Relativistically Boosted Psi and B Meson Decays

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Outline

Introduction

- Aim of project is to examine the product particles of various meson decays, in particular B, D and $\psi(3770)$ meson decays.
- The invariant mass distributions of the product particles are examined in three decays:
  - Two body $\psi(3770) \to D^0\overline{D^0}$
  - Three body $B^+ \to D^0\overline{D^0}K^+$
  - Four body $D^0 \to K^+K^-K^-\pi^+$
- The decay angles of the resultant particles are then examined in the lab frame in the following decays:
  - $\psi(3770) \to D^0\overline{D^0}$
  - $B \to (\psi(3770) \to D^0\overline{D^0})K$

Purpose

- $\psi(3770)$ decays are interesting because in a $\psi(3770)$ decay, the D^0 and $\overline{D^0}$ are produced in a quantum correlated state.
- This quantum correlation allows better access to D^0 strong phase information (the phases introduced by the strong force). D^0 phase information is critical information that allows us to accurately measure CP violation in beauty decays ($B \to D\ K$, a big part of Bristol's LHCb programme).
- The amount of CP violation that occurs in such processes is important because CP violation helps to explain matter-antimatter asymmetry (i.e. why is the universe full of matter and not anti-matter?).

Purpose

- **But** at present the amount of CP violation measured to occur does not account for the asymmetry that we see; there simply is not enough CP violation to justify the amount of asymmetry we see.
- Interestingly, $\psi(3770)$ decays can also be used to measure symmetry violations in the **charm** system, thanks to the quantum correlations in the decay.
- Analysis of the amount of CP violation in both beauty and charm could lead to a better explanation of matter-antimatter asymmetry, or to the discovery of *New Physics*™.

ROOT

- The ROOT C++ libraries were used to simulate and analyse the decay events.
- In particular the TGenPhaseSpace class was used to generate Monte Carlo (MC) phase space for n-body decays of constant cross-section as per Frederick James' 1968 paper, *Monte Carlo Phase Space*.
- The GetDecay() method, inheriting from TGenPhaseSpace, generates Lorentz vectors for the decay products given.

Code

```
TLorentzVector parent(0.0,0.0,0.0, PARENTMASS);
Double_t masses[2] = {DAUGHTER1MASS, DAUGHTER2MASS};

TGenPhaseSpace event;
event.SetDecay(parent, 2, masses);

TLorentzVector *daughter1 = event.GetDecay(0);
TLorentzVector *daughter2 = event.GetDecay(1);
```

Code

This example code demonstrates the basic method; once you start looking at longer decay chains and relativistically boosting and analyzing them, it gets a lot more complicated! (And uglier...)

Invariant Mass Distributions

- The invariant mass distributions of the daughter particles was calculated by summing the TLorentzVectors of the decay products and applying ROOT's TLorentzVector::M() method:

```
TLorentzVector particleSum = *daughter1 + *daughter2;
Double_t      invariantMass = particleSum.M();
```

- This method sums the square of each component of the four momentum to find the Minkowski norm of the four momentum, or the proper mass.
- If the right products are used, this invariant mass is the mass of the parent particle.

Invariant Mass Distributions

The equations determining this in natural units ($c = 1$) are:

$$\mathbf{P} = \begin{pmatrix} P^0 \\ P^1 \\ P^2 \\ P^3 \end{pmatrix} = \begin{pmatrix} E \\ p_x \\ p_y \\ p_z \end{pmatrix} \tag{1}$$

