Master 2 Defense

Speciality : Subatomic physics and astroparticles

Positronium discrimination for the JUNO neutrino oscillation experiment

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Overview

1 THEORETICAL AND EXPERIMENTAL CONTEXT

2 TREATMENT AND ANALYSIS OF THE PHOTO-ELECTRON HIT TIME DISTRIBUTION

3 RESULTS AND DISCUSSION

4 CONCLUSION

Theoretical and Experimental Context

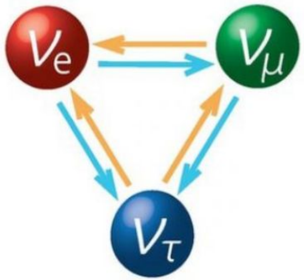
Neutrino Oscillation

Problem

Anomaly in the atmospheric and solar neutrino flux (deficit of about 50% in relation to what was expected) led us to a new theory beyond the standard model…

Solution

…Neutrinos can oscillate from a flavour to another.



Mechanism

Flavour eigenstates correspond to superimposition of mass eigenstates related by an unitary matrix:

U_{PMNS}

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Neutrino Oscillation

Mechanism

- The propagation in time of the mass eigenstates $|\nu_k(t)\rangle$ is described by the Schrödinger equation.

↳ It is possible to obtain the transition probability from a flavour α to another β:

$$P_{\nu_\alpha \to \nu_\beta} = \delta_{\alpha\beta} - 4 \sum_{i>j} \mathrm{Re}\{(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j})\} \sin^2\left(1.27 \Delta m^2_{ij} \frac{L}{E}\right)$$
$$+ 2 \sum_{i>j} \mathrm{Im}\{(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j})\} \sin\left(2.54 \Delta m^2_{ij} \frac{L}{E}\right).$$

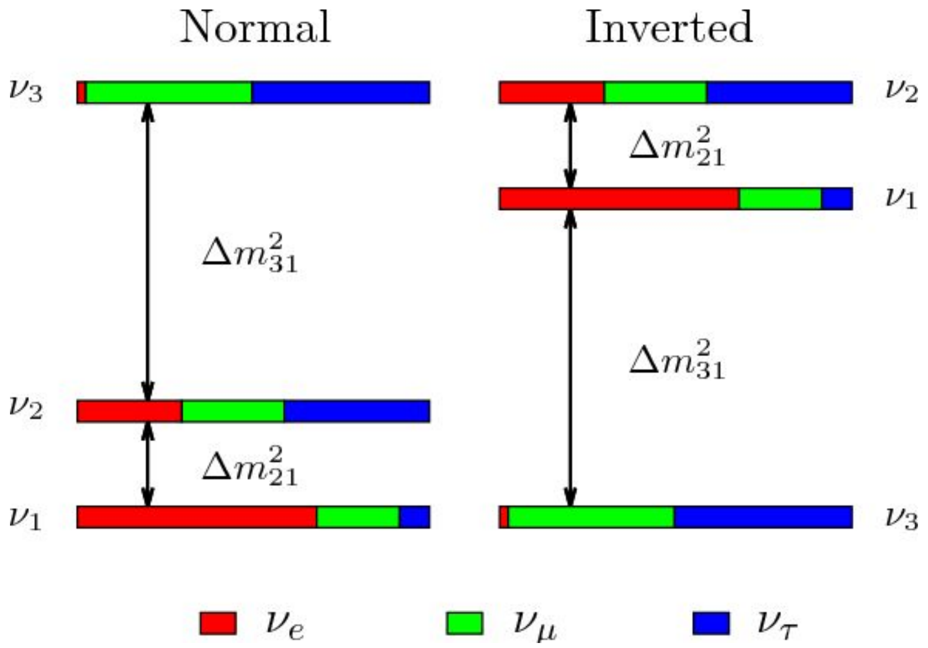
with L the distance from the creation of the neutrino flavour eigenstate, E the average energy eigenvalue of the neutrino mass eigenstates and $\Delta m^2_{kj} = m^2_k - m^2_j$ the mass splitting of the mass eigenstates.

Normal and Inverse Ordering

In vacuum $\mathcal{P}_{\nu_\alpha \to \nu_\beta}(L, E)$ depends of Δm^2_{kj} which are within a square sine. But in matter, the oscillation probability is modified in a way that depends on the sign of the mass splitting.

Only the sign of the mass splitting Δm^2_{12} has been determined.

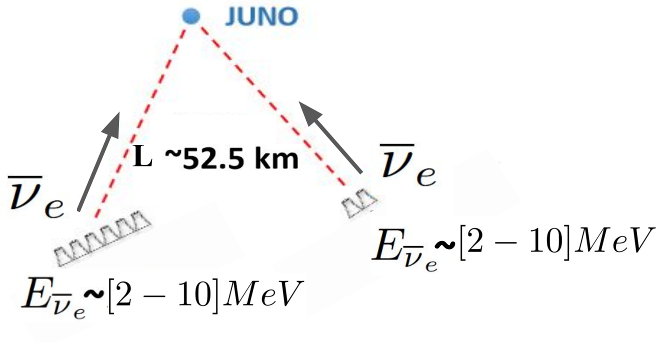
There are 2 possibilities concerning the sign of Δm^2_{31}.

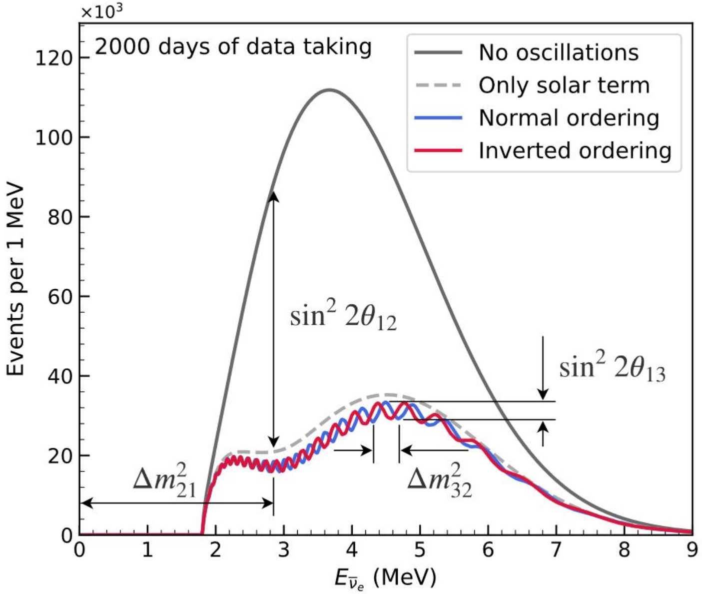


Normal and Inverse Ordering

Considering the transition probability in the case
we are dealing with (disappearance of reactor antineutrinos):

$$\mathcal{P}(\overline{\nu_e} \to \overline{\nu_e}) = 1 - \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2\left(\frac{\Delta m^2_{21} \times L}{4E_\nu}\right) - \sin^2(2\theta_{13}) \cdot \left(\frac{\Delta m^2_{31} \times L}{4E_\nu}\right)$$
$$- \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m^2_{21} \times L}{4E_\nu}\right)\cos\left(\frac{2|\Delta m^2_{31}| \times L}{4E_\nu}\right)$$
$$\pm \frac{\sin^2(\theta_{12})}{2}\sin^2(2\theta_{13})\sin\left(\frac{2\Delta m^2_{21} \times L}{4E_\nu}\right)\sin\left(\frac{2|\Delta m^2_{31}| \times L}{4E_\nu}\right)$$



