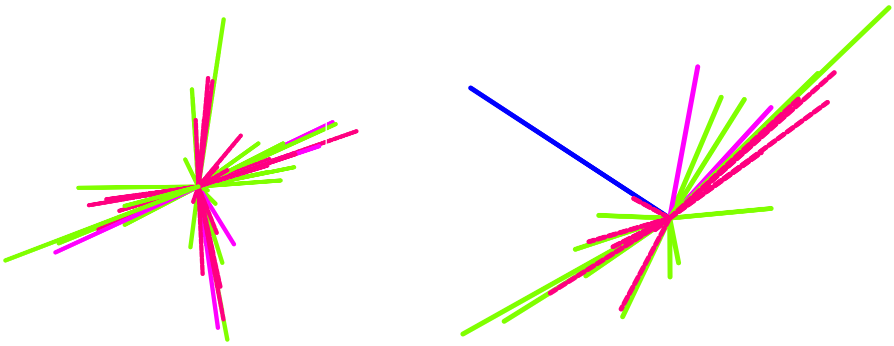
Colour Reconnection Studies in W^+W^-



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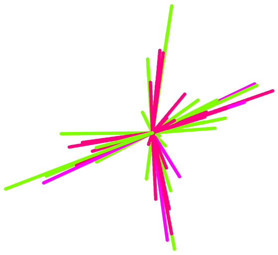
Outline

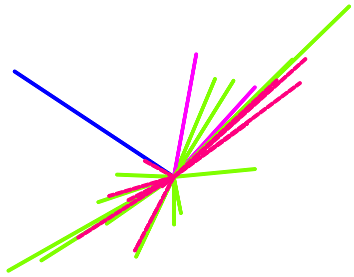
- Event properties in W^+W^-
- Event properties in Z^0
- Influence on M_W from data
- Summary/Prospects

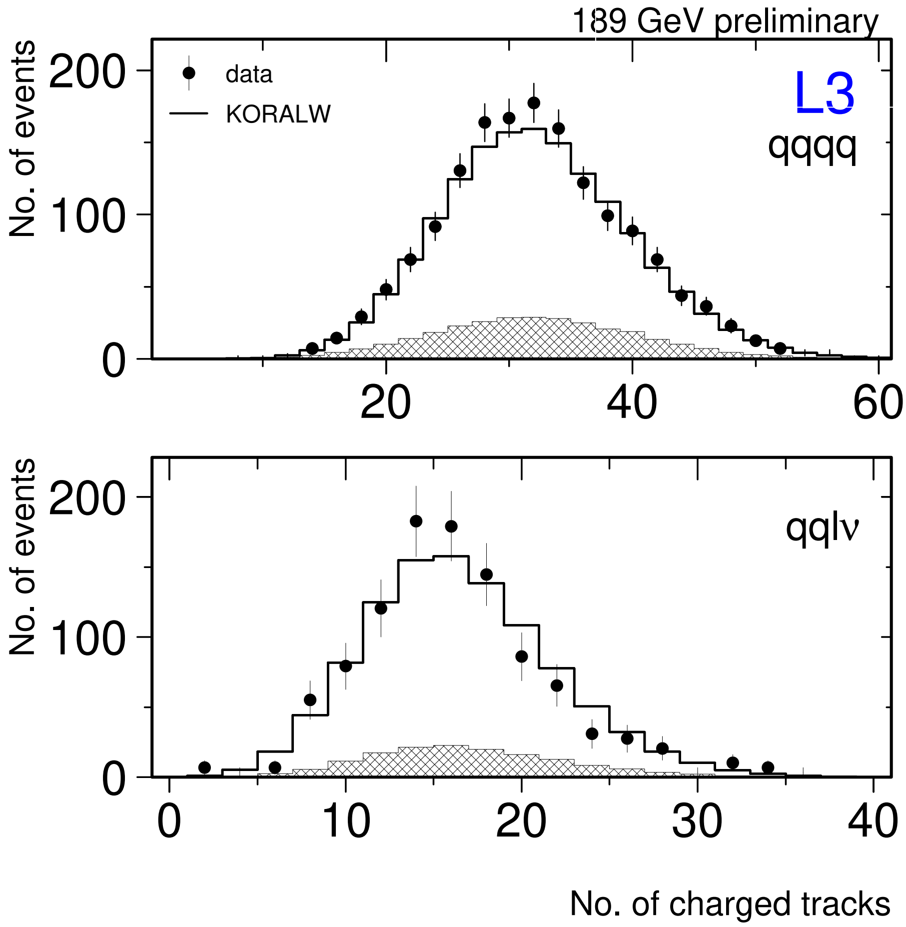
Charged Particle Multiplicity

Construct $\Delta\langle n\rangle = \langle n^{4q}\rangle - 2\,\langle n^{qql\nu}\rangle$ excluding $l^{\pm}$



-2 x





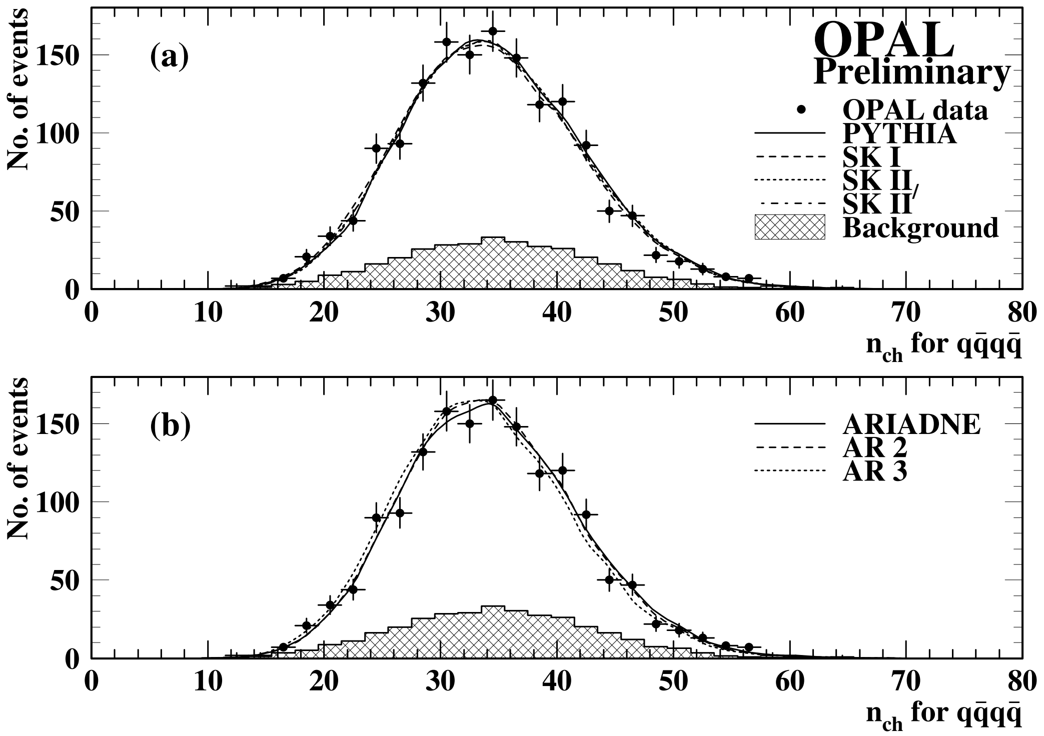
uncorrected 189 GeV data

normal QCD models

Extract charged multiplicity

- Direct measurement (matrix unfolding)
- Fragmentation function, rapidity distribution, etc.

Charged Particle Multiplicity



uncorrected 189 GeV data with CR models

Typical model predictions for $\Delta\langle n\rangle$ small, **e.g.**

- Sjostrand-Khoze (SK) I ~ -0.3
- SK II, II′ ~ -0.2
- ARIADNE 2 ~ -0.2
- ARIADNE 3 ~ -0.7
- GAL ~ -0.6

O(1%) $\langle n^{4q}\rangle$

<u>One approach</u>

- Correct to full acceptance (detector,selection, ISR)
- Include systematic from unfolding with CR models

Charged Particle Multiplicity

Compilation of (mostly) preliminary 183-189 GeV results

Define $\Delta\langle n\rangle = \langle n^{4q}\rangle - 2\langle n^{qql\nu}\rangle$

All errors are stat.⊕syst.

Expt.	$\langle n^{4q}\rangle$	$\langle n^{qql\nu}\rangle$	$\Delta\langle n\rangle$
ALEPH*	35.33±0.73	17.01±0.37	+1.31±0.83
189 GeV	35.52±0.52	17.53±0.31	+0.52±0.52
DELPHI#	37.79±0.80	20.07±0.66	−2.4±1.4
189 GeV	38.32±0.73	19.62±0.60	−0.9±1.1
L3	36.3±0.9	18.6±0.6	−1.0±0.9
189 GeV	37.12±0.81	18.68±0.45	−0.23±0.66
OPAL	39.4±0.8	19.3±0.4	+0.7±1.0
189 GeV	38.31±0.44	19.23±0.27	−0.15±0.58

∗ (Intentionally) not corrected for selection topology

Updated since 7/1998, where $\Delta\langle n\rangle = -1.6\pm1.5$

Average, assuming experiments 100% uncorrelated

(183 GeV) $\Delta\langle n\rangle = +0.03 \pm 0.49$ (stat.⊕syst.)

