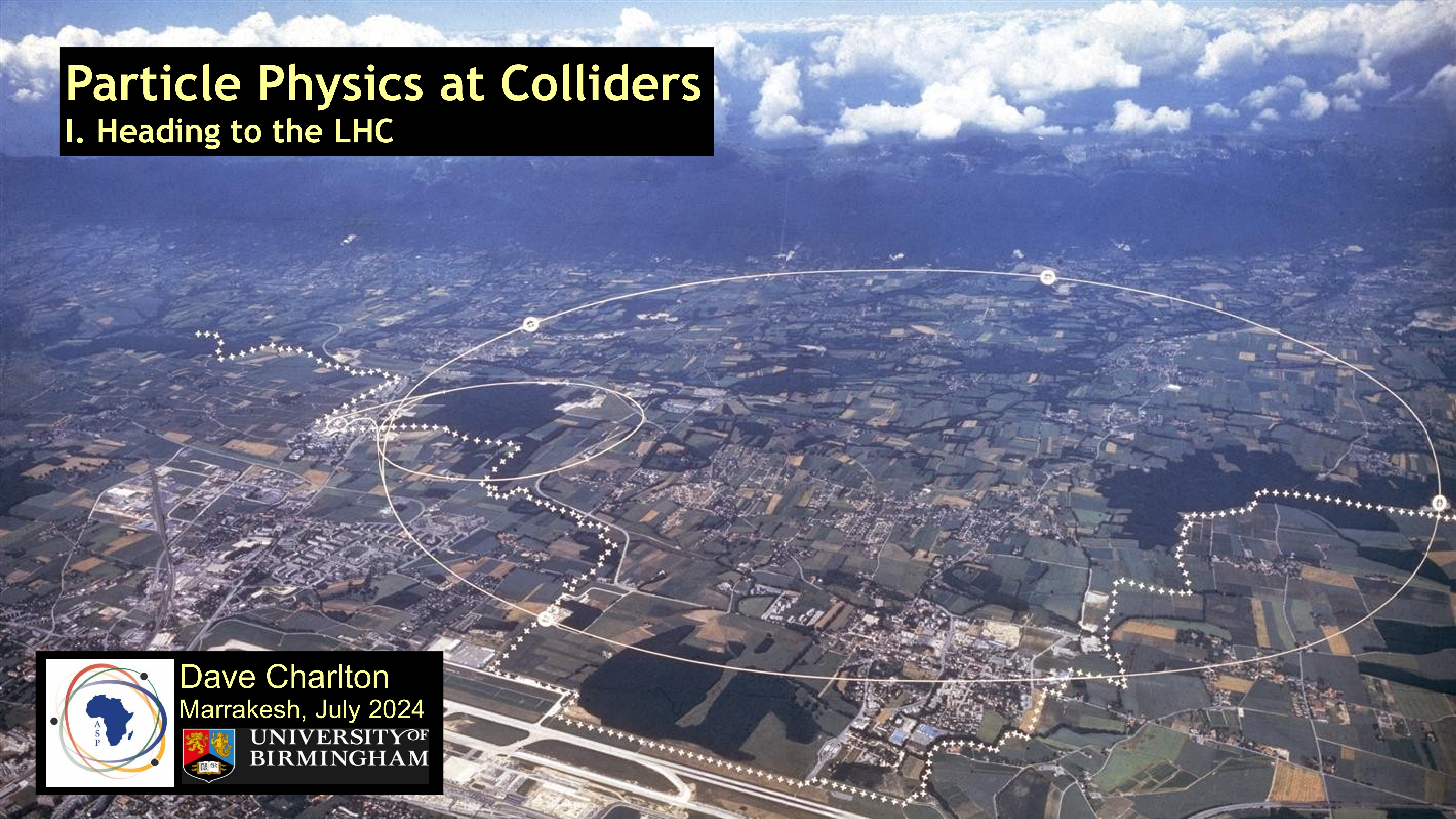
Particle Physics at Colliders

I. Heading to the LHC

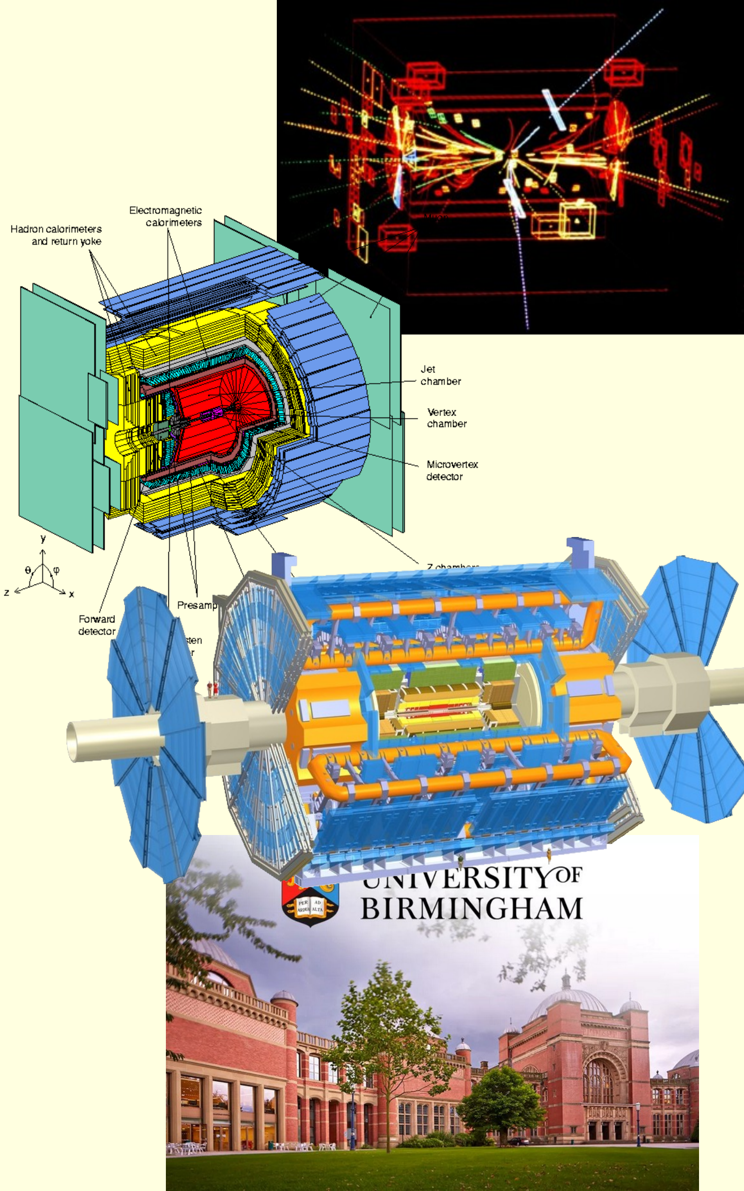


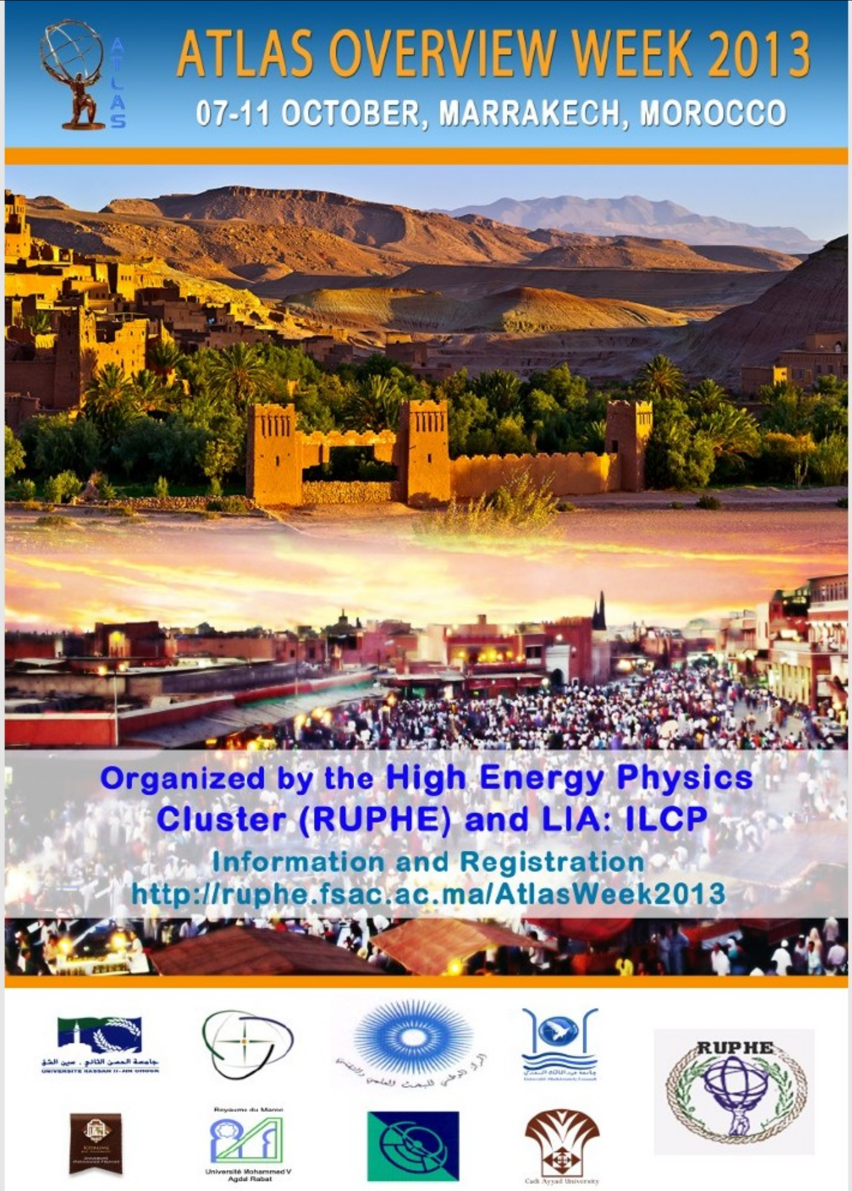
Dave Charlton
Marrakesh, July 2024
UNIVERSITY OF BIRMINGHAM

Dave Charlton

About me:

- PhD student on UA1 experiment 1985-1988 (search for the top quark)
- Moved at start of 1989 to OPAL experiment at LEP, stayed to the end (2000) – electroweak physics with Z and W bosons
- Since 1998, ATLAS experiment at the LHC at CERN
  - Spokesperson (Head) of ATLAS 2013-2017
  - Previously deputy Spokesperson (2009-2013), Physics Coordinator (2008-2009)
  - Worked on calorimeter triggering, silicon tracker construction, analysis of multi-boson production
- Poynting Professor of Physics at the University of Birmingham in the UK since 2017 (I've been with Birmingham since 1994, professor since 2005)





ATLAS OVERVIEW WEEK 2013

07-11 OCTOBER, MARRAKECH, MOROCCO

Organized by the High Energy Physics Cluster (RUPHE) and LIA: ILCP

Information and Registration
http://ruphe.fsac.ac.ma/AtlasWeek2013

ATLAS Week Introduction

Dave Charlton
7 October 2013

Welcome to the first ATLAS Week in Africa!

Links to other lectures

These lectures build on material you have seen in earlier lectures – I will give an experimental viewpoint, only linking briefly to theory, and mainly using Feynman diagrams to explain what's happening

Relevant earlier lectures

- The Standard Model of Particle Physics – Prof Rachid Benbrik
  - For the Standard Model formalism
- Beyond the Standard Model – Prof Shabaan Khalil
  - For motivations for BSM physics and an overview of theoretically-favourite models
- Basics of accelerator physics – Dr Karie Badgley
  - For the idea how accelerators work, for charged particles in a *B* field, and for luminosity
- Detector lectures: Fundamentals of detectors – Prof Sally Seidel, and Particle Interactions with matter and Advanced Detectors – Prof Ulrich Goerlach
  - Concepts and principles of measurements of particles in composite detectors like ATLAS and CMS
- Fundamentals of Statistical Analysis in Physics – Prof Bob Cousins
  - Especially for likelihoods, confidence levels (CL) and p-values

Structure of these lectures

I will adopt a "coarsely historical" approach

- Part I: Experimentally establishing the Electroweak part of the Standard Model – before the LHC
- Part II: Progress on measuring the Standard Model at the LHC, including the Higgs sector
- Part III: Searching for BSM, and a look to the future (medium and longer term)

The parts correspond roughly to the lectures, though part 2 is longest!

Relativistic kinematics revision

I assume you are OK with simple relatistic kinematics, such as the relation

$$E^2 = p^2c^2 + m^2c^4$$

which I'll write (setting c=1) $\quad E^2 = p^2 + m^2 \quad$ ("natural units" ħ=c=1)

trivially giving $\quad m^2 = E^2 - p^2$

The rest mass of the particle, *m*, can be evaluated in any inertial frame and is always the same – it is a *Lorentz invariant*

This generalises to a system of particles, where we talk about the *invariant mass*

$$m_{inv}^2 = \left(\sum_i E\right)^2 - \left(\sum_i \vec{p}\right)^2$$

For a system of two colliding particles, m_{inv} is normally written $\sqrt{s}$ (the centre-of-mass energy) - it too is (naturally) a Lorentz invariant quantity

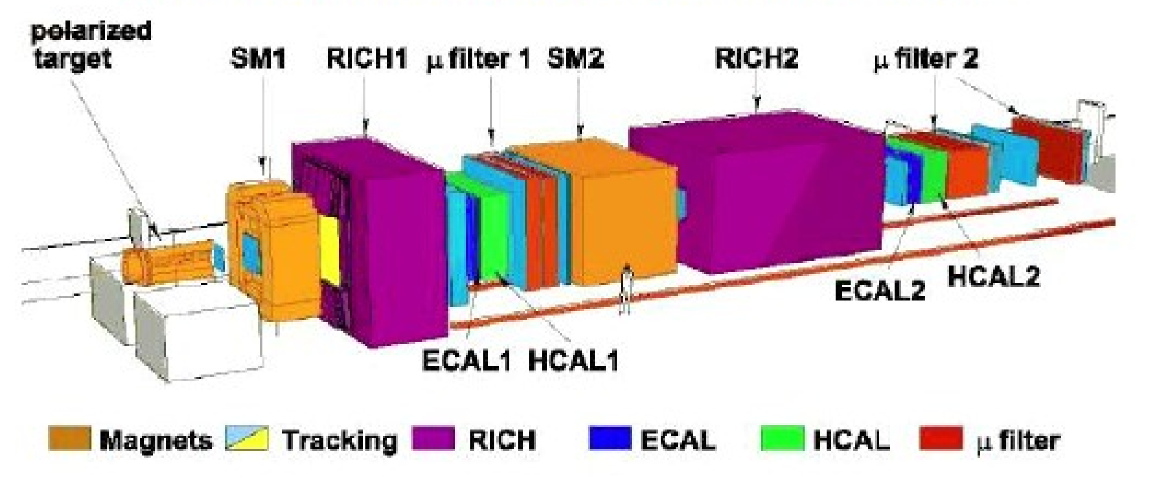
Why colliders?

High-energy *experiments* use accelerators in two ways: fixed targets or colliders

- Fixed target
  - Beam of energy E strikes a target particle with mass m

$$(E,\boldsymbol{p}) \longrightarrow \bullet \quad (m,\boldsymbol{0})$$

  - Provided $E \gg m$, centre-of-mass energy $\sqrt{s} \approx \sqrt{(2Em)}$
  - Because the beam can be stopped by the target, high luminosities are possible
  - Boosted collision system in the lab frame (can be good or bad)



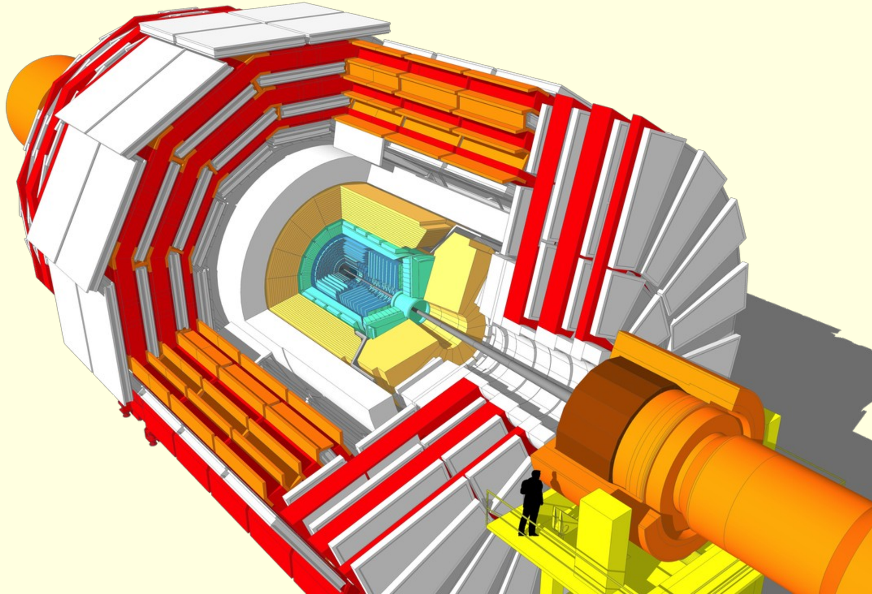
Why colliders?

High-energy *experiments* use accelerators in two ways: fixed targets or colliders

- Colliders
  - Two beams collide, usually particles having same *m* and equal and opposite momenta

$$(E,p) \longrightarrow \longleftarrow (E,-p)$$

  - Provided $E \gg m$, centre-of-mass energy **$\sqrt{s} \approx 2E$** – *grows with E rather than* $\sqrt{E}$
  - *Much* higher $\sqrt{s}$ for e.g. 100 GeV to TeV beams
  - Big challenge to have high luminosities → squeezed beams, many bunches ... ...
  - Must accelerate two beams - complexity



Why colliders?

