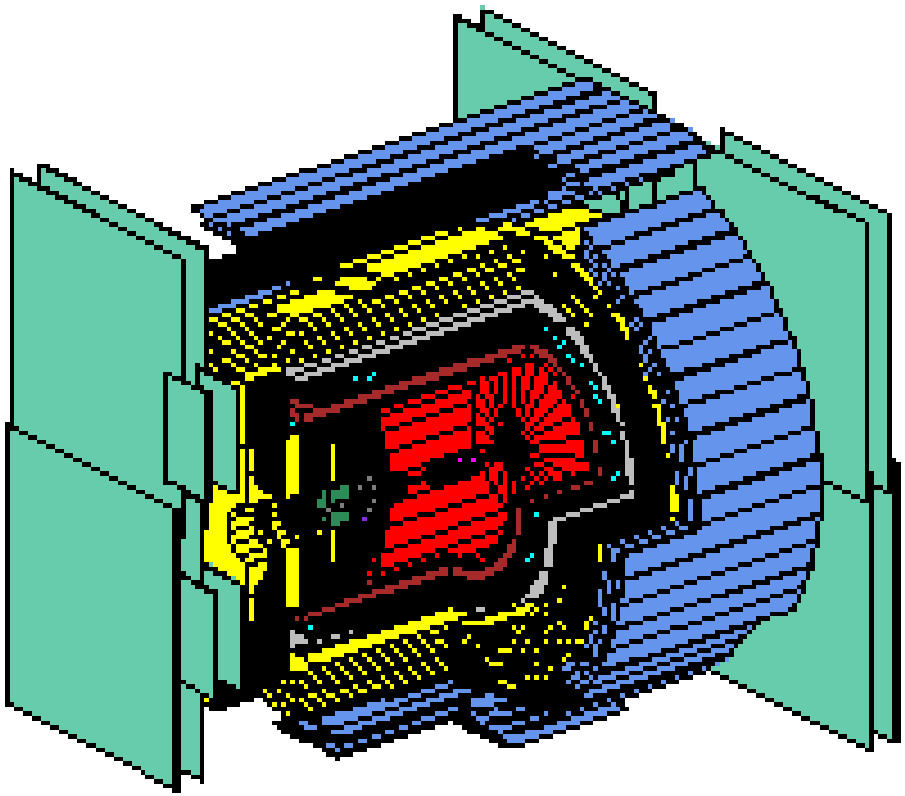
OPAL physics highlights

Richard Hawkings

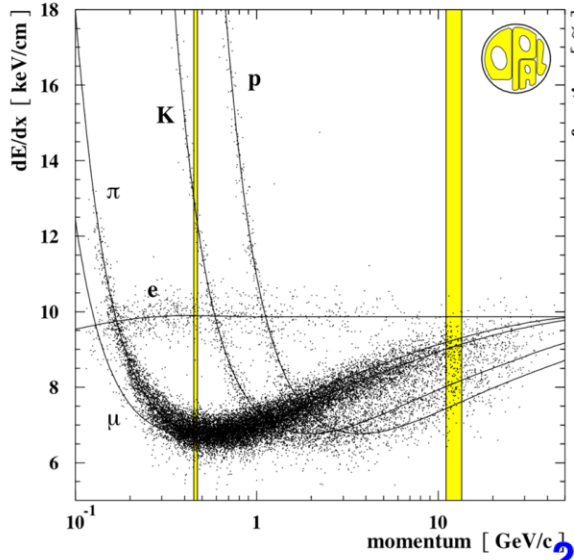
OPAL 10-year reunion, 21/10/2010

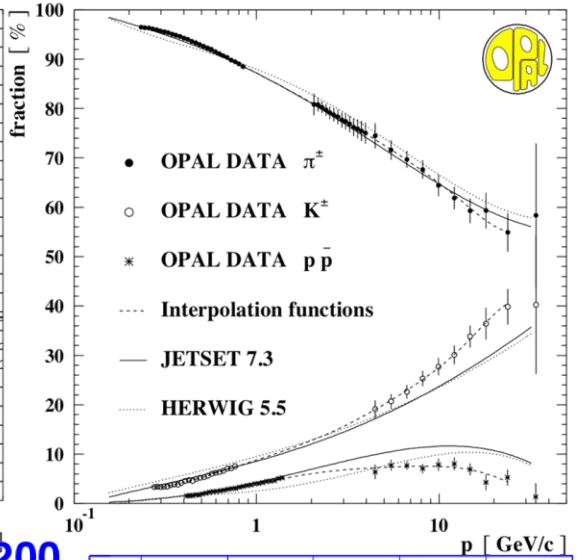


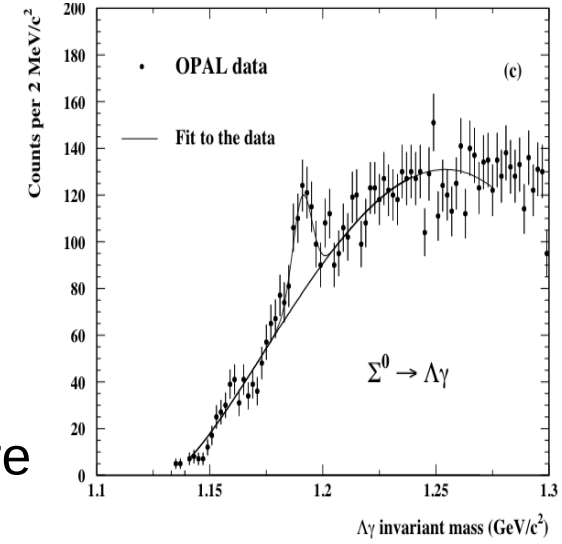
- A challenge – OPAL physics in 20’
  - 430 papers = 2.8 sec/paper
- Instead focus on some personally-selected ‘highlights’:
  - ‘The twelve highlights of OPAL’ – a pre-Christmas carol
    - Hopefully triggers some memories
    - Certainly not complete
  - Will not mention zedometry or Higgs – covered elsewhere
- Music …♭♩♫♪

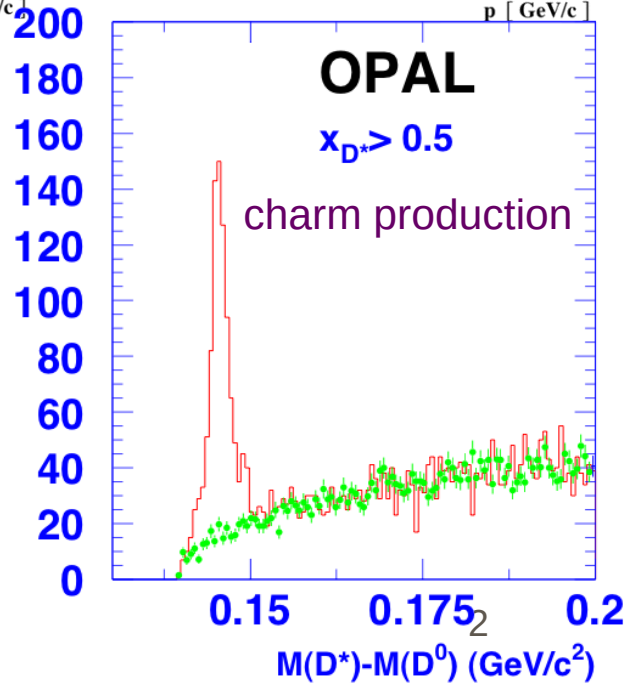
One to begin - particle production

- Basic properties in had. Z decay
  - Charged particle production using the jet chamber dE/dx
    - Pions, kaons and protons – fragmentation fns vs MC prediction
- More exotic states
  - Sigma baryons: $\Sigma^+ \to p\pi^0$; $\Sigma^- \to n\pi^-$; $\Sigma^0 \to \Lambda\gamma$ all different modes!
    - Latter with converted photons
- Charm and bottom mesons
  - $D^{*+} \to D^0\pi^+$; $D^0 \to K^-\pi^+$
  - Separate b, c and $g \to cc$ contributions using lifetime, event shape and lepton information
- Important for tuning MC models
- 2-particle correlations: BEC & more
  - With many species of particle



