Standard Model of Particle Physics

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Ulrich Uwer
Tutorials: *Kentaru Mawatari*

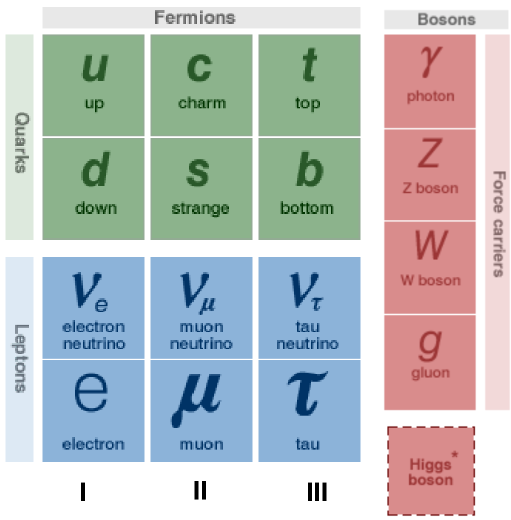
Monday	9:15 - 11:00	Phil 12 kHS
Wednesday	9:15 - 11:00	Phil 12 kHS
Tutorials	Tue or Thu, 14:15, Phil 12	

http://www.physi.uni-heidelberg.de/~uwer/lectures/StandardModel/

Contents

1) Introduction to quantum field theory
2) QED
(1–2: Mostly theory)
3) Electroweak Standard Model
4) Strong interaction: QCD
5) Physics beyond the Standard Model
(3–5: Theory + experimental tests)

Standard Model*) of Particle Physics



Based on the principle of local gauge invariance

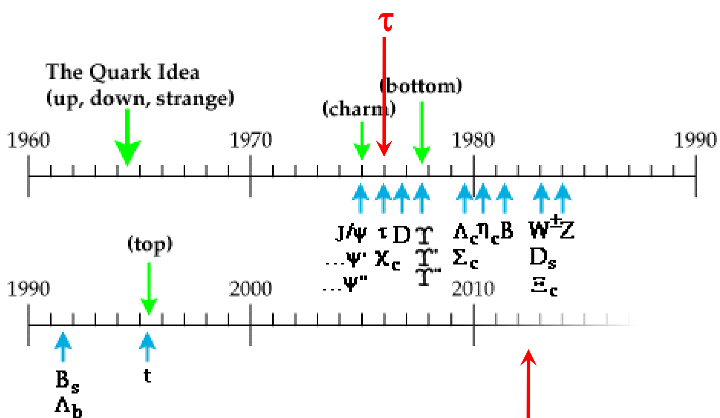
$SU_C(3)\times SU_L(2)\times U_Y(1)$

⇦ 12 gauge fields

⇦ Not yet directly observed

*) S. L. Glashow, A. Salam and S. Weinberg, 1967/8

Timeline of Particle Discoveries



Higgs?

Origin of symmetry breaking?

Experimental SM Tests (selection)

1967/8 Standard Model, S. L. Glashow, A. Salam and S. Weinberg

1971 Renormalizability of non-abelian gauge theories, G. `t Hooft and M. Veltman

1973 Asymptotic freedom of QCD, D. Gross, D. Politzer and F. Wilzcek;
Explaination of CP violation: 3 quark generation, M.Kobayashi, T.Maskawa

1973 Discovery of Neutral Currents: „Z-Boson exchange“ (Gargamelle, CERN)

1974 Discovery of the 4th quark (SLAC / BNL) $\rightarrow$ „November Revolution“

1975 Discovery of the Tau-Lepton

1979 Discovery of the gluon (DESY)

1983 Observation of W and Z bosons (UA1/2, CERN)

1989 Start of LEP I: Precision Z-physics measurement of radiative corrections

1995 Discovery of the Top-Quark at TEVATRON

1996 Start of LEP II: W Pair production and Higgs search (until Nov 2000)

2001 Start of TEVATRON Run II:
Precision measurement of Top-Quark and W-Boson properties, B physics

2009 Start of LHC: Discovery of the Higgs boson, New Physics?

Discovery of Tau-Lepton

Unexpected, although predicted by Kobayashi and Maskawa

MARK I (SLAC), 1975, M.Perl et al.

Nobel Prize 1995 for M.Perl

Evidence for Anomalous Lepton Production in e^+-e^- Annihilation*

M. L. Perl, G. S. Abrams, A. M. Boyarski, M. Breidenbach, D. D. Briggs, F. Bulos, W. Chinowsky, J. T. Dakin,† G. J. Feldman, C. E. Friedberg, D. Fryberger, G. Goldhaber, G. Hanson, F. B. Heile, B. Jean-Marie, J. A. Kadyk, R. R. Larsen, A. M. Litke, D. Lüke,‡ B. A. Lulu, V. Lüth, D. Lyon, C. C. Morehouse, J. M. Paterson, F. M. Pierre,§ T. P. Pun, P. A. Rapidis, B. Richter, B. Sadoulet, R. F. Schwitters, W. Tanenbaum, G. H. Trilling, F. Vannucci,‖ J. S. Whitaker, F. C. Winkelmann, and J. E. Wiss

Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720, and Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

(Received 18 August 1975)

We have found events of the form $e^+ + e^- \rightarrow e^\pm + \mu^\mp$ + missing energy, in which no other charged particles or photons are detected. Most of these events are detected at or above a center-of-mass energy of 4 GeV. The missing-energy and missing-momentum spectra require that at least two additional particles be produced in each event. We have no conventional explanation for these events.

We have found 64 events of the form

$$e^+ + e^- \rightarrow e^\pm + \mu^\mp + \geq 2 \text{ undetected particles} \quad (1)$$

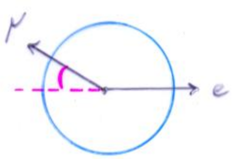
for which we have no conventional explanation. The undetected particles are charged particles or photons which escape the 2.6π sr solid angle of the detector, or particles very difficult to detect such as neutrons, K_L^0 mesons, or neutrinos. Most of these events are observed at center-of-mass energies at, or above, 4 GeV. These events were found using the Stanford Linear Accelerator Center–Lawrence Berkeley Laboratory (SLAC-

1489

TABLE I. Distribution of 513 two-prong events, obtained at $E_{c.m.} = 4.8$ GeV, which meet the criteria $|\vec{p}_1| > 0.65$ GeV/c, $|\vec{p}_2| > 0.65$ GeV/c, and $\theta_{copl} > 20°$. Events are classified according to the number N_γ of photons detected, the total charge, and the nature of the particles. All particles not identified as e or μ are called h for hadron.

