Highlights from LEP, Tevatron & LHC

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with thanks to:

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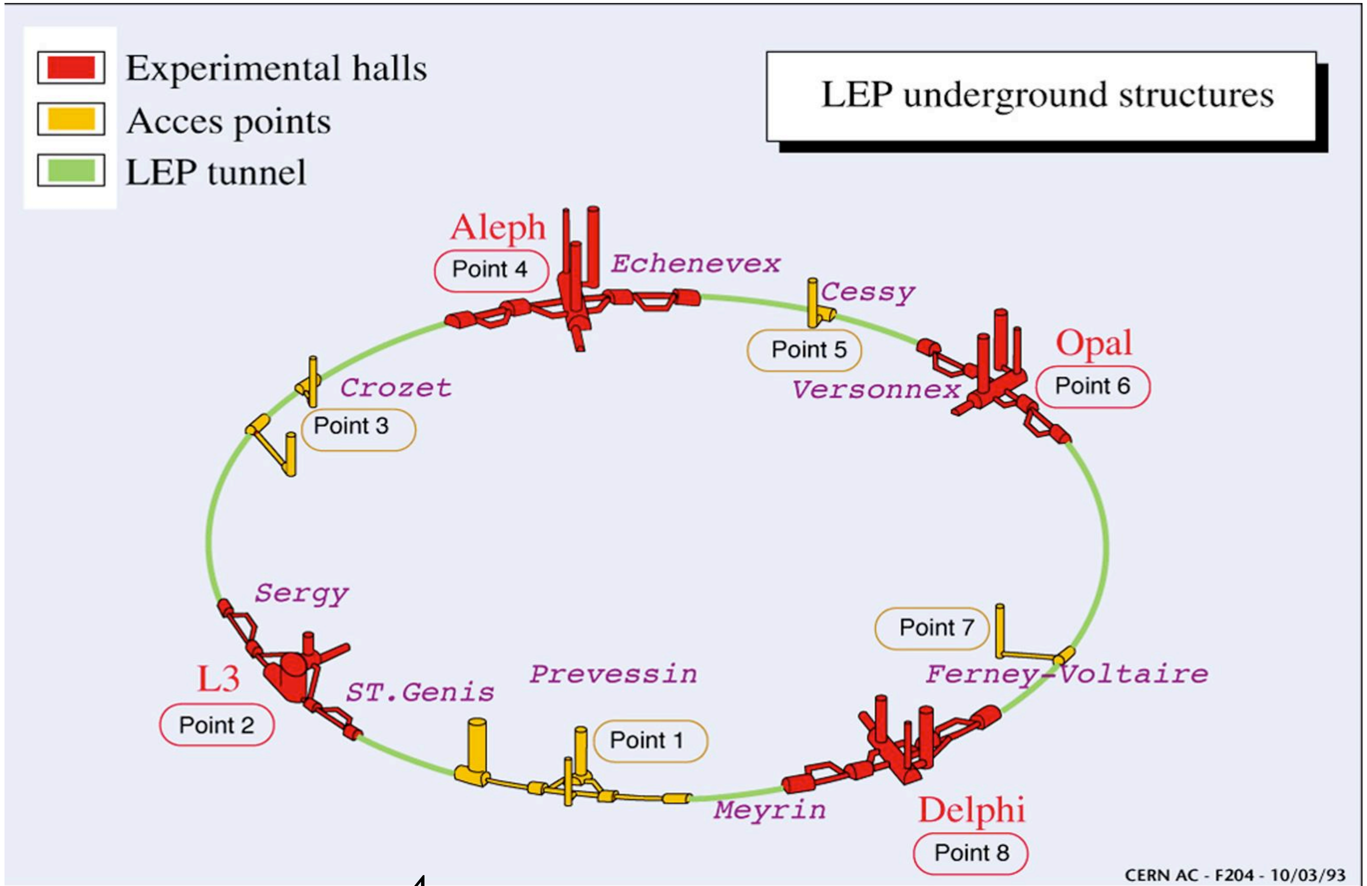
Highlights of LEP, Tevatron & LHC

- Lecture 1,2: LEP physics results
  - Construction & running
  - Physics of the W and Z
  - QCD at LEP
- Lecture 3,4: Tevatron results
  - Running D0 and CDF
  - QCD, jets, dijets
  - Heavy quarks, top quarks
  - W,Z physics, Higgs searches
- Lecture 5,6: LHC physics programme & results
  - Construction & running of LHC
  - QCD, jets
  - W, Z physics, top quark
  - Higgs prospects

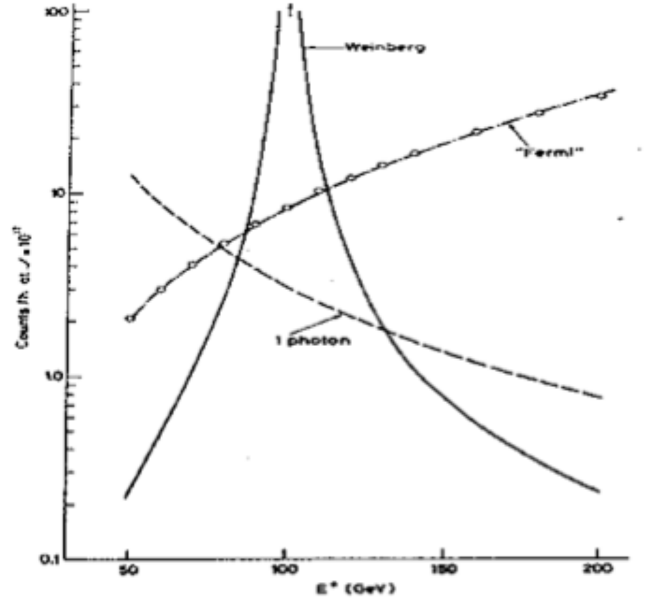
Physics results of LEP



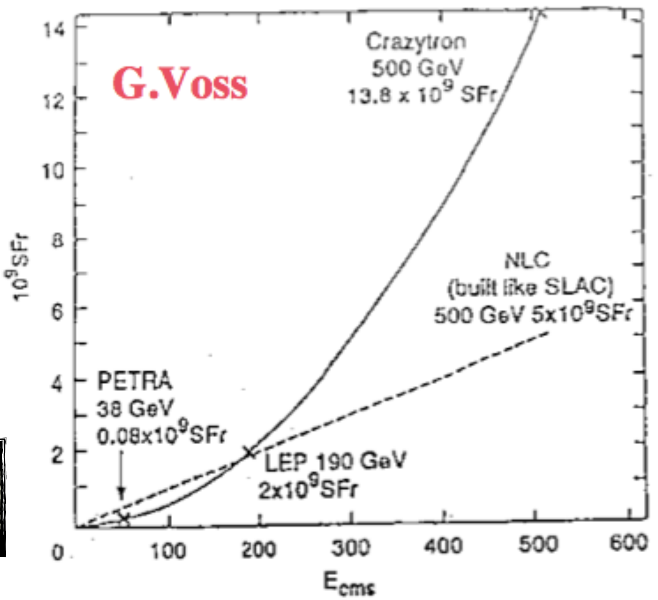
Constructing LEP

first draw of Z resonance

- March 76
  - B.Richter's note launches the idea of building a high energy e+e-, up to 200 GeV CM.
  - LEP scenery correctly anticipated.



- Guess of costs of a circular and linear collider
  - It shows that the cross-over occurs roughly at the top of LEP range



cost as function of E_{cm}

Constructing LEP

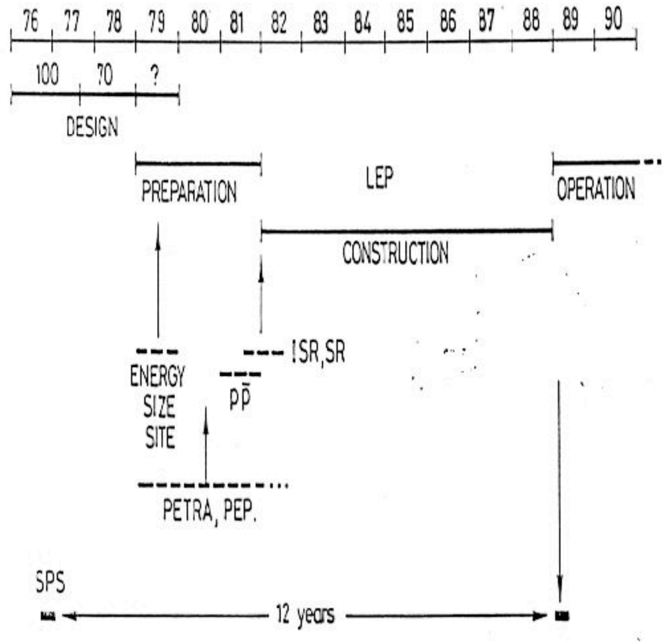
- LEP circumference and beam energy oscillating
  - Blue Book 78 22 km 100 Gev
  - Pink Book 79 30.6 km 130 GeV
  - LEP Design Report 84 26.6 km 125 GeV

- 1979 Les Houches prospective meeting
  - S.Glashow considers four possible scenarios, "the least probable" being the SM.
    - " It would be both arrogant and unhistorical to believe that our naive extrapolation from physics at 2 GeV to physics at 200 GeV is likely to be correct in detail". On the contrary he thought the "most likely" would be a scenario leading to a complete surprise. On the same year he got the Nobel Prize with S.Weinberg and A.Salam.

Constructing LEP

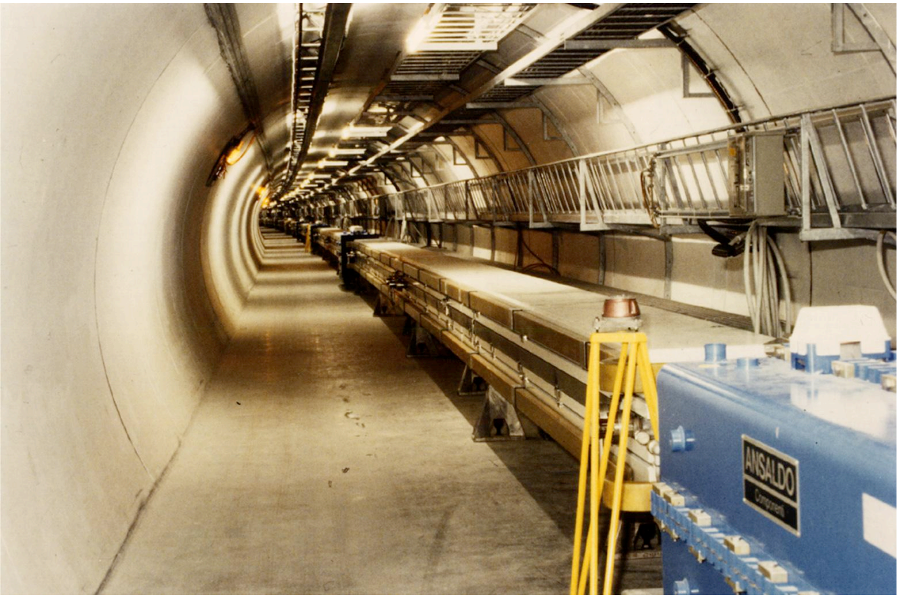
- The planning of LEP
  - presented in les Houches by J.Adams. LEP is foreseen for end 1988.

Possible LEP construction plan
shown by John Adams at Les Houches



- In 1982 the LEP project got its final authorization
  - Unconditional support of all Member States.
  - In 1983 the Declaration d'Utilite Publique for the LEP machine was signed, and the civil engineering could start. *Collisions were foreseen for the second half of 88.* The same year the Z^0 was discovered at some 92 GeV, the mass predicted by theory, well within LEP's grasp.

Digging the LEP tunnel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Constructing LEP

- 1986 Workshop on Physics at LEP
  - The foundations of the program of accurate tests of the electroweak theory were laid and the experimental methods defined in already great detail. However we were still in the dark concerning the top mass, and a lot of work was devoted to scenarios where the top-antitop threshold bound states was close to the Z0, and even degenerate with it.
- Around 1986
  - Ideas about the “after-LEP”, namely the LHC (17 TeV, 10^{33} $cm^{-2}s^{-1}$), were quite clearly defined.
  - The 10^{34} high luminosity option appeared in 1987 after the la Thuile ECFA meeting. In february 1988 the LEP tunnel excavation was completed. In july 1989 the first Z^0 were registered in the four experiments.
- LEP came six months after the date foreseen a decade earlier.
  - Its cost (tunnel plus LEP1) was ~1100 MSF
  - The experiments cost 480 MSF in total.
    - The cost of LEP2 was 400 MSF. About 2000 men-year were invested in the project.

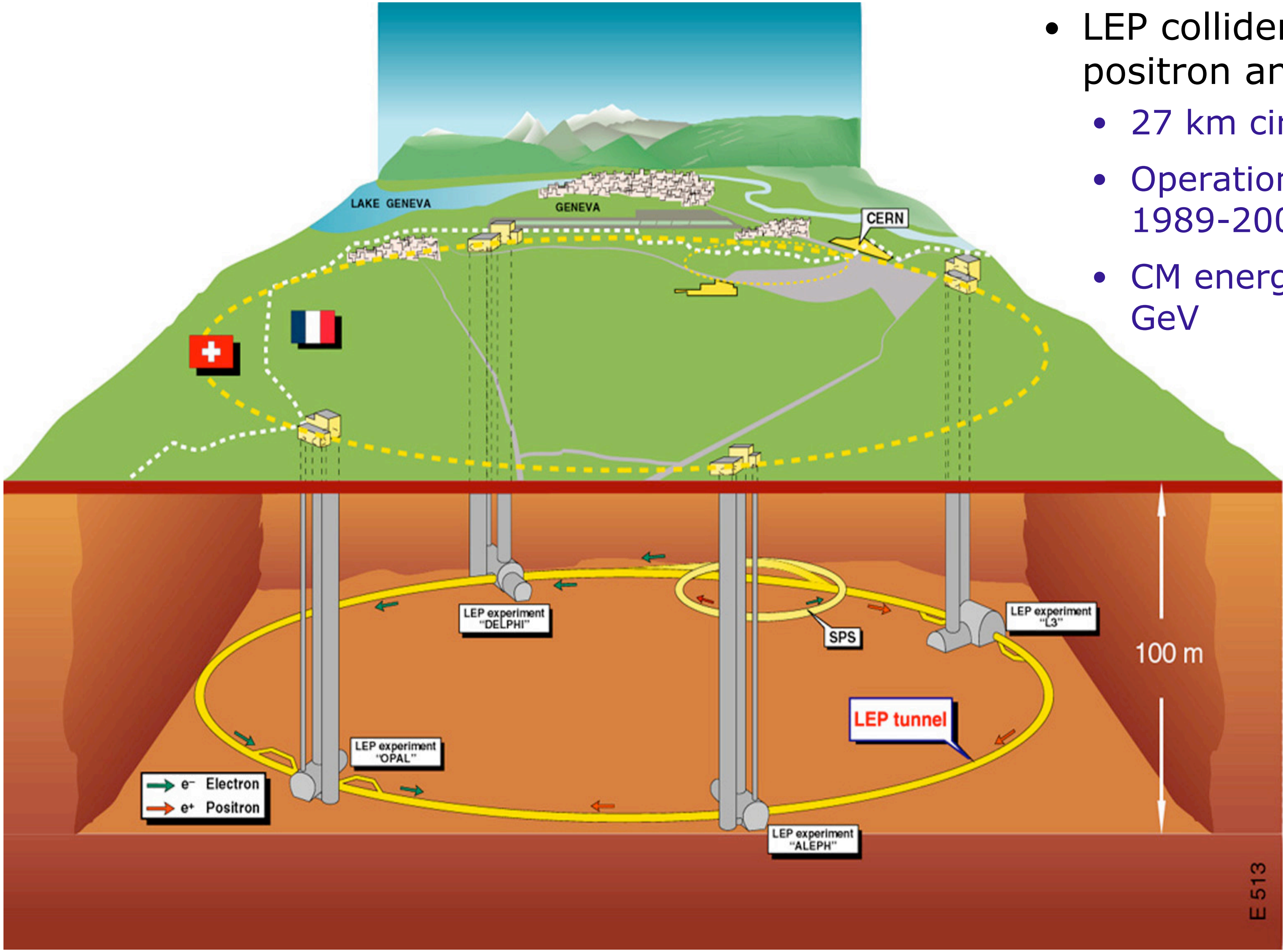
Constructing LEP

- In all respects LEP did better, sometimes much better, than expected
- Examples:
  - For the Z^0 mass measurement:
    - In 1988 the ideas of an optimized scan and of using spin-resonance energy calibration were present. The foreseen statistical error was ± 10–15 MeV, while the systematic one was about ±17 MeV.
    - LEP finally achieved an overall uncertainty of 2.1 MeV, one order of magnitude better.
  - For the W mass measurement:
    - "Each of the four LEP experiments can measure in at least three ways the mass of the W boson at LEP200 with an accuracy of the order of 100 MeV or better.
    - The final LEP uncertainty is ± 42 MeV.

Standard Model program

1960's	Glashow-Weinberg-Salam $SU(2) \times U(1)$ theory of electroweak interactions, prediction of W and Z gauge bosons.
1972	$SU(3)_{\text{colour}}$ QCD theory of strong interactions
1976	CERN study group considers Large Electron-Positron storage ring, $\sqrt{s} = 2 \times 100$ GeV, $\mathcal{L} \approx 10^{32}\text{cm}^{-2}\text{s}^{-1}$
1979	Observation of gluon at PETRA.
	December: 27 km design approved by CERN council
1983	Chose LEP experiments.
	W and Z observed at CERN SPS
1989	Scooped! e^+e^- collisions at Z in MARK II at SLC.
	First collisions in LEP with $\sqrt{s} \approx M_Z$
1995	Gradual installation of LEP2 SC RF system starts
	Energy raised to $\sqrt{s} = 140$ GeV at end of year.
	Top quark observation at Fermilab confirmed
1996	W pair threshold crossed at LEP...
1999	Nobel Prize for 't Hooft and Veltman for "for elucidating the quantum structure of electroweak interactions in physics"
2000	Last year of LEP running with $\sqrt{s}$ up to 209 GeV.

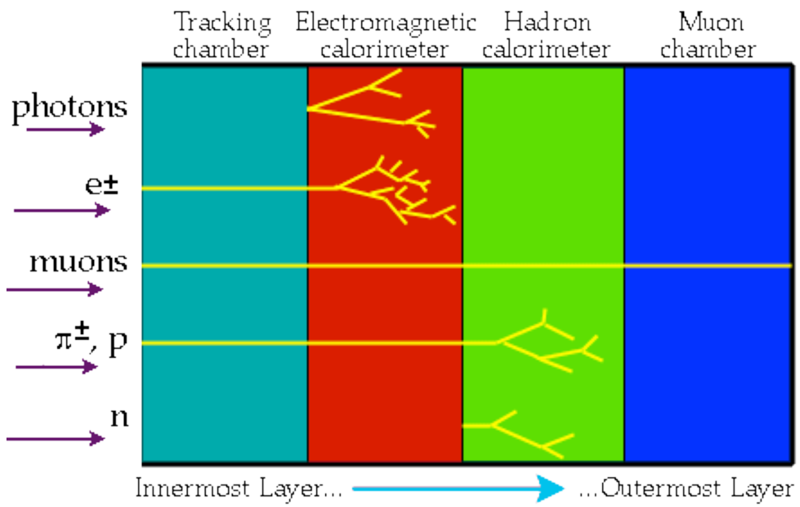
Good old LEP

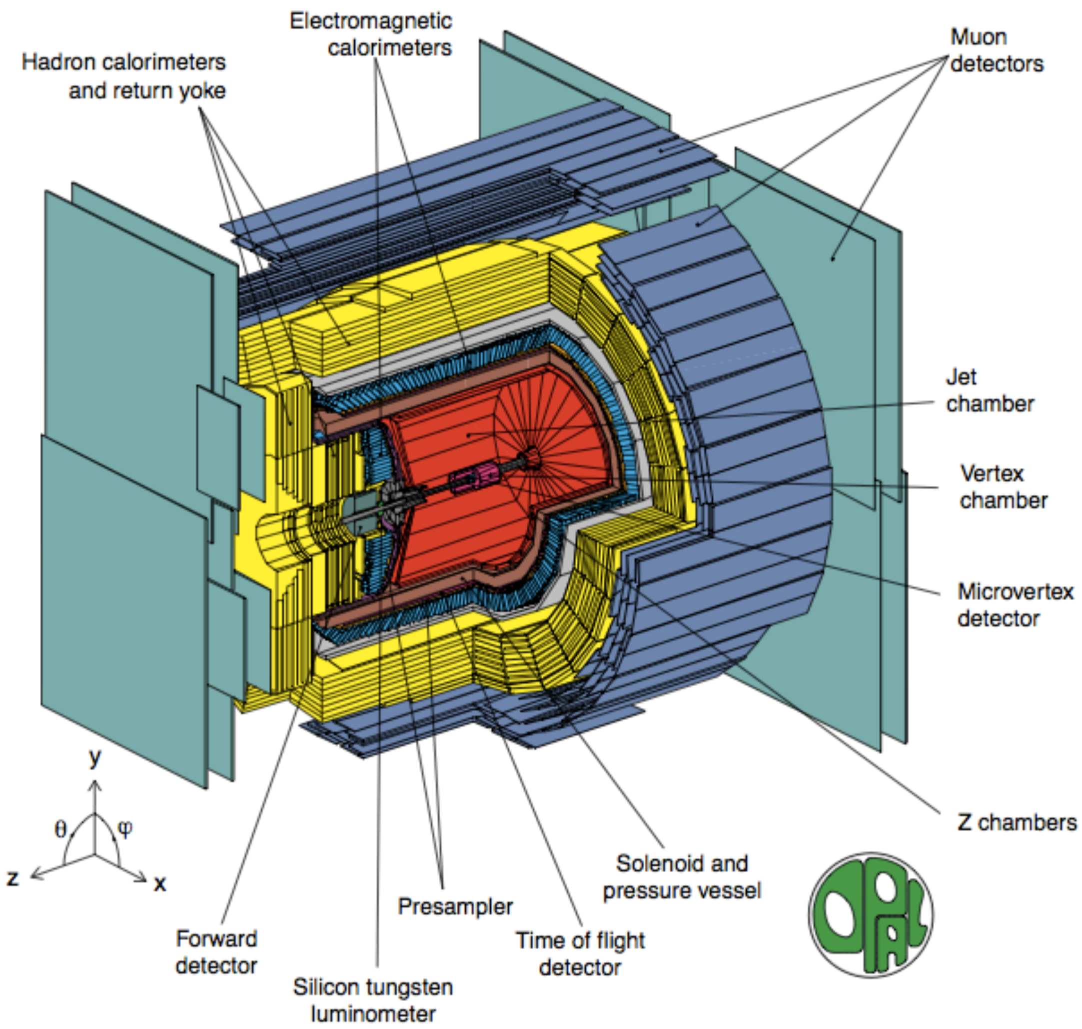


- LEP collider: Electron-positron annihilations
  - 27 km circumference
  - Operational between 1989-2000
  - CM energies: 91 - 207 GeV