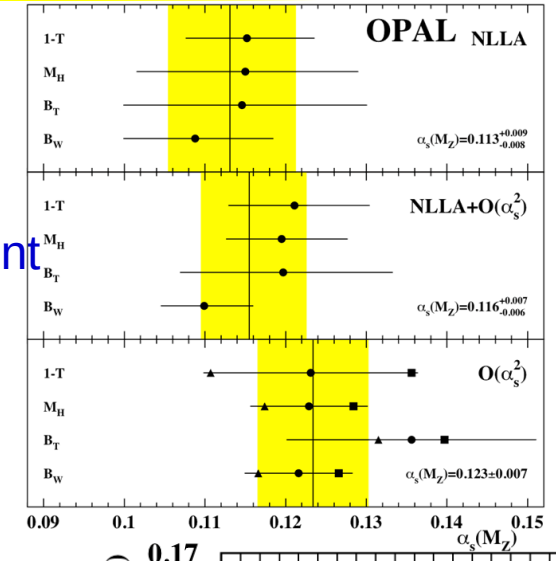


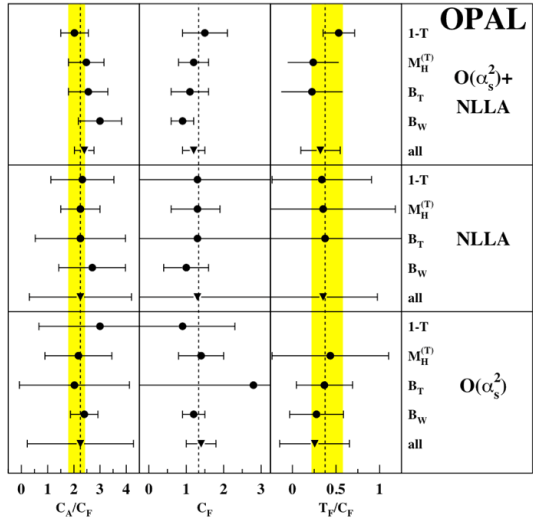


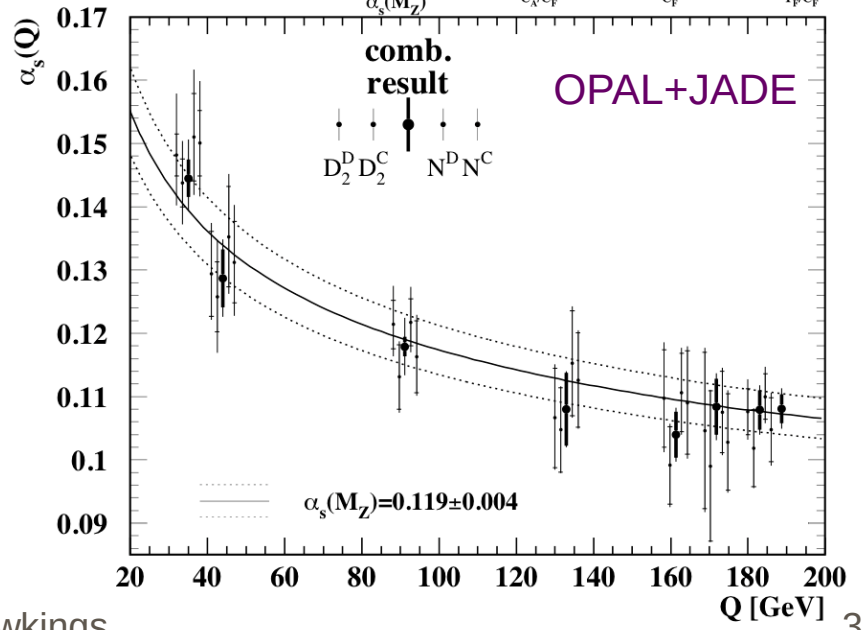


QCD measurements - two related experiments

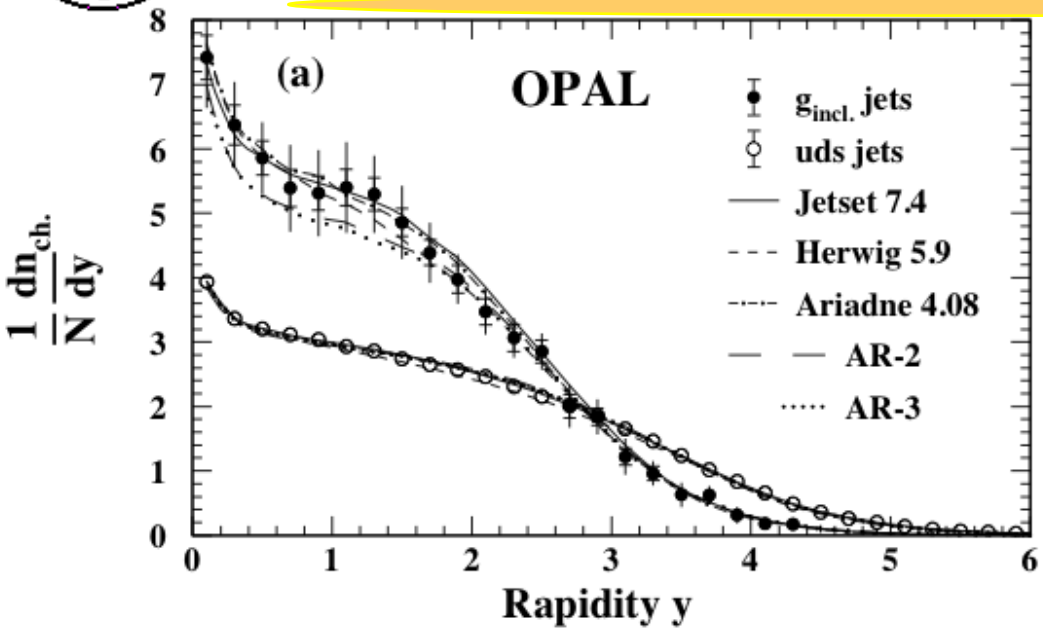
- Decay of Z→qq is a QCD laboratory
  - Very clean initial state, production of different flavours (some taggable)
  - Measurements of α_s with jet rates, event shape observables, etc
    - Here thrust, jet mass & broadening
  - Measurements of colour factors
  - Repeated for flavour tagged samples, and at various LEP2 energies
    - Interplay between improved theoretical and experimental techniques …
- Reanalysis of JADE data with OPAL
  - Cover E_{CM}-range of 35-189 GeV
  - Take advantage of theoretical developments since JADE
    - And some computer archaeology
  - α_s from jet fractions and differential dists

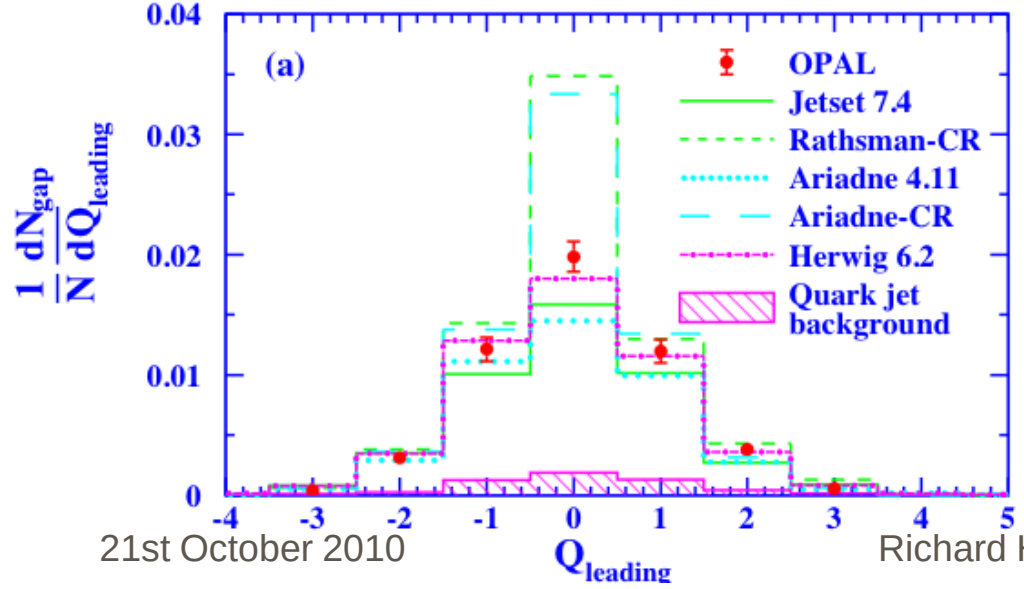






Three well-spaced jets: Quarks, gluons and colour reconnection

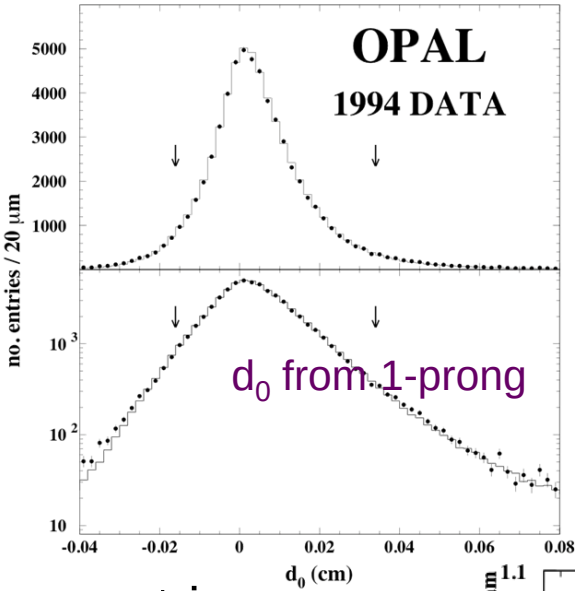


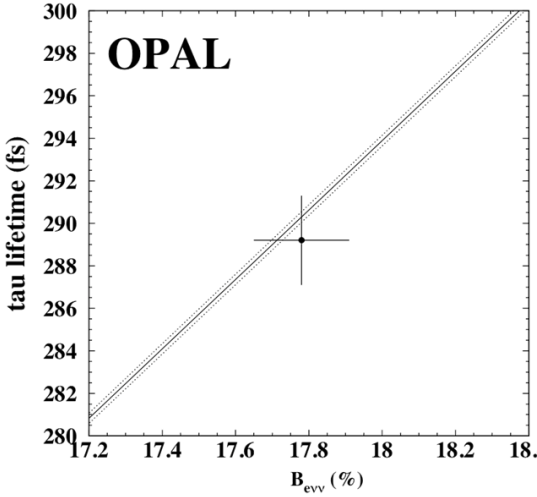


- Studies of quark vs. gluon jets
  - Use events with 3 widely-separated jets, 2 are b-tagged (hence q-tag)
    - Opposite hemisphere is a clean gluon jet – effectively a point source
    - Compare properties with uds jets
  - QCD predictions for particle multiplicity ratio of ~2 (from C_A/C_F)
- Also sensitive to colour recon (AR3)
- Studies extended to look for rapidity gaps in gluon jets
  - Signature of colour reconnection
  - Also look at charge of leading part of gluon jet – expect 0-charge excess
  - Disfavour some colour recon models, and search for glueballs
    - Production favoured in gluon-rich environment ?

