Standard Model Physics at the LHC

Outline of part 2

- **Tests of the Standard Model (QCD)** using jets, top quarks, W/Z – bosons
- **High precision measurements of the** W boson mass and top quark mass
tests of the Standard Model (QCD): jets in pp collisions
**Why do we want to study Jets?**

**QCD Jets at LHC:**

**Motivation: why jets?**

- **Hard QCD subprocess:**
  - Hard (=perturbative=calculable) QCD gives us partons.

- **Jet:**
  - Collimated bundle of particles.

- **Jets are formed in fragmentation:**
  - Colorless ≠ partons.

However:

- **Jets = footprints of partons:**
  - Sensitive to hard subprocess parton dynamics.

Reminder: pp collisions **hard** and **soft** QCD.

- **study QCD – look at jets.**
Why do we want to study Jets?

QCD Jets at LHC: Motivation: why hard QCD?

- Cross section of hard subprocess and jet cross section calculable
- Compare data and theory = test of Standard Model, test of QCD
  - Find problems in theory?
  - Hints of new physics?
    e.g. quarks substructure?
    Known: not down to $10^{-18}$ m
  - Need to understand QCD jets in our detector, in order to find new physics
    “yesterdays signal = tomorrows bgr”
Historic Jet Events

What do jets look like?

Di-Jet event  JADE at PETRA

e+e- collisions at  $\sqrt{s} = 30$ GeV
Historic Jet Events

What do jets look like?

Famous three jet event from PETRA

first hint of gluons

\[ E_{cm} = 35 \text{ GeV} \]
Jet Events at pp colliders

What do jets look like?

Dijet event in CDF
Jet Events in the CDF track detector

2 jet event

Multijets not so clearly seen by unaided eye

helps: calo info!

3 jet event
Jet Events in the CDF calorimeter

Same events as before
now jets clearly visible

but anyway: don't want to do this by eye, need algorithm!
many, introduce just 2 on the next pages...
Jet algorithm \(1\): Cone algorithm

Sum over all calorimeter activities within a certain cone of radius \(R\) around a high energetic cluster

**cut criteria for jet-cone:**

\[
R = \sqrt{(\Delta \varphi)^2 + (\Delta \eta)^2} < y(cut)
\]

\(y(cut)\) typically 0.5 ... 1.0

jet definition depends on \(y\)

**problem:** overlapping jets

**Merge or split?**

\[
\frac{E_{\text{overlap}}}{E_{\text{tot}}} > f \quad \text{merge}
\]

\[
\frac{E_{\text{overlap}}}{E_{\text{tot}}} < f \quad \text{split}
\]

additional parameter \(f\)
Jet not well defined physical object but depend on definition e.g. “cone algorithm with a given y-cut”
Jet algorithm 2: $k_T$ algorithm

Make a list of all particles (e.g. calorimeter clusters)

Calculate for each particle: $d_i = p_{T,i}^2$

Calculate for each pair particle: $d_{ij} = \min(p_{T,i}^2, p_{T,j}^2) \cdot R_{i,j}^2$

where $R_{i,j} = (\Delta \eta_{i,j}^2 + \Delta \phi_{i,j}^2)$

is $d_{i,j} < d_i$ ?

Yes: add clusters $i$ and $j$ to the same jet
No: put cluster $i$ on the list of new jets

repeat until the list is finished
Cone vs $k_T$ algorithm

unambiguous mapping
particles -- jets
soft particles at edges neglected

(complicated boundary
(speed $\sim N^3$ meanwhile: implementation
with $\sim N \ln N$ available, ok!)