4 experiments

- Detectors at LEP
  - Four similar detectors:
  - Aleph,
  - L3,
  - Delphi,
  - Opal

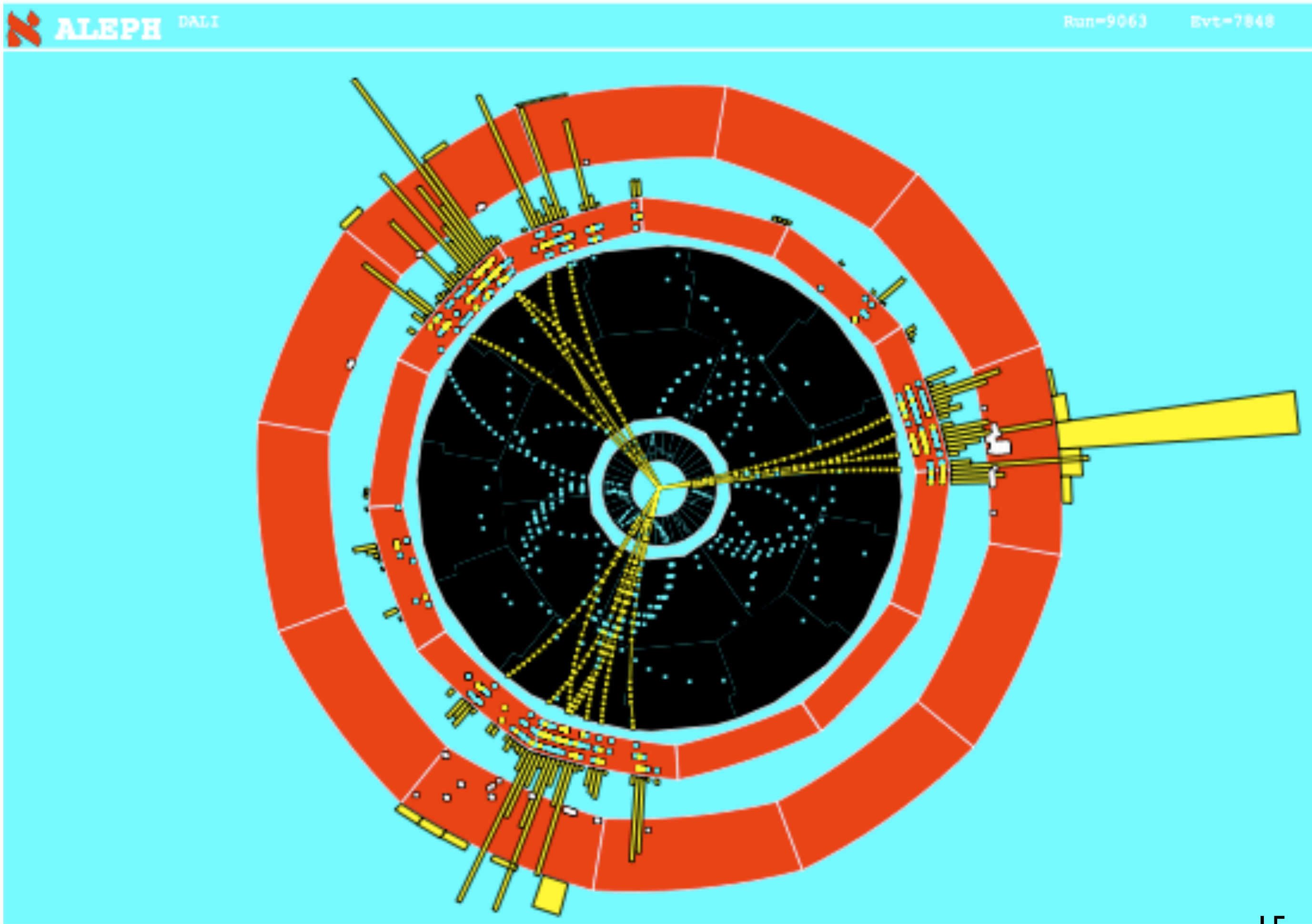




Overall size 12×12×12 m

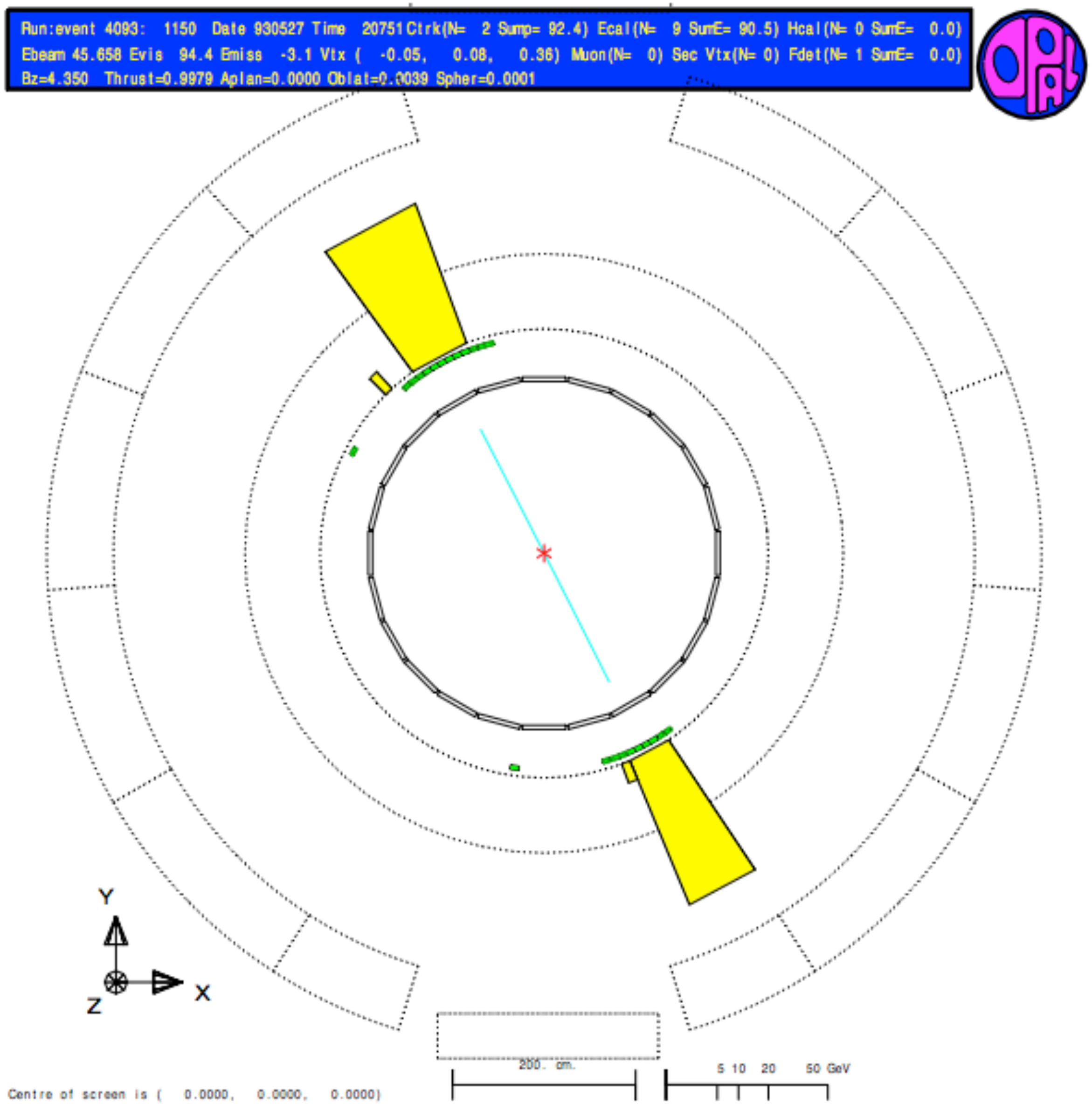
Hadronic event in Aleph

- This example: 3 jets e+e− → qqg
  - Curved tracks in B field (ALEPH and DELPHI have superconducting solenoids - B field about 1.5 T compared to about 0.5 T in OPAL and L3)
    - Many tracks and clusters in calorimeters



$e^+e^- \to e^+e^-$ event in OPAL

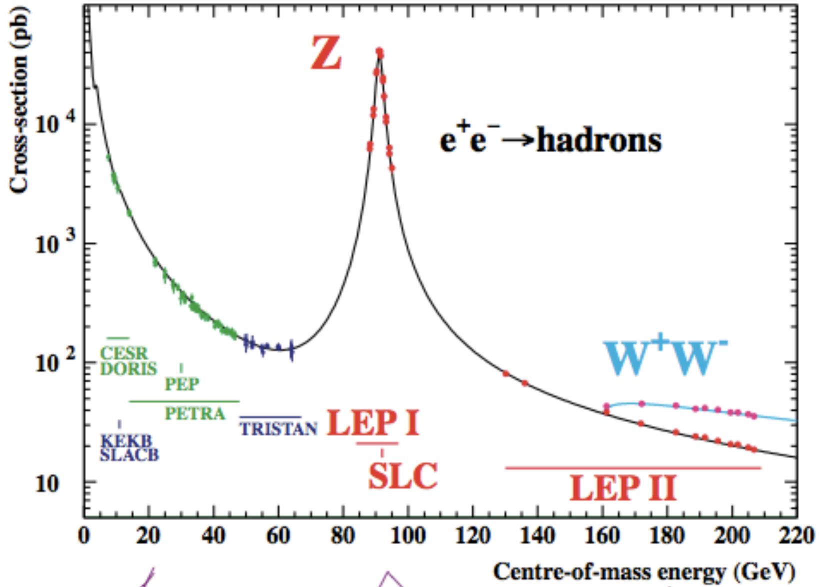
- lepton pair has low multiplicity
  - Electrons are identified by a track in the central detector, and a large energy deposit in the electromagnetic calorimeter, $E/p = 1$

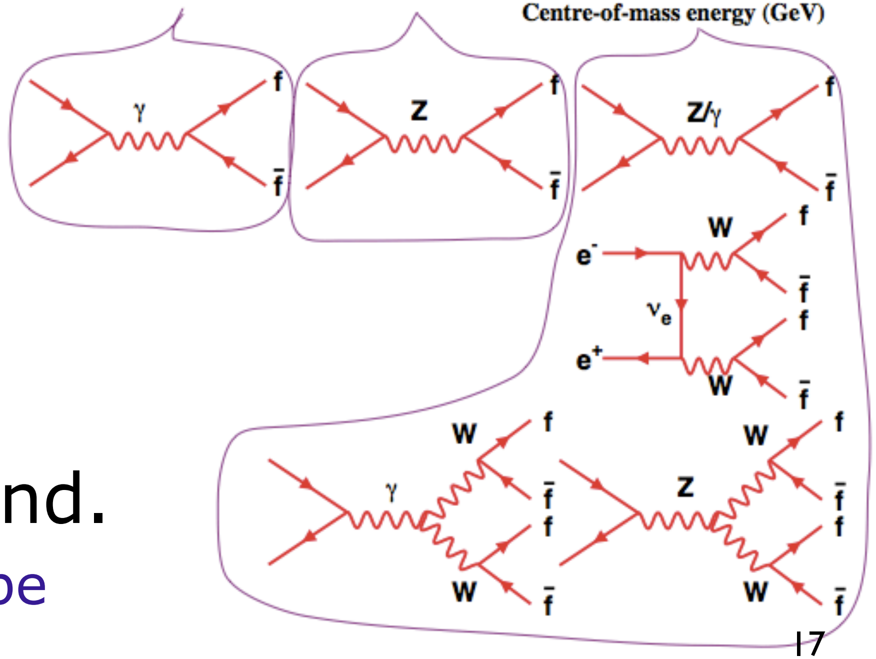


Electron-positron annihilation

LEP collected 4.5 million Z, 12 thousand WW per experiment

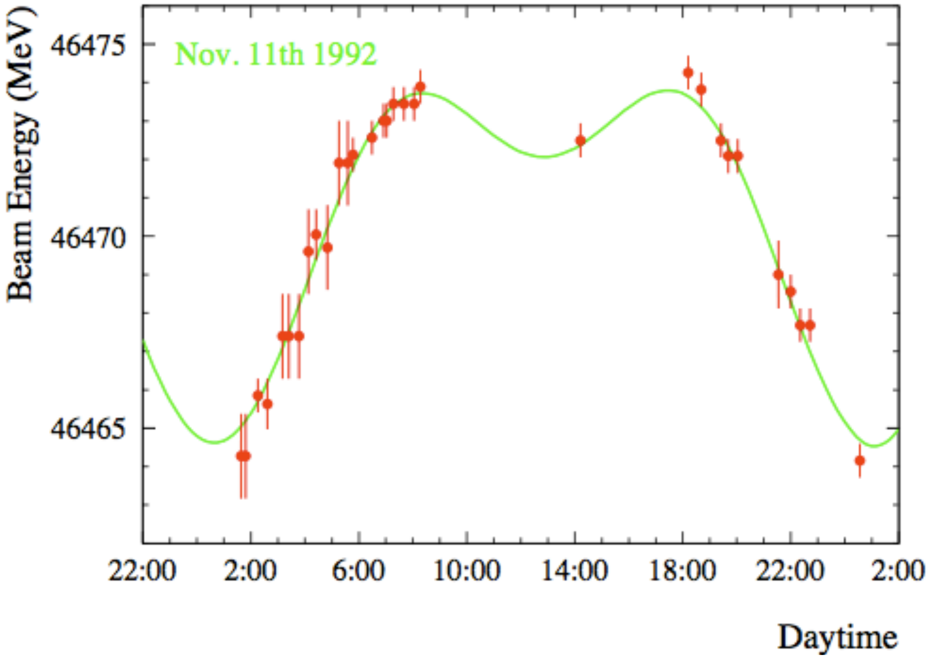
- To measure the Z mass,
  - Total width and cross-section, partial widths (branching ratios) and couplings
- Collisions at a few energies on and near the Z peak
  - and precise measurement of E_{beam}
    - Detectors distinguish Z final states and measure the luminosity from QED t-channel process $e^+e^- \rightarrow e^+e^-$ (Bhabha scattering)
  - $\sigma(\sqrt{s}) = (N_{observed} - N_{background})/\varepsilon$
- Monte Carlo simulation of the signal efficiency and background.
  - Theoretical prediction of the lineshape





Stability?

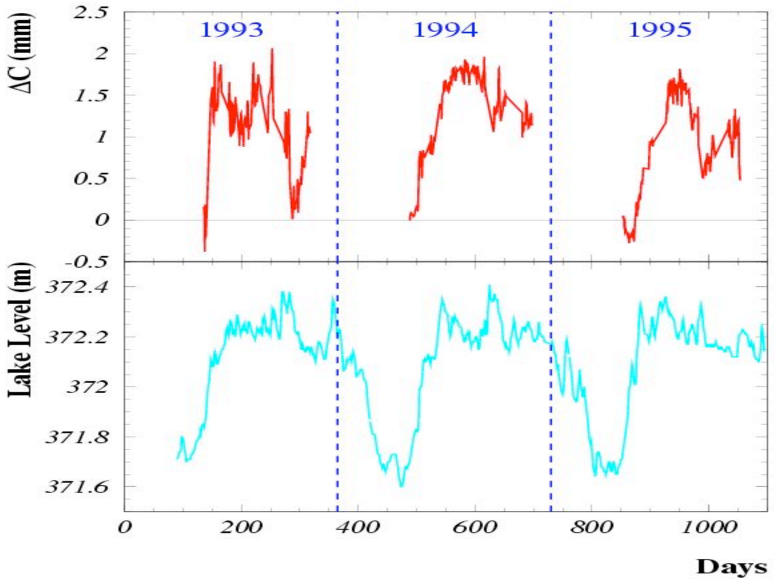
- Earth tides driven by moon and sun.



- Determination E_{beam} drives the M_Z accuracy

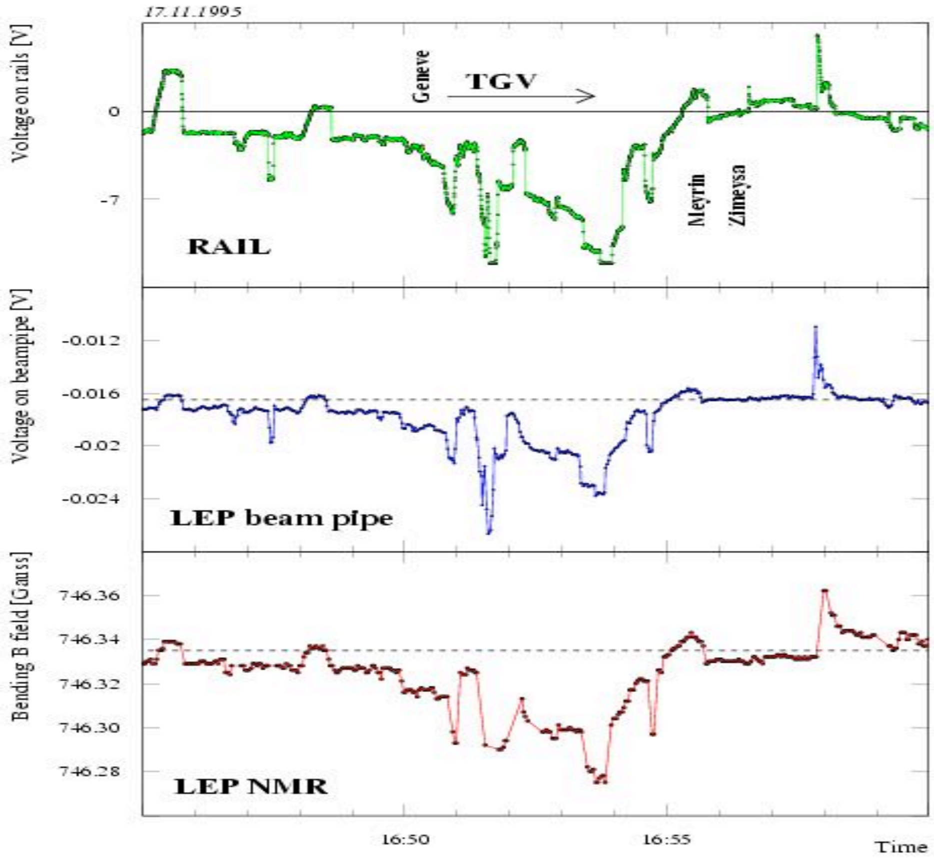
- Quadrupole movements
  - first calibrations saw fluctuations of order 10 MeV.
  - Length of orbit fixed by RF system, but magnets move with ground. Beam no longer goes through centre of quadrupoles. Sensitive to 1mm change in 27 km, typical 10 MeV.

