Lehrstuhl E15
Physik-Department
Technische Universität München

Positronium Lifetime Determination in Linear Alkylbenzene based Scintillator for JUNO

SFB 1258 Neutrinos Dark Matter Messengers

JUNO

DFG Deutsche Forschungsgemeinschaft

<u>JUNO Forschergruppentreffen Hamburg</u>

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Outline

1. Motivation
2. Measurement Setup and Principle
3. Results
4. Simulation
5. Lifetime Calculation
6. Conclusion and Outlook

Motivation

- Main detection channel of anti-neutrinos: inverse beta decay

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

- Positron stopped and annihilates → prompt signal
- Neutron thermalized and captured by H → delayed signal

- Most positrons form positronium (Ps)
- Two spin states:
  - Singlet → para-positronium (p-Ps) → lifetime ~ 100 ps
  - Triplet → ortho-positronium (o-Ps) → lifetime ~ 140 ns in vacuum

Motivation

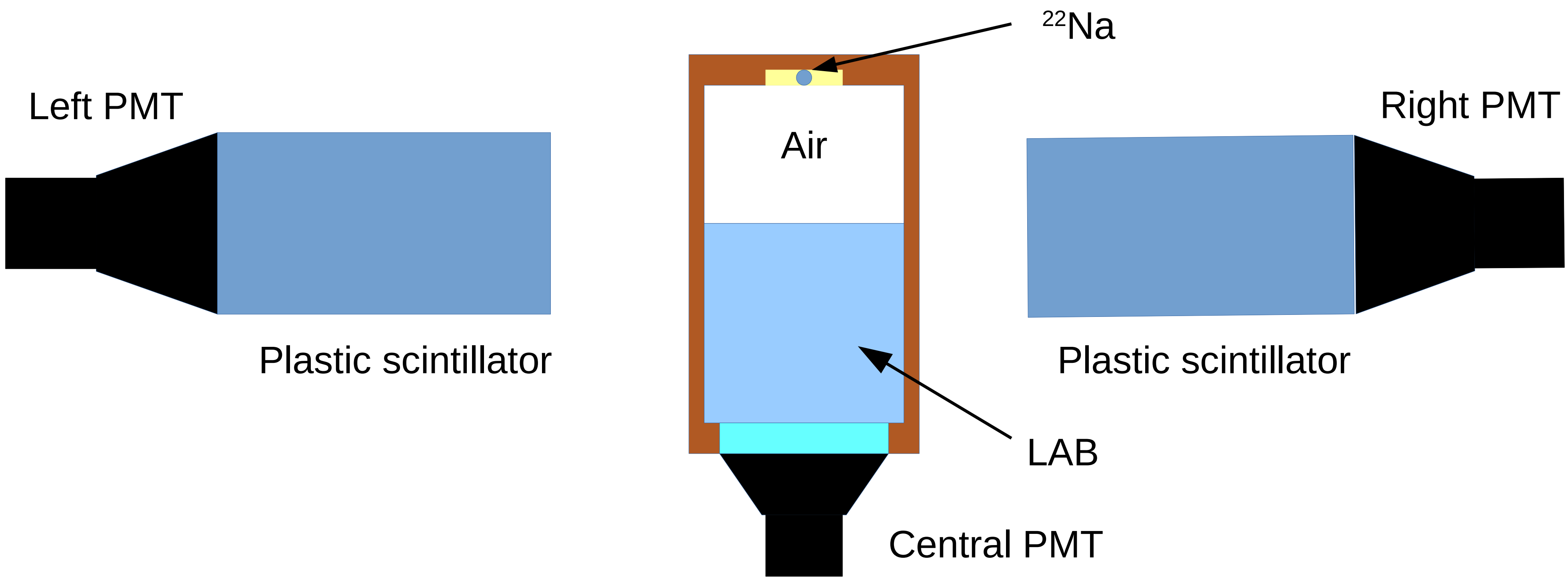
- Formation probability dependent on material
- Interaction with material causes spin-flips
  - Effective lifetime of o-Ps in liquid scintillators ~ 3 ns
  - Decay into two 511 keV gammas
- Delay between scintillation & annihilation signal changes pulse shapes ➞ possibility to discriminate e^+ from e^- events
  - Already in use in Borexino (different scintillator)
  - JUNO: try to understand different background components

    enhance simulations

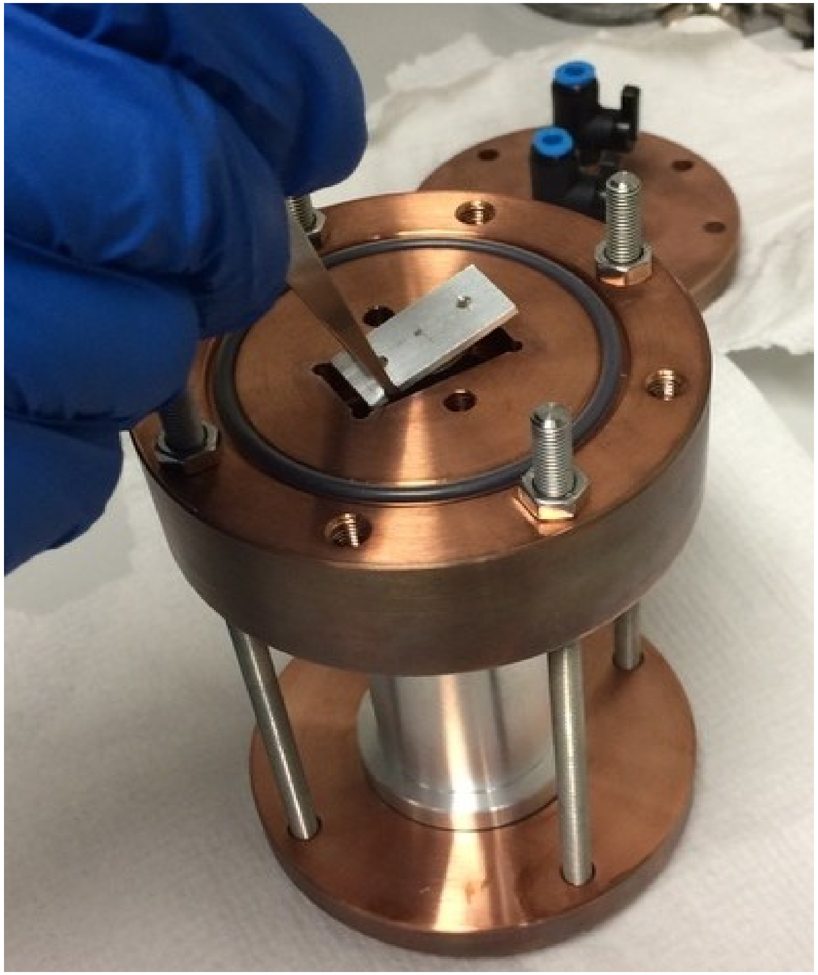
⇛ Measure the o-Ps lifetime in LAB-based scintillator

