Physics at Hadron Colliders

Part 2

Standard Model Physics

Test of Quantumchromodynamics
(Jet production, W/Z production, top-quark production, ...)

Precision measurements
(W mass, top-quark mass, ...)

QCD processes at hadron colliders

• Hard scattering processes are dominated by QCD jet production

• originating from quark-quark, quark-gluon and gluon-gluon scattering

• Due to fragmentation of quarks and gluons in final state hadrons → Jets with large transverse momentum $P_T$ in the detector

• Cross sections can be calculated in QCD (perturbation theory)

Comparison between experimental data and theoretical predictions constitutes an important test of the theory.

Deviations? → Problem in the experiment? Problem in the theory (QCD)? New Physics, e.g. quark substructure?
A two jet event at the Tevatron (CDF)

Dijet Mass = 1364 GeV/c²

$E_T = 666 \text{ GeV}$
$\eta = 0.43$

$E_T = 633 \text{ GeV}$
$\eta = -0.19$

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A two jet event in the DØ experiment

$M_{jj} = 838 \text{ GeV/c}^2$
$p_T(1) = 432 \text{ GeV/c}$
$p_T(2) = 396 \text{ GeV/c}$
Test of QCD Jet production

Data from the DØ experiment (Run II)

Inclusive Jet spectrum as a function of Jet-P_T

very good agreement over many orders of magnitude!

within the large theoretical and experimental uncertainties

Similar data for the CDF experiment

contributions of the various sub-processes to the inclusive jet cross section
Main experimental systematic uncertainty: Jet Energy Scale

- A Jet is NOT a well defined object (fragmentation, detector response)
  - one needs an algorithm to define a jet, to measure its energy
  (e.g., a cone around a local energy maximum in the calorimeter, cone size
  adapted such that a large fraction of jet energy is collected,
  typical values: $\Delta R = \sqrt{\Delta \phi^2 + \Delta \eta^2} = 0.7$

- Cluster energy ≠ parton energy

Main corrections:
- In general, calorimeters show different response to electrons/photons and
  hadrons (see lectures on detector physics)

- Subtraction of offset energy not originating from the hard scattering
  (inside the same collision or pile-up contributions, use minimum bias data to
  extract this)

- Correction for jet energy in/out of cone
  (corrected with jet data + Monte Carlo simulations)

Jet response correction in DØ:
- measure response of particles making up the jet
- use photon + jet data - calibrate jets against the better calibrated photon energy
Comparison with Theory

- Fully corrected inclusive jet cross section

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Test of W and Z production

Number of detected W-bosons:

Tevatron: expected rates for 2 fb\(^{-1}\): 3 Mio \(W \rightarrow \ell \nu\) events
LHC: expected rates for 10 fb\(^{-1}\): 60 Mio \(W \rightarrow \ell \nu\) events
How do W and Z events look like?

As explained, leptons, photons and missing transverse energy are key signatures at hadron colliders.

→ Search for leptonic decays: \( W \rightarrow \ell \nu \)
\( Z \rightarrow \ell \ell \)

A bit of history: one of the first W events seen; UA2 experiment

W/Z discovery by UA1 and UA2 experiments at CERN (1983/84)

Today’s W / Z → ev / ee signals

Trigger:
- Electron candidate > 20 GeV, shower shape cut

Electrons
- Isolated EM Cluster in the Calorimeter
- \( E_T > 25 \) GeV with large EM fraction
- Shower shape consistent with MC expectation
- Matched with tracks

\( Z \rightarrow ee \)
- \( 70 \) GeV < \( m_{ee} < 110 \) GeV

\( W \rightarrow ev \)
- Missing transverse momentum > 25 GeV
**$W \rightarrow e\nu\nu$ Cross Section**

Background subtracted distributions compared to Monte Carlo predictions

![Graphs showing $E_\text{t}$ distribution for $W \rightarrow e\nu\nu$ and $W \rightarrow \mu\nu\nu$ channels.]