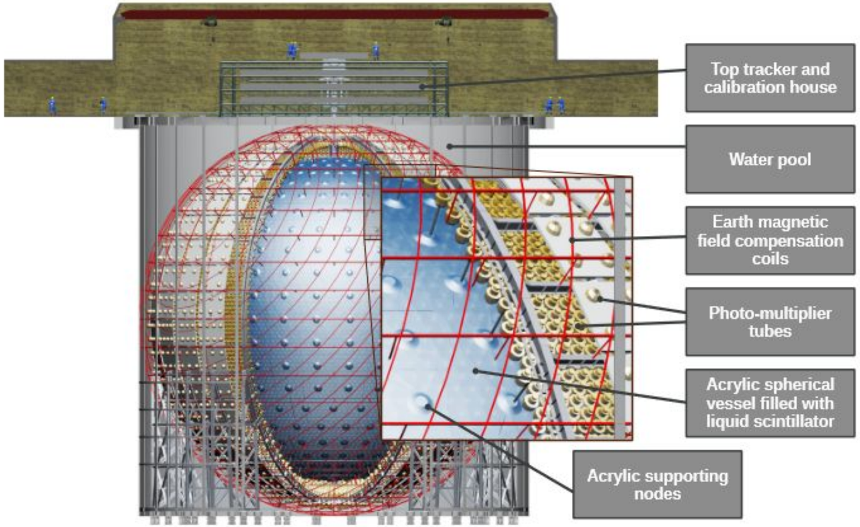


It is possible to determine the neutrino mass hierarchy (Δm^2_{31}) if we have an excellent energy resolution.

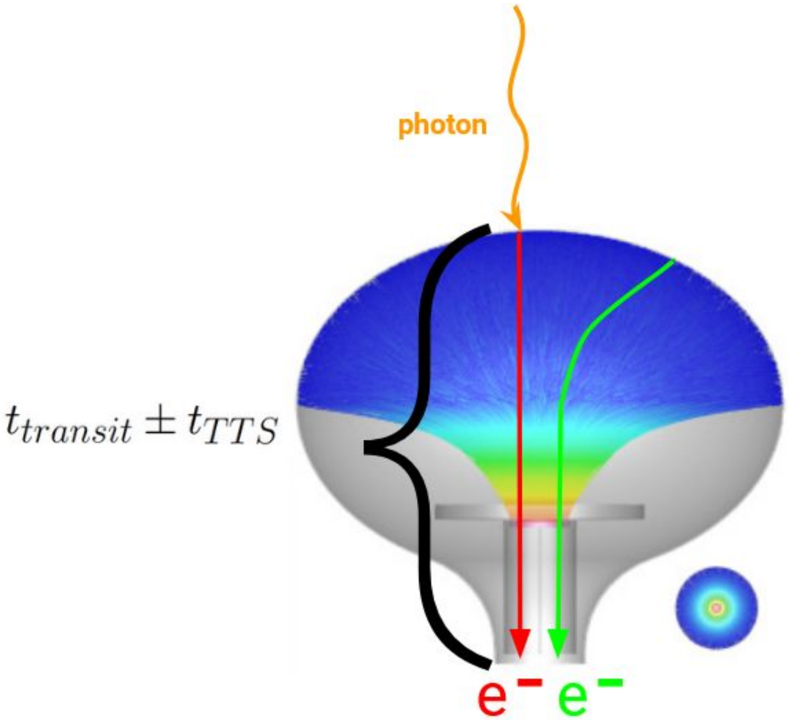
The JUNO Experiment

JUNO Characteristics

- 35m of diameter sphere
- 20kton of liquid scintillator
- Muon tracker and veto system
- ~53km from 2 nuclear power plants
- 17,612 20-inch large photo-multiplier tubes (LPMT)
- 25,600 3-inch small photo-multiplier tubes (SPMT)
- Complete detector system collects about 1,700 photo-electrons/MeV



The JUNO Experiment



PMTs Characteristics

➢ Large photo-multiplier tubes (LPMTs):

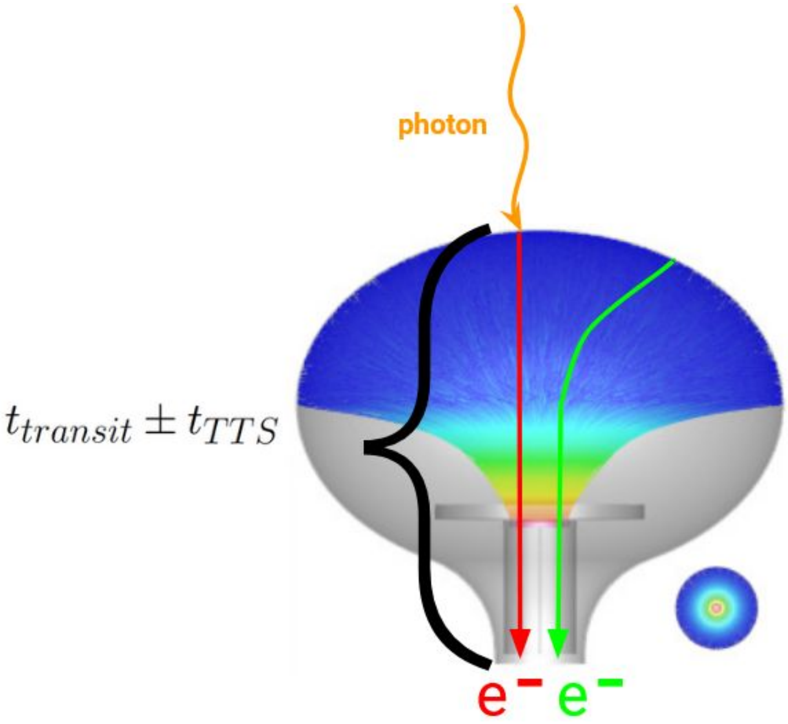
- 5,000 Hamamatsu PMTs:
  Transit Time Spread: 1.1ns
  Dark Noise: 15kHz

- 12,612 MCP-PMTs:
  Transit Time Spread: 5.0ns
  Dark Noise: ~49kHz

➢ Small photo-multiplier tubes (SPMTs):

  Transit Time Spread : 1.5ns
  Dark Noise: 500Hz

The JUNO Experiment



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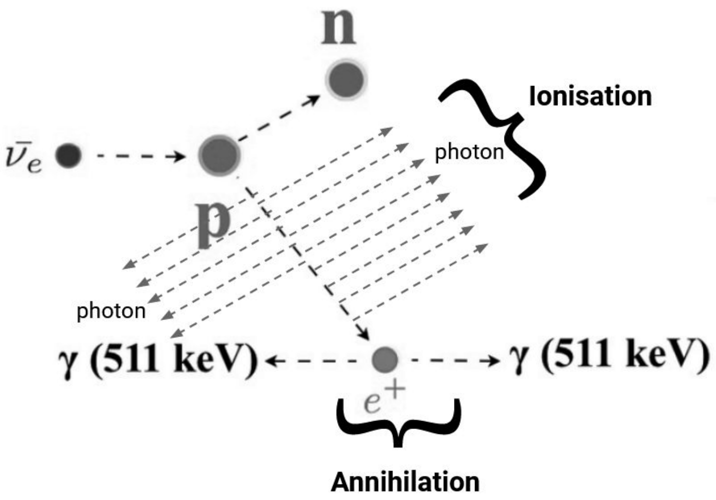
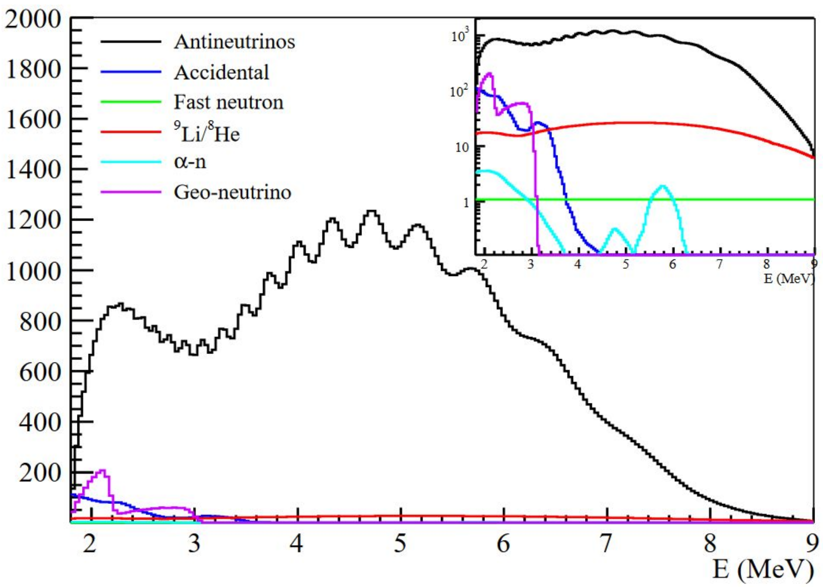
Real signal and Background

