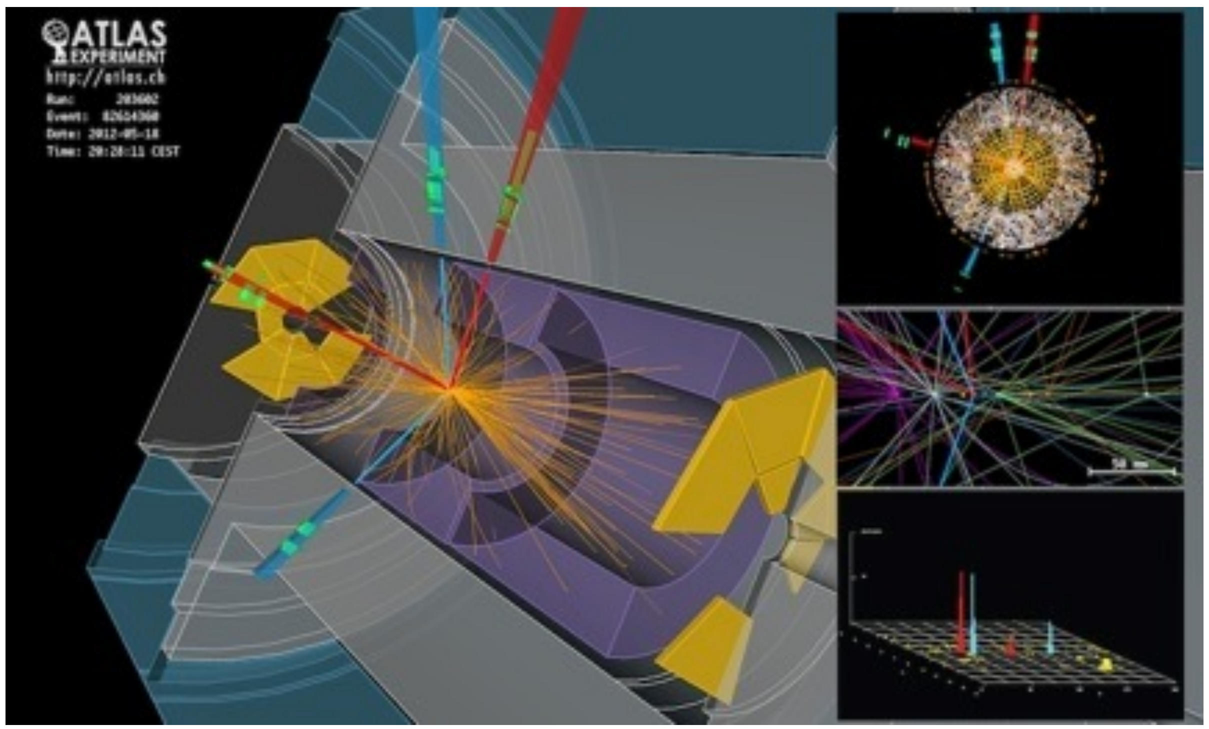
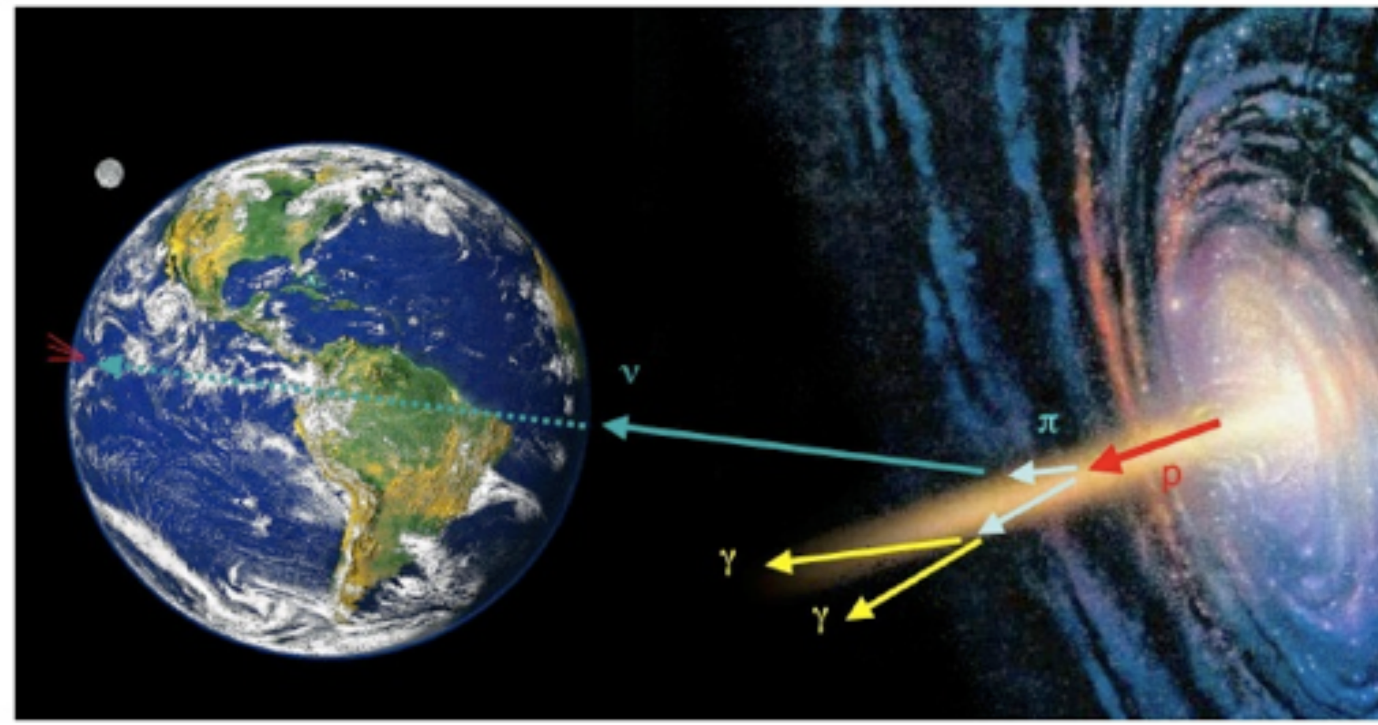
Particle Physics with
Accelerators and Natural Sources





05. Precision Tests of the Standard Model

27.05.2019

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Overview

- The Standard Model: Intro & History
- e^+e^- collisions for precision tests
- The Z^0 resonance
- Direct and indirect measurements

Reminder: The Standard Model

- The SM describes our visible Universe by a (reasonably small) set of particles:
  - The particles that make up matter: Spin 1/2 Fermions
  - … and the force carriers: Spin 1 Vector bosons

Elementary Particles				Elementary Forces		
	Generation				exchange boson	relative strength
	1	2	3			
Quarks	**u** **d**	**c** **s**	**t** **b**	**Strong**	g	1
				el.-magn.	γ	1/137
Leptons	ν_e **e**	ν_μ μ	ν_τ τ	**Weak**	$W^\pm$, Z^0	10^{-14}
				Gravitation	*G*	10^{-40}

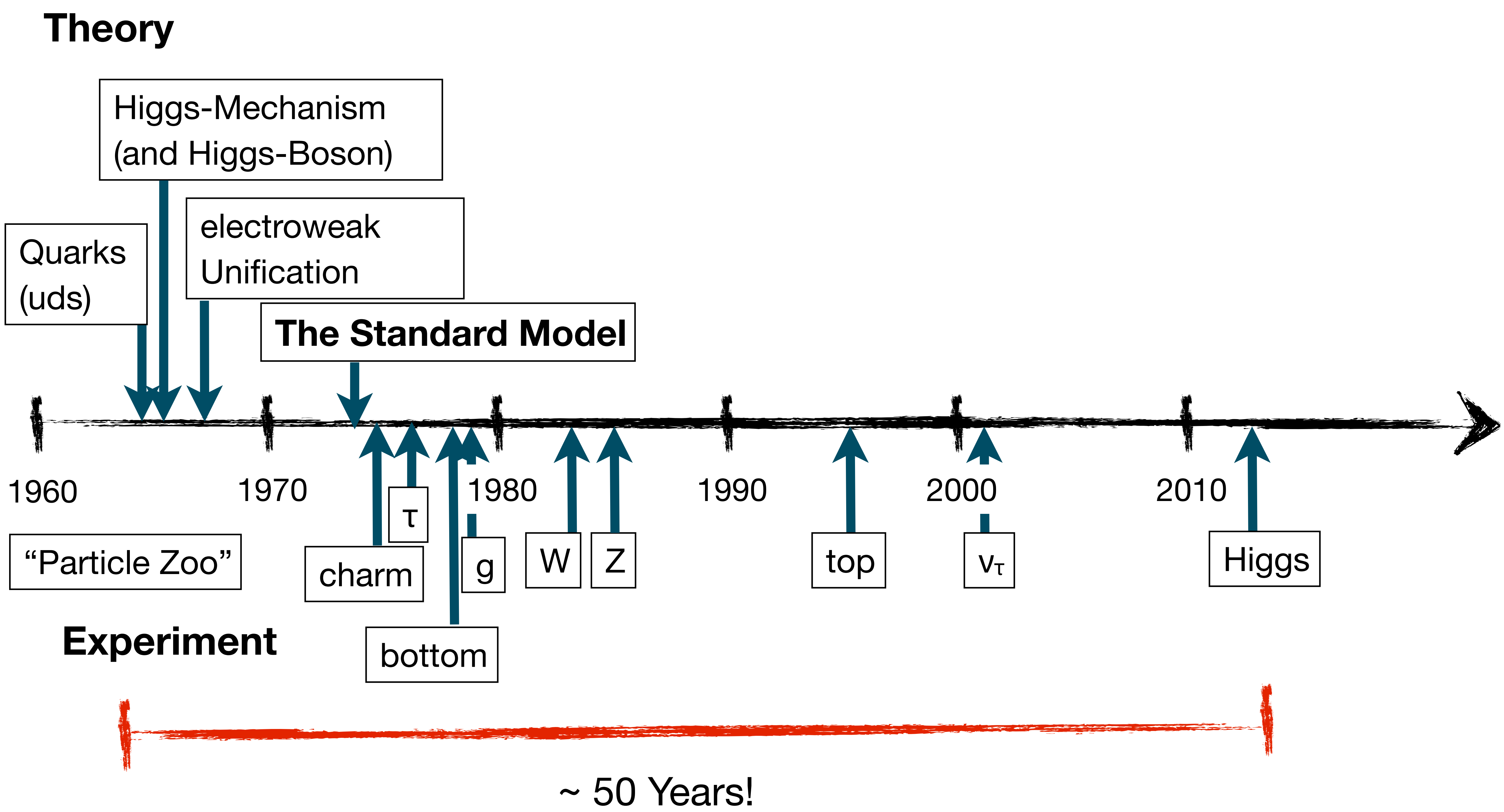
… plus the Higgs particle as a consequence of the mechanism to generate mass

Underlying theories: QCD; QED / weak interaction ➯ electroweak unification (GSW)

The Structure of the Standard Model

- The electroweak part of the SM is based on the gauge group SU(2) x U(1)
- This gives rise to the gauge bosons W^+, W^-, Z for SU(2) and γ for U(1)
- Left-handed fermion fields transform as doublets under SU(2) - right handed fermions as singlets (no coupling of right-handed fermions to W; V-A structure of the weak interaction)
- There are three fermion families
- A complex scalar Higgs field is added for mass generation through spontaneous symmetry breaking to give mass to the gauge bosons and fermions -> Gives rise to one physical neutral scalar particle, the Higgs boson
- The electroweak SM describes in lowest order ("Born approximation) processes such as $f_1 f_2 \rightarrow f_3 f_4$ with only 3 free parameters: α, G_f, $\sin^2\theta_W$

The History of the Standard Model



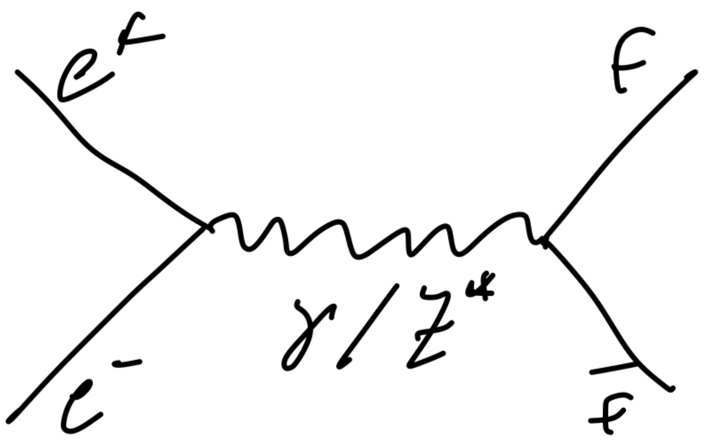
The Standard Model (and its components) has withstood all tests & attempts to break it / find inconsistencies!

Testing the Standard Model

- The “vanilla” Standard Model (ignoring neutrino masses & mixings) has 18 free parameters that need to be measured
  - 9 fermion masses (= couplings to the Higgs Field)
  - 3 CKM mixing angles + 1 CKM phase
  - 3 coupling constants (electromagnetic, weak, strong)
  - 1 Z^0 mass
  - 1 Higgs mass

- Other measurable parameters, such as the Weinberg angle and the W mass can be calculated taking the 18 parameters as input: A direct possibility to test SM prediction
- In addition: Particles occur “in loops” and modify measurable properties and cross sections: Calculable - can be tested, and used to indirectly search for new particles

The Tool for Precision Tests: e^+e^- Collisions



- e^+e^- annihilation:
  - point-like particles
  - well-known quantum numbers and energies of initial and final states
  - no hadronic (strong) interactions in and with initial state:
    - no underlying or “remnant” event
    - couplings << 1: calculable in perturbation theory