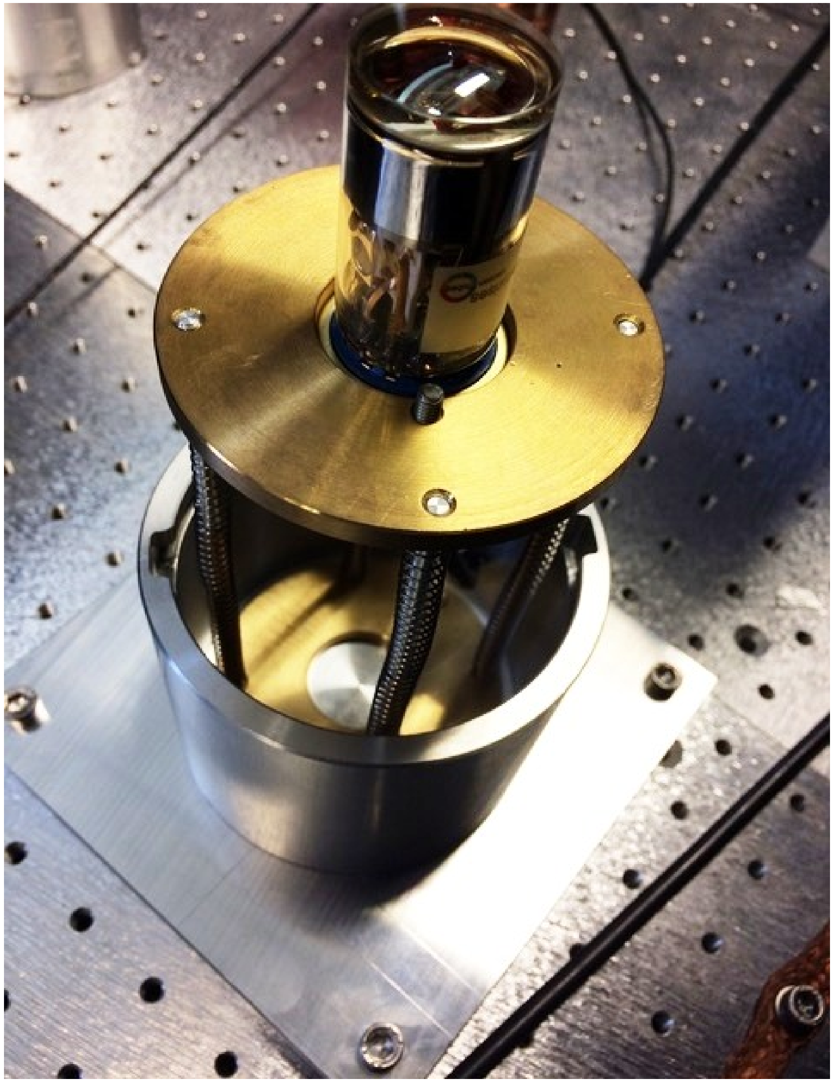
Measurement Setup

- Central vessel filled with LAB-based scintillator and connected to a PMT
- Two plastic scintillators at opposite sides connected with PMTs
- Positron emitter ^{22}Na fixed above the liquid scintillator



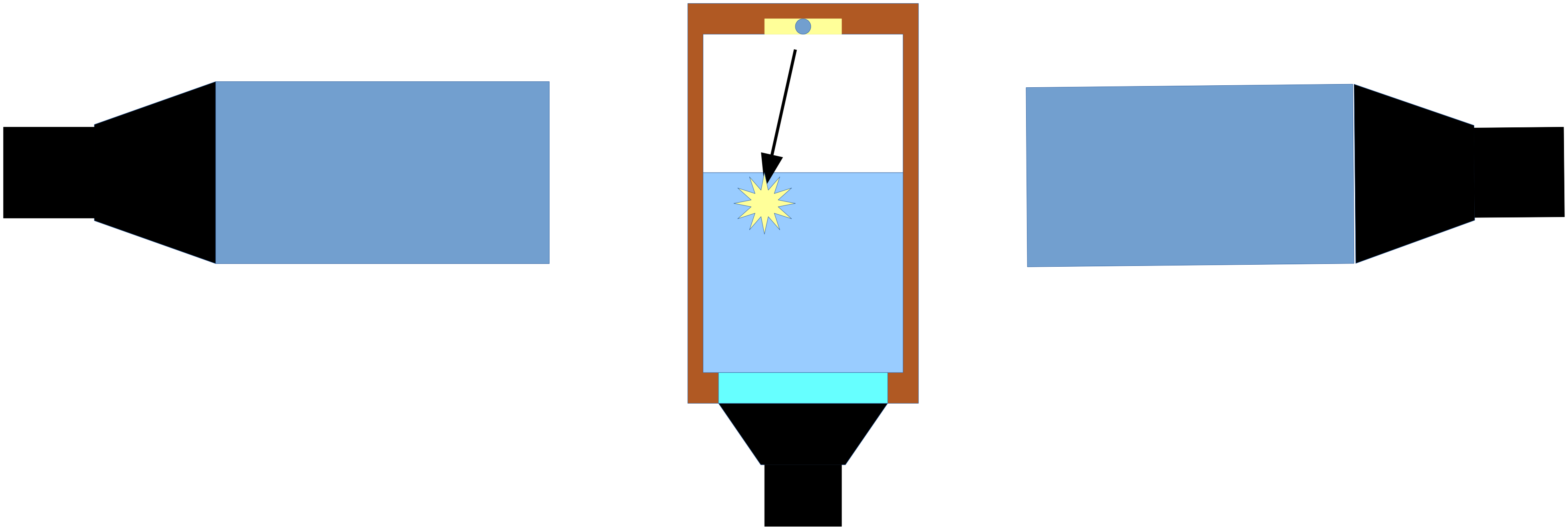
Measurement Setup





Measurement Principle

- Some positrons from ^{22}Na hit the liquid scintillator
- With some possibility o-Ps or p-Ps is formed



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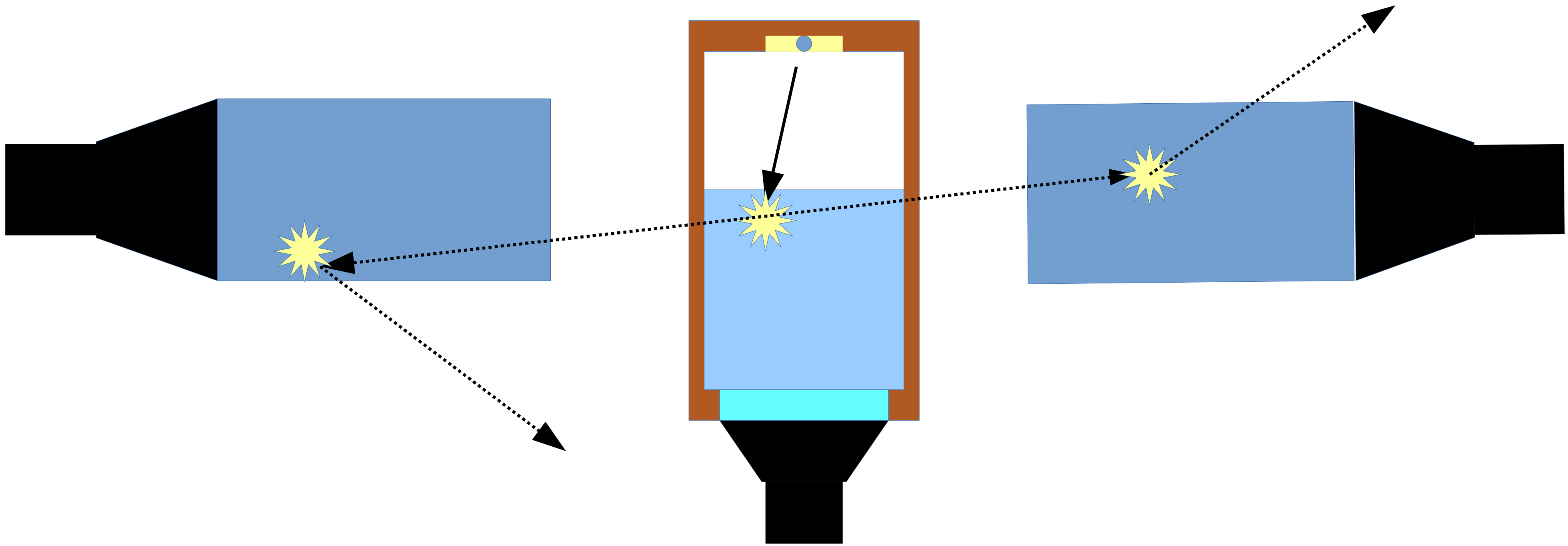
- Right angle → signals in both plastic scintillators



