Standard Model (SM) of Particle Physics

- Overview: components of the SM
- Giving Mass to the Intermediate Vector Bosons
- Key Experiments confronting the SM
  - Neutral currents
  - W and Z Boson discovery
  - Total number of neutrinos
  - Higgs search
Electroweak unification and mixing

• Glashow (1961): aim to unify electromagnetic and weak interactions in a single theoretical description, building on work by Schwinger

• Several difficulties had to be overcome...
  - Enormous difference in strength of em and weak interactions
    - Glashow (and others) recognized that this could be solved, if the weak interactions were mediated by extremely massive particle
    - Glashow did not know how to introduce a heavy mediator:
      • Quoting Glashow: ‘Is is a stumbling block, we must overlook’
  - Difference in electromagnetic (only vector coupling $\gamma^\mu$) and weak vertex factors $\gamma^\mu (1 - \gamma^5)$
    - This problem was solved by spinor treatment, as discussed in previous lecture

• And one bold assertion to be stipulated…
Electroweak Mixing

• In the Glashow-Weinberg-Salam (GWS) theory:
  - The three weak isospin currents couple to isotriplet of vector bosons $W$ with strength $g_W$
  - Weak hypercharge current to isosinglet vector boson $B$ with $g'/2$
• These four particles correspond to the four mediators (but with a very clever twist) : $W^+$, $W^-$, $Z^0$, $\gamma$
• In Glashow’s theory the neutral states ($W^3$, $B$) mix to produce one massless linear combination (the photon) and an orthogonal, massive combination, introducing a new parameter, $\theta_W$

\[
A_\mu = B_\mu \cos \theta_W + W_\mu^3 \sin \theta_W
\]
\[
Z_\mu = - B_\mu \sin \theta_W + W_\mu^3 \cos \theta_W
\]
• $\theta_W$ is the ‘Weak mixing angle’, also ‘Weinberg’ angle; is a parameter in SM, to be determined experimentally (neutrino scattering)
• $\sin^2 \theta_W = 0.231$
W and Z masses

• In electroweak theory the coupling constants are related
  \[ g_e = g_w \sin \theta_W \] ; \[ \sin \theta_W \] and \[ g_e = \sqrt{4\pi \alpha_{\text{em}}} \] \( \rightarrow \) \( g_w \)

• The masses of W and Z are related and can be derived from experimental observations
  \[ M_W = M_Z \cos \theta_W \]
  - Ex: from muon life time \( \rightarrow \)
  \[ G_F / (\hbar c)^3 = \frac{\sqrt{2}}{8} \left( \frac{g_W}{M_W c^2} \right)^2 \]
  \[ = 1.166 \times 10^{-5} \text{ GeV}^{-2} \]

• \( M_W \approx 75 \text{ GeV}/c^2 \); \( M_Z \approx 86 \text{ GeV}/c^2 \)
Example: Muon decay

- Muon lifetime $\tau = 1/\Gamma$ expressed in terms of the ‘Fermi coupling constant’

$$G_F \equiv \sqrt{2} \left( \frac{g_W}{M_W c^2} \right)^2 (\hbar c)^3 \quad \tau = \frac{192 \pi^3 \hbar^7}{G_F^2 m_\mu c^4}$$

- With the observed muon lifetime and mass, $M_W$, one obtains for $g_W = 0.653$ and for the ‘weak fine structure constant’ $\alpha_W = g_W^2/4\pi = 1/29.5$

- Surprise: number is larger than the electromagnetic fine structure constant $\alpha_{em} \sim 1/137$

- Explanation: weak interactions are feeble not because the intrinsic coupling is small (it is not!), but because of the massive mediators and usually observing effects at energies $<< M_W$ where the denominator $|q^2 - M^2 c^2|$ in the propagator is large!
One further big issue: Giving mass to the gauge bosons

- Principle of local gauge invariance worked beautifully for QED and QCD;
  - Provided a procedure for calculating the couplings
  - Provided renormalizable theories
- Note: consequence of local gauge invariance are massless gauge bosons (photon, gluon)
- Manifestly not true for the electroweak interactions with massive W and Z-bosons
- Can one derive a theory with local gauge invariance (to obtain a renormalizable theory!) and massive gauge bosons?
- YES! -> spontaneous symmetry breaking and ‘Higgs mechanism’
  - A very subtle story!
  - I will explain in steps
Lagrangians with mass terms