Precision

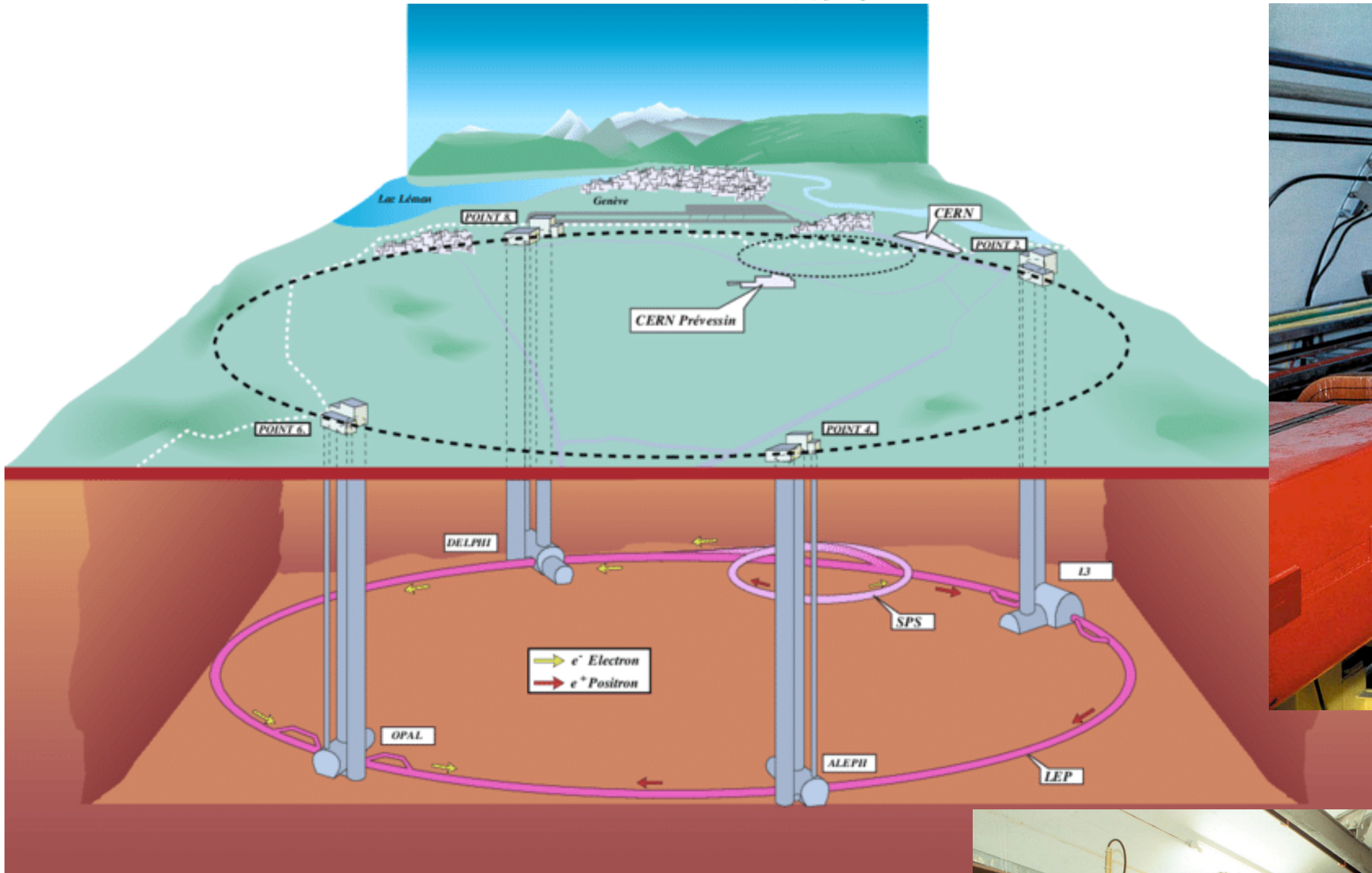
- Technical requirements:
  - precise knowledge of e^+e^- energies (accelerator)
  - precise knowledge of luminosity (special detectors)
  - precise measurement & classification of all final states (detectors)

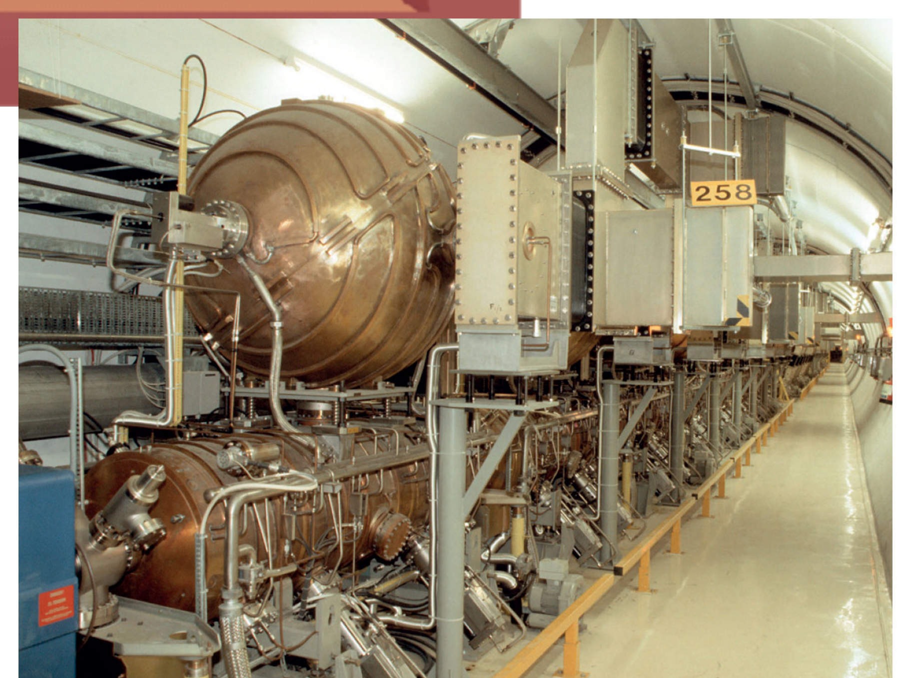
Electron-Positron Colliders

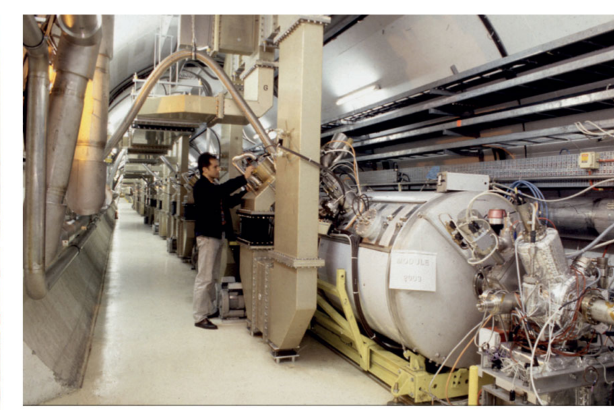
High-energy e^+e^- Colliders: SLC, LEP

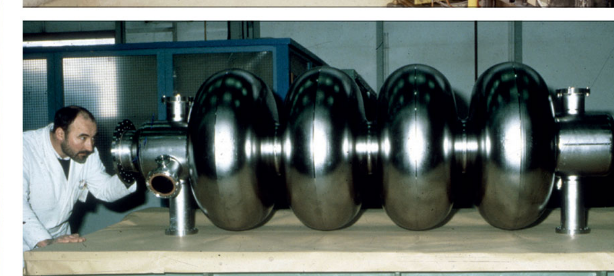
- SLC (1989 - 1999): Center-of-mass energy ~ 91 GeV (on the Z^0 resonance)
- LEP: 1989 - 2000
  - LEP I: Center-of-mass energy ~ 91 GeV (on the Z^0 resonance)
  - LEP II: Center-of-mass energy up to 209 GeV
- For precision measurements:
  - Need precise measurement of collider energy
    - At LEP measured via resonant depolarisation of self-polarisation of beam which builds up over time (up to a beam energy of 55 GeV), extrapolation via flux-loop measurements beyond :
      - Energy uncertainty at 90 GeV center of mass: 1.4 MeV
      - Energy uncertainty at 200 GeV center of mass: 25 - 30 MeV
  - For SM precision measurements: polarisation of beams valuable: A strength of linear accelerators: 80% e^- polarisation at SLC - not possible at LEP

LEP in one Slide





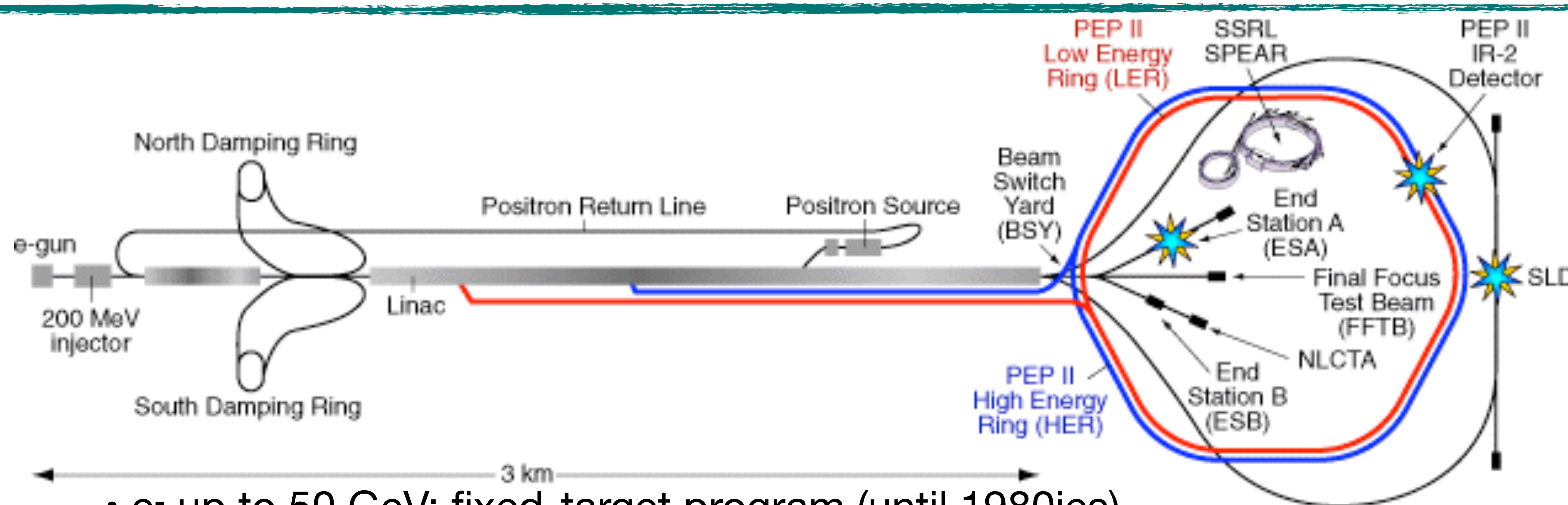




27 km circumference

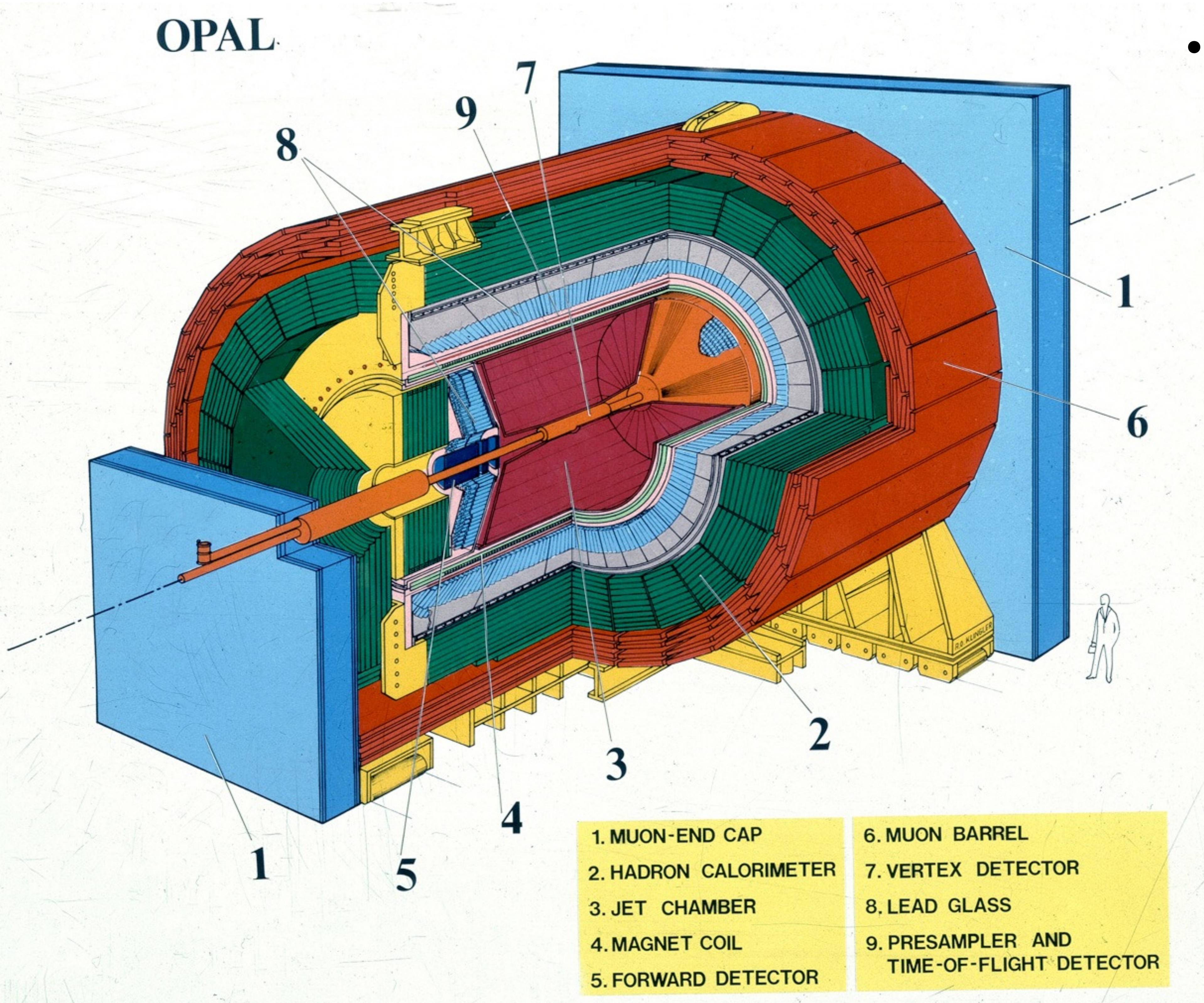
maximum energy 209 GeV

SLC in one Slide



- e^- up to 50 GeV; fixed-target program (until 1980ies)
- e^- und e^+ for PEP-I storage ring (E_{cm} = 29 GeV; early 1980ies)
- e^- und e^+ for SLC collider ($E_{cm} = M_Z$ ~ 91 GeV; 1989 - 1999)
- e^- und e^+ for PEP-II storage ring (E_{cm} ~10 GeV; 1999 - 2008)

