Searching for J/$\psi \rightarrow$ 3γ at BESIII

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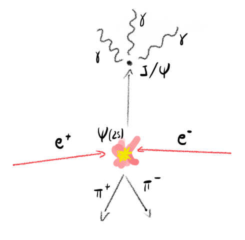
Decay Channel in Analysis

My Master's degree project concerns the search for the process:

$$J/\psi \;\to\; 3\gamma\,.$$



Setup

The study will use the **complete dataset of** $\Psi(3686)$ events. There are 3 dataset taken in 2009, 2012, and 2021. The data presented today are based on the Dataset Monte Carlo that reproduce **only the 2021 data**.

Present Measures

The previous measurements of the **branching fraction** $\mathbf{B}(J/\psi \to 3\gamma)$ are:

- CLEO Collaboration, 2008: $(1.2 \pm 0.3 \pm 0.2) \times 10^{-5}$
- BESIII, 2013: $(11.3 \pm 1.8 \pm 2.0) \times 10^{-6}$

The branching fraction theorized using **Lattice QCD** (2020) is:

- $(1.614 \pm 0.016 \pm 0.261) \times 10^{-5}$ with $a \simeq 0.085\,\text{fm}$;
- $(1.809 \pm 0.051 \pm 0.295) \times 10^{-5}$ with $a \simeq 0.067\,\text{fm}$;

where a is the lattice spacing used in the simulation.

Why do we study the process?

There are two main reasons why this analysis is interesting:

1. We have a much **larger dataset**; this means that the process can be measured with much higher precision; this is useful to build a complete picture of the decay of J/ψ. In particular, for the process $J/\psi \to 3\gamma$, we can try to verify the **NRQCD** predictions with higher precision but also confirm the latter **lattice QCD** calculations.
2. Since the energy region we explore coincides with where **glueballs** are predicted to exist, our analysis can therefore help narrow down the phase space where glueball contributions might still be hiding.

Decay Channel in Analysis

In particular the process is studied in the $\Psi(2S)$ production through the channel:

$$\Psi(2S) \;\rightarrow\; \pi^+\pi^- J/\psi;$$

$$J/\psi \;\rightarrow\; \gamma\gamma\gamma$$

It is helpful to use this decay chain because we are able to tag the whole process thanks to the signal given by the two charged tracks, to identify a J/ψ event via the recoiling mass of the $\pi^+\pi^-$ system.

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Recognition of the J/ψ events.

The first step of the analysis is to recognize the J/ψ events through the recoil of $\pi^+\pi^-$.

Making a fit the J/ψ mass using the $\pi^+\pi^-$ tracks we are able to impose a cut to the combined mass:

$$3.092\,\mathrm{GeV}/c^2 \leq \mathrm{m}_{\pi\pi} \leq 3.101\,\mathrm{GeV}/c^2$$

.

Fit of $\pi^+\pi^-$ over the J/ψ mass

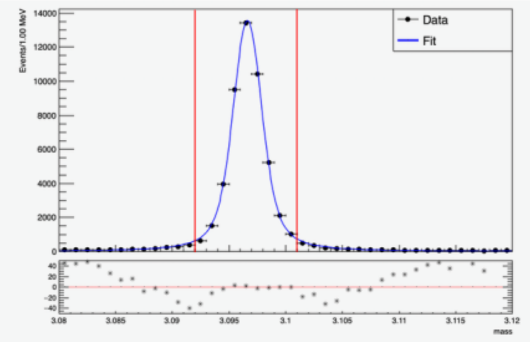

Figure 1: Fit of the $\Psi(2S)$ using the $\pi^+\pi^-$ mass.

Doing so we could select the best pion candidates for the J/ψ mass reconstruction.

$\gamma\gamma\gamma$ events selection

Once selected the good J/ψ events the analysis shifted to the more challenging **recognition of pure** 3γ **events**. This is the **principal goal** of the analysis and it is still a work in progress.

The first selection of γ's is composed by some **fiducial cuts** that are typical to gamma signals. In our case we saved only the events that presented **at least three good candidates**.

