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Updated analysis of Sigma- Antihyperon correlations

P.Bock
Physikalisches Institut der Universität Heidelberg

1 The principle

Combined baryon number and strangeness conservation in multihadronic events containing a Σ^- hyperon.

The correlated particles looked at are:

$\overline{\Sigma^-}$, $\overline{\Sigma^+}$, $\overline{\Lambda}$ (including decays of $\overline{\Sigma^0}$) and $\overline{\Xi^-}$.

It is the understanding that the equivalent antiparticle correlations are always added.

Signatures

- Σ^- decays are reconstructed explicitly
- Reconstructed $\overline{\Lambda}$'s are either produced directly, or they arise from decays of $\overline{\Sigma^0}$ or $\overline{\Xi^-}$. The last case is characterized by large values of the impact parameter $d_{0,\Lambda}$.
- Pions from weak decays are a common signature for all antihyperons.
  The intensities depend on the particle type.
  They are characterized by finite impact parameters $d_{0,\pi}$.

2 Event selection

- Search for Sigma candidates: kink analysis, see PR

  Additional cut: The reconstructed Σ mass has to be lower than 1.50 GeV (charge asymmetric background at higher masses)

- Search for Lambda candidates:

  - V0 finder, as used in Λ search paper.
  - The angle between the flight directions of the Λ and the Σ candidates at the primary vertex is required to be less than 90 degrees (hemisphere cut,new).
  - If reconstructed Λ direction points back to the (r,ϕ) position of the kink, it is believed that the kink is due to a decay $\Xi \to \Lambda\pi$ and this autocorrelation is dropped (new).

- Search for delayed pion emission

  The following cuts have been applied for track selection:

  - $p_T > 0.15$ GeV/c
  - $|\cos\theta| \leq 0.80$
  - $N_{dE/dx} \geq 20$
  - $W_{dE/dx}(\pi) \geq 0.02$
  - The angle between the flight directions of the pion and the Σ at the primary vertex is requested to be less than 90 degrees (hemisphere cut).

The hemisphere cut is motivated by the fact that it almost never happens that baryon number and strangeness are compensated by an antihyperon in the opposite event hemisphere. This cut reduces the track background by a factor 2.

The observables:

- Position of a kink in a 2-dimensional plane of the reconstructed Σ mass vs. the reconstructed pion decay angle in the rest frame of the hypothetical Σ (see figure 6). Three regions have been defined with enrichment of Ξ,Σ and Kaons. Around the Sigma mass a fourth region has been introduced, in which Sigmas overlap strongly with Kaons.

  This variable is used for Sigma counting and for the analysis of correlations.

- $d_{0,\pi}$ distribution of the selected tracks.

- $d_{0,\Lambda}$ distribution of the selected Lambda candidates. The Lambda candidates have to lie between the masses 1.10 and 1.13 GeV.
  These two distributions are used for the analysis of correlations.

- the reconstructed mass distribution of the selected Lambda candidates from threshold up to 1.2 GeV. This last distribution is used to adjust the combinatorial background and the K^0 background in the search for Λ's.

3 Monte Carlo event classes

Monte Carlo events are classified according to their physical origin.

Track kinks (negative charge) may arise from

1. Σ^-
2. $\overline{\Sigma^+}$
3. $\overline{\Xi^-}$
4. K^-
5. Background: Secondary interactions (mainly particle scattering) or combinatorial background.

The same classification is introduced for positive charge.

Seven sources for correlated positive particles have been defined:

1. $\overline{\Lambda}$
2. $\overline{\Xi^-}$
3. K^0
4. combinatorial V^0 background
5. $\overline{\Sigma^-}$ and Σ^+.
   Two sources are combined here, because the fraction of Σ^+'s correlated to Σ^- kinks is not very large.
6. K^-
7. charged particles not from hyperon decays.
   - Mainly from hadronic interactions.
   - Track reconstruction errors are another possibility.
   - It should be noted that, due to the lower $d_{0,\pi}$ cut, charged particles from charm or bottom decays are not selected.

Sources 5 to 7 are irrelevant for the Λ search channel, source 4 does not contribute to the correlated track search.

The same classification is introduced for negative charge.

