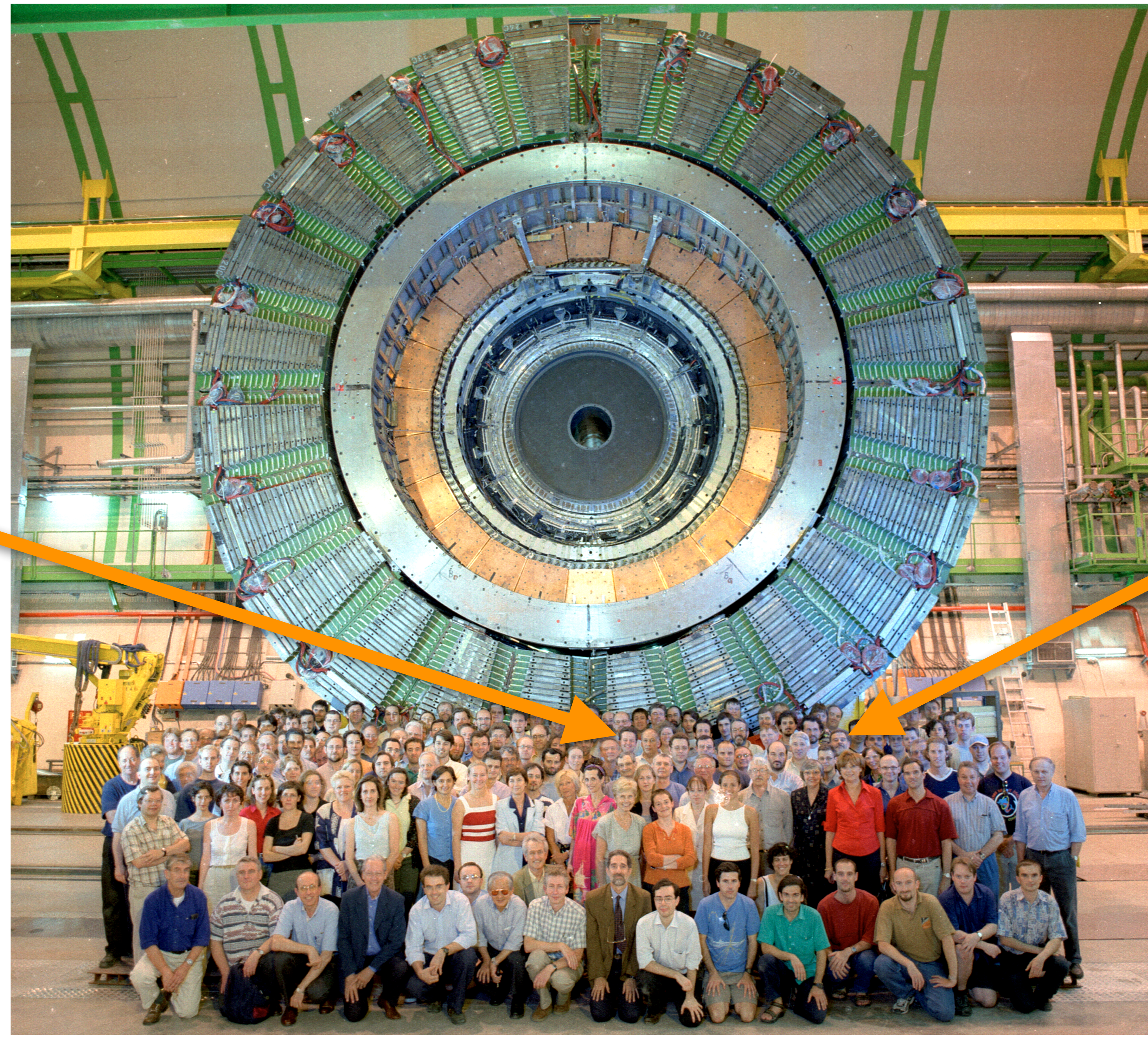
The Exciting Years of DELPHI

Markus Elsing



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Klaus Hamacher

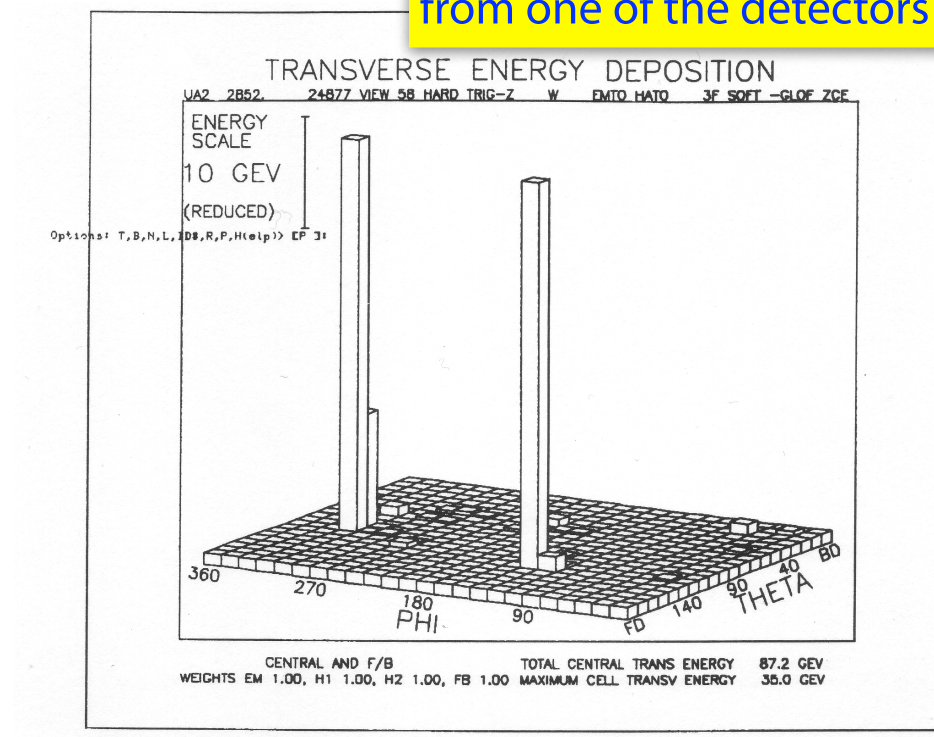
Seminar in honour of **Dr. Klaus Hamacher**

First speaker is Dr. Markus Elsing, CERN

The Large Electron-Positron Collider

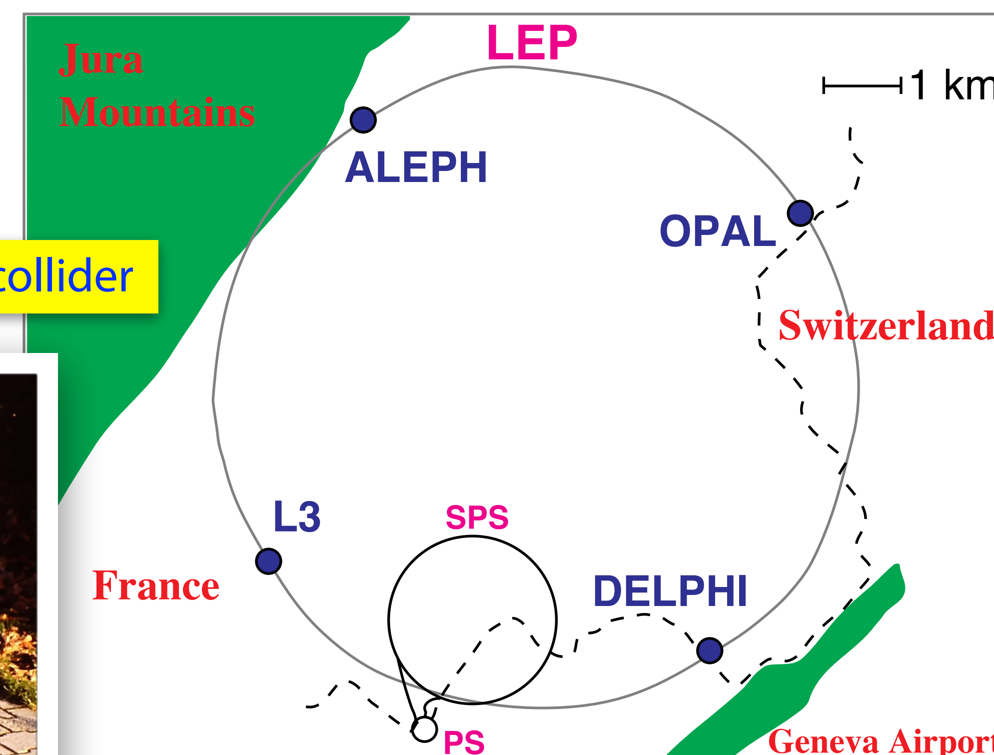
- LEP story began in late 70th
  - ➡ machine to study the emerging picture of the unification of the electromagnetic and weak forces
  - ➡ beginning of 80th saw discovery of W and Z bosons by UA1 and UA2
  - ➡ 1981 LEP was formally approved
- construction to first collisions
  - ➡ 1983 start of civil engineering for 27 km LEP tunnel and experimental halls
  - ➡ 4 experiments: ALEPH, **DELPHI**, L3 and OPAL
  - ➡ 13.August 1989 first collisions, less than 6 years later

very early $Z \rightarrow e^+e^-$ online display from one of the detectors (UA2)



