Standard Model at the LHC
(Lecture 4: Precision Measurements)

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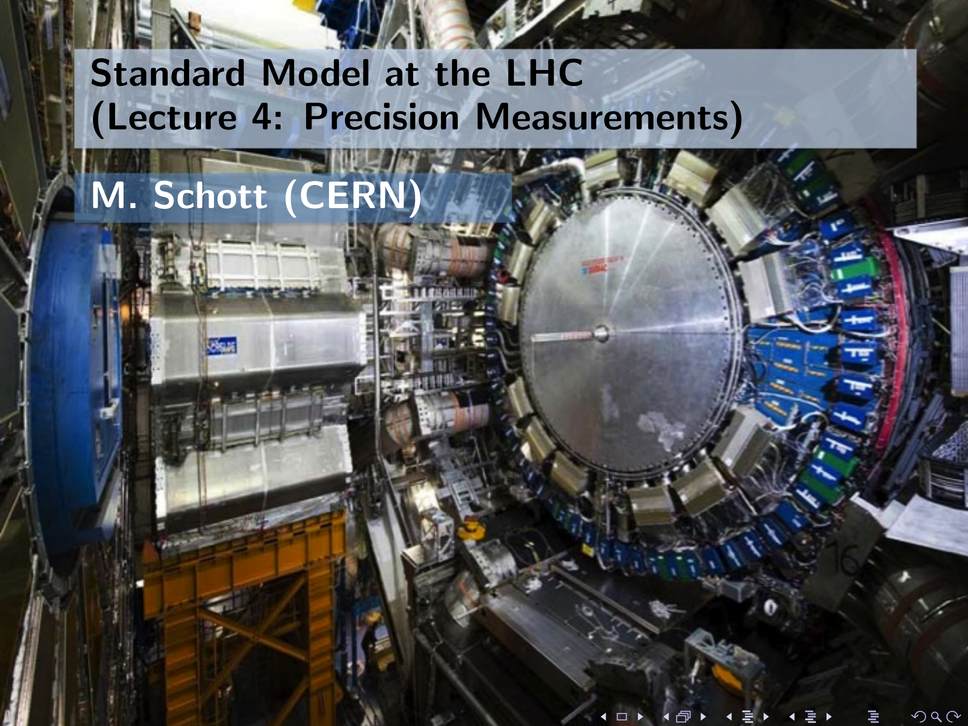


Content

Location of Lecture Slides

http://mschott.web.cern.ch/mschott/ShareDocus/Lecture_Vietnam/

Free Parameters in the Standard Model (1/2)

28 free parameters of the Standard Model

- Masses of fermions (6 quarks, 6 leptons)
- couplings of the three interactions: g_W, α_{EM}, α_S
- Gauge Boson masses: m_Z and m_W
- Higgs-Sector: Shape parameters of potential λ, ν
- Flavour-Mixing: Two unitary matrices with (4 parameters each)
- CP-violating phase parameter in QCD ($\theta = 0$)

Fermion Masses and flavour mixing is decoupled from the rest.
So we are left with: $g_W, \alpha_{EM}, \alpha_S, \nu, \lambda, m_W, m_Z$

Free Parameters in the Standard Model (2/2)

We can rewrite these parameters, in terms of observables which we can measure very precisely in the experiment

$$G_F = \frac{g_W^2}{4\sqrt{2}m_W^2}$$

$$e = g_W \sin\theta_W (\rightarrow \alpha_{EM})$$

With the electroweak symmetry breaking we can expressed λ and ν with

$$m_W = \frac{1}{2} g_W \nu$$

This leaves us with four parameters which we can freely choose in the electroweak sector: $G_F, \alpha_{EM}, m_Z, m_H$. And we will see in a seond that also m_t is important.

Radiative Corrections (1/2)

Let us look carefully at the m_W. It is given by

$$m_W = \frac{\pi\alpha_{EM}}{\sqrt{2}G_F \frac{1}{sin^2\theta_W}}$$

But a direct measurements yields to

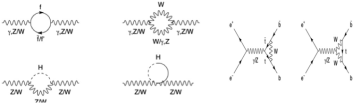
$$m_W^{ind} = 78.1 \pm 0.4 GeV$$

$$m_W^{direct} = 80.4 \pm 0.02 GeV$$

What went wrong?

Radiative Corrections (2/2)

We have forgotten to take virtual loop corrections into account!



The W and Z Boson masses and coupling vertizes depends also on m_H and m_{top}.

$$m_{W,Z} \sim m_{top}^2 - ln(m_H^2)$$

$$\Delta\kappa \sim m_{top}^2$$

By measureing m_W, m_Z and m_{top} precisely, we can estimate the mass of the SM-Higgs Boson! $\rightarrow$ how do we measure this?