- Consider the following Lagrangian

\[ \mathcal{L} = \frac{1}{2} (\partial_\mu \Phi)(\partial^\mu \Phi) + e^{-(\alpha \Phi)^2} \]

with \( \Phi \) being a scalar field and \( \alpha \) a real constant

- Although not apparent, this Lagrangian contains a mass term; expanding the exponential

\[ \mathcal{L} = \frac{1}{2} (\partial_\mu \Phi)(\partial^\mu \Phi) + 1 - \alpha^2 \Phi^2 + \frac{1}{2} \alpha^4 \Phi^4 - \ldots \]

- 2\textsuperscript{nd} Term has form of mass term in Klein-Gordon Lagrangian with \( \alpha^2 = \frac{\gamma}{2} \left( \frac{mc}{\hbar} \right)^2 \); higher-order terms represent more complex couplings

- Just an example to show that a mass term can be ‘disguised’ in a Lagrangian-> to expose it, one expands the Lagrangian

- New level of subtlety: consider

\[ \mathcal{L} = \frac{1}{2} (\partial_\mu \Phi)(\partial^\mu \Phi) + \frac{1}{2} \mu^2 \Phi^2 - \frac{1}{4} \lambda^2 \Phi^4 \]

with \( \mu \) and \( \lambda \) being real constant

- 2\textsuperscript{nd} term looks like a mass term ( 3\textsuperscript{rd} term like an interaction), BUT

- With wrong sign (+ instead of -); would correspond to imaginary mass! Nonsense
Lagrangians with non-zero ground states

- So far we have dealt with Lagrangians, which have the ground state – i.e. the field configuration with minimum energy, the ‘vacuum’- with $\Phi=0$; in calculations a la Feynman one effectively follows a perturbation procedure, where the fields are considered to fluctuate about the ground state
- However, the last Lagrangian considered has a ground state not equal to 0
- The potential term $U(\Phi) = -\frac{1}{2} \mu^2 \Phi^2 + \frac{1}{4} \lambda^2 \Phi^4$ has its minimum at $\Phi = \pm \mu/\lambda$
- Introducing a new field variable $\eta \equiv \Phi \pm \frac{\mu}{\lambda}$
- Which transforms the Lagrangian to

$$L = \frac{1}{2} (\partial_\mu \eta) (\partial^\mu \eta) - \mu^2 \eta^2 \pm \mu \lambda \eta^3 - \frac{1}{4} \lambda^2 \eta^4 + \frac{1}{4} (\mu^2 / \lambda^2)$$
Lagrangians with non-zero ground states and mass terms

• Rewritten in the new field variable $\eta$ the Lagrangian now exhibits a physical mass term with a particle mass $m = \sqrt{2\mu \hbar / c}$

• Nota bene: both Lagrangians describe exactly the same physical system; however the first form is not suitable to the Feynman calculus (perturbation expansion about $\Phi=0$, which is an unstable point)

• The 2$^{nd}$ form exhibits explicitly the ground state and allows to identify the mass term

• Next subtlety: ‘Spontaneous Symmetry Breaking’
  - 1$^{st}$ form of Lagrangian is even in $\Phi$; is invariant under $\Phi \rightarrow - \Phi$
  - 2$^{nd}$ form is not even in $\eta$; the symmetry has been ‘broken’
Spontaneous Symmetry Breaking

- **Symmetry Breaking:**
  - The chosen ground state (‘vacuum’) does not exhibit the symmetry of the Lagrangian (however: the collection of all possible ground states does show, of course, the symmetry; but for physical calculation one has to make a choice)
  - Classic analogue: Newton’s law of gravitation is spherically symmetric, but a specific planet orbit is elliptical

- **‘Spontaneous’**
  - Symmetry violated *without* intervention of an ‘external agent’
  - The intrinsic symmetry of the system is ‘concealed’ by the arbitrary evolution into a particular (asymmetric) ground state
Spontaneous Symmetry Breaking: examples in classical physics

