Properties of Light Particles Produced in Z^0 Decays

Results from DELHI, L3 and OPAL

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- Vector meson spin alignment in hadronic Z^0 decays
- Λ baryons in hadronic Z^0 decays
- Ξ production at LEP1
- Production of $f_0(980)$, $f_2(1270)$ and Φ in hadronic Z^0 decays
- Two Photon Collisions
- Summary

Vector meson spin alignment in hadronic Z^0 decays

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$$e^+e^- \to Z^0 \to V + \ldots \qquad V = \text{ vector meson}$$

Contributions:

# 235	DELPHI	ρ^0, K^{*0}, Φ
# 190	OPAL	Φ, $D^{*\pm}$, B^*
# 191	OPAL	K^{*0}

Helicity density matrix $\rho_{\lambda\lambda'}$, with z-axis along the direction of motion in the cms.

Element ρ_{00} determined from decay angular distribution:

- for decay into two pseudo scalars

$$W(\cos\vartheta_H) = \frac{3}{4}\left[(1-\rho_{00}) + (3\rho_{00}-1)\cos^2\vartheta_H\right]$$

after φ_H integration ($-\pi \leq \varphi_H \leq +\pi$).

	$\rho_{00} =$	$W(\cos\vartheta_H) =$
no spin alignment	$1/3$	isotropic
helicity ±1 state	0	$\sin^2\vartheta_H$
helicity 0 state	1	$\cos^2\vartheta_H$

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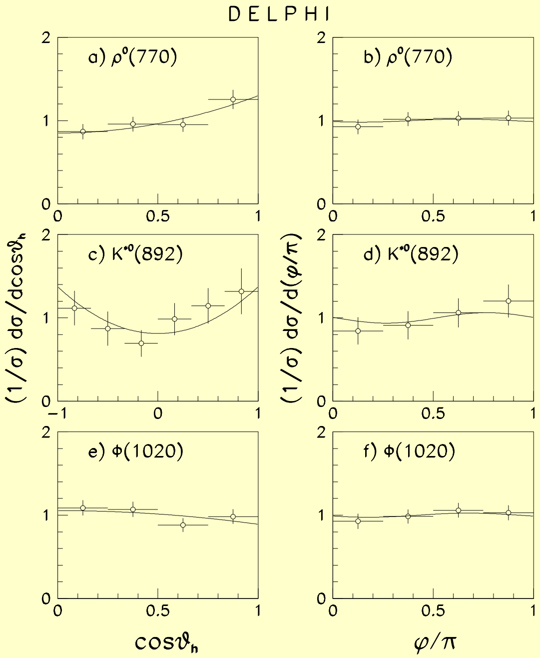
Spin alignment for ρ, K^{*0} and Φ

DELPHI result for $x_p \geq 0.4$:



- ρ^0 and $K^{*0}(892)$ unequal populations in the three helicity states
- Φ no spin alignment observed for $x_p \geq 0.4$ (but for $x_p \geq 0.7$)

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Models for spin aligment

- Statistical model:
  fragmentation process produces $q\bar{q}$ pair with all helicity states being equally probable.
  Spin of primary quark and of secondary quark

  parallel: vector meson with $\lambda = \pm 1$
  antiparallel: pseudo scalar (P) or vector (V) with $\lambda = 0$

$$\rho_{00} = \frac{1}{2}\left(1 - \frac{P}{V}\right) = 0 \ldots 0.5$$

  $\rho_{00} = 1/3$ corresponds to $P/V = 1/3$ (spin counting)
  ($P/V = 1$ in commonly used Monte Carlo models)

- HQET:
  light quarks from heavy quark fragmentation equally likely to be aligned along either direction relative to fragmentation axis
  $P/V = 1/3 \leadsto \rho_{00} = 1/3$ (isotropy)

- QCD-inspired model: (fragmentation process as emission of soft gluons from fast primary quark)
  fast quark combines with antiquark (same hel.) from gluon emission $\leadsto \rho_{00} = 0$ for vector meson

- vector meson production through $q \to qV$ with vector meson coupling to the quark like a vector current
  $\leadsto \rho_{00} = 1$ (vector meson $\lambda = 0$) from helicity-conserving vector current

Results on ρ_{00}

Results on element ρ_{00} of helicity density matrix from DELPHI and OPAL

	DELPHI		OPAL	
ρ_0	0.43 ± 0.05	$x_p \geq 0.4$		
K^{*0}	0.27 ± 0.06	$x_p \leq 0.3$		
	0.46 ± 0.08	$x_p \geq 0.4$	0.66 ± 0.11	$x_p \geq 0.7$
Φ	0.30 ± 0.04	$x_p \leq 0.3$		
	0.30 ± 0.04	$x_p \geq 0.4$		
	0.55 ± 0.10	$x_p \geq 0.7$	0.54 ± 0.08	$x_E \geq 0.7$
$D^{*\pm}$			0.40 ± 0.02	(charm only)
B^*			0.36 ± 0.09	$(+-0\ B^*)$