27370 Candidates in $\int Ldt = 42 \text{ pb}^{-1}$

$$\sigma \text{BR (} W \rightarrow e\nu\nu \text{)} = 3054 \pm 100 \text{ (stat.)} \pm 86 \text{ (syst.)} \pm 305 \text{ (lumi)} \text{ pb}$$

$$\sigma \text{BR (} W \rightarrow \mu\nu\nu \text{)} = 3226 \pm 128 \text{ (stat.)} \pm 100 \text{ (syst.)} \pm 323 \text{ (lumi)} \text{ pb}$$

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**Recent CDF and DØ $Z \rightarrow \mu\mu$ event sample**

![Graphs showing $M_{\mu\mu}$ distribution for $Z \rightarrow \mu\mu$ events.]

1631 events

$\int L = 72 \text{ pb}^{-1}$

$|\eta| < 1.0$

6126 events

$\int L = 117 \text{ pb}^{-1}$

$|\eta| < 1.8$
Top Quark Physics

- Discovered by CDF and DØ collaborations at the Tevatron in 1995
- Run I top physics results are consistent with the Standard Model (Errors dominated by statistics)
- Run II top physics program will take full advantage of higher statistics
  - Better precision
  - Search for deviations from Standard Model expectations
**Top Quark Production**

Pair production: $qq$ and $gg$-fusion

Electroweak production of single top-quarks (Drell-Yan and $Wg$-fusion)

<table>
<thead>
<tr>
<th></th>
<th>Run I 1.8 TeV</th>
<th>Run II 1.96 TeV</th>
<th>LHC 14 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$qq$</td>
<td>90%</td>
<td>85%</td>
<td>5%</td>
</tr>
<tr>
<td>$gg$</td>
<td>10%</td>
<td>15%</td>
<td>95%</td>
</tr>
<tr>
<td>$\sigma$ (pb)</td>
<td>5 pb</td>
<td>7 pb</td>
<td>600 pb</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Run I 1.8 TeV</th>
<th>Run II 1.96 TeV</th>
<th>LHC 14 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma$ (qq) (pb)</td>
<td>0.7</td>
<td>0.9</td>
<td>10</td>
</tr>
<tr>
<td>$\sigma$ (gW) (pb)</td>
<td>1.7</td>
<td>2.4</td>
<td>250</td>
</tr>
<tr>
<td>$\sigma$ (gb) (pb)</td>
<td>0.07</td>
<td>0.1</td>
<td>60</td>
</tr>
</tbody>
</table>

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**Top Quark Decays**

BR ($t\rightarrow Wb$) $\sim$ 100%

Both W's decay via $W\rightarrow \ell\nu$ ($\ell=e$ or $\mu$; 5%)
- **dilepton channel**

One W decays via $W\rightarrow \ell\nu$ ($\ell=e$ or $\mu$; 30%)
- **lepton + jet channel**

Both W's decay via $W\rightarrow qq$ (44%)
all hadronic, not very useful

**Important experimental signatures:**
- Lepton(s)
- Missing transverse momentum
- b-jet(s)
DØ top candidate event with two leptons

\[ p_T(e) = 20.3 \text{ GeV/c}^2 \]
\[ p_T(\mu) = 58.1 \text{ GeV/c}^2 \]
\[ E_T = 141.0, 55.2 \text{ GeV} \]
\[ E_T = 91 \text{ GeV} \]

DØ (100 pb\(^{-1}\)):
\[ \sigma_{tt} = 8.7^{+6.4}_{-4.7} \text{ (stat)} +^{2.7}_{-2.0} \text{ (syst)} \pm 0.9\text{ (lumi)} \text{ pb} \]

CDF (200 pb\(^{-1}\)):
\[ \sigma_{tt} = 6.9^{+2.7}_{-2.4} \text{ (stat)} \pm 1.2\text{ (syst)} \pm 0.4\text{ (lumi)} \text{ pb} \]

Run II preliminary

tt cross section (dilepton)

2 high-\(p_T\) isolated leptons

Large missing \(E_T\), \(\geq 2\) jets
A CDF Lepton + Jet event

K. Jakobs, Universität Freiburg

CERN Summer Student Lectures, July 2004

\[ p_T(\mu) = 54.4 \text{ GeV} \]
\[ E_T = 96.7, 65.8, 54.8, 33.8 \text{ GeV} \]
\[ \text{Missing } E_T = 40.8 \text{ GeV} \]

tt cross section (lepton + jets) (topology, no b-jet identification)