- In total, there are $5 \cdot 7 = 35$ Monte Carlo classes. Some of them are very important, other ones have only a few entries.

- To define the MC event class, only the particle origin is used, the particle type is not checked.
- It is not garanteed that a selected charged particle is a pion. Kaons and protons may be accepted too, which is considered as a reconstruction error.
- Selected protons may introduce correlations with the wrong sign. The effect is incorporated in the Monte Carlo simulation. Nevertheless, a systematic error has to be assigned to this.

4 Determination of correlations

- The data (unlike sign minus like sign) can be described by a weighted sum of the 35 d_0 distributions from the MC:
$$D(d_0) = \sum_{i=1}^{5} \sum_{k=1}^{7} F_{ik} \cdot D_{MC}(d0) \qquad (1)$$
where i is the kink source and k the correlated particle source.

- The determination of rescaling factors is described later.

- The particle and Lambda d_0 distributions are fitted simultaneously.

- The distribution of the Sigma candidates in the mass vs. angle plane can be disentangled according to the kink sources, which gives a data to MC rescaling factor F_Σ for counted Σ candidates.

- The correlated antihyperon rate per Σ is then given by
$$R_k = \frac{F_{\Sigma,k}}{F_\Sigma} \cdot R_{MC,k} \qquad (2)$$
Here, $R_{MC,k}$ is the Monte Carlo prediction for the number of compensating antiparticles k per Σ.

- Note: The detection probability for Σ's cancels out.

- Note: The error of the single particle unfolding does not cancel out.

- The word 'efficiency' is not used here. The efficiencies are hidden in the Monte Carlo distributions.

5 Total correlated Monte Carlo rates

According to the preceding section, the produced numbers of correlated particles have to be known for the Monte Carlo samples which were used to analyse the data.

Dirk Wetterling had produced special 'efficiency n-tuples' which are analogous to the n-tuples used for data analysis. These were originally used to determine the detection efficiency of pions and Λ's.

MC events with Σ^- were selected.

The Monte Carlo tree is scanned backwards:

For pions, protons, kaons (charged and neutral), the start flags, the mother particle types and the start flags of the mother were extracted.

The correlated production rates can be computed from the unlike sign - like sign differences of Σ - particle pairs.

The table shows for MC run 5021 the extracted numbers. For comparison, results from dedicated simulations of Dirk Wetterling (PYTHIA 5.6) and Paul Utzat(HETSET 7.4) are given, both with a popcorn parameter 0.5.

- **Important**: A negative sign in the table means, that the corresponding selection in the data gives a correlation with the opposite sign.

correlated particle	requested in MC tag	from efficiency file	PYTHIA simulation	JETSET simlation
$\overline{\Sigma^-}$	π^+	0.288	0.344	0.252
$\overline{\Sigma^+}$	π^-	-0.0234	0.013	0.016
	$\overline{p}$	-0.0183		
$\overline{\Xi^-}$	π^+	0.145	0.151	0.181
	$\overline{\Lambda}$	0.142		
	$\overline{p}$	0.144		
$\overline{Xi^0}$	$\overline{\Lambda}$	0.014	0.013	0.018
$\overline{\Lambda}$	π^+	0.271	0.290	0.292
	$\overline{\Lambda}$	0.279		
	$\overline{p}$	-0.265		
prompt K^+	K^+	0.042		
prompt $\overline{p}$	$\overline{p}$	-0.067	0.042	0.05
prompt $\overline{n}$	—	0.18	0.16	0.19

Table 1: The unlike sign minus like sign difference of antiparticle production per Σ at generator level.

- Because the like sign part is not the same in different tag channels, some statistical MC fluctuations survive.
- Furthermore, there are, in the MC, conflicting associations of the particle charge and the type of the mother particle at a level of 1%.
- The proton start flags seem to be completely wrong, but this effect cancels out in the sum of pairs and anti-pairs.
- **Consistency check:** In the sum over all events, a test on strangeness conservation can be done with the correlated production rates R_k (k is the source of the correlated particle). The following weighted sum, which should be 1, is for the MC run

  $$R_{\Sigma^-} + |R_{\Sigma^+}| + R_\Lambda + 2 \cdot R_{\Xi^-} + 2 \cdot R_{\Xi^0} + 2 \cdot R_{K^-} = 0.987$$

  (the Ξ has strangeness 2, correlated K^0's are lost in the unlike sign minus like sign difference).
- A similar sum can be set up for the baryon number. It can be used to extract the number of antineutrons, which is not stored in the n-tuple. The result and its comparison with the dedicated simulations is included as the last row in the table. The selection of the charge for the Σ destroys the neutron-proton symmetry: Without popcorn mechanism, a $\overline{d}$ diquark from the Σ creates an antineutron.

