Recent results from OPAL

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LEP physics jamboree, 6/3/03

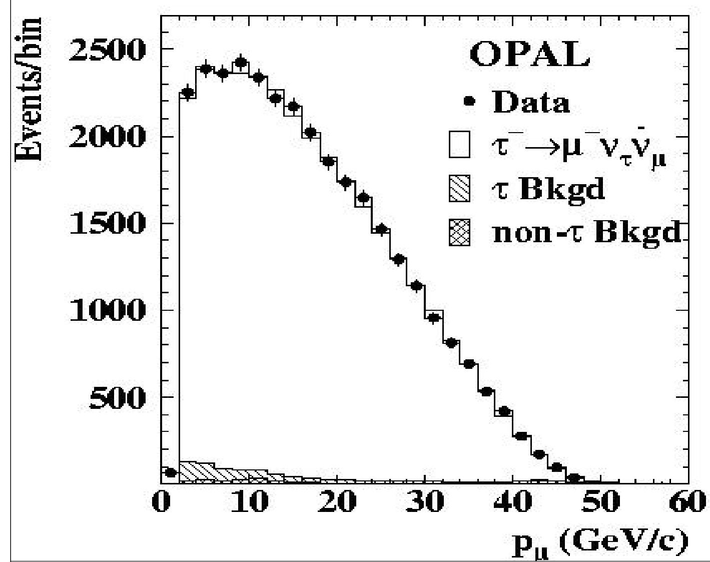
- An overview of some recent OPAL results:
  - Electroweak physics: τ decays
  - B-physics – B semileptonic decays
  - Final state interactions: Bose-Einstein and colour reconnection at LEP1
  - QCD studies at LEP2
  - Two photon physics: di-jet studies

  - OPAL long term plans and 'archiving'

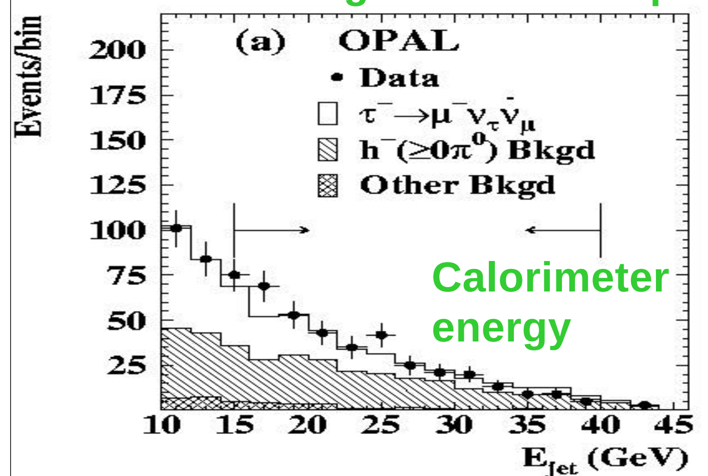
See http://opal.web.cern.ch/.Opal/PPwelcome.html for more details …

$\tau \to \mu$ branching ratio

- Precise BR($\tau \to \mu$) from all LEP1 data
  - Select $\tau^+\tau^-$ events
    - 97k events; 1.1±0.2% background
  - Select $\tau \to \mu$ candidates
    - Selection based mainly on tracking and muon chambers
    - 31k candidates, 3.0±0.3% background
  - Key is good understanding and control of backgrounds:
    - Dedicated selections to enhance and study particular backgrounds
    - Independent selection of $\tau \to \mu$ events based on calorimeter information
    - E.g. study hadron punch-through by looking at calorimeter response:
- Result from full OPAL data sample:
  - BR($\tau \to \mu$)=0.1734 ± 0.0009 ± 0.0006



Hadron bkgd control sample:

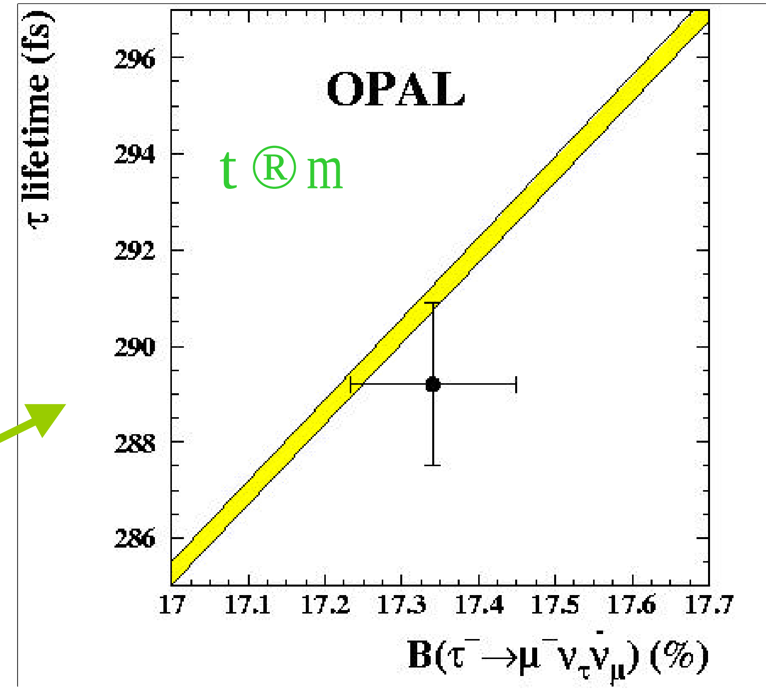


Testing lepton universality

- Ratio of $\tau \to \mu$ and $\tau \to e$ branching ratios tests equality of g_e and g_μ:

  $(g_m/g_e) = 1.0005 \pm 0.0044$
- Include μ and τ lifetimes and masses to test equality of g_e and g_τ:

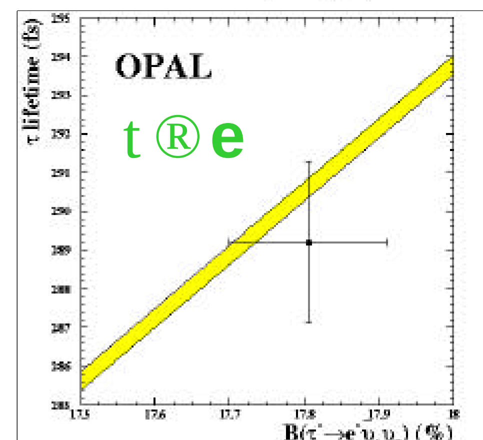
  $(g_t/g_e) = 1.0031 \pm 0.0048$
- Alternatively, assume lepton universality
  - Relation between BR and lifetime …



- Michel parameter η:
  - Structure of leptonic decay spectrum; depends on $\tau \to \mu$ and $\tau \to e$ BRs

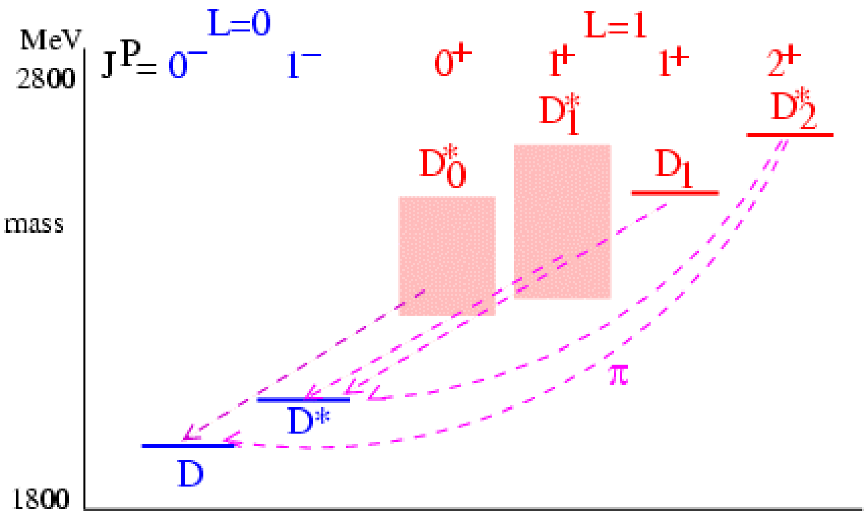
    $h = 0.004 \pm 0.037$
  - Can be used to limit scalar couplings in τ decay – limit on H^+ mass in MSSM:

    $m_H > 1.28 \tan\beta$ at 95% CL
    - Complementary to constraint from B→tX



Measurement of B→D**lν branching ratio

- Spectroscopy of D mesons:



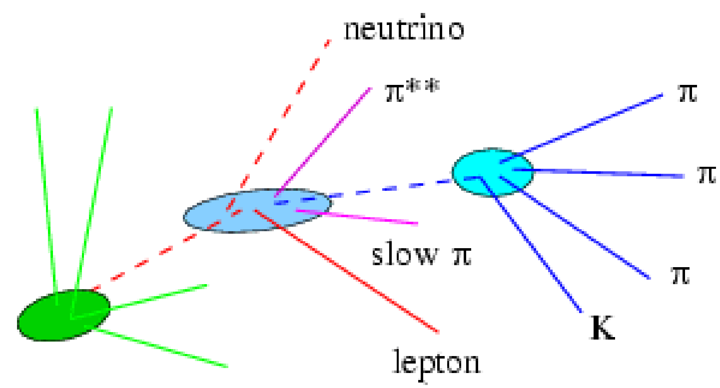
  - B semileptonic decays can involve all these states: B→(D,D*,**D****) lν
  - Contribution of D** states is particularly interesting:
    - Sum of exclusive BR < inclusive BR
    - Irreducible background to LEP measurements of $|V_{cb}|$