1 high-\( p_T \) isolated lepton

Large missing \( E_T \) 

\( \geq 3 \) jets

\[ H_T = \text{scalar sum of all high } P_T \text{ objects} \]

(jets, leptons, \( E_T^{\text{miss}} \))

Before b-tagging: background from W+jet events clearly dominates
Tagging a b-quark

Soft lepton tagging

- $b \rightarrow \ell \nu c$ (BR $\sim 20\%$)
- $b \rightarrow c \rightarrow \ell \nu s$ (BR $\sim 20\%$)

Search for non-isolated soft lepton in a jet

Silicon Vertex tag

B mesons travel $\sim 3$ mm before decaying:
- Search for secondary vertex

Silicon detectors

Run II: silicon detectors cover a large region of acceptance
**μ + jets double-tagged event**

B tagging established in both experiments!

Important for the top physics measurements

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**tt cross section (lepton + jets) (including b-tagging)**

1 high-\(p_T\) isolated lepton, at least one b-tagged jet

Large missing \(E_T\)

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Excess above the W+ jet background in events with high jet multiplicity
tt cross section summary (preliminary)

<table>
<thead>
<tr>
<th>CDF and DØ Run II Preliminary</th>
</tr>
</thead>
<tbody>
<tr>
<td>DØ Dileptons 90-107 pb$^{-1}$</td>
</tr>
<tr>
<td>CDF Dileptons 200 pb$^{-1}$</td>
</tr>
<tr>
<td>CDF L+Track 126 pb$^{-1}$</td>
</tr>
<tr>
<td>DØ L+jets/CSIP 45 pb$^{-1}$</td>
</tr>
<tr>
<td>DØ L+jets/SVT 45 pb$^{-1}$</td>
</tr>
<tr>
<td>DØ L+jets/topo 92 pb$^{-1}$</td>
</tr>
<tr>
<td>DØ L+jets/soft muon 92 pb$^{-1}$</td>
</tr>
<tr>
<td>DØ L+jets combined 92 pb$^{-1}$</td>
</tr>
<tr>
<td>CDF L+jets/SVX 108 pb$^{-1}$</td>
</tr>
<tr>
<td>CDF L+jets/HT 195 pb$^{-1}$</td>
</tr>
<tr>
<td>CDF L+jets/SVX/kine 108 pb$^{-1}$</td>
</tr>
<tr>
<td>DØ Combined 90-107 pb$^{-1}$</td>
</tr>
</tbody>
</table>

$$\sigma (pb)$$

Good agreement among various exp. measurements and with QCD prediction

QCD prediction:
- Cacciari et al. hep/ph0303085
- Kidonakis hep-ph/0303086

8.1$_{-2.0}^{+2.2}$(stat)$_{-1.4}^{+1.6}$(syst) ± 0.8(lum)

Precision measurements of $m_W$ and $m_{top}$

Motivation:
- W mass and top quark mass are fundamental parameters of the Standard Model;
- The standard theory provides well defined relations between $m_W$, $m_{top}$ and $m_H$

Electromagnetic constant measured in atomic transitions, e+e- machines, etc.

$$m_W = \left( \frac{\pi \frac{\alpha_{EM}}{\sqrt{2}}}{G_F} \right)^{1/2}$$

Fermi constant measured in muon decay

Weak mixing angle measured at LEP/SLC

$G_F$, $\alpha_{EM}$, $\sin \theta_W$ are known with high precision

Precise measurements of the W mass and the top-quark mass constrain the Higgs-boson mass

(and/or the theory, radiative corrections)

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CERN Summer Student Lectures, July 2004
The W-mass measurement

$$m_W = \left( \frac{\pi \alpha_{EM}}{\sqrt{2} G_F} \right)^{1/2} \frac{1}{\sin \theta_W \sqrt{1 - \Delta r}}$$

**W-Boson Mass [GeV]**

<table>
<thead>
<tr>
<th>pp-colliders</th>
<th>LEP2</th>
<th>Average</th>
<th>NuTeV</th>
<th>LEP1/SLD</th>
<th>LEP1/SLD$m_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>m_W [GeV]</td>
<td>80.452 ± 0.059</td>
<td>80.412 ± 0.042</td>
<td>80.425 ± 0.034</td>
<td>80.136 ± 0.084</td>
<td>80.373 ± 0.033</td>
</tr>
</tbody>
</table>

- **$m_W$ (from LEP2 + Tevatron)** = 80.425 ± 0.034 GeV
- **$m_{top}$ (from Tevatron)** = 178.0 ± 4.3 GeV

Ultimate test of the Standard Model: comparison between the direct Higgs boson mass (from observation, hopefully) and predictions from rad. corrections….

