DoE-INFN Summer Student exchange program report

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Contents

1 Introduction to project

INFN-SLAC student exchange program offered the opportunity for 3 Italian students to work on 3 running projects.
The project I am involved in is finalized to the search of a Dark Matter (DM) particle; in particular the analysis aims to a leptophilic Dark Scalar (DS, or φ) with a mass less than the one needed for decaying into 2 muons.
The analysis will be operated over all 6 runs of BaBar experiment during which electrons and positrons have collided; total amount of such kind of events is about $9.1 \cdot 10^9$.

In this project I've been working together with Brian Shuve and Bertrand Echenard, my two tutors.

2 Quick theoretical overview abot reasons for this search

2.1 Brief view about Dark Matter

We know DM exists basically due to its gravitational effects, one for all the rotation velocity of the galaxies, that is different from what we could expect from evaluations based only on visible matter.

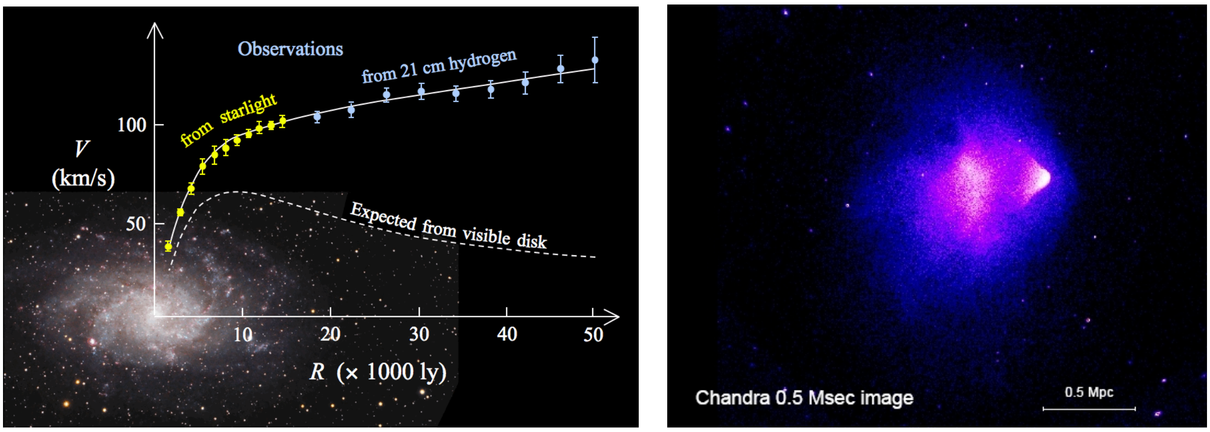

Figure 1: Examples of evidences of the presence of DM; on the left we have a graph plotting foreseen and measured galaxy rotation velocity, on the right we have an image of the Bullet Cluster, whose mass distribution, inferred via the effect of gravitational lens, should be highly different if DM didn't exist.

A lot of models arose in order to explain this except-than-gravitationally invisible matter, for example as due to sterile neutrinos, one WIMP or a lot of other; the one we are interested in is the Dark Sector one (Figure 2).
For Dark Sector we basically mean a sort of dark brother of the Standard Model, so a new group of Dark Particle interacting with each other but not with us (where "us" here means ordinary matter), expect for a couple of so-called Portal Particle that interact not only with DM but with ordinary one too.

A Dark Photon, so a spin 1 Portal Particle has yet been searched at BaBar, while there were no running analysis aiming to a Dark Scalar. Now there are!

2.2 Muon's magnetic moment discrepancy

Before continuing and looking at the investigated physic process we should take into account the possibility for this particle φ for being responsible for the muon's magnetic moment (g_μ) discrepancy between calculus from QED and experimental results: these two values are not negligibly different (order of 4 σ difference), and this difference could be explained if another particle contributed to the loops.
φ is being considered a possible candidate for this explanation, even if in recent times people are turning less optimistic about this possibility, due to excluding plots growing in excluded zone's vastness.

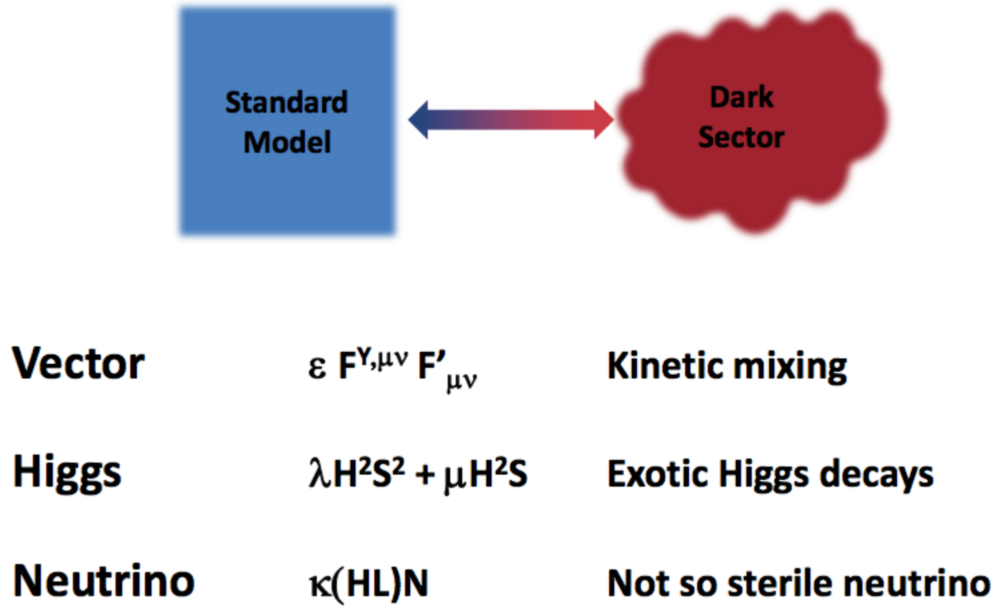

Figure 2: Scheme and examples about Dark Sectors model and Portal Particle.

3 Investigated physic process

Here we go into the details of the searched process.

As said we are searching for a leptophilic Dark Scalar, so that means a spin 0 particle, so with an Higgs-like coupling, that interacts only with leptons. An Higgs-like coupling means that the particle φ interacts more with heavier particle.
Putting these information together it straightforwardly follows that our φ prefers interacting with τ.
If we put no constraint, that would means that φ is mainly produced by "irradiation" by τ and that it mainly decays into $\tau^+\tau^-$, but having assumed a limit on its mass these last assertion is no more true.

We have put a limit on its mass because another analysis is being currently conduced in order to search (or exclude, of course) a φ with a mass between the one of 2 τ and the one of 2 μ (φ with mass so high to allow decay into 2 τ have yet been excluded by other experiments).

This means that we have imposed the following condition:

$$M_\varphi \leq 211\text{MeV} \tag{1}$$

Since φ is leptophilic the decay mode will be:

$$\varphi \to e^+e^- \tag{2}$$

On the other hand the production has no constraints of this kind, so it happens through τ.

Combining these two observation we can assume the following process for being the most frequent:

$$\tau \to \tau\varphi \to \tau e^+e^- \tag{3}$$

This process is depicted in Figure 3.

We first of all could ask ourselves *how more frequent* is with the respect to, for example, the irradiation via muons.
The answer comes from the behavior of the Higgs-like interaction, with a coupling proportional to the mass squared:

$$\frac{\Gamma(\tau \to \varphi)}{\Gamma(\mu \to \varphi)} \sim \frac{M_\tau^2}{M_\mu^2} \sim 300 \tag{4}$$

So production associated with τ is about 300 times more frequent than production via μ.

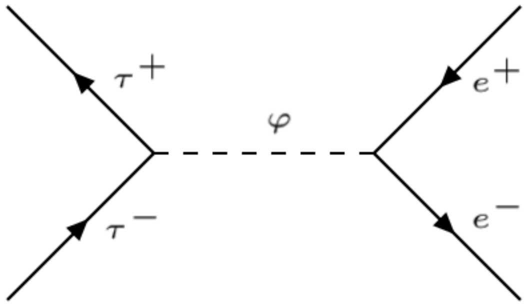

Figure 3: Most frequent production channel and unique possible decay channel for a leptophilic DS with a mass lower than 211 MeV.

