Top Quark Highlights

Christian Schwanenberger
University of Manchester

The 2009 Europhysics Conference on High Energy Physics, Krakow
21/07/2009

Thanks to Florencia Canelli, Yvonne Peters, Verónica Sorin, Frédéric Déliot, Stefan Söldner-Rembold, George Velet for helping in preparing this talk!
The Top Quark

- needed as isospin partner of bottom quark
- discovered in 1995 by CDF and DØ: $m_{\text{top}} \sim \text{gold atom}$
- 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
Top History

1995, CDF and DØ experiments, Fermilab

- PRL 74, 2632 (1995)
- PRL 74, 2626 (1995)
Top History

Discovery

1995, CDF and DØ experiments, Fermilab

PRL 74, 2632 (1995)
PRL 74, 2626 (1995)

Today

\(17 \text{ events} \quad \text{DØ}
\)

\(1 \text{ b-tag} \quad \text{l+4 jets}
\)

\(~1000 \text{ events}\)

\(19 \text{ events} \quad \text{CDF}
\)

\(\text{l+4 jets} \quad 1 \text{ b-tag}\)

Reconstructed Mass (GeV/c²)

Fitted Mass (GeV/c²)

Events/(20 GeV/c²)

Events/(10 GeV/c²)

\(\sim 1000 \text{ events}\)

Prelim. DØ, \(L=3.6 \text{ fb}^{-1}\)

Data

\(Z' (650 \text{ GeV})\)

Other MC

Multijet
1995, CDF and DØ experiments, Fermilab

Top History

discovery

PRL 74, 2632 (1995)
PRL 74, 2626 (1995)

precision

Top Quark Mass Uncertainty

Tevatron

17 events

DØ

~1000 events

19 events

CDF

1 b-tag

1+4 jets

19 events

PRL 74, 2632 (1995)
PRL 74, 2626 (1995)

today
**Top History**

**discovery**

1995, CDF and DØ experiments, Fermilab

**precision**

~1000 events

**today**

PRL 74, 2632 (1995)
PRL 74, 2626 (1995)

Top Quark Mass Uncertainty

- l+jets DØ measurement
- Combined DØ measurement
- Tevatron combination
- Projected future uncertainty range

**searches**

Tevatron

19 events

PRL 74, 2626 (1995)

21 events

PRL 74, 2632 (1995)

17 events

PRL 74, 2626 (1995)
Top History

**Discovery**

17 events

DØ

19 events

CDF

1995, CDF and DØ experiments, Fermilab

**Precision**

~1000 events

**Today**

**Searches**

Top Quark Mass Uncertainty

LHC: top factory

PRL 74, 2626 (1995)

PRL 74, 2632 (1995)
Outline

- Top physics at the Tevatron
  - Top production cross sections
  - Top properties
- Searches in production and decay
- Prospects at the LHC
- Conclusions
Outline

**Top physics at the Tevatron**
- top production cross sections
- top properties
- searches in production and decay

**Prospects at the LHC**

**Conclusions**
Top Quark Analyses at the Tevatron

analyses with up to 4 fb$^{-1}$ of data:
several thousand top candidate events per experiment

top pair production

spin correlations
charge asymmetry $A_{FB}$
production cross-section
production kinematics
production through resonances
new particles

anomalous couplings
rare decays
branching ratios
CKM-Matrix-Element $|V_{tb}|$
new particles

mass, charge, width, lifetime

W helicity

single top production

observation by CDF and DØ!

searches for new particles
Top Quark Analyses at the Tevatron

analyses with up to 4 fb\(^{-1}\) of data:
several thousand top candidate events per experiment

top pair production

S. Greder
- spin correlations
- charge asymmetry \(A_{FB}\)

R. Erbacher
- mass, charge, width, lifetime

Y. Peters
- anomalous couplings
- rare decays
- branching ratios
- CKM-Matrix-Element \(|V_{tb}|\)
- new particles

A. Lister
- production cross-section
- production kinematics
- production through resonances
- new particles

R. Schwienhorst
- single top production

B. Casal Laraña
- particles

observation by CDF and DØ!
Outline

top physics at the Tevatron

top production cross sections

top properties

searches in production and decay

prospects at the LHC

conclusions
Top Quark Pair Production

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

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

PRD 78, 034003 (2008)
Top Pair Signatures

top decay:

\[ t \rightarrow W^+ b, \ell^- + q' \sim 100\% \]

\[ W^- \rightarrow \ell^- + q, \nu \]

\[ W^+ \rightarrow \ell^+ + q', b \]

