Update in the detector alignment and Lambda studies
DIRAC NOTE 2016-01

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February 12, 2016

1 Introduction

In order to improve the aligment and the general geometry description of the DIRAC experiment, we use the Λ and $\bar{\Lambda}$ particles that decay in our setup into $p\pi^-$ and $\pi^+\bar{p}$. The Lambda mass is very well determined [1] and comparing the value reconstructed in our data with the published one we can be confident that our geometrical description is correct. This work is an update of the work presented in [2], after the update in the Multiple Scattering description in the simulation [3] and some improuvement in the tracking and analysis techniques it has been necessary to re-check and update the alignment.

2 Event selection

We select Λ and $\bar{\Lambda}$ particle events from the experimental data 2008, 2009 and 2010 that have been collected using a dedicated trigger. The following cuts are applied :

- in prompt events, the time difference in the vertical hodoscope (VH) is $|\Delta T_{VH}| < 0.5ns$
  - for the alignment study: the transverse momentum between pion and proton $Q_T < 10$ MeV/c
  - for the Lambda mass measurement: $|Q_X| < 4MeV$ and $|Q_y| < 4MeV$, cut applied by the trigger T4 and T1 on data for the year 2008-2009.
- to avoid mis-matching in the reconstruction, pion and proton tracks should be separated in at least two planes of the SFD detector, then two of the following criteria on the distance of the hit columns, Δn_{SFD}, associated to the tracks should be true :$|\Delta n_{SFDx}| > 5$, $|\Delta n_{SFDy}| > 5$, $|\Delta n_{SFDw}| > 7$
- in order to take into account any difference between the distributions of the generated momenta for the simulated Lambda particles and the experimental one, we apply a weight on the MC events to correct for this effect
- we have generated Lambda events using the last results we have on the multiple scattering in the SFD detector [3]

The simulated data have been submitted to the same selection cuts.

3 Lambda mass

The study has been performed on the experimental data for the years 2008, 2009 and 2010. For every year data-set we have used the appropriate corresponding simulation, the different calibration of the detectors, and the different conditions of background.

Following what has been already done in the past [2], looking at the Lambda mass value after changing the geometrical parameters, we have verified that the position of the Aluminum membrane and the opening angle of the downstream arms are correctly evaluated. As a first approximation the best value for z coordinate of the Aluminum membrane from the center of the magnet is:

$$PosMembrane = 143.385 \text{ cm}$$

this value is then used during the tracking procedure as the z coordinate of the track in the exit plane of the magnetic field of the spectrometer magnet.

Using the alignment given by the detector survey we obtain from the experimental data the invariant mass distribution of the proton/pion system for Lambda and Anti-Lambda and we obtain M_Λ and $M_{\bar{\Lambda}}$ respectively.

We have the possibility to reconstruct again the same events with a new alignment changing the angles, a_1 and a_2 that are defined as the corrections of the angles between the setup axis and the axes of the negative and positive arms in the XY plane.

We change a_1 and a_2 till we obtain the same value of the mass for the Lambda and the Anti-Lambda particles.

Once we find this pair of angles (a_1^0 and a_2^0) we calculate the middle axis between the two and we vary the angles a_1 and a_2 of the same amount δ, keeping fixed the axis center. The angle variation δ leads to a variation of Λ and $\bar{\Lambda}$ masses in opposite direction. Therefore the variation like $a_1 = a_1^0 - \delta$ and $a_2 = a_2^0 + \delta$ allows to synchronously change of M_Λ and $M_{\bar{\Lambda}}$ till the value of both the Λ and $\bar{\Lambda}$ masses are the same as the PDG value. As a test we verify that the Anti-Lambda mass $M_{\bar{\Lambda}}$ is compatible with M_Λ, the results are in 1.

year	$\bar{\Lambda}$ mass - 1.11 GeV/c^2	$\bar{\Lambda}$ width
2007 noMDC 2pl	$5.68\ 10^{-3} \pm 2.5\ 10^{-5}$	$4.3\ 10^{-4} \pm 3.\ 10^{-5}$
2008 3pl	$5.68\ 10^{-3} \pm 1.6\ 10^{-5}$	$4.6\ 10^{-4} \pm 2.\ 10^{-5}$
2009 3pl	$5.65\ 10^{-3} \pm 2.2\ 10^{-5}$	$4.5\ 10^{-4} \pm 3.\ 10^{-5}$
2010 3pl	$5.64\ 10^{-3} \pm 2.0\ 10^{-5}$	$4.3\ 10^{-4} \pm 2.\ 10^{-5}$

Table 1: Anti-Lambda mass and width in GeV/c^2 for the 2007, 2008, 2009 and 2010 experimental data.

The opening angle of the DC arms (in the XZ-plane) should be corrected by the quantities presented in Table 2.

