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Sigma- Antihyperon correlations in multihadronic Decays of the Z^0 Boson

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1 The principle

- Z^0 Boson has baryon number 0, baryon number is conserved in multihadronic decays.
- Question: Quark flow between baryons and antibaryons?
- To study this, quark tagging is needed.
- Use s quark, because hyperons are produced with small rate.
- Measurements already available: $\Lambda\overline{\Lambda}$ correlation, total rate per Z^0 and rapidity difference (OPAL,DELPHI). No other independent information.
- Other possibility: events containing a Σ^- hyperon.
- Strangeness may be compensated by an antihyperon, or baryon numer and strangeness are balanced by associated production of an antinucleon and a kaon.
- Particle species to look at in a multihadronic final state: all weakly decaying antihyperons (directly produced of via decays of baryon resonances).

- $\overline{\Sigma^-}$, $\overline{\Sigma^+}$, $\overline{\Lambda}$ (including decays of $\overline{\Sigma^0}$ and $\overline{\Xi^0}$), and $\overline{\Xi^-}$.
- It is the understanding that the equivalent antiparticle configurations are always added.
- Theoretical description has to rely on fragmentation model: String model with diquark production, modified by introduction of the popcorn mechanism (see fig.1).
- Correlated $\overline{\Sigma^+}$'s and $\overline{\Xi^0}$'s can be produced with the popcorn mechanism only. Their rates are low and could not be measured independently.
- $\overline{\Sigma^0}$ hyperons appear as part of the $\overline{\Lambda}$ correlation.

Signatures

- Σ^- decays are reconstructed explicitly by searching for tracks with kinks.
- Pions from weak decays have a significant impact parameter $d_{0,\pi}$ and are a common signature for all antihyperons.
  Number of pions from antihyperons:
  - $\overline{\Sigma^-} \to \overline{n}\pi^+$: 1
  - $\overline{\Sigma^+} \to \overline{n}\pi^-$: 0.5
  - $\overline{\Lambda} \to \overline{p}\pi^+$: 0.6
  - $\overline{\Xi^-} \to \overline{\Lambda}\pi^+ : 1.6 \to \overline{p}\pi^+\pi^+$.
- Reconstructed $\overline{\Lambda}$'s are either produced directly or they are decay products of $\overline{\Sigma^0}$, $\overline{\Xi}$ or heavy antibaryons with charm or bottom.
  - Search for V^0 topology.
  - $\overline{\Lambda}$'s from $\overline{\Xi}$ decays are characterized by large values of the impact parameter $d_{0,\Lambda}$.
  - Impact parameter distribution is used to separate the $\overline{\Xi}$ contribution.

2 Event selection

2.1 Σ reconstruction.

Selection of track kinks.

- transversal momentum of second track: $p_{T2} > 0.10$ GeV/c
- track angle with respect to beam: $-0.75 < \cos\theta_1 < +0.75$
- impact parameter of track 1: $d_0 < 5$ cm
- distance between end of track1 and start of track 2: $d_{12} < 10$cm
- track overlaps: $\mu_1, \mu_2 < 7$cm
- number of secondary tracks = 1
- radius of the secondary vertex: 35 cm $< r_{Vtx} <$ 170 cm
- distance of vertex from endcap in z direction > 40 cm
- χ^2 test for identity of track parameters 1 and 2 in the r, ϕ plane $\chi^2 > 2000$
- kink angle at the secondary vertex $\alpha_{12} > 50$ mrad.

bf new:

- not cut on transversal momentum of first track (automatically > 0.5GeV/c
- no cut on track angle with respect to beam
- no cut on kink angle at the secondary vertex (in most cases > 50 mrad anyway).

Compute a hypothetical Σ^- mass from the two particle momenta.

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

To reduce the background from charged kaon decays, a lifetime cut is applied (l = track lenght in cm, momentum p in GeV/c)

- $l/p < 15$

2.2 Selection of delayed pion candidates

The following cuts have been applied for track selection:

- transversal momentum $p_T > 0.15$ GeV/c
- angle with respect to beam axis: $|\cos\theta| \leq 0.80$
- impact parameter $d_{0,\pi} > 0.2$cm (with respect to primary vertex) and $d_{0,\pi} < 10$cm
- number of dE/dx points $N_{dE/dx} \geq 20$
- dE/dx probability for pion $W_{dE/dx}(\pi) \geq 0.02$
- 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.
It should be noted that, due to the $d_{0,\pi}$ cut, charged particles from charm or bottom decays are not selected.

2.3 Lambda selection.

V0 finder, as used in Λ search paper, with the default cuts.

- momenta of p and π: $p > 0.15$ GeV/c
- angles with respect to beam: $-0.9 < \cos\theta < 0.9$
- number of CJ hits to the maximum number consistent with track geometry ≥ 0.25
- minimum number of CJ hits 20
- fit quality: $\chi^2 \leq 50$
- impact parameters: $d_0(p) \geq 0.1$ cm, $d_0(\pi) \geq 0.3$ cm
- dE/dx cuts
- radial position of secondary vertex: 1 cm $\leq r_{Vtx} \leq 150$ cm
- z distance of tracks at secondary vertex $\leq$80 cm
- angle between Λ momentum to direction of flight $\delta < 2^o$.
- radius difference of first hit to secondary vertex: $R_{diff} \leq$ 5 cm
- maximum difference between reconstructed and true Λ mass ≤ 0.01 GeV/c^2
- invariant mass under e^+e^- hypothesis ≥ 0.04 GeV/c^2

In addition to the cuts of the V^0 finder the following selection criteria were introduced:

- The reconstructed Λ mass has to be less than and 1.2 GeV.
- 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).
- If the reconstructed Λ hyperon points back to the (r,ϕ) position of the kink within 2^o, the decay $\Xi \rightarrow \Lambda\pi$ is a possible kink interpretation and the particle pair is rejected.

Otherwise, one would introduce some disturbing autocorrelations of Ξ's with itself in the data. This last cut removes only 1.6% of the correlated $\overline{\Lambda}$ candidates from the data and Monte Carlo samples.

3 Monte Carlo event classes

Monte Carlo events are classified according to their physical origin.

Track kinks

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.

To disentangle the kink sources, the decay angle θ^* of the pion in the rest frame of the hypothetical Σ^- particle is computed with respect to the Σ^- flight direction.

- Five 2-dimensional regions are introduced in the $\cos\theta^*$-mass plane to enrich the specific kink sources (see fig.2)

Correlated particles

Eight sources for correlated antiparticles have been defined:

1. $\overline{\Sigma^-}$
2. Σ^+
3. $\overline{\Xi^-}$
4. K^-
5. K^0
6. combinatorial V^0 background
7. charged particle background (all selected pion candidates not in the other classes)
8. $\overline{\Lambda}$

The first 4 sources are identical to the first 4 kink sources. Sources 1,2,4 and 7 are irrelevant for the Λ search channel, source 6 does not contribute to the correlated track search.

The same classification is introduced for the antiparticles.

- In total, there are $5 \cdot 8 = 40$ 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. Muons, kaons and protons may be accepted too.
- Wrong classification is treated in the Monte Carlo simulation, but systematic errors may be introduced.
- Example: Selected protons from Λ decays introduce wrong sign correlations.
- Genuine Σ^+ correlations with Σ^- introduce an effect with the oppsite sign, compared to $\overline{\Sigma^-}$ - Σ^-.