Technique used for W-mass measurement at hadron colliders:

Event topology:

```
Event topology:

<table>
<thead>
<tr>
<th>Electron</th>
<th>Neutrino</th>
</tr>
</thead>
<tbody>
<tr>
<td>P_T(e)</td>
<td>P_T(ν)</td>
</tr>
<tr>
<td>P_T(had)</td>
<td>P_T(had)</td>
</tr>
</tbody>
</table>
```

Observables: $P_T(e)$, $P_T$(had)

$$\Rightarrow P_T(\nu) = - (P_T(e) + P_T($had$))$$

$$\Rightarrow M_W^T = \sqrt{2 \cdot P_T^e \cdot P_T^\nu \cdot (1 - \cos \Delta \phi_T)}$$

In general the transverse mass $M_W^T$ is used for the determination of the W-mass (smallest systematic uncertainty).
Shape of the transverse mass distribution is sensitive to $m_W$, the measured distribution is fitted with Monte Carlo predictions, where $m_W$ is a parameter.

$\begin{aligned} m_W &= 79.8 \text{ GeV} \\ m_W &= 80.3 \text{ GeV} \end{aligned}$

$\mathcal{M}_W$ (GeV)

*Main uncertainties:*

result from the capability of the Monte Carlo prediction to reproduce real life:

* detector performance (energy resolution, energy scale, ….)

* physics: production model $p_T(W), \Gamma_W, \ldots.$

* backgrounds

**Dominant error** (today at the Tevatron, and most likely also at the LHC):

Knowledge of lepton energy scale of the detector!

(if the measurement of the lepton energy wrong by 1%, then measured $m_W$ wrong by 1%)

Calibration of the detector energy scale:

Example: EM calorimeter

$\begin{aligned} e^- &\rightarrow \text{beam} \\ E &= 100 \text{ GeV} \end{aligned}$

$\text{CALO} \rightarrow \text{E}_{\text{measured}}$

- if $E_{\text{measured}} = 100.000 \text{ GeV}$ for all calorimeter cells
  $\rightarrow$ calorimeter is perfectly calibrated

- to measure $m_W$ to $\sim 20 \text{ MeV}$, need to know energy scale to $0.2 \%$,
  i.e., if $E_{\text{electron}} = 100 \text{ GeV}$ then $99.98 \text{ GeV} < E_{\text{measured}} < 100.02 \text{ GeV}$

$\Rightarrow$ one of most serious experimental challenges
Calibration strategy:

- detectors equipped with calibration systems which inject **known pulses**:
  
  ![Diagram of a cell with input and output](in-cell-out.png)
  
  → check that all cells give same response: if not → correct

- calorimeter modules calibrated with test beams of **known energy**
  
  → set the energy scale

- inside LHC detectors: calorimeter sits behind Inner Detector
  
  → electrons lose energy in material of Inner Detector
  
  → need a final calibration "**in situ**" by using physics samples:

  e.g. $Z \rightarrow e^+ e^-$ decays
  
  constrain $m_{ee} = m_Z$
  
  known to $\approx 10^{-5}$ from LEP

What precision can be reached in Run II and at the LHC?