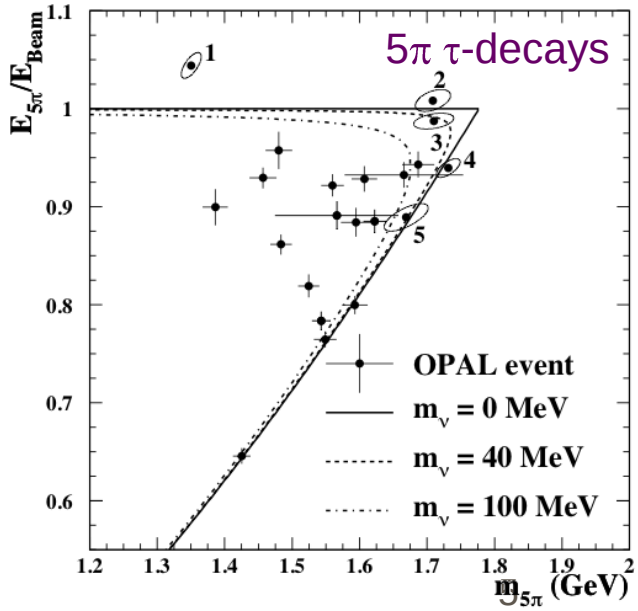
Tau physics (four = 1 + 3 prongs)

- LEP1 produced O(100k) $Z \rightarrow \tau^+\tau^-$
  - Rich τ-physics program – 2 examples
- τ-lifetime measured to ~0.7%
  - 1-prong decay: impact parameter
  - 3-prong decay: secondary vertex
    - Reconstruction of beamspot crucial
  - τ-lifetime and $\tau \rightarrow e$ BR together allow test of lepton universality wrt μ





- τ-decays also allow setting a limit on τ-neutrino mass
  - Look for decays into 3 or 5 charged hadrons (π)
  - Study energy and invariant mass of nπ system
    - Also technique based on missing mass
  - Combined limit of $m_{\nu\tau}$<27.6 MeV @ 95% CL
    - Unfortunately ALEPH got a lucky event (18 MeV)
  - Also many measurements of tau branching ratios, and studies of QCD in hadronic tau decays

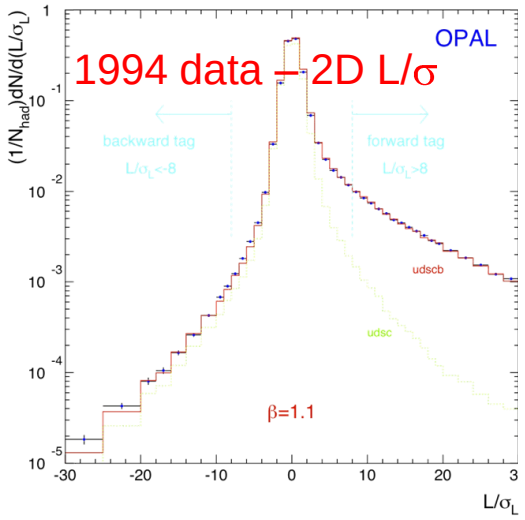


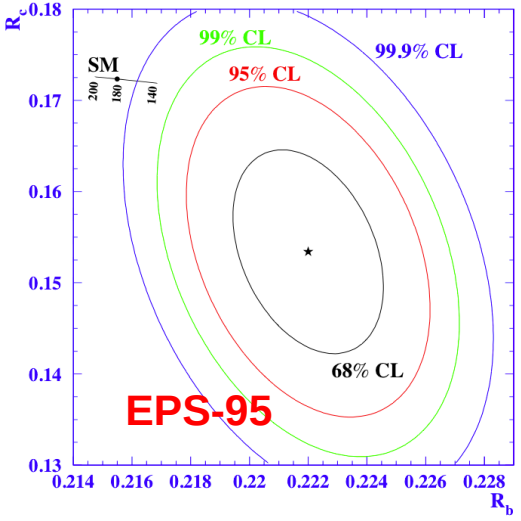
The fifth flavour - measurement of R_b

- Tagging b-decays with leptons and displaced vertices – R_b

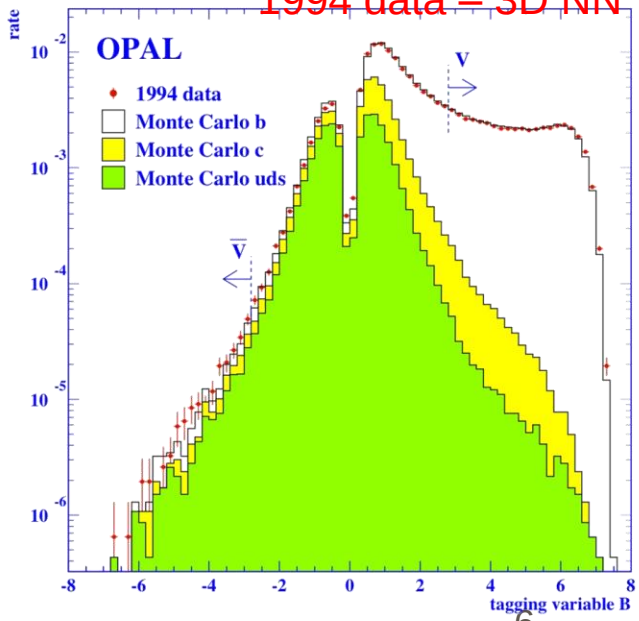
$$R_b \equiv \frac{\Gamma(Z^0 \to b\bar{b})}{\Gamma(Z^0 \to \text{hadrons})}$$

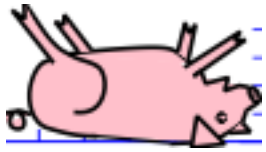
- Initial results higher than SM
  - EPS-95 Brussels – the 'flying pig'
  - R_b=0.2219±0.0017 c.f. 0.2155 SM
    - Some interplay between R_b and R_c
- A long road to resolve this 'R_b-crisis'
  - Improved tagging: 3D vertex, alignment, NN tag
  - Understanding of tag correlations (ALEPH pvtx)
  - Multitag measurements with charm
  - Measurement of g→bb
  - Systematics and more systematics…
- Finally, Rb=0.2163±0.0007 from LEP combined