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⇛ We have a start and a stop signal in order to extract the lifetime of positronium!

- Correlated background: a 1275 keV gamma emitted 3.6 ps after the decay of ^{22}Na

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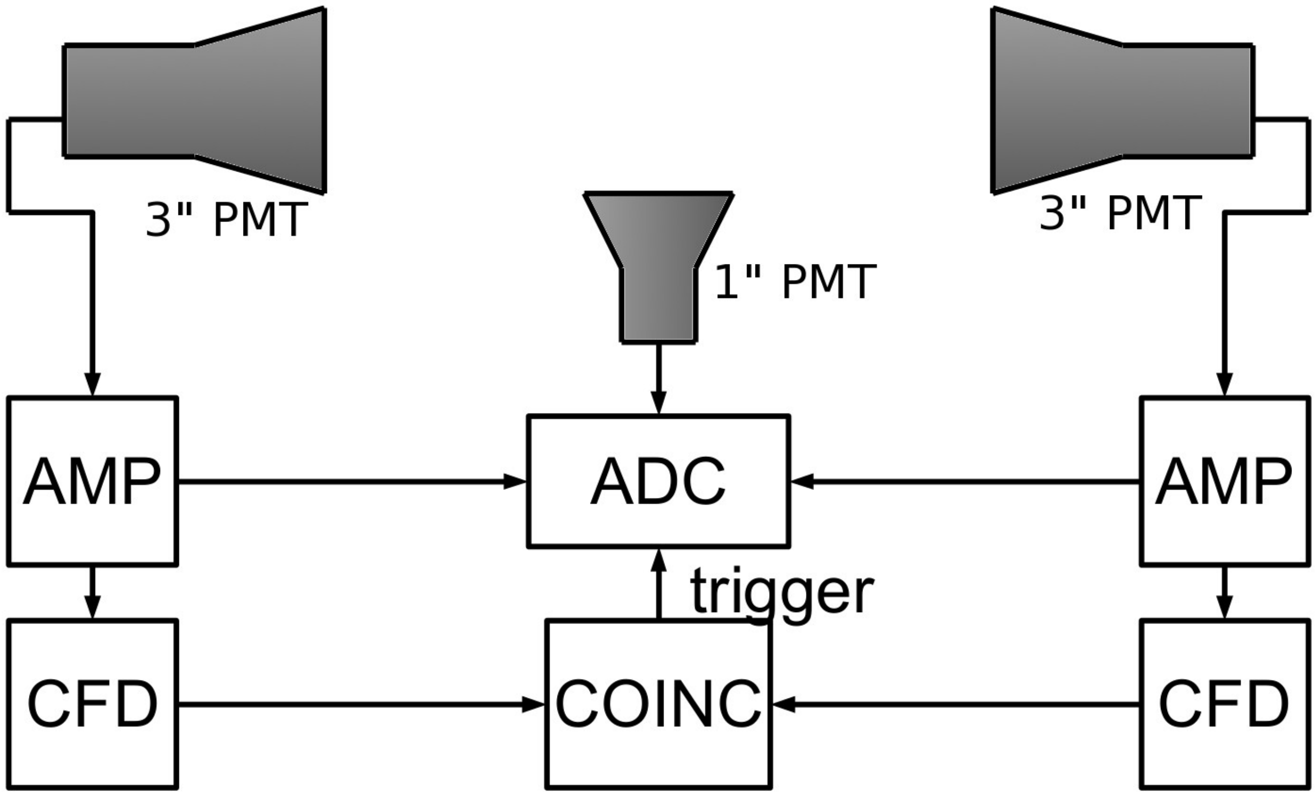
Readout

- Trigger on every annihilation gamma coincidence
- Time & energy reconstruction offline



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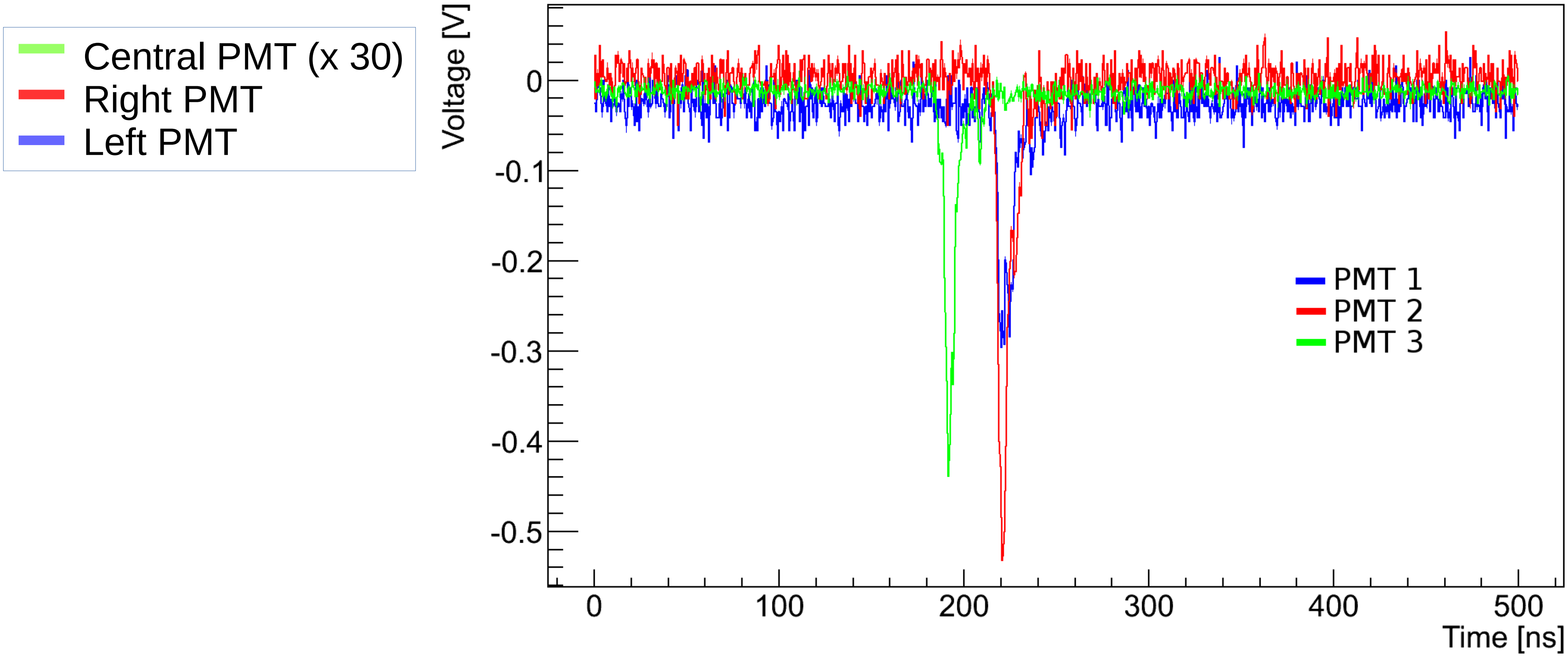