In total, the extraction passes the consistency checks successfully within 1%.

6 The fit of the unlike sign-like sign difference

- Due to the low statistics, it is only possible to adjust a few of the 35 distributions (4).
- There are cases with identical fit parameters (swapping of kink source and correlated particle, for instance, $\Sigma - \overline{\Xi^-}$ and $\Xi - \overline{\Sigma^-}$)
- Correlations with V_0's or tracks from K^0 should vanish and are neglected.
- Correlations with combinatorial V_0 background should vanish and are neglected.
- Some background asymmetries to be subtracted rely still on Monte Carlo predictions, which will be invalidated during the fit process.

An **effect has been found**, which looks at first sight very shocking:

- The MC predicts an asymmetry of all kink sources with respect to the non-hyperon track background. Ignoring this, the final result would change by as much as 40% (the number of correlated antihyperons moves from 50% to 70%)!
- The effect is, after the real correlations of hyperons, the most important contribution to the asymmetry.

- The **simple explanation:** statistical charge correlation due to charge conservation in the events.
- direct result from MC:
  number of kinks= 14194
  non-hyperon tracks selected = 8617
  unlike-like = 353
  unlike-like per kink = 0.025 ± 0.0065
- Statistical estimate:
  - Spallation protons are not counted after track selection.
  - Therefore, charge conservation is kept by the secondary interactions, which are the origin of the track backgound.
  - For all observed kinks (all sources!), the fraction of charge conservation, which is reconstructed directly by track counting (unlike sign minus like sign), is 13 %.
  - On average over all MC events, the rest of the charge is distributed statistically over the remaining charged particles of the events.
  - Effective number of compensating particles
    = number of tracks/charged multiplicity = 8617/20 = 430
    unlike-like per kink = $(1-0.13) \cdot 430/14194 = 0.026$
  - Agreement with 0.025!

correlated particle	Σ^- kink	$\overline{\Sigma^-}$ kink	Ξ^- kink	K kink	background
$\overline{\Lambda}$	F_2	RS	F_4	RS	0
$\overline{\Xi^-}$	F_3	RS	F_4	RS	0
K^0	0	0	0	0	0
V_0 background	0	0	0	0	0
$\overline{\Sigma^-}$	F_1 RS	F_3	RS		0
K^-	RS	RS	RS	RS	RS
track background	RS	RS	RS	RS	RS

Table 2: The mask for the fit of the unlike sign - like sign difference for all kink classes and all correlation classes. A factor F_j means that the correlated rate is fitted, the value '0' means that correlations are set to 0, and the letters 'RS' mean rescaled subtraction from MC.

correlated particle	Σ^- kink	$\overline{\Sigma^-}$ kink	Ξ^- kink	K kink	background
$\overline{\Lambda}$	F_{L4}	F_{L4}	F_{L4}	F_{L4}	F_{L4} F_{L5}
$\overline{\Xi^-}$	F_{L1}	F_{L1}	F_{L1}	F_{L2}	F_{L5}
K^0	F_{L3}	F_{L3}	F_{L3}	F_{L2}	F_{L5}
V_0 background	0	0	0	0	0
$\overline{\Sigma^-}$	F_{L1}	F_{L1}	F_{L1}	F_{L2}	F_{L5}
K^-	F_{L2}	F_{L2}	F_{L2}	F_{L2}	F_{L5}
track background	F_{L4}	F_{L4}	F_{L4}	F_{L4}	F_{L5}

Table 3: The mask for the fit of the like sign pairs for all kink classes and all correlation classes. A factor F_j means that the correlated rate is fitted, the value '0' means that correlations are set to 0, and the letter 'S' means subtraction from MC. The fit result goes into the statistical error of the asymmetry fit. Furthermore, the non-hyperon track background is adjusted.