Particles \ N_γ	0	1	>1	0	1	>1
	Total charge = 0			Total charge = ±2		
$e-e$	40	111	55	0	1	0
$e-\mu$	24	8	8	0	0	3
$\mu-\mu$	16	15	6	0	0	0
$e-h$	20	21	32	2	3	3
$\mu-h$	17	14	31	4	0	5
$h-h$	14	10	30	10	4	6

$e^+e^- \rightarrow$



Explanation:

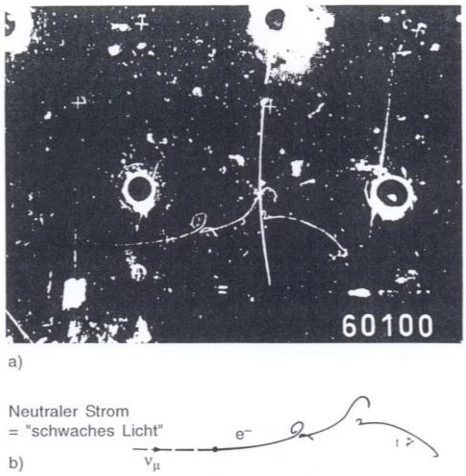
$$e^+e^- \rightarrow \tau^+ \tau^-$$

$$\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau$$

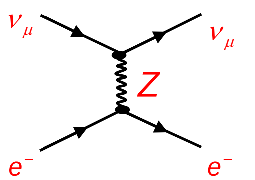
$$\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$$

Discovery of Neutral Currents (1973)

Gargamelle, CERN



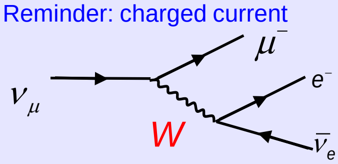
$$\nu_\mu + e^- \to \nu_\mu + e^-$$



$$R_\nu = \frac{\sigma_{NC}(\nu N \to \nu X)}{\sigma_{CC}(\nu N \to \mu X)} = 0.307 \pm 0.008$$

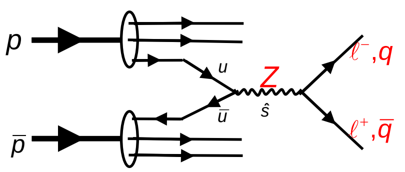
(1 out of 3 (!) recoded $\nu e \to \nu e$ events)

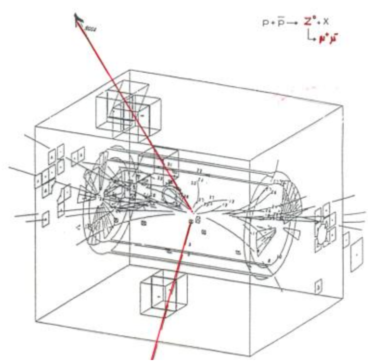
Reminder: charged current



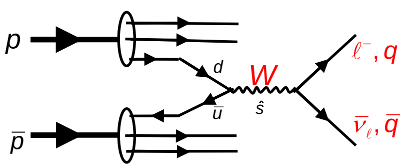
Discovery of Z and W Boson (1983)

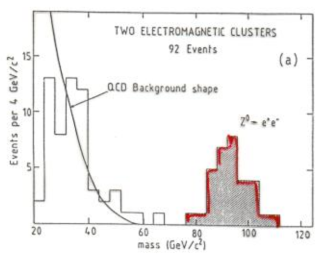
$$p\bar{p} \to Z \to f\bar{f} + X \quad (\sqrt{s} = 540\,\text{GeV})$$



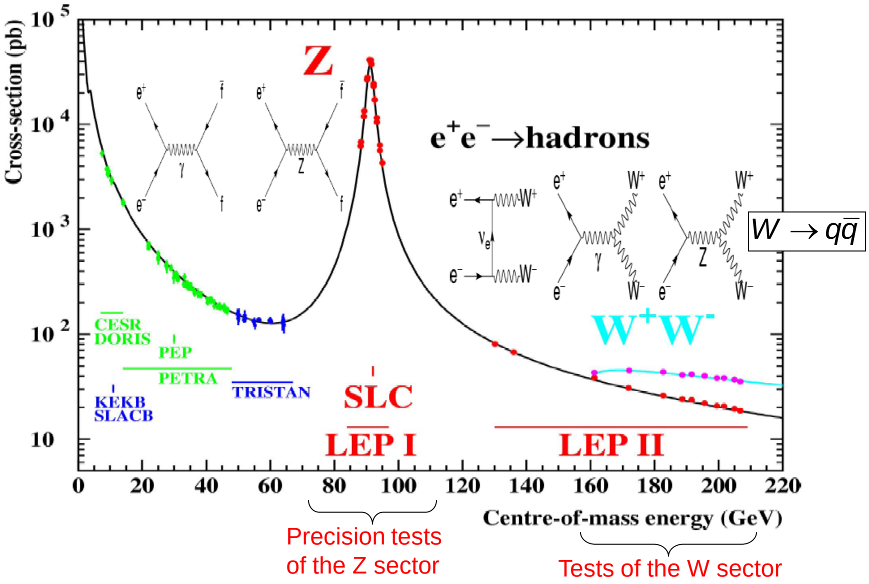


$$p\bar{p} \to W \to \ell\bar{\nu}_\ell + X$$





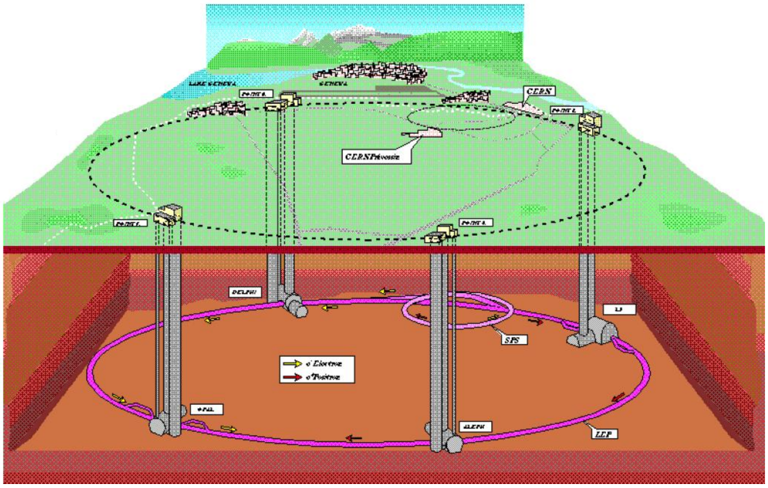
SM Test in e+e- Annihilation



Large Electron Positron Collider

Electron Positron Annihilation: LEP-I: $\sqrt{s} \approx 90$ GeV (1989-1995)

