Top Quark at LHC

2011-2012 Intercollegiate PostGraduate Course in Elementary Particle Physics

London, UCL Bloomsbury Campus
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Francesco Spanò

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Outline

• Why top quark?

• The tools of the trade
  ‣ LHC: a top factory at work
  ‣ The ATLAS and CMS detectors: top observers

• Measuring top quark production
  ‣ top pair
  ‣ single top

• Top Properties
  ‣ Top mass
  ‣ Angles: spin correlations (production)

• Top pair production as a window on new physics
  ‣ Resonances in $t\bar{t}$
Standard (model) successes

W, Z, bosons unify Electro-weak force

Only 3 standard neutrinos

Top quark is found
Standard (model) questions

• What is the origin of mass?

• Why 3 generations with different quantum numbers?

• Why different forces (ranges, strengths)?

• What accounts for the energy balance of the universe?
Standard (model) questions

• What is the origin of mass?
  Higgs, SuperSymmetry, New Strong forces..

• Why 3 generations with different quantum numbers?
  4th generation...?

• Why different forces (ranges, strengths)?
  String theory..

• How is gravity incorporated?
  Quantum gravity Extra dimensions...

• What accounts for the energy balance of the universe?
  Dark matter, Dark energy...
Standard (model) questions

• What is the origin of mass?
  Higgs, SuperSymmetry, New Strong forces..

• Why 3 generations with different quantum numbers?
  4th generation...?

• What accounts for the energy balance of the universe?
  Dark matter, Dark energy...

• How is gravity incorporated?
  Quantum gravity, Extra dimensions...

• Why different forces (ranges, strengths)?
  String theory...

• Higgs, SuperSymmetry, New Strong forces...
No flavour changing neutral currents: no b iso-singlet

\[ \begin{bmatrix} c \\ s' \end{bmatrix}_L \quad b' \rightarrow s + l^+l^- \]

\( I_3 = -1.2 \) for b quark required by Z width in \( b\bar{b} \) decay. Need additional quark, isospin partner of b, with \( I_3 = +1.2 \)

No triangular fermion loops anomalies i.e. additional quark required for lept.-ferm. cancellation

\[ \sum L I_{3A} Q^2 = - \sum L I_3 \left( I_3 + \frac{1}{2} Y \right)^2 \]

\[ \sum L Y \sim \sum L Q \]
1995: top is discovered! \[ \sqrt{s} = 1.8 \text{ TeV} \]

\[ m_{\text{top}} = 176 \pm 8 \text{(stat.)} \pm 10 \text{(sys.)} \text{ GeV/c}^2 \]

\[ \sigma_{\bar{t}t} = 6.8^{+3.6}_{-2.4} \text{ pb.} \]

**p\bar{p} collisions**

19 sel. events
exp bkg: 6.9
4.8 s.d. significance

**mass from lkl fit to shape**

17 sel. events
exp bkg: 3.8
4.6 s.d. significance

\[ m_{\text{top}} = 199^{+19}_{-21} \text{(stat.)} \pm 22 \text{(syst.)} \text{ GeV/c}^2 \]

\[ \sigma_{\bar{t}t} = 6.4 \pm 2.2 \text{ pb.} \]
From bottom to top: the global picture

2009: single top observed!

Table 2 summarises the history of searches for the top quark.

<table>
<thead>
<tr>
<th>Year</th>
<th>Collider</th>
<th>Particles</th>
<th>References</th>
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<tbody>
<tr>
<td>1987–90</td>
<td>TRISTAN (KEK)</td>
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<td>1979–84</td>
<td>PETRA (DESY)</td>
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<td>1990</td>
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<tr>
<td>1991</td>
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<tr>
<td>1992</td>
<td>TEVATRON (FNAL)</td>
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<th>Collider</th>
<th>Particles</th>
<th>References</th>
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<tbody>
<tr>
<td>1990</td>
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<tr>
<td>1991</td>
<td>CDF direct</td>
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<td>1992</td>
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<td>1993</td>
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<td>1994</td>
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indirect bound from EWK data
world average direct measurement
CDF direct
D0 direct pub
Why Top (quark)?

Most massive constituent of matter

$M_{\text{top}} \sim$ electroweak symmetry breaking scale

Decay and strong production rate are tests of standard model

Various scenarios with direct/indirect coupling to new physics:
from extra dimensions to new strong forces

Background to possible new physics (Higgs, SUSY)
LHC : a Top producer
counter-rotating high intensity proton bunches colliding at center of mass
energy ($E_{cm}$) = 7 TeV in 27 Km tunnel
eventually: $E_{CM}=14$ TeV (7 TeV per beam, design value)

bunches of $10^{11}$ protons guided to
collision by ~2000 superconducting
magnets operating at 1.9 K

$$dN_{\text{events}}/dt = \text{Luminosity} \times \text{cross section}$$

$$N_{\text{events}}(\Delta t) = \int L dt \times \text{cross section}$$

Key parameters:
- $N_i$ = bunch intensity
- $n_b$ = number of bunches
- $\sigma$ = colliding beam size
LHC: a Top producer
counter-rotating high intensity proton bunches colliding at center of mass
energy ($E_{cm}$) = 7 TeV in 27 Km tunnel

$E_{cm}$(Tevatron) = 1.96 TeV

$L \propto \frac{N_1 N_2 n_b}{\sigma^2}$

parameters:
$N_i$ = bunch intensity
$n_b$ = number of bunches
$\sigma$ = colliding beam size

---

Ad maiora..

2010

$E_{cm}$ = 7 TeV

- peak instantaneous luminosity: $2.1 \times 10^{32}$ cm$^{-2}$s$^{-1}$
- delivered integrated luminosity $\sim 50$ pb$^{-1}$

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2011

$E_{cm}$ = 7 TeV

- peak lumi: $\sim 0.5$ to $1 \times 10^{33}$ cm$^{-2}$s$^{-1}$
- $\int L dt$ between 1 and 3 fb$^{-1}$/exp
- $\int L dt \sim 5.2$ fb$^{-1}$/exp


design lumi $10^{34}$ cm$^{-2}$ s$^{-1}$

($\sim$ 30 times Tevatron p$p$ collider)

---

$N_{events}(\Delta t) = \int L dt \ast$ cross section
To produce $tt$

$$\hat{s} \geq 4m_t^2 \quad \Rightarrow \quad x_i x_j = \frac{\hat{s}}{s} \geq 4m_t^2/s.$$  

$f_i(x)$ falls with larger $x$ \quad typical $x_i x_j$ near threshold

$$x \approx \frac{2m_t}{\sqrt{s}} = 0.19 \text{ @ Tevatron } \sqrt{s}=1.8 \text{ TeV}$$

$$0.18 \text{ @ Tevatron } \sqrt{s}=1.96 \text{ TeV}$$

$$0.048 (0.025) \text{ @ LHC with } \sqrt{s}=7 (14 \text{ TeV})$$
Top quark @ LHC: production

probe low $x$ in pdfs $\rightarrow$ gluon fusion dominated

<table>
<thead>
<tr>
<th></th>
<th>Tevat</th>
<th>LHC(7)</th>
<th>LHC(14)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$gg$</td>
<td>$\sim$10%</td>
<td>$\sim$85%</td>
<td>$\sim$90%</td>
</tr>
<tr>
<td>$qq$</td>
<td>$\sim$90%</td>
<td>$\sim$15%</td>
<td>$\sim$10%</td>
</tr>
</tbody>
</table>

