Standard Model @ Hadron Colliders
III. Triple Bosons & Top Quark

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W mass result

D0 measurement same precision as previous world average

A huge achievement after 20 years of work!
High precision possible at proton colliders
Important constraint on Standard Model Higgs

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Into the heart of gauge theories
Looking for TGVs
(Triple Gauge Boson Vertices)

W – Boson weakly and electrically charged
⇒ coupling to $Z^0$ and $\gamma$

Very fine compensation of contributions
- motivation to introduce $Z^0$
- Relates couplings to fermions and bosons

First measurements at $e^+e^-$ collider LEP
Onset of cancellation process seen

Quantify with ‘anomalous couplings’

$$\frac{\mathcal{L}_{WWZ}}{g_{WWZ}} = i \left[ g_1^Z \left( W_{\mu\nu}^+ W_{\mu}^\mu Z^\nu - W_{\mu\nu} W_{\mu}^\mu Z^\nu \right) + \frac{k^2}{m_W^2} W_{\mu}^\mu W_{\rho\mu}^\pm W_{\nu}^\pm Z_{\rho\nu}^\rho \right]$$
Signatures of anomalous couplings

Clearest signature in excess of events with high $p_T$

Selection of ZW events: three hard leptons + missing $E_T$

Step 1: $Z^0 \rightarrow e^+e^-, \mu^+\mu^-$  Step 2: transverse mass  Step 3: $p_T$ of Z

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Anomalous 3 – boson couplings

Measurements agree with Standard Model expectation

Sensitivity to possible deviations at LHC approaches LEP: a few %

Increased statistics and higher energies during the next years will significantly boost precision
Special interest: W pairs from VBF

1960s: event rate for $W_L W_L \rightarrow W_L W_L$ explodes at 1.2 TeV. Higgs boson should cure this: theory works fine.

Require high $jj$ mass + high $|\Delta y|$.

Expected background: 16.9
Expected $WWjj$: 15.2
Observed nb. Events: 34

$\rightarrow$ Evidence for VBF
Testing electroweak theory at LHC/Tevatron

- Millions of $Z^0$, $W^\pm$ allow tight constraints on pdfs, strong interactions
- Electroweak theory probed at multi – TeV scale: no deviation found
- The mass of the W boson improved by factor 2
- Precision of Vector boson self interactions (triple, quartic) will soon superseed LEP
Top quark
Basic facts
The mysterious top quark

Top quark: no internal structure but heavy as a gold atom

\[ M_t = 173.3 \pm 1.1 \text{GeV} \]

i.e. coupling strength to Standard Model Higgs Boson

\[ m_t = \frac{\lambda_t \cdot v}{\sqrt{2}} \]

\[ \Rightarrow \lambda_t = 0.996 \pm 0.006 \]

Suggests a special role of top quark?
A constrained giant?

Top quark has same role as up-quark (electron, \( \nu \)) ..... All are 'matter' particles, but

\[
\frac{m_{\text{up}}}{m_{\text{top}}} \sim 10^{-5} \\
\frac{m_{\nu}}{m_{\text{top}}} \sim 10^{-11}
\]

Does the top quark have the same properties as light fermions?
- Coupling strengths to photons, gluons, \( W \) – bosons?
- Charge
- Weak parity violation

......
A brief history of the top quark

Known to exist since 1973 ➔ search for 20 years

Phenomenological prejudice: around 15 GeV

(s\bar{s}) = 1 \text{ GeV}, (c\bar{c}) = 3.1 \text{ GeV}, (b\bar{b}) = 9.4 \text{ GeV}, ➔ (t\bar{t}) = 30 \text{ GeV} ??

motivation for several accelerators: PETRA/PEP, TRISTAN, SppS, LEP, ....

No signature found!

Observed in 1995 at Tevatron, a few 1000 top’s collected

LHC currently produces ~ 50000 tt events/day

In net years: close to 1M/day
Phenomenology of heavy top

For lighter quarks:
strong interaction $>>$ weak interactions
$\Rightarrow$ colour neutral hadrons

competing interactions: who’s faster?

For top quark: strong interaction $<$ weak interactions
$\Rightarrow$ top quarks decay before hadrons formed, ’free quark‘
**Phenomenology of heavy top**

Decay properties of top quark unambiguously predicted by SM
Decay fractions largely determined by fractions of $W$ – decay

<table>
<thead>
<tr>
<th>Top Pair Decay Channels</th>
<th>$t\bar{t}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(only) 6 quarks</td>
</tr>
<tr>
<td></td>
<td>largest fraction, very high background</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>$e+csudt+m+$</td>
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<tr>
<td></td>
<td>$e–csudt–m–$</td>
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<td>$\tau+jets$</td>
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<th>Decay properties of top quark</th>
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<tr>
<td></td>
<td>$\rightarrow$ 2 quarks, 2 charged lepton, 2 neutrinos</td>
</tr>
<tr>
<td></td>
<td>Only 5% 'usable', very low background, difficult to reconstruct</td>
</tr>
</tbody>
</table>