All jet: 46%

Lepton + jets: 34%

Dilepton (e/\mu): 6%

\[ \tau^- \rightarrow e^-/\mu^- + q, \nu, s \]

\[ \tau^+ \rightarrow \ell^+ + q', s \]

\[ \bar{\tau}^- \rightarrow \ell^- + q, \nu, \bar{s} \]

\[ \bar{\tau}^+ \rightarrow e^-/\mu^- + q', \bar{s} \]
Lepton+jets Signatures

**Signal**

- Lepton + jets
- $e/\mu + jet$

**Background**

- $W + jets$
- multijets

3000 times higher rate

$10^{10}$ times higher rate
Top Pair Production Cross Section

measure if production rate is as predicted by NLO QCD

**lepton+jets channel:**
- topological information (NN)

**all hadronic channel:**
- b-tagging

\[ \sigma_{\bar{t}t} = 6.9 \pm 0.4 \text{ (stat)} \pm 0.4 \text{ (syst)} \pm 0.1 \text{ (Z theo)} \text{ pb} \]

\[ m_{\text{top}} = 175 \text{ GeV} \pm 8\% \]

\[ \sigma_{\bar{t}t} = 7.2 \pm 0.5 \text{ (stat)} \pm 1.4 \text{ (syst)} \pm 0.4 \text{ (lumi)} \text{ pb} \]

\[ m_{\text{top}} = 172.5 \text{ GeV} \pm 21\% \]
Top Pair Production Cross Sections

DØ Run II  * = preliminary  May 2009

- l+jets, dilepton, \( \tau + \)lepton (PRD) (1.0 fb\(^{-1}\))
  - 7.84 \(\pm 0.46 \pm 0.66 \pm 0.54 \pm 0.46\) pb

- l+jets (b-tagged & topological, PRL) (0.9 fb\(^{-1}\))
  - 7.42 \(\pm 0.53 \pm 0.46 \pm 0.45\) pb

- l+jets (neural network b-tagged, PRL) (1.0 fb\(^{-1}\))
  - 8.20 \(\pm 0.52 \pm 0.77 \pm 0.53 \pm 0.50 \pm 0.67 \pm 0.45\) pb

- dilepton (topological, PLB) (1.0 fb\(^{-1}\))
  - 6.98 \(\pm 1.12 \pm 0.78 \pm 0.64 \pm 1.04 \pm 0.59 \pm 0.51\) pb

- l+track (b-tagged)\(^{*}\) (1.0 fb\(^{-1}\))
  - 5.0 \(\pm 1.6 \pm 0.9 \pm 1.4 \pm 0.8 \pm 0.3\) pb

- \(\tau +\)lepton (b-tagged)\(^{*}\) (2.2 fb\(^{-1}\))
  - 7.32 \(\pm 1.34 \pm 1.20 \pm 1.24 \pm 1.06 \pm 0.45\) pb

- \(\tau +\)jets (b-tagged)\(^{*}\) (0.4 fb\(^{-1}\))
  - 5.0 \(\pm 4.3 \pm 0.7 \pm 3.5 \pm 0.7 \pm 0.3\) pb

- alljets (b-tagged, PRD) (0.4 fb\(^{-1}\))
  - 4.5 \(\pm 2.0 \pm 1.4 \pm 1.9 \pm 1.1 \pm 0.3\) pb

\[ m_{\text{top}} = 175 \text{ GeV/}c^{2} \]
CTEQ6.6M

\[ m_{\text{top}} = 175 \text{ GeV/}c^{2} \]