$\sigma = 165^{+11}_{-16}$ pb

$t$ channel

$\sigma = 64^{+3}_{-3}$ pb

$Wt$ channel

$\sigma = 15.7^{+1.3}_{-1.4}$ pb

$s$ channel

$\sigma = 4.6^{+0.3}_{-0.3}$ pb

Aliev et al 2011
Beneke et al 2010
Langefeld Moch
Uwer 2009
Moch, Uwer 2008

Kidonakis 2010

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Top Quark @ LHC
Top @ LHC: in the context

proton - (anti)proton cross sections

tt cross section

<table>
<thead>
<tr>
<th>√s (TeV)</th>
<th>xsec (pb)</th>
<th>Rate at L = 10^{33} cm^{-2} s^{-1}</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.96 (pp)</td>
<td>~7</td>
<td>0.2 Hz</td>
</tr>
<tr>
<td>7 (pp)</td>
<td>~165</td>
<td></td>
</tr>
<tr>
<td>14 (pp)</td>
<td>~900</td>
<td>0.9 Hz</td>
</tr>
</tbody>
</table>

for \( \int Ldt = 1 \text{ fb}^{-1} @ 7 \text{TeV} \), expect \( 1.6 \cdot 10^4 \) events

Tevatron (lower energy collider): \( \int Ldt = 9.4 \text{ fb}^{-1} \) on tape, expect \( \sim 6.6 \cdot 10^4 \) events

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Top signatures

• High $P_T$ jets
• $b$-jets
• 1 to 2 high $P_T$ leptons
• Missing energy

$\ell\nu$ $\sim$ 32.4%
$qq$ $\sim$ 67.6%

$\bar{t}t$ decays

(di-lepton) $(e,\mu,\tau)$
$\text{had } \tau + \text{jets}$ $13.5%$
$\text{lep } \tau + \text{jets}$ $4.7%$
$\text{all jets}$ $29.6%$

$W$ $t$ $b$

$p = \cdots$ $\downarrow$ $\uparrow$

$Wt$ $Wt$

$q'/q'b$, $b$

bkgs$_{\text{tt}}$: $W/Z(+\text{jets})$, single top, QCD, Di-bosons

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### ATLAS & CMS: Top observers

<table>
<thead>
<tr>
<th></th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Magnetic field</strong></td>
<td>2 T solenoid + toroid (0.5 T barrel 1 T endcap)</td>
<td>4 T solenoid + return yoke</td>
</tr>
<tr>
<td><strong>Tracker</strong></td>
<td>Si pixels, strips + TRT</td>
<td>Si pixels, strips</td>
</tr>
<tr>
<td></td>
<td>$\sigma/p_T \approx 5 \times 10^{-4} p_T + 0.01$</td>
<td>$\sigma/p_T \approx 1.5 \times 10^{-4} p_T + 0.005$</td>
</tr>
<tr>
<td><strong>EM calorimeter</strong></td>
<td>Pb+LAr</td>
<td>PbWO4 crystals</td>
</tr>
<tr>
<td></td>
<td>$\sigma/E \approx 10% / \sqrt{E} + 0.007$</td>
<td>$\sigma/E \approx 2-5% / \sqrt{E} + 0.005$</td>
</tr>
<tr>
<td><strong>Hadronic calorimeter</strong></td>
<td>Fe+scint. / Cu+LAr/W+LAr (10λ)</td>
<td>Cu+scintillator (5.8λ + catcher)/Fe+quartz fibres</td>
</tr>
<tr>
<td></td>
<td>$\sigma/E \approx 50% / \sqrt{E} + 0.03$ GeV (central)</td>
<td>$\sigma/E \approx 100% / \sqrt{E} + 0.05$ GeV</td>
</tr>
<tr>
<td><strong>Muon</strong></td>
<td>$\sigma/p_T \approx 2% @ 50$GeV to 10% @ 1$\text{TeV}$ (ID+MS)</td>
<td>$\sigma/p_T \approx 1% @ 50$GeV to 5% @ 1$\text{TeV}$ (ID+MS)</td>
</tr>
<tr>
<td><strong>Trigger</strong></td>
<td>L1 + Rol-based HLT (L2+EF)</td>
<td>L1+HLT (L2 + L3)</td>
</tr>
</tbody>
</table>

3 (ATLAS) or 2(CMS) trigger levels for event selection.

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**ATLAS and CMS:** Top observers…..

Top events are real commissioning tool: full detector at play!!

e+jets candidate

di-lepton (μμ+jets) candidate
...with excellent data taking performance

Analyses use 36 pb\(^{-1}\) (2010) and 0.2 to 1.14 fb\(^{-1}\) (2011)

**2011**

**ATLAS**

- Total Delivered: 5.61 fb\(^{-1}\)
- Total Recorded: 5.25 fb\(^{-1}\)

Luminosity uncertainty \(\sim 3.7\) to \(4.5\%\) (prel)%

**CMS**

Luminosity uncertainty \(\sim 4.5\%\)

**ATLAS (2010)**

Total Recorded (Delivered) Lumi:
- 45.0 (48.1) pb\(^{-1}\)
- Lumi uncertainty \(\sim 3.4\%\)

Data sample for first top paper \(\sim 3\) pb\(^{-1}\)

**CMS (2010)**

Total Recorded (Delivered) Lumi:
- 47.03 (43.17) pb\(^{-1}\)
- Lumi uncertainty \(\sim 4\%\)
Ingredients I: leptons

A=ATLAS, C=CMS

Electrons

• (A) $E$ scale from data known at 0.3 to 1.6% up to 1 TeV
• (C) ECAL scale known at level of 0.6% to 1.5%

• isolated central* combination of shower shape, track/calo-cluster match (correct for Bremsstrahlung, veto conversions)
  - $|\eta_{\text{cluster}}|<2.4$ (A) or 2.5 (C), $p_T>25$ (A) or 30 (C) GeV
  - remove duplicate close-by ($\Delta R<0.2$) jets (A) or reco objects (with Particle Flow (PF))

• Muons
  - $p_T$ scale known at $\approx<1\%$
  - isolated central combined fitted track from primary vertex
    - $|\eta_{\text{track}}|<2.5$ (A) $<2.1$ (C), $p_T>20$ GeV
    - suppress heavy flavour decays: no $\mu$ with $\Delta R<0.4$ (A) or 0.3 (C) from a jet

scale factors to correct small data/MC mismatch

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Ingredients II: jets

**Reco:** particle flow objects (C) or 3d calo clusters (A) → **anti-k_T algorithm** (R=0.4(A),0.5(C))
- \( p_T > 25(A) \) or \( 30(C) \) GeV
- \( |\eta_{\text{jet}}| < 2.4(A) \) or 2.5 (C)

**Calibrate jet energy scale** with \((\eta, p_T)\) dependent weight from simulated “true” jet kinematics+ pile-up offset correction

**Scale uncertainty:** between 2% to 8% in \( p_T \) and \( \eta \)
- Contributions from physics modelling, calo response, det simulation
- in-situ validation

\begin{align*}
\text{Jet} p_T \text{ range in single lepton top pair events} & \approx \text{average jet } p_T \text{ in single lepton top pair events} \\
\text{CMS, L = 36 pb}\^{-1} & \quad \sqrt{s} = 7 \text{ TeV}
\end{align*}
Ingredients III: missing transverse energy ($E_T^{\text{miss}}$)

A=ATLAS, C=CMS

• **Negative vector sum of**
  - A: energy in calorimeter cells, projected in transverse plane associated with high $p_T$ object + $\mu$ mom. + dead material loss
  - C: energy/momentum from 1) PF particle flow objects or 2) Calo towers + $\mu$ or 3) TC: Track +Calo, no double counting projected in transverse plane