(189 GeV) $\Delta\langle n\rangle = +0.02 \pm 0.32$ (stat.⊕syst.)

All models except ARIADNE 3, VNI consistent with data

For future use, note $\sqrt{s}$ behaviour is model dependent

Charged Particle Dispersion

Compilation of preliminary 183-189 GeV results

Define $\Delta D = D^{4q} - \sqrt{2}\, D^{qql\nu}$

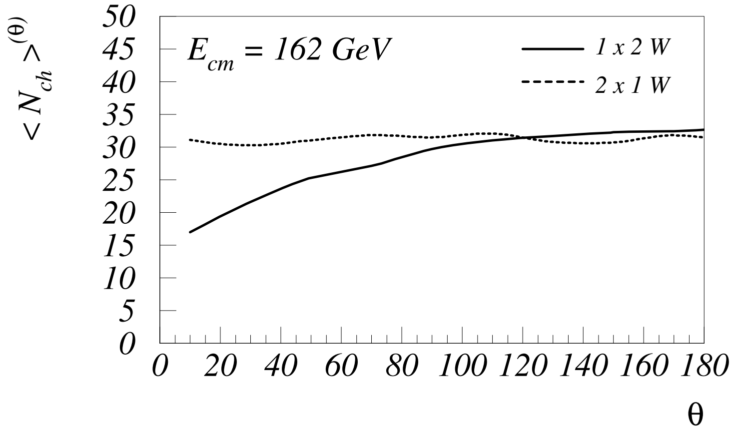
All errors are stat.⊕syst.

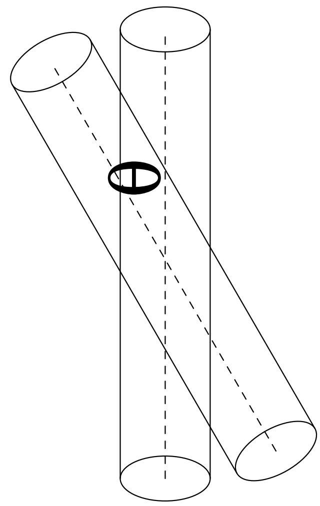
Expt.	D^{4q}	$D^{qql\nu}$	ΔD
DELPHI#	8.59±0.45	6.39±0.41	−0.14±0.72
189 GeV	8.46±0.51	6.39±0.48	−0.58±0.84
L3 189 GeV	8.12±0.46	5.97±0.40	−0.32±0.44
OPAL	8.8±0.6	6.1±0.5	+0.2±0.6
189 GeV	8.35±0.38	6.06±0.34	−0.23±0.32

Updated since 7/1998, where $\Delta\langle D\rangle$=+0.09±0.84

No indication of differences between qqqq and qqlν

Data Correction in W^+W^-





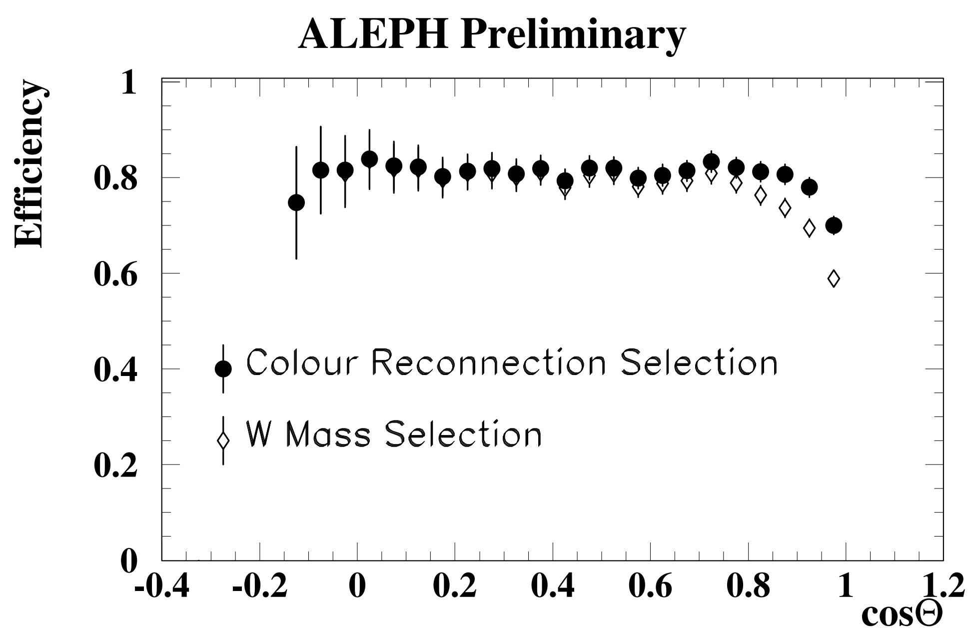
[From JE+KKG PL **B404**('97)70]

Predict largest effects when qq′ axes parallel, high T

Problem, Z^0/γ background dominates 2-jet like region!!

— experimental selections low signal efficiency

Dedicated selection to improve this by ALEPH



MC study

Check selection efficiency with opening angle of qq′ axes

How to correct? Model dependence important

Present analyses

- A: subtract background, correct to p>0.2 GeV,
  do not unfold for selection bias
- D: unfold to full acceptance
- L,O: unfold, add systematic from CR model unfolding

Unfolding may bias data towards model

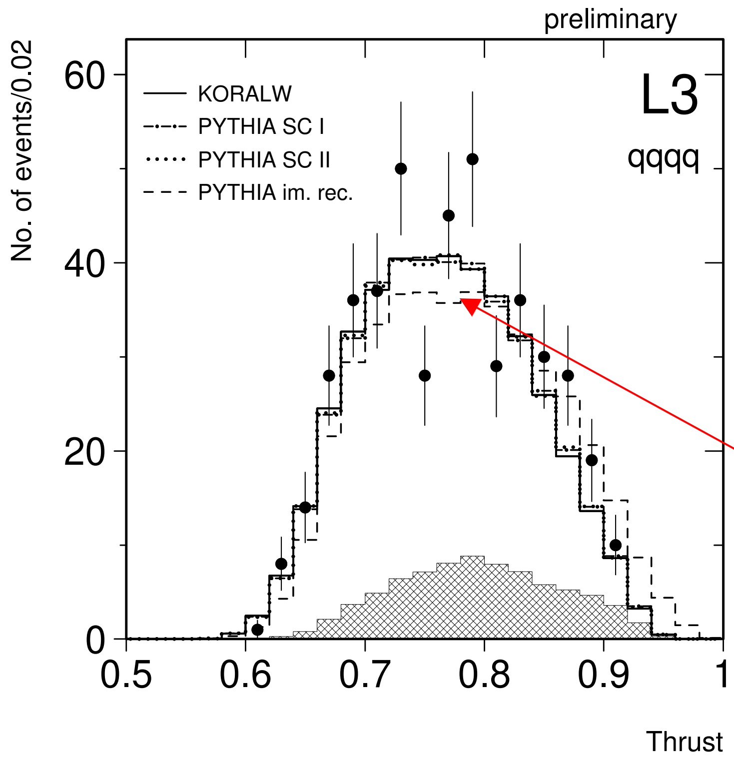
– better to avoid, or to unfold using CR models

No unfolding

– can only compare with predictions using full detector simulation/selection

– potential problem to combine ADLO results

Thrust



Uncorrected 183 GeV data

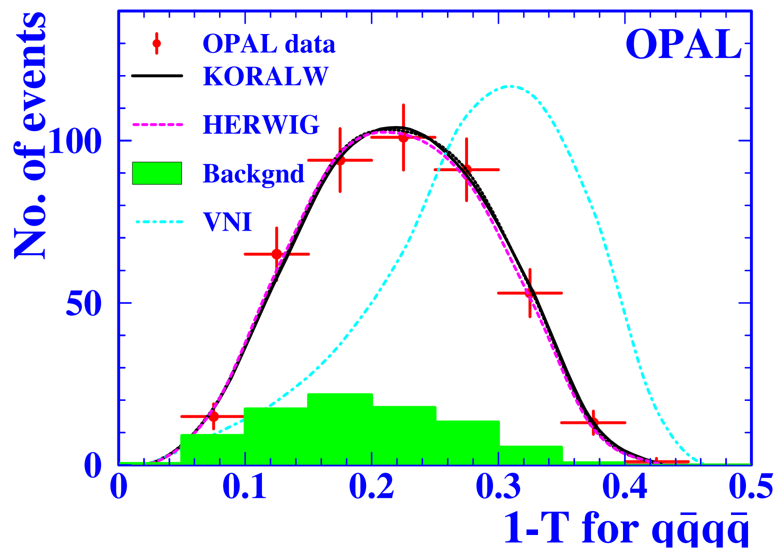
Perturbative CR (toy) model

$\Rightarrow$ upper limit of effects

Sjostrand-Khoze models only Jetset74 to tune

ARIADNE, HERWIG must be retuned

Ellis-Geiger model not recently tuned by authors/expts.