antihyperon	the new analysis error: see remarks	Dirk Wetterlings thesis error: stat. and syst.
$\overline{\Sigma^-}$	0.137 ± 0.135	$0.120 \pm 0.150 \pm 0.120$
$\overline{\Lambda}$	0.306 ± 0.068	$0.240 \pm 0.073 \pm 0.056$
$\overline{\Xi^-}$	0.071 ± 0.061	$0.112 \pm 0.082 \pm 0.070$
all	0.514 ± 0.128	$0.472 \pm 0.126 \pm 0.090$

Table 4: Antihyperon rates per Σ: The individual results and their sum.

7 Preliminary results

The **error treatments** of the old and the new analysis are **not compatible**!

- Statistical errors of the Monte Carlo predictions, commonly given as systematic errors, are integrated part of the fit in the new analysis.
- So, the fit errors include all statistical **efficiency errors** and statistical errors of the **subtracted MC background asymmetries**.
- Because the Ξ **contribution** is fitted, no additional systematic error for Ξ kink subtraction is needed.
- In the **old analysis**, the statistical errors of detection efficiencies for pions and Lambdas are part of the systematic error, but the statistical error of MC background subtraction was included in the statistical error.

error source	$\overline{\Sigma^-}$	$\overline{\Lambda}$	$\overline{\Xi^-}$	total
unfolding of the Sigma single rate	4%	4%	4%	4%
errors from charge asymmetric detection efficiencies				
variation of the cuts				
sum				

Table 5: Systematic errors in the new analysis.

This makes a review of Dirk's systematic errors nessessary (a part of it disappears).

8 Comparison with the thesis of Dirk Wetterling

- **Good news:** The new, completely different analysis gives a similar result as the old analysis.

Differences of the procedures

- old: no hemisphere cut
  new: hemisphere cut
- old: event counting in the Σ enriched (mass/decay-angle) region
  new: full (mass/decay-angle) plane included
- old: one d_0 bin for the pions
  new: d_0 distribution used
- old: 2 d_0 bins for the correlated Λ's
  new: d_0 distribution used
- old: all background asymmetries subtracted as predicted by MC
  new: The contribution of Ξ kinks is fitted
- old: The non-hyperon track background was subtracted, but not isolated explicitly.
  (everything was subtracted which was not a pion from hyperon decay)
  new: The non-hyperon track background is rescaled according to the number of selected correlated tracks (like sign).

- The order of analysis steps has been changed completely.
  old: Σ and $\overline{\Sigma}$ parts added at the very end and invidual efficiencies were used
  new: Σ and $\overline{\Sigma}$ parts added at the beginning and the MC contributions were added too.

Within the new scheme it is possible to produce plots, which demonstrate the understanding (or non-understanding) of the data (MC rescaling needed).

It was hoped that the accuracy of the result could be improved, especially due to the hemisphere cut. At the moment it is not clear to me, why the new approach did not reduce the error (one more fit parameter?)

9 To-do list

The setup of the improved analysis had top priority!

- add missing MC run 2790.
- more plots (straight forward)
- better rescaling of the contribution from kaons. (respect the sum rule as discussed above) (simple)
- inclusion of the opposite event hemisphere in the fit? (simple)
- inclusion of more K^-? (no principal problem, but a lot of work).
- look at more systematic errors ($\ln(1/x_p)$ spectra, approximation of 'equal d_0 distributions' made to get smoother functions) (hopefully no surprises)

kink source	Σ^-	$\overline{\Sigma^+}$	Ξ^-	K^-	background
	4704	838	1591	5774	1287

Table 6: Total numbers of kinks from Monte Carlo simulation. The MC sample consists of $4.6 \cdot 10^6$ events.

correlated particle	Σ^- kink	$\overline{\Sigma^+}$ kink	Ξ^- kink	K^- kink	background
$\overline{\Lambda}$	129	66	58	121	82
$\overline{\Xi^-}$	76	21	101	38	25
K^0	558	86	194	869	154
$\overline{\Sigma}$	88	15	18	57	25
K^-	112	22	38	185	42
track background	1188	192	354	1840	558