This means that the opening angle between the downstream arms axes are few tenths of a milliradian wider that the default GEANT description of the experiment.

Fig 1 shows the distribution of the Lambda and Anti-Lambda masses for the 2008, 2009 and 2010 data run, the events are selected according with the event selection described above, with the additional cut of $|Q_X| < 4MeV$ and $|Q_y| < 4MeV$, this cut is applied by the trigger on data for the year 2008-2009, and the comparison data and MC is more accurate in this region. The distributions are fitted by ROOT with a gaussian and a second degree polynomial, that describes

year	Correction 1st arm in radians a_1	Correction 2st arm in radians a_2
2007	$-0.04\ 10^{-3}$	$0.08\ 10^{-3}$
2008	$-0.03\ 10^{-3}$	$0.11\ 10^{-3}$
2009	$-0.015\ 10^{-3}$	$0.08\ 10^{-3}$
2010	$-0.035\ 10^{-3}$	$0.085\ 10^{-3}$
2012	$-0.039\ 10^{-3}$	$0.087\ 10^{-3}$

Table 2: Corrections of the opening angle in the XZ plane of the arms respect to the survey measurement.

the background, the results are given for $M_\Lambda - 1.11$ GeV/c^2 and $M_{\bar{\Lambda}} - 1.11$ GeV/c^2 in Tables 1 and 3.

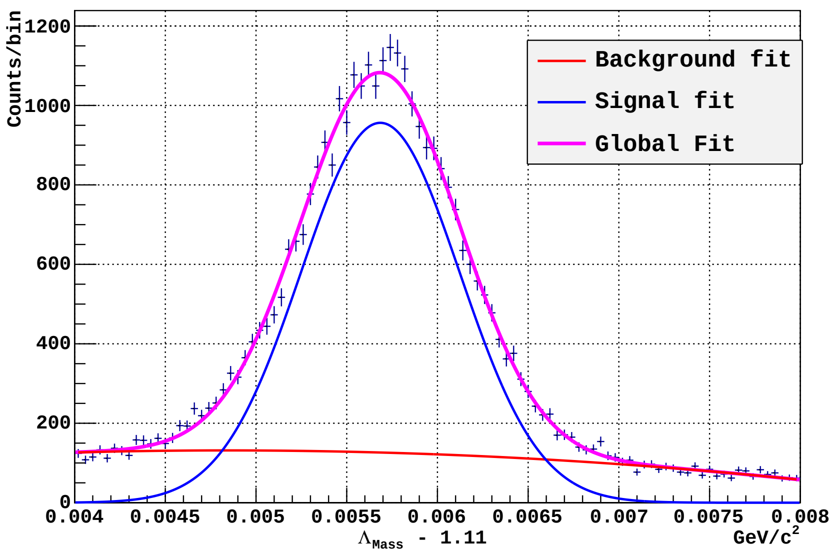

Figure 1: Lambda mass distributions for the 2008-9-10 experimental data.

The weighted average of the Dirac experimental value for the Λ particle mass is

$$M_\Lambda^{Dirac} = 1.115680 \pm 2.9\ 10^{-6}\mathrm{GeV/c^2}$$

for the entire set of data of 2007, 2008, 2009 and 2010, in very good agreement with the PDG value.

$$M_\Lambda^{PDG} = 1.115683 \pm 6\ 10^{-6}\mathrm{GeV/c^2}$$

This confirms that the geometry of the Dirac experiment is well described.

Λ mass - 1.11 GeV/c^2	Data	MC
2007 noMDC 2pl	$5.679\ 10^{-3} \pm 5.0\ 10^{-6}$	$5.679\ 10^{-3} \pm 2.7\ 10^{-6}$
2008 2pl	$5.679\ 10^{-3} \pm 4.5\ 10^{-6}$	$5.678\ 10^{-3} \pm 2.8\ 10^{-6}$
2008 3pl	$5.689\ 10^{-3} \pm 6.7\ 10^{-6}$	$5.683\ 10^{-3} \pm 2.9\ 10^{-6}$
2009 3pl	$5.676\ 10^{-3} \pm 5.9\ 10^{-6}$	$5.675\ 10^{-3} \pm 4.3\ 10^{-6}$
2010 3pl	$5.692\ 10^{-3} \pm 6.1\ 10^{-6}$	$5.689\ 10^{-3} \pm 4.5\ 10^{-6}$

Table 3: Lambda mass in GeV/c^2 for the 2007, 2008, 2009 and 2010 experimental and MC data.

4 Lambda mass width

The width of the Lambda mass distribution is a test of how well we reproduce the momentum and angle resolution of the setup in the simulation. From Table 4 we see a good agreement between the Lambda width in the simulation and in the experimental data.