LEP-II: $\sqrt{s} = 160\ldots207$ GeV (1996-2000)



ALEPH

LEP I: Z-Boson Factory

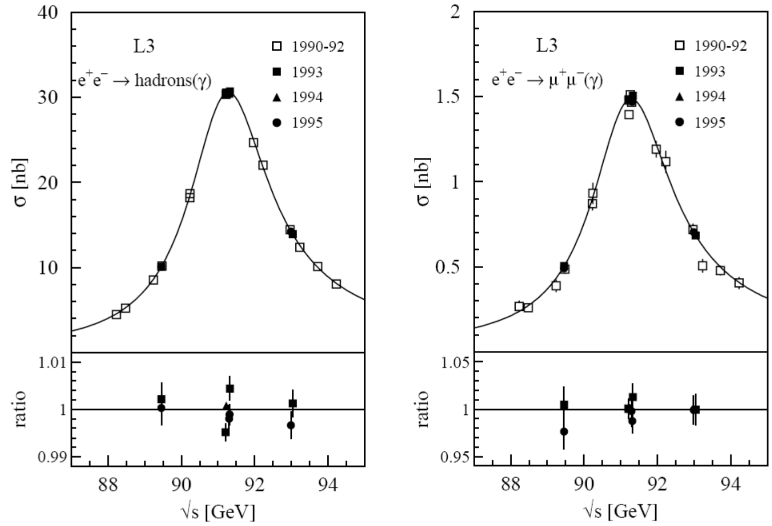
4 experiments: ALEPH, DELPHI, L3, OPAL

	Number of Events									
	$Z \to q\overline{q}$					$Z \to \ell^+\ell^-$				
Year	A	D	L	O	LEP	A	D	L	O	LEP
1990/91	433	357	416	454	1660	53	36	39	58	186
1992	633	697	678	733	2741	77	70	59	88	294
1993	630	682	646	649	2607	78	75	64	79	296
1994	1640	1310	1359	1601	5910	202	137	127	191	657
1995	735	659	526	659	2579	90	66	54	81	291
Total	4071	3705	3625	4096	15497	500	384	343	497	1724

Table 1.2: The $q\overline{q}$ and $\ell^+\ell^-$ event statistics, in units of 10^3, used for Z analyses by the experiments ALEPH (A), DELPHI (D), L3 (L) and OPAL (O).

Resonance Shape

$e^+e^- \to hadrons$ $\qquad$ $e^+e^- \to \mu^+\mu^-$



Resonance looks the same, independent of final state: Propagator the same

Z Boson Properties

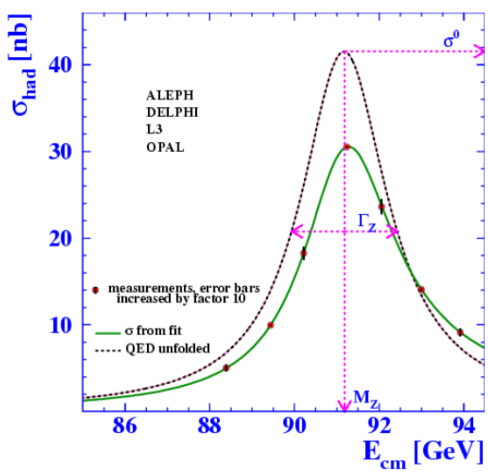
At the Z pole: $\sigma \approx \sigma_Z$

$$\sigma(s) = 12\pi \frac{\Gamma_e \Gamma_\mu}{M_Z^2} \cdot \frac{s}{(s - M_Z^2)^2 + M_Z^2 \Gamma_Z^2}$$

Peak: $\sigma_0 = \frac{12\pi}{M_Z^2} \frac{\Gamma_e \Gamma_\mu}{\Gamma_Z^2}$

- Resonance position → M_Z
- Height → $\Gamma_e \Gamma_\mu$
- Width → Γ_Z

$e^+e^- \to$ Hadrons



Z line shape parameters (LEP average)

M_Z = 91.1876 ± 0.0021 GeV ±23 ppm (*)

Γ_Z	= 2.4952 ± 0.0023 GeV	±0.09 %
Γ_{had}	= 1.7458 ± 0.0027 GeV	
Γ_e	= 0.08392 ± 0.00012 GeV	3 leptons are treated independently
Γ_μ	= 0.08399 ± 0.00018 GeV	
Γ_τ	= 0.08408 ± 0.00022 GeV	

test of lepton universality

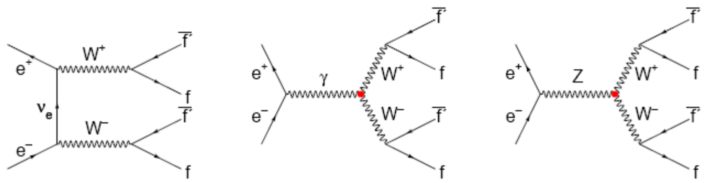
Γ_Z	= 2.4952 ± 0.0023 GeV	Assuming lepton universality: $\Gamma_e = \Gamma_\mu = \Gamma_\tau$
Γ_{had}	= 1.7444 ± 0.0022 GeV	
Γ_e	= 0.083985 ± 0.000086 GeV	

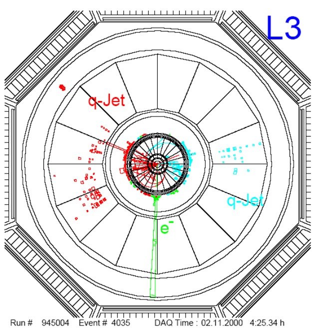
*) error of the LEP energy determination: ±1.7 MeV (19 ppm)