At high beam energy

Fixed target
- **$\sqrt{s} \approx \sqrt{(2Em)}$**
- very high luminosities "easily" possible
- boosted collision system in the lab

Colliders
- **$\sqrt{s} \approx 2E$**
- high luminosities difficult
- must accelerate two beams – complexity
- may be in CM frame of final system (e^+e^-)

If you want to study very rare processes, fixed target often wins
e.g. neutrino experiments!
(but not always – B factories)

If you want to search for new physics at high masses/energies – better build a collider

Rates, luminosities and cross-sections

In a collider, the rate, dN_a/dt, of events produced for a given process a is:

$$dN_a/dt = \sigma_a L$$

where

- σ_a is the *cross-section* for the process
  - units of area (1 barn = 10^{-28} m^2 = 10^{-28} cm^2)
  - typically mb, μb, nb, pb and fb are (all) met for different processes!
  - it depends on the physics process, eg. pp → W + anything and the centre-of-mass energy $\sqrt{s}$
- L is the instantaneous luminosity, usually called the luminosity
  - units of inverse-area per unit time (typically ~10^{34} cm^{-2} s^{-1} at LHC)
  - Process-independent, depends only on the beam characteristics

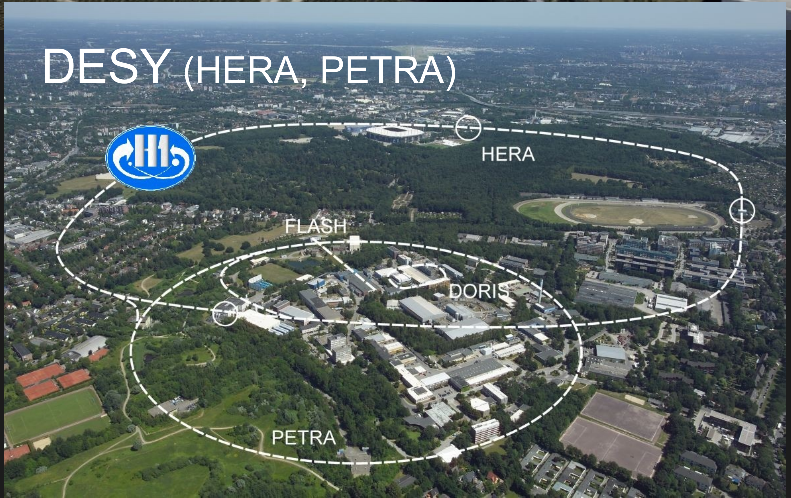
Integrated version:

$$N_a = \sigma \int L dt$$

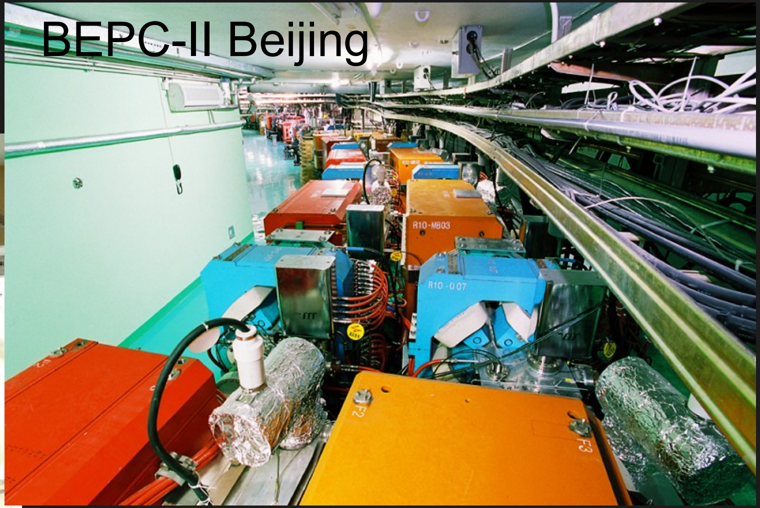
where $\int L dt$ is the integrated luminosity, typically expressed in fb^{-1}

Particle colliders have a long history


CERN ISR (pp, $p\bar{p}$)


DESY (HERA, PETRA)

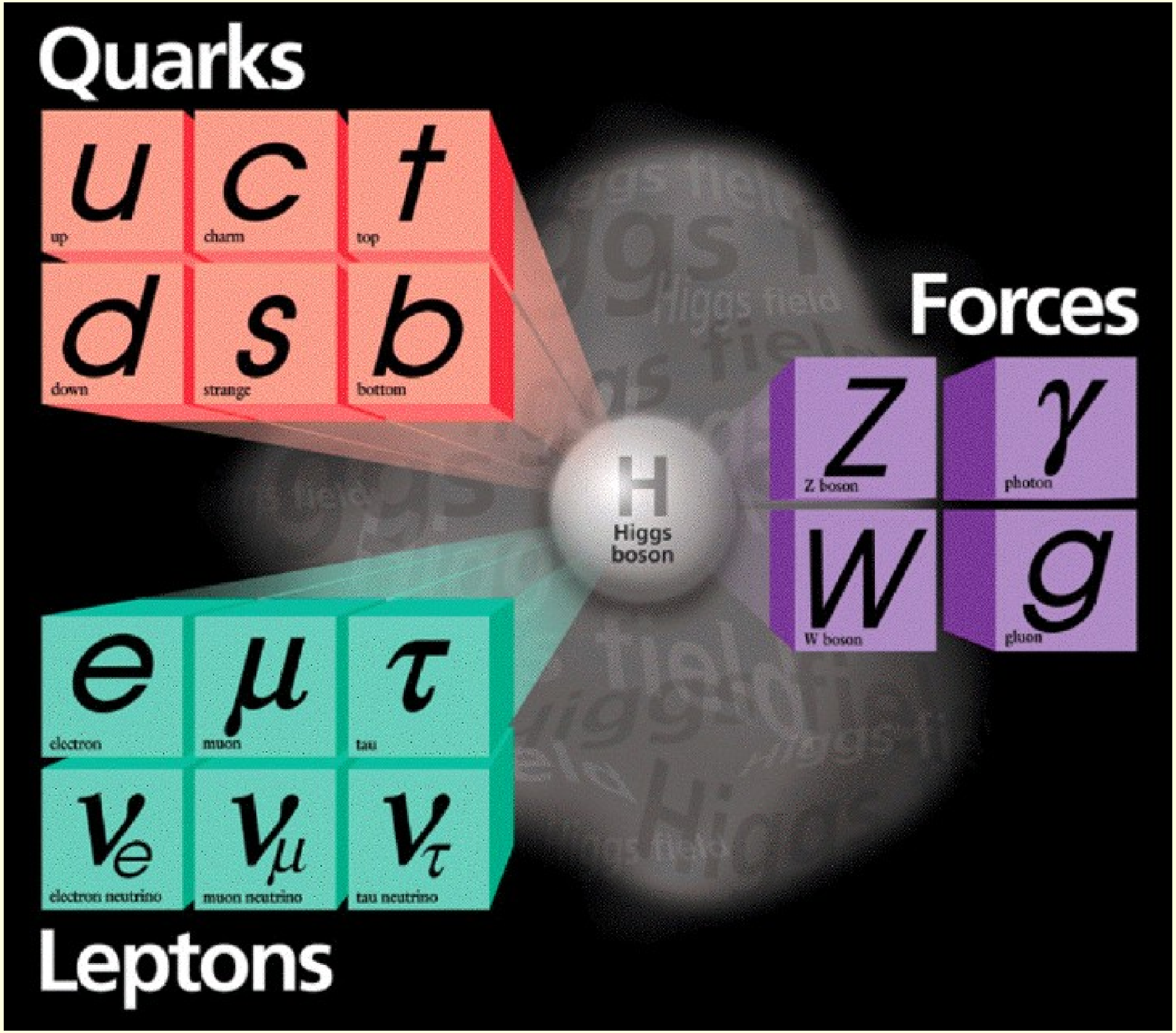

VEP-1 (e^-e^-)
Novosibirsk


BEPC-II Beijing


SuperKEKB

The Standard Model

The particle content of the SM is familiar to you



The Standard Model

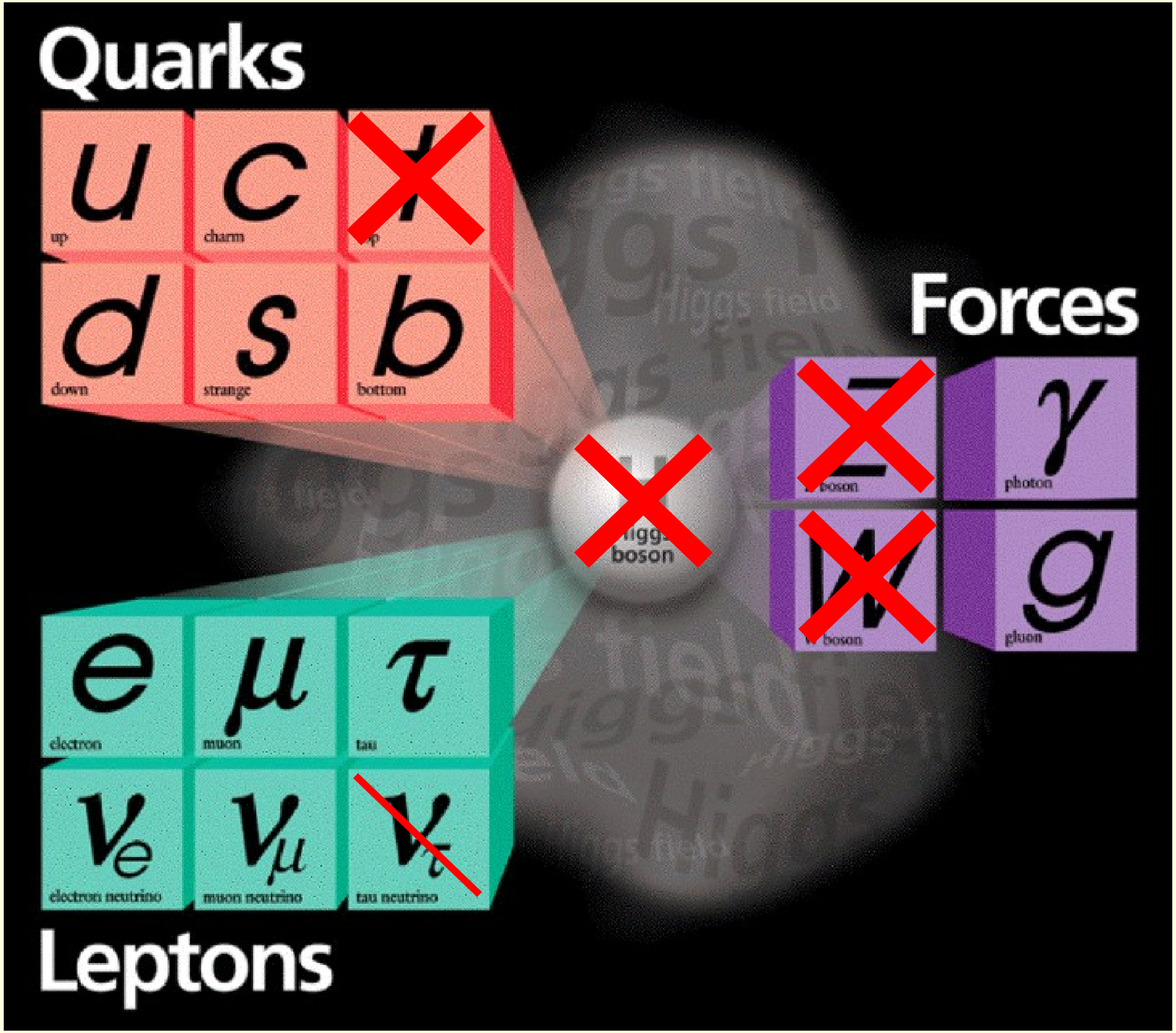
The particle content of the SM is familiar to you

At the **end of the 1970's,** the discovered particles were fewer

Motivated the construction of large *electroweak-scale* colliders, and beyond

Goals to reach sensitivity to

- make 100 GeV objects (W,Z)
- find the top quark
- eventually, test if the Brout-Englert-Higgs mechanism is right



CERN SPS accelerator layout (1980's)

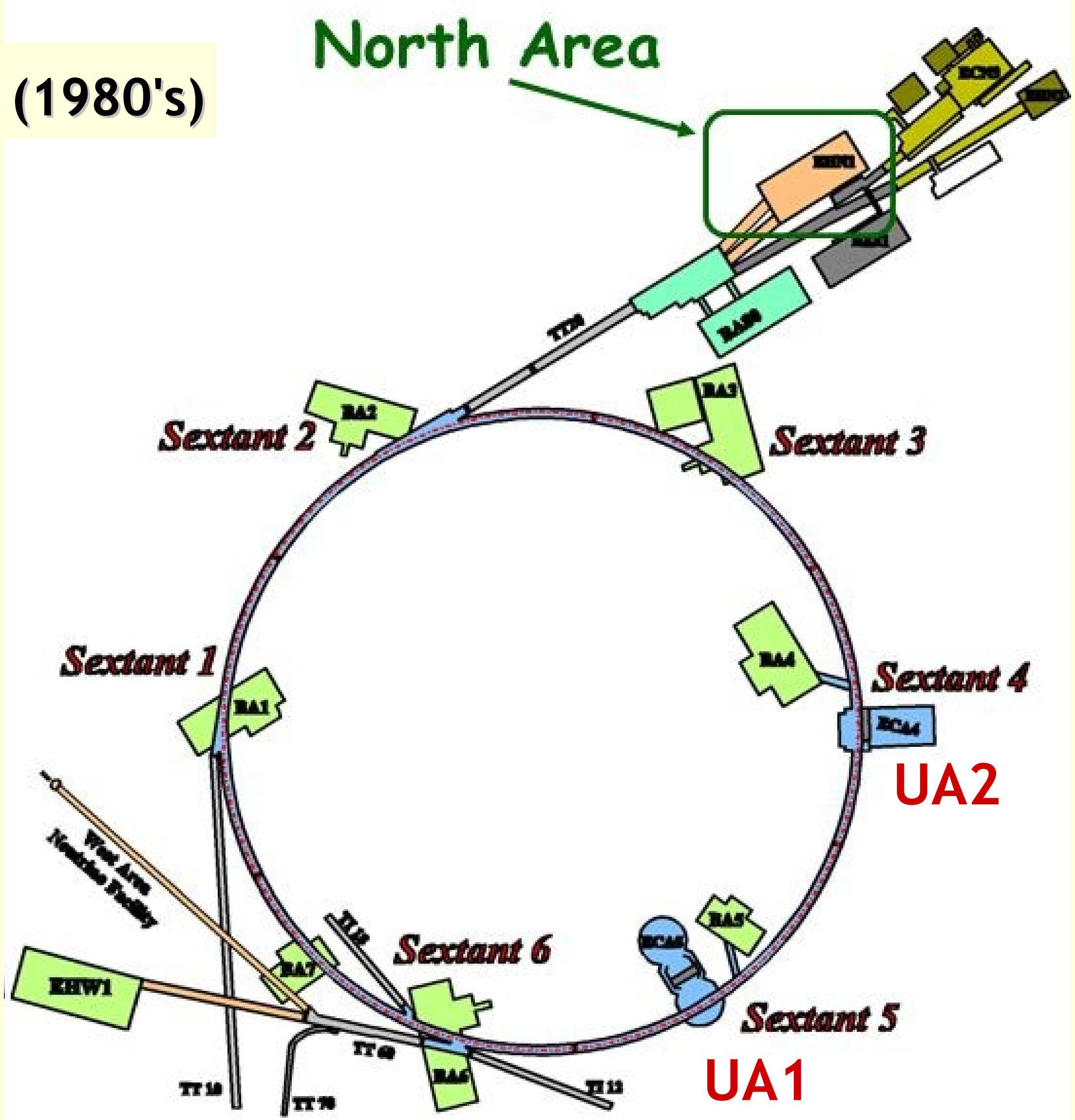
SPS = Super Proton Synchrotron

Protons reached 300 GeV in **1976**

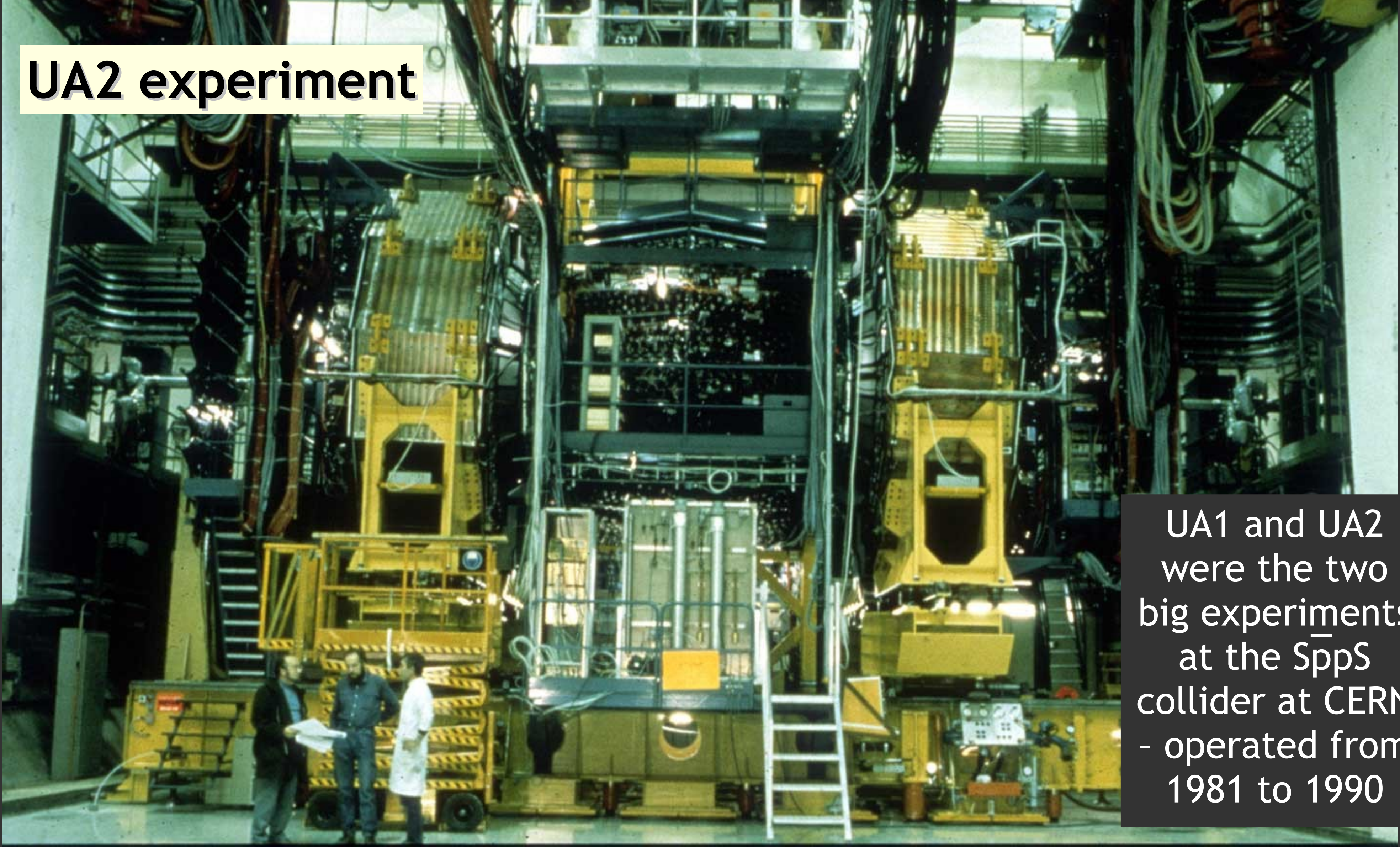
Fixed target programme includes(-ded) neutrinos, proton, π, K beams

Collider programme (1980's) started at 546 GeV, raised to 630 GeV
Known as "**Sp$\bar{p}$S** collider"

Today SPS is still used for fixed target experiments (e.g. NA62 kaons) and as an injector for LHC

