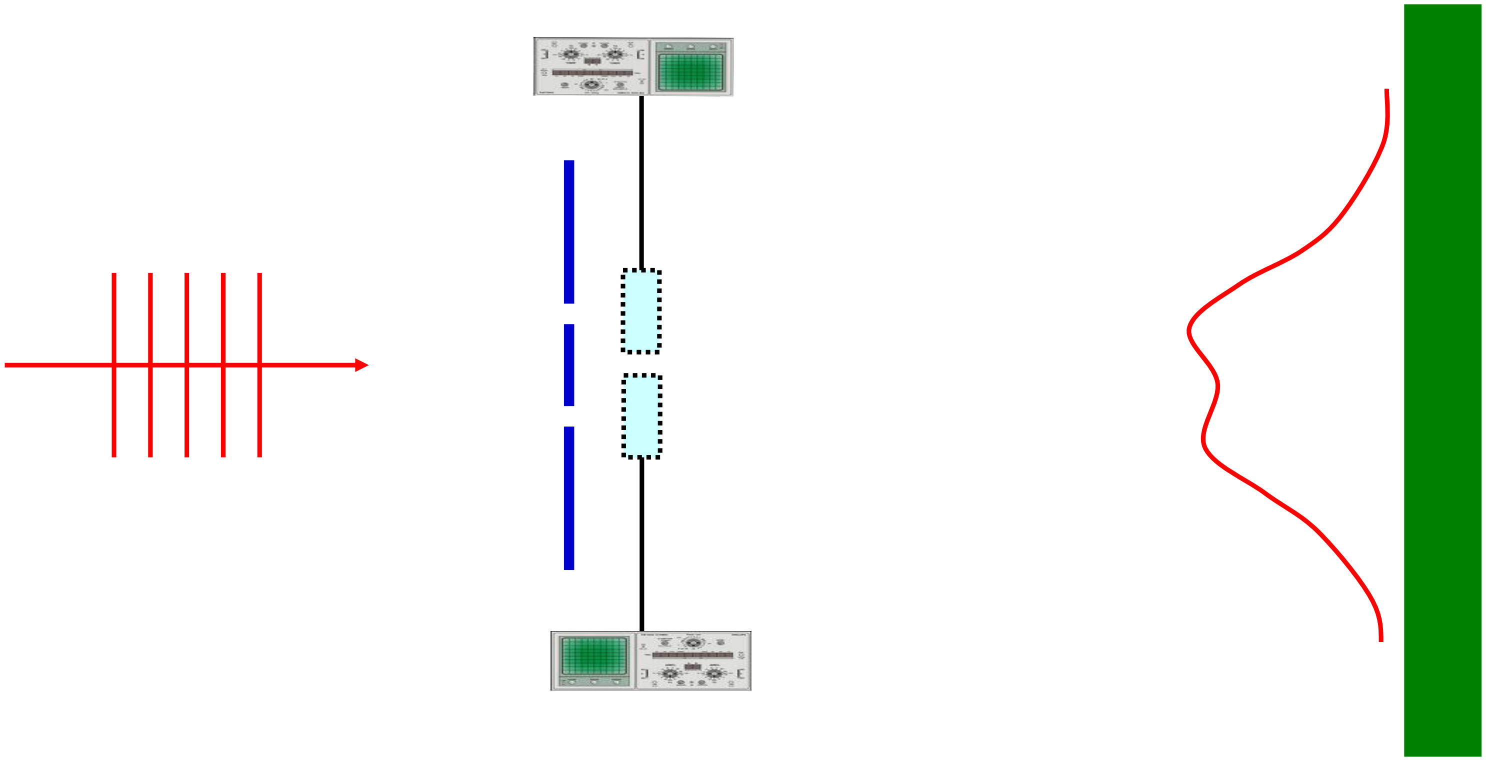
- Observe pattern P_1

Entanglement - a primer



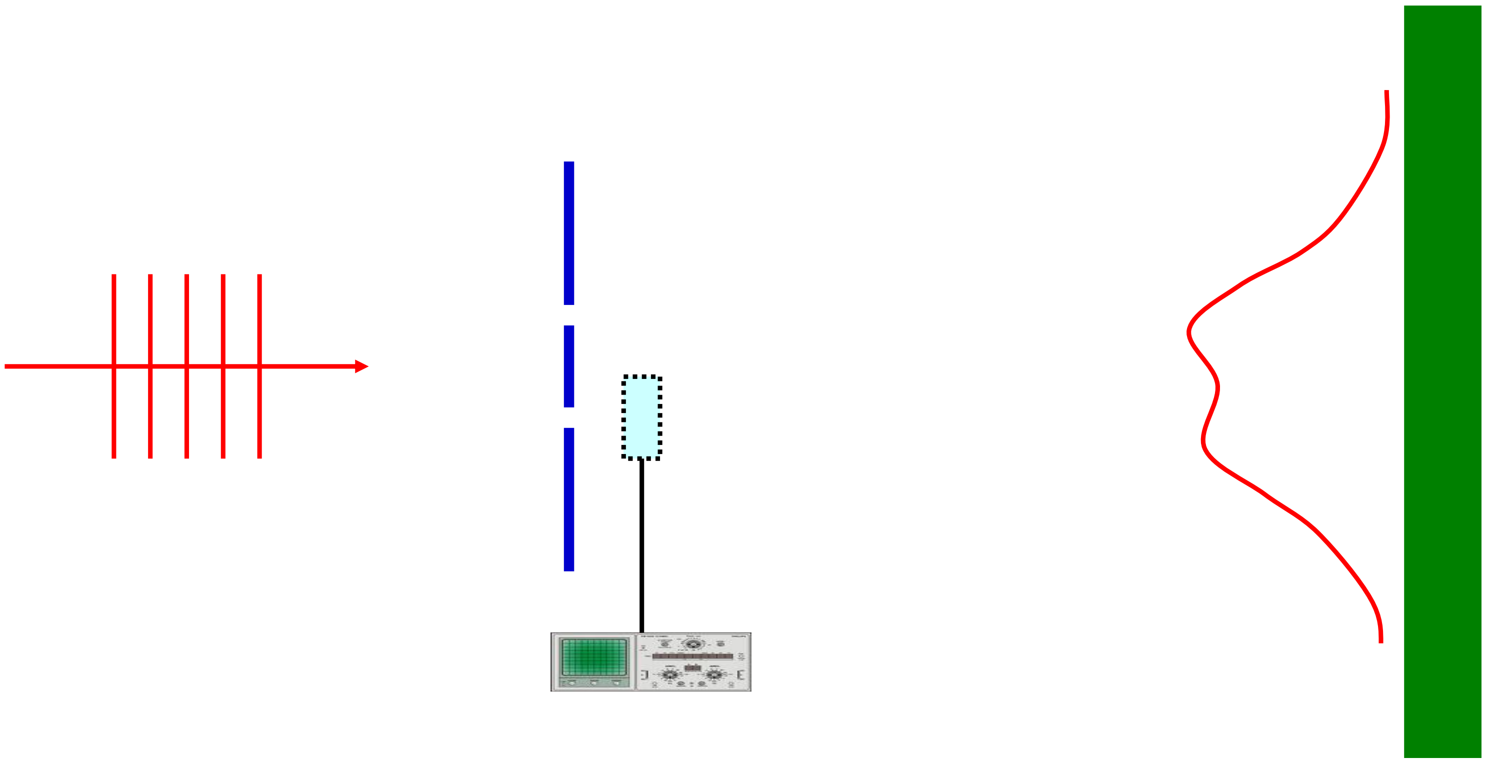
- Observe pattern P_2

Entanglement - a primer



- This is the combination $P_1 + P_2$ not P_{12}

Entanglement - a primer



- This is also the combination $P_1 + P_2$

Entanglement - a primer

If we do not observe which path is taken, we must sum the ψ for each path first:

$$\psi_{total}(x,t) = \psi(x,t)_1 + \psi(x,t)_2$$

And then calculate:

$$|\ \psi_{total}\ (x,t)\ |^2$$

Wave function
Is entangled

If we observe which path we simply sum the probabilities for each path separately:

$$|\psi_{total}\ (x,t)|^2 = |\ \psi_1(x,t)\ |^2 + |\ \psi_2\ (x,t)\ |^2$$

Wave function
is separable

Entanglement - a primer

- A quantum system can be described by the SUPERPOSITION of two or more states, each described by a different wave function:

$$\psi(x,t) = p\ \psi_1(x,t) + q\ \psi_2(x,t) + \ldots$$

- p and q are just the "amount" it is in each state.

- e.g. 2 slits in the 2-slit experiment,
  2 spin states of electron (spin up and spin down),
  2 polarisation states of a photon.

Entanglement - a primer

- If you make a measurement (assume the apparatus detects 1 or 2) then the system is forced into one state or another:

$$\psi(x,t) \rightarrow \psi_1(x,t) \text{ with probability } p^2$$

or

$$\psi(x,t) \rightarrow \psi_2(x,t) \text{ with probability } q^2$$

This is is often referred to as "collapsing" of the wavefunction.

