Standard Model @ Hadron Colliders
X. Top Quark: production (cont.)
A semileptonic $tt$ event
Is the top quark a normal fermion?

- Weak t coupling (V-A)
- CKM – elements
- Electric charge
- Top mass

- gtt couplings
- spin correlations
- tt - resonances

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Production of top quarks

What $x$ required for top production?

$$\sqrt{x_1 \cdot x_2} \geq \frac{2 \cdot M_t}{E_{pp}}$$

- 0.18 at Tevatron
- 0.05 at LHC (0.025 @ 14 TeV)

Dominant at LHC for low $M_{tt}$
Suppressed @ Tevatron

Relevant at LHC for high $M_{tt}$
Dominant @ Tevatron
How to measure $t\bar{t}$ cross section

(Why should we?):
Sensitive to gluon –$t\bar{t}$ couplings
Test of QCD with massive quarks

Select events:
- 4 jets with $p_T > 25$ GeV
- isolated electron, muon $p_T > 20$ GeV
- missing transverse energy $> 20$ GeV

$$\sigma_{t\bar{t}} = \frac{N_{\text{measured}} - N_{\text{background}}}{\epsilon L}$$

What fraction of $t\bar{t}$ events are retained after selection

Luminosity:
How many proton-collisions?
Cross section determination

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

Key issue determine efficiency

Largest uncertainties:
- Jet energy scale
- bottom identification
- Background yield
- Jets from QCD
- selection efficiency e, µ, .....
Background estimation

Dominant background: $W + 4$ jets $\rightarrow$ same final objects
- assume QCD generators to be correct, i.e templates
- data driven method (ATLAS):
  \[ \text{tt – events: same number of } W^+, W^- \]
  \[ \text{W+jets method: more } W^+ \text{ than } W^- \]

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

\[ r_{MC} = \frac{N_{W^+}}{N_{W^-}} \]

$\rightarrow$ Further step: estimate $W+b(b)+2$ jets fraction based on bottom tagging in $W+2$jets $\rightarrow$ extrapolated to 4 jets via MC

Other background: QCD with $b \rightarrow$ lepton with high $x_{\text{Feynman}}$

Estimate from 'non – isolated‘ leptons

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Background in semileptonic $tt$

**Contribution to sample no $b$ – tag**

$S/B \sim 1/3$

$W+Jets/tt \sim 1.4$

**Contribution to sample with $b$ – tag**

$S/B \sim 4$

$W+Jets/tt \sim 0.15$

*price: somewhat reduced statistics*

$Wb+jets$ more uncertain
Dileptons + fully hadronic

Dileptonic:
Very pure tt – sample
Note: for X-section
no need to use any other property
... But loss in statistics

Fully hadronic:
Huge QCD background
Advantage: M(t), M(W)
⇒ Kinematic fit
Dileptonic and semi-leptonic measurements similar precision
All hadronic larger errors
Experiments have smaller uncertainty than theoretical calculation
Cross section measurement

Very good agreement between data and expectation

Theoretical uncertainty 7-10% partly NNLO

Theory & experiment uncertainty about equal
Tevatron fwd-bkw asymmetry

Count
- top quarks in forward hemi \( N_{fwd} \)
- top quarks in backward hemi \( N_{bwd} \)

\[ A_C = \frac{N_{fwd} - N_{bwd}}{N_{fwd} + N_{bwd}} \]
Standard Model: small asymmetry

Dominant production @ Tevatron  
→ charge direction 'lost'

LO: no asymmetry in Standard Model

NLO: Interference  
→ small $A_C$

Standard Model: (4.8±0.5)%
**Tevatron: larger asymmetry**

More events with $q_{\text{top}} \cdot y_{\text{top}} > 0$

Low mass: consistent with Standard Model
Masses $> 450$ GeV $3 – 4 \sigma$ deviation from expectation
\( A_{FB} \) vs \( m_{tt} \)