Idea of the W-Boson Mass Measurement (1/3)

For the Z boson it is easy, at least in principle

- Both decay leptons are measured in the calorimeters
- We can then combine their four-momenta and compute the invariant mass of the pair
- The distribution of this invariant should display a peak at the resonance. The position of the peak will give the resonance mass.

And for the W?

- We measure one decay lepton; the neutrino escapes
- We can however estimate the transverse momentum of the neutrino, by summing all measured signals in the calorimeter and imposing momentum conservation in the transverse plane!
  - Remember: E_T^{miss} !

Idea of the W-Boson Mass Measurement (2/3)

The transverse momentum distributions of the charged lepton and neutrino are sensitive to the W boson mass!
Suppose the W is produced with longitudinal momentum (induced by the proton PDFs), and with small transverse momentum. Then in the W rest frame we have

$$\frac{d\sigma}{dcos\theta} \sim 1 + cos^2\theta$$

Change variables to

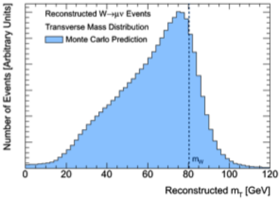
$$p_T = \frac{m_W}{2} sin\theta$$

and we get

$$\frac{d\sigma}{dp_T} \sim \frac{p_T/m_W - (p_T/m_W)^3}{\sqrt{1 - (2p_T/m_W)^2}}$$

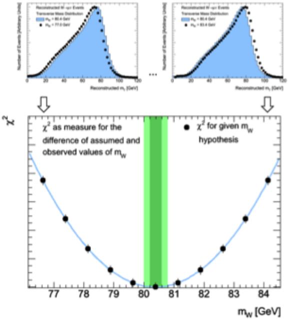
Idea of the W-Boson Mass Measurement (3/3)

- Hence the above relation diverges at $p_T = m_W/2$.
- Divergence is cured by many effects, but a peak remains, allowing to estimate m_W from the distribution.



Template Fit method

- Choose distribution which is sensitive to the parameter p
- Use different values of p at MC-generator level and produce new distributions
- Compare measured spectrum with generated



W-Boson Mass Measurement at Tevatron (1/3)

Use two observables

- Lepton transverse momentum p_T
  - $m_W \sim 2p_T$
  - insensitive to recoil
  - p_T^W modelling crucial
- Transverse mass m_T
  - $m_T^2 = 2p_T E_T^{miss}(1 - cos(\Delta\phi))$
  - $m_W \sim 2p_T + u_{||}$
  - low sensitivity to p_T^W
  - Recoil modelling crucial

W-Boson Mass Measurement at Tevatron (2/3)

Event Selection

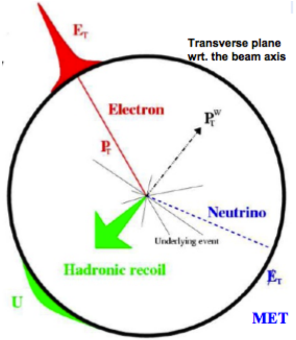
- Isolated, high p_T lepton (electron or muon)
- missing energy from neutrino

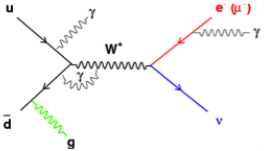
A relative precision of 0.03% on m_W requires :

- accuracy of lepton energy scale: 0.02$accuracyofhadronicrecoilscale$:1

Blind analysis

- m_W returned by fits was deliberately shifted by some unknown offset before the final fitting





W-Boson Mass Measurement at Tevatron (3/3)

Current most precise measurement from the CDF-experiment at Tevatron: $m_W = 80387Â \pm 19MeV$

- Expect to achieve a precision of $< 10MeV$ at the LHC

Transverse Mass

Systematic (MeV)	Electrons	Muons	Common
Lepton Energy Scale	10	7	5
Lepton Energy Resolution	4	1	0
Recoil Energy Scale	5	5	5
Recoil Energy Resolution	7	7	7
$u_{\|\|}$ Efficiency	0	0	0
Lepton Removal	3	2	2
Backgrounds	4	3	0
$p_T(W)$ Model (g_2, g_3, α_s)	3	3	3
Parton Distributions	10	10	10
QED Radiation	4	4	4
Total	18	16	15

Transverse Momentum

Systematic (MeV)	Electrons	Muons	Common
Lepton Energy Scale	10	7	5
Lepton Energy Resolution	4	1	0
Recoil Energy Scale	6	6	6
Recoil Energy Resolution	5	5	5
$u_{\|\|}$ efficiency	2	1	0
Lepton Removal	0	0	0
Backgrounds	3	5	0
$p_T(W)$ model (g_2, g_3, α_s)	9	9	9
Parton Distributions	9	9	9
QED radiation	4	4	4
Total	19	18	16