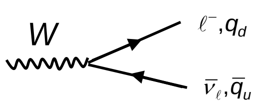
http://lepewwg.web.cern.ch/

LEP 200: W Pair Production

$$e^+e^- \to WW \to f\bar{f}f\bar{f}$$

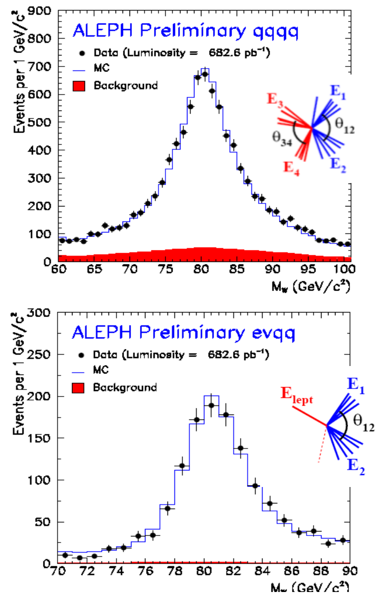


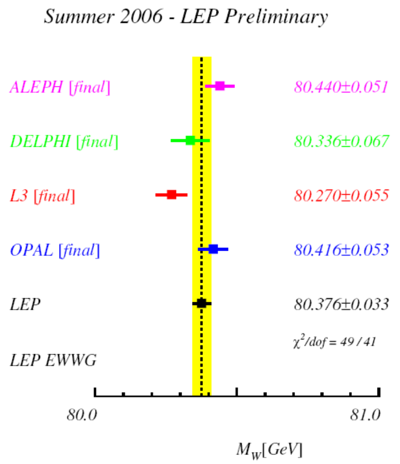




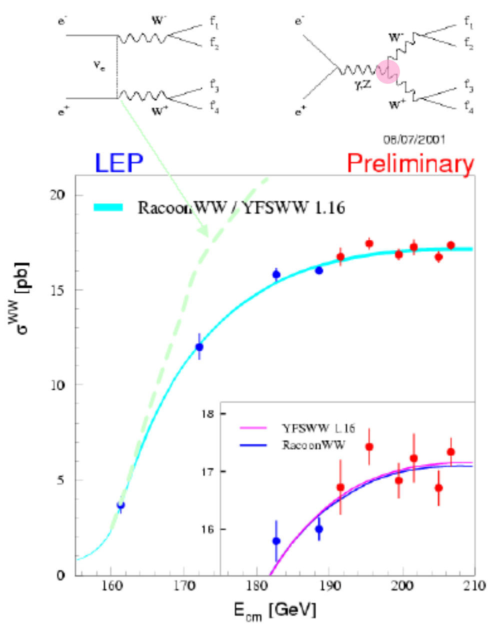
WW → { $qq\ell\nu$ 44%, $qqqq$ 45%, $\ell\nu\ell\nu$ 11% }

W Mass Measurement at LEP





Measurement of triple boson coupling



Data confirms the existence of the γ/ZWW triple gauge boson vertex

Sensitivity to Higher Order Corrections

Lowest order SM predictions:

$$\rho = \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = 1 \quad\Longrightarrow\quad \bar{\rho} = 1 + \Delta\rho$$

$$\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2} \quad\Longrightarrow\quad \sin^2\theta_{eff} = (1 + \Delta\kappa)\sin^2\theta_W$$

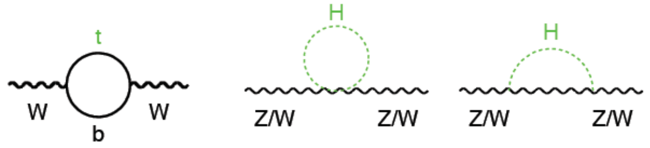
$$m_W^2 = \frac{\pi\alpha}{\sqrt{2}\sin^2\theta_W G_F} \quad\Longrightarrow\quad m_W^2 = \frac{\pi\alpha}{\sqrt{2}\sin^2\theta_W G_F}(1 + \Delta r)$$

$$\alpha(0) \quad\Longrightarrow\quad \alpha(m_Z^2) = \frac{\alpha(0)}{1 - \Delta\alpha}$$

Including radiative corrections

with : $\Delta\alpha = \Delta\alpha_{lept} + \Delta\alpha_{top} + \Delta\alpha_{had}^{(5)}$

$$\Delta\rho, \Delta\kappa, \Delta r = f\left(m_t^2, \log(m_H), \ldots\right)$$



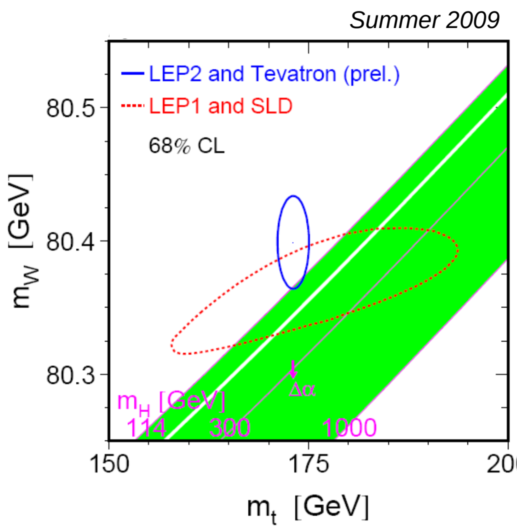
Status of Theoretical Calculation

S.Heinemeyer, Summer 2007

- Δr: $\mathcal{O}\left(\alpha^2\right)$: full electroweak two-loop results
  [A. Freitas, W. Hollik, W. Walter, G. Weiglein '03]
  [M. Awramik, M. Czakon '04] [Onishenko, Veretin '04]
- $\Delta\rho$: $\mathcal{O}\left(\alpha\alpha_s^2\right)$: leading three-loop contributions
  [K. Chetyrkin, J Kühn, M. Steinhauser '95] [L. Avdeev et al. '95]
- $\Delta\rho$: $\mathcal{O}\left(\alpha^2\alpha_s\right)$, $\mathcal{O}\left(\alpha^3\right)$: limit of $M_H \to 0$
  [J. Van der Bij, K. Chetyrkin, M. Faisst, G. Jikia, T. Seidensticker '01]
- $\Delta\rho$: $\mathcal{O}\left(\alpha^2\alpha_s\right)$, $\mathcal{O}\left(\alpha^3\right)$: limits with $M_H \neq 0$
  [M. Faisst, J. Kühn, T. Seidensticker, O. Veretin '03]
- $\Delta\rho$: $\mathcal{O}\left(\alpha\alpha_s^3\right)$: various four-loop contributions
  [Y. Schröder, M. Steinhauser '05]
  [K. Chetyrkin, M. Faisst, J. Kühn, P. Maierhoefer, C. Sturm '06]
  [R. Boughezal, M. Czakon '06]