Λ width -1.11 GeV/c^2	Data	MC
2007 noMDC	$4.22\ 10^{-4} \pm 4.6\ 10^{-6}$	$4.15\ 10^{-4} \pm 2.9\ 10^{-6}$
2008 2pl	$4.34\ 10^{-4} \pm 3.8\ 10^{-6}$	$4.31\ 10^{-4} \pm 3.0\ 10^{-6}$
2008 3pl	$4.33\ 10^{-4} \pm 8.2\ 10^{-6}$	$4.38\ 10^{-4} \pm 4.6\ 10^{-6}$
2009 3pl	$4.42\ 10^{-4} \pm 7.4\ 10^{-6}$	$4.42\ 10^{-4} \pm 4.4\ 10^{-6}$
2010 3pl	$4.41\ 10^{-4} \pm 7.5\ 10^{-6}$	$4.37\ 10^{-4} \pm 4.5\ 10^{-6}$

Table 4: Lambda width in GeV/c^2 for the 2007, 2008, 2009 and 2010 experimental and MC data.

In order to understand if the differences between data and MC are significant or are just due to statistical flctuations we have built Monte Carlo distributions with the width artificially squeezed and enlarged. For every simulated event we have calculated x, the Lambda mass as the invariant mass of the system pion-proton and calculated the new variable $x^{'}$:

$$x^{'} = (x - M_{MC}) * f + M_{DATA}$$

where f is a parameter that shrinks or enlarge the Lambda distribution of ±20% with a step of 2%. We then compare (bin by bin) the experimental and MC distributions building a χ^2 distribution using the following formulae

$$\chi^2 = \Sigma_i \frac{(Data(i) - MC_j(i))^2}{(\sigma^2_{Data(i)} + \sigma^2_{MC(i)})}$$

Then we find for which value of f the χ^2 has the minimum. Dependence of χ^2 on f is fitted by function on Figure 2. In the plot value along abscissa $X = 10$ corresponds to $f = 1$. (no enlargement in the width), and $X = 11$ means $+2\%$ smearing, $X = 9$ means -2% squeezing.

The difference between data and MC width could be the consequence of the imperfect description of the downstream part of the detector and can be fixed introducing a gaussian smearing in the reconstructed momenta. We apply event by event the smearing given by the formulae below where p(p) and $p(\pi^-)$ are the reconstructed proton and pion momenta respectively, and Gauss(0,0.0001) is a random number generated accordingly to a Gaussian distribution with mean = 0 and sigma=0.0001.

```
Double_t fitf(Double_t *x, Double_t *par)
{
  Double_t arg = 0;
  Double_t arg1 = 0;

  arg1 = (x[0]-10.)*0.02 + 1.;

  if (arg1 > 0) {
   if (arg1 > par[1]) arg= par[0] + par[2]*(arg1/par[1]-1.)**2;
    if (arg1 <= par[1]) arg= par[0] + par[2]*(par[1]/arg1-1.)**2;
  };

  return arg;
}
```

Figure 2: Fitting function for the χ^2.

$$p(\mathrm{p})^{smeared} = p(\mathrm{p})\ (1 + j \times Gauss(0, 0.0001))$$

$$p(\pi^-)^{smeared} = p(\pi^-)\ (1 + j \times Gauss(0, 0.0001))$$

We let j vary between 0 and 18, and for every value of j we build a new Lambda mass distribution. Width of distribution increases with j (see Table 5). It allows to find values of j for f value which provides minimal χ^2 (if $f \geq 1$). This technique is used to prepare Monte-Carlo distributions over relative momentum Q in a pair CM system and its projection for analysis of experimental data, taking into account difference between resolution at experiment and GEANT-based simulation. Also we then compare (bin by bin) the experimental and MC distributions for Λ as function of j (see Figure 4), building a χ^2 distribution, using the same formulae as above.

5 2007

During the 2007 data taking the X plane of the SFD detector was not available so the tracking is performed with the two planes: Y and W, and it's marked as 2pl. The data presented here are the one taken at the beginning of the run when the MDC were not istalled and were we have the most of the statistics. In order to compare the results of the 2007 with only two planes tracking we have run the tracking algorithm on the 2008 data and MC where we artificially switch off the X plane of the SFD, SFDX. The results on the Lambda width are different between 2007 and 2008, and this is due to the extra multiple scattering in the MDC detector that we have in 2008 but not in 2007. While interesting fact is that we need for both 2007 and 2008 with the 2pl tracking similar enlargements of the Lambda of width. For 2007 it is 2.7%. This increment in the Lambda width can be obtained with a smearing in momentum of 0.68 per mille according to Table 5.

In figure 6 is shown the χ^2 dependence of the experimental data 2008 2pl and the MC distributions, the minimum of the χ^2 is found for a smearing $f = 1.019 \pm 0.002$.