P.Jenni, Terascale Alliance WS, DESY

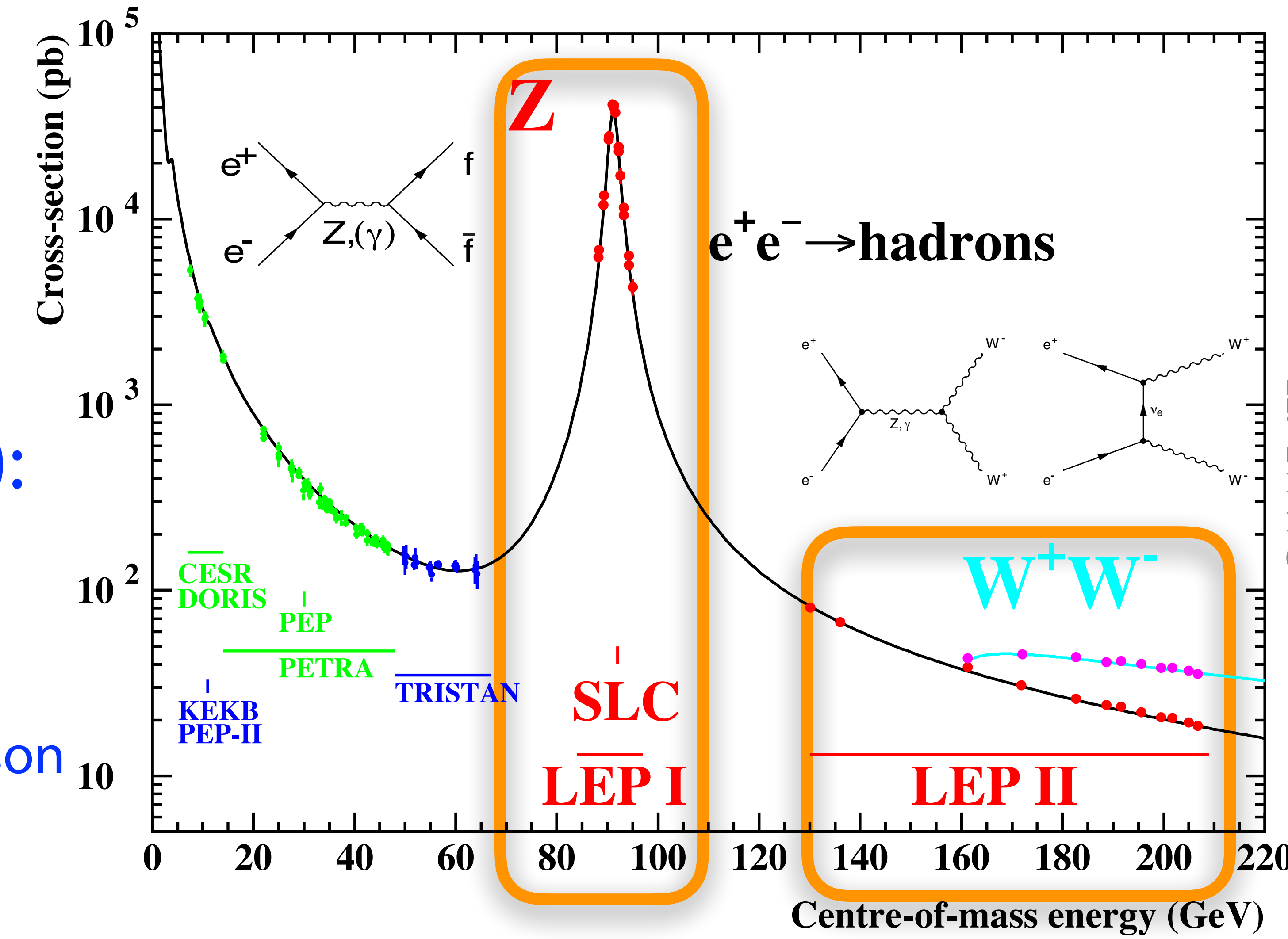
the LEP collider



another particle accelerator

Physics Goals of the LEP Programme

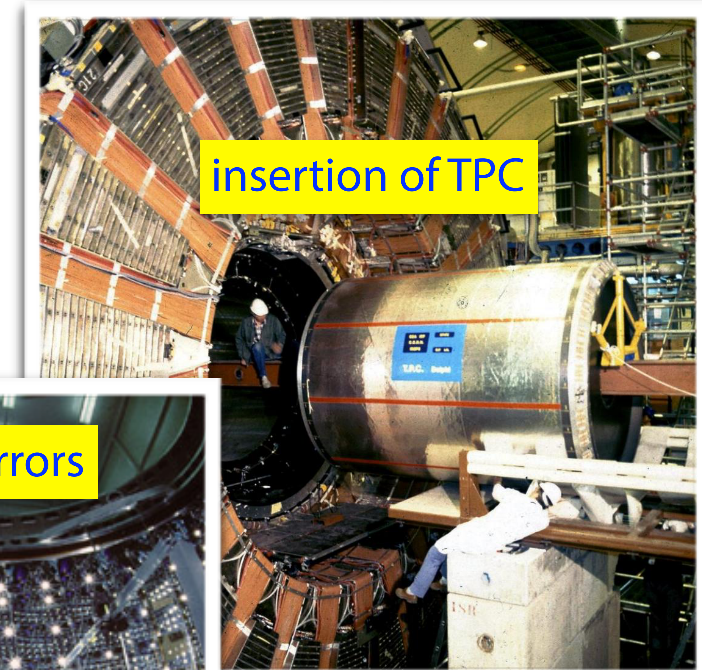
- LEP was a fantastic machine !
  - ➡ broad physics programme
  - ➡ clean e^+e^- environment
- goals as defined in Yellow Report "Physics at LEP" (1986):
  - ➡ precision studies at the Z peak
  - ➡ QCD, γγ and heavy quark physics
  - ➡ running beyond the WW threshold
  - ➡ search for toponium and the Higgs boson
  - ➡ searches for new particles

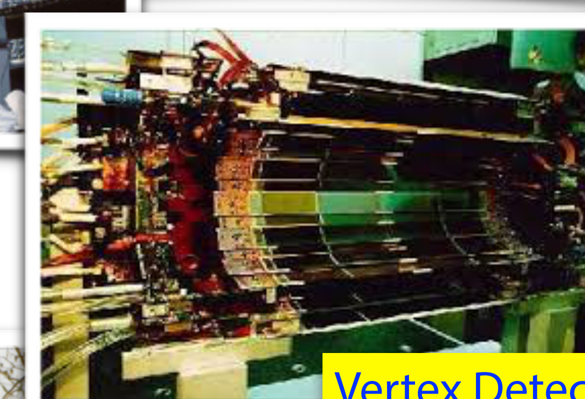


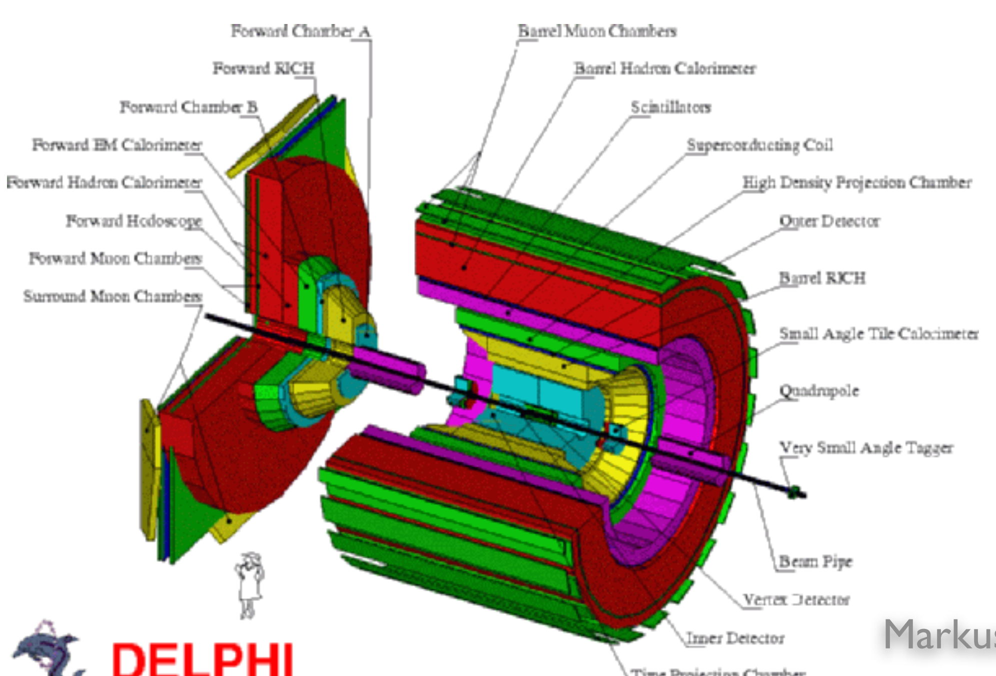
- two phases of the experimental program
  - ➡ LEP-I running on the Z peak (1989-1995)
    - most events taken on peak, plus scans around the peak to measure Z resonance
  - ➡ LEP-II running above the WW threshold (1996-2000)
    - increasing the energy year-by-year from 163 GeV to 209 GeV

The DELPHI Experiment

- "**DE**tector with **L**epton, **P**hoton and **H**adron **I**dentification"
  - ➡ 18 sub-detectors, many innovative technologies, e.g.:
    - Silicon Vertex Detector (VD) - the first of its kind
    - Time Projection Chamber (TPC) - 3D tracking
    - Ring Imaging Cherenkov Counters (RICH) - particle ID
    - High Density Projection Chamber (HPC) - e.m. calorimeter
  - ➡ the largest superconducting coil ever build
    - length 7.4 m, diameter 6.2 meters, 1.2 T field
- DELPHI collaboration
  - ➡ 550 physicists from 56 universities and institutes from 22 countries
  - ➡ Wuppertal: group of Prof. Drees (Prof. Becks)



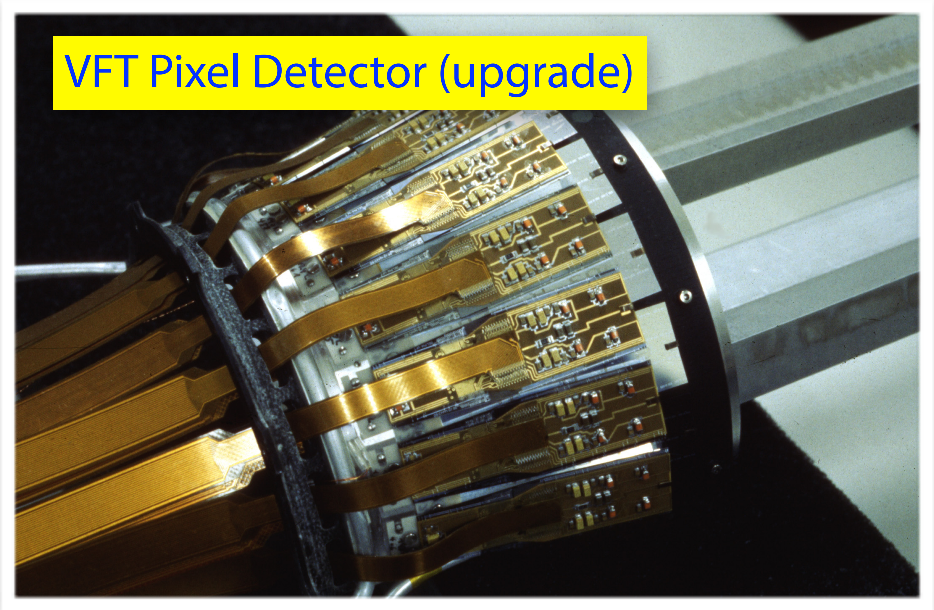


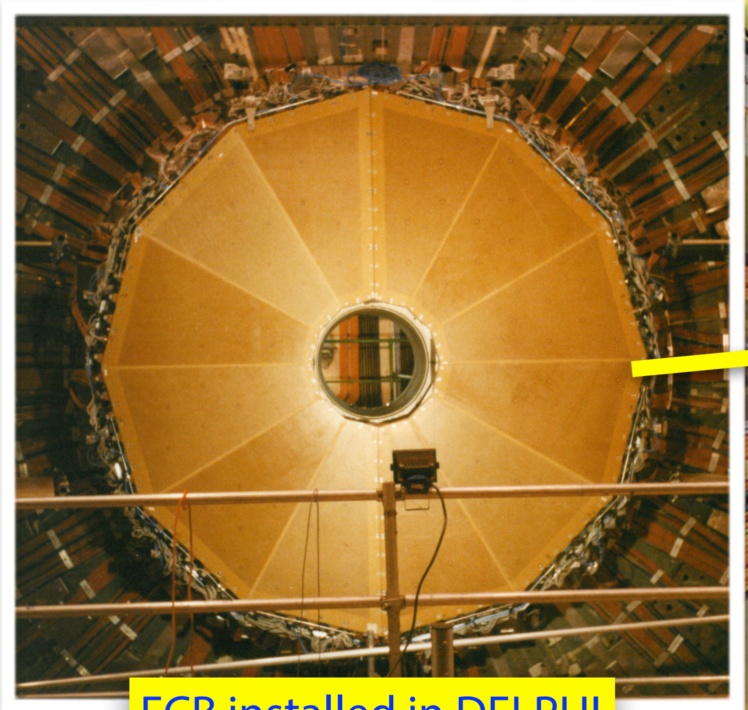


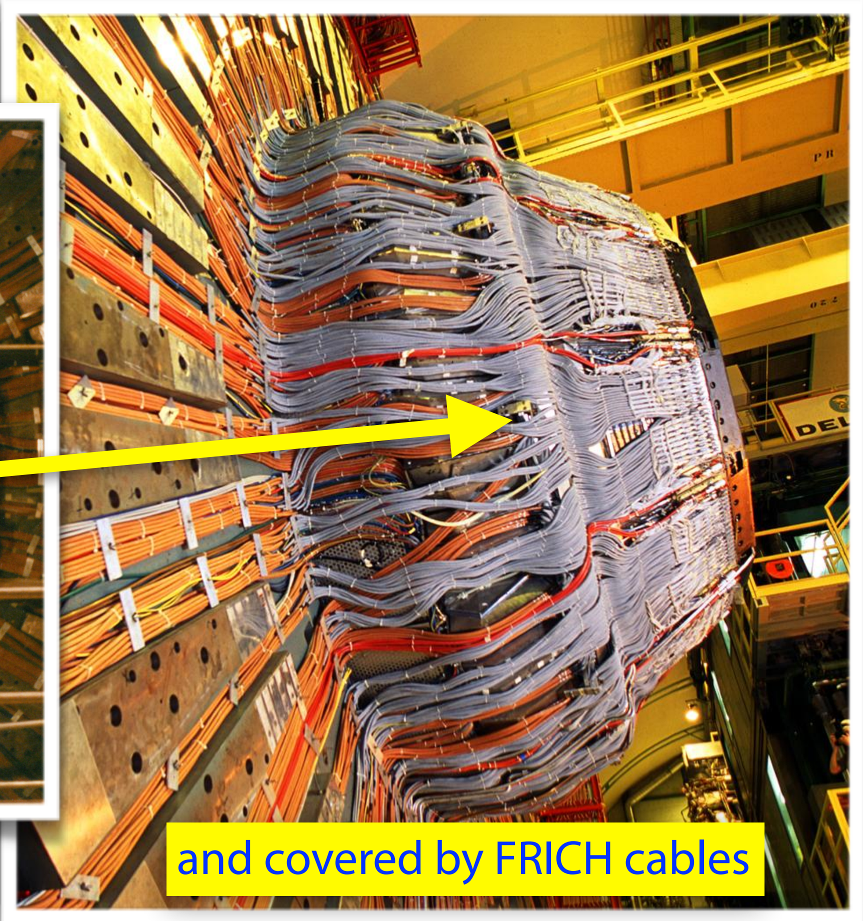
Detector Construction in Wuppertal

- **Forward Chamber B (FCB)**
  - ➡ large "classical" wire chamber for precise charged particle tracking
  - ➡ detector had 6 wire planes, X/U/V geometry for 3D reconstruction
  - ➡ designed and constructed in Wuppertal, transported to CERN, installed in both end-caps