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Spin alignment of K^{*0}

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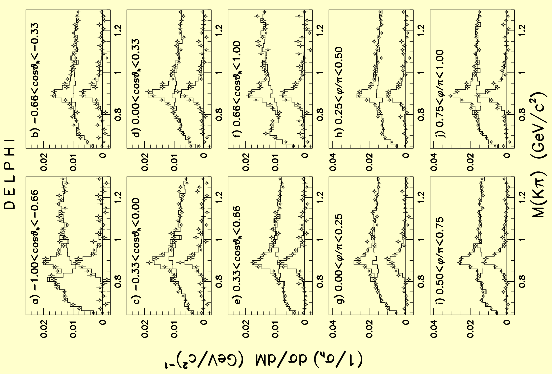
- DELPHI result: $K^\pm$ identified by RICH detector $K^\pm\pi^\mp$ mass distributions for $x_p \geq 0.4$



$0.1 \leq x_p \leq 0.3$	0.27 ± 0.06
$x_p \geq 0.3$	0.41 ± 0.07
$x_p \geq 0.4$	0.46 ± 0.08
$x_p \geq 0.5$	0.47 ± 0.10

- For small x_p no spin alignment (as expected for light mesons from decay of heavier objects).
- For high x_p helicity 0 state preferred.
- Off-diagonal elements small, consistent with zero.

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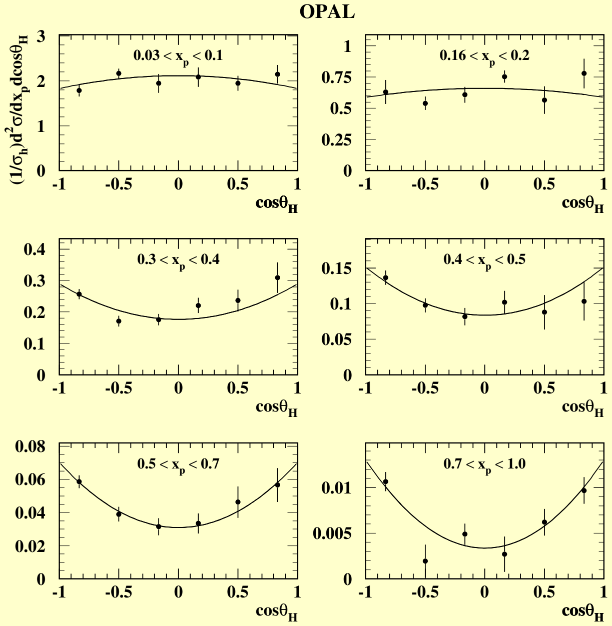
K^{*0} distributions

Six bins in x_p - curves show the fits to obtain the helicity density matrix element ρ_{00}:



... increasing value of ρ_{00} for increasing x_p.

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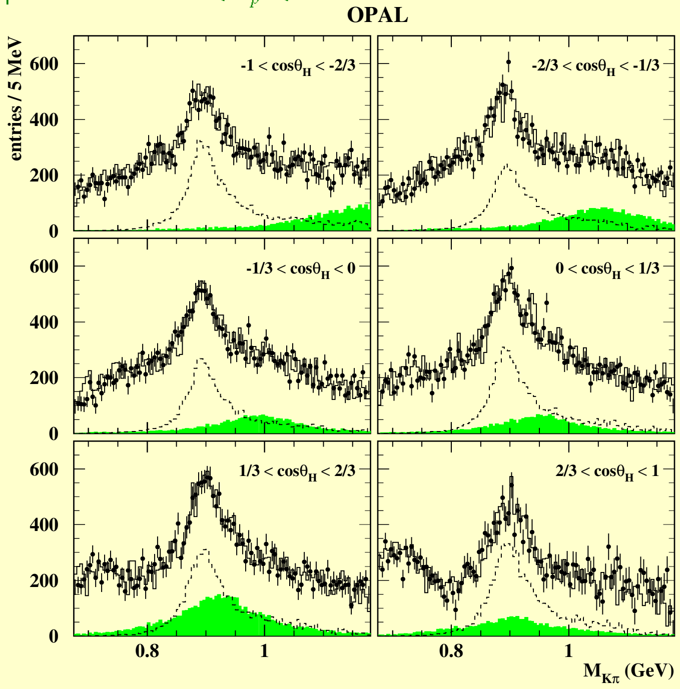
Spin alignment of K^{*0}

- OPAL result: $K^{\pm}$ identified by dE/dx except for $0.6 < p < 2.0$ GeV/c; contamination by $\rho^0 \to \pi^+\pi^-$.

Example: inclusive background-subtracted $K^{\pm}\pi^{\mp}$ mass spectra for the $0.3 < x_p < 0.4$ bins



... in total 216 mass spectra (12 bins in x_p).

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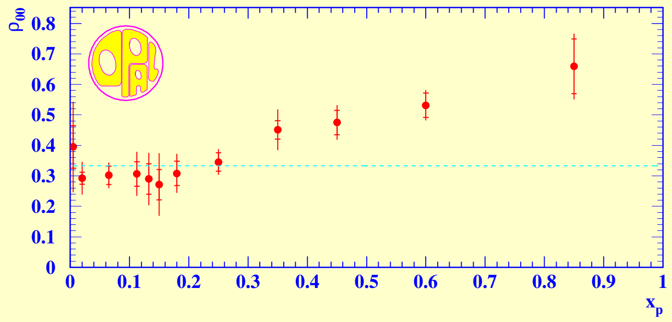
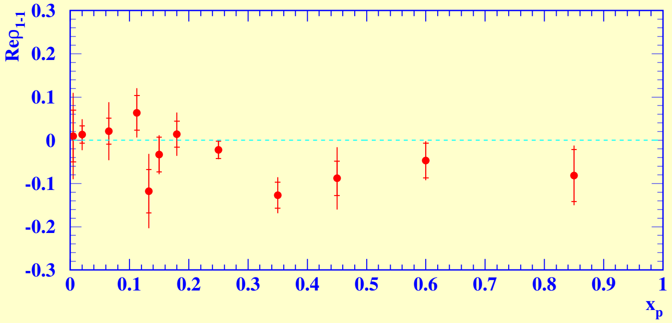
Results for K^{*0}