We then apply the smearing of 0.00068 to the reconstructed momenta, and as expected the data and simulated distributions are in perfect agreement, Fig 5.

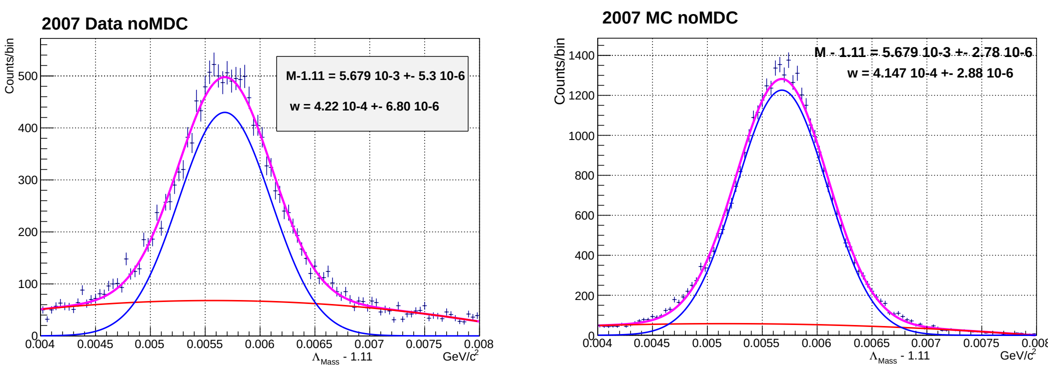

Figure 3: Lambda mass distribution for the 2007 data and MC without the MDC installed.

For data 2007, the study of the systematic error due to the uncertainty of the j parameter gives : 0.00067. The values for $\chi^2 \pm 1$ give the values of $j_{min} = 0.00038$ and $j_{max} = 0.00088$.

j parameter	Λ width -1.11 GeV/c^2
0	$4.1507\ 10^{-4} \pm 3.\ 10^{-6}$
1	$4.1661\ 10^{-4} \pm 3.\ 10^{-6}$
2	$4.1713\ 10^{-4} \pm 3.\ 10^{-6}$
3	$4.1893\ 10^{-4} \pm 3.\ 10^{-6}$
4	$4.2081\ 10^{-4} \pm 3.\ 10^{-6}$
5	$4.2258\ 10^{-4} \pm 3.\ 10^{-6}$
6	$4.2375\ 10^{-4} \pm 3.\ 10^{-6}$
7	$4.2954\ 10^{-4} \pm 3.\ 10^{-6}$
8	$4.3096\ 10^{-4} \pm 3.\ 10^{-6}$
9	$4.3999\ 10^{-4} \pm 3.\ 10^{-6}$
10	$4.4079\ 10^{-4} \pm 3.\ 10^{-6}$
11	$4.45630\ 10^{-4} \pm 3.\ 10^{-6}$
12	$4.52605\ 10^{-4} \pm 3.\ 10^{-6}$
13	$4.56474\ 10^{-4} \pm 3.\ 10^{-6}$
14	$4.57813\ 10^{-4} \pm 3.\ 10^{-6}$
15	$4.67780\ 10^{-4} \pm 3.\ 10^{-6}$
16	$4.73579\ 10^{-4} \pm 3.\ 10^{-6}$
17	$4.85415\ 10^{-4} \pm 3.\ 10^{-6}$
18	$4.92269\ 10^{-4} \pm 3.\ 10^{-6}$

Table 5: Lambda width in GeV/c^2 for the 2007 no MDC for different momentum smearing as function of j.