Experiments at LEP

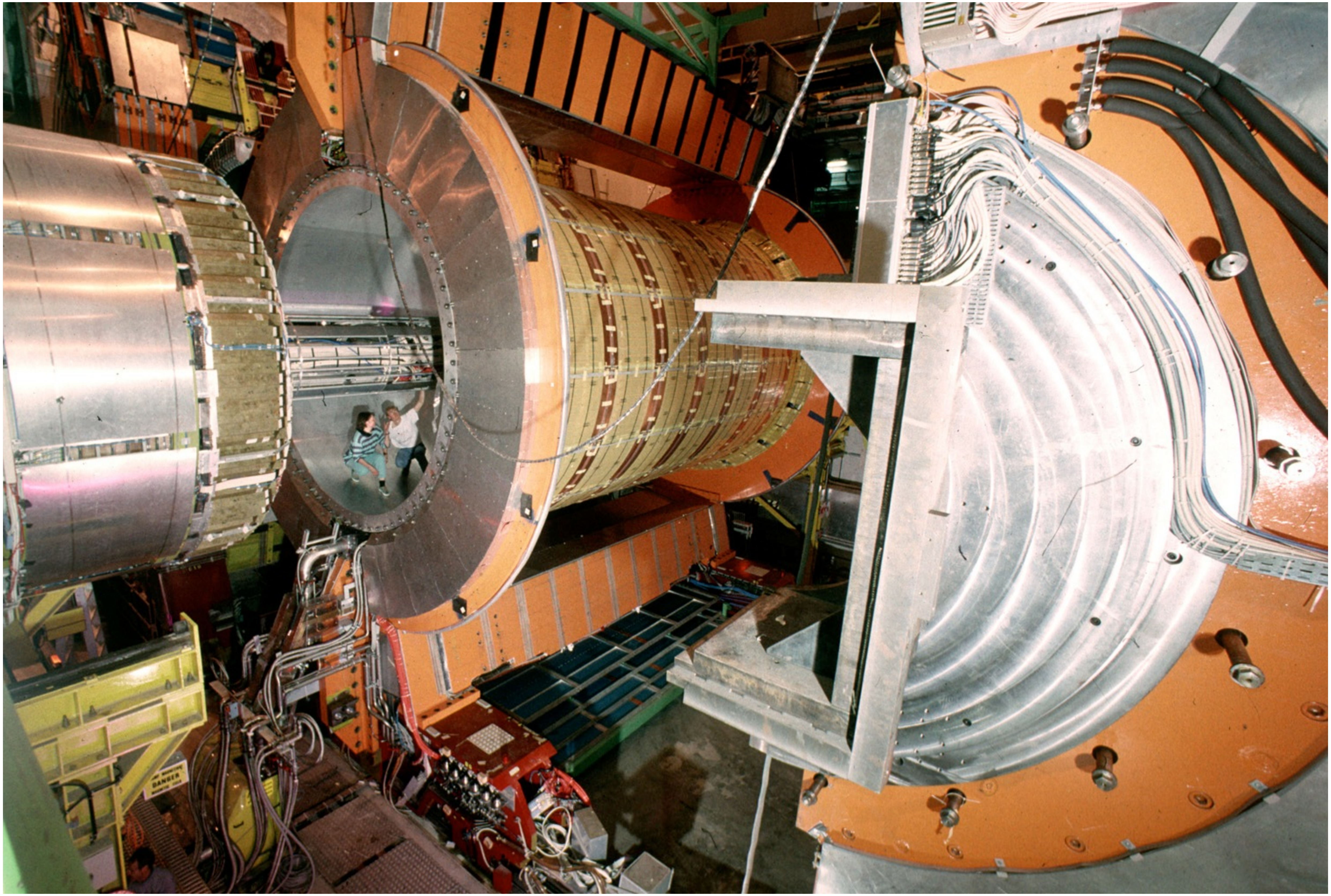


- The beginning of the (very) large collaborations in particle physics: several 100 members (~ 300 - 700, changing with time)

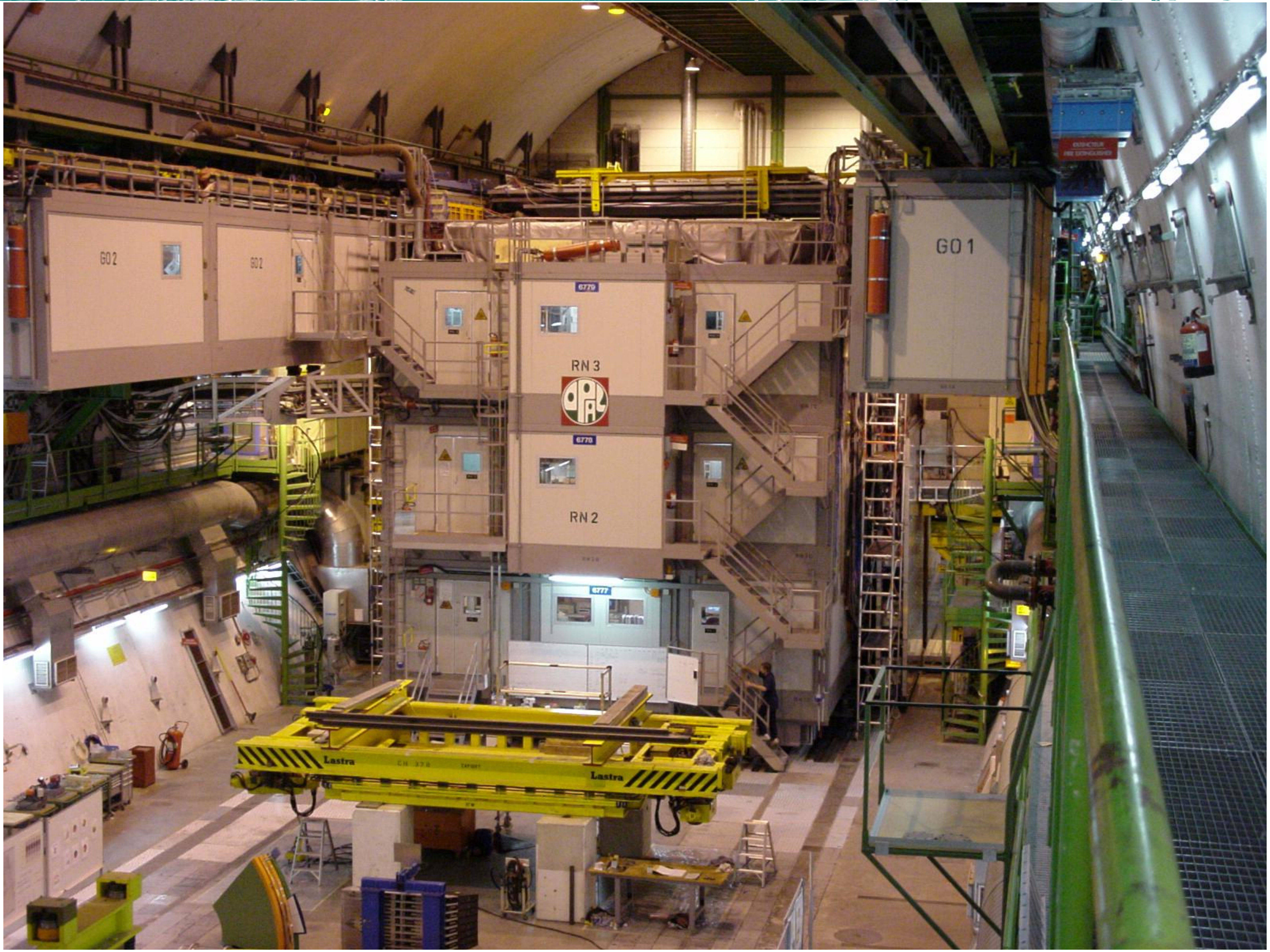
International collaboration on a new scale, required tools for free exchange of information and data

One consequence: Invention of WWW at CERN in 1989

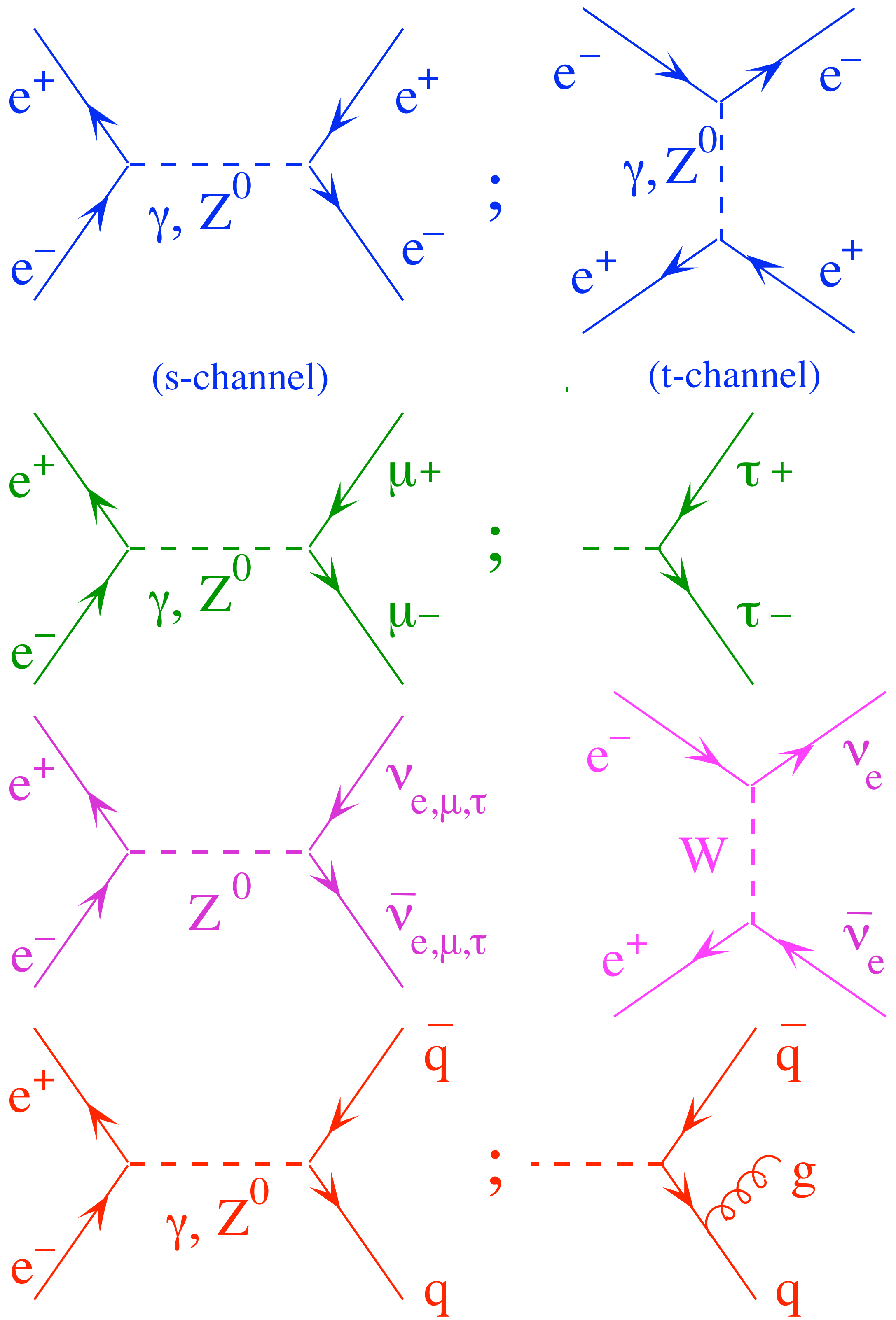
e^+e^- Experiments: One Example - OPAL @ LEP



e^+e^- Experiments: One Example - OPAL @ LEP



Final States in e+e- Annihilation: 91+ GeV



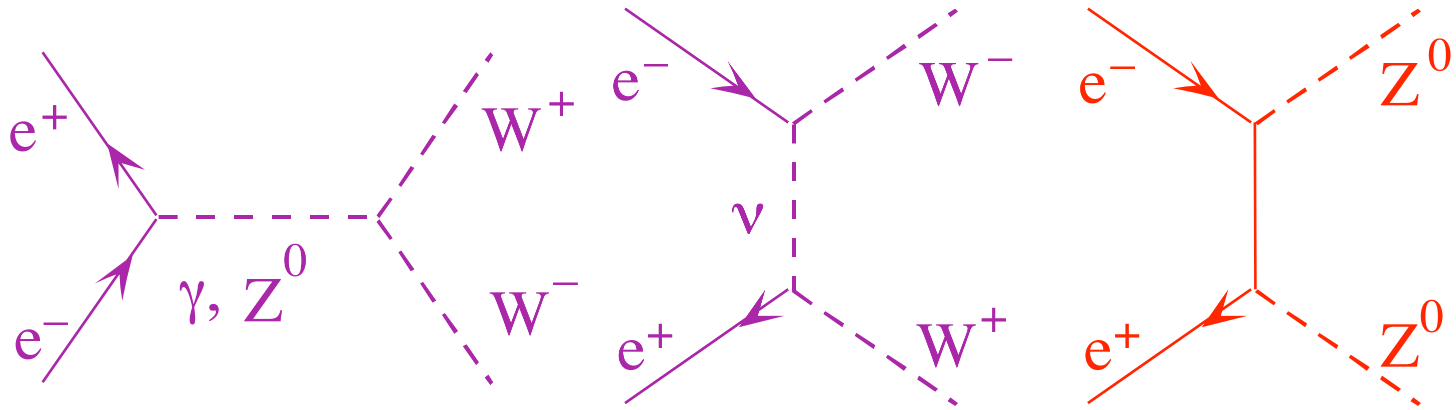
Bhabha-scattering

$\mu-$, $\tau-$ pair-production

Neutrino-pair-production
("invisible")

Quark-Antiquark-pairs
plus Gluons:
hadronic final states
(dominant channel!)

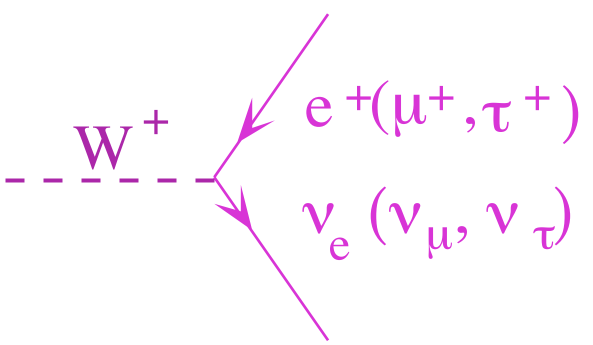
Final States in e^+e^- Annihilation: LEP II

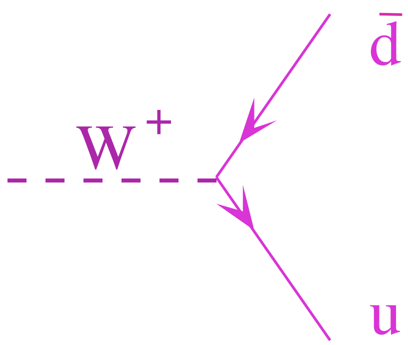


(s-channel) (t-channel)

W/Z - pair production (LEP - II)

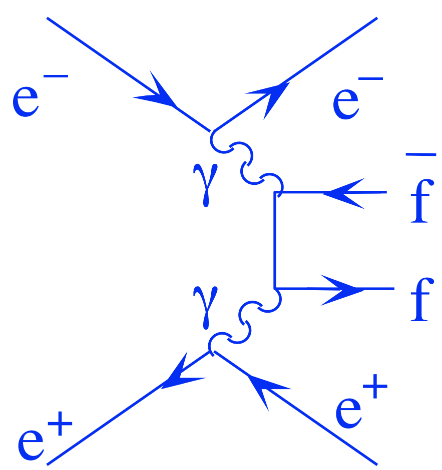
with:



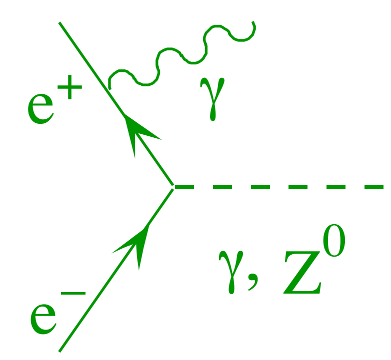


(W-decays;
Z-decays as above)

further important processes:



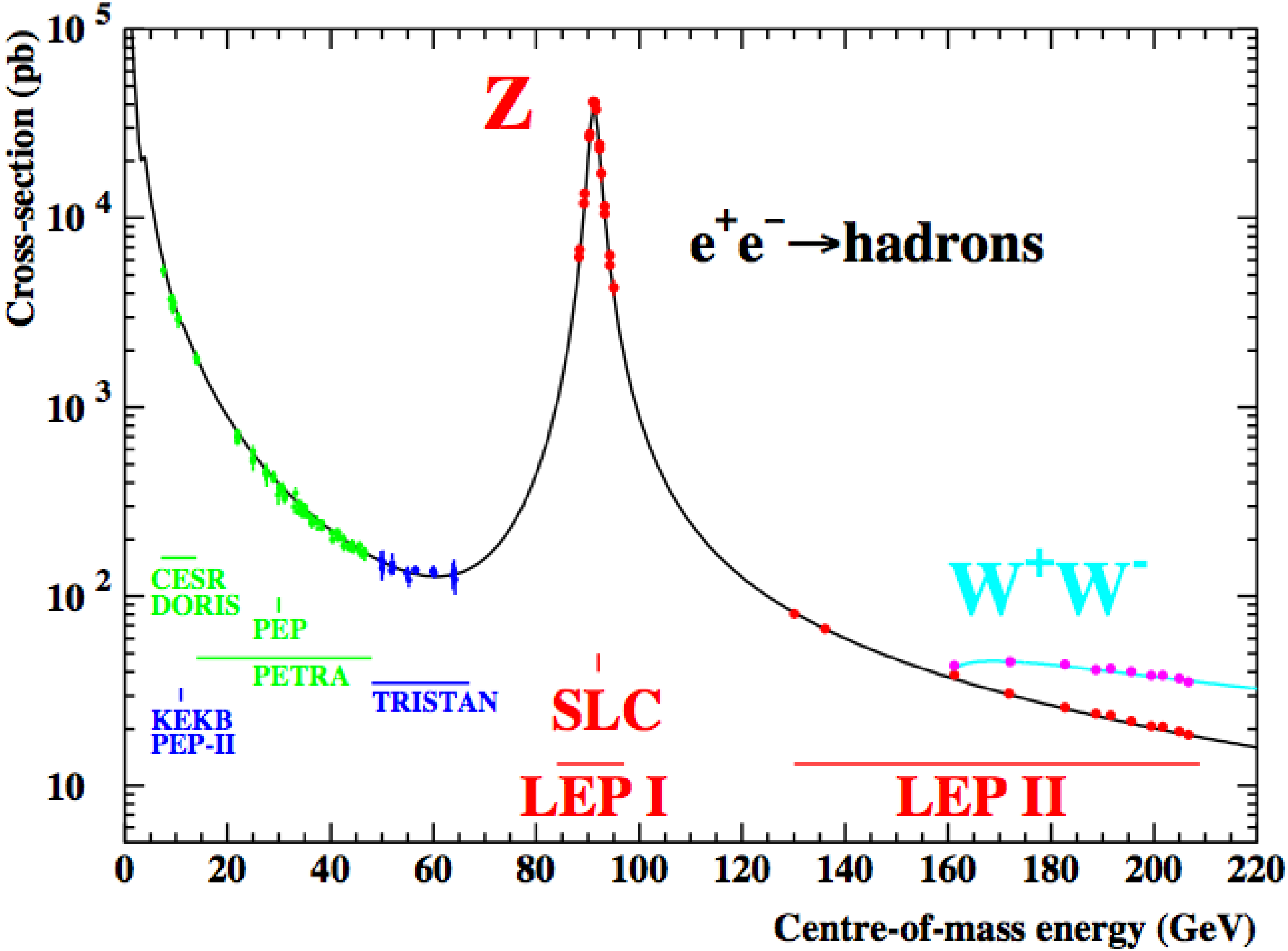
2-Photon - processes



initial state Bremsstrahlung

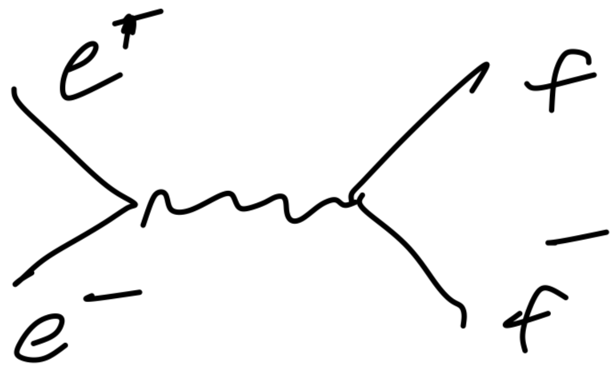
Physics at LEP and SLC
- a few Examples -

The Hadronic Cross Section in e+e- Collisions



Cross sections in Electroweak Interactions

- The minimal SM in lowest order ("Born approximation" describes processes like:



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

by just three free parameters:

α_{em}	fine structure constant (electromagnetic interaction)
G_F	Fermi constant (weak interaction), obtained from μ lifetime
$\sin^2\theta_W$	weak mixing angle, obtained from neutrino - Nucleon scattering

or:

$$\alpha_{em},\ G_F,\ M_Z \quad \Longleftrightarrow \quad \sin^2\theta_W \cos^2\theta_W = \frac{\pi\alpha_{em}}{G_F\cdot\sqrt{2}} \cdot \frac{1}{M_Z^2}$$

The Z^0 Resonance

- For resonant production through a Z, the width of the Z influences the cross section (Breit-Wiegner resonance):

$$\sigma(e^+e^- \to Z \to f\bar{f}) = \frac{12\pi}{m_Z^2} \frac{s}{(s-m_Z^2)^2 + m_Z^2\Gamma_Z^2} \Gamma_{ee} \cdot \Gamma_{ff}$$

c.o.m. energy (s) total width (Γ_Z) partial widths (Γ_{ee}, Γ_{ff})

Maximum at: $\sigma^0_{f\bar{f}} = \frac{12\pi}{m_Z^2} \frac{\Gamma_{ee}\Gamma_{ff}}{\Gamma_Z^2}$

The partial widths (decay into a given fermion pair) can be calculated in the SM:

$$\Gamma_f = \frac{G_F M_Z^3}{6\pi\sqrt{2}} \cdot \left[g_{a,f}^2 + g_{v,f}^2 \right] \cdot N_{c,f}$$

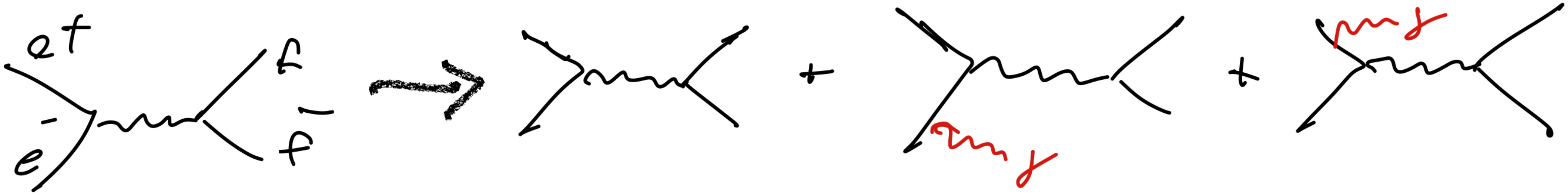
color factor:
3 for quarks, 1 for leptons

$g_{a,f} = I_{3,f}$ — 3rd component of weak isospin: (up-type q, ν +1/2, others -1/2)

$g_{v,f} = I_{3,f} - 2Q\sin^2\theta_W$ — Q: electric charge

It's not quite that simple: Initial State Radiation

- The e^+ and e^- can radiate photons before colliding, changing the energy:

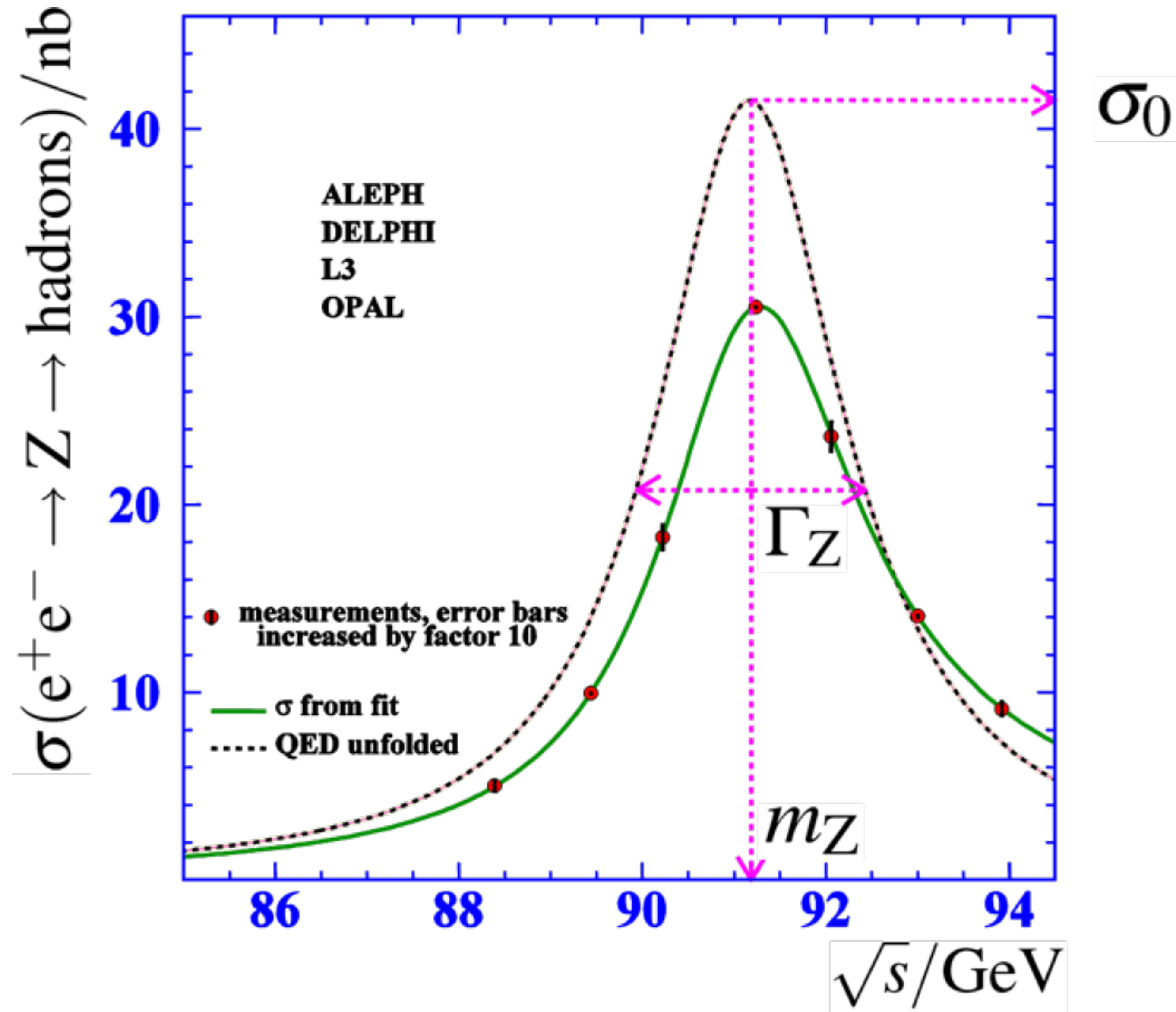


Initial state radiation (ISR)

Results in a change in the collision energy:

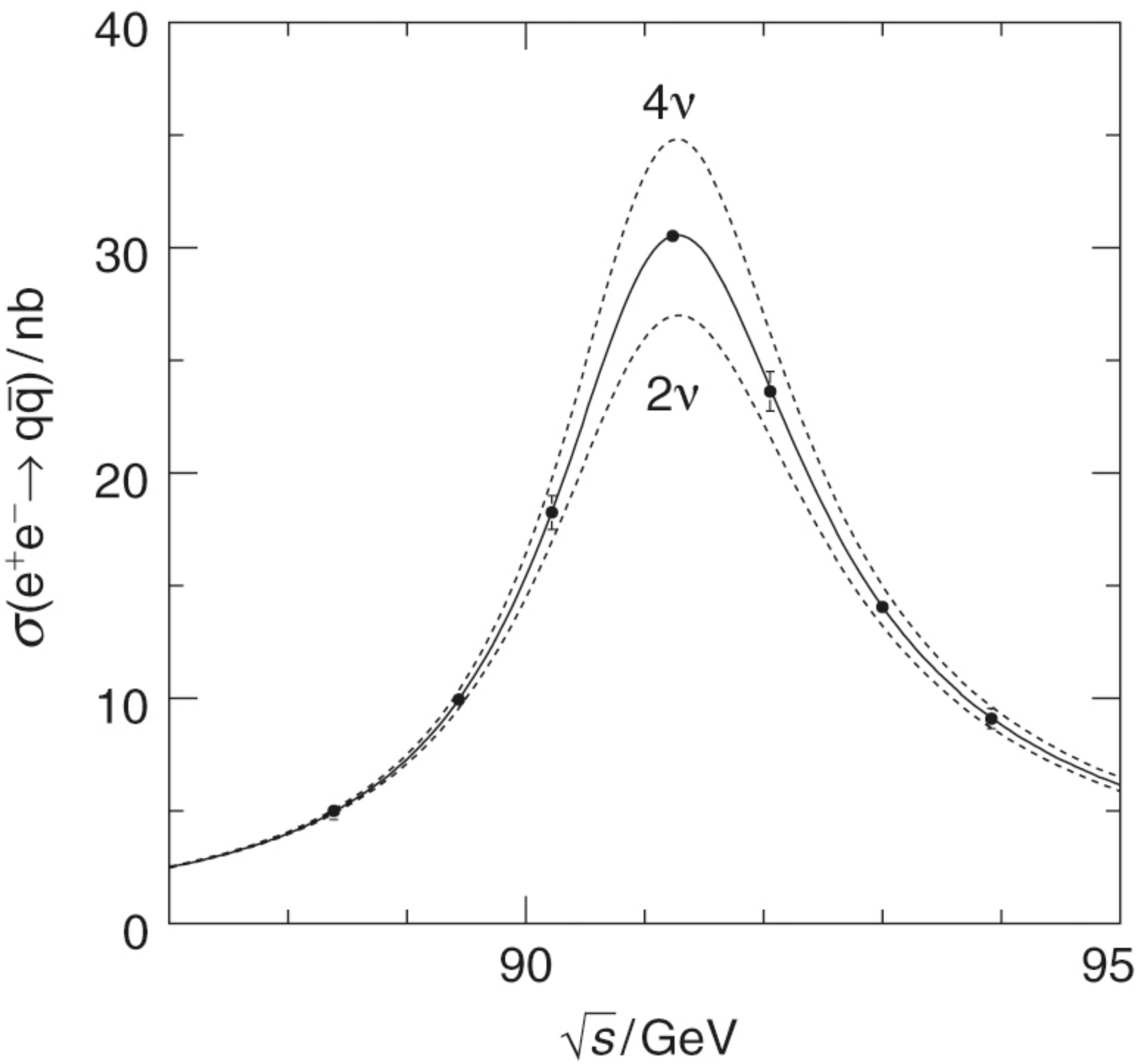
$$\sqrt{s} = 2E \rightarrow \sqrt{s'} \approx 2E\left(1 - \frac{E_\gamma}{2E}\right)$$

changes in cross section: Reduced since events move below resonance energy



Can be calculated precisely in QED!