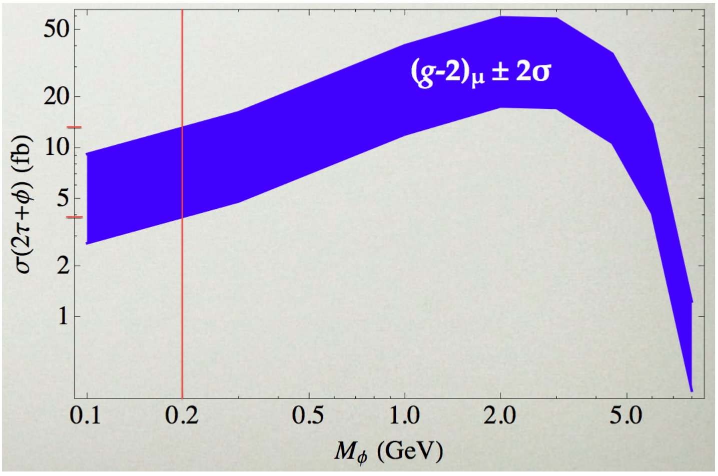

Figure 4: Expected cross section for the process of irradiation of the φ via τ, as a function of the mass of the φ. We are interested in the region on the left of the red vertical line, so mass belows 211 MeV.

Another very reasonable question we can ask is the order of magnitude of the cross section of this process. From theoretical models we can foresee the possible cross section for φ production if we assume φ being responsible for g_μ discrepancy, as we can see in Figure 4.

The expected cross section for this process, under the explained conditions, is something of the order of:

$$\sigma \sim 3 \div 12 \text{ fb} \tag{5}$$

Given the M_φ we are investigating, so less than 200 MeV, and the total integrated luminosity of BaBar:

$$\mathcal{L} = 514 \text{ fb}^{-1} \tag{6}$$

we can infer the expected number of produced φ, that being:

$$\#\varphi \sim 10^{3\div4} \tag{7}$$

This number is such that we can hope to save, after all the cuts that we need in order to reduce background (bkg), a number of events enough to have a statistically significant result.

We asked ourselves *if* we can see something and *how much* we can see, so in some manner we should question ourselves about *what* we can see, or in other word, what we will be able to exclude or see.
In order to do so let's take a look at the exclusion plots (Figure 5).

Looking in particular at the second one we can see the BaBar sensitivity region in blue, the region yet excluded by another experiment (E137) as brown, the region where φ could explain the g_μ discrepancy in green while the red one is where it cannot.
Since there is a relation between mass and coupling constant (vertical axis, express with the respect to Higgs

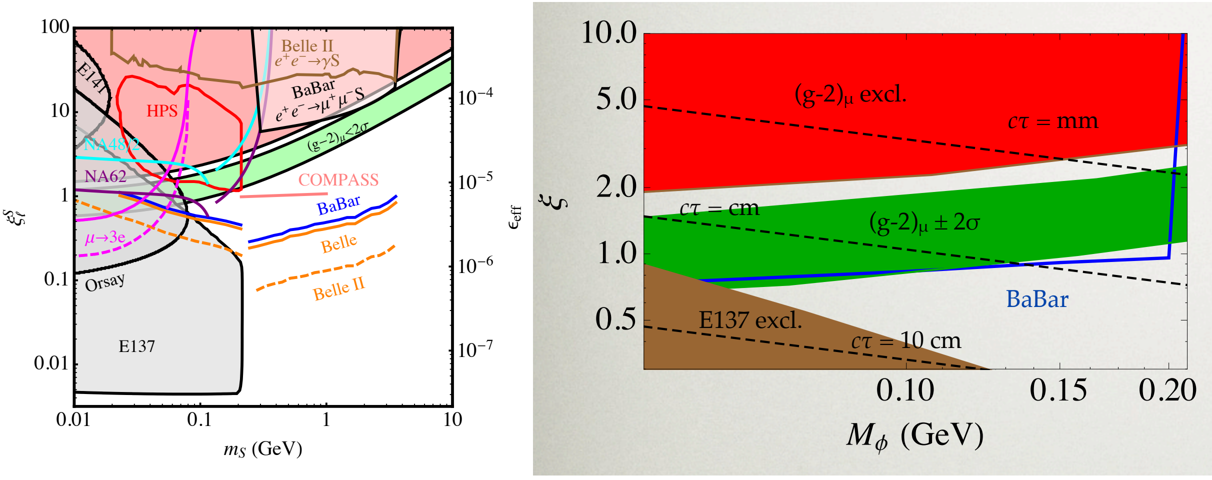

Figure 5: Left: exclusion plot with BaBar foreseen sensitivity region. Right: exclusion plot with lifetimes; we are interested in the mm ÷ cm range.

coupling) giving the lifetime of the particle, we can find some lines at constant lifetime, the black dashed ones.
From the graph we can see we are interested in the mm ÷ cm range; also the mass has some inferior limits, so searching far below 50 MeV would result in a pretty pointless effort.

4 BaBar

BaBar was an experiment taking place at SLAC; it recorded data from 1999 to 2008.

4.1 Structure and characteristic of BaBar

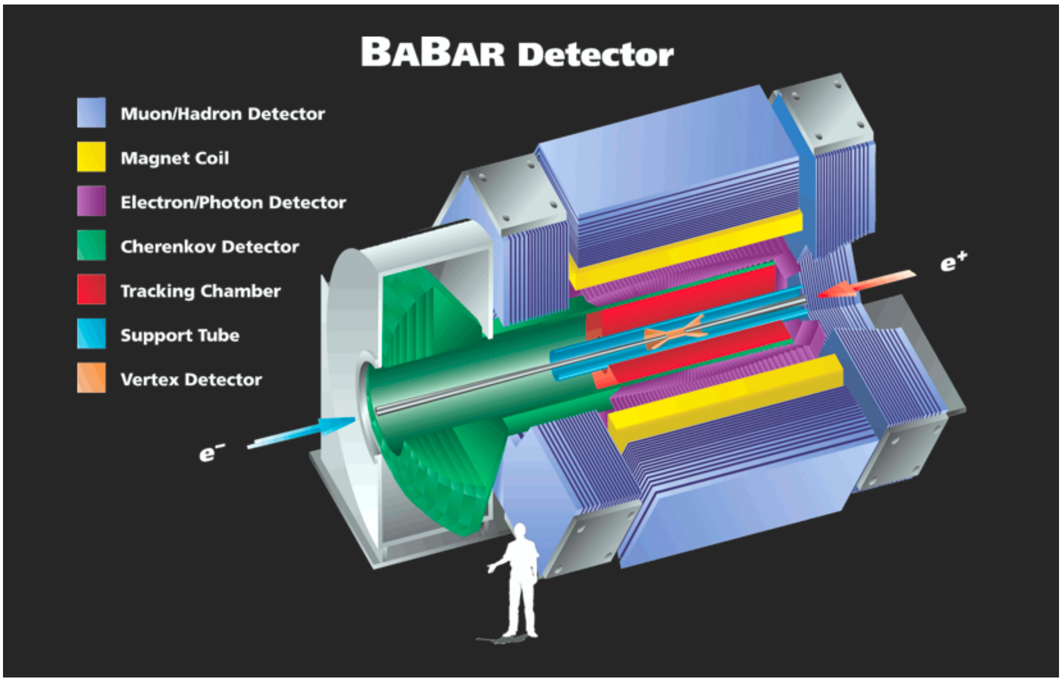

Figure 6: BaBar detector.

BaBar experiment, throughout a period of 9 years, produced about $9.1 \cdot 10^9$ e^+e^- collisions.
Electronic beam is 9 GeV while the positronic beam is 3.1 GeV.
This results in a Center of Mass (CM) frame in motion with the respect to the laboratory (lab) frame. The

energy available in the CM is 10.58 GeV, just enough to produce a $\Upsilon(4S)$, whose decay study was one of the purposes of BaBar.
BaBar received beams from the Linac, the longest linear accelerator in the world.