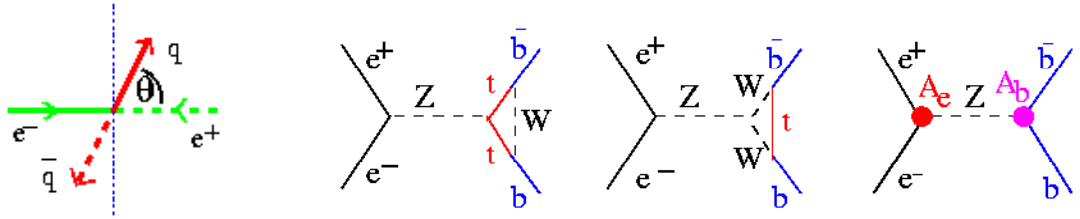
1994 data – 3D NN



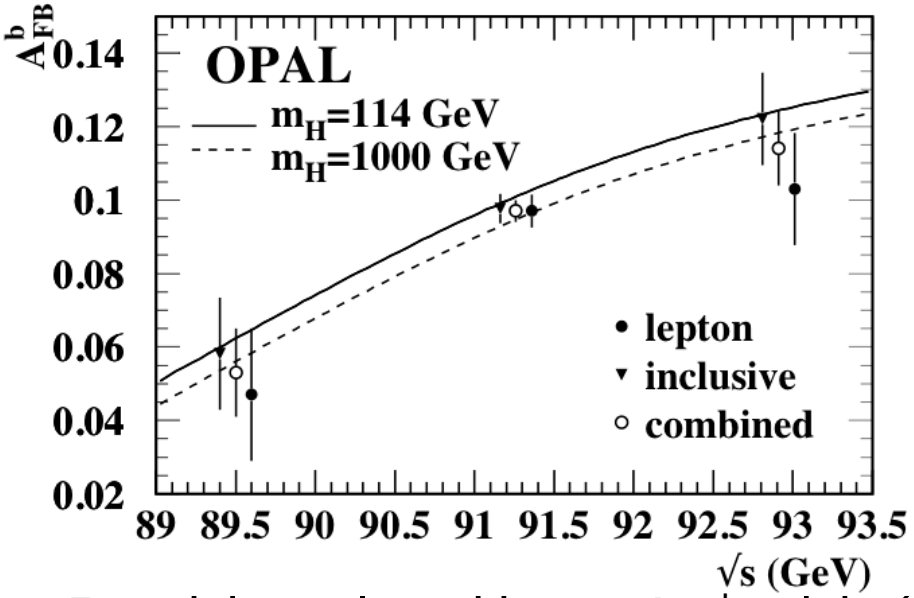


Five alive – an inconvenient asymmetric legacy

- Vertex/NN techniques used to measure A_{FB}^{b}

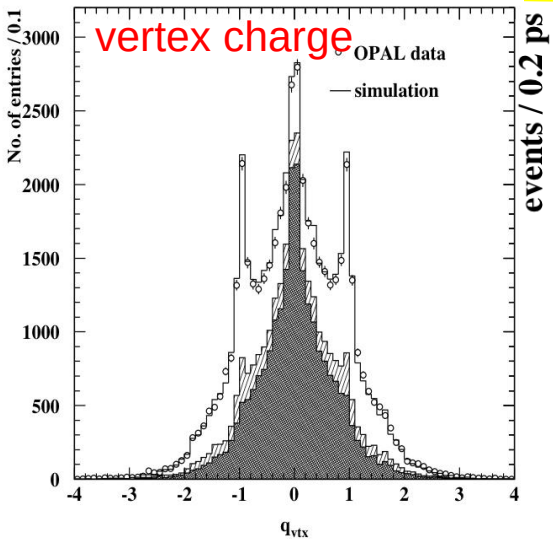


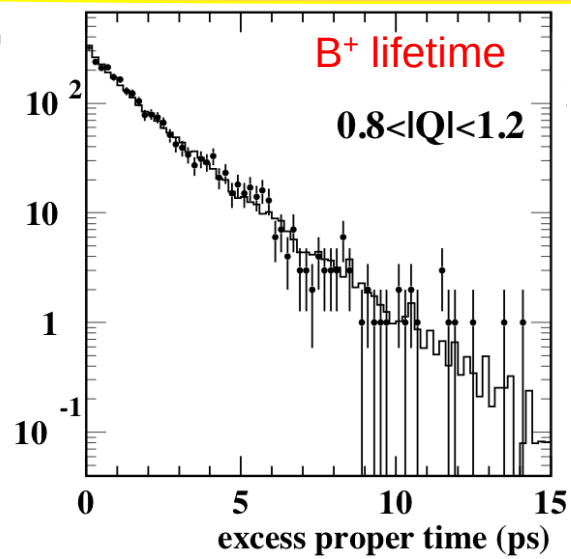
  - Separate b/bbar with jet/vertex charge
  - Also measure b/c asymmetries with leptons/D*

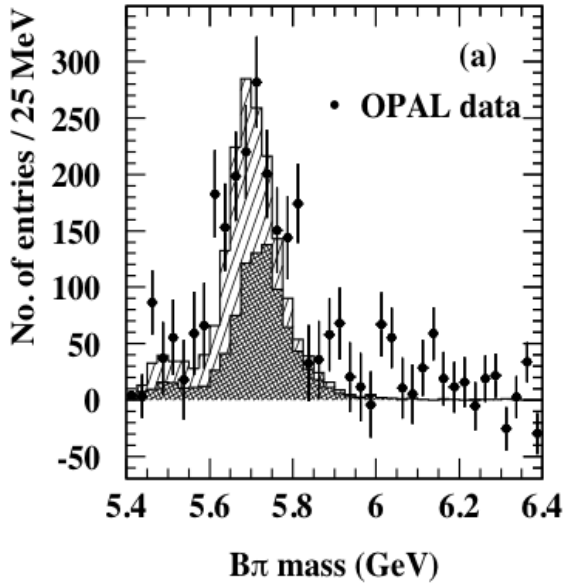


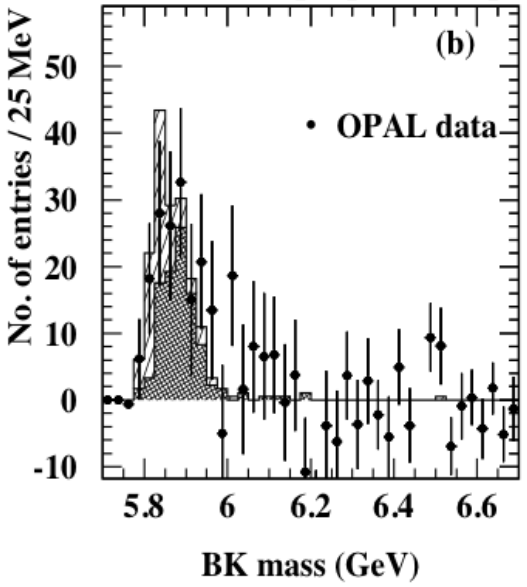
- R_b-crisis replaced by an A_{FB}^{b} crisis (tension with A_{LR} from SLD)
  - This will remain unresolved for a long time (until a Giga-Z factory?)

Many fives - Inclusive b-hadrons





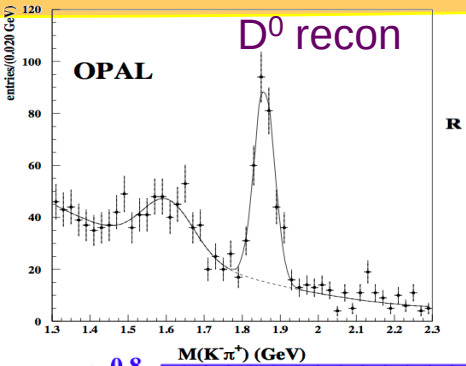


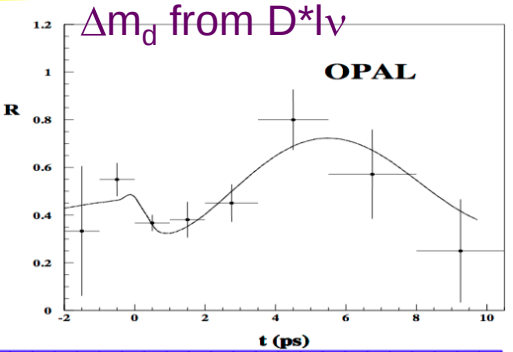


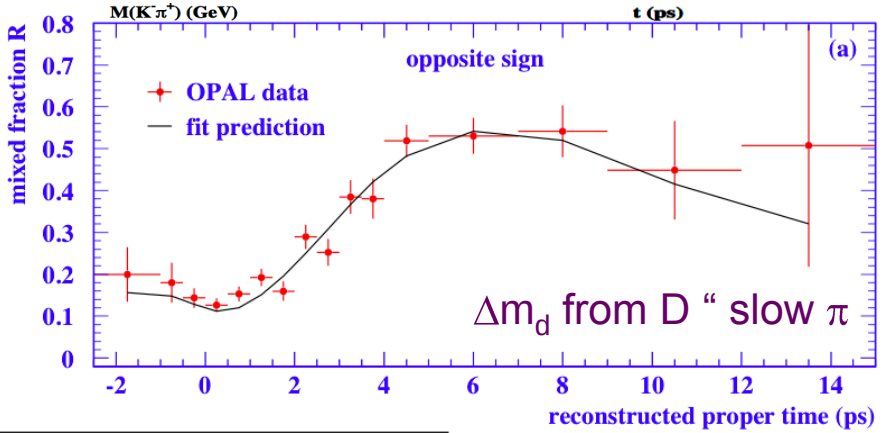
- Vertexing techniques also allows inclusive B-hadron reconstruction
  - Separate charged and neutral b-hadrons using charge of sec vtx
  - Precise measurement of B^+/B^0 lifetimes and CP-violation tests
- Study of pions produced with B
  - Charge correlations between B and pions from fragmentation
    - Basis of B0/B0bar tagging method later used at hadron colliders for oscillations/CP
  - Evidence for resonant Bπ and BK production
    - First observation of orbitally excited B** mesons

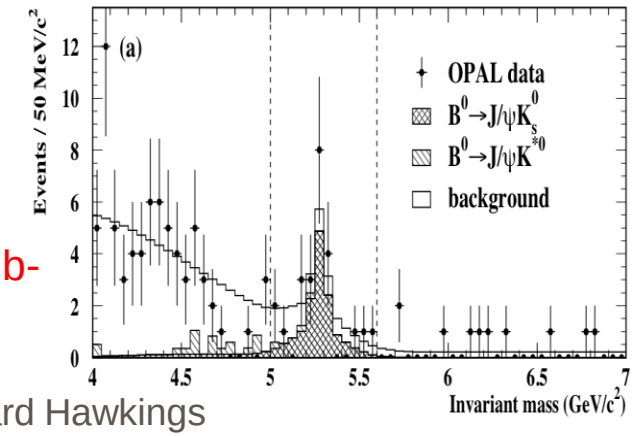
Enter the sixth flavour: B-oscillations and CP violation

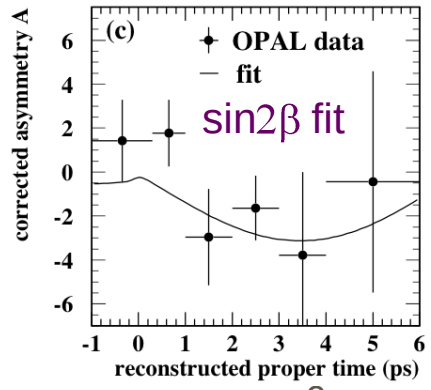
- Many measurements of B^0 oscillations
  - $B^0 \to D^* l\nu$, $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$
  - Higher statistics from inclusive slow π
    - B^0 production flavour from opposite side lepton, jet charge, vertex charge,…
  - Inclusive single and dilepton analyses also sensitive to Δm_s
    - Heroic efforts to push limits to $\Delta m_s > 5\ ps^{-1}$
    - Time resolution not enough – mesaurement had to wait for Tevatron
- Same machinery cheekily recycled …
  - First investigation of CP-violation in decay $B^0 \to J/\psi K_s$
  - Sample of 24 candidates, 60% pure
  - Result of $\sin 2\beta = 3.2 \pm 2.0$
    - Later confirmed by CDF, ALEPH and b-factories (~0.7) – the sign was right!