Precision Measurements at the Z



$M_Z = 91.1875 \pm 0.0021$ GeV

$\Gamma_Z = 2.4952 \pm 0.0023$ GeV

- Determining the number of light neutrino flavors from the Z width:

Given by:

$\Gamma_Z = \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{\tau\tau} + \Gamma_{had}$
$\quad + \Gamma_{\nu e \nu e} + \Gamma_{\nu\mu\nu\mu} + \Gamma_{\nu\tau\nu\tau}$
$\quad = 3\,\Gamma_{ll} + \Gamma_{had} + N_\nu\,\Gamma_{\nu\nu}$

The partial width into visible final states can be directly measured

Taking the SM prediction for $\Gamma_{\nu\nu}$ from the measured cross section and total width the number of (light) neutrinos can be determined

$N_\nu = 2.984 \pm 0.008$

This precision can not be reached at hadron colliders - LEP input used for calibration at LHC

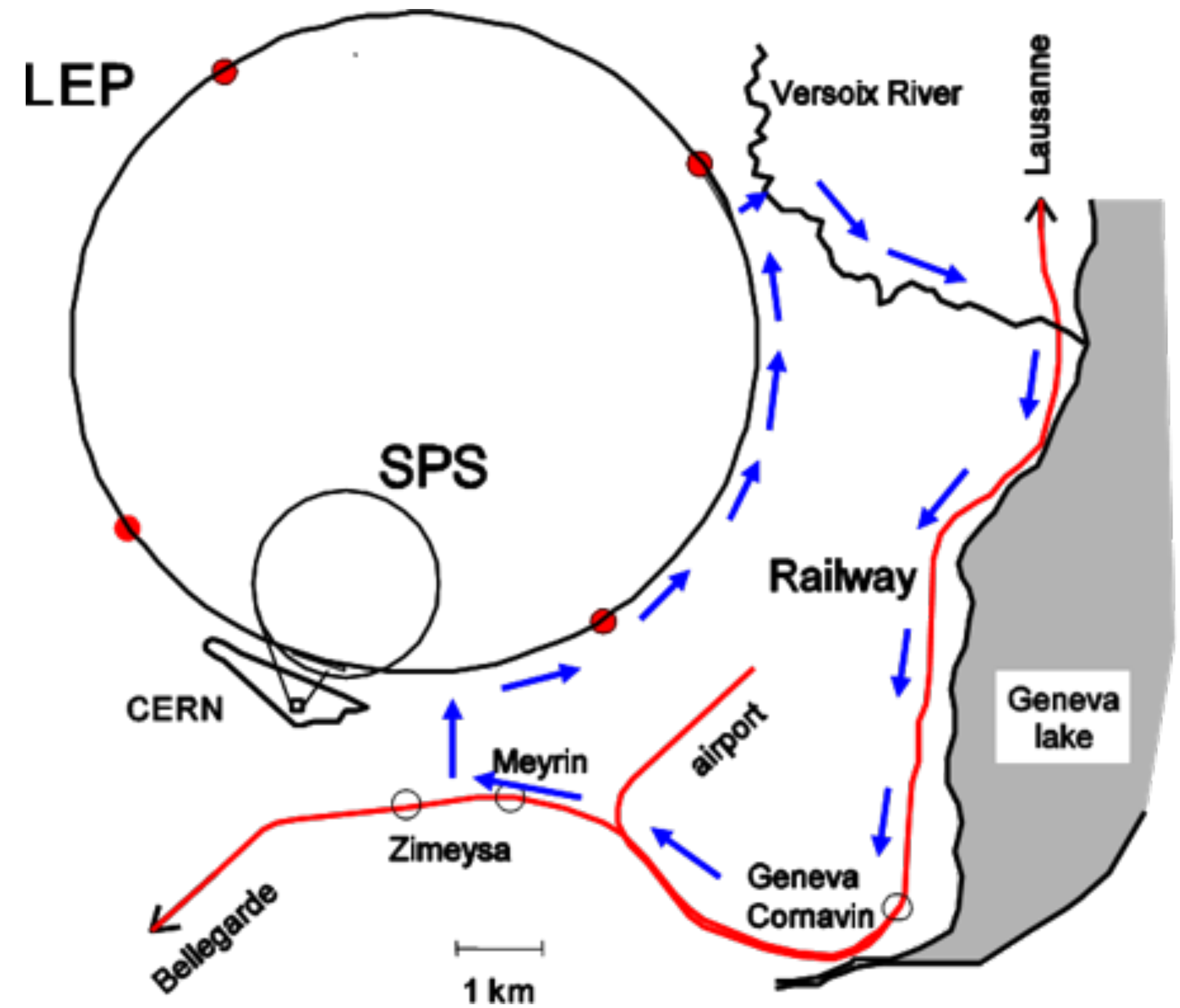
Challenges imposed by Precision Goals

Moon

- As the moon orbits the Earth it distorts the rock in the Geneva area very slightly !
- The nominal radius of the accelerator of 4.3 km varies by ±0.15 mm
- Changes beam energy by ~10 MeV : need to correct for tidal effects !

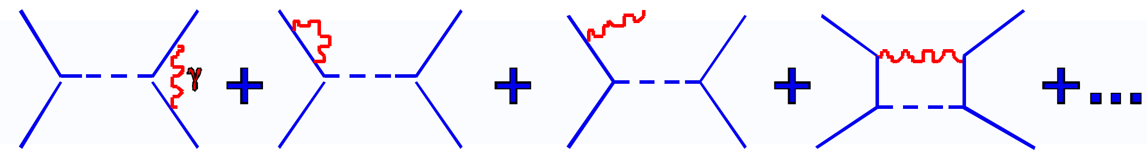
Trains

- Leakage currents from the TGV railway line return to Earth following the path of least resistance.
- Travelling via the Versoix river and using the LEP ring as a conductor.
- Each time a TGV train passed by, a small current circulated LEP slightly changing the magnetic field in the accelerator
- LEP beam energy changes by ~10 MeV



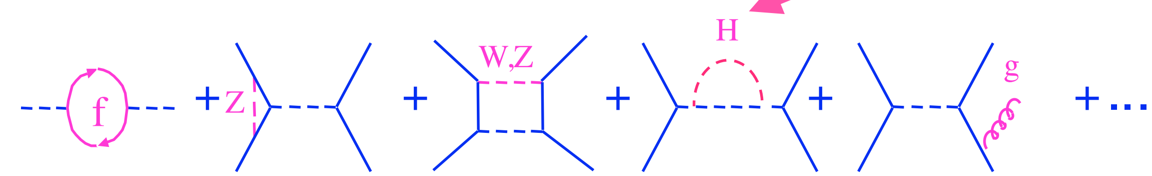
Radiative Corrections

photonic corrections:



corrections ~ 100%, selection dependent;
factorisable: $(1 + \delta_{rad})$

non-photonic corrections:



corrections ~ 10%, selection independent;
can be absorbed in running couplings:

- $\sin^2\theta_{eff}(s)$
- $\alpha(s) = \dfrac{\alpha}{1-\Delta\alpha}$; $\Delta\alpha = 0.064$ bei $\sqrt{s} = M_Z$
- $N_{c,f}\left(1+\dfrac{\alpha_s}{\pi}+1.4\left(\dfrac{\alpha_s}{\pi}\right)^2+\ldots\right)$ (für Quarks)
- $\dfrac{M_W^2}{M_Z^2} = \rho\cdot\cos^2\theta_w$ mit $\rho = \dfrac{1}{1-\Delta\rho}$; $\Delta\rho = 0.0026\,\dfrac{M_t^2}{M_Z^2} - 0.0015\,\ln\left(\dfrac{M_H}{M_W}\right)$

Modifications of the Cross Sections by Corrections

insertion of running couplings in "Born"-approximation :

partial Z decay widths $\Gamma_f = \frac{G_f M_Z^3}{6\pi\sqrt{2}}\left[g_{a,f}^2 + g_{v,f}^2\right] N_{c,f}$ (and also

cross sections) acquire dependence on:

- $\mathbf{M_t}$
- $\mathbf{M_H}$
- α_s

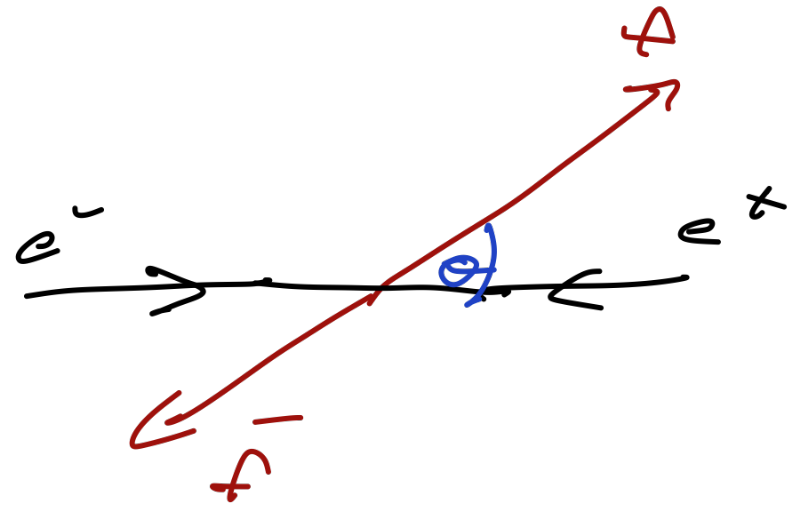
==> indirect determination (fit) of M_t , M_H , and α_s from combination of all available electroweak observables

(differential cross sections, partial decay widths, forward-backward asymmetries, τ-polarisation, left-right asymmetries (SLC))

Beyond Cross Section Measurements

- Differential cross sections

$$\frac{d\sigma_f}{d\cos\theta} \propto A\cdot(1+\cos^2\theta) + B\cdot\cos\theta$$



depends on γ and Z0 exchange & interference, spin orientations (helicities) of initial and final state, on resonance, ...

- Can be studied in a compact way as forward - backward asymmetries:

$$\sigma_F \equiv \int_0^1 \frac{d\sigma}{d\cos\theta}\, d\cos\theta \qquad 0<\theta<\frac{\pi}{2}$$

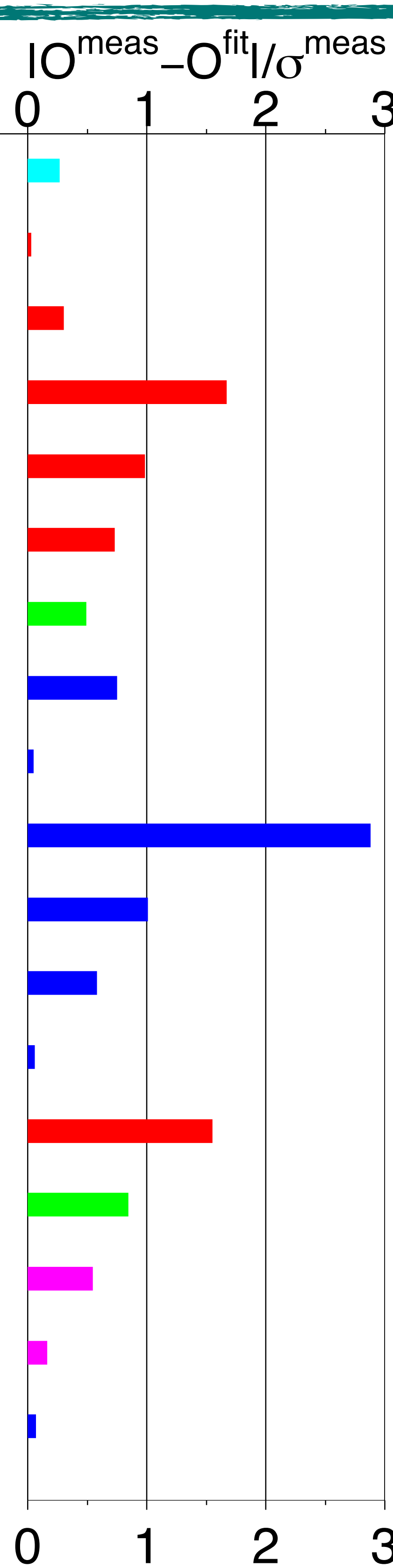
$$\sigma_B = \int_{-1}^0 \frac{d\sigma}{d\cos\theta}\, d\cos\theta \qquad \frac{\pi}{2}<\theta<\pi$$

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

Sensitive to vector and axial-vector couplings: non-zero A_{FB} because the coupling of the Z to lefthanded and righthanded particles is different (for pure QED interactions A_{FB} would be zero)

Summary of Precision Measurements at LEP & SLC

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02750 ± 0.00033	0.02759
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
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	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.385 ± 0.015	80.377
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.20 ± 0.90	173.26

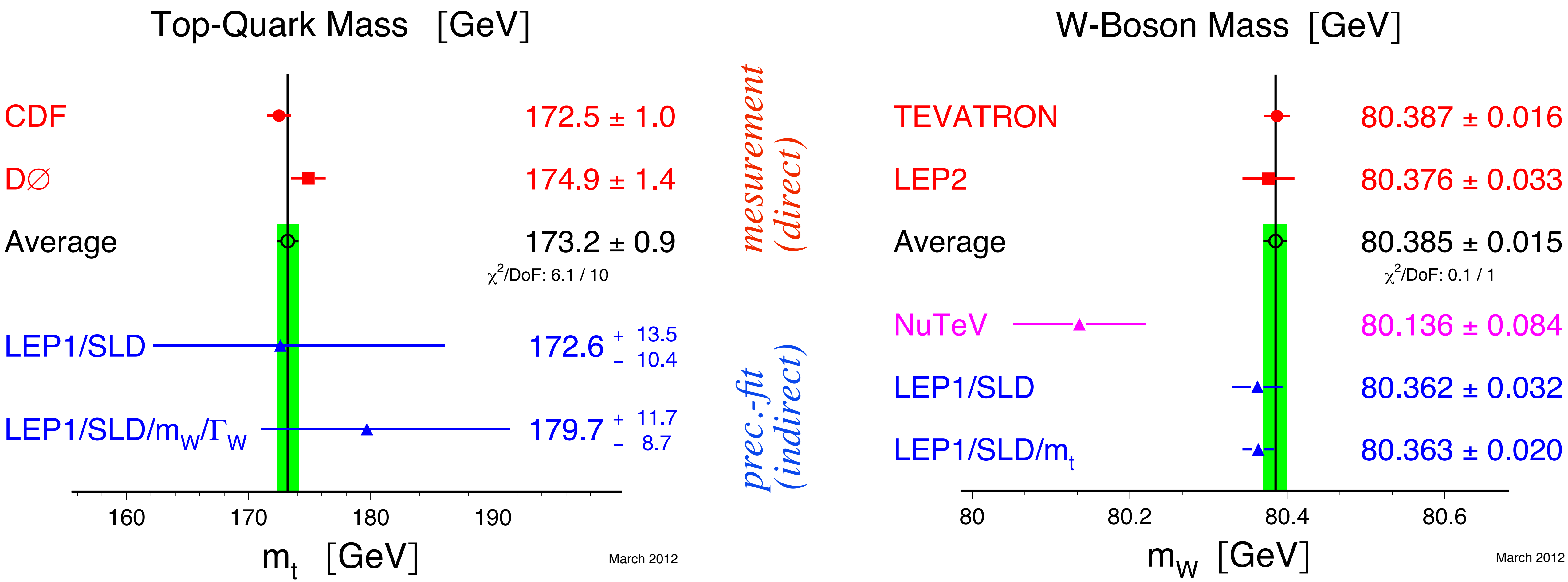


March 2012

- Good overall consistency of a wide range of measurements with SM precision calculations observed