(speed)
simple shape of jets

max. procedure not unique
overlap of jets
Jet Energy Scale (JES)

correct from measured energy to energy of the jet of hadrons

take into account:
- offset due to underlying event, pile-up, ...
  subtract $E_0$ that does not belong to this jet:
- leakage in/out cone of jet $R_{ooc}$
- calorimeter response to Jet $R_{jet}$
  different for electrons / photons and hadrons

$$E_{\text{jet}} = \frac{E_{\text{meas}} - E_0}{R_{\text{jet}} R_{ooc}}$$

JES = main experimental uncertainty
typical uncertainty of JES: few%
QCD jet production: example from Tevatron

Inclusive Jet spectrum as a function of Jet-\(P_T\)

Data from the DØ experiment (Run II)

Compared to QCD prediction

Very good agreement over many orders of magnitude!
similar analysis by CDF

data corresponding to $\sim 1 \text{ fb}^{-1}$
double differentially in $P_T$ and $\eta$

Jets = footprints of partons?
contributions of the various
hard subprocesses to the inclusive
jet cross section at different $p_T^{\text{JET}}$

**Quark/Gluon Contributions to Cross Section**

**Leading Order QCD (MRS0')**

- $\eta_1 = \eta_2 = 0$
- $GG$: Gluon-Gluon Scattering
- $QQ$: Quark-Quark scattering
- $GQ$: Quark-Gluon scattering

**CDF Run II Preliminary**

\[
\int L = 0.98 \text{ fb}^{-1}
\]

\[d^2G / dy^{\text{JET}} dp_T^{\text{JET}} [\text{nb/(GeV/c)}]\]

- $K_T$, $D=0.7$
- Data
- Systematic uncertainties
- NLO: JETRAD CTEQ6.1M
- corrected to hadron level
- $\mu_R = \mu_F = \max p_T^{\text{JET}} / 2 = \mu_0$
- PDF uncertainties

\[|y^{\text{JET}}| < 0.1 \left( \times 10^6 \right)\]
\[0.1 < |y^{\text{JET}}| < 0.7 \left( \times 10^6 \right)\]
\[0.7 < |y^{\text{JET}}| < 1.1\]
\[1.1 < |y^{\text{JET}}| < 1.6 \left( \times 10^6 \right)\]
\[1.6 < |y^{\text{JET}}| < 2.1 \left( \times 10^6 \right)\]
Angular correlation in di-jet events

Study angular correlations between jets

- reduced sensitivity to JES
- sensitive to higher orders of QCD
  - 2 partons - 2 jets: back-to-back $\Delta \phi \approx 180^\circ$ “leading order QCD”
  - additional hard partons = “higher orders of QCD”
    not back-to-back any more! smaller $\Delta \phi$ between 2 hardest partons/jets

Good agreement with QCD-predictions if higher orders are included!
W and Z bosons
W and Z bosons

Production in Drell-Yan process

\[ q\bar{q} \rightarrow W(Z) \rightarrow e^+e^- \]

- comparison of data with theory
- test of model
- test of pdf!
- pdf uncertainties!

QCD production

W(Z) + jets

- W/Z = “clean” probe of hard subprocess
- test of QCD
Discovery of W and Z bosons

predicted by electroweak theory as result of Higgs mechanism needed to explain weakness of interaction

discovery in proton-antiproton collisions at SppS at CERN by UA1 and UA2

W and Z event in UA2 experiment

Nobel Prize 1984
Rubbia, van der Meer
CDF and DØ at Tevatron measure inclusive cross section for 
\[ W \rightarrow l\nu \text{ and } Z \rightarrow ll \]
compared to theory

CDF and DØ Run 2 Preliminary

\[ p \bar{p} \rightarrow W + X \rightarrow l \nu + X \]

\[ p \bar{p} \rightarrow Z + X \rightarrow ll + X \]
**W/Z + jets = test of QCD**

*Z + jets pT distribution*

**Z+jets: jet multiplicity**

**D0 Run II Preliminary**

- Z/γ* → e+e- + n jets, 343 pb
- Jets: p_T > 20 GeV, |η| < 2.5
- Data (errors: stat)
- ALPGEN+PYTHIA MC (CTEQ5L)

**Z + 1 jet**

**Z + 2 jets**

**Z + 3 jets**

*comparison with models*

**MC generator SHERPA***
Top quark physics
Top Quark Physics

the top quark is the HEAVIEST fermion in the standard model!
... and the least well known

- discovered only 1995 at Tevatron: CDF and D0
- Tevatron data from RunI: consistent with SM .. so far statistics limited
- new Tevatron data (and LHC!) : better precision deviations from standard model ?

