Reconnection and BE effects in WW Decay

results from ALEPH, DELPHI, L3, OPAL

Paul de Jong
CERN-EP

September 1998
XXVIII International Symposium on Multiparticle Dynamics
Delphi, Greece, Sept 6-11, 1998

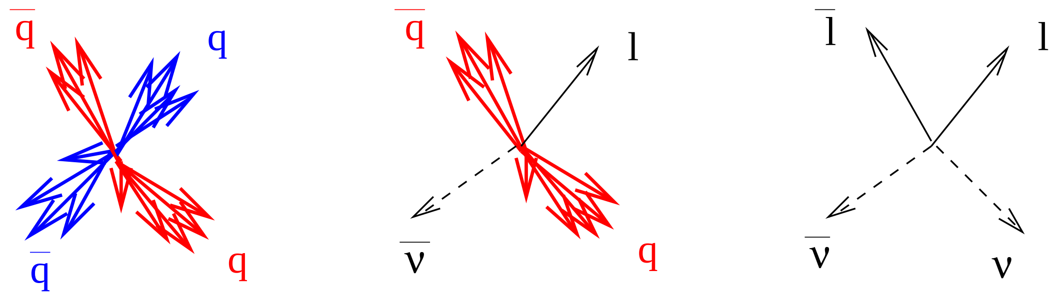
- Motivation
- CR and BEC models
- Charged Multiplicities
- Event Properties
- Analyses of BEC

Motivation

Major topic of study at LEP 2: $e^+e^- \rightarrow W^+W^-$

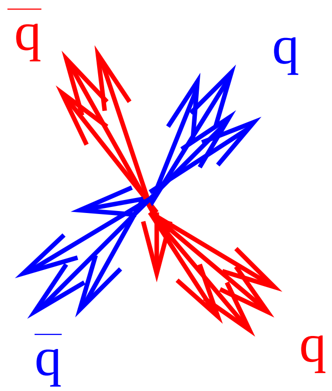
$\Rightarrow$ mass, width, gauge-couplings and decay properties of the W boson.

WW decays can be classified in 3 topologies:



with branching fractions 46%, 44% and 11% respectively.

For the $qqqq$ final state:

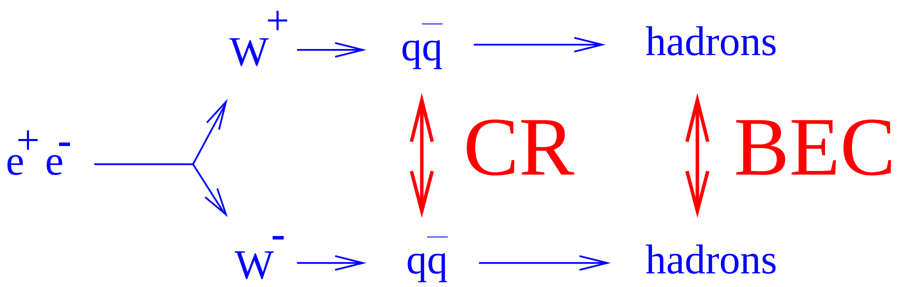


WW decay vertices $\sim$ 0.1 fm
hadronic scale $\sim$ 1 fm
$\Rightarrow$ large spacetime overlap

Motivation

WW Decays: originally treated in MC's as two colour singlets without interactions.

However, interconnections are imaginable:



• Colour reconnection: QCD interactions between partons from different W's. ⇒ Study event shapes, particle multiplicities;

• Bose-Einstein correlations: quantum mechanical effect for identical bosons. ⇒ Study particle correlations.

Interest:

- Insight in QCD vacuum structure and hadronisation
- May affect W mass measurement in $qqqq$ channel

Interest of W mass measurement

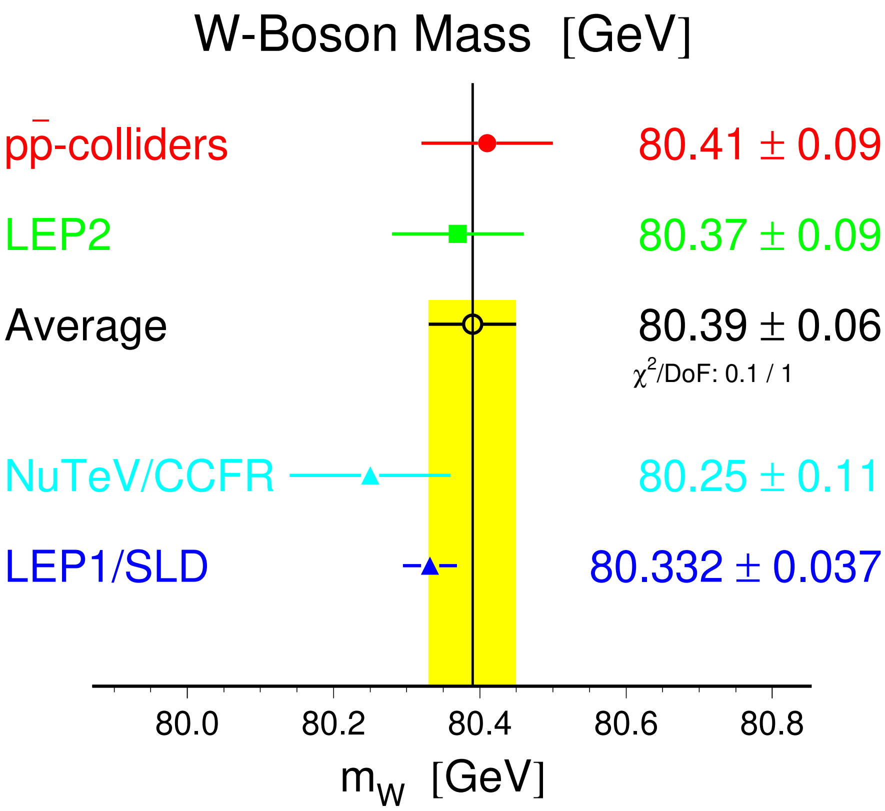
At LEP 1 (1989-1995): 16 M events at $\sqrt{s} \approx M_Z$

$\Rightarrow$ detailed study of electroweak SM

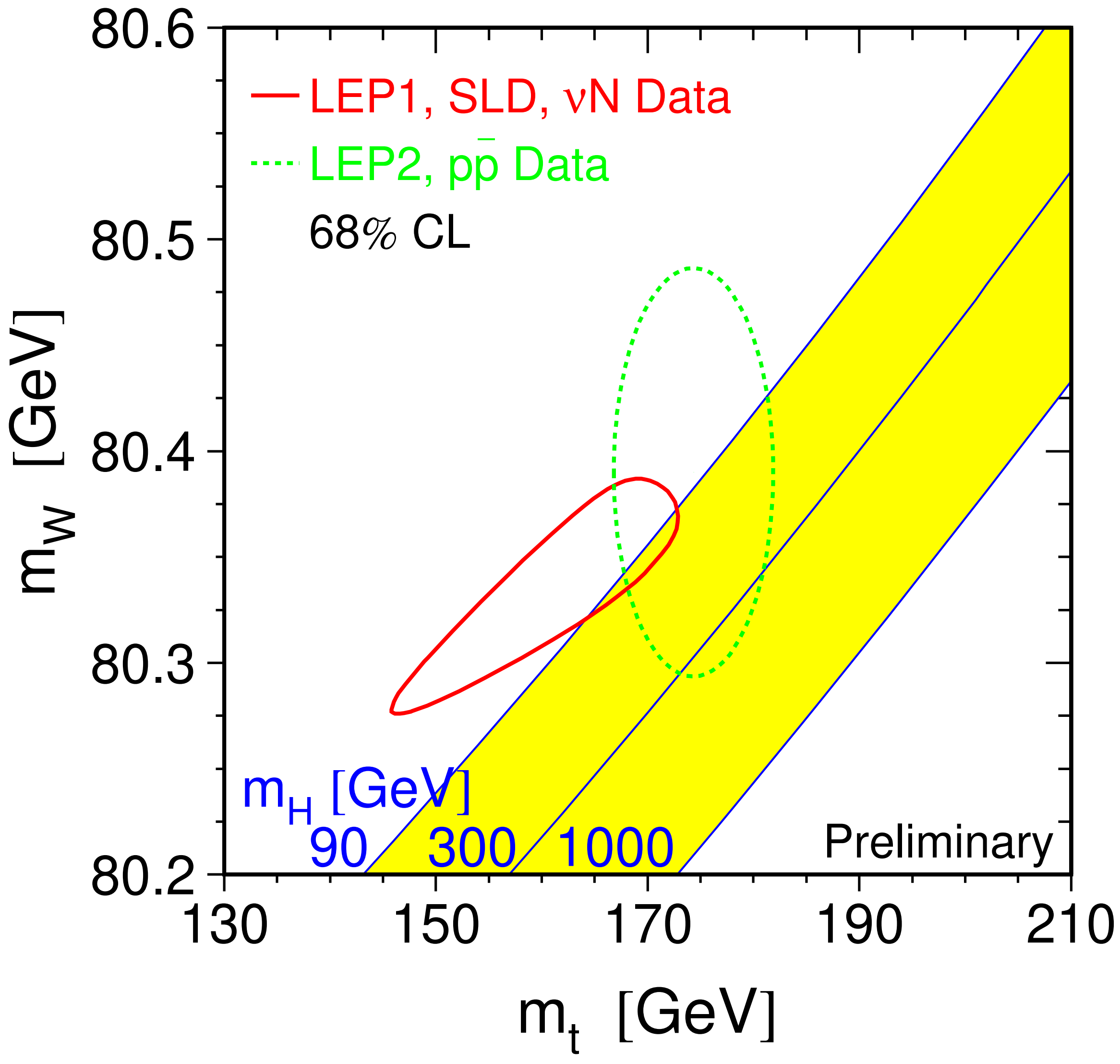
LEP 1 data is sensitive to weak corrections, and thus to the mass of heavy particles (t, W, H) (SM fit)

LEP 2: direct measurement of W mass, independent of SM assumptions

$\Rightarrow$ Comparison of indirect and direct M_W is a test of the SM



- Together with $M_{\rm t}$ and LEP 1/SLD data, a direct $M_{\rm W}$ measurement constrains $M_{\rm H}$:



Aim for LEP 2: measure W mass with 30-40 MeV accuracy

Method: direct reconstruction of W decay products $\rightarrow$ W mass follows from kinematics:

1. Reconstruct jets, leptons, missing energy
2. Kinematic fit (energy-momentum conservation)
3. Fit m_{inv} spectrum

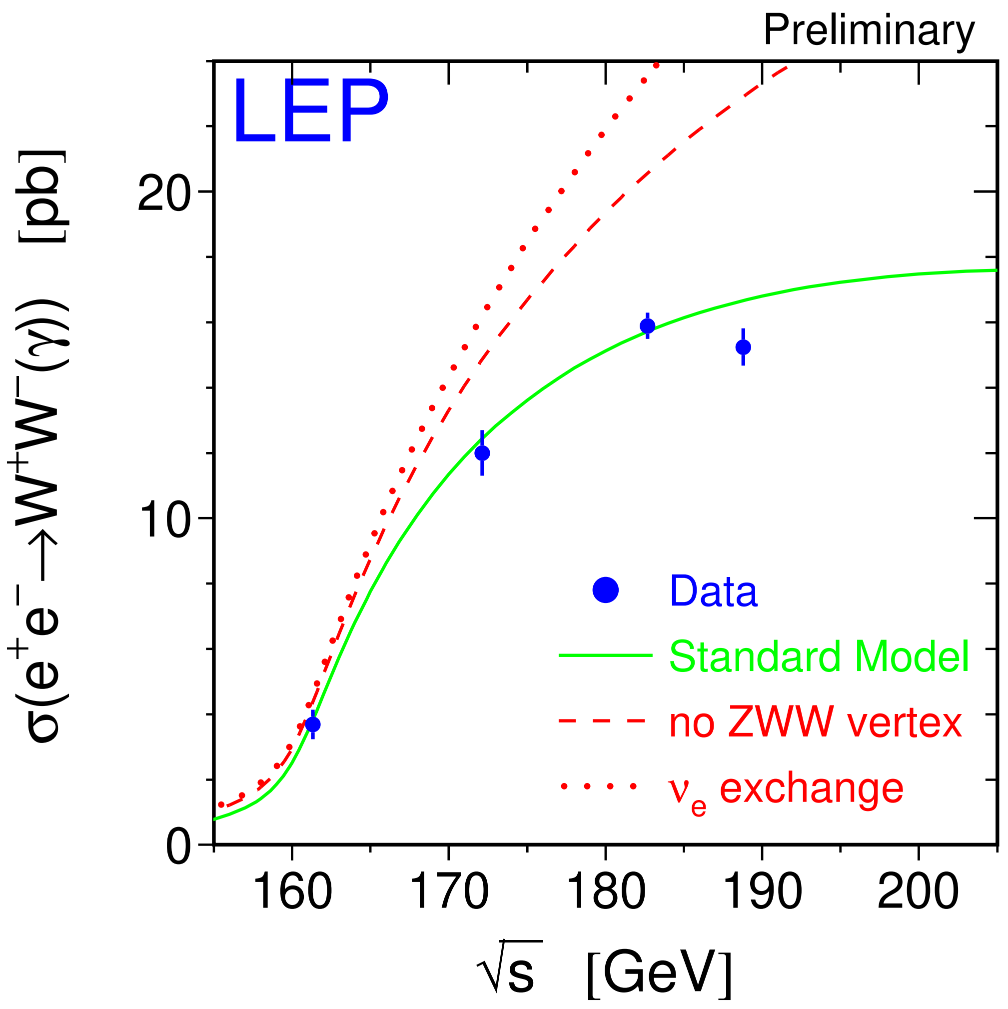
Typical list of systematic errors now (MeV) (OPAL):
(status summer 1998, preliminary!)