4 Determination of correlations

- s quark flow from hyperons into antihyperons or kaons appears as excess of unlike sign over like sign particle pairs.

- Unlike sign pair means: Σ^- kink candidate in combination with an $\overline{\Lambda}$ candidate or a π^+ candidate; alternatively, a $\overline{\Sigma^-}$ candidate in combination with a Λ candidate or a π^- candidate.

- Count unlike and like pairs in the data sample and the MC.

- Data asymmetry (unlike sign minus like sign) can be described by a weighted sum over the 40 d_0 distributions from the MC:

$$D^{data}(j, d_0) = \sum_{j=1}^{5} \sum_{i=1}^{5} \sum_{k=1}^{8} F_{ik} \cdot D^{(MC)} j, ik(d_0) \qquad (1)$$

  where i is the kink source, j the 2-dimensional bin 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

$$R_{\Sigma,k} = \frac{F_{\Sigma,k}}{F_{\Sigma}} \cdot R_{\Sigma,k}^{(MC)} \tag{2}$$

  Here, $R_{\Sigma,k}^{(MC)}$ 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 efficiencies are hidden in the Monte Carlo distributions and do not appear in the final formula.

correlated particle	simulation all MC runs
$\overline{\Sigma^-}$	0.294
$\overline{\Sigma^+}$	0.018
$\overline{\Xi^-}$	0.139
$\overline{\Xi^0}$	0.016
$\overline{\Lambda}$	0.272
K^+	0.054

Table 1: Unlike minus like sign difference of strange particle production per $\Sigma^-, \overline{\Sigma^+}$ at generator level, as extracted from all Monte Carlo runs.

5 Total correlated Monte Carlo rates

According to the previous section, the produced numbers of correlated particles have to be known at generator level.

- **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 all MC runs

$$R_{\Sigma^-,\Sigma^-} + |R_{\Sigma^-,\Sigma^+}| + R_{\Sigma^-,\Lambda} + 2 \cdot R_{\Sigma^-,\Xi^-} + 2 \cdot R_{\Sigma^-,\Xi^0} + 2 \cdot R_{\Sigma^-,K^-} = 1.002 \qquad (3)$$

(the Ξ has strangeness 2, correlated K^0's are lost in the unlike sign minus like sign difference).
Consistency check ok within 0.2%.

- An equivalent relation can bewritten down for Ξ correlations:

$$R_{\Xi^-,\Sigma^-} + |R_{\Xi^-,\Sigma^+}| + R_{\Xi^-,\Lambda} + 2 \cdot R_{\Xi^-,\Xi^-} \\ +2 \cdot R_{\Xi^-,\Xi^0} + 2 \cdot R_{\Xi^-,K^-} = 2 \tag{4}$$

6 The fit of the like sign correlations

- The fit is needed for technical reasons only
- (1) Reliability of the MC
- (2) In the asymmetry fit, the statistical errors of both the unlike sign and like sign combinations are needed.
- Fit is done iteratively: the adjusted rates are used to compute the combined d_0 distributions, which are smoothened to get the statistical error.
- $\chi^2 = 175$ (146 degrees of freedom)

7 The fit of the unlike sign-like sign difference

The MC predicts an asymmetry of all kink sources with respect to the non-hyperon track and the V^0 background. The correction for this effect is quite important; ignoring it, the final result would change by as much as 30%. The effect is, after the real correlations of hyperons, the most important contribution to the asymmetry.

Explanation:

- Statistical correlation due to charge conservation in the events.
- Spallation protons are not counted after track selection. (no excess of positive particles observed after cuts)
- Therefore, the charges of particles from secondary interactions measure the charges of the interacting particles, which is, on average, opposite to the charge of the particle producing the kink.

Due to the low statistics, it is impossible to adjust more than 4 of the 40 distributions. The other coefficients, including the have to fixed somewhere else:

- Correlations with tracks or V_0's from K^0 decays should vanish and are neglected.
- There are cases with identical fit parameters.
  The coefficient is the same, if kink source and correlated particle source can be swapped, for instance $\Sigma^{-(+)} - \overline{\Xi^-}$ or $\Sigma^{-(+)} - K^+$.
- For the small contribution of Σ^+ $\overline{\Sigma^+}$ correlations, the rescaling factor is set to the value for Σ^- $\overline{\Sigma^-}$, assuming isospin invariance.
- The ratio of Σ^- $\overline{\Sigma^+}$ to Σ^- $\overline{\Sigma^-}$ was ficed to the MC value (too small).
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- The ratio of $\Sigma^- \ \overline{\Xi_0}$ to $\Sigma^- \ \overline{\Xi^-}$ was fixed to the MC value (too small).

- The rescaling of the Σ-kaon correlation is fully determined by the Σ-antihyperon result and given by the constraint (3). The rescaling of kaon-Σ events is the same.

- There is not enough experimental information about kaon-Ξ correlations. For simplicity, the rescaling factor of the kaon-Σ correlations is applied.

- The fit of the like sign correlations showed that the non-hyperon track background and the V0 background are well modelled by the Monte Carlo program. Because local charge conservation in particle jets is incorporated into the physics generator, it is then natural to extract the Σ^--background asymmetry from the Monte Carlo predictions:

$$R_{\Sigma^-,background} = R^{(MC)}_{\Sigma^-,background} \cdot \frac{R^{data}_{\Sigma^-}}{R^{MC}_{\Sigma^-}} \tag{5}$$

  Equivalent relations are used for the other kink sources.

- The remaining small background asymmetries to be subtracted are fixed to the Monte Carlo predictions. Systematic errors have to be assigned to account for possible shifts.

antihyperon	number per $\Sigma^-, \overline{\Sigma^-}$ P.B.12/04	D.W.	now
$\overline{\Sigma^-}$	0.137 ± 0.135	$0.120 \pm 0.150 \pm 0.120$	0.156 ± 0.096
$\overline{\Lambda}$	0.306 ± 0.068	$0.240 \pm 0.073 \pm 0.056$	0.225 ± 0.055
$\overline{\Xi^-}$	0.071 ± 0.061	$0.112 \pm 0.082 \pm 0.070$	0.052 ± 0.047
all	0.514 ± 0.128	$0.472 \pm 0.126 \pm 0.090$	0.432 ± 0.088

Table 2: Antihyperon rates per Σ: The individual results and their sum.

8 Results now

Systematic errors almost completed.
Try to avoid error estimates limited by statistics.

- New procedure used to adjust the z resolution: Optimize Σ mass and decay angle distributions.
  Sets the error for unfolding the kink sources.
- Correction for mismodelling the momentum distribution of the correlated sources (6 % effect)
- dE/dx distribution slightly mismodelled (proton background !!!). Is under control: error estimate by correction of the MC dE/dx weight.
- The effect of some cuts (ndE/dx, cos(Θ) for correlated tracks) is very small (1% only).
- $K\ \Lambda$??? No reweighting factor known (opinion of the EB?)