99.1% of all top quarks decay into a bottom quark!
A semileptonic $tt$ event
Surveying the top quark
Cross Section

Test of QCD with massive quarks
Measure coupling strength gtt

Event selection
- 4 high $p_T$ jets
- isolated electron/muon
- missing transverse energy

What fraction of $tt$ events are retained after selection

Luminosity: How many proton collisions?
Cross section determination

Experimental precision depends on how well
- background, efficiency, luminosity can be controlled

Key issue determine efficiency

Largest uncertainties:
- modelling of top
- parton distribution fct.
- Background yield
- Jet energy scale
- selection efficiencies e, μ

Experimental uncertainty ~ 2.3%
Luminosity uncertainty ~ 3.1%
Beam energy ~ 1.7%

Total uncertainty 4.3%

Improvement by factor 2–3 within a year!

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Cross section measurement

Theoretical uncertainty <5 % (significant improvement last 10y)
Theory & experiment uncertainty about equal

Very good agreement between data and expectation
Weighting the top quark
Mass of the top quark

A fundamental parameter of the Standard Model

A broad spectrum of decays and methods

Note: first time a quark mass can be measured directly

(Lighter quarks to be inferred indirectly from hadron masses)
Top mass from $l+\text{jet}$ decays

Favoured topology: $t\bar{t} \rightarrow 4 \text{ Jets (2 b \text{–jets})} + e/\mu + \nu$

The problems:
- How to get the $z$ – component of $\nu$
- Out of 4 (or more) jets: which jet belongs to which top?
- What is the energy scale of jets (and electrons)

$M^2 = \left( \sum_{\text{jet } i} E_{\text{jet } i} + E_l + E_\nu \right)^2 - \left( \sum_{\text{jet } i} \tilde{p}_{\text{jet } i} + \tilde{p}_l + \tilde{p}_\nu \right)^2$

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Problem 1: $p_z(\nu)$

Constraint from $W$ - mass

\[
M_W^2 = (E_1 + E_\nu)^2 - (p_x(l) + p_x(\nu))^2 - (p_y(l) + p_y(\nu))^2 - (p_z(l) + p_z(\nu))^2
\]

\[
E_\nu = \sqrt{p_x^2(\nu) + p_y^2(\nu) + p_z^2(\nu)}
\]

Note: $\nu$ – mass completely negligible

Quadratic equation $\Rightarrow$ 2 solutions

physics: in 70% the solution with smaller $p_z$ correct
Problem 2: which jets?

Two facettes:
- if more than 4 jets (initial state rad.) mostly jets with highest $p_T$
- if exactly 4 jets: which belongs to which top quark?

4 jets $\rightarrow$ 4 possible assignments
$(j_A j_B j_C / j_D, j_A j_B j_D / j_C, \text{ ....})$

Note: if b – jets identified, reduced to 2 possibilities

Important constraints
- mass $(jjj) = \text{mass}(jlv) (= M_t)$
- mass $(jj) = M_W$

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Problem 3: jet energy scale

Measure signals in calorimeter $\rightarrow$ derive jet energy
Implies uncertainty!
$\rightarrow$ relates directly to top mass

$$M^2 = \left( \sum_{\text{jet }i} E_{\text{jet }i} + E_l + E_\nu \right)^2 - \left( \sum_{\text{jet }i} \tilde{p}_{\text{jet }i} + \tilde{p}_l + \tilde{p}_\nu \right)^2$$

Top – quarks offer ‘self calibration’
$M(jj)$ has to be equal $M_W$
$\rightarrow$ change JES such that fulfilled
Still dominant uncertainty of $M_t$
Use all information

Theoretical pred with $M_1$(top)  

Theoretical pred with $M_2$(top)  

Convolute with experimental effects

Sum over all events and find combine weights

$W(M_1$(top$)) = w_A \cdot w_B \cdot w_C \cdot \ldots = \Pi w_i \implies \mathcal{L}(M_1$(top$))$

$W(M_2$(top$)) = w_A \cdot w_B \cdot w_C \cdot \ldots = \Pi w_i \implies \mathcal{L}(M_2$(top$))$

......

Find $M$(top) with maximum weight

Recent CMS: $172.04 \pm 0.19 \pm 0.75$ GeV  
statistical & systematic uncertainty

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Measurements of $M_{\text{top}}$

**Combination of all measurements (March 2014)**

$173.3 \pm 0.3 \pm 0.7 \text{ GeV}$

$\Rightarrow 0.4\%$ precision!