Source	$qqqq$	$qq\ell\nu$	combined
Beam Energy	28	28	28
ISR	24	28	18
Hadronisation	52	26	20
Four-fermion	19	21	14
Detector Effects	49	41	34
Fit proc. and bg.	31	28	22
CR and BEC	100	0	50
Total	133	72	76

End of 2000:

With 500 pb^{-1} per experiment: $\sim 4 \times 7500$ events

LEP combined statistical error $\sim$ 23 MeV.



This talk: data from 1997, $\sqrt{s} \approx 183$ GeV, $\int \mathcal{L}dt \approx 55$ pb^{-1}/experiment

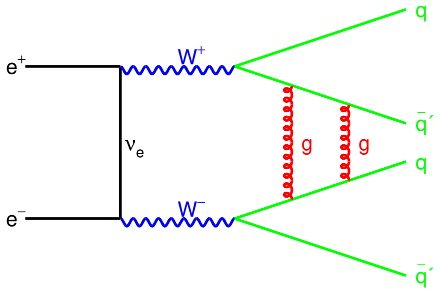
All results preliminary!

Data sample (events):

	A	D	L	O
$qq\ell\nu$	284	225	297	361
$qqqq$	500	421	473	433

Colour Reconnection Models

QCD interactions between different W's can be expected:



In fact, perturbative effects are expected to be small $(\sim (\frac{C_F \alpha_s(\Gamma_W)}{\pi})^2 \frac{1}{N_C^2 - 1} \frac{\Gamma_W}{M_W})$, but non-perturbative effects may be large $\rightarrow$ models.

Problem not restricted to WW production, but appears for example also in top quark production at hadron colliders.

In fact, reconfiguration of colour flow also possible at LEP 1, e.g. in $q\bar{q}gg$ events (HERWIG, ARIADNE).

In a colour-reconnected event, the event topology is changed w.r.t. the original event $\Rightarrow$ Search for colour reconnection effects by studying event topologies, e.g. (charged) particle production, event shape variables.

Needed: reference sample without interconnections.

Compare data to data: $qqqq$ vs $qq\ell\nu$ (but low statistics).

Also possible: mixed Z or W events (but difficult).

Note: MC models treat either CR or BEC, but not both!

Colour Reconnection Models

- PYTHIA:
  - toy model: immediate perturbative reconnection;
  - intermediate model: perturbative reconnection, but after parton shower $\rightarrow$ effects close to models I and II;
  - I: analogy colour strings $\leftrightarrow$ superconducting vortex of type I (with finite lateral extent). Free parameter ρ;
  - II: idem for SC type II, strings have zero radius, reconnection when two strings cross;
  - II': as II, but reconnection only at first crossing if total string length reduced;
  - GH: PYTHIA implementation of Gustafson-Häkkinen model.
- HERWIG: allow for reconfiguration of colour flow based on space-time structure at end of parton shower. Free parameter P_{RECO};
- ARIADNE: Implementation of Gustafson-Häkkinen model, reconnection allowed if total string length decreased. For WW:
  - Model 2: reconnection only after radiation of gluons with energy $> \Gamma_{\mathrm{W}}$;
  - Model 3: all reconnections allowed.

  Note: OPAL analysis of Z data (properties of quark- and gluon jets) disfavours ARIADNE reconnection models.

- VNI: MC for Ellis-Geiger model

Ellis-Geiger model: space-time development of hadronic showers.

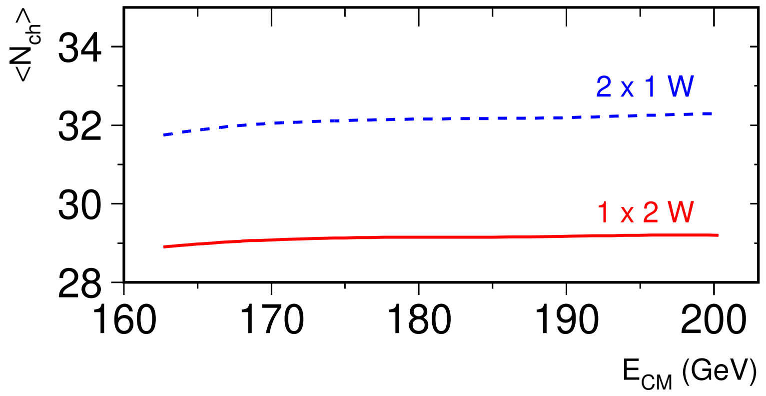
Perturbative QCD transport theory for parton evolution

Ansatz for parton-hadron conversion: stricly spatial criterion
$\rightarrow$ combination with nearest neighbours

$\Rightarrow$ allows for recombination of partons from different W's.

In "colour-full" scenario two combining partons need not form a colour singlet but can have any colour (then accompanied by additional partons to get correct colour flow).

Result: large effects on multiplicity:



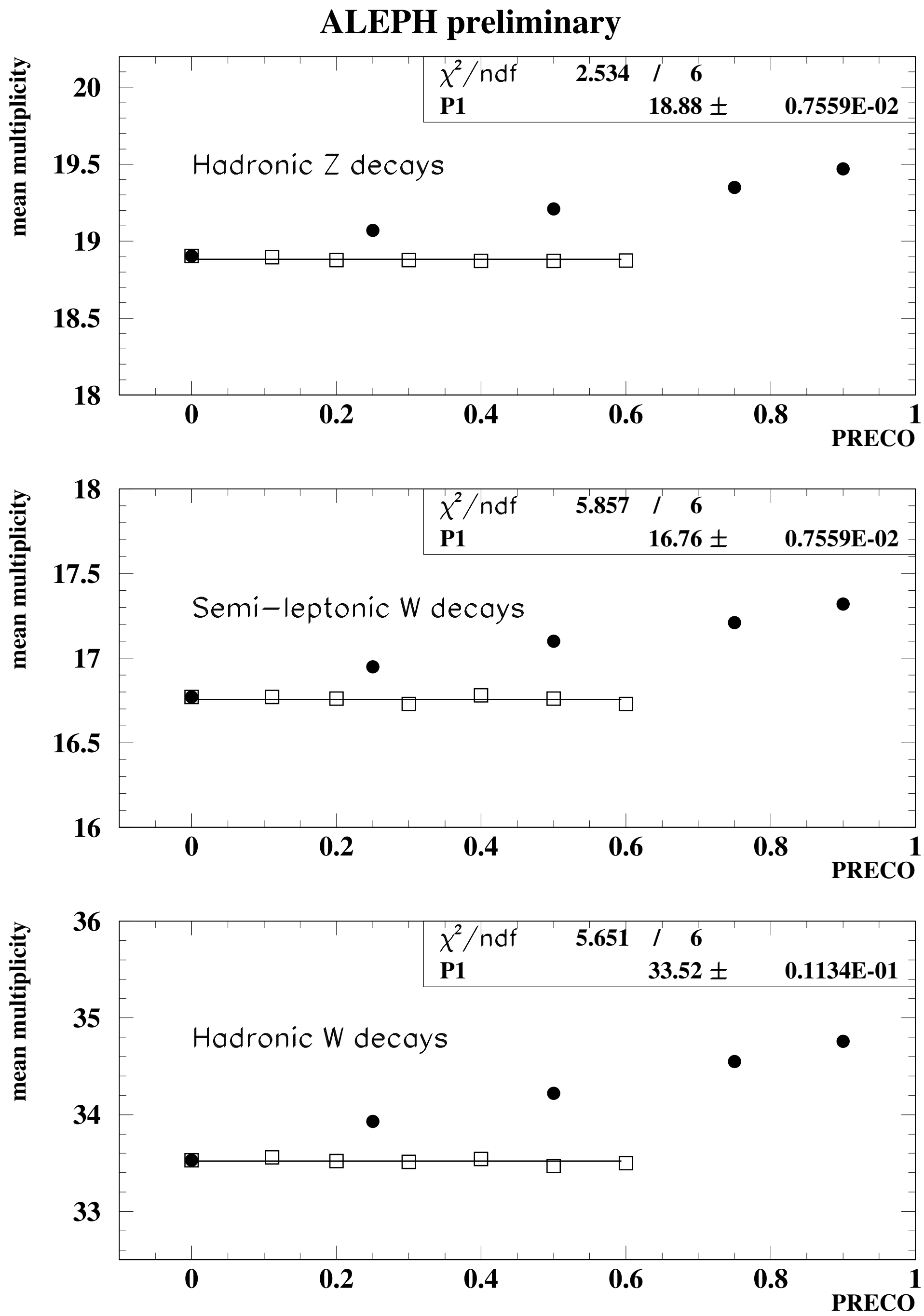
VNI: implementation of this model in MC, but (ALEPH, OPAL): cannot reproduce model predictions, nor data.

$\Rightarrow$ do not use for $M_{\rm W}$ systematics.

Model Tuning

Important: Models predicting effects in Z data (LEP 1) (BEC, HW, AR) must be tuned to that data:

(HERWIG; full dots: no retuning; open squares: retuned)



⇒ After tuning: effects at LEP 2 much reduced.