CDF Run II  Preliminary\(^{*}\)  July 2008

- Assume \( m_{\text{top}} = 175 \text{ GeV/}c^{2} \)

- Lepton+Track  (L= 1.1 fb\(^{-1}\))
  - 8.3 \(\pm 1.3 \pm 0.7 \pm 0.5\) pb

- Lepton+Track: Vertex tag  (L= 1.1 fb\(^{-1}\))
  - 10.1 \(\pm 1.8 \pm 1.1 \pm 0.6\) pb

- Dilepton  (L= 2.8 fb\(^{-1}\))
  - 6.7 \(\pm 0.8 \pm 0.4 \pm 0.4\) pb

- Lepton+Jets; Kinematic ANN  (L= 2.8 fb\(^{-1}\))
  - 6.8 \(\pm 0.4 \pm 0.6 \pm 0.4\) pb

- Lepton+Jets; Vertex Tag  (L= 2.7 fb\(^{-1}\))
  - 7.2 \(\pm 0.4 \pm 0.5 \pm 0.4\) pb

- Lepton+Jets; Soft Electron Tag  (L= 2.0 fb\(^{-1}\))
  - 7.8 \(\pm 2.4 \pm 1.5 \pm 0.5\) pb

- Lepton+Jets; Soft Muon Tag  (L= 2.0 fb\(^{-1}\))
  - 8.7 \(\pm 1.1 \pm 0.9 \pm 0.5\) pb

- MET+Jets; Vertex Tag  (L= 0.3 fb\(^{-1}\))
  - 6.1 \(\pm 1.2 \pm 0.8 \pm 0.4\) pb

- All-hadronic; Vertex Tag  (L= 1.0 fb\(^{-1}\))
  - 8.3 \(\pm 1.0 \pm 2.0 \pm 0.5\) pb

- CDF combined  (L= 2.8 fb\(^{-1}\))
  - 7.0 \(\pm 0.3 \pm 0.4 \pm 0.4\) pb

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

\[ \sigma(p\overline{p} \rightarrow t\overline{t}) (pb)\]

⇒ good agreement with SM in all channels
Single Top Quark Production

**direct measurement of** $|V_{tb}|$

**s-channel:** $\sigma_{tb} = 1.04 \pm 0.04 \text{ pb}$

$\text{NNNLO}_{\text{approx}}, m_{\text{top}} = 172.5 \text{ GeV}$

$V_{\text{CKM}} = \begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix}$

**t-channel:** $\sigma_{tb} = 2.26 \pm 0.12 \text{ pb}$

$\text{NNNLO}_{\text{approx}}, m_{\text{top}} = 172.5 \text{ GeV}$

- jets
- lepton
- missing $E_T$
- $b$-jets
It has been challenging for years...

\[ \begin{array}{cccc}
\text{Cross section (barns)} & 1 & \text{Total inelastic} & 2 \cdot 10^{10} \\
\text{mb} & 10^{10} & b \bar{b} & 1 \cdot 10^{7} \\
\mu b & 10^{8} & W & 6,000 \\
\text{nb} & 10^{6} & Z & 600 \\
\text{pb} & 10^{4} & t \bar{t} & 2 \\
\text{fb} & 10^{2} & \text{single top} & 1 \\
100 & 120 & 140 & 160 & 180 & 200 \\
\text{Higgs mass (GeV}/c^2) & \text{Higgs (ZH + WH)} & \text{H}^0 & W^+ & W^+
\end{array} \]

\[ \text{ multivariate analysis techniques } \]
Multivariate Analyses

- Boosted Decision Trees
- Boosted Neural Networks
- Matrix Elements

combine up to 12 different analysis channels:

DØ Single Top 2.3 fb⁻¹

Event Yield

Discriminant Output

Data

$tb + tqb$

$W + jets$

$tt$

Multijets

Signal Region

single top
Multivariate Analyses

- Boosted Decision Trees
- Neural Networks
- Matrix Elements
- Likelihood

combine up to 8 different analysis channels:

single top

- $E_T + \text{jets selection}:
  - recover badly reconstructed $e, \mu$; include $\tau$