• **Cells/towers/tracks are calibrated according to association** to high $p_T$ object (electron, photon, tau, jet, muon)

• **Calo cells with overlapping association are counted once**
Selecting top pairs - single lepton

- **Trigger on** high $p_T$ single lepton (e, $\mu$)

- Good collision and no jet from noise/out-of-time activity

- $\geq 1$ high $p_T$ central lepton, reject di-leptons
  - A: exactly one lepton
  - C: $\geq 1$ electron, reject if $|m(\text{ee}) - M_Z| < 15$ GeV for any ee pair, no lower $p_T \mu$ OR only one $\mu$, no lower $E_T \ell e$

- $\geq 3$ central high $p_T$ jets

- **A:** high $E_T^{\text{miss}}$ and large transverse leptonic $W$ mass ($M_T^W$) * to reduce QCD bkg
  - $E_T^{\text{miss}} > 35$ (25) GeV for e ($\mu$) chan
  - $M_T^W > 25$ GeV (60 GeV - $E_T^{\text{miss}}$) for e ($\mu$) chan

NEW! ATLAS-CONF-2011-121
arxiv:1106.0902
TOP-10-003

$A=\text{ATLAS}, C=\text{CMS}$

$$\int L dt = \sim 690 \text{ pb}^{-1} (A) \quad \text{(2011), } 36 \text{ pb}^{-1} (C) \text{ (2010)}$$

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>C</th>
</tr>
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<tbody>
<tr>
<td>e</td>
<td>5232</td>
<td>7478</td>
</tr>
<tr>
<td>$t\bar{t}$ bkg</td>
<td>18920</td>
<td>33482</td>
</tr>
<tr>
<td>$\mu$</td>
<td>7478</td>
<td>948</td>
</tr>
<tr>
<td>bkg</td>
<td>325</td>
<td>757</td>
</tr>
<tr>
<td>TotEx</td>
<td>24152</td>
<td>1273</td>
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<tr>
<td>Data</td>
<td>23824</td>
<td>1165</td>
</tr>
</tbody>
</table>

$\mu$ channel: $p_T^{\ell} > 25$ GeV for each lepton, $E_T^{\text{miss}} > 25$ GeV

$\sim 7500 \text{ pb}^{-1}$ for ATLAS $\sim 4200 \text{ pb}^{-1}$ for CMS

$\Delta M_{WW} > 40$ GeV and $E_T^{\text{miss}} > 150$ GeV

$\text{Significance} = \text{N_{obs}} - \text{N_{exp}} = \frac{25}{\text{N_{exp}}}$

$\text{Expected} = 3.5$ for ATLAS $\text{Expected} = 2.2$ for CMS

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Backgrounds estimates - single lepton

- **W+jets**
  - simulated shape
  - normalization from charge asymmetry of W prod before b-tag (A), floating (C)

- **QCD**
  - mis-id jets, $\gamma \rightarrow e^+e^-$, non-prompt leptons (b/ jet c-decays)

- **Single top**
  - A:Combine isol. prob for real and fake lep in control region with N(isol. lep) and N(non-isol lep)$\rightarrow$ isolated fake lep
  - C:shape from non-isolated or failing el-ID/quality, floating norm.

- **Di-bosons (WW, WZ, ZZ)**

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**ATLAS Preliminary**

\[ \int L \, dt = 0.70 \text{ fb}^{-1} \]

**CMS**

\[ 36 \text{ pb}^{-1} \text{ at } \sqrt{s} = 7 \text{ TeV} \]

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\( \sigma_{tt} \) - single lepton

- Build discriminant from signal + bkg templates of
  - A: lepton \( \eta, p_T \) of highest \( p_T \) jet aplanarity (\( \text{top is more spherical} \)), \( H_{T,3p} \), ratio of transverse to longitudinal activity (\( \text{top is more transverse} \))
  - C: \( E_T^{\text{miss}} \) for 3-jet bin (vs QCD), M3 for \( \geq 4 \)-jet bin, mass of 3-jet system with highest vectorially combined \( p_T \)

- Extract \( \sigma_{tt}, \sigma_{bkg} \) by binned likelihood fit of discriminant to data in A: 3, 4 and \( \geq 5 \)-jet bins, C: 3 and \( \geq 4 \)-jet bins
\[ \sigma_{\text{tt}} \text{ and syst. uncertainties - single lepton} \]

**Results**

- **\( \sigma_{\text{tt}} = 179.0 \pm 3.9 \, \text{(stat)} \pm 9.0 \, \text{(syst)} \pm 6.6 \, \text{(lumi)} \, \text{pb} \) NEW!**

**\( A=\text{ATLAS}, C=\text{CMS} \)**

**\( \sigma_{\text{tt}} = 173 \pm 14 \, \text{(stat)} +36^{+29}_{-29} \, \text{(syst)} \pm 7 \, \text{(lumi)} \, \text{pb} \)**

- **Most syst uncertainties part of lkl fit** as Gaussian nuisance parameters \( \rightarrow \) reduction in JES,ISR/FSR (20% to 70% of initial value)
- **Still syst-dominated: generator \( \sim 3\% \) lepton scale \( \sim 2\% \)
- **\( \delta \sigma/\sigma = 6.6\% \, \text{(stat} \sim 0.5\%, \text{sys} \sim 5\%) \)

**CMS**

\[ \beta_{\text{fit}} \leq 3.5 \]

\[ \beta_{\text{in}} \leq 1.10 \]

**Neyman CL belt for max lkl fit**

- **Syst-dominated (JES-18\%, factorization scales-7%)**
- **\( \delta \sigma/\sigma \sim 23\% \, \text{(stat} \sim 8\%, \text{sys} \sim 21\%) \)**

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Ingredients IV : enter b-jets
B-hadrons~ long lifetime ~observable flight (few mm)

Tagging \[ \frac{d_0}{\sigma_{d_0}} \]
\[ \frac{L_{3D}}{\sigma_{L_{3D}}} \]

• A: (1) jet prob from track impact parameter (IP) (2) 3D decay length significance of sec. vertex (SV) (3) Neural net with 1), 2) + mass of SV tracks + \( N_{2\text{track}} \) vertices+ \( E_{SV} \) (tracks)/\( E_{PV} \) (tracks)

• C: (1) 3D SV decay length significance (& \( N_{\text{tracks}} >3 \)) (2) track IP signif. & \( \geq 2 \) or 3 high IP signif. tracks

Performance
• Efficiency: fit fraction of b-jets in sample with muons in jets, count # b-tagged
• Mis-tag rate: from SV properties (invariant mass of tracks (A), rate of negative decay length / impact par significance (A,C))

Efficiency/mis-tag : from 80%/10% (track/NN based) to 40%/0.1% (SV based)

\[ p_T \] dependent scale factors to correct MC

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\( \sigma_{tt} - \text{single lepton with } b\text{-tag} \quad A=\text{ATLAS}, C=\text{CMS} \)

- Standard single lepton selection + large \( E_T^{\text{miss}} \) and \( M_T^W \)
- Bkg shapes/normalization as no-btag

**C**

- \( \geq 1 \) \( b \)-tagged central high \( p_T \) jet
- Max likl fit to secondary vertex mass in 2d plane of \((N_{\text{jet}}, N_{b\text{-jet}})\)

\[
\sigma_{tt} = 164.4 \pm 2.8\,\text{(stat.)} \pm 11.9\,\text{(syst.)} \pm 7.4\,\text{(lum.)}\, \text{pb}
\]