• Buckling of a pipe
  - Applying pressure to the ends: pipe will buckle into curved position (because is state of lower energy), but with arbitrary orientation -> original spherical symmetry is broken

• Ferromagnet:
  - In ground state all spins are aligned
  - Direction of alignment is accidental, although the theory is symmetrical

• Round (spherically symmetric!) Dinner Table (A. Salam; Pakistani physicist, one of the fathers of the electroweak theory, Nobel prize 1976)
  - Bread roll symmetrically arranged between dinner plates
  - First to chose the bread roll breaks right-left symmetry
Higgs mechanism: more subtleties

• Generalizing the Lagrangian from discrete to spontaneously broken continuous symmetry
  - Involves two fields, $\Phi_1, \Phi_2$; $\Phi = \Phi_1 + i\Phi_2$
• With this notation one can construct a Lagrangian of the form
  $$\mathcal{L} = \frac{1}{2} (\partial_{\mu} \Phi)^* (\partial^{\mu} \Phi) + \mu^2 (\Phi^* \Phi) - \frac{1}{4} \lambda^2 (\Phi^* \Phi)^2$$
• Lagrangian can be made invariant under local gauge transformation
  $$\Phi \rightarrow e^{i\theta(x)} \Phi$$, defining two fields $\eta \equiv \Phi_1 - \mu / \lambda$, $\xi \equiv \Phi_2$
  resulting in a Lagrangian which contains terms representing
  - a scalar particle ($\eta$) with mass $m = \sqrt{2\mu \hbar / c}$ and a massless boson
    (‘Goldstone boson’) $\xi$
  - a free gauge field $A^{\mu}$ with MAGIC !-
    mass $m_A = 2\sqrt{\pi} (q\mu / \lambda c^2)$
  - various couplings of $\xi$, $\eta$, $A^{\mu}$
Higgs mechanism

- **Origin of the mass of $A^\mu$**
  - Lagrangian contains a term of $\Phi^* \Phi A^\mu A^\mu$
  - Because of spontaneous symmetry breaking, $\Phi_1 \rightarrow \mu / \lambda$
    generating the mass term (see original example)

- **Remaining issues**
  - What to do with the massless Goldstone boson $\xi$ and a suspicious looking quantity in the Lagrangian $(\partial_{\mu} \xi) A^\mu$, which looks like a non-physical interaction between two different fields $\xi$ and $A^\mu$
  - Both issues involve the field $\xi = \Phi_2$ and can be solved due to local gauge invariance with the transformation $\Phi \rightarrow \Phi' = (\cos \theta + i \sin \theta) (\Phi_1 + i \Phi_2)$; with $\theta^{-1} (\Phi_2 / \Phi_2)$ will make $\Phi'$ real

- **This particular choice of gauge removes $\xi$ and the offending part of the Lagrangian**
Higgs Mechanism

• Note that this particular choice of gauge has not changed the Lagrangian -> it still describes the same system
• Convenient way of thinking about the effect
  - Massless vector field $A^\mu$ carries two degrees of freedom (transverse polarization; e.g. the photon)
  - When $A^\mu$ acquires mass, it acquires a third degree of freedom (longitudinal polarization), coming from the Goldstone boson, which disappeared from the theory
• According to the Standard Model the Higgs Mechanism gives the mass to the Weak interaction bosons ($W, Z$)
Higgs mechanism: summary

- Achieving a Lagrangian which exhibits local gauge invariance (needed for renormalization) and has massive gauge particles:
  - Needs a Lagrangian which exhibits spontaneously broken continuous symmetry
  - Need to impose local gauge invariance
  - Need to apply a judicious choice of gauge to transform away the unwanted parts of the Lagrangian (still describing the same physical system!)
- Final result: the ‘Higgs mechanism’ (also proposed by Englert, Brout and Guralnik, Hagen, Kibble).
  - A single massive scalar $\eta$: the ‘Higgs’ particle and a massive gauge field $A^{\mu}$
- Is this Nature’s choice? Only Experiment can tell -> we will probably know in about three years
Higgs Cartoon
(inspired by Prof. Miller / University College London)
Key Experiments confronting and …confirming Standard Model (SM)