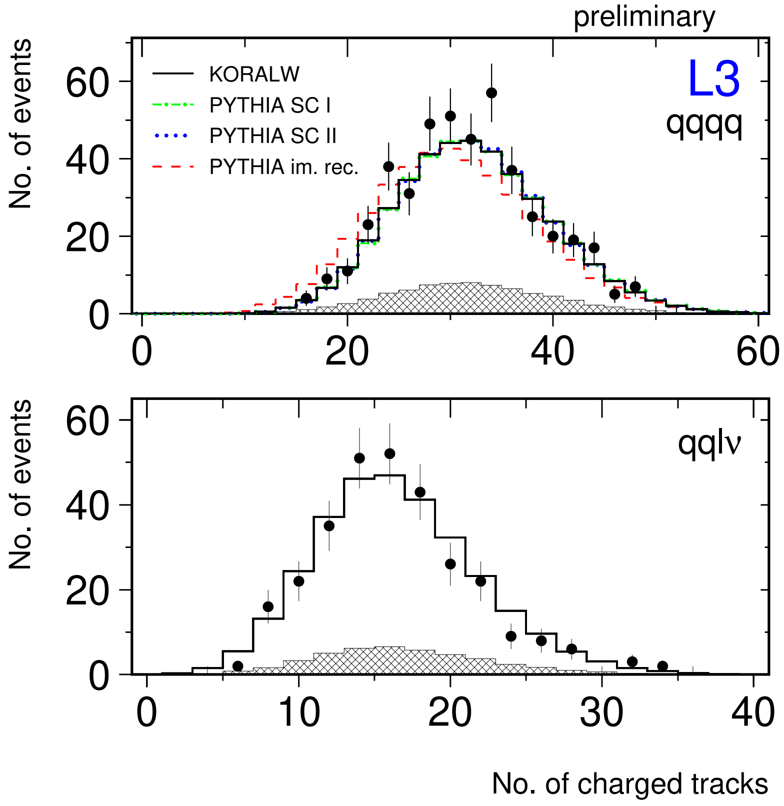
Prediction of various models:

$$< n_{ch}^{qqqq} > \neq 2 < n_{ch}^{qq\ell\nu} > .$$

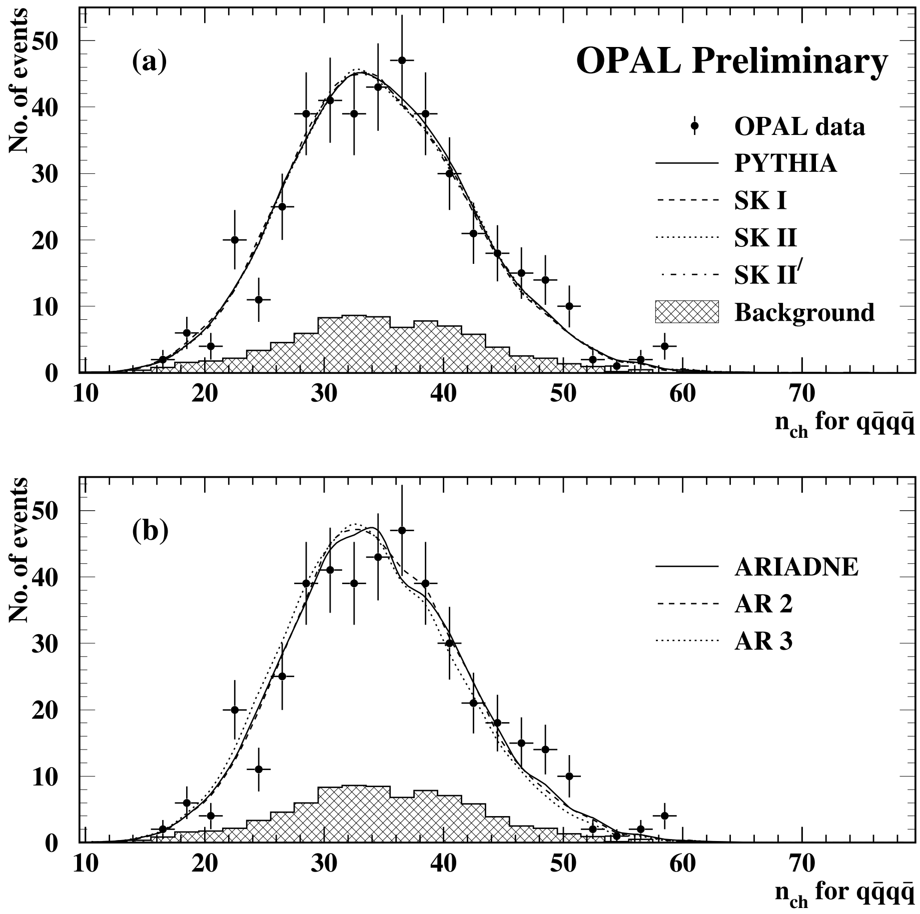
$\Rightarrow$ hadronisation of two W's not independent

- Study with charged tracks
- Track multiplicity is converted to multiplicity of stable charged particles (correction for detector response)
  - ❖ D,L,O: correct to full acceptance (but MC model dependence $\rightarrow$ systematics!);
  - ❖ A: no correction for topological biases.
- Calculate $< n_{ch} >$ from multiplicity distribution, or from integrated fragmentation function.

Charged track multiplicity distribution:



Charged particle multiplicity



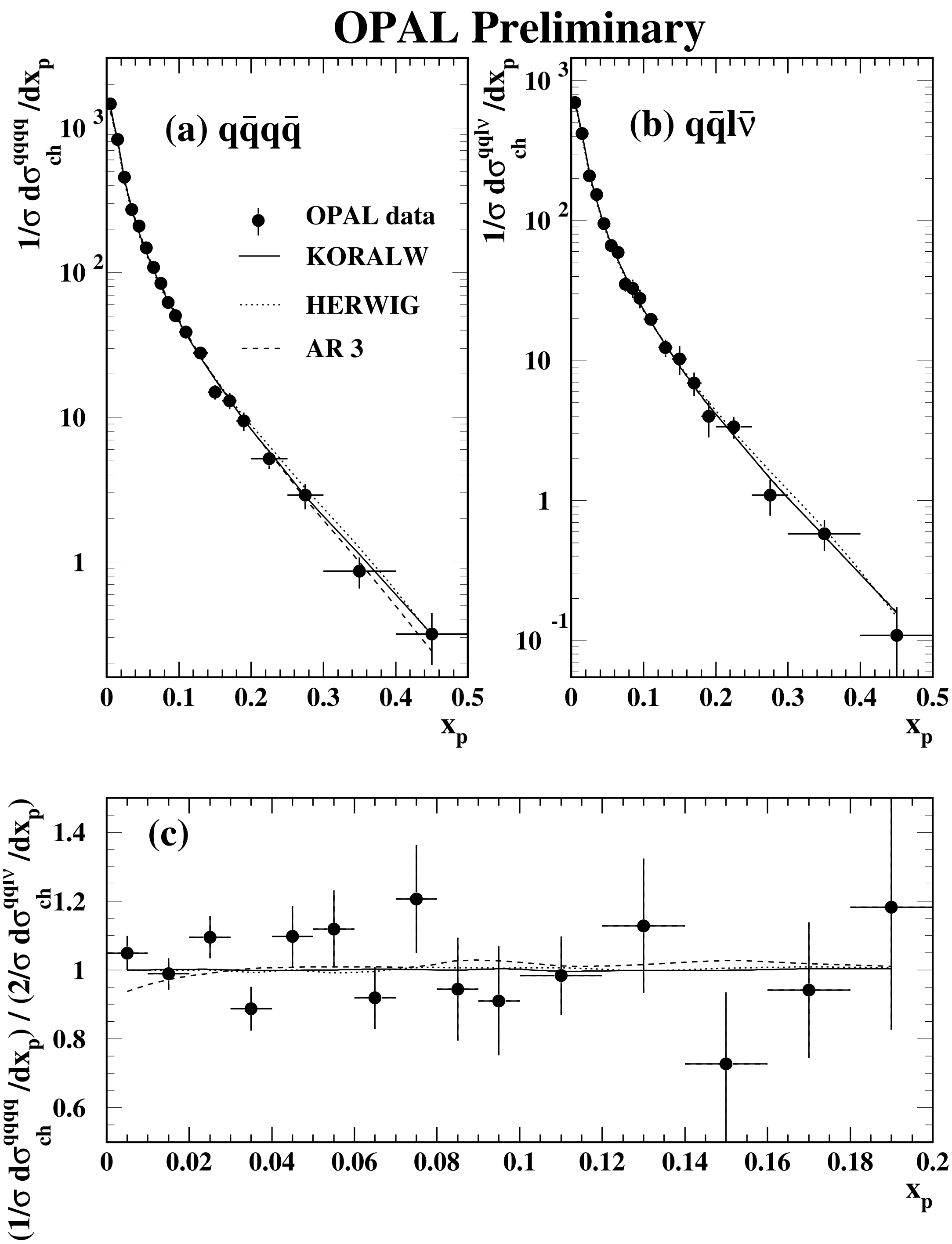
Systematics: track selection and MC simulation (use 183 GeV $q\bar{q}(\gamma)$ data), event selection and track selection cut variation, background subtraction, correction procedure, MC dependence.

Predictions of various models for $\Delta < n_{ch} >$: PYTHIA toy model and Ellis-Geiger ~ -3; ARIADNE 3 ~ -1, others $\sim -0.1 - -0.3$.

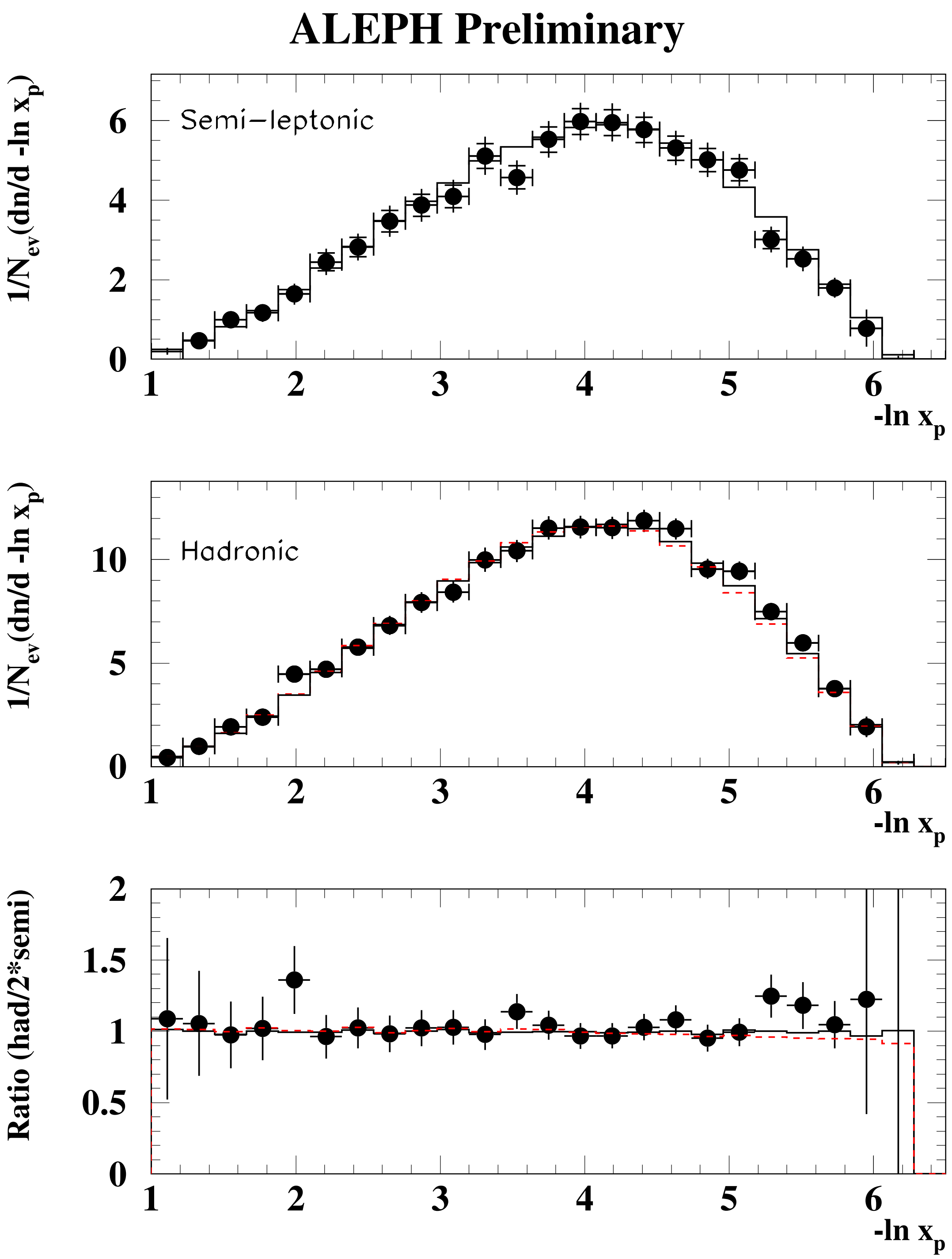
Some BEC models: $\Delta < n_{ch} >> 0$.

x_p *distribution*

Charged particle multiplicity distribution as a function of particle momentum $x_p = 2p/\sqrt{s}$ (fragmentation function):



x_p distribution



Particle Multiplicities Summary

Summary of hadronic charged multiplicity measurements ($\sqrt{s} = 183$ GeV):

	$< N_{had}^{qqqq} >$	$< N_{had}^{qq\ell\nu} >$	$\Delta < N_{had} >$
ALEPH ($*$)	$35.3 \pm 0.4 \pm 0.6$	$17.0 \pm 0.3 \pm 0.2$	$+1.3 \pm 0.8$
DELPHI	$37.4 \pm 0.5 \pm 0.9$	$19.5 \pm 0.4 \pm 0.6$	-1.6 ± 1.5
L3	$36.3 \pm 0.4 \pm 0.8$	$18.6 \pm 0.3 \pm 0.4$	-1.0 ± 0.9
OPAL	$39.4 \pm 0.5 \pm 0.7$	$19.3 \pm 0.3 \pm 0.3$	$+0.7 \pm 1.0$

($*$): not unfolded to full acceptance

Unofficial average: $\Delta < N_{had} >= +0.2 \pm 0.5$

(172 GeV: DELPHI $+3.9 \pm 1.6$; L3 and OPAL $\sim$ 0)

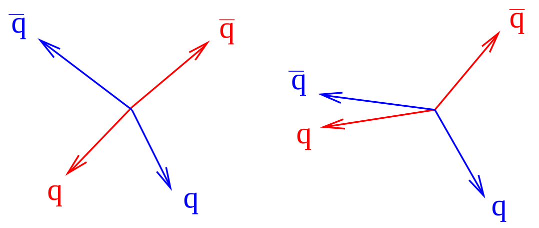
Also interesting: shape of multiplicity distribution.