BaBar detector was built with the usual concentric structure of detector, as can be seen in Figure 6. Referring indeed to Figure 6, starting from the center, we find the following detectors:

- Vertex Detector
- Tracking Chamber
- Cherenkov Detector
- Electromagnetic Calorimeter
- Muon Chamber and Hadronic Calorimeter

4.1.1 Vertex Detector

The vertex detector is optimized to reconstruct trajectories close to the origin (alias interaction point). Its main constituents are 340 silicon detectors that allow a 0.1 mm spatial resolution.

4.1.2 Tracking Chamber

The tracking chamber is a drifting chamber made up with a total of about 30000 wires, finalized to the reconstruction of the tracks of charged particles. It allows a resolution of 1 mm.

4.1.3 Cherenkov Detector

Cherenkov detector is basically a big container of purified water that allows Cherenkov radiation, which is collected, via a system of mirrors, in the left part of the detector (where "left" refers to the above-mentioned Figure 6). This part of the detector has not been simulated in our Monte Carlo (MC).

4.1.4 Electromagnetic Calorimeter

Electromagnetic calorimeter is constituted of 6600 CsI crystals, for energy absorption and light guiding, and 13200 photodiodes.

4.1.5 Muon Chamber and Hadronic Calorimeter

Also known as IFR (Instrumented Flux Returner), this part of the detector is basically nothing more that the iron of the flux returner, here used to make muons and hadrons interact, with some added scintillators et similia in order to collect the shower energy. This part of the detector has been barely used in the simulation.

4.2 Why using BaBar?

BaBar has the two main characteristics useful to discover new particles: a high integrated luminosity and being an electron-positron collider.

The first feature is self-explaining: high statistic is of course required to claim a discover (or to widen the excluded zone).

For what concern the nature of the collider, having an e^+e^- collider instead of a hadron one means that:

- We know what particle have interacted, so basically we know we have the equivalent quantum state of the vacuum, differently from a hadron collider where we just know the PDF of the various partons that could have taken part at the interaction;
- We know the momentum of the colliding electrons since we know their energy; in a hadron collider the momentum of the partons is just an unknown fraction of the total momentum of the colliding hadron;

- There's no pile-up: in BaBar there is less than a collision for crossing, while in LHC there can be tens of interaction at any bunch crossing (after all in the hadronic case what is in play is strong interaction versus the weak and electromagnetic interaction ruling e^+e^- annihilation);

- Running at lower energy than, for example, LHC implies that there are less decay products since there are less quark that can get "dressed".

These points together means that e^+e^- colliders provide far cleaner environment, so a better place where to notice something new.

Together with BaBar, Belle too is a good candidate for a search of this kind.

4.3 Expected process and final states

Now we can combine the reasonings that have led us to draw Figure 3 with the fact that BaBar is an e^+e^- collider, in order to obtain the key process we are interested in, depicted in Figure 7.

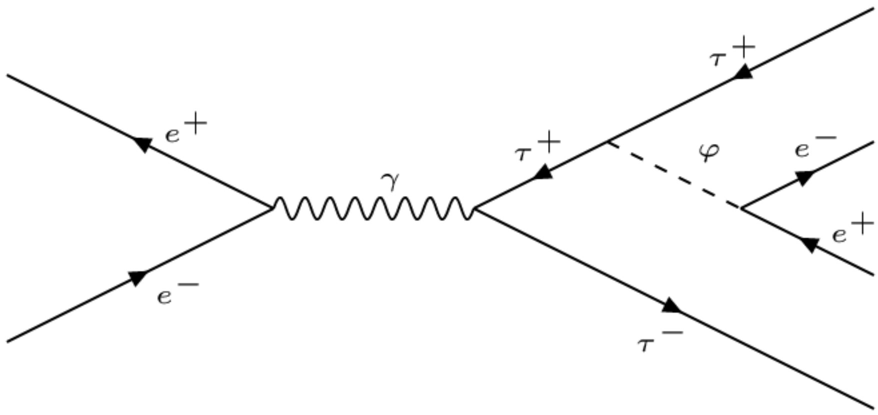

Figure 7: Most frequent searched event in BaBar.

Now we can add the decay of the τ[1] to the previous diagram and obtaining, for example, the overall process drawn in Figure 8.

From the Figure 8 we can deduce the following typical features of the searched signal:

- For conservation of leptonic flavor each τ has to decay into at least 1 ν, so that implies the presence of at least 2 neutrinos, so a not-negligible amount of missing (transverse) momentum;

- For conservation of electric charge each τ has to decay into at least 1 charged track (from here and following, "tracks" would generally means "charged track");

- φ decays into e^+e^-, so in the final state there will be at least 1 electron and 1 positron.

The 2 or more tracks from tauonic decay add to the 2 tracks from φ decay for a total of 4 or more tracks; for now (October 2016) we have limited our search at just 1-prong τ decay, so in the cases where τ decays into just 1 track, that corresponds to about 85% of decay of the τ.
So, summarizing, the key characteristics of the process are:

- 2 electrons;

- 4 tracks;

- Missing momentum.

I'll talk in more detail about the signal features in the following chapters, when discussing cuts.

[1] tauons decay inside the detector: we can assume, rounding up, an energy of 10 GeV for a mass of, round down, 1 GeV, so obtaining a relativistic γ for the τ no greater than 10. Given a lifetime of $\sim 100\ \mu$m, we obtain that in average tauons fly less than 1 mm before decaying, and since the vertex detector is about half a meter wide that means that every τ decays inside the detector.

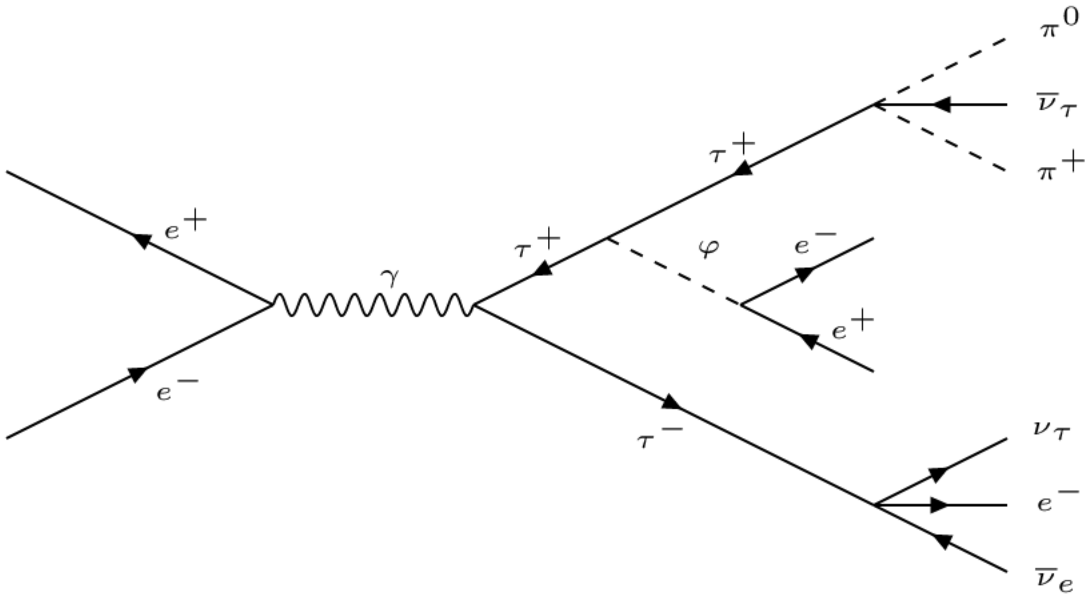

Figure 8: Example of complete process searched in BaBar.

5 Simulation and reconstruction of φ

5.1 Simulation

As mentioned above there are some constrains about φ, in particular mass and lifetime, that are the free parameters of this model.

5.1.1 φ mass

φ mass is limited between 211 MeV and $\sim$ 50 MeV. The lower limit is partially due to other experiments, as said, and partially for other experimental reasons that will be explained in the end.