• **Neutral currents:**
  - Need for a neutral vector boson: a key ingredient of the electroweak theory

• **Discovery of the Intermediate Vector Bosons (IVB):**
  - Existence required by SM
  - Measured mass confirms the prediction of the SM

• **LEP tests of the SM:**
  - High-precision confirmation of SM predictions establish SM as the description of our world up to the ~ 100 GeV energy scale
  - Direct measurement of the total number of neutrinos
  - Severe constraints on the ONE missing ingredient: Higgs particle
  - Precision tests clearly establish limits of SM -> justification for LHC

• **LHC: search for Higgs (or alternatives)**
• **LHC: search for Physics Beyond SM (BSM)**
Discovery of Weak Neutral Current Interaction (CERN 1973)

Muon antineutrino – electron scattering producing energetic electron and antineutrino

First event: beginning of several months of intensive further searches

A major additional contribution to the emergent idea of electroweak theory

\[ \nu_\mu + e^- \rightarrow \nu_\mu + e^- \]
Discovery of the IVBs

• **Background story**
  - Discovery of Neutral Currents was major boost to concept of SM
  - The know weak mixing angle $\sin \theta_w$ from neutrino scattering experiments allowed to estimate the mass of the IVBs ->
    - Mass $\sim 90$ GeV/c$^2$
  - Within frame of SM cross section for production as a function of collision energy can be calculated -> if produced in a proton-proton(antiproton) collision: needs collision energies of $\sim 1000$ GeV

• **Catalyst for discovery:**
  - one brilliant experimental particle physicist: Carlo Rubbia
  - one brilliant accelerator physicist: Simon van der Meer
Discovery of the IVBs

- Brilliant idea of Rubbia and colleagues (1976):
  - The CERN Super Proton Synchrotron, an accelerator for protons to energies up to 450 GeV could be converted into a proton-antiproton collider with CMS energy $\sqrt{s} = 900$ GeV, provided

- Brilliant idea of van der Meer:
  - A sufficiently adequate collision rate (‘luminosity’) requires focusing of the produced antiproton beam to calculably small transverse geometrical cross section -> can be achieved by
  - ‘Cooling’ of the antiprotons
    - Van der Meer had shown in 1972 that particles can be cooled by applying electric correction pulses to damp transverse velocity components of particle: ‘stochastic cooling’
    - Novosibirsk: cooling with cold electrons through electron-particle scattering (1974-75)
Experimental Strategy

- Experimental signatures were known:
  - Need to identify and momentum analyze electrons
    - Magnet and charged particle detector (drift chamber)
    - Electromagnetic calorimeter to discriminate between electron and charged hadrons
  - Need to reconstruct the neutrino momentum with the ‘missing energy’ technique
    - Requires a detector which measure all charged and neutral particles -> 4π calorimeter
  - Need to suppress background and select (‘trigger’) on the very rare W and Z candidates
  - Total interaction cross section : 4* 10^{-26} cm^2
  - Production cross section for W : \sigma (W-> e \nu_e) \sim 10^{-33}

- Need cross check: two independent experiments (UA1: Rubbia; UA2: Darriulat) were developed
This is "Liouvillian cooling", taking advantage of the fluctuations inherent in a finite number of particles.

At each passage, the "kicker" corrects the average value measured by the "pick-up" to zero.

Needs a continuous "randomizer" of the sample, naturally provided by the momentum spread (mixing) i.e. memory must be short!
Accumulating antiprotons

The CERN-AA accumulator

- 3.5 MeV/c
- 161.08 m at injection (CPS/4)
- 155.84 m at stack centre
- \( \theta_x = 2.284 \quad \theta_y = 2.276 \)
  at stack centre
- \( \pm 30 \times 10^{-3} \)
- 10^{-10} Torr
- Tungsten rod 110 mm long, 3 mm \( \varnothing \)
  followed by magnetic horn
- 1 \times 10^{13} every 2.4 sec
- 2.5 \times 10^{7} in AA acceptance
- 100 hor., 100 vert. mm mrad
  at \( \Delta p/p = 7.5 \times 10^{-3} \)
- 7.6 hor., 4.5 vert. mm rad
  at \( \Delta p/p = 1.1 \times 10^{-3} \)
- 50,000 pulses, 33 hrs
- 30,000 pulses, 20 hrs