  - Also seen fluctuation caused by water level of the lake



Determination of M_Z

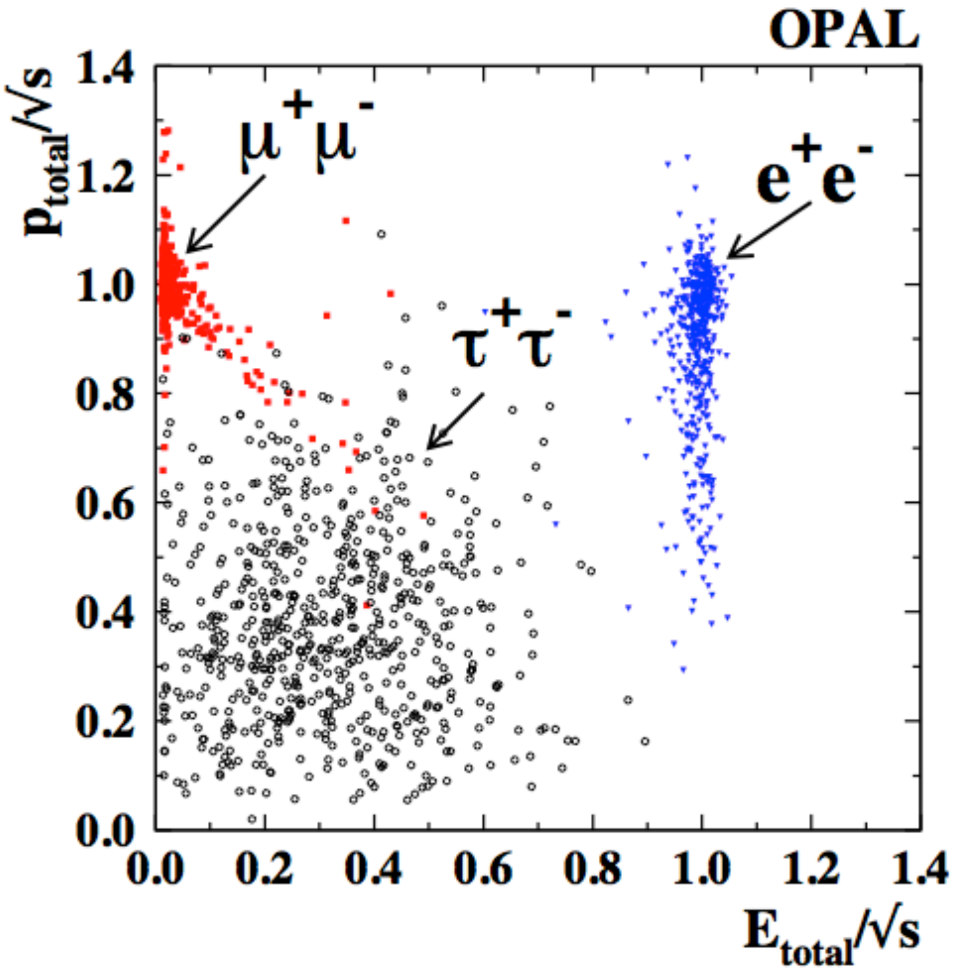
- The last systematic
  - Human activity increasing dipole fields during fill: BIAS ≈ 5 MeV
    - Long investigation revealed cause - Vagabond electric currents from nearby trains. Correct earlier years using model of average train behaviour.



- Final M_Z a fantastic systematic of 1.7 MeV

Event selection: how easy!

- Selection:
  - A few very simple cuts can distinguish hadronic, e+e−, μ+μ− and τ+τ− events, and also background from γγ, cosmic rays...
  - The difficult task is to control systematic errors -



Representative values (vary from experiment to experiment)

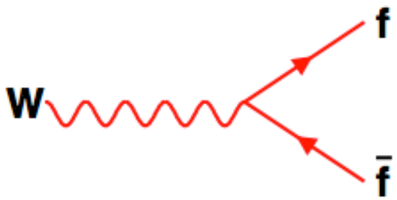
Channel	hadron	e^+e^-	$\mu^+\mu^-$	$\tau^+\tau^-$
Efficiency %	99	98	98	80
Background %	0.5	1	1	2
Syst error %	0.07	0.2	0.1	0.4

Standard Model recap

- Relationships
  - Masses of heavy gauge bosons and their couplings to fermions depend on mixing angle $\cos\theta_W = M_W/M_Z$
  - SU(2)×U(1) coupling constants g, g′, proportional to electric charge e: $g = e\sin\theta_\mathrm{W},\, g' = e\cos\theta_\mathrm{W}$

$$-ieQ\gamma_\mu$$

$$ie\gamma_\mu(g_v - g_a\gamma_5)\frac{1}{2\sin\theta_\mathrm{W}\cos\theta_\mathrm{W}}$$



$$ie\gamma_\mu(1-\gamma_5)\frac{1}{2\sqrt{2}\sin\theta_\mathrm{W}}$$

$$g_a = T^3 = \pm\frac{1}{2}$$

$$g_v = (T^3 - 2Q\sin^2\theta_W) = \pm\frac{1}{2}(1 - 4|Q|\sin^2\theta_W)$$

Standard Model relationships

- Relate to best measured parameters:

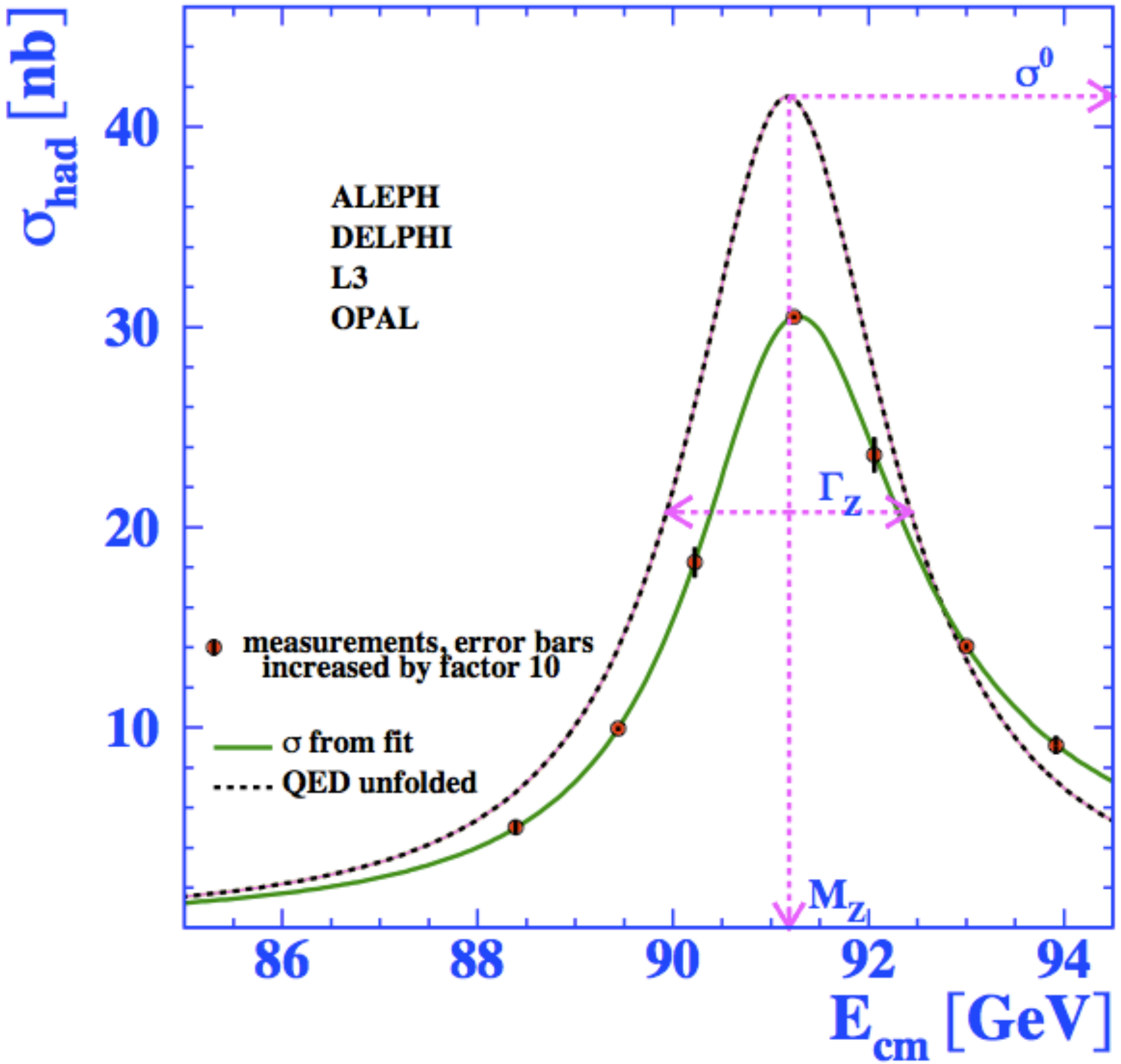
$$\alpha \equiv \frac{e^2}{4\pi} = 1/137.035\,999\,76(50)$$

$$G_F \equiv \frac{\pi\alpha}{\sqrt{2}M_W^2 \sin^2\theta_W} = 1.166\,39(1) \times 10^{-5}\,\text{GeV}^{-2}$$

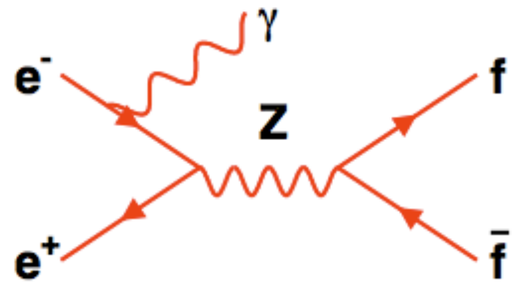
$$M_Z = 91.1875(21)\,\text{GeV}$$

- G_F measured from muon decay; M_Z from LEP.
  - These relations are true at tree level, but to check that they are valid, must take into account radiative corrections, which give sensitivity to virtual heavy particles, and possibly new physics!
- Aside:
  - Other SM inputs needed are fermion masses, Higgs mass, CKM matrix (quark mass eigenstates are not weak eigenstates), strong coupling constant, α_s

QED corrections

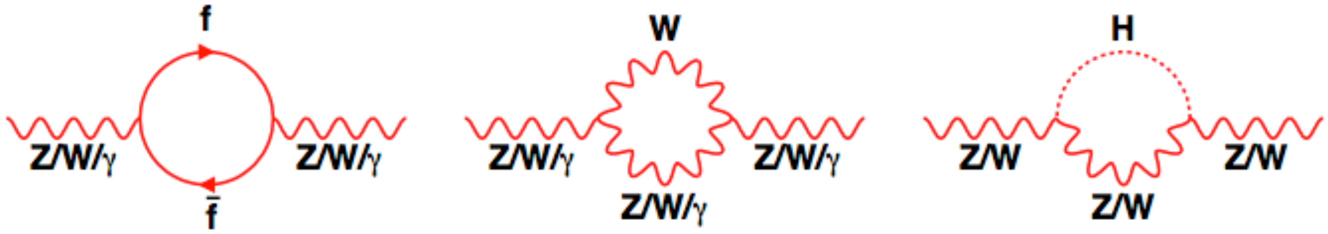


- Real photon emission
  - Initial State Radiation modifies the Breit-Wigner shape of the Z resonance



Observing radiative corrections

- Propagator corrections are the same for each fermion type.



- Electroweak corrections absorbed into effective couplings:
  - define:

$$\Delta\rho = \frac{3G_F M_W^2}{8\sqrt{2}\pi^2}\left(\frac{M_t^2}{M_W^2} - \tan^2\theta_W\left[\ln\frac{M_H^2}{M_W^2} - \frac{5}{6}\right]\right) + \cdots$$

$$\Delta\kappa = \frac{3G_F M_W^2}{8\sqrt{2}\pi^2}\left(\cot^2\theta_W\frac{M_t^2}{M_W^2} - \frac{11}{9}\left[\ln\frac{M_H^2}{M_W^2} - \frac{5}{6}\right]\right) + \cdots$$

  - used in effective couplings:

$$g_V \equiv g_V^{\mathrm{eff}} = \sqrt{(1+\Delta\rho)}(T^3 - 2Q\sin^2\theta_{\mathrm{eff}})$$

$$g_A \equiv g_A^{\mathrm{eff}} = \sqrt{(1+\Delta\rho)}T^3$$

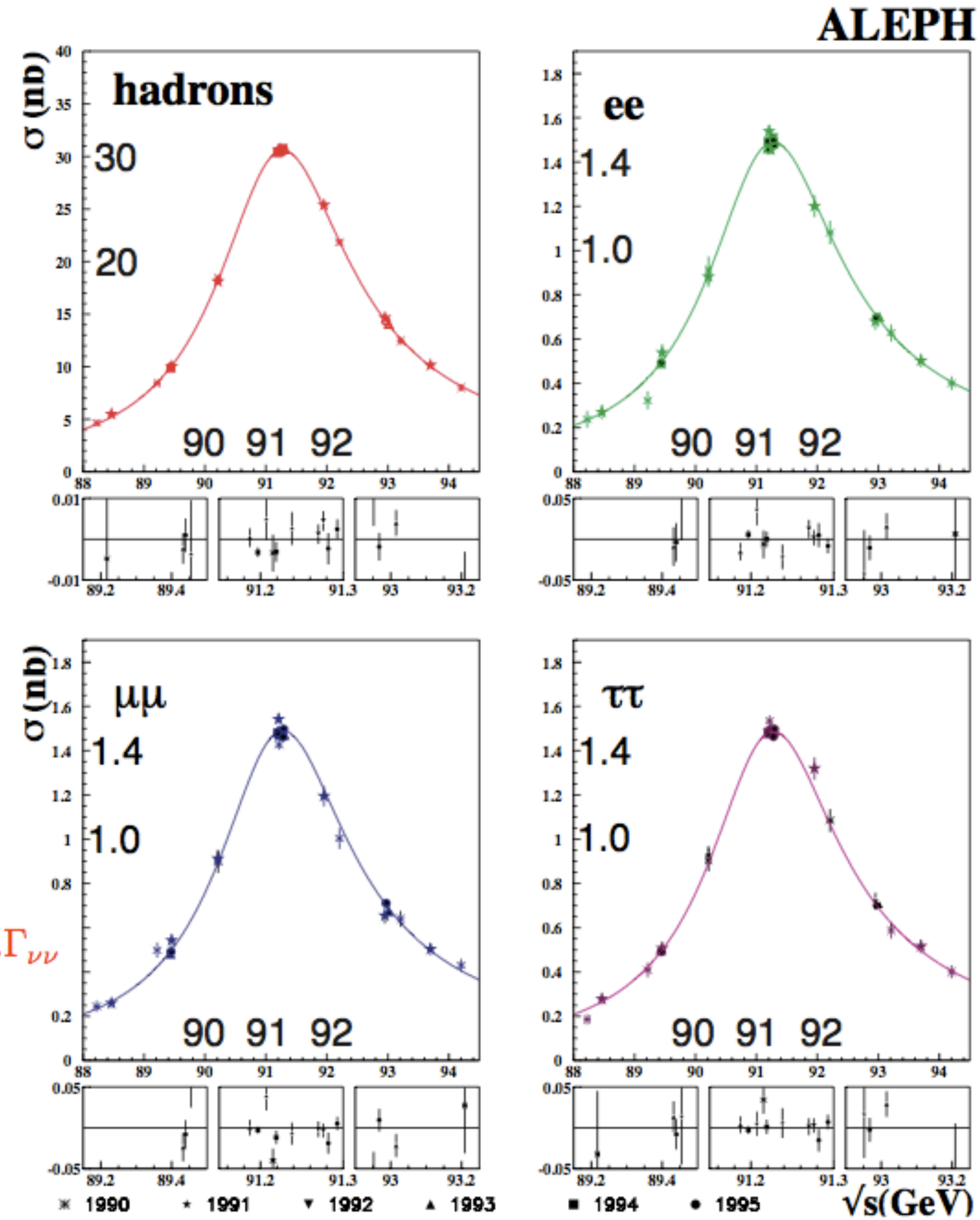
$$\sin^2\theta_{\mathrm{eff}} = (1+\Delta\kappa)\sin^2\theta_W$$

Quadratic dependence on M_t
Logarithmic dependence on M_H
Can fit both M_t and M_H

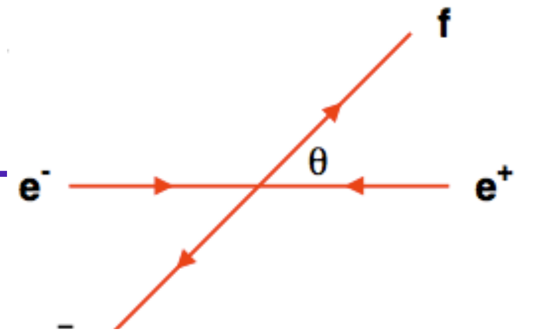
Cross sections

- Extensive studies of lineshape
    - lepton universality
    - cross sections
    - FB asymmetries as result of parity violating couplings
    - determination number of neutrinos

$$\Gamma_Z = \Gamma_{\mathrm{had}} + 3\Gamma_{\ell\ell} + \Gamma_{\mathrm{inv}} = \Sigma\Gamma_{q\bar{q}} + 3\Gamma_{\ell\ell} + N_\nu\Gamma_{\nu\nu}$$



Differential cross sections



- 2→2 differential cross section

$$\frac{d\sigma_{\rm ew}}{d\cos\theta} = \frac{\pi N_c^{\rm f}}{2s} 16|\chi(s)|^2 \times$$
$$\left[(g_{\rm Ve}^2 + g_{\rm Ae}^2)(g_{\rm Vf}^2 + g_{\rm Af}^2)(1+\cos^2\theta) + 8 g_{\rm Ve} g_{\rm Ae} g_{\rm Vf} g_{\rm Af} \cos\theta\right]$$
$$+[\gamma \text{ exchange}] + [\gamma Z \text{ interference}]$$

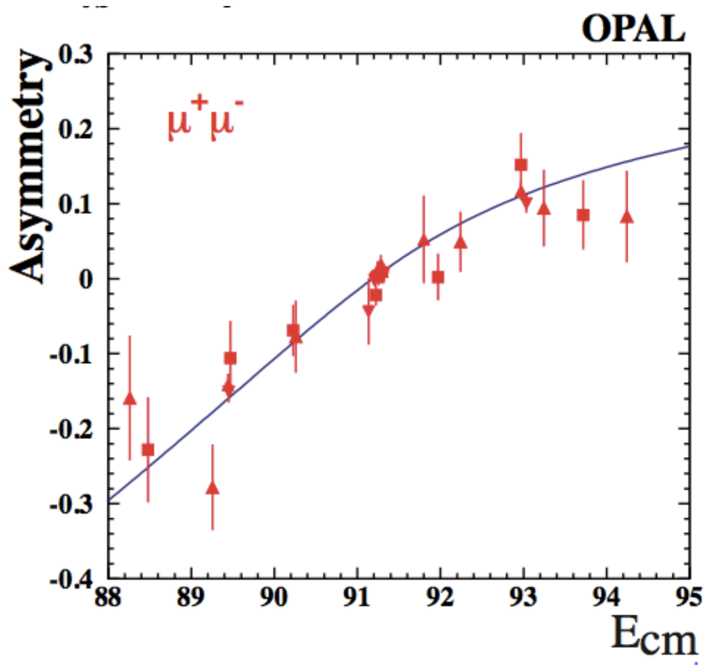
- with the lineshape Breit-Wigner: $\chi(s) = \frac{G_{\rm F} M_{\rm Z}^2}{8\pi\sqrt{2}} \frac{s}{s - M_{\rm Z}^2 + is\Gamma_{\rm Z}/M_{\rm Z}}$
  - define: $\sigma_{\rm F} = \int_0^1 (d\sigma/d\cos\theta) d\cos\theta$
- Odd term in cos θ leads to forward-backward asymmetry:

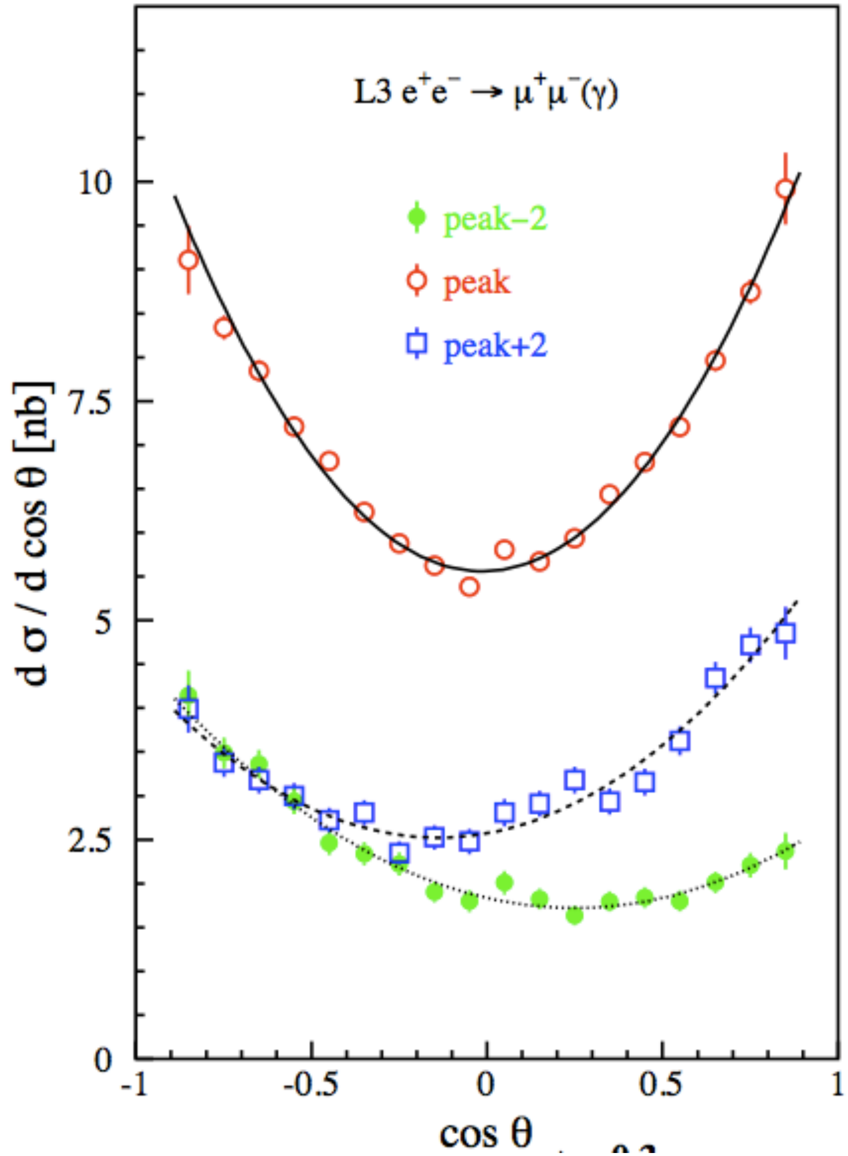
$$A_{\rm FB} = \frac{\sigma_{\rm F} - \sigma_{\rm B}}{\sigma_{\rm F} + \sigma_{\rm B}} \qquad A_{\rm FB}^{0,\,\rm f} = \frac{3}{4} \frac{2 g_{\rm Ve} g_{\rm Ae}}{g_{\rm Ve}^2 + g_{\rm Ae}^2} \frac{2 g_{\rm Vf} g_{\rm Af}}{g_{\rm Vf}^2 + g_{\rm Af}^2}$$

- Cross-section plus AFB allow $g_{\rm Vf}$ and $g_{\rm Af}$ to be derived.

