Polarization and Spin Alignment in Multihadronic Z0 Decays

ISMD 2000

Review covers results from:

ALEPH DELPHI OPAL

- LEP-1
- Hadron Production in Electron-Positron-Annihilation
- Baryon Polarization
- Theory of Spin Density Matrices
- Vector Meson Spin Alignment
- Conclusions

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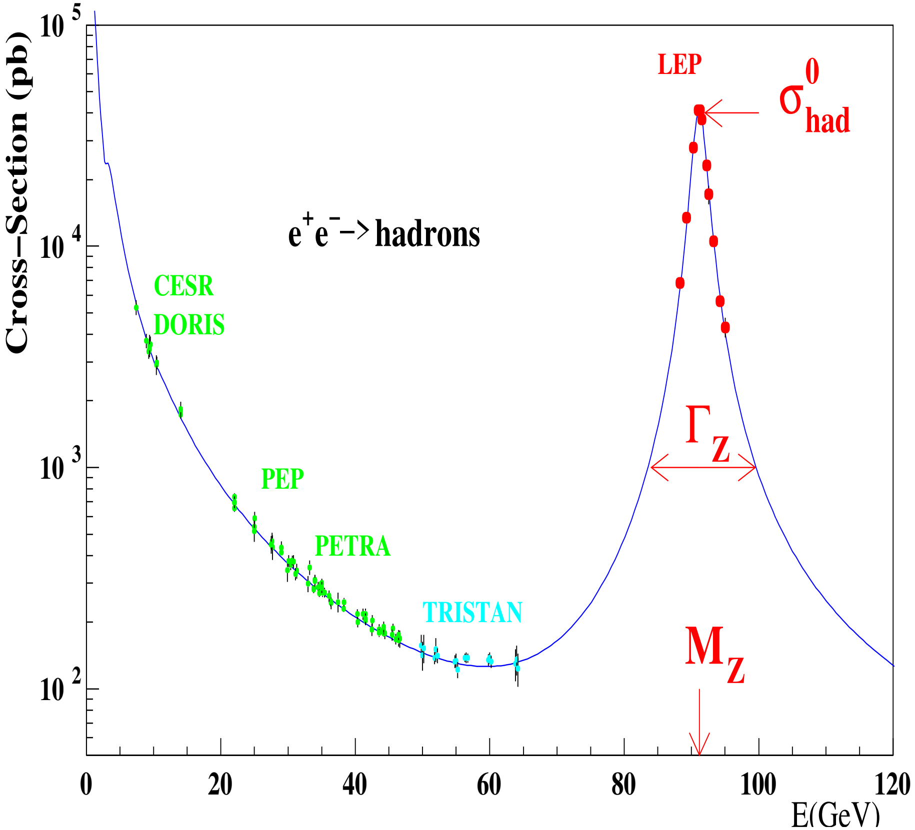
The Large Electron Positron Collider: LEP

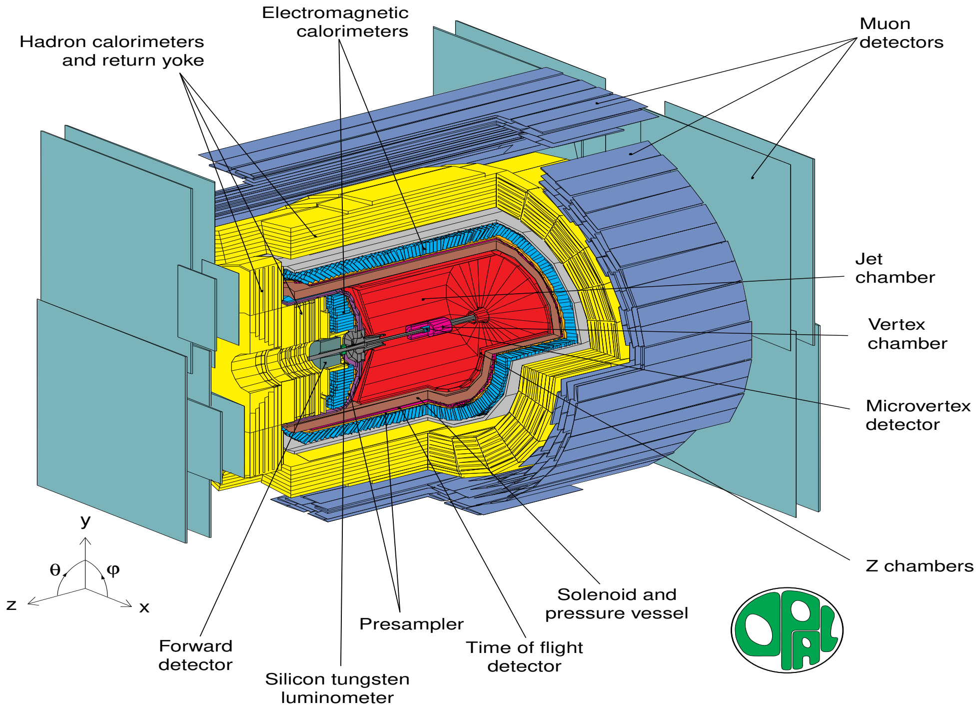
Data taken around the Z^0 resonance 1989-1995



Each of the four experiments recorded:

- A total integrated luminosity of 170 pb^{-1}
- More than 4 million hadronic Z^0 decays