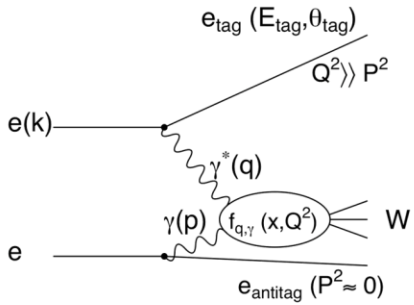
Seven swans (?) a-swimming

- Interlude - The OPAL duck-pond

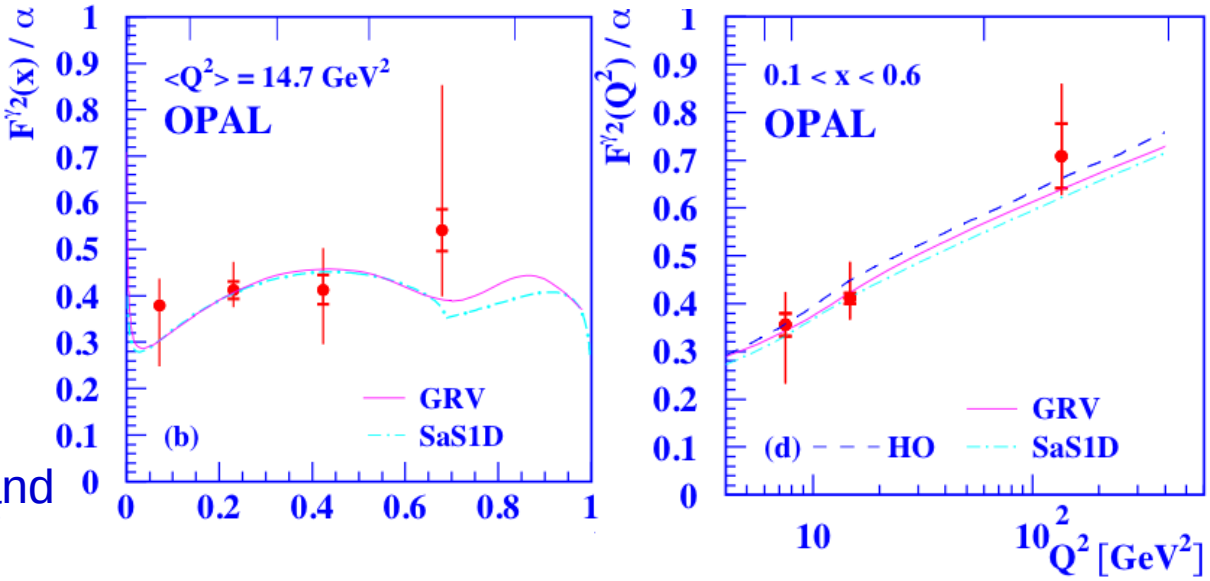
- I cannot find a way to link ‘seven’ with two-photon physics…

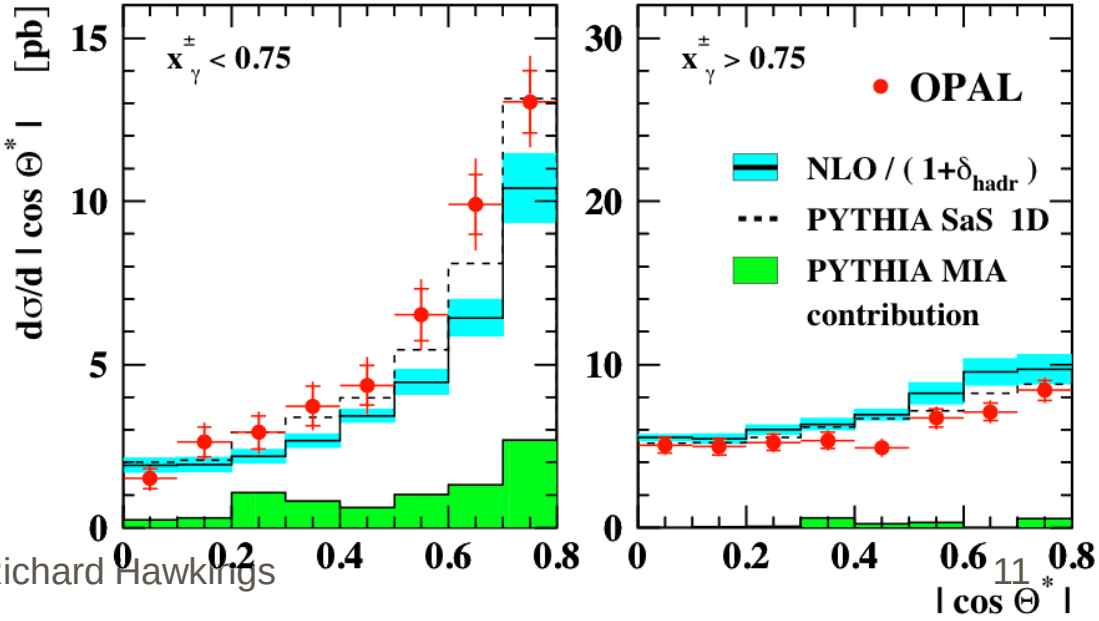
Seventh heaven? 2-photon physics at LEP1 & 2

- Structure function $F_2^\gamma(x,Q^2)$



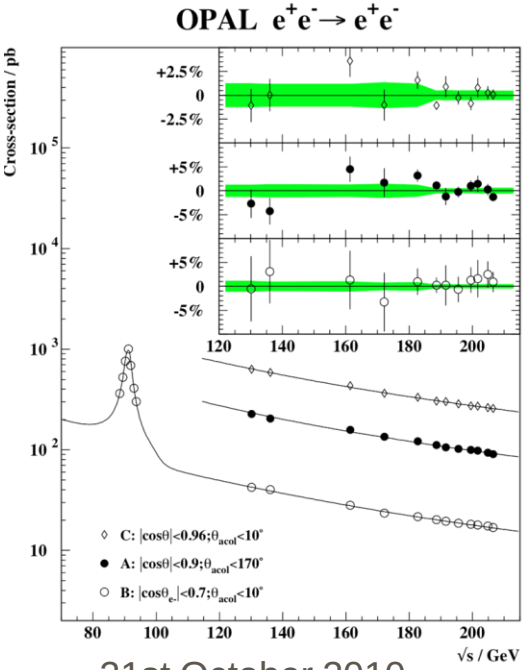
- LEP gives large range of Q^2
  - Can test evolution of F_2^γ vs. Q^2 and modeling of hadronic final state
- Dijets in untagged $\gamma\gamma$ events
  - Mix of direct (x_γ>0.75) & resolved (x_γ<0.75) photon interactions
    - Latter has large contribution from gluon initiated jets (peaked cosθ*)
  - Dataset with only one resolved photon sensitive to hadronic structure of photon, free from MPI
    - Complementary to HERA studies