Kalman Fit of γ signals

The selection of the neutral particles that best reproduce the J/ψ is done using a **Kalman Fit**.

For each event we try to find the best triplet of γ candidates that, added to the two π selected , better fit the center of mass of $\Psi(3686)$.

It is interesting to notice that the only constraint is the $\Psi(2S)$ mass and not the J/ψ one; this had been originally done but resulted in forcing backgrounds signals in the fit of the J/ψ.

The Kalman fit produced a cut based of the χ^2, each event is considered good if:

$$\chi^2 \leq 45 \ \wedge \ \chi^2 \neq 0 \, .$$

Kalman Fit optimization

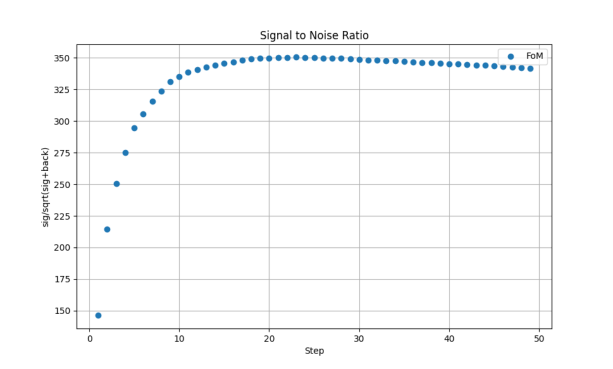

Figure 2: The optimization of this cut had been done by maximizing the significance $S/\sqrt{S+B}$. In this graphic each step correspond to 2 unit of χ^2.

Intermediate Particles Events Rejection

The principal problem of this type of process is the presence of many **intermediate events** that can produce 3 γ's. Two essential tools that can be used to discriminates this events are: **Topology studies** and **Dalitz Plots**

Topology

This is a technique typical of the Monte Carlo simulations where, knowing what we are simulating, we can reveal the decay channels remaining after some cuts. Using the topology we can give a direction to the analysis and understand when the selection is sufficiently good and try to use the real dataset.

Topology table

rowNo	decay tree (decay initial-final states)	iDcyTr	nEtr	nCEtr
1	$\psi' \rightarrow \pi^+\pi^- J/\psi, J/\psi \rightarrow \eta\gamma, \eta \rightarrow \gamma\gamma$ $(\psi' \dashrightarrow \pi^+\pi^-\gamma\gamma\gamma)$	0	7419	7419
2	$\psi' \rightarrow \pi^+\pi^- J/\psi, J/\psi \rightarrow \eta'\gamma, \eta' \rightarrow \gamma\gamma$ $(\psi' \dashrightarrow \pi^+\pi^-\gamma\gamma\gamma)$	3	1865	9284
3	$\psi' \rightarrow \pi^+\pi^- J/\psi, J/\psi \rightarrow \pi^0\gamma$ $(\psi' \dashrightarrow \pi^0\pi^+\pi^-\gamma)$	5	678	9962
4	$\psi' \rightarrow \pi^+\pi^- J/\psi, J/\psi \rightarrow \pi^0\pi^0\gamma$ $(\psi' \dashrightarrow \pi^0\pi^0\pi^+\pi^-\gamma)$	1	575	10537
5	$\psi' \rightarrow \pi^+\pi^- J/\psi, J/\psi \rightarrow f_4(2050)\gamma, f_4(2050) \rightarrow \pi^0\pi^0$ $(\psi' \dashrightarrow \pi^0\pi^0\pi^+\pi^-\gamma)$	2	358	10895
6	$\psi' \rightarrow \pi^+\pi^- J/\psi, J/\psi \rightarrow f_2(1270)\gamma, f_2(1270) \rightarrow \pi^0\pi^0$ $(\psi' \dashrightarrow \pi^0\pi^0\pi^+\pi^-\gamma)$	7	204	11099
7	$\psi' \rightarrow \pi^+\pi^- J/\psi, J/\psi \rightarrow \gamma\gamma\gamma$ $(\psi' \dashrightarrow \pi^+\pi^-\gamma\gamma\gamma)$	4	181	11280
8	$\psi' \rightarrow \pi^+\pi^- J/\psi, J/\psi \rightarrow f_0(1710)\gamma, f_0(1710) \rightarrow \pi^0\pi^0$ $(\psi' \dashrightarrow \pi^0\pi^0\pi^+\pi^-\gamma)$	8	120	11400
9	$\psi' \rightarrow \pi^+\pi^- J/\psi, J/\psi \rightarrow f_0'\gamma, f_0' \rightarrow \gamma\gamma$ $(\psi' \dashrightarrow \pi^+\pi^-\gamma\gamma\gamma)$	6	58	11458