Uncorrected data at 183 GeV

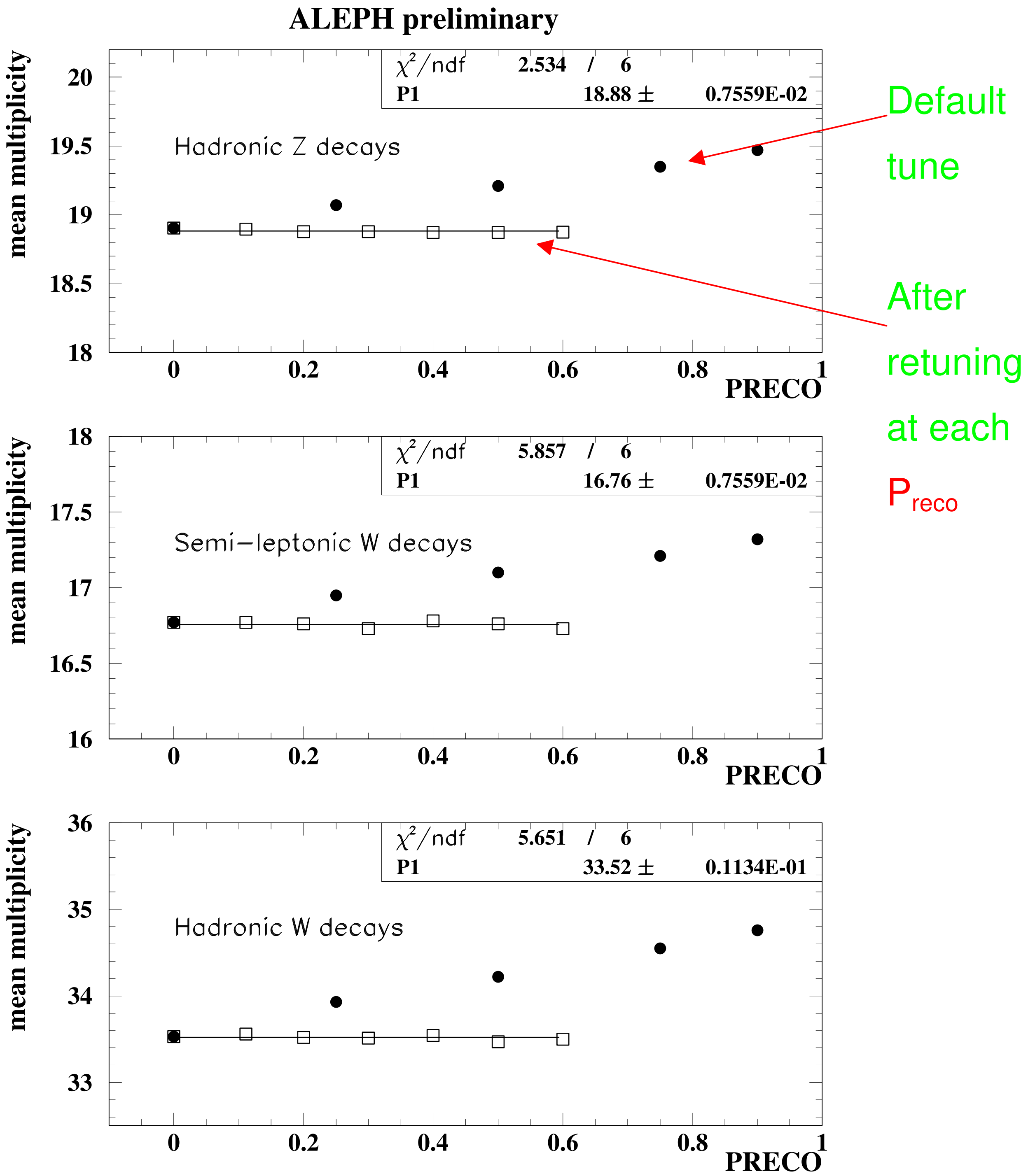
[Phys.Lett. B453('99)153]

VNI W^+W^- events more spherical than other models

Expect events well within experimental acceptance

Model Tuning

Tuning essential for reliable conclusions, e.g. HERWIG



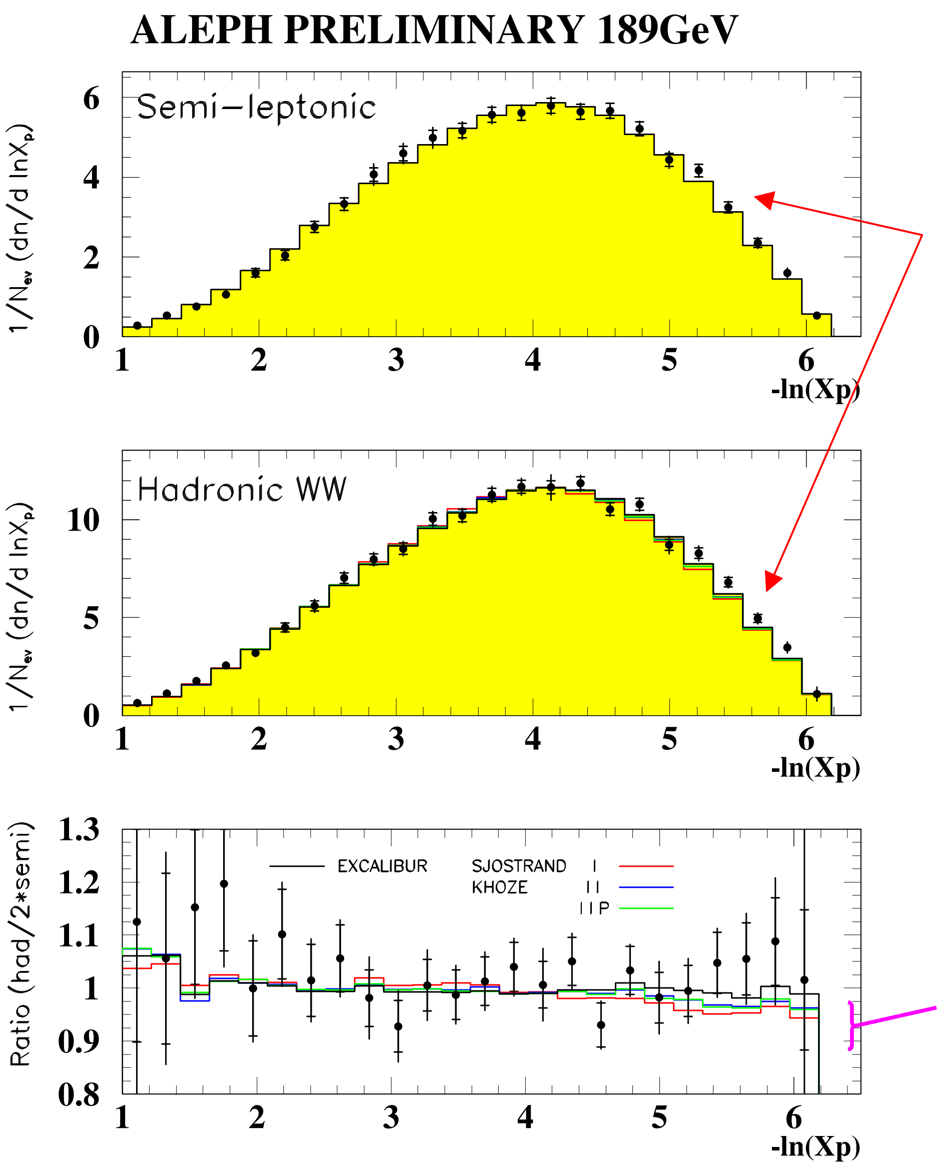
Large effects disappear over wide range P_{reco}