- ρ_{00} and
- Re$\rho_{1,-1}$

as a function of x_p:





Results for $x_p \geq 0.3$:

$\rho_{00} > 1/3$

Re$\rho_{1,-1}$ negative

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Off-diagonal elements

Off-diagonal elements, for example $\rho_{1,-1}$, from azimutal decay distribution:

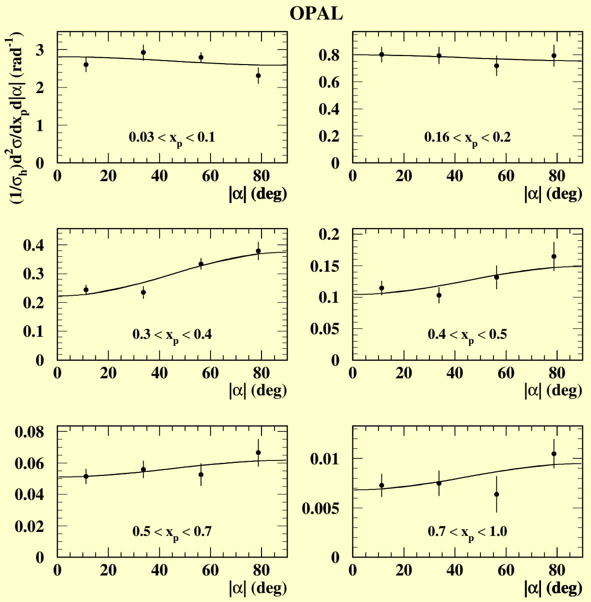
$$W(\varphi_H) = \frac{1}{2\pi}\left(1 + 2\text{Im}\rho_{1,-1}\sin 2\varphi_H - 2\text{Re}\rho_{1,-1}\cos 2\varphi_H\right)$$

(used by DELPHI), or

$$W(|\alpha|) = \frac{2}{\pi}\left(1 + 2\text{Re}\rho_{1,-1}\cos 2|\alpha|\right)$$

(used by OPAL) with $\alpha = |\varphi_\text{H}| - \pi/2$, removing dependence on Im$\rho_{1,-1}$.

$|\alpha|$ distribtion in six x_p bins



Conclusion on K^{*0}

$\rightsquigarrow$ leading particle effect.

- ρ_{00}: Probability for mesons to contain one of the primary quark rises with scaled momentum.

Anselmino et al. (hep-ph/97004420): negative values of Re$\rho_{1,-1}$ generated for leading vector mesons by coherence in the production and fragmentation of the primary quark and antiquark for Z_0.

Expectation quantitatively:

$$\text{ratio} \quad \frac{\text{Re}\rho_{1,-1}}{(1-\rho_{00})} \approx -0.10$$

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OPAL result for ratio:

x_p	Re$\rho_{1,-1}/(1-\rho_{00})$
$0.3\ldots0.4$	-0.24 ± 0.08
$0.4\ldots0.5$	-0.17 ± 0.13
$0.5\ldots0.7$	-0.11 ± 0.09
$0.7\ldots1.0$	-0.24 ± 0.22

- Re $\rho_{1,-1}$ weighted average -0.19 ± 0.05 for $x_p > 0.3$
- Other off-diagonal elements found to be consistent with zero, as expected, over the entire x_p range.

B^* spin alignment

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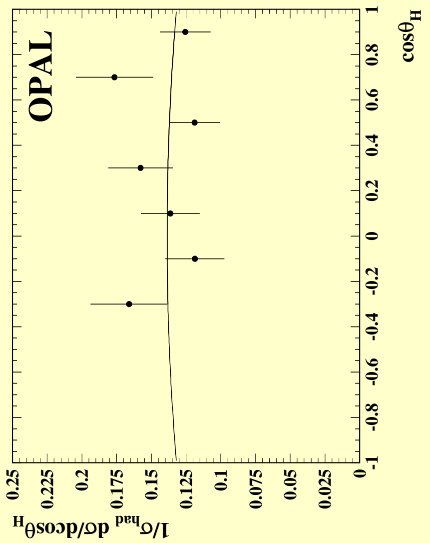
$B^* \to B\gamma$ e.m. decay to pseudo scalar and vector

$$W(\cos\vartheta_H) = \frac{1}{2}\left[1 - \frac{3\rho_{00}-1}{4}\left(3\cos^2\vartheta_H - 1\right)\right]$$

	$\rho_{00} =$	$W(\cos\vartheta_H) =$
no spin alignment	$1/3$	isotropic
helicity ±1 state	0	$1+\cos^2\vartheta_H$
helicity 0 state	1	$\sin^2\vartheta_H$

About 1900 decays with photon identified by conversion; fitting $B^* - B$ mass difference distribution:



Result: $\rho_{00} = 0.36 \pm 0.06 \pm 0.07$ consistent with *no spin alignment* (consistent with $P:V = 1:3$).