Until now we have generated ntuples with M_φ of 100 MeV and 200 MeV but we have concentrated our analysis on the second one.

$$M_\varphi = 200 \text{ MeV} \tag{8}$$

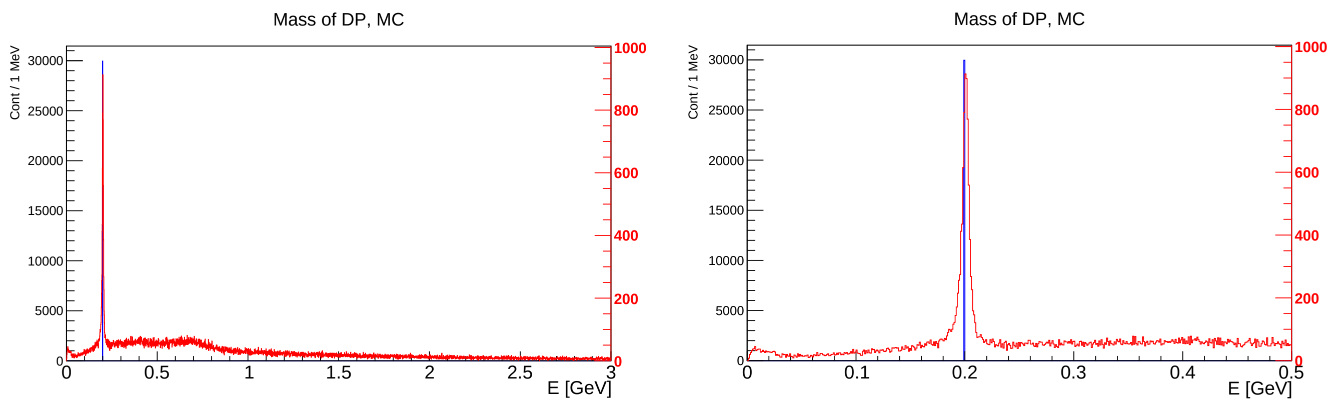

Figure 9: φ MC and reconstructed mass. Tail is due to combinatoric noise. Brem-recovery used. On the right there is a zoom.

5.1.2 φ lifetime

Lifetime, that can be express in terms of $c\tau$, as said has to be in the mm $\div$ cm range, approximately.
For now we have generated ntuples with φ with lifetimes of: 0.0001 mm, 0.1 mm, 1 mm, 10 mm, 100 mm, 1000 mm.

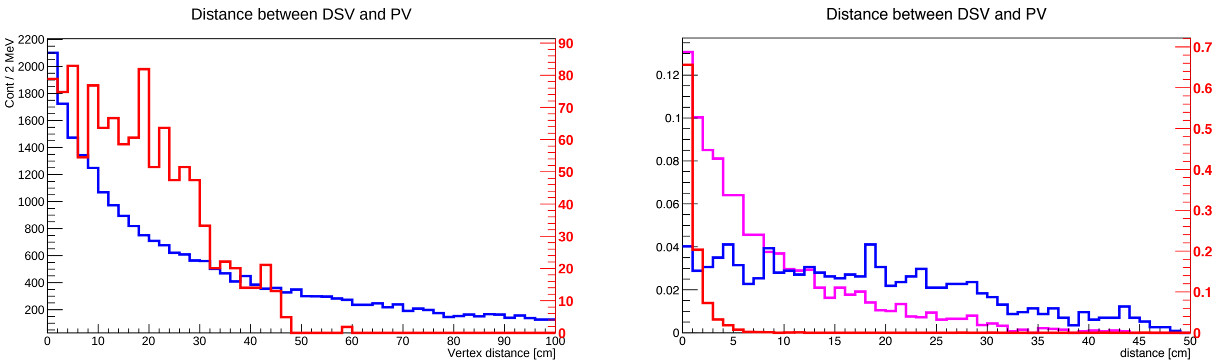

Figure 10: Transverse φ flight length. Left: comparison between MC and reconstruction ($c\tau = 100$ mm); the vast difference is due to the fact that detector is not infinite, so after about half a meter the reconstruction became practically impossible. Right: comparison amongst different lifetime, reconstruction (red: 1 mm, magenta: 10 mm, blue: 100 mm); note the different scale in respect with before, in particular the blue line on the right is the same graph of the red line on the left; vertical axis here represents fraction of the total.

5.2 Reconstruction

φ is reconstructed as any couple of tracks with opposite charge. This way of reconstruct it of course generate a lot of combinatoric noise that will be eliminated later through some quality requirement. Its decay vertex is called Secondary Vertex (or "Dark Scalar Vertex", DSV) and is obtained through a fit.

Here and on I'm calling "Υ" or "Upsilon" or "Upsi" or "PV" the Primary Vertex.
PV was initially reconstructed as the combination of a φ and 2 other opposite charged tracks, through another fit; now is extracted by the Beam Spot, that is the mean value of the coordinates of the interaction point, obtained for each BaBar run via direct measurements.

6 My work at SLAC

My work-period at SLAC has been roughly divided into 3 main parts.

6.1 Getting used to the environment and study of Monte Carlo and reconstruction

I spent the very first days in getting used to all the new stuff I've never or rarely seen before, like the SLAC or BaBar informatic systems, tree-structure of Root, remote working, bash scripting and so on.

After this sort of "introduction" I went to analyze the characteristic of the Monte Carlo and the reconstruction information in order to search for some missing part, errors, strangeness etc.
Reporting every single step I took would be too long and very uninteresting, so I'll focus on the main "discoveries" I made.

6.1.1 Energy bump

One of the first weirdness I saw was a bump in the product energy distribution at the energy of 1 GeV, as can be seen in Figure 11.

This bump has been seen been due to an excess of neutrons produced by π^0 interaction with the matter of the detector.

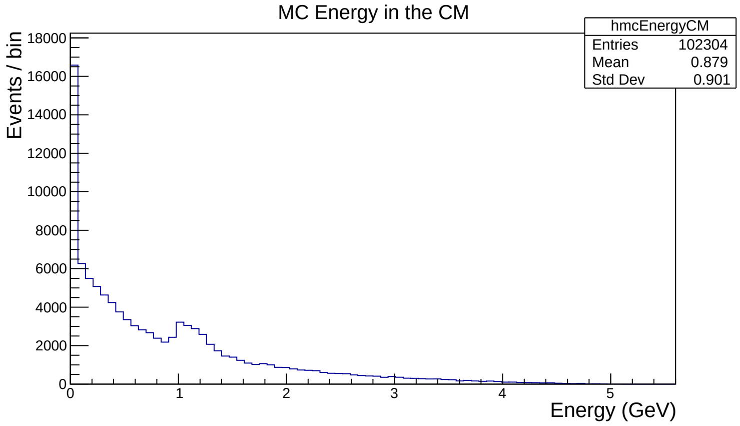

Figure 11: Bump in MC particle energy distribution.

6.1.2 Missing Lunds

Every particle has a "identity number" assigned, called Lund. Since φ, if existing, has not been discovered yet, it has no corresponding Lund, so we gave them a arbitrary one.
Problems came while looking at the MC decay chain, where I found that φ appeared to be absent. τ too was missing from the decay chain, as it decayed right at the PV (that could be true in practical term since decay length is similar, or smaller, than the vertex spatial resolution, but it was expected to be present in the MC).
These problem were solved by my tutors correcting the codes and re-generating the ntuples.

6.1.3 Primary vertex offset

Before becoming aware that the PV was not right in the origin we were a little concerned about the small offset that I saw, but that preoccupation vanished after we discovered it was just to simulate true offset, changing run by run.

6.1.4 φ decay length

We wanted to make sure if φ decayed in the correct way, so we tried to fit its decay distance via an exponential distribution, but that fit failed because the distribution is altered by the relativistic boost of each particle. An example for $c\tau_\varphi = 1$ cm can be seen in Figure 12, together with a reduced χ^2 (χ^2_R) for an exponential fit of 60.

6.1.5 Other analysis

Together with these information I "zoomed" into other quantity's distributions, such as angular spread of φ daughters, mass distribution, electronic selector maps and so on; I will talk in details in the following sections of the ones that we have been using for discriminating between signal and bkg.