Other Particle Distributions

CR effects expected larger for soft particles, $p<\Gamma_W$

Look at observables with implicit scale, e.g. $\ln(1/x_p)$, p_T, y

$\ln(1/x_p)$



data excess also seen in Z^0 events

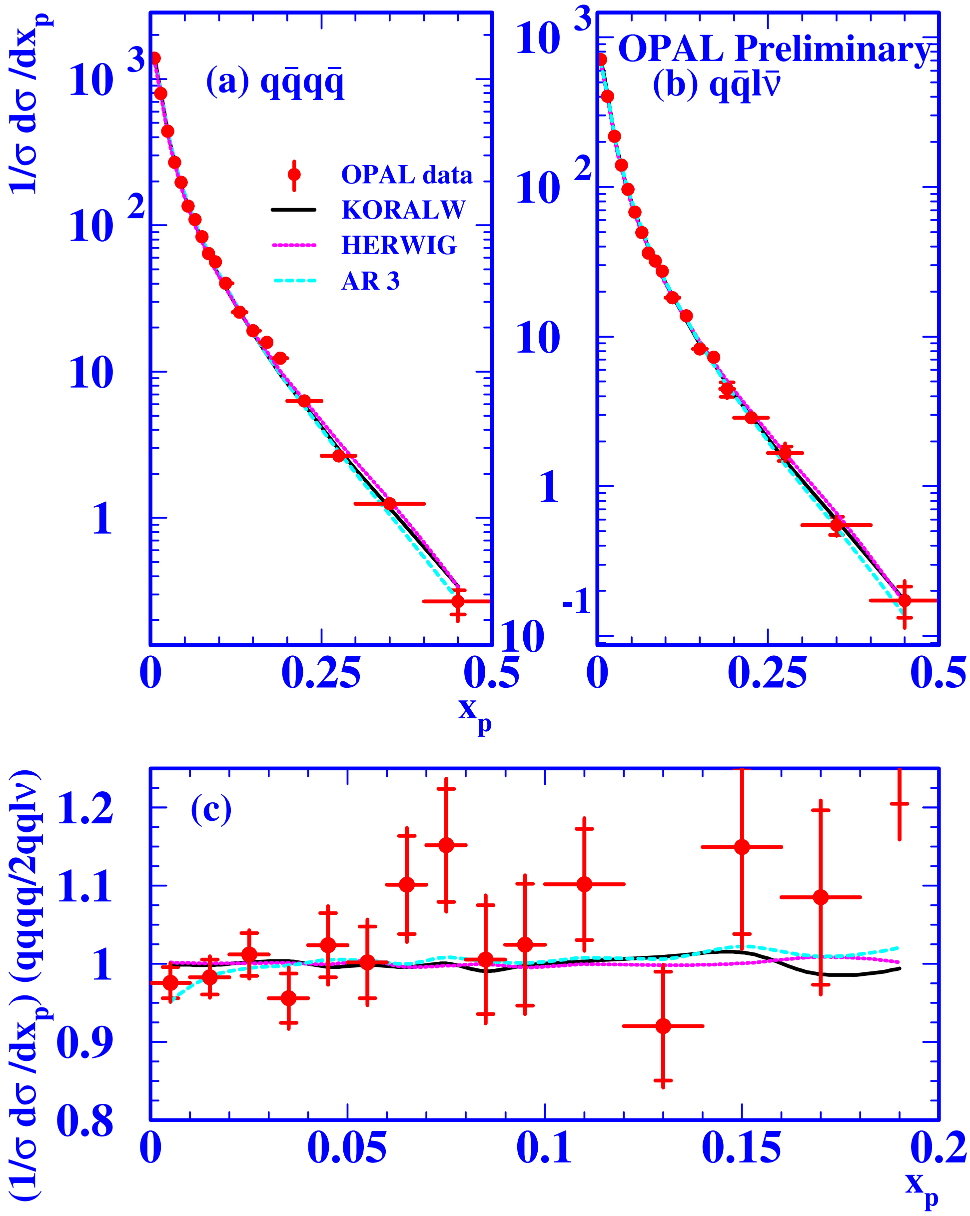
EXCALIBUR vs. SK models is predicted CR effect

Uncorrected data, ratio 4q/qqlν not expected

No evidence for difference in data vs. data

Cannot exclude SK models

fragmentation function



corrected
189 GeV
data

Corrected data, ratio 4q/qqlν should be flat

AR 3 predicts most significant effect but not excluded

O measure 4q $\langle x_p \rangle = (+3.348 \pm 0.029 \pm 0.022) \mathrm{x} 10^{-2}$

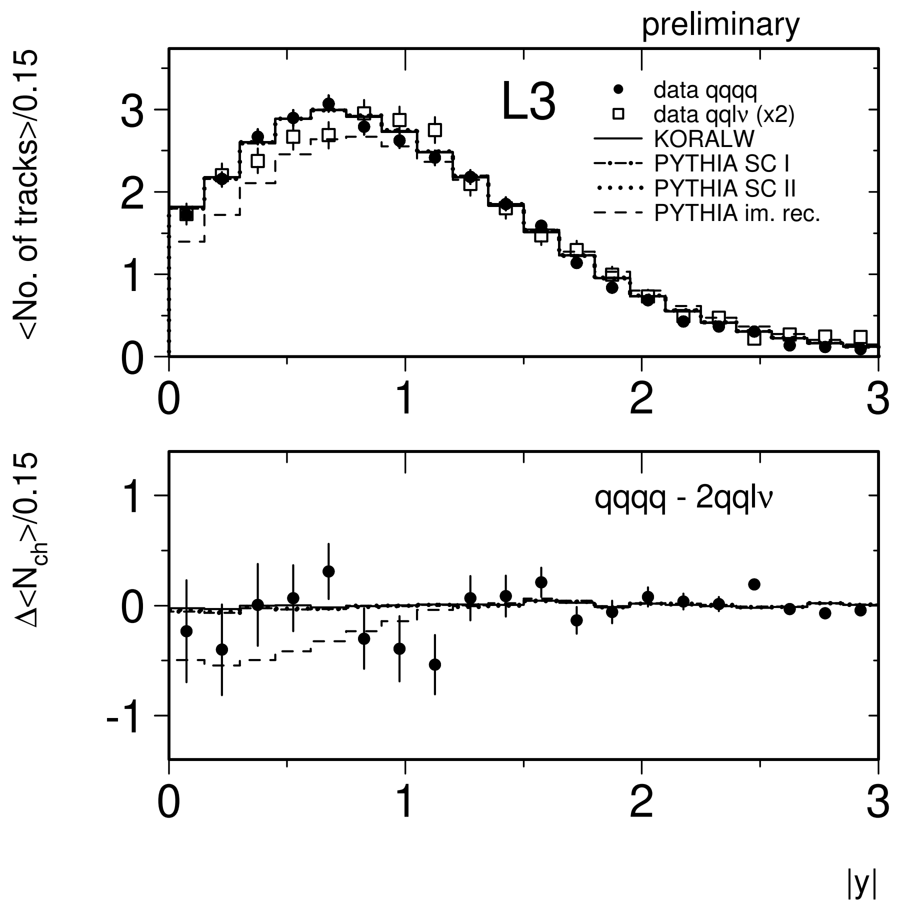
qqlν $\langle x_p \rangle = (+3.244 \pm 0.03 \pm 0.046) \mathrm{x} 10^{-2}$

difference $\Delta\langle x_p \rangle = (+0.104 \pm 0.052 \pm 0.051) \mathrm{x} 10^{-2}$

rapidity

Slightly less inclusive, defined relative to thrust axis

For qqlν, include p_ν = unobserved momentum



uncorrected average track multiplicity at 183 GeV

corrected $\Delta\langle n\rangle$, data and MC

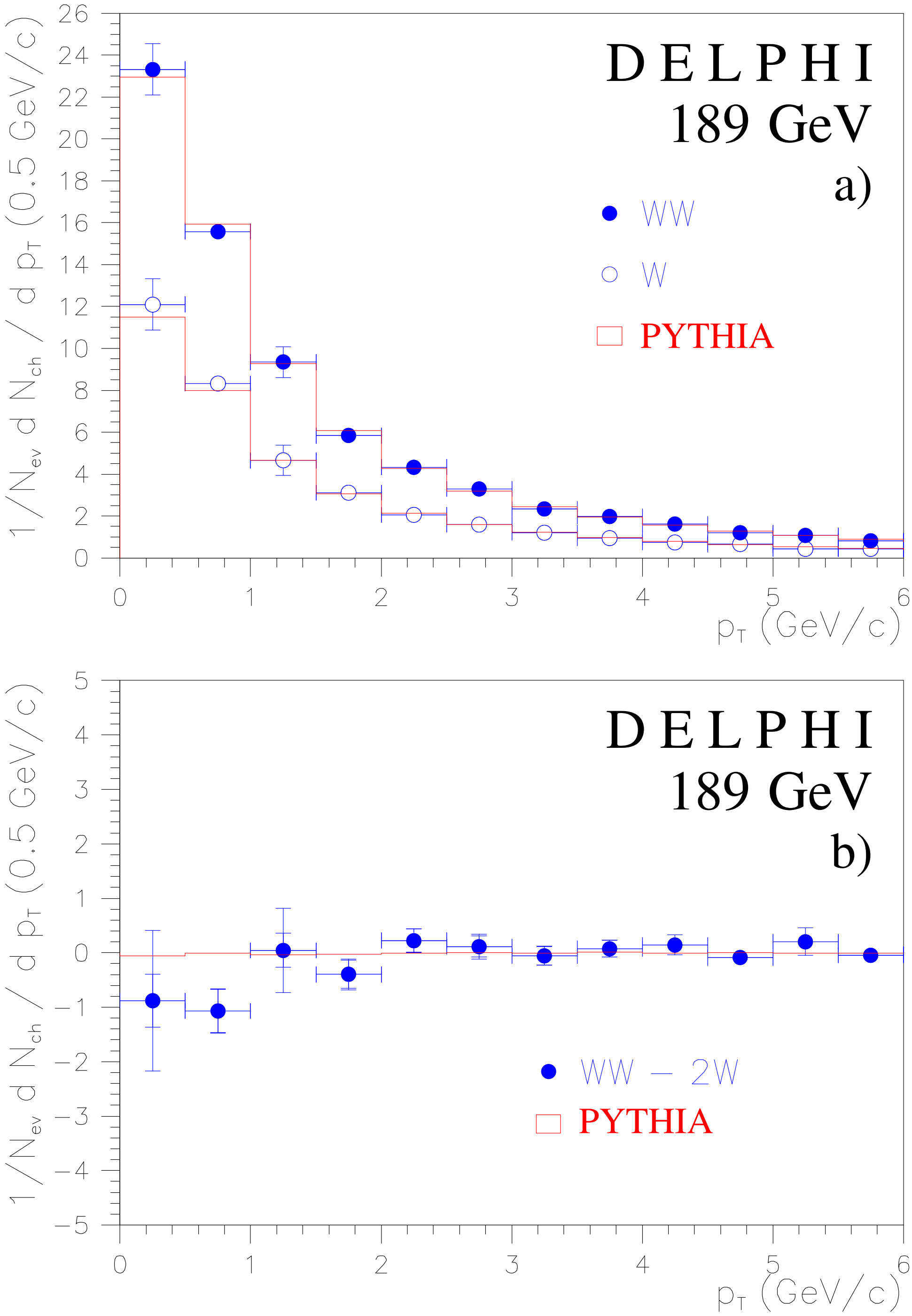
No significant difference observed between 4q, qqlν

Most models still consistent with data

No enhanced difference in central, low $|y|$ region

transverse momentum

Relative to thrust axis, as with rapidity



corrected data at 189 GeV

$\Delta\langle n\rangle$, data and no-CR model

Bias in procedure, estimate some systematics from data

- replace jet pairs in 4q by qq′ from qqlν

No significant indication of CR effects at low p_T

Misc. measurements

OPAL measure <|y|>, <1-T> for 4q events (189 GeV)

$\langle |y^{4q}| \rangle = 1.018 \pm 0.008 \pm 0.010$

$\langle 1 - T^{4q} \rangle = 0.240 \pm 0.013 \pm 0.0068$

- very limited sensitivity to CR, except extremes

DELPHI quote explicit ratios for $0.1 < p < 1.0$ GeV

$\langle n^{4q} \rangle / 2 \langle n^{qql\nu} \rangle = 0.966 \pm 0.017 \pm 0.027$ 189 GeV

$\langle n^{4q} \rangle / 2 \langle n^{qql\nu} \rangle = 0.926 \pm 0.041 \pm 0.023$ 183 GeV

Relative systematic assumed same as in full p range

a priori clear this is true?