- hemisphere cut: good MC statistics for correlated tracks (no significant effect found, should be less than 3%).
- Take Λ error from hyperon paper.
- Good: $\overline{\Lambda}$ correlation is relatively stable and $\overline{\Xi}$ and $\overline{\Sigma}$ have 70% anticorrelation, so that the sum (last row) is more stable than the individuals.
- Bad: Low correlated MC kaon statistics (has to be multiplied with 4 !!!) (opinion of the EB) ?

error source	$\overline{\Sigma^-}$	$\overline{\Lambda}$	$\overline{\Xi^-}$	total
unfolding of kink sources (z resolution)				
cut on number of track hits				
cut on $\cos(\Theta)$ of correlated tracks				
mismodelling of dE/dx				
mismodelling of correlated track momenta				
error on detection efficiency for Λ				
possible charge asymmetries of detection efficiencies				
sum				

Table 3: Systematic errors $\delta p_{\Sigma,k}$ and $\sum_k \delta p_{\Sigma,k}$, where $k = \overline{\Sigma^-}$, $\overline{\Lambda}(+\overline{\Sigma^0})$, $\overline{\Xi^-}(+\overline{\Xi^0})$.

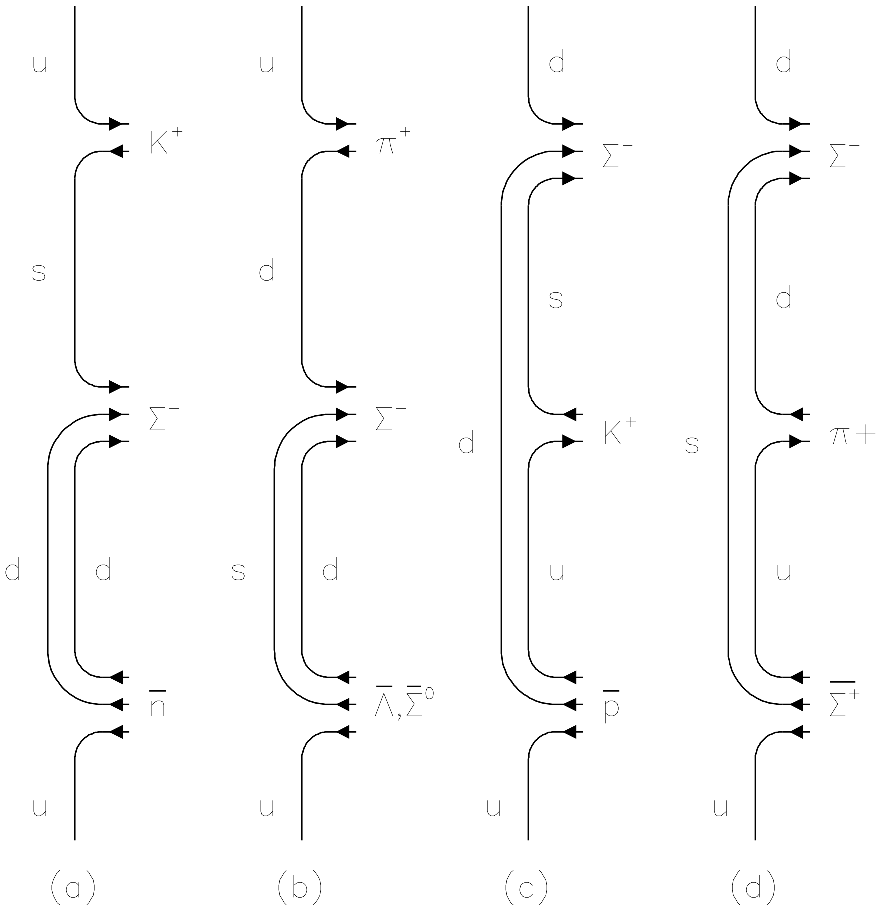

Figure 1: Quark fragmentation into Σ hyperons according to the diquark model without and with popcorn mechanism. Baryon number and strangeness are conserved by associated production of (a) K^+ and $\overline{n}$, (b) $\overline{\Lambda}$, $\overline{\Sigma}$, (c) K^+ and $\overline{p}$, (d) $\overline{\Sigma^+}$. The final states (c) and (d) can not be produced without popcorn mechanism.

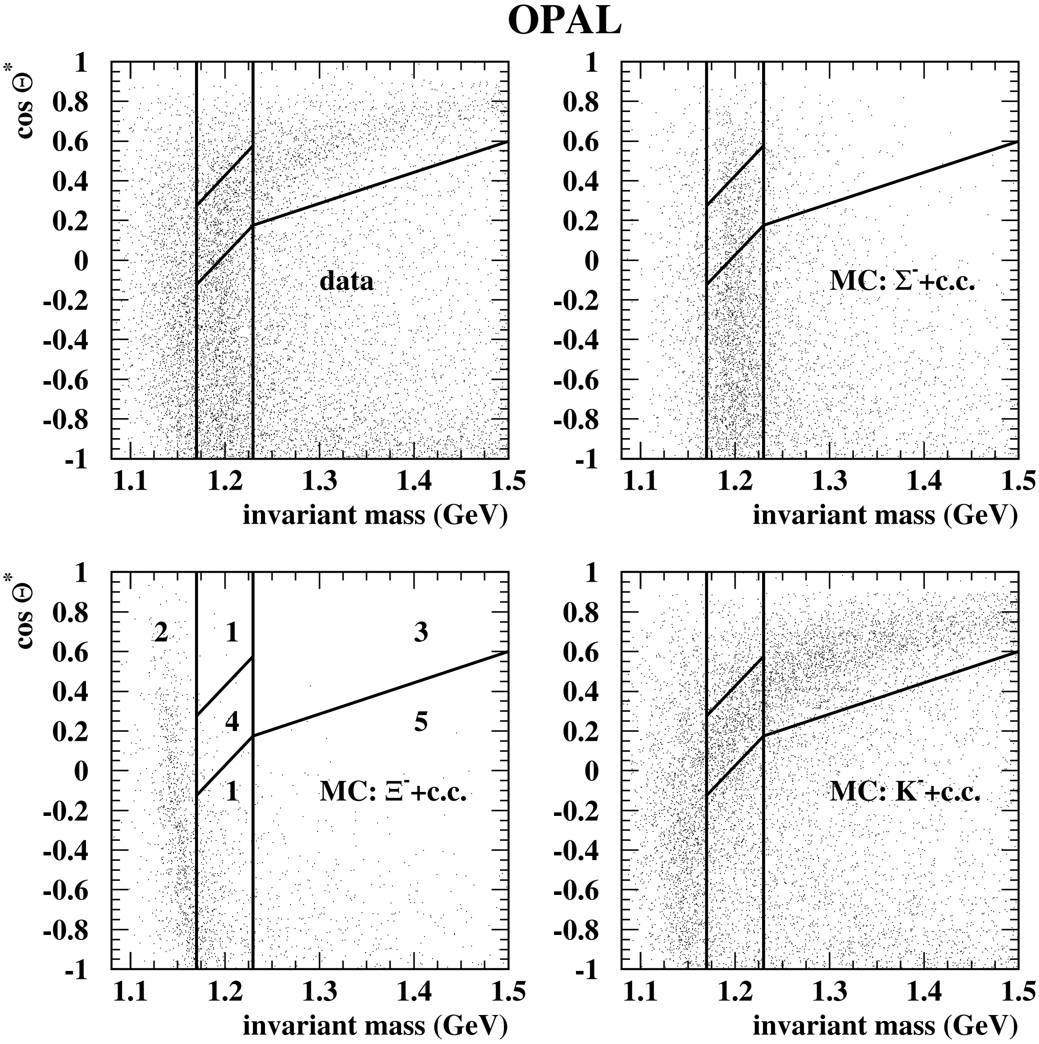

Figure 2: Monte Carlo distribution of track kinks in the hypothetical (Σ mass,pion decay angle) plane. Upper left: Data. Upper right: Σ source (MC). Lower left: Ξ source (MC). The numbers indicate the 2-dimensional bins used to unfold the components. Lower right: Charged kaon source (MC). The background intensity is much lower, has a flat mass distribution and is localized close to $\cos(\Theta^*) = -1$.