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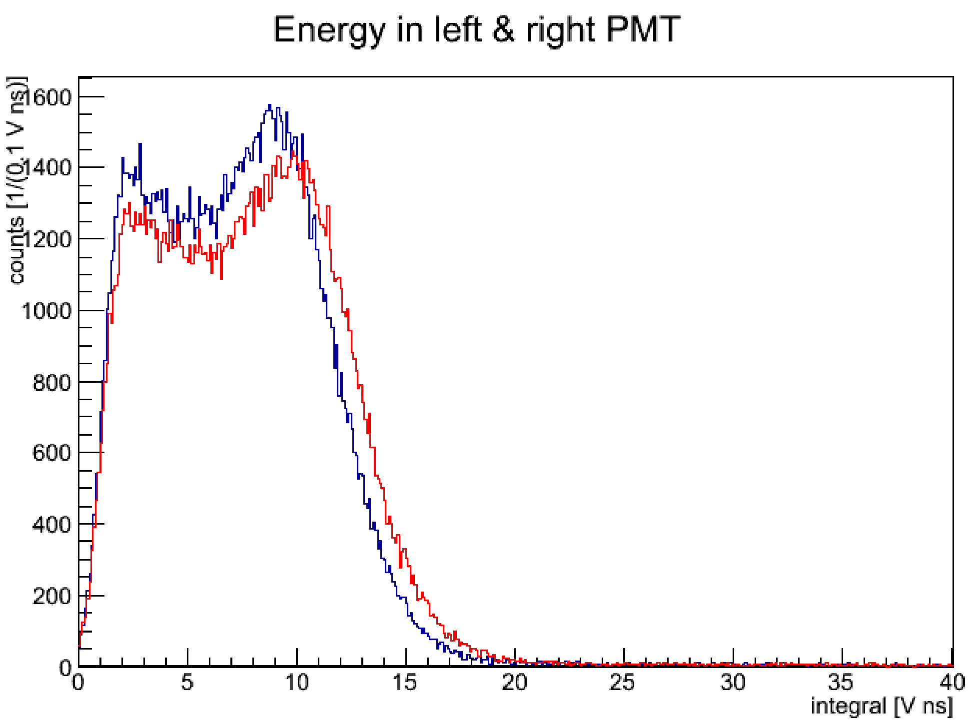
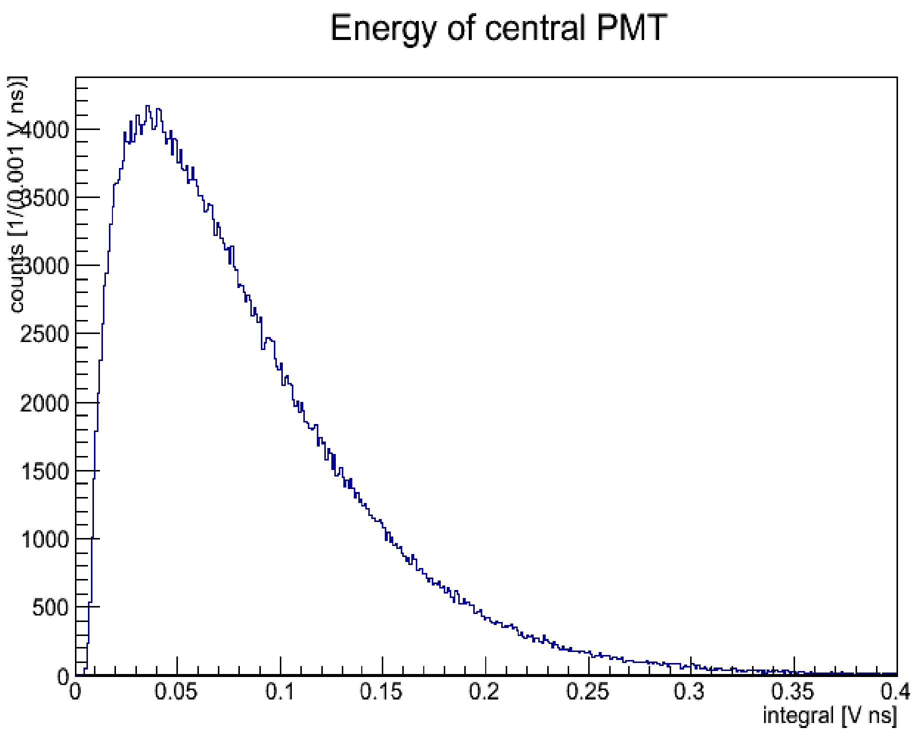
Results