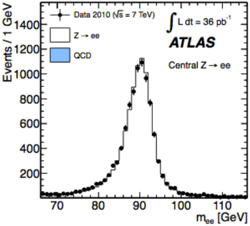
Measurement of the Z-Boson Mass (1/3)

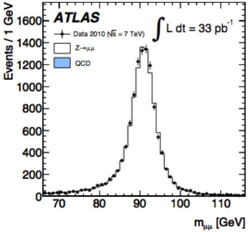
We already performed a mass-measurement of the Z-Boson mass during the excersise:

- just plotted the invariant mass-spectrum of the decay muons
- peak-position was the Z-Boson mass

In principle we can use a similar template-fit approach as we used for the W-Boson mass

- Problem: Similar systematic uncertainties
- The LEP-experiments achieved a precision of 0.002%





Measurement of the Z-Boson Mass (2/3)

Remember the cross-section of the first lecture for $\sigma(e^+e^- \to \gamma \to \mu^+\mu^-)$

$$\sigma = \frac{4\pi\alpha^2}{3s}$$

The cross-section changes when we introduce the Z-Boson. I.e. for $\sigma(e^+e^- \to Z \to f^+f^-)$ we get

$$\sigma(e^+e^- \to Z \to f^+f^-) = \frac{12\pi}{s} \frac{\Gamma_{ee}\Gamma_{f_1 f_2}}{(s - M_Z^2)^2 + s^2\Gamma_{tot}^2/M_Z^2}$$

Idea: Measure the cross-section at different collision energies s. Then fit line-shape (=cross-section prediction) $\to M_Z$

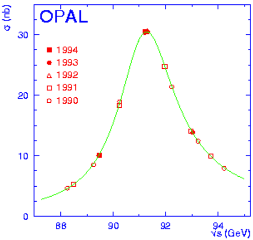
Measurement of the Z-Boson Mass (3/3)

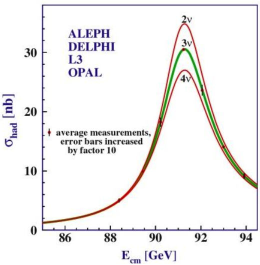
Cross-section measurement is a simple counting problem

- just count how many Z-Bosons you observe in your detector
- many systematic, experimental uncertainties due not play a large role!

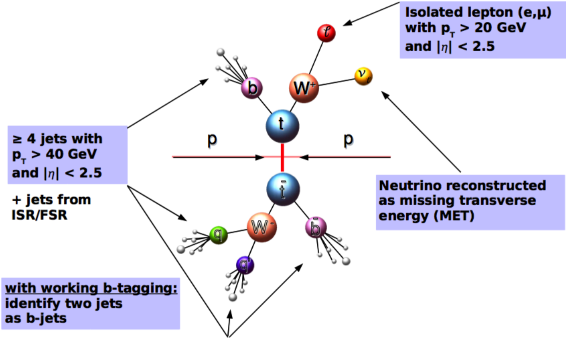
The Line-shape measurements at the LEP-colliders provide

- Very precise determination of the Z-Boson mass (and its width)
- Determination of the Weinberg mixing angle θ through the measurement for





Measurement of the Top-Quark Mass (1/2)



Selection of Top-Events: b-tagging!

Background Processes: W+jets, Z+jets, WW, WZ, ZZ

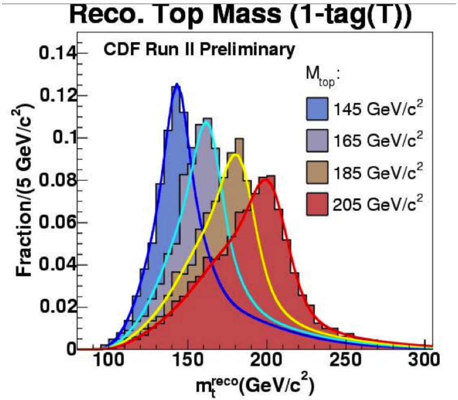
Measurement of the Top-Quark Mass (2/2)

Top-Mass Measurement

- Basic idea as W-Boson mass
- Template Fit in reconstructed Top-Quark Mass

Systematic Uncertainties

- Jet Energy Scale



Basic Idea

The precision measurement of $\alpha_s, \alpha_{EM}, G_F$ and $\theta_W, m_Z, m_W, m_{top}$ allows to