Real Signal

When an antineutrino from the reactor source arrives in the liquid scintillator, it can manifest itself as an IBD:



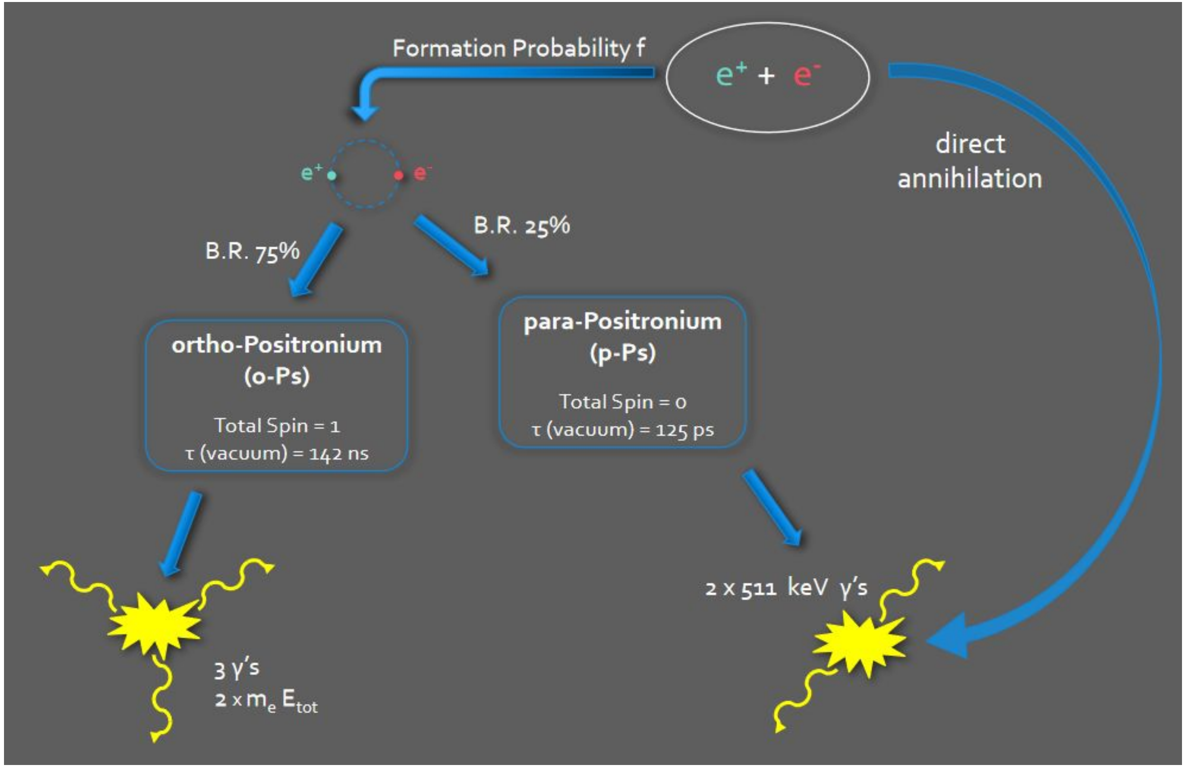
Background



Ortho-positronium formation (in vacuum)

Positronium Properties

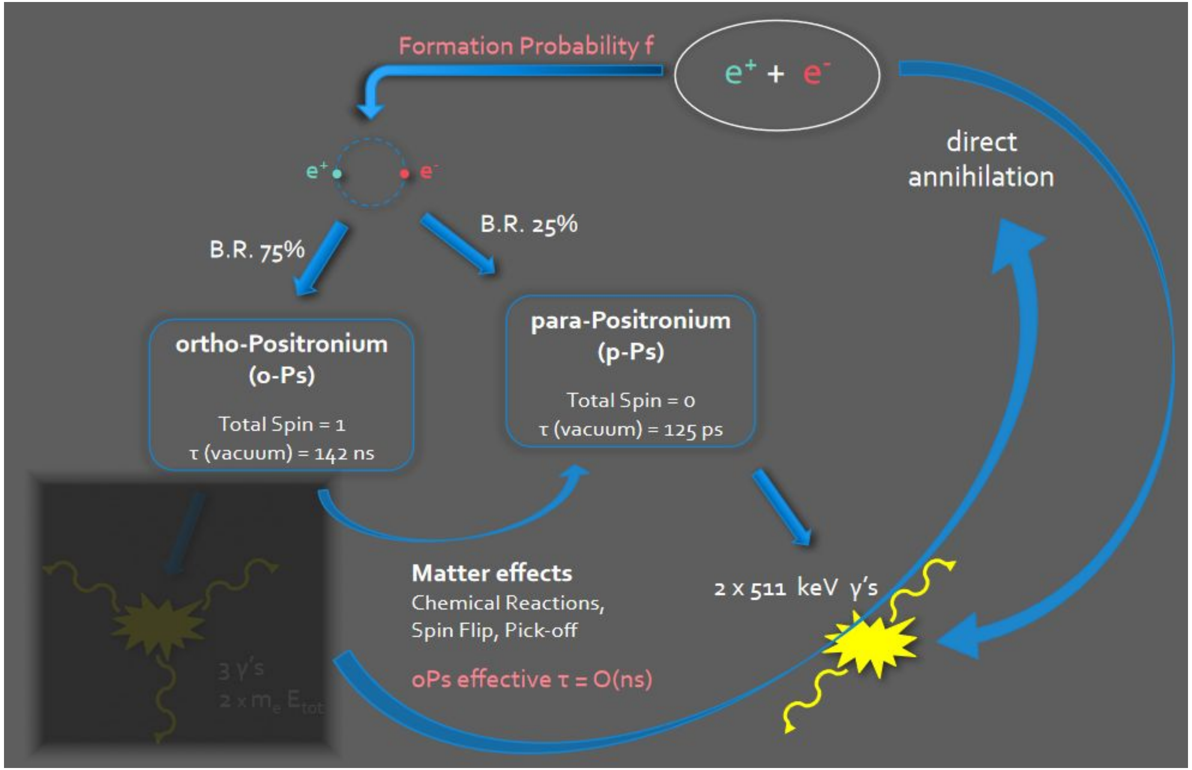
- ➔ Before annihilating, the positron can form a positronium metastable state
- ➔ The ortho-positronium (o-Ps) state leads to a delayed annihilation
- ➔ While the lifetime of the para-positronium is too short, that of ortho-positronium is longer enough to be used in particle discrimination