Measuring A_{FB}

- Lepton forward-backward asymmetries
  - Forward-backward asymmetry for lepton pairs is straightforward to measure.
  - Charge of lepton from tracking.



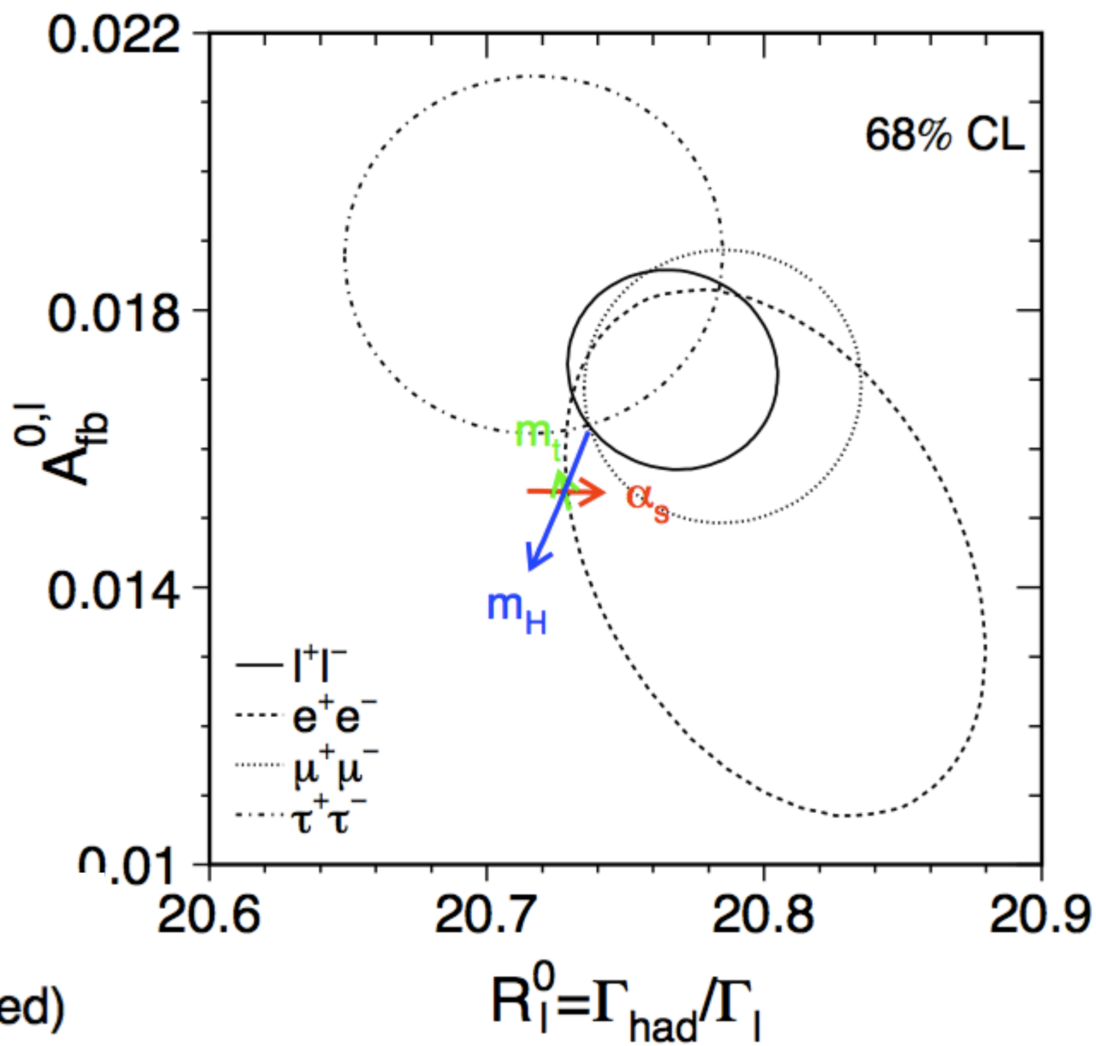


Asymmetry varies with centre-of-mass energy.

Lepton universality

$R_\ell^0 \equiv \Gamma_{\text{had}}/\Gamma_{\ell\ell}$

- Fit of SM parameters
  - Plot asymmetry AF versus $R_0 = \Gamma_{had}/\Gamma_{ll}$.
  - Contours contain 68% probability.
- Lepton universality OK.
  - Results agree with SM (arrows)



$M_t = 174.3 \pm 5.1$ GeV

$M_H = 300^{+700}_{-186}$ GeV (low M_H preferred)

$\alpha_s(M_Z^2) = 0.118 \pm 0.002$

LEP1 results

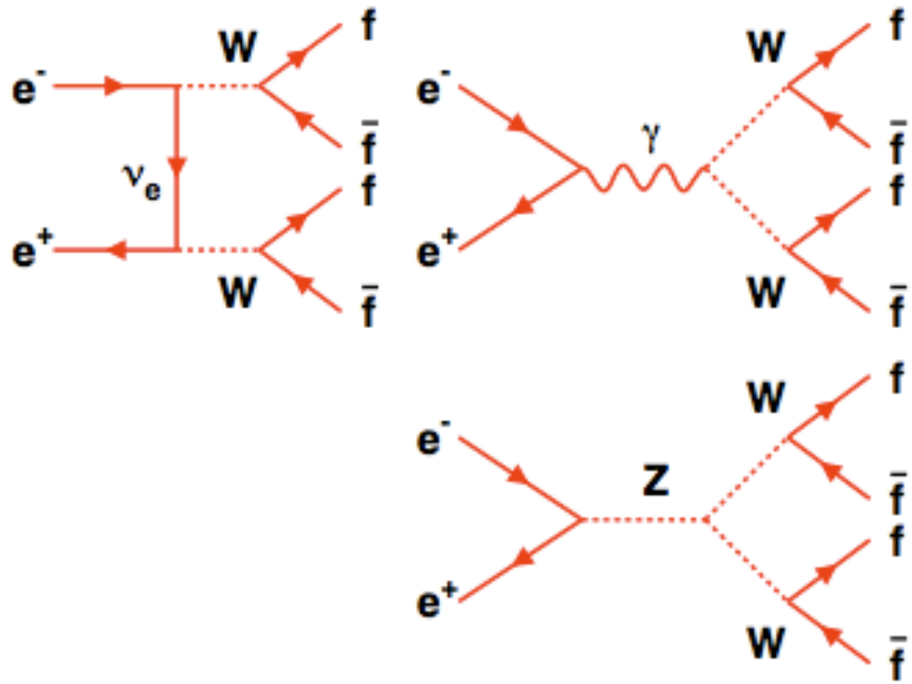
- Summary -
  - Very precise measurements of Z mass, width, cross-sections, partial widths and lepton forward-backward asymmetries.
  - High statistics data samples. Careful control of systematic errors.
- Number of generations determined
  - recall: original hope was precision $\sigma(N_\nu)\sim0.2$

Fitted	M_Z [GeV]	91.1875 ± 0.0021
	Γ_Z [GeV]	2.4952 ± 0.0023
	σ_h^0 [nb]	41.540 ± 0.037
	R_ℓ^0	20.767 ± 0.025
	$A_{FB}^{0,\ell}$	0.0171 ± 0.0010

Derived	Γ_{inv} [MeV]	499.0 ± 1.5
	Γ_{had} [MeV]	1744.4 ± 2.0
	$\Gamma_{\ell\ell}$ [MeV]	83.984 ± 0.086
	N_ν	2.984 ± 0.008

LEP2: opening WW

- W-pair production
  - LEP2: raising the E_{cm} gradually to ~200 GeV
  - At $E_{cm} > 2M_W$ W-pair production opens
- W-decay democratic
  - 2/3 quarks
  - 1/3 leptons
    - 46% $q\bar{q}q\bar{q}$ – typically 4 jets
      effic/purity ∼ 90%/80%
    - 44% $q\bar{q}\ell\nu$ – 2 jets, one charged lepton, missing p
      effic/purity ∼ 80%/90%
    - 10% $\ell\nu\ell\nu$ – two charged leptons, missing p
      effic/purity ∼ 60–80%/90%

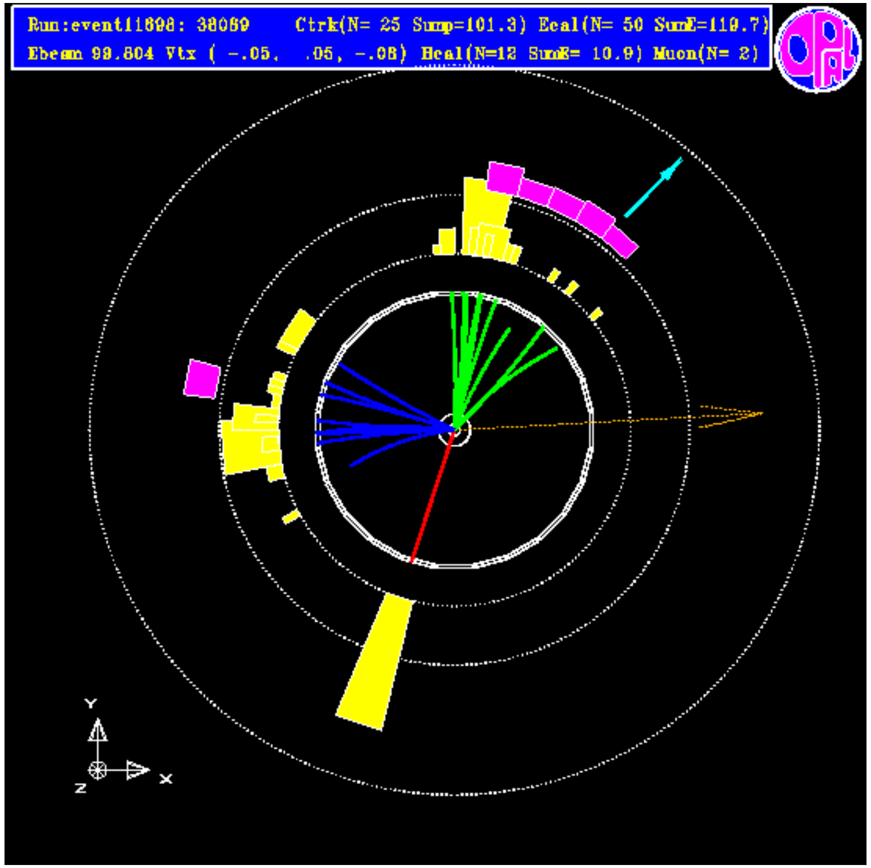


Direct probe of triple gauge couplings

WW events in OPAL

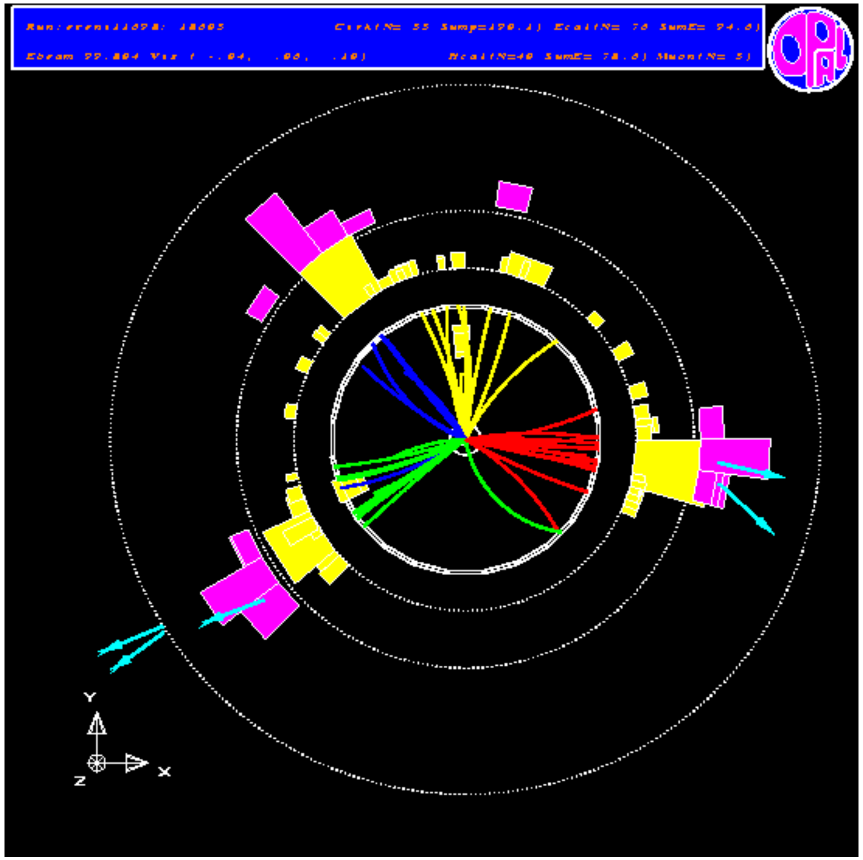
Semi-leptonic decay

Ÿ $WW \rightarrow \bar{q}qe\nu_e$



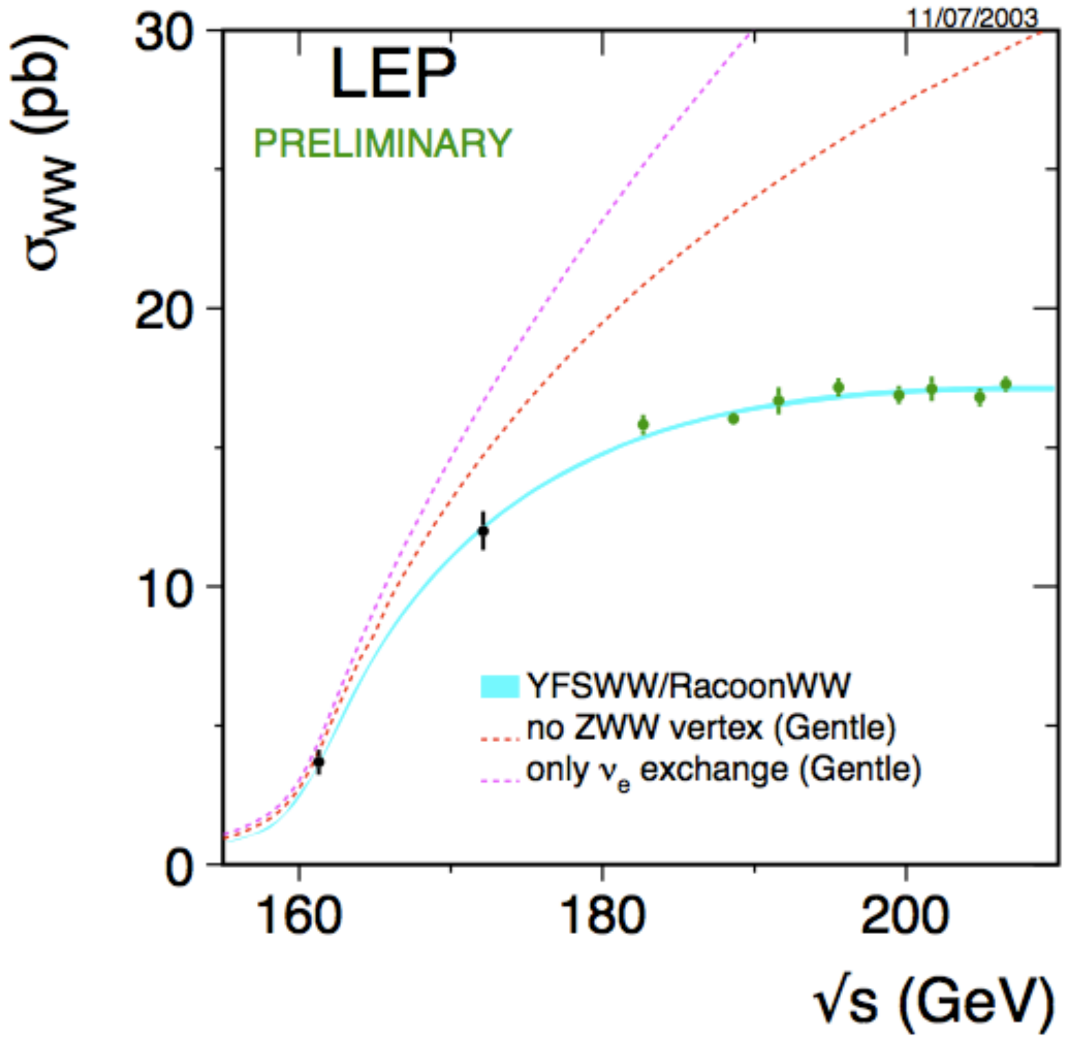
Fully hadronic decay

Ÿ $WW \rightarrow q\bar{q}q\bar{q}$



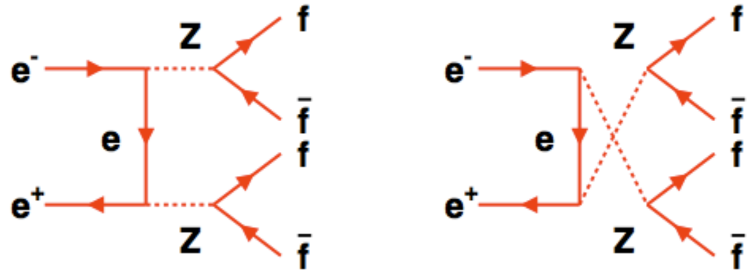
WW production cross section

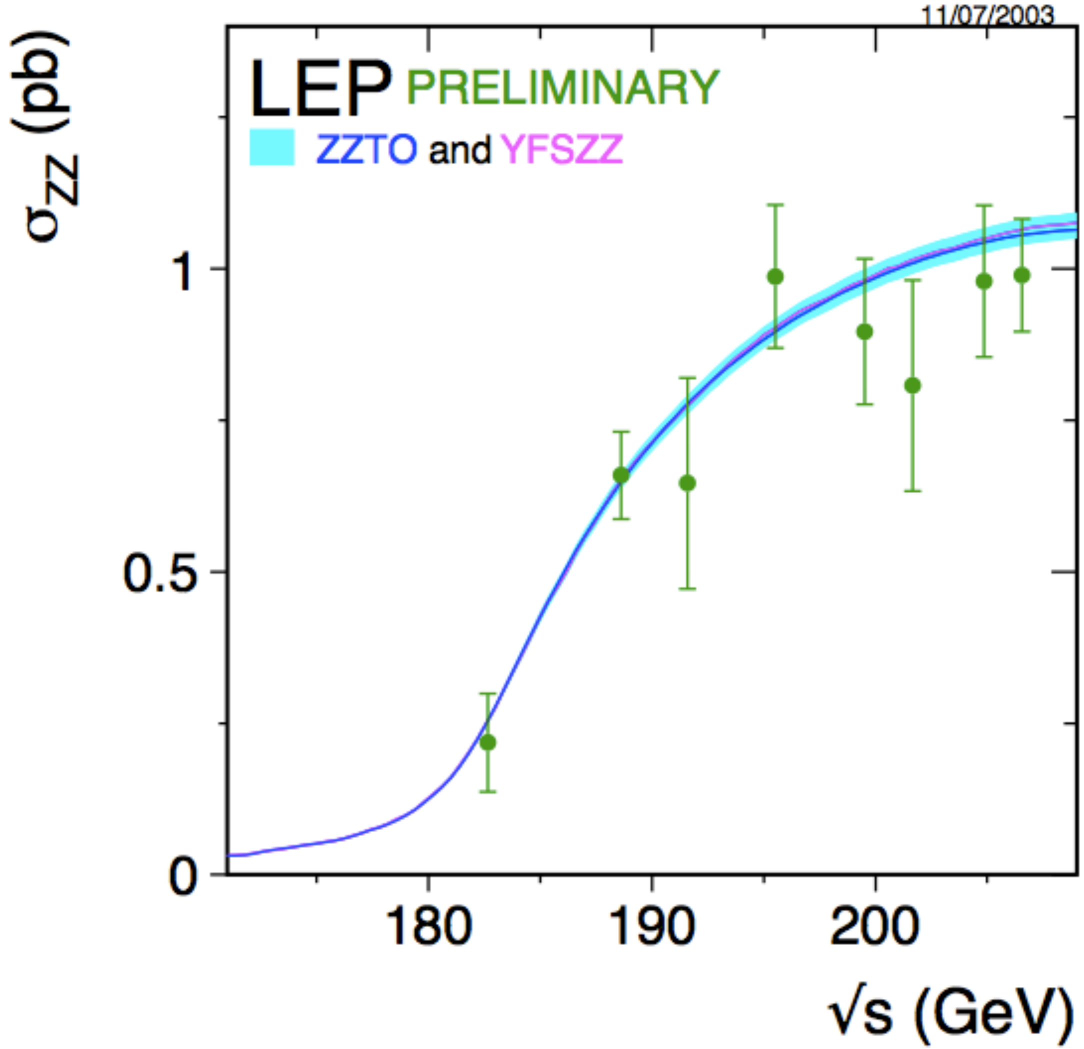
- Production W-pairs at threshold
  - cross section determines the W-mass
  - at higher energies M_W from direct reconstruction final state
- Sensitivity to gauge couplings
  - Beautiful demonstration of non-abelian nature of electroweak theory.