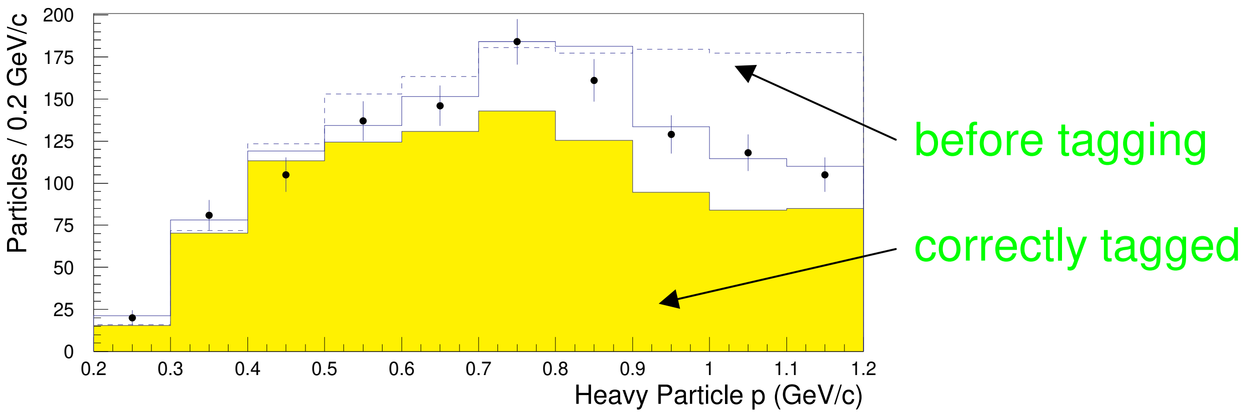
For ALO, same comparison possible directly from distributions x_p, p_T, y

Similar conclusion, no significant effects seen

Identified Hadrons (DELPHI)

- Heavy hadrons (K,p), soft region $0.2<p<1.4$ GeV
  - CR effects predicted 2-3x larger   [TS+VAK]
  - improved significance? Not clear.
    - finite data sample
    - Low tagging efficiency
    - increased systematics
- Particle identification TPC, RICH, VD
- (K,p) tagging, efficiency ~ 90–50%, purity ~ 90–75%

183 GeV preliminary results



#(K,p) observed   181 in $qq'qq'$ 88 in $qql\nu$

After unfolding for all tagging effects (stat. errors only)

	$4q/2qql\nu$	4q/MC
⟨heavy particles⟩	1.03±0.15	0.85±0.09

using ~10% LEP2 sample

Project to canonical 500 pb^{-1}/expt. LEP2 luminosity

4q data vs. qqlν data → stat. error ~5%

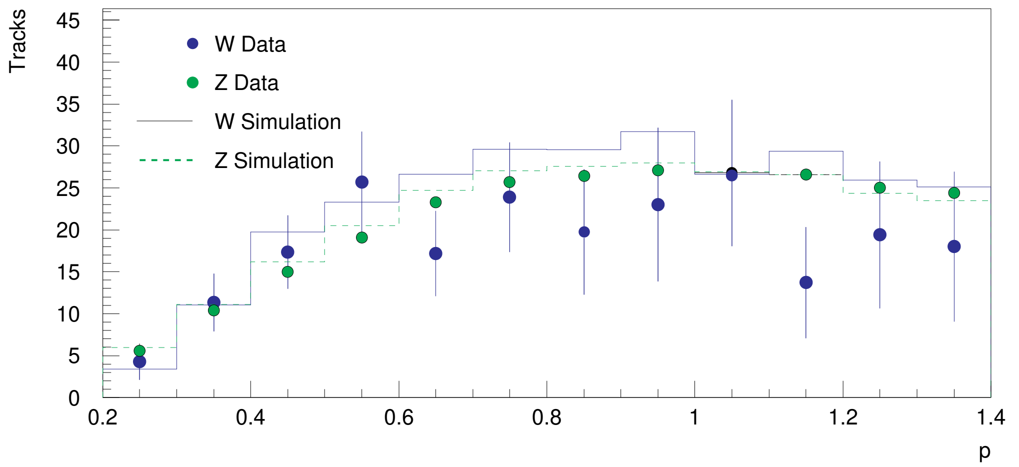
4q data vs. 4q MC → stat. error ~3%

detector+generator modelling ⇒ larger systematics….

use Z^0 calibration data as reference sample [TS+VAK]

Take pairs of Z^0, boost using $W^\pm$ kinematics

emulate background subtracted W^+W^-



Z^0, W^+W^- MC fair agreement

<u>Systematics from W^+W^-</u>

- bg subtraction ~ 2%
- particle id $Z^0/W^\pm$ ~ 1%

<u>Systematics from Z^0 pairs</u>

- particle id f(θ) ~ 3%
- low p cutoff ~1.7%

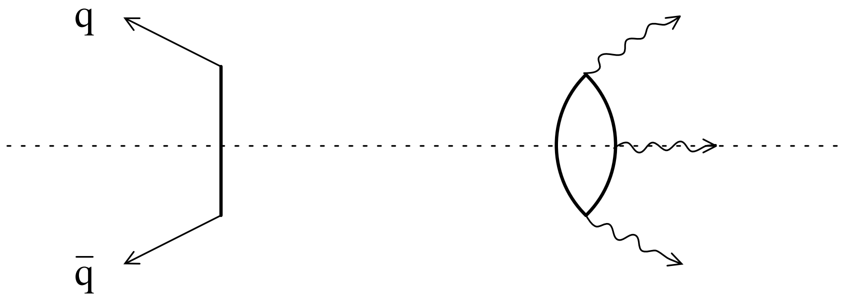
Prospects good to reduce systematics further

$$\boxed{n^{heavy},\ \langle W^+W^-\rangle/\langle Z^0+Z^0\rangle = 0.870 \pm 0.090 \pm 0.044}$$

Consistent with both CR and normal QCD models

Z^0 Event Properties (OPAL)

Idea from ~ '95, very rare $Z^0 \to qqgg$ may form glue ring



From Friberg *et al*, Nucl.Phys. **B490** ('97) 289

Experimental selection from existing analysis!

Require 2 heavy quark tags same hemisphere

$\Rightarrow$ other hemisphere energetic gluons

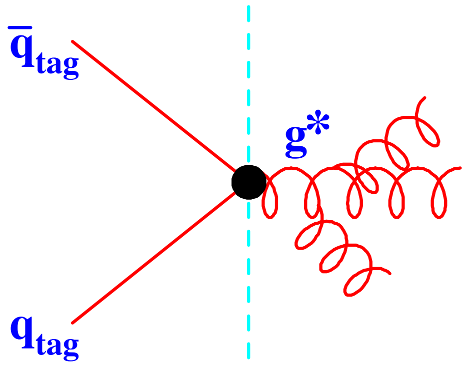
Find 439 events entire LEP1 sample CERN-EP/99-28

Improve $g_{incl.}$ purity

15^0<(jet-thrust)<70^0

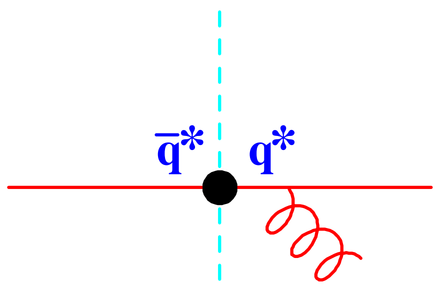
70^0<(jet-jet)