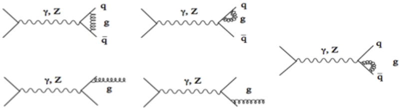
- test if the predictions of the SM are consistent with the measurements
    - keep in mind: We have an overconstrained system
- set a mass-range where the SM Higgs-Boson is expected:

Indirect Determination of the Higgs-Boson Mass

- 1-sigma limit: $72 GeV < m_H < 119 GeV$
- 2-sigma limit: $50 GeV < m_H < 144 GeV$
- LEP Experiments: $114 GeV < m_H$

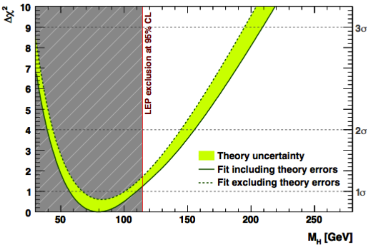
Why is α_s important?

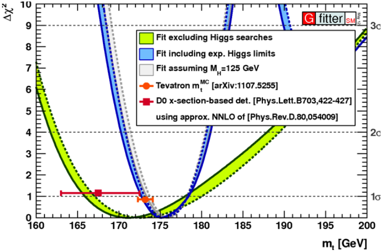
The following diagrams corresponding to final state strong interaction corrections

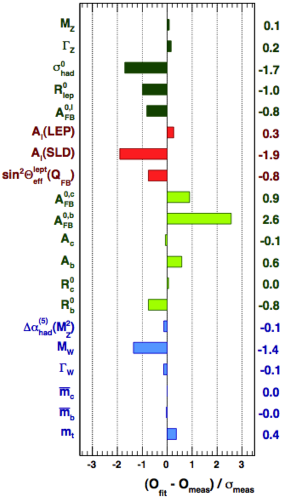


- QCD corrections suffer from large uncertainties
- The choice of the electroweak observable of interest must be made such that the interpretation of its measurement is not plagued by unmastered QCD effects
- Example
  - $\Gamma(Z \to bb)$ is subjected to a QCD correction at the level of 4% known to an accuracy of 20%
  - $\to$ Prefer to measure the partial width $\Gamma(Z \to bb)/\Gamma(Z \to hadrons)$ for which those corrections are suppressed by a factor 20.

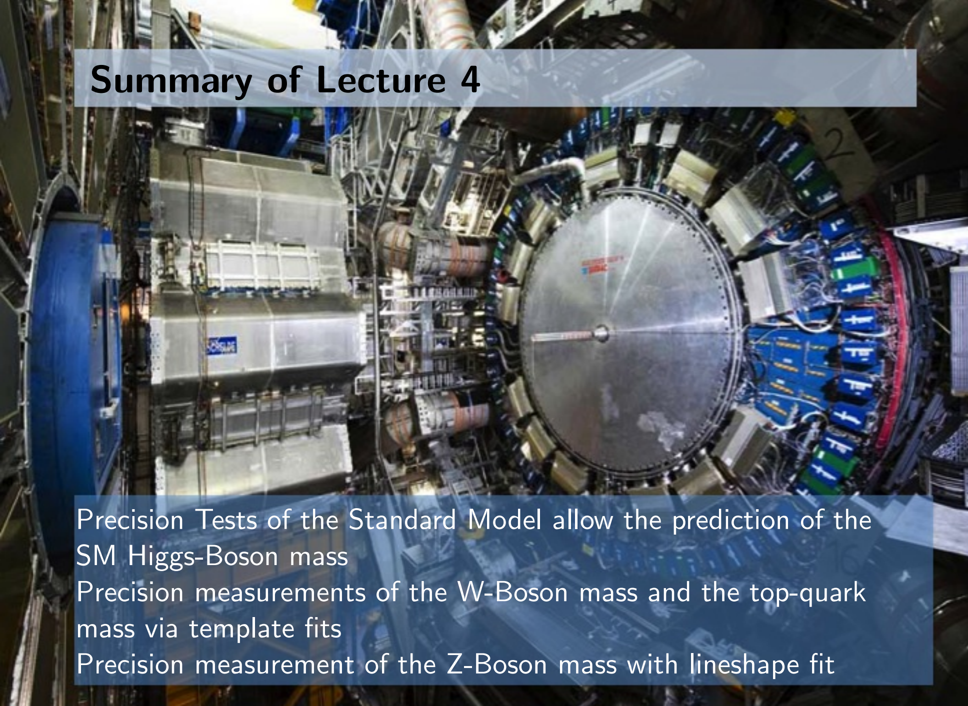
Results of the Electroweak Fit







Summary of Lecture 4



Precision Tests of the Standard Model allow the prediction of the SM Higgs-Boson mass

Precision measurements of the W-Boson mass and the top-quark mass via template fits

Precision measurement of the Z-Boson mass with lineshape fit