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Summary on vector meson spin alignment

- Leading vector mesons (other than the B^*) are spin-aligned, with preference for helicity zero state, shown for: ρ^0, K^{*0}, Φ and $D^{*\pm}$.
- Negative off-diagonal element for Re$\rho_{1,-1}$ by OPAL:

-0.09 ± 0.03	K^{*0}	$x_p > 0.3$
$-0.11 \pm 0.05 \pm 0.05$	Φ	$x_E > 0.7$
-0.09 ± 0.03	$D^{*\pm}$	$x_E > 0.5$

- All other helicity density matrix elements consistent with zero.

Remarks on MC:

- No spin alignment of vector mesons expected in the simplest string model.
- No mechanism to produce spin-aligned elements of the helicity density matrix in QCD cluster model of HERWIG.
- Neither model will generate non-zero values for the off-diagonal elements of the helicity density matrix.

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Λ baryons in hadronic Z_0 decays (OPAL)

Contribution 197: Polarization and Forward-Backward Asymmetry of Λ Baryons in Hadronic Z^0 Decays
The OPAL collaboration

Longitudinal polarization $P_{\rm L}$ of -0.91 expected for s quarks from Z^0 decay.
Weak decay of Λ: $\leadsto P_{\rm L}$ from decay distribution

$$\frac{1}{N}\frac{dN}{d\cos\vartheta_{\rm H}} = 1 + \alpha P_{\rm L} \cos\vartheta^*_{\rm H}$$

(with $\alpha = 0.642 \pm 0.013$ Λ decay parameter).

A certain fraction of the Λ rate will contain a primary s quark at high momentum.
Relative contribution of direct s quark from JETSET:
15.2 % for $x_{\rm E} > 0.15$ 35.5 % for $x_{\rm E} > 0.4$

Λ source	Λ polarization
direct s	-0.91
fragmentation	0
u, d	0
Σ, Σ^*, Ξ	≈ 0.5
Ω	0
c baryon	-0.25
b baryon	-0.25
b meson	0

Longitudinal Λ polarization (OPAL)

$$P_{\rm L} = -32.9 \pm 7.6\% \quad \text{for} \quad x_{\rm E} > 0.3$$

(no significant evidence for any transverse polarization).

- consistent with earlier ALEPH result.

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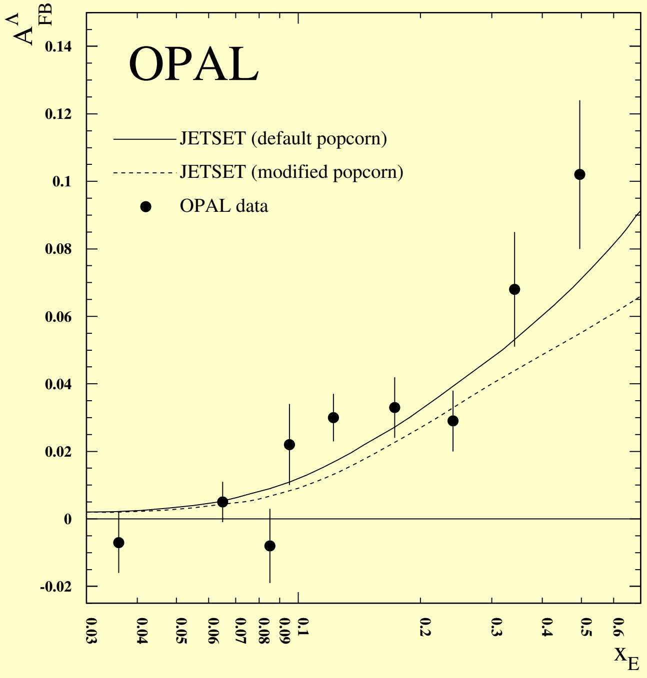
Λ *forward-backward Asymmetry*

Λ will reflect the original s quark asymmetry:

$$A_{\mathsf{FB}} = \frac{N_{\mathsf{F}} - N_{\mathsf{B}}}{N_{\mathsf{F}} + N_{\mathsf{B}}} \quad \text{from} \quad B\cos\vartheta \text{ distribution } (B = \text{baryon nr})$$

x_{E} dependence of A_{FB}, compared to JETSET



$\rightsquigarrow$ no distinction between models

OPAL: $A_{\mathsf{AB}} = 0.083 \pm 0.013$ for $x_{\mathsf{E}} > 0.3$

consistent with earlier ALEPH and DELPHI results.

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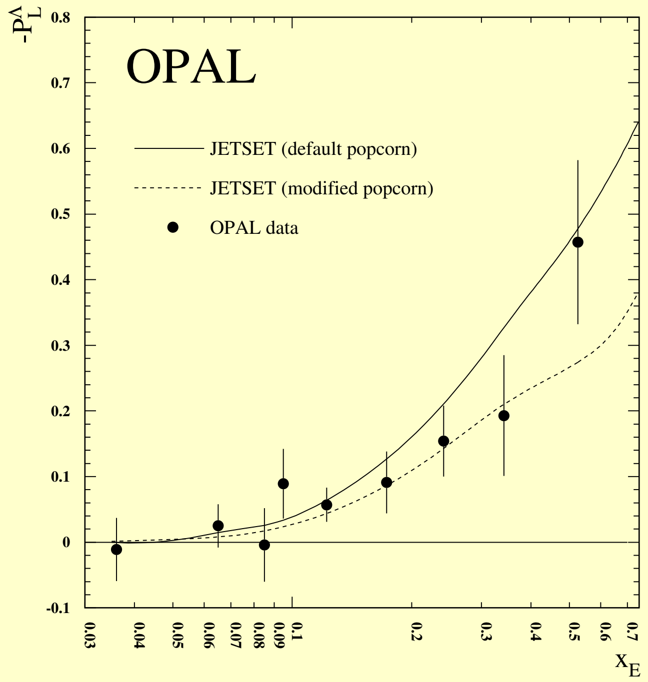
Longitudinal Λ *polarization* P_L

x_{E} dependence of P_L, compared to JETSET



Two versions of JETSET 7.4:

- default version of the "popcorn" model for baryon production, tuned by OPAL in a global fit
- modified "popcorn" (P. Edén), more complete implementation of baryon production within LUND string fragmentation model.