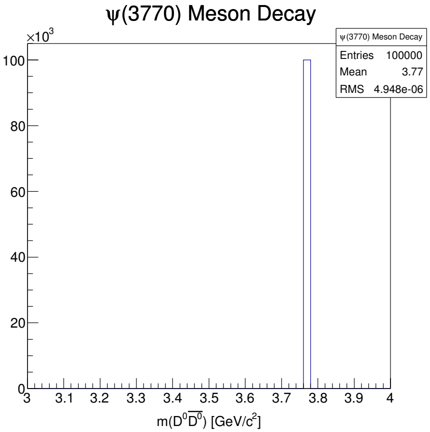
$$\|\mathbf{P}\|^2 = P^\mu P_\mu = P^\mu \eta_{\mu\nu} P^\nu = E^2 - |\mathbf{p}|^2 = m^2 \tag{2}$$

where $\eta_{\mu\nu}$ is the Minkowski metric, here defined as:

$$\eta_{\mu\nu} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} \tag{3}$$

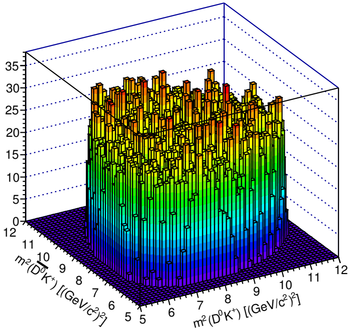
Two body $\psi(3770) \rightarrow D^0 \overline{D^0}$

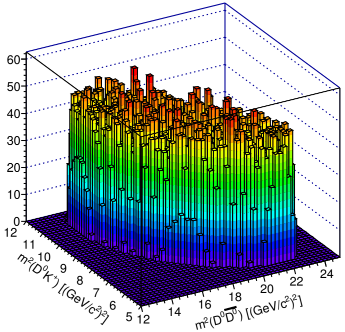
Invariant mass distribution of the D^0 and $\overline{D^0}$ matches exactly with the mass of the parent particle:



Three body $B^+ \to D^0 \overline{D^0} K^+$

Three bodies, so more complicated (and prettier):





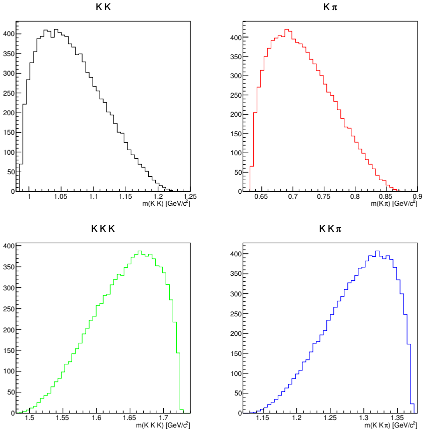
Three body $B^+ \to D^0 \overline{D^0} K^+$

- A three body decay has a two-dimensional phase space, so this is best visualised as a density plot of the invariant mass distributions of combinations of two of the particles.
- They are not unique and can be inferred from one another due to momentum conservation laws.
- If there were no intermediate resonances in the decay, this should decay roughly uniformly throughout the phase space, meaning given if this MC were repeated an infinite number of times, the distribution would be approximately flat-topped. Considering the finite number of iterations made, this isn't bad!
- An example of an intermediate resonance in this decay that we are very interested in is $B \to \psi(3770)K$, which is not simulated here but which we will look at later.

Four body $D^0 \to K^+K^-K^-\pi^+$

- Also looked at phase space for uniform four body decays.
- These produce five dimensional phase space, which is hard to visualise. I've just projected these onto axes to turn them into 1D projections which **can** easily be plotted and understood.
- (If you want to know more about visualising multi-dimensional phase spaces, talk to Dan Saunders.)

Four body $D^0 \to K^+K^-K^-\pi^+$



Four body $D^0 \to K^+K^-K^-\pi^+$

- If I had simulated intermediate resonances in the decay we would see rich strong phase information arising from the interference between these decays.
- If you're interested in this, the structure of such decays using "Dalitz Plot Analysis" has been done by Bristol's particle physics team for $D^0 \to KK\pi\pi$ deacys, and Jack Benton is now doing a Dalitz plot analysis of $D \to \pi\pi\pi\pi$ decays.
- The $D^0 \to K^+K^-K^-\pi^+$ decay strong phase information has never been observed! For interest, I tabulated the possible intermediate resonances:

Light Unflavored Mesons ($S = C = B = 0$)

Particle Name	Mass [MeV]	Full width, Γ [MeV]	J^P	Decay Channel
$f_0(980)$	980 ± 10	$40 \rightarrow 100$	0^+	$f_0(980) \rightarrow K\bar{K}$
$a_0(980)$	980 ± 20	$50 \rightarrow 100$	0^+	$a_0(980) \rightarrow K\bar{K}$
$\phi(1020)$	1019.45 ± 0.02	4.26 ± 0.04	1^-	$\phi(1020) \rightarrow K^+K^-$
$b_1(1235)$	1229.5 ± 3.2	142 ± 9	1^+	$b_1(1235) \rightarrow [\phi \rightarrow K^+K^-]\pi$ and $b_1(1235) \rightarrow [K^*(892)^\pm \rightarrow K\pi]K^\pm$
$a_1(1260)$	1230 ± 40	$250 \rightarrow 600$	1^+	$a_1(1260) \rightarrow [f_0(1370) \rightarrow K\bar{K}]\pi$ and $a_1(1260) \rightarrow [f_2(1270) \rightarrow K\bar{K}]\pi$ and $a_1(1260) \rightarrow K[\bar{K}^*(892) \rightarrow K\pi] + c.c.$
$f_2(1270)$	1275.1 ± 1.2	$185.1^{+2.9}_{-2.4}$	2+	$f_2(1270) \rightarrow K\bar{K}$
$f_1(1285)$	1281.8 ± 0.6	24.3 ± 1.1	1^+	$f_1(1285) \rightarrow K\bar{K}\pi$
$\eta(1295)$	1294 ± 4	55 ± 5	0^-	$\eta(1295) \rightarrow a_0(980)\pi$
$a_2(1320)$	1318.3 ± 0.6	107 ± 5	2^+	$a_2(1320) \rightarrow K\bar{K}$
$f_0(1370)$	$1200 \rightarrow 1500$	$200 \rightarrow 500$	0^+	$f_0(1370) \rightarrow K\bar{K}$
$\eta(1405)$	1409.8 ± 2.5	51.1 ± 3.4	0^-	$\eta(1405) \rightarrow [a_0(980) \rightarrow K\bar{K}]\pi$ and $\eta(1405) \rightarrow K\bar{K}\pi$ and $\eta(1405) \rightarrow [K^*(892) \rightarrow K\pi]K$
$f_1(1420)$	1426.4 ± 0.9	54.9 ± 2.6	1^+	$f_1(1420) \rightarrow K\bar{K}\pi$ and $f_1(1420) \rightarrow K[\bar{K}^*(892) \rightarrow K\pi] + c.c.$
$a_0(1450)$	1474 ± 19	265 ± 13	0^+	$a_0(1450) \rightarrow K\bar{K}$
$\rho(1450)$	1465 ± 13	265 ± 13	0^+	$\rho(1450) \rightarrow K[\bar{K}^*(892) \rightarrow K\pi] + c.c.$
$\eta(1475)$	1476 ± 4	85 ± 9	0^-	$\eta(1475) \rightarrow K\bar{K}\pi$ and $\eta(1475) \rightarrow [a_0(980) \rightarrow K\bar{K}]\pi$ and $\eta(1475) \rightarrow K[\bar{K}^*(892) \rightarrow K\pi] + c.c.$
$f_0(1500)$	1505 ± 6	109 ± 7	0^+	$f_0(1500) \rightarrow K\bar{K}$
$f_2'(1525)$	1525 ± 5	73^{+6}_{-5}	2^+	$f_2'(1525) \rightarrow K\bar{K}$

Light Unflavored Mesons ($S = C = B = 0$)