- Top and new physics:
  high mass – probe el. weak symmetry breaking and fermion mass generation
  other massive particles?

- Top at LHC: \[ \sigma(t\bar{t}) = 800 \text{pb} \]
  80 mio \( t\bar{t} \) pairs per year (design Lumi )
- Background to searches for new physics

<table>
<thead>
<tr>
<th>lepton masses</th>
<th>quark masses</th>
<th>[MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>electron 0.511</td>
<td>electron neutrino 0</td>
<td>up 5</td>
</tr>
<tr>
<td>muon 107</td>
<td>muon neutrino 0</td>
<td>down 8</td>
</tr>
<tr>
<td>tau 1777</td>
<td>tau neutrino 0</td>
<td>charm 1500</td>
</tr>
<tr>
<td></td>
<td></td>
<td>strange 160</td>
</tr>
<tr>
<td></td>
<td></td>
<td>top 175 000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>beauty 4200</td>
</tr>
</tbody>
</table>
Top Production in pp collisions

Top pair production

\[
\begin{align*}
\text{cross sections:} & \quad \text{at Tevatron} \sim 5 \text{pb} \\
& \quad \text{at LHC} \sim 800 \text{ pb}
\end{align*}
\]

relative contribution qq-gg :

\[
\begin{align*}
90\% & \quad 10\% \quad \text{at TeV} \\
5 \% & \quad 95 \% \quad \text{at LHC}
\end{align*}
\]

Single top production

Drell-Yan process and Wg fusion

\[
\begin{align*}
\text{cross sections:} & \quad \text{Tevatron} & \quad \text{LHC} \\
\sigma (qq) (\text{pb}) & \sim 1 & 10 \\
\sigma (gW) (\text{pb}) & \sim 2 & 250 \\
\sigma (gb) (\text{pb}) & \sim 0.1 & 60
\end{align*}
\]
Top Quark Decays

- top quark decays before it hadronises – no top mesons or baryons!

- decays to $\sim 100\%$ into W bosons and beauty $t \rightarrow Wb$

  - **dilepton channel**
    - both $W$ decay into leptons
    $$ W \rightarrow l \nu \quad l=e \text{ or } \mu, \ 5\% $$

  - **lepton + jets**
    - one $W$ decays into lepton, the other hadronic
    $$ W \rightarrow l \nu \quad W \rightarrow q\bar{q}' \quad l=e \text{ or } \mu, \ 30\% $$

  - **All hadrons**
    - both $W$ decay into quarks $44\%$
    $$ W \rightarrow q\bar{q}' $$

- signatures: leptons, missing ET, b-jets
Discovery of top Quark at Tevatron

\[ t\bar{t} \text{ Event} \]

SVX Display

CDF

- b-quark lives for \(~10^{-12}\) s
- vertex displace by few mm

Njet distribution w and w/o shifted vertex compared to bgr+top
Discovery of top Quark at Tevatron

combining 3 techniques:

for lepton+jet events:
- shifted vertex of b-decay
- additional leptons from b decay
also
- dilepton events

<table>
<thead>
<tr>
<th>Channel</th>
<th>SVX</th>
<th>SLT</th>
<th>Dilepton</th>
</tr>
</thead>
<tbody>
<tr>
<td>observed</td>
<td>27 tags</td>
<td>23 tags</td>
<td>6 events</td>
</tr>
<tr>
<td>expected bkgd</td>
<td>$6.7 \pm 2.1$</td>
<td>$15.4 \pm 2.0$</td>
<td>$1.3 \pm 0.3$</td>
</tr>
<tr>
<td>bkgd prob</td>
<td>$2 \times 10^{-5}$</td>
<td>$6 \times 10^{-2}$</td>
<td>$3 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

The numbers of tags or events observed in the three channels along with the expected background and the probability that the background would fluctuate to the observed number or more.