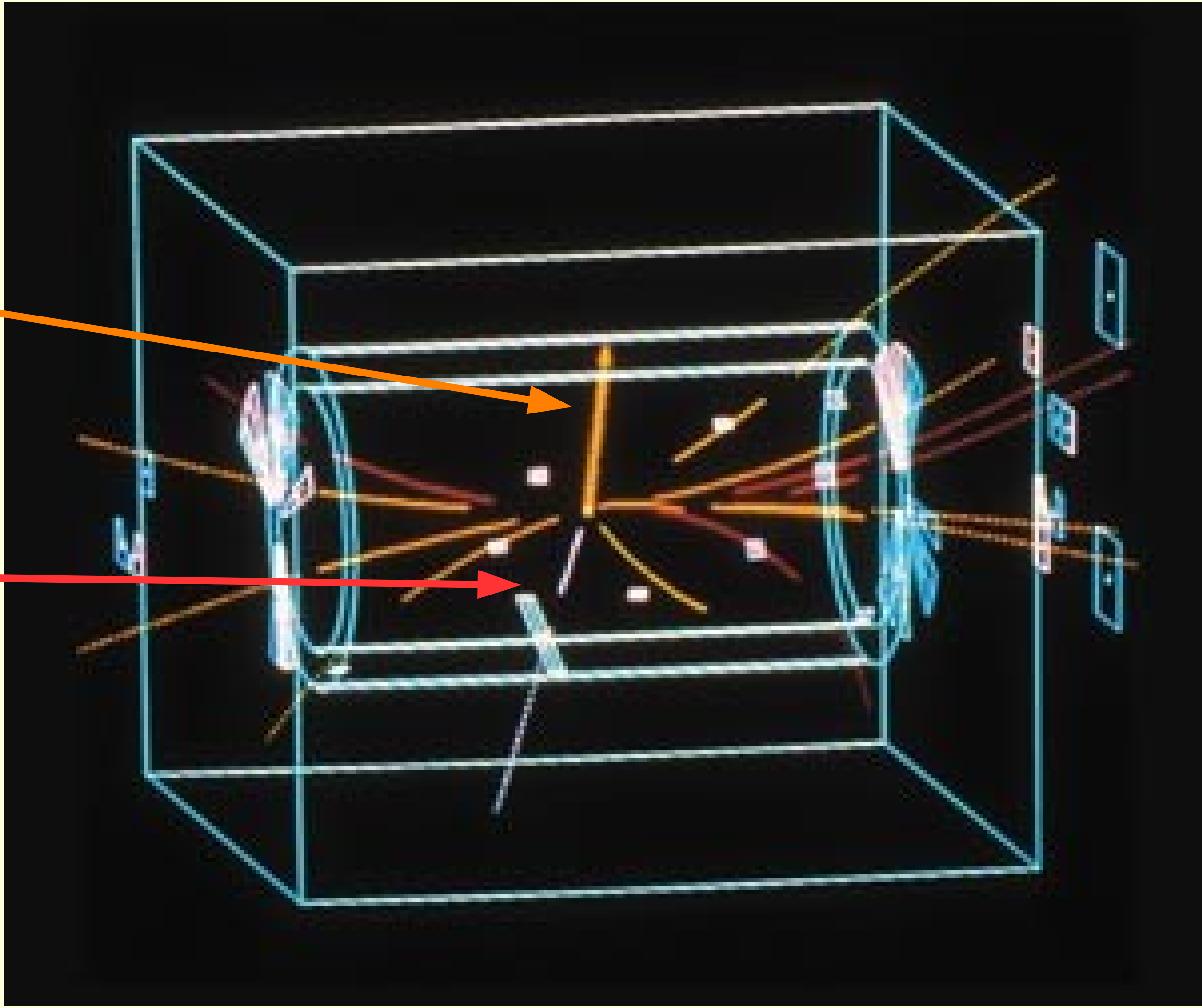


UA2 experiment



UA1 and UA2 were the two big experiments at the SppS collider at CERN – operated from 1981 to 1990

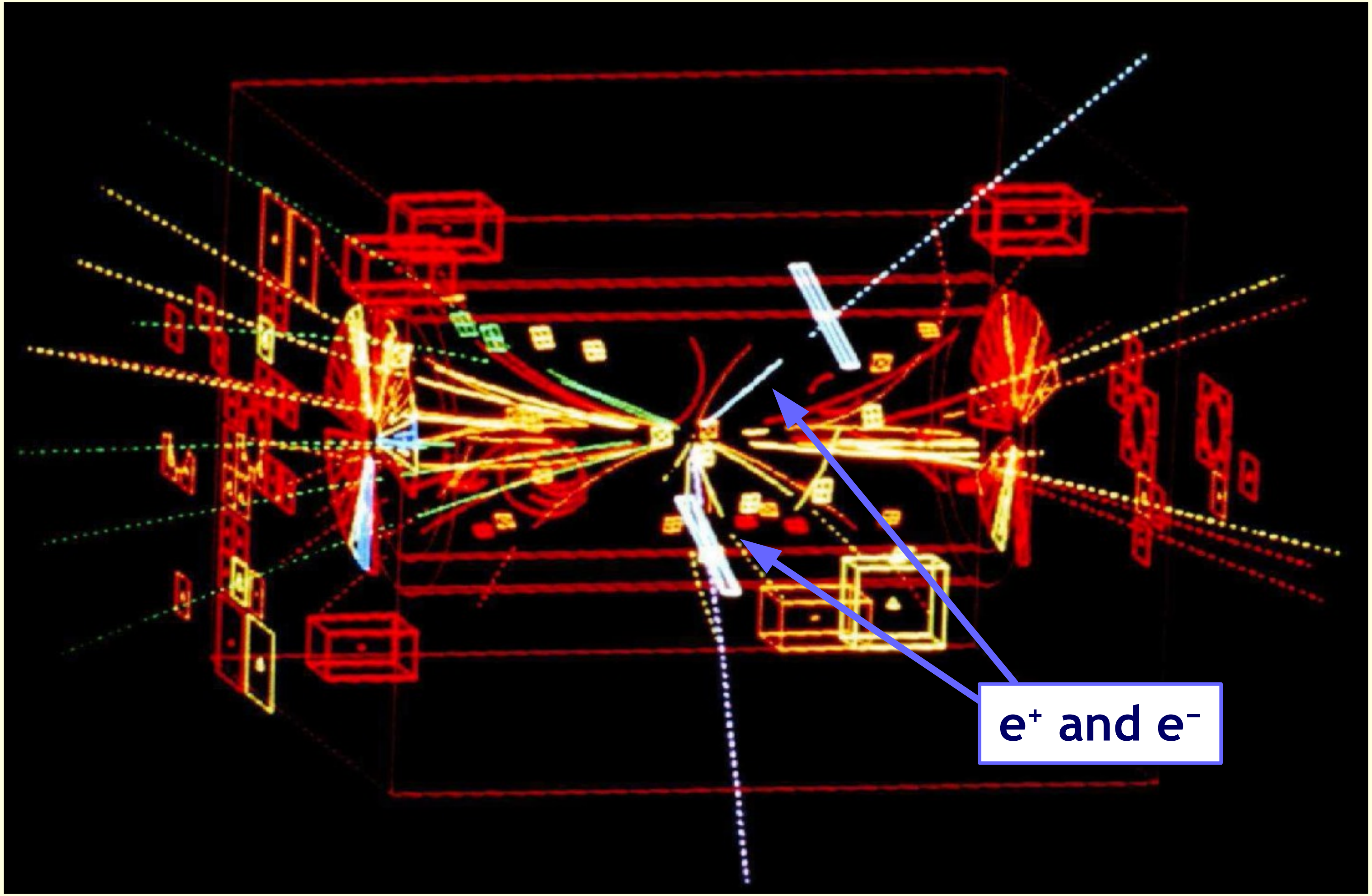
$W \rightarrow e\nu_e$ candidate



Missing-E_T (reconstructed from transverse momentum imbalance)

Electron – seen as a high-p_T charged track with matching energy deposit in calorimeter

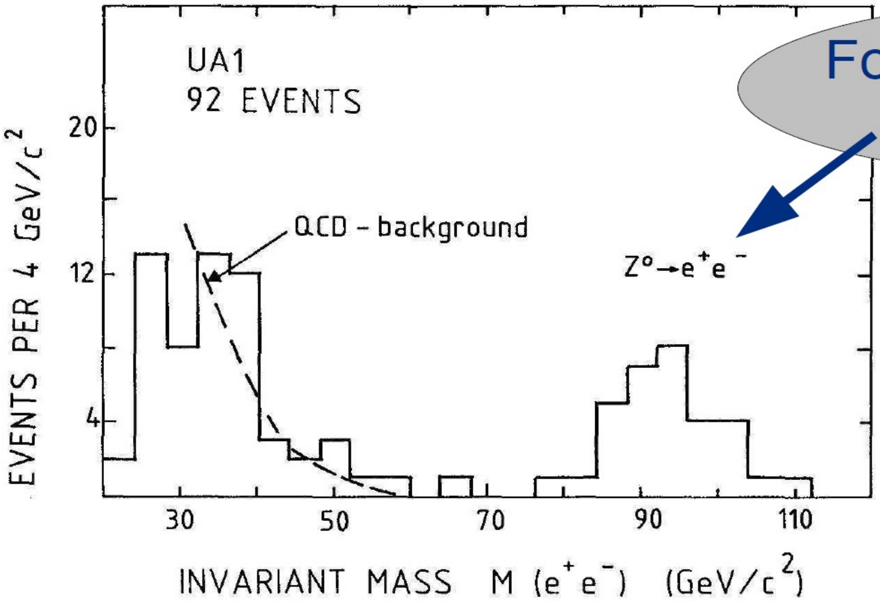
Z→ℓℓ candidate



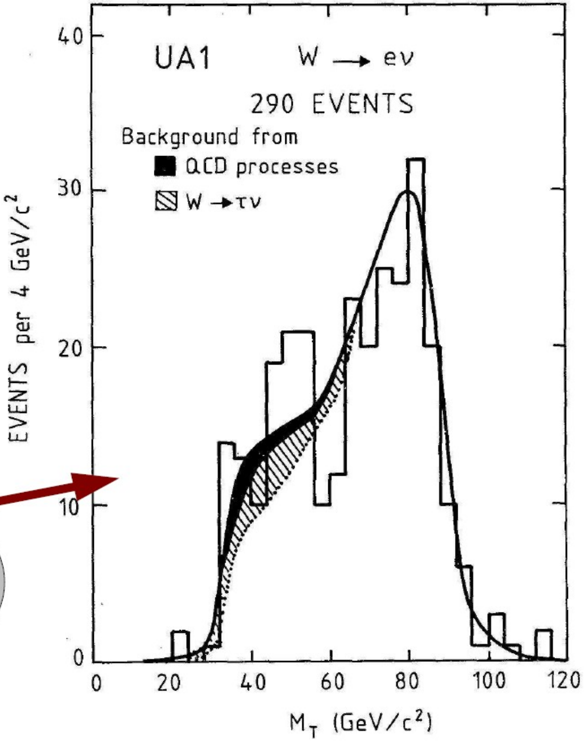
We measure the two electrons quite well → so we can construct event by event the invariant mass $m(e^+e^-)$

If we hypothesise that an object decayed exclusively to the e^+e^- pair, this invariant mass is the (measured) mass of the object

Later data from UA1



For Z, invariant mass of e^+e^- should be M_Z



For W, have to infer *v* momentum from overall momentum balance – and cannot measure component along beam axis at all

W, Z discovery

UA1 and UA2 discovered the W and Z bosons in their leptonic decay modes

- $W \to \ell\nu$ ($\ell = e$ or μ)
- $Z \to \ell\ell$

UA2 measured both masses with a precision of about 1% (~1 GeV error)

- $m_W \approx 81$ GeV
- $m_Z \approx 92$ GeV

Much other physics besides, but no time to discuss here!

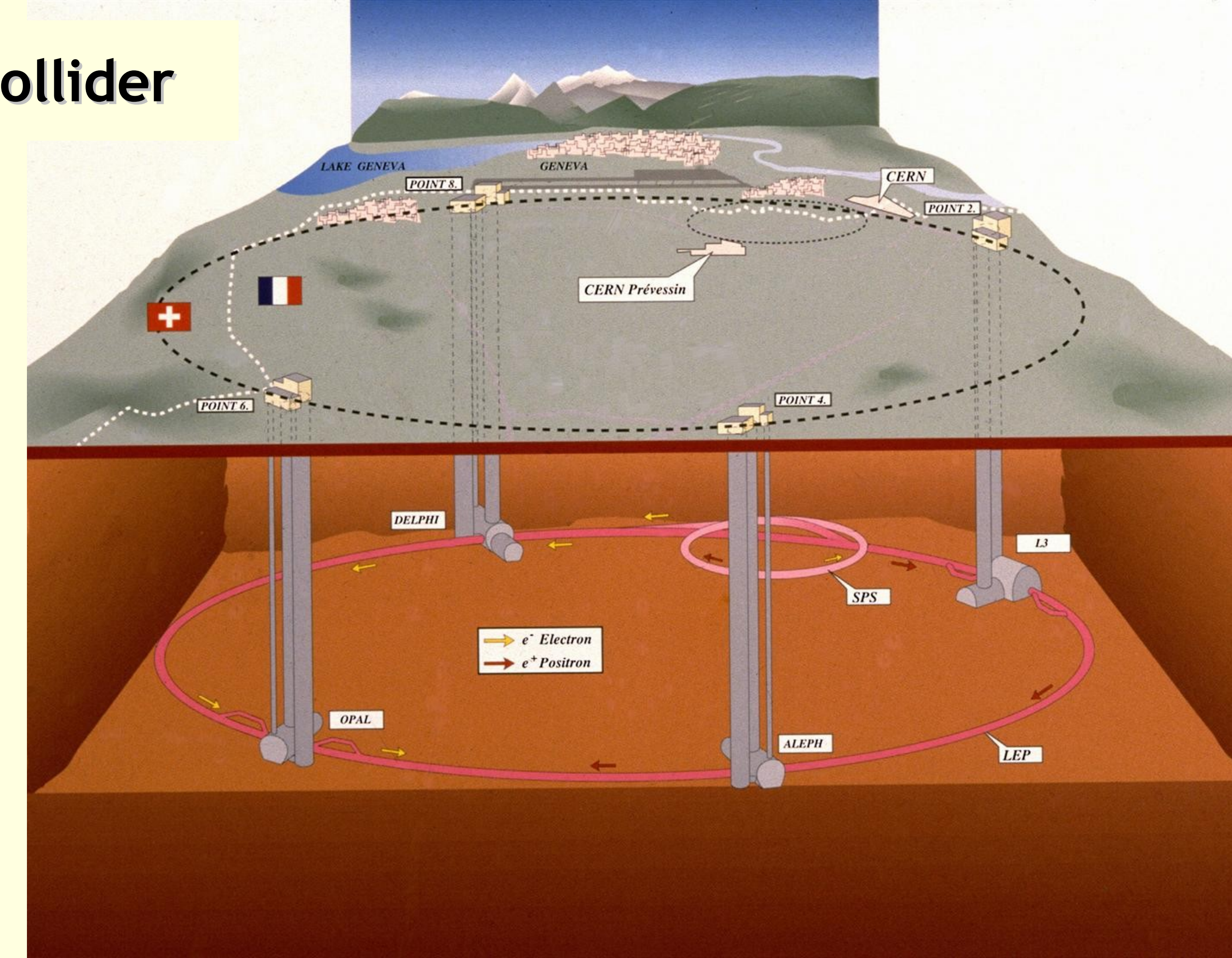
The Nobel Prize in Physics 1984 was awarded jointly to Carlo Rubbia and Simon van der Meer "for their decisive contributions to the large project, which led to the discovery of the field particles W and Z, communicators of weak interaction"

The LEP e^+e^- Collider

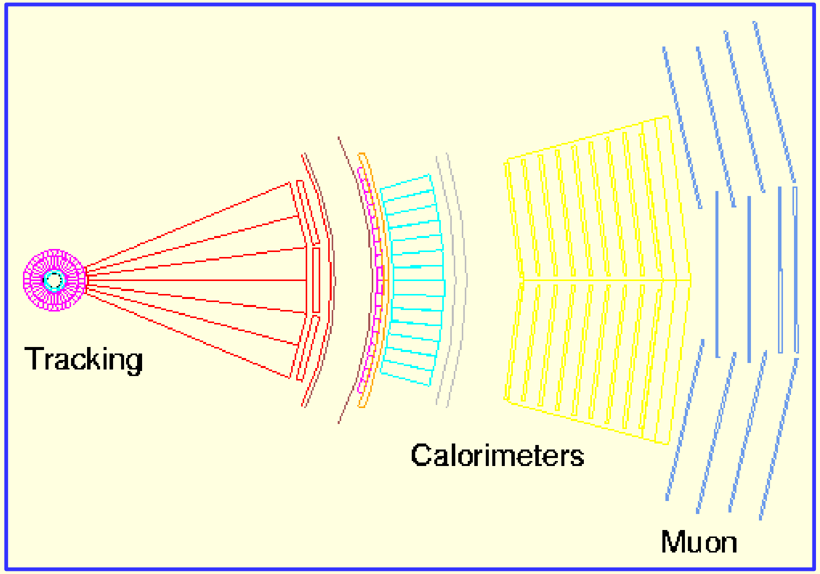
Large Electron-Positron Collider

Huge 27km circumference tunnel excavated in the 1980's

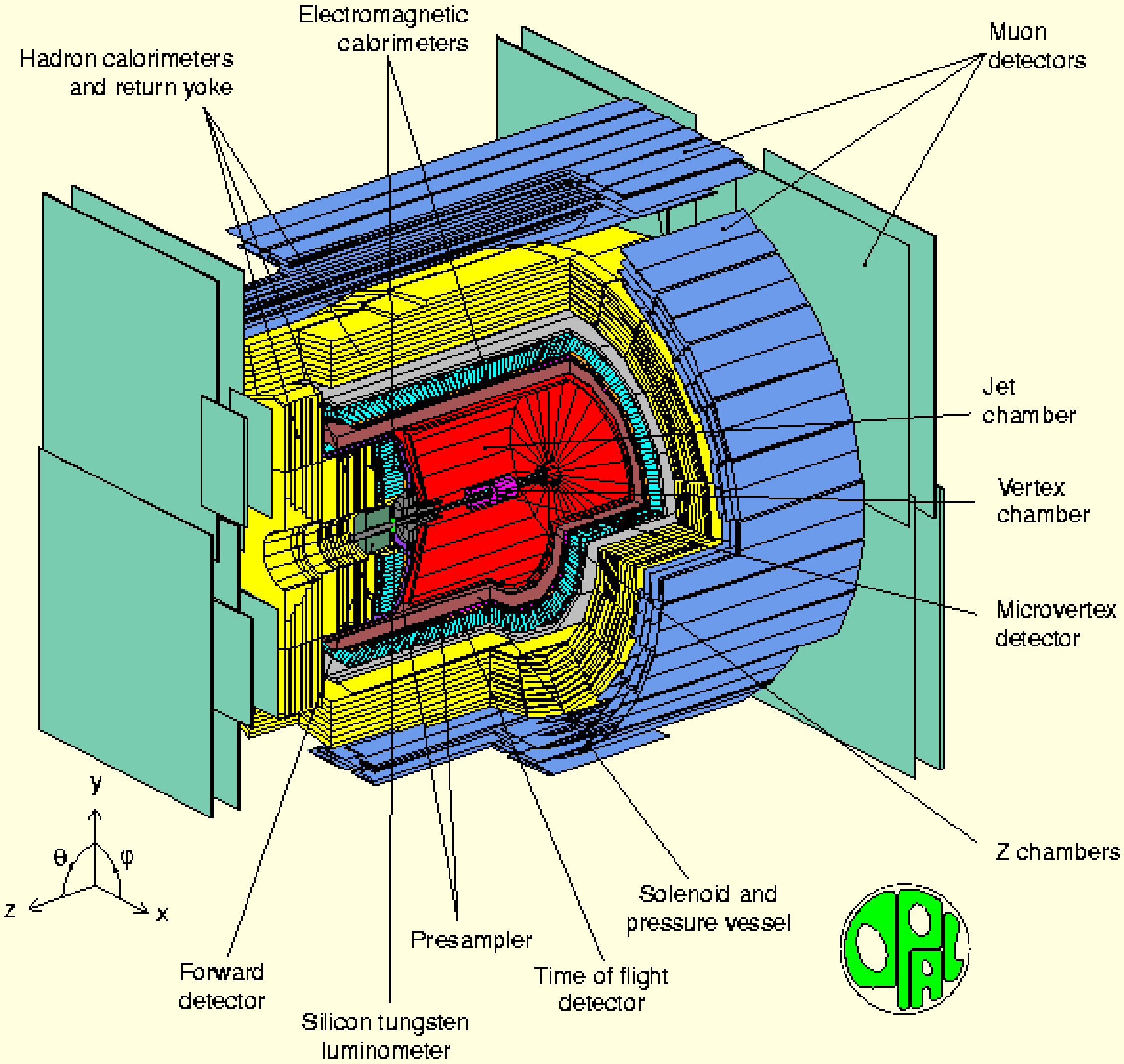
Four experiments, all aiming at all physics topics accessible ("general purpose detectors")