➡ Calculation of M_W from muon decay (G_F): $\delta M_W \approx 4$MeV

W Mass: Prediction versus Measurement



Top Mass from Radiative Corrections

$$\Delta r(m_t, M_H) = -\frac{3\alpha\cos^2\theta_w}{16\pi\sin^4\theta_w}\frac{m_t^2}{M_W^2} - \frac{11\alpha}{48\pi\sin^2\theta_w}\ln\frac{M_H^2}{M_W^2} + \dots$$

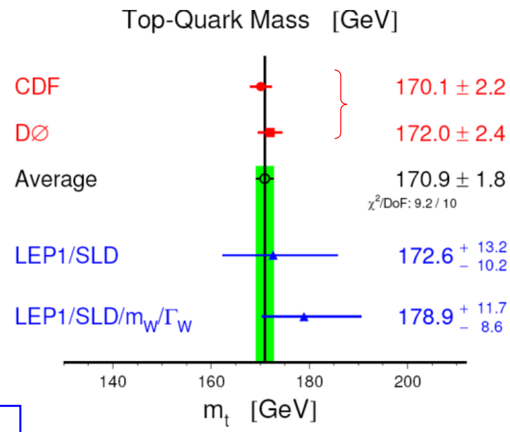
The measurement of the radiative corrections:

$$\sin^2\theta_{eff} \equiv \frac{1}{4}(1-\bar{g}_V/\bar{g}_A)$$

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

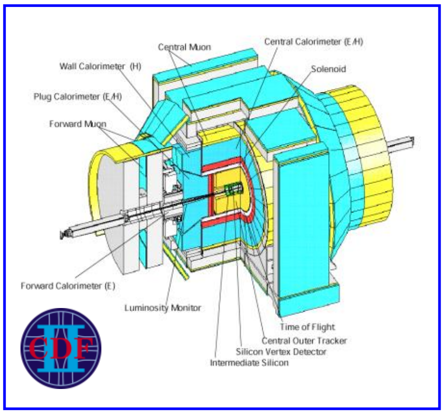
Allows the indirect determination of the unknown parameters m_t and M_H.

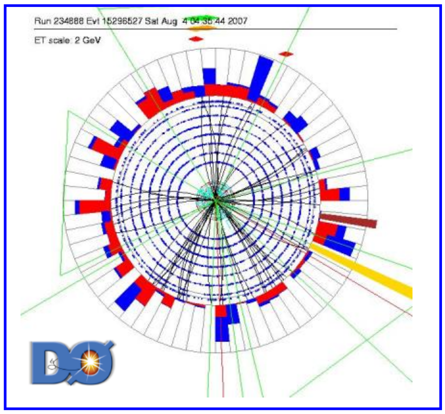
Prediction of m_t by LEP before the discovery of the top at TEVATRON.



TEVATRON

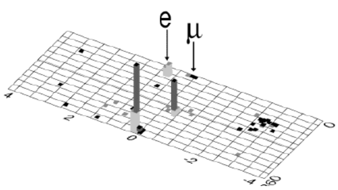
$p\bar{p}$ **Collider with $\sqrt{s}$=1.96 TeV**

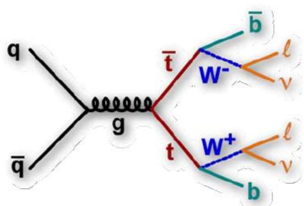


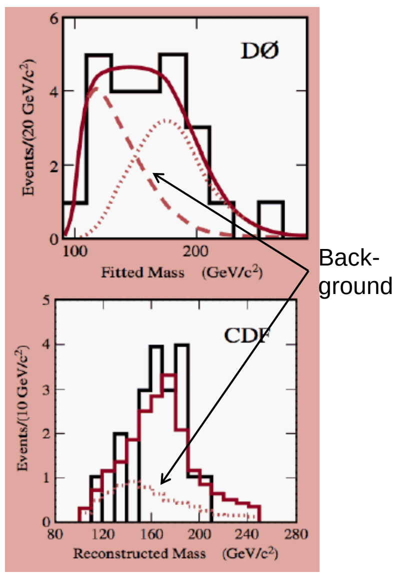


Top Quark Discovery at TEVATRON

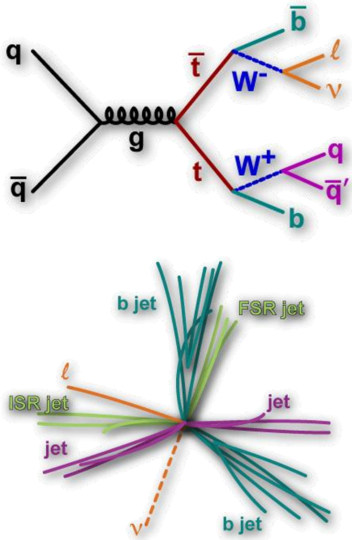
Tevatron Run 1
1994-5

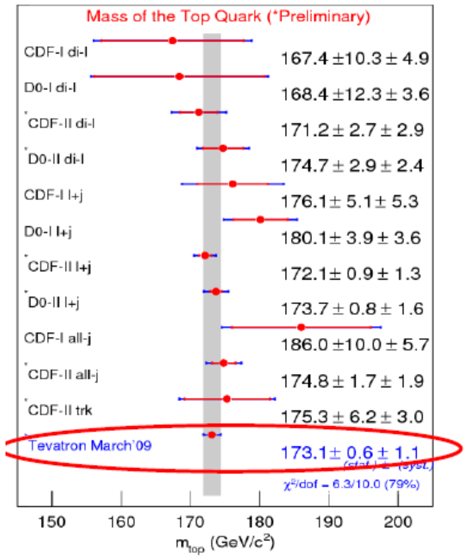






Precision Top Mass Measurement





Higgs Mass from Radiative Corrections

… using all available electro-weak data

$$\Delta r(m_t, M_H) = -\frac{3\alpha\cos^2\theta_w}{16\pi\sin^4\theta_w}\frac{m_t^2}{M_W^2} - \frac{11\alpha}{48\pi\sin^2\theta_w}\ln\frac{M_H^2}{M_W^2} + \dots$$