Particle Name	Mass [MeV]	Full width, Γ [MeV]	J^P	Decay Channel
$\eta_2(1645)$	1617 ± 5	181 ± 11	2^-	$\eta_2(1645) \to [a_2(1320) \to K\bar{K}]\pi$ and $\eta_2(1645) \to K\bar{K}\pi$ and $\eta_2(1645) \to [K^*(892) \to K\pi]\bar{K}$ and $\eta_2(1645) \to [a_0(980) \to K\bar{K}]\pi$
$\pi_2(1670)$	1672.2 ± 3.0	260 ± 9	2^-	$\pi_2(1670) \to [f_2(1270) \to K\bar{K}]\pi$ and $\pi_2(1670) \to K[\bar{K}^*(892) \to K\pi] + c.c.$
$\phi(1680)$	1680 ± 20	150 ± 50	1^-	$\phi(1680) \to K\bar{K}$ and $\phi(1680) \to K[\bar{K}^*(892) \to K\pi] + c.c.$
$\rho_3(1690)$	1688.8 ± 2.1	161 ± 10	3^-	$\rho_3(1690) \to K\bar{K}\pi$ and $\rho_3(1690) \to K\bar{K}$ and $\rho_3(1690) \to [a_2(1320) \to K\bar{K}]\pi$
$\rho(1700)$	1720 ± 20 ($\eta\rho^0$ & $\pi^+\pi^-$)	250 ± 100 ($\eta\rho^0$ & $\pi^+\pi^-$)	1^-	$\rho(1700) \to K\bar{K}$ and $\rho(1700) \to K[\bar{K}^*(892) \to K\pi] + c.c.$
$f_0(1710)$	1720 ± 6	135 ± 8	0^+	$f_0(1710) \to K\bar{K}$
$\pi(1800)$	1812 ± 12	208 ± 12	0^-	$\pi(1800) \to [K^*(892) \to K\pi]K^-$
$\phi_3(1850)$	1854 ± 7	87^{+28}_{-23}	3^-	$\phi_3(1850) \to K\bar{K}$ and $\phi_3(1850) \to K[\bar{K}^*(892) \to K\pi] + c.c.$
$f_2(1950)$	1944 ± 12	472 ± 18	2^+	$f_2(1950) \to K\bar{K}$
$f_2(2010)$	2011^{+60}_{-80}	202 ± 60	2^+	$f_2(2010) \to K\bar{K}$
$a_4(2040)$	1996^{+10}_{-9}	255^{+28}_{-24}	4^+	$a_4(2040) \to K\bar{K}$ and $a_4(2040) \to [f_2(1270) \to K\bar{K}]\pi$
$f_4(2050)$	2018 ± 11	237 ± 18	4^+	$f_4(2050) \to K\bar{K}$ and $f_4(2050) \to [a_2(1320) \to K\bar{K}]\pi$
$f_2(2300)$	2297 ± 28	149 ± 40	2^+	$f_2(2300) \to K\bar{K}$

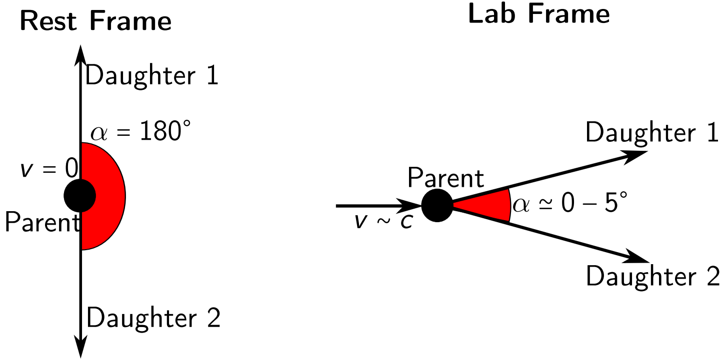
Strange Mesons ($S = \pm 1, C = B = 0$)

