Top physics and the top mass

Lecture 1/3

2013 CERN-Fermilab HCP Summer School

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Vrije Universiteit Brussel, Belgium
(and this year also: LHC Physics Centre, Fermilab)
Outline

• Wednesday:
  – Lecture 1: Intro to top physics and its jargon.
    • Historic perspective
    • Experimental aspects

• Thursday:
  – Lecture 2: SM top physics and the top mass

• Friday:
  – Lecture 3: SM and top physics, the portal to physics searches
The building blocks of matter

**QUARKS**
- **u** (up): mass $\approx 2.3$ MeV/c$^2$, charge $2/3$, spin $1/2$
- **c** (charm): mass $\approx 1.275$ GeV/c$^2$, charge $2/3$, spin $1/2$
- **t** (top): mass $\approx 173.07$ GeV/c$^2$, charge $2/3$, spin $1/2$
- **d** (down): mass $\approx 4.8$ MeV/c$^2$, charge $-1/3$, spin $1/2$
- **s** (strange): mass $\approx 95$ MeV/c$^2$, charge $-1/3$, spin $1/2$
- **b** (bottom): mass $\approx 4.18$ GeV/c$^2$, charge $-1/3$, spin $1/2$
- **Higgs boson**

**LEPTONS**
- **e** (electron): mass $0.511$ MeV/c$^2$, charge $-1$, spin $1/2$
- **μ** (muon): mass $105.7$ MeV/c$^2$, charge $-1$, spin $1/2$
- **τ** (tau): mass $1.777$ GeV/c$^2$, charge $-1$, spin $1/2$
- **ν$e$** (electron neutrino): mass $<2.2$ eV/c$^2$, charge $0$, spin $1/2$
- **ν$μ$** (muon neutrino): mass $<0.17$ MeV/c$^2$, charge $0$, spin $1/2$
- **ν$τ$** (tau neutrino): mass $<15.5$ MeV/c$^2$, charge $0$, spin $1/2$
- **W** (W boson): mass $80.4$ GeV/c$^2$, charge $\pm 1$

**GAUGE BOSONS**
- **γ** (photon): mass $0$, charge $0$
- **Z** (Z boson): mass $91.2$ GeV/c$^2$, charge $0$

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The building blocks of matter

<table>
<thead>
<tr>
<th>LEPTONS</th>
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<tbody>
<tr>
<td>Charge</td>
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<tr>
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<td>Electron neutrino</td>
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<td>1</td>
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<tr>
<td>Electron</td>
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<tr>
<td>Mass: 0.511</td>
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<table>
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<th>MASS (MeV/c^2)</th>
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<td>Electron</td>
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<td>0.511</td>
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<tr>
<td>Muon neutrino</td>
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<td>0.000</td>
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<td>Tau neutrino</td>
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<table>
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<th>QUARKS</th>
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<tbody>
<tr>
<td>Charge</td>
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<tr>
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<tr>
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<tr>
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</tr>
<tr>
<td>Charm</td>
</tr>
<tr>
<td>Mass: 1,500</td>
</tr>
<tr>
<td>-1/3</td>
</tr>
<tr>
<td>Down</td>
</tr>
<tr>
<td>Mass: 8</td>
</tr>
<tr>
<td>Strange</td>
</tr>
<tr>
<td>Mass: 160</td>
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<td>Bottom</td>
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<tr>
<td>Mass: 4,250</td>
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<table>
<thead>
<tr>
<th>MASS (MeV/c^2)</th>
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<tbody>
<tr>
<td>Up</td>
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Masses are in millions of Electron Volts [MeV/c^2]

Lepton and quark sizes represent proportional mass
Top quark is heavy!!!

Freya
**History of the top quark**

- 1989: Indirect constraints on top from precision measurements at LEP

- 1995: Observation of Top-quark at the TeVatron collider at Fermilab

- Historic perspective indirect -> direct measurements -> precision
History of the top quark

**discovery**

PRL 74, 2632 (1995)

PRL 74, 2626 (1995)

**precision**

17 events

DØ

19 events

CDF

10000s of events

LHC:

top quark factory

1995, CDF and DØ experiments, Fermilab

Tevatron

searches

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Top quark – special?

