Measurements of the inclusive cross section and of differential distributions in top quark pair production

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on behalf of

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The Top Quark

- needed as isospin partner of bottom quark
- discovered in 1995 by CDF and DØ: $m_{\text{top}} \sim$ gold atom
- large coupling to Higgs boson $\sim 1$: important role in electroweak symmetry breaking?
- short lifetime: $\tau \sim 5 \cdot 10^{-25} \text{s} \ll \Lambda_{\text{QCD}}^{-1}$: decays before fragmenting → observe “naked” quark

Is the top quark the particle as predicted by the SM?
The Tevatron at FERMILAB: \( pp \) Collisions

Is the top quark the particle as predicted by the Standard Model?

- Run I 1987 (92)-95
- Run II 2001-11: 100x larger dataset at increased energy

\[ \sqrt{s} = 1.96 \text{ TeV} \]
\[ \Delta t = 396 \text{ ns} \]
Tevatron Integrated Luminosity

Run II Integrated Luminosity

19 April 2002 - 30 September 2011

Delivered
Recorded

up to 5.4 fb$^{-1}$

Thanks to accelerator and computing divisions!
Inclusive production cross section
Differential cross section
Top mass
Lorentz invariance violation
Conclusions
Outline

Inclusive production cross section

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Top Quark Pair Production

\[ \sigma_{tt} = 7.46^{+0.48}_{-0.67} \text{ pb in NNLO} \text{ (approx)} \]

\( m_{\text{top}} = 172.5 \text{ GeV} \)

PRD 78, 034003 (2008)
Top Pair Signatures

top decay:

\[ \sim 100\% \]

\[ t \rightarrow w^+ l^+ \bar{q}' \]

\[ b \rightarrow \nu, q \]

\[ \tau^{'s} \]

\[ 14\% \]

\[ \text{tt decay modes} \]

\[ \text{all jet} \]

\[ 46\% \]

\[ \text{lepton + jets} \]

\[ \text{tau + jets} \]

\[ \text{all hadronic} \]

\[ \text{dilepton (e/\mu)} \]

\[ 6\% \]

\[ \text{e/\mu + jet} \]

\[ 34\% \]
Lepton+Jets Topological Cross Section

Powerful test of QCD and search for new physics

- Kinematic properties allow separation between signal and background

Use variables such as:

Energy-dependent quantities:
- E.g. transverse mass of leptonic top

Angular dependent:
- E.g. sphericity

Random Forests of Boosted Decision Trees
Lepton+Jets Topological Cross Section

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Random Forests of Boosted Decision Trees

W+jets

W+jets
Lepton+Jets Topological Cross Section

\[ \sigma_{tt} = 7.68^{+0.71}_{-0.64} \text{ (stat+syst+lumi) pb} \]

\[ m_{\text{top}} = 172.5 \text{ GeV} \]

DØ, L=5.3 fb^{-1}

\[ \geq 4 \text{ jets} \]

\[ \geq 3 \text{ jets} \Rightarrow 4 \text{ jets} \]

\[ e \text{ and } \mu \]

up to 6 variables

combine:
- 2 jets
- 3 jets
- \( \geq 4 \) jets
- e and \( \mu \)
**b-tagging**

- $B$ hadron lifetime $\tau \sim 1$ ps
- $B$ hadrons travel $L_{xy} \sim 3$ mm before decay

**secondary vertex tagger**
- 45% $b$-jet tagging efficiency (with fake rate of 1%)

**form a 7-variable neural network**
- $b$-jet tagging efficiency 59% (with fake rate of 1%)

*Secondary vertex measurement flowchart*

*Secondary vertex measurement comparison chart*
Lepton+Jets Cross Section with b-tagging

very powerful tool to reduce the background

\[
\sigma_{tt} = 8.13^{+1.02}_{-0.90} \text{ pb}\]