- 2 years after approval, the first antiprotons were accumulated in summer 1980.
Race towards a ‘Predicted Nobel Prize’
Production and decay of W and Z

- production of $W^+$
  
  \[ u, \bar{d} \]

- decay
  
  \[ q = u, d, s, c \]
  
  \[ l = e, \mu, \tau \]
  
  \[ \nu = \nu_e, \nu_\mu, \nu_\tau \]

- production of $Z$
  
  \[ u, \bar{u} \text{ or } d\bar{d} \]

- decay
  
  \[ q = u, d, s, c, b \]
  
  \[ l = e, \mu, \tau \]
  
  \[ \nu = \nu_e, \nu_\mu, \nu_\tau \]
Measurement of $M_W$ mass

$W$ production

$\sigma\ (W \rightarrow e \nu_e) \sim 10^{-33} = 1 \text{ nb}$

$\sigma_{\text{total}} \sim 40 \text{ mb} = 4.10^7 \text{ nb}$

Transverse momentum

$p_T = p \sin \theta$

$W$ is produced at rest

$p_T$ of electron $\sim M_W/2 \sin \theta$

$p_{\text{Tmiss}} = \sum_i p_T$

$m_T$ distribution

$m_T^2 = 2 p_T^e p_T^\nu (1 - \cos \phi_{e\nu})$

measurement of $p_\nu$ needs hermetic detector
Initial discovery of W signal

Neutrino detection by missing energy balance
Initial discovery of Z signal

Lego plots of Z events
W Event in UA1
First Z event in UA1

Camac Date 30–04–83
Camac Time 18:53

First Z event in UA1
Announcing to the world the discovery

First observation of W (1983)

52 authors;
HEPHY was a collaborating institute
Stockholm 1984

"for their decisive contributions to the large project, which led to the discovery of the field particles W and Z, communicators of the weak interaction"
Production of Z and W at LEP

**Proton-Antiproton Collider**
‘Discovery Machine’

**LEP: Large Electron-Positron Coll.**
‘Precision Test Machine’

**LHC: Large Hadron Collider**
‘Discovery Machine’

**ILC: International Linear Collider**
‘Precision Test Machine’
Z’s and W’s at LEP

$e^+e^- \rightarrow Z \rightarrow 2 \text{ jets}$

$e^+e^- \rightarrow WW \rightarrow 4 \text{ jets}$
Precision Z Mass Determination: an intriguing saga

- Effect of tidal forces deforming the LEP machine
- Currents induced by passage of the TGV a few km away from LEP
- And the level of water in Lake Geneva
Number of Neutrino families

- Decay width of $Z$ is $\Gamma_{tot} = \sum f \Gamma(Z \rightarrow f\bar{f})$
  - Decay width into neutrinos is given by Total width – width into all charged channels
- Result: from measurement of $Z$ width
  \[ N_\nu = 2.994 \pm 0.012 \]
  - number of neutrino families with mass less than $M_z/2$
- $M_z = 91.1876 \pm 0.0021$ GeV
- $\Gamma_z = 2.4952 \pm 0.0023$ GeV
Determining the spin of $W$ from $W \rightarrow e \nu$

$\theta^*$ … angle between $e^+(e^-)$ from $W^+ (W^-)$ decay and direction of antiproton (in $W$ rest frame)

Angular distribution, calculated in electroweak theory, consistent with $S = 1$ for $W$ (Vector boson)

$W(\cos \theta^*) \sim (1 + Q \cos \theta^*)^2$

$Q$ is charge of $W$ boson ($= \pm 1$)
SM Higgs search at LEP

- Dominant Feynman diagrams for production

- Accessible mass range: $m_H \leq \sqrt{s} - m_Z$

  - for $\sqrt{s} = 209$ GeV (top energy of LEP): $m_H \leq 119$ GeV
  - From SM calculations: at this mass range HIGGS decays predominantly into b-quark and anti b-quark jets
  - Z decays into two leptons or two quark jets
Final LEP results of Higgs search