ZZ production cross section

- Cross section factor ~15 smaller
  - Yet another test of SM physics
  - Prelude to Higgs searches at LEP

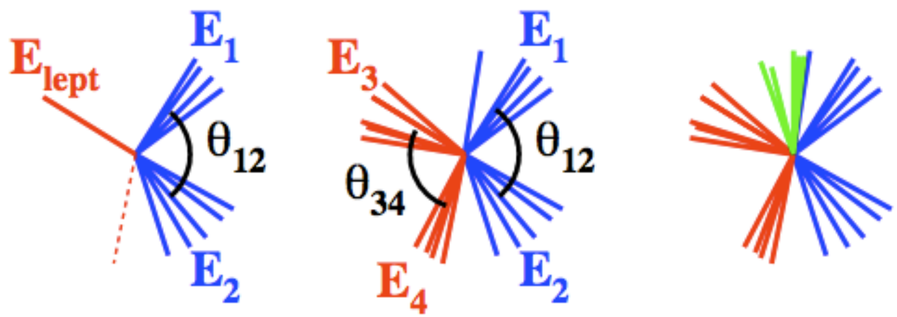


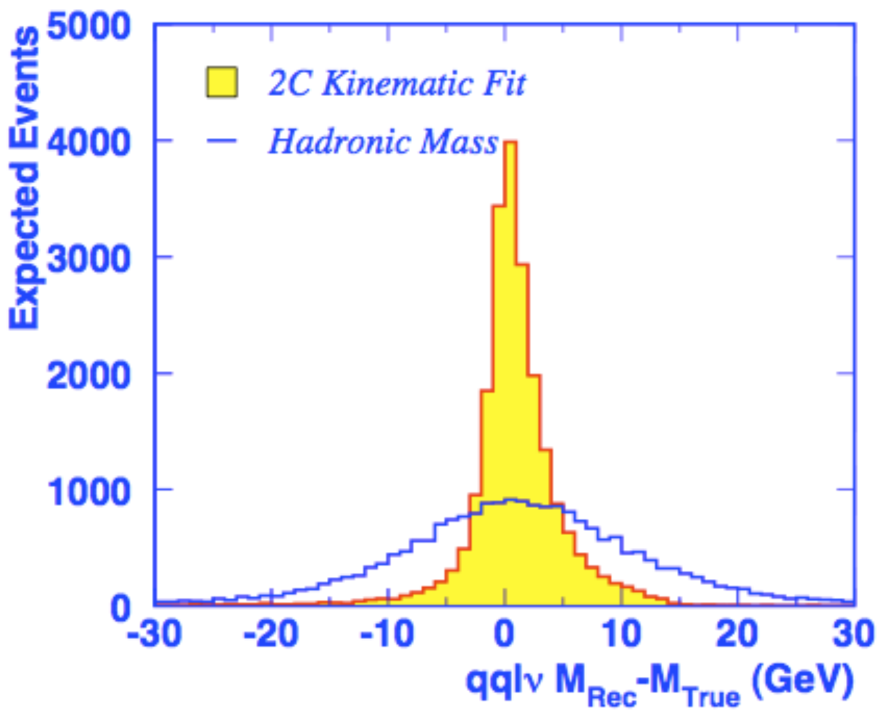


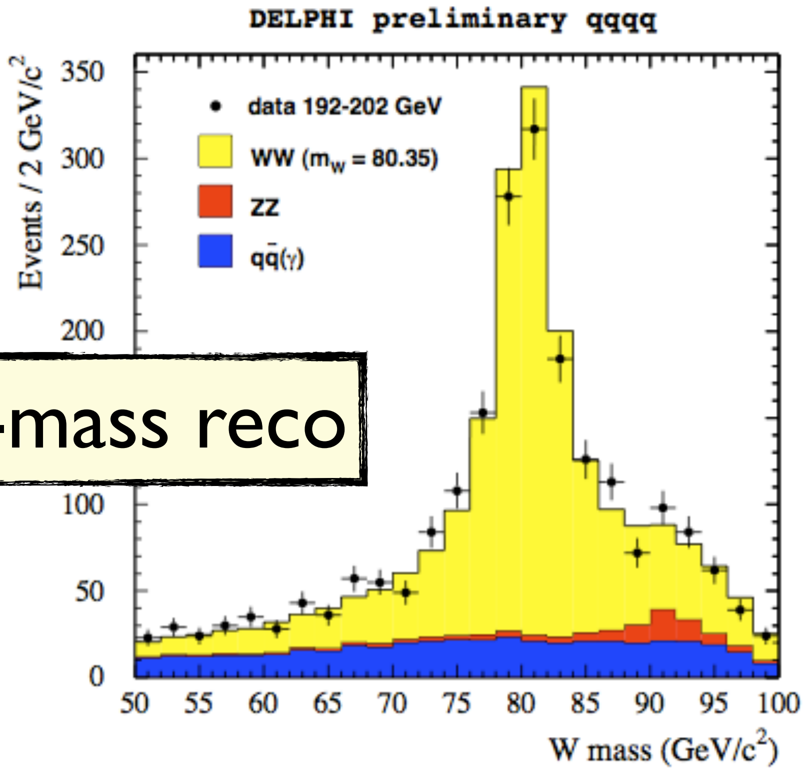
W mass measurement

uncertainty ~ 40 MeV

- Reconstruct final state W masses
  - depending on topology, make kinematic fit
  - Use constraint on energy-momentum



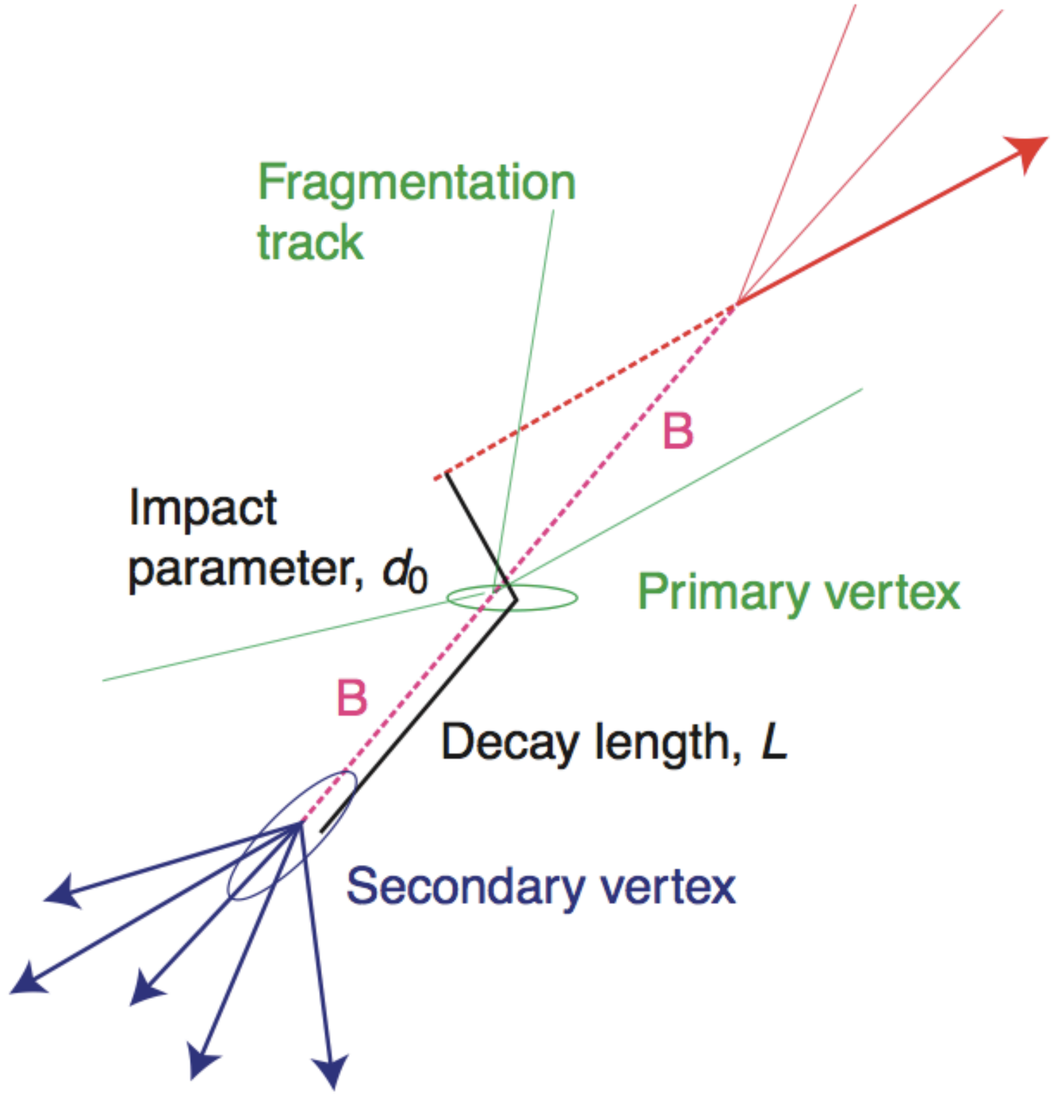




W-mass reco

Tagging heavy quarks

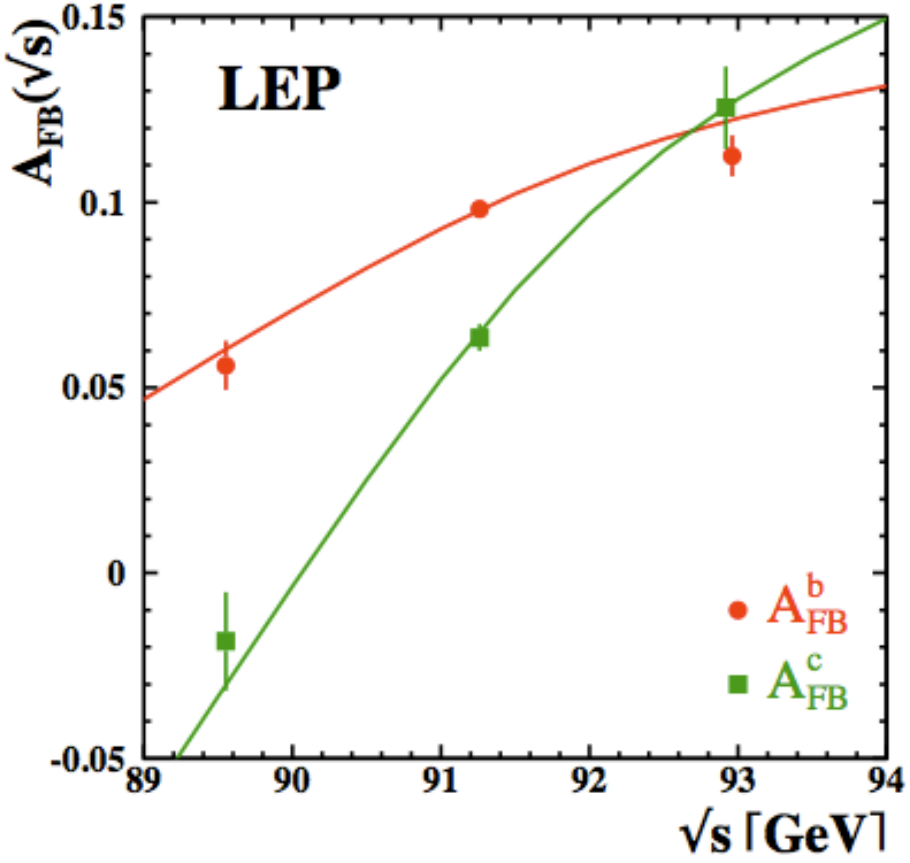
- Heavy hadrons
  - have long lifetime and large boost at LEP
- Reconstruction of 2nd vertex
  - Technique depends critically on vertex detectors
  - Used throughout Tevatron and LHC as well



d_0 and L are signed quantities.
A badly measured track may intercept the “wrong-side” of the beam spot.

Heavy flavor program

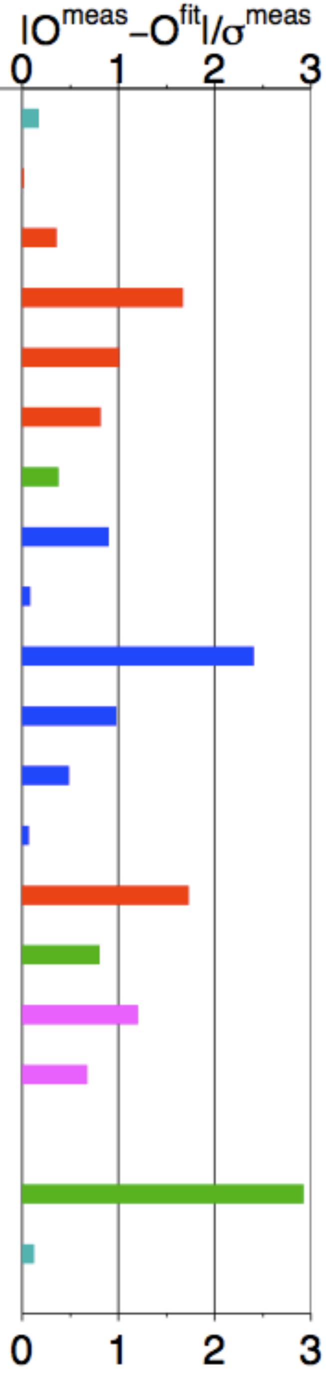
- Large program opens with b-tagging



  - e.g. the forward-backward asymmetry of b-quarks
  - Differs in E_{cm} dependence from light quarks due to mass of the b-quark

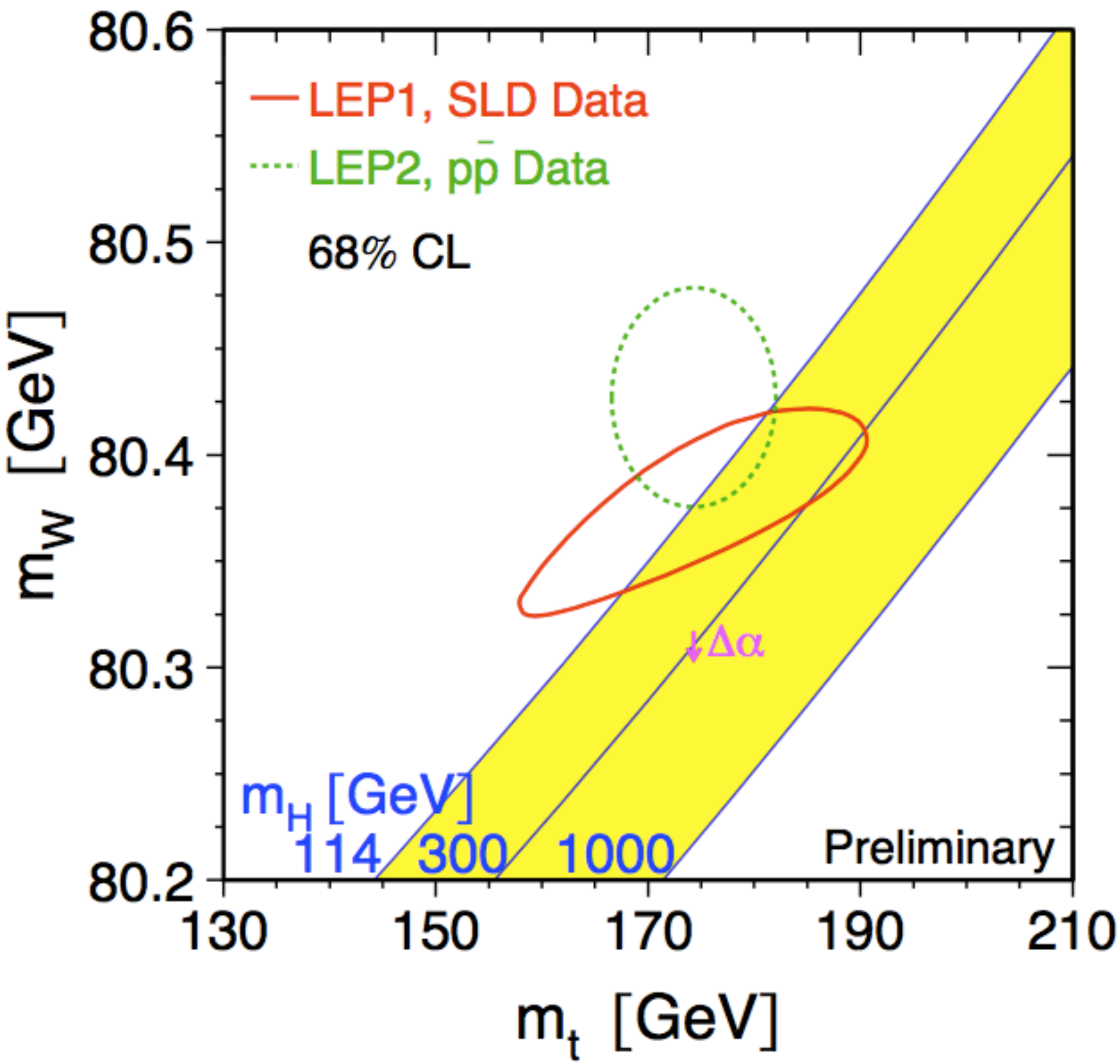
Fit to SM

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02761 ± 0.00036	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1875
Γ_Z [GeV]	2.4952 ± 0.0023	2.4960
σ_{had}^{0} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01636
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1477
R_b	0.21638 ± 0.00066	0.21579
R_c	0.1720 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0997 ± 0.0016	0.1036
$A_{fb}^{0,c}$	0.0706 ± 0.0035	0.0740
A_b	0.925 ± 0.020	0.935
A_c	0.670 ± 0.026	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1477
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.426 ± 0.034	80.385
Γ_W [GeV]	2.139 ± 0.069	2.093
m_t [GeV]	174.3 ± 5.1	174.3
$\sin^2\theta_W(\nu N)$	0.2277 ± 0.0016	0.2229
$Q_W(Cs)$	-72.84 ± 0.46	-72.90



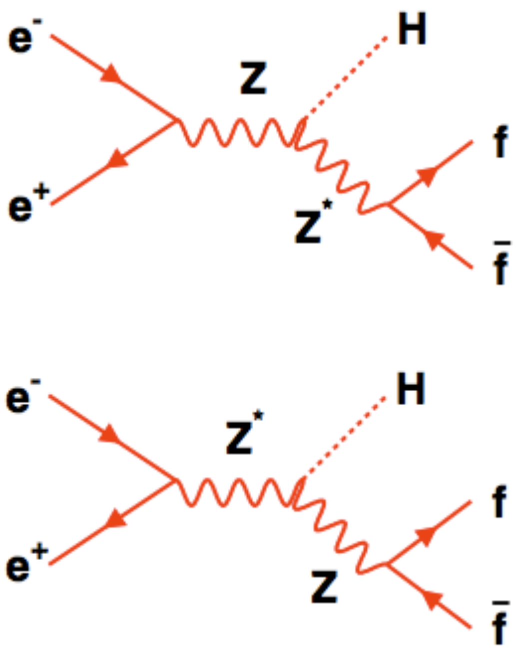
Radiative corrections

- Sensitivity on Higgs mass M_W and M_{top}
  - logarithmic dependence Higgs mass
  - preference for a "light" Higgs