- Reconstruction of decay chain:
  - $B \to D^{**0} l \nu X$

    $D^{**0} \to D^{*+} \pi^-$

    $D^{*+} \to D^0 \pi^+$

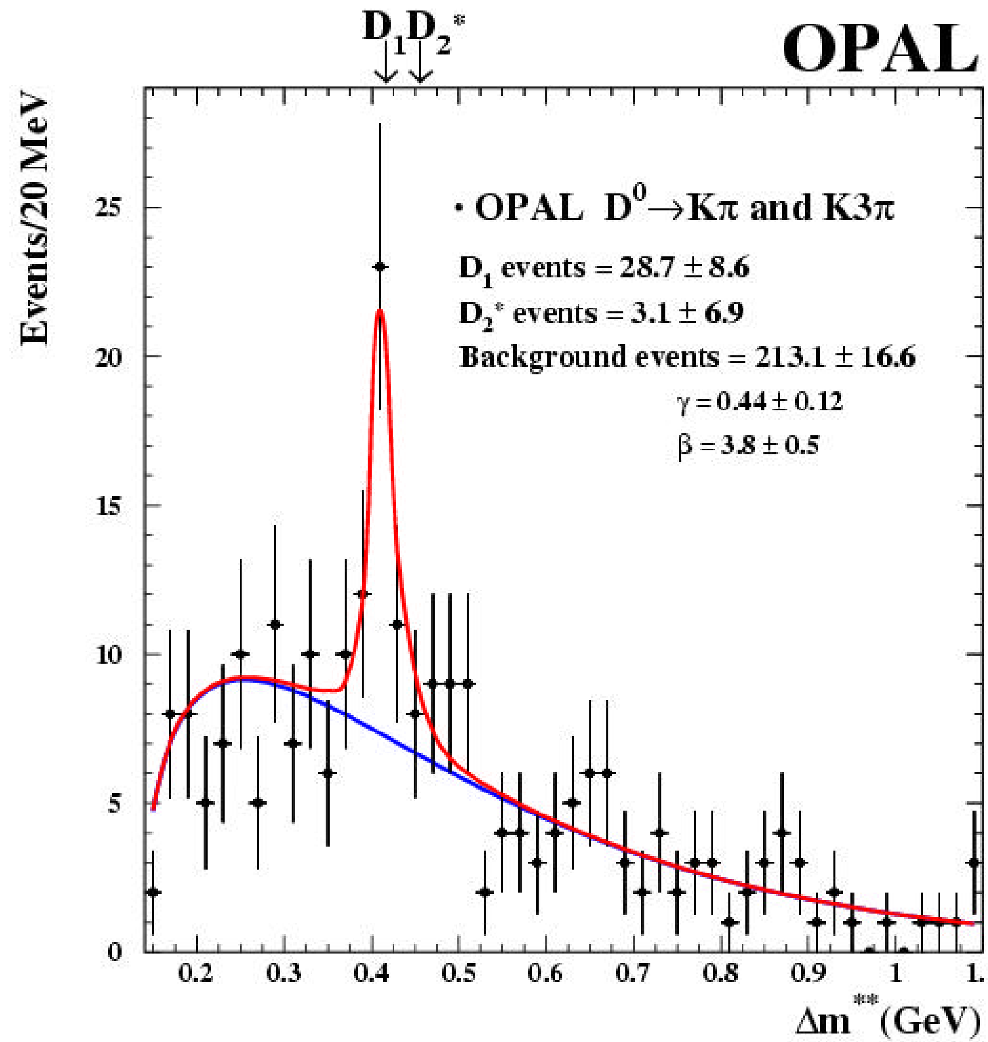
    $D^0 \to K^- \pi^+$ or $K^- \pi^+ \pi^- \pi^+$
  - Look for narrow states D_1^0 and D_2^{*0}
    - Branching ratios are small, expect only a handful of events
    - Five or seven tracks to reconstruct in the final state – a challenge



Looking for the D^*_1 and D_2

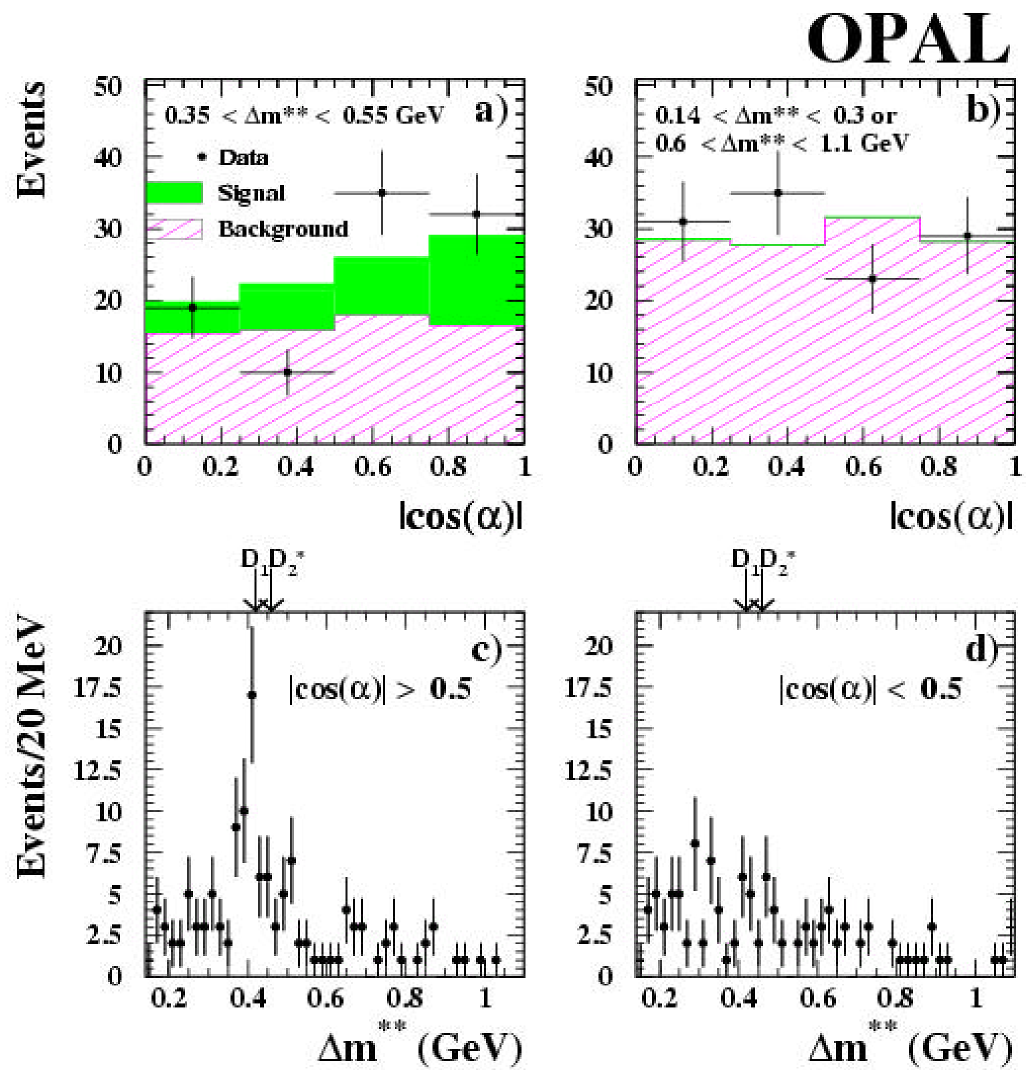
- Analysis strategy:
  - Identify lepton from B decay
  - Reconstruct D^0 in $K\pi$ and $K3\pi$ modes
    - Add 'slow' π for D^*, kinematic fit
    - Look for π from D^{**} decay
    - Require appropriate vertex topology
  - Examine $D^*\pi$ mass spectrum:

    $\Delta m^{**}=m(D^*\pi)-m_{D*}-m_\pi$
    - Background from mass sidebands and wrong sign $D^{*+}\pi^+$ Δm^{**} distribution
- See signal from D_1^0 in both modes:
  - $BR(b\to B)(B\to D_1^0 l\nu)(D_1^0\to D^{*+}\pi^-) = (2.64 \pm 0.79 \pm 0.39) \times 10^{-3}$
- No evidence of D_2^{*0} mass peak
  - $BR(b\to B)(B\to D_2^{*0} l\nu)(D_2^{*0}\to D^{*+}\pi^-) < 1.4 \times 10^{-3}$ at 95% CL