**CDF Run II Preliminary** \( L = 8.7 \text{ fb}^{-1} \)

- **I+Jets Data**
  \( \alpha_{M_t} = (8.9 \pm 2.6) \times 10^{-4} \)
- **NLO (QCD + EW) \( t\bar{t} + \text{Bkg} \)**
  \( \alpha_{M_t} = 2.4 \times 10^{-4} \)

**Forward-Backward Top Asymmetry, %**

Reconstruction Level

\( m_{\tilde{t}} < 450 \text{ GeV} \)
- DØ, 5.4 \( \text{ fb}^{-1} \):
  \( +2.5 \pm 3.1 \)
- CDF, 5.3 \( \text{ fb}^{-1} \):
  \( -2.2 \pm 4.3 \)

\( m_{\tilde{t}} > 450 \text{ GeV} \)
- DØ, 5.4 \( \text{ fb}^{-1} \):
  \( 11.5 \pm 6.0 \)
- CDF, 5.3 \( \text{ fb}^{-1} \):
  \( 19.8 \pm 4.3 \)
  \( 26.6 \pm 6.2 \)
  \( \text{S. Frixione and B.R. Webber, JHEP 06, 029 (2002)} \)

**Note:** These are earlier CDF results!!

**Low mass:** consistent with Standard Model

**Masses > 450 GeV** 3 – 4 \( \sigma \) deviation from expectation (CDF)
A glimpse of multi – TeV physics?

BSM interpretation:
asymmetry due to interference high mass particle + Standard Model

Type 1: Gluon with axial coupling
Type 2: \( t \) –channel Colour neutral vector with FCNC
Type 3: \( t \) –channel coloured scalar with FCNC

Such massive particles should become visible @ LHC
tt – asymmetries @ LHC

Differences: pp – collider, symmetric initial state

Enhance qq production by large ∆y

high x valence quark on low x sea anti-quark

Tevatron → LHC
qq → tt to gg → tt

Tevatron

LHC 8 TeV

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tt – asymmetries @ LHC

\[ A_c = \frac{N(\Delta | y > 0) - N(\Delta | y < 0)}{N(\Delta | y > 0) + N(\Delta | y < 0)} \]
Interpretation in models

For concrete model: compare Tevatron & LHC
vary mass and couplings of new particles

Many of the 'Tevatron' allowed models disfavoured by ATLAS (and CMS)
Jets in top events

QCD effects imply a potential strong bias to studies

Production properties:
$p_T$ and $y$ of $tt$ – system
Good description by QCD calculations

Jet multiplicities:
Deficiencies at higher $N_{\text{jets}}$
Mass spectrum of $t\bar{t}$ - events

$p_T$ of top quarks & mass of $t\bar{t}$ – pairs predicted by QCD

,Resolved‘ four jet (+ lepton, $\nu$)  
Standard top selection

High mass region:  
Boosted tops $\Rightarrow$ merged jets  
Appropriate algorithms required
Production properties: e.g. $M_{tt}$

'Fat jet'

Closer look shows substructure
Fat jet & substructure

Highly boosted tops: close by jets $\rightarrow$ 'Fat jet' of $R = 1.0$

Require: $M_{\text{fat jet}} > 100$ GeV

Next step: look for substructure
- use $k_T$ jet finder to 'uncluster'
- $d_{ij} > (40 \text{ GeV})^2$

Require opposite jet/lepton system

Possible improvements: trimming of jets:
Reject any subjet with some $p_{T,i} / p_{T,\text{jet}} < f_{\text{cut}}$