- **later DELPHI upgrade (1995)**
  - ➡ contribution to Very Forward Tracker (VFT)
  - ➡ first hybrid pixel detector in collider experiment







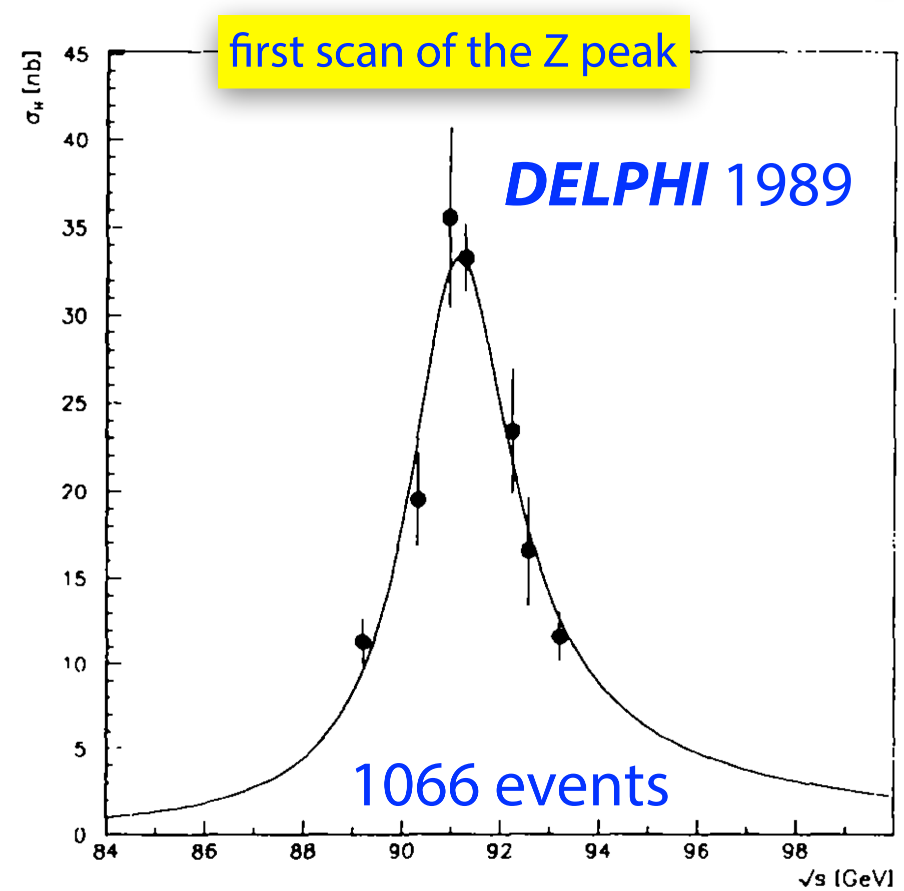
Commissioning and First Results

Pandora's box

EWS

Chocolate

- **DELPHI had a "rocky" start**
  - ➡ electrical fault on the magnet during installation
  - ➡ experiment was late, in particular readout and trigger not ready in time
- **LEP startup in 1989**
  - ➡ first beam in machine — July 12th
  - ➡ pilot run (5 days) started — August 13th
  - ➡ 1st physics run (2 weeks) — September 22nd
    - first scan of the Z peak !
  - ➡ 2nd physics run (2 months) — October 22nd
    - 2nd scan of the Z peak
- **major commissioning effort**
  - ➡ but good data was taken, leading to first DELPHI physics papers
  - ➡ start of an amazing success story...



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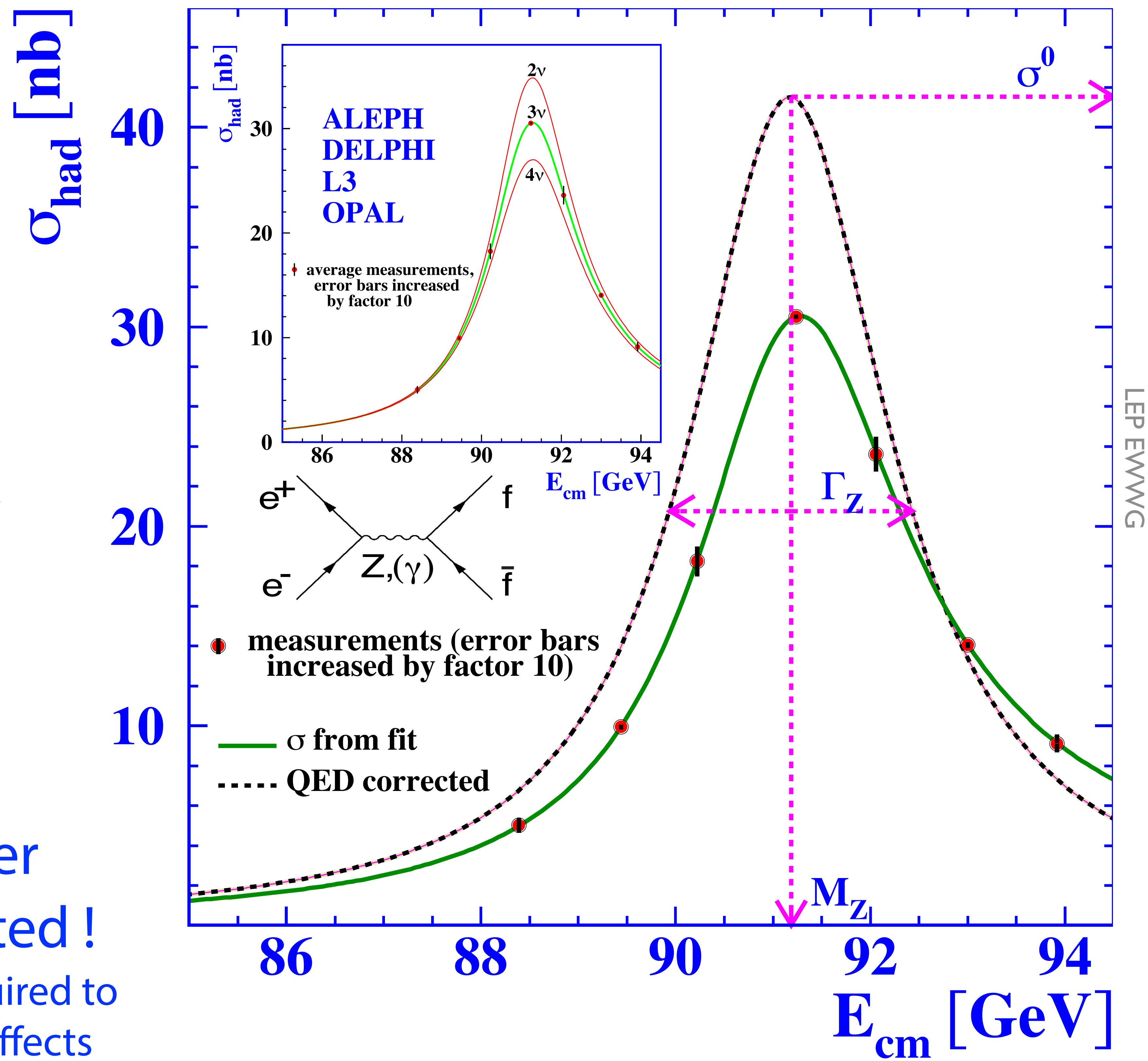
Precision Measurement of the Z Peak

- 4 million Z decays per experiment
  - ➡ hadronic cross section, measured and QED corrected
  - ➡ large, but well known radiative corrections
- precision results:

  m_Z = 91.1875 ± 0.0021 GeV
  Γ_Z = 2.4952 ± 0.0023 GeV
  σ^0_{had} = 41.540 ± 0.037 nb

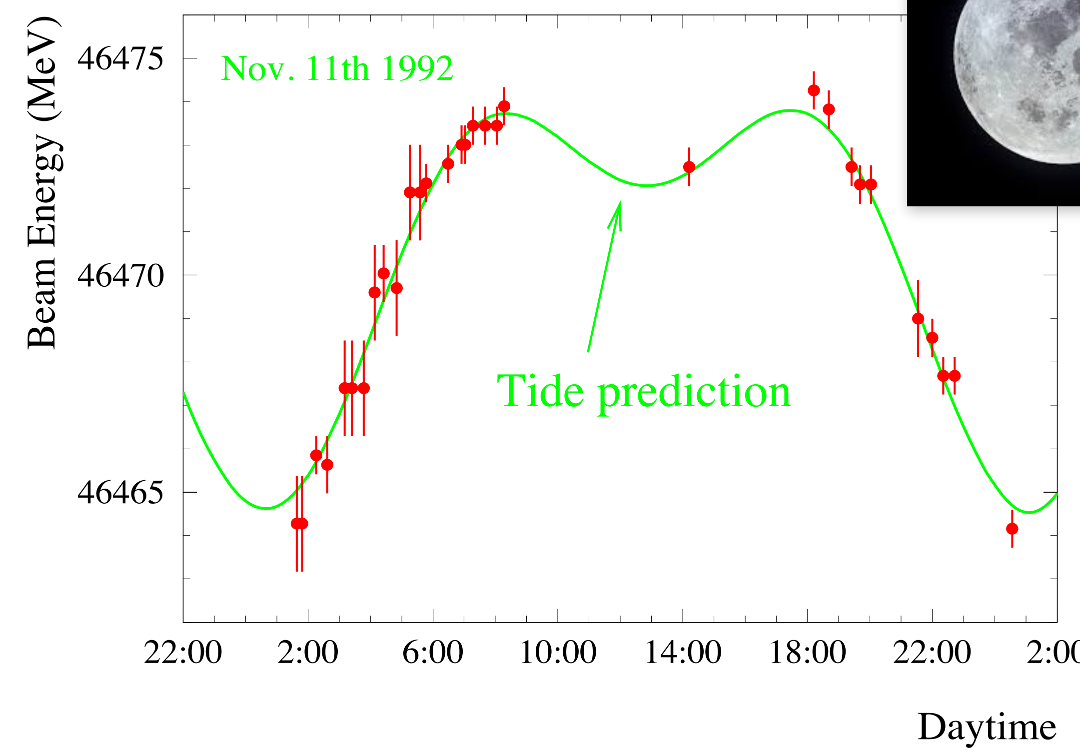
  - ➡ number of light neutrinos:

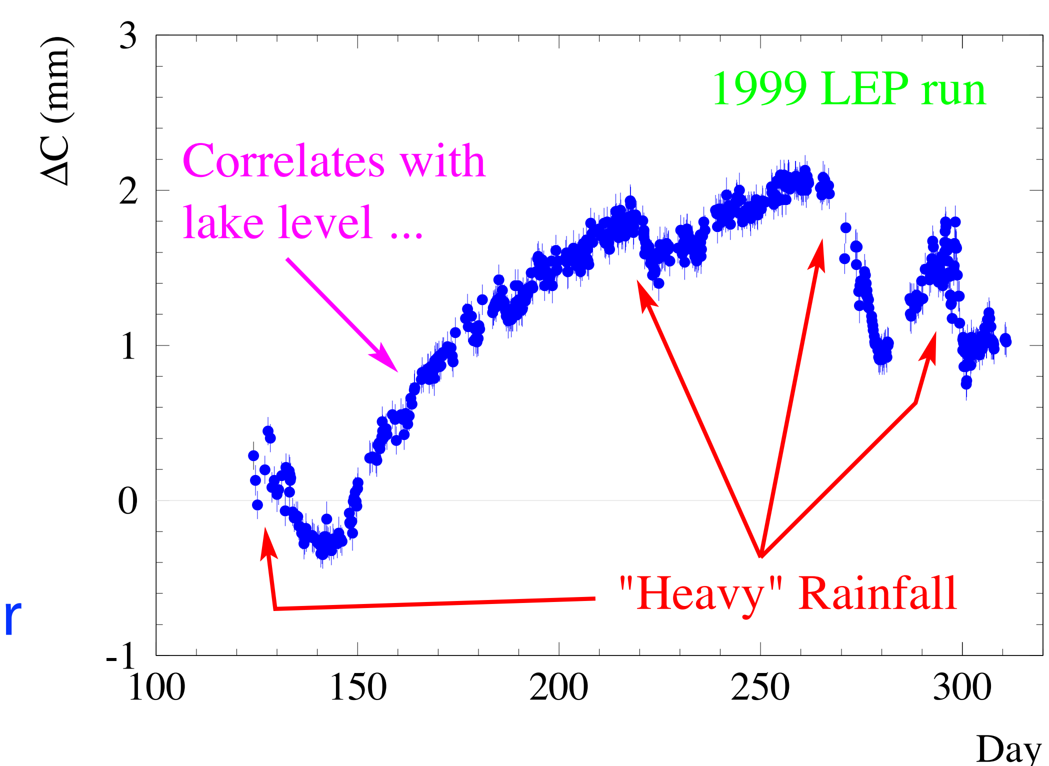
  N_ν = 2.9840 ± 0.0082
  (2 σ below 3)
- most LEP results better than originally expected !
  - ➡ reaching precision required to allow for many subtle effects



Surprises in LEP Energy Calibration

- LEP energy uncertainty important systematics on M_Z
- resonant depolarisation used to measure beam energy
  - ➡ calibration outside physics runs
    - extrapolated to different collision points
  - ➡ precision $\Delta E < 0.4$ MeV or $\Delta E/E < 10^{-5}$
    - but: large variations detected
- earth tides deforming LEP ring
  - ➡ tidal earth deformation: 2/3 moon, 1/3 sun
  - ➡ total change of circumference $\Delta C \sim 1$ mm and of beam energy $\Delta E \sim 10$ MeV
- underground water levels
  - ➡ circumference changes by $\Delta C \sim 2$ mm / year results in slow drift on LEP energy

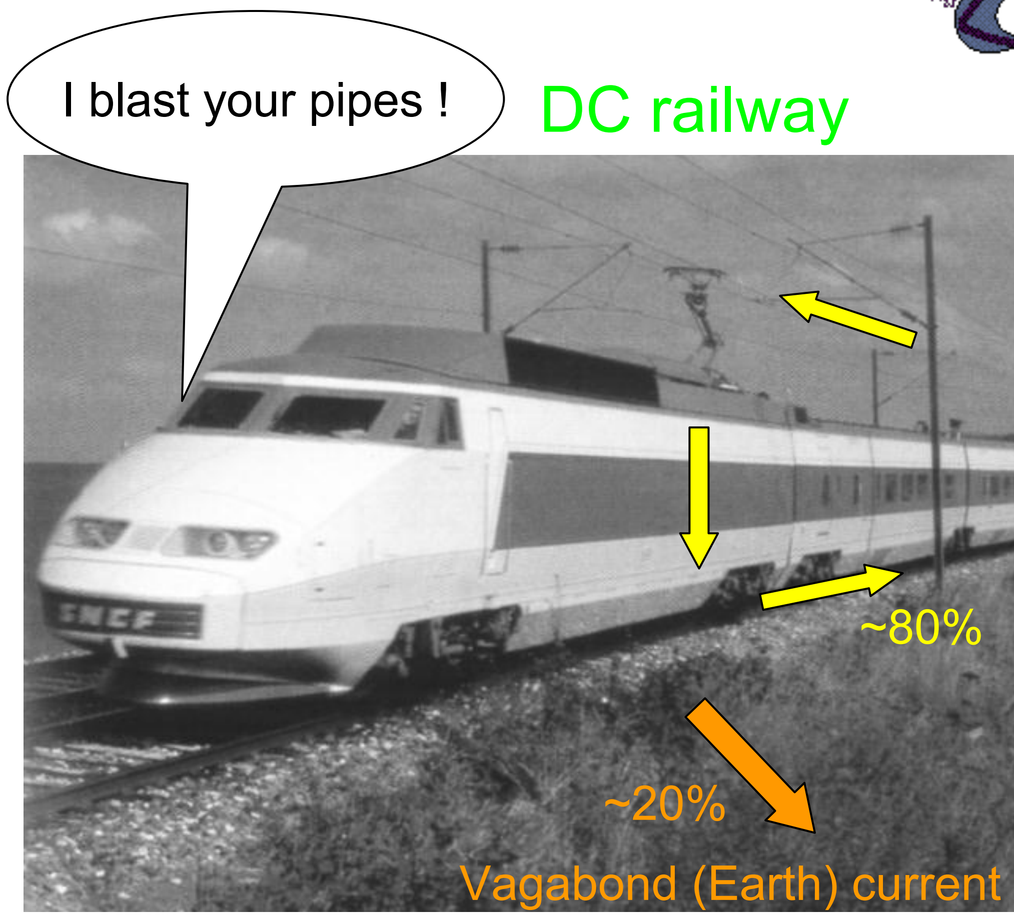


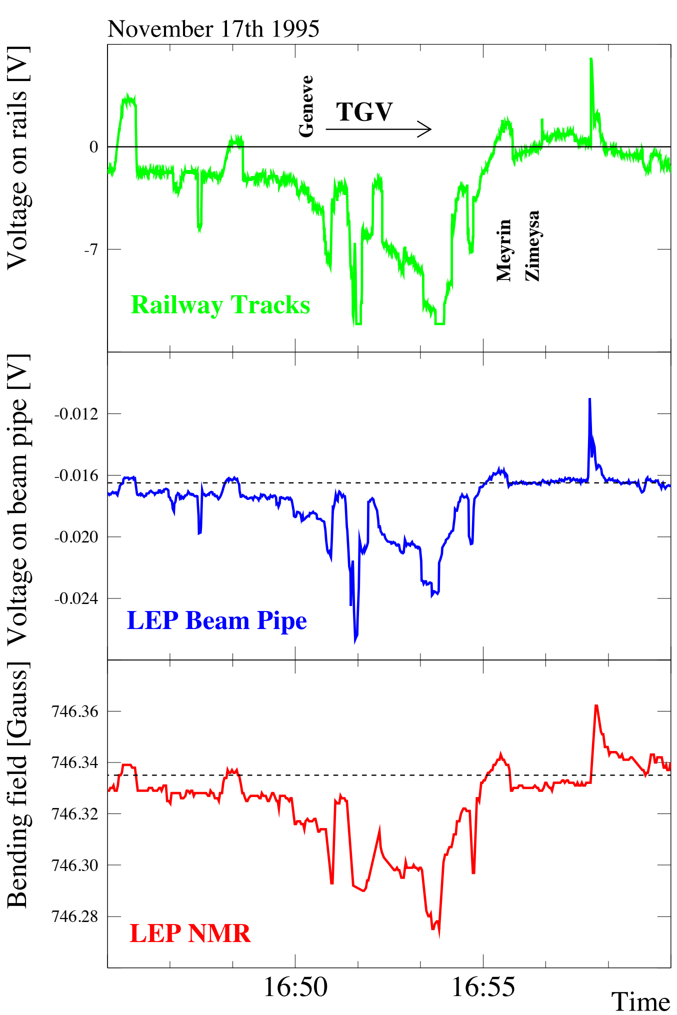


J. Wenninger, LEP Fest

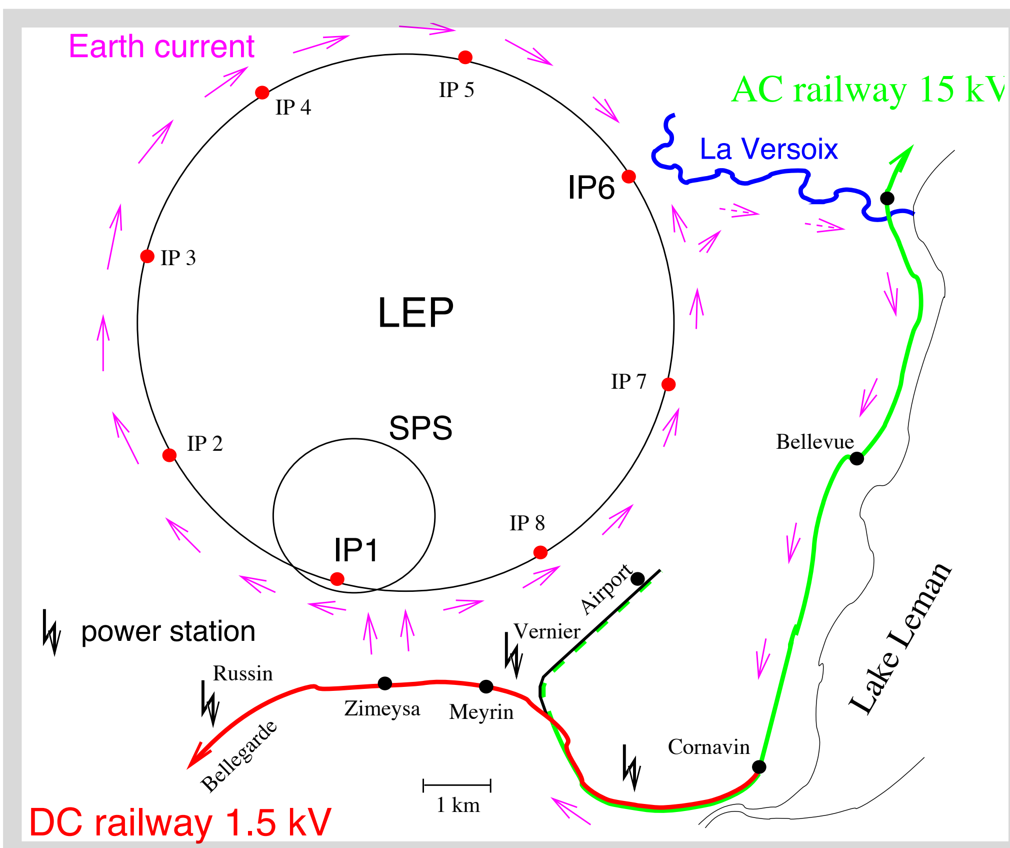
The "Train Effect"

- unexpected short term fluctuations
  - ➡ up to ΔE ~ 5 MeV over the day, quiet periods at night
    - human activity ! (but which one ?)
  - ➡ explanation given by Swiss electric company
    - vagabond currents from trains, known since 1898 !!!
- french DC railway Geneva-Bellegarda
  - ➡ DC current of 1 A flowing on LEP vacuum chamber





- measurements of
  - current on railway tracks
  - current on vacuum chamber
  - dipole field in LEP magnets
  - ➡ correlated perfectly
- final systematics of ±1.7 MeV on m_Z
  - ➡ still dominating