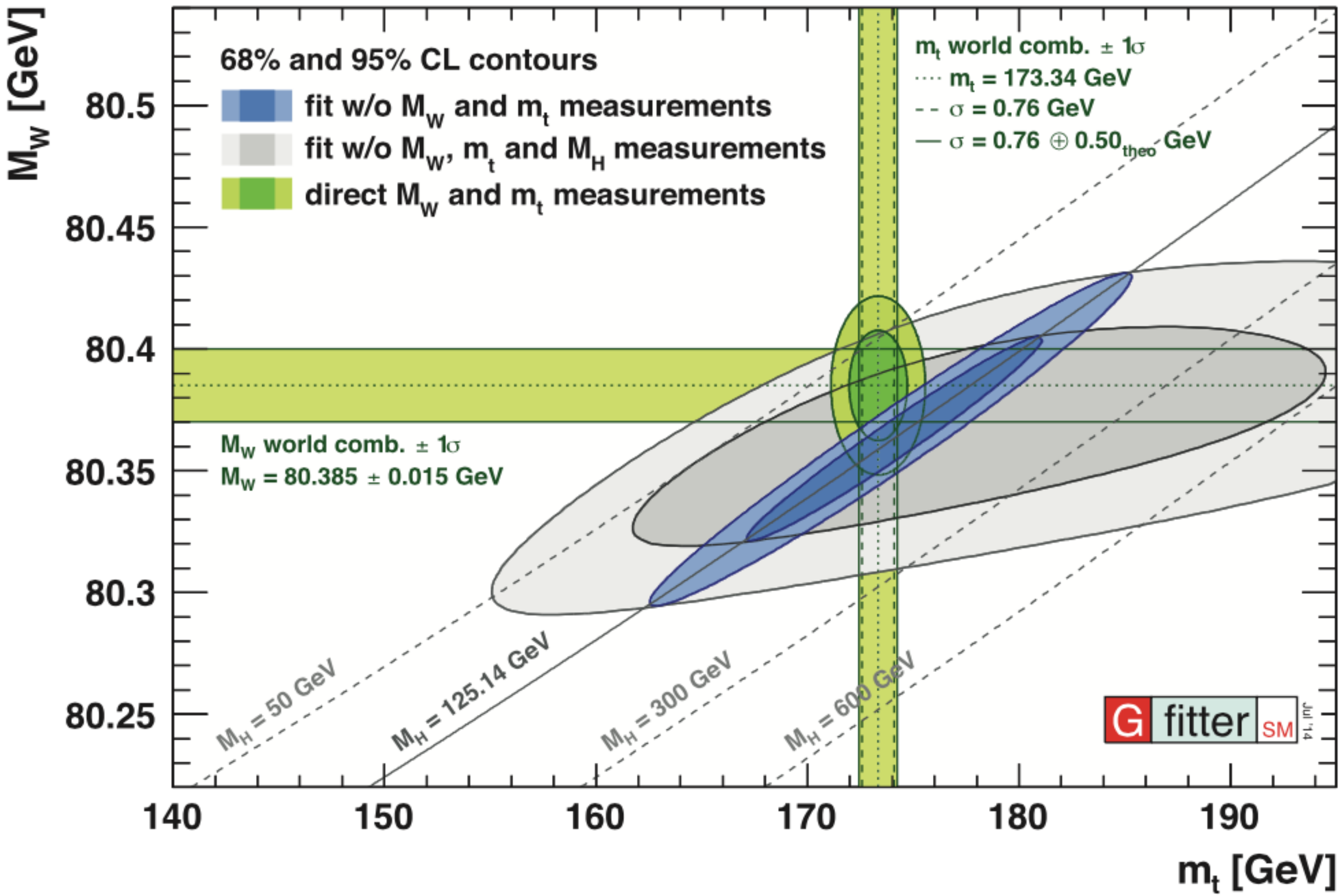
includes data from Tevatron: M_t, M_W

Indirect vs direct Measurements

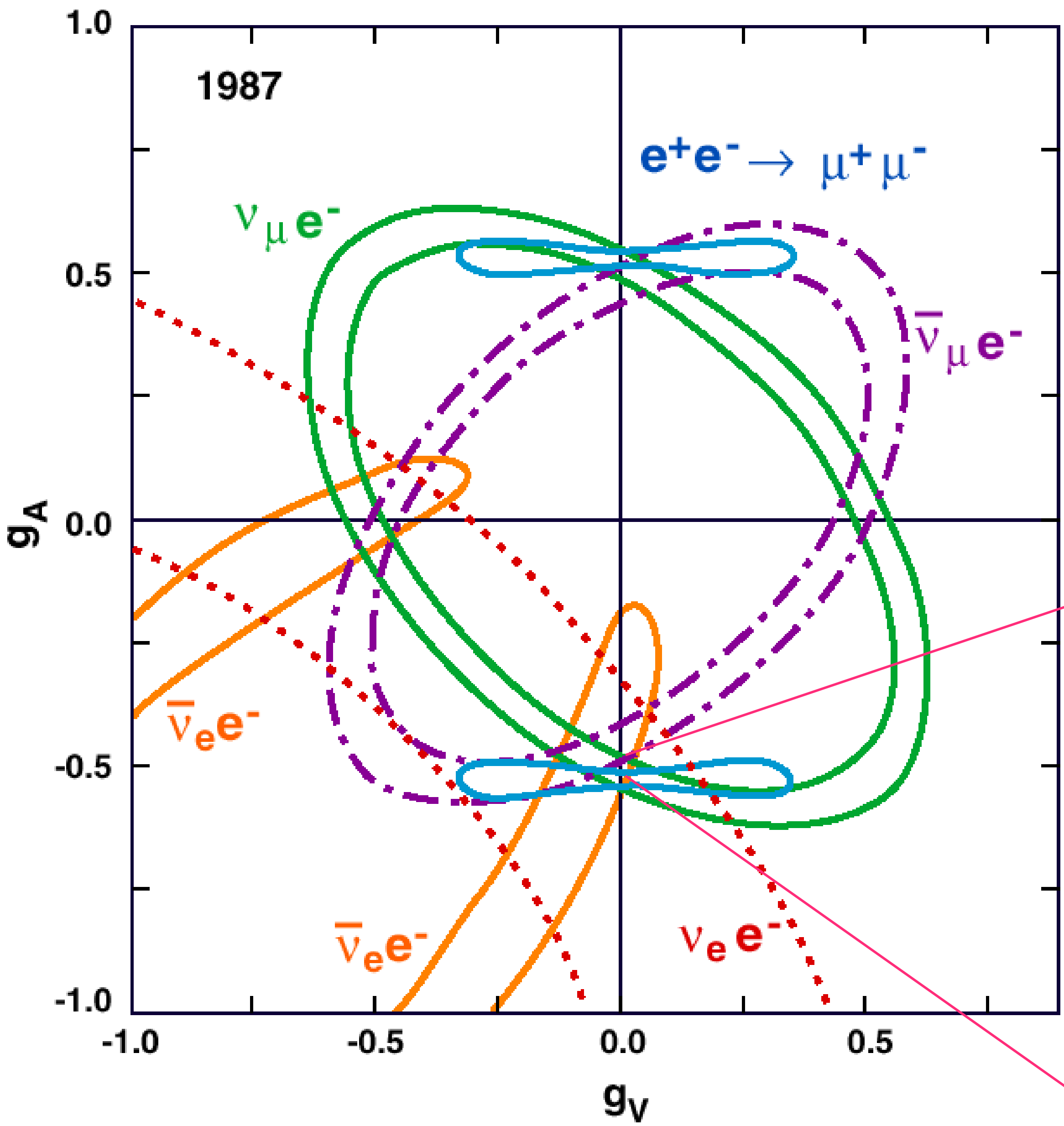


- Indirect measurements use SM “as-is”, fitting unknown particle masses using radiative / loop corrections sensitive to these particles

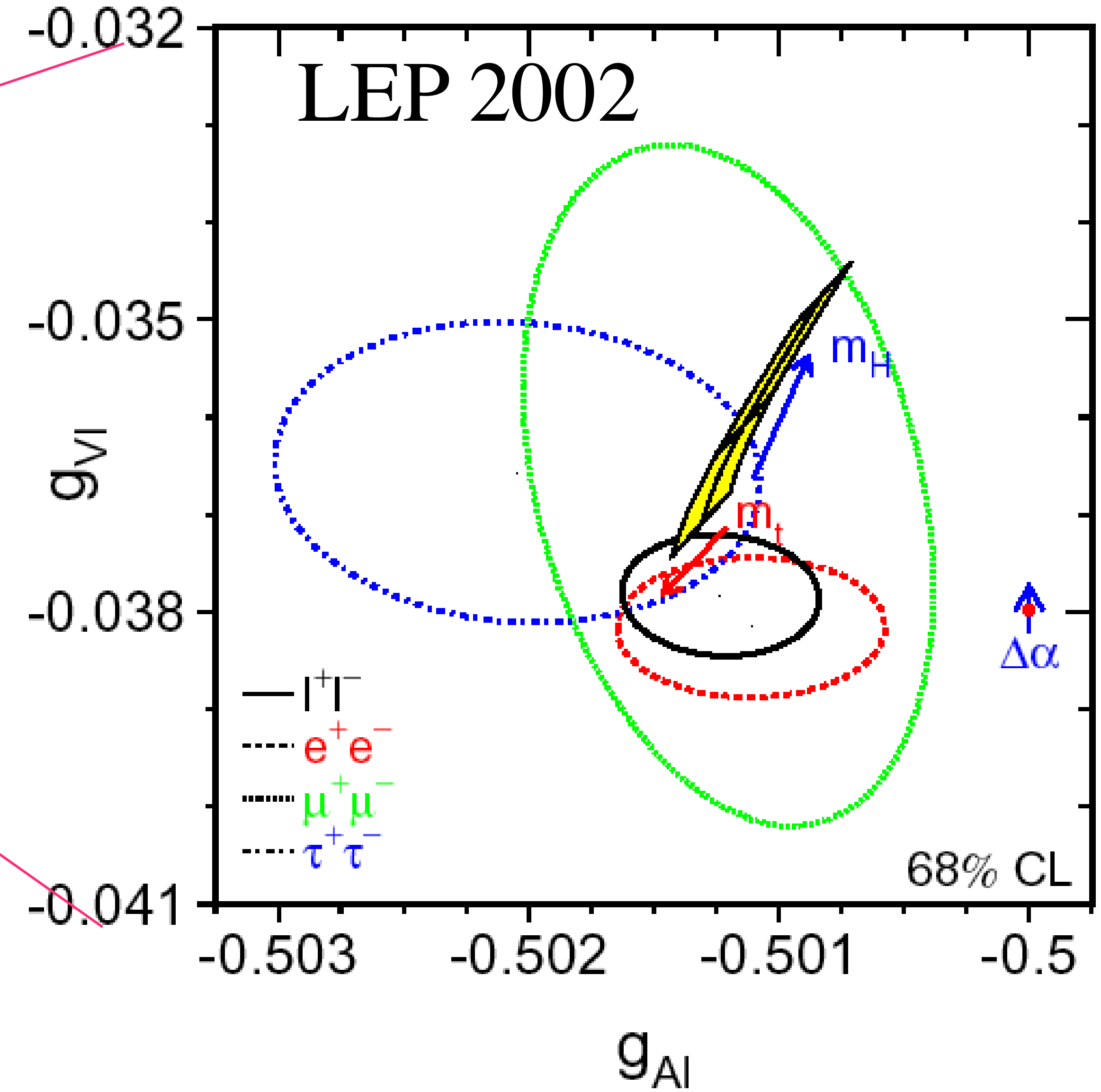
Consistency of direct & indirect Mass Measurements