6.2 BaBar Jamboree

Around the end of the experience (in particular 13th and 14th of September) I participated at the annual BaBar meeting.
In this occasion I presented my work and our results, and met in person Bertrand, who works in Los Angeles.
In order to prepare the talk I spent about a week, helped by my tutors and my boss, Concetta Cartaro. The talk can be read here.

6.3 Search for the best cuts

The main part of my experience was finalized to write an algorithm useful to find the best cuts to apply in order to maximize signal and minimize bkg in the sense that will be specified down here.

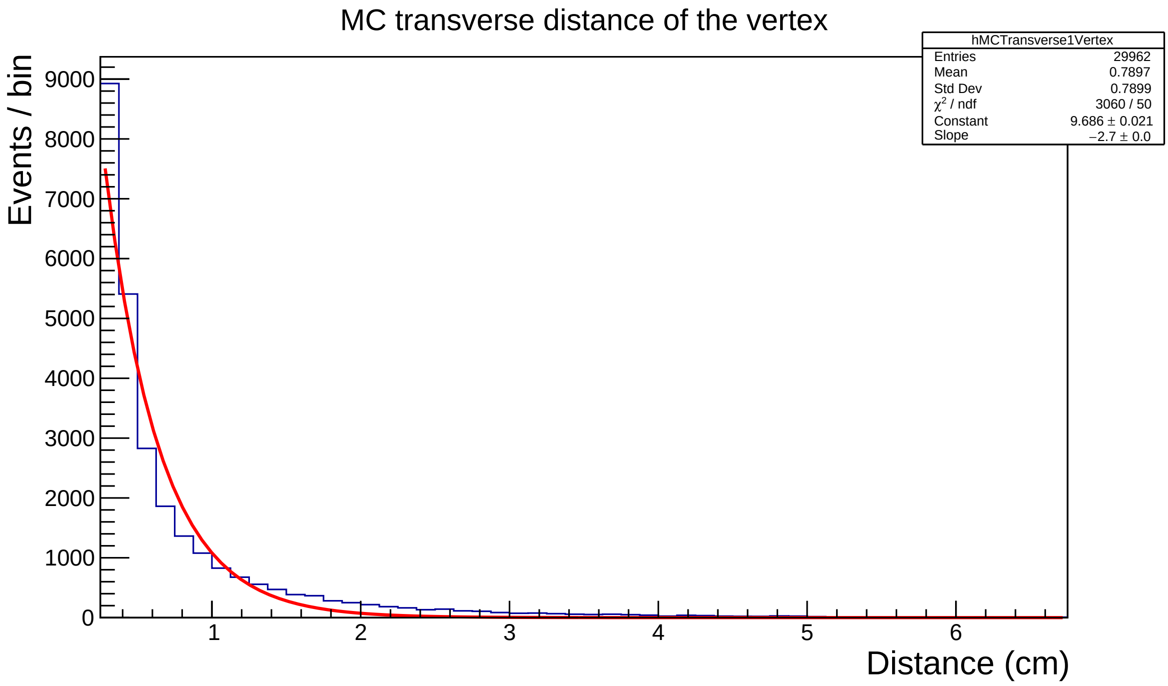

Figure 12: MC transverse distance for 1 cm lifetime.

6.3.1 Significance

Significance (S) is the quantity we want to maximize.

We want a quantity that quantify how significant is our signal, so we want to compare the signal to the fluctuations of the expected bkg. We can assume Poissonian fluctuations for bkg, so we are looking at the following quantity:

$$S = \frac{n_{signal}}{\sqrt{n_{bkg}}} \tag{9}$$

We can evaluate the value of n_{signal} and n_{bkg}, given the cross section σ of the process and the luminosity $\mathcal{L}$, through the results of the Monte Carlo. In particular, given a number N_i^{tot} (i stands for signal or bkg) of generated events and a number N_i^{fid} of events that passed all the cuts, we have that a fraction $\frac{N_i^{fid}}{N_i^{tot}}$ of the $\mathcal{L} \cdot \sigma_i$ physically produced event will pass all the cuts.
For the bkg the reasoning is a little more complicated because we have to take in account all the different process that contribute to the bkg; we can so write an expression like this:

$$n_{bkg} = \mathcal{L} \cdot \sum_j \sigma_j \frac{N_j^{fid}}{N_j^{tot}} \tag{10}$$

where the index j runs over all the kind of contributing bkg.
Combining these expressions we obtain the following:

$$S = \sqrt{\mathcal{L}} \frac{N_{signal}^{fid}}{N_{signal}^{tot}} \left[\sum_j \sigma_j \frac{N_j^{fid}}{N_j^{tot}} \right]^{-\frac{1}{2}} \tag{11}$$

We can notice that there are values that are not dependent from the chosen cuts, so we can simplify the expression: we want to maximize the quantity X, directly proportional to S:

$$X = N_{signal}^{fid} \left[\sum_j \sigma_j \frac{N_j^{fid}}{N_j^{tot}} \right]^{-\frac{1}{2}} \tag{12}$$

So all our work was finalized to find the best way to maximize X, keeping in mind to save the highest amount of data (of course saving 1 event data, even if we managed to totally kill all bkg, would be pretty useless).

6.3.2 Important backgrounds

The ones in Table 1 are the most important background we have to face during our analysis.

Process	Cross Section (pb)
$B^0\overline{B^0}$	550
Bhabha	25100
B^+B^-	550
$c\bar{c}$	1300
$\mu^+\mu^-$	1150
$\tau^+\tau^-$	890
uds	2090

Table 1: Main backgrounds (BKG) and respective cross sections.

I'll focus on the most dangerous, that are, for different reasons, Bhabha and $\tau\tau$.

6.3.2.1 Bhabha bkg Bhabha bkg is the one with the largest cross section, so we have a lot of these kind of signals. By the other hand its behavior is a lot different from the one of the signal; in particular:

- It often presents less than 4 tracks;
- It's not uncommon to have 4 electrons (for example through a conversion of an irradiated photon, $e^+e^- \to e^+e^-\gamma \to e^+e^-e^+e^-$);
- Since there is a lot of energy available for each of the (few) products, they are high energetic, so they tend to be very collinear (to be more precise: an irradiated photon is probably irradiated very close to the electronic daughter because each electron bring an energy of ~ 5 GeV);
- Neutrinos are basically not produced in this process so there is a very low missing transverse momentum.

All these features, differing from the ones of the signal, helps us to elaborate cuts helpful to discriminate between them.

6.3.2.2 $\tau\tau$ bkg $\tau\tau$ bkg, even if is not the most frequent one, is of course one of the most dangerous because it mimics a lot the behave of the signal: they share of course the presence of 2 τ and so their decay products.

Also it present 2 electronic tracks; electron can came from the following:

- τ decay products:
  - $\pi^0 \to \gamma\gamma \to \gamma e^+e^-$ (photon conversion)
  - $\pi^0\gamma \to \gamma e^+e^-$ (Dalitz decay)
- $\tau \to \tau\gamma \to \tau e^+e^-$

6.3.3 Chosen cuts

Here I'm gonna list and explain all the cuts we have used this far.

6.3.3.1 4 tracks Nothing surprising, we are simply requiring for event to present no more and no less than 4 tracks; this is, as said, very effective in order to reduce Bhabha bkg, for example.

6.3.3.2 φ decay vertex reconstruction's χ^2_R As quickly mentioned above the φ is reconstructed as any possible pair of opposite charged tracks: this means that, given 4 tracks, 2 positive and 2 negative, there are at priori 4 possible φ candidates. In order to quickly eliminate the wrong ones (the combinatoric bkg) one powerful tool is to check the χ^2_R of the reconstruction fit.
This comparison allow not only to eliminate combinatoric bkg but also to reduce a little bkg from physic sources.
Graphs about signal, Bhabha and $\tau\tau$ can be seen in Figure 13.