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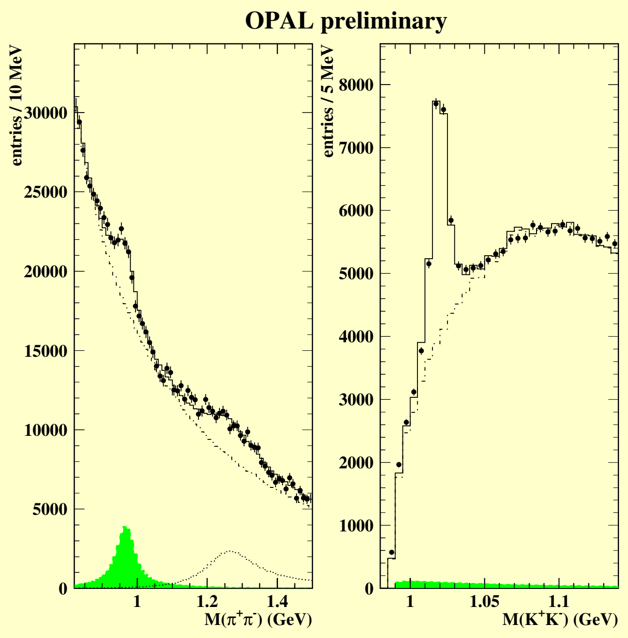
f_0, f_2 and Φ in Z^0 decay (OPAL)

Contribution 193: Production of $f_0(980)$, $f_2(1270)$ and $\Phi(1020)$ in hadronic Z^0 decay
The OPAL collaboration mass spectra of
$\pi^+\pi^-$ (like-sign spectra subtracted) (left)
K^+K^- for $x_p > 0.14$ (right)



$f_0(980) \to \pi^+\pi^-$ shaded green histogram $\Phi \to K^+K^-$
$f_2(1270) \to \pi^+\pi^-$ dotted histogram

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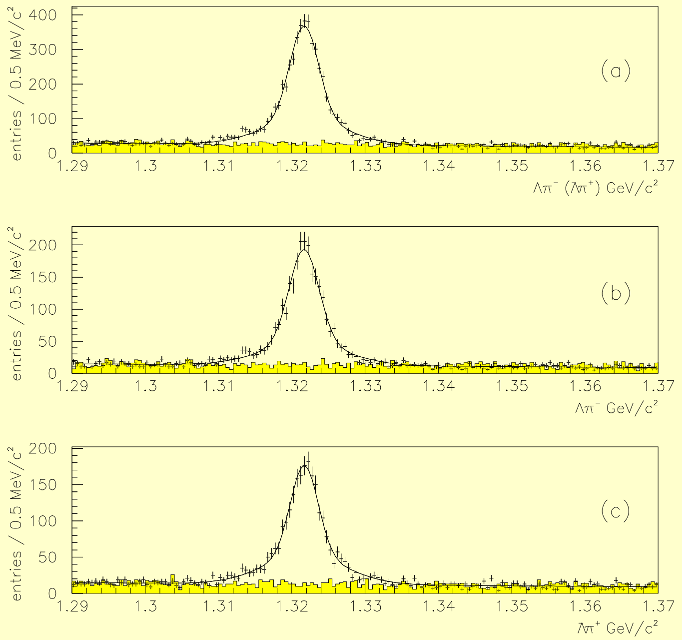
Ξ^- and $\bar{\Xi}^+$ at LEP1 (DELPHI)

Samples of 2500 Ξ^- and 2300 $\bar{\Xi}^+$ observed in 92 . . . 95 data.
Right-sign $\Lambda\pi^-$, $\bar{\Lambda}\pi^+$ combinations:



DELPHI: 1321.61 ± 0.06 (stat) ± 0.33 (syst) MeV/c^2
PDG: 1321.34 ± 0.14 MeV/c^2
Preliminary: substantial reduction of syst. errors expected.
Inclusive production rates for $\langle \Xi^- + \bar{\Xi}^+ \rangle_{q\bar{q}}$:

DELPHI: 0.0233 ± 0.0007 (stat) ± 0.0024 (syst)
JETSET: $0.0251 \ldots 0.0273$
HERWIG: 0.0730 (disagreement)