\[m_{\text{top}} = 172.5 \text{ GeV}\]
Combined Method

W+jets & heavy flavor scale factor $f_H$

systematically limited:
- luminosity
- JES and JER
- b-tagging

$b$-jet counting

$m_{top} = 172.5$ GeV

$\sigma_{tt} = 7.78^{+0.77}_{-0.64}$ (stat+syst+lumi) pb

Phys. Rev. D 84, 012008 (2011)
Dilepton Cross Section with b-tagging

$\sigma_{\text{tt}} = 7.36^{+0.90}_{-0.79}\,\text{(stat+syst+lumi)}\,\text{pb}$

$\pm 11\%$

$m_{\text{top}} = 172.5$ GeV

Top Pair Production Cross Sections

Combination: \( l + \text{jets and dilepton} \)

\[ \sigma_{\text{tt}} = 7.56^{+0.63}_{-0.56} \text{ pb} \]

\( m_{\text{top}} = 172.5 \text{ GeV} \)

→ good agreement with higher order QCD calculations

DØ Run II

\( \sigma(p\bar{p} \rightarrow t\bar{t} + X) \) [pb]

\[ \begin{align*}
\text{lepton+jets + dileptons (PLB)} & : 7.40^{+0.19}_{-0.19}^{+0.54}_{-0.54} \text{ pb} \\
\text{lepton+jets (topo + b-tagged, PRD)} & : 7.65^{+0.25}_{-0.25}^{+0.75}_{-0.67} \text{ pb} \\
\text{dileptons (topo + b-tagged, PLB)} & : 7.27^{+0.45}_{-0.45}^{+0.76}_{-0.63} \text{ pb} \\
\text{lepton+track (b-tagged)*} & : 5.0^{+1.0}_{-1.0}^{+1.0} \text{ pb} \\
\text{tau+lepton (b-tagged)*} & : 7.32^{+1.34}_{-1.09}^{+1.34}_{-1.09} \text{ pb} \\
\text{tau+jets (b-tagged, PRD)} & : 6.30^{+1.15}_{-1.09}^{+0.72}_{-0.67} \text{ pb} \\
\text{all jets (b-tagged, PRD)} & : 6.9^{+1.3}_{-1.3}^{+1.4}_{-1.4} \text{ pb} \\
\end{align*} \]

\( m_{\text{top}} = 175 \text{ GeV} \)

CTEQ6.1M

M. Cacciari et al., JHEP 0809. 127 (2008)
S. Moch and P. Uwer, PRD 78, 034003 (2008)

* = preliminary
red = 2011 result
blue = 2010 results

\( \frac{\text{stat}}{\text{syst}} \) (lumi)
Outline

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Differential Cross Section

- important test of NLO QCD
- unfolding of distributions

need NLO QCD to describe normalisation correctly


Differential Cross Section

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shape described well by PYTHIA and ALPGEN

DØ

- data, 1 fb^{-1}
- NLO pQCD
- Approx. NNLO pQCD
- MC@NLO
- PYTHIA
- ALPGEN

(tree level LO)

(tree level incl. higher orders)

Shape ratio to NLO pQCD

(0 50 100 150 200 250 300 350 400)
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What mass do we measure?

\[ L = \ldots - \bar{\psi} M \psi (1 + \frac{H}{\nu}) \ldots \]

- **LO QCD**: free parameter
- **NLO QCD**: dependent on the renormalisation scale \( M \)

"Bare" parameters of QCD:
\[ g_s, m_u, m_d, m_s, m_c, m_b, m_t \]

Renormalised parameters of QCD:
\[ g_s(M), m_u(M), m_d(M), m_s(M), m_c(M), m_b(M), m_t(M) \]

**the concept of quark mass is convention-dependent!**
Important to know...

- measurement reconstructing decay products: depends on MC mass details
- how does MC mass relate to pole mass or running mass scheme?

• can we measure pole or MS mass in direct and well-defined way?

![Graph showing a relationship between M_w and M_t with shaded regions indicating excluded masses and a peak at pole mass.](image-url)
Important to know...

- measurement reconstructing decay products: depends on MC mass details
- how does MC mass relate to pole mass or running mass scheme?

![Graph showing relationship between pole mass and world average mass interpreted as MS mass with a deviation of ~10 GeV (3-loop)].