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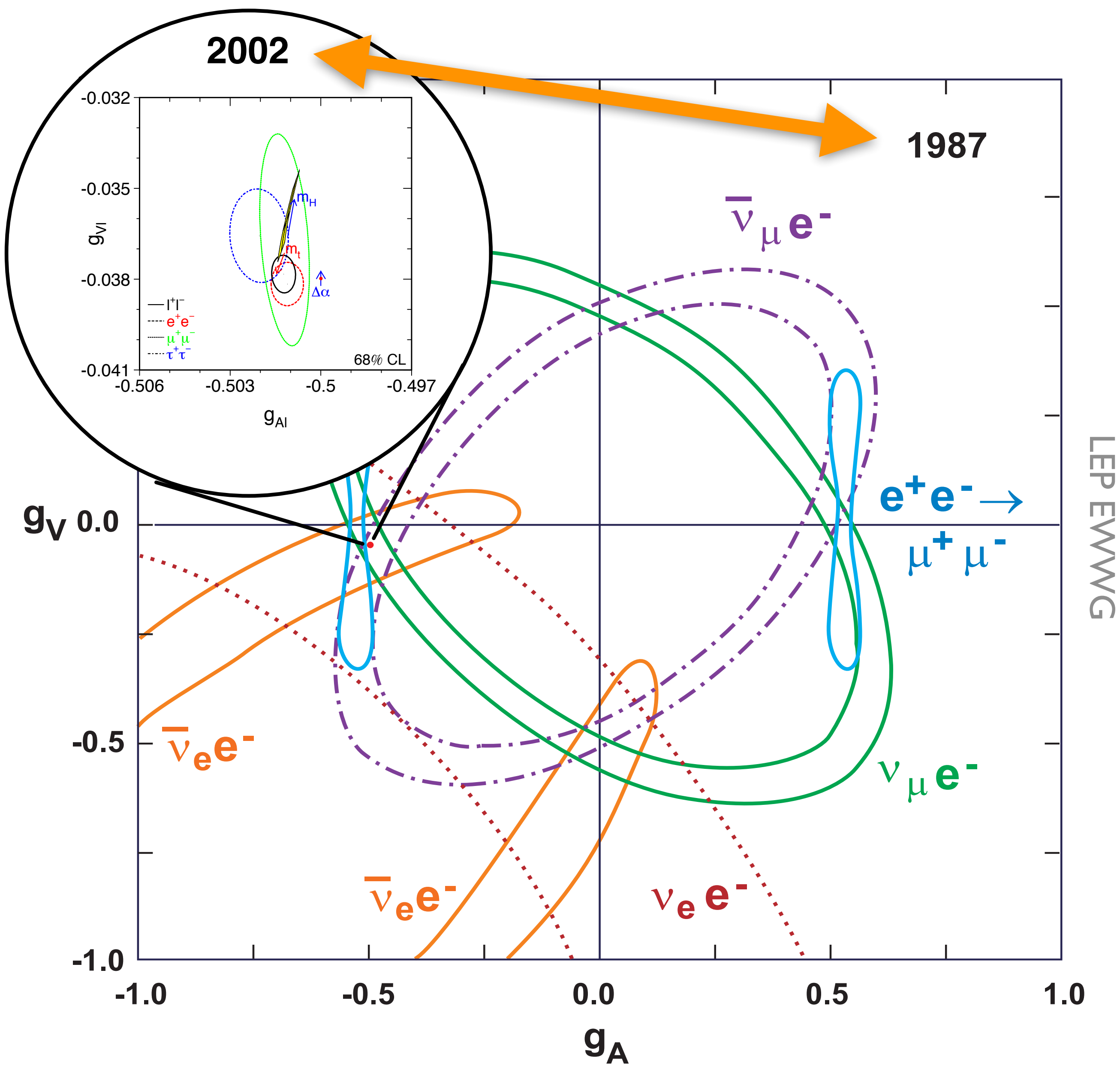
Z Pole Electroweak Precision Data

- LEP-I yielded huge harvest of electroweak precision results:



➡ new quality compared to pre-LEP situation (e.g. lepton axial and vector couplings)

➡ combined LEP-I results:

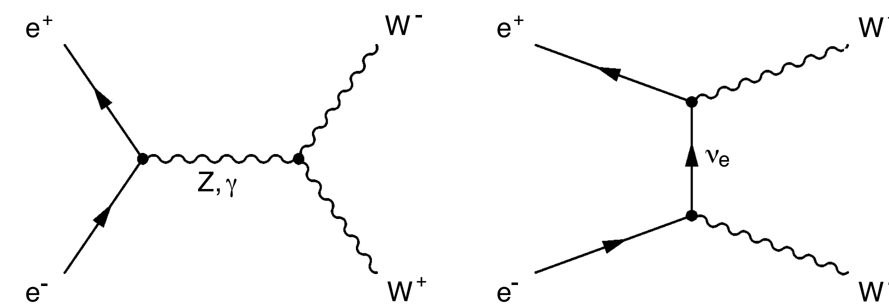
m_Z [GeV]	91.1875 ± 0.0021
Γ_Z [GeV]	2.4952 ± 0.0023
σ^0_{had} [nb]	41.540 ± 0.037
R_l	20.767 ± 0.025
$A^{0,l}_{fb}$	0.01714 ± 0.00095
$A_l(P_\tau)$	0.1465 ± 0.0032
R_b	0.21629 ± 0.00066
R_c	0.1721 ± 0.0030
$A^{0,b}_{fb}$	0.0992 ± 0.0016
$A^{0,c}_{fb}$	0.0707 ± 0.0035
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012

LEP EWWG

➡ results and interpretation of electroweak data will be discussed by **next speaker !**

LEP-II opened new Physics Programme

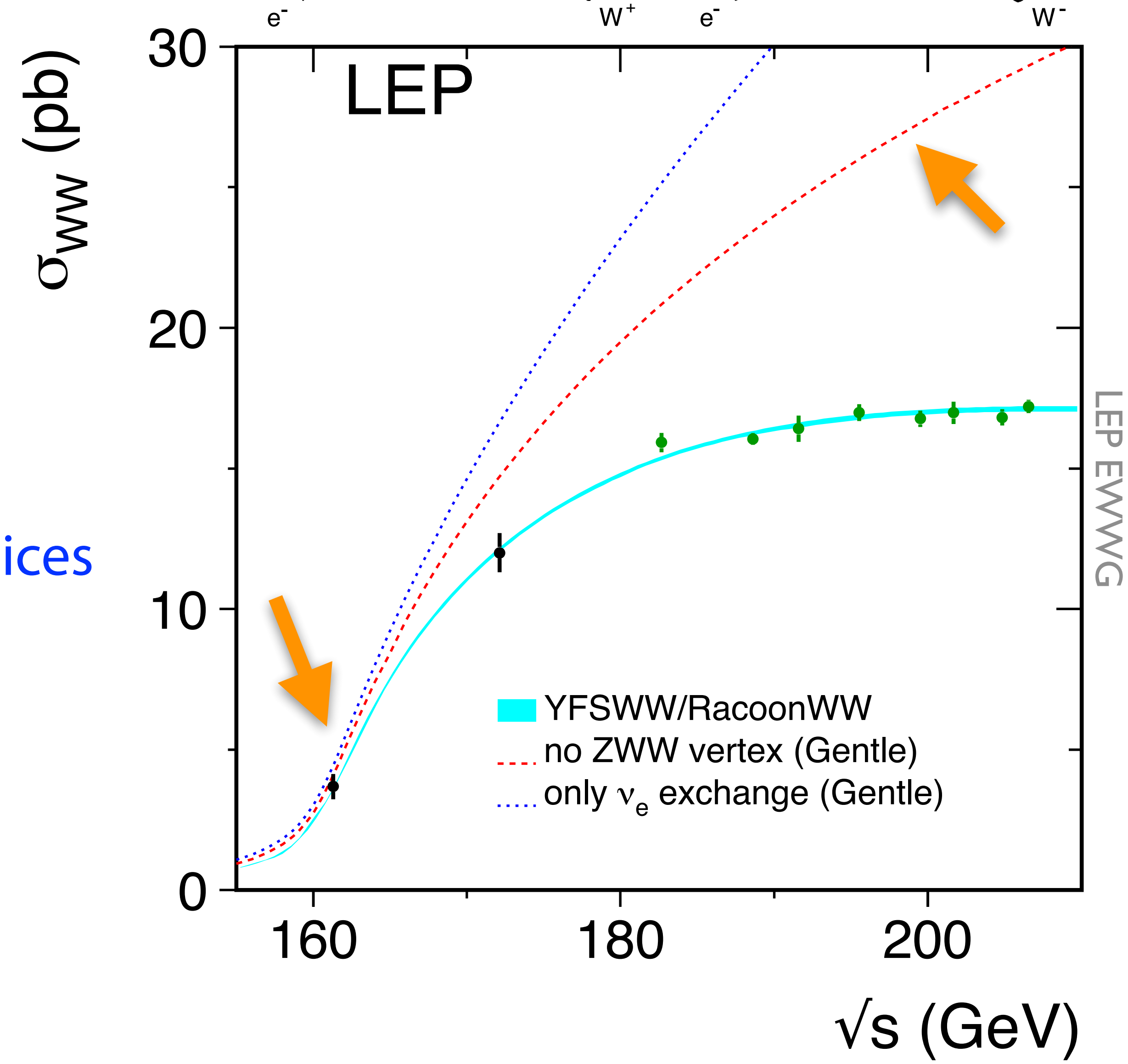
- machine reached energies well above WW threshold
  - ➡ precision measurement of W mass, branching ratios, etc.
  - ➡ study di-fermion production well above Z pole
  - ➡ processes like γγ, Zγ*, ZZ, WWγ, Zee, Weυ...
  - ➡ searches for Higgs boson and new physics



- measured WW cross-section
  - ➡ different final states
    - WW→lυlυ ~ leptonic channel
    - WW→q$\bar{q}$lυ ~ semi-leptonic channel
    - WW→q$\bar{q}$q$\bar{q}$ ~ fully hadronic channel
  - ➡ results illustrate "effect" of γWW and ZWW vertices
  - ➡ cross-section at threshold sensitive to W mass

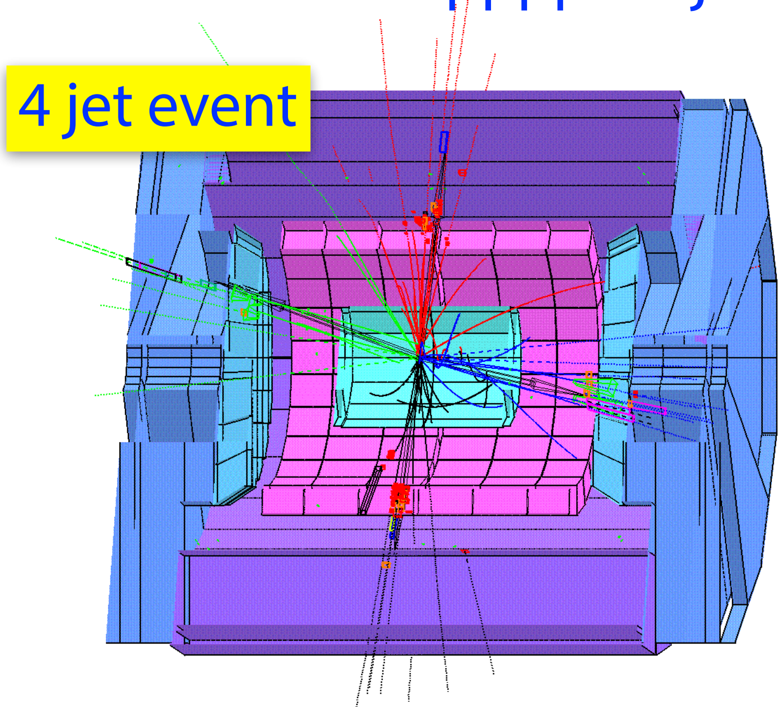
$$m_W = 80.42 \pm 0.20 \,(\text{stat.}) \pm 0.03 \,(E_{LEP})\ \text{GeV}$$

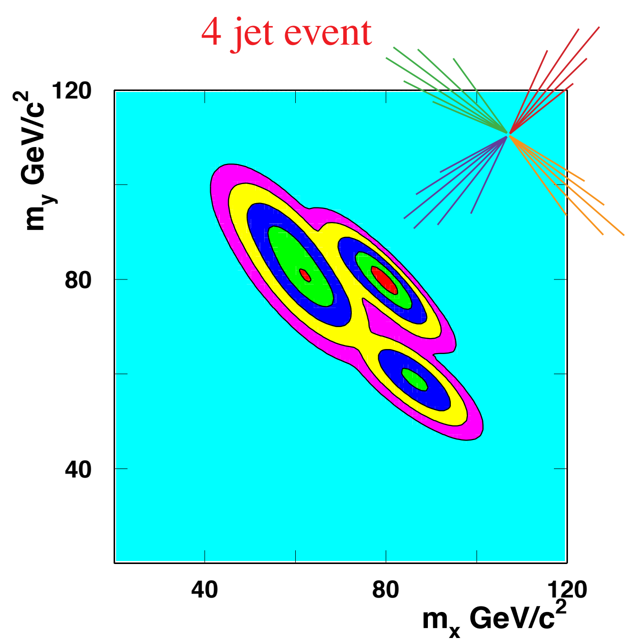
- statistically dominated !