<table>
<thead>
<tr>
<th>Int. Luminosity</th>
<th>0.08 fb$^{-1}$</th>
<th>2 fb$^{-1}$</th>
<th>10 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stat. error</td>
<td>96 MeV</td>
<td>19 MeV</td>
<td>2 MeV</td>
</tr>
<tr>
<td>Energy scale, lepton res.</td>
<td>57 MeV</td>
<td>20 MeV</td>
<td>16 MeV</td>
</tr>
<tr>
<td>Monte Carlo model ($P_{T,W}$, structure functions, photon-radiation,...)</td>
<td>30 MeV</td>
<td>20 MeV</td>
<td>17 MeV</td>
</tr>
<tr>
<td>Background</td>
<td>11 MeV</td>
<td>2 MeV</td>
<td>1 MeV</td>
</tr>
<tr>
<td>Tot. Syst. error</td>
<td>66 MeV</td>
<td>28 MeV</td>
<td>24 MeV</td>
</tr>
<tr>
<td>Total error</td>
<td>116 MeV</td>
<td>34 MeV</td>
<td>25 MeV</td>
</tr>
</tbody>
</table>

- Total error per lepton species and per experiment at the **LHC** is estimated to be $\pm 25$ MeV at the **Tevatron** $\pm 34$ MeV

- Main uncertainty: lepton energy scale (goal is an uncertainty of $\pm 0.02\%$

- Many systematic uncertainties can be controlled in situ, using the $Z \rightarrow \ell \ell$ sample ($P_{T}(W)$, recoil model, resolution)

**Combining both experiments (ATLAS + CMS, 10 fb$^{-1}$), both lepton species and assuming a scale uncertainty of $\pm 0.02\%$**

$\Rightarrow \Delta m_{W} \sim \pm 15$ MeV

**Tevatron:** 2 fb$^{-1}$:

$\Delta m_{W} \sim \pm 30$ MeV
Signature of $Z$ and $W$ decays

$Z \rightarrow l^+l^-$

$W \rightarrow l\nu$

Top mass measurement (CDF) (preliminary)

- Top mass calculation:
  - Kinematic fit under (tt) hypothesis
  - compute likelihood for observed events as a function of the top quark mass

Maximum likelihood $\rightarrow m_{top}$

$\int L = 108 \text{ pb}^{-1}$

$177.5^{+12.7}_{-9.4} \text{ (stat)} \pm 7.1 \text{ (syst) GeV/c}^2$

$\int L = 124 \text{ pb}^{-1}$

$175.0^{+17.4}_{-16.5} \text{ (stat)} \pm 7.9 \text{ (syst) GeV/c}^2$
Tevatron results on the top quark mass

Summary of the 2. Lecture

• Hadron Colliders Tevatron and LHC play an important role in future tests of the Standard Model

• Predictions of Quantum Chromodynamics can be tested in
  - High $P_T$ jet production
  - $W/Z$ production
  - Top quark production
  - .......

• In addition, precise measurements of Standard Model parameters can be carried out.

Examples: $W$ mass can be measured to $\sim 15$ MeV
Top-quark mass to $\sim 1$ GeV

$\rightarrow$ Higgs mass constrained indirectly to $\sim 25\%$

Prospects for top-quark mass measurements at the LHC

Year 2007: $\Delta m_{t\bar{t}} \sim 2-3$ GeV (Tevatron)

Best channel for mass measurement:

$tt \rightarrow Wb \ Wb \rightarrow \ell \nu b \ \text{jet jet b}$

(trigger) (mass measurement)

**Experimental numbers:**
- Production cross section: 590 pb
- After exp. cuts: 130,000 $tt$ events in 10 fb$^{-1}$ $S/B \sim 65$

*Estimated syst. uncertainties:*

<table>
<thead>
<tr>
<th>Contribution</th>
<th>$\Delta m_{t\bar{t}}$ (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>statistics</td>
<td>$&lt; 0.07$</td>
</tr>
<tr>
<td>$u,d,s$ jet scale</td>
<td>0.3</td>
</tr>
<tr>
<td>$b$-jet scale</td>
<td>0.7</td>
</tr>
<tr>
<td>$b$-fragmentation</td>
<td>0.3</td>
</tr>
<tr>
<td>initial state rad.</td>
<td>0.3</td>
</tr>
<tr>
<td>final state rad.</td>
<td>0.2</td>
</tr>
<tr>
<td>background</td>
<td>0.2</td>
</tr>
<tr>
<td>Total</td>
<td>$\sim 1.5$ GeV</td>
</tr>
</tbody>
</table>

Syst. uncertainties dominated by final state radiation effects

**Combination of various methods:** $\Delta m_{t\bar{t}} < \sim \pm 1$ GeV