CDF Run II Preliminary, $L = 3.2 \, \text{fb}^{-1}$
- Single Top
- W+HF
- $t\bar{t}$
- QCD+Mistag
- Other
- Other
- Data
Single Top Observation

DØ 2.3 fb⁻¹

<table>
<thead>
<tr>
<th>Top Quark Mass [GeV]</th>
<th>Yield [Events/30GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>1</td>
</tr>
<tr>
<td>200</td>
<td>20</td>
</tr>
<tr>
<td>300</td>
<td>30</td>
</tr>
</tbody>
</table>

 Ranked Combination Output > 0.92

<table>
<thead>
<tr>
<th>Single Top Cross Section</th>
<th>Signal Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>DØ 2.3 fb⁻¹ arXiv:0903.0850</td>
<td>m_{top} = 170 GeV</td>
</tr>
<tr>
<td>3.94 ± 0.88 pb</td>
<td>4.5 σ</td>
</tr>
<tr>
<td></td>
<td>5.0 σ</td>
</tr>
<tr>
<td>CDF 3.2 fb⁻¹ arXiv:0903.0885</td>
<td>m_{top} = 175 GeV</td>
</tr>
<tr>
<td>2.3 ±0.6 pb</td>
<td>&gt;5.9 σ</td>
</tr>
<tr>
<td></td>
<td>5.0 σ</td>
</tr>
</tbody>
</table>

⇒ observation with 5.0σ!

|V_{tb}| = 1.07±0.12

|V_{tb}| = 0.91±0.13
First Evidence for t–Channel Production

- remove s/t channel constraint which could be changed by
  - additional quark generation
  - new heavy bosons
  - FCNC
  - anomalous top quark couplings

DØ Run II preliminary 2.3 fb\(^{-1}\)

\[ \sigma(t\text{-channel}) = 3.14^{+0.94}_{-0.81} \text{ pb} \]

evidence with 4.8\(\sigma\)
Single Top Production at HERA

- not possible in SM, but via flavour changing neutral currents
- results complementary to LEP and Tevatron
- full data set analysed

\[ \Gamma_{\ell} \nu_{\ell} \rightarrow u, c \]
Outline

top physics at the Tevatron
  top production cross sections
  top properties
  searches in production and decay
prospects at the LHC
conclusions
The Top Quark Mass

- free parameter in the Standard Model
- check the self-consistency of the Standard Model in combination with W mass measurement
- prediction on Higgs mass
Extraction Techniques

**template method:**
- reconstruct \( m_{\text{top}} \)
- compare data to MC with different \( m_{\text{top}} \) hypotheses

**matrix element method:**
- probability densities for every event as function of \( m_{\text{top}} \)

\[
P_{\text{sig}}(x; m_{\text{top}}, JES) = \frac{\text{Acc}(x)}{\sigma} \int d^n \sigma(y; m_{\text{top}}) dq_1 dq_2 f(q_1) f(q_2) W(x, y; JES)
\]

Acceptance (selection, trigger, ...)

LO-Matrix element x phase space

PDF’s

Transfer Functions (Probability to measure x when y was produced)
**Extraction Techniques**

**template method:**
- use variables strongly correlated with $m_{\text{top}}$
- compare data to MC with different $m_{\text{top}}$ hypotheses

**matrix element method:**
- probability densities for every event as function of $m_{\text{top}}$

$$P_{\text{sig}}(x; m_{\text{top}}, JES) = \frac{\text{Acc}(x)}{\sigma} \int d^n \sigma(y; m_{\text{top}}) dq_1 dq_2 f(q_1) f(q_2) W(x, y; JES)$$

- Acceptance (selection, trigger,...)
- LO-Matrix element x phase space
- PDF’s
- Transfer Functions (Probability to measure x when y was produced)
Results in $l$+jets Channel

**maximum Likelihood fit to data:**

![Graph showing the maximum likelihood fit to data with contours for different likelihood changes and a central value indicating the top quark mass.](image)