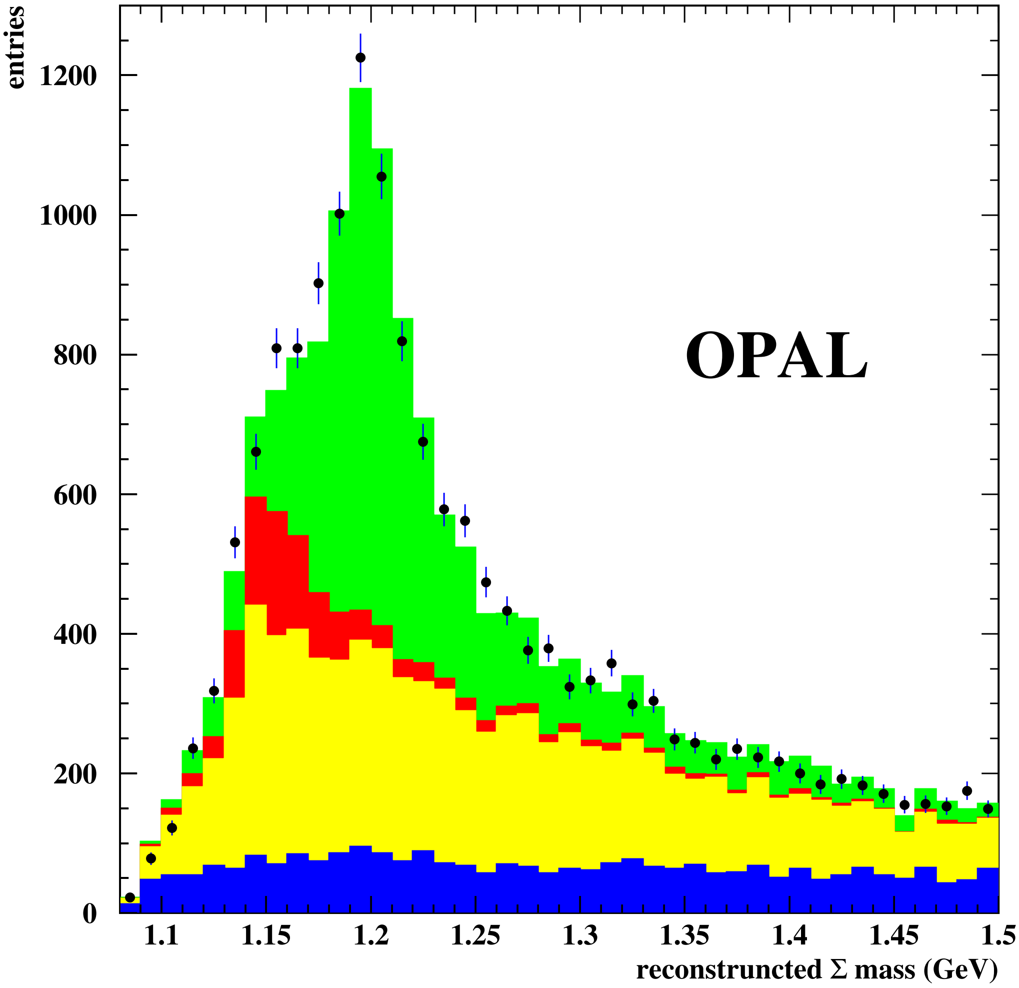

Figure 3: Reconstructed Sigma mass distribution for all candidates. Green: Σ^- and Σ^+, Blue: Ξ, Yellow: K^- and K^+, Dark blue: Secondary interactions and combinatorial background.

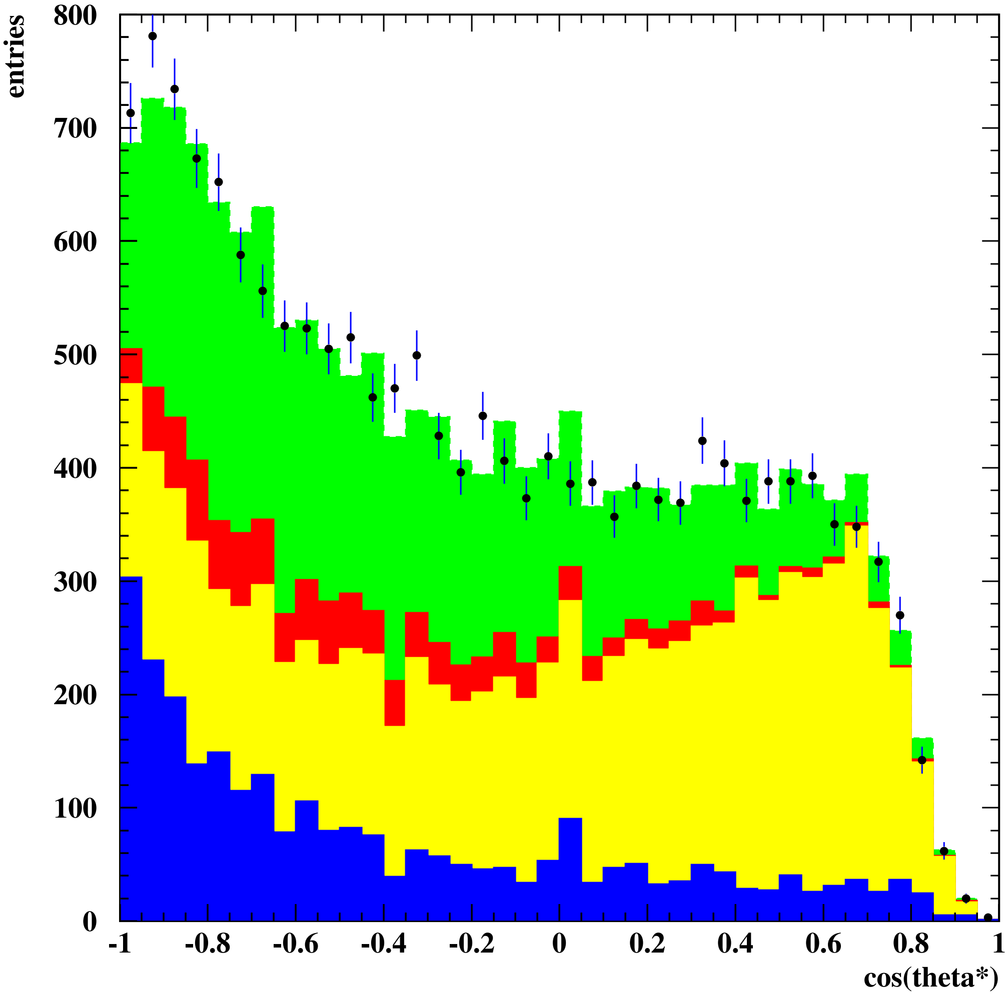

Figure 4: Reconstructed pion decay angle distribution for all candidates. Green: Σ^- and Σ^+, Blue: Ξ, Yellow: K^- and K^+, Dark blue: Secondary interactions and combinatorial background.