Fits to electro-weak data:

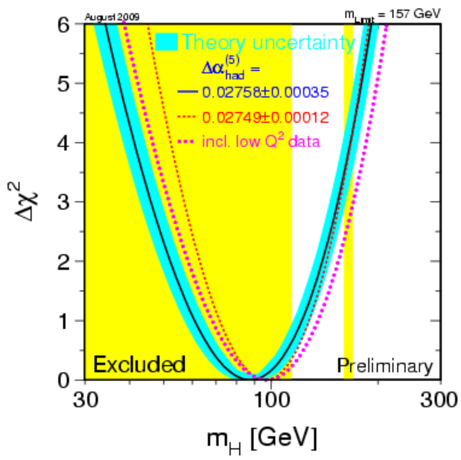
$m_H = 87\,^{+35}_{-26}$ GeV

$m_H < 157$ GeV (95% CL)

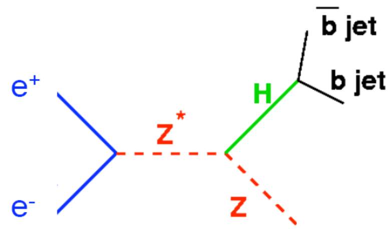
Assumption for fit:

- SM including Higgs
- No confirmation of Higgs mechanism

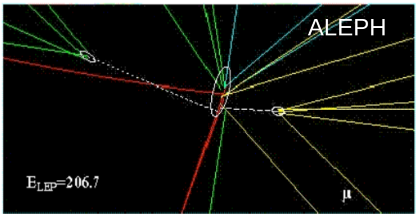
Higgs seems to be light!

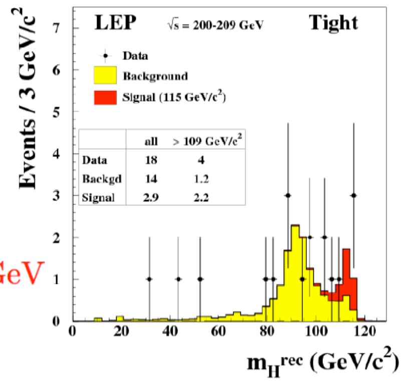


Direct Higgs Searches at LEP



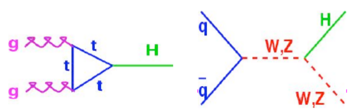
$$\sqrt{s} - m_Z = 206.6 - 91.2 = 115.4 \text{ GeV}$$

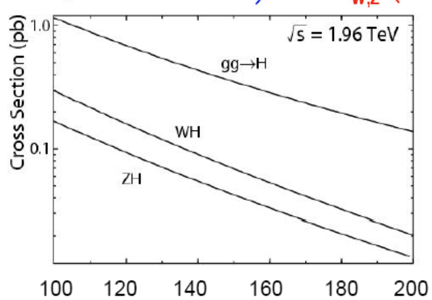




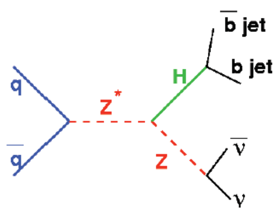
Search for the Standard Model Higgs boson at LEP
Phys. Lett. B565 (2003) 61.

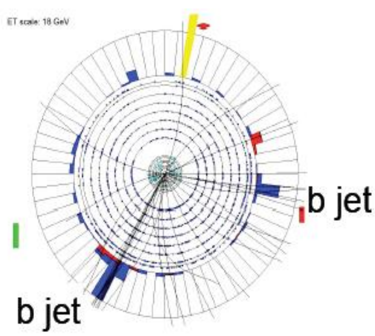
Higgs Search at TEVATRON





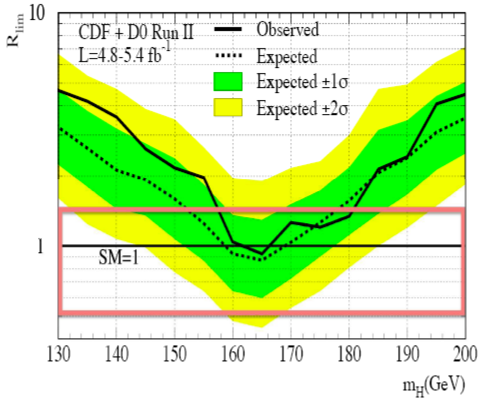
~1 Higgs event every 10^{12} events





Higgs Search at TEVATRON

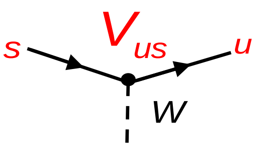
Moriond 2010



More data … but weaker limits

Quark Mixing and CP Violation

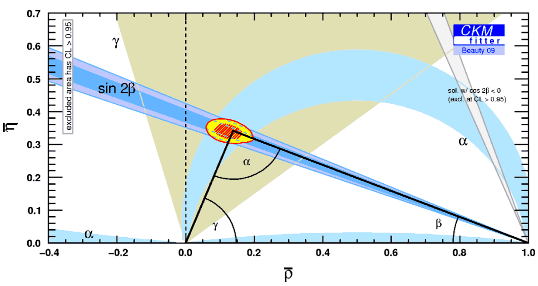
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



Unitarity $\Rightarrow$ $V_{ud}V^*_{ub} + V_{cd}V^*_{cb} + V_{td}V^*_{tb} = 0$

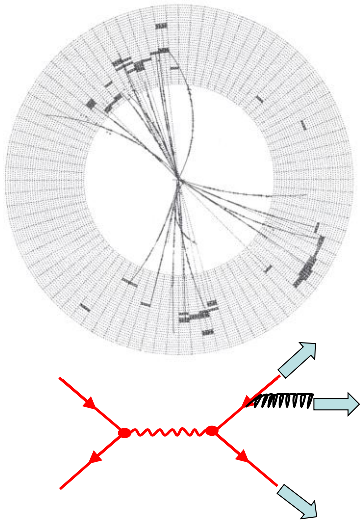
CKM mechanism explains CP violation and predicts large effect in B decays

Angles measured from CP violation in B decays:
CKM mechanism confirmed !