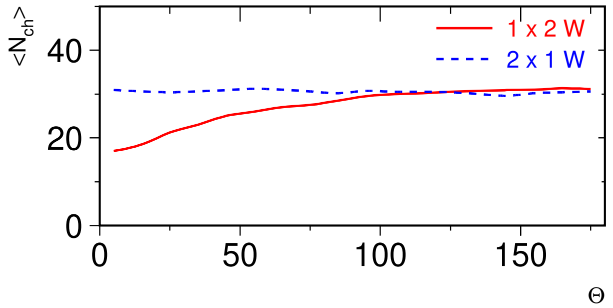
$\Rightarrow$ Dispersion: D^{qqqq}, $D^{qq\ell\nu}$, $\Delta D = D^{qqqq} - \sqrt{2} D^{qq\ell\nu}$

	D^{qqqq}	$D^{qq\ell\nu}$	ΔD
DELPHI	8.2 ± 0.5	5.8 ± 0.5	$+0.1 \pm 0.8$
L3	7.7 ± 0.7	5.8 ± 0.5	-0.5 ± 0.7
OPAL	8.8 ± 0.7	6.1 ± 0.5	$+0.2 \pm 0.6$

Event properties

Colour reconnection might be enhanced for certain topologies:

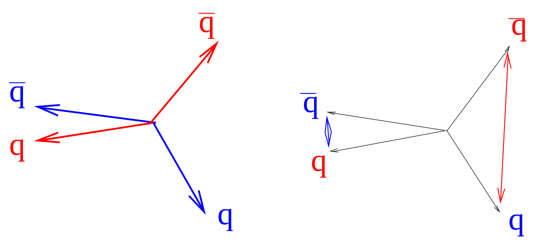




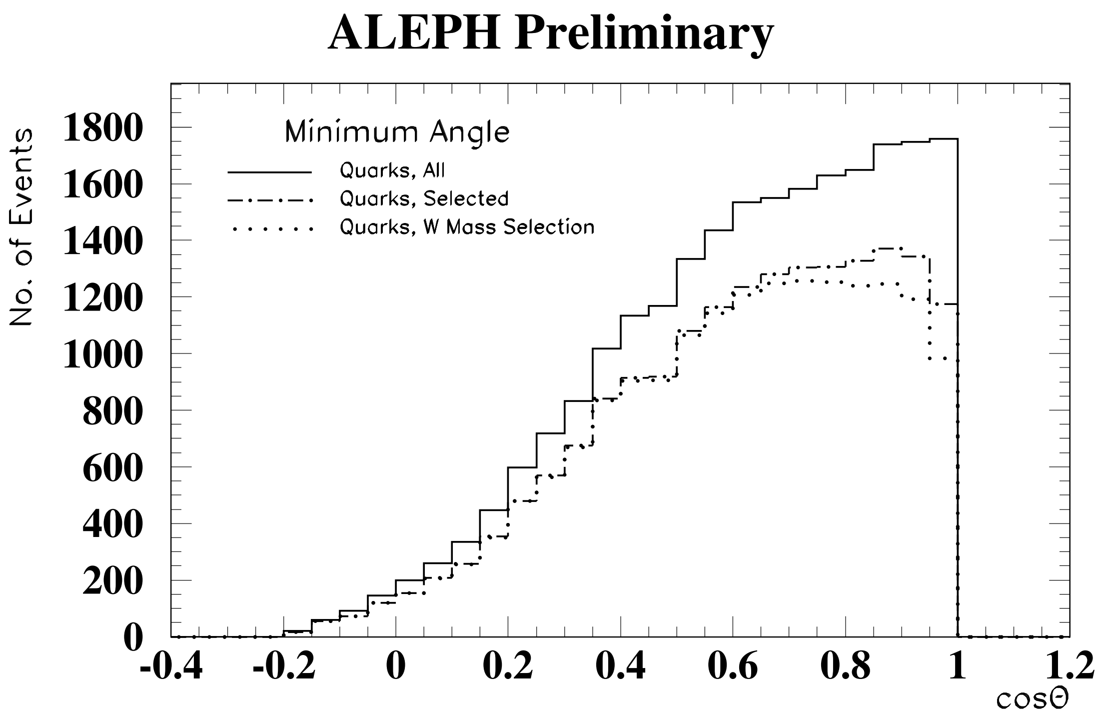
⇒ larger effects when Θ small (high thrust) ?

Beware: Decreasing Θ → events less 4-jet like

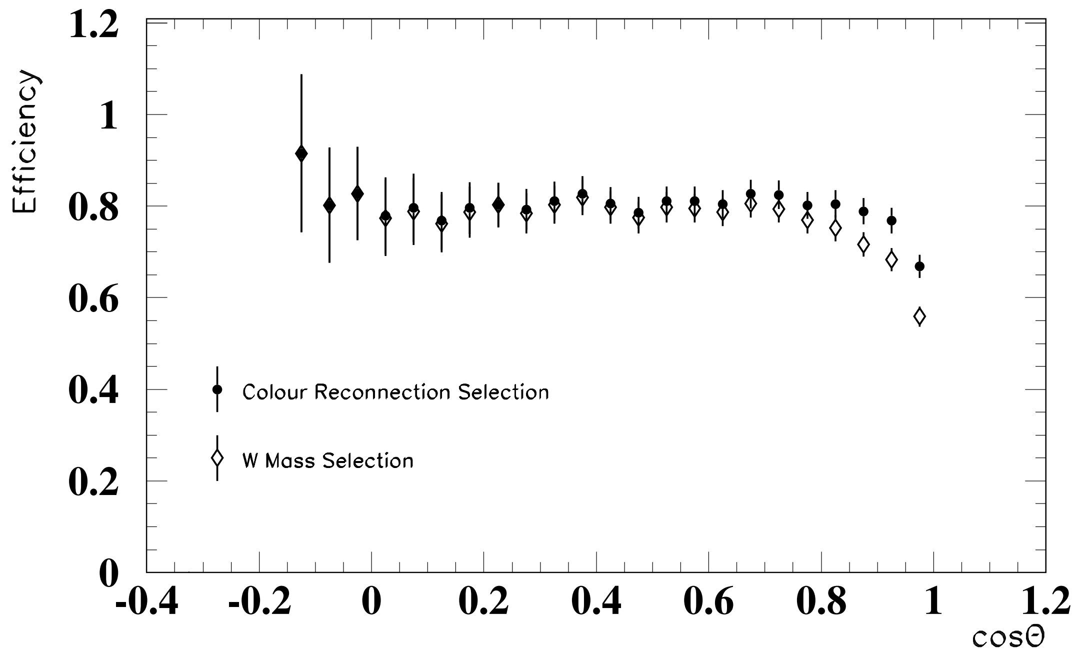
⇒ selection efficiency somewhat smaller at low Θ (or high thrust), but still good.



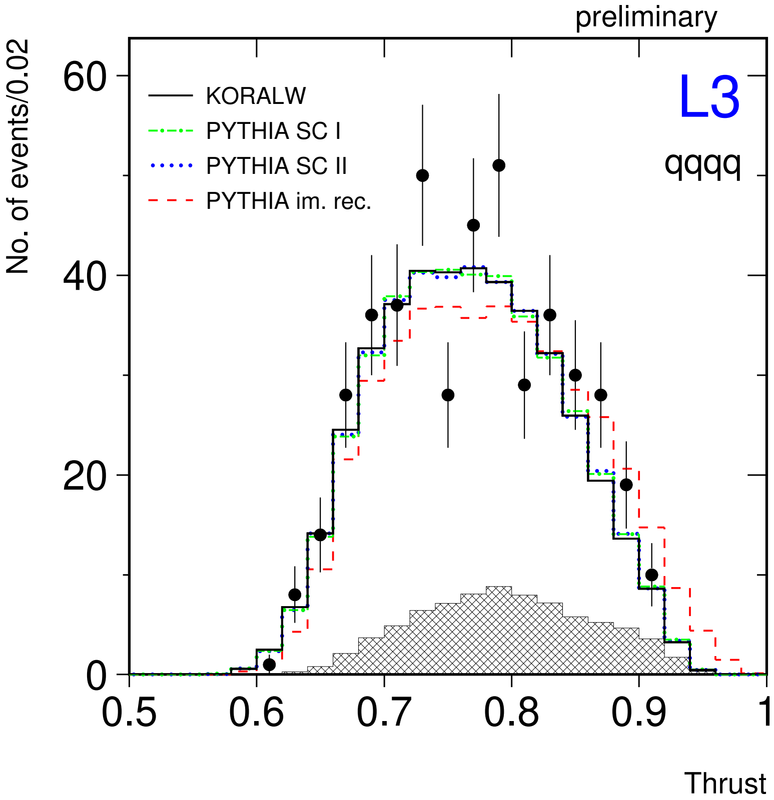
Extreme case of colour reconnection
Effects at low rapidity?
Rapidity gap events?

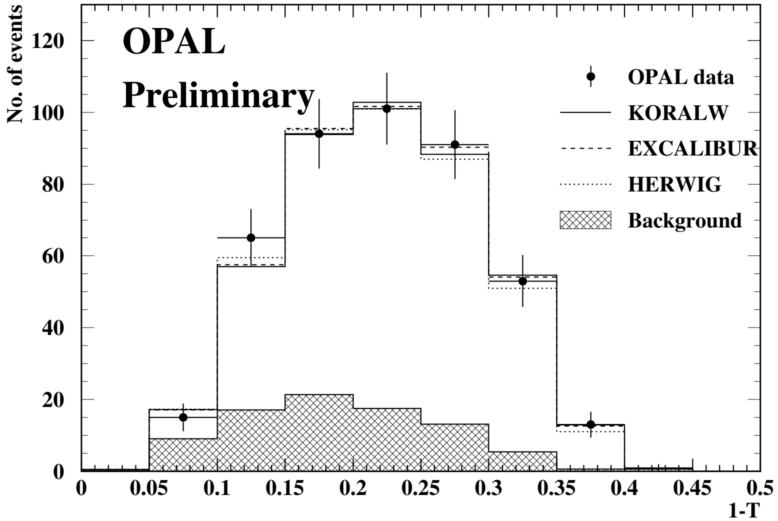


ALEPH Preliminary
Minimum Angle
Quarks, All
Quarks, Selected
Quarks, W Mass Selection
No. of Events
0
200
400
600
800
1000
1200
1400
1600
1800
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
1.2
cosΘ