Table 7: The number of like sign Monte Carlo pairs for all kink classes and all correlated charged particle classes.

correlated particle	Σ^- kink	$\overline{\Sigma^+}$ kink	Ξ^- kink	K^- kink	background
$\overline{\Lambda}$	256	-41	127	1	25
$\overline{\Xi^-}$	375	-13	132	11	6
K^0	-17	-11	38	-45	53
$\overline{\Sigma}$	579	+39	261	6	-2
K^-	16	-9	24	81	22
track background	137	30	38	109	39

Table 8: The asymmetry of Monte Carlo pairs for all kink classes and all correlated charged particle classes.

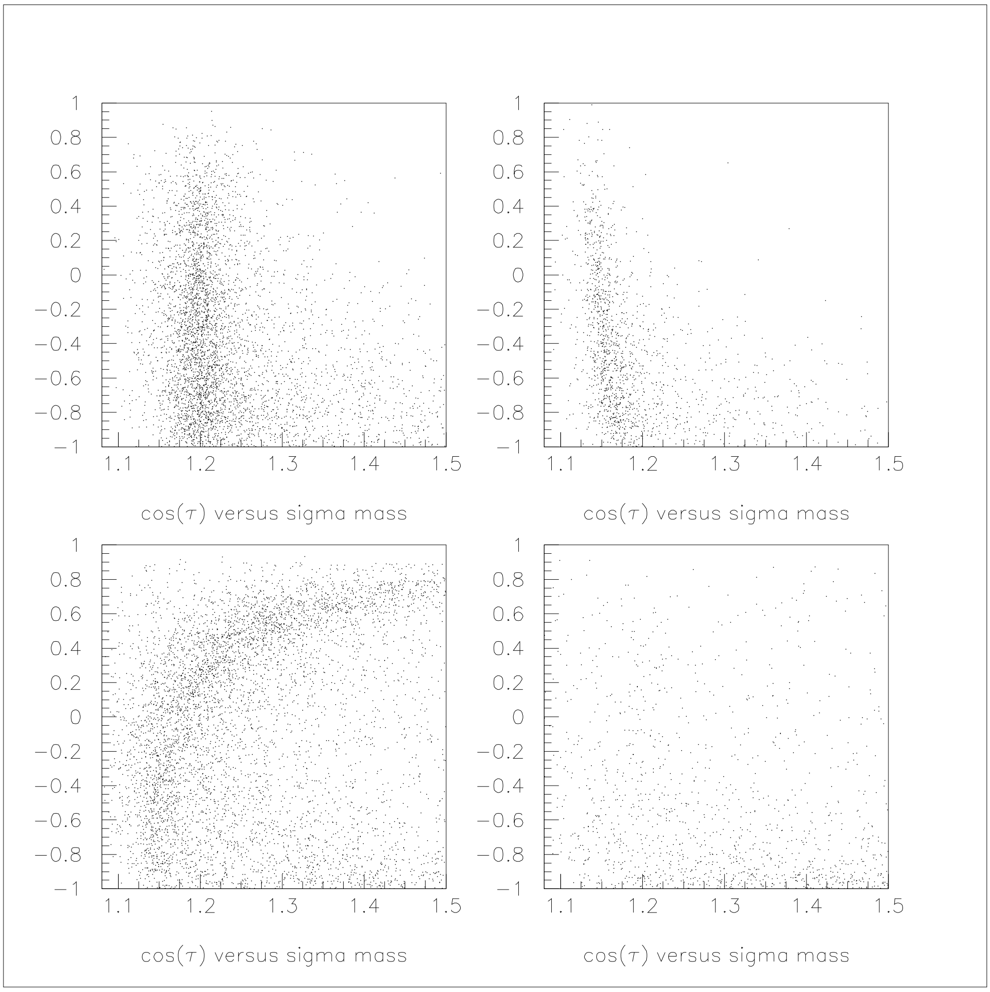

Figure 1: Monte Carlo distribution of track kinks in the hypothetical (Σ mass,pion decay angle) plane. Upper left: Σ source. Upper right: Ξ source. Lower left: Charged kaon source. Lower right: Background.