**jet energy scale:**
translate jet into parton energy

\[
m_{\text{top}} = 173.7 \pm 0.8 \text{ (stat)} \pm 1.6 \text{ (syst)} \text{ GeV}
\]

\[
m_{\text{top}} = 172.1 \pm 0.9 \text{ (stat)} \pm 1.3 \text{ (syst)} \text{ GeV}
\]
Mass of the Top Quark (*Preliminary*)

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Value (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF-I di-l</td>
<td>167.4 ± 10.3 ± 4.9</td>
</tr>
<tr>
<td>D0-I di-l</td>
<td>168.4 ± 12.3 ± 3.6</td>
</tr>
<tr>
<td>CDF-II di-l</td>
<td>171.2 ± 2.7 ± 2.9</td>
</tr>
<tr>
<td>D0-II di-l</td>
<td>174.7 ± 2.9 ± 2.4</td>
</tr>
<tr>
<td>CDF-I l+j</td>
<td>176.1 ± 5.1 ± 5.3</td>
</tr>
<tr>
<td>D0-I l+j</td>
<td>180.1 ± 3.9 ± 3.6</td>
</tr>
<tr>
<td>CDF-II l+j</td>
<td>172.1 ± 0.9 ± 1.3</td>
</tr>
<tr>
<td>D0-II l+j</td>
<td>173.7 ± 0.8 ± 1.6</td>
</tr>
<tr>
<td>CDF-I all-j</td>
<td>186.0 ± 10.0 ± 5.7</td>
</tr>
<tr>
<td>CDF-II all-j</td>
<td>174.8 ± 1.7 ± 1.9</td>
</tr>
<tr>
<td>CDF-II trk</td>
<td>175.3 ± 6.2 ± 3.0</td>
</tr>
</tbody>
</table>

**Heinemeyer et al.**

$$m_{top} = 173.1 \pm 1.3 \text{ GeV} \pm 0.75\%$$

- **Theory & Experiment: Uniform Treatment of Systematics**
- **Experimental Errors 68% CL:**
  - LEP2/Tevatron (today)
  - MSSM

**Theory & Experiment: Uniform Treatment of Systematics**
mass difference would imply CPT-violation

- l+jets channel
- use matrix element method
- modified MC to allow for different top and anti-top masses

\[ m_t - m_{\bar{t}} = 3.8 \pm 3.7 \text{ GeV} \]

\( m_t \) and \( m_{\bar{t}} \) are measured for the first time for 'bare' quarks

agreement with SM

\( \Rightarrow \) measured for the first time for 'bare' quarks
Spin Correlation in Dilepton Channel

spins correlated only if top lifetime is short enough

$$\begin{align*}
\text{SM spin} & & \text{no spin} \\
\cos \theta^+ \cos \theta^- & & 
\end{align*}$$
Spin Correlation in Dilepton Channel

- spins correlated only if top lives short enough

\[ {^3S_1} \quad \Rightarrow \quad t \quad \Rightarrow \quad \begin{array}{c} q \quad \Rightarrow \quad \bar{q} \\ t \quad \Rightarrow \quad \bar{t} \end{array} \]

\[ \cos \theta \cos \phi \]

**SM spin**

**no spin**

DØ Run II preliminary (4 fb⁻¹)
Spin Correlation in Dilepton Channel

• spins correlated only if top lives short enough

\[ t \rightarrow ^3S_1 \]

\[ q \rightarrow \bar{q} \]

\[ t \rightarrow \bar{q} \]

\[ q \rightarrow t \]

\[ \cos \theta_b \]

\[ \cos \theta \]

\[ \kappa = \frac{N(\uparrow\uparrow) + N(\downarrow\downarrow) - N(\uparrow\downarrow) - N(\downarrow\uparrow)}{N(\uparrow\uparrow) + N(\downarrow\downarrow) + N(\uparrow\downarrow) + N(\downarrow\uparrow)} \]

NLO QCD: \( \kappa \approx 0.78 \)


\( \kappa = -0.17^{+0.64}_{-0.53} \)