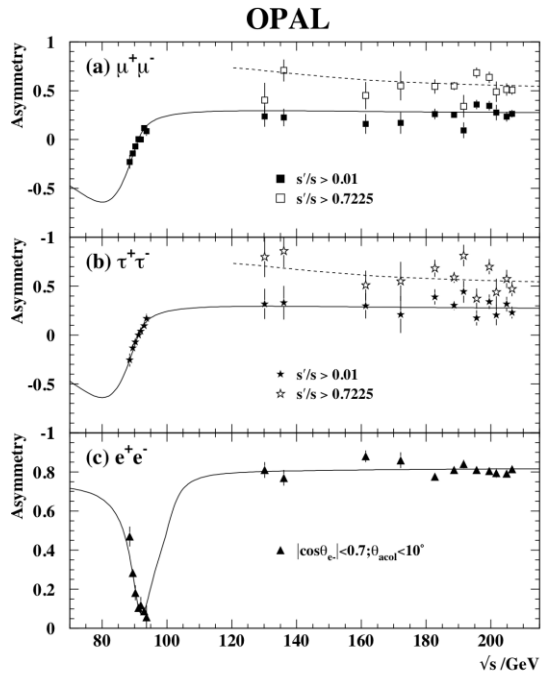


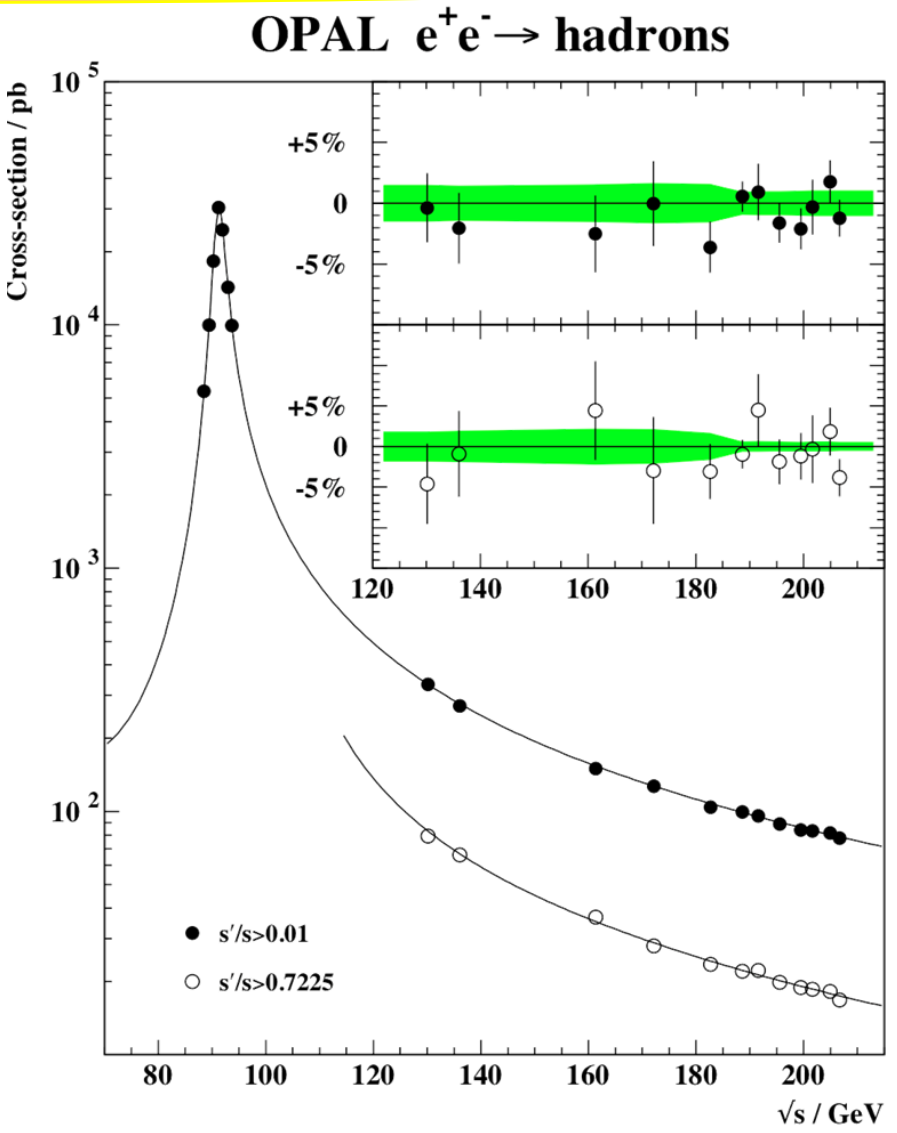


2-fermions at LEP2 – eight new observables

- Repeat of ‘zedometry’ at higher energies
  - Measurements of cross-sections and asymmetries for qq / ee / μμ / ττ
  - New feature of ‘radiative return’ to Z pole
    - Hard ISR photon, remainder is like Z
  - Non-radiative events (large s’/s) have increased photon contribution

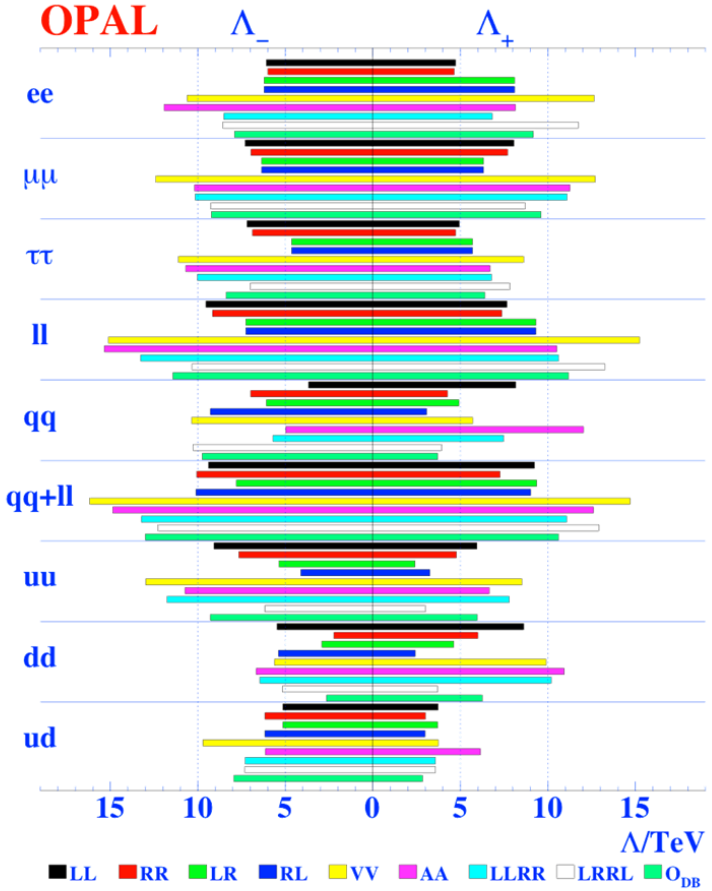


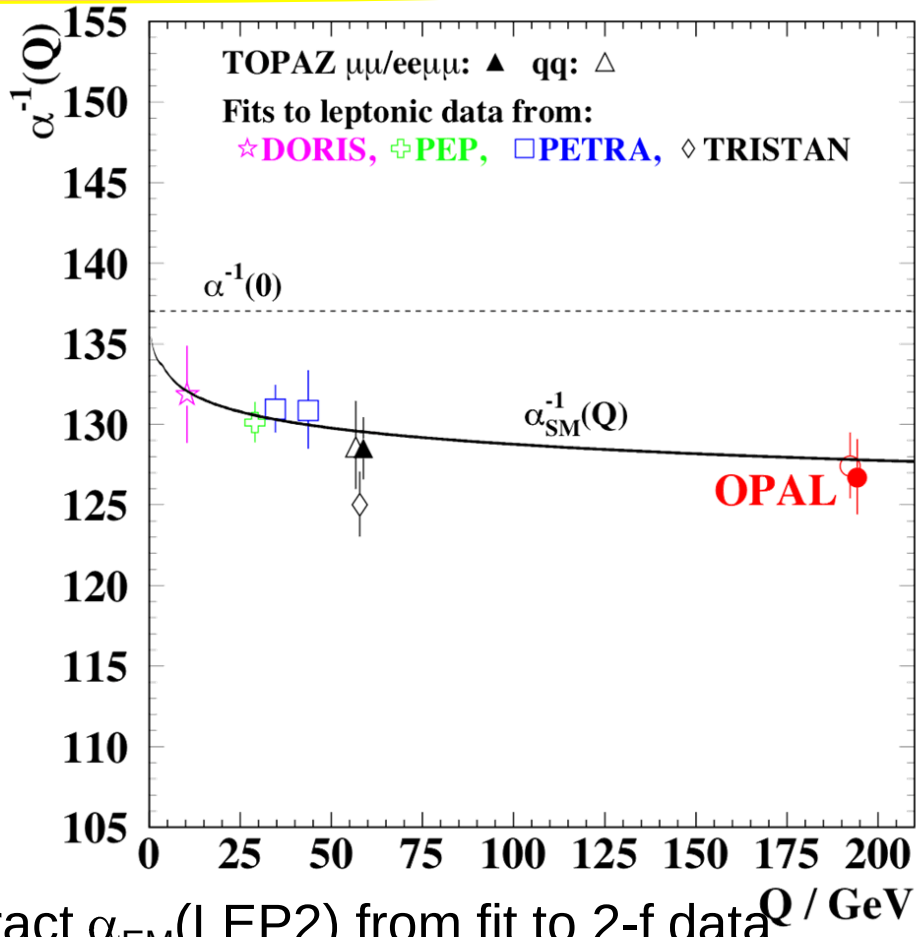




2-fermions – eight all agree

- All 2-fermion measurements in beautiful agreement with SM prediction
  - Place limits on various 4-fermion contact interaction terms