- can we measure pole or MS mass in direct and well-defined way?
Top Quark Pole Mass

- MC mass = pole mass
- use b-tagged cross section since less dependent on mass
- difference due to MC mass interpretation is included into systematics

\[ m_t^{\text{pole}} = 166.7^{+5.2}_{-4.5} \text{ GeV} \pm 2.9\% \]
Top Quark Pole Mass

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\[ m_t = 166.7^{+5.2}_{-4.5} \text{ GeV} \pm 2.9\% \]

$1\sigma$ consistent with Tevatron average: $m_t = 173.3 \pm 1.1$ GeV
Top Quark $\overline{\text{MS}}$ Mass

- Better convergence of higher order resummation

**MC mass = pole mass**

- First extraction of $\overline{\text{MS}}$ mass taking selection efficiency into account

\[ m_t^{\overline{\text{MS}}} = 160.0^{+4.8}_{-4.3} \text{ GeV} \pm 2.8\% \]

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Top Quark Mass

- First extraction of MS mass taking selection efficiency into account
  
  \[ m_t^{\text{MS}} = 160.0^{+4.8}_{-4.3} \text{ GeV} \]  
  \[ \pm 2.8\% \]

- \(2\sigma\) consistent with Tevatron average: \(m_t = 173.3 \pm 1.1\) GeV

- Tevatron average is more consistent with a pole mass!
Inclusive production cross section
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Search for Lorentz invariance violation

General Lorentz invariance violating terms added to SM Lagrangian:

\[ |M|^2 = P F \bar{F} + (c_R + c_L)_{\mu\nu} (\delta P_p + \delta P_v)^{\mu\nu} F \bar{F} + (c_L)_{\mu\nu} \left( P(\delta F)^{\mu\nu} \bar{F} + P F (\delta \bar{F})^{\mu\nu} \right) \]

symmetric traceless matrices:
strength of Lorentz invariance violation
Search for Lorentz invariance violation

\[ N_i \approx N_{\text{tot}} \frac{\mathcal{L}_i}{\mathcal{L}_{\text{int}}} [1 + f_S f_{\text{SME}}(\phi_i)] \]

- \( \mathcal{L}_i \) is the integrated luminosity over appropriate bin of sidereal phase \( \phi_i \)
- \( f_S \) is the fraction of signal (\( t\bar{t} \)) events

\[ R_i \equiv \frac{1}{f_S} \left( \frac{N_i}{N_{S+B}} \frac{\mathcal{L}_i}{\mathcal{L}_{\text{int}}} - 1 \right) \]

\[ \rightarrow \text{no indication of time dependence of } t\bar{t} \text{ cross section} \]

\[ \rightarrow \text{first constraints on LIV in free quark sector } (c_L)_{XX}, (c_L)_{XY}, \ldots, (c_R)_{XX}, \ldots \]
Conclusions

Highlights of top pair production physics:

- top pair production cross section
  8% precision, many channels analyzed, good agreement with NLO QCD predictions, no new physics observed

- differential cross section is investigated
  e.g. top quark transverse momentum, powerful QCD tests

- pole and MS mass
  pole mass agrees with Tevatron combination within 1σ

- top quark production as expected in SM
  new tests using NNLO+NNLL calculations: 3% uncertainty
Backup
Lepton+jets Signatures

**signal**

- $e/\mu + \text{jet}$

- $W + \text{jets}$

- Multijets

**background**

- $q'\bar{q}$

- $W^{+}$

- $b$ and $\bar{b}$

- $W^{-}$

3000 times higher rate

10$^{10}$ times higher rate

Jet 1

Jet 2

SV
Dilepton Signatures

**signal**

- ee, eμ, μμ

**background**

300 times higher rate

- Z + jets

- less statistics
- less background

→ electron+muon event with b-tagging
Top Pair Production Cross Section

- check if production rate is as expected in the SM
- test of the underlying theory: QCD
- powerful search for new physics beyond the SM

Measurement: \[ \sigma = \frac{N_{\text{obs}} - N_{\text{bg}}}{\varepsilon L} \]

5.4 fb^{-1}
Top Pair Production Cross Sections

- Good agreement with SM in all channels
- All channels measured except for $\tau$-hadrons
- Combination: ±6%
Differential Cross Section

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no deviation from the SM

Differential Cross Section

- important test of NLO QCD
- unfolding of distributions

- need NLO QCD to describe normalisation correctly
- no deviation from the SM
- NLO+NNLL: improvement


Ahrens, Ferrogia, Neubert, Pecjak, Yang
Which top mass does a LO MC contain?