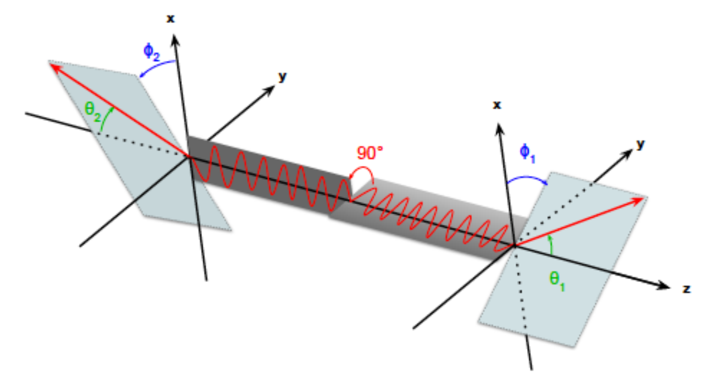
Entanglement in positron annihilation gamma

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

Annihilation at rest dominant (L=0, negative parity)

γ polarisations perpendicular (conservation of momentum)

1 entangled combination of directions **(-,+)** and polns. ***(x,y)*** also conserves parity.



$$|\psi> = \frac{\mathbf{1}}{\sqrt{\mathbf{2}}}(|x>_{-}|y>_{+} - |y>_{-}|x>_{+})$$

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

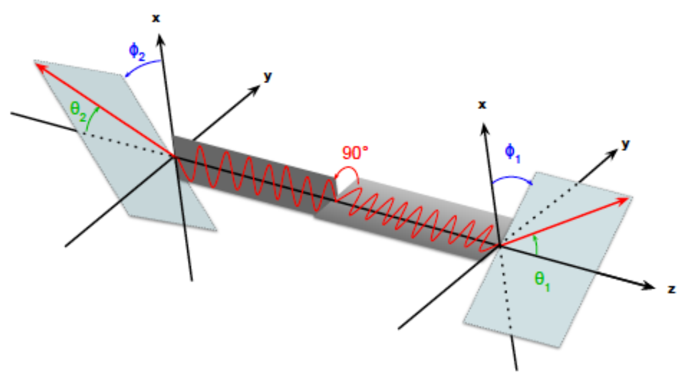
Entanglement in double Compton scattering

Compton scattering c.s depends on γ polarization (polarized Klein Nishina prop $\sin^2\Phi$)

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

Incorporate polarised KN

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



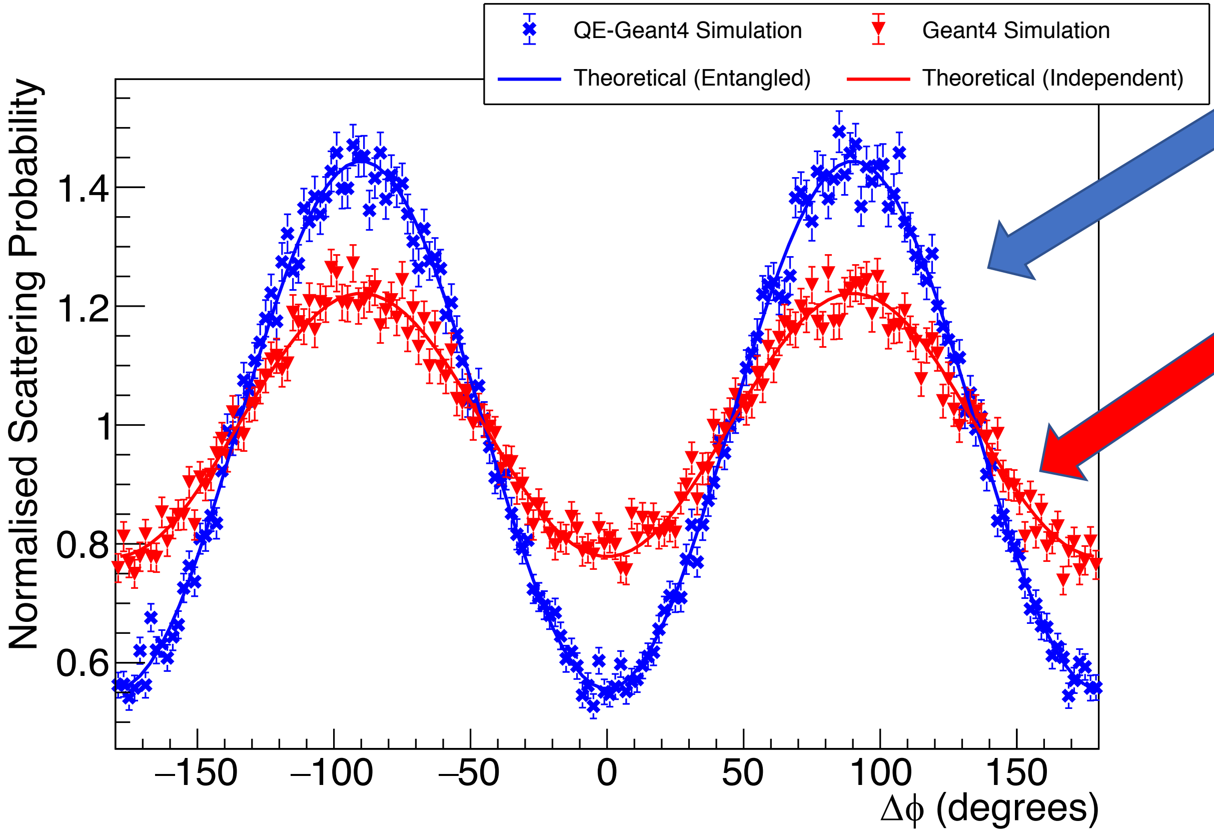
e.g. Snyder et. al. , Phys Rev 73 440 (1947)
Pryce and Ward, Nature 160 435 (1947)
Bohm and Aharonov, PRC 108 1070 (1957)
Caradonna et. al., JPC 3, 105005 (2019)