Particle Name	Mass [MeV]	Full width, Γ [MeV]	J^P	Decay Channel
$K^*(892)$	895.5 ± 0.8	46.2 ± 1.3	1^-	$K^*(892) \to K\pi$
$K^*(892)^\pm$	891.66 ± 0.26	50.8 ± 0.9	1^-	
$K^*(892)^0$	895.94 ± 0.22	48.7 ± 0.8	1^-	
$K_1(1270)$	1272 ± 7	90 ± 20	1^+	$K_1(1270) \to K[f_0(1370) \to K\overline{K}]$
$K_1(1400)$	1403 ± 7	174 ± 13	1^+	$K_1(1400) \to K[f_0(1370) \to K\overline{K}]$
$K^*(1410)$	1414 ± 15	232 ± 21	1^-	$K^*(1410) \to K\pi$
$K_0^*(1430)$	1425 ± 50	270 ± 80	0^+	$K_0^*(1430) \to K\pi$
$K_2^*(1430)^\pm$	1425.6 ± 1.5	98.5 ± 2.7	2^+	$K_2^*(1430) \to K\pi$
$K_2^*(1430)^0$	1432.4 ± 1.3	109 ± 5	2^+	
$K^*(1680)$	1717 ± 27	322 ± 110	1^-	$K^*(1680) \to K\pi$
$K_2(1770)$	1773 ± 8	186 ± 14	2^-	$K_2(1770) \to K[f_2(1270 \to K\overline{K}]$ and $K_2(1770) \to K[\phi \to K^+K^-]$
$K_3^*(1780)$	1776 ± 7	159 ± 21	3^-	$K_3^*(1780) \to K\pi$
$K_2(1820)$	1816 ± 13	276 ± 35	2^-	$K_2(1820) \to K[f_2(1270) \to K\overline{K}]$
$K_4^*(2045)$	1045 ± 9	198 ± 30	4^+	$K_4^*(2045) \to K\pi$

Decay Angles

- TGenPhaseSpace simulates decays in the rest frame of the decay parent. In this frame, all decay pairs decay in opposite directions, so the decay angle is 180°.
- I'm interested in what this angle looks like in the *lab frame*. In other words, in the frame relativistically boosted by the Lorentz vector of the decay parent. These are typically moving with $v \sim c$, so where in the rest frame two particles decayed 180° apart, in the lab frame the angle is very small.
- The distribution of this angle allows us to distinguish the important decays that we are looking for from the background.

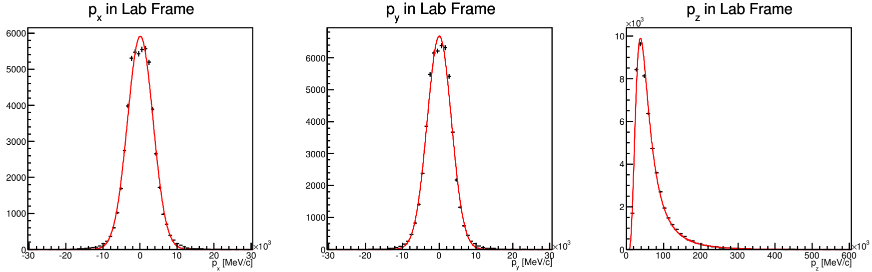
Decay Angles



$\psi(3770) \rightarrow D^0 \overline{D^0}$

- Before the decay angle in the lab frame can be calculated, first you need the Lorentz vector of the parent $\psi(3770)$.
- To this end, momentum component distributions were obtained from a LHCb Monte Carlo simulation.
- These momentum component distributions were fitted to mathematical functions.
- The MC simulation of the $\psi(3770) \rightarrow D^0 \overline{D^0}$ decay was then repeated a large number of times and each time the products' 4-momenta were boosted by a random vector fitting the momentum distributions from the mathematical fit to the MC simulation.

$\psi(3770) \to D^0 \overline{D^0}$



Note that these are not perfect fits, but they are sufficiently accurate for our purposes.