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Models predict resonances $X \rightarrow \ttbar$

| spin $|h|$ | colour representation | parities $(1, \gamma_5)$ | type | Interference | example |
|---|---|---|---|---|---|
| 0 | [1] | (1,0) | scalar colour singlet | + | SM, MSSM, 2HDM |
| 0 | [1] | (0,1) | pseudoscalar colour singlet | + | MSSM, 2HDM |
| 0 | [8] | (1,0) | scalar colour octet | | techni-$\pi^0$ |
| 0 | [8] | (0,1) | pseudoscalar colour octet | | techni-$\pi^0$ |
| 1 | [1] | (SM,SM) | excitation of $Z^0$ | | sequential $Z'$ |
| 1 | [1] | (1,0) | vector colour singlet | | |
| 1 | [1] | (0,1) | axial vector colour singlet | | |
| 1 | [1] | (1,1) | left-handed vector colour singlet | | |
| 1 | [1] | (1,-1) | right-handed vector colour singlet | | |
| 1 | [8] | (1,0) | vector colour octet | - | coloron, KK gluon |
| 1 | [8] | (0,1) | axial vector colour octet | | axigluon |
Models predict resonances $X \rightarrow \ttbar$

Higher masses: long tails due to $gg/qq$ luminosity

Example:
5 dim theories, Randall–Sundrum etc. predict Kaluza–Klein gluons

No significant resonance
$\Rightarrow M_{KK} > 1.5 \text{ TeV}$

ATLAS
Simulation $\sqrt{s}=7$ TeV
- $m_1=500$ GeV
- $m_2=700$ GeV
- $m_2=1000$ GeV
- $m_3=1300$ GeV

Reconstructed $\ttbar$ mass [GeV]

Example:
$\int L \, dt = 2.05 \text{ fb}^{-1}$

$\sigma \times \text{BR}(g_{KK} \rightarrow \ttbar) \, [\text{pb}]$

Syst.+stat. errors
- Obs. 95% CL upper limit
- Exp. 95% CL upper limit
- Exp. 1\sigma uncertainty
- Exp. 2\sigma uncertainty
- Kaluza-Klein gluon

$\sqrt{s} = 7$ TeV

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tt + Z/W events

Measurement of Ztt & Wtt coupling
Possible resonance search or heavy quark
Important background for SUSY searches

Search for
a. (Z→ll)+1+b(b), → ttZ
b. equal charge lepton pair + b(b) → ttW/Z

Expected low X-section, fair agreement with expectation
Is the top quark a normal fermion?

- Weak $t$ coupling ($V-A$)
- CKM – elements
- Electric charge
- Top mass
Mass of the top quark

A fundamental parameter of the Standard Model

A broad spectrum of decays and methods

Note: first time a quark mass can be measured directly

(Lighter quarks to be inferred indirectly from hadron masses)
Top mass from l+jet decays

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

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

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

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Problem 1: $p_z(\nu)$

Constraint from $W$ - mass

$$M^2_W = (E_l + E_\nu)^2 - (p_x(l) + p_x(\nu))^2 - (p_y(l) + p_y(\nu))^2 - (p_z(l) + p_z(\nu))^2$$

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

Note: $\nu$ – mass completely negligible

Quadratic equation $\rightarrow$ 2 solutions

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

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

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

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

Important constraints
- mass $(jjj) =$ mass$(jlv) (= M_t)$
- mass $(jj) = M_W$
Problem 3: jet energy scale

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

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

Top – quarks offer 'self calibration'
\(M(jj)\) has to be equal \(M_W\)

\(\rightarrow\) change JES such that fulfilled

Still the (slightly) dominant uncertainty of \(M_t\)

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Most precise: matrix method

Theoretical pred with $M_1$(top)

$w_1$

$w_2$

$\Rightarrow$ probability density for $M_1$
use 24 integration variables

Next step:
convolute with exptl. effects

$\Rightarrow$ Assign weight to each event

Example: energy resolution

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Likelihood from different masses

Sum over all events and find combine weights

\[ W(M_1(\text{top})) = w_A \cdot w_B \cdot w_C \cdot \ldots = \Pi w_i \Rightarrow \mathcal{L}(M_1(\text{top})) \]
\[ W(M_2(\text{top})) = w_A \cdot w_B \cdot w_C \cdot \ldots = \Pi w_i \Rightarrow \mathcal{L}(M_2(\text{top})) \]

......