OPAL experiment at LEP



Cross-sectional slice through barrel – see the main detector layers



LEP data

Centre-of-mass energy √s=88-209 GeV

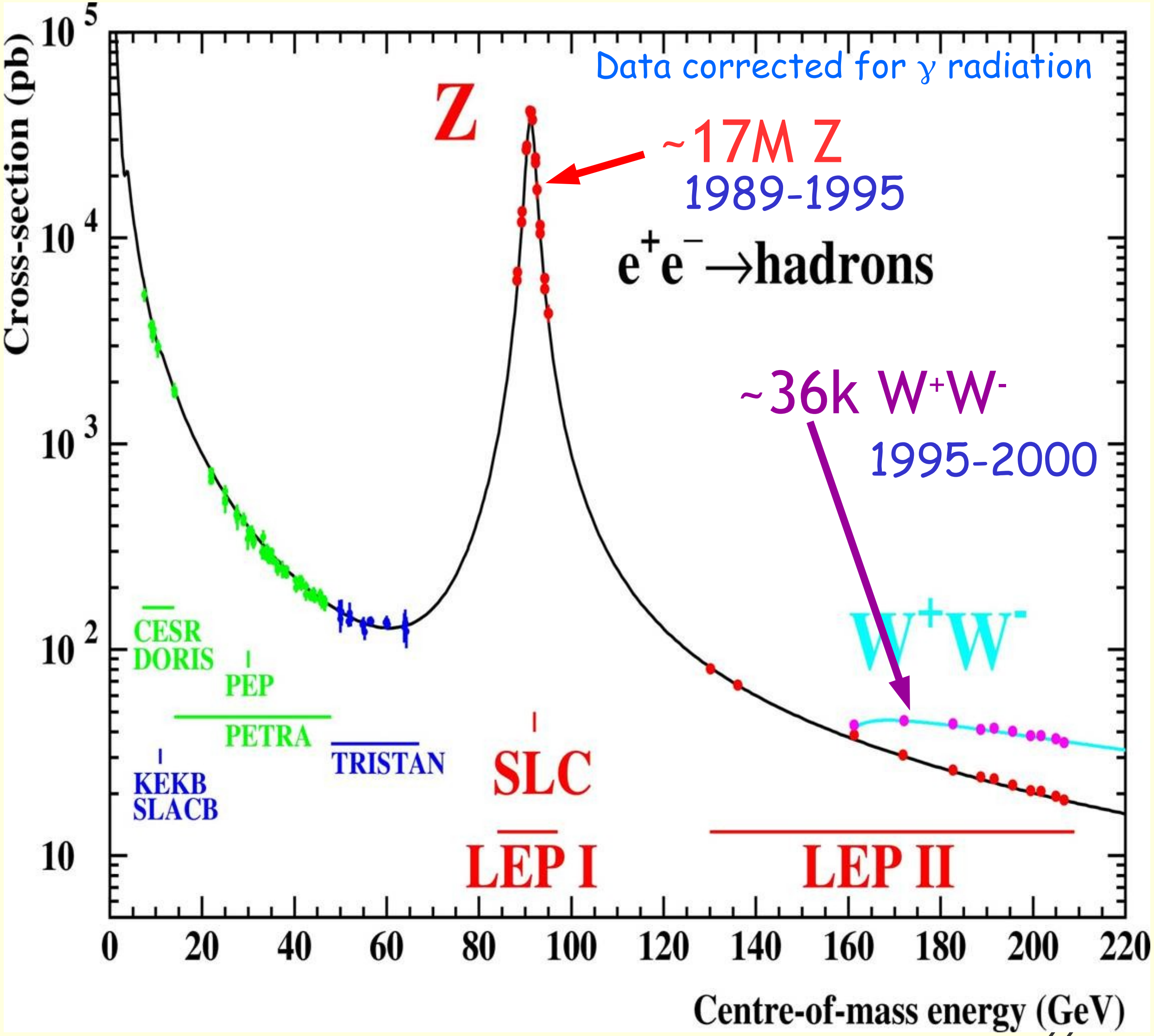
- LEP-1 at Z peak
- LEP-2 at high energy

LEP-1: high precision measurements of Z

- Z mass, width, couplings to fermions
- Number of light neutrino species …

LEP-2: WW and ZZ production

- W mass and couplings
- Searches …


Data corrected for γ radiation

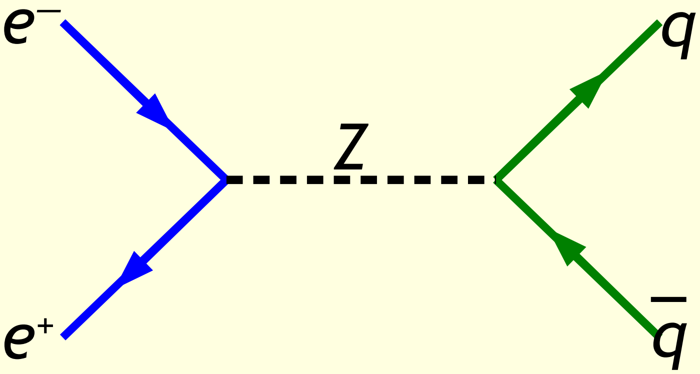
~17M Z

1989-1995

~36k W^+W^-

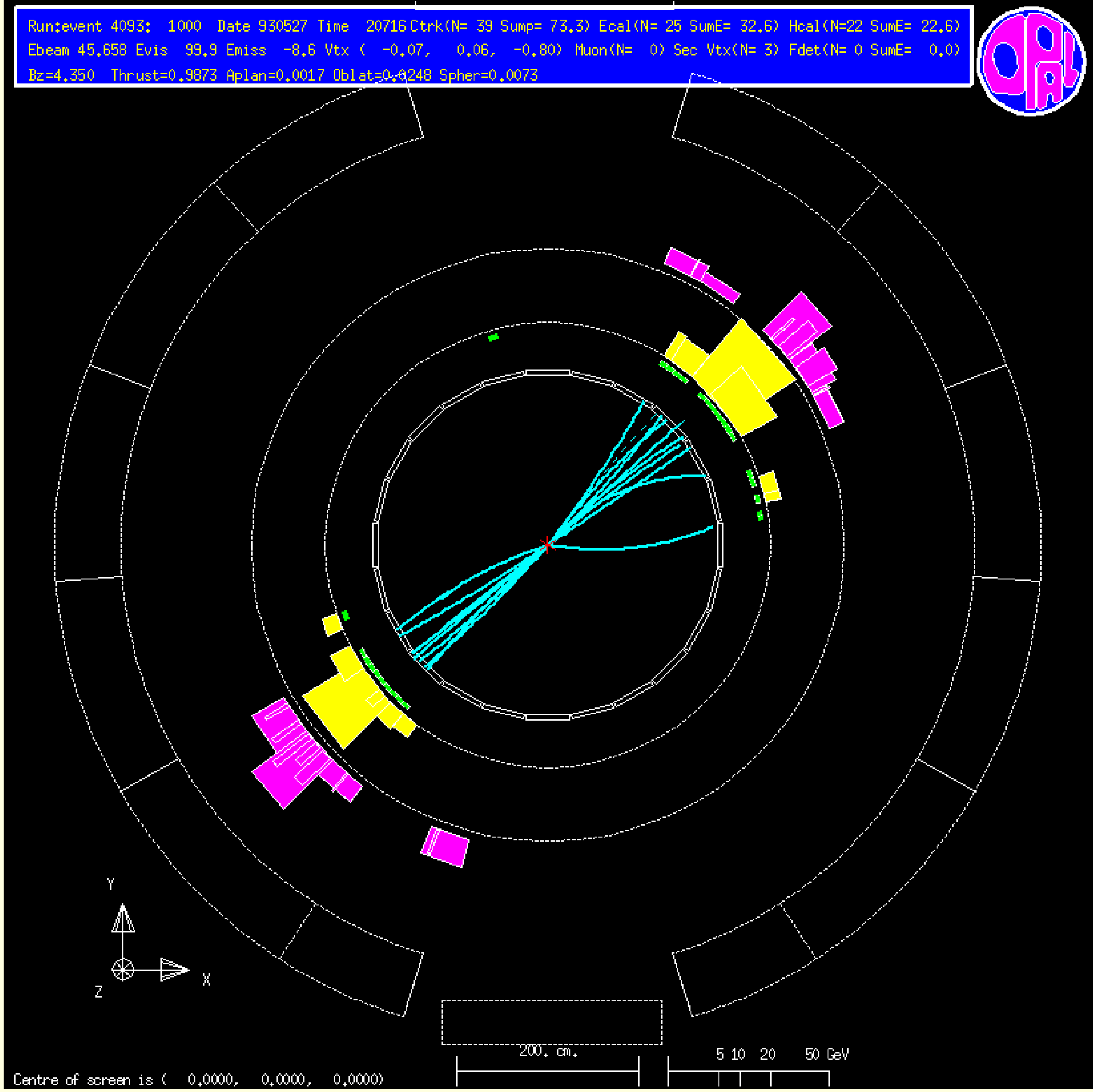
1995-2000

$e^+e^- \rightarrow$ hadrons at LEP "2-jet" event



$e^+e^- \rightarrow q\bar{q}$
Quarks hadronise to form two back-to-back jets

Rest of event is very clean in e^+e^- collisions – no “underlying event” as seen in hadron collisions


```
Run:event 4093:  1000  Date 930527 Time  20716 Ctrk(N= 39 Sump= 73.3) Ecal(N= 25 SumE= 32.6) Hcal(N=22 SumE= 22.6)
Ebeam 45.658 Evis  99.9 Emiss  -8.6 Vtx (  -0.07,   0.06,  -0.80)  Muon(N=  0) Sec Vtx(N= 3) Fdet(N= 0 SumE=  0.0)
Bz=4.350  Thrust=0.9873 Aplan=0.0017 Oblat=0.0248 Spher=0.0073
```

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Centre of screen is (  0.0000,   0.0000,   0.0000)
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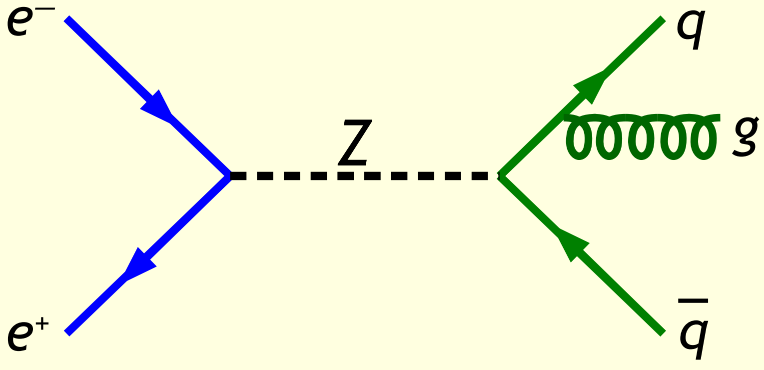
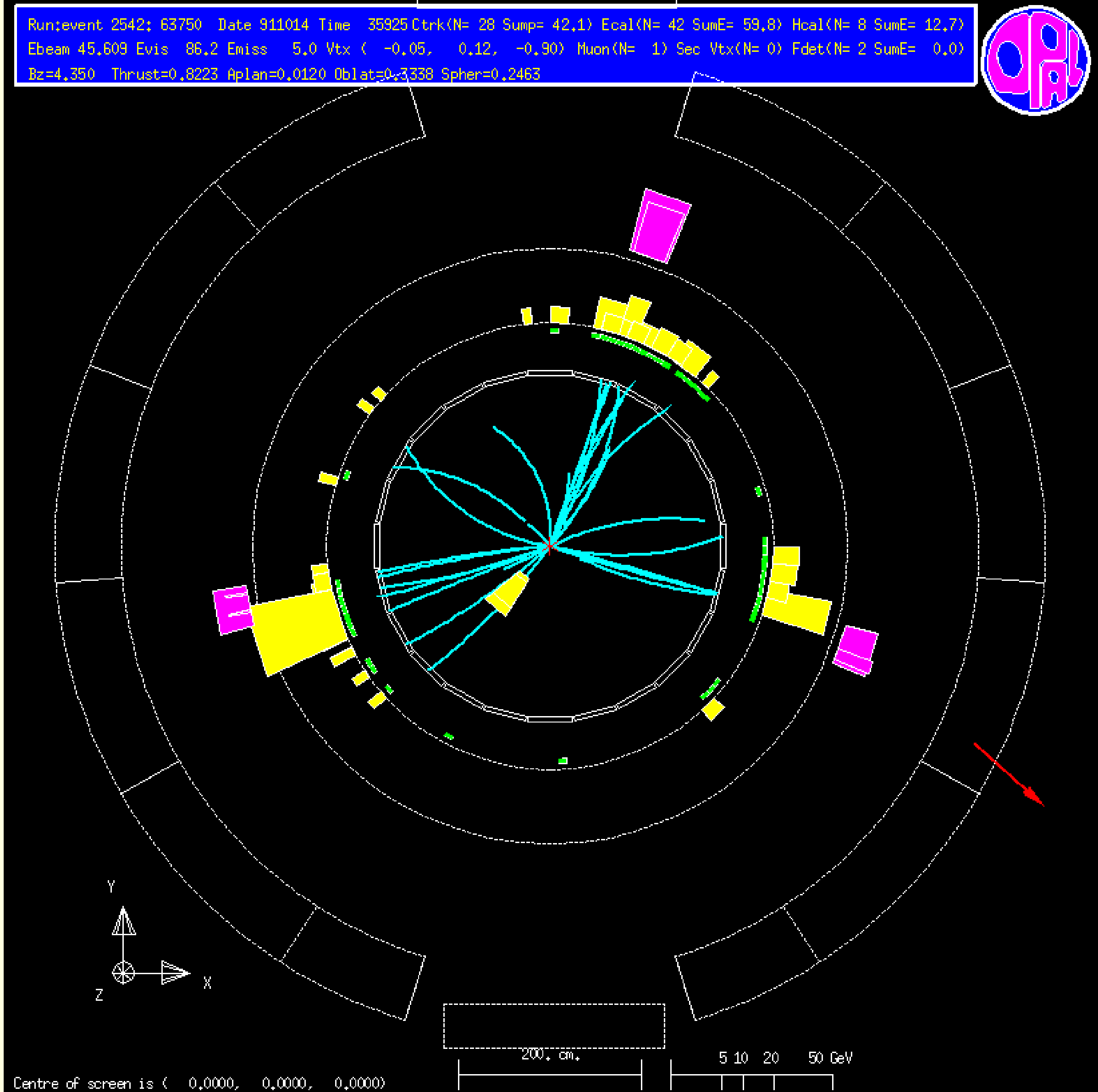
$e^+e^- \rightarrow$ hadrons at LEP "3-jet" event



$e^+e^- \rightarrow q\bar{q}g$_
Partons q, $\bar{q}$ and g each hadronises to form jets

Relative rates of 3- and 2-jet events measures α_S



```
Run:event 2542: 63750  Date 911014 Time   35925 Ctrk(N= 28 Sump= 42.1) Ecal(N= 42 SumE= 59.8) Hcal(N= 8 SumE= 12.7)
Ebeam 45.609 Evis  86.2 Emiss   5.0 Vtx (  -0.05,   0.12,  -0.90) Muon(N=  1) Sec Vtx(N= 0) Fdet(N= 2 SumE=  0.0)
Bz=4.350  Thrust=0.8223 Aplan=0.0120 Oblat=0.3338 Spher=0.2463
```

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Centre of screen is (   0.0000,   0.0000,   0.0000)
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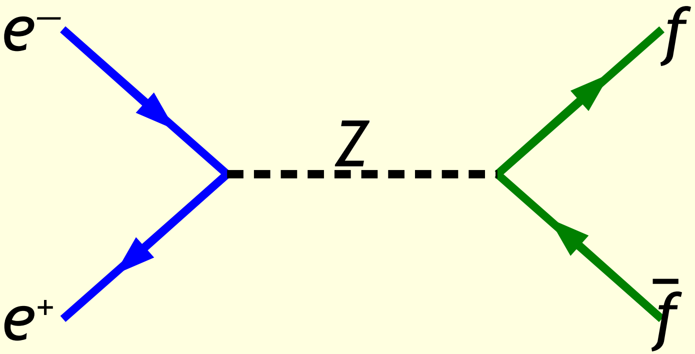
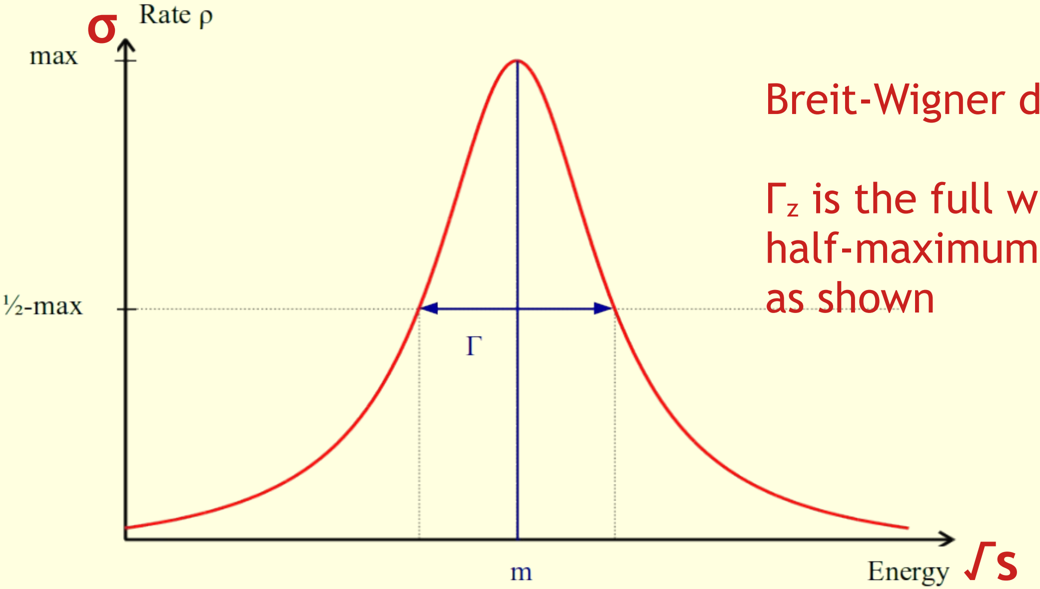
LEP-1 - Measuring the Z properties



Close to the Z peak, *at lowest-order* the cross-section for Z production and decay varies with √s as:

$$\sigma\left(e^+e^- \to Z \to f\bar{f}\right) = \frac{12\pi}{m_Z^2}\frac{s\,\Gamma_e\Gamma_f}{\left(s-m_Z^2\right)^2+m_Z^2\Gamma_Z^2}$$