Ortho-positronium formation (in matter)

Positronium Properties

- ➔ In matter, ortho-positronium (o-Ps) lifetime is quenched and its formation probability changes
- ➔ In the JUNO liquid scintillator, the lifetime of the o-Ps becomes 3.08ns
- ➔ The o-Ps formation in the liquid scintillator is expected in 50% of cases

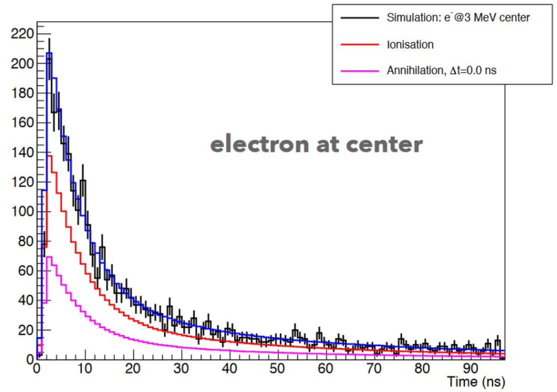


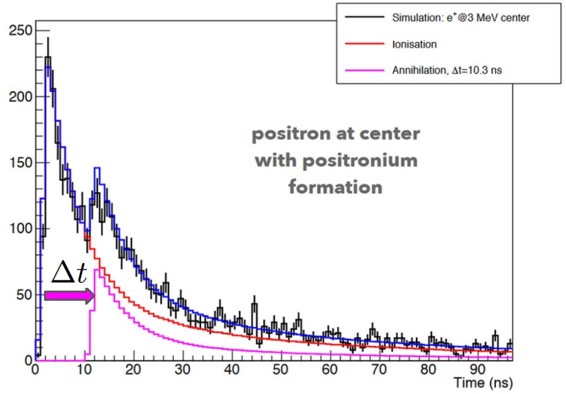
Treatment and analysis of the photo-electron hit time distribution

Discrimination methods

Electron/Ortho-positronium temporal distribution

- For each event, the photo-electrons received by the PMTs will be used to reconstruct the position vertex and get the time distribution of hits
- The time distribution takes several nanoseconds due to the light emission time profile of the liquid scintillator
- Concerning the o-Ps, the photo-electrons from the annihilation will be delayed inducing another peak in the ionisation peak's tail
- Particle discrimination methods can be applied to the time distribution of certain events

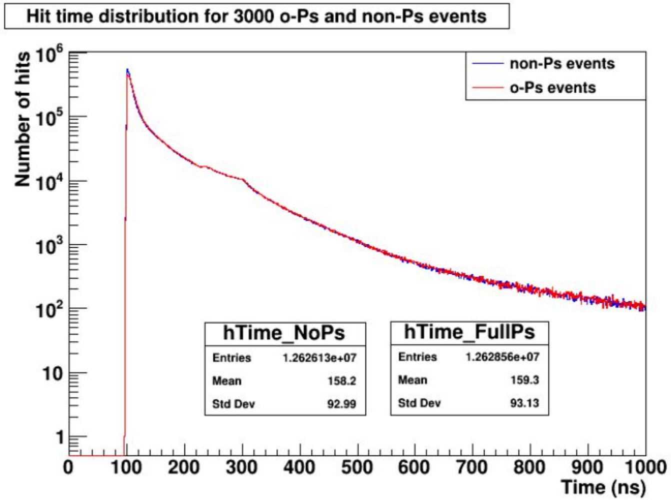




Discrimination methodology

To study the ortho-positronium discrimination, we used :

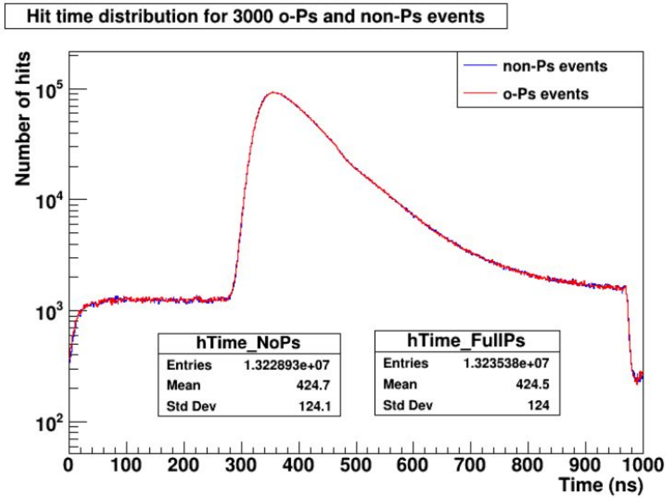
- A sample of identical positrons without o-Ps formation
- A sample of positrons with o-Ps formation with a lifetime of 3.08ns



G4 + Optical Simulation

Transit time spread effects

Dark noise effects



Electronics Simulation

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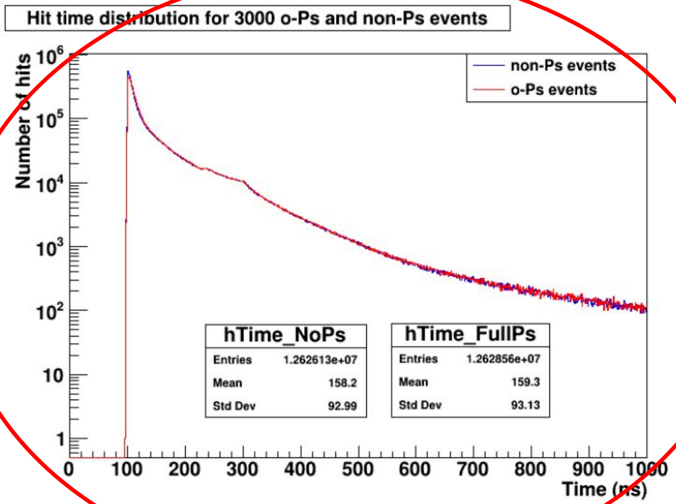

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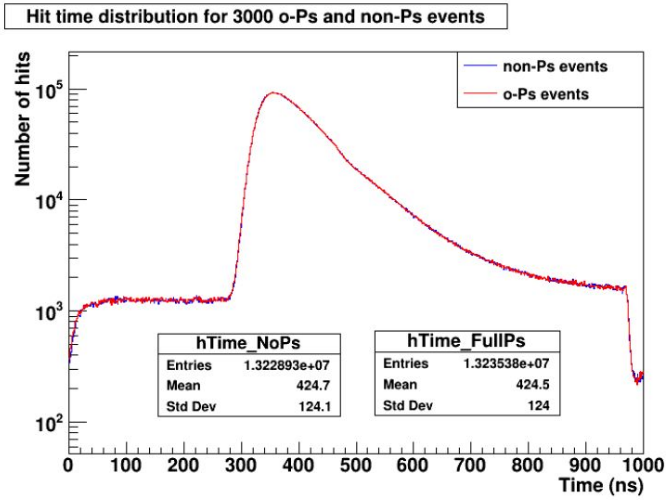