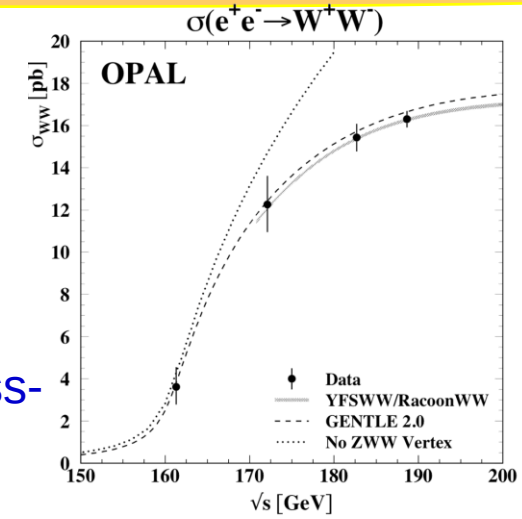


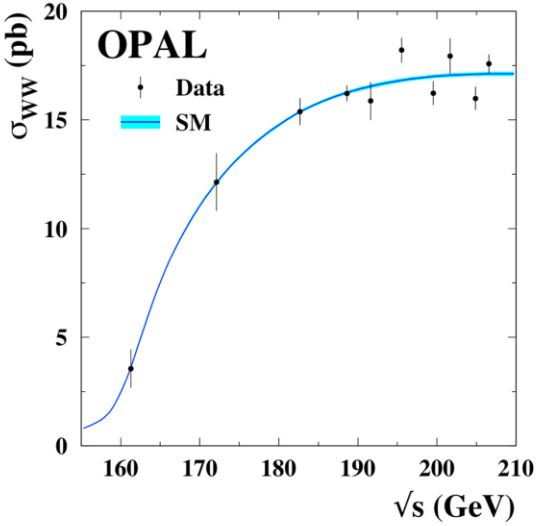


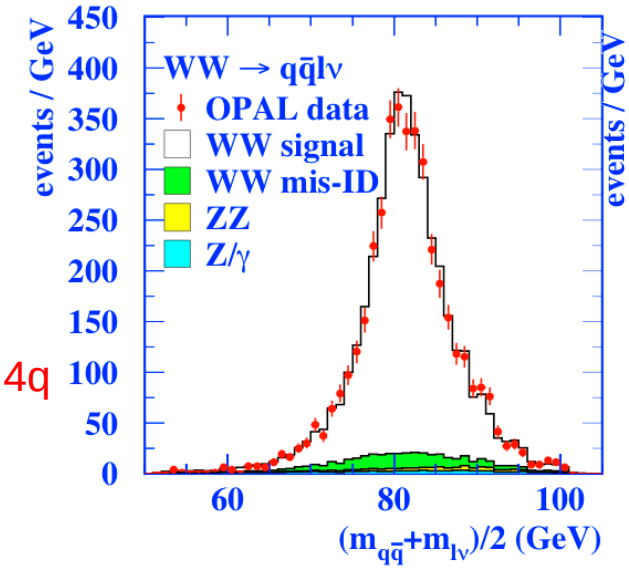
- Extract α_{EM}(LEP2) from fit to 2-f data
  - Assumes SM behaviour for 0-4 GeV (lumi)
  - Use ratios of cross-sections to get a fully independent α_{EM}; 4.3σ different from $\alpha_{EM}(0)$

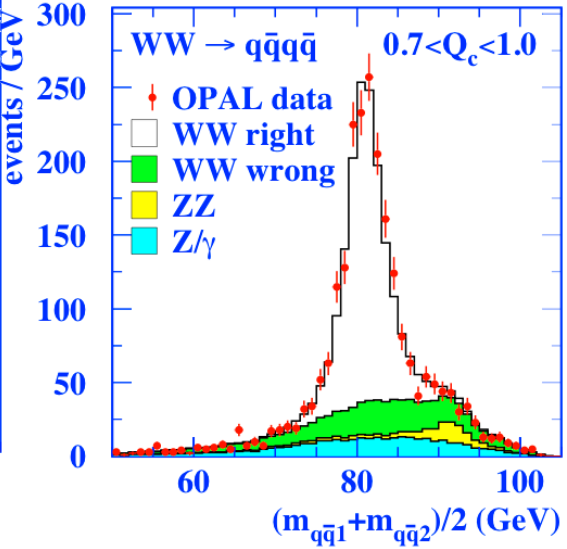
WW and the W mass – nine years of effort

- WW physics central @ LEP2
  - First opportunity to study W in clean environment of e^+e^- collider
  - O(10k) WW events reconstructed in $l\nu l\nu$, $qql\nu$ and $qqqq$ final states
  - Measurement of WW production cross-section and W branching ratios
- Measurement of W-boson mass
  - Natural complement to LEP1 m_Z
  - Many challenges to reach 0.06%
    - Detector response (calib Zs)
    - Hadronisation and precision electroweak effects
    - LEP energy calibration
    - Colour reconnection and BEC in 4q
  - Also a measurement in $l\nu l\nu$!

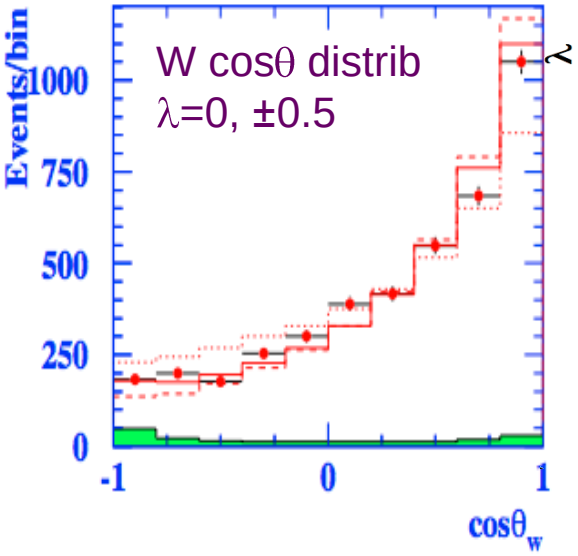


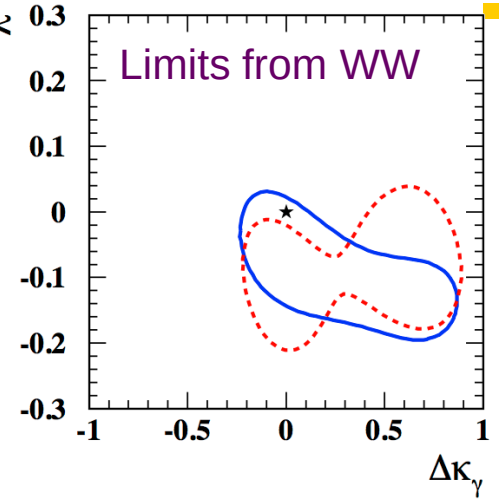




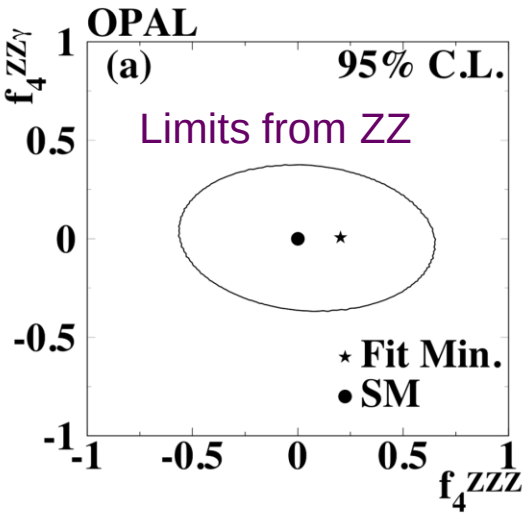


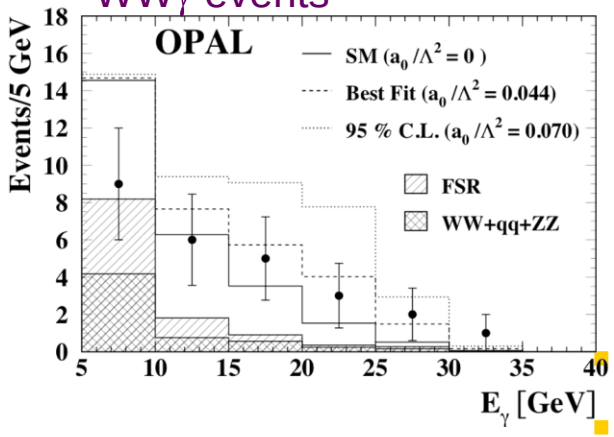
Ten triple gauge couplings
(g_1^Z, κ_Z, κ_γ, λ_Z, λ_γ, g_5^Z; f_4^{ZZZ}, $f_4^{ZZ\gamma}$, f_5^{ZZZ}, $f_5^{ZZ\gamma}$)

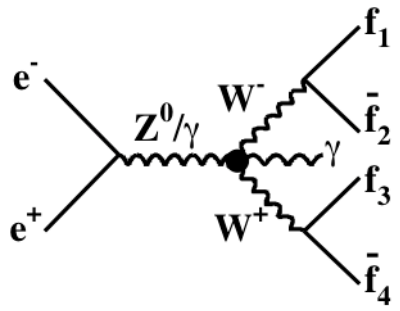




- Diboson production allows study of triple gauge couplings (TGC)
  - WWγ, WWZ, ZZγ, ZZZ
    - Precisely predicted in SM – look for anomalies indicating new physics
  - Cross-sections and angular distributions measured in WW and WZ, as well as single-W production
    - No deviations from SM seen
  - Also QGC: WWγγ and WWγZ