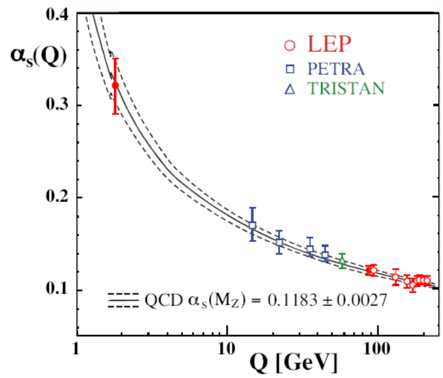


Strong Interaction

Discovery of the gluon (1979)

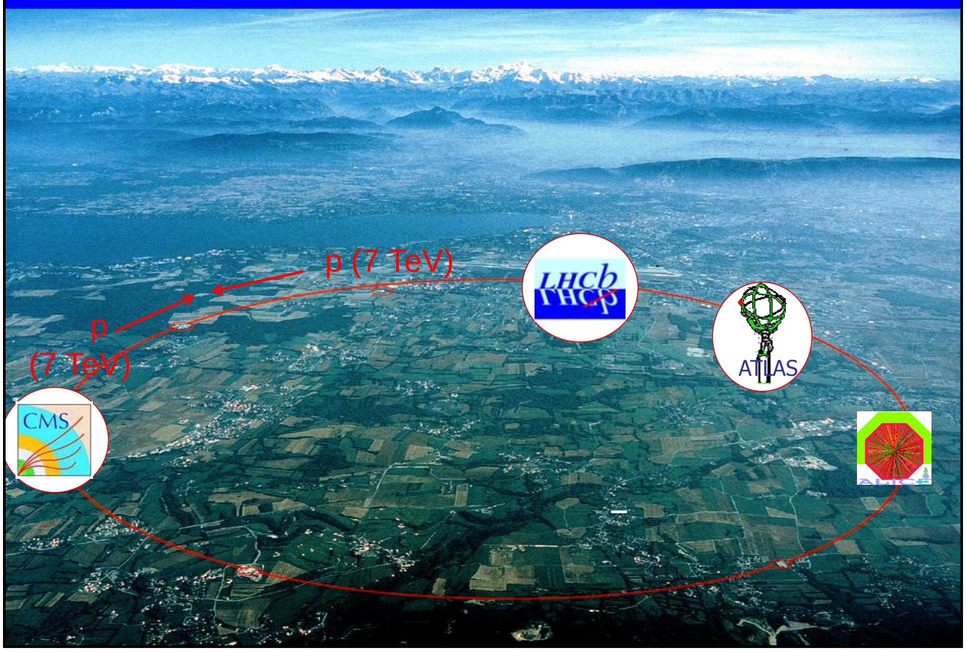


Running of α_s

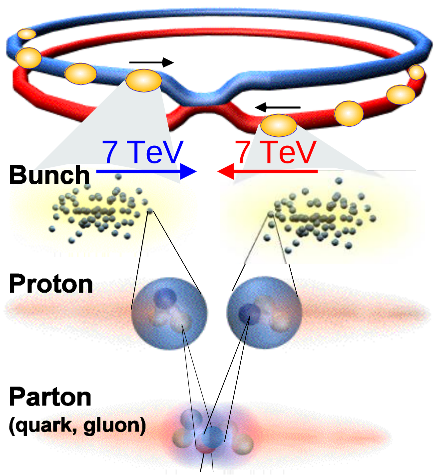


… and asymptotic freedom

Large Hadron Collider



Large Hadron Collider



Design:

Proton – Proton Pakete:

2835 x 2835

10^{11} Protonen / Paket

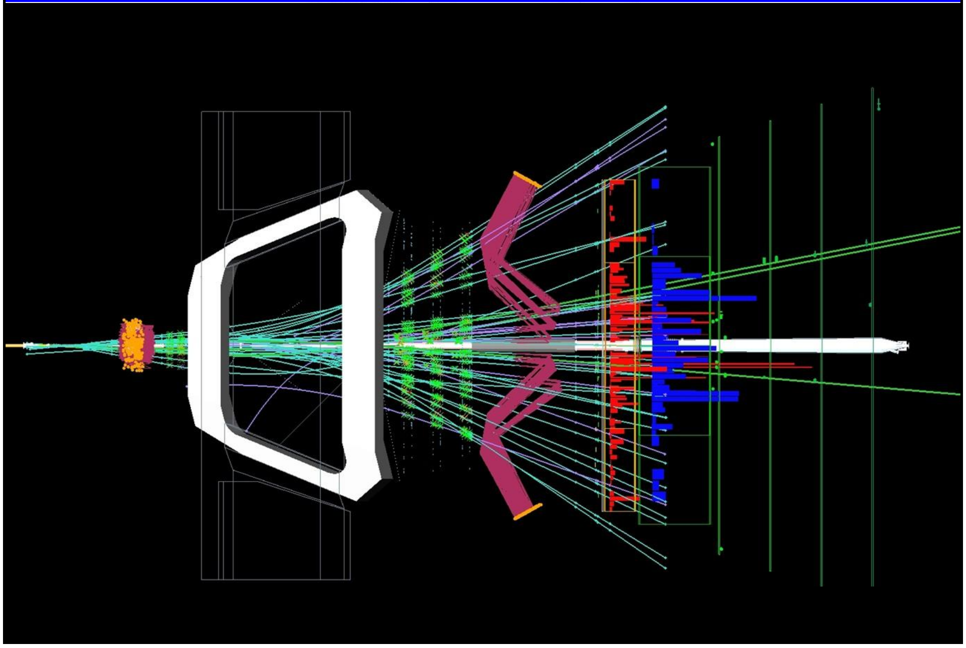
Crossing-Rate: 40 MHz

Kollisionen: 10^8 bis 10^9 Hz

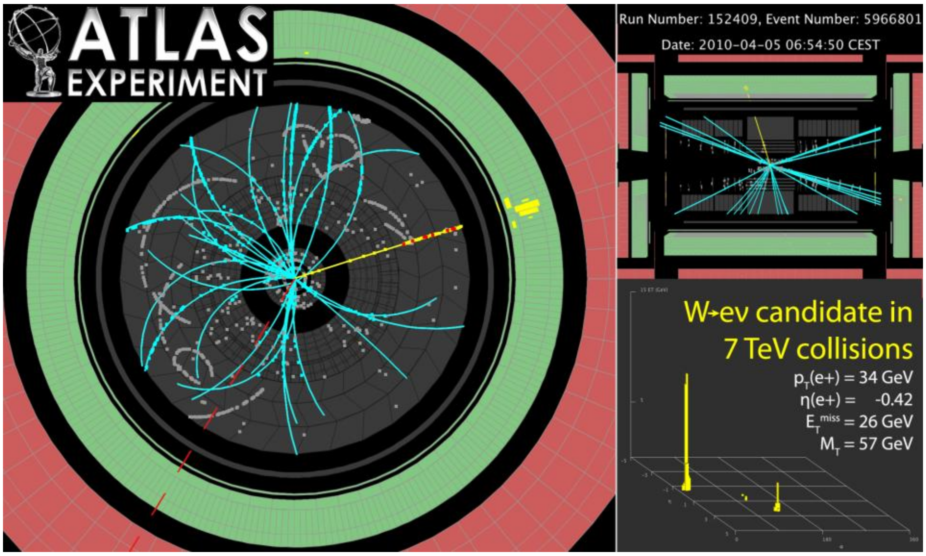
33

Large Hadron Collider

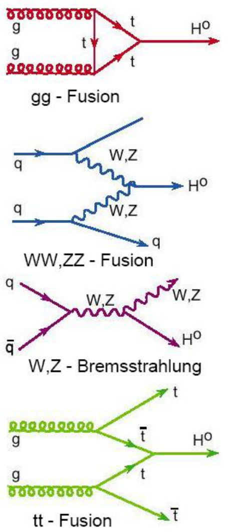
First 7 TeV pp event in LHCb



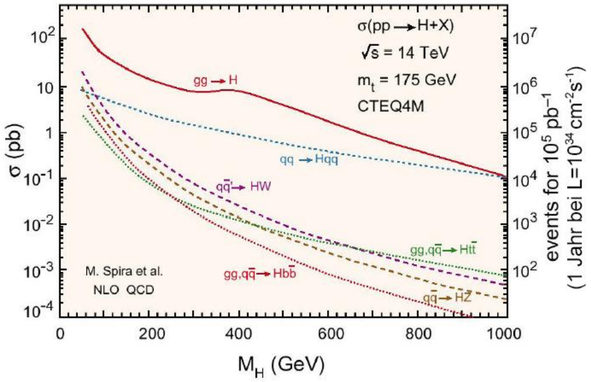
First ATLAS W→eν



Higgs Physics at LHC

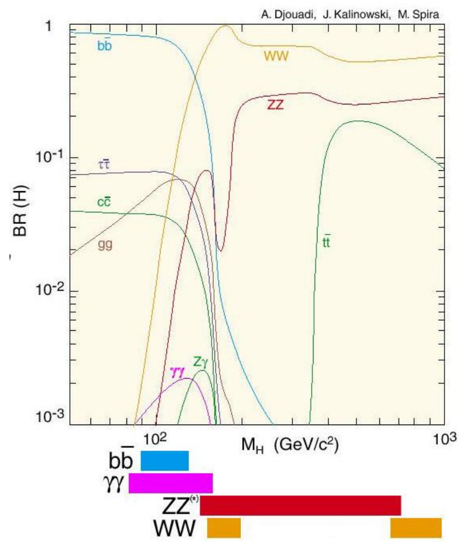


- $p + p \rightarrow H + X$

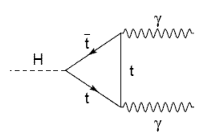


2 orders of magnitude larger than at TEVATRON.

Relevant Higgs Decay Channels

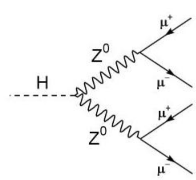


- $m_H < 150$ GeV:

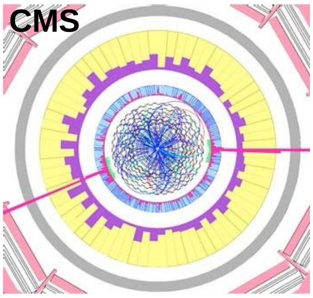


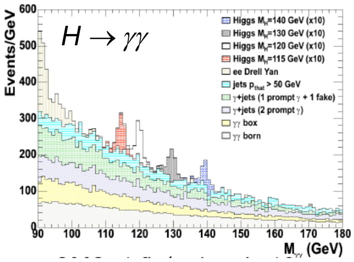
- $150 \text{ GeV} < m_H < 1 \text{ TeV}$

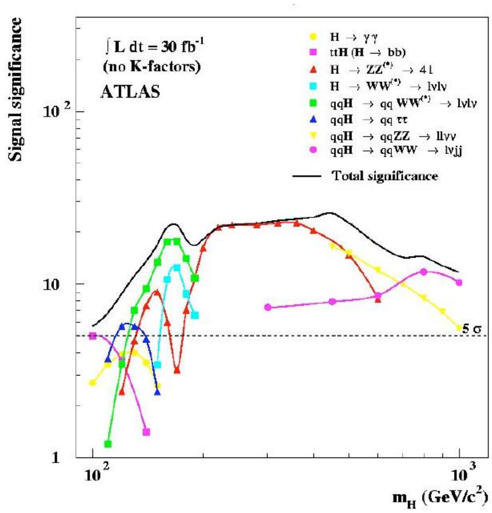
$$H \rightarrow ZZ^{(*)}$$
$$H \rightarrow W^+W^-$$



LHC Sensitivity







Shortcomings of the Standard Model

Empirical problems

- Neutrino masses and mixing
- Baryogenesis (matter anti-matter symmetry)
- Dark matter

Conceptual problems

- Quadratic divergences in radiative Higgs mass corrections: „fine tuning“ problem
- Origin of the three generations
- Explanation of masses
- Origin of gauge symmetries / quantum numbers
- Unification with gravity