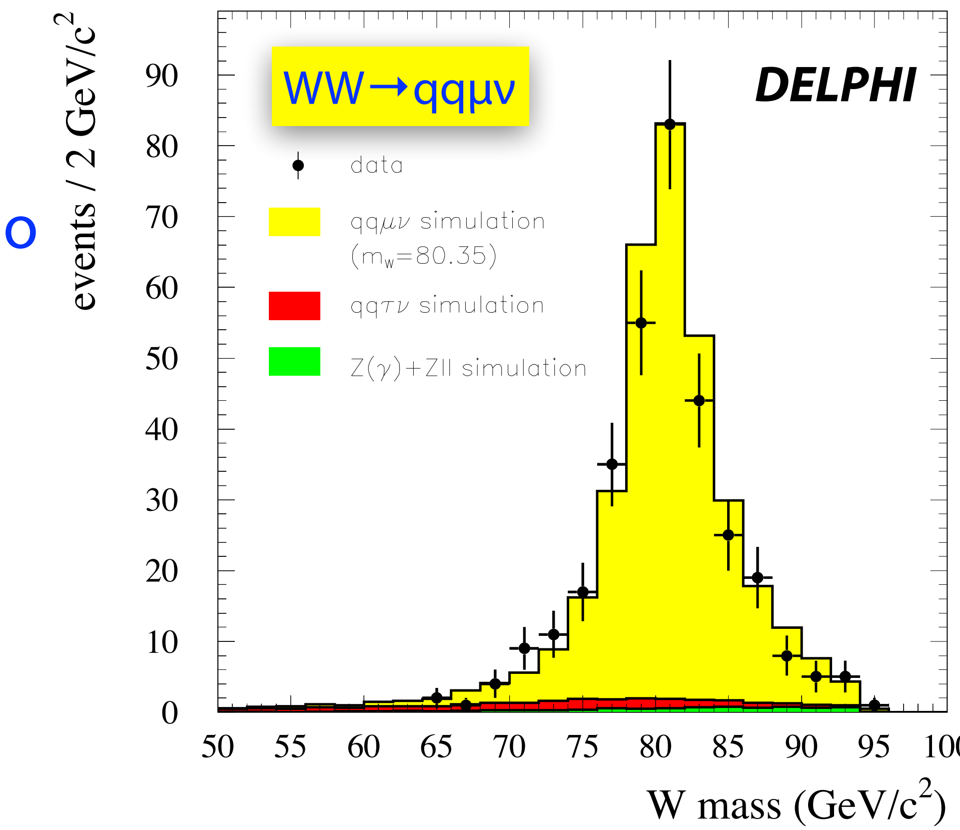


W Mass from direct Reconstruction

- reconstruct mass spectrum from final state particles
  - ➡ spectrum as well sensitive to W width (Γ_W)
  - ➡ kinematic fits to improve experimental resolution
    - $WW \to q\bar{q}l\nu$ ~ missing momentum from neutrino
    - $WW \to q\bar{q}q\bar{q}$ ~ 4 jets give 3 combinations







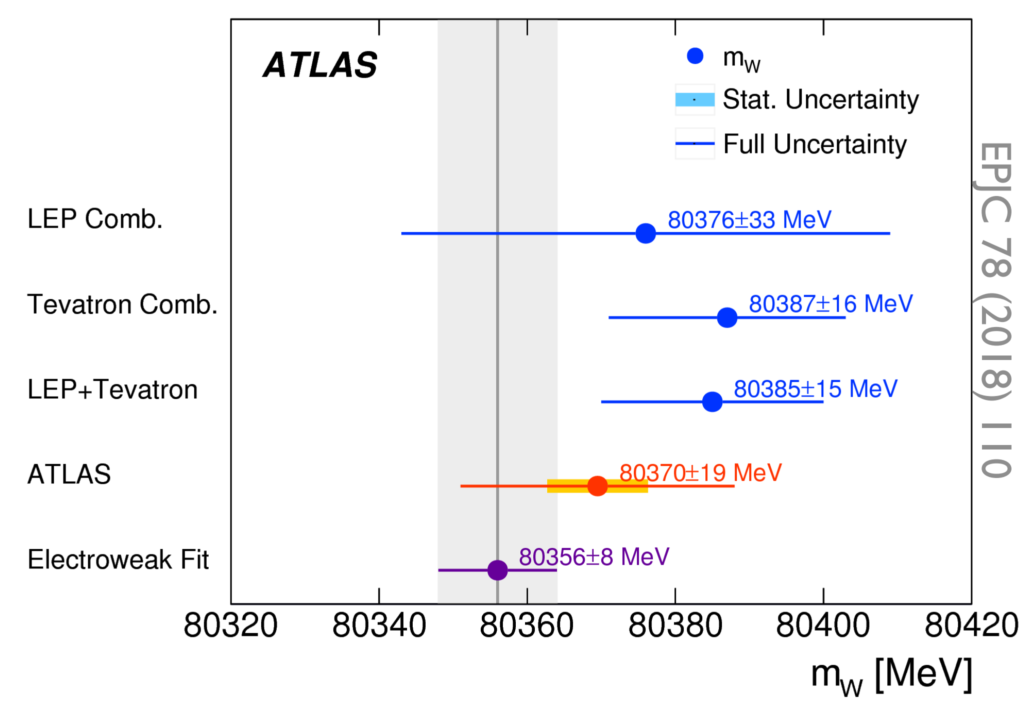
- ➡ results:

$$m_W = 80.375 \pm 0.025(\text{stat.}) \pm 0.022(\text{syst.})\ \text{GeV}$$

LEP EWWG

$$\Gamma_W = 2.195 \pm 0.063(\text{stat.}) \pm 0.055(\text{syst.})\ \text{GeV}$$

- ➡ compare to recent Tevatron and ATLAS results



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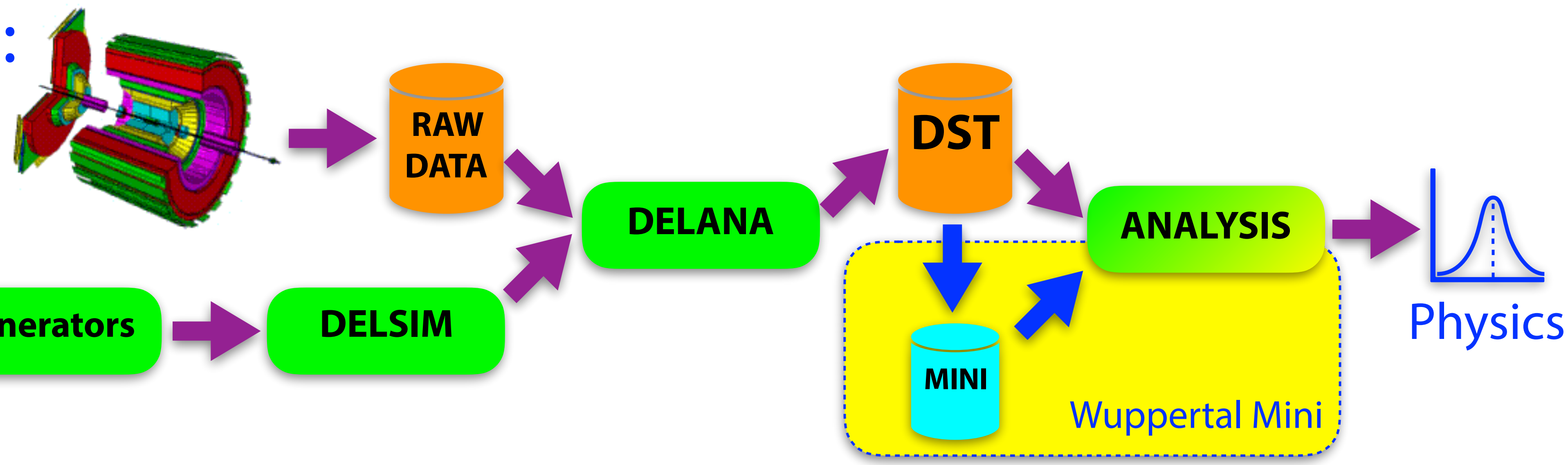
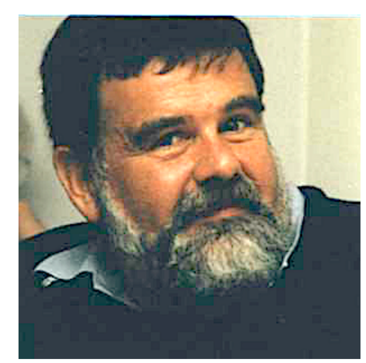
Enabling Data Analysis in Wuppertal

- data flow:



- group got VAX cluster to analyse DELPHI data
  - ➡ but: DST format too large to store in Wuppertal

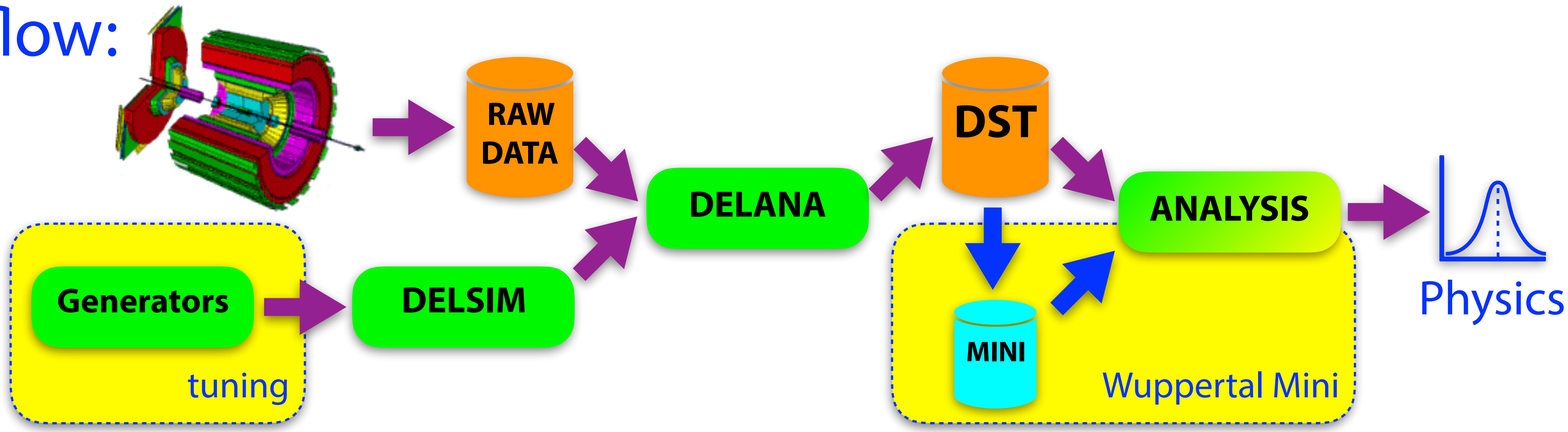
- invention of the "Wuppertal Mini"
  - ➡ reduced data format stored on cluster
  - ➡ software skeleton + tools for analysis (today this is called an analysis framework)
  - ➡ scheme later adopted by DELPHI overall