Angular information

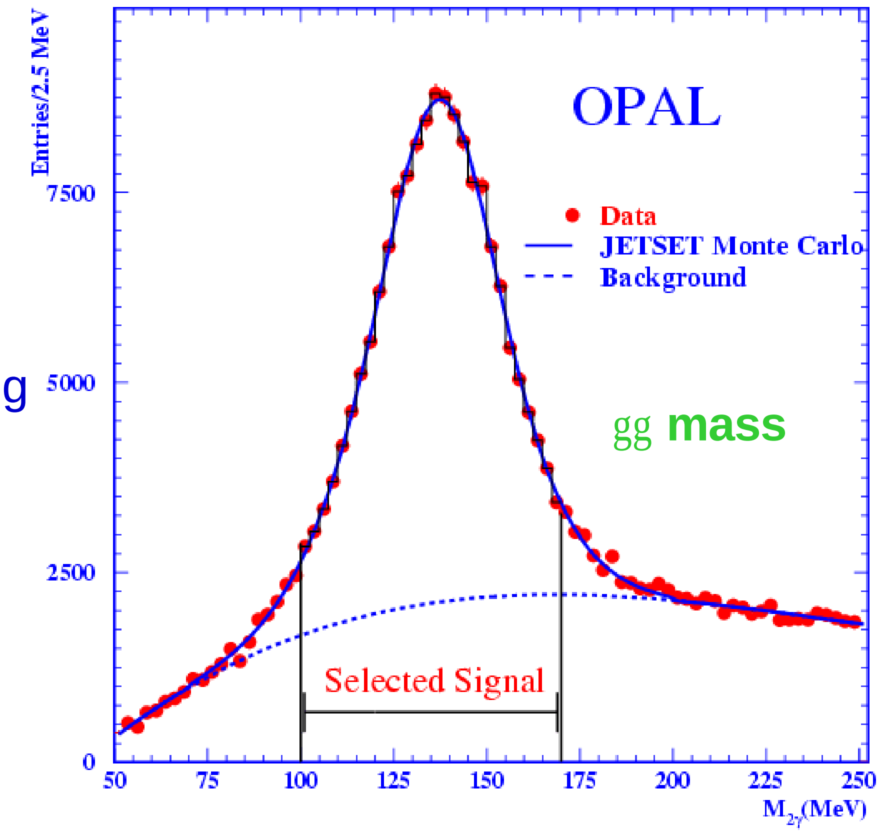
- Angular decay distributions:
  - For D_1 (1^+ state): $\frac{1}{4}(1+3\cos^2\alpha)$
  - For D_2^* (2^+ state): $\frac{3}{4}\sin^2\alpha$
    - a = angle between the two pions in the D^* rest frame
  - Expect D_1 signal to be concentrated at high $|\cos\alpha|$
    - It is… no sign of of D_1 or D_2^* signals at low |cos a |
    - Supports assignment of observed state to D_1
- Results agree with other expts.
  - Substantial D_1 contribution
  - D_2^* contribution is small – not expected by HQET
  - Substantial room for broad states (D_0^* and D_1^*) and non-resonant contributions to $B \to D^* \pi l \nu$



Bose-Einstein correlations in π^0 pairs

- Many BEC studies in Z^0 decays
  - So far, only a few studies of π^0 pairs
  - String model predicts larger strength and smaller source radius for π^0 pairs cf. $\pi^{\pm}$
  - Cluster model predicts no difference.
  - Neither model accounts for BEC connecting pions from different strong decays
- Experimental analysis:
  - Define correlation function:

    $C(Q)=\rho(Q)/\rho_0(Q)$, where $Q^2=-(p_1-p_2)^2$
    - ρ is phase space density in data
    - ρ_0 is reference distribution without BEC
    - BEC gives an increase in C(Q) as $Q\rightarrow 0$
  - Take reference distribution ρ_0 from pairs of π^0 from different events
    - Model detector inefficiency, independent of Monte Carlo simulation



- π^0 from photon pairs in barrel ECAL
  - Purity around 70% for 100-170 MeV
  - Combine π^0 to form pairs for BEC analysis – 60% purity for events with exactly 2 π^0 candidates

Bose-Einstein results

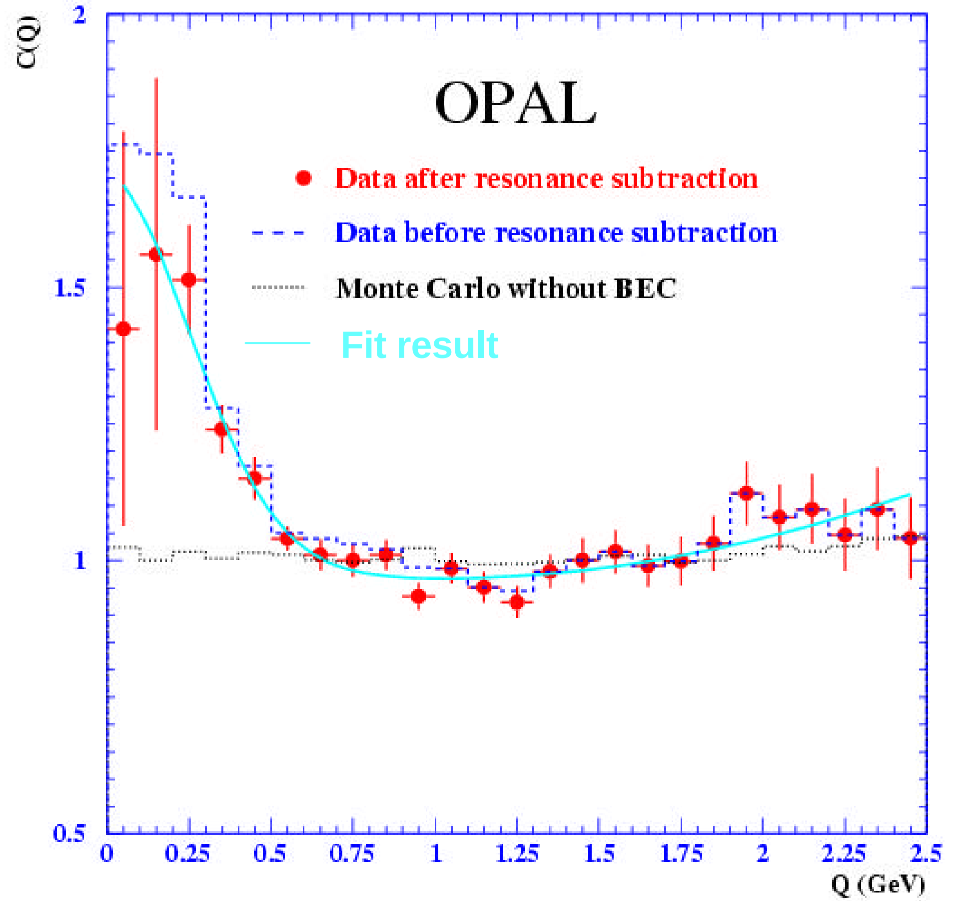
- Correlation function fit:

  $C(Q) = N(1+\lambda\ \exp(-\mathbf{R^2}Q^2))(1+\delta Q+\varepsilon Q^2)$

    - After subtracting resonance background
  - Clear BEC enhancement seen:
    - $\lambda = 0.55 \pm 0.10 \pm 0.10$
    - $\mathbf{R} = 0.59 \pm 0.08 \pm 0.05$ fm
    - Main systematics from changing fit range
  - Note results obtained for back-to-back two-jet events with $p_{\pi 0}>1$ GeV.
- Compare with LEP average for $\pi^{\pm}$

  $R=0.74 \pm 0.01 \pm 0.14$ fm

  … no significant difference
- But note:
  - Pions from **strong decays** dominate
    - BEC exist between strong decay product:
    - Cannot test string/cluster predictions for R

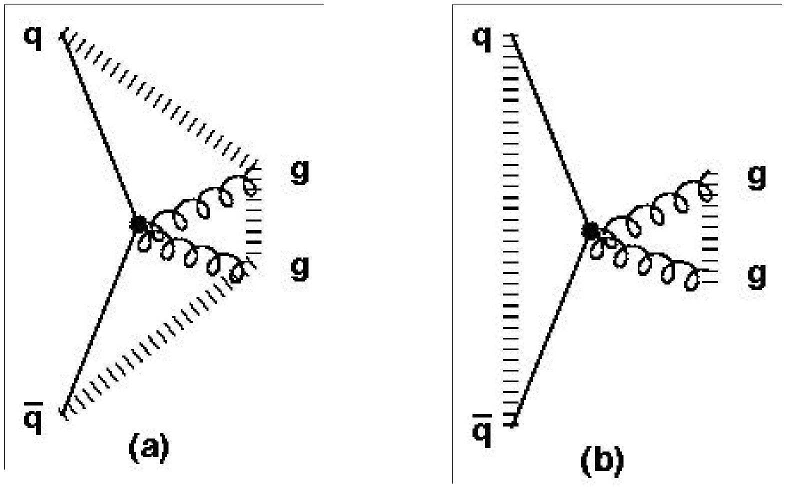


Rapidity gaps and colour reconnection

- Rapidity with respect to an axis:

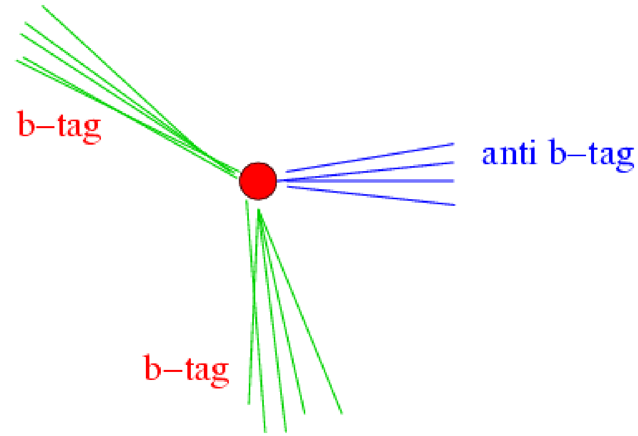
  $y=\frac{1}{2}\ln((E+p_{||})/(E-p_{||})$

  - Rapidity gaps studied in ep and pp
    - Colour singlets, pomerons ?
  - Can also arise from colour reconnection:



  - Disconnected string segment in (b)
    - Gap between the isolated part and the rest of the event

- Look for rapidity gaps in Z→qqg
  - Select 3-jet events with exactly two b-tagged jets:



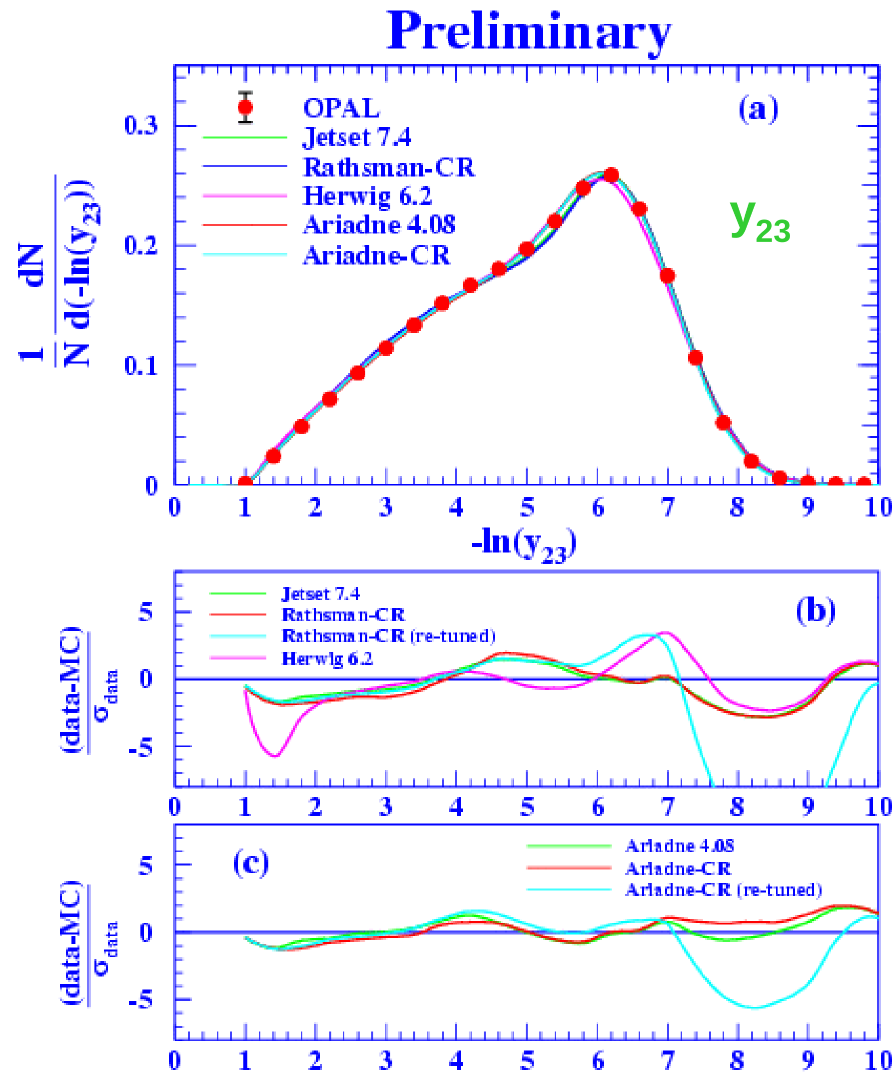
  - Define gluon jet 'scale' κ_{jet}

    $\kappa_{jet}=E_{jet}\sin(\theta_{min}/2)$

    θ_{min} is angle to closest other jet
    - Require κ_{jet} > 8 GeV
  - Select sample of 10k hard isolated jets from 10-35 GeV
    - Gluon jet purity around 94%

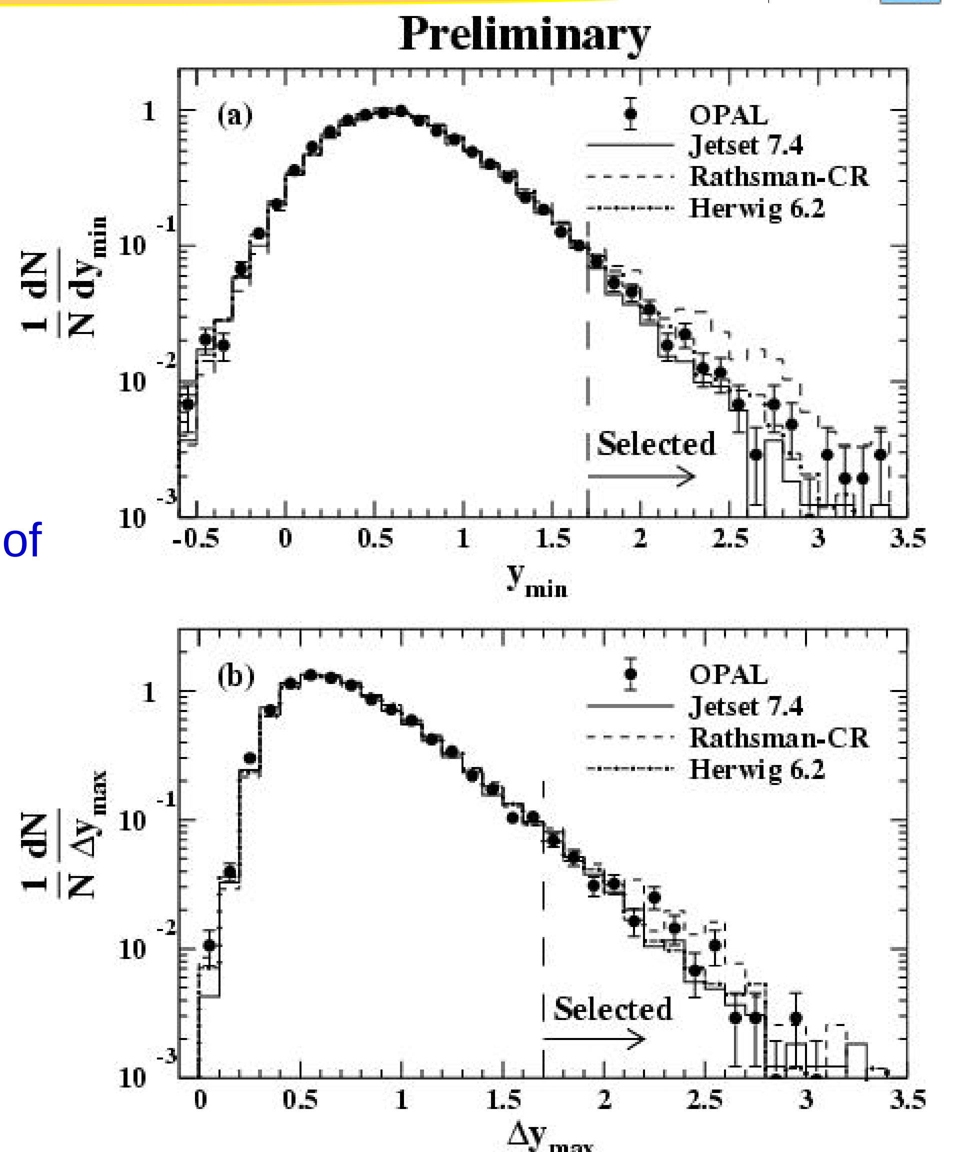
Colour Reconnection Models

- Two CR models considered:
  - Rathsmann-CR (in PYTHIA framework)
    - Adjustable CR-suppression parameter $R_0=0.1$ to describe rapidity gaps in ep and pp data
  - Ariadne-CR model (AR3 in Ariadne)
  - Compare with Jetset, Ariadne, Herwig
- Do these models describe Z^0 data ?
  - Test event shape distributions:
    - Thrust, aplanarity, jet broadening, y_{23}, rapidity, p_{out}
  - Both give reasonable descriptions of Z^0 data – as good as their 'non-CR' counterparts
- Now look at the gluon jets in more detail…