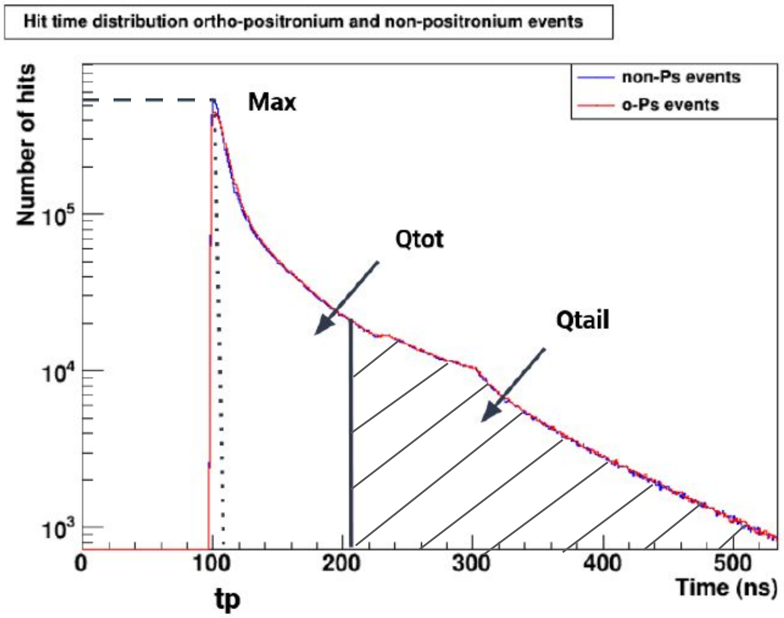
Electronics Simulation

Qtail/Qtot and Max/Qtot methods

Discrimination methods

- Qtail/Qtot method : Take the ratio of the number of hits in the tail to the total number of hits
- Max/Qtot method : Take the maximum of the signal over the total number of hits

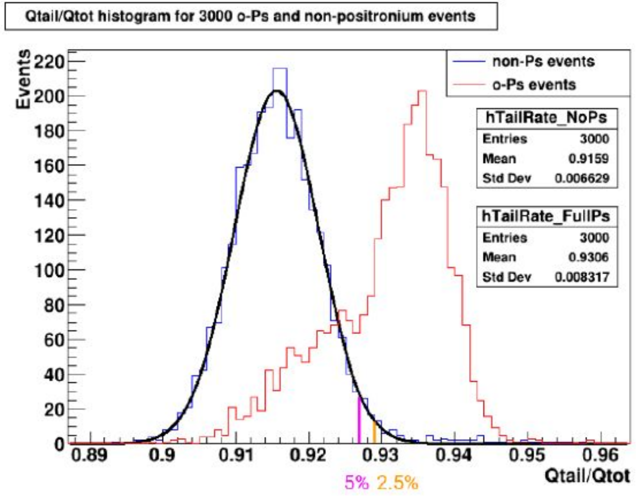
➔ Given the temporal distribution event per event, both ratio should be different

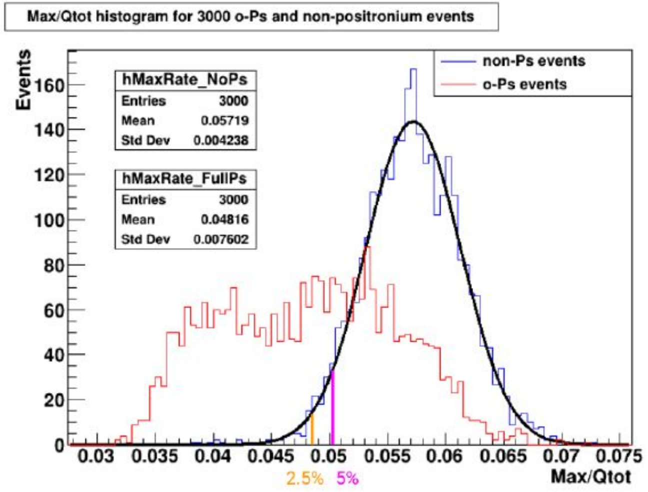


Qtail/Qtot and Max/Qtot methods

Distribution of Qtail/Qtot and Max/Qtot :

- ➢ Discrimination of o-Ps appears
- ➢ Different distribution shape because of the differents annihilation delay time of o-Ps events
- ➢ It is possible to discriminate o-Ps events admitting a certain tolerance of non-positronium ones (left- right- tailed hypothesis test)





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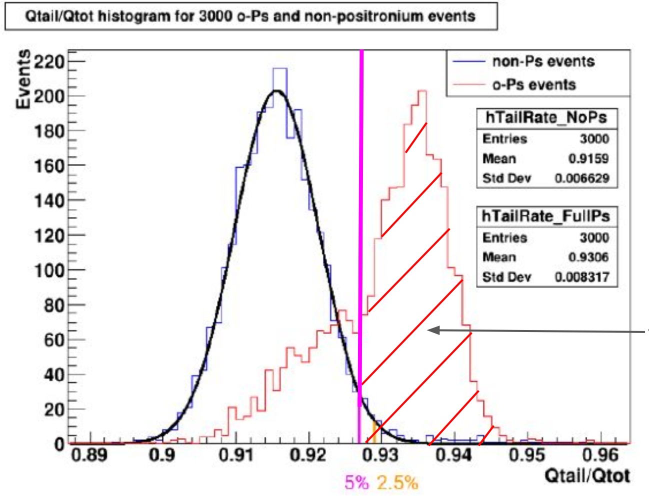
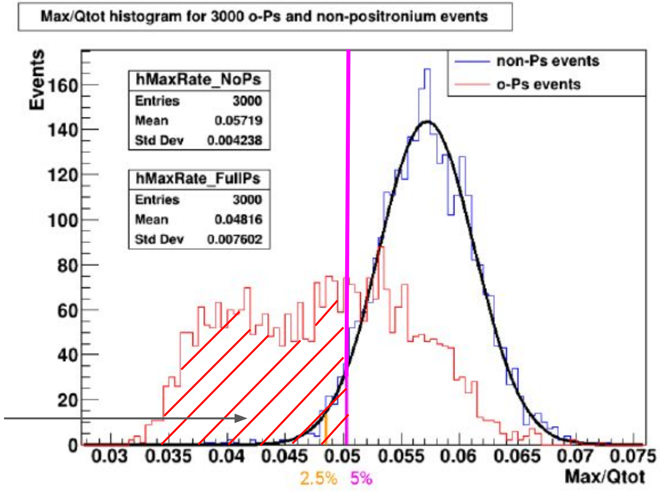


$\frac{N_{disc}}{N_{evt}} \approx 70\%$

$\frac{N_{disc}}{N_{evt}} \approx 50\%$



Treatment and analysis of the photo-electron hit time distribution

Electronics impact

Discrimination methodology

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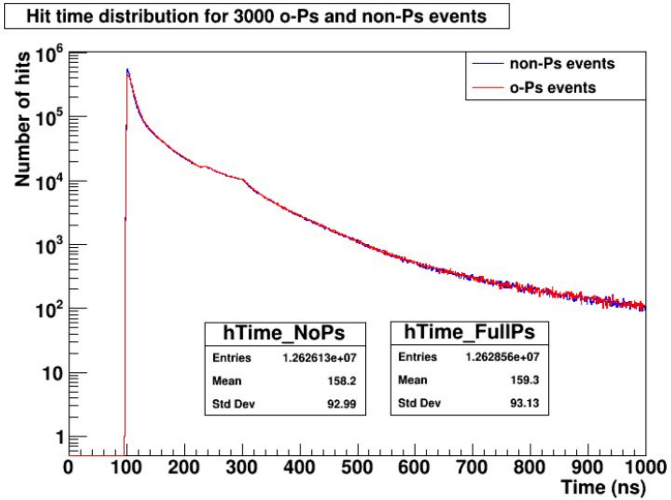
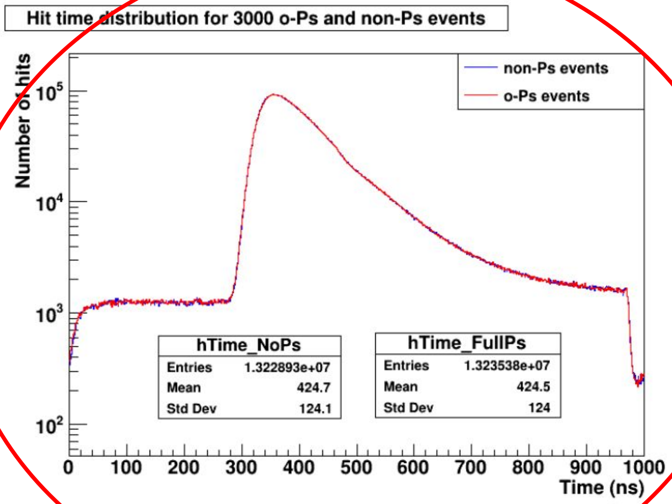