Breit-Wigner distribution

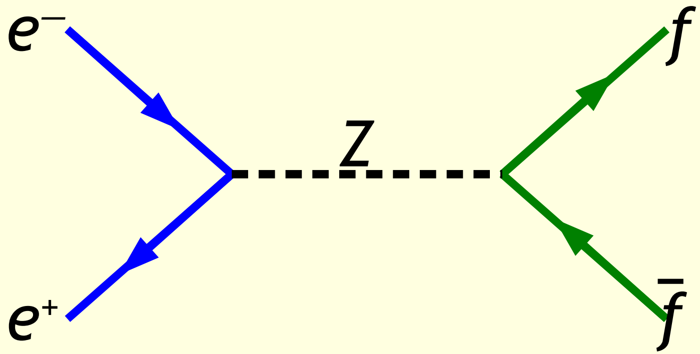
Γ_Z is the full width at half-maximum (FWHM), as shown

Γ_e and Γ_f are the *partial* decay widths (= decay rates) of the *Z* to e^+e^- and $f\bar{f}$

$$\Gamma_Z = \sum_j \Gamma_j$$

Sum over all decay modes

LEP-1 - Measuring the Z properties



Close to the Z peak, *at lowest-order* the cross-section for Z production and decay varies with √s as:

$$\sigma\left(e^+e^- \rightarrow Z \rightarrow f\bar{f}\right)=\frac{12\pi}{m_Z^2}\frac{s\,\Gamma_e\Gamma_f}{\left(s-m_Z^2\right)^2+m_Z^2\Gamma_Z^2}$$

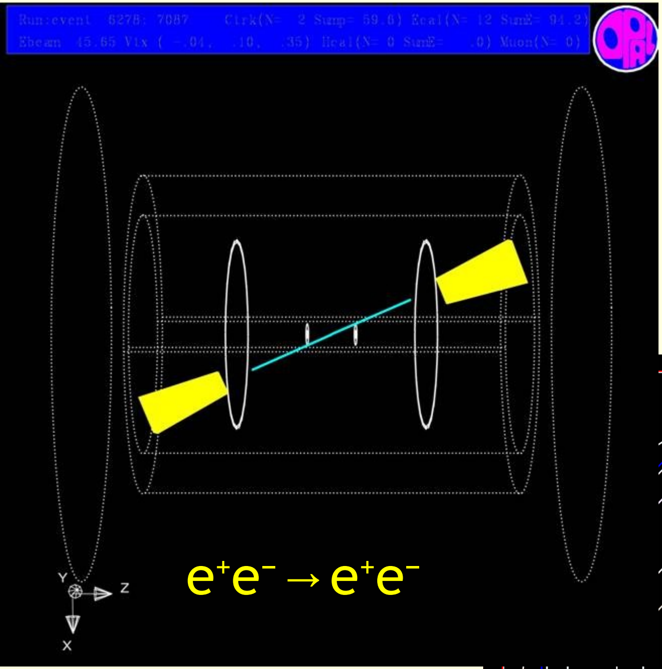
Right on the Z peak, $\sqrt{s}=m_Z$:

$$\sigma\left(e^+e^- \rightarrow Z \rightarrow f\bar{f}\right)=\frac{12\pi}{m_Z^2}\frac{\Gamma_e\Gamma_f}{\Gamma_Z^2}$$

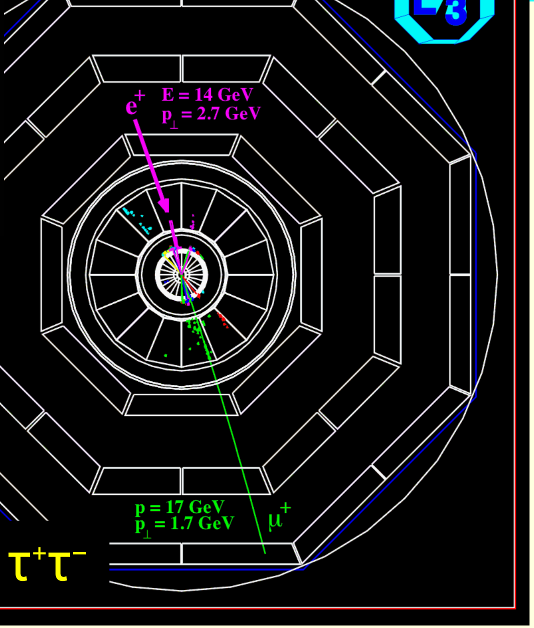
Measuring the peak cross-section for all visible decay modes of the Z → allows to extract all the visible decay partial widths Γ_f

Also measured the overall Z lineshape (σ vs $\sqrt{s}$) → directly measures Γ_Z

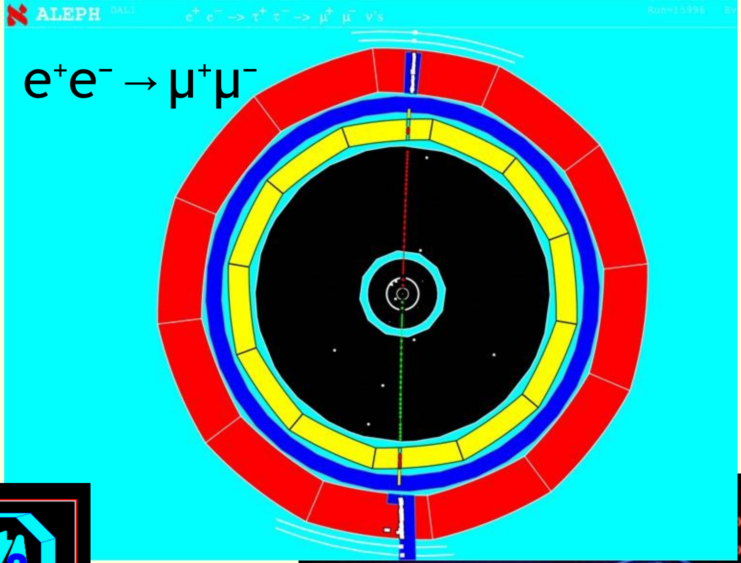
LEP-1 events at the Z peak



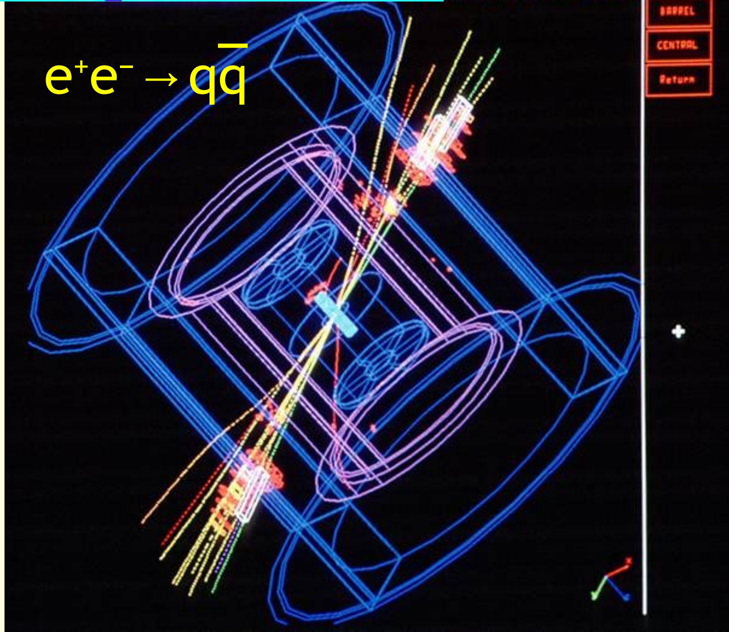
$e^+e^- \rightarrow e^+e^-$



$e^+e^- \rightarrow \tau^+\tau^-$



$e^+e^- \rightarrow \mu^+\mu^-$



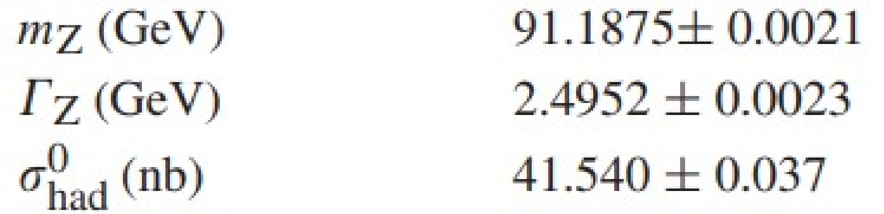
$e^+e^- \rightarrow q\bar{q}$

Z lineshape

The actual Z “lineshape” is affected by effects beyond lowest-order, but these are calculated with high precision, and are corrected for

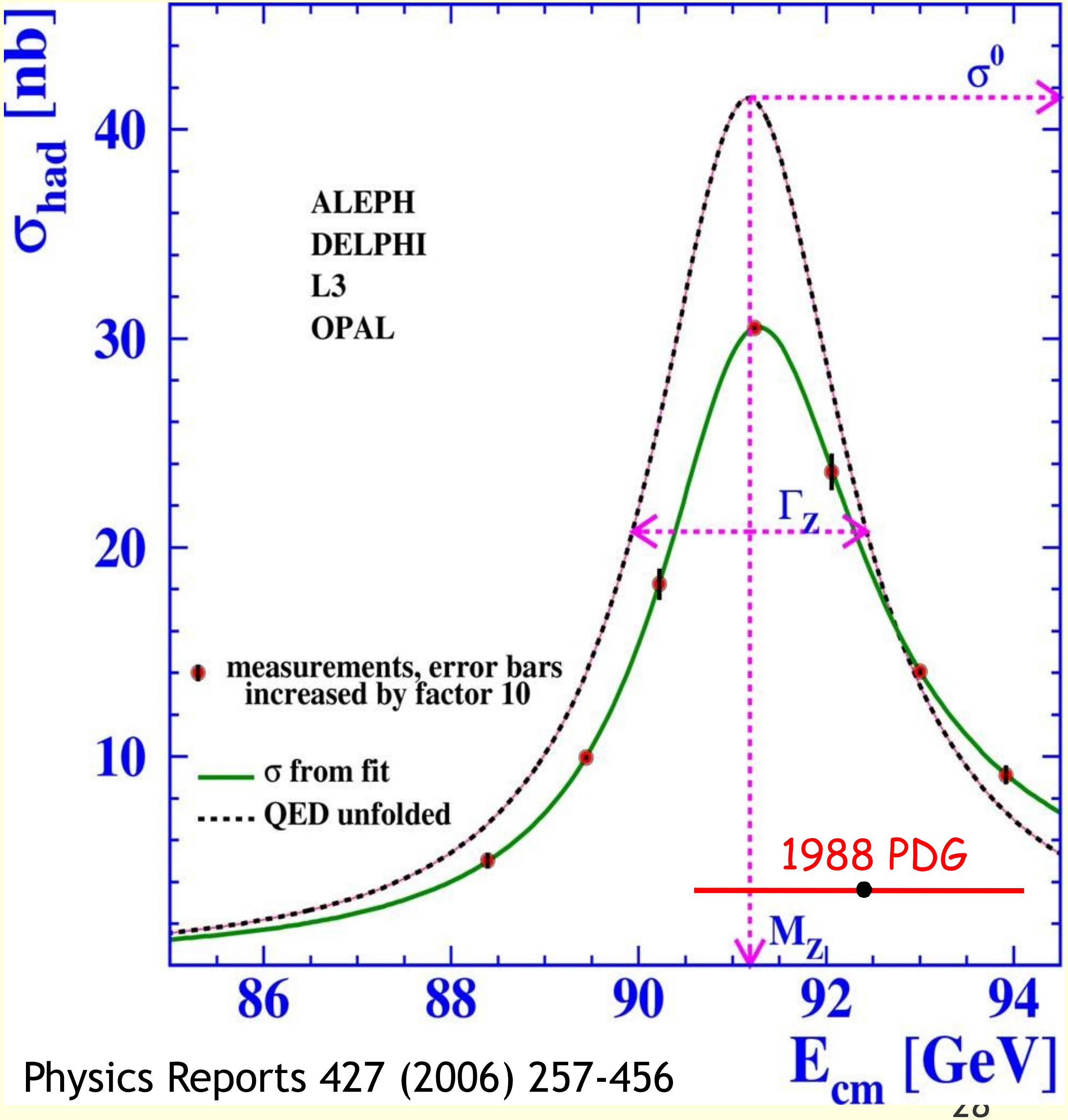
From the Z lineshape (right), we measure m_Z and Γ_Z from the peak position and FWHM width as shown

Final results (4 experiments combined):



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

Relative precision on m_Z: 2.3×10^{-5}



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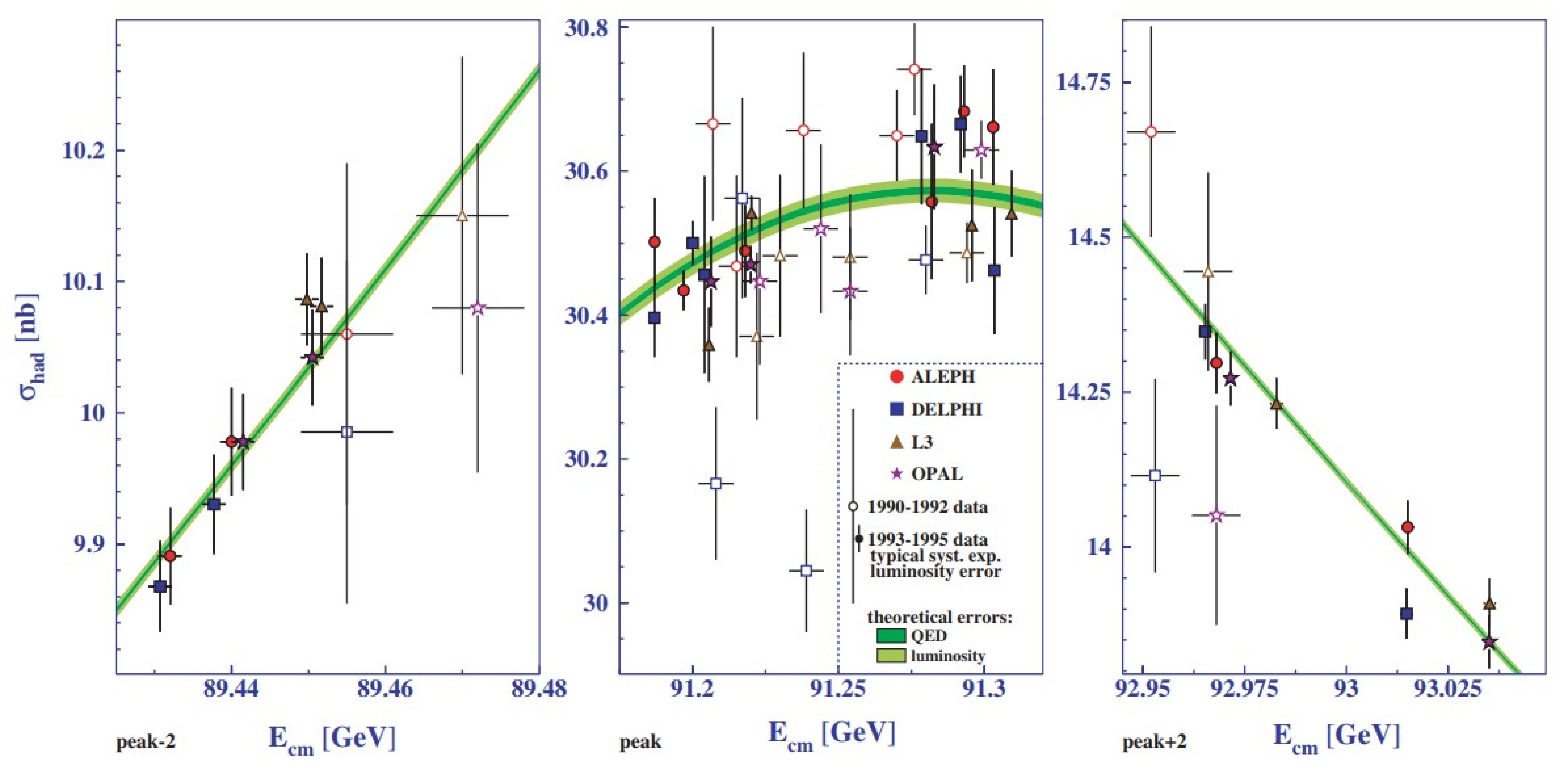
Fine detail of LEP-1 cross-section data



Z decay branching ratios

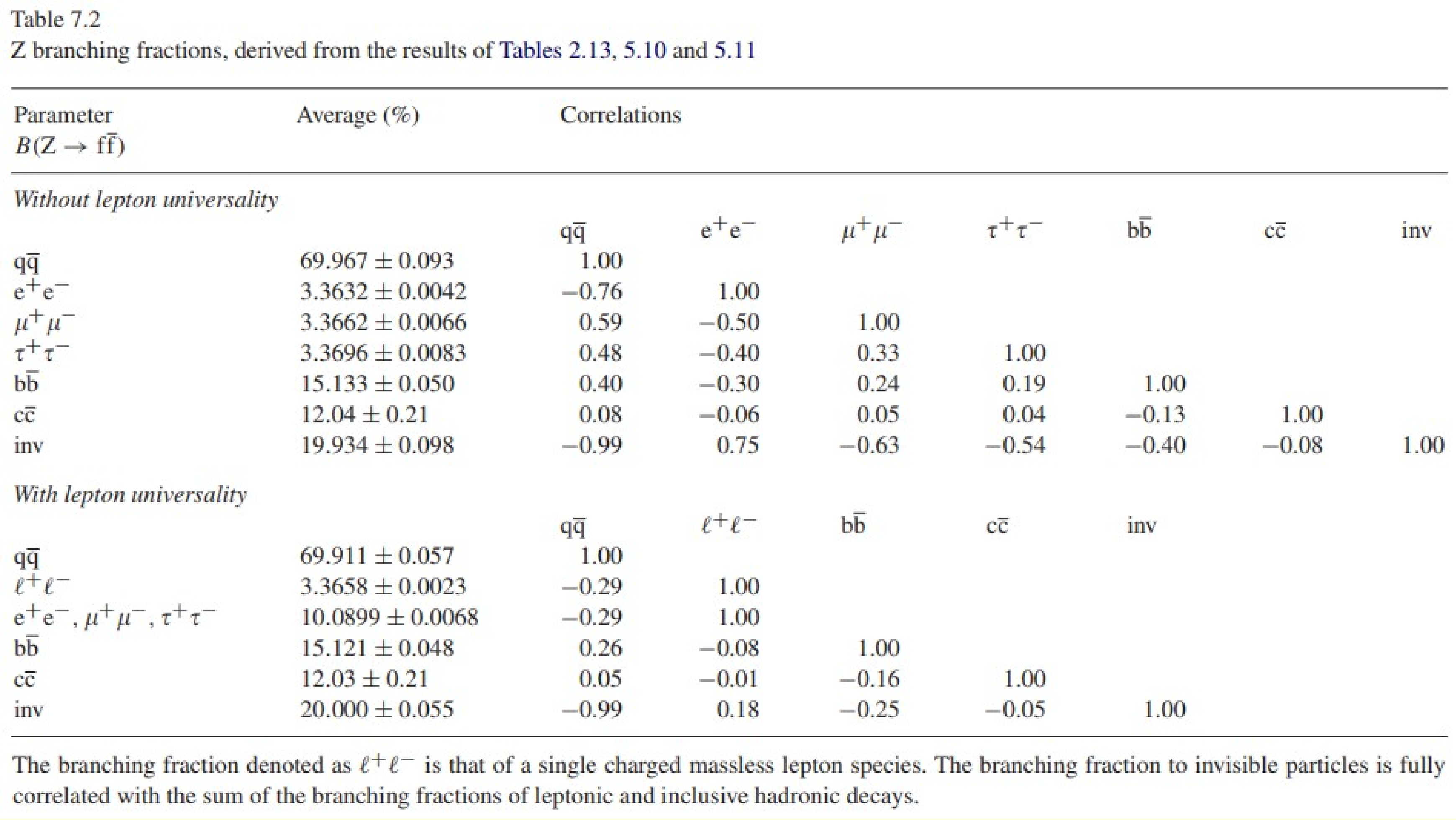


Table 7.2

Z branching fractions, derived from the results of Tables 2.13, 5.10 and 5.11

Parameter $B(Z \to f\bar{f})$	Average (%)	Correlations						
Without lepton universality								
		$q\bar{q}$	e^+e^-	$\mu^+\mu^-$	$\tau^+\tau^-$	$b\bar{b}$	$c\bar{c}$	inv
$q\bar{q}$	69.967 ± 0.093	1.00						
e^+e^-	3.3632 ± 0.0042	−0.76	1.00					
$\mu^+\mu^-$	3.3662 ± 0.0066	0.59	−0.50	1.00				
$\tau^+\tau^-$	3.3696 ± 0.0083	0.48	−0.40	0.33	1.00			
$b\bar{b}$	15.133 ± 0.050	0.40	−0.30	0.24	0.19	1.00		
$c\bar{c}$	12.04 ± 0.21	0.08	−0.06	0.05	0.04	−0.13	1.00	
inv	19.934 ± 0.098	−0.99	0.75	−0.63	−0.54	−0.40	−0.08	1.00
With lepton universality								
		$q\bar{q}$	$\ell^+\ell^-$	$b\bar{b}$	$c\bar{c}$	inv		
$q\bar{q}$	69.911 ± 0.057	1.00						
$\ell^+\ell^-$	3.3658 ± 0.0023	−0.29	1.00					
e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$	10.0899 ± 0.0068	−0.29	1.00					
$b\bar{b}$	15.121 ± 0.048	0.26	−0.08	1.00				
$c\bar{c}$	12.03 ± 0.21	0.05	−0.01	−0.16	1.00			
inv	20.000 ± 0.055	−0.99	0.18	−0.25	−0.05	1.00		

The branching fraction denoted as $\ell^+\ell^-$ is that of a single charged massless lepton species. The branching fraction to invisible particles is fully correlated with the sum of the branching fractions of leptonic and inclusive hadronic decays.