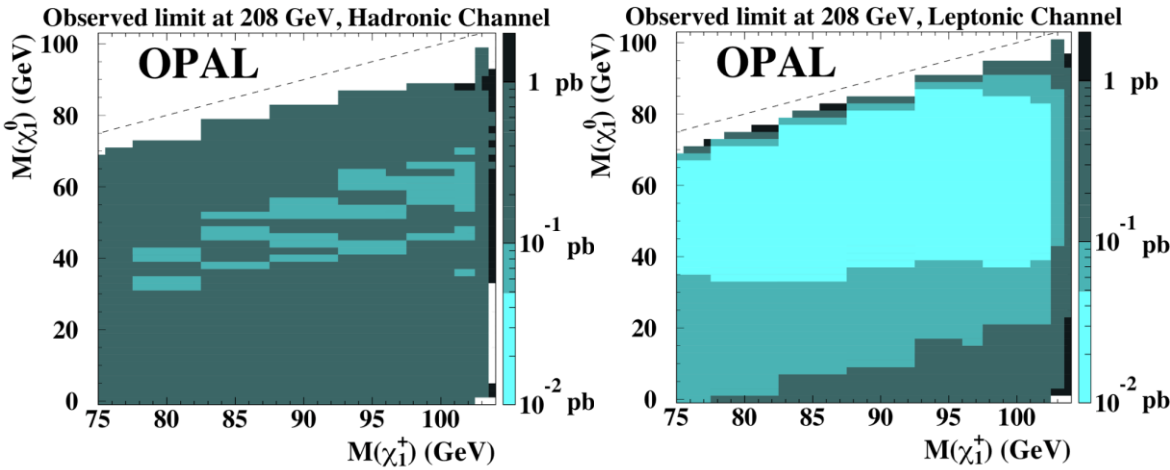


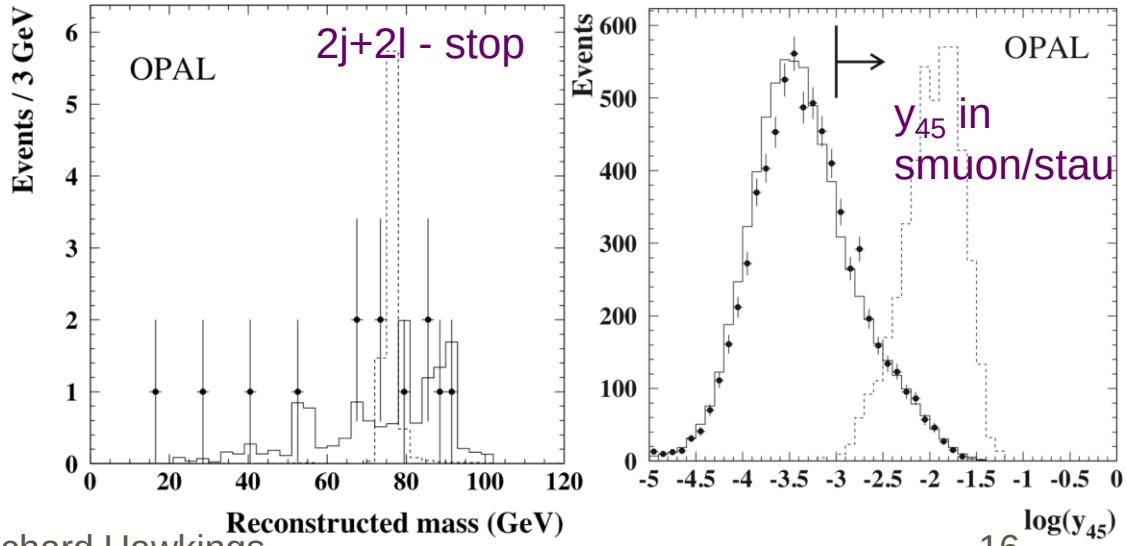


- Measurement of WWγ cross-section
- First (weak) limits on quartic couplings

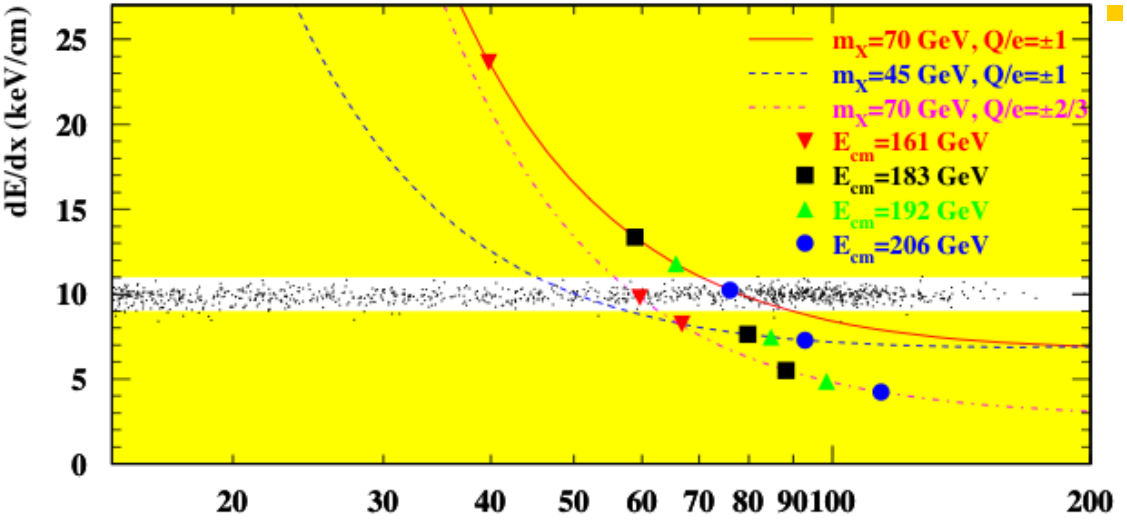
Searching for SUSY – eleven null results

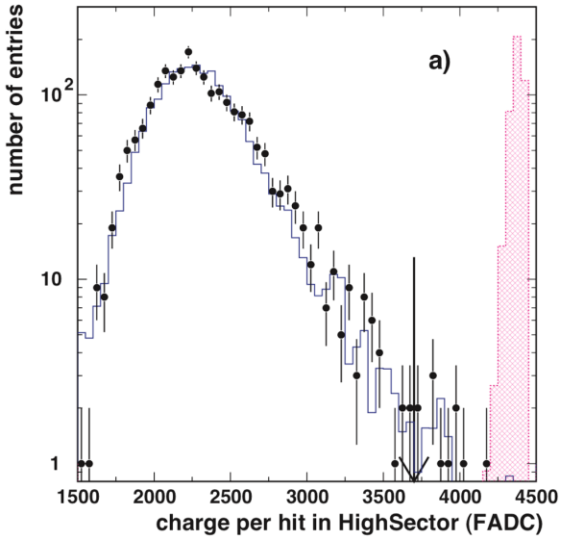
- LEP2 searches – found nothing!
  - But a big industry along the way – keen expectation at each new energy from LEP1.5 @ 130 GeV
- Searches for SUSY via chargino or neutralino pair production
  - Final states with jets, or jets and leptons – tricks to fight WW b/g
- And for R-parity-violating SUSY
  - Search for scalar fermions – e.g. pair-produced stops giving 2l+2j
  - Smuon and stau giving 4j+2l
- And many more …
  - Leptoquarks, radions, exotic Higgs, excited leptons, $\gamma\gamma$ states
  - Model-independent searches
  - Invisible objects …

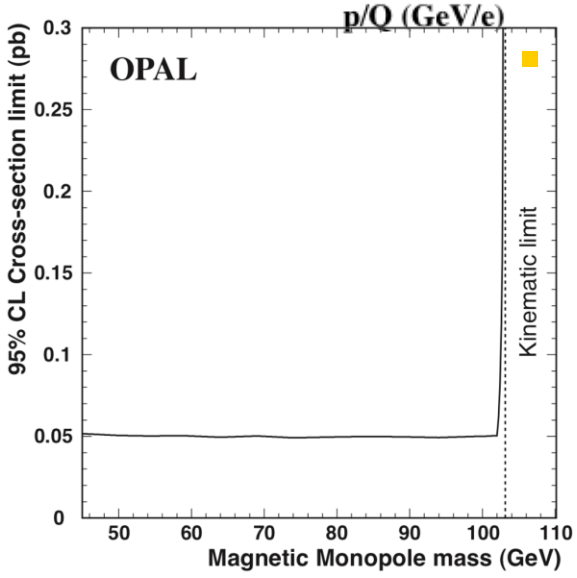




Searching with CJ – twelve wires in overflow







- Jet chamber dE/dx allows searches for anomalously-behaving particles
  - Long-lived heavy charged particles produce 'wrong' dE/dx vs p/Q
  - Pair production of spin-0 and ½ particles – limits on smuons and staus in CMSSM
  - Also set limits on fractionally-charged particles
- Magnetic monopoles more difficult
  - Very-heavily ionizing – saturation of FADC readout
    - Special monopole trigger looking for high dE/dx on groups of 12 wires
  - Parabolic trajectory – not reconstructed by standard software
    - Look for isolated heavy ionisation
  - Monopole limits from 45-102 GeV

Final remarks

- Fantastic breadth and depth of physics results from OPAL at LEP1 and 2
  - High-statistics Z decays at LEP1 – precision QCD, tau and heavy flavour physics
  - Physics at the energy frontier with LEP2 – searches, 2f and gauge boson physics
  - Not forgetting zedometry and Higgs searches …
  - A triumph for the Standard Model – it did not crack
- Some of these results have/will be overtaken (Tevatron, B-factories, LHC)
  - But form a 'reference point' for later experiments
    - Invaluable data for refining our understanding and models
- Some will be with us 'forever', or until repeated at a linear collider Z-factory

- OPAL was a 'small' experiment – and a great opportunity
  - With 400+ papers, plenty of physics topics to study, write PhD theses, etc.
  - Excellent opportunities for young people to learn, to take positions of responsibility
  - And a great working environment – (nearly) always fun …
    - Can we replicate this 'spirit' in the mega-experiments of today?