Duarte EPJ H 37 311 (2012) - historical overview

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

-> Implemented into GEANT4 simulation

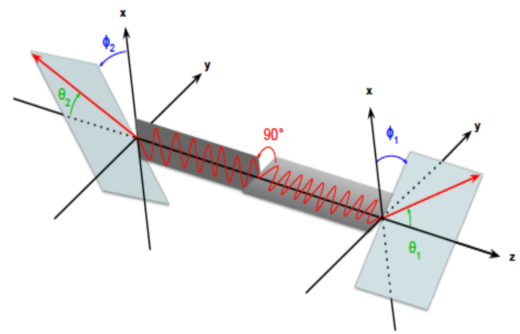
Comparison of entangled GEANT4 with analytic theory



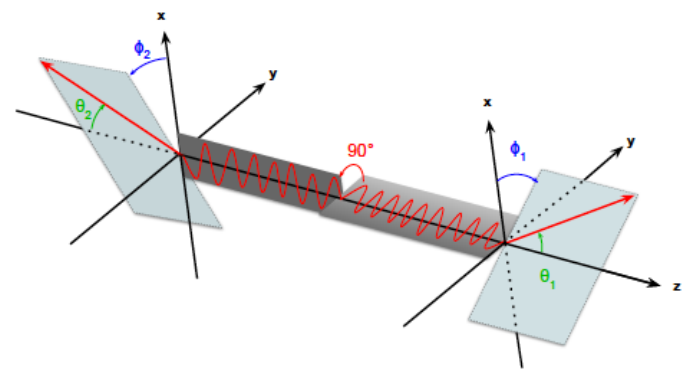
Entangled

$$|\psi> = \frac{1}{\sqrt{2}}\left(|x>_{-}|y>_{+} - |y>_{-}|x>_{+}\right)$$

Non-entangled



Assumptions in the theory



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

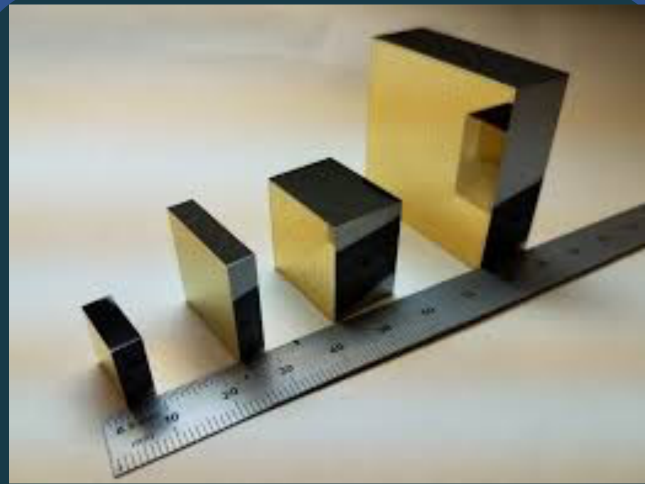
This entangled wavefunction (Bell state) is the **ONLY** allowed state from gs positronium annihilation