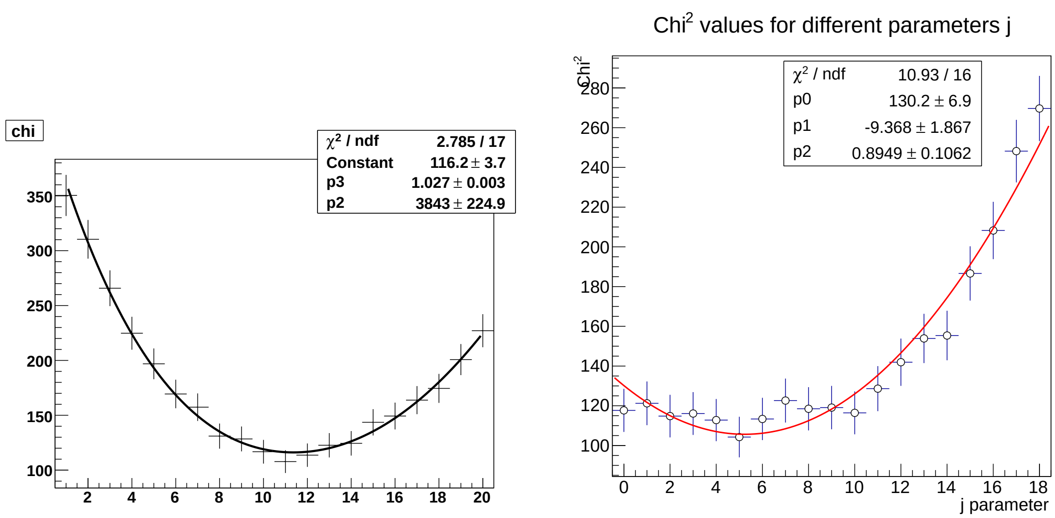

Figure 4: χ^2 dependence for the 2007 2pl tracking, on the left for different f parameters that squeezes and enlarges of the width, on the right for different j parameter.

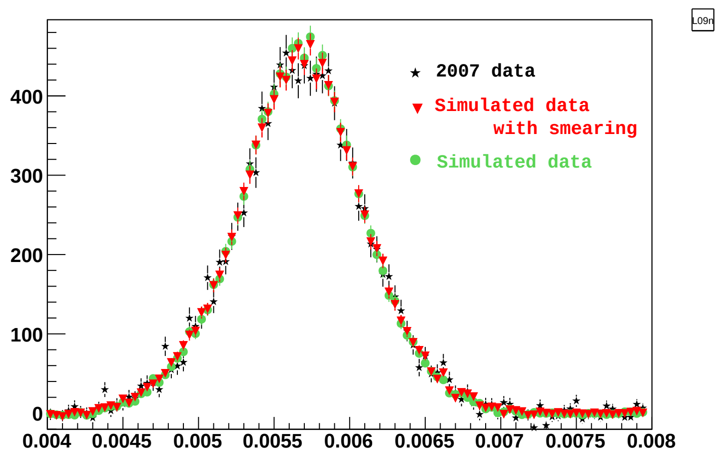

Figure 5: Lambda mass distribution for the 2007 data taken without the MDC. In green is the MC distribution with no smearing applied, in red is the MC simulation with the momentum smearing of 0.0005 applied, in black is the experimental data distribution.

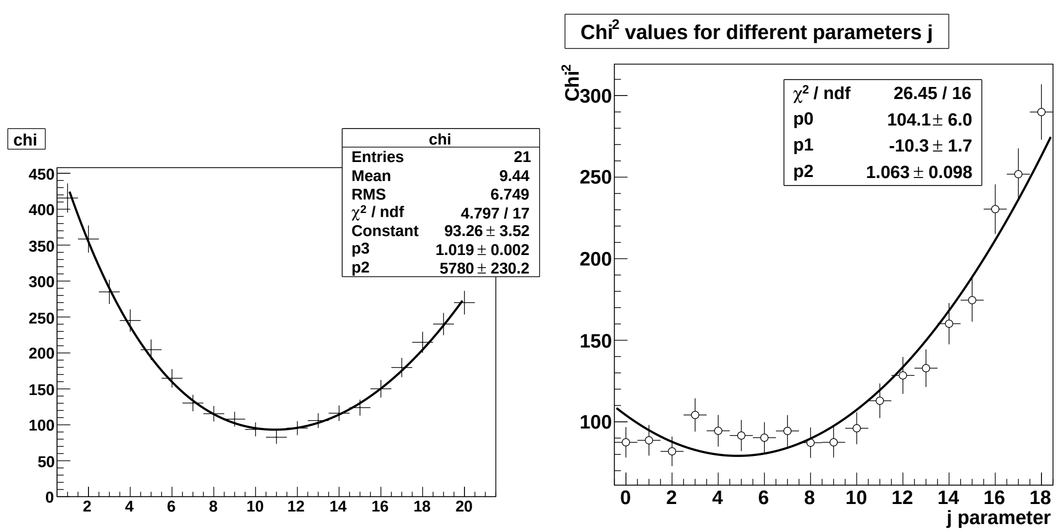

Figure 6: χ^2 dependence for the 2008 2pl tracking, on the left for different f parameters that squeezes and enlarges of the width, on the right for different j parameter.

6 2008 3pl

The analysis of the 2008 with the 3pl tracking gives good results, the Lambda width for data and MC is compatible, from the analysis of the χ^2 result that we do not need any extra smearing.