Combining the results of all 4 LEP experiments (likely hood distribution)

M(Higgs) \sim 115 \text{ GeV} with a 1.7 sigma significance

M(Higgs) > 114.4. \text{ GeV} (95\% \text{ CL})
Concept of precision tests and measurements
Consistency of electroweak data

![Graph showing consistency of electroweak data measurements and fits.](image-url)
Examples for Higgs Signals at LHC

Higgs -> ZZ* -> 4 leptons

one Higgs in $10^{14}$ to $10^{15}$ collisions...
LHC Priority 1A: find the Higgs Particle
Experimental indication for mass of Higgs

Precision measurements of W mass @ LEP & Tevatron

Probability distribution of Higgs mass

![Graph showing the probability distribution of Higgs mass with a green shaded region indicating the 68% confidence level (CL)]

![Graph showing the precision measurements of W mass at LEP and Tevatron with the m_W versus m_t plot, showing the mass of W and the mass of t, with the green shaded region indicating the 68% CL]
Simulation eines ‘Higgs’ Ereignisses
Standard Model of Particle Physics

• At CERN-LEP (1988-2000) tested with 0.01% accuracy with essentially perfect agreement

• LEP $\rightarrow$ 3 Families of Particles

Higgs Particle, responsible for giving mass to the quarks and leptons.
## Comparing the three fundamental interactions

<table>
<thead>
<tr>
<th>Interaction</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>QED</strong></td>
<td>Local phase invariance ⇒ introduces photon; change of phase corresponds to rotation in one-dimensional space: U(1)</td>
</tr>
<tr>
<td></td>
<td><img src="image1.png" alt="Diagram" /></td>
</tr>
<tr>
<td><strong>Weak Isospin</strong></td>
<td>To change $e^-$ into $\nu_e$ in each space – time point ⇒ needs the introduction of $W$; corresponds to rotation in two-dimensional space: SU(2)</td>
</tr>
<tr>
<td></td>
<td><img src="image2.png" alt="Diagram" /></td>
</tr>
<tr>
<td><strong>QCD</strong></td>
<td>To change q-color in each space – time point ⇒ needs to introduction of gluons (octett of bi-colored vector bosons); corresponds to rotation in three-dimensional space: SU(3)</td>
</tr>
<tr>
<td></td>
<td><img src="image3.png" alt="Diagram" /></td>
</tr>
<tr>
<td>Differences between QED and QCD:</td>
<td></td>
</tr>
<tr>
<td>$\gamma$ has no electric charge</td>
<td></td>
</tr>
<tr>
<td>$g$ has color charge ⇒ basis of quark confinement; no free (colored) quarks</td>
<td></td>
</tr>
</tbody>
</table>
Effective range of forces

\[ m_g = 0: \text{however; effective range of force limited, because of } gg \text{ interaction; for } d > 1 \text{fm: energy of color field so large that quark-antiquark pairs are produced} \]

\[ m_\gamma = 0: \text{range infinite; potential } \sim \frac{1}{r} \]

\[ M_w = 80 \text{ GeV/c}^2; \text{effective range } \sim 10^{-18} \text{ m} \]
altogether 19 parameters, to be determined experimentally; difficult to believe that this is the final story…