Find M(top) with maximum weight

\[ m_t = 176.0 \pm 1.3 \text{ GeV} \]
Top mass from dileptons & hadronic

Dileptons:
No direct mass peak visible
➔ use energies of electrons (& bottom jets)
➔ using MET adjust neutrino energies to yield same $M_W$ and $M_{top}$

All hadrons:
Fight huge background
➔ suppress by neural network
A lot of measurements, a lot of methods
all decay channels by now better than 2 GeV!
Combination    $173.2 \pm 0.6 \pm 0.8$ GeV
How to interpret result?

For Standard Model fit → 'pole mass' required
Instead: all methods based on simulation of QCD effects of mass

'top quark not totally free':
colour flow - how does this affect mass determination?

e.g. colour reconnection

Different models → mass differences of a few GeV

Skands&Wicke
**Top mass from cross section**

Mass measurements based on MC simulation ➔ not well defined QCD corrections

Difficult to interpret in Electroweak fits

➔ pole mass from NNLO calculations on Xsection
Current results

Theoretically better motivated

But errors of ~ 5 -8 GeV mostly due to theory uncertainty

note: MS – mass around 160 GeV!

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Speculations about the top mass

Top mass and the $10^{18}$ GeV scale

Naturalness problem:
Renormalising the Higgs mass
Contributions to $\Delta m_H$
$\Rightarrow$ 'most relevant' compensate top

Higgs potential:
$\lambda(m_H) = 0.125$ (+uncertainties)
$\Rightarrow \lambda(Q^2)$
If $\lambda < 0 \Rightarrow$ universe unstable

Nice to speculate .....
But can we really extrapolate safely over 14 orders of magnitude?

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Helicity structure of top decay

Is the top a normal weakly decaying particle?
Note: first time helicity structure of quark can be determined

W – polarisation against direction of t – quark momentum
Longitudinal polarosation also possible

Polarisation reflected in decay angle of fermions
Helicity structure of top decay

\[ \frac{1}{\sigma} \frac{d\sigma}{d \cos \theta^*} = \frac{3}{4} (1 - \cos^2 \theta^*) \cdot F_0 + \frac{3}{8} (1 - \cos \theta^*)^2 \cdot F_L + \frac{3}{8} (1 + \cos \theta^*)^2 \cdot F_R \]

Rather straight forward for e, \( \mu \)

For W \( \rightarrow \) qq identify q vs. \( \bar{q} \)

Challenging!

angle related to lepton energy, \( M_{bl} \), .....
Measurements

Agreement with NNLO expectation:
'no' right handed W's, most W's are longitudinal
Limits on additional couplings

Several BSM models → deviations

General approach Effective Lagrangian:
Parametrisation into higher dimension operators

\[ \int L \, dt = 1.04 \text{ fb}^{-1} \]

\( g_L, g_R \): left/right handed coupling of dim-6 operator
Top spin correlations @ LHC

'Bare' quark $\rightarrow$ direct information on spin configuration
Spin correlations offer test of production of $tt$ – pairs
Potentially important tool to identify new particles

Close to threshold:
$S = 0$ state, gluon helicities like
Top spins aligned

High $tt$ masses:
$gg \rightarrow tt$: helicity conservation
Top spins opposite

Use leptons to identify spin directions and correlations
Dilepton decay needed $\rightarrow$ rest system cannot be determined
Experimental method

Define quantisation axis, e.g. beam

\[ a \text{*Signal templates} + b \text{* background template} = \text{DATA} \]
Spin correlations @ Tevatron

Note: Tevatron tops via qq – scattering!

\[
\frac{1}{\sigma} \frac{d^2 \sigma}{d \cos \theta_+ d \cos \theta_-} = 1 + \frac{1 + \kappa \cos \theta_+ \cos \theta_-}{4}
\]

Tevatron no or marginal evidence for spin correlations

\[
f = 0.85 \pm 0.29
\]
Measure $\Delta \phi$ of leptons in transverse plane

Note experimental distortion:
Alignment means on lepton low energetic

Spin correlations @ LHC

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Comparison with SM expectation