\( \kappa = 0.32^{+0.55}_{-0.78} \)

first results in Run-II, agreement with SM within 1\( \sigma \) (CDF), 2\( \sigma \) (DØ)

\( \text{beam axis} \)

\( 4.2 \text{ fb}^{-1} \)

\( \text{off diag. axis} \)

\( 2.8 \text{ fb}^{-1} \)
Outline

top physics at the Tevatron
  top production cross sections
  top properties
searches in production and decay
prospects at the LHC
conclusions
Search for New Physics in Top Production
Search for $t\bar{t}$ Resonances

- no resonance production in $t\bar{t}$ system is expected in SM
- some models predict $t\bar{t}$ bound states: e.g. leptophobic $Z'$ with strong 3rd generation coupling

**Search for bumps in $t\bar{t}$ reconstructed mass spectrum**

![Graph showing search for $Z'$ resonance](image)

- $M_{Z'} > 820$ GeV (CDF)
- $M_{Z'} > 805$ GeV (D0)

**L+jets, 3.6 fb$^{-1}$**

CDF Run II preliminary, $L=2.8$ fb$^{-1}$
Forward Backward Charge Asymmetry

- test coupling to top pairs

\[ \begin{array}{c}
\text{q} \\
\text{Z'} \\
\text{V-A} \\
\text{q'} \\
\text{t} \\
\text{W^+} \\
\text{\ell^+} \\
\text{b} \\
\text{W^-} \\
\text{\bar{q}} \\
\text{\bar{t}} \\
\text{\bar{b}} \\
\end{array} \]
Forward Backward Charge Asymmetry

- test coupling to top pairs

\[
\begin{array}{c}
\text{g} \\
\text{V} \\
\end{array}
\begin{array}{cc}
q & t \\
\bar{q} & \bar{t} \\
W^+ & \ell^+ \\
W^- & \bar{b} \\
\end{array}
\]
Forward Backward Asymmetry

- test coupling to top pairs

$$A_{fb} = 0.193 \pm 0.065 \text{ (stat)} \pm 0.024 \text{ (syst)}$$

NLO QCD in $O(\alpha_s^3)$: $A_{fb} = 0.05 \pm 0.015$ \implies agrees within $2\sigma$

$$A_{fb}^{\text{det}} = 0.12 \pm 0.08 \text{ (stat)} \pm 0.01 \text{ (syst)}$$ with 1 fb$^{-1}$

PRL 100, 062004 (2008)
Search for New Physics in Top Decays

$q \rightarrow W^+ b \nu \ell^+$

$q' \rightarrow W^- b \bar{q}$
Search for Charged Higgs Bosons

- supersymmetry can remedy shortcomings of the SM

$$M_{H^+} = 80 \text{ GeV}$$
Search for Charged Higgs Bosons

- supersymmetry can remedy shortcomings of the SM

\[ M_{H^+} = 80 \text{ GeV} \]

\[ B(H^+ \rightarrow \tau \nu) = 1 \]

- Data
- \( \bar{t} \bar{t} \text{ Br}(t \rightarrow H^+ b) = 0.0 \)
- \( \bar{t} \bar{t} \text{ Br}(t \rightarrow H^+ b) = 0.3 \)
- \( \bar{t} \bar{t} \text{ Br}(t \rightarrow H^+ b) = 0.6 \)
- background

\[
\begin{align*}
N_{\text{event}} & \begin{cases}
10^4 & \text{for } \bar{t} \bar{t} \text{ events} \\
10^3 & \text{for } \bar{t} \bar{t} \text{ events} \\
10^2 & \text{for } \bar{t} \bar{t} \text{ events} \\
10 & \text{for } \bar{t} \bar{t} \text{ events}
\end{cases}
\end{align*}
\]

- decrease
- decrease
- increase

\[
\begin{align*}
\text{l+jets 1 tag} & \quad \text{l+jets 2 tag} & \quad \text{dilepton} & \quad \tau+\text{lepton}
\end{align*}
\]
MSSM Interpretations