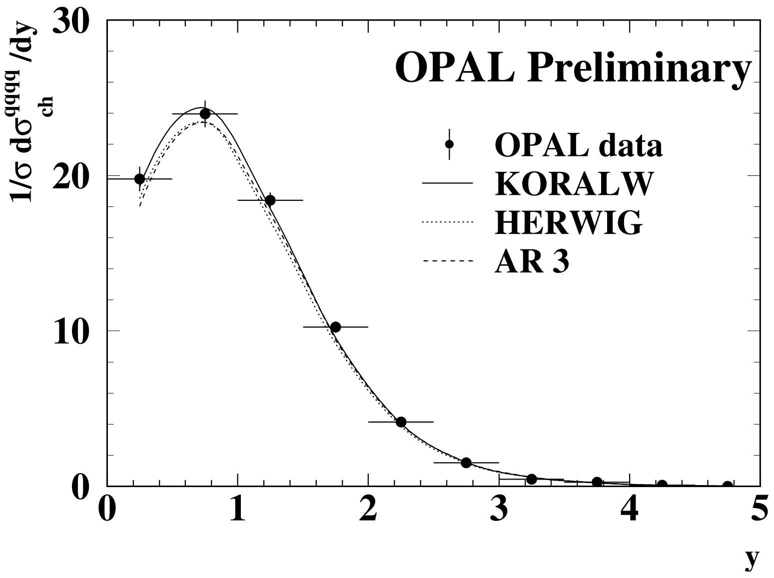


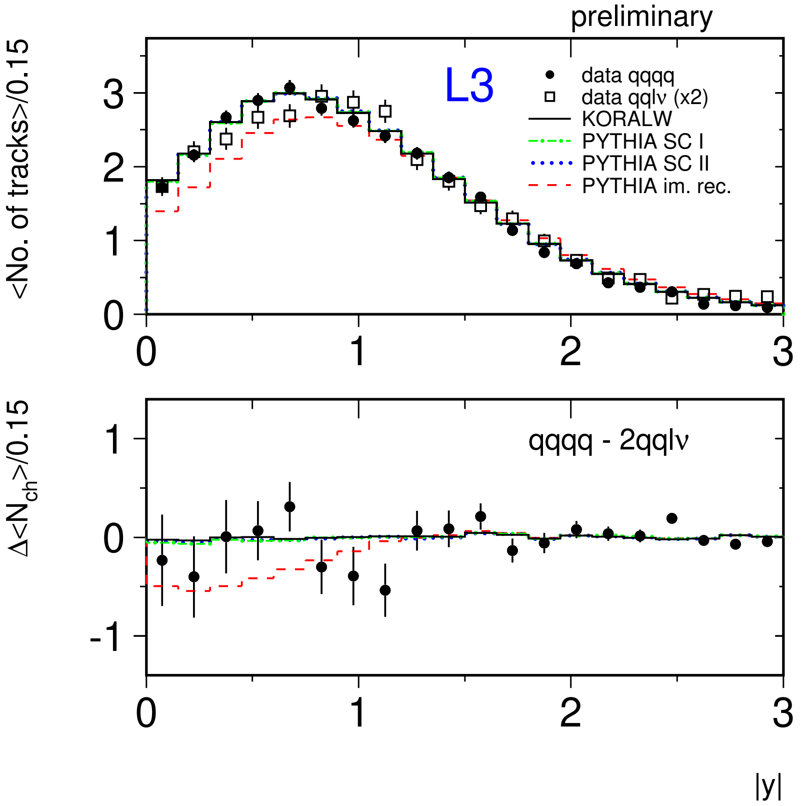
Efficiency
0
0.2
0.4
0.6
0.8
1
1.2
Colour Reconnection Selection
W Mass Selection
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
1.2
cosΘ


preliminary
L3
qqqq
KORALW
PYTHIA SC I
PYTHIA SC II
PYTHIA im. rec.
No. of events/0.02
Thrust
0
20
40
60
0.5
0.6
0.7
0.8
0.9
1

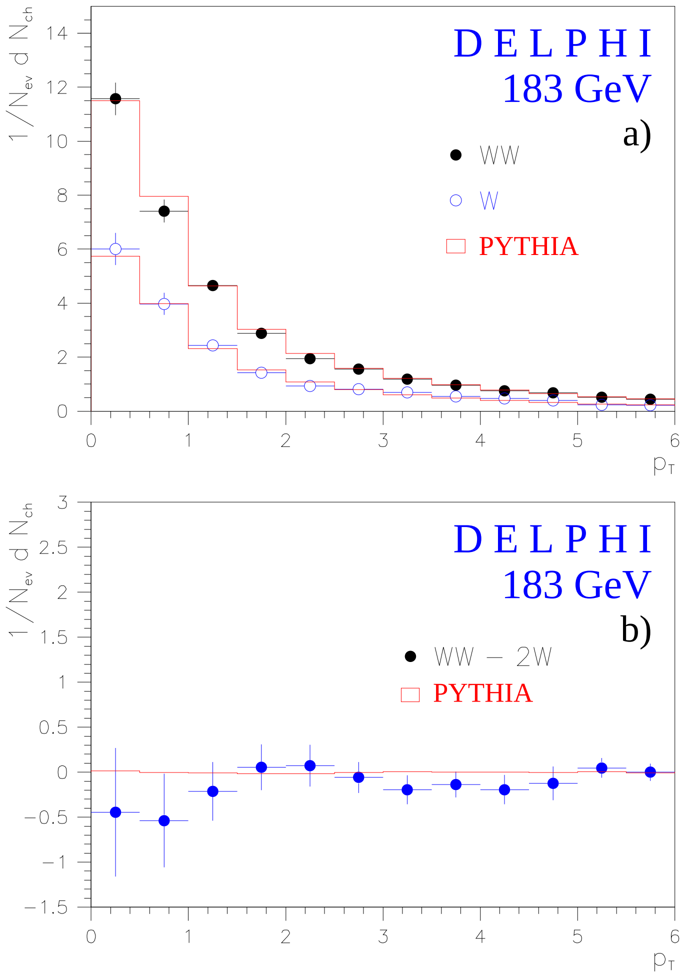

OPAL
Preliminary
OPAL data
KORALW
EXCALIBUR
HERWIG
Background
No. of events
1-T
0
20
40
60
80
100
120
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5

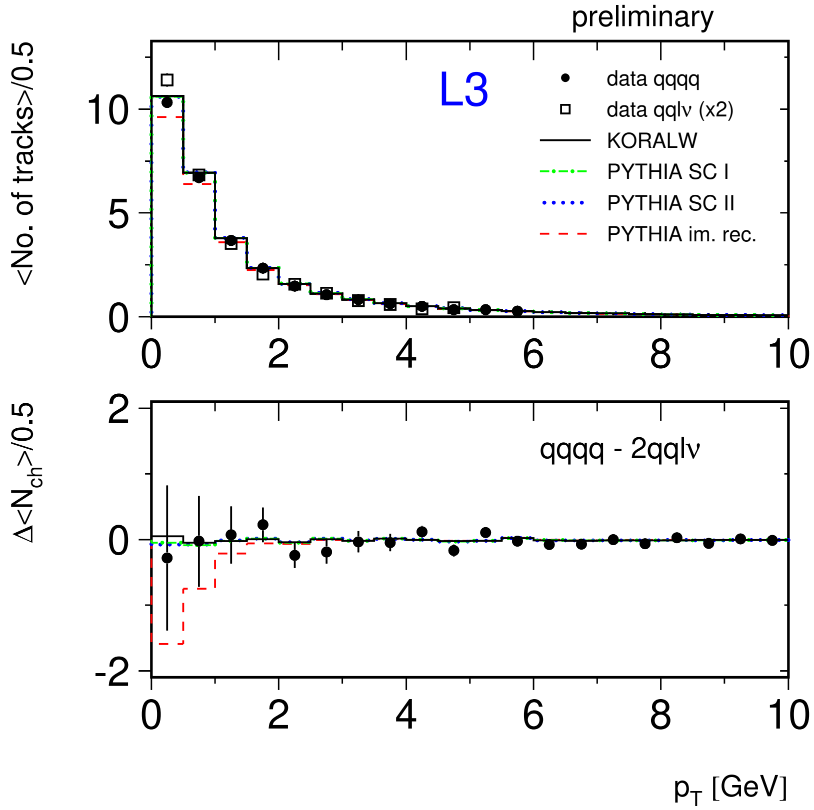
Charged particle multiplicity distribution as a function of particle rapidity with respect to the thrust axis:





Charged particle multiplicity distribution as a function of particle transverse momentum with respect to the thrust axis:





Conclusions: no evidence for significant difference $qqqq$ vs $qq\ell\nu$. Data consistent with no CR as well as with "realistic" models.

Heavy Hadrons

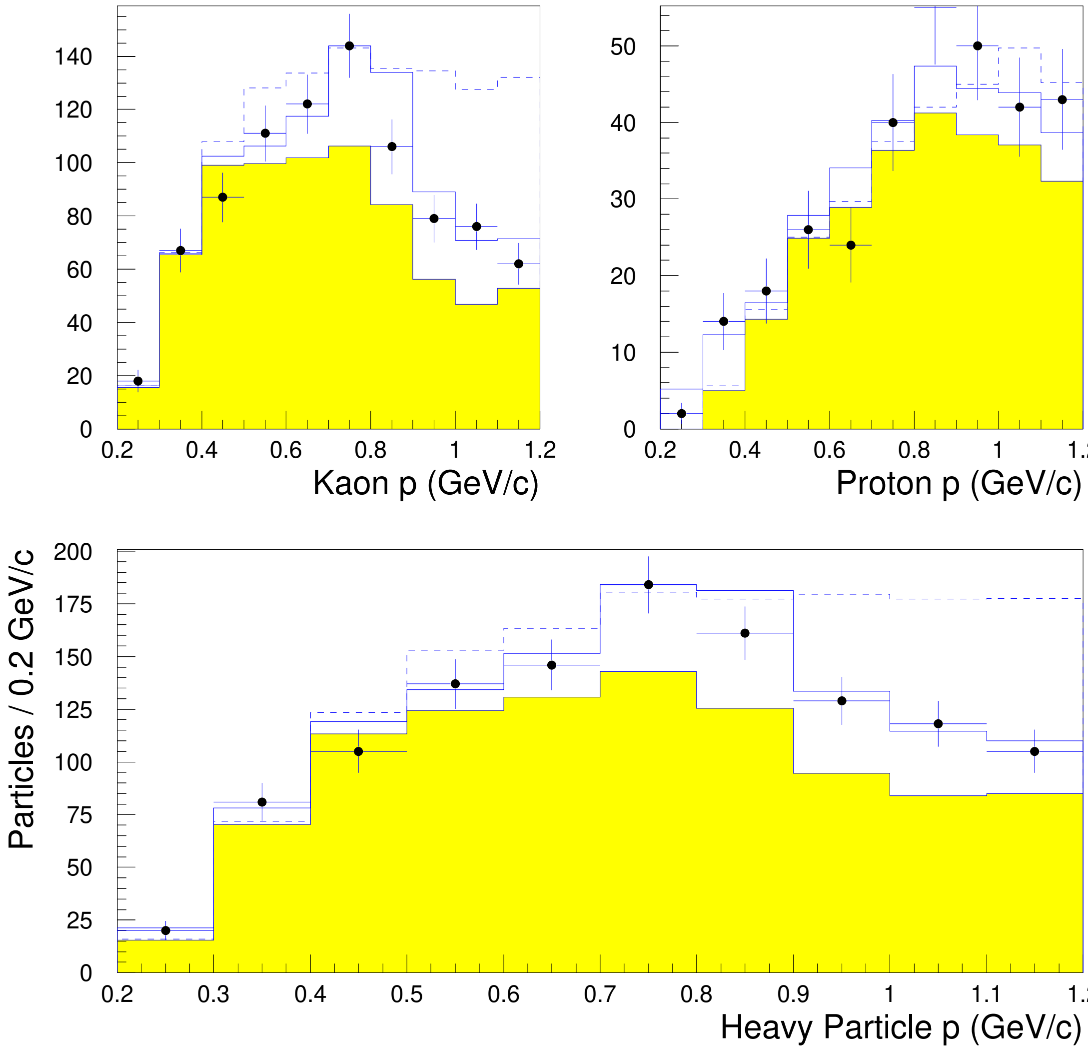
Recent suggestion Sjöstrand and Khoze: effects for K, p more pronounced?

$\Rightarrow$ PYTHIA, ARIADNE: indeed 2-3 $\times$ larger effect at low p, but also smaller statistics.

DELPHI analysis: tag K and p, using RICH and dE/dx in VD and TPC, 0.2 GeV $< p <$ 1.4 GeV.