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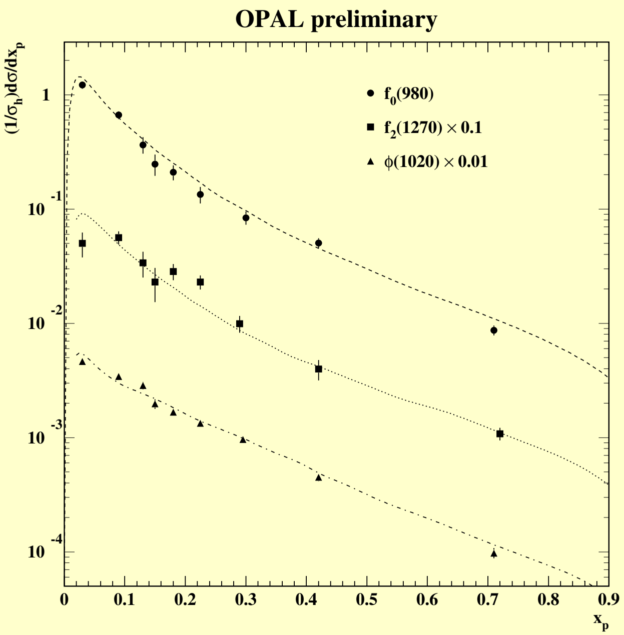
Fragmentation functions

Measured fragmentation functions: $(1/\sigma_{\mathrm{h}})\mathrm{d}\sigma/\mathrm{d}x_{\mathrm{p}}$ for $f_0(980)$, $f_2(1270)$ and Φ.

Curves from JETSET 7.4 (normalized to data rate)



Total inclusive rates (per hadronic Z^0 decay):

$f_0(980)$	0.160 ± 0.014
$f_2(1270)$	0.119 ± 0.016

Values consistent with f_0 and f_2 being $q\bar{q}$ mesons in the ${}^3P$ state composed mainly of $u\bar{u}$ and $d\bar{d}$.

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The $f_0(980)$

$f_0(980)$ well established as a scalar ($J^{PC} = 0^{++}$) state (${}^3P_0$?)

but: small total width, small $\gamma\gamma$ width, relative large coupling to $K\bar{K}$.

What is the $f_0(980)$?

- "cryptoexotic" $qq\bar{q}\bar{q}$ state [Jaffe and Johnson]
- $K\bar{K}$ molecule [Weinstein and Isgur]
- glueball (but lightest scalar glueball $\rightarrow 1500$ MeV)
- $f_0(980)$ plays the role of a novel "vacuum scalar" state (bound state of q and $\bar{q}$ with negative kinetic energy) [Gribov]

Signature of "vacuum scalar" state: larger yield ...

- in low multiplicity events, and
- in events with f_0 isolated in rapidity.

Approach to analyse the $f_0(980)$: Compare production with

- production of Φ (close in mass) and of $f_2(1270)$ ($q\bar{q}$ in ${}^3P_2$ state)
- LUND string model of hadronization (f_0 treated as conventional meson)

Charged particle multiplicity and rapidity gap dependence

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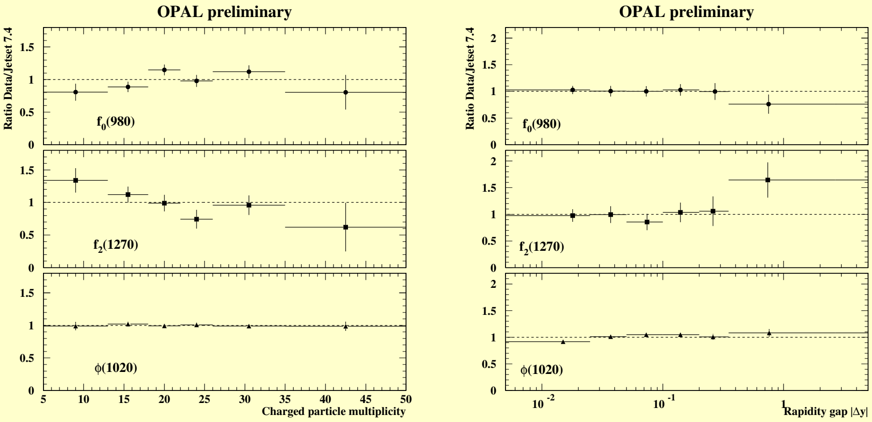
Ratio of Data rate : JETSET 7.4 versus charged particle multiplity (left) rapidity gap (right)



- no significant differences in production characteristics
- no evidence for enhanced f_0 production at low multiplicities or at large rapidity gaps
- no evidence to identify the f_0 with the vacuum scalar state proposed by Gribov

Light-quark Resonances in Two-Photon Collisions (L3)

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- $\pi^+\pi^-\gamma$:
  $\Gamma_{\gamma\gamma}(\eta')$ and η' transition form factor
- $\pi^+\pi^-\pi^0$:
  spin-parity and helicity analysis in two mass regions
- $K^0_S K^0_S$ and $\pi^+\pi^-$, K^+K^- :
  f_2-a_2 interference, $f_2'(1525)$ and further peak around 1750 MeV

Contribution 474:
Formation of Light-quark Resonances in Two-Photon-Collisions at LEP
The L3 collaboration

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$\pi^+\pi^-\gamma$ *final state*

η' transition form factor from:

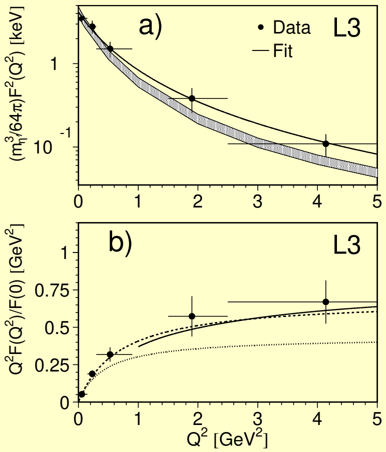
- Q^2 measured from $p_T(\eta')$: $0.01 \leq Q^2 < 0.9$ GeV^2
- singly tagged events: $1.5 \leq Q^2 \leq 10$ GeV^2