\( \delta \sigma/\sigma \approx 9\% \)

**A**

- Max likl fit of 4-variable discriminant
- replace leading jet \( p_T \) with average of two largest jet \( b \)-tagging probability (\( \leftarrow \) top has more \( b \)-jets)

\[
\sigma_{tt} = 186 \pm 10\, \text{(stat)} \pm 21\,-20\, \text{(syst)} \pm 6\, \text{(lumi)}\, \text{pb}
\]

\( \delta \sigma/\sigma \approx 13\% \)

**A,C:** Syst uncertainties fitted as nuisance pars in profile likl

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Selecting top pairs: di-lepton

- Vertex and quality cuts
- After single (A,C) lepton and di-el (C) trigger (A), exactly (A) or at least (C) two opposite sign high $p_T$ central leptons (ee, eμ, μμ)

- ≥ 2 central high $p_T$ jet

- High $E_T^{miss}$ for (ee, μμ) (at least >30 GeV) or transverse activity (eμ)
  - $H_T = \sum_{jets,leptons} |\rho_T|$ (A) or $\sum_{leptons}$ transv. mass (C)

- for (ee, μμ) veto low di-lep mass (<15(A), 12(C) GeV) & Z-like (mass window) events
- if ≥ 1 b-tag, relax $E_T^{miss}$

Backgrounds:
- $Z/\gamma^*+jets$
- QCD, Di-bosons
- single lepton

$A=\text{ATLAS}, C=\text{CMS}$

$(2011) \int Ldt = 0.7 \text{ pb}^{-1} (A), 1.14 \text{ fb}^{-1} (C)$

CMS-TOP-11-005 NEW!
Di-lepton $\sigma_{tt}$ - main backgrounds

$A=$ATLAS,$C=$CMS

(2011) $\int L dt = 0.7$ pb$^{-1}$ ($A$), 1.14 fb$^{-1}$ ($C$)

• “Fake” leptons from data
  
  ‣ Get probability for loose “fake” (A, C) and real (A) leptons to be in signal region (A)$\leftarrow$ control samples enriched with real (in Z window) or “fake” (low $E_T^{\text{miss}}$) leptons (A), multi-jet single loose lepton sample (C)
  
  ‣ Combine with N(di-lep) for all loose/tight pairs (A) or only loose pair (fail tight) (C)$\rightarrow$fake tight (i.e. signal) lep

• $Z/\gamma^*$ bkg (ee, $\mu\mu$) : scale non-$Z/\gamma^*$-bkg-subtracted data in Z-mass window control region with ratio of N($Z/\gamma^*$) in signal region to control region from simul.

$\geq 1$-btag

<table>
<thead>
<tr>
<th></th>
<th>ee (A)</th>
<th>ee(C)</th>
<th>$\mu\mu$(A)</th>
<th>$\mu\mu$(C)</th>
<th>$e\mu$(A)</th>
<th>$e\mu$(C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>tt</td>
<td>167</td>
<td>427</td>
<td>314</td>
<td>559</td>
<td>666</td>
<td>1487</td>
</tr>
<tr>
<td>Bkg</td>
<td>25</td>
<td>78</td>
<td>45</td>
<td>100</td>
<td>68</td>
<td>141</td>
</tr>
<tr>
<td>Tot Exp</td>
<td>192</td>
<td>505</td>
<td>359</td>
<td>659</td>
<td>734</td>
<td>1628</td>
</tr>
<tr>
<td>Data</td>
<td>202</td>
<td>589</td>
<td>349</td>
<td>688</td>
<td>823</td>
<td>1742</td>
</tr>
</tbody>
</table>

\[ \int L dt = 0.70 \text{ fb}^{-1} \]

NEW!
Di-lepton $\sigma_{tt}$ results

**Include** estimated background

**Cross section from likelihood fit** combining channels and including systematics as nuisance parameters

$$A$$

no b-tag

$$\sigma_{\bar{t}t} = 171 \pm 6\text{(stat.)}^{+16}_{-14}\text{(syst.)} \pm 8\text{(lum.)}\text{ pb.}$$

b-tag

$$\sigma_{\bar{t}t} = 177 \pm 6\text{(stat.)}^{+17}_{-14}\text{(syst.)}^{+8}_{-7}\text{(lum.)}\text{ pb.}$$

$$\delta\sigma/\sigma \sim 11\%$$ (no-tag) and b-tag

$$\delta\sigma/\sigma \sim 11\%$$

$$A=\text{ATLAS, } C=\text{CMS}$$

$\delta\sigma/\sigma \sim 11\%$ 

NEW!

$\delta\sigma/\sigma \sim 11\%$

$169.9 \pm 3.9\text{(stat.)} \pm 16.3\text{(syst.)} \pm 7.6\text{(lumi.)}\text{ pb}$

**ATLAS** Preliminary

**all channels**

- Data
- $\bar{t}t$
- $Z/\gamma^{*}+\text{jets}$
- Fake leptons
- Other EW

$\int L \, dt = 0.70\text{ fb}^{-1}$

distributions after all cuts, except $N_{\text{jets}}$

**syst dominated!**

- $JES\sim 5\%$ (A),
- $b$-tag $\sim 4-5\%$ (A-tag, C)
- $C$: pile-up $\sim 5\%$, lep sel $\sim 4\%$
- $A$: ISR $\sim 2.6\%$

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31
** Combined top pair cross section results

**ATLAS** Preliminary, $\sqrt{s} = 7$ TeV

<table>
<thead>
<tr>
<th>Channel</th>
<th>Theory (approx. NNLO)</th>
<th>Ljet (_{b}), 2010</th>
<th>Ljet (_{b}), 2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>L+jets w/ (_{b}) tagging</td>
<td>$186 \pm 10$</td>
<td>$171 \pm 17$</td>
<td>$177 \pm 6$</td>
</tr>
<tr>
<td>Dilepton w/o (_{b}) tagging</td>
<td>$171 \pm 17$</td>
<td>$171 \pm 6$</td>
<td>$177 \pm 6$</td>
</tr>
<tr>
<td><strong>Combination</strong></td>
<td>$176 \pm 5$</td>
<td>$171 \pm 6$</td>
<td>$177 \pm 6$</td>
</tr>
</tbody>
</table>

+ $\sigma_{\text{tot.}}(\pm \text{syst.} \pm \text{lumi})$

**NEW!**

- $\sigma = 179 \pm 3.9 \pm 9.0 \pm 6.6 \text{ pb}$
- $\sigma = 169.9 \pm 3.9 \pm 16.3 \pm 7.6 \text{ pb}$
- $\sigma = 164.4 \pm 2.8 \pm 11.9 \pm 7.4 \text{ pb}$

**Combined uncertainty is ~10% dominated by systematics. Comparable to theory**

- **ATLAS**: $176 \pm 5^{+13}_{-10} + 7 \text{ pb}$
- **CMS**: $154 \pm 10^{+17}_{-17} + 6 \text{ pb}$

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• Exactly 1 high $p_T$ central lepton ($e,\mu$), high $E_T^{miss}$ ($A$) and $M_T^W(A,C)$, require exactly 2 ($A,C$) or 3 jets ($A$) in $|\eta|<4.5(A)$ or 5($C$)

• 2 samples: pre-tag, 1 b-tag ($A,C$), $\geq$1b-tag ($C$)
• QCD and $W+$jets norm from data

• $C$: combine 2 results: 2D-max $L_{kl}$ fit to lepton-untagged jet angle & $\eta$ of untagged jet + Bayesian estimate from BDT

• $A$: cut/count on angular jet var., top mass and $H_T$, confirmed by max $L_{kl}$ fit to neural network discriminant (13 var.)

syst dominated!