G4 + Optical Simulation

Transit time spread effects

Dark noise effects



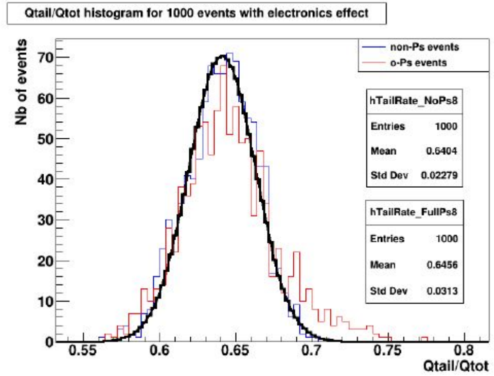
Electronics Simulation

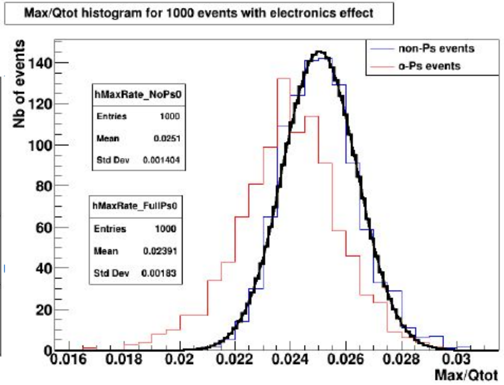
Dark noise and Transit time spread effects

Comparing the different discrimination methods for events with full electronics simulation at the same energy (2MeV):

➔ There is a sharp decrease in the discrimination rate mainly due to the TTS effects

➔ The Max/Qtot method is more efficient than the Qtail/Qtot for electronics simulation





Simulation 2 MeV	Qtail/Qtot method : 2.5% of non-Ps tolerance	Max/Qtot method : 2.5% of non-Ps tolerance
Optical simulation (3000 evts)	$(71.2 \pm 1.6)\%$	$(52.2 \pm 1.3)\%$
Electronics simulation (1000 evts)	$(11.0 \pm 1.1)\%$	$(18.3 \pm 1.4)\%$

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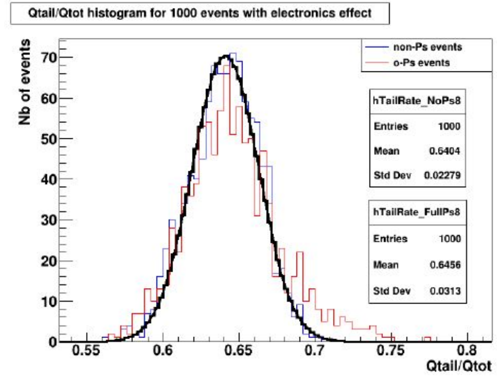
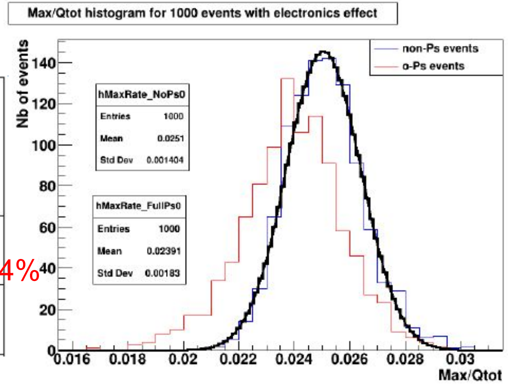


Simulation 2 MeV	Qtail/Qtot method : 2.5% of non-Ps tolerance		Max/Qtot method : 2.5% of non-Ps tolerance	
Optical simulation (3000 evts)	$(71.2 \pm 1.6)\%$	-60%	$(52.2 \pm 1.3)\%$	-34%
Electronics simulation (1000 evts)	$(11.0 \pm 1.1)\%$		$(18.3 \pm 1.4)\%$	



Dark noise and Transit time spread effects

Comparing the different discrimination methods for events with full electronics simulation at the same energy (2MeV):

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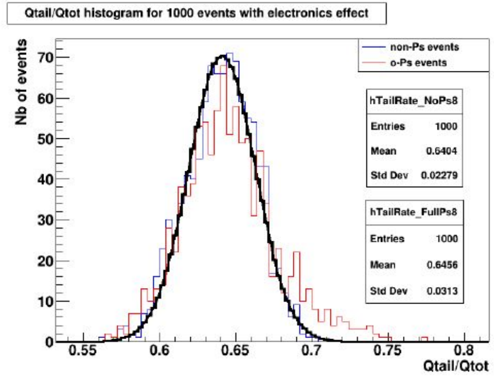

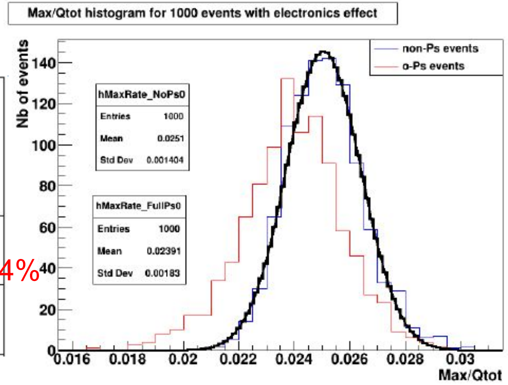

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Electronics simulation (1000 evts)	$(11.0 \pm 1.1)\%$	$(18.3 \pm 1.4)\%$

-60% -34%

Reduction of TTS through PMTs selection

The TTS is the main reason for the fall in the discrimination rate

↳ Selection of small PMTs and Hamamatsu PMTs which have the smallest TTS

Simulation 2 MeV (with time of flight reconstruction)	Qtail/Qtot method : 2.5% of non-Ps tolerance	Max/Qtot method : 2.5% of non-Ps tolerance
Electronics simulation (3000 evts)	$(9.0 \pm 0.6)\%$	$(18.2 \pm 0.8)\%$
Electronics simulation with small and Hamamatsu PMTs (3000 evts)	$(8.2 \pm 0.5)\%$	$(6.6 \pm 0.5)\%$

➢ The efficiency of discrimination of o-Ps events is dominated by the photo-electrons collection

Treatment and analysis of the photo-electron hit time distribution

Energy impact

Energy impact (optical simulation)