Tagging efficiency: 90-50%, purity: 90-75%

Hadronic events at $\sqrt{s} = 183$ GeV:



Results in WW events, after unfolding for tagging effects: (stat error only) (181 tagged K, p in $qqqq$, 88 in $qq\ell\nu$)

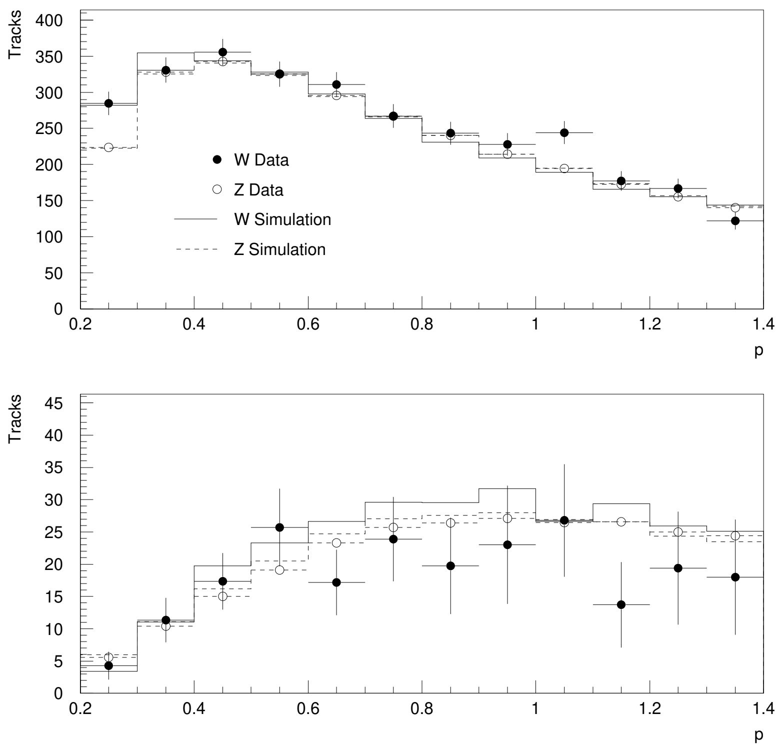
$$\frac{< n^{K,p} > (qqqq)}{2 < n^{K,p} > (qq\ell\nu)} = 1.03 \pm 0.15$$

$$\frac{< n^{K,p} > (qqqq)}{< n^{K,p} > (\text{simulation})} = 0.85 \pm 0.09$$

Alternative: use Z calibration data as reference $\rightarrow$ more statistics (but beware of diff. flavour content).

Pairs of Z's $\rightarrow$ boost $\rightarrow$ emulate WW $\rightarrow$ $qqqq$.

Particle Rates from WW $\rightarrow$ qqqq



$$\frac{< n^{K,p} > (WW)}{< n^{K,p} > (ZZ)} = 0.87 \pm 0.09 \pm 0.04$$

M_{W} *bias estimates*

Estimate of bias on M_{W} (in MeV) from various models:

	Aleph	Delphi	L3	Opal
PYTHIA I	$+25 \pm 21$	$+40 \pm 12$	$+60 \pm 13$	$+50 \pm 17$
PYTHIA II	$+5 \pm 15$		$+14 \pm 13$	$+17 \pm 17$
PYTHIA II'	$+17 \pm 15$	$+3 \pm 10$		$+18 \pm 17$
PYTHIA GH		$+13 \pm 18$		
HERWIG	-31 ± 25			
ARIADNE 2				$+73 \pm 18$
ARIADNE 3				$+146 \pm 18$

Important: numbers cannot just be taken from literature, but the models must be applied to the experimental circumstances (detector simulation, selections, fit procedure)

Bose-Einstein Correlations in WW Events

BEC well established in nucleus-nucleus, hadron-hadron, e^+e^- interactions: QM interference between identical bosons due to symmetrisation of wave function, leading to enhanced production close in phase space.

Given two pions with 4-momenta k_1 and k_2, then define correlation function

$$C(k_1, k_2) = \frac{\rho(k_1, k_2)}{\rho_0(k_1, k_2)}$$

with $\rho(k_1, k_2)$ 2-particle density function, and $\rho_0(k_1, k_2)$ idem for reference sample without BEC.

Define:

$$Q^2 = -(k_1 - k_2)^2 \qquad = M^2(\pi\pi) - 4m_\pi^2$$

Then, correlation function can be written as:

$$C(Q) = \frac{\rho(Q)}{\rho_0(Q)}$$

Fit with function

$$C(Q) \sim (1 + \lambda e^{-Q^2R^2})(1 + \delta(Q))$$

with λ = correlation strength, R = source radius.

BEC should be present also in hadronic W decays. Three cases:

1. between pions within same jet;
2. between pions in two jets from same W;
3. between pions in two jets from different W.

If sizable BEC between decay products of different W's: invariant mass spectrum disturbed.

There is no fundamental reason why there should be no BEC between different W's. However, dynamics of W production and decay may lead to different effective strength.

Much progress in last year on implementation of BEC in MC programs for e^+e^- interactions
(see talks of Š. Todorova-Nová and K. Fialkowski)

Roughly 3 categories of MC:

- shifting and readjusting particle momenta (LUBOEI, PYTHIA) (ad-hoc method);
- global event weights (Jadach and Zalewski, Kartvelishvili et al., Fialkowski and Wit);
- QM approach: amplitude symmetrization in string fragmentation (Todorova-Nová and Rameš, Andersson and Ringnér).

Care should be taken in the interpretation of quoted λ's.

Very sensitive to track selection; large dilution if not only direct pions (secondaries, lack of particle id.):

$\lambda_{\text{direct}\,\pi} \approx 1 \Rightarrow \lambda_\pi \approx 0.35 \Rightarrow \lambda_{\text{all}} \approx 0.25$

In Z decay: $R \sim 0.5 - 1.0$ fm

Important part of analysis: reference sample

- $\pi^+\pi^-$ pairs: $C(Q) = \frac{\rho^{\pm\pm}(Q)}{\rho^{+-}(Q)}$
  but: resonances in $\pi^+\pi^-$, different long range correlations (OPAL, DELPHI cross-check)
- idem, but correction with MC: double ratio
  $C^* = \frac{\rho^{\pm\pm}}{\rho^{+-}} / \left(\frac{\rho^{\pm\pm}}{\rho^{+-}}\right)_{\text{MC, no BE}}$ (ALEPH, L3)
- MC reference sample: $C = \frac{\rho^{\pm\pm}}{\rho^{\pm\pm}_{\text{MC, no BE}}}$ (DELPHI)
- Event mixing: pairs from two different events, difficult in 4-jet events, many correlations missing

BEC analyses in overview:

	ALEPH	DELPHI	L3	OPAL
$\sqrt{s}$ (GeV)	172 + 183	183	183	172 + 183
$\int \mathcal{L}dt$ (pb^{-1})	10 + 57	54	55	10 + 57
Track selection	All charged	All charged	All charged	π^+, π^-
Reference	$\pi^+\pi^-$	MC	$\pi^+\pi^-$	$\pi^+\pi^-$
Double Ratio	yes	n.a.	yes	no
Statistical subtraction of $C^{\text{same}}(Q)$	yes	no (yes crosscheck)	no	n.a.
Simultaneous Fit $\Rightarrow C^{\text{same}}, C^{\text{diff}}, C^{Z^*}$	no	no	no	yes
Jet pairing	no	no	yes	no
Coulomb correction	no	in. sys. error	yes	yes

ALEPH: Use double ratio $C^*(Q)$.

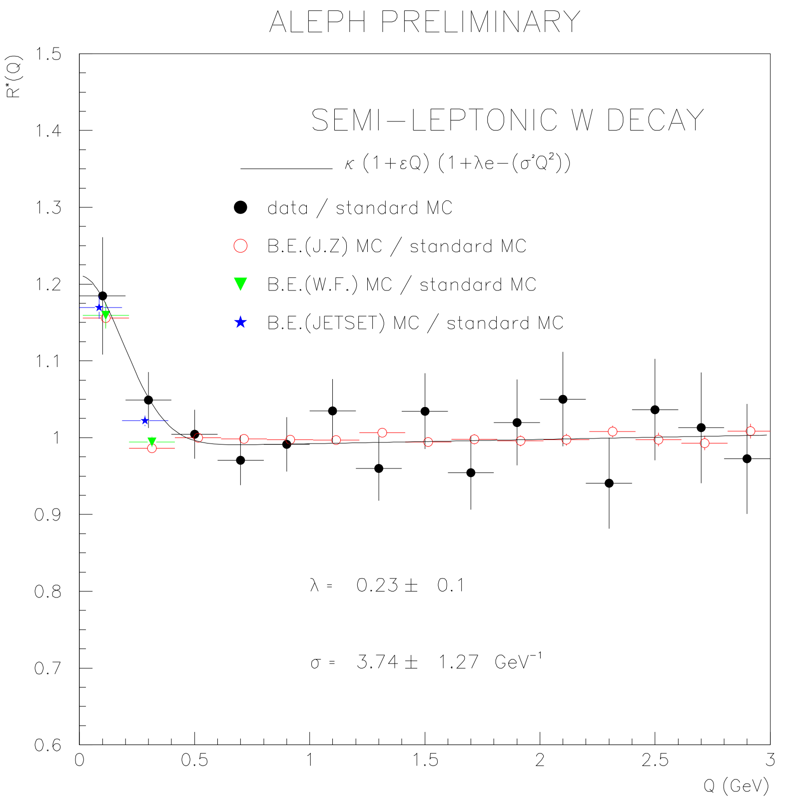
Correlation functions for $qq\ell\nu$ and $qqqq$ events separately.

Attempt to extract BEC between different W's by making the following correlation function:

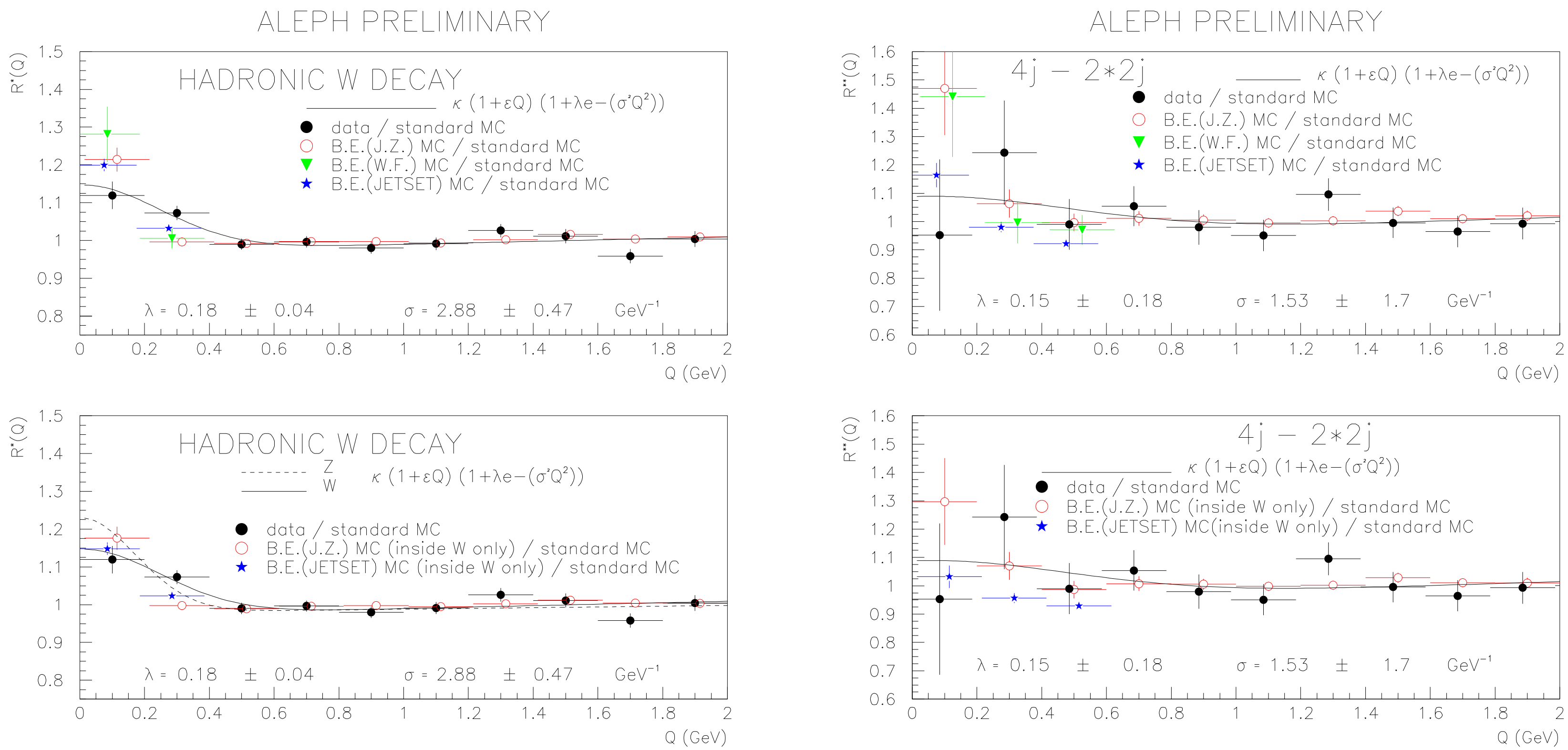
$$C(Q) = \frac{\rho^{\pm\pm}_{qqqq}(Q) - 2\rho^{\pm\pm}_{qq\ell\nu}(Q)}{\rho^{+-}_{qqqq}(Q) - 2\rho^{+-}_{qq\ell\nu}(Q)}$$

(divided by same expression for MC)

Beware: recent suggestion (ANL-HEP-PR-98-84): this expression does not isolate BEC between W's and underestimates the error.