• Many models predict that top is special in order to explain large mass

• Or top quark has special role because of its large mass
  – some more in lecture 3
Top pair production at hadron colliders

- Pair production in 8 TeV pp collisions:

\[
\begin{align*}
&g & t & g & t \\
&g & \bar{t} & g & \bar{t} \\
&\bar{q} & g & t & \bar{t} \\
&\bar{q} & t & \bar{t} \\
\end{align*}
\]

\(~90\%
\)

\(~10\%\)

Figure 1: MSTW 2008 NLO PDFs at \(Q^2 = 10^2\) GeV\(^2\) and \(Q^2 = 10^4\) GeV\(^2\).

The contents of this paper are as follows. The new experiment al information is summarised in Section 2. An overview of the theoretical framework is presented in Section 3 and the treatment of heavy flavours is explained in Section 4. In Section 5 we present the results of the global fits and in Section 6 we explain the improvements made in the error propagation of the experimental data to the PDF uncertainties, and their consequences. Then we present a more detailed discussion of the description of different data sets included in the global fit: inclusive DIS structure functions (Section 7), dimuon cross sections from neutrino–nucleon scattering (Section 8), heavy flavour DIS structure functions (Section 9), low-energy Drell–Yan production (Section 10), \(W\) and \(Z\) production at the Tevatron (Section 11), and inclusive jet production at the Tevatron and at HERA (Section 12). In Section 13 we discuss the low-

\(x\)

\text{-gluon and the description of the longitudinal structure function, in Section 14 we compare our PDFs with other recent sets, and in Section 15 we present predictions for \(W\) and \(Z\) total cross sections at the Tevatron and LHC. Finally, we conclude in Section 16. Throughout the text we will highlight the numerous refinements and improvements made to the previous MRST analyses.}
Single Top production

- Electroweak production of top quarks

- Dominant channels at LHC @ 8 TeV:
  - t-channel: 87 pb
  - tW channel: 22 pb
  - s-channel: 5.6 pb
Top pair branching fractions

- "alljets" 44% = six jets
- τ+jets 15%
- μ+jets 15%
- e+jets 15%
- "dileptons" = two jets, two leptons, MET
- "lepton+jets" = four jets, lepton, MET

B-quark identification used to reduce background
Top physics: decay channel choice

- selection of top quark events inversely proportional to the complexity of the mass reconstruction

<table>
<thead>
<tr>
<th></th>
<th>Isolation signal</th>
<th>Reconstruction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Di-lepton</td>
<td>Relatively easy</td>
<td>Two neutrinos, ambiguities</td>
</tr>
<tr>
<td>Lepton+jets</td>
<td>Reasonable</td>
<td>One neutrino, use missing transverse energy</td>
</tr>
<tr>
<td>All-hadronic</td>
<td>Very difficult</td>
<td>Possibility to observe top as ‘peak’ in invariant mass spectrum, no energetic neutrinos</td>
</tr>
</tbody>
</table>
Observation of single top production:
- cross section $\propto V_{tb}^2$
- study top-polarization and EWK top interaction

Test of non-SM phenomena:
- 4th generation
- FCNC couplings
- $W'$, $H^\pm$
- anomalous $W_{tb}$ couplings

Main backgrounds:
- s-channel: Top pair, $W + (HF)$ jets, QCD
- t-channel: Top pair, $W + (HF)$ jets, QCD
- Wt-channel: Top pair, $Z + (HF)$ jets, QCD

Signal – background discrimination:
- Tevatron: multivariate methods (neural networks, boosted decision trees, matrix element method)
- LHC: cut-based or multivariate method

<table>
<thead>
<tr>
<th>Collider</th>
<th>s-channel: $\sigma_{tb}$</th>
<th>t-channel: $\sigma_{tq_b}$</th>
<th>Wt-channel: $\sigma_{r_W}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tevatron: p\bar{p} (1.96 TeV)</td>
<td>1.05 pb</td>
<td>2.08 pb</td>
<td>0.22 pb</td>
</tr>
<tr>
<td>LHC: pp (7 TeV)</td>
<td>4.6 pb</td>
<td>66 pb</td>
<td>15.7 pb</td>
</tr>
</tbody>
</table>
How to find top quarks?
Top quark physics – benchmark physics

- To find and reconstruct top quarks, a fully operational and hermetic General Purpose Detector is needed.
- This is why top quarks were used to confirm and check calibrations and detector performance at the start of the LHC runs at 7 and 8 TeV.