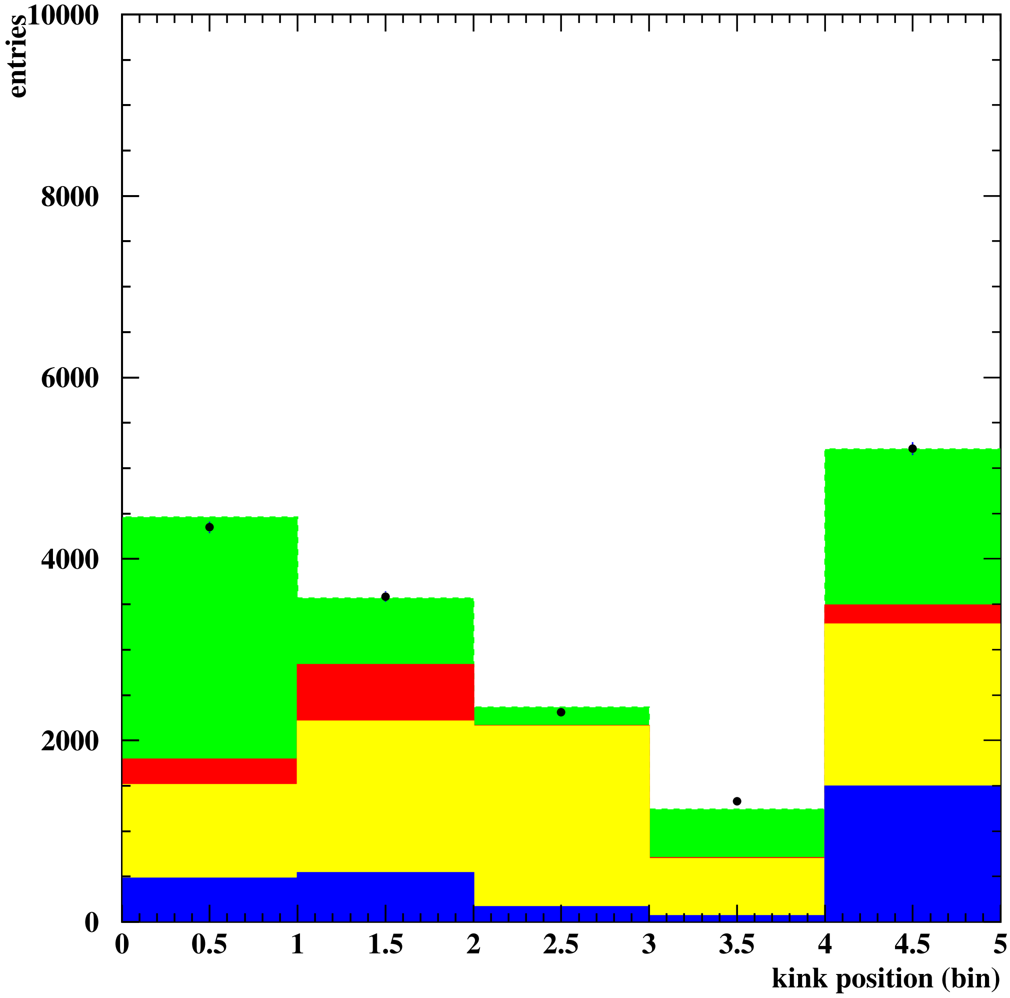

Figure 5: Intensitities in the 2-dimensional bins for the unfolding of kink sources. Colors: see fig. 3.
************* not foreseen for draft *************

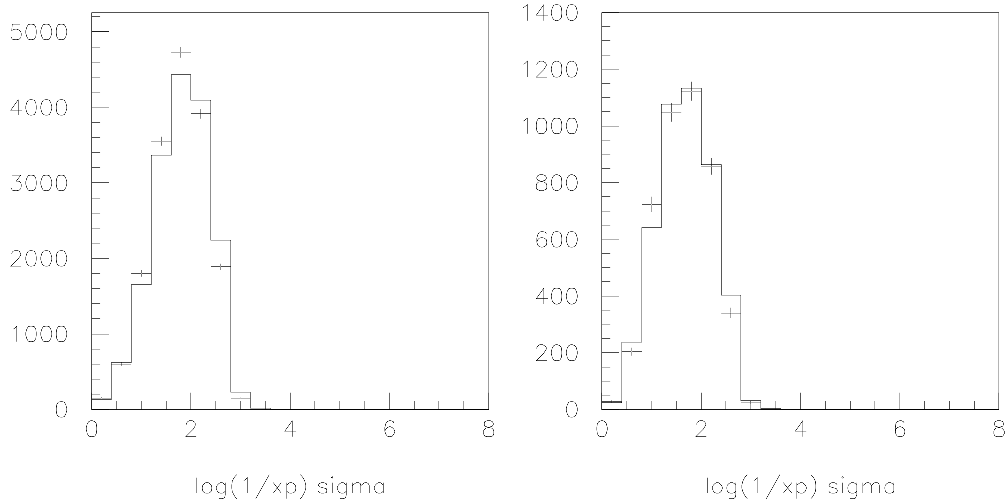

Figure 6: Reconstructed values of $\ln(1/x_p)$ under the Σ hypothesis. Left: All candidates. Right: Σ enriched bin.
************* not foreseen for draft *************

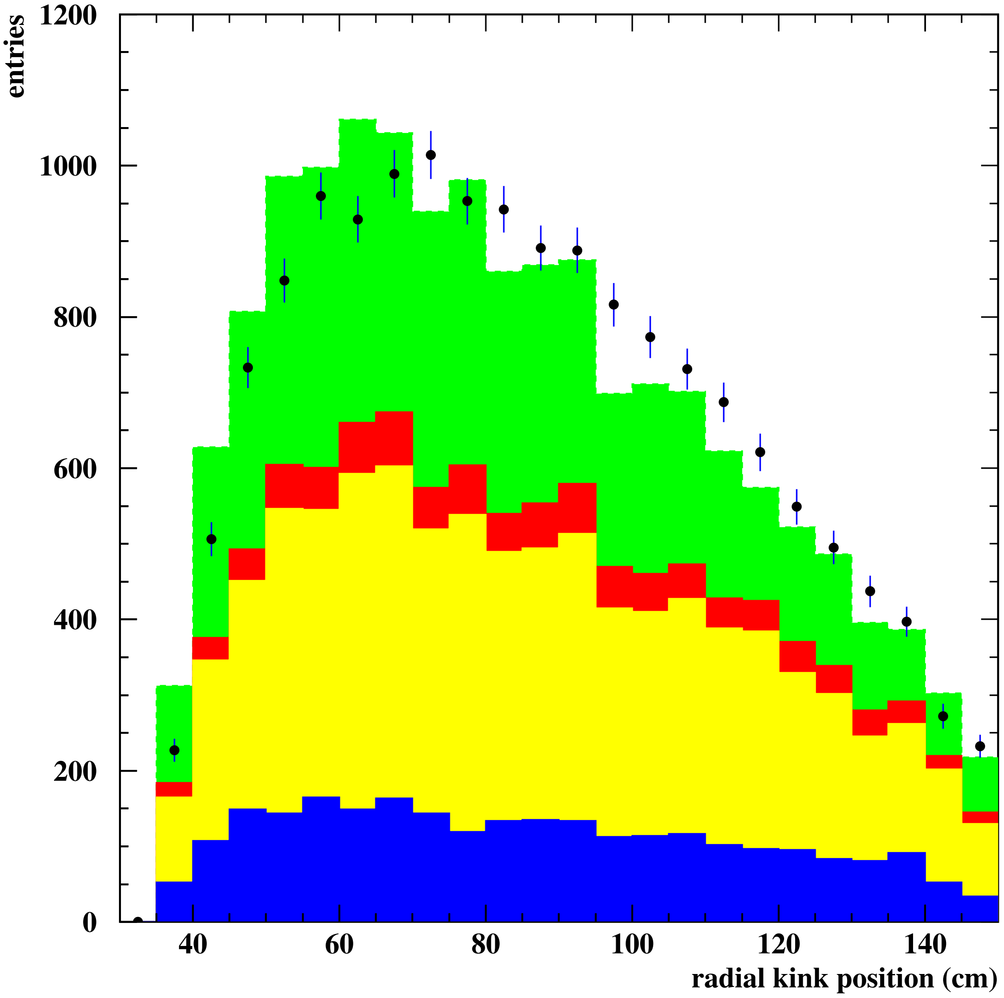

Figure 7: Reconstructed radial kink distribution. All candidates. Colors: see fig. 3.
************* not foreseen for draft *************