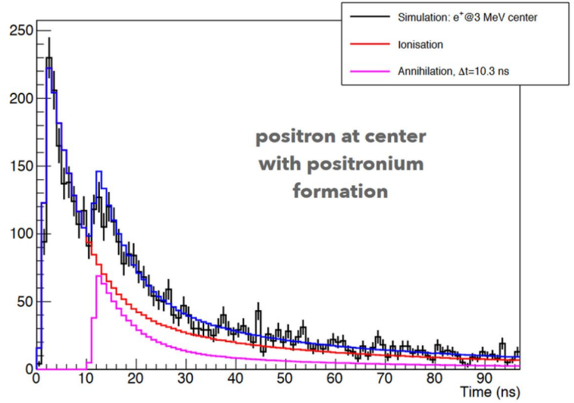
Comparing the different discrimination methods for different incoming energy (2MeV, 5MeV, 10MeV) corresponding to antineutrino energy from reactor source:

➔ There is a decrease in the discrimination rate due to the temporal distribution of photo-electron from ionisation

➔ We loose ~20% of the discrimination rate between 2MeV and 10MeV for the G4 with optical simulation

Optical simulation	Qtail/Qtot method : 2.5% of non-Ps tolerance	Max/Qtot method : 2.5% of non-Ps tolerance
2 MeV (3000 evts)	$(71.2 \pm 1.6)\%$	$(52.2 \pm 1.3)\%$
5 MeV (3000 evts)	$(61.8 \pm 1.4)\%$	$(48.0 \pm 1.3)\%$
10 MeV (1000 evts)	$(48.6 \pm 2.2)\%$	$(29.7 \pm 1.7)\%$

-20%



Energy impact (electronics simulation)

Applying the different methods after electronics simulation:

➔ Max/Qtot method remains better than the Qtail/Qtot method regardless of the positron incoming energy

➔ Max/Qtot start to be limited to form pure sample and those of Qtail/Qtot are much less so

Electronics simulation	Qtail/Qtot method : 2.5% of non-Ps tolerance	Max/Qtot method : 2.5% of non-Ps tolerance
2 MeV (3000 evts)	$(9.0 \pm 0.6)\%$	$(18.2 \pm 0.8)\%$
5 MeV (3000 evts)	$(9.3 \pm 0.6)\%$	$(14.0 \pm 0.7)\%$
10 MeV (1000 evts)	$(7.4 \pm 0.9)\%$	$(10.6 \pm 1.0)\%$

Results and discussion

Results

All the previous analysis enabled us to characterise the noise and see the limits of our discrimination methods :

- ➢ Simulation at the center of the detector

➔ What can we expect for JUNO experiment (2MeV, 5MeV):

- ➢ Simulation uniformly distributed in the sphere taking into account the time of flight computed with reconstructed vertices

Electronics simulation (uniform vertex distribution)	Qtail/Qtot method : 2.5% of non-Ps tolerance	Max/Qtot method : 2.5% of non-Ps tolerance
2 MeV (6000 evts)	$(10.4 \pm 0.4)\%$	$(15.7 \pm 0.5)\%$
5 MeV (6000 evts)	$(9.1 \pm 0.4)\%$	$(11.6 \pm 0.4)\%$

- ➢ Max/Qtot method remains the more efficient but does not allow to form a very pure sample

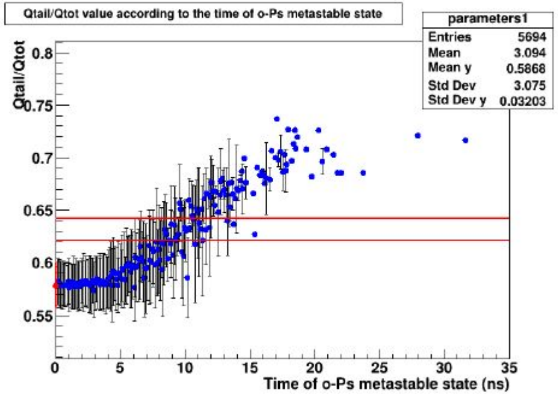
Results

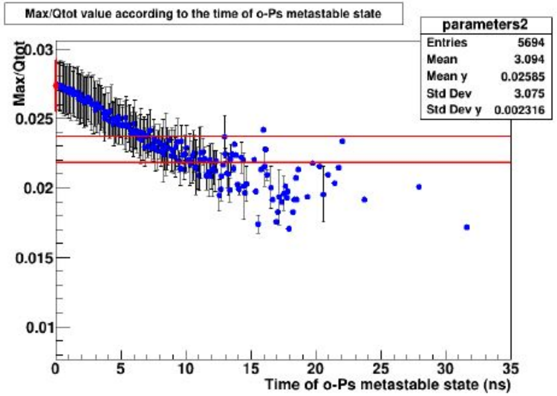
We wanted to characterise the most discriminating events:

➔ See the correlation between the Max/Qtot and Qtail/Qtot value in function of the annihilation delay time Δt of o-Ps events

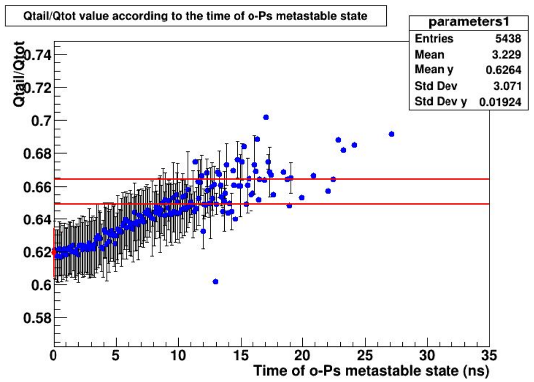
For 2MeV

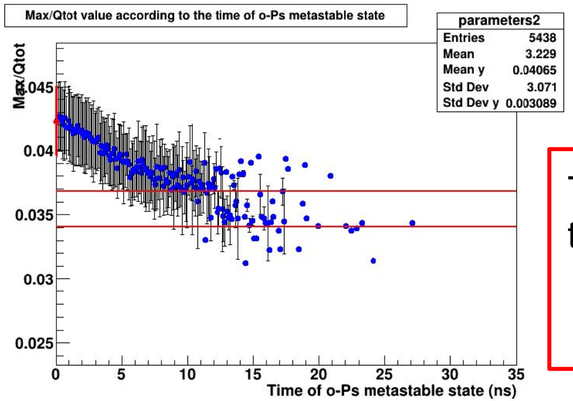
- All o-Ps events should have a $\Delta t \geq 7ns$ to be discriminated at 3σ for both methods
- All events with $\Delta t \geq 16ns$ will be discriminated by Qtail/Qtot at 3σ
- All events with $\Delta t \geq 23ns$ will be discriminated by Max/Qtot at 3σ





Results





For 5MeV

- All o-Ps events should have a $\Delta t \geq 9ns$ to be discriminated at 3σ for both methods
- It is difficult to know whether there is a Δt limit value above which all events are discriminated

The loss of discrimination rate between 2MeV and 5MeV corresponds to the number of o-Ps events with a Δt between 7ns and 9ns

➔ 48% of the o-Ps events with $\Delta t \geq 7ns$ is lost

Discussion

JUNO is expected to detect around 60 $\overline{\nu}_e$ /day from the reactors

- 50% of ortho-positronium
- Assuming they have energy of around 2MeV
- $\Delta t \geq 16ns$ to be discriminated at 3σ

A sample of 1000 events with an antineutrino purity greater than 94% would require more than 16 years

Conclusion

Conclusion

The objective of the internship was to study the background for the JUNO experiment:

- Focusing of the o-Ps metastable state we have been able to develop 2 discrimination methods to distinguish the background from the antineutrino signals
- These methods used for optical simulation first enabled us to understand the physics inside JUNO's liquid scintillator before seeing the impact of the electronics
- Analysis showed us that the formation of a pure sample of o-Ps by our methods depends mainly on the TTS of the PMTs
- A very pure sample of o-Ps events using our methods for the JUNO experiment is complicated (more than 16 year to form a sample of 1000 events with a purity of antineutrino higher than 94%)