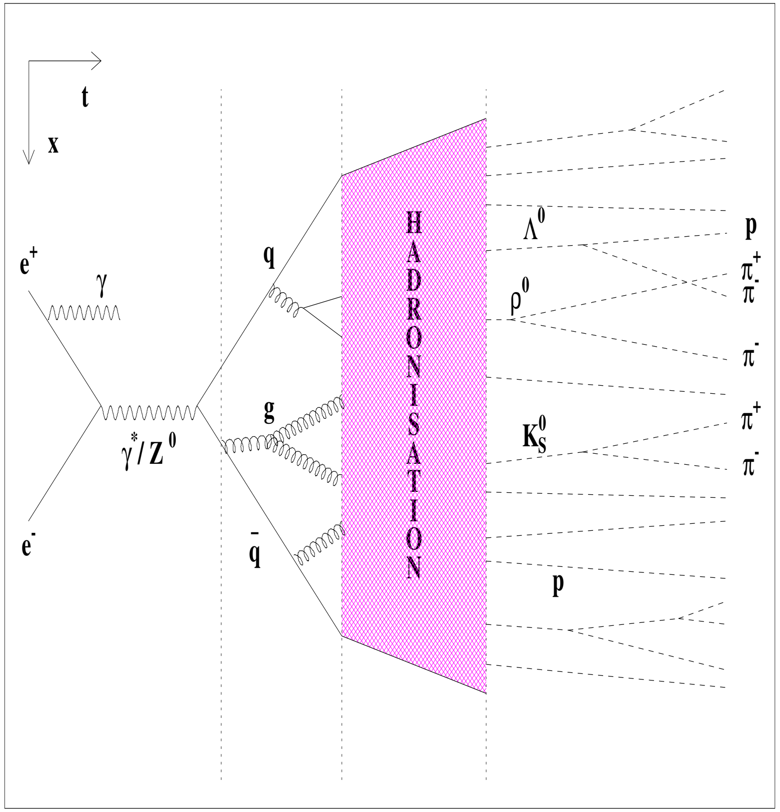
A typical LEP detector:



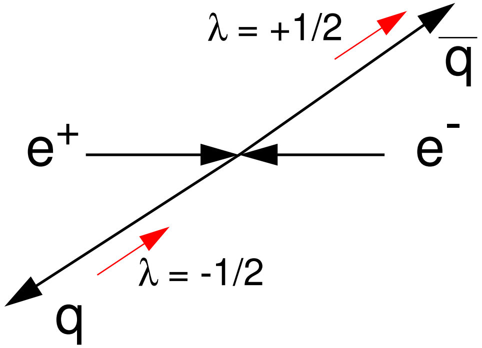
- Microvertex detector
- Tracking chambers with possibility of particle ID
- Electromagnetic calorimeters
- Hadron calorimeters
- Muon detectors
- Luminometers

Hadron Production at LEP-1

$e^+e^- \to Z^0 \to \bar{q}q \to hadrons$



About 21 charged particles & 21 photons



Primary quarks are longitudinally polarized

$$P_q \approx (-2v_q a_q)/(v_q^2 + a_q^2)$$

$$P_{q\,=\,d,\,s,\,b} \approx -0.94$$

$$P_{q\,=\,u,\,c} \approx -0.67$$

- Slight variation with polar angle
- Small higher order corrections

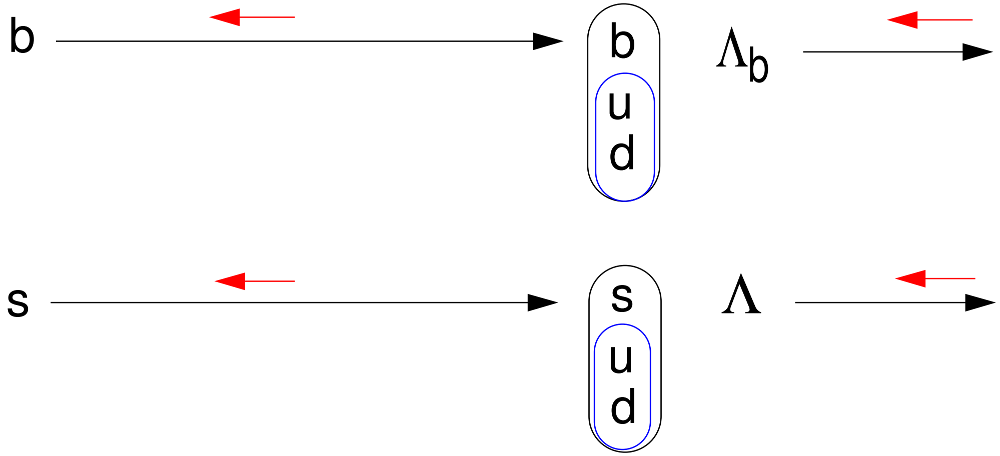
(Almost) no transverse quark polarization

Lambda Polarization

Valence Dominance Hypothesis:

Primary quarks are likely to become valence quarks in leading hadrons

- Leading particles have large $X_E = E_{hadron}/E_{quark}$



J = 1/2 of hyperon carried by the heavy quark

In constituent quark model spin of hyperon is carried by the heavy quark and the light diquark is in Spin-0, Isospin-0 state

Do leading hyperons remember the primary quark polarization ?

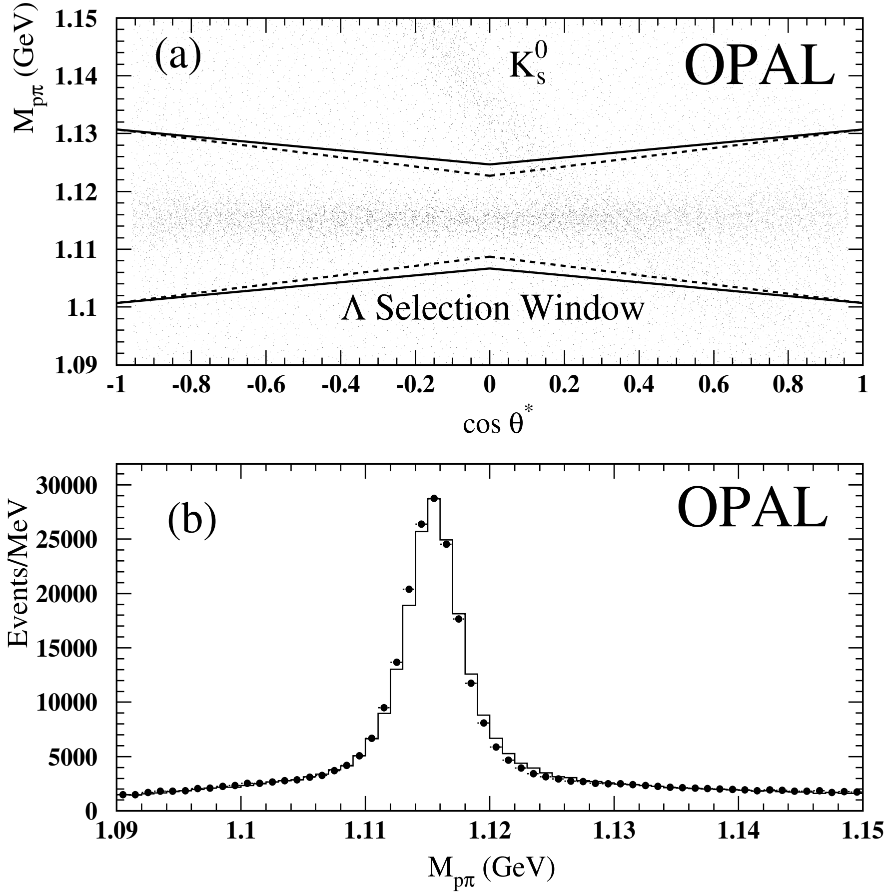
Are there any de/polarization mechanisms in hadronization ?