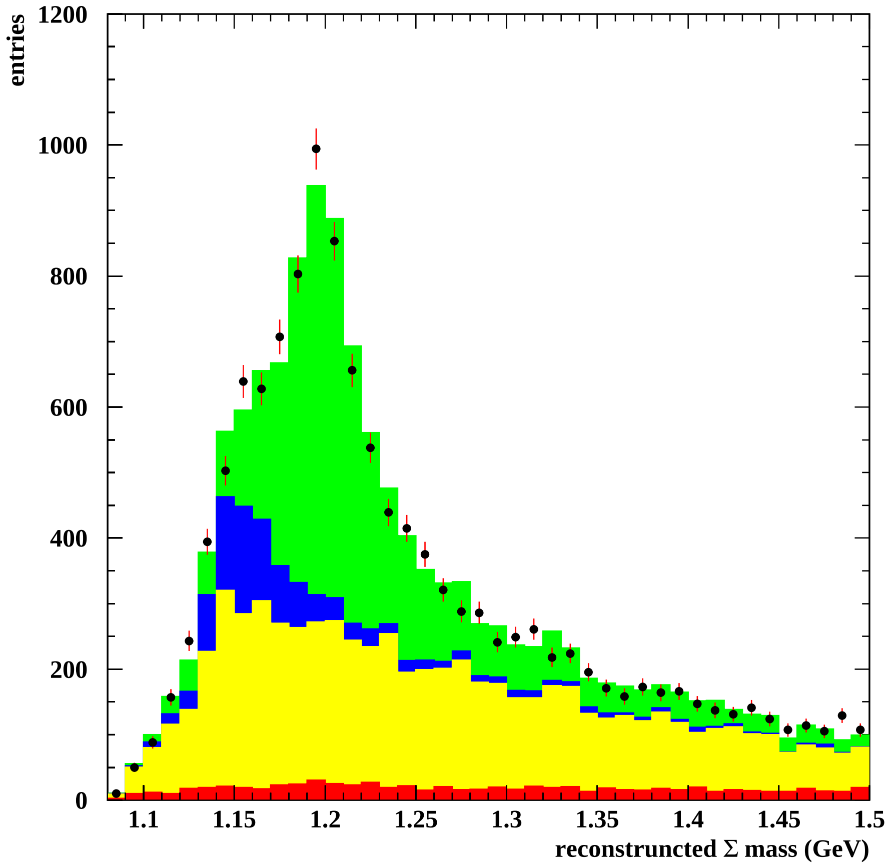

Figure 2: Reconstructed Sigma mass distribution. Green: Sigma, Blue: Xi, Yellow: K, Red:background.