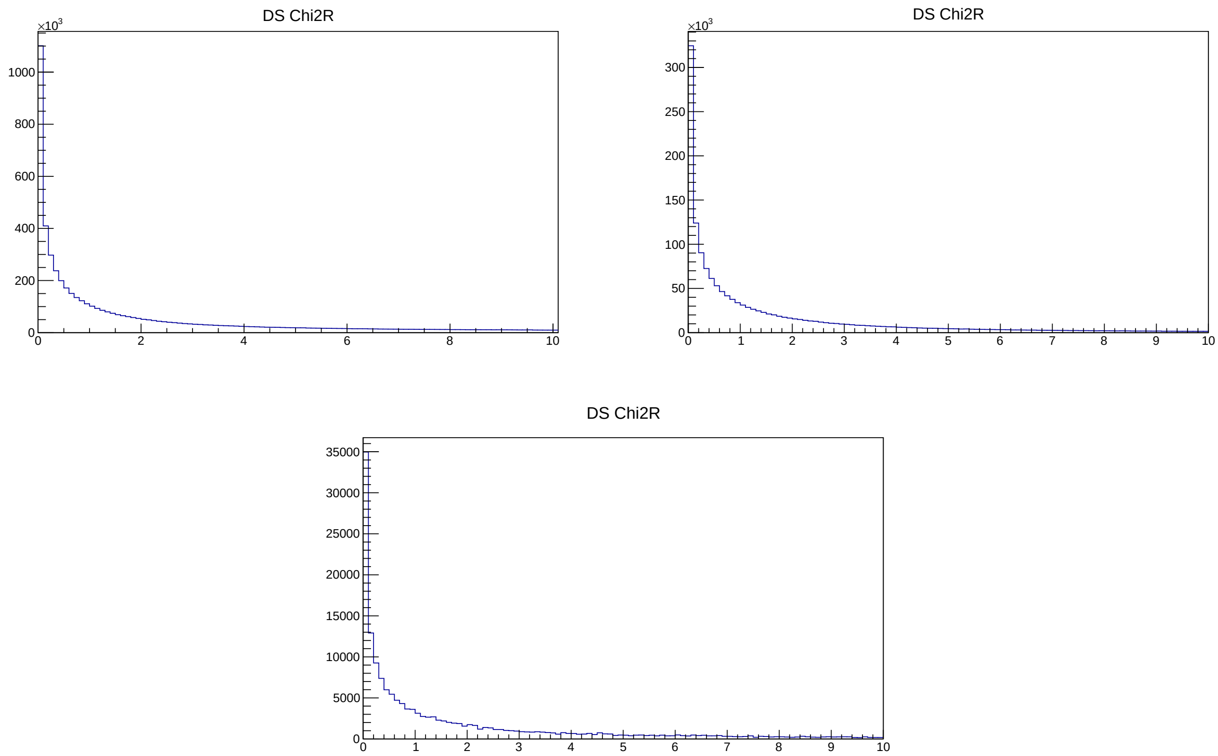

Figure 13: Bhabha, $\tau\tau$ and signal distributions for φ's χ^2_R.

We have chosen to save events with

$$\chi^2_R(\varphi) < 4 \tag{13}$$

6.3.3.3 Primary vertex reconstruction's χ^2_R Very similar to previous point, here we look at the primary vertex's reconstruction's χ^2_R.
We are recently abandoning this criteria in order to adopt a "beam spot", obtained as an average value for every block of events, instead of an event-for-event calculated primary vertex, difficult operations with a low number of tracks has we have; for sake of completeness I include graphs (Figure 14) and chosen value for this cut.

We have chosen to save events with

$$\chi^2_R(\Upsilon) < 4 \tag{14}$$

6.3.3.4 Missing $p_\perp$ As mentioned above, signal presents on average a high missing momentum due to the presence of (at least) 2 neutrinos.
Bhabha bkg, otherwise, has generally no neutrinos at all, so missing momentum is due to acceptance and/or detector's deficit only.
In order to brutally reduce Bhabha bkg, so, eliminating low-missing-momentum events results very effective.
In Figure 15 we can see the highly different behavior of signal and Bhabha.

We have chosen to save events with

$$\text{missing } p_\perp > 0.7 \text{ GeV} \tag{15}$$

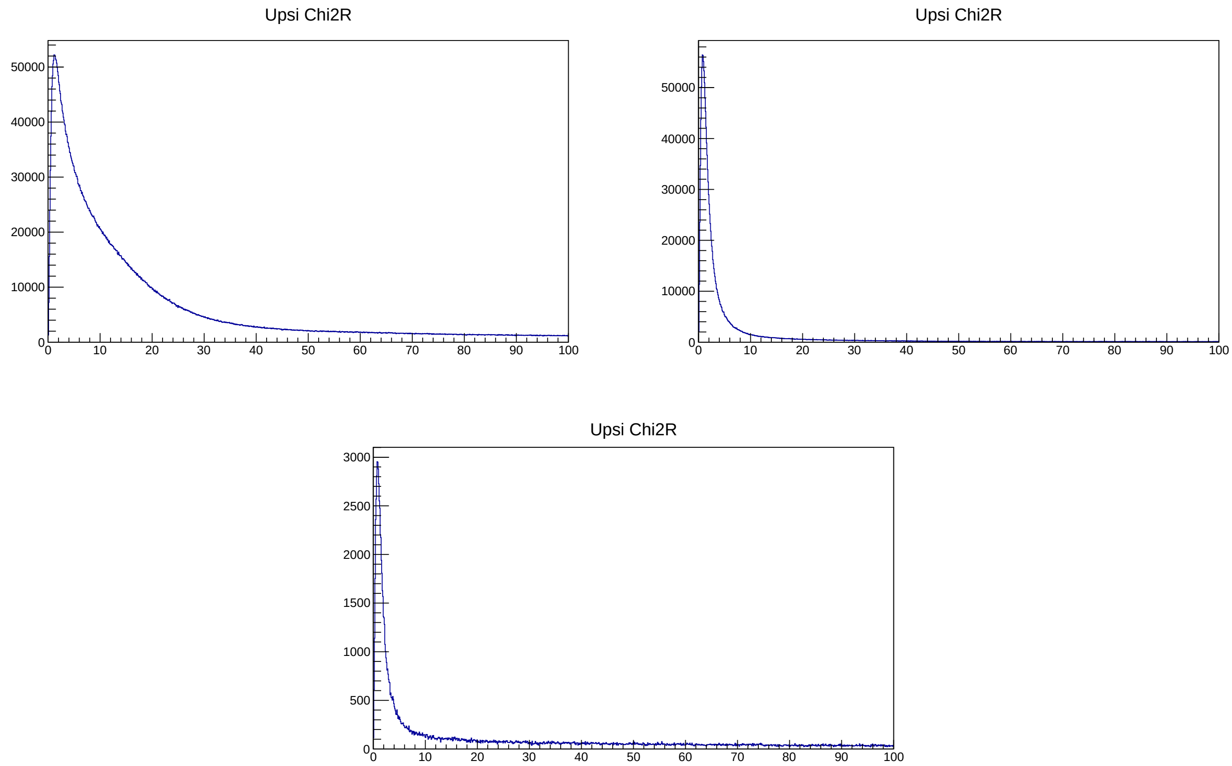

Figure 14: Bhabha, $\tau\tau$ and signal distributions for Υ's χ^2_R.

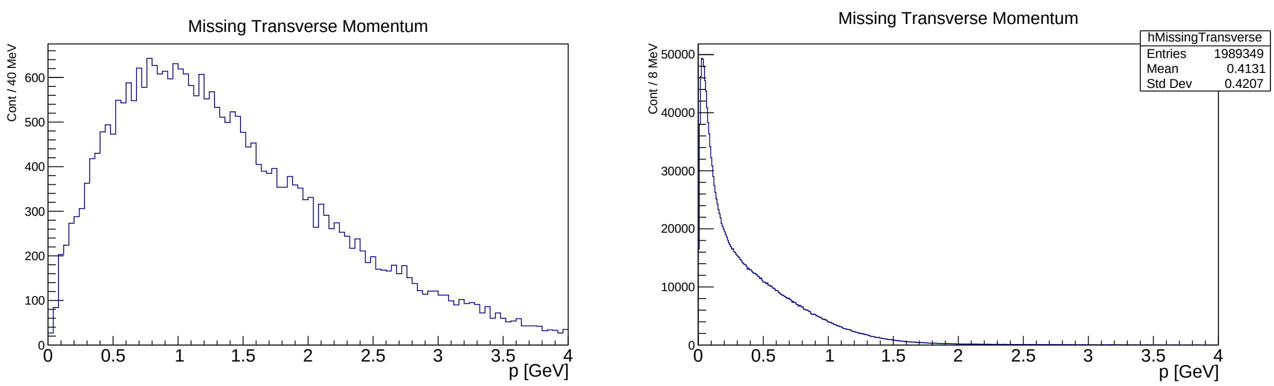

Figure 15: Bhabha and signal distributions for missing transverse momentum.