But what about other possibilities?:

-> Annihilation in flight at the few percent level – neglected

-> Annihilation from excited positronium state – no evidence when using different media (glass, metal, ..)
(e.g Bruno, M., D'Agostino, M. & Maroni, C..Il Nuovo Cimento B40, 143–152 (1976))

CZT Demonstrator apparatus

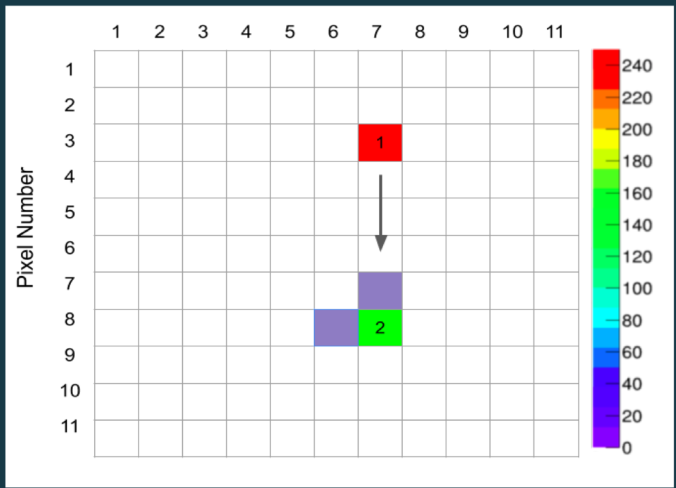


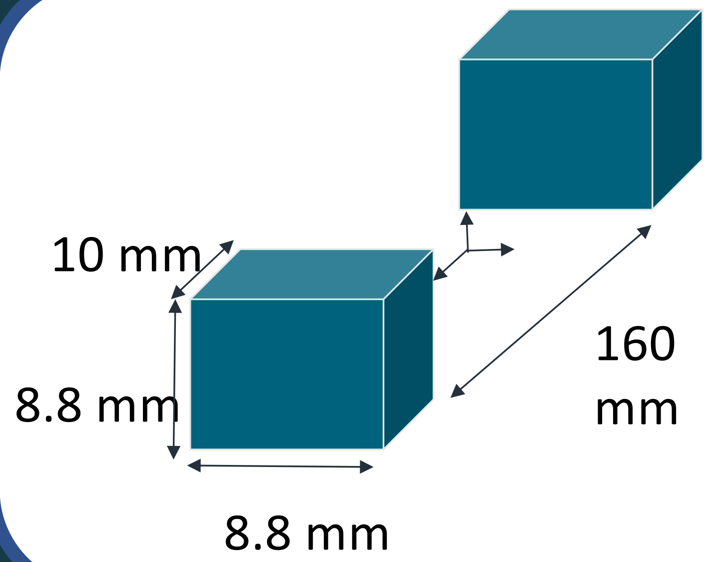
High density semiconductor (CZT)
Highly pixelated (121 0.8 x 0.8 x 10mm pixels)
Double-head system

kromek

-> Track Compton scattering with high acceptance and efficiency

CZT – Compton scatter reconstruction





Comparison of entangled GEANT4 and data (^{22}Na)