- Integral over PMT signal gives deposited energy





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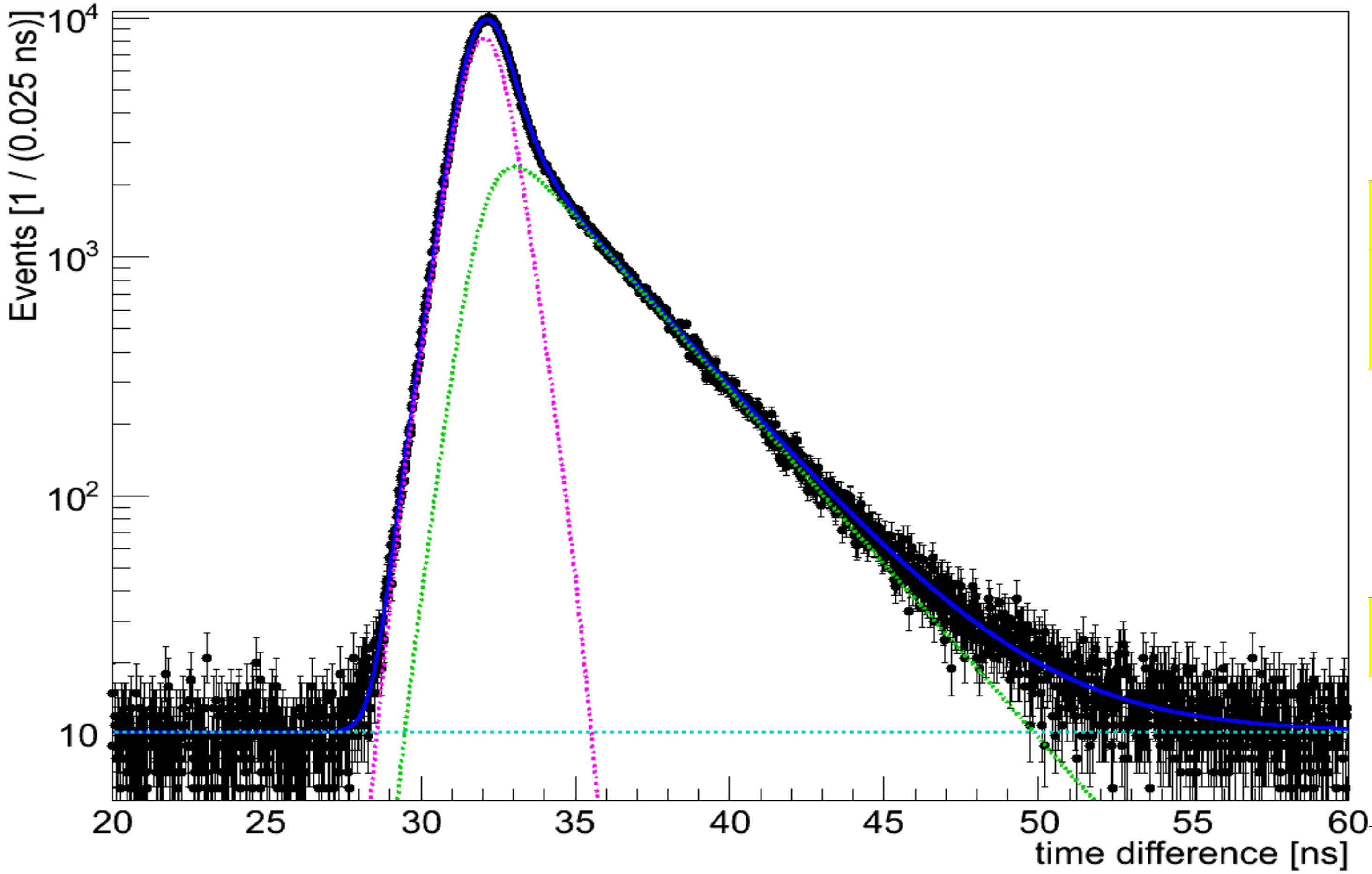
Time difference: stop - start



$$f(t)=\left(n1\cdot e^{\frac{-t}{\tau_1}}+n2\cdot e^{\frac{-t}{\tau_2}}\right)*\left(\sum_{i=1}^{2}\frac{\eta_i}{\sqrt{2\pi\sigma_i^2}}\cdot e^{\frac{-(t-\mu)^2}{2\sigma_i^2}}\right)+n3$$

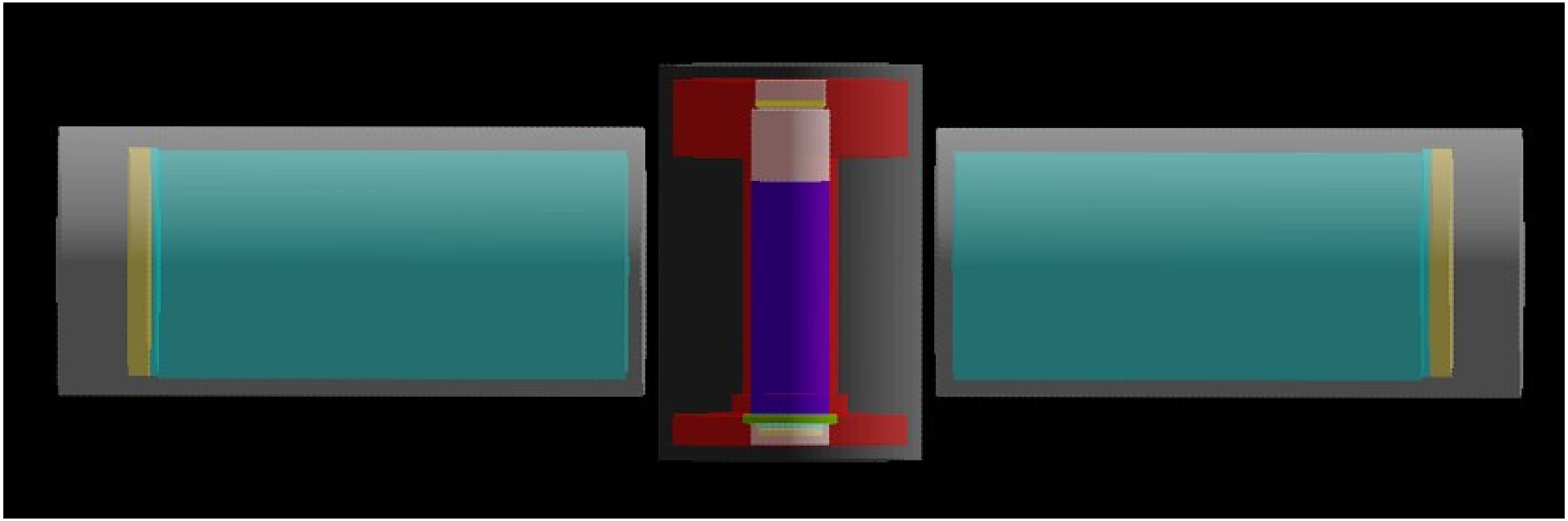
Fit results:

	value	error
Chi²	0.97	
o-Ps fraction	42.3%	0.2%
Signal fraction	98.50%	0.02%
τ_1 [ns]	0.005	0.008
τ_2 [ns]	2.987	0.007
μ [ns]	32.040	0.008
σ_1 [ns]	1.054	0.008
σ_2 [ns]	0.641	0.005
η_1	0.39	0.01

16 000 000 double coincidences
1 223 418 triple coincidences after quality cuts (= 7.6 %)