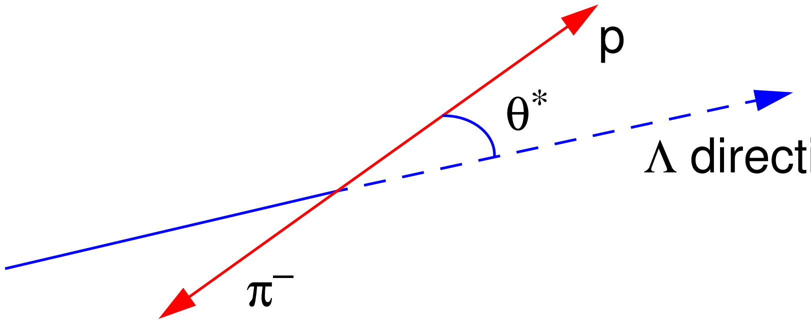
Extraction of the Λ Polarization

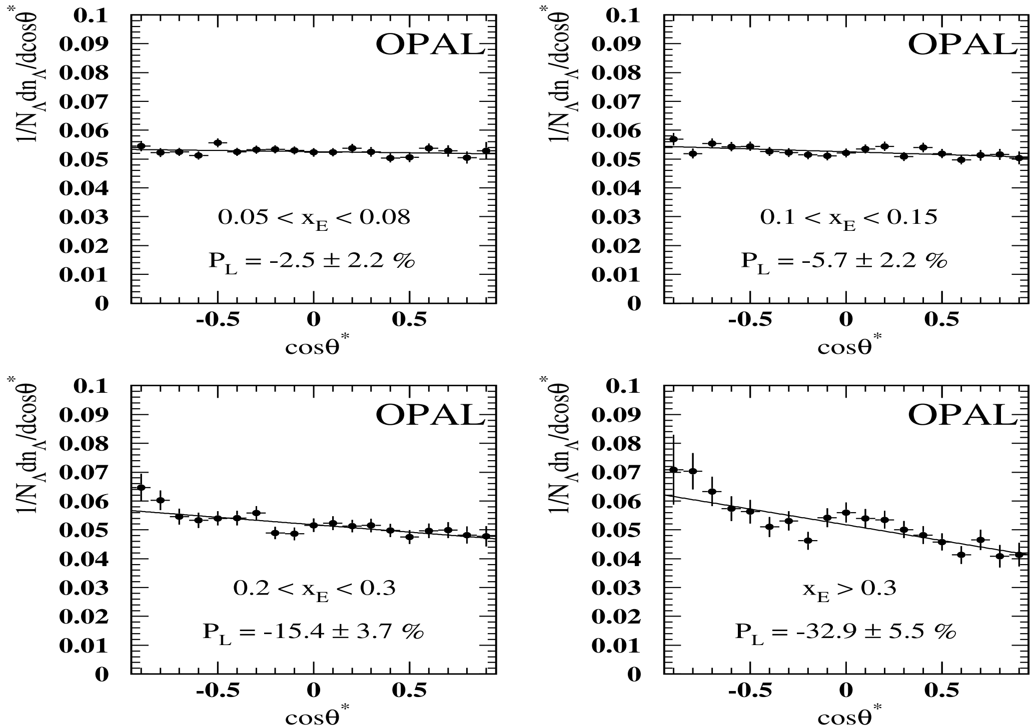
$$1/N \cdot \frac{dN}{d\cos\theta^*} = 1 + \alpha P_L \cos\theta^*$$