For boosted jets see S. Fleischmann on Thursday.
A Toroidal Lhc ApparatuS

Muon Detectors
Electromagnetic Calorimeters
Solenoid
Forward Calorimeters
End Cap Toroid
Barrel Toroid
Inner Detector
Hadronic Calorimeters
Shielding

Detector characteristics
Width: 44m
Diameter: 22m
Weight: 7000t

CERN AC - ATLAS V1997

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Compact Muon Solenoid

CMS Detector

- **Pixels**
- **Tracker**
- **ECAL**
- **HCAL**
- **Solenoid**
- **Steel Yoke**
- **Muons**

**Crystalline Electromagnetic Calorimeter (ECAL)**
- 76k scintillating PbWO₄ crystals

**Silicon Tracker**
- Pixels (100 x 150 μm²)
- ~1 m², 66M channels
- Microstrips (50-100μm)
- ~210 m², 9.6M channels

**Steel Return Yoke**
- ~13000 tonnes

**Superconducting Solenoid**
- Niobium-titanium coil carrying ~18000 A

**Hadron Calorimeter (HCAL)**
- Brass + plastic scintillator

**Forward Calorimeter**
- Steel + quartz fibres

**Muon Chambers**
- Barrel: 250 Drift Tube & 500 Resistive Plate Chambers
- Endcaps: 450 Cathode Strip & 400 Resistive Plate Chambers

**Total weight**: 14000 tonnes
**Overall diameter**: 15.0 m
**Overall length**: 28.7 m
**Magnetic field**: 3.8 T

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Typical GPD coordinate system

\[ \eta = - \ln \left( \tan \left( \frac{\theta}{2} \right) \right) \]
\[ y = \frac{1}{2} \ln \left( \frac{E + p_L}{E - p_L} \right) \]

\( Y \)
\( \eta = 0 \)
\( \theta = 90^\circ \)
\( \theta = 45^\circ \)
\( \theta = 10^\circ \)
\( \theta = 0^\circ \rightarrow \eta = \infty \)
\( Z \)

**XYZ Right handed coordinate system**

with \( z \) in beam direction

+ cylindrical coordinates around \( Z \) axis

Typical inputs of 4-vector:
\( p_T, \phi, \eta, E \)
• ATLAS and CMS: outstanding performance during LHC Run I

• Detector performance consistent during full run, sometimes even improved from between-fill repairs

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Luminosity comes at a price: Pileup

Lots and lots of low energy deposits

Tracking worked

78 (!) vertices

One electron

2 muons
LHC 2012 run: Pile-Up

- Outstanding LHC performance comes at a price:
  - 2011:
    - Run A: 5 PU
    - Run B: 8 PU
  - 2012:
    - Average: 21 PU

![Graph showing ATLAS Online Luminosity](image)

**ATLAS Online Luminosity**
- $\sqrt{s} = 8$ TeV, $\int L dt = 6.3$ fb$^{-1}$, $\langle \mu \rangle = 19.5$
- $\sqrt{s} = 7$ TeV, $\int L dt = 5.2$ fb$^{-1}$, $\langle \mu \rangle = 9.1$
Two kinds of pile-up

• In-time pile-up:
  – Multiple interactions from a single LHC bunch crossing

• Out-of-time pile-up:
  – Particles from previous bunch – 50 ns bunch spacing
  – But detectors can have much longer response time so there might still be some ‘remaining’ signal from previous collision
Identify pile-up

- Tracking and identification of primary vertices used to identify which particle belongs to which collision
- Evident for charged particles but more difficult for neutral hadrons…
- ATLAS uses fraction of tracks in jet associated with hard scatter interaction
Particle flow

HCAL deposit

ECAL deposit

Charged hadron

Muon

Photon

Neutral hadron
**Particle flow in practice**

- PF combines information from all subdetectors in a global event description
  - reconstruct ‘particles’ such as charged/neutral hadrons, photons, muons, electrons

- These particles are used to construct composite objects such as jets, taus, missing transverse energy
  - Reject tracks from non-leading collisions before creating composite objects
  - And make assumptions for background from neutral particles

- Widely used in CMS, LHCb
  - CMS: big improvements in energy resolution jets, MET, tau identification,
Object reconstruction

Background from long lived non-b jets?
Increased track multiplicity from pile-up degrades performance?