Figure 3: Table of topology showing the 9 channels with higher count. The dataset used is the Inclusive Monte Carlo one after the Kalman selection.

Dalitz plot of Signal vs Inclusive MC

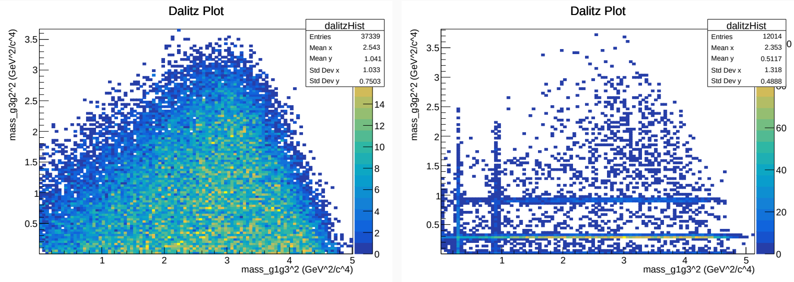

Figure 4: Here you can see a comparison of the Dalitz Plots of the combined mass $\gamma_1\gamma_3$ vs $\gamma_2\gamma_3$. On the left you can see a **pure signal** of 3γ while on the right we have the **inclusive Monte Carlo**; both are produced with a cut dataset (fiducial cuts + Kalman Fit).

Fit of resonances

From both the Topology and the Dalitz plot we see clearly that are present various **resonances**, the first three in number (η, η' and π^0) are also the easiest to cut out.

To do so we did a **fit** of the masses obtainable combining $\gamma\gamma$ and we fitted them over the mass of the three particles using a **sum of a Breit-Wigner and a Crystal ball**.

Fit of Backgrounds

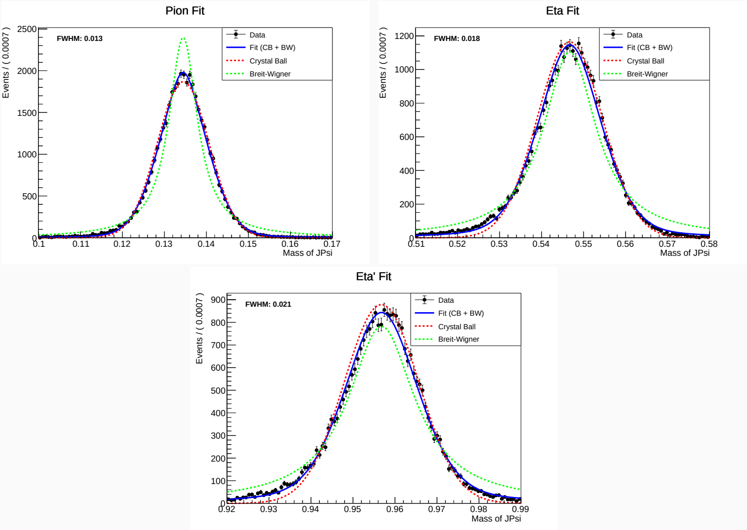

Figure 5: Data from an MC of each signal

Optimization of phase space cut

Found the FWHM of each fit, we used it to impose a cut, optimized using the significance. The cuts fixed are:

- Resonance η:
$$0.5103\,\mathrm{GeV}/c^2 \;\leq\; \mathrm{mass}_{\gamma\gamma} \;\leq\; 0.5854\,\mathrm{GeV}/c^2;$$
- Resonance η':
$$0.9277\,\mathrm{GeV}/c^2 \;\leq\; \mathrm{mass}_{\gamma\gamma} \;\leq\; 0.9878\,\mathrm{GeV}/c^2;$$
- Resonance π^0:
$$0.1149\,\mathrm{GeV}/c^2 \;\leq\; \mathrm{mass}_{\gamma\gamma} \;\leq\; 0.1550\,\mathrm{GeV}/c^2.$$

Kalman fit of many γ events
To reduce the presence of multiple π^0, we decided to include an additional Kalman fit made only when we have more than 3γ, and rejected each event that contained a fitted combined mass $\gamma\gamma$ inside the π^0 mass interval.

Resume of Cuts

Here you can see the number of events saved after each cut:

Cut	Counts
Total Events Analyzed	$2.30 \cdot 10^9$
Fiducial cuts for charged tracks	$2.15 \cdot 10^9$
At least 3 good γ tracks	$1.64 \cdot 10^9$
Good Charged Tracks	$6.35 \cdot 10^8$
Vertex Fit	$6.34 \cdot 10^8$
J/ψ Events as $\pi^+\pi^-$ recoil	$3.99 \cdot 10^7$
Kalman Fit with 3γ tracks	$7.66 \cdot 10^4$
Resonances Cut	$1.30 \cdot 10^4$
Kalman fit of pions	$1.12 \cdot 10^4$

Resume of Cuts: Efficiency

Cut	Efficiency
Total Events Analyzed	100,00%
Fiducial cuts for charged tracks	72,12%
At least 3 good γ tracks	48,20%
Good Charged Tracks	18,48%
Vertex Fit	18,45%
J/ψ Events as $\pi^+\pi^-$ recoil	15,95%
Kalman Fit with 3γ tracks	12,89%
Resonances Cut	11,31%
Kalman fit of pions	11,25%

Table 1: Here is shown the efficiency of each cut over a sample of 300000 events of signal simulated.

Backgrounds still to remove

The backgrounds still present at this point are: f_0, f_2, f_4 and $\pi^0\pi^0$, with the last one being the more present.

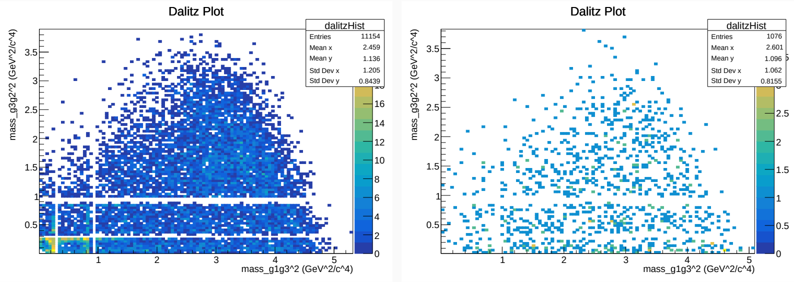

Figure 6: On the left, the Dalitz plot of the Inclusive MC after the cuts, on the right, the one for the $\pi^0\pi^0$ background.

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Kalman Fit

We tried also another way of cutting the dataset, trying to use Kalman to **fit also the resonances**. In this way we thought that could be possible to avoid to cut out of the analysis entire sectors of the Phase Space. This method produced a **worse result** than the cut based one.

rowNo	decay tree (decay initial-final states)	iDcyTr	nEtr	nCEtr
1	$\psi' \rightarrow \pi^+\pi^- J/\psi, J/\psi \rightarrow \pi^0\pi^0\gamma$ $(\psi' \dashrightarrow \pi^0\pi^0\pi^+\pi^-\gamma)$	0	223	223
2	$\psi' \rightarrow \pi^+\pi^- J/\psi, J/\psi \rightarrow f_4(2050)\gamma, f_4(2050) \rightarrow \pi^0\pi^0$ $(\psi' \dashrightarrow \pi^0\pi^0\pi^+\pi^-\gamma)$	1	141	364
3	$\psi' \rightarrow \pi^+\pi^- J/\psi, J/\psi \rightarrow \gamma\gamma\gamma$ $(\psi' \dashrightarrow \pi^+\pi^-\gamma\gamma\gamma)$	2	80	444
4	$\psi' \rightarrow \pi^+\pi^- J/\psi, J/\psi \rightarrow \eta\gamma, \eta \rightarrow \gamma\gamma$ $(\psi' \dashrightarrow \pi^+\pi^-\gamma\gamma\gamma)$	6	73	517