$\sigma_t$ - Single top - $t$ channel  
$\int L dt = 0.7 \text{ fb}^{-1}$ ($A$) (2011), $\sim 36 \text{ pb}^{-1}$ ($C$) (2010)

$A=\text{ATLAS}$, $C=\text{CMS}$

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All we study about the Top

- Top mass
- Top mass difference
- Top charge
- Lifetime
- Top width

- Branching ratios $|V_{tb}|$
- Anomalous coupling
- New/Rare decays

- Production cross section
- Production kinematics
- Production via resonance
- New particles

- W helicity

- Spin correlation
- Charge asymmetry
- Color Flow

- s- & t- channel production, properties and searches in single top events
Top Quark Mass

- Free parameter of the SM
- Together with W mass: puts constraint on Higgs mass

Measurement done with several methods: Template method, ideogram, matrix element, etc.
- Methods also used for other analyses, e.g. W helicity & spin correlations
- Construct **mass dependent template**, fit to data
- Alljets and $l+$jets: Take info from hadronically decaying $W$ mass to **constrain jet energy scale**

- **Dilepton**: Construction of templates more complicated due to presence of two neutrinos
  - Neutrino weighting, Matrix Weighting,…

---

**Top Quark Mass: Template Method**

---

**29.08.2011**

Yvonne Peters - Manchester
Top Quark Mass: Ideogram

- Use kinematic fit to reconstruct complete kinematics of the event → yields fitted $m_t$ for each jet to quark assignment

- Calculate event likelihood as function of $m_t$
- Used in l+jets & alljets
Top Quark Mass: Matrix Element Method

- Use full event kinematics → most precise method
- For each event calculate probability to belong to certain top mass
  \[ P_{\text{sig}}(x;m_t) \propto \int \text{PDF} \times \text{Matrix element} \times \text{Transfer function} \]
- Perform likelihood fit of event probabilities
- Probability depends on top mass (& JES for in-situ fit)
- Used in l+jets & dilepton final states
Most Recent Mass Results

- **Template:**
  - CDF (alljets), 5.8fb⁻¹: $m_t = 172.5 \pm 2.0 \text{(stat+syst)}\, \text{GeV}$
  - CDF (dilepton), 5.6fb⁻¹: $m_t = 170.3 \pm 3.7 \text{(stat+syst)}\, \text{GeV}$
  - Atlas (l+jets), 0.7fb⁻¹: $m_t = 175.9 \pm 0.9 \text{(stat)} \pm 2.7 \text{(syst)}\, \text{GeV}$
  - CMS (dilepton), 36pb⁻¹: $m_t = 175.5 \pm 4.6 \text{(stat)} \pm 4.6 \text{(syst)}\, \text{GeV}$

- **Ideogram:**
  - CMS (l+jets), 36pb⁻¹: $m_t = 173.1 \pm 2.1 \text{(stat)}^{+2.8}_{-2.5} \text{(syst)}\, \text{GeV}$

- **Matrix Element technique:**
  - DØ (l+jets), 3.6fb⁻¹: $m_t = 174.9 \pm 1.5 \text{(stat+syst)}\, \text{GeV}$
  - DØ (dilepton), 5.4fb⁻¹: $m_t = 174.0 \pm 3.0 \text{(stat+syst)}\, \text{GeV}$
  - CDF (l+jets), 5.6fb⁻¹: $m_t = 173.0 \pm 1.2 \text{(stat+syst)}\, \text{GeV}$
Top Quark Mass: Combinations

- Systematics limited!
  - Main effort for experiments: detailed understanding of systematics
  - Main systematics at Tevatron: JES-related
  - Main systematics at LHC: JES-related and ISR/FSR

- Tevatron combination: first time uncertainty below 1GeV!

Mass of the Top Quark

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Mass (GeV/c²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF-I dilepton</td>
<td>167.4 ± 11.4 (±10.3 ± 4.9)</td>
</tr>
<tr>
<td>DØ-I dilepton</td>
<td>168.4 ± 12.8 (±12.3 ± 3.8)</td>
</tr>
<tr>
<td>CDF-II dilepton</td>
<td>170.6 ± 3.8 (± 2.2 ± 3.1)</td>
</tr>
<tr>
<td>DØ-II dilepton</td>
<td>174.0 ± 3.1 (± 1.8 ± 2.5)</td>
</tr>
<tr>
<td>CDF-I lepton+jets</td>
<td>176.1 ± 7.4 (± 5.1 ± 3.0)</td>
</tr>
<tr>
<td>DØ-I lepton+jets</td>
<td>180.1 ± 5.3 (± 3.9 ± 3.6)</td>
</tr>
<tr>
<td>CDF-II lepton+jets</td>
<td>173.0 ± 1.2 (± 0.6 ± 1.1)</td>
</tr>
<tr>
<td>DØ-II lepton+jets</td>
<td>174.9 ± 1.5 (± 0.8 ± 1.2)</td>
</tr>
<tr>
<td>CDF-I alljets</td>
<td>186.0 ± 11.5 (±10.0 ± 5.7)</td>
</tr>
<tr>
<td>CDF-II alljets *</td>
<td>172.5 ± 2.1 (± 1.4 ± 1.5)</td>
</tr>
<tr>
<td>CDF-II track</td>
<td>166.9 ± 9.5 (± 9.0 ± 2.9)</td>
</tr>
<tr>
<td>CDF-II MET+Jets *</td>
<td>172.3 ± 2.6 (± 1.8 ± 1.8)</td>
</tr>
<tr>
<td>Tevatron combination *</td>
<td>173.2 ± 0.9 (± 0.6 ± 0.8) (± stat ± syst)</td>
</tr>
</tbody>
</table>

χ²/df = 8.3/11 (68.5%)
Top spin correlation

- Top quark decays before hadronization: $1/\Gamma_{\text{top}} < 1 \text{ fm} \rightarrow \text{top polarization preserved in angular dist of decay products}$

- Massless fermions: fixed helicity = chirality
- QCD conserves chirality
- If $m \rightarrow 0$, chirality -> helicity = projection of spin along direction of motion

- $s \approx 2m_{\text{top}}$
- Mostly $^3S_1$
- $L=0, J=1 \rightarrow \text{parallel}$
- Spins along given axis
- Opposite helicity

- Mostly $^1S_0$
- $L=J=0 \rightarrow \text{anti-parallel}$
- Spins along given axis
- Same helicity

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Top Quark @ LHC
t\bar{t} Spin Correlations at LHC

- LHC: 85% gg \rightarrow t\bar{t}: dominated by like helicity gluons at low $\sqrt{s}$
- Simple variable in dilepton channel: $\Delta\phi=|\phi_1-\phi_2|
  - No kinematic fit needed!
- Result of template fit: $f=1.06\pm0.21^{+0.40}_{-0.27}\text{(syst)}$
  - Main systematics: ISR; modeling of signal
  - Corresponds to $C_{\text{helicity}}=0.34^{+0.15}_{-0.11}$
    (SM: $C_{\text{helicity}}=0.32$)
- Agreement with SM
- Already dominated by systematics
Top production as a window on new physics

**Top partner + stable scalar (dark matter)**

- **Production cross section**
- **Resonant production**
- **Production kinematics**
- **Spin polarization**