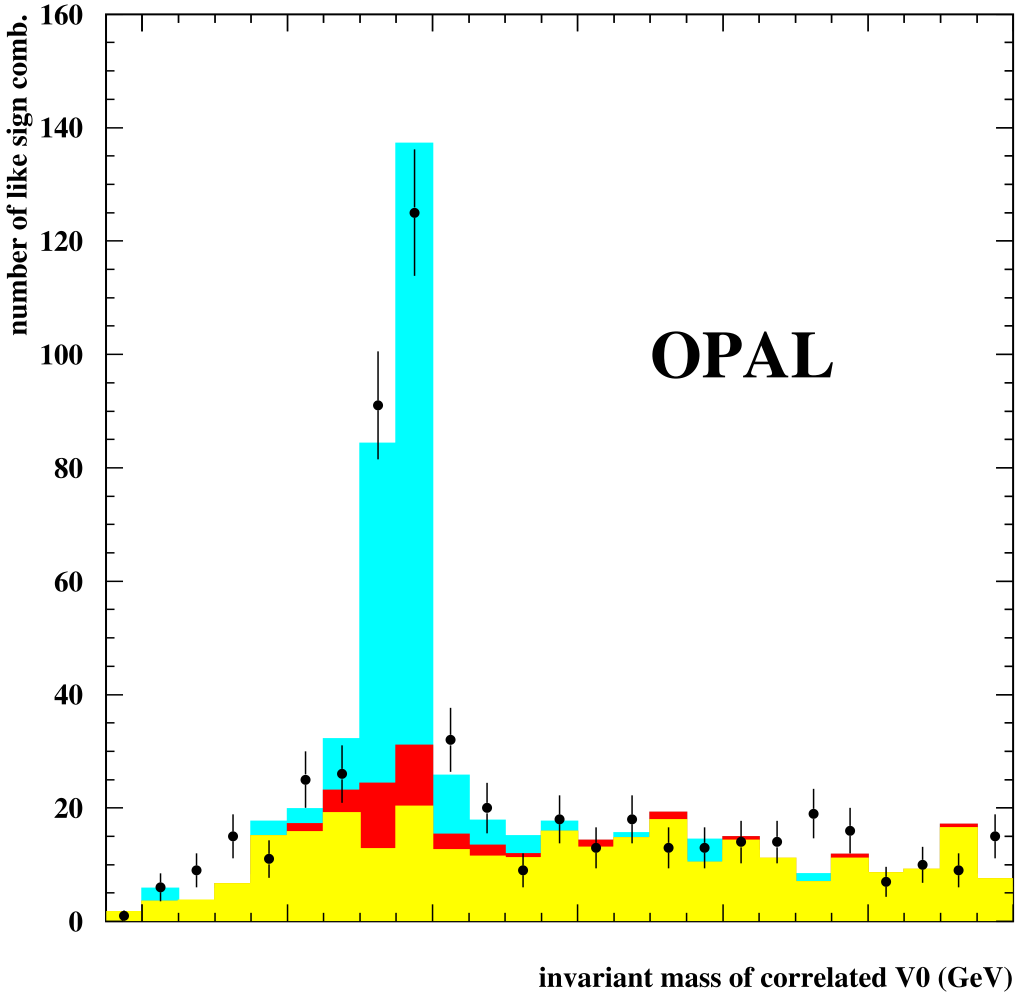

Figure 8: Mass distribution of correlated like sign Λ candidates. All kinks are included. Points: Data. Light blue: prompt Λ's. Red: Delayed Λs from Ξ decays. Yellow: $K0$ mesons and other background, especially secondary interactions.

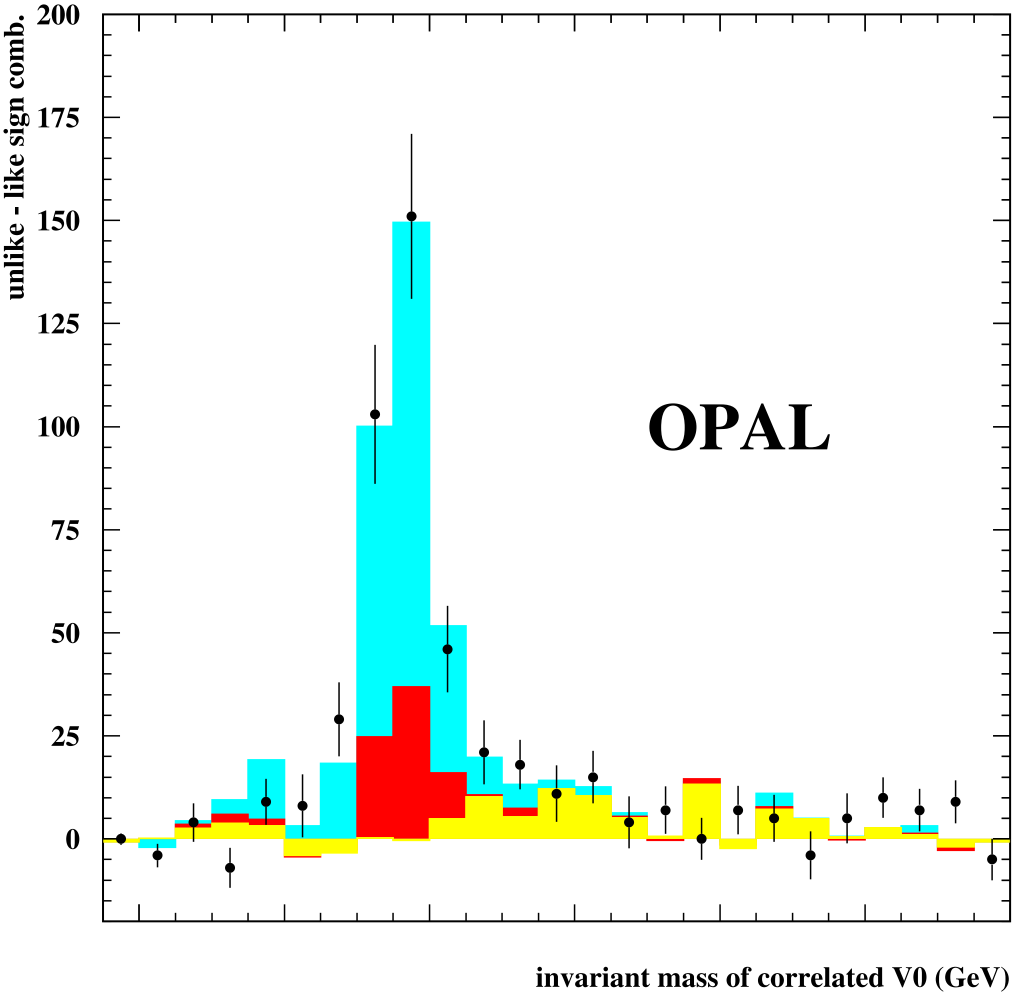

Figure 9: Difference between mass distributions of correlated unlike sign and like sign Λ candidates. All kinks are included. Points: Data. Light blue: prompt Λ's. Red: Delayed Λs from Ξ decays. Yellow: V_0 background.