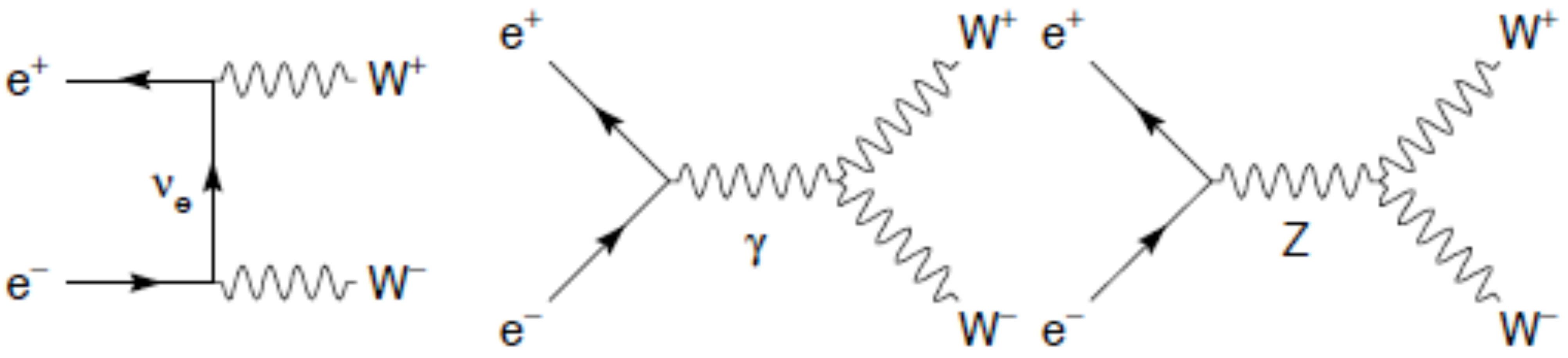
Measuring Axial and Vector Couplings



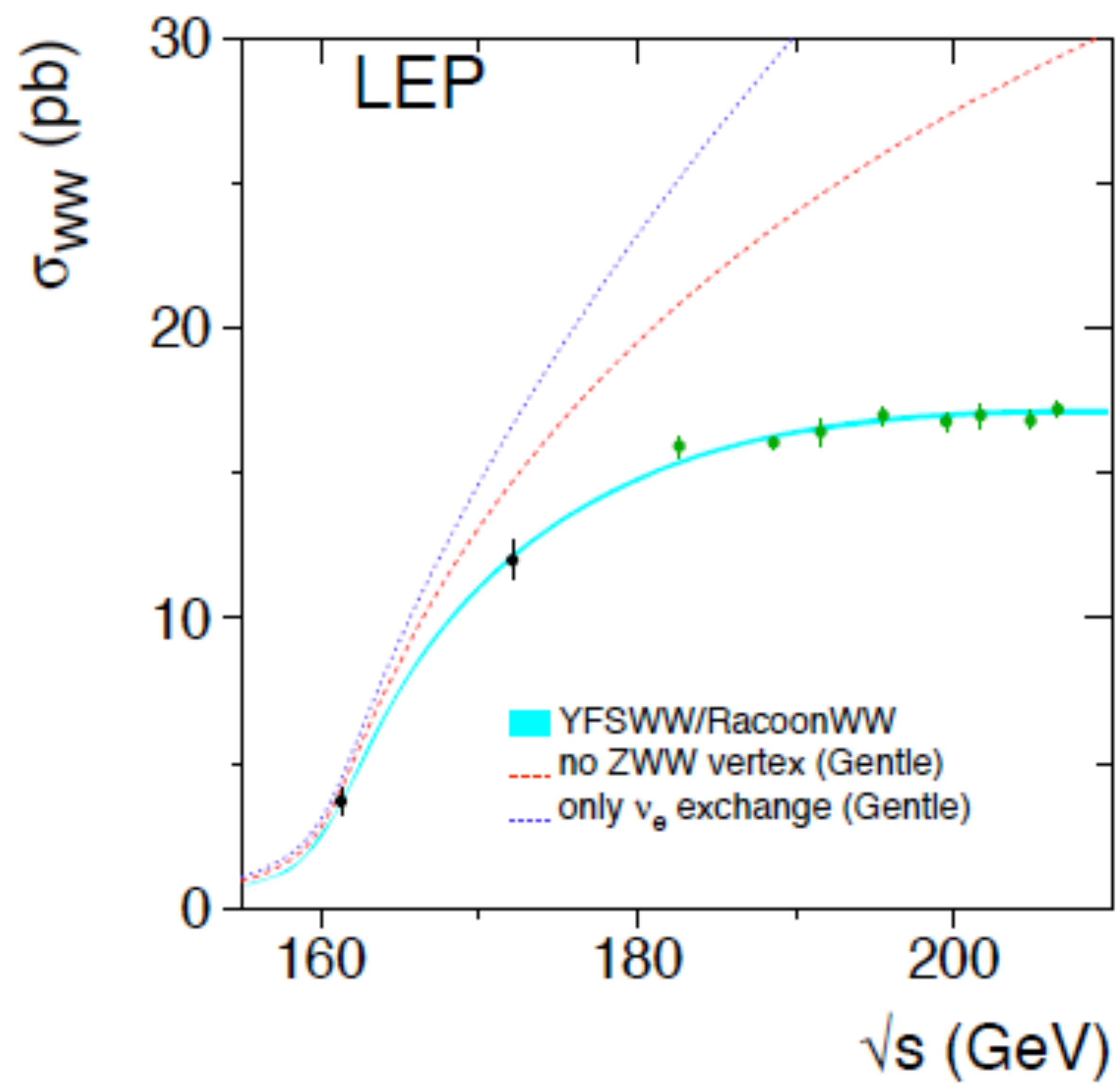
- Precision result on Vector and Axial-vector couplings: Precision provided by LEP



Coupling of Vector Bosons

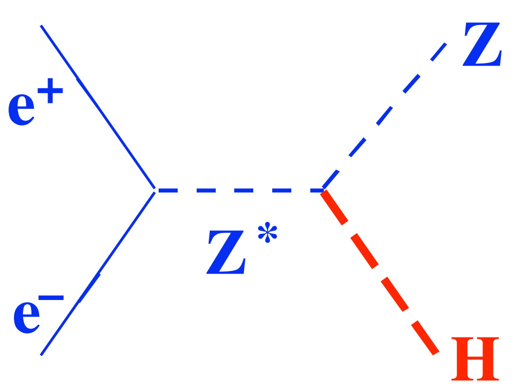


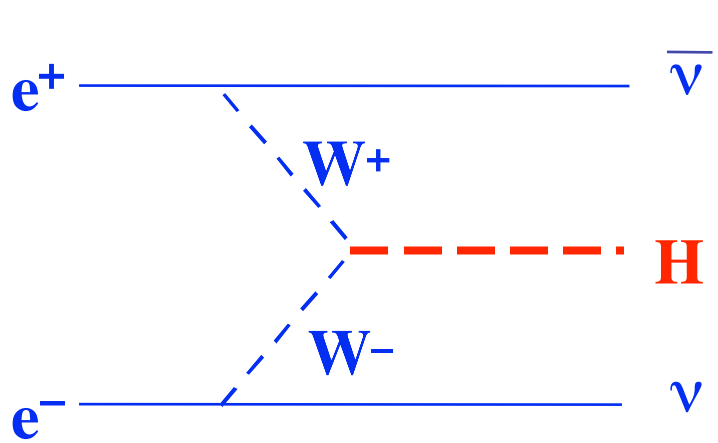
- Coupling of vector bosons: A key element of the group structure of the SM
- Observed in energy dependence of W pair production cross section



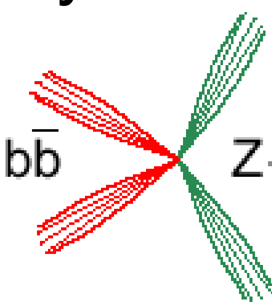
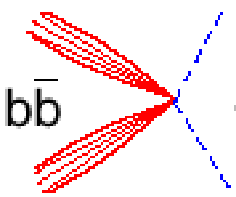
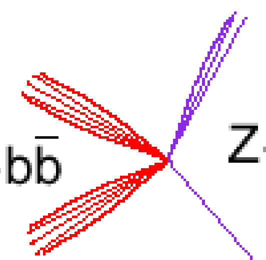
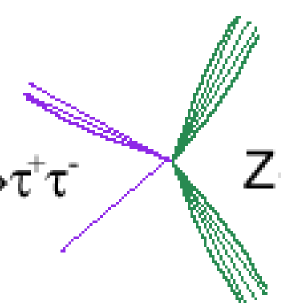
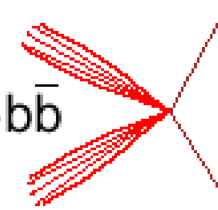
Searching for the Higgs @ LEP

Production:





includes about 80% of all final states with about 40-50% selection efficiencies

decay channel ($e^+e^- \to HZ$):				background:
$H \to b\bar{b}$  $Z \to q\bar{q}$	**4-Jet-Kanal**	51%	$WW \to qqqq, ZZ \to bbqq$ QCD 4jets
$H \to b\bar{b}$  $Z \to \nu\bar{\nu}$	**Neutrino-Kanal**	15%	$WW \to qql\nu, ZZ \to bb\nu\nu$
$H \to b\bar{b}$  $Z \to \tau^+\tau^-$	**Tau-Kanal**	2.4%	$WW \to qq\tau\nu, ZZ \to qq\tau\tau$ QCD (low-mult. jets)
$H \to \tau^+\tau^-$  $Z \to q\bar{q}$		5.1%	
$H \to b\bar{b}$  $Z \to e^+e^-, \mu^+\mu^-$	**Lepton-Kanal**	4.9%	$ZZ \to bbll$

Higgs Searches at LEP: History

status July 2000: no hint for the Higgs; $M_H > 113.3$ GeV/c² (95% CL)

[final status July 2001: $M_H > 114.1$ GeV/c²]

5. Sept. 2000: ALEPH sees excess in 4-Jet channel, compatible with $M_H \sim 115$ GeV/c².
LEP-combination: 2.2 σ excess over background

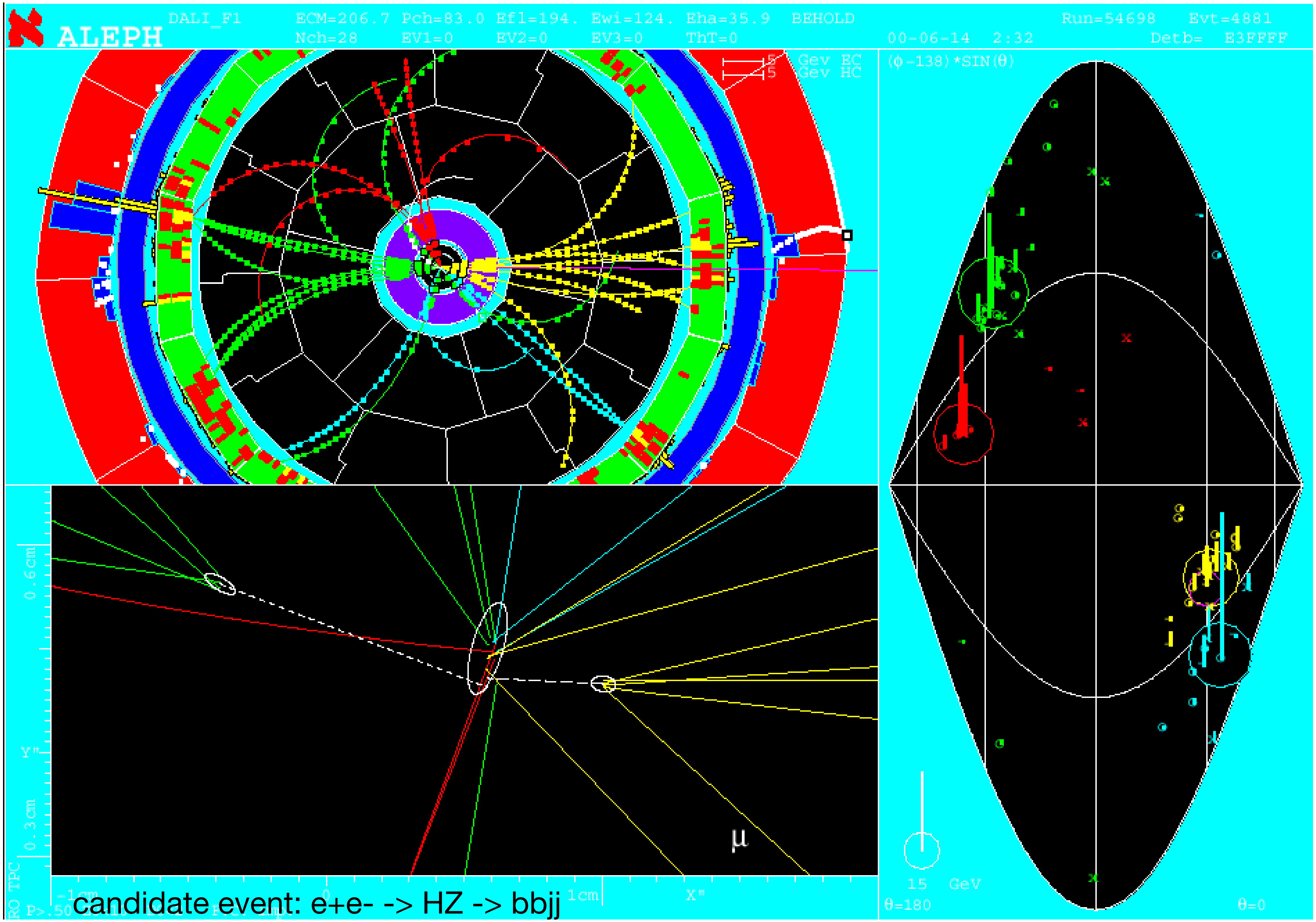
14. Sept. 2000: LEP-shutdown extended by 1 month, until 2. November 2000

3. Nov. 2000: further candidate events increase significance to 2.9 σ.
LEP-experiments ask for LEP run in 2001

[status July 2001: after re-analyses (calibration) only 2.1 σ !]

8. Nov. 2000: LEP irrevocably shut down.

An Event that got People excited…



candidate event: e+e- -> HZ -> bbjj

Indirect Higgs Constraints before LHC

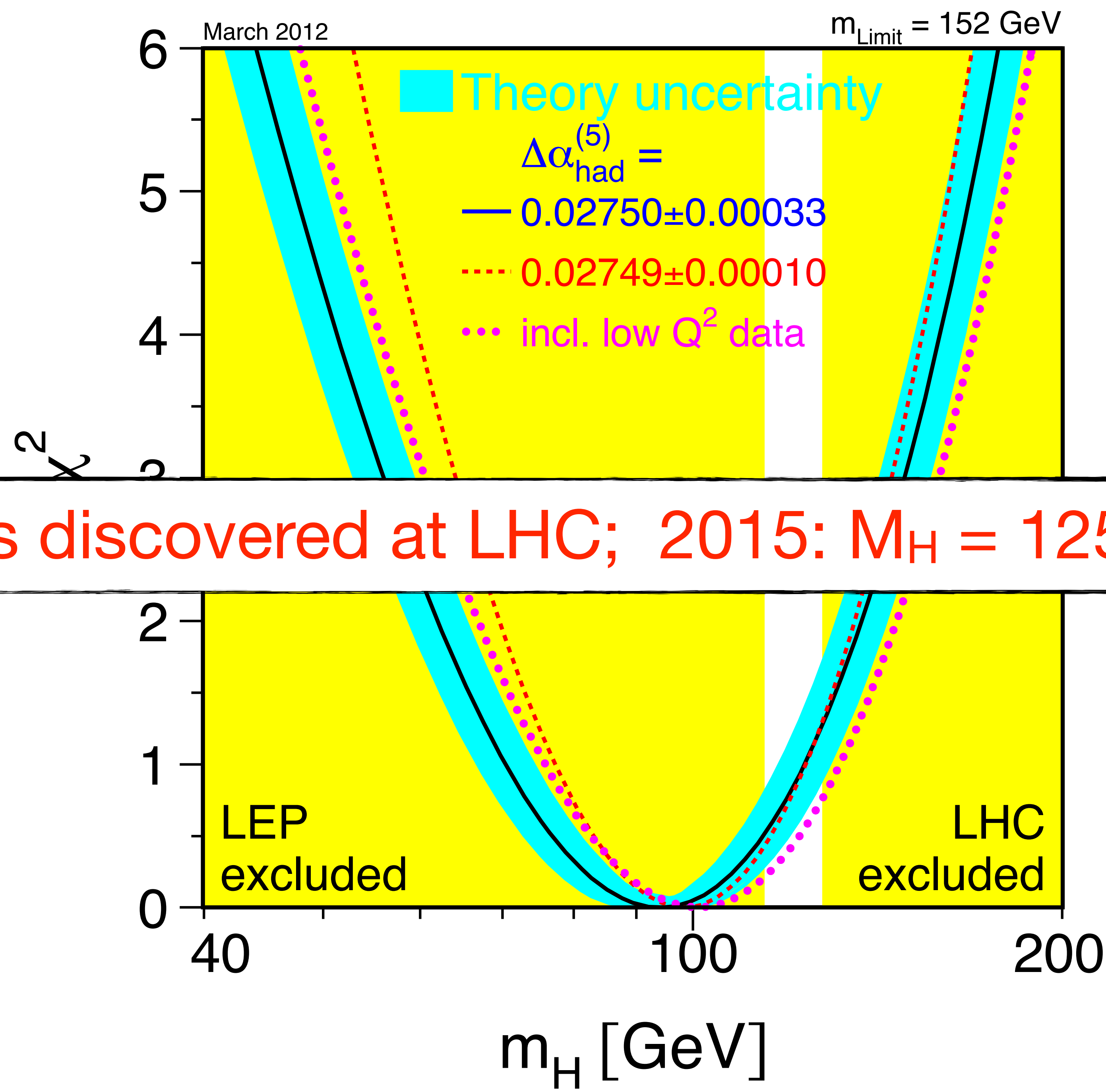
- Constraints from global fits, using radiative corrections that are sensitive to H

