Confronting Theory with Experiment at the LHC

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*21st IPM Physics Spring Conference*

May 21-22, 2014
Introduction

• Standard Model: a theory of interactions

- Gauge symmetry $SU(3) \times SU(2) \times U(1)$ based on quantum field theory
- Properties of fermions are inputs
- Properties of interaction bosons in terms of couplings, propagations, masses are linked

➢ Measuring a few parameters allows us to predict the rest, then measure and compare with expectation

➢ It’s remarkably successful:

- Predictions verified to be correct at sometimes incredible levels of precision

- After ~30 years, still no serious cracks!
EW symmetry (SU(2)xU(1)) breaking & mass generation

\[ F_{\mu\nu} F^{\mu\nu} \text{-term contains self couplings between gauge bosons.} \]

\[ \Rightarrow WW \rightarrow WW \text{ possible; cross section:} \]

\[ \sigma_{WW} \sim E_{cm}^2 \]

WW scattering probability becomes larger than unity for \( E_{cm} > 1.2 \text{ TeV} \) ...

Violation of unitarity if force remains weak at this scale ...

To restore unitary it needs some scalar boson “H” with

\[ g_{HH} \sim M_H \]
\[ g_{Ht} \sim m_t \]
\[ M_H < 1 \text{ TeV} \]

\[ \sigma \rightarrow \text{const} \]

for large energies
EW symmetry breaking (SU(2)xU(1)) & mass generation

Higgs field fills space with uniform distribution of EW charge

Longitudinal polarization isn’t present for on-shell massless particles.

Waves with new degree of freedom i.e. longitudinal components are generated!!

Tool:
- to find the Higgs → By Dr. A. Mohammadi
- to measure the polarization of the W,Z-bosons
- Test all aspects of the SM
- Search for BSM if any!
The Large Hadron Collider (LHC) at CERN

- Proton-proton collider in the former LEP tunnel at CERN (Geneva)

- Highest ever energy per collision: 7, 8, 13, 14, 33 TeV in the pp-system
- Conditions as $10^{-13} – 10^{-14}$ s after the Big Bang
- 4 experiments:
  - ATLAS
  - CMS
  - LHC-B specialised on b-physics
  - ALICE specialised for heavy ion collisions
The Large Hadron Collider LHC

CMS

ATLAS
Physics at Proton Colliders

- Protons are composite, complex objects
  - partonic substructure
  - quarks and gluons

- Interesting hard scattering processes
  quark-(anti)quark
  quark-gluon
  gluon-gluon

- Proton beam can be seen as beam of quarks and gluons with a wide band of energies
- The proton constituents (partons) carry only a fraction $0 \leq x \leq 1$ of the proton momentum
⇒ Low luminosity phase
10^{33}/cm^2/s = 1/nb/s
approximately

- 10^8 pp interactions
- 10^6 bb events
- 200 W-bosons
- 50 Z-bosons
- 1 tt-pair

will be produced per second and

- 1 light Higgs
per minute!

The LHC is a b, W, Z, top, Higgs, ...
factory!
The problem is to detect the events!
W-polarization measurement

\[ \mathcal{L}_{\text{int}}^{W} = -\frac{g}{\sqrt{2}} W_{\mu}^{+} \bar{b} \gamma^{\mu} t_{L} \]
W-polarization measurement

\[
\frac{d\sigma}{d\cos\theta^*} \approx \frac{3}{8} (1 - \cos\theta^*)^2 F_{\text{LH}} + \frac{3}{4} (1 - \cos^2\theta^*) F_{\text{long}} + \frac{3}{8} (1 + \cos\theta^*)^2 F_{\text{RH}}}
\]

left-handed \hspace{2cm} \text{longitudinal} \hspace{2cm} \text{right-handed}

SM prediction for helicity fractions: [LO, \( m_b = 0 \)]:

\[
F_{\text{LH}} = \frac{2m_w^2}{m_t^2 + 2m_w^2} \approx 0.3 \quad F_{\text{long}} = \frac{m_t^2}{m_t^2 + 2m_w^2} \approx 0.7 \quad F_{\text{RH}} \approx 0
\]

Physical picture:

Top quark: large mass \( \rightarrow \) large Higgs (Yukawa) coupling

Longitudinal d.o.f. of W bosons generated by Higgs mechanism

Thus: top quark prefers to couple to longitudinal W ... [see later]
W-polarization measurement

Backgrounds!!!
W-polarization measurement

\[ F_L = 0.288 \pm 0.035 \text{(stat)} \pm 0.040 \text{(syst)} \]
\[ F_0 = 0.698 \pm 0.057 \text{(stat)} \pm 0.063 \text{(syst)} \]
W-boson mass: TH vs. EXP importance of quantum corrections

SM is a quantum theory. The vacuum is a busy place!
Particle-antiparticle pairs can be produced out of nothing, borrowing an energy $E$ for a time $t$:  
\[ E \cdot t \approx \hbar \]

Discovery at: \[ m_H = 125.6 \pm 0.4 \text{ (stat.)} \pm 0.2 \text{ (syst.) GeV} \]
The observation of the physical Higgs boson with $m_H$ well consistent with the (indirect) prediction of the e.w. precision tests is a great success of the SM.