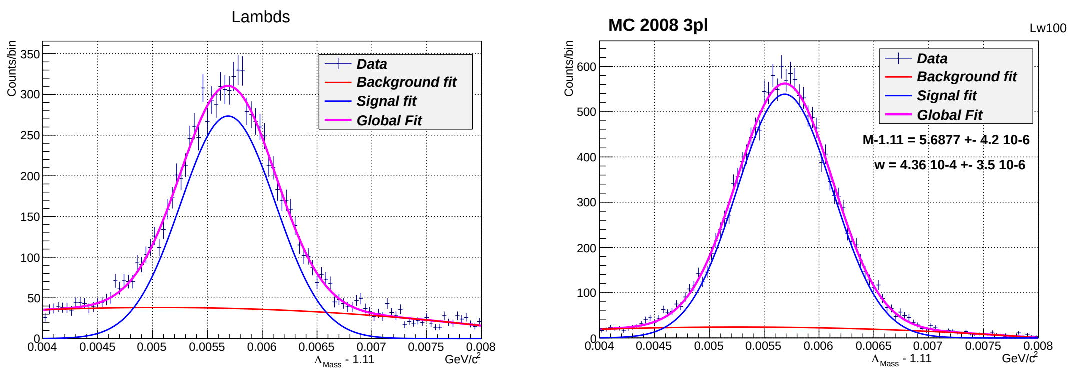

Figure 7: Lambda mass distribution for the 2008 data and MC.

j parameter	Λ width -1.11 GeV/c^2
0	$4.3676\ 10^{-4} \pm 4.\ 10^{-6}$
1	$4.3679\ 10^{-4} \pm 4.\ 10^{-6}$
2	$4.4018\ 10^{-4} \pm 4.\ 10^{-6}$
3	$4.4074\ 10^{-4} \pm 4.\ 10^{-6}$
4	$4.4182\ 10^{-4} \pm 4.\ 10^{-6}$
5	$4.4099\ 10^{-4} \pm 4.\ 10^{-6}$
6	$4.5043\ 10^{-4} \pm 5.\ 10^{-6}$
7	$4.4881\ 10^{-4} \pm 4.\ 10^{-6}$
8	$4.5303\ 10^{-4} \pm 5.\ 10^{-6}$
9	$4.5502\ 10^{-4} \pm 5.\ 10^{-6}$
10	$4.5883\ 10^{-4} \pm 5.\ 10^{-6}$
11	$4.6702\ 10^{-4} \pm 5.\ 10^{-6}$
12	$4.7237\ 10^{-4} \pm 5.\ 10^{-6}$
13	$4.7476\ 10^{-4} \pm 5.\ 10^{-6}$
14	$4.8642\ 10^{-4} \pm 5.\ 10^{-6}$
15	$4.8928\ 10^{-4} \pm 6.\ 10^{-6}$
16	$4.9786\ 10^{-4} \pm 6.\ 10^{-6}$
17	$4.8944\ 10^{-4} \pm 7.\ 10^{-6}$
18	$4.9999\ 10^{-4} \pm 7.\ 10^{-6}$
19	$5.1578\ 10^{-4} \pm 6.\ 10^{-6}$

Table 6: Lambda width in GeV/c^2 for the 2008 for different momentum smearing as function of j.

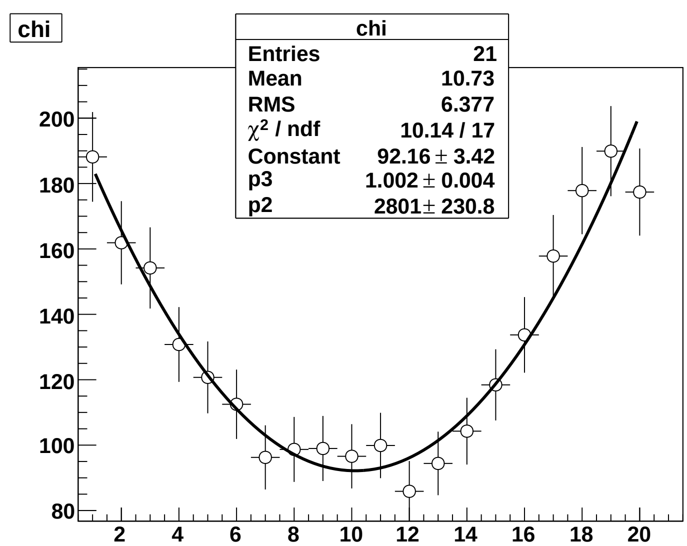

Figure 8: χ^2 dependence for the 2008 3pl tracking, for different f parameters that squeezes and enlarges of the width.

7 2009

The analysis of the 2009 with the 3pl tracking gives good results, the Lambda width for data and MC is compatible, from the analysis of the χ^2 result that we do not need any extra smearing. Figure 9 shows the Lambda mass distributions for data and MC, figure 10 shows the χ^2 values of the fit between the data and the MC distribution with different f parameters. The minimum is compatible with no smearing.