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Renormalization scheme (point)</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_e$</td>
<td>Electron mass</td>
<td></td>
<td>511 keV</td>
</tr>
<tr>
<td>$m_\mu$</td>
<td>Muon mass</td>
<td></td>
<td>106 MeV</td>
</tr>
<tr>
<td>$m_\tau$</td>
<td>Tauon mass</td>
<td></td>
<td>1.78 GeV</td>
</tr>
<tr>
<td>$m_u$</td>
<td>Up quark mass</td>
<td>$\mu_{\text{MS}} = 2 \text{ GeV}$</td>
<td>1.9 MeV</td>
</tr>
<tr>
<td>$m_d$</td>
<td>Down quark mass</td>
<td>$\mu_{\text{MS}} = 2 \text{ GeV}$</td>
<td>4.4 MeV</td>
</tr>
<tr>
<td>$m_s$</td>
<td>Strange quark mass</td>
<td>$\mu_{\text{MS}} = 2 \text{ GeV}$</td>
<td>87 MeV</td>
</tr>
<tr>
<td>$m_c$</td>
<td>Charm quark mass</td>
<td>$\mu_{\text{MS}} = m_e$</td>
<td>1.32 GeV</td>
</tr>
<tr>
<td>$m_b$</td>
<td>Bottom quark mass</td>
<td>$\mu_{\text{MS}} = m_b$</td>
<td>4.24 GeV</td>
</tr>
<tr>
<td>$m_t$</td>
<td>Top quark mass</td>
<td><strong>On-shell scheme</strong></td>
<td>172.7 GeV</td>
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<tr>
<td>$\theta_{12}$</td>
<td>CKM 12-mixing angle</td>
<td></td>
<td>13.1°</td>
</tr>
<tr>
<td>$\theta_{23}$</td>
<td>CKM 23-mixing angle</td>
<td></td>
<td>2.4°</td>
</tr>
<tr>
<td>$\theta_{13}$</td>
<td>CKM 13-mixing angle</td>
<td></td>
<td>0.2°</td>
</tr>
<tr>
<td>$\delta$</td>
<td>CKM <strong>CP-violating</strong> Phase</td>
<td></td>
<td>0.995</td>
</tr>
<tr>
<td>$g_1$</td>
<td>U(1) gauge coupling</td>
<td>$\mu_{\text{MS}} = m_Z$</td>
<td>0.357</td>
</tr>
<tr>
<td>$g_2$</td>
<td>SU(2) gauge coupling</td>
<td>$\mu_{\text{MS}} = m_Z$</td>
<td>0.652</td>
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<tr>
<td>$g_3$</td>
<td>SU(3) gauge coupling</td>
<td>$\mu_{\text{MS}} = m_Z$</td>
<td>1.221</td>
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<tr>
<td>$\theta_{\text{QCD}}$</td>
<td>QCD <strong>vacuum angle</strong></td>
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<tr>
<td>$\mu$</td>
<td>Higgs quadratic coupling</td>
<td></td>
<td>Unknown</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Higgs self-coupling strength</td>
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<td>Unknown</td>
</tr>
</tbody>
</table>
Major open questions of the SM

- Origin of particle mass -> Higgs?
- Masses and properties of neutrinos
- The ‘Hierarchy problem’ in the Higgs sector -> next lecture
- Origin of Dark matter? Supersymmetry?
- Unification of the threee interactions -> Supersymmetry?
- Fundamental scale in physics -> extra dimensions?
Final words....

• ...the world formula allows to derive the entirety of physics from it are some technical details. (Werner Heisenberg, 1958)

• ... This empty square shall show the world that I am able to draw like Tizian. All that is missing are some technical details. (Wolfgang Pauli, in reply to above claim)

• Nature has always looked like a horrible mess, but as we go along we see patterns and put theories together; a certain clarity comes and things get simpler (Feynman).
Projekte, Summer-, Diplom-, Dissertationsstellen

- **CERN Genf**
  - Technisches Studenten Programm: - 4 bis 12 Monate
  - Naechster Termin: 5. Maerz

- Sommerstudenten Programm: 8 bis 13 Wochen im Sommer
  - Naechster Termin: 27. Jaenner

- Doktoratsstudenten Programm: 12 bis 36 Monate
  - Naechster Termin: 5. Maerz


- **GSI- Darmstadt**
  - 30th Summer Student Program for students on the advanced undergraduate level (Bachelor, Master or Diploma) in physics and related natural science and engineering disciplines .

  Further information for applicants can be found on this link [http://www.gsi.de/stud-pro](http://www.gsi.de/stud-pro)

  Applications and recommendations must reach us before 31.1. 2010.

- **Themenkatalog**
  - fuer Projektarbeiten ist in Vorbereitung