Number of light neutrino species

At LEP-1, we:

- Measured the total width Γ_Z from the width of the cross-section lineshape
- Measured the cross-sections for Z production and decay into different visible decay modes

Allowed to extract the fraction of times the Z decays invisibly, characterised by the invisible width Γ_{inv}:

$$\Gamma_Z = \sum_j \Gamma_j = \sum_{\text{visible } j} \Gamma_j + \Gamma_{\text{inv}}$$

If we assume Γ_ν (one neutrino species) from SM, we can measure the number of light neutrino species

$$N_\nu = \frac{\Gamma_{\text{inv}}}{\Gamma_\nu^{SM}} = 2.9840 \pm 0.0082$$

This method worked at LEP because Z is broad, *and* we could see all visible decays

Electroweak unification "GSW"

Now, the Z boson is not simply the neutral partner of the W (“W^0”)

- its mass differs from that of the W
- it does not have a universal coupling to different particle species, as the W does

Electroweak unification instead postulates that the γ and the Z are a *mixture* of two states which are not physical, the W^0 and a B^0:

$$\begin{aligned} Z &= W^0 \cos\theta_w - B^0 \sin\theta_w \\ \gamma &= W^0 \sin\theta_w + B^0 \cos\theta_w \end{aligned}$$

Mixing angle θ_w : weak mixing angle (sometimes “Weinberg angle”)

Makes some predictions, *e.g.*

- *Relation between the weak coupling* g_W *and the electron charge* e *at lowest-order*:

$$e = g_W \sin\theta_w$$

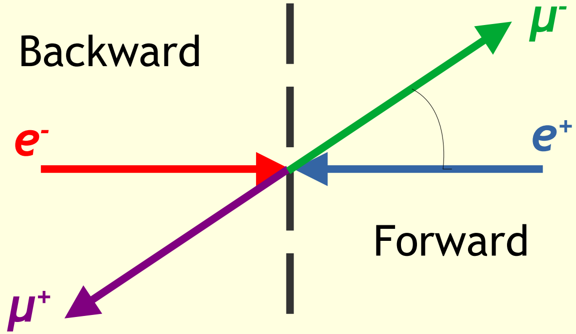
- *All* of the *Z* couplings to all the fermions – in terms of the electron charge e and θ_w

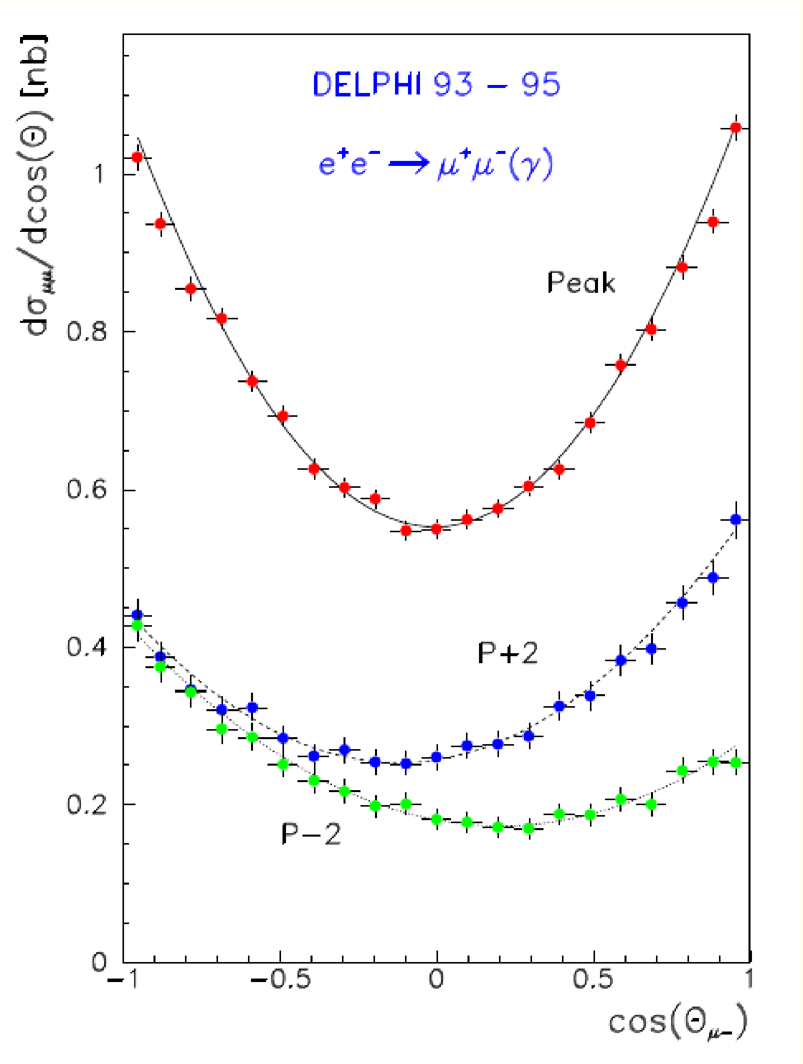
Measuring θ_W at LEP

Couplings of the Z to fermions is different for right-handed and left-handed fermions
(RH, LH: spin direction relative to direction of flight)

Affects distributions measured at LEP
Example: forward-backward asymmetry, A_{FB}

$$A_{\mathrm{FB}} = \frac{\sigma_{\mathrm{F}} - \sigma_{\mathrm{B}}}{\sigma_{\mathrm{F}} + \sigma_{\mathrm{B}}}$$



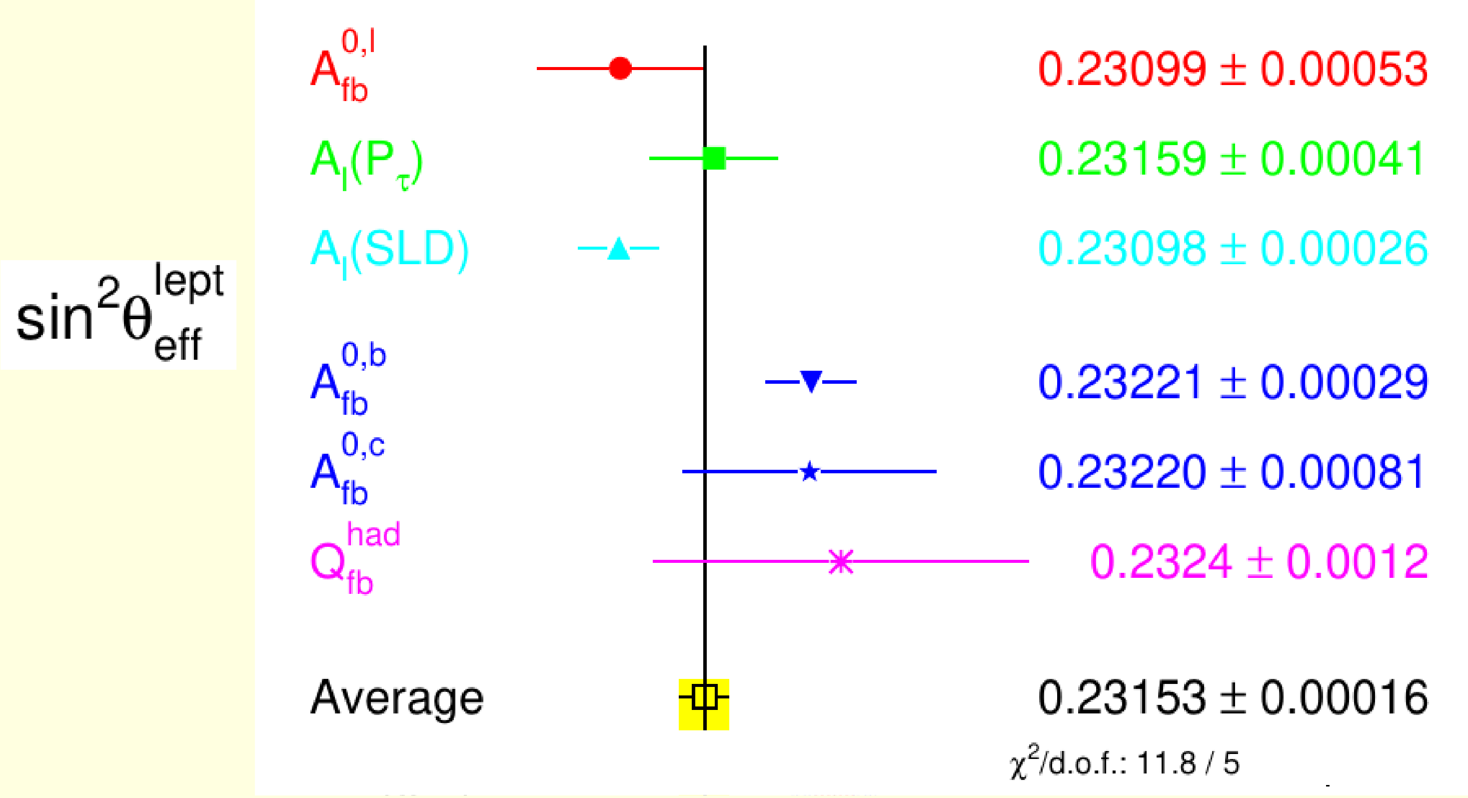


A_{FB} depends on $\sin^2\theta_W$, and also varies with energy due to γ-Z interference

Measured θ_W at LEP

Consistent measurements in different processes at LEP and SLD

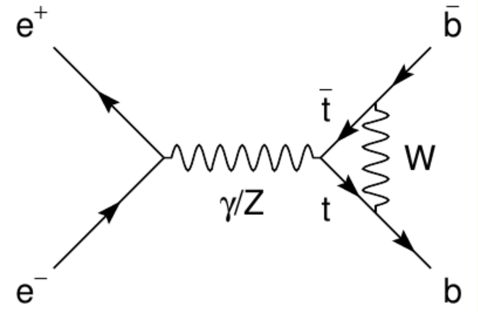
Precision very high – sensitive to radiative electroweak corrections → “ $\sin^2\theta_{eff}^{lept}$ ”

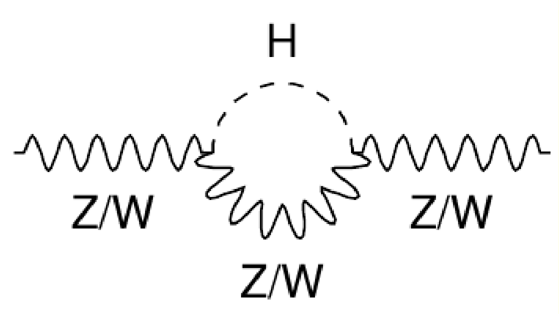


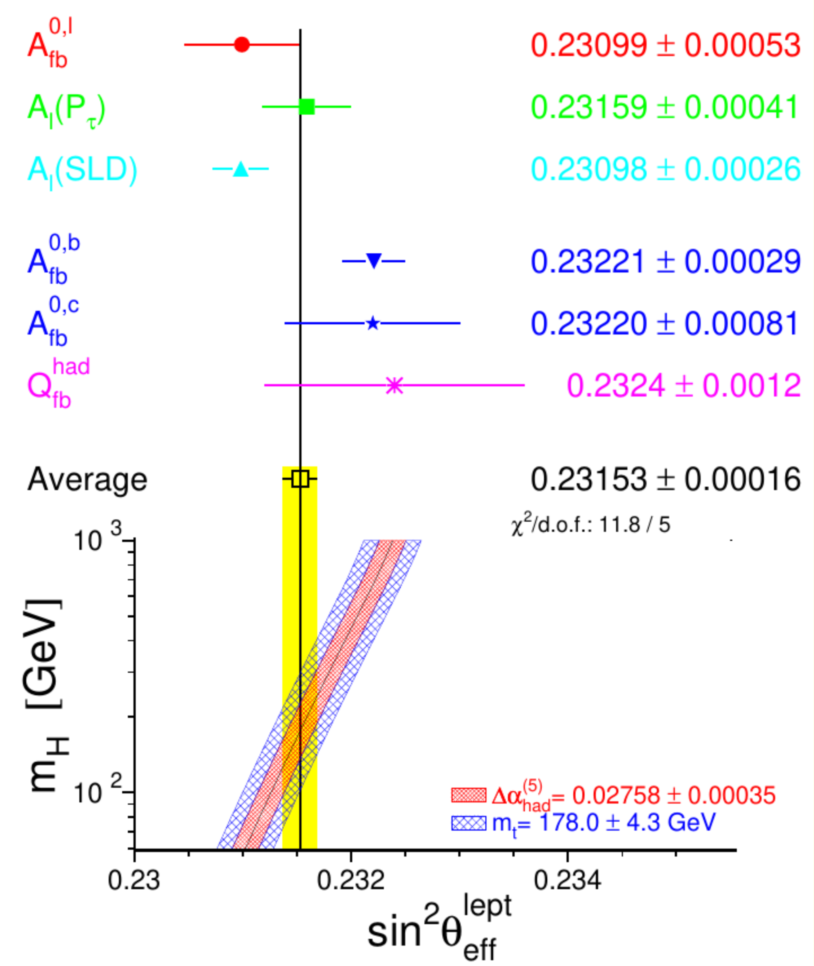
Precision electroweak fits

Precision of LEP measurements was so high that they are sensitive to radiative corrections

- Photon radiation (larger effect)
- Loop corrections with particles in loops which could not be produced at LEP!
  - Top quark
  - Higgs bosons







Precision electroweak fits

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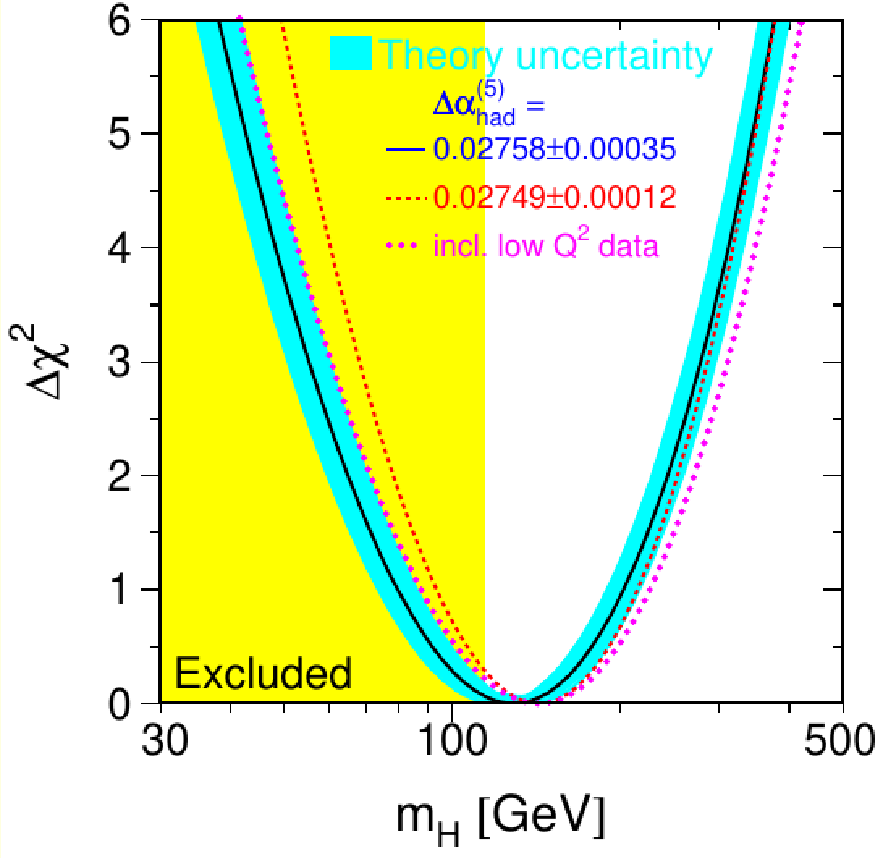
Full fits done to all of the precise EW data

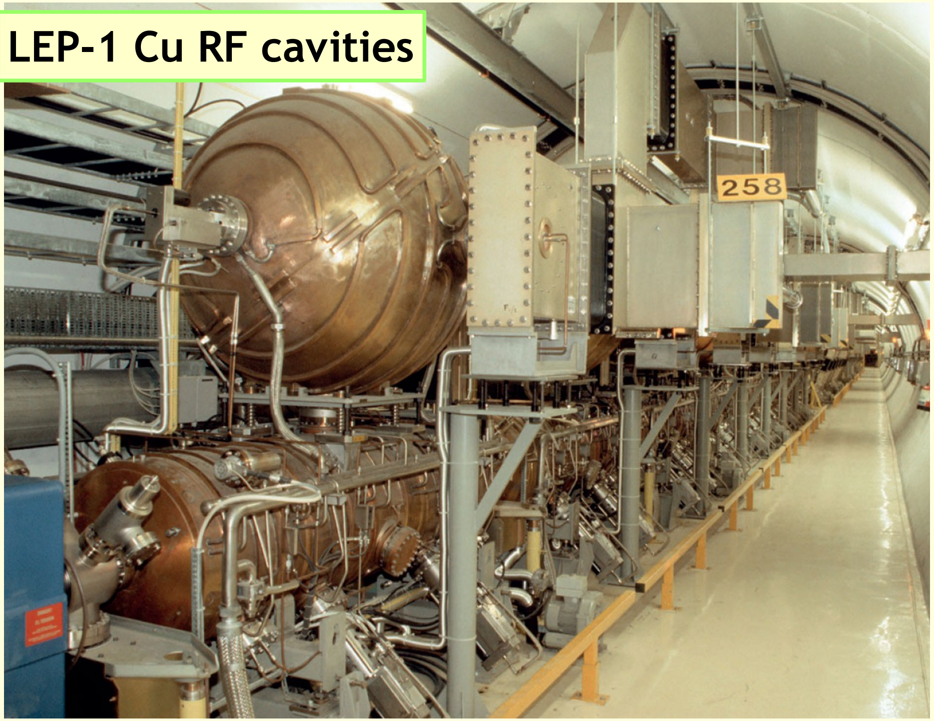
- Fit results consistent – SM seems OK!
- Constraints derived on unknown, or poorly measured, SM parameters