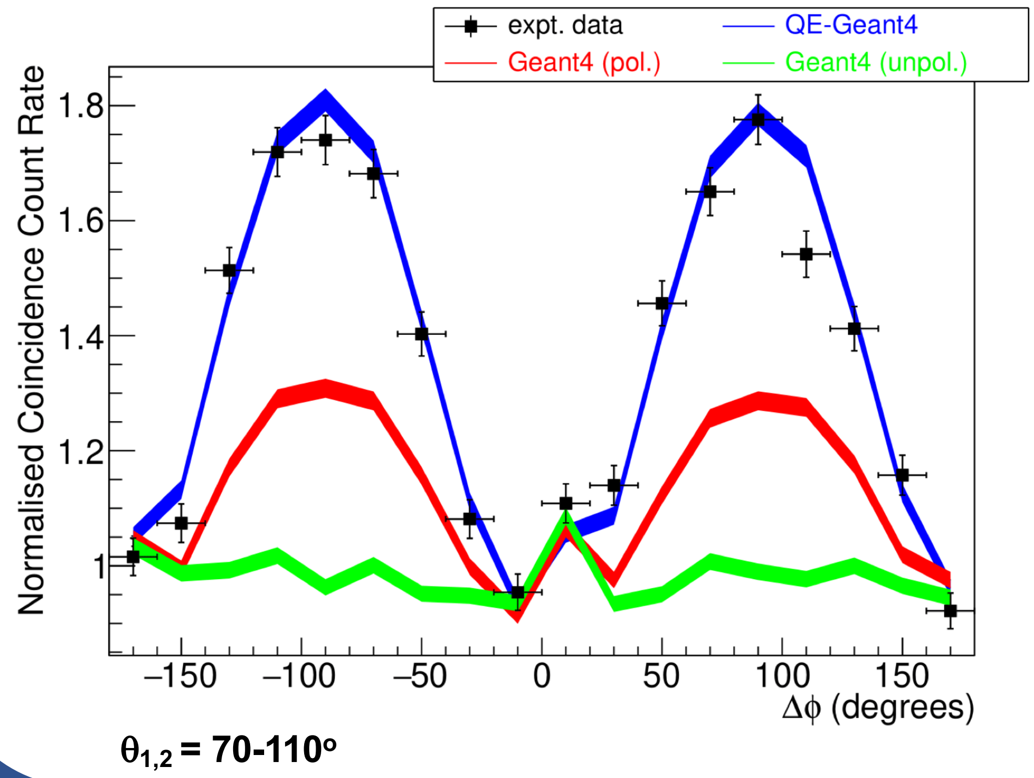
G4 simulation of CZT setup

Analysed with same code and cuts as the experimental data

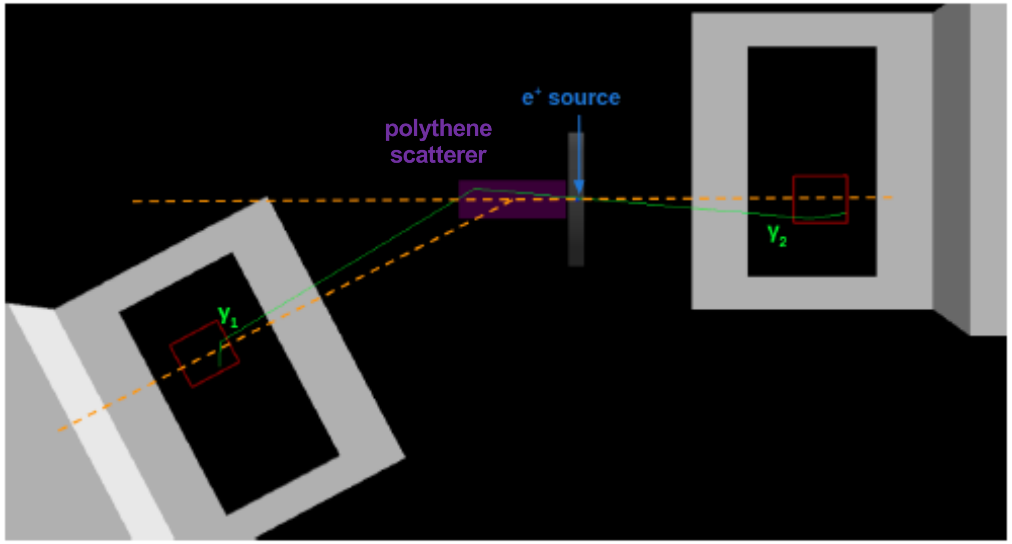
Agreement with **entangled prediction**

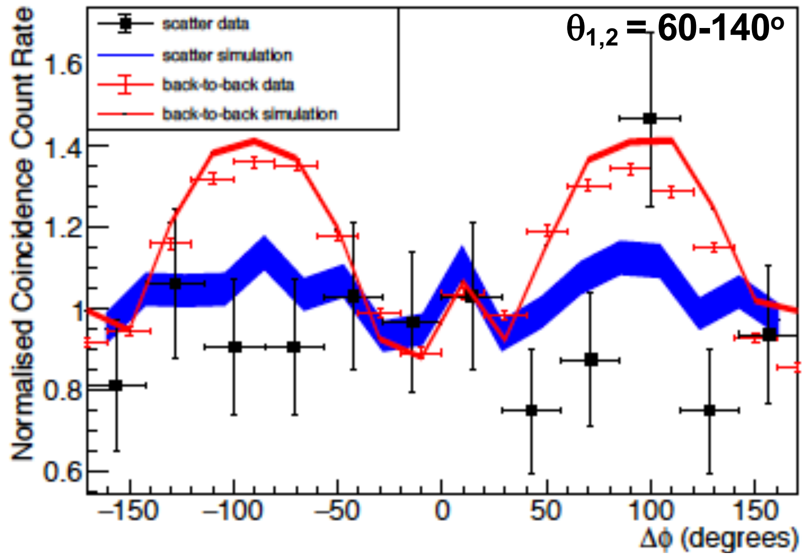
Clear disagreement with **standard G4**
(a separable state - orthogonally polarised)

Unpolarised ~flat -> uniform acceptance
(a mixed state)



Entanglement loss – a first measurement





1st measurement of residual ΔΦ **following an intermediate scatter**

Consistent with "collapse" approximation incorporated in the G4 model

More data needed..