**q/g**

**q/g**

**t/t**

**tt + E_T^{miss}**

**FCNC-induced same sign top pair**

**For ΔR=0.8, M_{tt} ~ 1.7 TeV, P_T ~ 600 GeV**

**P_T^Top**

**M_{tt} = 1 TeV & anti-k_T**

(R=0.4): **86% resolved**

**M_{tt} = 2 TeV & antikt**

(R=0.8): **60% boosted**

**Light quark**

**b quark**

**lepton**

**neutrino**

**l+jets**

**di-lep**

**fully had**

**KK Gluon**

**ν**

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Search for excess in $\bar{t}t$ production vs $M_{\bar{t}t}$ - single-lepton

**A=ATLAS, C=CMS**

- **A**: standard single lep (e μ) sel: ≥4 jets, ≥1 b-tag
- **C**: single μ, boosted top sel.
  - ≥ 2 jets with $p_T>50$ GeV, lead jet $p_T>250$ GeV
  - one non-iso μ with $\Delta R>0.5$ from closest jet OR $p_T$ rel. to jet >15 GeV
  - high $p_{T,lep}+E_T^{miss}$ >150 GeV

- **Data-driven QCD** (jet template method normalize to low $E_T^{miss}$ (A), shape from ev. failing mu 2D cut (C)), **W+jets normalization (A)** (extrapol. from $N_{jet}$ in W+jets-enriched sample)

- **Reconstruct leptonic W** from $E_T^{miss}$, lepton & W mass, then $M_{\bar{t}t}$
  - sum leptonic W to (A) 4 leading $p_T$ jets or (C) jets giving back-to-back top-jets $\leftarrow$ minimal $\sum \Delta R$ (lep/b-jet, leptonic top) & max $\Delta R$ betw. tops

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Search for excess in $t\bar{t}$ production vs $M_{t\bar{t}}$ - single lepton

- No excess found $\rightarrow$ 95%
- Bayesian credible interval for $Z'$ & RS KKGlueon $\sigma*BR$, including systematics as integrated (CMS), averaged(A) nuisance pars.

- Upper observed (expected) limit at 95% prob on $Z'$ $\sigma*BR$ (with $\Gamma_{Z'}/m_{Z} \sim 1\%$)
  - C: sub-pb for $m_{Z'} > 1.3$ TeV, <0.2 pb for $m_{Z'} > 2.3$ TeV
  - A: 38 (40) pb for $m_{Z'} = 500$ GeV to 3.2 (5) pb for $m_{Z'} = 1.3$ TeV

- C: For $Z'$ with 3% width exclude 805 GeV $<m_{Z'} <$ 935 GeV and 960 GeV $<m_{Z'} <$ 1060 GeV at 95% CL

- A: KK Gluons with masses $< 650$ GeV are excluded with 95% prob

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Search for excess in $t\bar{t}$ production vs $M_{t\bar{t}}$ - fully hadronic

- **Trigger on $\geq 1$ jet with $p_T>200$ GeV**

- **“1+1”: $\geq 2$ R=0.8 Cambridge-Aachen (CA) jets**
  - $p_T>350$ GeV & large $\Delta \phi >2.1$
  - top-tagged ($m_{\text{jet}} \sim m_{\text{top}}, N_{\text{sub-jets}}$ in last 2 jet-making steps $\geq 3$, $\min(m_{2 \text{sub-jets}}) > 50$ GeV)

- **“1+2”: $\geq 3$ R=0.8 CA jets**
  - leading top-tagged jet with $p_T>350$ GeV
  - 2nd(3rd) pruned (discard soft, wide-angle clusters) jet with $p_T>200$ (30) GeV, large $\Delta \phi >2.1(1.7)$ from 1st
  - $j_2$ is W-tag ($m_{\text{jet}} \sim m_W, 2$ sub-jets, max ($m_{\text{sub-jet}})/m_{\text{jet}} < 0.4), m(j_2,j_3) \sim m_{\text{top}}$

- **Data-driven QCD**: weight 1-top or W-tag control sample with mis-tag prob $\leftarrow$ anti-tag (fail top tag cuts) & probe in semi-lep evs

\[ \int L dt = 0.89 \text{ fb}^{-1} (2011) \]
Search for excess in $\bar{t}t$ production vs $M_{tt}$ - fully hadronic

\[
\int L dt = \sim 0.89 \text{ fb}^{-1} \ (2011)
\]

- $M_{tt}$: sum top jets in “1+1”, sum top jet, Wjet and closest jet in “1+2”
  - QCD: sum tag(s) & probe jet, random $m_{\text{probe}}$ around $m_{\text{top}}$

- No excess found $\rightarrow$ 95% Bayesian credible interval for $Z'/\text{RS} \text{ KKGlueon } \sigma*BR$
  including systematics as integrated nuisance pars.
- Sub-pb limit on $Z'$ $\sigma*BR$
- exclude $1 \text{ TeV} < m_{\text{KKGlueon}} < 1.5 \text{ TeV} @ 95\%CL$

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Search for excess in top pair production vs $M_{tt}$

fully hadronic di-top-jet candidate

semi-leptonic di-top-jet candidate

CMS-PAS-EXO-11-006

ATL-CONF-2011-087
Conclusions

• **Top analysis at LHC is in full swing** thanks to the combined performance of LHC & detectors: a very rich program is already underway.

• **Top pair production cross section is measured** in nearly all expected final states. It is consistent with the standard model at $\sqrt{s}=7$ TeV and most precise channels/combination are
  ‣ systematics dominated
  ‣ entering the realm of precision physics: $\frac{\delta \sigma}{\sigma} < \sim 10\%$ comparable with theory uncertainty

• **Single top production is clearly observed** in the t-channel; need more data to observe it in Wt and s-channel.

• **Top properties** are rapidly reaching precision level with $m_{\text{top}}$ already syst dominated

• The rapidly increasing data-set and detector understanding is quickly opening unprecedented phase space for new physics searches linked to top production ranging from resonances to
Additional (useful) references


• Chris Quigg, Top-ophilia, FERMILAB-FN-0818-T

and references therein
BACK-UP
Math Appendix: Mass, $P_T$ and DR

As we know that for any 4-momentum

\[ E = m_T \cosh y, \quad p_x, p_y, p_z = m_T \sinh y \]

where \[ m_T^2 = m^2 + p_x^2 + p_y^2. \]

The invariant mass $M$ of the two-particle system

\[ M^2 = m_1^2 + m_2^2 + 2[E_T(1)E_T(2) \cosh \Delta y - p_T(1) \cdot p_T(2)], \]

This can be re-written as

\[ M^2 = m_1^2 + m_1^2 + 2[E_T(1)E_T(2) \cosh(Dy) - p_T(1) p_T(2) \cos(DPhi)]. \]

Now if 1) the masses of the particles are small w.r.t. their momenta and 2) the splitting is quasi collinear i.e. $\cos(DPhi) \sim 1 - (DPhi)^2/2$ and $\cosh(Dy) \sim 1 + Dy^2/2$, so $E_T(i) \sim p_T(i)$

\[ M^2 \sim 2[p_T(1) p_T(2) (1+Dy^2/2 - 1 + (DPhi)^2/2)] = p_T(1) p_T(2) (Dy^2/2 + (DPhi)^2) = p_T(1) p_T(2)(DR(1,2))^2 \]

So

Labelling $i$ and $j$ such that $p_{tj} < p_{ti}$ and defining $z = p_{tj}/p_t$

\[ (p_t = p_{ti} + p_{tj}), \]

\[ m^2 \simeq z(1-z)p_i^2 \Delta R_{ij}^2, \]

\[ d_{ij} = z^2 p_i^2 \Delta R_{ij}^2 \simeq \frac{z}{(1-z)} m^2. \]
Techniques for BKG estimation
Example background estimates: QCD multi-jet - single lep