LEP data suggested m_H less than ~300 GeV at 95% CL

LEP-1 → LEP-2

LEP-1 Cu RF cavities



LEP-2 SC RF cavities (x288)

LEP-1 synchrotron radiation loss *per turn*: 0.25 GeV
LEP-2 at 105 GeV: 3.4 GeV *per turn*!
→ 20 MW of power radiated by the beams

$$E_{rad} \propto (E/m)^4 (1/\rho)$$

LEP-2 required a new, high efficiency, superconducting accelerating cavity system

Physics at LEP-2

At LEP-2, √s > 160 GeV

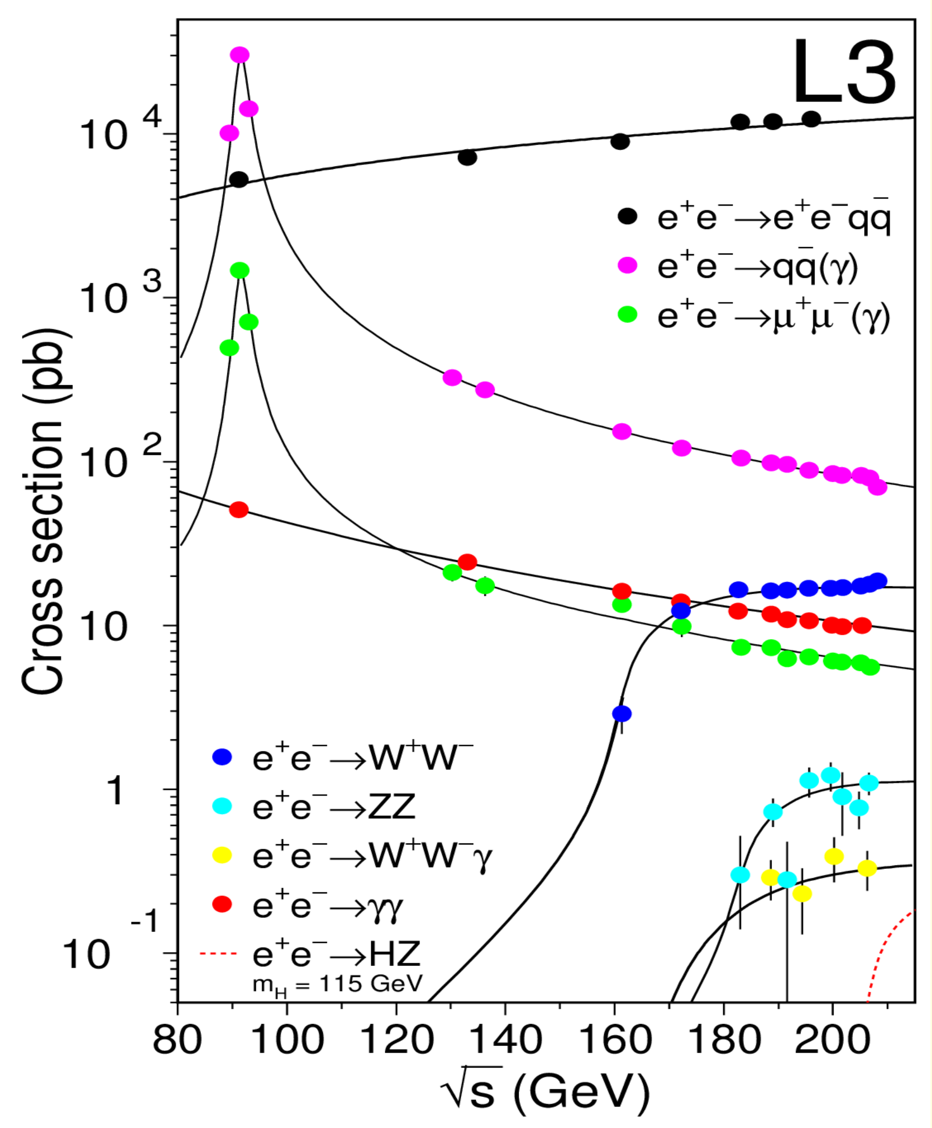
- above threshold to make pairs of *W* bosons

Above the *Z* resonance peak, many processes have cross-sections not different by many orders of magnitude

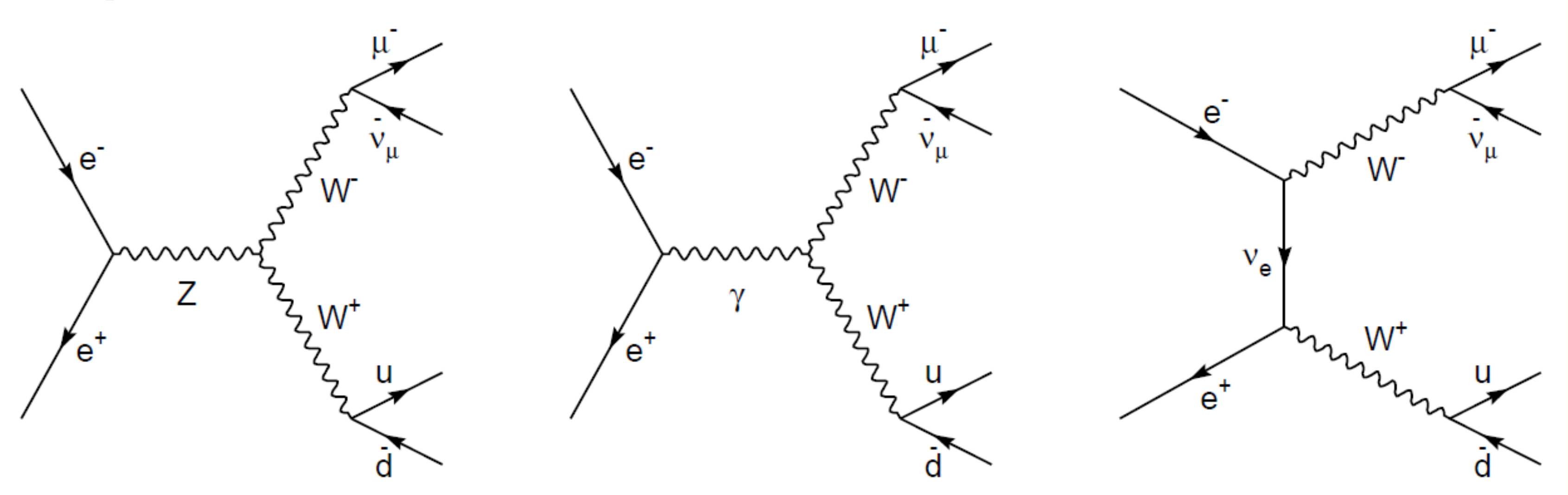
With high integrated luminosity

→ studied many of them, e.g. as shown

W^+W^- production was the flagship channel at LEP-2



LEP-2: WW production



Three Feynman diagrams for WW production at LEP

- Two involve a “triple gauge-boson” vertex (left and centre)
- These interfere *negatively* with the neutrino exchange diagram (right), *reducing* the cross-section!

LEP-2: WW event

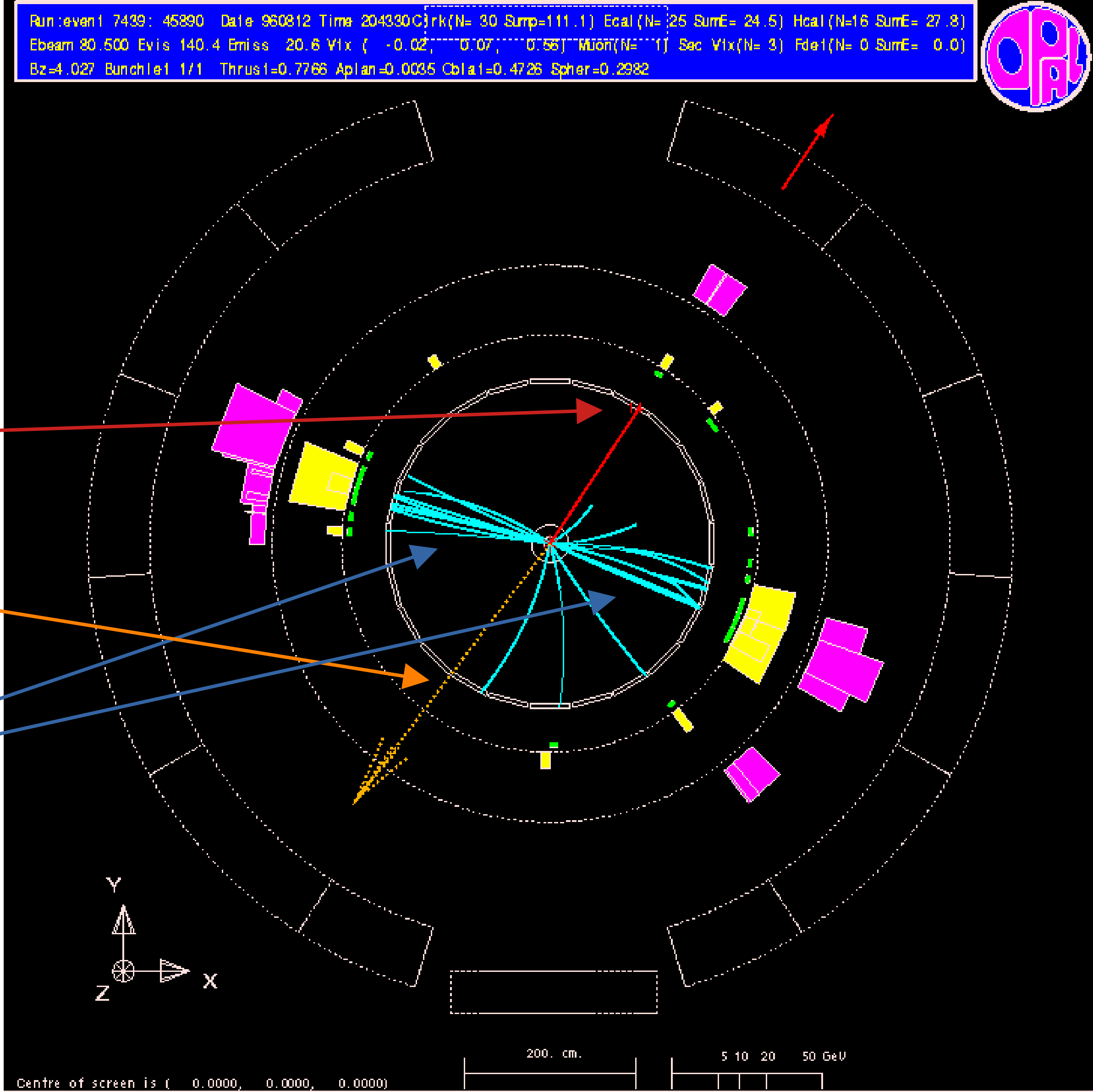
Interpretation of this event:

One W decays leptonically

- One muon
- Unseen neutrino – reconstructed from overall momentum balance

Other W decays to $q\bar{q}'$

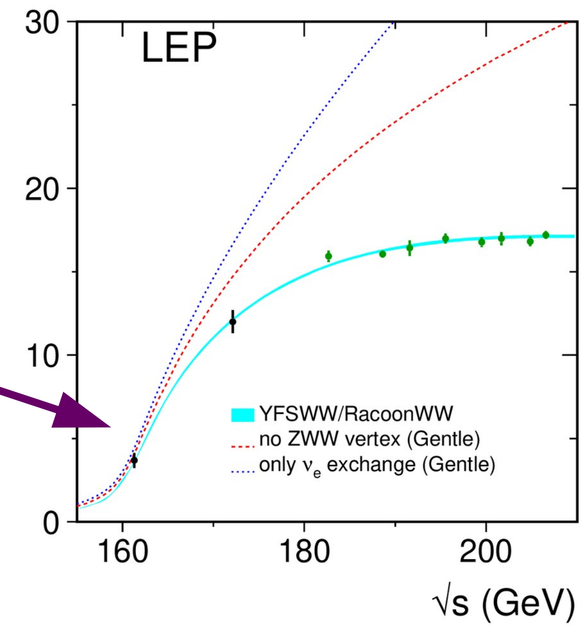
- *Two hadronic jets*

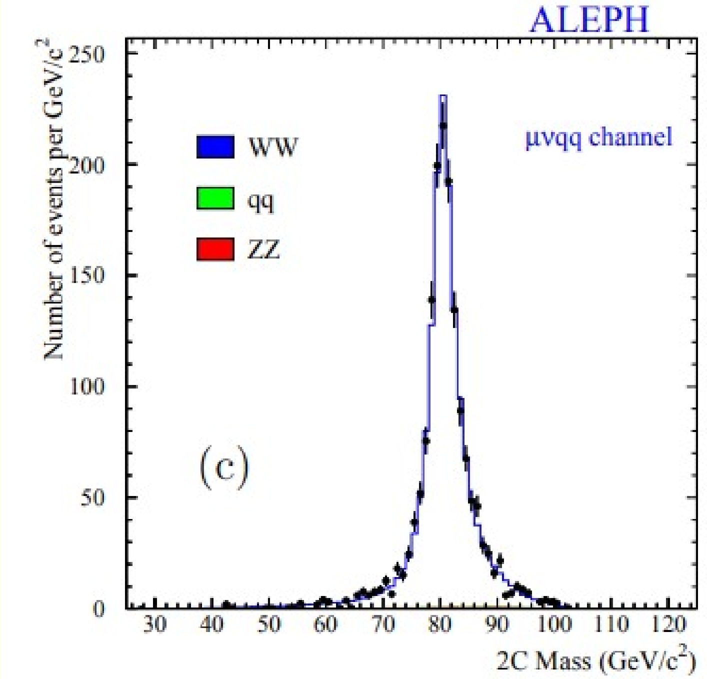


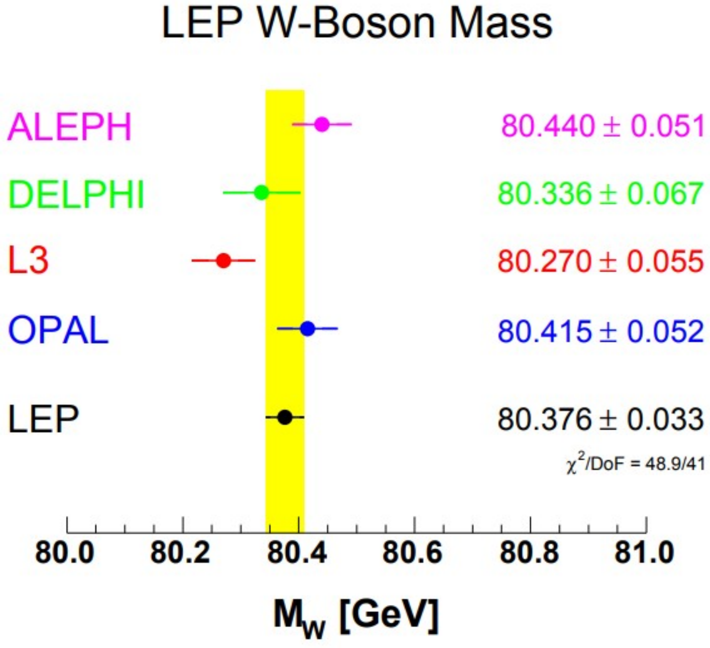
Measuring the W mass at LEP-2

Two methods to measure m_W at LEP-2

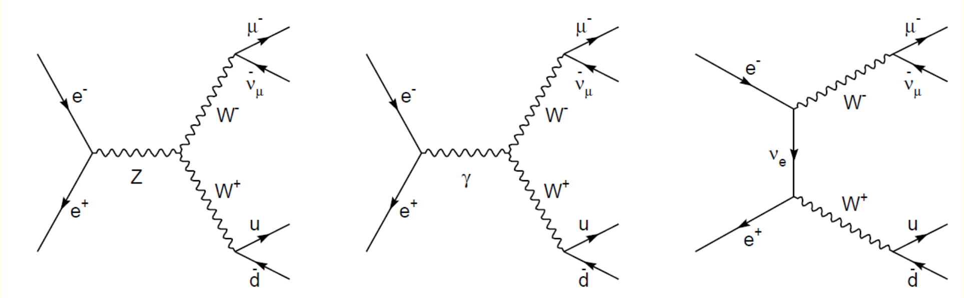
- From the cross-section curve – position of threshold is at ~$2m_W$
  - Gradual turn-on because of W width, and kinematics
  - Cross-section at eg. 161 GeV sensitive to m_W
- By reconstructing the W decay products at higher √s