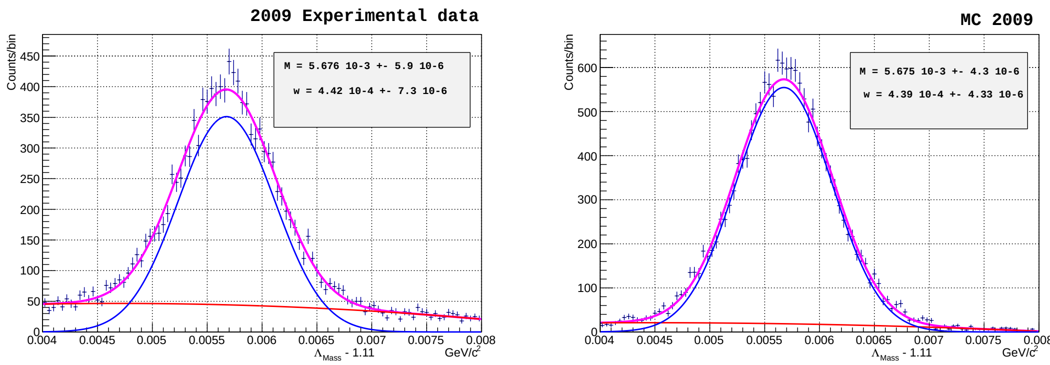

Figure 9: Lambda mass distribution for the 2009 data and MC.

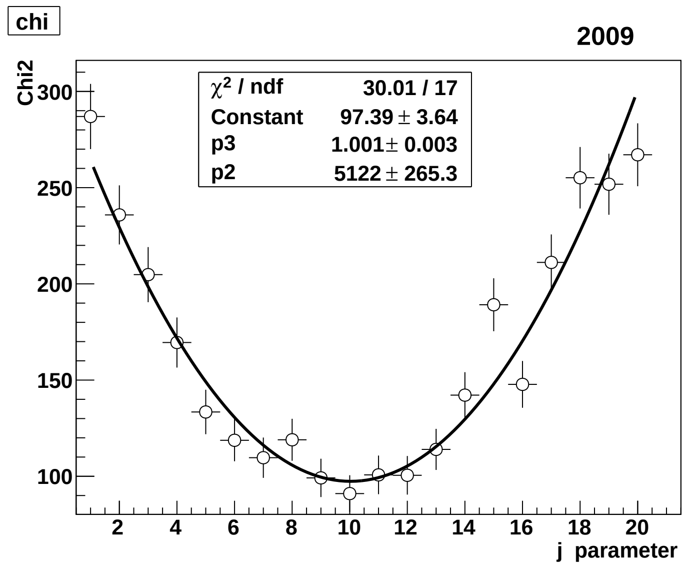

Figure 10: χ^2 dependence for the 2009 3pl tracking, for different f parameters that squeezes and enlarges of the width.

j parameter	Λ width -1.11 GeV/c^2
0	$4.3953\ 10^{-4} \pm 4.\ 10^{-6}$
1	$4.5121\ 10^{-4} \pm 4.\ 10^{-6}$
2	$4.4292\ 10^{-4} \pm 4.\ 10^{-6}$
3	$4.4193\ 10^{-4} \pm 4.\ 10^{-6}$
4	$4.4213\ 10^{-4} \pm 4.\ 10^{-6}$
5	$4.4317\ 10^{-4} \pm 4.\ 10^{-6}$
6	$4.4760\ 10^{-4} \pm 5.\ 10^{-6}$
7	$4.5318\ 10^{-4} \pm 4.\ 10^{-6}$
8	$4.5344\ 10^{-4} \pm 5.\ 10^{-6}$
9	$4.5709\ 10^{-4} \pm 5.\ 10^{-6}$
10	$4.6092\ 10^{-4} \pm 5.\ 10^{-6}$
11	$4.6586\ 10^{-4} \pm 5.\ 10^{-6}$
12	$4.7033\ 10^{-4} \pm 5.\ 10^{-6}$
13	$4.7499\ 10^{-4} \pm 5.\ 10^{-6}$
14	$4.8765\ 10^{-4} \pm 5.\ 10^{-6}$
15	$4.8695\ 10^{-4} \pm 6.\ 10^{-6}$
16	$4.8868\ 10^{-4} \pm 6.\ 10^{-6}$
17	$4.8907\ 10^{-4} \pm 7.\ 10^{-6}$
18	$4.8783\ 10^{-4} \pm 7.\ 10^{-6}$
19	$4.8815\ 10^{-4} \pm 7.\ 10^{-6}$

Table 7: Lambda width in GeV/c^2 for the 2009 for different momentum smearing as function of j.

8 2010

The analysis of the 2010 with the 3pl tracking gives good results, the Lambda width for data and MC is compatible, from the analysis of the χ^2 result that we do not need any extra smearing. Figure 11 shows the Lambda mass distributions for data and MC, figure 12 shows the χ^2 values of the fit between the data and the MC distribution with different f parameters. The minimum is compatible with no smearing.