**CPX benchmark scenario: strangephilic Higgs**

\[
\text{Br}(H^+ \rightarrow \tau^+ \nu) + \text{Br}(H^+ \rightarrow c \bar{s}) = 1
\]

DØ Run II preliminary 1.0 fb\(^{-1}\)
MSSM Interpretations

**CPX benchmark scenario: strangephilic Higgs**

\[
\text{Br}(H^+ \rightarrow \tau^+ \nu) + \text{Br}(H^+ \rightarrow c\bar{s}) = 1
\]

DØ Run II preliminary 1.0 fb\(^{-1}\)

\[M_{H^+} > 154 \text{ GeV}\]

⇒ first limit on a CP-violating MSSM scenario in H\(^+\) searches
top physics at the Tevatron

top production cross sections

top properties

searches in production and decay

prospects at the LHC

conclusions
Top Pair Production at the LHC

10 top pairs per day @ Tevatron ↔ 1 top pair per second @ LHC

- rediscovery possible already with 10 pb$^{-1}$ at 10 TeV
  - cross section uncertainty ~20% for dilepton channels
  - test lepton identification, jet identification, b-tagging, etc.

\[ \Delta \sigma_{tt} = 15\% \text{ (stat)} \pm 10\% \text{ (syst)} \pm 10\% \text{ (lumi)} \]
Single Top Production

4 single tops per day @ Tevatron ↔ 30 single tops per minute @ LHC

t-channel: most sensitive

Δ|V_{tb}| = 12% (stat+syst+theo)

dominated by systematic uncertainties due to b-tagging, JES, luminosity

Δ|V_{tb}| = 11%

Δ|V_{tb}| = 14%

Boosted Decision Trees

ATLAS
1 fb⁻¹

BDT > 0.6

Leptonic Top M (GeV)

Entries
Top Properties

- systemically limited Tevatron analyses hard to beat: $\Delta m_{\text{top}} \sim 1$ GeV (instead of 1 – 1.3 GeV at the Tevatron)
- measure basic quantities as spin, charge and couplings with high precision
- measure some quantities for first time, as e.g. spin correlation

Tevatron:

- NLO QCD: $\kappa \approx 0.78$
- measurements (dilepton) cannot separate yet between SM and 0

LHC:

- NLO QCD: $\kappa \approx 0.33$
- l+jets with 220 pb$^{-1}$ gives already $\sim 50\%$ uncertainty with ATLAS

\[ \begin{align*}
  \text{Tevatron:} & & \text{LHC:} \\
  q & \rightarrow & t & g \\
  q & \rightarrow & \bar{q} & g \\
  \bar{t} & \rightarrow & \bar{t} & g \\
  \bar{t} & \rightarrow & \bar{t} & g
\end{align*} \]
Searches for New Physics

- in many cases LHC has a better sensitivity by orders of magnitude as e.g. flavour changing neutral currents with $10 \text{ fb}^{-1}$
- new development: tagging of boosted top jets

**Constraints:**
- top mass
- W mass

⇒ 46% efficiency, 2% fake rate for $p_T = 600$ GeV top quarks
Outline

- top physics at the Tevatron
- top production cross sections
- top properties
- searches in production and decay
- prospects at the LHC
- conclusions
Highlights of top quark physics:

- single top observation + direct measurement of $V_{tb}$
- precision measurements
  - top mass with 0.75% uncertainty
- top properties
  - new analyses possible such as spin correlation
- searches for new physics in top sector
  - general agreement with SM
- excellent prospects for top physics at the LHC
Backup
The Tevatron at FERMILAB: $p\bar{p}$ Collisions

$\sqrt{s} = 1.96$ TeV
$\Delta t = 396$ ns

Run I 1987 (92)-95: 125 pb$^{-1}$
Run II 2001-11: ~100x larger dataset at increased energy

top quark discovery
measure properties with high precisions:
is it really the particle expected in the SM?
Top mass from cross section measurement