LEP-2: WW production



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- Two involve a “triple gauge-boson” vertex (left and centre)
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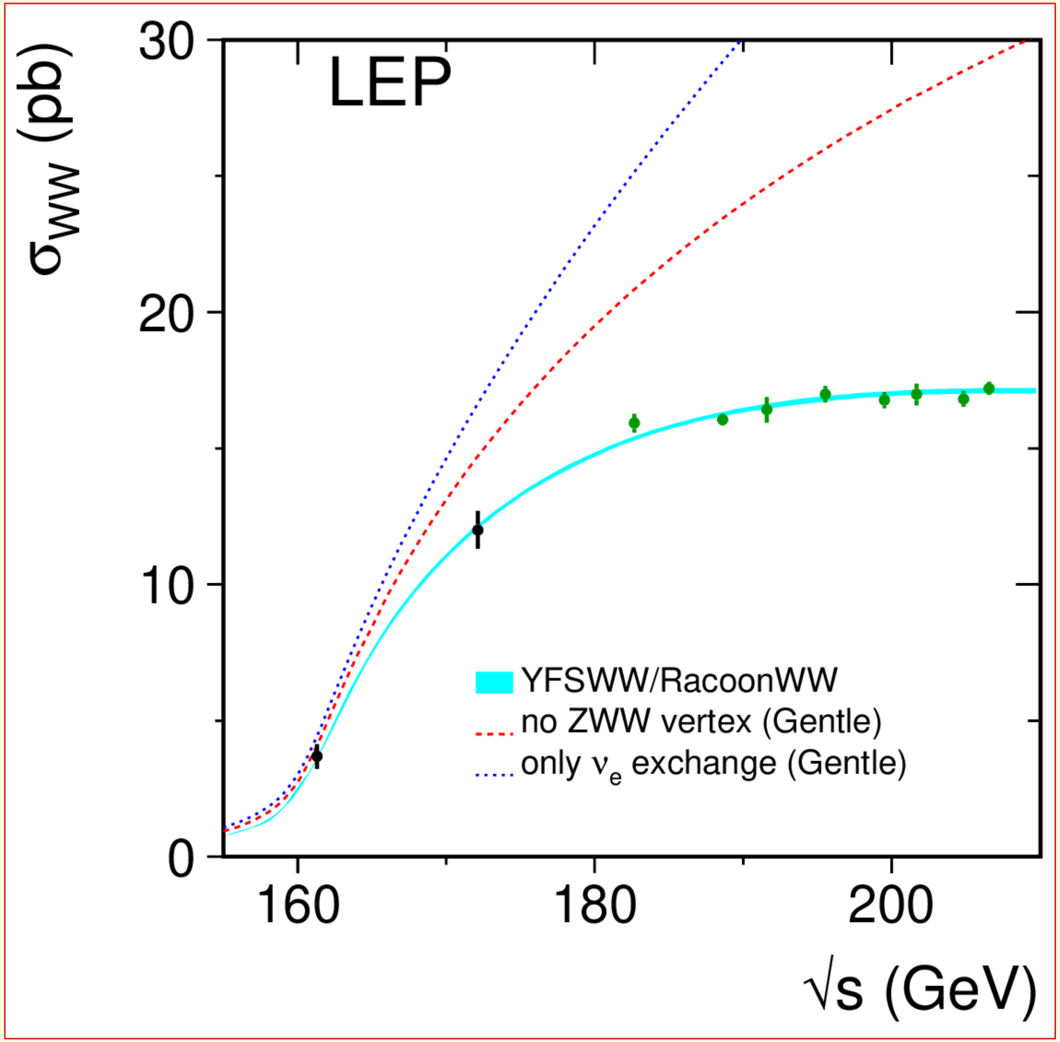
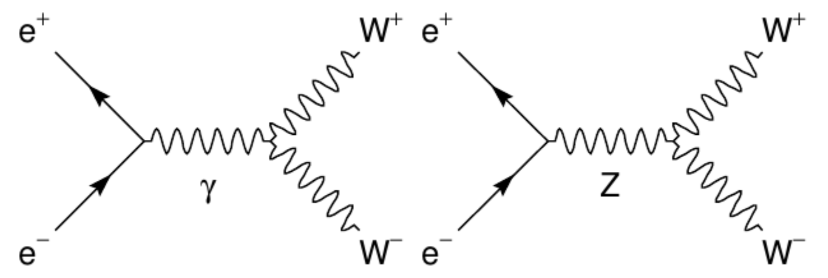
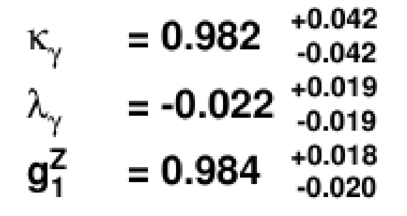


Triple and quartic gauge couplings

Measuring cross-sections and angular distributions of “multiboson” production (WW, WZ, Zγ, WWγ) allowed to constrain whether triple and quartic gauge couplings are consistent with SM predictions



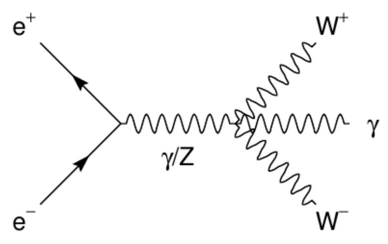
Coupling strength parameters κ_γ, λ_γ, g_1^Z



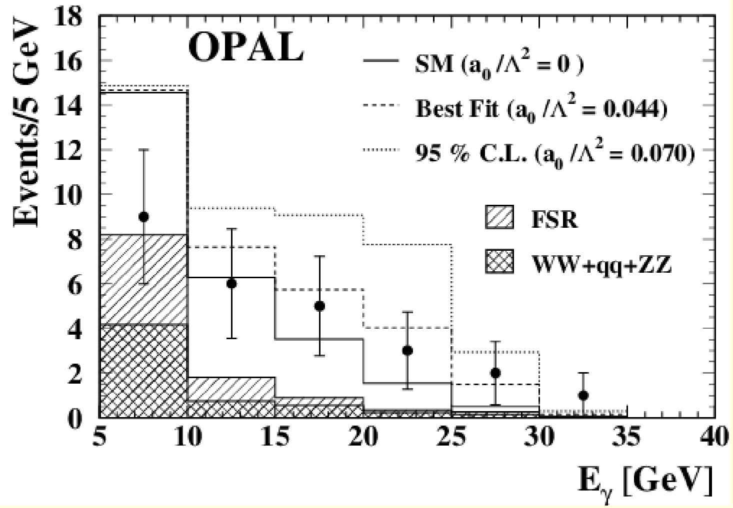
$\kappa_\gamma = 0.982^{+0.042}_{-0.042}$

$\lambda_\gamma = -0.022^{+0.019}_{-0.019}$

$g_1^Z = 0.984^{+0.018}_{-0.020}$



Anomalous coupling strength parameters a_0, a_c



Tevatron

Tevatron at Fermilab, USA

Ran from 1986 – 2011

Proton-antiproton collisions at $\sqrt{s}$=1.8 to 1.96 TeV

Two experiments CDF and D0

Numerous physics measurements and observations (e.g. first observation of B-$\bar{\text{B}}$ time dependent oscillations)

The Tevatron's most famous achievement was to complete the family of quark flavours…

Discovery of the top quark

Co-discovered by CDF+D0 in 1995

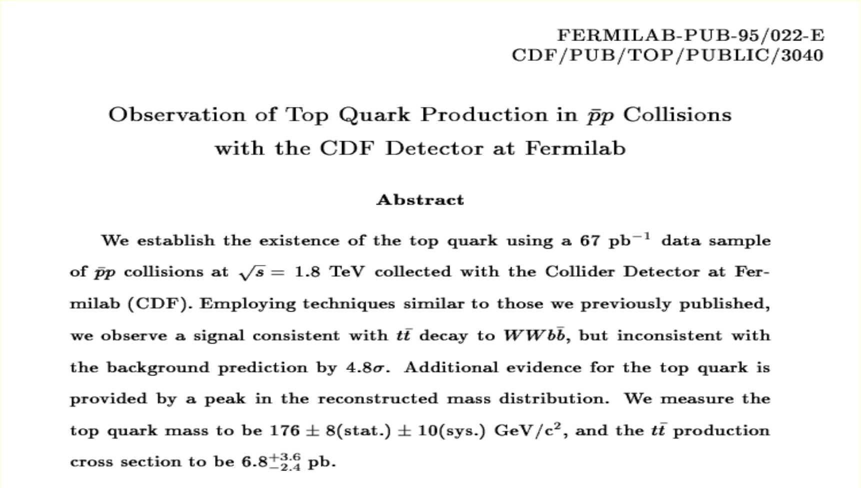
Decay chain:

$t\bar{t} \rightarrow WbW\bar{b}$

$W \rightarrow \ell\nu$, $W \rightarrow q\bar{q}'$

At least one *b*-jet identified by looking for a displaced *b*-hadron decay

Reconstruct m($t\bar{t}$) from decay products (jets, leptons, missing-p_T)

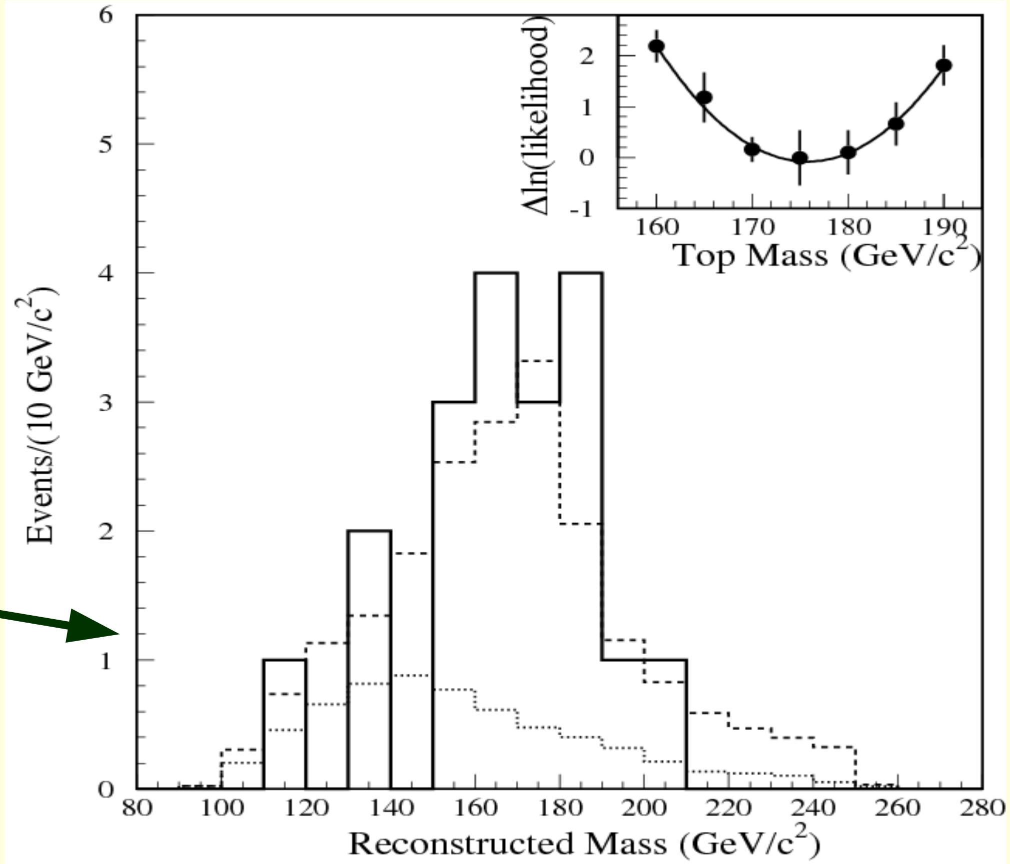


FERMILAB-PUB-95/022-E
CDF/PUB/TOP/PUBLIC/3040

Observation of Top Quark Production in $\bar{p}p$ Collisions with the CDF Detector at Fermilab

Abstract

We establish the existence of the top quark using a 67 pb^{-1} data sample of $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV collected with the Collider Detector at Fermilab (CDF). Employing techniques similar to those we previously published, we observe a signal consistent with $t\bar{t}$ decay to $WWb\bar{b}$, but inconsistent with the background prediction by 4.8σ. Additional evidence for the top quark is provided by a peak in the reconstructed mass distribution. We measure the top quark mass to be 176 ± 8(stat.) ± 10(sys.) GeV/c^2, and the $t\bar{t}$ production cross section to be $6.8^{+3.6}_{-2.4}$ pb.

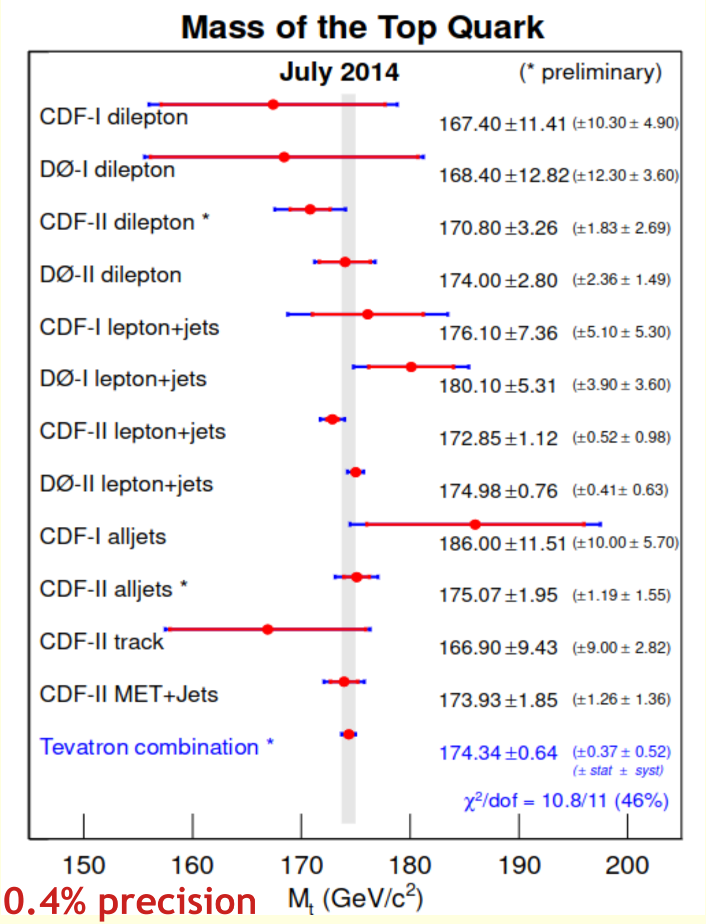


Mass of top quark ~ 175 GeV!!!

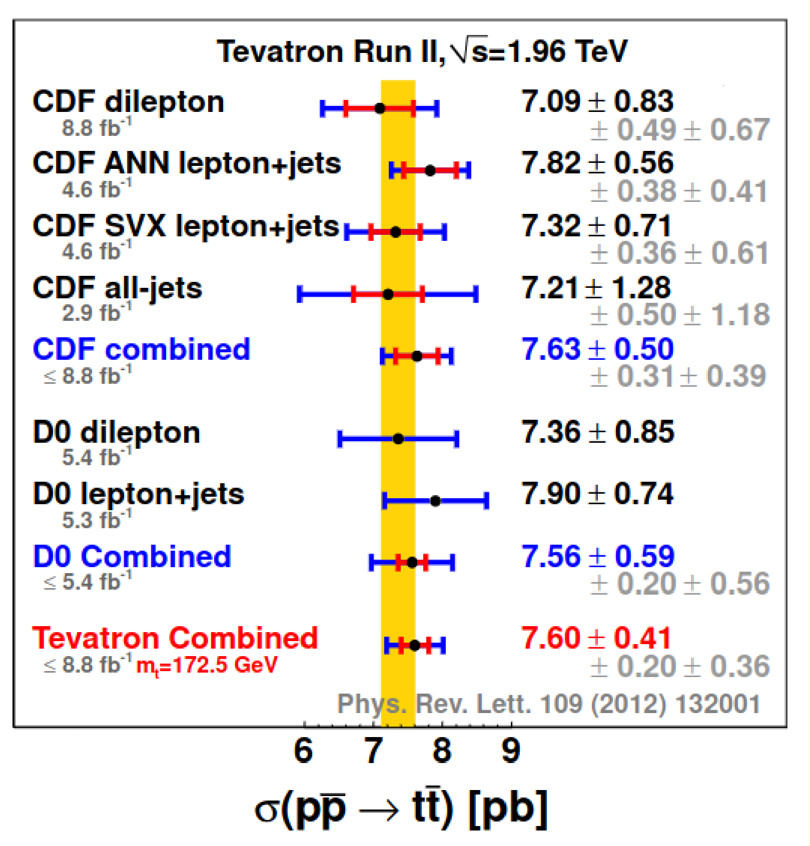
"Who ordered that?"

Tevatron measurements of the top quark

Many measurements of top quarks made with the final, much larger data samples



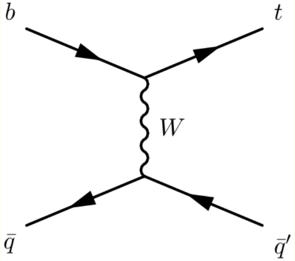
0.4% precision



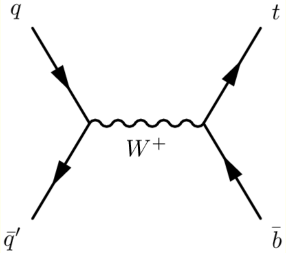
Single-top production

Possible to produce just one t quark, in diagrams containing a W

- "t-channel"

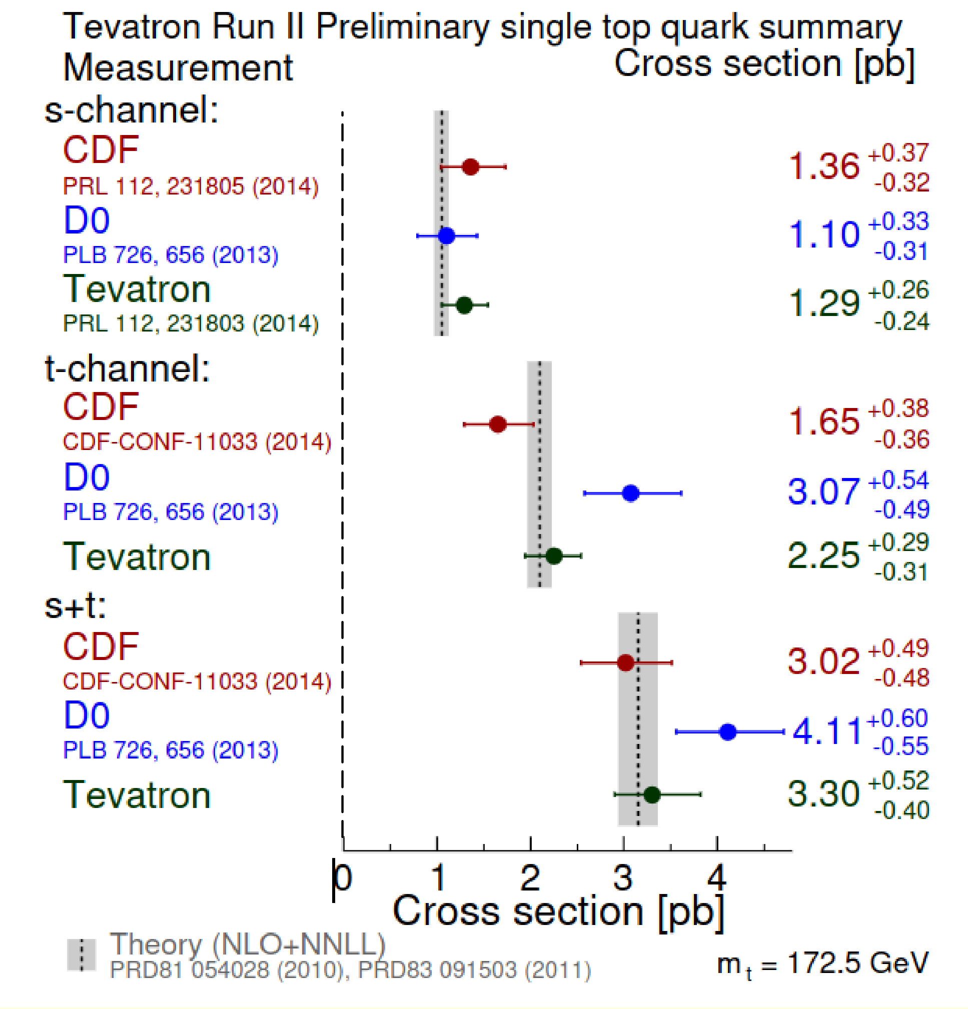


- "s-channel"



- "Wt production" (tiny at Tevatron)

Both t and s channels observed at Tevatron, consistent with expected production cross-sections



Summary of part I

- The CERN-SppS, CERN-LEP and Fermilab-Tevatron colliders in the 1980's and 1990's established and measured many processes, masses and interactions

- The electroweak bosons W, Z of the Standard Model were discovered by UA1/UA2, and measured with very high precision at LEP(+SLD)
  - Couplings of the Z to fermions very precisely probed
  - Interactions between gauge bosons started to be probed, but weakly

- Highly convincing that gauge theories are at the root of fundamental physics
  - Nobel prize to 't Hooft and Veltman in 1999

- The top quark was discovered at the Tevatron, and found to be shockingly heavy!

- However, many questions left, requiring the LHC
  - What breaks the electroweak symmetry (making the W,Z massive and the photon light)
  - What gives mass to fermions?
  - Is there new physics at the TeV energy scale?
  - Dark matter?
  - …