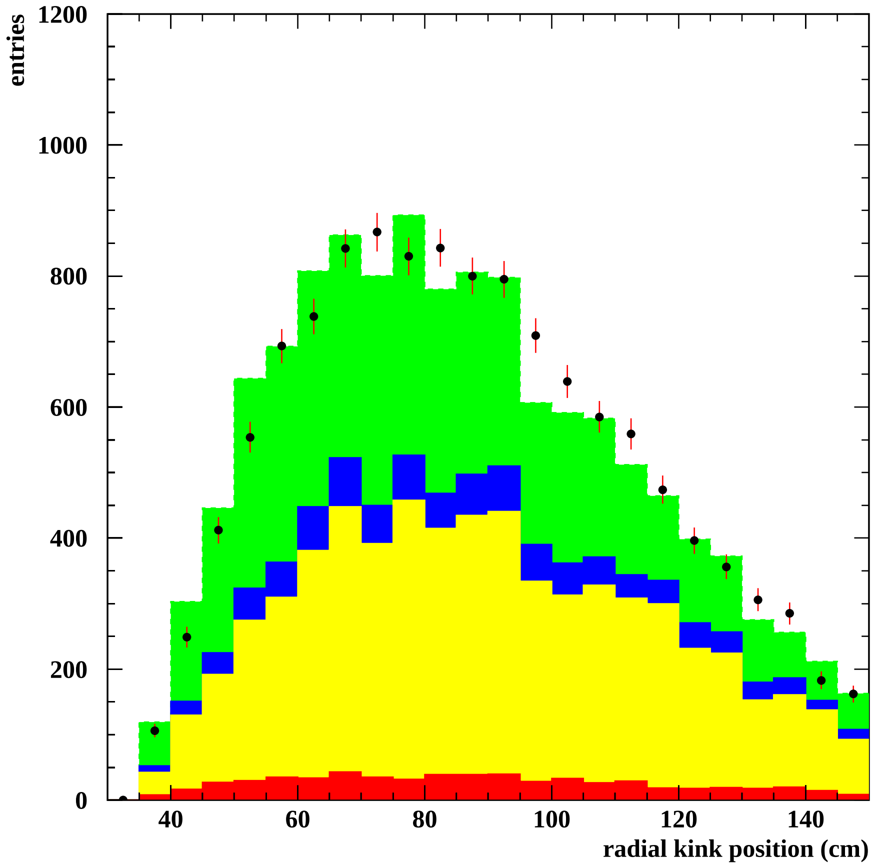

Figure 3: Reconstructed radial kink distribution. Green: Sigma, Blue: Xi, Yellow: K, Red:background.

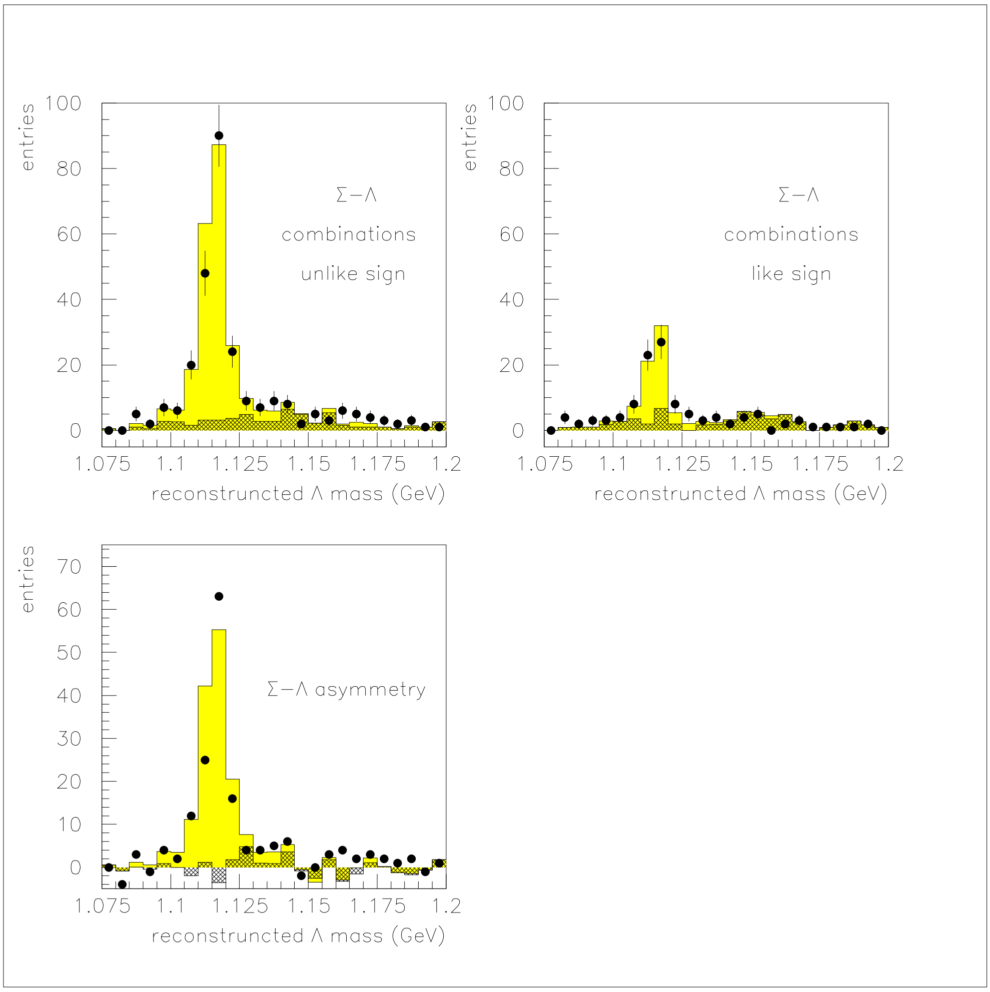

Figure 4: mass distribution for correlated Λ's. All kinks in the Σ enriched (mass/decay-angle) region are included. Yellow: All Λ's (including Ξ). Dark: Background. Upper left: unlike sign. Upper right: like sign. Lower left: Difference.