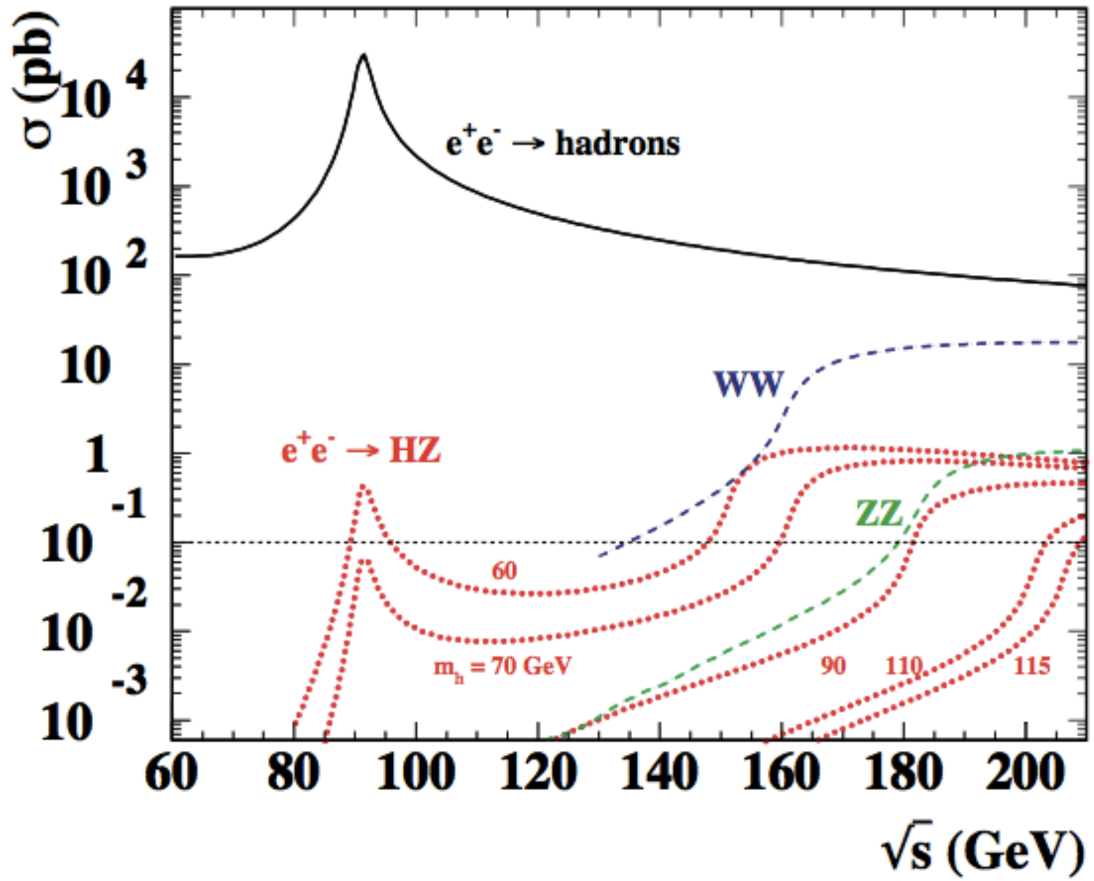


Higgs production at LEP

- Higgs radiation of Z-boson



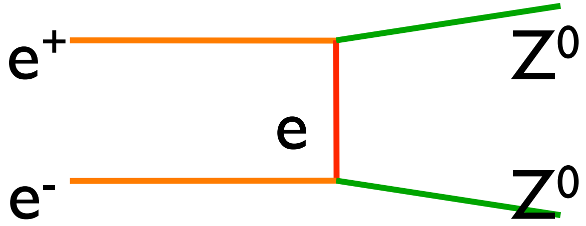
(Plus WW fusion)



$$M_{\mathrm{H}} \lesssim \sqrt{s} - M_{\mathrm{Z}}$$

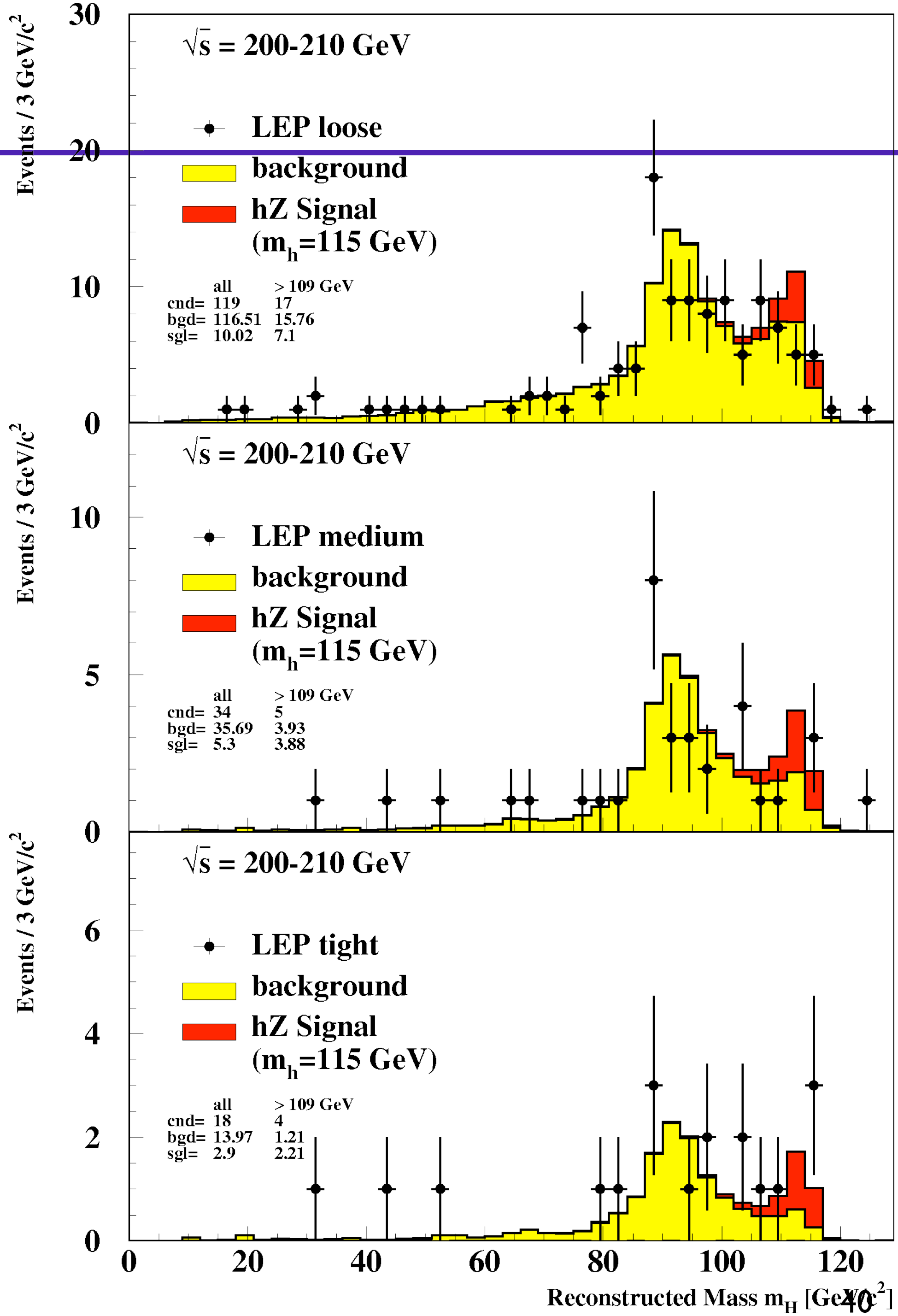
Systematic search

- Main source of background:



  - Production of 2 Z^0 bosons
  - Z^0 decay to b-quarks
  - Irreducible background from Z^0Z^0 contaminates the Higgs search
  - Extremely difficult search–region!

LEP combined,
Various values for background reduction criteria

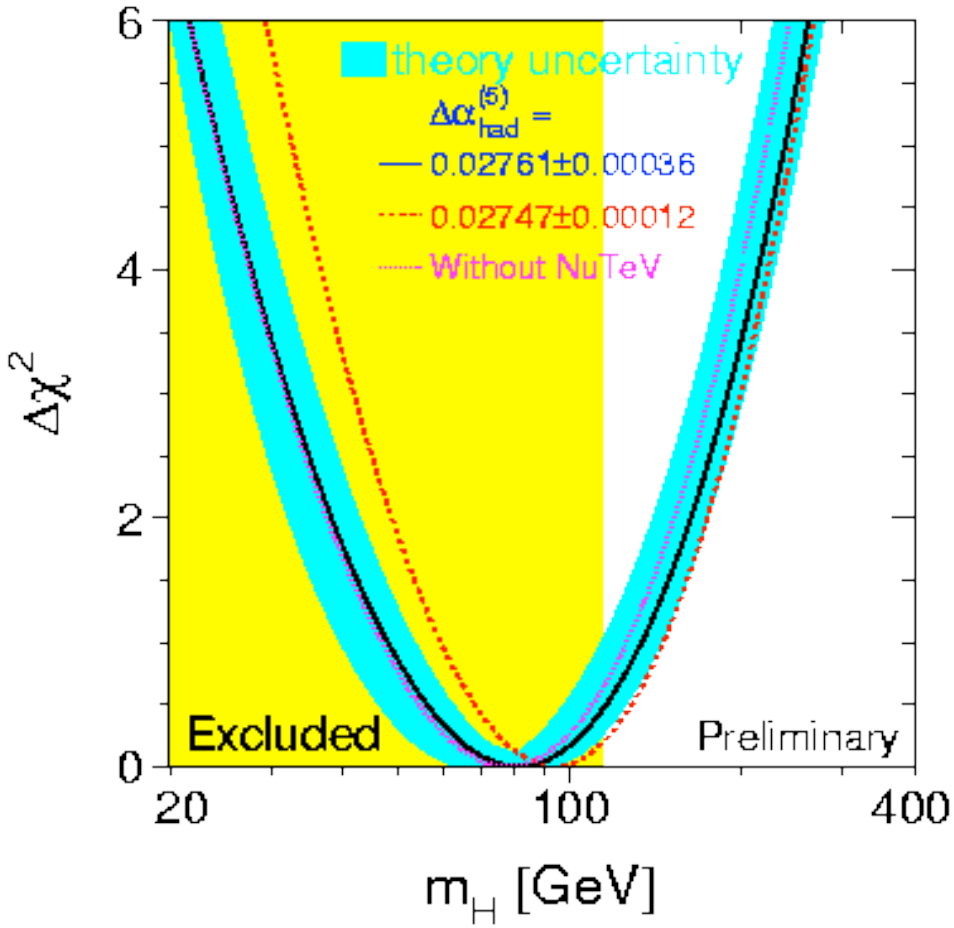


Higgs limits

- LEP Higgs result:
  - Limit on the (Standard Model) Higgs mass:

$$m_H > 114.4 \text{ GeV}$$

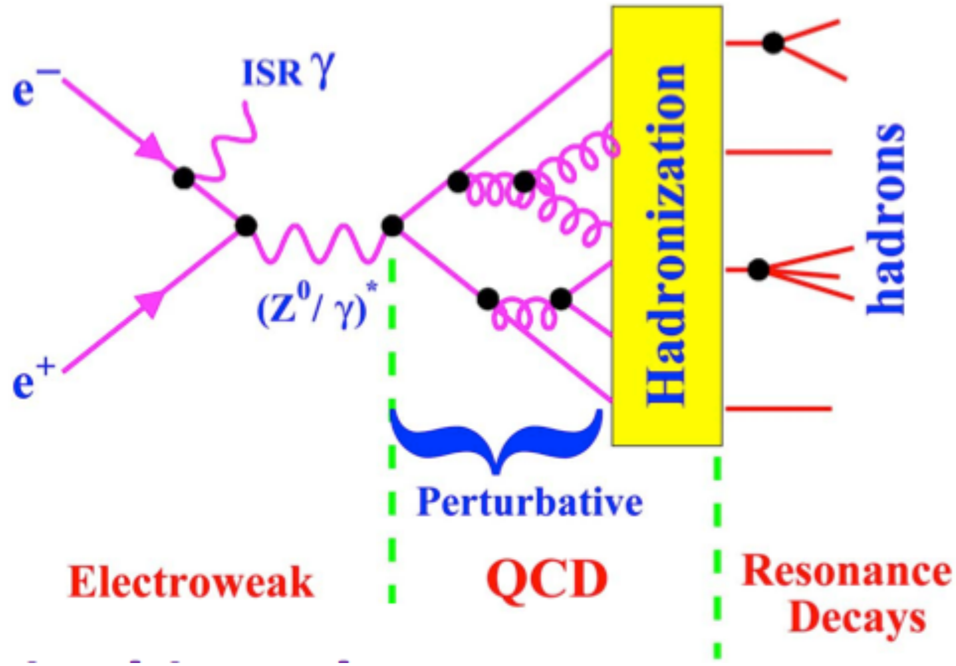
  - at the 95% confidence level
  - using all available data (up to cm energy √s=206 GeV)
- Above this limit:
  - a modest indication for a possible signal with m_H=116-118 GeV (~2σ level)



By 1-11-2000 LEP closed definitively
Stirred emotions involved!

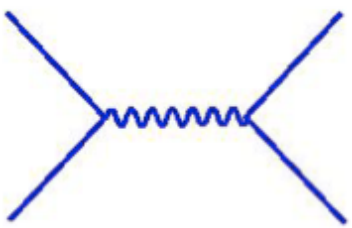
QCD at high energy e^+e^- colliders

- QCD events in e^+e^- annihilations:
  - perturbative regime
  - hadronization

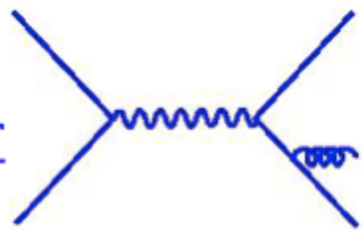


- Perturbative hierarchy:

2-jets (tree): α_S^0
→ no QCD

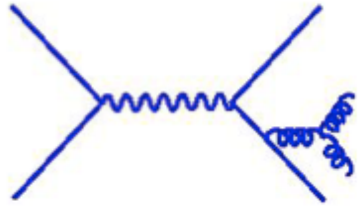


3-jets (tree): α_S^1
→ Leading order (LO) one loop

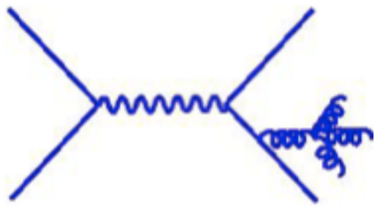


Perturbative calculations (recap)

- <u>NLO</u>: α_s^2
  - Tree level for e+e- → 4 jets
  - 2-loop corrections to e+e-→ 2 jets

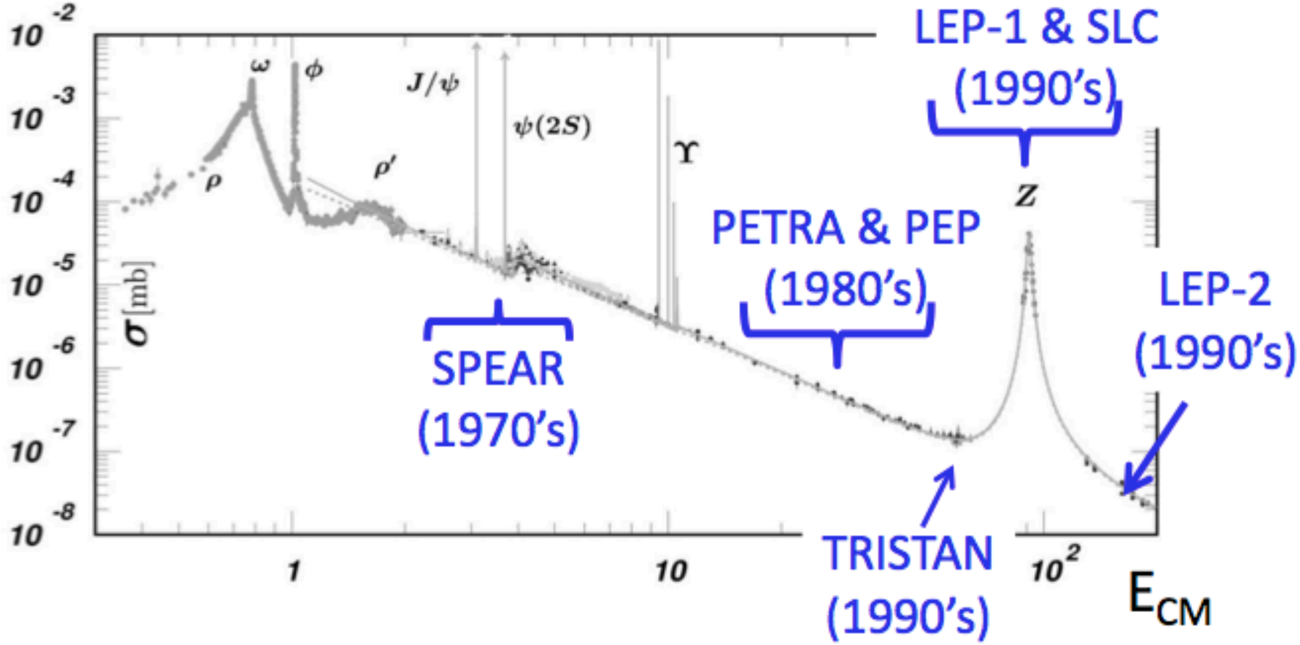


- <u>NLLA</u>: Next-to-leading-log approximation
  - Summation of collinear terms in all orders in α_S
- <u>NLO+NLLA</u>:
  - The standard at the end of LEP data taking
- <u>NNLO</u>: $\alpha^3{}_S$ → 3 loop corrections
  - Total e+e- → hadrons cross section
  - Event shapes (Thrust etc)



- State of the art: <u>NNLO+matched NLLA</u>

jets in e^+e^- accelerators



- SPEAR (SLAC):
  - discovery of quark jets
- PETRA (Desy) & PEP (SLAC):
  - first high energy jets (> 10 GeV)
  - discovery of gluon jets, many pionering QCD studies
- LEP (Cern) and SLC (Slac):
  - Large energies, small α_S, i.e. more reliable calculations, smaller hadronic uncertainties
  - Large data samples
  - Precision tests of QCD

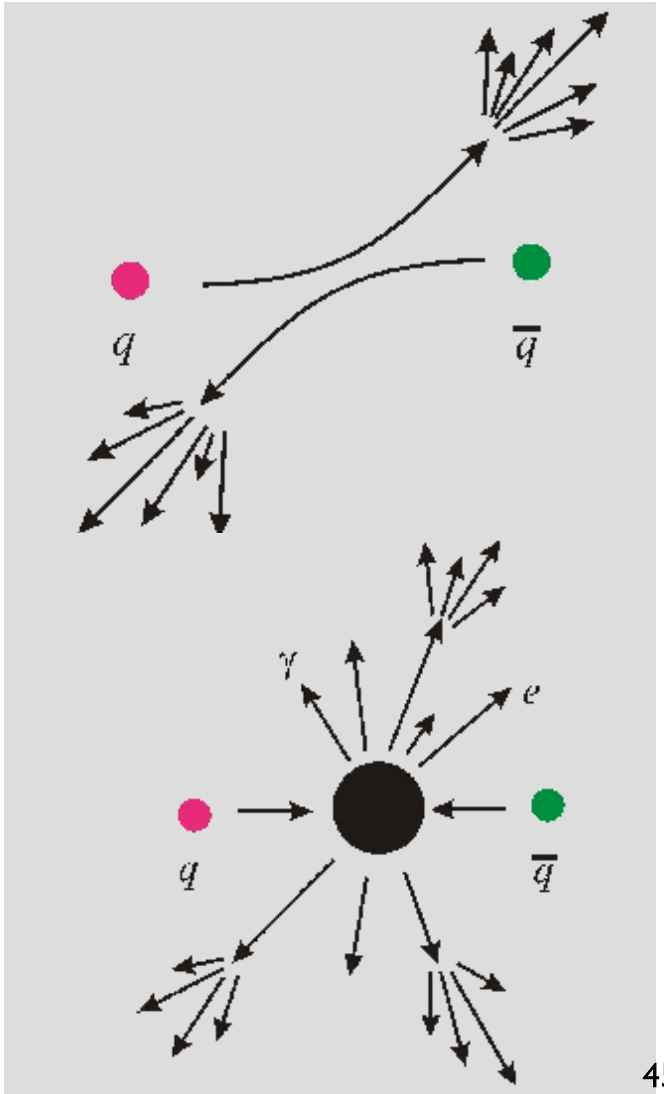
Event shapes

- Four-momentum vectors: $p_i = (E_i, \vec{p}_i)$

- Sphericity tensor:

$$S^{\alpha\beta} = \frac{\sum_i p_i^\alpha p_i^\beta}{\sum_i |\vec{p}_i|^2}$$

  - Eigenvalues with $\lambda_1 \geq \lambda_2 \geq \lambda_3$, $\lambda_1 + \lambda_2 + \lambda_3 = 1$
  - Sphericity $S = \frac{3}{2}(\lambda_2 + \lambda_3)$
  - 2-jet event: $S \sim 0$
  - isotropic event: $S \sim 1$



Event shapes

- Aplanarity $A = \frac{3}{2}\lambda_3$ $0 \leq A \leq \frac{1}{2}$
  - Planar event: $A \sim 0$
  - Isotropic event: $A \sim \frac{1}{2}$
    - Distinguish 3- 4 parton final states

- Eigenvectors $\vec{\nu}_j$ corresponding to eigenvalues λ_j
  - $\vec{\nu}_1$ is called the sphericity axis
  - Sphericity event plane is spanned by $\vec{\nu}_2$ and $\vec{\nu}_3$

Event shapes

- Thrust

$$T = \min_{|\vec{n}|=1} \frac{\sum_i |\vec{p} \cdot \vec{n}|}{\sum_i |\vec{p}|}$$

  - Thrust axis $\vec{\nu}_1$ is given by the vector $\vec{n}$ for which the maximum is obtained
  - Allowed range: $\frac{1}{2} \le T \le 1$