Pile-up affects reconstruction?
Jets where only lepton seen?
Actual fakes?

Good enough resolution to see W mass peak?

From pile-up?
Electronics/detector noise?

Affected by pile-up?
Electronics/detector noise?
Leptons – trigger

- Most important: **trigger** and get the events on tape

- Different triggers used for different channels
  - ATLAS: extremely good one-lepton triggers
    - $p_T$ thresholds of 20 GeV or lower
  - CMS: strong at lepton+jets triggers
    - $p_T$ thresholds of 24-27 GeV for single leptons
    - Lower lepton $p_T$ thresholds using lepton+jets requirements
  - Di-lepton triggers have low thresholds and high priority
  - Multijet triggers need very stringent requirements and tuning to keep rate low

---

ATLAS Preliminary
Data 2011 $\int L dt = 206$ pb$^{-1}$
e20_medium trigger
- L1 ($E_T > 14$ GeV)
- L2 ($E_T > 19$ GeV)
- EF ($E_T > 20$ GeV)
Muons combine inner tracking and outer muon system information in track fit.
• Both ATLAS and CMS combine info from tracking and (em) shower shape calorimeter in multivariate technique.

Electron isolation and efficiency:

- Created summing energy deposits from individual particles within a cone around the lepton.
- Negligible contribution from charged hadrons from primary vertex.
- Neutral contribution corrected using the average energy density.

Efficiency is stable in a high Pile up environment.

Data 2011: \( \int L dt = 4.7 \text{ fb}^{-1} \)

Electron identification efficiency [%]:

- ATLAS Preliminary
- Data 2011

Loose++:
- 2012 selection
- 2011 selection

Medium++:
- 2012 selection
- 2011 selection

Tight++:
- 2012 selection
- 2011 selection
• Both ATLAS and CMS use Z bosons to check performance for muons and electrons
Leptons and pileup

Electron isolation and efficiency

Efficiency is stable in a high Pileup environment!

Isolation very stable with pile up!

Created summing energy deposits from individual particles.

\[ \Delta R = 0.4 \] cone around the lepton!

Negligible contribution from charged hadrons from primary vertex!

Neutral contribution corrected using the average energy density!

Electron efficiency stable vs # vertices!

Muon identification efficiency!

\[ \mu \] > 20 GeV

\[ |\eta(\mu)| < 2.1 \]

Efficiency very stable in a high Pileup environment!

Efficiency higher than 95% for \( p_T > 35 \) GeV!

BarrelMuon identification efficiency vs # vertices!

Probes in barrel: \( 0 < |\eta_{\text{probe}}| < 1.479 \)

Substantial effort necessary to achieve this stability!
Isolation

- Since hard processes produce large angles between the final state partons and the beam remnant jets stay close to the beam line, the objects we are interested in for our studies are usually well separated or "isolated" from other objects in the event.

- Isolation is applied by drawing a cone around the object of interest in $\eta$-$\phi$ space; adding up the extra $E_T$ in the cone (exclusive of the $E_T$ of the candidate); and rejecting the object if the "extra $E_T$" is more than a certain fraction of the $E_T$ of the candidate.

- Example of isolation: discriminating an isolated muon from a W from a muon coming from the semileptonic decay inside a b-jet.
Jets

- For most analyses, CMS and ATLAS use anti-\(k_T\) jets with a distance parameter \(d\)
  - ATLAS: \(d=0.4\)
  - CMS: \(d=0.5\)
- ATLAS relies on outstanding quality of calorimeter to get good jet performances
- CMS Particle flow algorithm allows very good agreement between data and MC with small uncertainties and good resolution
- Both experiments carefully correct for pile-up vertices
- CMS has need for very detailed understanding of fraction of different particles per jet and fraction of pile-up particles in jet as these are subtracted by the particle flow algorithm.