rowNo	decay tree (decay initial-final states)	iDcyTr	nEtr	nCEtr
1	$\psi' \rightarrow \pi^+\pi^- J/\psi, J/\psi \rightarrow \pi^0\pi^0\gamma$ $(\psi' \dashrightarrow \pi^0\pi^0\pi^+\pi^-\gamma)$	0	563	563
2	$\psi' \rightarrow \pi^+\pi^- J/\psi, J/\psi \rightarrow f_4(2050)\gamma, f_4(2050) \rightarrow \pi^0\pi^0$ $(\psi' \dashrightarrow \pi^0\pi^0\pi^+\pi^-\gamma)$	1	352	915
3	$\psi' \rightarrow \pi^+\pi^- J/\psi, J/\psi \rightarrow f_2(1270)\gamma, f_2(1270) \rightarrow \pi^0\pi^0$ $(\psi' \dashrightarrow \pi^0\pi^0\pi^+\pi^-\gamma)$	6	238	1153
4	$\psi' \rightarrow \pi^+\pi^- J/\psi, J/\psi \rightarrow \gamma\gamma\gamma$ $(\psi' \dashrightarrow \pi^+\pi^-\gamma\gamma\gamma)$	3	161	1314

Figure 7: On the left we have the fit based topology, on the right we have the cut based one. As we can see the signal count in the fit version is halved wrt the cut version.

Kalman Fit of missing Tracks

Since the most difficult background to reject is the $\pi^0\pi^0\gamma$ one; we tried to reject it using the an option of the Kalman fit that is the AddMissTrack() function of Kalman Fit.

In such a way we wanted to test the possibility to have a t least **one missing photon** per π^0, due to the low energy of γ's coming from the decay of a π^0.

This method was also discarded because it produced empty dataset with no good data.

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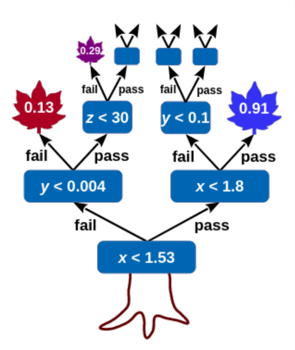
The Solution: Boosted Decision Trees

We are now trying to implement a **Boosted Decision Tree (BDT)** in the analysis in order to discriminate the Background events from the signal ones.

BDT is a **machine learning method**, included in the TMVA class of ROOT, and is based on the concept of Decision Trees

Decision Tree
A decision tree is an algorithm that, using multiple variables, start by imposing a condition on one variable (e.g.: a rectangular cut over the energy), and verify if that condition bring to an improvement of the dataset, each branch than split into a secondary decision, that can be over the same or over another variable and so on until an objective is reached.



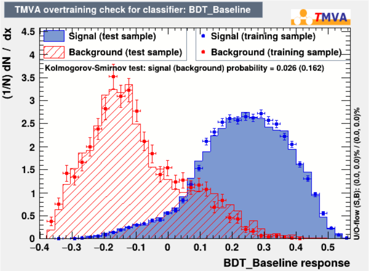
Boosting

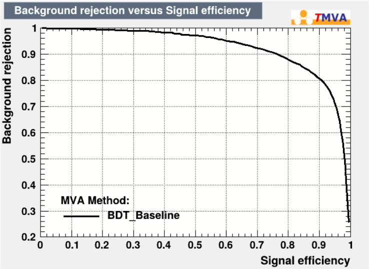
The BDT take the concept of decision trees but **iterates** it by creating a **forest** of many small trees (which stops already at the third/forth branch). In such a way it is possible to evaluate many different picture of the same condition.