$m_W - m_{\text{top}}$ plane

+/- 1 GeV in top mass $\rightarrow$ +/- 10 GeV in Higgs mass
Precise Measurement is NEEDED!

$m_w - m_{\text{top}}$ plane

OR

References:
Top Mass: 173.16\pm0.08 GeV (arXiv:1107.5255)
Rare $B^0_s$-Meson Decay to di-muon
The Rare Decay $B_s^0 \rightarrow \mu^+ + \mu^-$

- $10^6$ bb events per second!!!

- Decays highly suppressed in SM forbidden at tree level
- $B^0 \rightarrow \mu^+ + \mu^-$ transition only through Penguin diagrams
- Suppressed by factors of $(m_\mu/m_B)^2$

[De Bruyn et al. PRL 109, 041801]; [A. Buras et al. arXiv:1303.3820]

**SM prediction:** $\text{BR}(B_s \rightarrow \mu^+ \mu^-) = (3.6 \pm 0.4) \times 10^{-9}$
Significance

An excess of $B_0 \to \text{dimuon}$ events with respect to background is observed with a significance of **4.3 standard deviations**.

<table>
<thead>
<tr>
<th>Expected</th>
<th>Observed</th>
</tr>
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<tbody>
<tr>
<td>4.8σ</td>
<td><strong>4.3σ (p-value = 9.8×10^{-6})</strong></td>
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Test of SM with high precision: $10^{-9}$
Sensitivity to new physics BSM

\[ B \sim (\tan \beta)^6 \text{ in MSSM} \]
\[ B \sim (\tan \beta)^4, \quad m_{H^+} \text{ in 2HDM} \]

Strong limits on new MSSM, ED, fourth Generation, ... parameters

arXiv:1205.1845
Strong Coupling Constant Measurement: $\alpha_s$
Strong Coupling Constant

Classical physics: force depends on distance
Quantum physics: charge depends on distance

A strange phenomenon

QED:
virtual particles screen the charge
→ charge gets weaker as we move away even stranger

QCD:
virtual particles anti-screen the charge
→ charge gets stronger as we move away

Coupling constant is not a “constant”

Verification of running of $\alpha_s$ and test of QCD at the smallest distance scale
- $\alpha_s = 0.118$ at $m_Z$
- $\alpha_s \approx 0.082$ at 4 TeV (QCD expectation)
Strong Coupling Measurement

- Runs with $Q^2$, accounts for vacuum polarization

\[
\alpha_s(Q^2) = \frac{\alpha_s(\mu^2)}{\left[1 + \left(\frac{33 - 2n_f}{12\pi}\right)\ln\left(\frac{Q^2}{\mu^2}\right)\right]}
\]

- $\alpha_s(Q^2) \to 0$, as $Q \to \infty$, $r \to 0$

Coupling very weak $\to$ partons are essentially free

In addition to its running, precise measurement is important:

- Higgs,... Productions

- Forces Unification
Multijet ratios for $\alpha_s$ measurements

- Ratios of inclusive cross-sections for event with $\geq 3$ jets and $\geq 2$ jets:
  - Sensitive to the value of $\alpha_s$
  - Cancellation of systematic uncertainties (luminosity, PDFs, etc) for more precise test of QCD

$$R_{3/2}(p_T^{\text{lead}}) = \frac{d\sigma_{N_{\text{jet}} \geq 3}}{dp_T^{\text{lead}}} \Bigg| \frac{d\sigma_{N_{\text{jet}} \geq 2}}{dp_T^{\text{lead}}} \sim \alpha_s$$

“Probability that a 2-jet event has a third jet”

- Cross-section can be measured relative to various quantities, typically jet transverse momenta
  - Collision energy at LHC means running of the coupling can be tested at new scales
Multijet ratios for $\alpha_s$ measurements: Running of Coupling Constant

QCD, as a theory, is a good description of strong interactions.

One universal coupling is sufficient to describe the strong interaction.

$\alpha_s(M_Z) = 0.1160 \pm 0.0025 \text{ (exp, PDF, NP)} \pm 0.0068 \pm 0.0021 \text{ (scale)}$

All LHC-era results are consistent with the current world average from the Particle Data Group:

$\alpha_s(M_Z) = 0.1184 \pm 0.0007$
Beyond Standard Models

Large Extra Dimensions:

CMS-PAS-EXO-12-031
CMS-PAS-EXO-12-027
Beyond Standard Models

Supersymmetry:

\[ \tilde{g} \rightarrow t \bar{t} \chi^0_1 \]

CMS Preliminary

\( \sqrt{s} = 8 \text{ TeV} \)

Moriond 2014

- Observed
- Observed - SUSY theory
- Expected

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS
THANKS!