- Expt - with intermediate scatter
- Entangled Geant4
- Expt - no scatter (back-to-back)
- Entangled Geant4 (back-to-back)

The missing cross section…

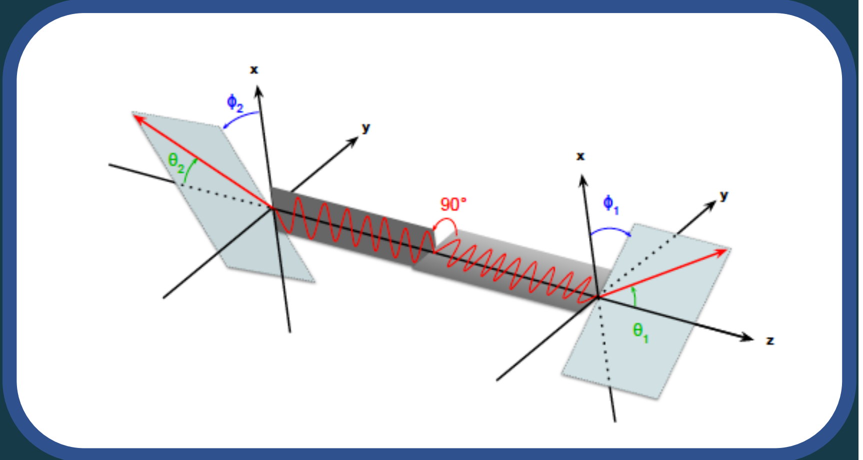
Only the correlations in Compton scatter planes have been measured
 - the predicted cross section has never been confirmed!

New Geant4 developments - important step on the road to achieving this

Backgrounds, non Compton scatter processes, detector acceptance, source simulation, detector resolutions ✓

Work in progress…

Well known to be a missing piece for fundamental tests (e.g Bells inequalities)



The missing cross section - Bell's inequalities

Already highlighted how lack of σ affects inferences on tests of Bell's inequalities
(e.g. Kasday, Ulmann and Wu, Il Nuovo Cimento B 25 (1971))

QM: A given state of a quantum system cannot specify with certainty the result of all possible measurements that can be made on a system

Hidden variable: EPR argued that associated with physical system was a set of variables which determine with certainty all possible measurements (hidden variables)

Bell's inequality: Two measuring instruments A and B.
A and B have "knobs" which are set to positions a and b respectively.
Locality implies the knob setting a has no effect on measurement B (and vice versa)

$$|\overline{\alpha_4\beta_2} + \overline{\alpha_4\beta_3}| + |\overline{\alpha_1\beta_2} - \overline{\alpha_1\beta_3}| \leqslant 2 \, ,$$

e.g. α and β output of 2 detectors, a and b angle of detectors. Measure terms. e.g $\overline{\alpha\beta} = -\cos 2(a-b);$

EPR tests and Bell's inequality

Unfortunately - experiment cannot be ***directly*** realized in Double Compton scattering
-> No ideal polarization detectors

Although Pa measurements cannot directly rule out hidden-variable theories
– provided the initial strong evidence against them

Assumptions: 1) It is in principle possible to construct an ideal linear-polarisation analyser
2) The results obtained in an experiment using ideal analysers and the results obtained in Compton scattering experiment are correctly related by quantum theory

-> Cross section measurement is important to put future fundamental tests on a firmer footing

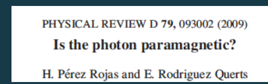
-> Also an important check for applications (e.g. PET)

Fundamental tests – why bother at MeV scale ??

Breaks new ground - Null results are still important….!