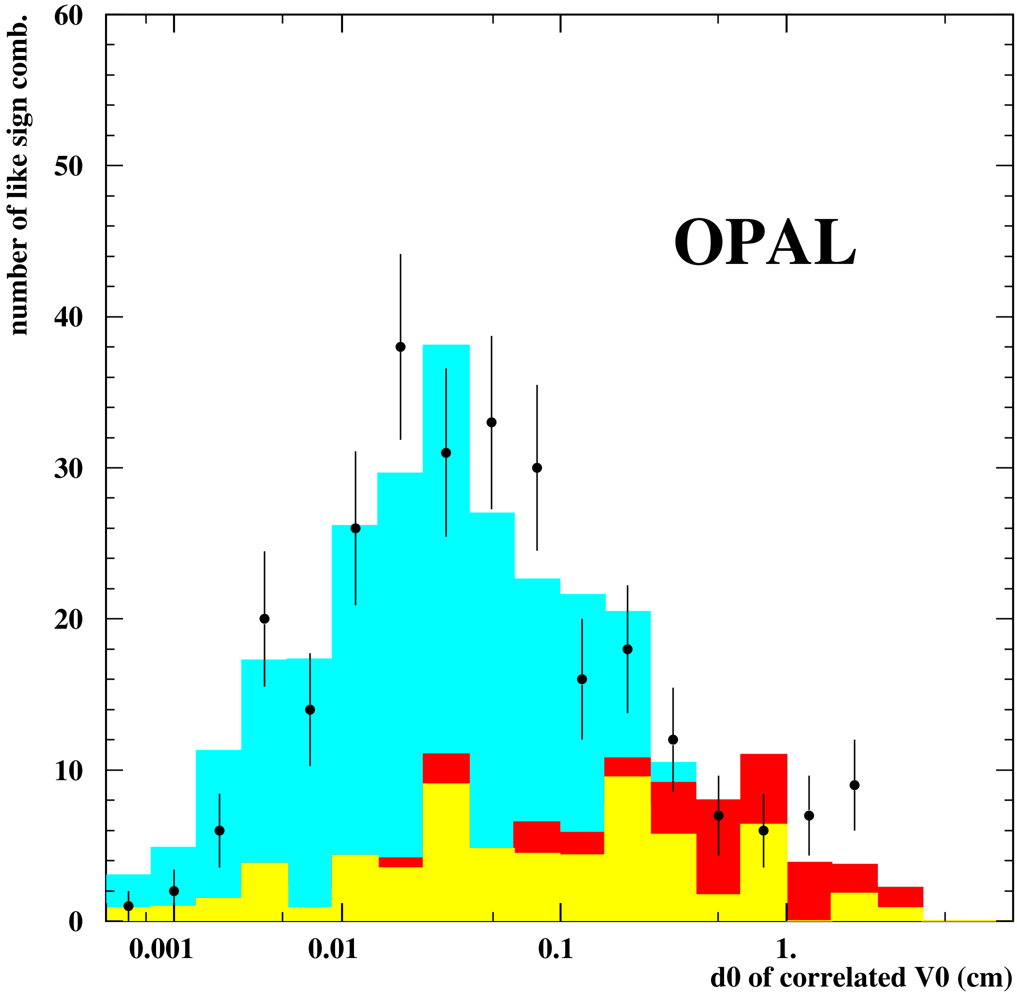

Figure 10: Impact parameter distribution for correlated like sign Λ candidates in the $r - \phi$ plane. All kinks are included. Colors: See fig. 8

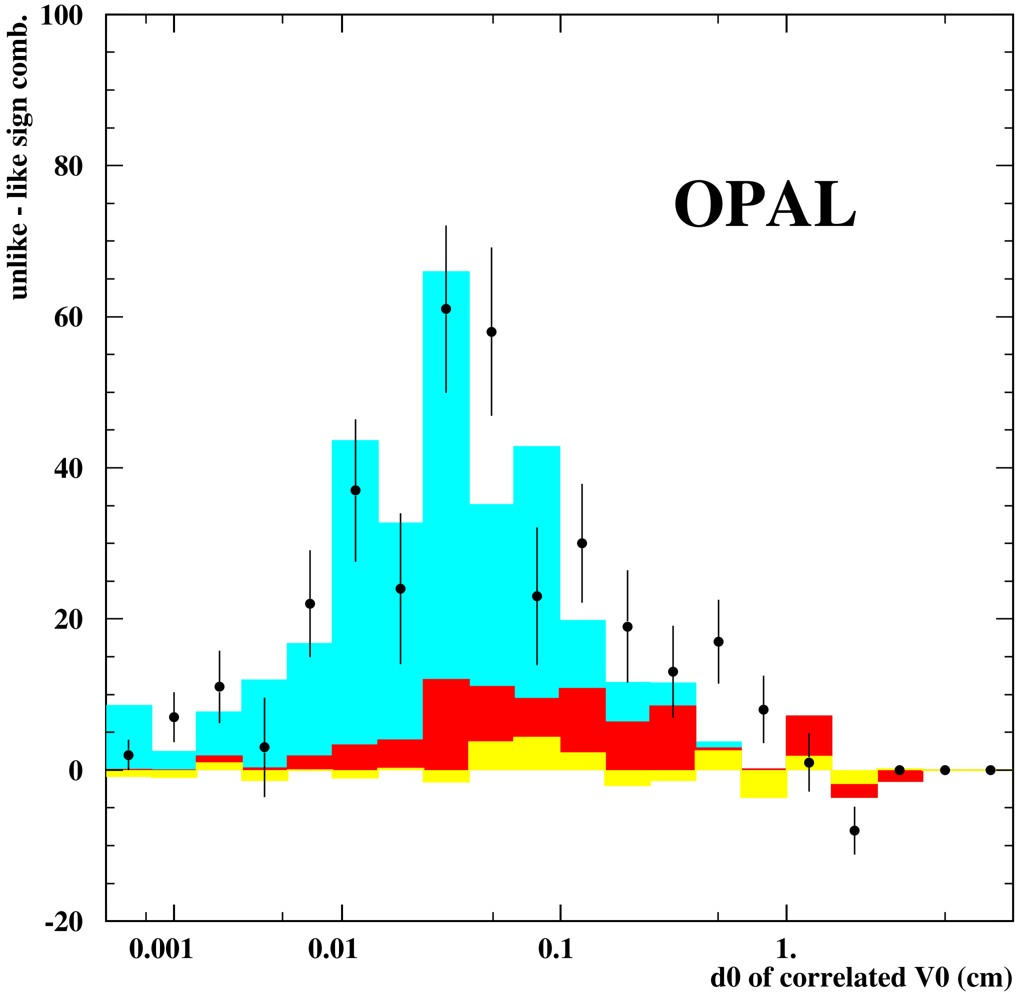

Figure 11: Difference between the impact parameter distributions for correlated unlike sign and like sign Λ candidates. All kinks are included. Colors: See fig. 8