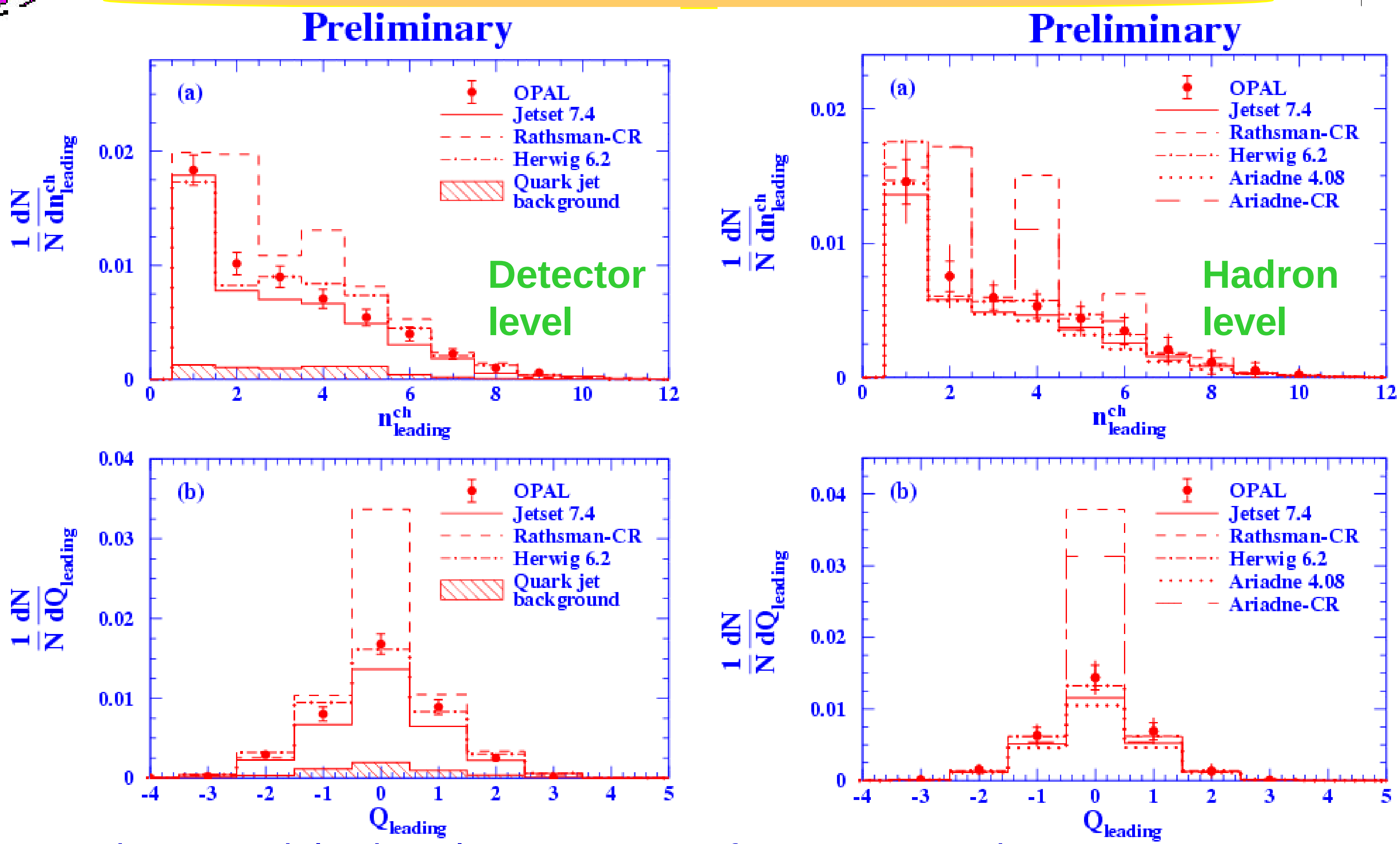


Gluon jet selection

- Select gluon jets with rapidity gap
  - Examine particles assigned to jet
  - Smallest y satisfies $y_{min}>1.7$
    - ⇒ 391 events
  - Or largest difference $\Delta y_{max}>1.7$
    - ⇒ 90 more events
- Jetset/Herwig (no CR) describe data
  - Rathsmann-CR model predicts excess of events with rapidity gap…
  - Similar result for Ariadne-CR model
- Going further – structure of jets:
  - Isolated gluon system should be electrically neutral
    - Look at charged multiplicity n_{ch} and charge Q of 'leading' part of jet beyond rapidity gap



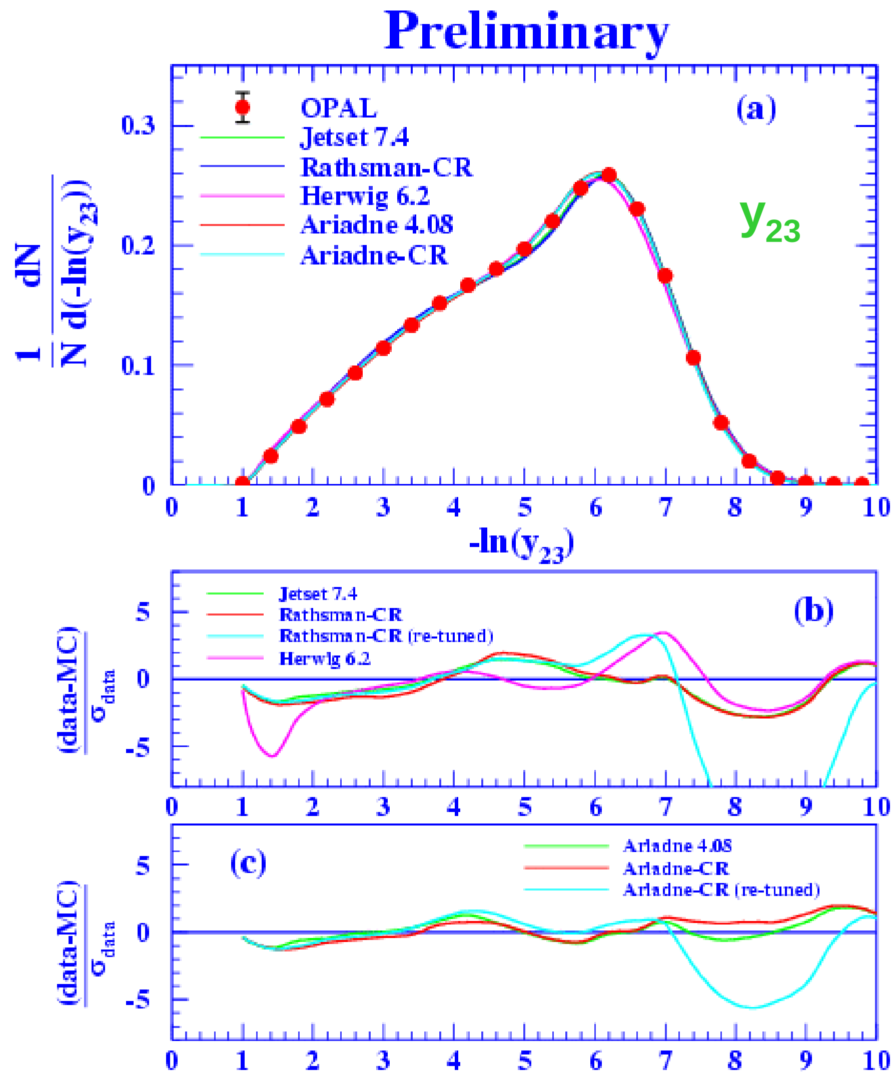
Properties beyond the rapidity gap



- Both CR models show large excesses for even n_{ch} and Q=0
  - The data clearly do not support this – these models are disfavoured