⟨jet-jet⟩ ~ 91^0



$g_{incl.}$ gluon jet hemisphere

Light quark jets used for comparison



uds event hemisphere

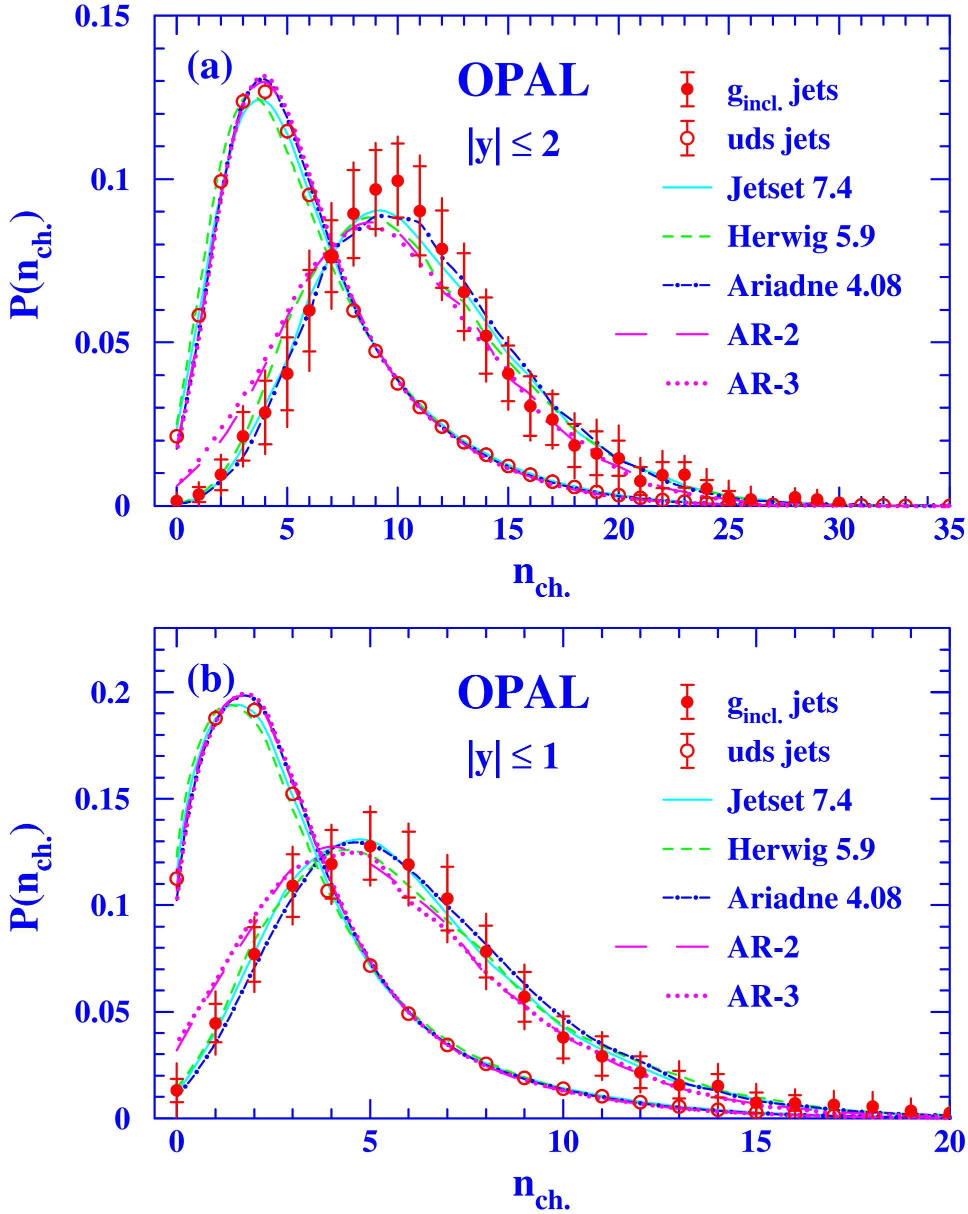
Purity g_{incl} = 81.9±1.2 % Tag rate ~ 10^{-4}

$\langle E \rangle g_{incl}$ = 40.1±0.7 GeV

$\langle n_{ch} \rangle$ in central rapidity

This region a suggested signature

Distributions corrected to hadron level



$|y| \leq 2$

Use ALEPH tune, +small changes for CR models

$|y| \leq 1$

$\langle E \rangle g_{incl}$ = 40.1±0.7 GeV $\langle E \rangle_{uds}$= 40.1±0.7 GeV

$r_{ch} = \frac{n(g_{inc})}{n(uds)}$

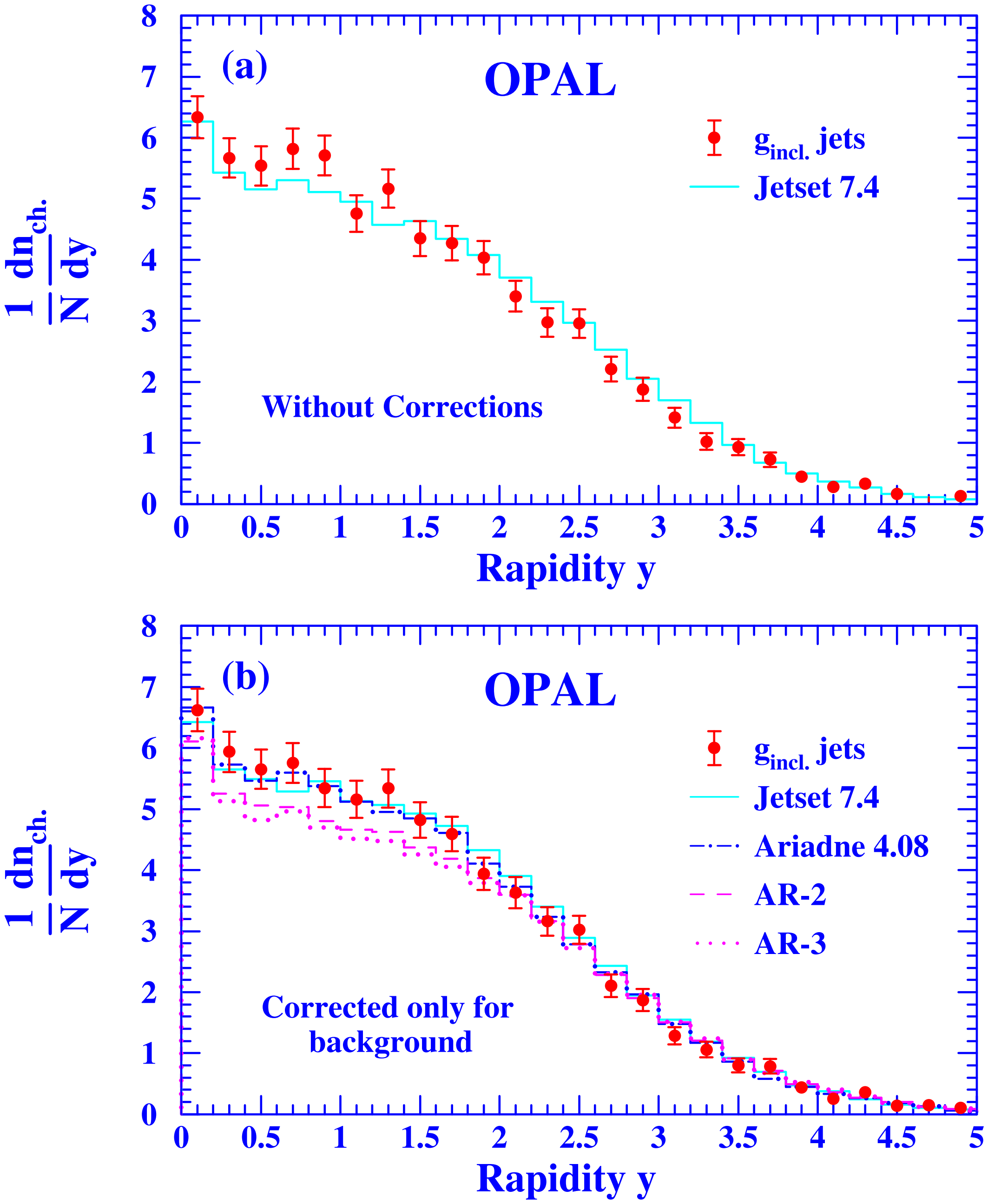
	data	AR 2	AR 3	JETSET, HW, AR
r_{ch}	1.514±0.039	1.43	1.42	1.54–1.55

Data described well by normal QCD models

AR 2, 3 agree with data at 2.2, 2.4 σ (total error)

Rapidity

Reduce uncertainty by comparison before correction



uncorrected

bg subtracted

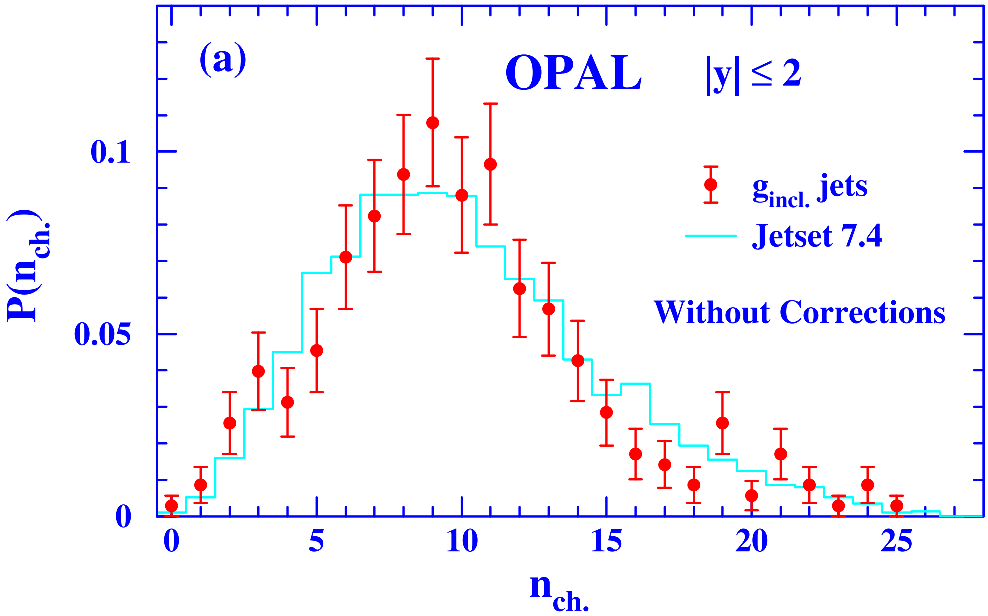
Lack of detector MC statistics ⇒ quark tagging by MC info.