5 of the 6 dilepton events have a b-tag unlikely for non-t bgr!

combined bgr-probability $10^{-6}$ corresponding to a 4.8 $\sigma$ discovery

reconstructed mass of leptons + 4jets with b tag

$M_{top} = 176 \pm 8 \pm 10 GeV/c^2$
### D0 top candidate with 2 leptons

- $p_T(e) = 20.3 \text{ GeV/c}^2$
- $p_T(\mu) = 58.1 \text{ GeV/c}^2$
- $E_T = 141.0, 55.2 \text{ GeV}$
- MET = 91 GeV
tt cross section measurements at Tevatron

Lepton + jet channel

signature:
1 isolated high-pT lepton
large missing Et
at least 3 jets

\[ H_T = \sum_{\text{jets,leptons}} p_T + E_T^{\text{miss}} \]

background from W+jet
events can be removed by requiring b-tags

CDF (195 pb\(^{-1}\))
tt cross section measurements at Tevatron

Lepton + jet channel with b-tag

signature:
1 isolated high-pT lepton
large missing Et
at least 1 b-tagged jet

both CDF and D0:
b-tag using silicon detectors

W+1jet, W+2 jet:
control region
sum of bgr describes data

W+3 and more jets:
signal region, top enriched
very clean sample!

Number of Events with W+n jets:
data compared with different MC distribution:
signal top MC and bgr MCs

Lepton + jet channel with b-tag
tt cross section measurements at Tevatron

Good agreement of different measurements and with QCD prediction (similar results for DØ)
Precision measurements of the W boson and top quark mass
Precision measurement of $W$ and top mass

Fundamental parameters of the standard model
relation between $m_t$, $m_W$ and $m_{Higgs}$

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

$\Delta r$, $m_t^2$ and $\log m_H$, 3%

Fermi constant, $\alpha_{em}$ and weak mixing angle known precisely
(from muon decay, $e^+e^-$-or atomic trans., LEP)

Precise measurement of $m_W$ and $m_{top}$:
Constraints on Higgs mass

$m_W$, $m_{top}$ and hopefully also $m_{Higgs}$: ultimate test of SM !!
Today's precision

$M_w$ (from LEP and Tevatron) = 80.410 ± 0.032
$m_t$ (from Tevatron) = 172.5 ± 2.3 GeV
precision: $M_w: 4 \cdot 10^{-4}$ and $m_t: 1.4\%$

Constraining the Higgs mass...
How can W mass be measured?

**Decay** \( W \rightarrow \nu e \) and \( W \rightarrow \nu \mu \)

missing Et and lepton ID

Use \( p_T(e) \) and \( p_T(\text{had}) \)

\[
p_T^\nu = -(p_T(e) + p_T(\text{had}))
\]

\[
M_W^T = \sqrt{2 \cdot p_T^l \cdot p_T^\nu \cdot (1 - \cos \Delta \phi(l, \nu))}
\]

**Transverse mass for** \( e\nu \) and \( \mu\nu \)

Fit of MC templates for different \( M_W \)

**Energy scale calibration using Z peak**

CDF II preliminary \( \int L \, dt = 200 \, \text{pb}^{-1} \)

\[
M_Z = (91190 \pm 67_{\text{stat}}) \, \text{MeV}
\]

\[
\chi^2/\text{dof} = 34/38
\]

CDF II preliminary \( \int L \, dt = 200 \, \text{pb}^{-1} \)

\[
M_W = (80493 \pm 48_{\text{stat}}) \, \text{MeV}
\]

\[
\chi^2/\text{dof} = 86/48
\]
Expected precision from future data

Sources of uncertainties and their expected contribution:

<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>

- **expected**:
  - total error (per lepton flavor, experiment) at LHC ± 25 MeV
  - total error at Tevatron ± 34 MeV

  main uncertainty: lepton energy scale
  systematic uncertainties – estimated by using \(Z \rightarrow ll\) sample

- combining ATLAS and CMS, 10 fb⁻¹ each, \(e \) and \(\mu\) and assuming a lepton energy scale uncertainty of ± 0.02% will be reached
  precision could be \(\Delta m_W \sim \pm 15\) MeV

- Tevatron 2 fb⁻¹ \(\Delta m_W \sim 30\) MeV
How can top mass be measured?