Jets in CMS

PFJets, reconstructed with anti-kT algorithm (Cone 0.5)

Well calibrated jets are important for any analysis

Factorized approach for jet calibration in CMS

1. Set corrections for pile-up and electronic noise
2. Corrections for detector calibrations and efficiencies from MC
3. Relative residual corrections for x dependence (data based)
4. Residual corrections to absolute p_T (data based)

Impact on mass measurement, cross-section, on total syst. uncertainty

JES uncertainty < 2% for most of the p_T range, JER about 10%
b-quark jets

Discriminants of b jets from light quark or gluon jets based on

- Long lifetime of b-hadrons in them
  \[ \tau = 1.512 \times 10^{-12} \text{ s}, \ c\tau = 455.4 \ \mu\text{m} \]
- High masses
- High fraction of semi-leptonic decays
  \[ \sim 10\% \ e, \ \mu \ (\text{and from charm}) \]
- Hard fragmentation

\[ L = \langle \gamma c\tau \rangle \]

\[ \theta \sim 1/\gamma \]

\[ \sigma_L \sim 1/\theta \sim \gamma \]

\[ L/\sigma_L \sim \text{independent of } p \text{ of } B \]

\[ \text{Impact parameter} \sim 1/2\pi c\tau \text{ independent of } p \]

Methods for discrimination

- Impact parameter based
  - Track counting high efficiency
  - Track counting high purity
  - Jet probability
  - Jet B probability
- Secondary vertices
  - Simple secondary vertex
  - Combined secondary vertex
- Lepton based algorithms
  - Soft muon by PTrel
  - Soft muon by IP significance
  - Soft electron
- Combined algorithm
  - Combined MVA

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Jets with b-tagging

- Long lifetime of b-hadrons in b-jets
  - $\tau = 1.512 \times 10^{-12}$ s
  - $c\tau = 455.4 \mu$m
- Combination of lifetime information in MVA
- Efficiency measured in top and QCD events (data) using multiple methods
Particle flow extremely powerful approach for missing ET reconstruction

Missing ET sensitivity to PU irreducible
- But well reproduced in MC
On the momentum of top quarks

- Once boost of top quarks high enough
- Decay products become collimated
  - W->qq in one jet
  - Or t->bqq in one jet
- Special reconstruction algorithms needed
Jets with substructure

Jet 1: Top Tagging
pt 589.1 GeV/c,
3 subjets,
mass = 186.7 GeV/c^2,
minMass = 87.2 GeV/c^2

Jet 2: Jet Pruning
pt 484.3 GeV/c,
mass = 68.8 GeV/c^2
Jet 2 + 3: Mass = 167

Jet 3:
pt 47.8 GeV/c,
b-tag discriminant 4.2
Jets with substructure
Validation in lepton+jets events

- Algorithm validated using muon+jets selection

- Data shows that W boson and top quark (using di-jet events) can be reconstructed this way and is reasonably well modeled
Jet:
\( p_T = 84.1 \text{ GeV/c} \)
\( \eta = -2.24 \)

Jet:
\( p_T = 89.0 \text{ GeV/c} \)
\( \eta = 2.14 \)

Jet:
\( p_T = 85.3 \text{ GeV/c} \)
\( \eta = 2.02 \)

Jet:
\( p_T = 90.5 \text{ GeV/c} \)
\( \eta = -1.40 \)

Muon:
\( p_T = 71.5 \text{ GeV/c} \)
\( \eta = -0.82 \)

\( m(t\bar{t}) = 1.2 \text{ TeV/c}^2 \)
Important: parton density functions determine all LHC cross sections!

**Proton structure probe**

Neutral current Deep Inelastic Scattering (DIS) cross section:

\[
\frac{d^2\sigma^\pm}{dx dQ^2} = \frac{2\pi\alpha^2 Y_+}{Q^4 x} \sigma_r^\pm =
\]

\[
= \frac{2\pi\alpha^2 Y_+}{Q^4 x} \left[ F_2(x, Q^2) - \frac{y^2}{Y_+} F_L(x, Q^2) \mp \frac{Y_-}{Y_+} x F_3 \right]
\]

where factors \( Y_\pm = 1 \pm (1 - y)^2 \) and \( y^2 \) define polarisation of the exchanged boson and \( y = Q^2/(S x) \).

Kinematics is determined by \( Q^2 \) and Bjorken \( x \).