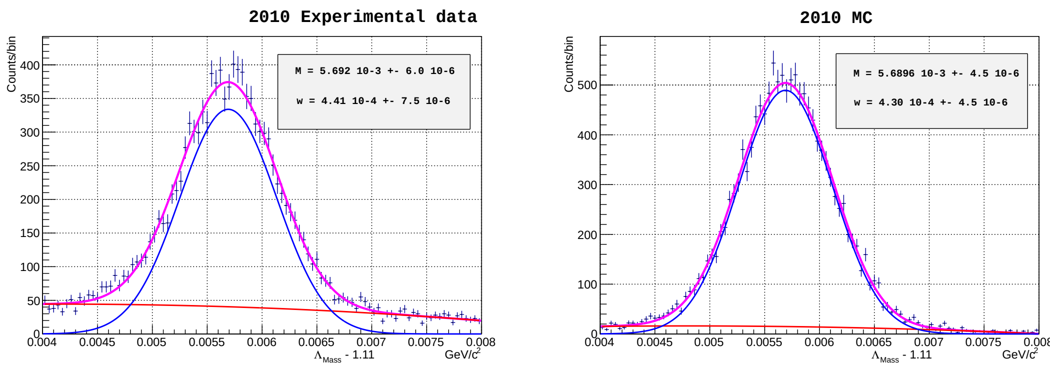

Figure 11: Lambda mass distribution for the 2010 data and MC.

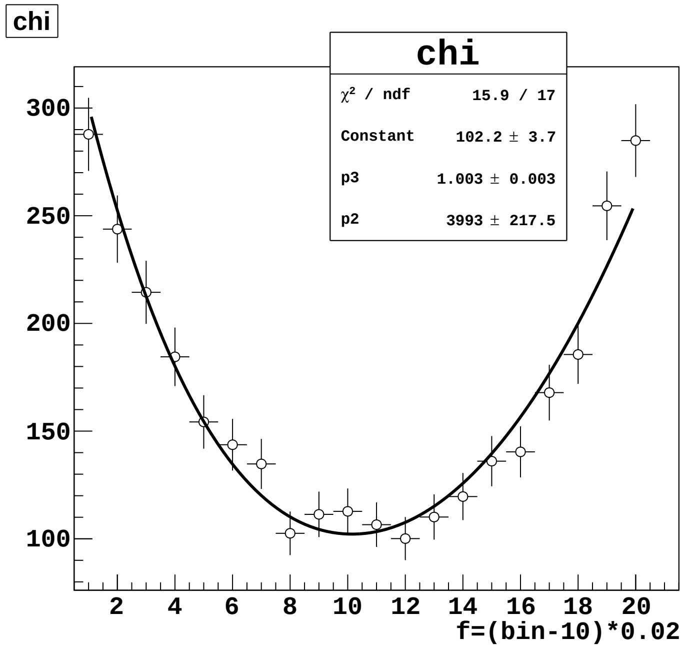

Figure 12: χ^2 dependence for the 2010 3pl tracking, for different f parameters that squeezes and enlarges of the width.

j parameter	Λ width -1.11 GeV/c^2
0	$4.368\ 10^{-4} \pm 4.\ 10^{-6}$
1	$4.375\ 10^{-4} \pm 4.\ 10^{-6}$
2	$4.399\ 10^{-4} \pm 4.\ 10^{-6}$
3	$4.391\ 10^{-4} \pm 4.\ 10^{-6}$
4	$4.416\ 10^{-4} \pm 4.\ 10^{-6}$
5	$4.422\ 10^{-4} \pm 4.\ 10^{-6}$
6	$4.467\ 10^{-4} \pm 5.\ 10^{-6}$
7	$4.466\ 10^{-4} \pm 4.\ 10^{-6}$
8	$4.566\ 10^{-4} \pm 5.\ 10^{-6}$
9	$4.558\ 10^{-4} \pm 5.\ 10^{-6}$
10	$4.615\ 10^{-4} \pm 5.\ 10^{-6}$
11	$4.680\ 10^{-4} \pm 5.\ 10^{-6}$
12	$4.761\ 10^{-4} \pm 5.\ 10^{-6}$
13	$4.715\ 10^{-4} \pm 5.\ 10^{-6}$
14	$4.877\ 10^{-4} \pm 5.\ 10^{-6}$
15	$4.949\ 10^{-4} \pm 6.\ 10^{-6}$
16	$4.981\ 10^{-4} \pm 6.\ 10^{-6}$
17	$4.998\ 10^{-4} \pm 7.\ 10^{-6}$
18	$5.055\ 10^{-4} \pm 7.\ 10^{-6}$
19	$5.124\ 10^{-4} \pm 7.\ 10^{-6}$

Table 8: Lambda width in GeV/c^2 for the 2010 for different momentum smearing as function of j.

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