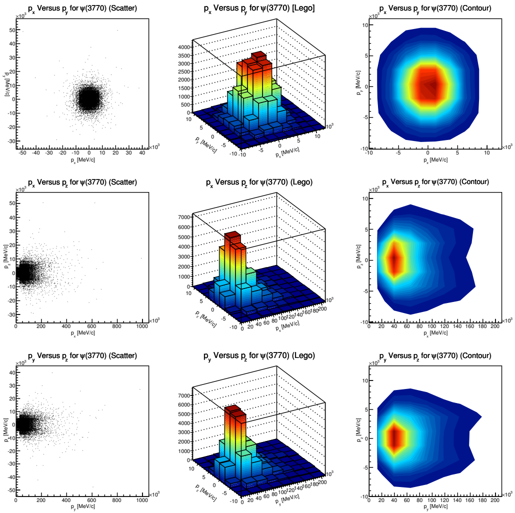
$\psi(3770) \to D^0 \overline{D^0}$

- Need to confirm independence of p_x, p_y and p_z in order to use them independently for TGenPhaseSpace simulation.
- Correlation factors between components calculated and tabulated:

	p_x	p_y	p_z
p_x	1	0.00640212	0.0150375
p_y	0.00640212	1	0.0167604
p_z	0.0150375	0.0167604	1

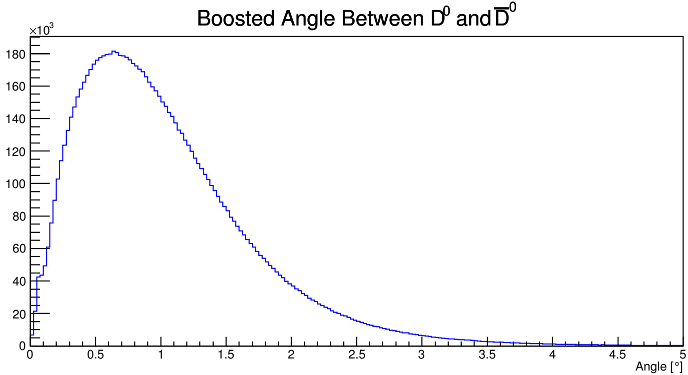
- Following plots visualise this independence:

$\psi(3770) \to D^0 \overline{D^0}$



$\psi(3770) \rightarrow D^0 \overline{D^0}$

Final plot of decay angle between D^0 and $\overline{D^0}$ in lab frame:



Note that all decays are below $\simeq 5°$.

$\psi(3770) \rightarrow D^0 \overline{D^0}$

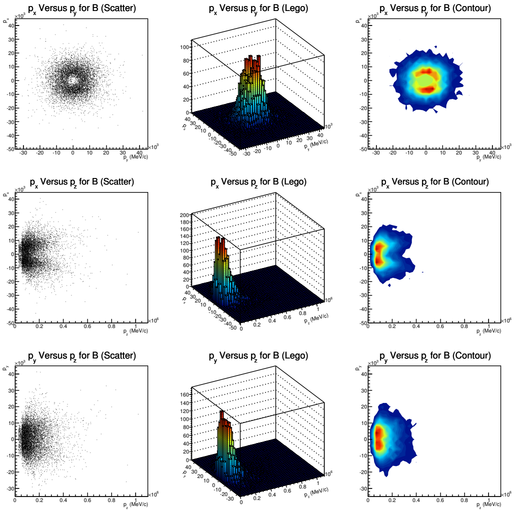
- Importance of this graph is that the decay angle is highly peaked around $\sim 0.5°$
- This makes it very useful for distinguishing this interesting decay channel from the uninteresting background, which should not be peaked but more evenly angularly distributed (although it may have some angular dependence).