At leading order:

\[
F_2 = x \sum e_q^2(q(x) + q(x))
\]

\[
xF_3 = x \sum 2e_q a_q(q(x) - q(x))
\]

\[
\sigma_{CC}^+ \sim x(u + c) + x(1 - y)^2(d + s)
\]

\[
\sigma_{CC}^- \sim x(u + c) + x(1 - y)^2(d + s)
\]

\( xg(x) \) — from \( F_2 \) scaling violation, jets and \( F_L \)

For most processes, LHC essentially is a \( gg \) collider
LHC: Top quark pair factory

- Cross sections $\sim 225$ pb
- In combination with $20 / fb$ datasets:
  - LHC is a top factory
  - Very productive program of Standard Model precision top physics
Top pair production
Production cross section overview

CMS Preliminary

- CMS combined 7 TeV (1.1 fb⁻¹)
- CMS combined 8 TeV (2.8 fb⁻¹)
- CDF
- D0

228 ±9 ±11 ±10 pb
(ICHEP’12 prelim)

7 TeV dominated by
162 ±2 ±5 ±4 pb
(JHEP 11 (2012) 067)

Approx. NNLO QCD (pp)
Scale uncertainty
Scale × PDF uncertainty
Approx. NNLO QCD (pp)
Scale uncertainty
Scale × PDF uncertainty

MSTW 2008 NNLO PDF, 90% C.L. uncertainty
Top cross sections

• Good benchmark to explain basic strategies in top physics and see main backgrounds

• Chosen result: ATLAS CONF-2012-149

• This is an analysis that uses the kinematical quantities of events with one lepton and (at least) 3 jets, including one b-tagged jet, to derive the total number of top quark events in the sample
  – And from that the production cross section
Event quantities

Expected from detailed MC simulation using full detector response (GEANT)
Events generated with full Standard Model matrix element at Next-to-leading order, and full modeling of hadronization of quarks/gluons
Simulation takes much time (typical: few min/event at least)
Events scaled to NNLO theory cross section predictions

<table>
<thead>
<tr>
<th>Event Type</th>
<th>$e+\geq 3$ jets</th>
<th>$\mu+\geq 3$ jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}$</td>
<td>$31000^{+2900}_{-3100}$</td>
<td>$44000\pm4000$</td>
</tr>
<tr>
<td>$W$+jets</td>
<td>$5700\pm2400$</td>
<td>$9000\pm4000$</td>
</tr>
<tr>
<td>Multijet</td>
<td>$1900\pm900$</td>
<td>$1100\pm500$</td>
</tr>
<tr>
<td>$Z$+jets</td>
<td>$1400\pm600$</td>
<td>$1200\pm500$</td>
</tr>
<tr>
<td>Single top</td>
<td>$3260\pm160$</td>
<td>$4610\pm230$</td>
</tr>
<tr>
<td>Dibosons</td>
<td>$115\pm6$</td>
<td>$158\pm8$</td>
</tr>
<tr>
<td>Total Expected</td>
<td>$43000\pm4000$</td>
<td>$61000\pm6000$</td>
</tr>
<tr>
<td>Data</td>
<td>$40794$</td>
<td>$58872$</td>
</tr>
</tbody>
</table>
EWK cross section overview

Question: why at LHC $W^+$ different than $W^-$?
Multijet background, aka ‘QCD’

‘Electron’s that are ‘QCD’
- Overlap track w/ photon
- Photon conversions
- b-quarks and c-quarks that decay to leptons
  - Rest of decay missed? Real leptons
- Jets with fluctuations in hadronization
  - Very few charged tracks
  - Very small hadronic energy fraction

‘Muons’ that are ‘QCD’
- Pions, kaons that decay in flight in tracking region
- b-quarks and c-quarks decaying to leptons
  - rest of decay missed? Real leptons
- Hadrons that did not shower in calorimeter?
- Punch-through hadrons

Simulation of fake electrons and muons using simulated QCD events is both unreliable and impractical
Data-driven methods

Many methods, all rely on isolating a control region enriched in fake leptons

- Select a sample of known lepton-like jets (looser version of your sample) and determine how often you see a muon or electron
  - Derive shapes from this and normalise to sideband (low Missing ET for example)
  - Good at modeling bad hadronization

- Or determine a sample of ‘anti’ electrons/muons by inverting one of the selection cuts (typically the isolation requirement)
  - Very good at modeling complex variables
  - Good at modeling HF jets that fake isolated leptons

arXiv:1108.3773
**Data-driven methods**

**Matrix method:**
Use two control regions with different, known, real/fake fraction and compare them to derive both fake rate and efficiency or vice versa