**Caveat:**
Relation to ‘theoretical’ top mass somewhat uncertain due to QCD models

**Other methods developed**
Top Quarks at Highest Energy

Top production at TeV energies: Deviations from Standard Model?

 Decay $t \rightarrow bqq$ at high $p_T$: quarks tend to merge in one jet

Low $p_T$ selection to be modified
One ‘Fat’ jet with substructures

Lorentz Boost

Several partons merge into a single jet

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Searching for a $t\bar{t}$ - resonance

Postulated in many BSM scenarios

$\Rightarrow$ at this stage no new particle observed

$\bar{t}t$ masses up to 3 TeV well described by Standard Model strong interactions

Sensitivity to new ultra-heavy particles

$X \rightarrow t\bar{t}$
Testing top quarks at LHC/Tevatron

- Proton colliders only source of information
- Measurements and theory of cross section by now uncertainty of \( \sim 5\% \)
- Top mass directly measured to 0.4%
- Theoretical interpretation limiting?
- Top decays and production show no deviation from SM expectation
The Higgs mechanism - basics
Electroweak symmetry breaking

Masses of bosons and fermions (w/o new mechanism)
In conflict with local gauge invariance
- Both for fermions and vector bosons

Also: boson masses lead to
a. infinite cross sections $W_L W_L \rightarrow W_L W_L$

\[ M_H \leq \left( \frac{8\pi\sqrt{2}}{3G_F} \right)^{1/2} \sim 1 \text{ TeV} \]

b. or a strongly coupling between $W$'s $\Rightarrow$ many $W$'s, ..... 

Way out: introduce new scalar (spin 0) particle
The solution 'Higgs mechanism'

The Standard Model answer:
- Higgs fields
  - gives mass to bosons
  - provides means for fermion mass
  - implies elementary physical particle
  - gives mass to Higgs Boson
- NOTE: no prediction of masses!

Introduce potential (by hand)
Two unknowns: $\lambda$, $\mu$

$V = -\mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$

$$\frac{\partial V}{\partial \phi} = 0 \implies \phi_0 = v^2 = \frac{\mu^2}{\lambda}$$

$v$: 'vacuum expectation value'
$M_W \implies v = 246$ GeV

Mass of $W$
Mass of Higgs
Mass of fermions

$M_W = \frac{1}{2} v \cdot g$
$M_h = \sqrt{2} \cdot \lambda \cdot v$
$M_f = \frac{1}{\sqrt{2}} G_f \cdot v$
A few notes on mass

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Dynamical generation of hadron masses →
99% of visible matter due to strong interaction

This principle does not work if particles are elementary!
The Higgs Boson: well known!

..... except its mass! (until 2012)

What is to be known to search for the Higgs boson:

- how is it produced?
- how strongly is it produced?
- how does it decay?

Devise search strategy along this line
Higgs searches at Hadron Colliders

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How the Higgs decays

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How strong is the coupling?

Width of higgs boson proportional to coupling

Threshold W/Z passed:
High coupling
Initial W/Z: high X-section

Very small width ...
Very small coupling!
How to interpret the measurements
Test if data EXCLUDE hypothesis

Step 1: X-section at mass $m_H$ that can be excluded @ 95% CL

Step 2: Plot ratio
\[ \frac{\sigma(\text{exclusion})}{\sigma(\text{Xsec of SM expectation})} \]

→ If below 1:
Higgs excluded in mass range

→ If above 1:
Higgs cannot be excluded since either: 'hint', ..... 'signal'
or: no sensitivity for exclusion

Compare to expectation (i.e. simulation assuming no signal)
IF expectation above SM Higgs X-section: no sensitivity to exclude
IF expectation below BUT data are high: a first hint

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95% CL Limits $ZZ \rightarrow (l^+l^-)(l^+l^-)$

Simulation with NO signal, but luminosity, detector effects, ....

$\rightarrow$ EXPECTED limit

Oscillations around expectation: more or less events than background expectation

No sensitivity
Small $\sigma \times BR$

INTERESTING!
Data can exclude less than expected by large margin

Regions of ratio $< 1$
EXCLUSION!

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p - value probability of stat. fluctuation

'p – value‘ : how likely is it that at a certain mass $M_H$
- the expected background fluctuates upward
- to produce at least the number of observed events

Observed dearth or excess reflected in wiggles
Convention:
Signal observed if $p > 5\sigma$
Combining all searches

High mass range:

- $ZZ \rightarrow l^+l^-l^+l^-$
- $ZZ \rightarrow l^+l^-\nu\nu$
- $ZZ \rightarrow l^+l^-qq$
- $WW \rightarrow l^+\nu l^-\nu$

Higgs EXCLUDED $2 \cdot M_W < M_H < 558$ GeV (CMS: 600 GeV)

High mass Standard Model Higgs boson (almost) excluded