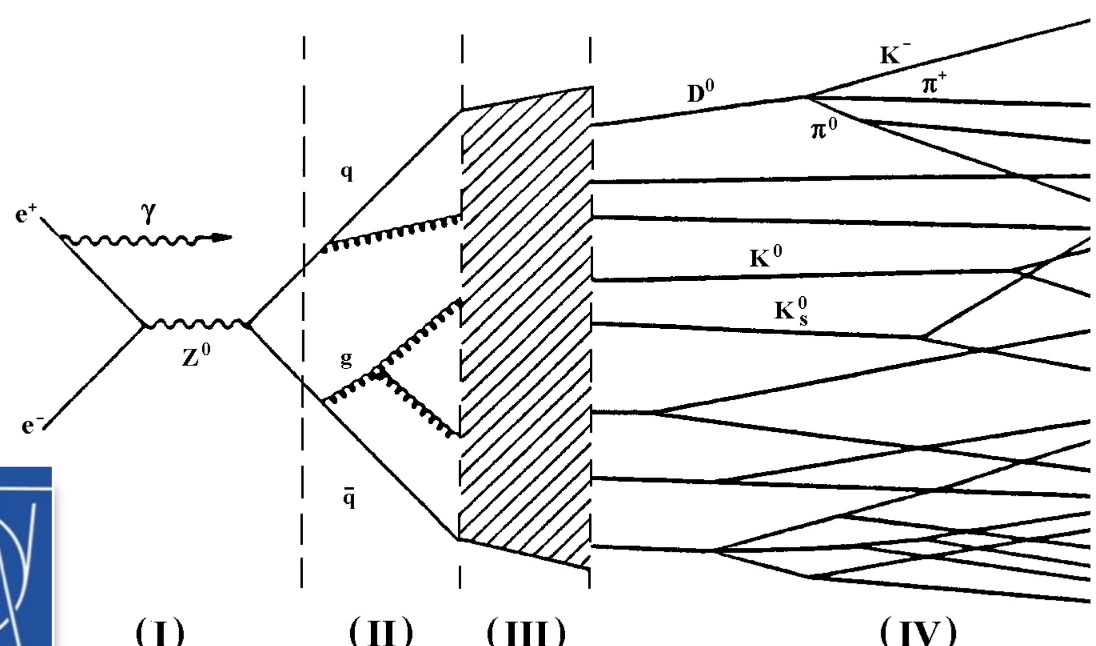
Digital VAX 6000 Series Computer (1989)

Tuning Monte Carlo Generators

- data flow:



- Monte Carlo generators and detector simulation
  - ➡ to unfold e.g. fragmentation effects in hadronic final states and detector effects
- generators modelling $e^+e^- \to Z/\gamma^* \to q\bar{q} \to$ hadronic final states
  - ➡ assumption that process can be factorised into 4 phases:



(I) hard electroweak production process
- ➡ cross-section calculate in perturbation theory

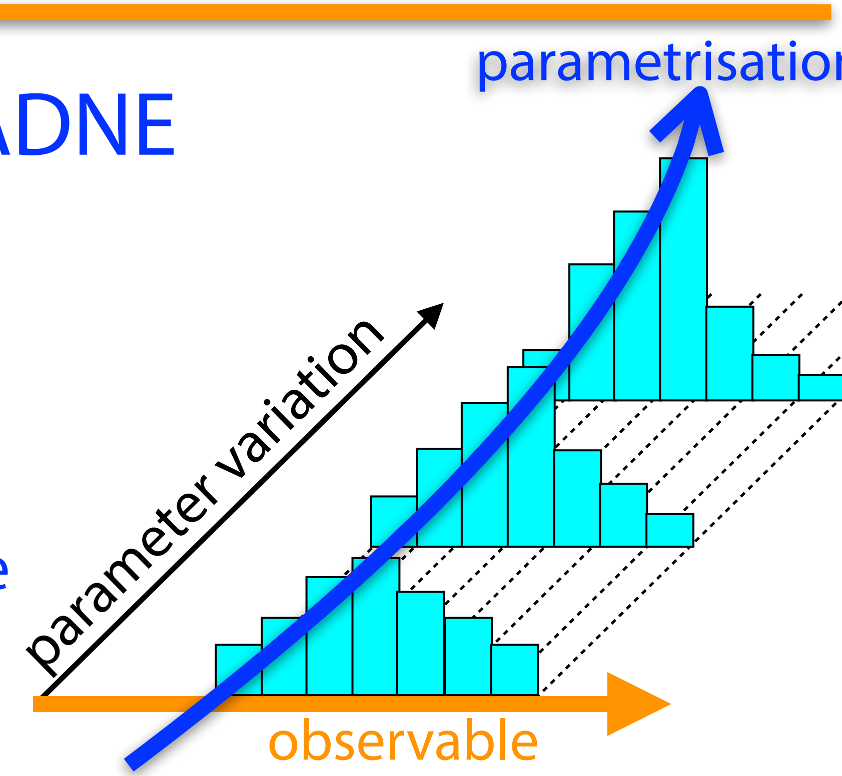
(II) partonic phase governed by perturbative QCD
- ➡ matrix elements, parton shower models

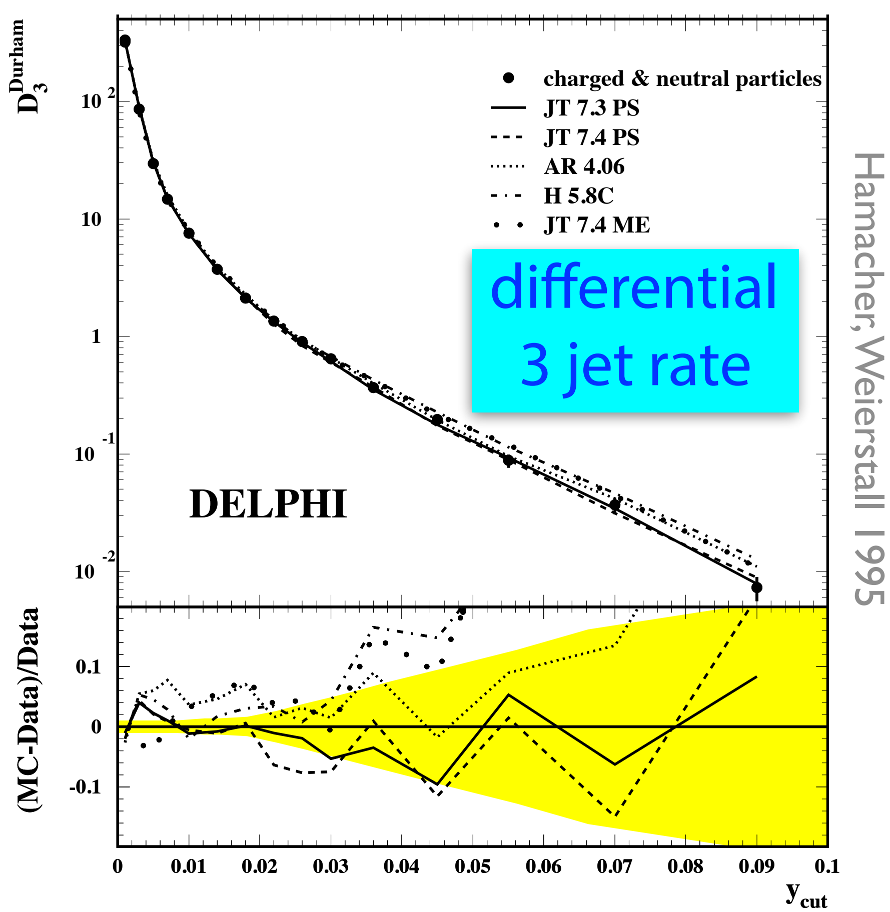
(III) fragmentation into stable hadrons
- ➡ phenomenological string or cluster models

(IV) decay of long lived particles
- ➡ known branching ratios (+modelling)

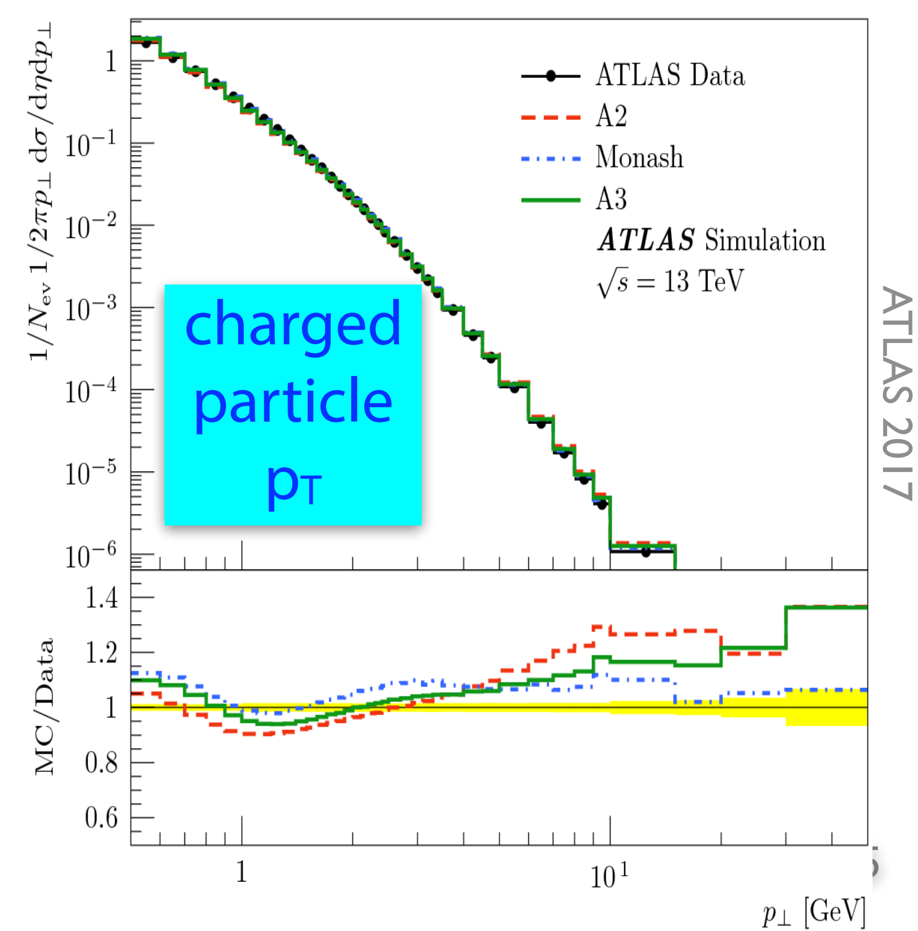
Tuning of Monte Carlo Generators

- generator codes like JETSET, HERWIG or ARIADNE
  ➡ many free parameters, need to be tuned to data
- complex optimisation problem
  ➡ parameters usually are highly correlated
  ➡ re-computing observables for each variation is CPU intensive
- parametrisation-based tuning approach
  ➡ sample parameter space, model variation of observables, fit model to data distributions