The **boosting** is given by the fact that, in the training phase, we give **different weights** to the trees based on how well that specific tree divide our dataset. In such a way we create a pattern that can then be applied to the dataset to separate background and signal

BDT Application

Right now we are working on the application of BDT. To do it we retrieved an MC dataset for each of the backgrounds still present in the dataset ($f_0\gamma$, $f_2\gamma$, $f_4\gamma$, and $\pi^0\pi^0\gamma$) and gave them as base background of the BDT.





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Future Goals

- Surely the analysis is still in progress, so the main focus is to obtain a sharp separation of the Decay channel in analysis, using the complete dataset.
- The future step would be then to use what we've learned in this analysis as a basis to study the decay channel:

$$J/\psi \;\to\; \gamma\gamma\gamma\,,$$

  using the same dataset.
  This is more challenging to do due to the absence of strong tagging given by the $\pi^+\pi^-$, so the hope is that the TMVA methods (and in particular the BDT) will be useful.

Thank you

BACKUP: Fiducial Cuts

Here are reported the cut on γs:

- Barrel cuts:

$$\text{rejected if: } |\cos(\theta)| < 0.80 \;\wedge\; \mathrm{E}_\gamma \leq 0.025\,\mathrm{GeV}$$

- Endcaps cuts:

$$\text{rejected if: } 0.86 < |\cos(\theta)| < 0.92 \;\wedge\; \mathrm{E}_\gamma \leq 0.05\,\mathrm{GeV}$$

- Timing cut:

$$0\,\mathrm{ns} \leq t \leq 700\,\mathrm{ns}$$

BACKUP: Branching fractions of intermediate Processes

The branching fractions for each intermediate decay involved are:

- Br($J/\psi \to \eta'\gamma$)= (5.13 $\pm$ 0.17) $\times$ 10^{-3}
- Br($J/\psi \to \eta\gamma$)= (1.104 $\pm$ 0.034) $\times$ 10^{-3}
- Br($J/\psi \to \pi\gamma$)= (3.49 + 0.33 - 0.30) $\times$ 10^{-5}
- Br($J/\psi \to \pi\pi\gamma$)= (1.15 $\pm$ 0.05) $\times$ 10^{-3}
- Br($J/\psi \to f_0\gamma \to \pi\pi\gamma$)= (3.8 $\pm$ 0.5) $\times$ 10^{-4}
- Br($J/\psi \to f_2\gamma \to \pi\pi\gamma$)= (1.64 $\pm$ 0.12) $\times$ 10^{-3}
- Br($J/\psi \to f_4\gamma \to \pi\pi\gamma$)= (2.7 $\pm$ 0.7) $\times$ 10^{-3}

BACKUP: fs Dalitz Plots

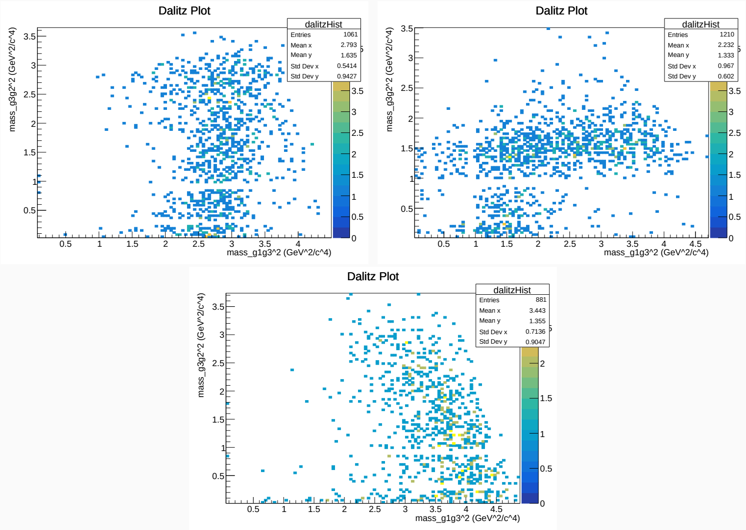

Figure 8: Dalitz plot respectively of f_0, f_2, f_4.