> - 2 jet event: $T \sim 1$
> - isotropic event: $T \sim \frac{1}{2}$

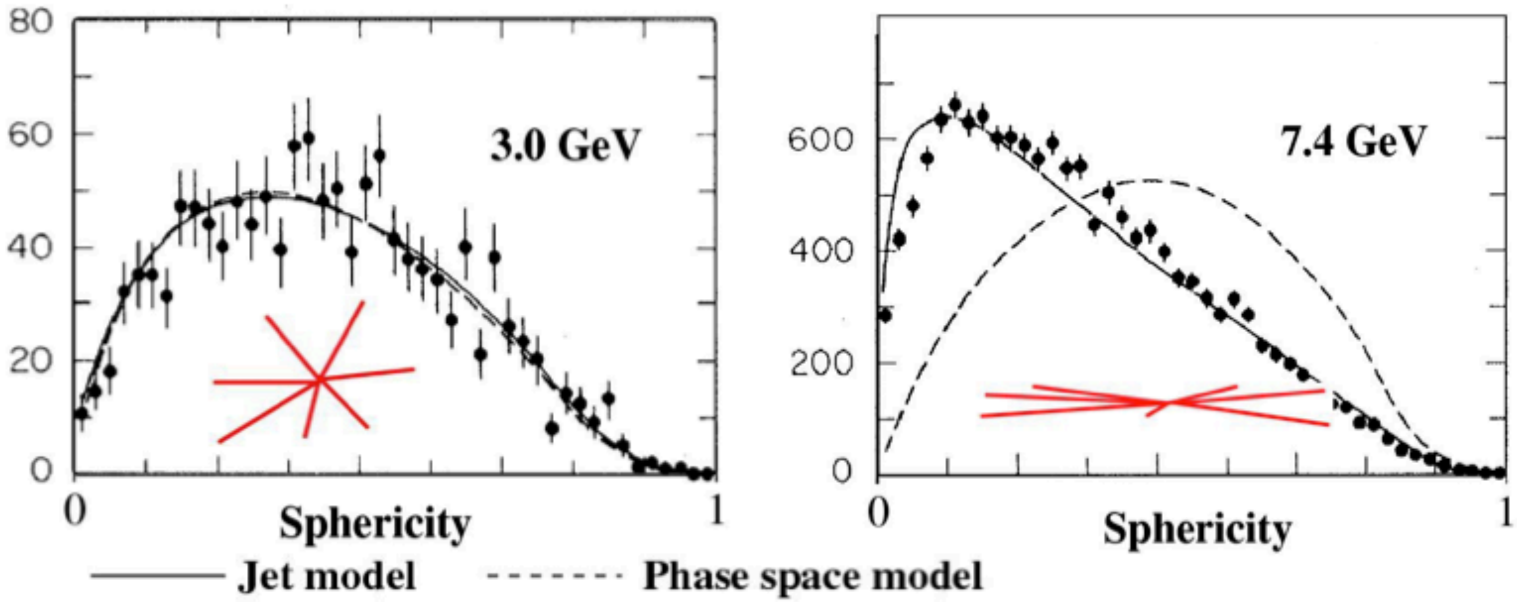
- Major Thrust
  - Major axis defined in the plane perpendicular to thrust

$$T_{major} = \max_{|\vec{n}|=1, \vec{n}\cdot\vec{\nu}_1=0} \frac{\sum_i |\vec{n} \cdot \vec{p}_i|}{\sum_i |\vec{p}_i|}$$

  - A minor axis is defined as well, as the third axis
- Oblateness:
  - $O = T_{major} - T_{minor}$

> Event symmetrical around thrust axis: $O \approx 0$
> High oblateness corresponds to a planar event

Discovery of jets



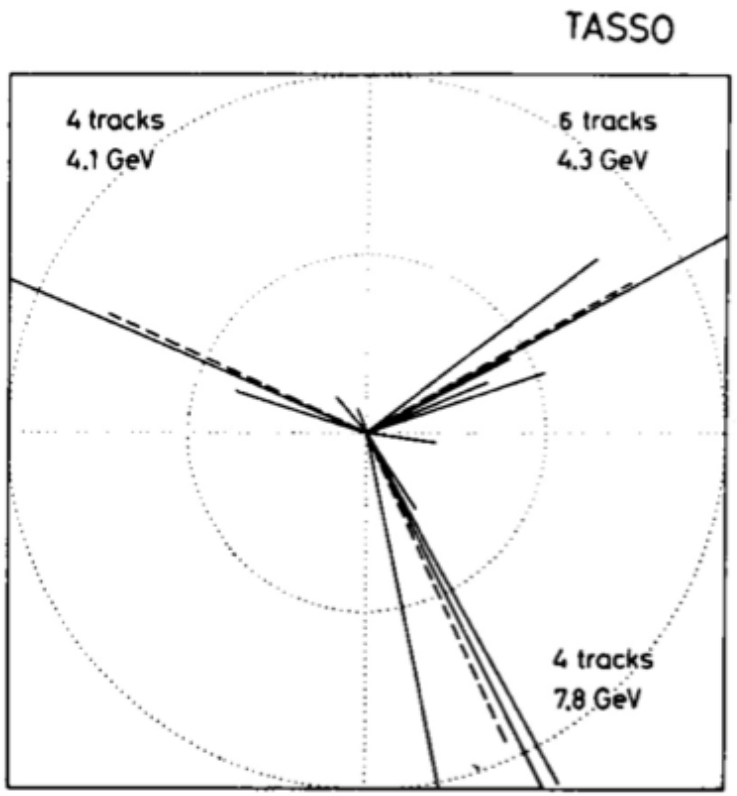
SPEAR

- Sphericity:
  - At higher energies:
    - particles cluster around an axis
    - first observation of jet structure

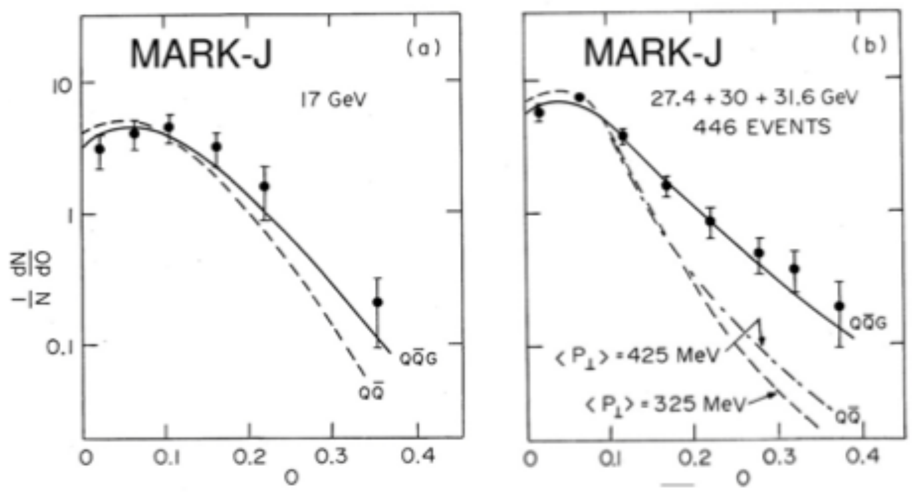
First observation of events with small sphericity

Discovery of gluon jets

- Three-jet events - seen by TASSO (PETRA)



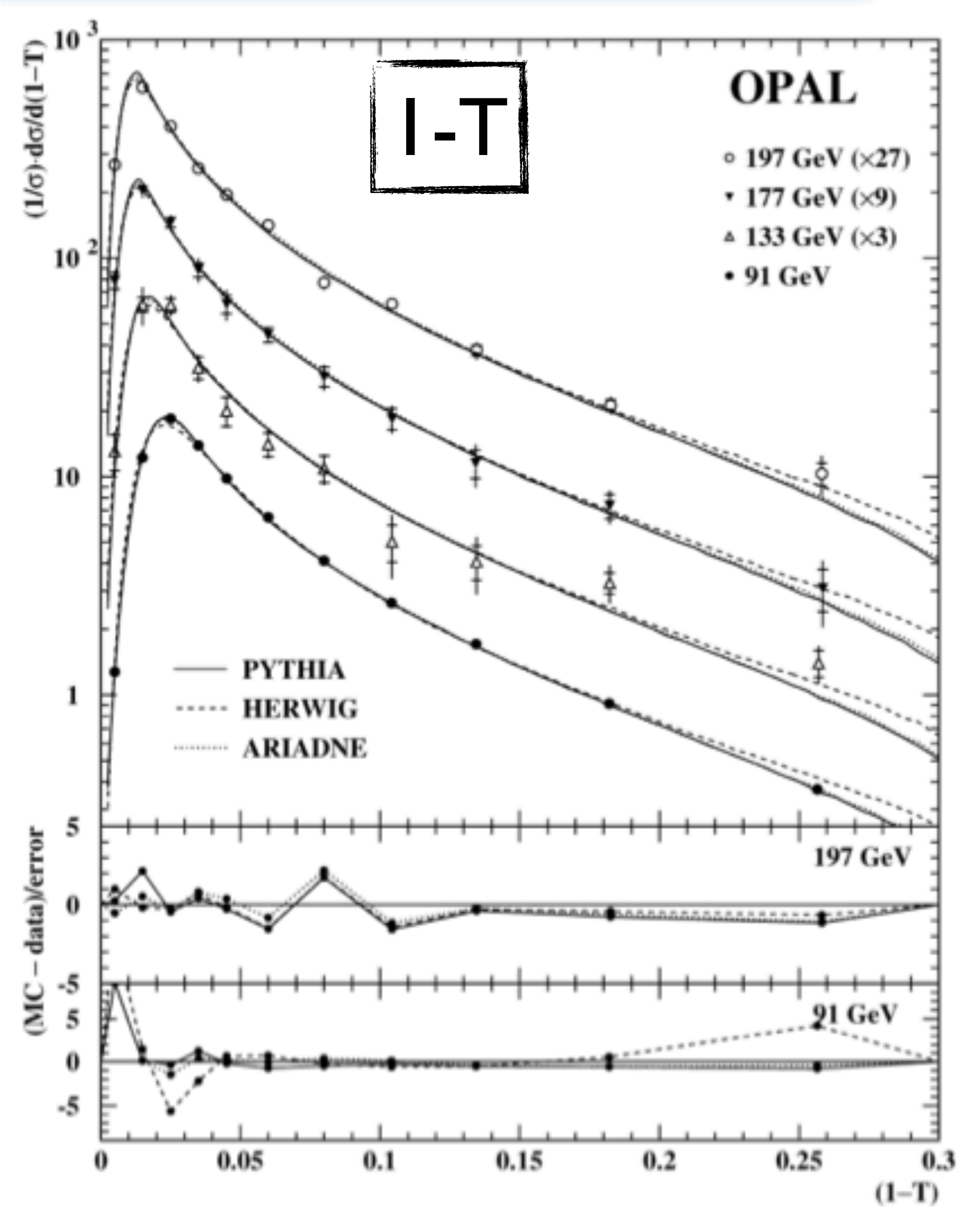
1st three-jet event seen by TASSO



- Oblateness:
  - Events at E_{cm}=30 GeV exhibit larger Oblateness (planar structure) than models without hard gluon radiation

Monte Carlo event generators

- Key ingredient
  - Detector response
  - Hadronization effects
  - Sensitivity to physics
- Principal programs
  - Pythia
  - Herwig
  - Ariadne
- Tuned to LEP-1 data
  - global properties
    - event shapes, multiplicity
  - Identiefied particle rates and spectra



Jet algorithms

- Many QCD tests group particles into jets

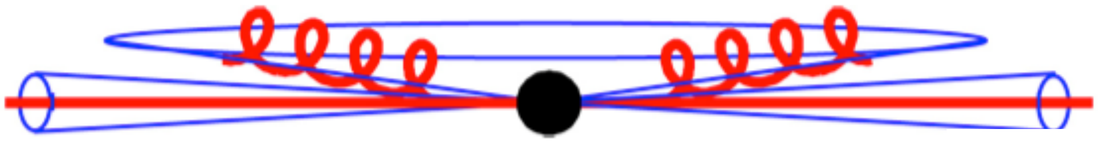
- Recombination (cluster) algorithms
  - most common choice for e+e- events
  - Metric: $y_{ij} = M_{ij}^2/s$
  - Combine particle pair ij with smalles value y_{ij}
    - E-scheme: add 4 momenta $p_k = p_i + p_j$
    - E0 scheme: require jets to be massless

$$E_k = E_i + E_j$$
$$\vec{p}_k = \frac{\vec{p}_i + \vec{p}_j}{|p_i + p_j|} E_k$$

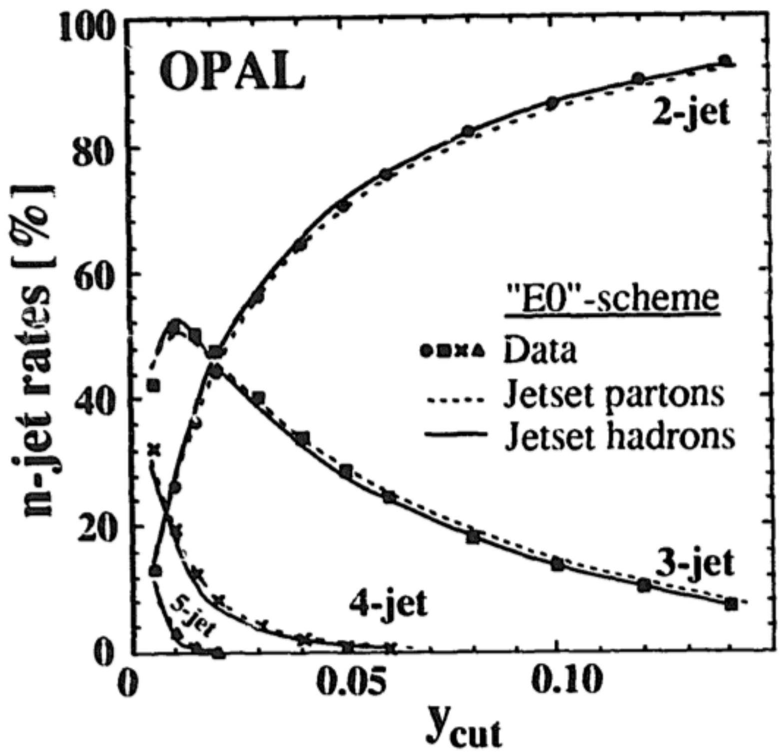
  - Iterate until all pairs satisfy $y_{ij} > y_{cut}$

JADE jet finder

- Original recombination jet algorithm
  - Metric: $M_{ij}^2 = 2E_iE_j(1 - \cos\theta_{ij})$

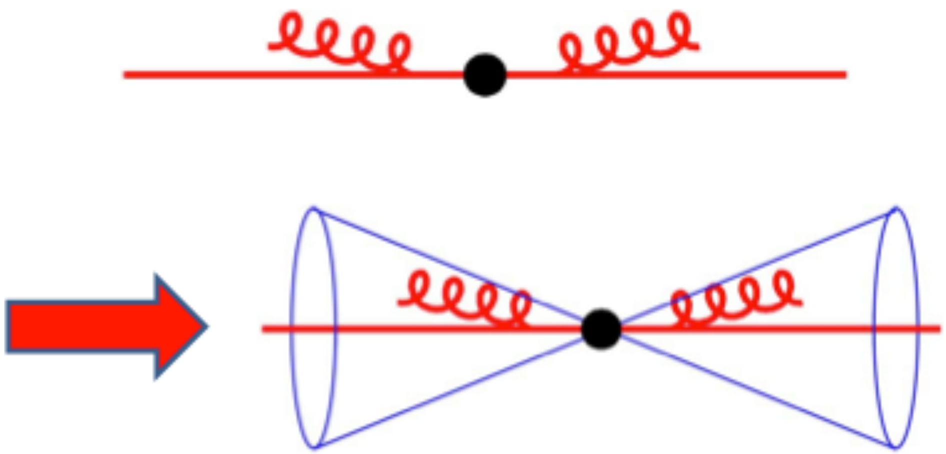


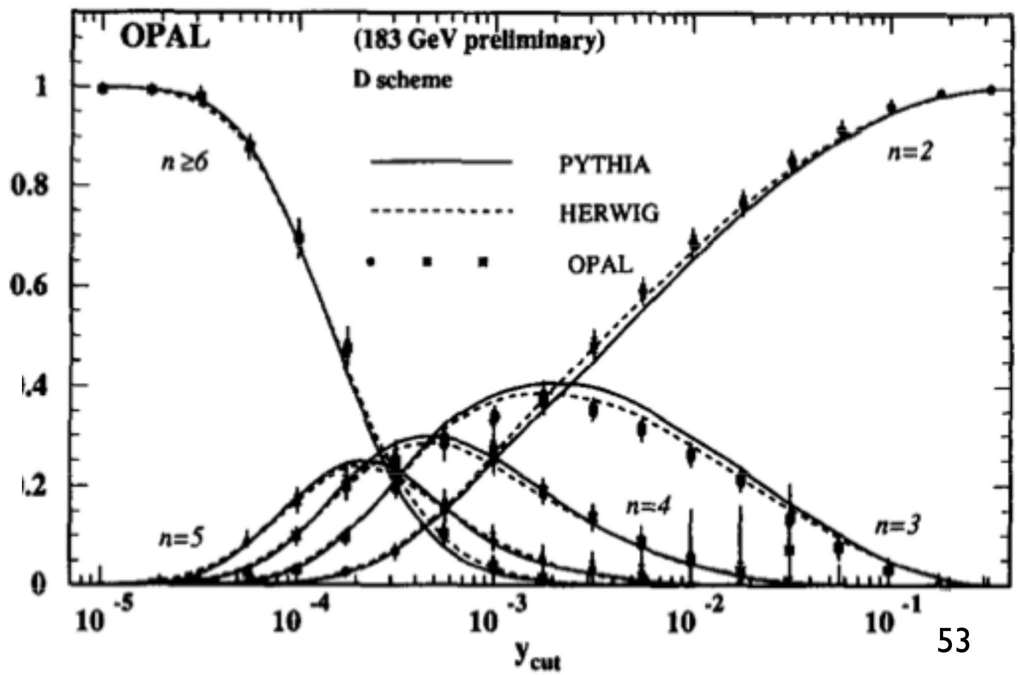
  - Original version: E0-scheme for combination of particles can lead to "junk-jets"
    - a 2-jet event with soft, colinear radiation can be classified, unnaturally, as a 3-jet event
  - Fraction of 'n-jets' as function of y_{cut}
    - for high y_{cut}: only 2-jet left



The K_T "Durham" jet finder

- Metric $$M_{ij}^2 = 2\min(E_i^2, E_j^2)(1-\cos\theta_{ij})$$
  - with E-scheme for combining particles
  - The metric is proportional to the perpendicular momentum of the smaller jet wrt the larger jet
  - As a result, soft colinear radiation is attached to the correct jet

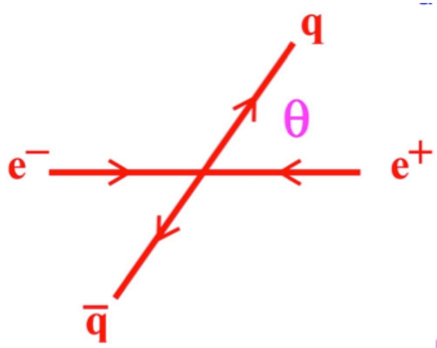




2-jet matrix: spin of the quark

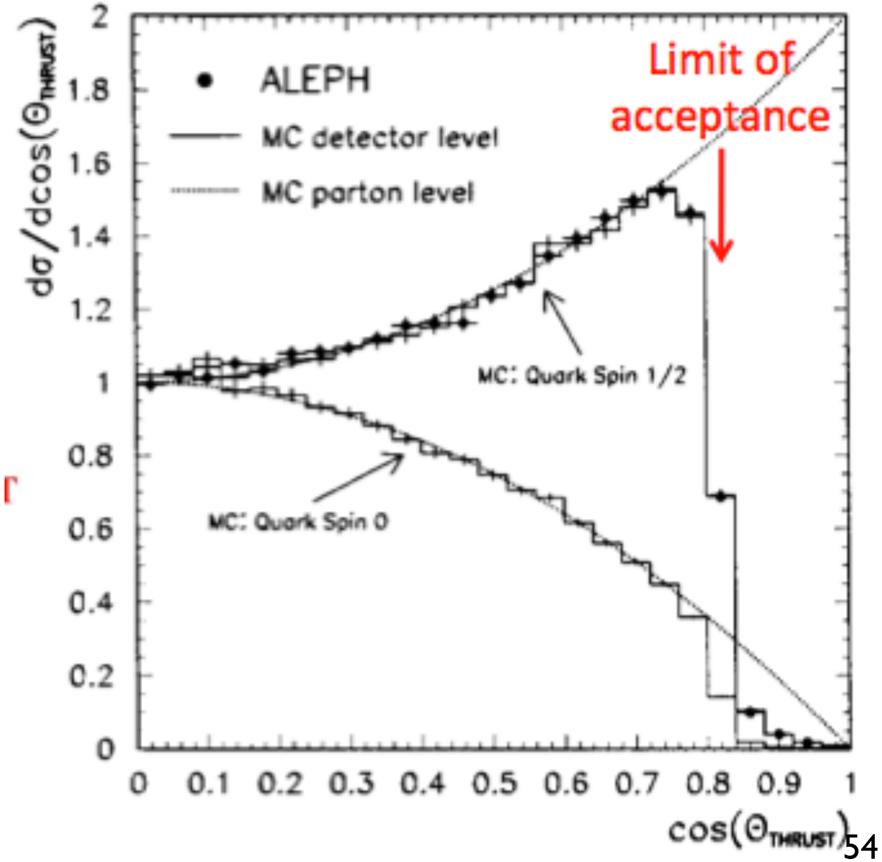
- Matrix element calculations

$$\frac{d\sigma}{d\Omega} \sim 1+\cos^2\theta \left(\text{spin} = \frac{1}{2} \right)$$
$$\sim \sin^2\theta \,(\text{ spin} = 0)$$