$B \to (\psi(3770) \to D^0 \overline{D^0})K$

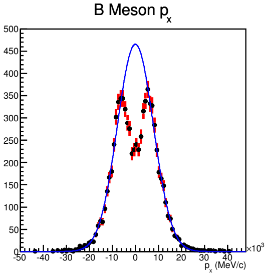
- The same was done of the B meson, using LHCb MC momentum data for $B \to D\ Bach$ decay. (The $Bach$ is either a kaon or a pion.)
- However, no B momentum data present, so used conservation of momentum to deduce B momentum components from the sum of the product D and $Bach$ mesons, using $P_{B,i} = P_{D,i} + P_{Bach,i}$ for $i \in \{x, y, z\}$.
- Correlation factor matrix:

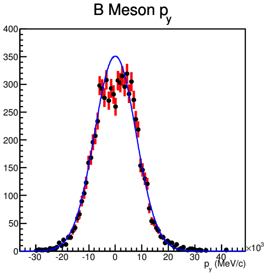
	p_x	p_y	p_z
p_x	1	0.0165178	-0.00486466
p_y	0.0165178	1	0.017408
p_z	-0.00486466	0.017408	1

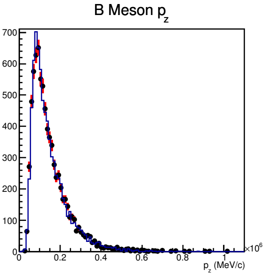
$B \to (\psi(3770) \to D^0 \overline{D^0}) K$



$B \to (\psi(3770) \to D^0 \overline{D^0}) K$



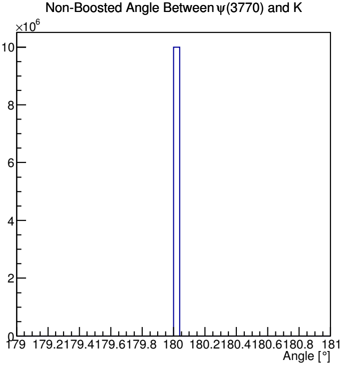


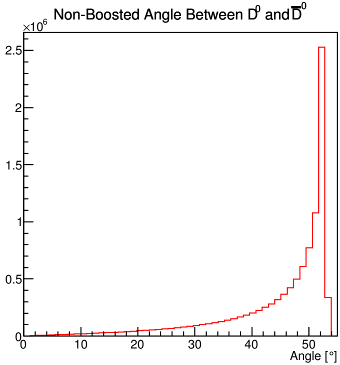


$B \to (\psi(3770) \to D^0 \overline{D^0}) K$

Final decay angle graphs:

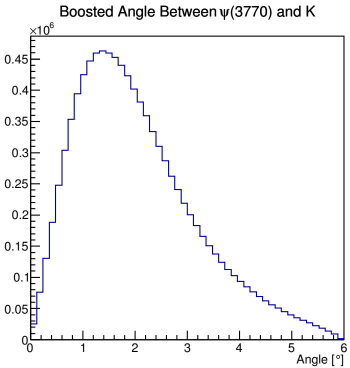
In rest frame of parent B:

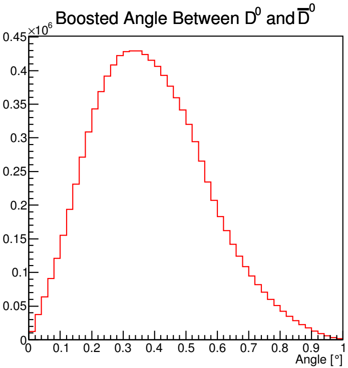




$B \to (\psi(3770) \to D^0 \overline{D^0}) K$

In lab frame:





$B \to (\psi(3770) \to D^0 \overline{D^0})K$

- Once again, we find that the decay angle is sharply peaked around $\simeq 1.5^\circ$ for the $\psi(3770) - K$ angle and $\simeq 0.4^\circ$ for the $D^0 - \overline{D^0}$ angle.
- This is good, because it means that the decay angle can accurately be used to distinguish this interesting decay from all the uninteresting background decays going on.
- This allows us to isolate more $\psi(3770)$ decays for symmetry violation studies.

References

- http://root.cern.ch/root/html/TGenPhaseSpace.html
- http://cds.cern.ch/record/275743