ALEPH Analysis



DELPHI Analysis

DELPHI reference sample: MC without BEC

$\Rightarrow$ all other correlations modeled, but assumes validity of underlying MC model.

$\Rightarrow$ Cross-check with Z events

Correlation functions for $qq\ell\nu$ and $qqqq$ events separately.

Analysis of BEC between different W's:

1. Compare to LUBOEI, with full BEC or within same W only;
2. Assume $\rho^{qqqq}(Q) = \rho^{qqqq}_{\text{same}}(Q) + \rho^{qqqq}_{\text{diff}}(Q)$

   and $\rho^{qqqq}_{x}(Q) = \rho^{qqqq}_{0,x}(Q)(1 + f_x(Q)\lambda_x e^{-R^2Q^2})$
   for $x = \{\text{same, diff}\}$

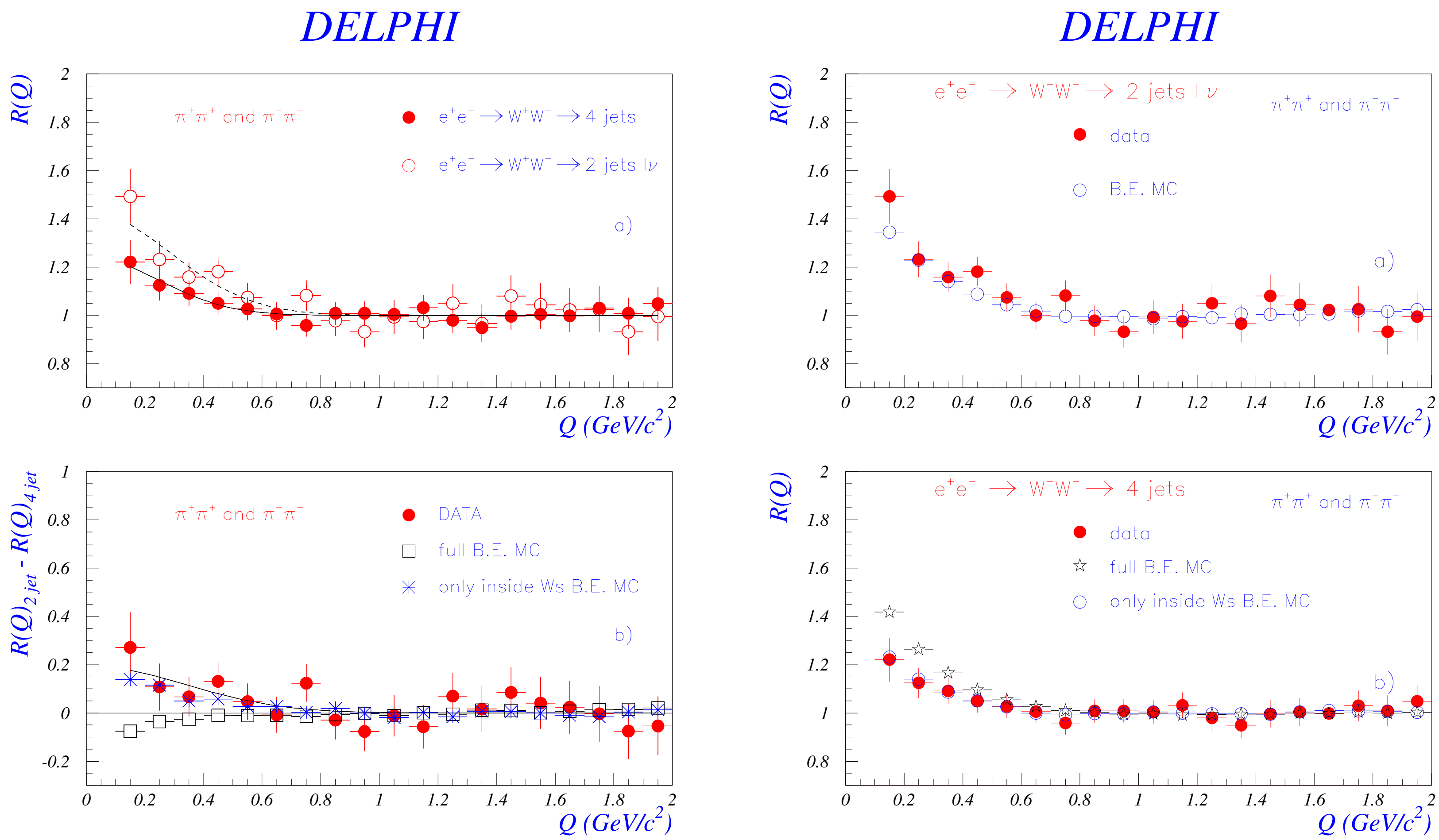
   Then two extreme scenarios:

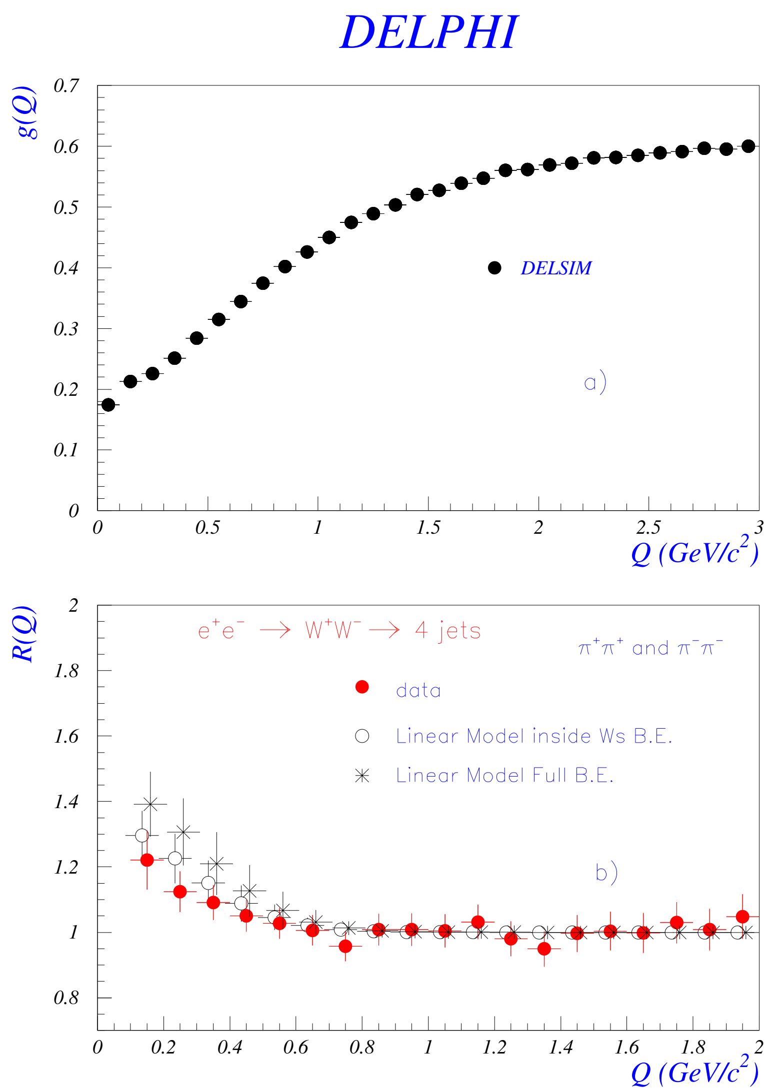
(a) $\lambda_{\text{diff}} = 0$: $C^{qqqq}(Q) = C^{qq\ell\nu}(Q) - g(Q) f_{\text{same}} \lambda e^{-R^2Q^2}$;

(b) $\lambda_{\text{diff}} = \lambda_{\text{same}}$:
$C^{qqqq}(Q) = C^{qq\ell\nu}(Q) + g(Q)(f_{\text{diff}} - f_{\text{same}})\lambda e^{-R^2Q^2}$

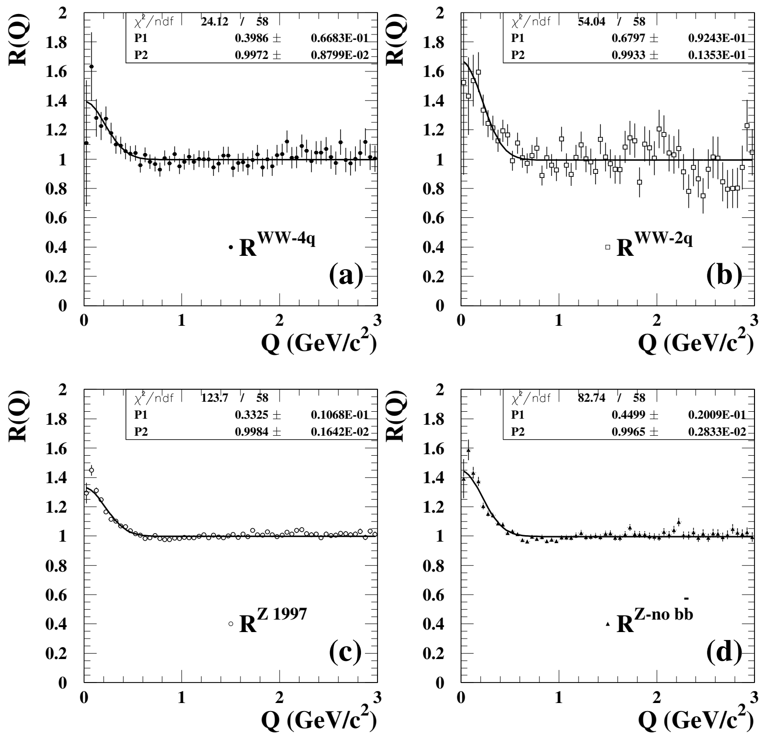
($g(Q)$ is fraction of pairs from different W's. MC study: $f_{\text{diff}} > f_{\text{same}}$ for small Q)

DELPHI Analysis





Cross-check with Z data:



Apparently: $\lambda^{Z,\,no\,bb} > \lambda^{Z}$

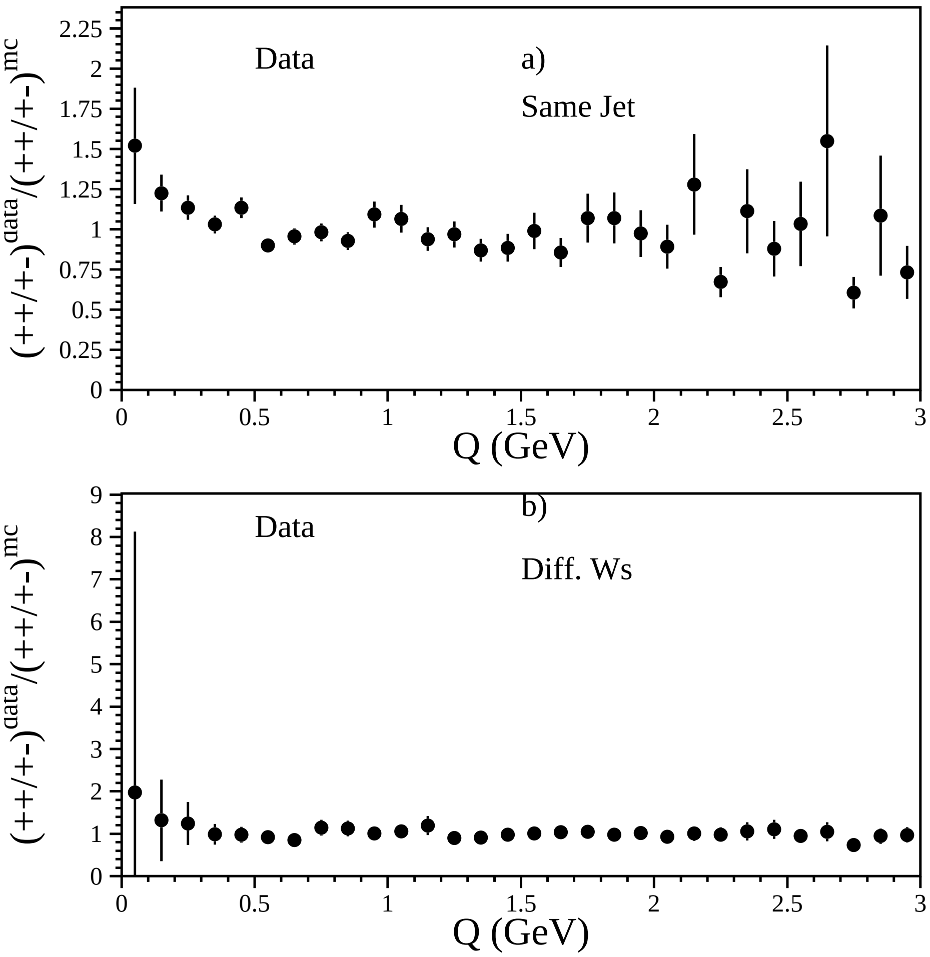
L3 Analysis

L3: Sample of $qqqq$ events, apply jet-finding, reconstruct W's.

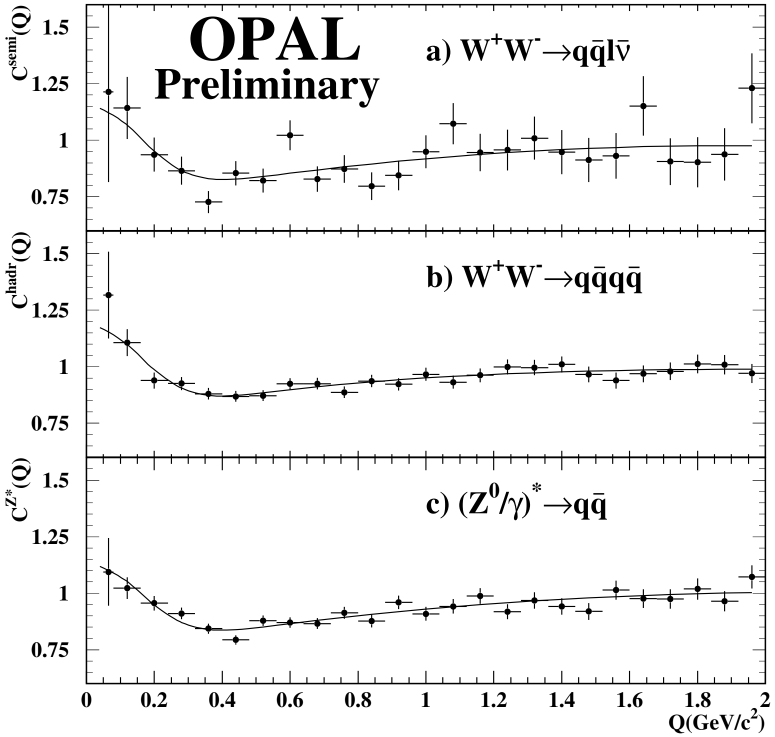
Then: take track pairs within single jet, between jets from single W, between jets from different W's.

Correct for mis-pairings of jets.

Use double ratio $C^*(Q)$.



OPAL: select 3 event samples: $\mathrm{WW} \to \mathrm{qq}\ell\nu$, $\mathrm{WW} \to \mathrm{qqqq}$, $(\mathrm{Z}^0/\gamma) \to \mathrm{q\bar{q}}$.



Construct 3 correlation functions (one for each sample): $C^{\mathrm{semi}}(Q)$, $C^{\mathrm{hadr}}(Q)$, $C^{\mathrm{non-rad}}(Q)$.

These can be written in terms of 3 other correlation functions:

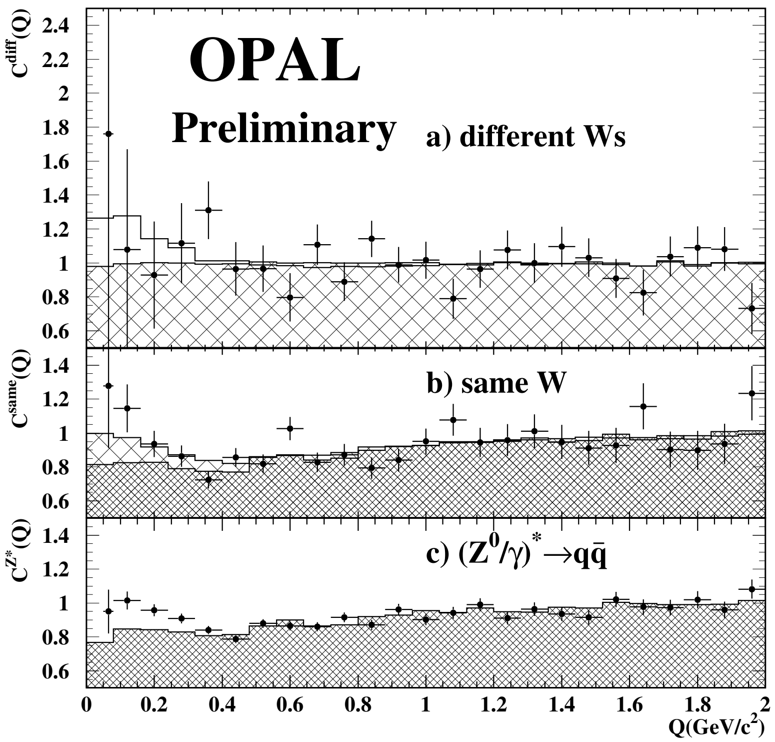
$$C^{\mathrm{same}}(Q), C^{\mathrm{diff}}(Q), C^{\mathrm{Z}^*}(Q),$$

taking into account the cross-feed (bg) of events between samples.

Then: simultaneous fit to experimental distributions, taking fractions of events in samples from MC, and taking common source radius R.

Result gives λ^{diff}, λ^{same}, λ^{Z^*}, and R.
Correlation between $(\lambda^{\mathrm{diff}}, \lambda^{\mathrm{same}})$ is -0.5

For illustration, distributions can be unfolded (plot).



(double hatched: MC without BEC; hatched: BEC within W only; open: BEC between W's)

Results

ALEPH $(N(1+\delta Q)(1+\lambda e^{-R^2Q^2}))$

	λ (all)	R (fm)
single W	$0.23 \pm 0.10 \pm 0.04$	$0.74 \pm 0.25 \pm 0.03$
WW (all)	$0.18 \pm 0.04 \pm 0.04$	$0.57 \pm 0.09 \pm 0.03$
diff W	$0.15 \pm 0.18 \pm \mathrm{negl}$	$0.30 \pm 0.34 \pm \mathrm{negl}$
Z^0	$0.26 \pm 0.01 \pm 0.04$	$0.812 \pm 0.016 \pm 0.030$

DELPHI $(N(1+\lambda e^{-R^2Q^2}))$

	λ (all)	R (fm)
single W	$0.43 \pm 0.09 \pm 0.04$	$0.49 \pm 0.07 \pm 0.02$
WW (all)	$0.24 \pm 0.08 \pm 0.04$	$0.57 \pm 0.12 \pm 0.06$
Z^0 (1997)	0.22 ± 0.01	0.61 ± 0.02

L3 $(N(1+\delta Q)(1+\lambda e^{-R^2Q^2}))$

	λ (all)	R (fm)
same jet	0.32 ± 0.17	0.80 ± 0.27
diff W	0.75 ± 1.80	1.03 ± 0.85
Z^0	0.303 ± 0.006	0.935 ± 0.024

OPAL $(N(1+\delta Q+\epsilon Q^2)(1+f_\pi \lambda e^{-R^2Q^2}))$

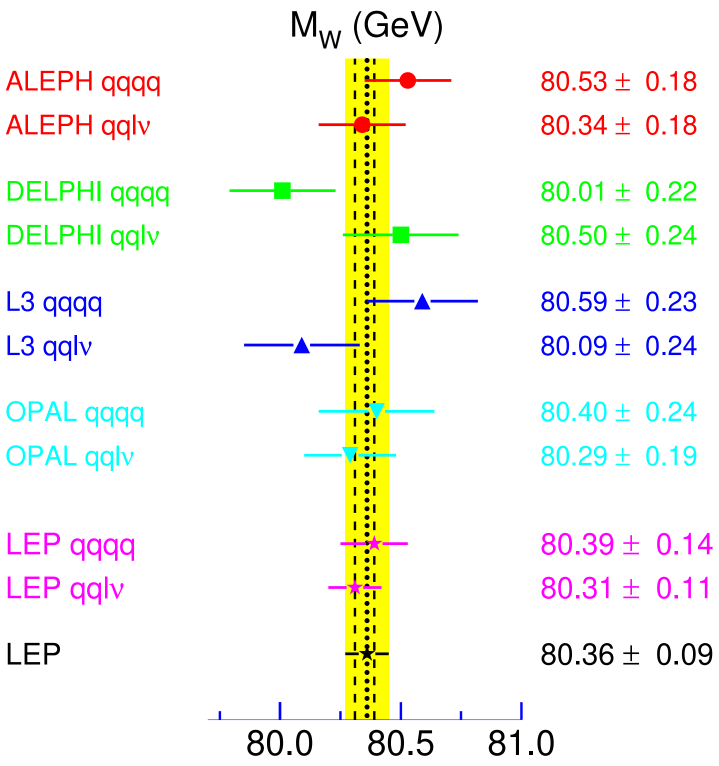
	λ $(\pi\pi)$	R (fm)
same W	$0.72 \pm 0.25 \pm 0.25$	$0.94 \pm 0.09 \pm 0.13$
diff W	$0.40 \pm 0.50 \pm 0.39$	
$(Z/\gamma)^*$	$0.64 \pm 0.13 \pm 0.35$	
Z^0	0.672 ± 0.027	0.955 ± 0.019

How about the actual LEP W mass measurement?

Some estimates of BEC effects on M_{W}:

- ALEPH: Model Jadach and Zalewski: 43 ± 25 MeV
  Modified LUBOEI: 50 ± 25 MeV
- DELPHI: Model Todorova-Nová and Rameš: consistent with zero
- L3: LUBOEI: 50 ± 20 MeV
- OPAL: PYTHIA: consistent with zero

Note: most recent models predict effects to be small.



$$M_{\mathrm{W}}^{qqqq} - M_{\mathrm{W}}^{qq\ell\nu} = 0.08 \pm 0.16 \text{ GeV}$$

Conclusions

• With current statistics, there is no evidence for a different hadronic multiplicity in $qqqq$ as compared to $qq\ell\nu$ events. This also holds for multiplicity as a function of x_p, rapidity, or p_T.

The properties of $qqqq$ events are in agreement with Monte Carlo without colour reconnection, as well as with models with ("realistic") CR scenario's.

• Only the most extreme colour reconnection models can be excluded (Ellis-Geiger, PYTHIA toy model).

For W mass: 30-60 MeV shifts in allowed models, only ARIADNE predicts larger effects (but disfavoured in LEP 1 data (OPAL)).

• DELPHI and ALEPH data prefer no BEC between different W's (or at least heavily suppressed); OPAL and L3 data are inconclusive. Although in agreement with latest BEC MC models, I find this puzzling nevertheless. Good news for W mass measurement!

• Outlook: In 1998, $\sqrt{s} \approx 189$ GeV, and expected $\int \mathcal{L}dt \approx 150$ pb^{-1}/experiment. Thus quadruple total statistics. Already on tape now: 88-110 pb^{-1}/experiment!