- matrix element in LO QCD
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- parton showers simulate higher orders, i.e. not only radiating additional gluons!
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Which top mass does a LO MC contain?

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- parton showers simulate higher orders, i.e. **not** only radiating additional gluons! (LL)
  
  \[ \Rightarrow \text{very hard to answer...} \]

- arguments that it should be close to pole mass
Top Quark Pole Mass

<table>
<thead>
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<th>Theoretical prediction</th>
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<th>$\Delta m_t^{\text{pole}}$ (GeV)</th>
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<td>MC mass assumption</td>
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<td>NLO [12]</td>
<td>$164.8^{+5.7}_{-5.4}$</td>
<td>$-3.0$</td>
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<tr>
<td>NLO+ NLL [13]</td>
<td>$166.5^{+5.5}_{-4.8}$</td>
<td>$-2.7$</td>
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**MC mass = pole mass**

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• $1\sigma$ consistent with Tevatron average: $m_t = 173.3 \pm 1.1 \text{ GeV}$
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**better convergence of higher order resummation**

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\(m_t^{\overline{\text{MS}}} = 160.0_{-4.3}^{+4.8} \) GeV \(\pm 2.8\%\)

- first extraction of \(\overline{\text{MS}}\) mass taking selection efficiency into account
- 2\(\sigma\) consistent with Tevatron average: \(m_t = 173.3 \pm 1.1\) GeV
- Tevatron average is more consistent with a pole mass!

arXiv:1104.2887 [hep-ex]

Moch, Uwer
Ahrens et al.
Different Top Mass Definitions

\[ \overline{m}_t \equiv m_t^{\overline{\text{MS}}} (m_t) = \frac{M_t}{1 + \frac{4}{3\pi} \alpha_s(M_t)} \]

\[ \overline{m}_t \approx m_t^{\overline{\text{MS}}} (m_t) = \frac{1}{p^2 - M_t^2 - i\Gamma_t M_t} \]

⇒ difference between \( \overline{\text{MS}} \) and pole mass is \( \approx 10 \text{GeV} \)...
Search for Lorentz invariance violation

- General Lorentz-violating terms added to SM Lagrangian
  - Effective field theory treatment for LV
  - Not constrained to be the same for all particle species

\[ |M|^2 = \left( P F \bar{F} + (c_R + c_L)_{\mu \nu} (\delta P^p + \delta P^v)_{\mu \nu} F \bar{F} + (c_L)_{\mu \nu} P (\delta F)_{\mu \nu} \bar{F} + P F (\delta \bar{F})_{\mu \nu} \right) \]

- \( c_R \) and \( c_L \) are symmetric, traceless matrices containing coefficients which parametrize the strength of Lorentz violation in the top quark sector
- Set limits on elements of \( c_R \) and \( c_L \), as well as linear combinations \( c = c_L + c_R \) and \( d = c_L - c_R \).
- Top sector only accessible to high-energy particle colliders
  - Tight limits already set on LV other particle sectors
Search for Lorentz invariance violation

- GOAL: Estimate components of $c_R$ and $c_L$ matrices

\[ c_{Apparatus}^{L(R)} = \hat{R}(\omega_{side} t)_{(Sun\rightarrow Apparatus)} c_{Sun}^{L(R)} \]

- D-Zero events projected onto different components of SME matrices $c_R$ and $c_L$
  - Varies with sidereal frequency as detector rotates with Earth
  - Unique signature!
  - Time-dependent event rate.