Form factor parametrization:

$$F^2(q^2, k^2) = \frac{64\pi}{m_{\eta'}^3}\Gamma_{\gamma\gamma}(\eta') \left[\frac{1}{1 - q^2/\Lambda^2}\right]^2 \cdot \left[\frac{1}{1 - k^2/\Lambda^2}\right]^2$$

Fit: $\Lambda = 0.900 \pm 0.046$ (stat) ± 0.022 (syst) GeV

Shaded band: prediction (Anisovich et al.), ranging from no gluonic component (upper line) to 15 % of gluonium content (lower line).



VDM: $\Lambda = 0.83$ GeV consistent with data (dashed line).
QCD (R. Jacob et al., include gluonic corr.) (continuous line)
QCD (Brodsky, Lepage): $\Lambda = 0.66$ GeV (dotted line)

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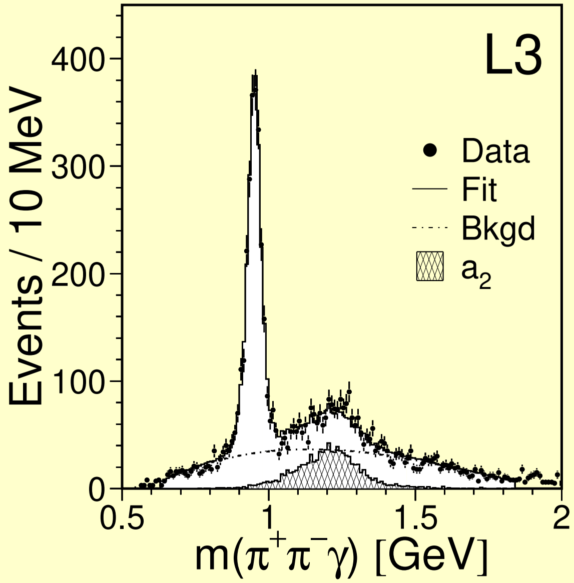
$\pi^+\pi^-\gamma$ *final state*

- Quasi-real photons: $Q^2 < 0.01$ GeV^2



Dominated by $\eta'(958)$,
with background from $a_2(1300)$ (one photon undetected).

Radiative width:

$$\Gamma_{\gamma\gamma}(\eta') = 4.17 \pm 0.10 \text{ (stat)} \pm 0.27 \text{ (syst)} \quad \text{keV}$$

(most precise value obtained in a single experiment).

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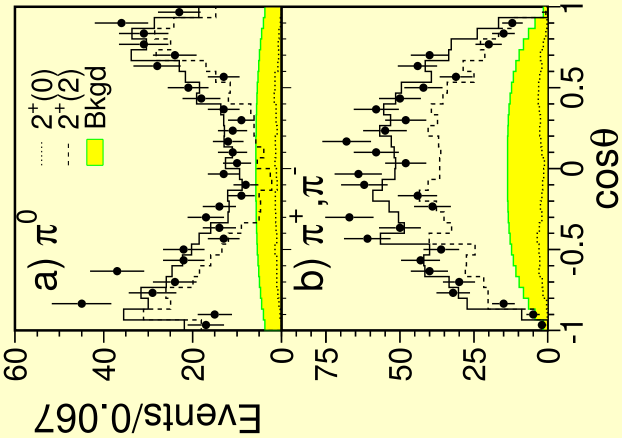
$\pi^+\pi^-\pi^0$ *final state*

- Low-mass sample $1.0 < m(\pi^+\pi^-\pi^0) < 1.55$ GeV

Dominated by
$J^{PC} = 2^{++}$ $a_2(1300)$ with decay $a_2 \to \rho^\pm\pi^\mp$.
Relative importance of helicity states 0 and 2
from $\cos\theta$ distribution:



Fit result: $P(\text{helicity} = 2) = 0.92 \pm 0.05$

with systematic uncertainty of 6 %.

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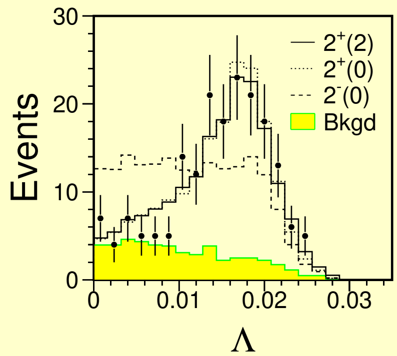
$\pi^+\pi^-\pi^0$ *final state*

- High-mass sample $1.55 < m(\pi^+\pi^-\pi^0) < 2.1$ GeV

Dalitz parameter

$$\Lambda = \left|\frac{\boldsymbol{p}_{\pi^+} \times \boldsymbol{p}_{\pi^-}}{Q_K^2}\right|^2$$

(π momenta normalized to maximum possible kinetic energy Q_K). Λ depends on spin-parity and amplitude and phase parameters for each spin-helicity state.