<table>
<thead>
<tr>
<th>Reconstructed asymmetries</th>
<th>Data</th>
<th>Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{\Delta \phi}$, inclusive region</td>
<td>$-0.158 \pm 0.010$</td>
<td>$-0.171 \pm 0.002$</td>
</tr>
<tr>
<td>$A_{c1c2}$, inclusive region</td>
<td>$-0.062 \pm 0.011$</td>
<td>$-0.087 \pm 0.002$</td>
</tr>
<tr>
<td>$A_{\Delta \phi}$, $M_{t\bar{t}} &gt; 450$ GeV/$c^2$</td>
<td>$-0.378 \pm 0.019$</td>
<td>$-0.384 \pm 0.003$</td>
</tr>
<tr>
<td>$A_{c1c2}$, $M_{t\bar{t}} &gt; 450$ GeV/$c^2$</td>
<td>$-0.019 \pm 0.016$</td>
<td>$-0.044 \pm 0.003$</td>
</tr>
</tbody>
</table>

First significant evidence of spin correlations
Agreement with Standard Model

Study of spin correlations:
A method to separate new resonances from QCD continuum (?)
Single top production

top pairs due to strong coupling, weak coupling $\Rightarrow$ single top quarks

Dominant
$\sigma(7 \, \text{TeV}) = 65 \, \text{pb}$

(half of tt - Xsection)

Remember:
$W^\pm$ couples to fermion doublets

\[
\begin{pmatrix}
\nu_e \\
e^-
\end{pmatrix},
\begin{pmatrix}
\nu_\mu \\
\mu^-
\end{pmatrix}, \ldots, 
\begin{pmatrix}
t \\
b
\end{pmatrix}
\]
Single top production

Allows detailed studies of the weak coupling of top quarks

- How often does $W \rightarrow tb$ (and not ts, td, or something else?)
  i.e. measuring CKM element $|V_{tb}|$
- Does the top couple completely left handed to the W?
  (as all other fermions do)

Example: $W^+ \rightarrow u\bar{d}$

Spin direction
Momentum

Forbidden in weak interactions

- new particles, additional couplings ........
Several observables with moderate sensitivity: combine all information likelihood

Peter Mättig, Graduiertenkolleg
Berlin/Dresden 2012
Measurements

CMS:
$$\sigma_{t\text{-}\text{channel}}(7 \text{ TeV}) = 70.2 \pm 12.1 \text{ pb}$$

ATLAS
$$\sigma_{t\text{-}\text{channel}}(7 \text{ TeV}) = 90.2^{+32}_{-22} \text{ pb}$$

Observation of single top production
Precision measurements to follow
Measurements

**t-channel single top quark production**

- CMS preliminary, 1.14/1.51 fb$^{-1}$
- D0, 5.4 fb$^{-1}$
- CDF, 3.2 fb$^{-1}$

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**Theory Models**

- NLO QCD (5 flavour scheme)
  - Theory uncertainty (scale $\oplus$ PDF)
  - Campbell, Frederix, Maltoni, Tramontano, JHEP 10 (2009) 042

- NLO+NNLL QCD
  - Theory uncertainty (scale $\oplus$ PDF)
  - Kidonakis, Phys.Rev.D 83 (2011) 091503
Measurements

$|V_{tb}| = 1.03^{+0.16}_{-0.19}$

Search for $tb$ resonances

$M_W' > 1.2$ TeV

Anomalous couplings

$B(t\rightarrow ug) < 5.7 \times 10^{-5}$, $B(t\rightarrow cg) < 2.7 \times 10^{-4}$
Conclusion

- Standard Model test a crucial element of LHC program
- Understanding SM processes pre – condition for understanding detector
- Studying SM at highest energies charters new territory and may reveal New Physics
- If New Physics will turn up in 'non- SM signatures', SM processes still must be considered as background

LHC: a first go on Standard Model processes
statistics by the end of the year 6 – 1000x higher
detailed systematic studies required
but: whole new phase space can be addressed