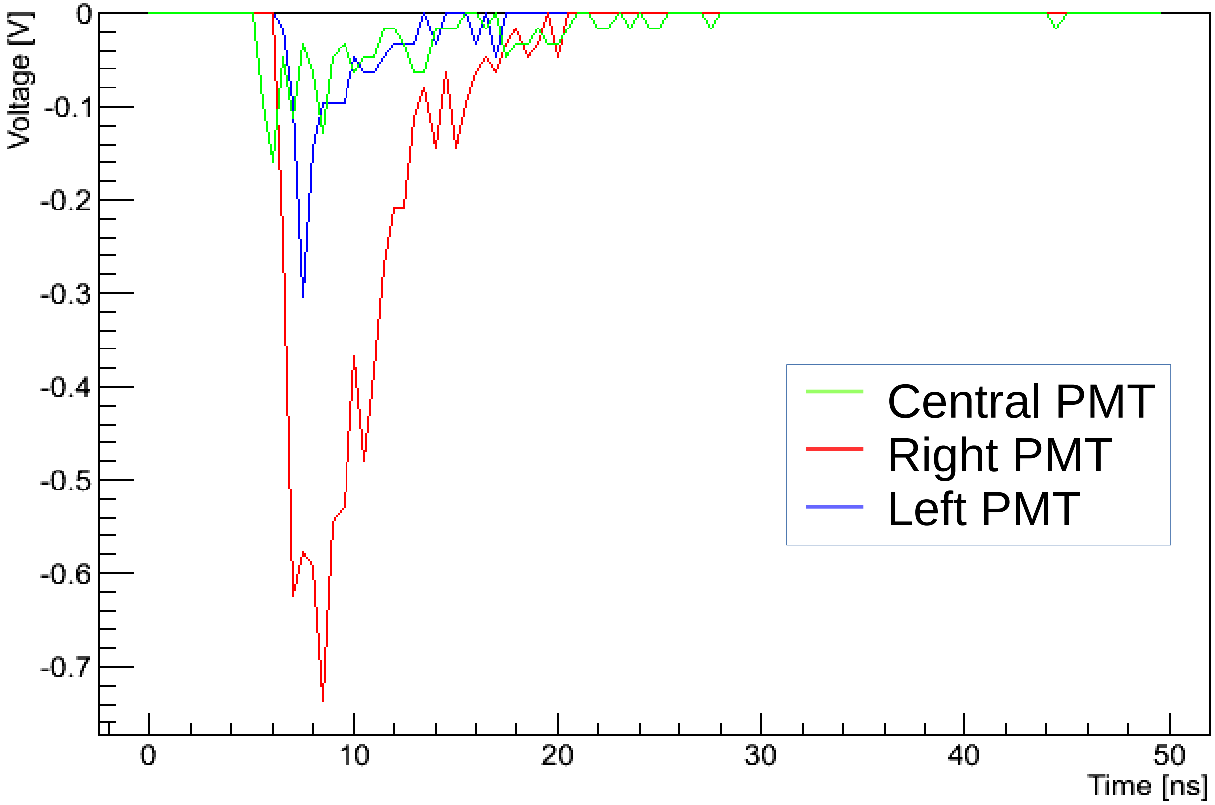
Simulation

- Simulation of the setup with Geant4
- Investigation & optimization of:
  - Geometry
  - Offline event discrimination



Simulation

- The physics are simulated from the decay of ^{22}Na until the optical photons hit the photocathode of one PMT
- The produced waveforms are analyzed with the same software tools as the real data



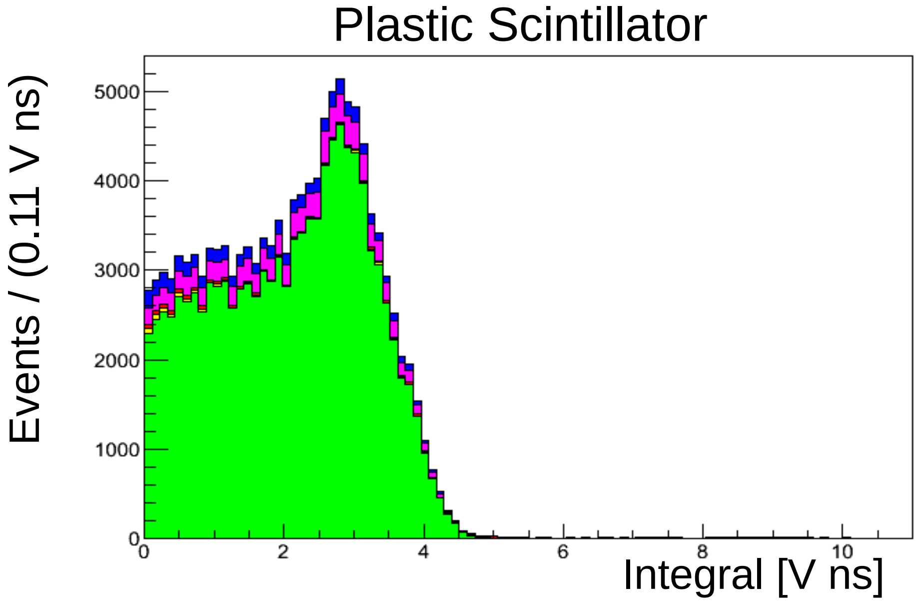
Simulation

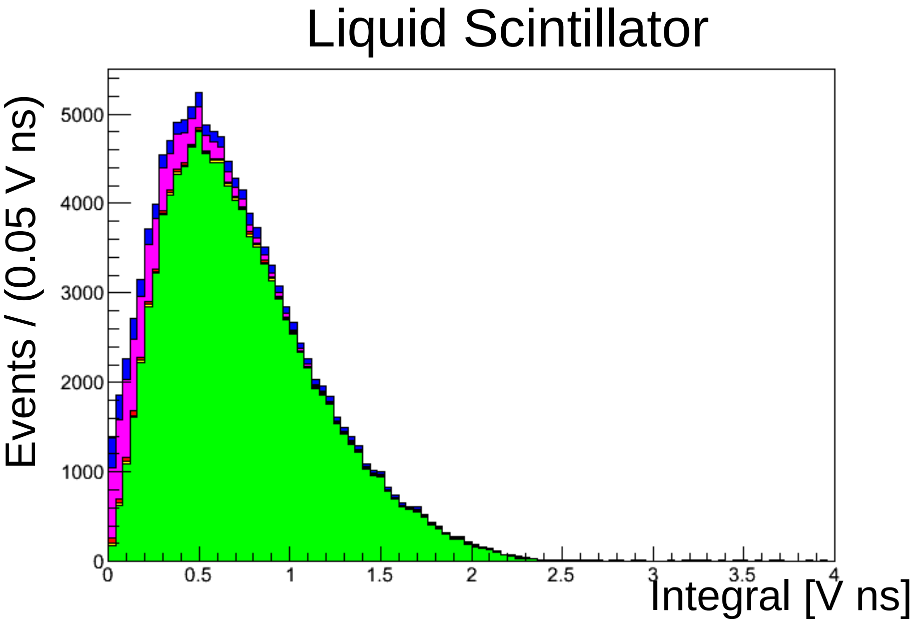
- Identify “good” events with the following properties:
  - Positron hits LAB and annihilates there
  - Both plastic scintillators are hit by a 511 keV gamma
  - No 511 keV gamma hits both plastic scintillators
  - The additionally produced 1275 keV gamma does not hit any scintillator
- Identify different fake triple events:
  - Positron scintillates in LAB but leaves it before annihilation
  - The 1275 keV gamma hits one or more scintillators
  - One 511 keV gamma hits both plastic scintillators

Simulation

- Study energy dependence of these events
  - Positron scintillates in LAB but leaves it before annihilation → (magenta)
  - The 1275 keV gamma hits this scintillator → (red)
  - One 511 keV gamma hits both plastic scintillators → (yellow)
  - Other fake events produced by the three gammas → (blue)