6.3.3.5 Electron quality For each track the reconstruction fit assigns some values, called "Selector Map", that indicate the probability for that track of being related to an electron, pion, muon etc...
For what concerns electrons, for example, we have numbers running from 0 to 11. In particular numbers from 6 to 11 are related to a particular kind of operated analysis, and they correspond to:

- 6: SuperLooseKMElectronMicroSelection;
- 7: VeryLooseKMElectronMicroSelection;
- 8: LooseKMElectronMicroSelection;
- 9: TightKMElectronMicroSelection;
- 10: VeryTightKMElectronMicroSelection;
- 11: SuperTightKMElectronMicroSelection.

Basically when a track is reconstructed we don't know for sure what particle has generated it: highest is the Electronic Selector Map (ESM), more probable is that it was generated by an electron/positron. Since $\varphi \to e^+e^-$ we can ask that the particle used to reconstruct φ have a sufficiently-high ESM, in order to help reduce bkg given by, just for example, a μ^+ and a K^- casually coming approximately from the same point.

Looking at Figure 16 we see two 2D histograms, referring to the signal.
On the axis there are the values of the ESM for the two tracks used to reconstruct the candidate φ. Left one depicts the distribution before any cut, while the right one is about the distribution after all other applied cuts.
The red square enlightens the chosen region for the cut, corresponding to LooseKMElectronMicroSelection.

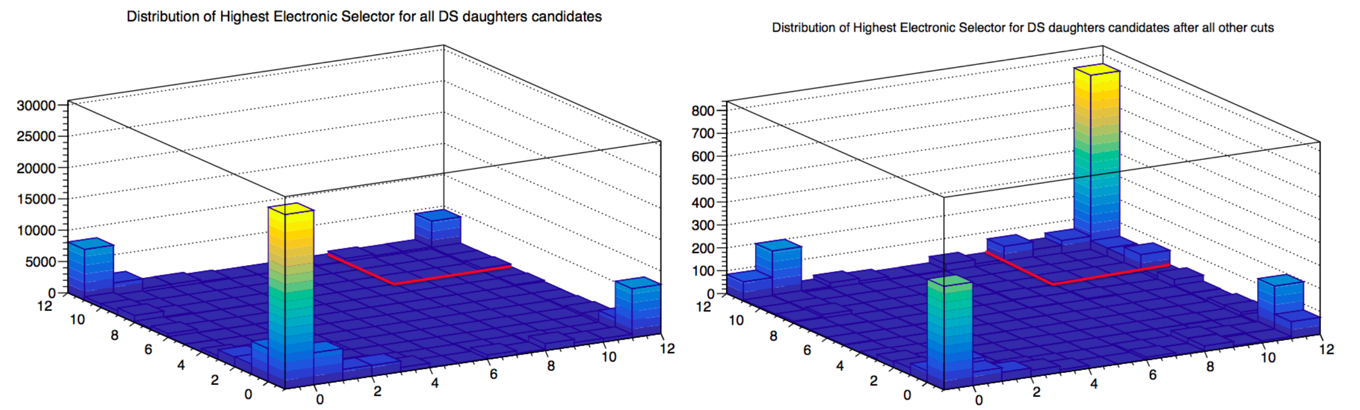

Figure 16: Signal. Distribution of max EMS for φ's daughters. See text for description.

For comparison we can look at $\tau\tau$'s distribution (Figure17); we can see that this cut results quite efficient since it eliminates bkg that is not reduced by other applied cuts.
For nature of Bhabha bkg, instead, this cut is not particularly efficient against it.

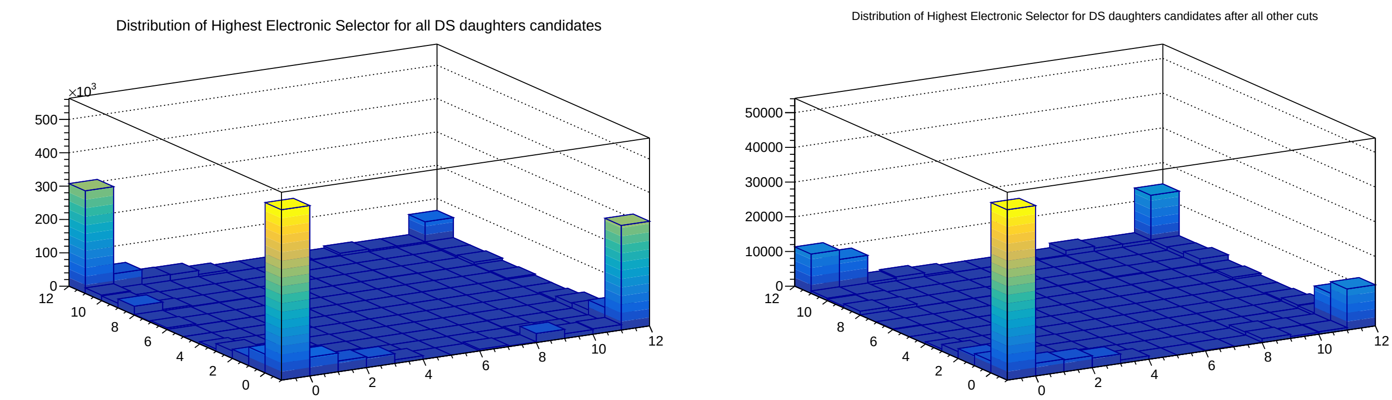

Figure 17: $\tau\tau$. Distribution of max EMS for φ's daughters. See text for description.

We have chosen to save events with

$$\text{ESM} \geq 8 \tag{16}$$

for *both* φ's daughters.

6.3.3.6 Collinearity This one is a general quality requirement: we want φ momentum and the direction between PV and DSV being "reasonably" collinear, where the adverb of course is quantified by the algorithm for the search for the best cuts.

I define the following: $cos(\alpha) \equiv \frac{\vec{p}_{\varphi} \cdot \overrightarrow{(PV-DSV)}}{|\vec{p}_{\varphi}||\overrightarrow{(PV-DSV)}|}$.
In order to have a well-defined distance between PV and DSV we ask for it being "not too small", so for now we've used it only for φ with a $c\tau \geq 10$ cm.

We have chosen to save events with

$$cos(\alpha) > 0.97 \tag{17}$$

6.3.3.7 PS-DSV distance

Following from the last reasoning above, we ask a certain minimal distance in order to well distinguish between the two vertexes.
This cut will probably be modified when the new PV approach will be completed.
Again we are using this one only for φ with a $c\tau \geq 10$ cm.

We have chosen to save events with

$$\text{PV-DSV} > 0.45 \text{ cm} \tag{18}$$

6.3.3.8 Angle between φ and τ

This cut results particularly useful against Bhabha bkg.
It is based on the above-mentioned high energy of the scattered electrons in comparison with the irradiated photon (if any, of course).

Let's take in consideration the simple case of e^+e^- scattered and 1 photon γ emitted by 1 of the electrons, then let's assume γ converts inside the detector: $\gamma \to e^+e^-$.
Since γ is far less energetic than the $e^{\pm}$ that has emitted it will be very close to it.
Now we have to remember that, from the point of view of the reconstruction fitter, the photon can mimic a φ while the two "original" electron can be seen as τ; so, looking at Figure 18 we have that the red circled electrons are read as τ while γ is reconstructed as φ.