- Involves matrix inversion of 2x2 matrix
- Needs well-understood sample composition of loose and tight sample
- Or needs known efficiency and known fake rate derived from other samples such as multijet and Z-\(\rightarrow\)ll resonance

- **Advantage:** can completely determine composition of samples and with small uncertainties
  - But is complicated and involves many cross checks

Non-prompt background in CMS 7 TeV dilepton cross section analysis derived this way

![Graph showing entries vs. jet multiplicity](image)

CMS 2.3 fb\(^{-1}\) at \(\sqrt{s} = 7\) TeV

Also commonly used in determination b-tag efficiency and fake rate from b-bbar events
Back to ATLAS’ cross section measurement

- **Muon multijet contribution derived with matrix method**
  - Used high MET (>100) region (few fakes) and low MET (<20) region to determine fake rate.
  - Low MET region of course contained W and Z bosons so those were subtracted using simulated contributions

- **Electron multijet contribution derived from jet-enriched sample**
Combined in likelihood

- Likelihood in this case means single number per event quantifying how top-like the event is

- Statistical fit that varies backgrounds within their uncertainties used to determine remaining number of ttbar events, which is then used:

\[
\sigma_{\text{fit}} = \frac{N_{\text{fit}}}{\mathcal{L} \times BR \times \varepsilon_{\text{sig}}}
\]

- Efficiencies: determined from simulation with corrections from data
Systematic uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>$e^+ \geq 3$ jets</th>
<th>$\mu^+ \geq 3$ jets</th>
<th>combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet/MET reconstruction, calibration</td>
<td>6.7, -6.3</td>
<td>5.4, -4.6</td>
<td>5.9, -5.2</td>
</tr>
<tr>
<td>Lepton trigger, identification and reconstruction</td>
<td>2.4, -2.7</td>
<td>4.7, -4.2</td>
<td>2.7, -2.8</td>
</tr>
<tr>
<td>Background normalization and composition</td>
<td>1.9, -2.2</td>
<td>1.6, -1.5</td>
<td>1.8, -1.9</td>
</tr>
<tr>
<td>b-tagging efficiency</td>
<td>1.7, -1.3</td>
<td>1.9, -1.1</td>
<td>1.8, -1.2</td>
</tr>
<tr>
<td>MC modelling of the signal</td>
<td>±12</td>
<td>±11</td>
<td>±11</td>
</tr>
<tr>
<td>Total</td>
<td>±14</td>
<td>±13</td>
<td>±13</td>
</tr>
</tbody>
</table>

- Each of these numbers involves rerunning the analysis taking into account known uncertainties on the lepton reconstruction, etc.
- Some, like the ‘MC modelling’ uncertainty, contain many effects such as ISR/FSR model uncertainty, parton density functions, parton shower models, uncertainties of the event generator used for the simulation
- More examples of systematic studies/uncertainties in next lectures
Final cross section

• Final cross sections traditionally (in top physics) have several uncertainties:

\[ \sigma_{t\bar{t}} = 241 \pm 2 \text{ (stat.)} \pm 31 \text{ (syst.)} \pm 9 \text{ (lumi.)} \text{ pb}. \]

• The analysis determined the cross section at 8 TeV, which of course also has theory predictions. Some examples:
  – (approximate) Next-to-next-to-leading order assuming QCD production of generic heavy quarks: 238±10% pb (HATHOR, arXiv:1007:1327)
  – Full next-to-next-to-leading order: 246±3%±2.6 pb (arXiv:1303.6254)
And in the end…

ATLAS Preliminary

\[ \sigma_{Z^0} [pb] \]

- NLO QCD (pp)
- Approx. NNLO (pp)
- NLO QCD (p\bar{p})
- Approx. NNLO (p\bar{p})

- Single Lepton (8 TeV) 241 ± 32 pb
- Single Lepton (7 TeV) 179 ± 12 pb
- Dilepton 173 ± 17 pb
- All-hadronic 167 ± 81 pb
- Combined 177 ± 11 pb
End of lecture one – questions?
Use to predict cross sections

CTEQ6L1: gg

Parton Luminosity [nb]

\( \sqrt{s} \) [TeV]

0.9 TeV
2 TeV
4 TeV
6 TeV
7 TeV
10 TeV
14 TeV

http://lutece.fnal.gov/PartonLum/

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