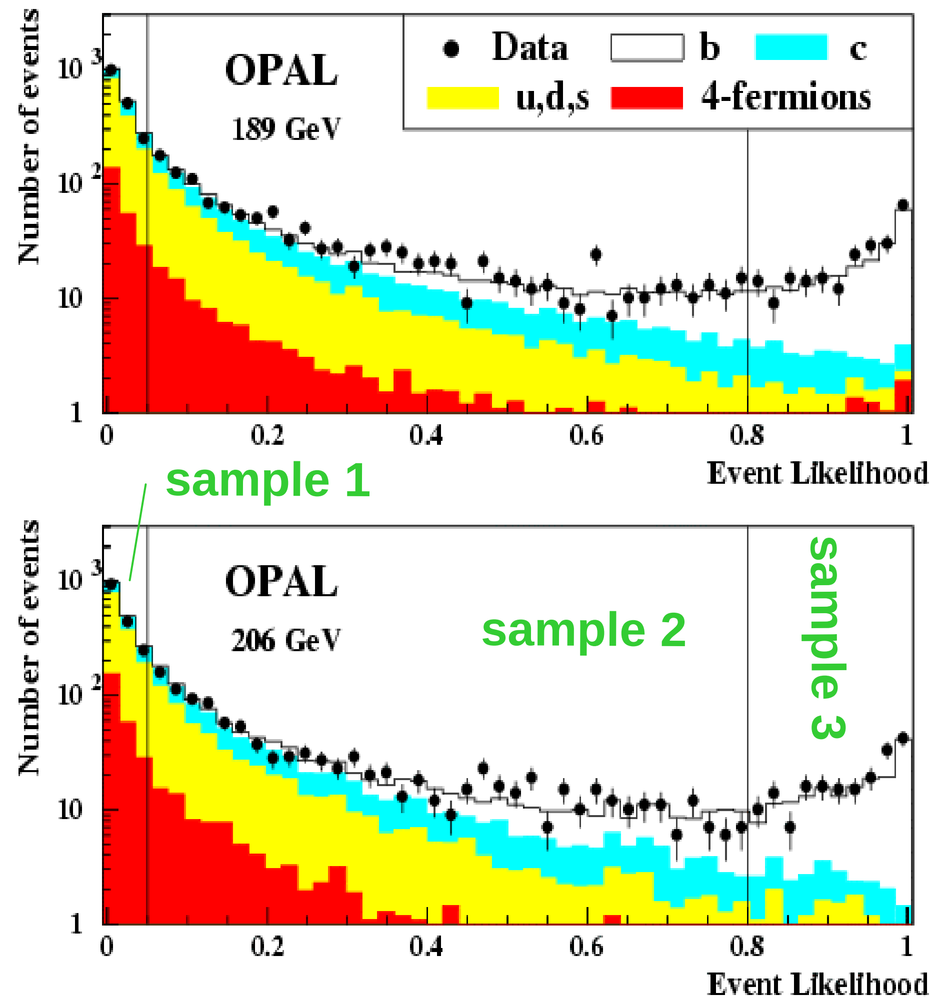
Can the models be saved by retuning ?

- Can we adjust parameters to:
  - Describe selected gluon jets
    - Remove Q=0 discrepancy
  - Maintain Z^0 data description
- Rathsmann-CR model:
  - Raise parton shower cutoff Q_0 to 3.5 GeV, reduce Lund b for $<n_{ch}>$
    - Poor Z^0 χ^2 : 2000→5000
  - Raise Λ_{QCD} to 1.4 GeV
    - Impossible to describe $<n_{ch}>$
- Ariadne-CR model:
  - Change $p_{T,min}$ and b for $<n_{ch}>$
    - Again, poor χ^2: 900→1900
- Both CR models are disfavoured…
  - Cannot describe all event properties
  - Does this help for CR in W events?

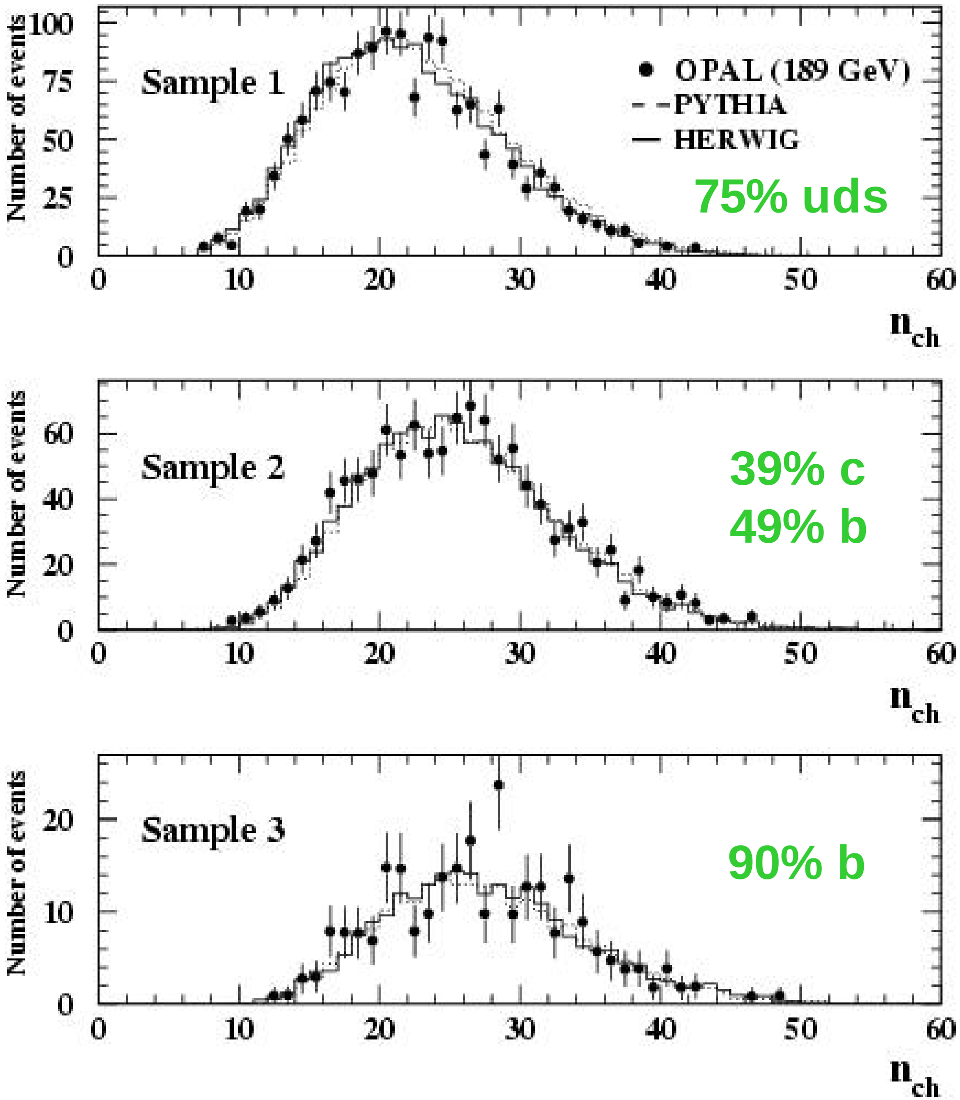


QCD studies at high energy

- Large energy range covered at LEP2:
  - Explore a basic QCD prediction:
  - Multiplicity difference between heavy and light flavour events ($\delta_{bl}=\langle n\rangle_b-\langle n\rangle_{uds}$) is **independent** of $\sqrt{s}$
    - Naïve model predicts δ_{bl} **decreases** with increasing $\sqrt{s}$
- Select non-radiative qq events and measure multiplicity
  - Use flavour tagging to isolate samples enriched in uds and b events.
  - Unfold multiplicities for pure samples of each flavour:
    - $\langle n\rangle_1 = f_1^b\langle n\rangle_b + f_1^c\langle n\rangle_c + f_1^{uds}\langle n\rangle_{uds}$
    - $\langle n\rangle_2 = f_2^b\langle n\rangle_b + f_2^c\langle n\rangle_c + f_2^{uds}\langle n\rangle_{uds}$
    - $\langle n\rangle_3 = f_3^b\langle n\rangle_b + f_3^c\langle n\rangle_c + f_3^{uds}\langle n\rangle_{uds}$



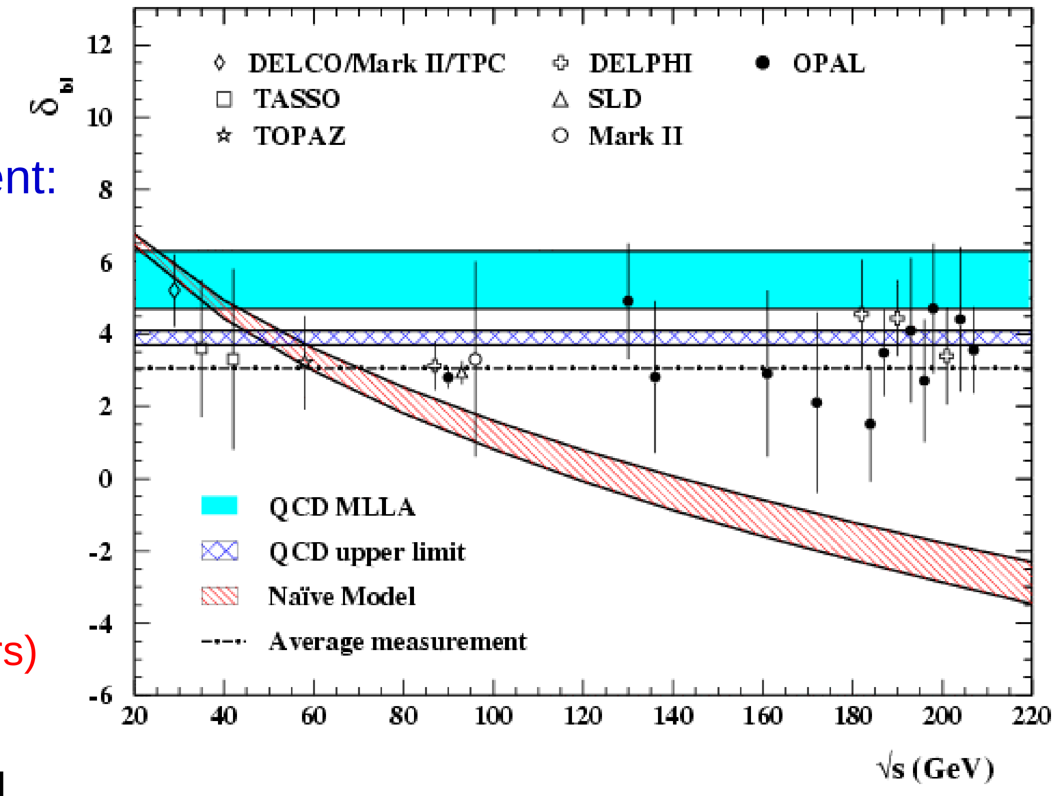
Multiplicity in heavy and light events



- Multiplicities $<n_i>$ in each sample:
  - Correct for biases introduced by flavour tagging procedure.
  - Correct for backgrounds (4f and radiative $qq\gamma$ events)
- Sample composition $f_i^{b,c,uds}$:
  - Evaluated from simulation
- Simulation gives a good description of OPAL data...
  - Systematics dominated by
    - Detector simulation (b-tagging)
    - Model dependence of corrections (PYTHIA vs HERWIG)