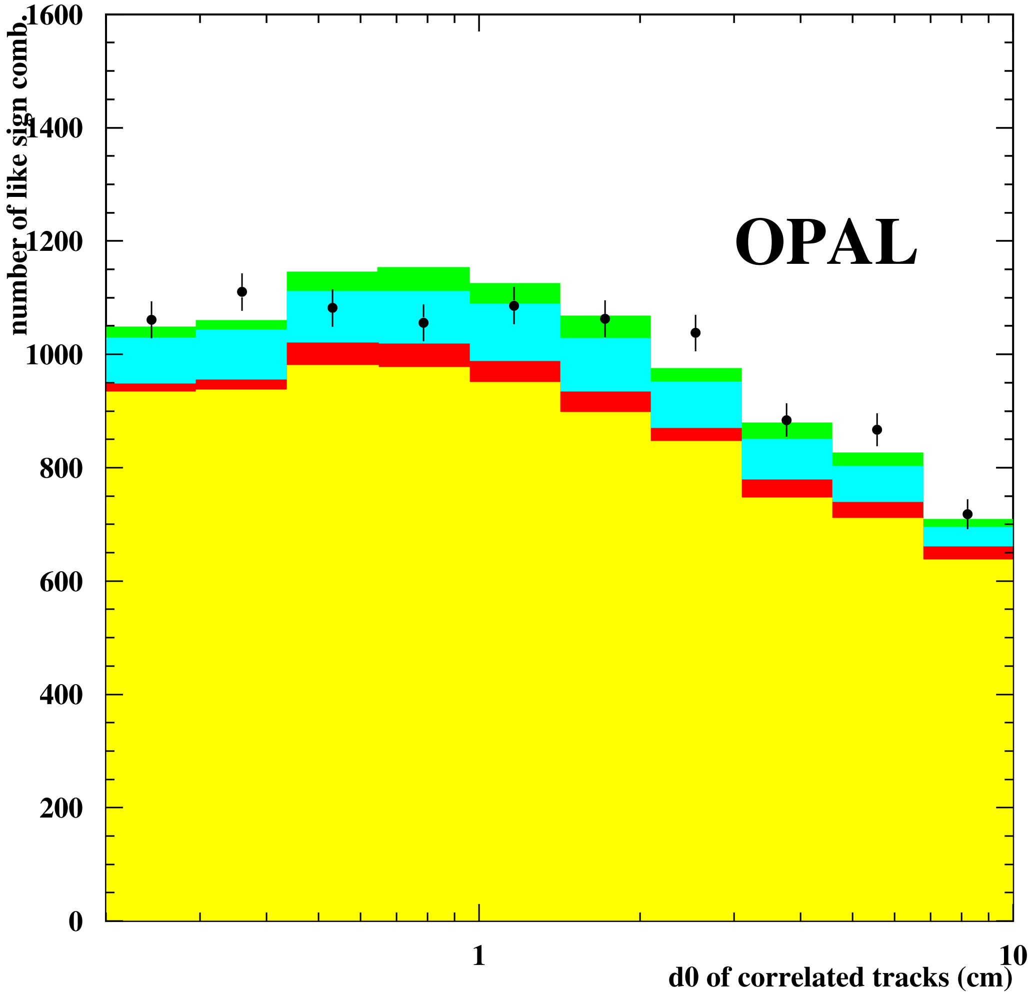

Figure 12: Impact parameter distribution for correlated like sign pion candidates in the $r - \phi$ plane. All kinks are included. Points: Data. Green: charged particles from Σ^- and Σ^+ decays. Light blue: particles from prompt Λ decays. Red: particles from Ξ decays, including cascade decays via Λ's. Yellow: Decay products of charged kaons and particles from secondary interactions.

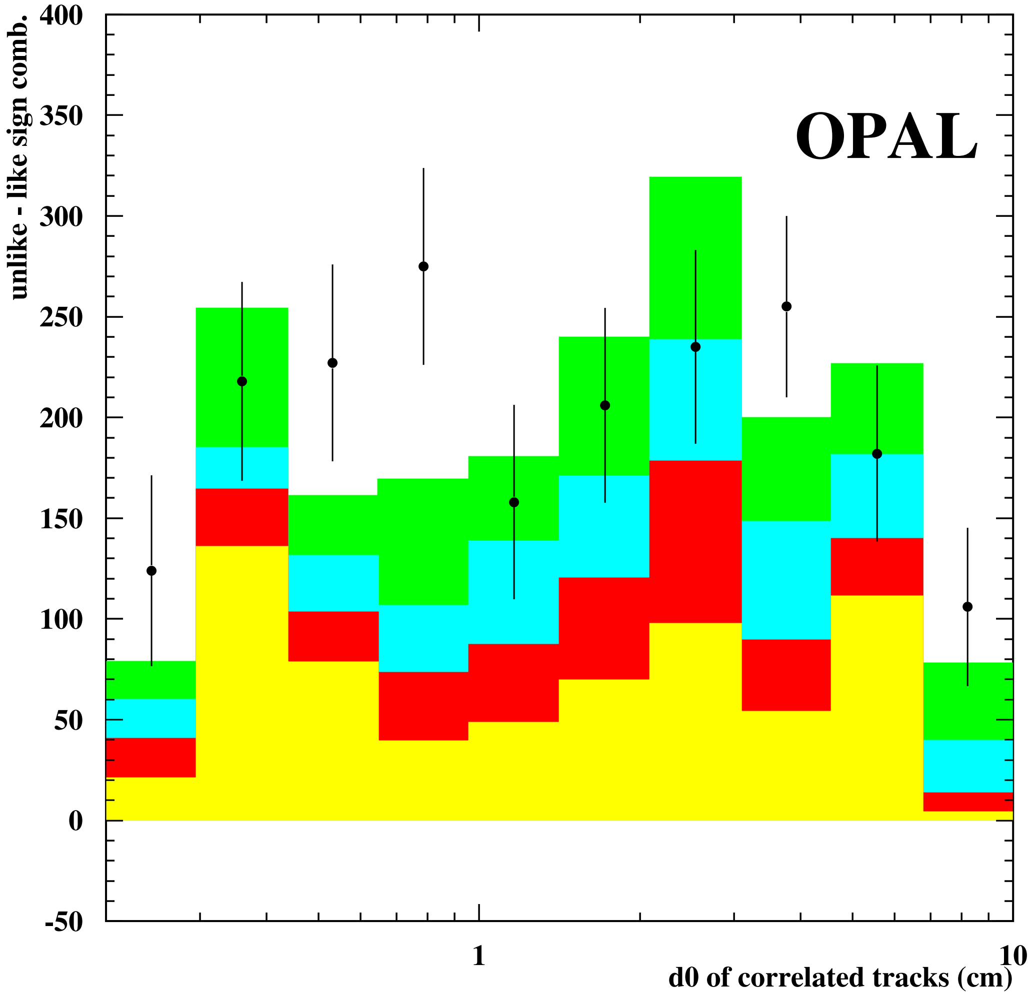

Figure 13: Difference between the impact parameter distributions for correlated unlike sign and like sign pion candidates. All kinks are included. Colors: See fig. 12