Subtracting background (18%) introduces no significant bias

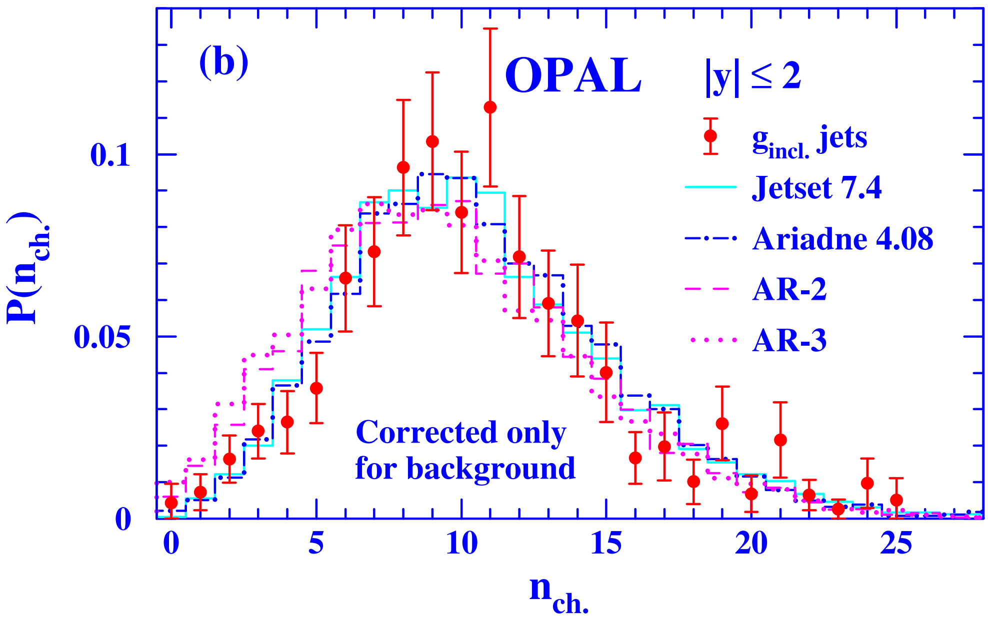
Data have more particles at low $|y|$ than AR 2, 3 model

$\langle n_{ch} \rangle$ in central rapidity

Uncorrected distribution



uncorrected



bg

subtracted

Clear discrepancy ARIADNE CR model and data

Study prob. $n \leq 4$ for $y \leq 2$ in $g_{incl.}$ (in %)

	data	AR 2	AR 3	JETSET	ARIADNE
r_{ch}	11.4±1.8	20.1±0.6	21.6±0.6	12.9±0.6	12.5±0.6