• "Fake" leptons: mis-id jets, $\gamma \rightarrow e^+e^-$ non-prompt leptons (b/c-decays)

$$\mu \text{ channel: matrix method}$$

• Measure $N_{\text{standard}}$ (isolated-$\mu$) and $N_{\text{loose}}$ (non-iso-$\mu$) events and find standard fake muons from

$$N_{\text{loose}} = N_{\text{loose fake}} + N_{\text{loose real}}$$

$$N_{\text{standard}} = \varepsilon_{\text{fake}} N_{\text{loose fake}} + \varepsilon_{\text{real}} N_{\text{loose real}}$$

$\varepsilon_{\text{fake}}$ from low $E_T^{\text{miss}}, M_T^W$ and $\varepsilon_{\text{real}}$ from $Z \rightarrow \mu^+\mu^-$

• Do it in bins of any variable to get proper estimate

$$e \text{ channel: template method}$$

• Derive QCD template from control region (electron fails one/more selection criteria)

• Normalize by fitting low $E_T^{\text{miss}}$ shape ($QCD$ template + MC samples) to data $\rightarrow$ extrapolate to standard region

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Example background estimates: QCD multi-jet - di-lepton

- Define tight (standard) and loose lepton samples relaxing
  - calo and track isolation for μ
  - calo isolation, TRT hits, E/p cuts for e
- Express measured (Tight,Loose) samples in terms of unknown (Real, Fake) and estimated probabilities \( r \) (\( f \)): for real (fake) leptons passing loose also to pass tight cuts
- Extract fake content by matrix inversion

\[
\begin{pmatrix}
N_{TT} \\
N_{TL} \\
N_{LT} \\
N_{LL}
\end{pmatrix} =
\begin{pmatrix}
rr & rf & fr & ff \\
r(1 - r) & r(1 - f) & f(1 - r) & f(1 - f) \\
(1 - r)r & (1 - r)f & (1 - f)r & (1 - f)f \\
(1 - r)(1 - r) & (1 - r)(1 - f) & (1 - f)(1 - r) & (1 - f)(1 - f)
\end{pmatrix}^{-1}
\begin{pmatrix}
N_{RR} \\
N_{RF} \\
N_{FR} \\
N_{FF}
\end{pmatrix}
\]

Measure \( r \) in \( Z \to \ell\ell \)

Measure \( f \) in QCD enriched sample: single loose lepton, low \( E_T^{miss} \)

(W+jets subtracted using simulation)
Example background estimates: W+jets - single lepton

• Shape from simulation
  pre-tag=all standard cuts, no b-tag requirement
tagged=all standard cuts, including at least 1 b-tag

• Normalization
  ‣ floating parameter to be determined from kinematic fit
  ‣ final normalization from fit, but starting value and variations
    constrained from data using

\[
W_{\geq 4, \text{tagged}} = W_{\geq 4, \text{pre-tag}} \cdot f_{2, \text{tagged}} \cdot k_{2 \rightarrow \geq 4}.
\]

1: Derive correction to fraction of heavy and light flavour events in the W+2jet bin before b-tagging

\[
N(\text{W+jets, pre-tag, N}_{\text{jets}}) = N(\text{W+jets, pre-tag, N}_{\text{jets}}) \cdot \left[ \sum_{\text{Type}} f_{\text{Type}, \text{N}_{\text{jets}}} \right] \cdot \sum f_{\text{Type, N}_{\text{jets}} = 1} \text{Type= Wbb+jets, Wcc+jets, Wc+jets, W+light jets; N}_{\text{jets}}=\text{jet mult bin (0,1,2,3...)}
\]

• Derive N(W+1jet) and N(W+2jet) with 1) standard single lepton selection and 2) subtraction of small backgrounds (tt, single t, di-boson, QCD from data)
• Write N(W+1jet, pre-tag), N(W+2jet, pre-tag) and N(W+2jet, tag) as a function \(f_{\text{Type, 2jets}}\). Assume fixed \(f_{\text{Type, 2jets}} / f_{\text{Type, 2jets}} + f_{\text{Wbb, N}_{\text{jets}}} = f_{\text{Wbb, N}_{\text{jets}}} \rightarrow \text{Derive } f_{\text{Type, 2jets}}\)
• Compare data-driven \(f_{\text{Type, 2jets}}\) to MC value: derive scaling factors for \(f_{\text{Type, 2jets}}\).
  Assume scaling \(f_{\text{Type, 4jets}}\) is the same as \(f_{\text{Type, 2jets}}\). So now \(\sum \text{alpha } f_{\text{Type, N}_{\text{jets}}}\)
Example background estimates: W+jets - single lepton (cont)

pre-tag=all standard cuts, no b-tag requirement
tagged= all standard cuts, including at least 1 b-tag

ATLAS

2: Derive pre-tag W+jets normalization W i.e. full selection except for =>1 b-tagged jet

In the proton there are more up (valence) quarks than down (valence) quarks \( \bar{u}d \rightarrow W^+ \)+jets events are more numerous than \( u\bar{d} \rightarrow W^- \)+jets

\[
W_{\geq 4,\text{pretag}} = N_{W^+} + N_{W^-} = \frac{(N_{MC}^{W^+} + N_{MC}^{W^-})}{(N_{MC}^{W^+} - N_{MC}^{W^-})} (D^+ - D^-) = \left( \frac{r_{MC} + 1}{r_{MC} - 1} \right) (D^+ - D^-),
\]

\( N_{W^+}^{MC} \) (\( N_{W^-}^{MC} \)) are the number of selected events with a W from MC, \( D \) is the number of selected events with a positive or negative lepton, \( r_{MC} \) is \( N_{W^+} / N_{W^-} \) : it is estimated using ALL the W components and by scaling the heavy and light flavour samples according to point 1

3: Derive tagged W+jets normalization W by scaling pre-tag estimate

\[
W_{\geq 4,\text{tagged}} = W_{\geq 4,\text{pretag}} \cdot f_{2,\text{tagged}} \cdot k_{2\rightarrow\geq 4}.
\]

Estimate \( f_{2,\text{tagged}} = N(W+jets,2jets,tagged)/N(W+jets,2jets,pre-tag) \) where \( N(W+jets,2jets,XX) \) are obtained from the data with 1) selection 2) small bkg subtraction

Estimate \( k_{2\rightarrow\geq 4} = f_{MC,\text{tagged},\geq 4jet}^{\text{MC,tagged,2jet}} \)

Simulate W+jets events: get fraction of those selected + at least 1 b-tag to simply selected. Get these fractions for 2 jet bin and 4 jet bin. Get the ratio.