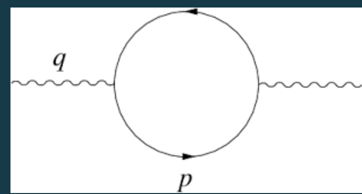
MeV measurements are virtually noise free, offer a clear entanglement witness

Optical and MeV photons have different properties -> synergy cannot be apriori assumed


PHYSICAL REVIEW D 79, 093002 (2009)

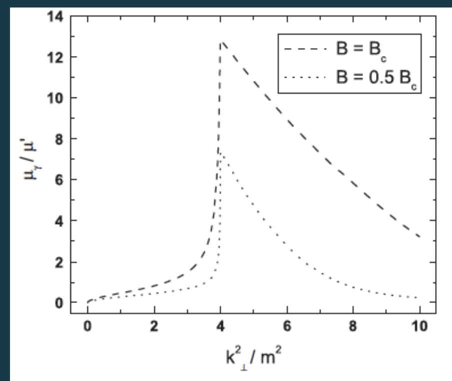
Is the photon paramagnetic?

H. Pérez Rojas and E. Rodriguez Querts



1) The wavelengths are 6 OOM smaller (more cycles of wf for given distance)

2) Higher energy -> Stronger interaction with the vacuum,
   MeV γ have magnetic moment, ..
   Larger gravitational redshift – proportional to Egh/c^2
   10^{12} larger coupling to hypothetical graviton than optical



MeVQE - Distance measurements

Record (optical photons) 1200km at $\lambda \sim 10^{-6}$m corresponding to 10^{12} wavelengths

Entangled gamma sent from satellite to separated ground stations

MeV scale -> Data sparse & contradictory, limited to ~1m separation
Entanglement witness - $\Delta\phi$ correlation at limited $\theta_{1,2}$

CZT : Benchmark measurements out to 10's m possible
Exceed current record (in terms of wavelengths) by orders of magnitude.
Measure for wide range of scatter angles $\theta_{1,2}$ simultaneously
Examine constancy of $\Delta\phi$ correlation and cross section with distance
Acceptance and backgrounds under control – GEANT4
Also obtain first measurement vertically (gravitational field)

MeVQE – entanglement in accelerating frame

Has been suggested that gravity and motion can have observable effects on QE
e.g. Aisling, Classical Quant Grav. 29 224001 (2012)

First measurement for optical photons in 2017

Entanglement witness measured measured from 30mg up to 30g on a centrifuge

Plans for similar measurement at MeV scale

Also possibilities for QE in accelerating frame
– laser-plasma acceleration

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]

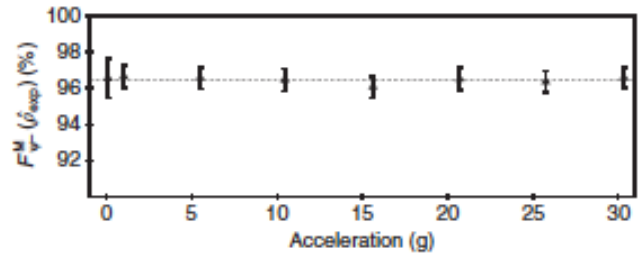


Figure 5 | Summary of experimental data. All data acquired during the experiments shown as the g-value versus lower bound on Bell-state fidelity ($F^{M}_{\Psi^-}(\tilde{\rho}_{exp})$), for g-values ranging from 3 mg to up to 30 g. The error bars shown in the graphs are calculated considering Poissonian 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.

MeVQE – Other possiblities

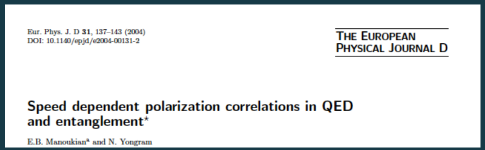
Cascade transitions -> Widely used entangled optical photon source (J= 0->1->0 transition)

-> Nuclear transitions – largely unexplored field

Energy frontier

-> Photon QE – max energy is 0.511 MeV

-> π^0 decays – Lifetime 10^{-16} s, 70 MeV in rest frame, GeV's decay from relativistically boosted frame.


Eur. Phys. J. D **31**, 137–143 (2004)
DOI: 10.1140/epjd/e2004-00131-2

THE EUROPEAN PHYSICAL JOURNAL D

Speed dependent polarization correlations in QED and entanglement*

E.B. Manoukian[a] and N. Yongram

-> Measuring polarisation is challenging at higher energies

-> Measure polarization from nuclear reactions ?

γ + A -> A + π^0 (100% analyzing power!)
γ + A -> A + π^+ (Easier to detect)

Summary

Quantum entanglement of positron annihilation photons included in Geant4

Double headed CZT system benchmarked – quality data

QE-G4 -> excellent description of measured scatter plane correlations in double
Compton scattering

Immediate application in PET imaging (Ruth Newton's talk)

Next steps: More detailed measurements of wavefunction collapse at MeV scale
First entangled cross section measurement
Fundamental tests, further applications,..

A new regime to challenge fundamental quantum physics