	- 1 - LEP including LEP-II m_W, Γ_W	- 2 - all Z-pole data	- 3 - all Z-pole data plus m_t	- 4 - all Z-pole data plus m_W, Γ_W	- 5 - all data except NuTeV	- 6 - all data
m_t [GeV]	184^{+13}_{-11}	171^{+11}_{-9}	$173.6^{+4.7}_{-4.6}$	180^{+11}_{-9}	$175.4^{+4.3}_{-4.2}$	$174.3^{+4.5}_{-4.3}$ *
m_H [GeV]	228^{+367}_{-136}	81^{+107}_{-40}	99^{+64}_{-40}	117^{+161}_{-63}	78^{+48}_{-31}	81^{+52}_{-33}
$\log(m_H/\text{GeV})$	$2.36^{+0.42}_{-0.39}$	$1.91^{+0.37}_{-0.30}$	$1.99^{+0.22}_{-0.23}$	$2.07^{+0.38}_{-0.33}$	$1.89^{+0.21}_{-0.22}$	$1.91^{+0.22}_{-0.23}$
$\alpha_S(m_Z^2)$	0.1199 ± 0.0030	0.1186 ± 0.0027	0.1187 ± 0.0027	0.1185 ± 0.0027	0.1181 ± 0.0027	0.1183 ± 0.0027
χ^2/d.o.f. (P)	13.3/9 (15%)	14.8/10 (14%)	14.9/11 (19%)	17.9/12 (12%)	20.5/14 (11%)	29.7/15 (1.3%)
$\sin^2\theta_{\text{eff}}^{\text{lept}}$	0.23160 ± 0.00018	0.23145 ± 0.00016	0.23145 ± 0.00016	0.23135 ± 0.00015	0.23131 ± 0.00015	0.23136 ± 0.00015
$\sin^2\theta_W$	0.22284 ± 0.00053	0.22313 ± 0.00063	0.22299 ± 0.00045	0.22240 ± 0.00045	0.22255 ± 0.00036	0.22272 ± 0.00036
m_W [GeV]	80.388 ± 0.027	80.373 ± 0.032	80.380 ± 0.023	80.410 ± 0.023	80.403 ± 0.019	80.394 ± 0.019

Table 16.2: Results of the fits to: (1) LEP data alone, (2) all Z-pole data (LEP-1 and SLD), (3) all Z-pole data plus direct m_t determinations, (4) all Z-pole data plus direct m_W and direct Γ_W determinations, (5) all data (including APV) except NuTeV, and (6) all data. As the sensitivity to m_H is logarithmic, both m_H as well as $\log(m_H/\text{GeV})$ are quoted. The bottom part of the table lists derived results for $\sin^2\theta_{\text{eff}}^{\text{lept}}$, $\sin^2\theta_W$ and m_W. See text for a discussion of theoretical errors not included in the errors above.

*** M_H < 185 GeV (95% c.l.)**

Indirect & Direct Higgs Constraints pre-2012

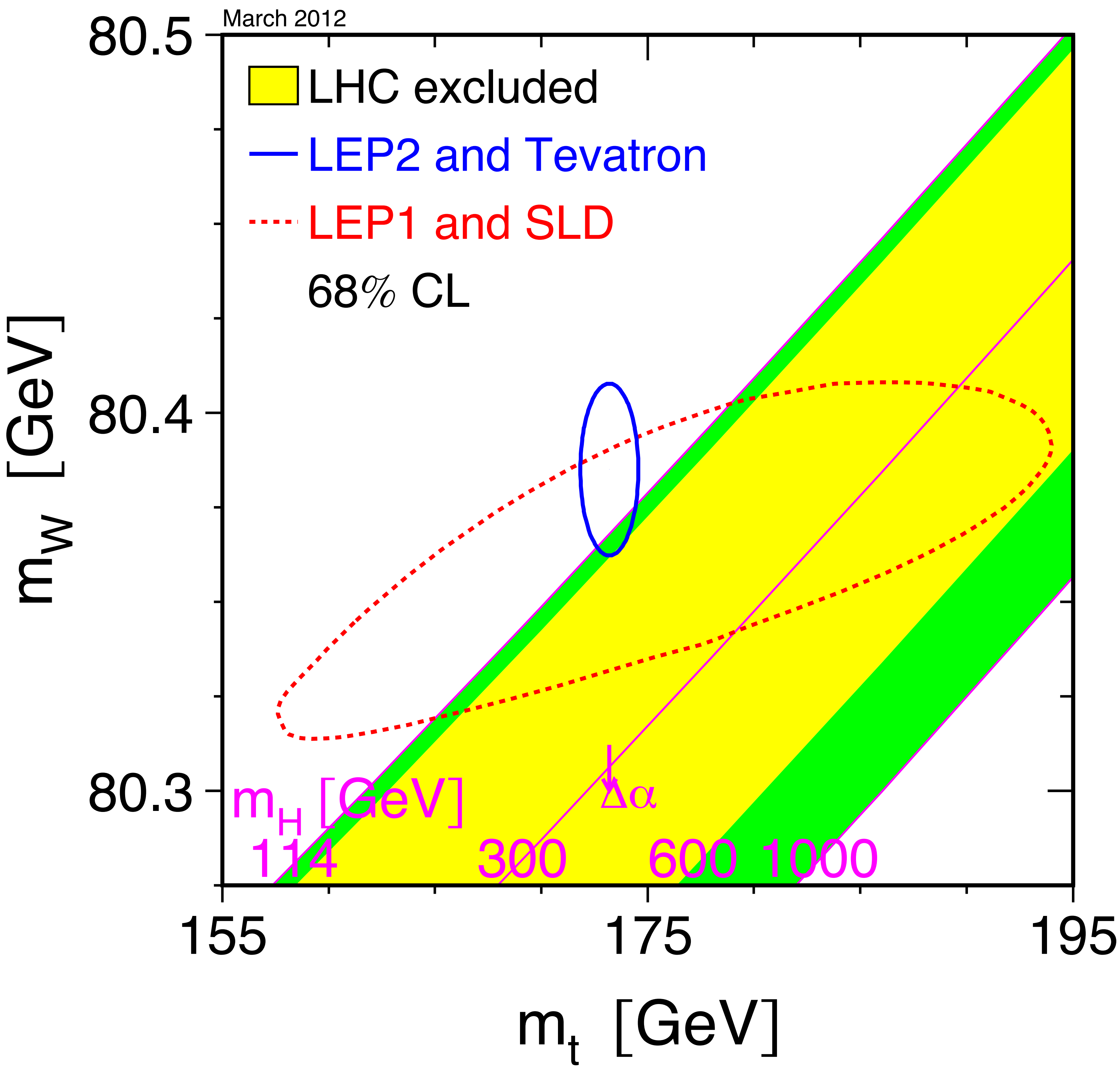


July 2012: Higgs discovered at LHC; 2015: $M_H = 125.09 \pm 0.24$ GeV

from direct search: 114.1(LEP) 115.5 (LHC) < M_H < 131 GeV/c² (LHC)

indirect: radiative corrections: $M_H < 186$ (157) GeV/c² (95% CL)

Direct & Indirect: Comparison



(m_t, m_w measured)

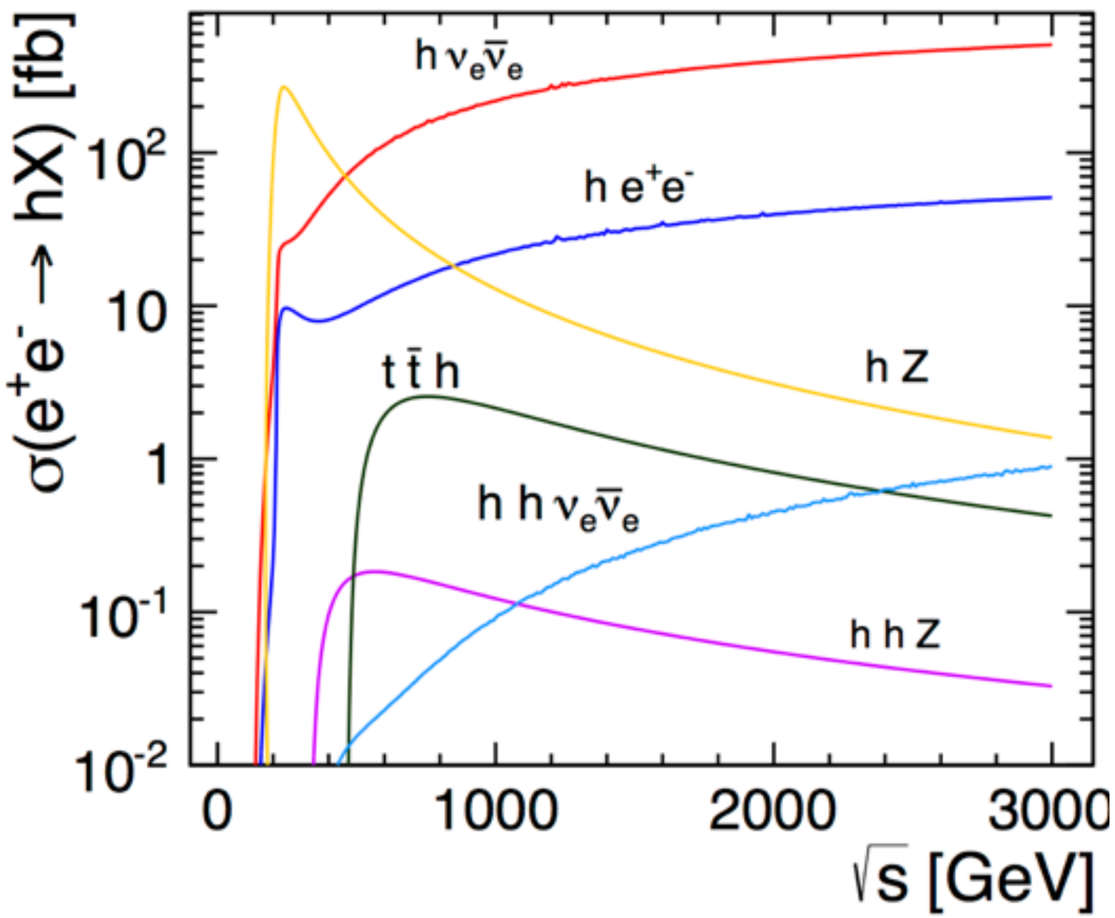
(fit, from rad. corr.)

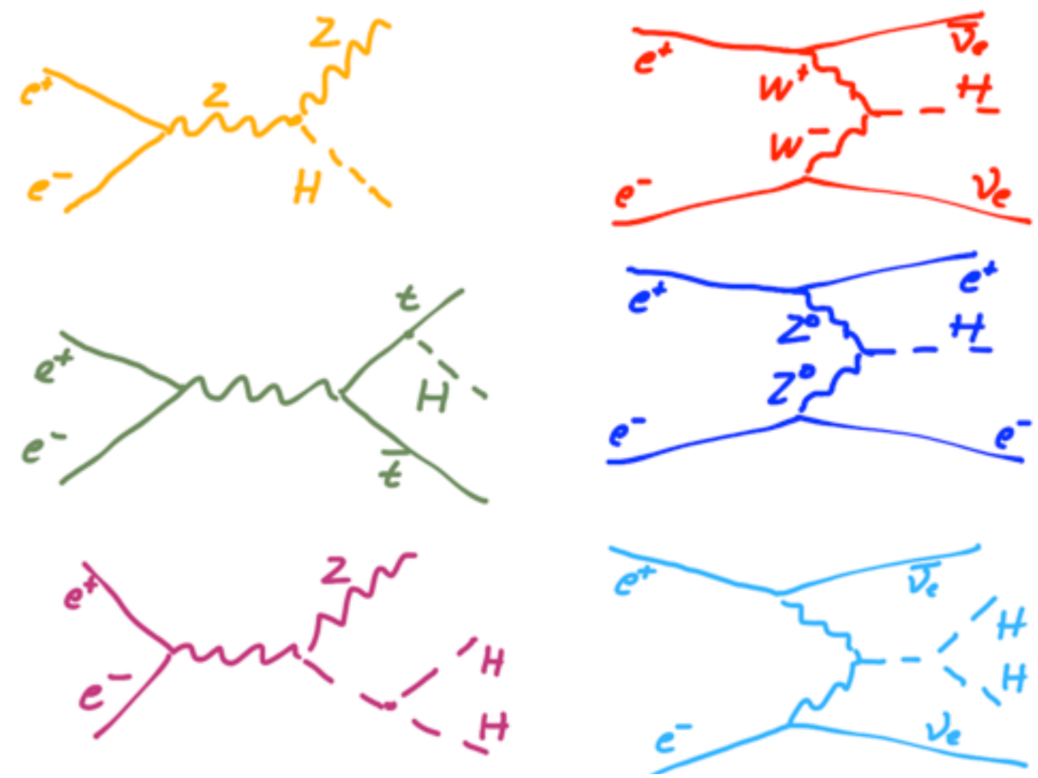
- Direct and indirect mass measurements in good agreement
- After LEP2 it was clear that the (SM) Higgs had to be light!

A Word on the Future

- Currently discussing the Update of the European Strategy for Particle Physics
  - Main focus: Plans for post-LHC colliders

    The emerging consensus: Highest priority for an e^+e^- collider to explore the Higgs particle with highest precision





- Access to various Higgs properties via several production mechanisms
- Different energy to access different processes - from **250 GeV** to **1 TeV** and beyond

Summary

- The (electroweak) Standard Model combines QED and the weak interaction theory to describe electromagnetic and weak interactions - based on the Gauge Group SU(2) x U(1)
- It has been extremely successful in describing all observations to date
- Measurements at e^+e^- colliders (LEP, SLC) have been crucial to prove the validity of the Standard Model
- The detailed study of the Z^0 in particular has provided key information
  - 3 families
  - Vector and axial-vector couplings
  - ...
- All together: Allowed to make prediction for not yet observed particles: Top Quark, Higgs
  - All particles in the SM now observed, no obvious "crack" found to date

Next Lecture: 03.06., "Neutrinos: Freeze out, cosmological implications, structure formation", B. Majorovits

Lecture Overview

29.04.	Introduction & Recap: Particle Physics & Experiments	*F. Simon*
06.05.	Dark Matter axions and ALPs: Where do they come from?	*B. Majorovits*
13.05.	Axions and ALPs detection	*B. Majorovits*
20.05.	Dark Matter WIMPs - origin and searches	*B. Majorovits*
27.05.	Precision Tests of the Standard Model	*F. Simon*
03.06.	Neutrinos: Freeze out, cosmological implications, structure formation	*B. Majorovits*
	Pentecost	
17.06.	Natural Neutrino Sources: What can we learn from them?	*B. Majorovits*
24.06.	Accelerator Neutrinos	*F. Simon*
01.07.	Precision Experiments with low-energy accelerators	*F. Simon*
08.07.	Neutrinoless Double Beta Decay	*B. Majorovits*
15.07.	Gravitational Waves	*F. Simon*
22.07.	Physics with Flavor: Top and Bottom	*F. Simon*