$\alpha = 0.642 \pm 0.013$

Invariant pπ-mass for selected V^0 candidates







- Mass resolution a few MeV
- Selection efficiency 10-25%

Results for the Λ Polarization

For $x_E > 0.3$: $P_L = -0.33 \pm 0.08$ OPAL

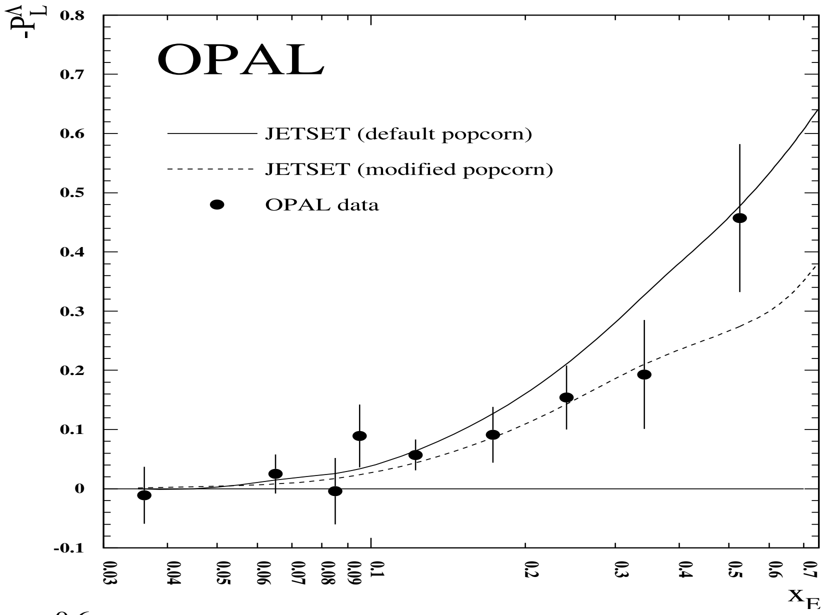
$P_L = -0.32 \pm 0.07$ ALEPH

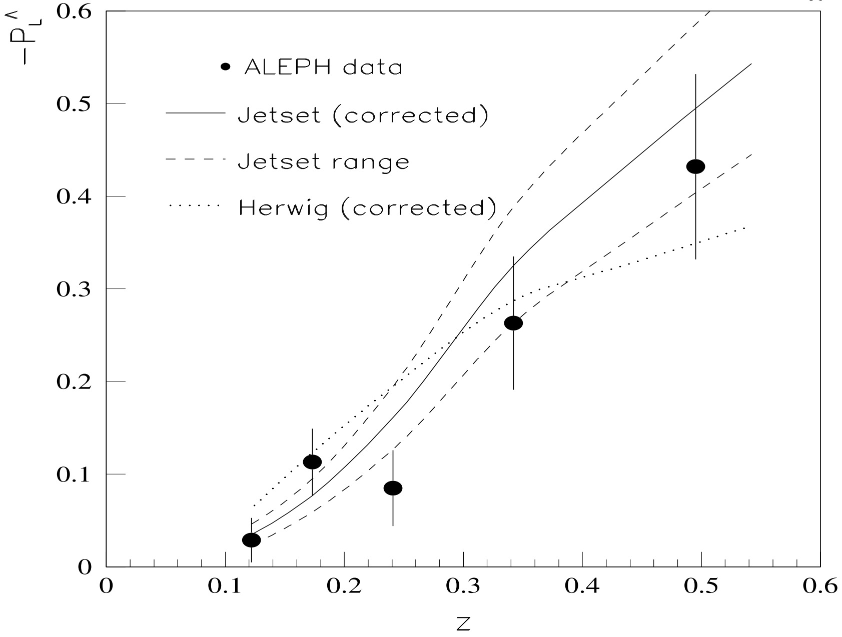
Longitudinal polarization as a function of x_E is in agreement with a SU(6) model:

- Primary Λ's polarized as primary s-quarks
- No contribution from primary polarized u-, d-quarks
- Heavier baryons containing the primary s-quark transfer polarization according to SU(6) model
- No polarization by quarks produced in fragmentation
- Differential production rates from JETSET

A model for spin transfer based on a g_1^Λ -sum rule is also consistent with the data