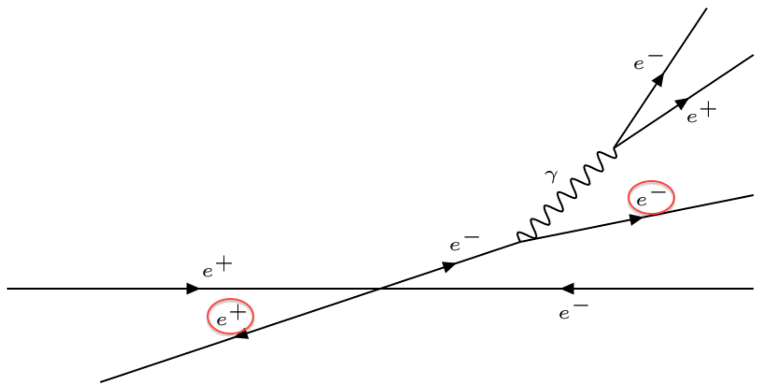

Figure 18: Possible Bhabha process.

For signal there is no constraint of this kind because φ is basically generated at the PV together with the 2 τ; so, if we eliminate the candidate φ very close to one of the "τ" we are able to drastically reduce Bhabha bkg.
We can see how much peaked is the distribution of the (max) cosine between φ and τ looking at Figure 19.

We have chosen to save events with

$$max(\cos(\tau - \varphi)) < 0.92 \tag{19}$$

6.3.3.9 Mass window

In order to simulate what will be done during real data analysis we have applied a mass window around the central value.

We have chosen to save events with

$$\Delta(M) < 6 \text{ MeV} \tag{20}$$

6.3.3.10 No-4-electrons

We are recently looking at another possible cut: requiring that there are *no* 4 electrons in the event, in order to better reduce Bhabha bkg.

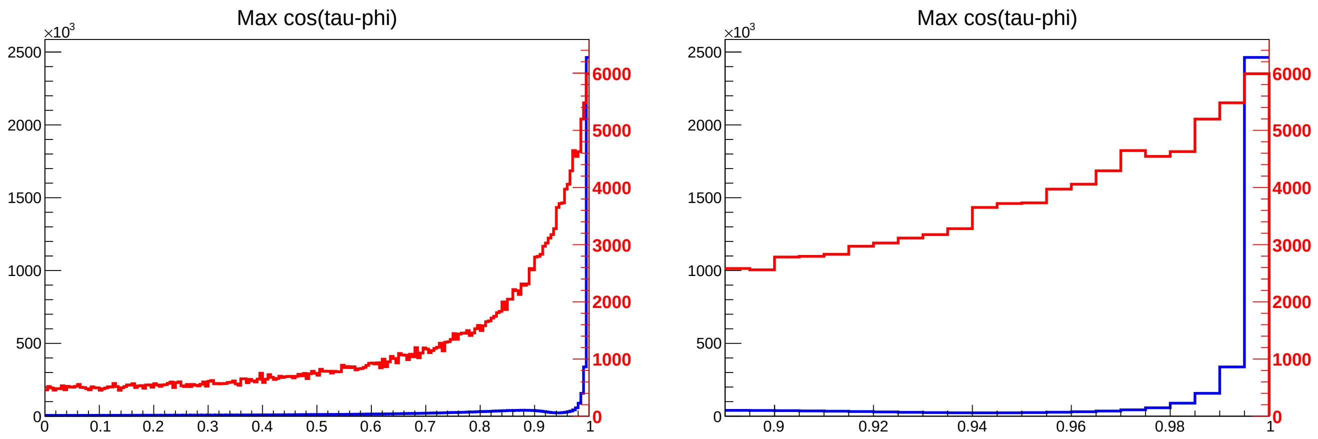

Figure 19: $max(\cos(\tau - \varphi))$. Red: signal, blue: Bhabha. On the right a zoom.

6.3.4 Algorithm

Here I'll quickly talk about the functioning of the algorithm I've wrote to search for the best cuts.
The idea is basically to access a group of data (signal or 1 of the 7 bkg) and run over all events, and for each event analyze all the (generally 4) possible combinations of tracks, as mentioned above. For each of them I try different values for 4 cuts (the others are kept fixed), and record if the "track combination" passed these cuts or not. After having done it for all group of data I calculate the parameter X and, after having finished, I search for the combinations of cuts that give the highest X.

6.3.5 Background reduction

Applying all the cuts above (expect the very last one) we remain with the bkg in Figure 20.

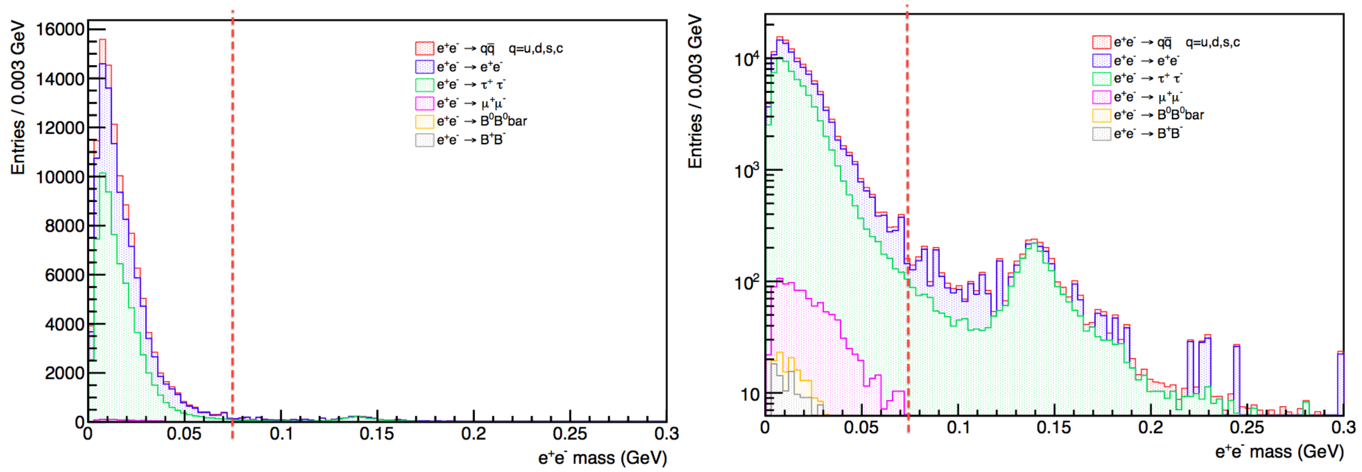

Figure 20: BKG e^+e^- mass distribution. Red dashed line is the approximate limit from other experiment. Bump is due to π^0 form $\tau^+\tau^-$ bkg. Left: linear scale. Right: logarithmic scale.

The graph is "adding"-type, so each level represents the contribute from that kind of bkg, so the total is given by the upper line. We can see that, as said, $\tau\tau$ bkg is the most dangerous, immediately followed by Bhabha one.

We can see there is a bump around the mass of the π^0; this is caused by physic pions, produced by the decay of the τ, that decay into e^+e^-; electrons are collected together with all emitted photons in the process and interpreted as a φ; we are actually concluding ways to eliminate this bump, like vetoing the near photons.

From the graph we can easily see that searching under 50 MeV, as said at the beginning, would be pretty useless, not only because partially yet searched by other experiments but also because of the almost irreducible bkg coming from conversion photon, whose e^+e^- decay products have an invariant mass peaked near 0, as it can be seen in the graph.

6.3.6 Expected significance

Now we can evaluate significance.

Given a cross section of 10 fb we obtain, with all above cuts (again, except the very last one), for $c\tau = 100$ mm:

$$S > 5 \tag{21}$$

The inequality is due to some bkg are reduced to 0; if we assume a value of 3 instead of 0 for these bkg we of course obtain a smaller value for the significance, a "fiducial" one.

- Keeping nullified bkg at 0 $\Rightarrow S = 6.5$
- Turning nullified bkg at 3 $\Rightarrow S = 5$

6.4 Future plans

Strictly speaking my collaboration with SLAC could be ended, but I got interested in this search and I'm really positive into turning it into my thesis. At the moment of writing (October 2016) I've not yet found a supervisor, but I hope it will be a matter of days.
In the meanwhile I can summarize next steps:

- We have to finish polishing other cuts in order to totally eliminate pi^0 bump;
- We have to test over other φ masses and lifetimes;
- We have to test over a sample of real data;
- And finally... We will run over all BaBar data!