  - Prediction for the energy and angular distributions of jets
  - Verify by investigating the Thrust-axis

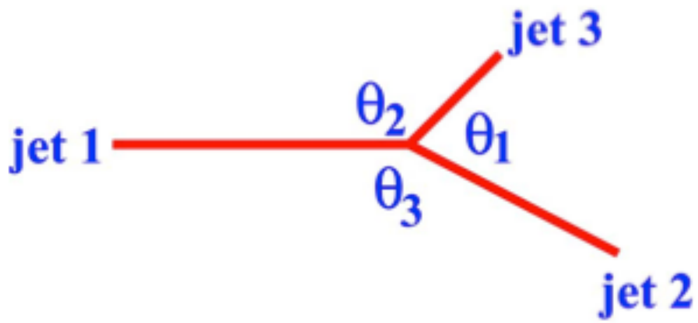
$$T = \min_{|\vec{n}|=1} \frac{\sum_i |\vec{p}\cdot\vec{n}|}{\sum_i |\vec{p}|}$$



- Quarks have spin s=1/2

3-jet matrix element; the gluon

- Likewise matrix elements for 3 parton final state



  - Select 3-jet events
    - JADE jet finder with y_{cut}=0.02
    - 25% of events are classified as 3-jets
  - Calculate the jet energies
    - Using angular information
    - More accurate than measured jet energies

$$E_i = E_{CM} \frac{\sin\theta_i}{\sum_i \sin\theta_i}$$

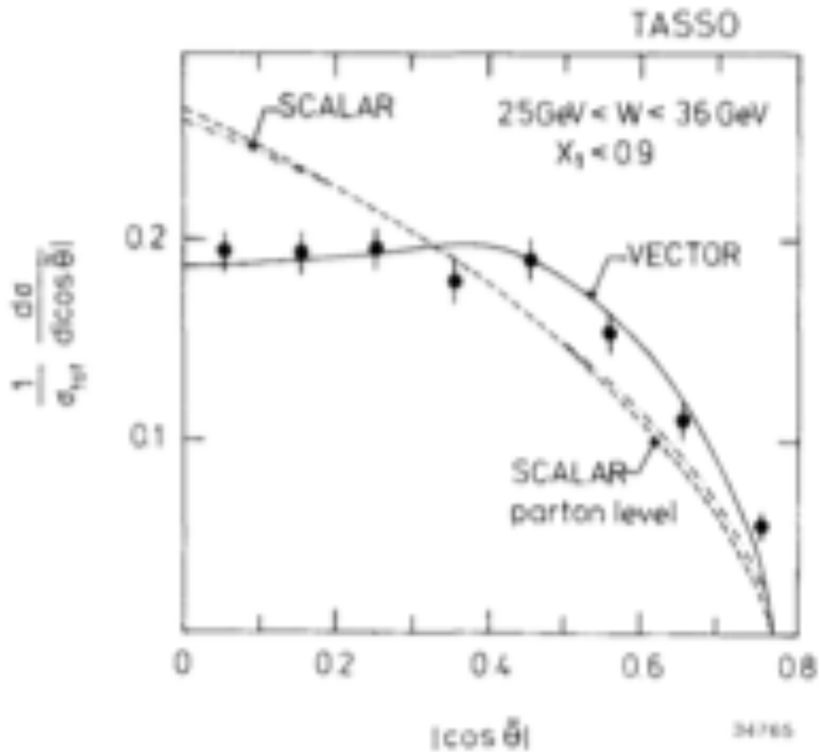
  - Order by jet energy $E_1 > E_2 > E_3$
    - jet 3 is gluon jet in 75% of the events
  - Define the scales jet energies

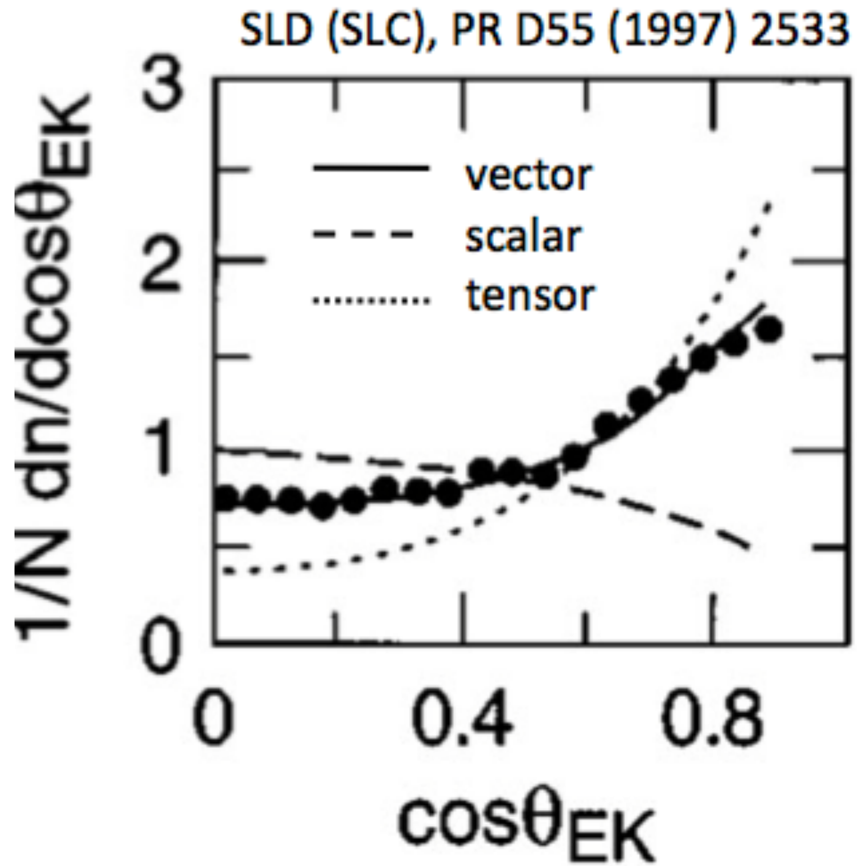
$$x_i = \frac{2E_i}{E_{CM}}$$

Spin of the gluon

- Define the Ellis-Karliner angle
  - Unambiguous: the gluon is a vector particle with s=1

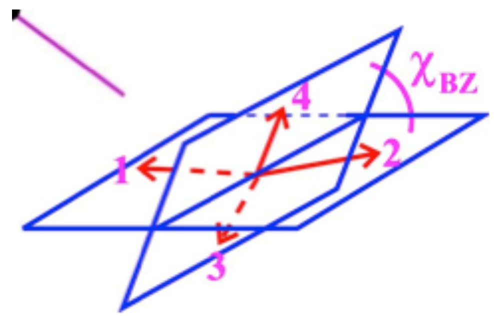
$$\cos\theta_{EK} = \frac{x_2 - x_3}{x_1}$$





4-jet matrix element

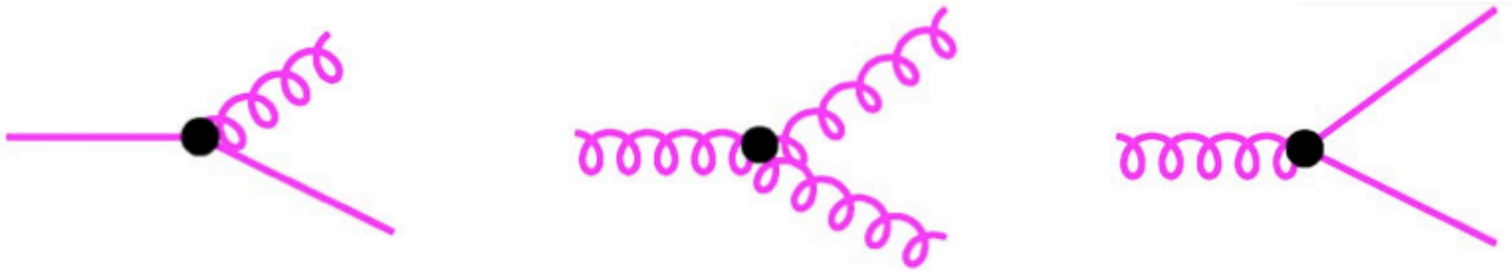
- Four parton final state
  - opens access to the triple gluon vertex



  - Select 4-jet events with y_{cut}=0.02
    - 9% of events classified as 4-jet events
  - Order by energy $E_1>E_2>E_3>E_4$
    - jets 3 and 4 more likely radiated particles
- Bengtsson-Zerwas angle
  - Discriminant variable for triple gluon vertex versus quark-anti-quark radiation
  - Based on spin structure difference between quarks and gluons

Color factors

- QCD is SU(3) gauge theory
  - The couplings of the fermion fields to the gauge fields and the self-interactions are determined by the coupling constant and the Casimir operators of the gauge group.
  - Measuring the eigenvalues of these operators, called colour factors, probes the underlying structure of the theory in a gauge invariant way.



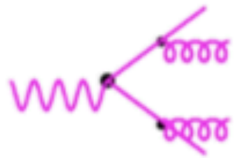
gluon radiation:	triple gluon vertex:	gluon splitting:
q → qg	g → gg	g → qq
$C_F = 4/3$	$C_A = 3$	$T_F = T_R n_f = ½n_f = 2.5$

$C_A/C_F = 2.25$

Color factors

- Calculation of $e^+e^- \rightarrow$ 4 jets
  - Separate the color structure
  - Angular observables 'y' differ for the three relevant diagrams

$$\frac{1}{\sigma_0}\frac{d\sigma}{dy} = \left(\frac{\alpha_S C_F}{\pi}\right)^2 \times [\, \sigma_A(y)$$



$$+ \left(1 - \frac{1}{2}\frac{C_A}{C_F}\right)\sigma_B(y) + \left(\frac{C_A}{C_F}\right)\sigma_C(y)$$

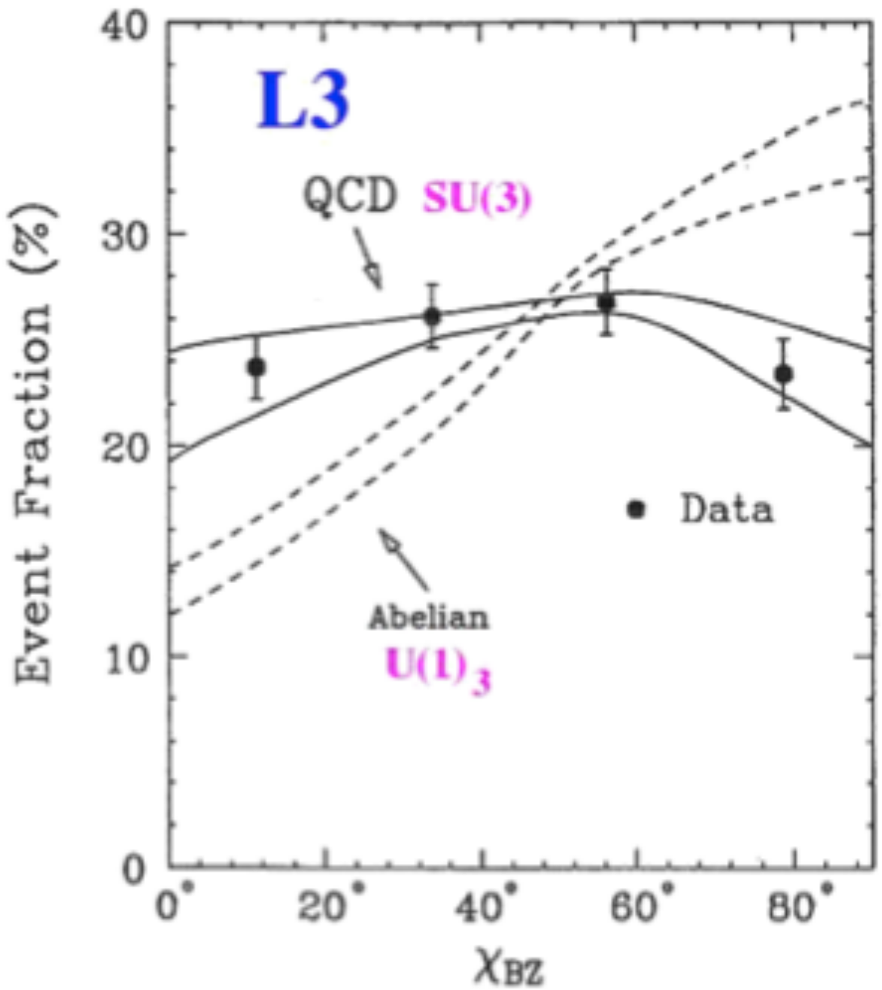
$$+ \left(\frac{T_F}{C_F} n_f\right)\sigma_D(y)$$

$$+ \left(1 - \frac{1}{2}\frac{C_A}{C_F}\right)\sigma_E(y)\,]$$

  - Determination of σ_A, σ_B, σ_C, σ_D gives access to color structure

Bengtsson-Zerwas angle

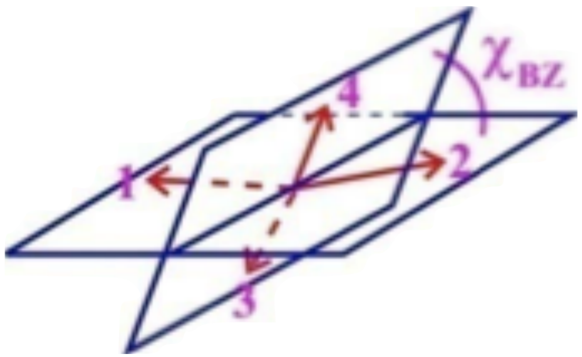
L3 (LEP), PL B248 (1990) 227



- SU(3) gauge structure of QCD
  - Abelian model U(1)3 as alternative
    - No 3-gluon coupling
  - Clear signal for triple gluon vertex
  - 4-jet angular structure sensitive to the gauge group structure of strong interactions
- QCD gauge structure experimentally verified

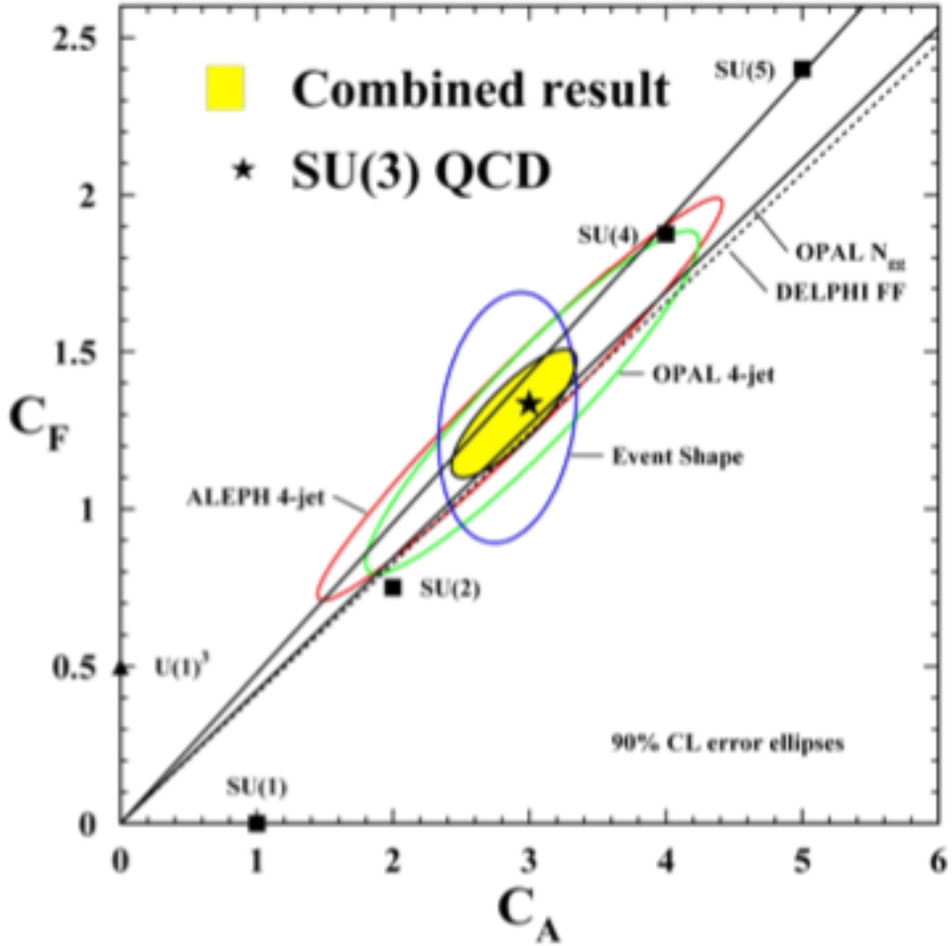
Ultimate precision color factors

- Construct observables to separate the contributions to the cross section
  - combine 4-jet and event shape results, accounting for correlations



  - Approx 8-14% accurcy on gauge structrue QCD!

C_A=2.89±0.21
C_F=1.30±0.09



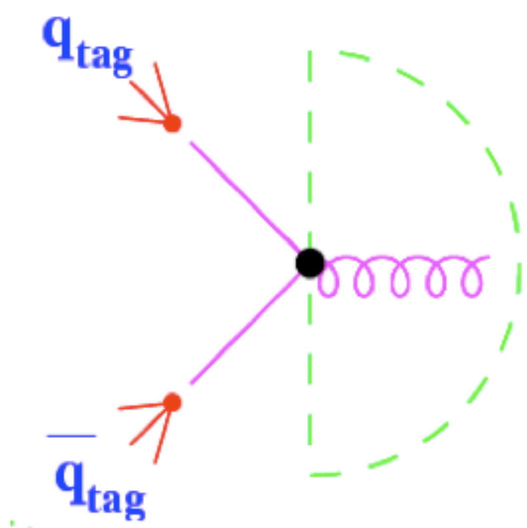
Difference quark and gluon jets

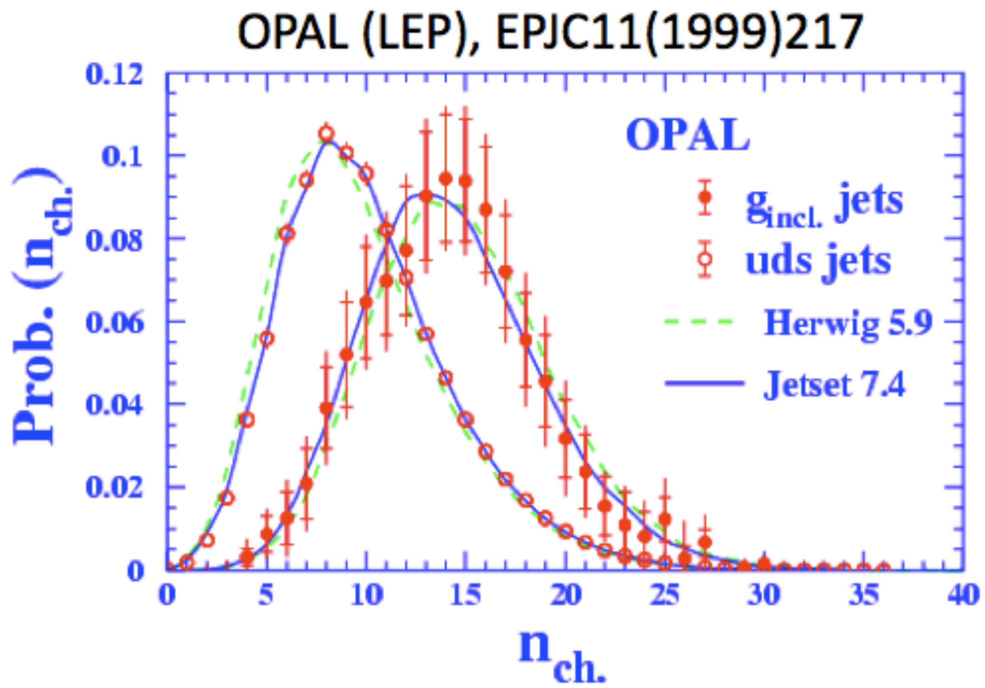
- Quark and gluon jets have different coupling strengths to emit gluons
  - Hence you expect 'gluon' and 'quark' jets to be different

- Naive expectation: $$r_{g/q} = \frac{\langle n_g \rangle}{\langle n_q \rangle} = \frac{C_A}{C_F} = 2.25$$
  - Gluon jets have a larger multiplicity, softer fragmentation function, and are broader, than quark jets
  - Expect large differences, on order ~ 2

Particle multiplicity difference

- Counting multiplicity
  - for quark jets its not so difficult:
    - define full hemisphere as “quark jet”
  - for gluon select specific topology:
    - using b-tagging in opposite hemisphere





$r_{G/Q} = 1.51 \pm 0.04$

This is not the naive expectation of r=2.25
However, perfect agreement with NLL calculations

Summary

- LEP has been a fantastic machine:
  - Standard Model physics tested with unprecedented precision
  - Comparison experiment and theory at level of radiative corrections
    - Enormous boost to theoretical calculations
  - LEP gave complete understanding of the Standard Model
    - Gauge structure of Electro Weak physics
    - Gauge structure of QCD

- Urging questions:
  - How is symmetry breaking realized?
  - Where is the Higgs?