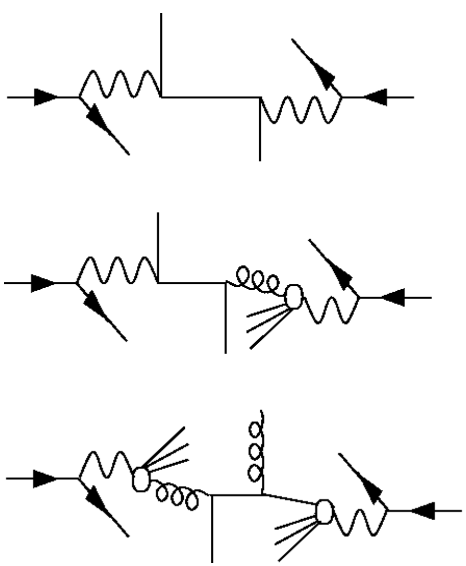
d_{bl} is independent of energy

- OPAL results show no dependence on energy $\sqrt{s}$.
  - Average over 130-208 GeV:
    - $d_{bl} = 3.44 \pm 0.40$ (stat) ± 0.89 (syst)
  - Compare with OPAL Z^0 measurement:
    - $d_{bl} = 2.79 \pm 0.30$
  - Average of all experimental results:
    - $d_{bl} = 3.05 \pm 0.19$
- Comparison with theory predictions:
  - Naïve model clearly ruled out
  - MLLA calculation:
    - $d_{bl} = 5.5 \pm 0.8$ (exp) ± 1.0 (higher orders)
  - Other QCD upper limits: 3.7-4.1
- A challenge to theory to determine d_{bl} more precisely…



Two-photon physics: di-jet production

- Study of di-jet production in two-photon collisions
  - Full LEP2 dataset (189-209 GeV)
    - (earlier studies at 172-183 GeV)
  - Look at inclusive jet cross-sections as a function of E_t^{jet}, η^{jet} and $|\Delta\eta^{jet}|$
  - Contributions from different processes:



direct

single resolved

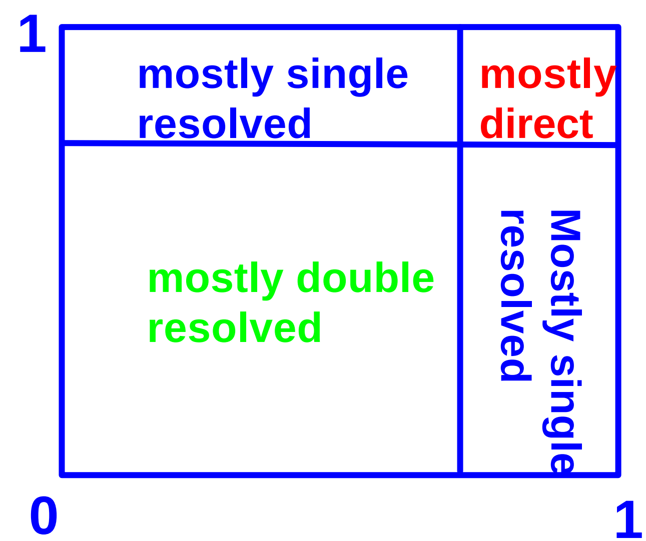
double resolved

- Want to separate the contributions:

$$x_\gamma^\pm = \Sigma_{jets}(E^{jet} \pm p_z^{jet}) / \Sigma_{hfs}(E^i \pm p_z^i)$$

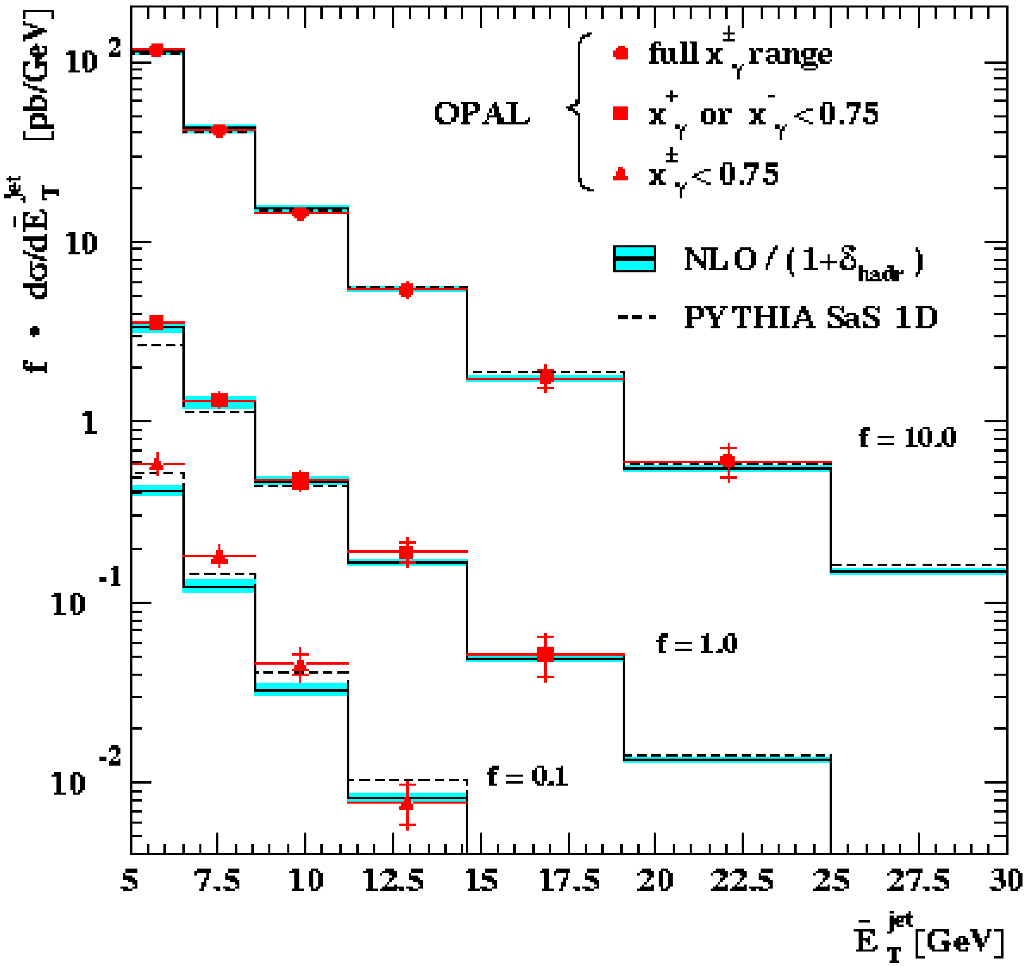
Sums over jets and hadrons in final state

  - x_γ estimates the fraction of the photon's momentum entering the hard scattering
  - Different regions in the (x_γ^+, x_γ^-) plane populated by different processes:



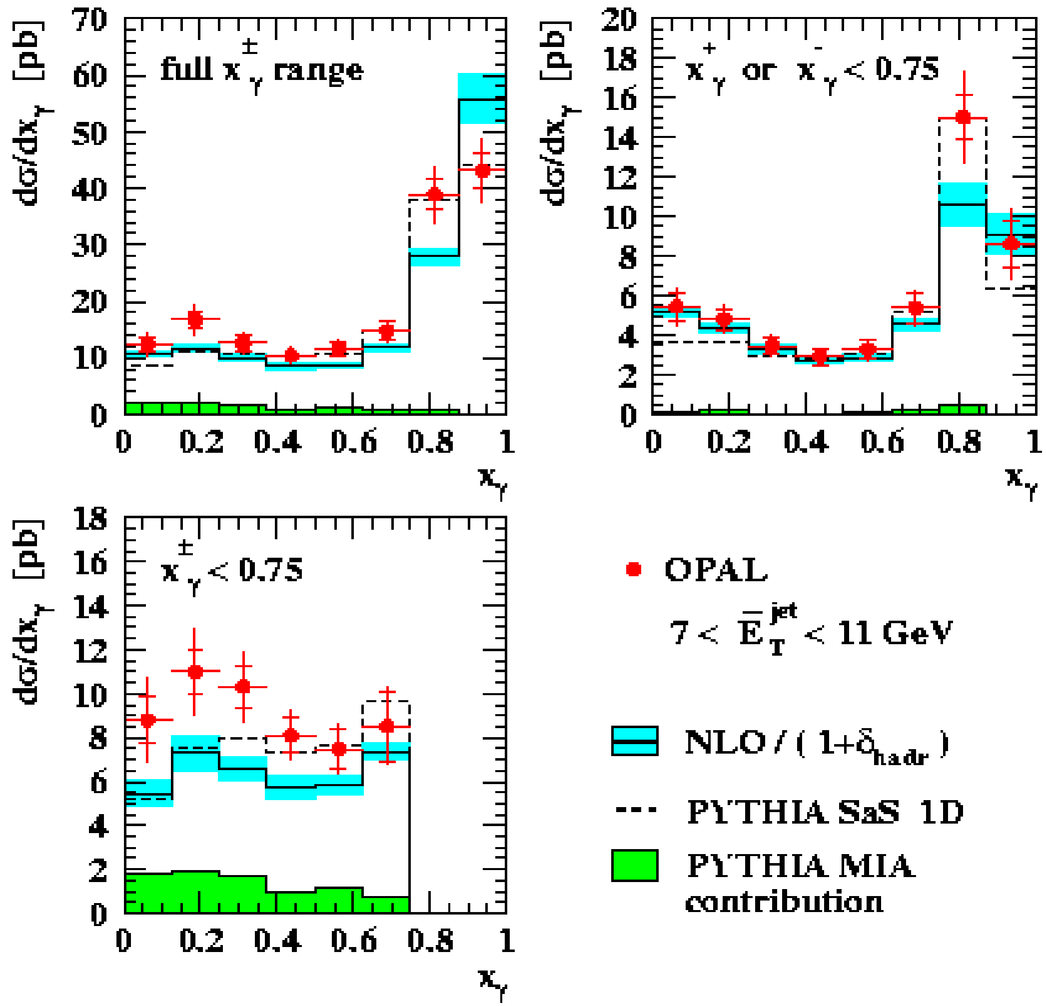
Inclusive di-jet cross-section

- Cross-section for different x_γ regions
  - Compare to NLO calculation (Klasen et al.) and to PYTHIA+SaS1D
    - Hadronisation corrections for NLO evaluated using PYTHIA & HERWIG
  - In full x_γ range, good agreement
    - Dominated by direct processes for high E_t^{jet} values.
  - Similar good agreement for one x_γ smaller than 0.75 (single resolved)
    - Conditions unique to LEP
  - Problems for both x_γ<0.75
    - Predictions are somewhat below the data…
    - In this region, multiple parton interactions (MIA) become important
    - Can we study them in more detail ?



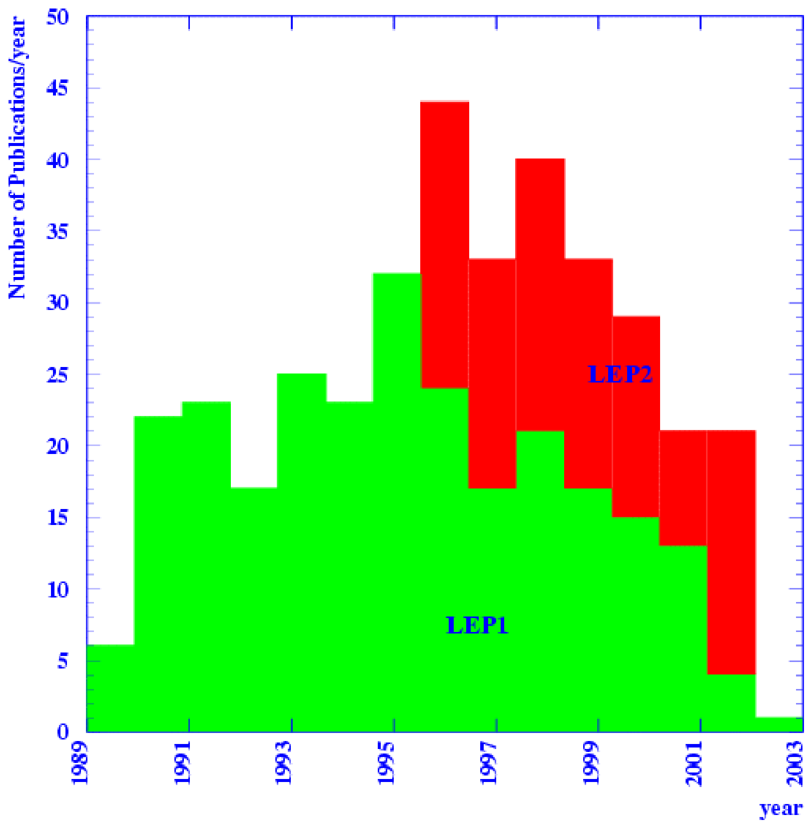
Separating the different contributions

- Look at cross-sections vs x_γ for restricted E_t^{jet}: $7<E_t^{jet}<11$ GeV
  - Fair agreement for full $x^{\pm}_\gamma$ range
    - Large hadronisation uncertainties for direct events, which have x_γ=1 at parton level, smeared out
  - Nice agreement for single resolved
    - LEP is unique in having 'clean' access to this region
    - NLO able to describe hadronic content of photon
  - Problems for both x_γ<0.75
    - NLO calculation and PYTHIA both underestimate cross-section
    - Note: PYTHIA MIA contribution is ~same size as part missing from NLO calculation …
  - Some sensitivity to gluon density



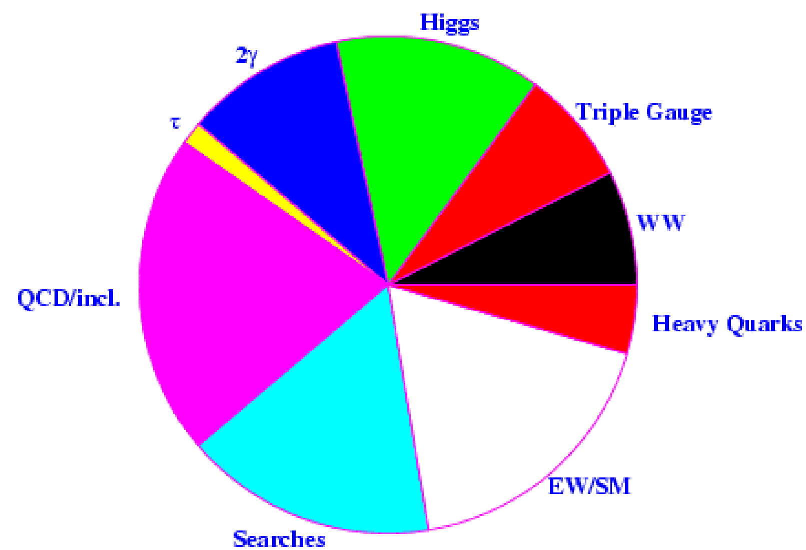
OPAL is still very active

- 21 OPAL papers published in 2002:



  - Similar to 2001 – still plenty of new results being finalised

- And there is more to come…
  - 67 ongoing analysis activties, most expected to lead to papers



  - OPAL has 37 PhD + 5 diploma students
    - Some new analysis topics, e.g. QCD studies & searches inspired by new theoretical developments

Long term analysis strategy – ‘archiving’

- Efforts to ensure long term viability of OPAL analysis:
  - Last year migrated OPAL analysis work from shift-SGI to Linux PC (lxbatch)
  - Monte Carlo production also on lxbatch (large productions continue)
  - Migrated data access to Castor (LHC-era solution) via Fatmen
    - Massive tape copying from obselete media; will be phasing out TMS
  - Validation suite used for checking SGI/HP $\rightarrow$ Linux migration
    - Now being used for Redhat 6 $\rightarrow$ Redhat 7 migration
  - Improving user-level documentation
- Comments on ‘archiving’:
  - OPAL analysis will continue at a ‘high’ level for ~2 more years
    - Then a lower (but not zero) level anticipated – responses to new ideas, e.g. from LHC
  - Maintain existing analysis software framework
    - Needs Fortran, (frozen) PAW/HBook, Castor for data/MC access, Cernlib
    - Maintain capability to produce Monte Carlo, but not to reprocess data
  - No ‘simplified’ or C^{++} analysis framework foreseen
    - Continue to use the existing tools and expertise within OPAL

Conclusions and outlook

- OPAL continues to produce many interesting new results
  - Shown results from electroweak / τ, final state interaction studies, b-physics, QCD and two-photons.
- Lots more to come, including …
  - Searches: finalisation of many results, comprehensive interpretations in various models.
  - Higgs: MSSM, exotic Higgs, CP-violating…
  - Electroweak: Final LEP1 A_{FB}^{b} and A_{FB}^{c} with leptons coming soon, two and four fermions at LEP2.
  - WW & ZZ: Final results on cross sections, W mass, WW FSI, gauge couplings
  - QCD and two-photon – many ongoing analyses, Photon 2003 in April
- OPAL is still very active and productive
  - Healthy collaboration with students, postdocs and senior physicists
  - Many new results to come this summer and beyond …