No compelling evidence for any considerable transverse polarization

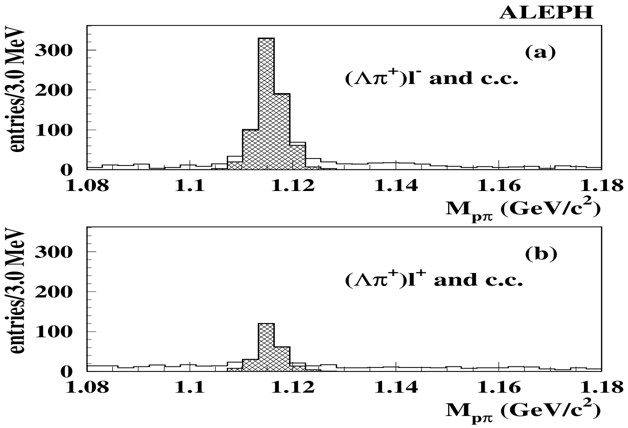




Lambda-B Polarization

$$\Lambda_b \rightarrow \Lambda_c l^- \bar{\nu} X$$

$$\Lambda_c \rightarrow \Lambda \pi^+ X$$

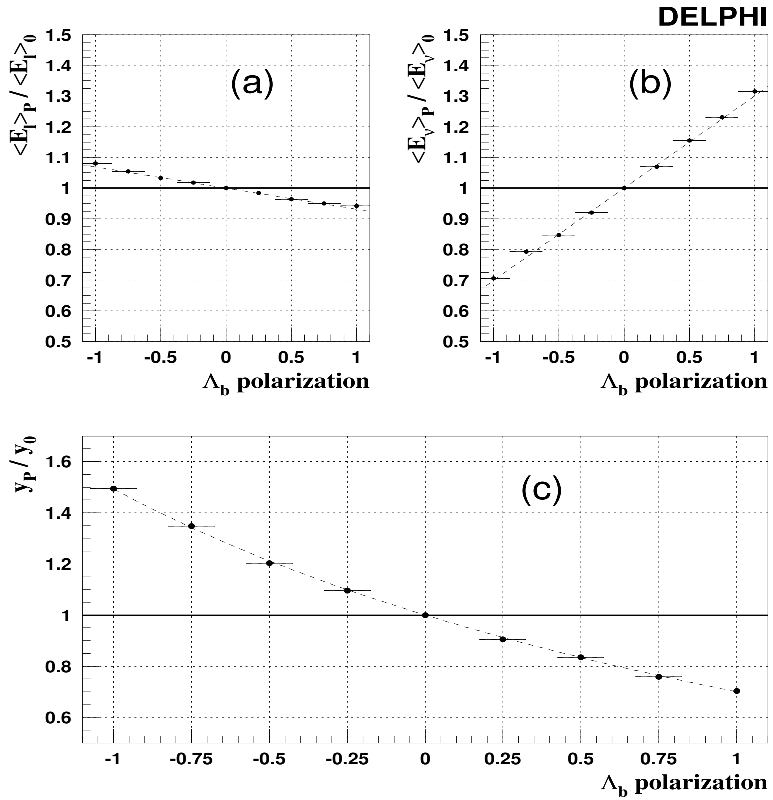


Right-sign combinations

Wrong-sign combinations

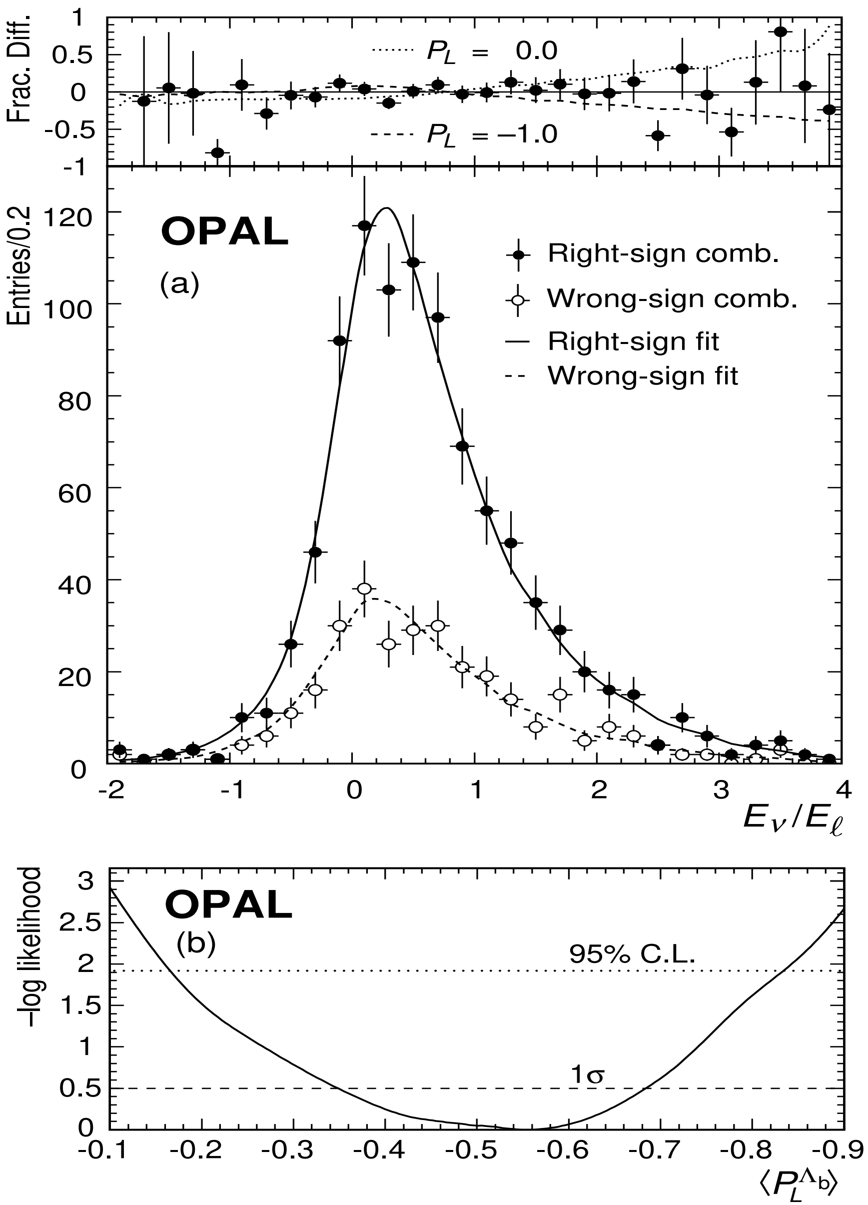
For V-A coupling lepton is preferentially emitted antiparallel to spin of b and ν tends to be emitted parallel to spin of b

In laboratory polarization gives harder lepton and softer neutrino energy spectrum



In particular $y=E_\nu/E_l$ is sensitive to polarization and robust against theoretical uncertainties

E_ν estimated from missing energy in signal hemisphere



$$P_L = -0.56^{+0.20}_{-0.13} \pm 0.09$$ OPAL

$$P_L = -0.23^{+0.24}_{-0.20} + {}^{+0.08}_{-0.07}$$ ALEPH

$$P_L = -0.49^{+0.32}_{-0.30} \pm 0.17$$ DELPHI

A model taking account of b baryons proceeding through intermediate states such as Σ_b and Σ_b^* gives a range of expected polarization

$$-0.54 < P_L < -0.88$$ Theory

for no b-quark depolarization during hadronization

Experimental results agree with the hypothesis that there is no loss of b polarization during the fragmentation

Theory of Spin Density Matrices

State for a vector meson (S=1, L=0) ensemble:

$$\begin{bmatrix} \rho_{1,1} & \rho_{1,0} & \rho_{1,-1} \\ \rho_{0,1} & \rho_{0,0} & \rho_{0,-1} \\ \rho_{-1,1} & \rho_{-1,0} & \rho_{-1,-1} \end{bmatrix}$$

with

$$\rho_{1,1} + \rho_{0,0} + \rho_{-1,-1} = 1$$

$$\mathrm{Im}(\rho_{\lambda,\lambda}) = 0$$

$$\rho_{1,0} = \rho_{0,1}^{*}$$

$$\rho_{1,0} = -\rho_{-1,0}$$

Helicity density matrix is a special case of the general spin density matrix

Diagonal elements $\rho_{\lambda,\lambda}$ give fractional intensity of helicity λ in sample

- In parity conserving decays (without FSI) only one independent diagonal element $\rho_{0,0}$