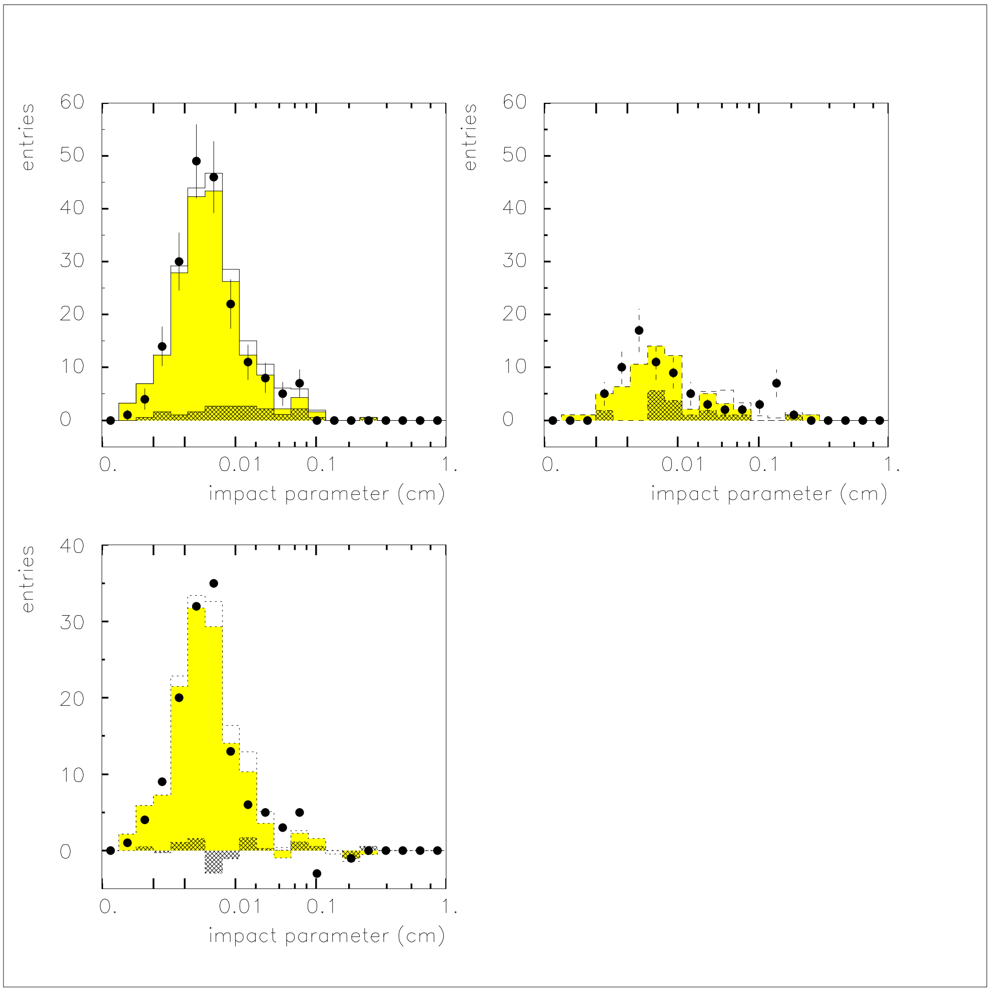

Figure 5: d_0 distribution for correlated Λ's. All kinks in the Σ enriched (mass/decay-angle) region are included. The reconstructed Λ mass had to agree with the true value within 10 MeV. White: Ξ contribution. Yellow: remaining Λ's. Dark: Background. Upper left: unlike sign. Upper right: like sign. Lower left: Difference.

Figure 6: Adjusted impact parameter distribution of correlated tracks: The unlikd sign minus like sign asymmetry.