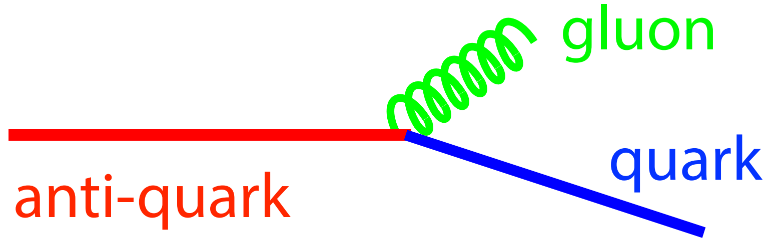


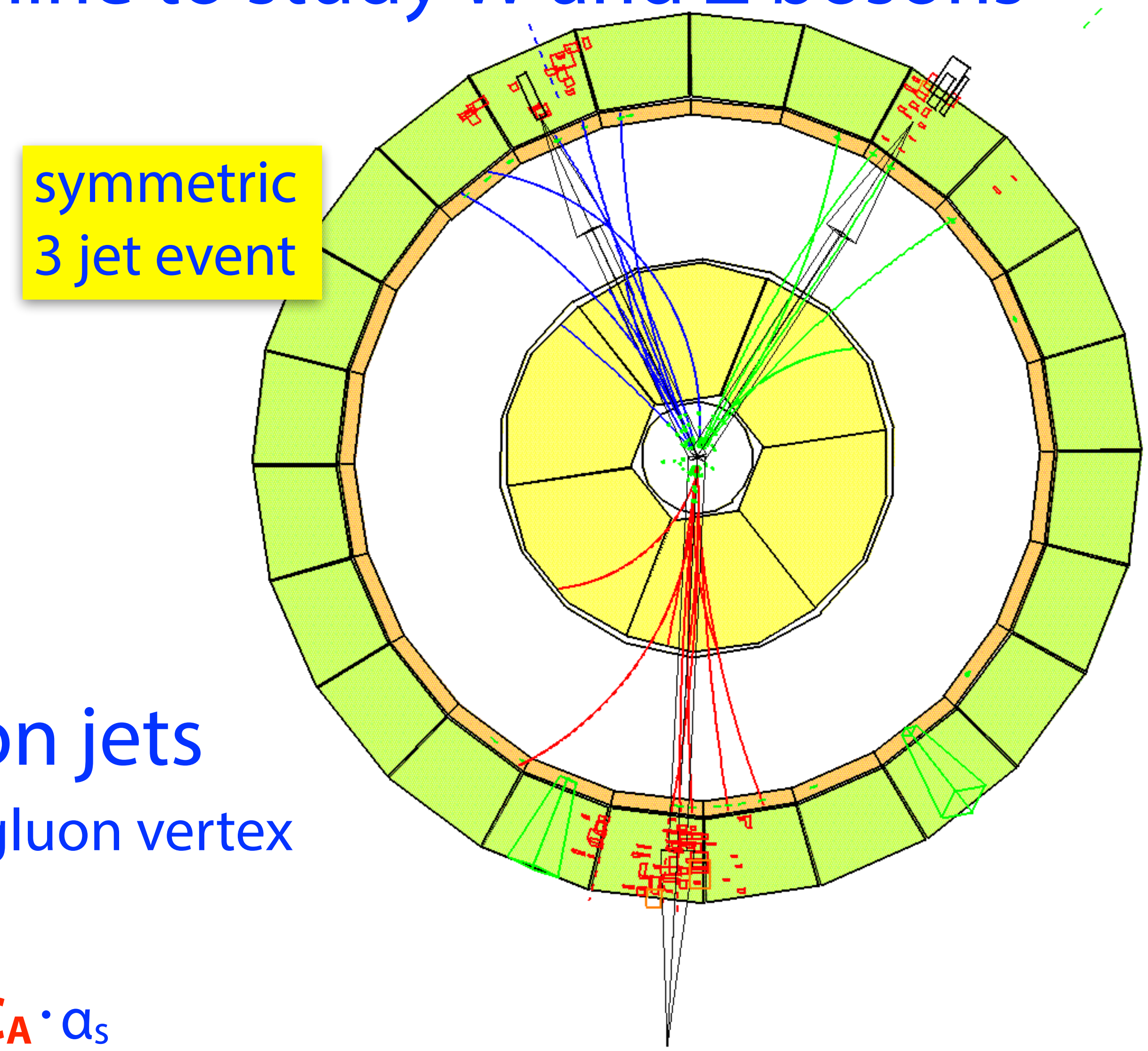
➡ approach later implemented in "Professor" framework, still used today



Properties of Quark and Gluon Jets

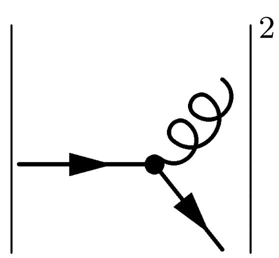
- LEP not only an excellent machine to study W and Z bosons
  - ➡ study QCD in a clean environment



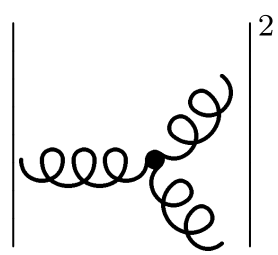


  - ➡ clean sample of gluons in 3 jets events
    - identify b-quark decays in other jets
    - or compare 3 jet to 2 jet events

- allows to study quark and gluon jets
  - ➡ relative coupling strength of quark and gluon vertex



$\propto C_F \cdot \alpha_s$



$\propto C_A \cdot \alpha_s$

C_A , C_F ~ QCD color factors

  - QCD : $C_A / C_F = 2.25$ ~ higher rate for gluon Bremsstrahlung in gluon jets
  - ➡ precise measurement of coupling ratio allows to determine QCD gauge group
    - can be extracted from comparing hadron multiplicities in quark and gluon jets
    - non perturbative / color coherence effects and hadronisation are important

Properties of Quark and Gluon Jets

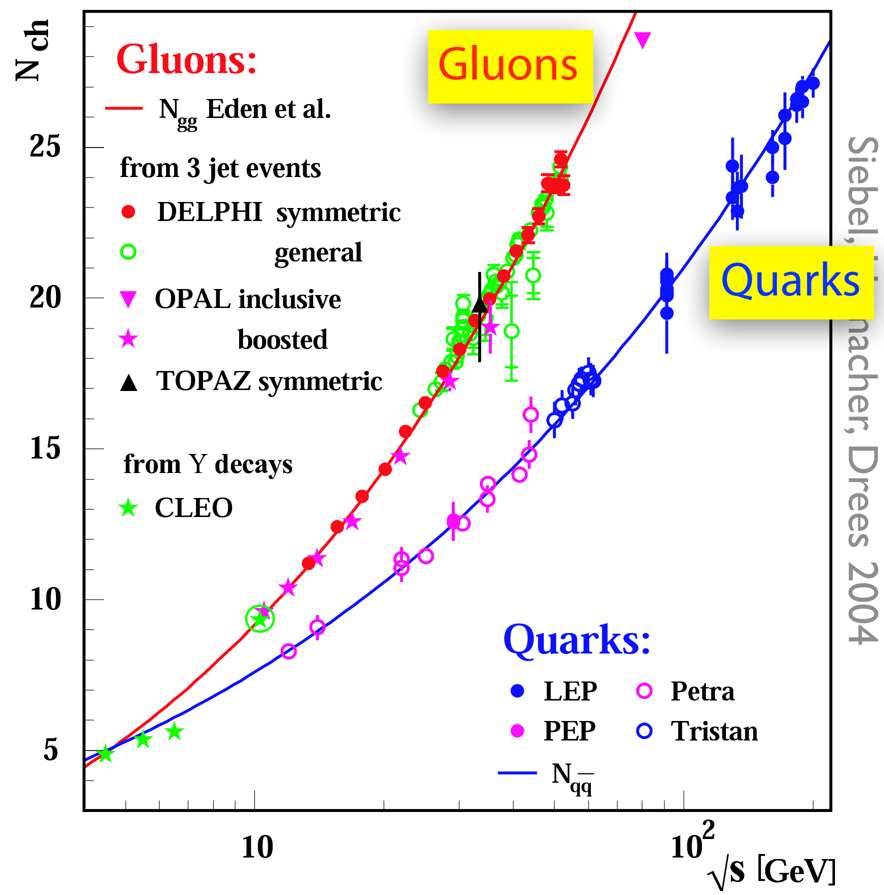
("Eden A")

- determine gluon multiplicity:

$$N_{gg}(\kappa_{Le}) = 2\cdot(N_{q\bar{q}g}(\theta_1) - N_{q\bar{q}}(L_{q\bar{q}},\kappa_{Lu}) - N_0)$$

➡ N_{gg} ~ hadron multiplicity in color singlet gg system

➡ stronger energy slope of N_{gg} ~ larger color factor



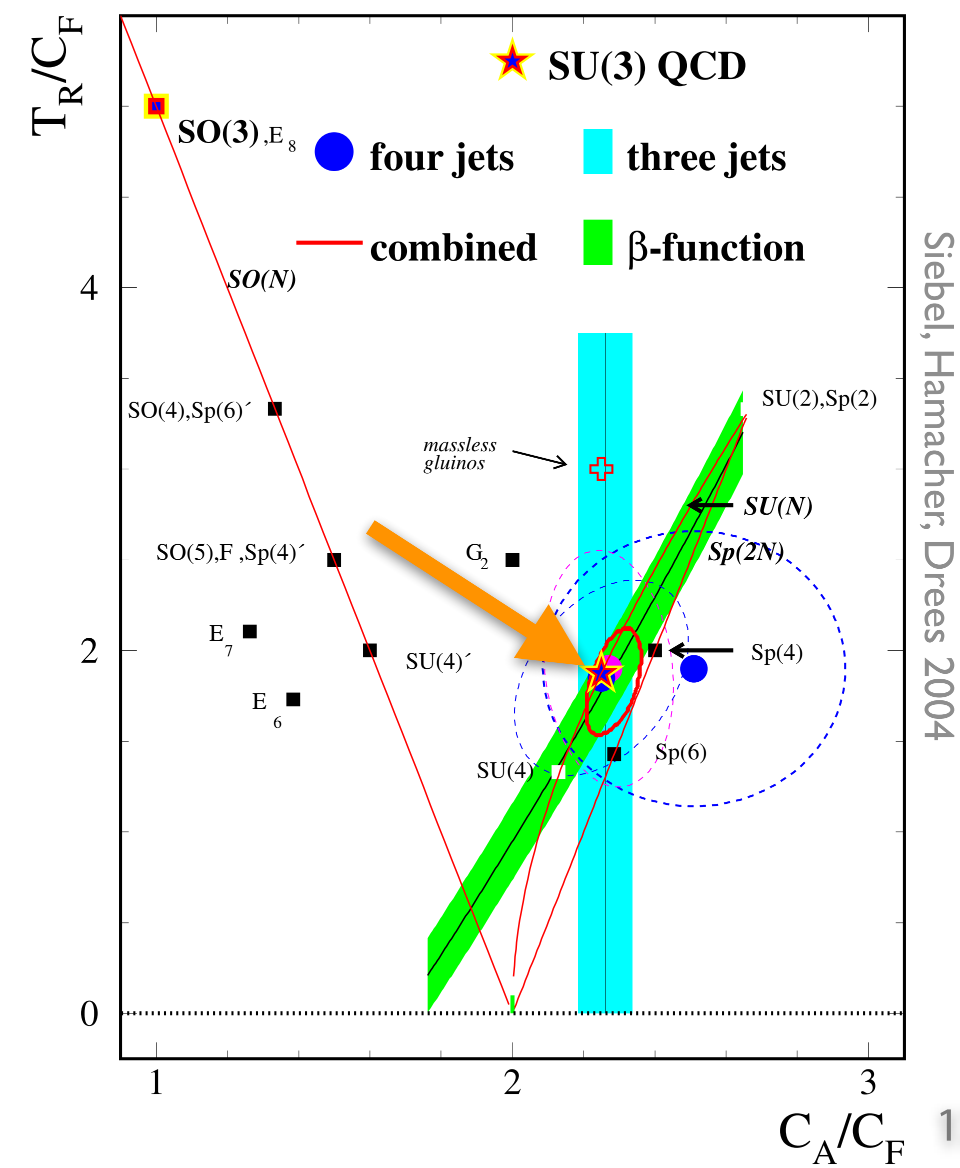
➡ in dipole model the energy slopes are related by:

$$\left.\frac{dN_{gg}(L')}{dL'}\right|_{L'=L+c_g-c_q} = \frac{C_A}{C_F}\left(1-\frac{\alpha_0 c_r}{L}\right)\frac{d}{dL}N_{q\bar{q}}(L)$$

➡ analysis yields:

$$\frac{C_A}{C_F} = 2.261 \pm 0.014_{\text{stat.}} \pm 0.036_{\text{exp.}} \pm 0.052_{\text{theo.}} \pm 0.041_{\text{clus.}}$$

➡ together with β-function fixes group structure of QCD to SU3:



The Exciting Years of DELPHI - End of Part I

- next speaker (Dr. Klaus Mönig) will cover more of the exciting physics we did in Wuppertal with DELPHI

- let me finish with a few personal words:

"When I look back at our DELPHI times, I remember Klaus for what he did for the installation and the commissioning of FCB (actually mostly before my time), as well as his many contributions to the data analysis and physics in Wuppertal. It strikes me that for many of us Klaus was not simply a supervisor. With his help, expertise and support he was mentoring our young scientific careers. His welcoming and positive attitude helped creating a 'group feeling' that I felt was unique."

All the best for your future, Klaus !

Many thanks to Susanne Kersten, Karl-Heinz Becks and others for providing material for this talk...