Non-zero values of off-diagonal elements indicate coherence betw. states

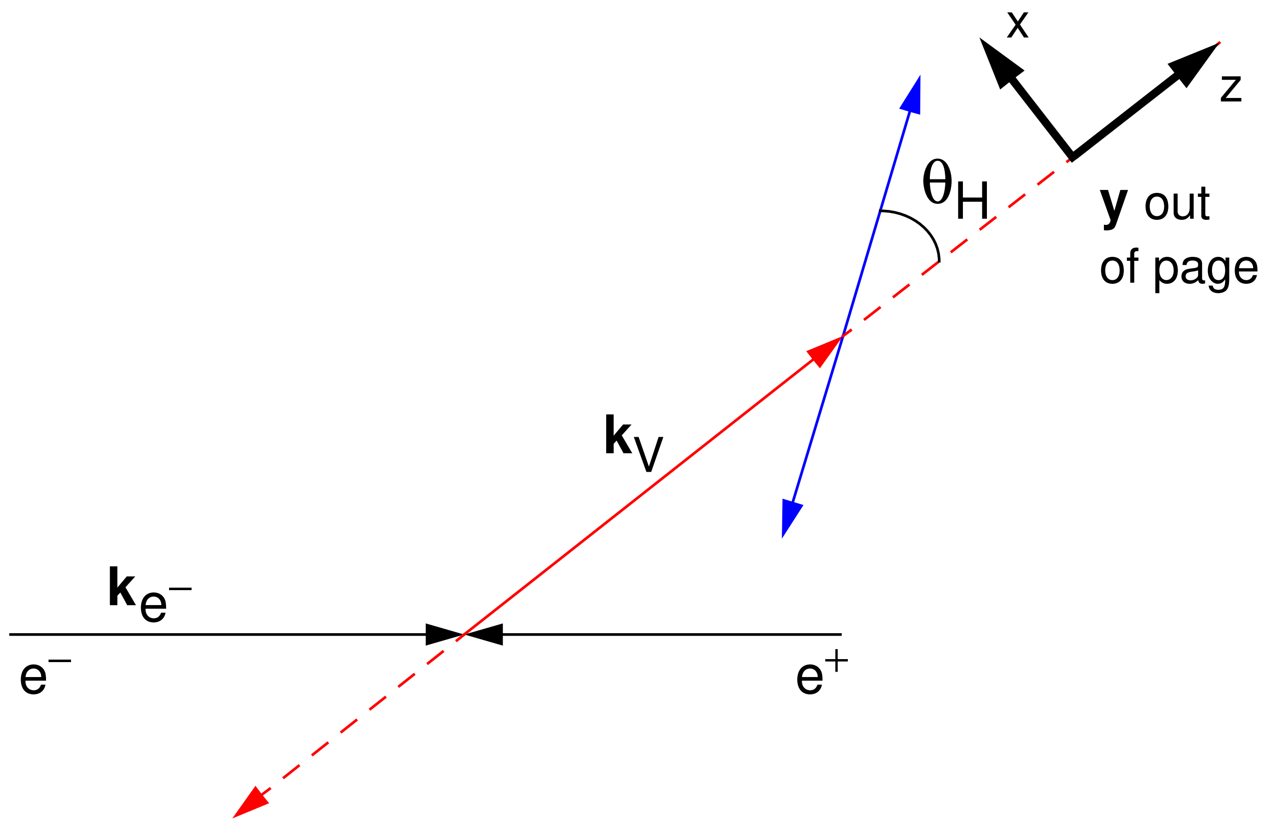
Matrix elements are measured using the decay angular distributions

The Vector Meson Helicity-Beam Frame

z is direction of vector meson in CMS (same as lab at LEP)

$\mathbf{y} = \mathbf{k_e} \times \mathbf{z}$

$\mathbf{x} = \mathbf{y} \times \mathbf{z}$



θ_H and ϕ_H are the polar and azimuthal angles of the decay analyser in the vector meson rest frame

Predictions for Meson Spin Alignment

Starting point:

Vector meson contains the polarized primary quark

Diagonal element $\rho_{0,0}$

- Statistical model $\rho_{0,0} = \frac{1}{2} \cdot \left(1 - \frac{P}{V}\right) \Rightarrow 0 < \rho_{0,0} < 0.5$

Fragmentation process produces extra quark and anti-quark pairs with all helicity states equally probable; $\rho_{0,0} = 1/3$ only for $V = 3 \times P$

- QCD-inspired model (longitudinal s.a.) $\rho_{0,0} \rightarrow 0$

Describes fragmentation process as the emission of soft gluons from primary quark. At the end of the fragmentation chain an antiquark from a soft gluon decay combines with the primary quark

- Coupling q -> q' V (transverse s.a.) $\rho_{0,0} \rightarrow 1$

Helicity conserving vector current

- HQET (no spin alignment) $\rho_{0,0} = \frac{1}{3}$

No prefered helicity state for B* and D* mesons

Non-diagonal elements

- ## Incoherent fragmentation models

Off-diagonal elements generated by transverse momentum relative to the primary quark direction should vanish in the limit p_T -> 0 and only be observable in frames referred to the internal properties of the jet, such as the helicity-quark frame

- ## Coherent (non-independent) fragmentation

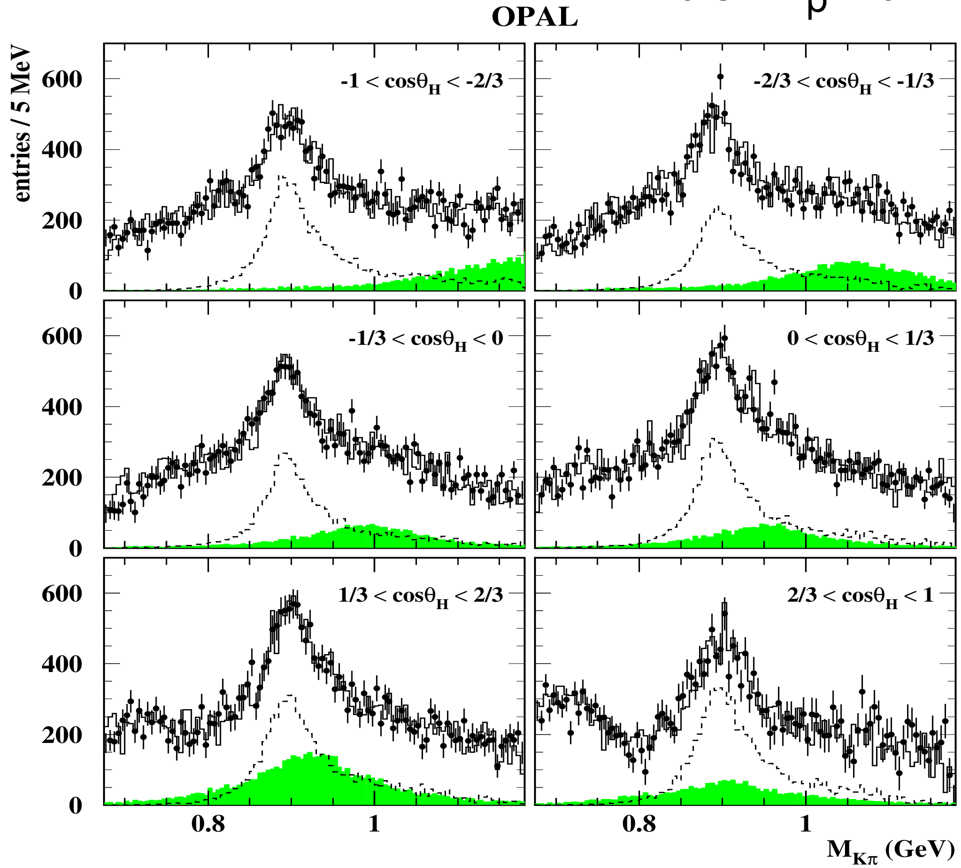
Final state interaction between primary quark and antiquark can lead to small negative values for $\mathrm{Re}(\rho_{1,-1})$ (and very small values for the imaginary component)