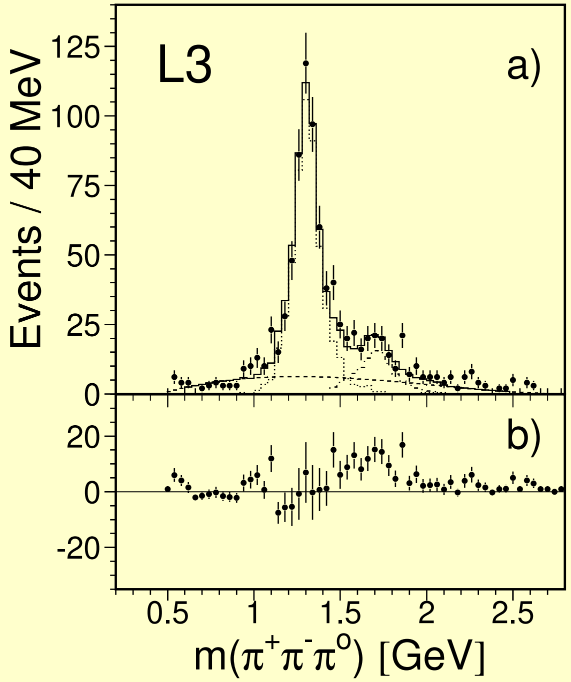


Spin-parity $J^P = 2^+$ favored; no sensitivity of helicity.

$\pi^+\pi^-\pi^0$ *final state*

- High-mass sample $1.55 < m(\pi^+\pi^-\pi^0) < 2.1$ GeV

Resonance parameters:
equal branching ratios for decays into the $f_2\pi$ and $\rho\pi$ final states, phase angle between the amplitudes consistent with $180°$.

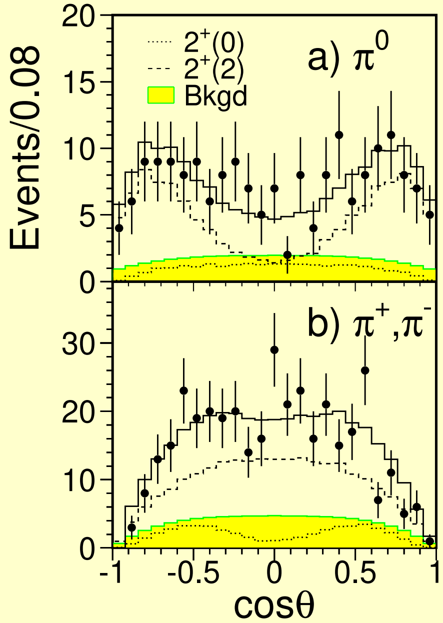


Fitted mass $1752 \pm 21 \pm 4$ MeV consistent with One Gluon Exchange Semi-Relativistic Quark Mass model (1740 MeV).

$\pi^+\pi^-\pi^0$ *final state*

- High-mass sample $1.55 < m(\pi^+\pi^-\pi^0) < 2.1$ GeV

Relative importance of helicity states 0 and 2 from $\cos\theta$ distribution:



Helicity 2 dominating:

$$P(\text{helicity } = 2) \approx 75\%$$

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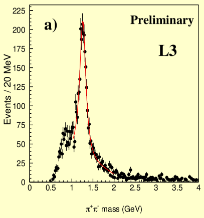
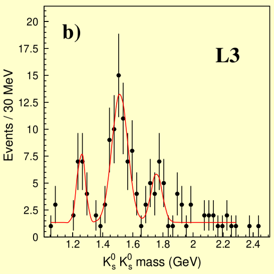
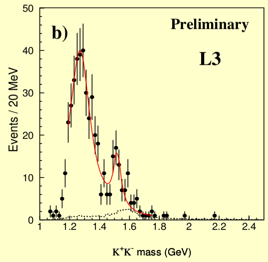
$K_S^0 K_S^0$ *and* $\pi^+\pi^-$, K^+K^- *final state*







Comments to the distributions on the right:
f_2-a_2 interference around 1300 MeV
- $K_S^0 K_S^0$ destructive
- K^+K^- constructive.

$f_2'(1525)$: two-photon width determined
$K_S^0 K_S^0$ at 1750 MeV: radially excited $f_2'(1525)$?
Mixing angle θ between singlet and octet members of the tensor meson nonet from $\Gamma_{\gamma\gamma}(f_2')/\Gamma_{\gamma\gamma}(f_2)$:

$$\theta = \left(29.4^{+1.4}_{-1.6}\right)^\circ$$

Mixing angle in agreement with Gell-Mann–Okubo mass formula
Deviation from ideal mixing (35.3°).

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Summary

- Vector meson spin alignment
  Leading (large x_p) vector mesons (ρ, K^{*0}, Φ, D^*) are spin-aligned with a preference for the helicity-zero state
  OPAL result on Re$\rho_{1,-1}$ (non-zero, negative) consistent with idea about coherence in $q\bar{q}$ production and fragmentation
  Can MC models be extended to explain measured helicity density matrices?
- Baryons: Λ
  Significant longitudinal polarization at higher momenta
  Significant FB asymmetry, described by JETSET
- Baryons: Ξ
  Large sample, allows mass measurement
  Rates measured, described by JETSET (disagreement for HERWIG)
- Production of $f_0(980)$, $f_2(1270)$ and Φ
  All measured properties consistent with hypothesis that the $f_0(980)$ is a conventional $q\bar{q}$ scalar meson
- Two-Photon production of η', a_2, f_2, $f_2'(1525)$
  Two-photon partial width measured: η' and $f_2'(1525)$
  Evidence for a radially excited state $a_2'(1750)$ of $J^P = 2^+$