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Top Quark @ LHC
HEP intercollegiate Post Graduate Lectures - 15th Nov 2011
Example background estimates: W+jets - single lepton

• Shape from simulation,

• Normalization

  ‣ floating parameter to be determined from kinematic fit
  ‣ final normalization from fit, but starting value and variations constrained from data

\[
N_{W^+} + N_{W^-} = \frac{(N_{W^+}^{MC} + N_{W^-}^{MC})}{(N_{W^+}^{MC} - N_{W^-}^{MC})} (D^+ - D^-) = \left(\frac{r_{MC} + 1}{r_{MC} - 1}\right) (D^+ - D^-)
\]

PDFs for up and down quarks are different in proton

\[ W^+ \] are obtained from \[ ud^+ \]
Additional measurements
Search for excess in $\bar{t}t$ production - di-lepton

$\int Ldt = 1.04 \text{ fb}^{-1} (2011)$

- **Standard:** di-lepton selection ($e_0$) + data-driven $Z/\gamma^*+\text{jets}$ ($E_{\text{miss}}$-dep $Z$-window) and QCD bkg estimates

- **No excess found in $H_T+E_T^{\text{miss}} \to 95\%$ Bayesian credible interval for RS KKGlueon $\sigma^*BR$ including systematics as integrated nuisance pars.**

- **Exclude RS KKGlueon with $M_{KK}$ below 0.84 TeV at 95% CL**

<table>
<thead>
<tr>
<th>$g_{000,gKK}/g_s$</th>
<th>Expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.20</td>
<td>0.80</td>
<td>0.84</td>
</tr>
<tr>
<td>-0.25</td>
<td>0.88</td>
<td>0.88</td>
</tr>
<tr>
<td>-0.30</td>
<td>0.95</td>
<td>0.92</td>
</tr>
<tr>
<td>-0.35</td>
<td>1.02</td>
<td>0.96</td>
</tr>
</tbody>
</table>

**NEW!**
Di-lepton: $\mu + \tau \ (\tau \rightarrow \text{had})$ channel

Check universality + sensitivity to $t\rightarrow H^\pm + b \rightarrow \tau \nu b$

• One central high $p_T \ \mu$, no low $p_T \ (C)$ electrons
• $\geq 1$ jet-seeded $\tau$ candidate ($\rightarrow$ cut-based algo on particle flow objects (C) or Boosted Decision Tree (BDT) (A)) with opposite charge to $\mu$ (OS)
• $\geq 2$ jets & $\geq 1$ b-tag
• Large $E_T^{\text{miss}} > 40 \text{ (C)}$ or $30 \text{ (A)}$ GeV & $H_T > 200 \text{ GeV (A)}$, update and go to back-up

• Data-driven dominant $t\bar{t}$ & $W + \text{jets}$
  (enriched low $N_{\text{jet}}$ region (A), weight $W + \geq 3$ jet with jet fake prob. from average of $W + \geq 1$ jet & QCD enriched (C), $QCD$ (non-iso mu sample normalized to low $E_T^{\text{miss}}$)

• $\sigma_{t\bar{t}} = N_{\mu+\tau} / A \times \text{Lumi}$. $N_{\mu+\tau}$ from
  • C: bkg-subtracted data
  • A: template likelihood fit of difference of BDT in OS & SS samples (cancel most gluon & b-jet fakes)

$\delta \sigma / \sigma \sim 21\%$

$\sigma_{t\bar{t}} = 148.7 \pm 23.6 \text{ (stat.)} \pm 26.0 \text{ (syst.)} \pm 8.9 \text{ (lumi.) pb}$

$\int L dt = 1.08 \text{ fb}^{-1} \ (A, C) \ (2011)$

ATLAS Preliminary

$\int L dt = 1.08 \text{ fb}^{-1}$

$\tau$, Data

A

$\sigma_{t\bar{t}} = 142 \pm 21 \text{ (stat.)} \pm 20^{+16}_{-15} \text{ (syst.)} \pm 5 \text{ (lumi.) pb}$

$\delta \sigma / \sigma \sim 21\%$

$\sqrt{s} = 7 \text{ TeV}, \ 1.09 \text{ fb}^{-1}$ CMS Preliminary

$\sigma_{t\bar{t}} = 148.7 \pm 23.6 \text{ (stat.)} \pm 26.0 \text{ (syst.)} \pm 8.9 \text{ (lumi.) pb}$

$\delta \sigma / \sigma \sim 24\%$
Fully hadronic channel

• $\geq 4$ jet trigger, good jets
• $\geq 6$ high $p_T$ jets, $\geq 2$ b-tags
  ‣ 4 jets with $p_T \geq 60$ GeV (A,C), 5th (6th) jet $p_T \geq 50$ (40) GeV (C)
• A: no e or $\mu$, small $E_T^{\text{miss}}$/ $\sqrt{E_T^{\text{calo}}}$ & large $H_T > 300$ GeV
• Reconstruct with $\chi^2$ kine fit

• Data-driven QCD bkg: weight control samples $\geq=6$ jets no b-tag (C) or 6,5 jets(A) with data driven b-tag prob

• $N_{tt}$ from lkl fit to top mass (C) checked by neural network descr. or $\chi^2(A) \rightarrow \sigma = N_{tt}/A \times \text{Lumi}$

Systematics from pseudo exp. (dominated by b-tag, jet scale, bkg norm)

syst dominated!

$\int L dt = 35 \text{ pb}^{-1} (A) (2010), \sim 1.0 \text{ fb}^{-1} (C) (2011)$
Luminosity, pile-up and simulation
Peak Luminosity per day in 2011
The maximum instantaneous luminosity versus day delivered to ATLAS. The luminosity determination is the same as described above for the integrated luminosity. Only the peak luminosity during stable beam periods is shown.
Number of Interactions per Crossing

Shown is the luminosity-weighted distribution of the mean number of interactions per crossing for 2011. The plot is shown for data taken before and after the September Technical Stop where the beta* was reduced from 1.5m to 1.0m. The integrated luminosities and the mean mu values are given in the figure. The mean number of interactions per crossing corresponds the mean of the poisson distribution on the number of interactions per crossing. It is calculated from the instantaneous luminosity as \( \mu = L \times \sigma_{\text{inel}} / (n_{\text{bunch}} \times f) \) where \( L \) is the instantaneous luminosity, \( \sigma_{\text{inel}} \) is the inelastic cross section which we take to be 71.5 mb, \( n_{\text{bunch}} \) is the number of colliding bunches and \( f \) is the LHC revolution frequency. More details on this can be found in arXiv: 1101.2185. The entries at \( \mu \approx 0 \) arise from pilot bunches that were present during many of the early LHC fills. The luminosity in these bunches is >100 times smaller than in the main bunches resulting in values \( \mu < 0.1 \).

also see arxiv:1101.2185
Simulation Monte Carlo used in top analyses

Generation

- **Top quark**: MC@NLO (A), MADGRAPH(C)
  - $\sigma$ is normalized to NNLO effects
  - variationas with ACER (A), POWHEG(A,C)
  - tau decays with TAUOLA

- **Single top**: MC@NLO(A), MADGRAPH (C)
  - $t$, $W_t$ and $s$ channels
  - normalized to MC@NLO, remove $W_t$ overlaps with tt final state

- **$Z$/$\gamma$+jets**: PYTHIA (A) for $Z_\tau\tau$, ALPGEN (A) for $Z$ to ee and $Z$ to mumu NLO factor of 1.25, MADGRAPH(C)

- **Di-boson**: WW, ZZ: ALPGEN (A) normalized to NLO from MCFM, PYTHIA(C)

- **$W$+jets**: ALPGEN (A), MADGRAPH(C)
  - $W+n$ light partons, $W+bb$, $W+cc$, $W+c$

Hadronization

- HERWIG + JIMMY for underlying event modelling (A), PYTHIA(C)

Detector

- GEANT4
Why Top (quark)?

Most massive constituent of matter

$M_{\text{top}}$ - electroweak symmetry breaking scale

Decay and strong production rate are tests of standard model

Various scenarios with direct/indirect coupling to new physics: from extra dimensions to new strong forces

Background to possible new physics (Higgs, SUSY)

Masses of known fundamental particles

$M_{\text{Top}} \sim M_{\text{Gold Atom}}$

$\Phi^0_{\text{Higgs}}$, $\Phi^0_{\text{SUSY}}$

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