Thanks for your attention

Main references

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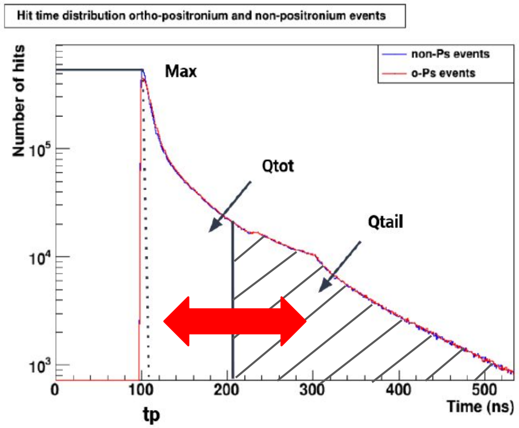
Annexe

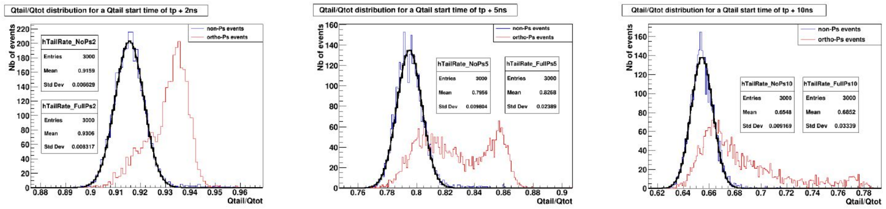
Qtail and Qtot windows optimisation

The rate of ortho-positronium discriminated out of the gaussian can be optimized :

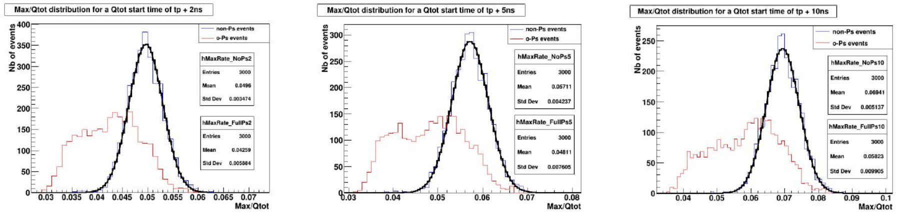
➔ For Qtail/Qtot : changing the starting time chosen for the Qtail integration window

➔ For Max/Qtot : changing the Qtot for a Qtail which digs differences of Max/Qtot





Qtail/Qtot



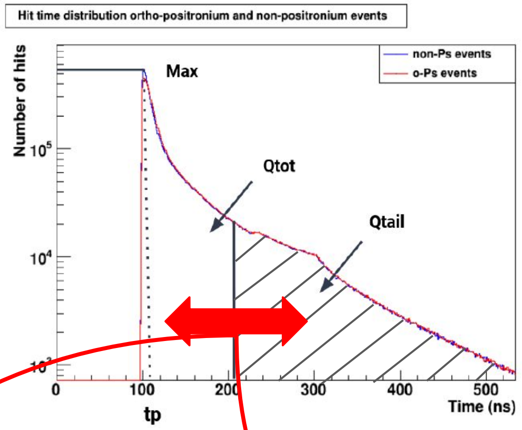
Max/Qtot

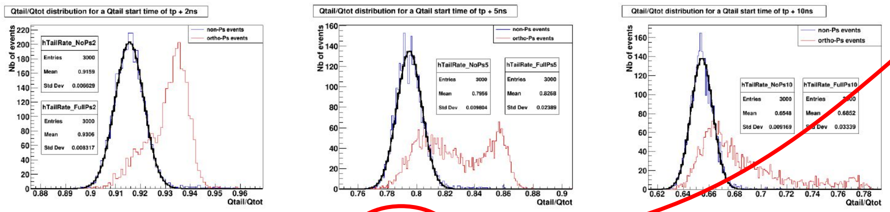
Qtail and Qtot windows optimisation

The rate of ortho-positronium discriminated out of the gaussian can be optimized :

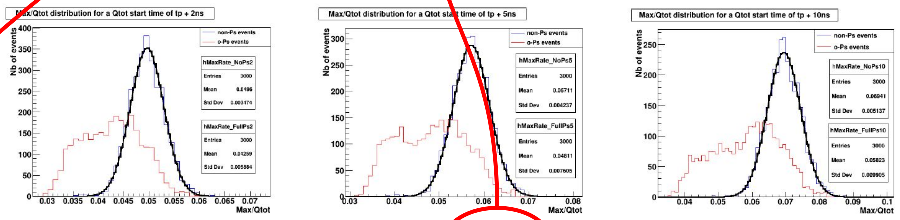
➔ For Qtail/Qtot : changing the starting time chosen for the Qtail integration window

➔ For Max/Qtot : changing the Qtot for a Qtail which digs differences of Max/Qtot





Qtail/Qtot



Max/Qtot

Qtail and Qtot windows optimisation

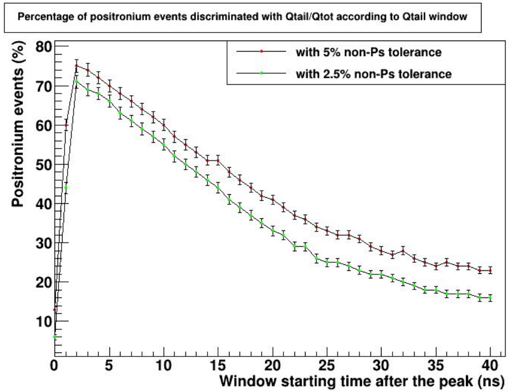
It is then possible to select the best integration windows according to the discriminated rate of o-Ps :

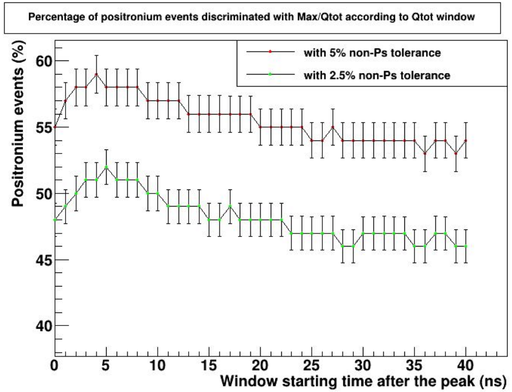
➔ Qtail/Qtot method : $t_p + 2ns$

➔ Max/Qtot method : $t_p + 5ns$

★ The discrimination efficiency is much better for the Qtail/Qtot method for simulation in a certain range

These windows optimisation only concern simulation at 2MeV, the same work need to be done if we change the incoming energy or if we add the electronics effects





Dark noise and Transit time spread effects

Comparing the different discrimination methods for events with full electronics simulation at the same energy (2MeV):

➔ There is a sharp decrease in the discrimination rate mainly due to the TTS effects

➔ The Max/Qtot method is more efficient than the Qtail/Qtot for electronics simulation

Simulation 2 MeV	Qtail/Qtot method : 2.5% of non-Ps tolerance	Max/Qtot method : 2.5% of non-Ps tolerance
Optical simulation (3000 evts)	$(71.2 \pm 1.6)\%$	$(52.2 \pm 1.3)\%$
Electronics simulation (1000 evts)	$(11.0 \pm 1.1)\%$	$(18.3 \pm 1.4)\%$
Electronics simulation without DN (1000 evts)	$(11.5 \pm 1.1)\%$	$(17.2 \pm 1.3)\%$