Conclude AR 2, 3 disfavoured by 4.7, 5.4σ

Combined LEP W^+W^-

Already recorded/analysed ~ 50% expected LEP2 data

Direct reconstruction, prel.,

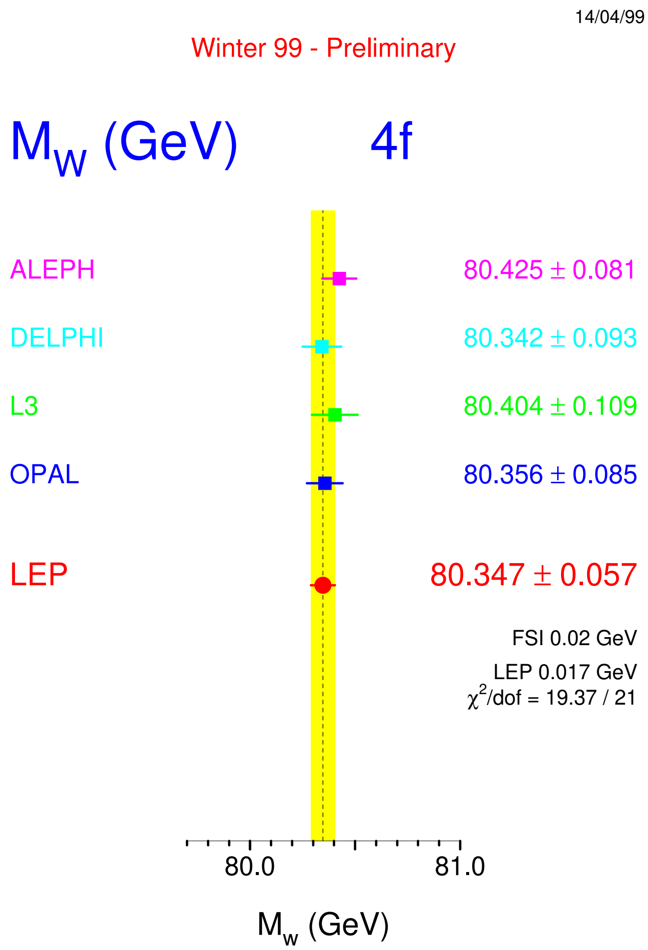
172–189 GeV data, χ^2=19.4/21

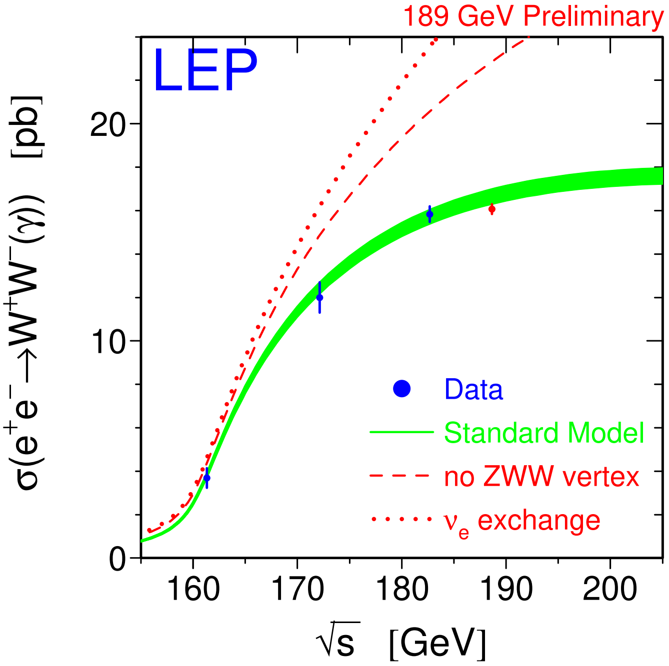
M_W=80.347±0.036±0.045GeV

ΔM_W=152±74 MeV χ^2=18/20

Including cross-section data,

M_W=80.350±0.056 GeV





prelim. 188.63 GeV, χ^2=2.98/3

σ_{WW}=16.05±0.22 pb

All LEP2 W^+W^- data, gives

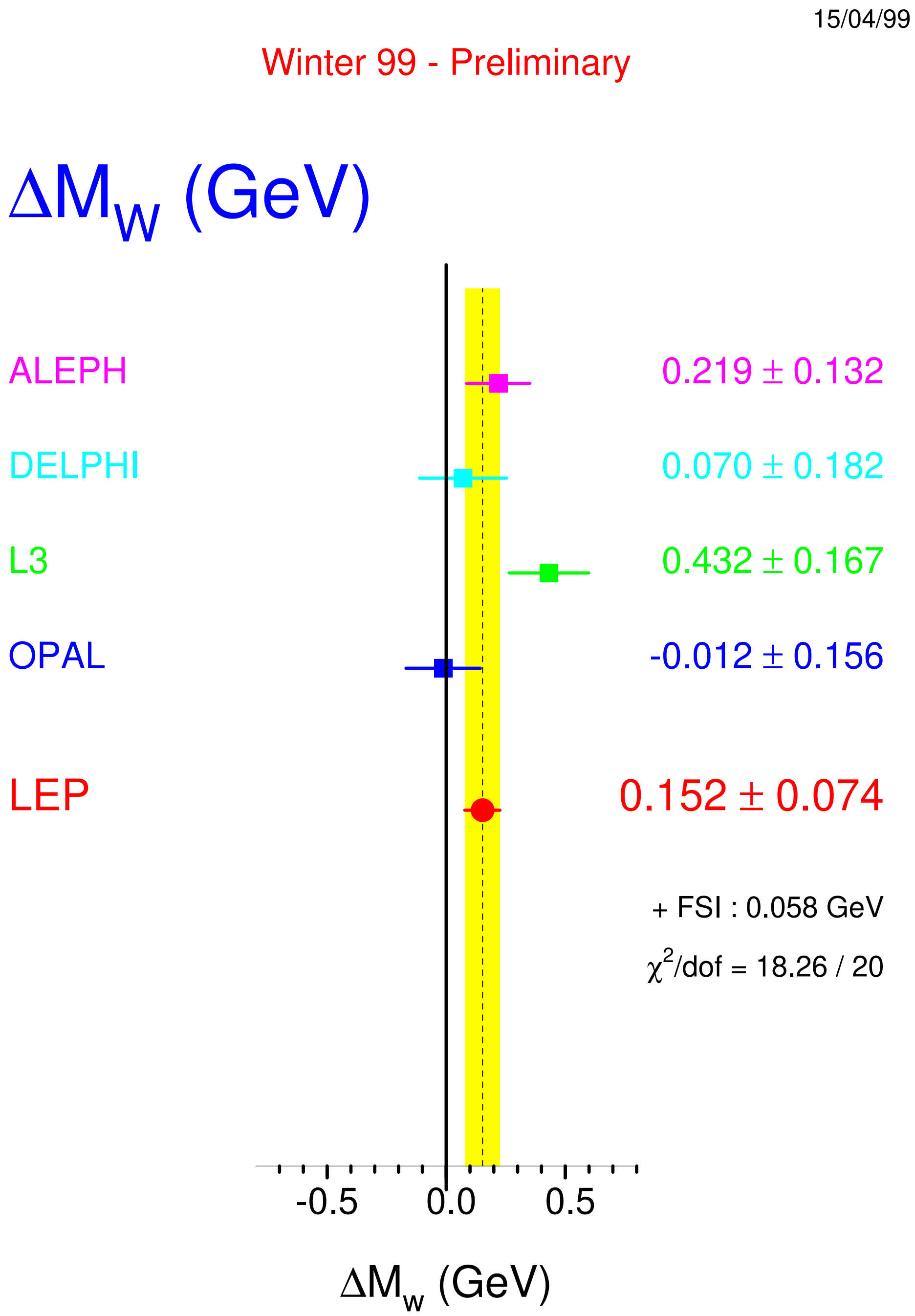
BR($W \to qq'$)=0.679±0.004

M_W Bias estimates from data?

1: M_W (qqqq) – M_W (qqlν)

$\Delta M_W(4q\text{-}qql\nu) = -0.01 \pm 0.13 \pm 0.08$ GeV

from 50% all LEP2 data



⇒ Should not consider as test for effects O(100 MeV)

2: M_Z from Z^0Z^0 events

2 colour singlets $\rightarrow$ CR effects present in qqqq channel

Reconstruct M_Z à la M_W analysis, compare LEP1 data

Total LEP2 luminosity expected $\approx 500\ pb^{-1}$/ experiment

$\sigma_{ZZ}(189\ GeV) \sim 0.95\ pb$ $\quad$ $BR(ZZ \rightarrow qqqq) \approx 0.7^2$

$\Rightarrow 4 \times 230$ events produced

Selection efficiency $<< 100\ \%$

non-radiative $Z/\gamma \rightarrow qq$ $\quad$ $\sigma_{Z/\gamma}(189\ GeV) \sim 25\ pb$

$W^+W^- \rightarrow qqqq$ $\quad$ $\sigma_{WW}(189\ GeV) \approx 7.5\ pb$

Assume similar mass resolution as W^+W^- case

e.g. OPAL MC studies at 189 GeV

$900 \times qqqq \rightarrow \delta M_W \approx 100 \pm 12\ MeV$

$\Rightarrow$ $\boxed{\delta M_Z = \sqrt{900/920} \times 100 \approx 100\ MeV}$ (stat. only)

Must also include: finite selection efficiency

experimental systematics

Good idea defeated by statistics

M_W Bias Estimates

Bias estimates (MeV) from models consistent with data

Expt.	Aleph	Delphi*	L3	Opal
SK I	+25±21#	+40±13		+11±25
SK II	+5±15	–	70	–23±25
SK II′	+17±15	+3±10		–22±25
GH	–	+13±18	–	–
HW	–31±25		–	–
AR 2	+27±25	+28±6	–	+49±14
AR 3	–	+55±6	–	+145±21
ΔM_W	**25**	**50**	**70**	**49**

\# Modified version of model * Fast detector simulation

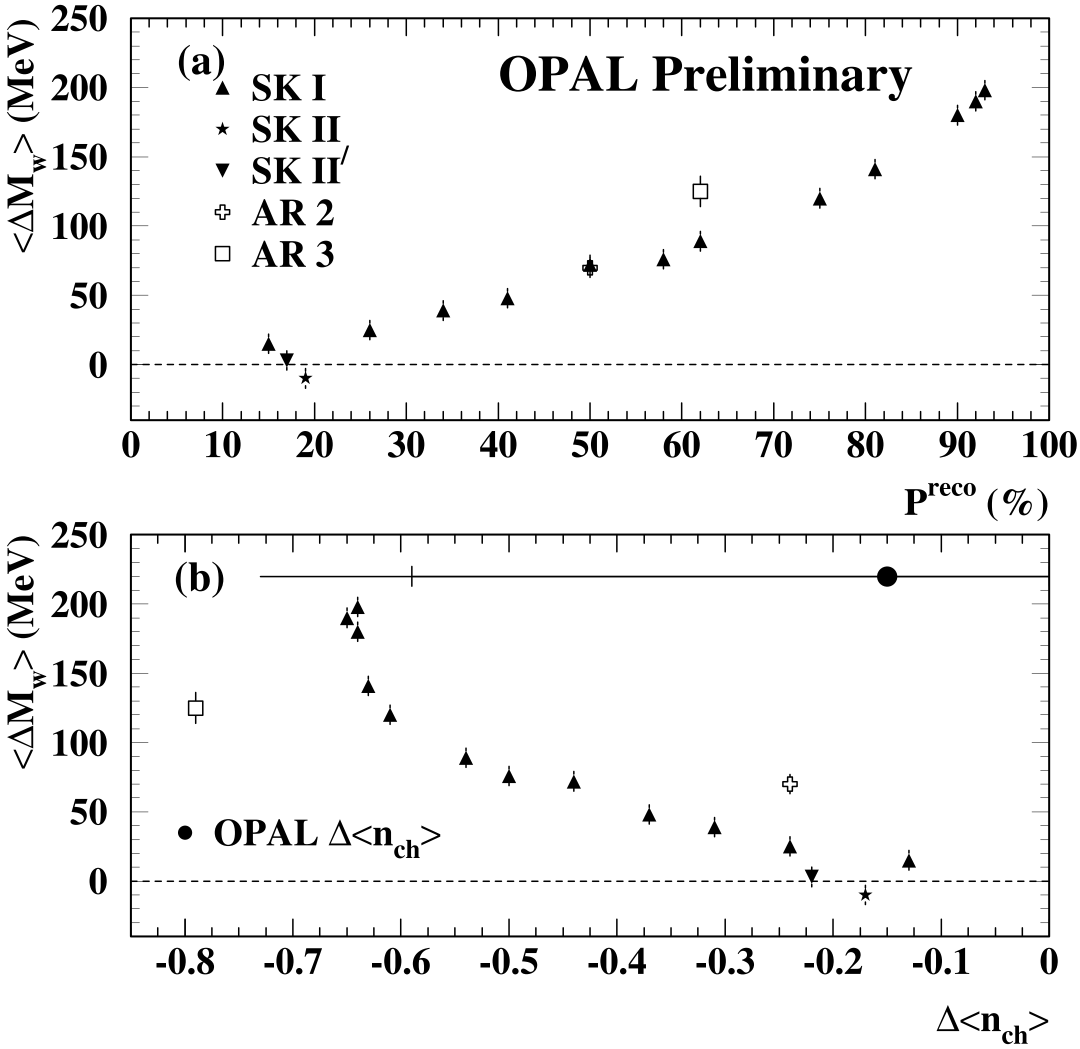
All estimates are from published/final 183 GeV analyses

Note

- A,L,O current version of M_W analyses, D a variant
- significant statistical uncertainty on bias estimates
- AR 3 model neglected on theoretical grounds
- no serious models excluded by W^+-W^- data yet
- new GAL model not studied yet by experiments

M_W Bias Estimates

Example of model dependent bias estimates



Compare with 189 GeV average $\Delta\langle n\rangle$=+0.02± 0.32

Some prospect for data to estimate biases, esp. with

$\Longrightarrow$ more exclusive observables

$\Longrightarrow$ ADLO combinations

Future Prospects

- More CR models will help ☺
- Better understanding of QCD/EW background
  - matrix element vs. parton shower MCs
- Less inclusive studies, e.g.
  - using W ↔ jet-jet pairing (interjet studies, …)
  - particle correlations (factorial correlator, etc.)
  - multivariate selections for rare CR events?
- Further studies using 91 GeV Z^0 data
- How to test physics (octet mechanism) of EG model?
  - many technical problems, VNI ☹
- Calibrate M_W bias vs. most sensitive observable
  - model dependent ☹

Prospects for improved common discussions

- This workshop, correlated M_W systematics
- LEP2 MC Workshop (ongoing)
- Timescale OK for 1999 data

Summary

- Most models consistent with data
- 1996-1998 data $\approx 50\%$ LEP2 luminosity
  - More progress by new ideas than new data now?
- Z^0 data used to test /exclude Ariadne models
- Identified/heavy particle studies ongoing (but difficult)
- Small statistical error $\Rightarrow$ M_w bias estimates important!