- **kinematic fit** under tt-hypothesis (each event)
- **likelihood** for observed events as function of top mass
- -log(likelihood) has minimum at most likely top mass

Measurements from D0 and CDF:

\[ m_{\text{top}} = 173.4 \pm 3.5 \text{ (stat+JES)} \pm 1.3 \text{ (syst)} \text{ GeV/c}^2 \text{ (CDF)} \]

\[ m_{\text{top}} = 170.6 \pm 4.4 \text{ (stat+JES)} \pm 1.4 \text{ (syst)} \text{ GeV/c}^2 \text{ (DØ)} \]

statistical and JES uncertainty dominant error
Expected precision from future data

**Mass of the Top Quark (\(^*\)Preliminary)**

<table>
<thead>
<tr>
<th>Measurement</th>
<th>(M_{\text{top}} ) [GeV/c(^2)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF-I (l\bar{l})</td>
<td>167.4 ± 11.4</td>
</tr>
<tr>
<td>D(\Phi)-I (l\bar{l})</td>
<td>168.4 ± 12.8</td>
</tr>
<tr>
<td>CDF-II (l\bar{l})*</td>
<td>164.5 ± 5.5</td>
</tr>
<tr>
<td>D(\Phi)-II (l\bar{l})*</td>
<td>176.6 ± 11.8</td>
</tr>
<tr>
<td>CDF-I (l\bar{\tau})</td>
<td>176.1 ± 7.3</td>
</tr>
<tr>
<td>D(\Phi)-I (l\bar{\tau})</td>
<td>180.1 ± 5.3</td>
</tr>
<tr>
<td>CDF-II (l\bar{\tau})*</td>
<td>173.4 ± 2.8</td>
</tr>
<tr>
<td>D(\Phi)-II (l\bar{\tau})*</td>
<td>170.6 ± 4.6</td>
</tr>
<tr>
<td>CDF-I all-(l)</td>
<td>186.0 ± 11.5</td>
</tr>
</tbody>
</table>

\(\chi^2 / \text{dof} = 8.1 / 8\)

**Expected precision from future data**

- **Current value** \(172.5 ± 2.4 \text{ GeV}\)
- **Precision expected from full Tevatron data set:** \(± 1.5 \text{ GeV}\)
- **Expected precision with 10 fb-1 LHC data:** \(± \sim 1 \text{ GeV}\)
Summary

- Hadron colliders can provide future tests of the standard model predictions of Quantum chronodynamics can be tested with jets, W/Z boson production, top quark production
- also precise measurements of standard model parameters
  - $W$ mass $\sim 15$ MeV
  - top quark mass $\sim 1$ GeV
  - providing indirect constraints on the Higgs mass (of $\sim 25\%$)
**tt cross section measurements at Tevatron**

**signature:**

- 2 isolated high-pT leptons from W decays
- Large missing Et
- At least 2 jets

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**Graphs:**

- **Left:**
  - DØ data
  - $t\bar{t}$ ($\sigma_t = 7$ pb)
  - Fake leptons
  - WW/WZ
  - Z/γ
  - Jet multiplicity

- **Right:**
  - CDF Run II preliminary (750 pb⁻¹)
  - Data
  - Background + 1σ uncertainty
  - $t\bar{t}$ ($\sigma_t = 8.3$ pb)
  - WW/WZ
  - DY
  - Fake

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