$\mathrm{Re}(\rho_{1,-1})$ is related to $\rho_{0,0}$ via the production angle θ of the vector meson relative to the electron direction

K*(892) Spin Alignment

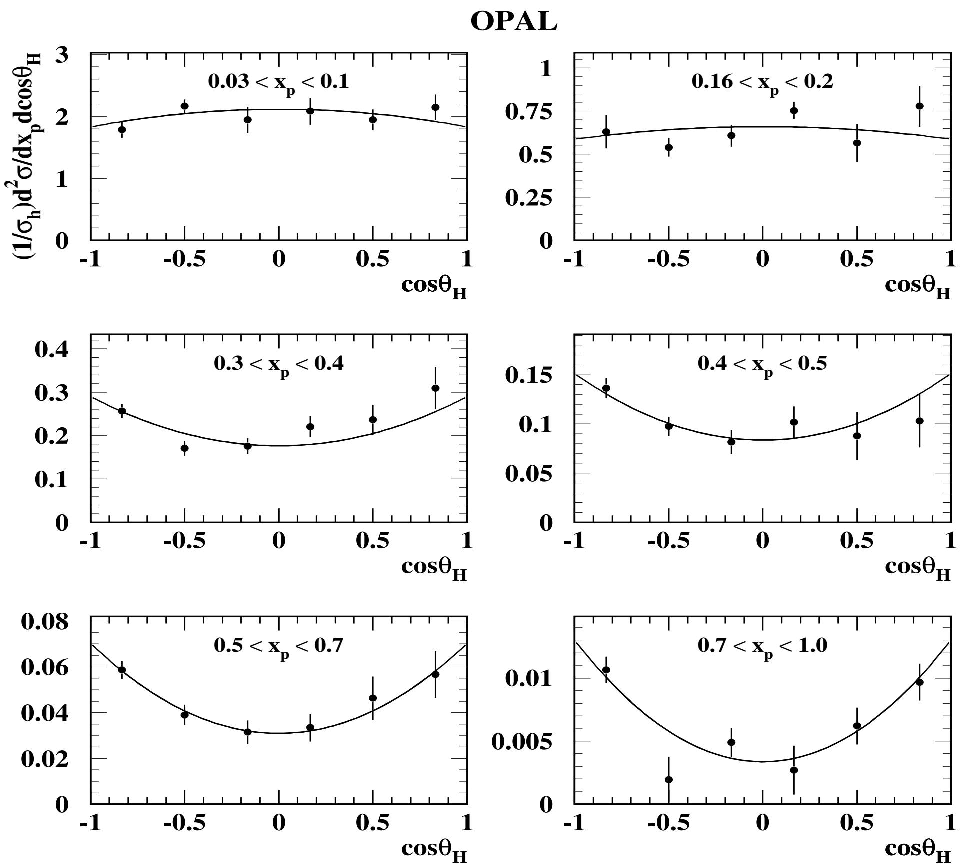
$K^+\pi^-$-invariant mass spectrum

$0.3 < x_p < 0.4$



Spectra fitted to signal, ρ^0 and ω reflections and combinatorical BG

Fully corrected differential cross-sections

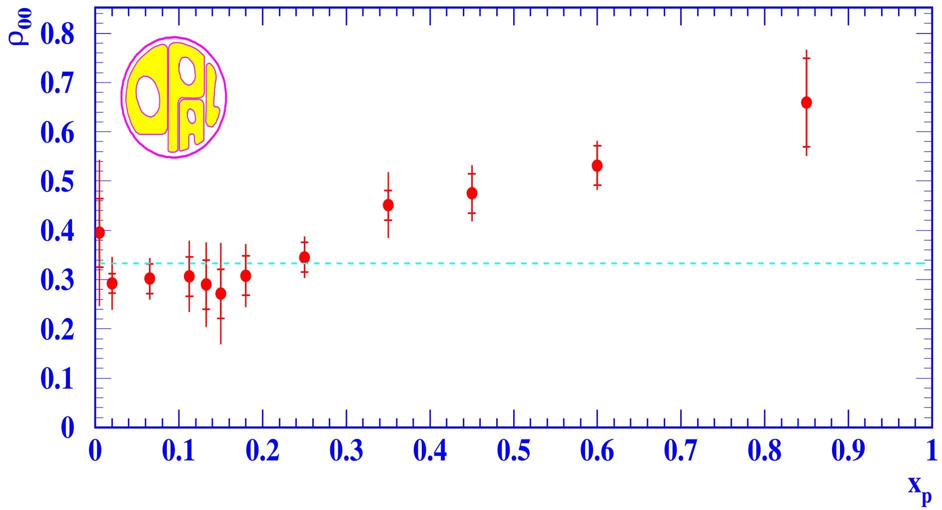


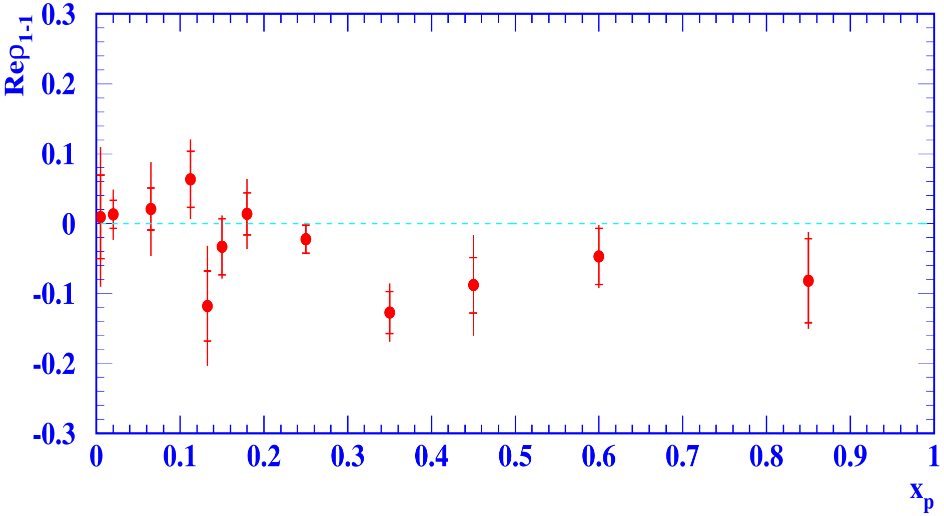
Charged Kaons identified by dE/dx

- Efficiency of 45%, purity of 30 - 50%

~ $\cos^2\theta_H$ ($\sin^2\theta_H$) for helicity 0 (-1,+1)

OPAL Results for the K*(892)





Other off-diagonal elements zero

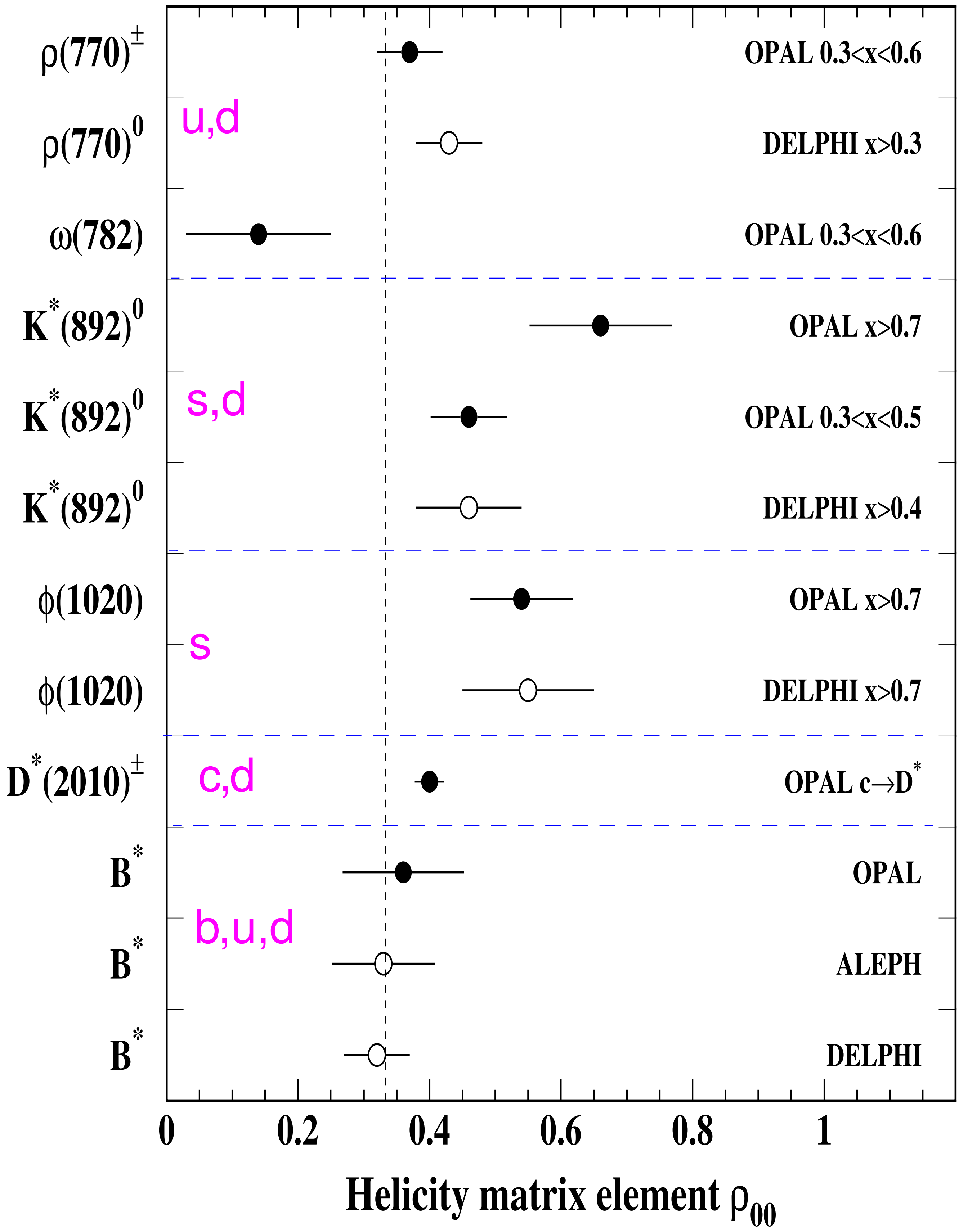
At low x_p data consistent with expectations of incoherent production populating all three helicity states equally

At larger x_p the K* is produced preferentially in the transverse helicity state

At larger x_p some indication for small negative values of $\mathrm{Re}(\rho_{1,-1})$; same for the $\Phi(1020)$ and D*; not confirmed by DELPHI measurements on K*, Φ, ρ^0

Relation between $\rho_{0,0}$ and $\mathrm{Re}(\rho_{1,-1})$ in good agreement with a theory based on coherent fragmentation

Summary of Measurements for ρ^{00}



Conclusions

- LEP provides a variety of measurements related to the spin transport in the fragmentation
- Significant longitudinal polarization is measured for Λ hyperons with intermediate and high momenta and Λ_b baryons consistent with the simple quark model and the assumption of no depolarization in hadronization
- Spin-alignment measurements for the vector mesons indicate a preference for production of $K^*(892)^0$, $\phi(1020)$ and possibly D^* in the helicity-zero (transverse) state, whereas other mesons appear to populate equally the 3 states
- Some indications that off-diagonal elements $Re(\rho_{1,-1})$ are small and negative for K^*, Φ, D^* as predicted by a theory of coherent production
- The pattern of observations would benefit from more experimental measurements and awaits a theoretical interpretation