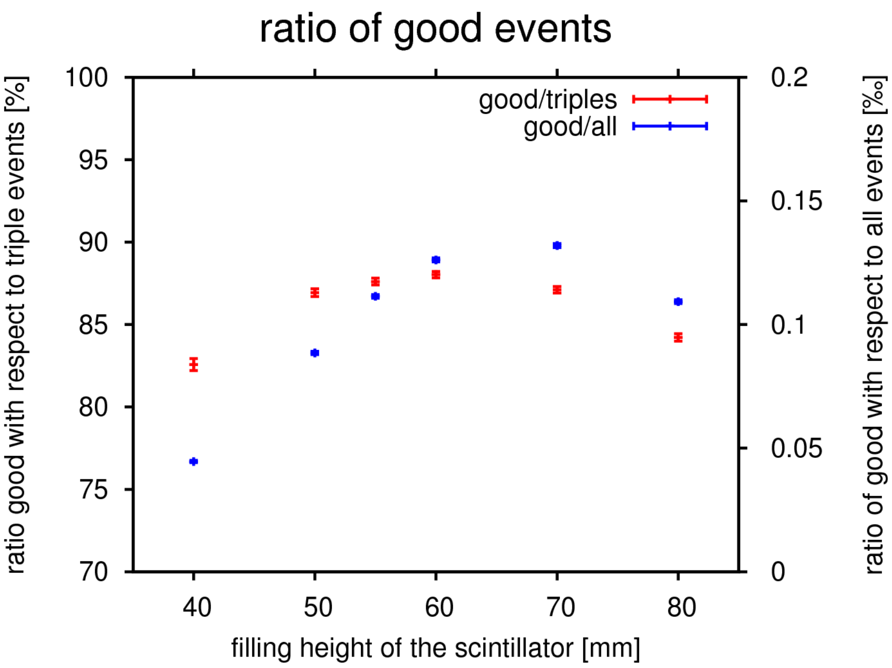
(good → (green))

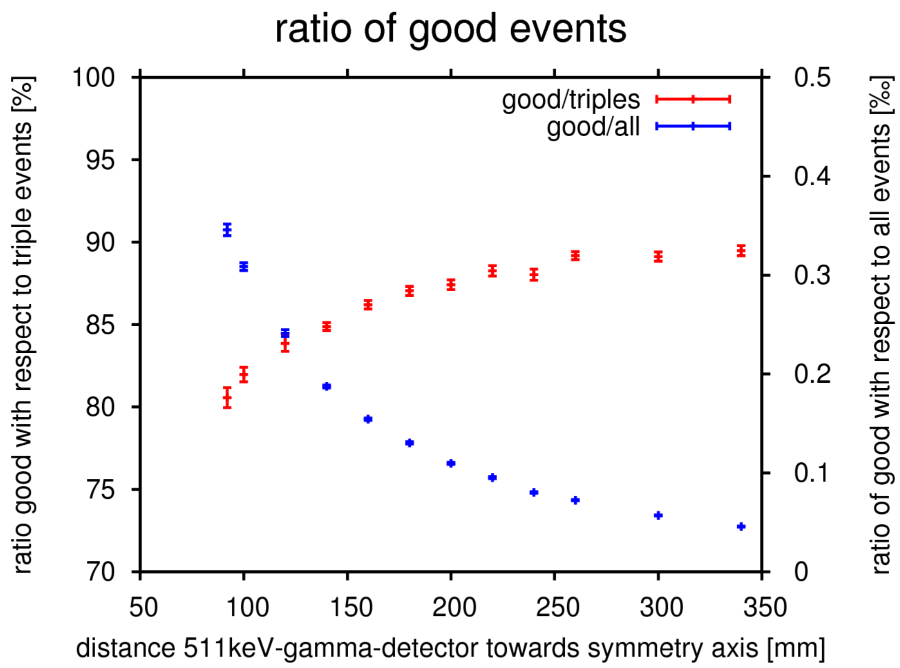


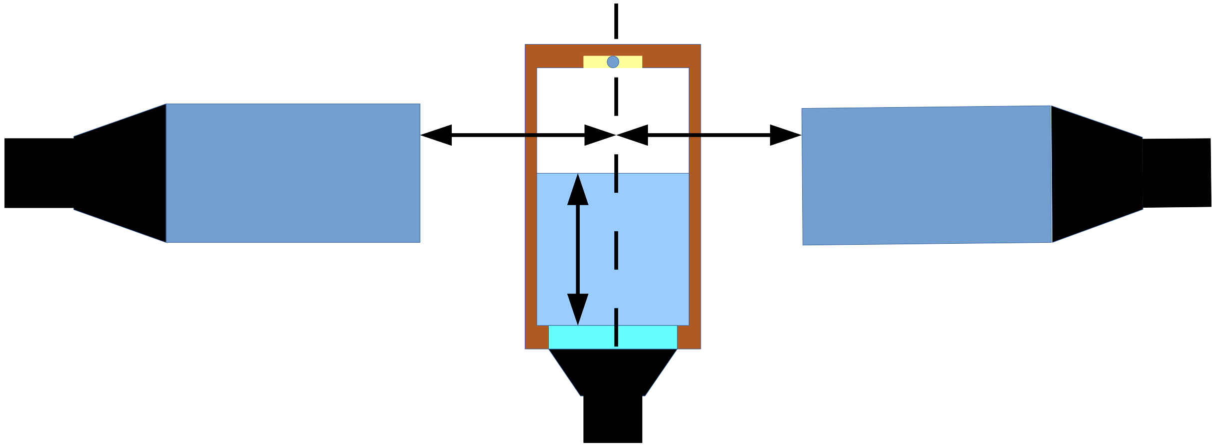


Simulation

- Try different geometries



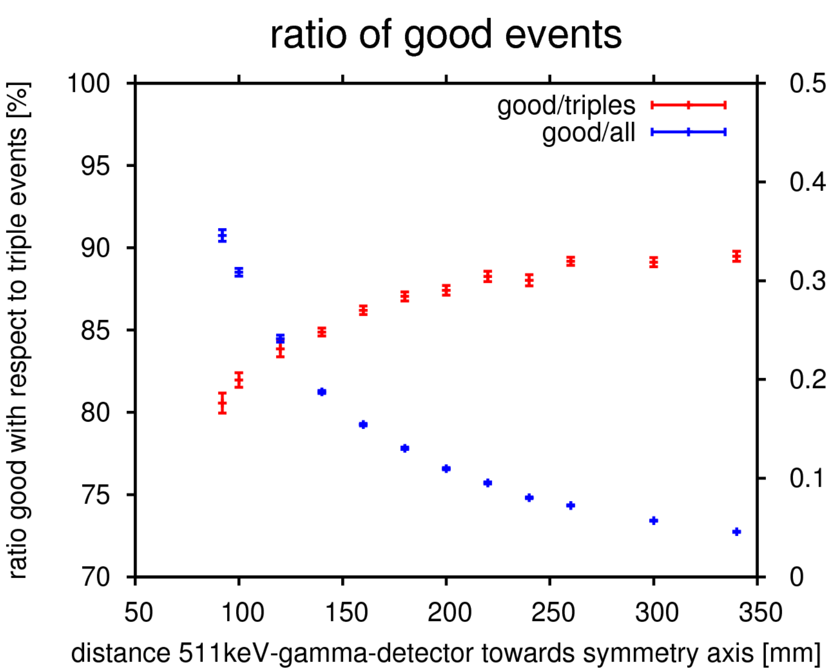




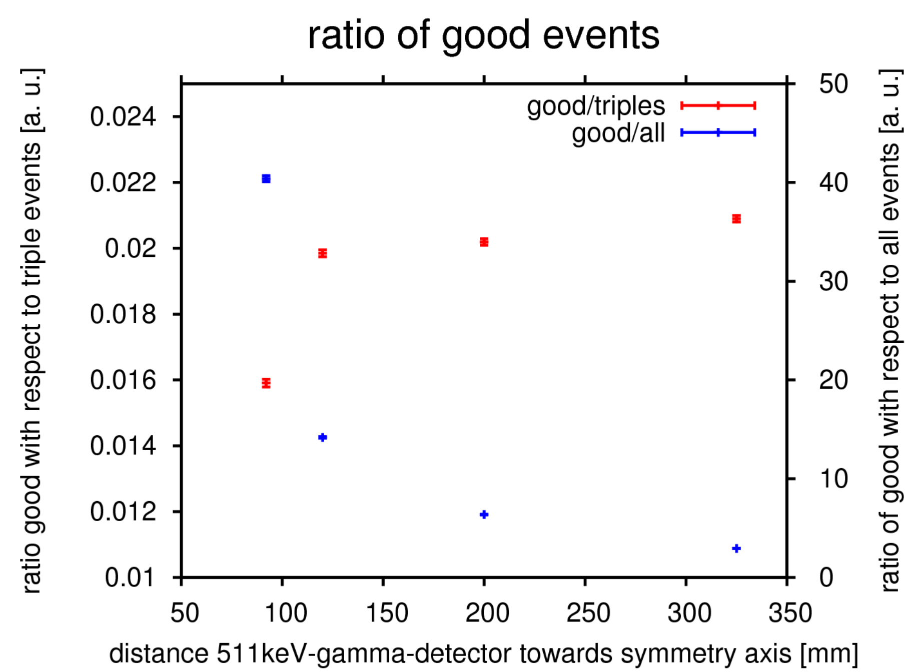
Simulation

- Reproduce simulated effects with measurements

Simulation



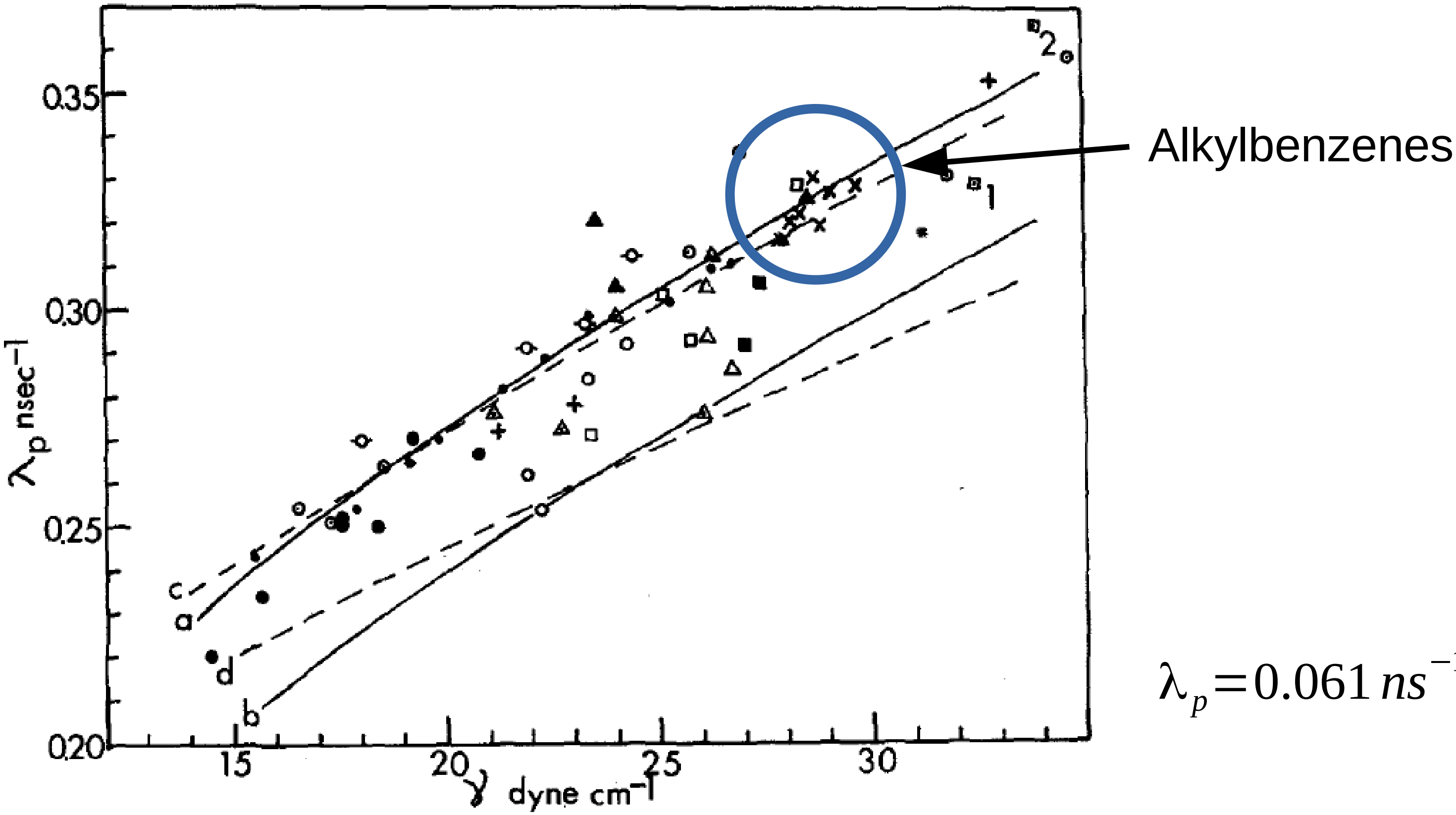
Experiment



Lifetime Calculation

- Connection between surface tension γ and lifetime of o-Ps: S. J. Tao, Positronium Annihilation in Molecular Substances, The Jounal of Chemical Physics **56**, 5499 (1972)
- Idea: Ps confined in “bubble”, equilibrium radius depends on pressure applied on Ps
- Lifetime of o-Ps in most organic liquids depends on overlap between wave functions of o-Ps and e^- of medium
- Overlap depends on size of “bubble”

Lifetime Calculation



$$\lambda_p = 0.061\, ns^{-1} \cdot \gamma^{0.50}$$

- Using γ = 30.12 dyne/cm for dodecylbenzene → τ_2 = 2.99 ns
- Theory allows prediction of lifetime change under application of external pressure → JUNO setup → change negligible

Conclusion and Outlook

- Lifetime and formation probability of o-Ps in LAB-based scintillator measured
- Simulation and measurement agree
- Calculated lifetime agrees with measurement
- Lifetime and formation probability of o-Ps enough to generate a measurable effect in some of the positron signals in JUNO
- Pressure will not produce significant changes

- Possibility to measure with different compositions of wavelength shifters and even different liquid scintillators