- lepton+jets/dilepton/lepton+tau combination

\[ M_{\text{top}} = 169.1^{+5.9}_{-5.2} \text{ GeV with NNLO}_{\text{approx}} \pm 3.3\% \]
Spin Correlation Result

κ = -0.17 $^{+0.64}_{-0.53}$

⇒ first results in Run-II, agreement with SM

κ = 0.32 $^{+0.55}_{-0.78}$

NLO QCD
Limits on Leptophobic Z'
Limits on Leptophobic Z' 

CDF Run II preliminary, L=2.8fb⁻¹

- Expected limit at 95% C.L.
- Expected limit at 95% C.L. ±1σ
- Expected limit at 95% C.L. ±2σ
- Observed limit at 95% C.L.
- Leptophobic Z', Γ_Z≈1.2% M_Z

M_{Z'} > 805 GeV

all hadronic

l+jets, 3.6 fb⁻¹

M_{Z'} > 820 GeV
Search for new particles

\[ \begin{align*}
q & \rightarrow \nu \ell^+ \bar{b} \\
\bar{q} & \rightarrow \bar{b} W^- \\
q' & \rightarrow W^+ b \\
\end{align*} \]
Search for $t'$ Quarks

e.g. 4$^{th}$ generation of top quarks

- analyse $m_t^{\text{reco}}$, $H_T$
- analyse $n_{\text{jets}}$, $n_{b-\text{jets}}$, $H_T$

$M_H > 146$ GeV

$m_{t'} > 311$ GeV
Forward backward asymmetry

\[ \Delta y \equiv y_t - y_{\bar{t}} \]

\[ A_{fb} = \frac{N_{\Delta y > 0} - N_{\Delta y < 0}}{N_{\Delta y > 0} + N_{\Delta y < 0}} \]
Charge asymmetry in SM

- no asymmetry in $O(\alpha_s^2)$
- asymmetry in $O(\alpha_s^3)$

Interference between:

```
\begin{align*}
\text{no asymmetry in } & O(\alpha_s^2) \\
\text{asymmetry in } & O(\alpha_s^3)
\end{align*}
```

```
\text{interference between:}

\begin{align*}
\text{interference}
q & \rightarrow \text{t} \\
\bar{q} & \rightarrow \text{t}
\end{align*}

\begin{align*}
\text{interference}
q & \rightarrow \text{t} \\
\bar{q} & \rightarrow \text{t}
\end{align*}
```

```
\begin{align*}
\text{interference}
q & \rightarrow \text{t} \\
\bar{q} & \rightarrow \text{t}
\end{align*}

\begin{align*}
\text{interference}
q & \rightarrow \text{t} \\
\bar{q} & \rightarrow \text{t}
\end{align*}
```
Lepton+Jets Channel

W mass constrains jet energy scale

jet energy scale:
translate jet into parton energy
Extraction techniques: matrix element

- probability densities for every event as function of $m_{\text{top}}$

\[
P_{\text{sig}}(x; m_{\text{top}}, JES) = \frac{\text{Acc}(x)}{\sigma(y; m_{\text{top}})} \times \frac{1}{\mathcal{O}} \int d^n \sigma(y; m_{\text{top}}) \, dq_1 \, dq_2 \, f(q_1) \, f(q_2) \, W(x, y; JES)
\]

Acceptance (selection, trigger, ...)

LO-Matrix element x phase space

PDF's

Transfer Functions (Probability to measure x when y was produced)

- maximum Likelihood fit:

\[
L(x_1, \ldots, x_n; m_{\text{top}}, JES, f_{\text{top}}) = \prod_{i=1}^{n} P_{\text{evt}}(x_i; m_{\text{top}}, JES, f_{\text{top}})
\]
Search for the SM Higgs boson

- contains Yukawa coupling

\[ \begin{align*}
q & \quad \bar{q} \\
\bar{t} & \quad H \\
W & \quad l \\
W & \quad b \\
W & \quad \bar{b} \\
j & \quad j \\
j & \quad j
\end{align*} \]

**good separation against background:**

- 4, \( \geq 5 \) jets with 1, 2, \( \geq 3 \) b-tags
  (lepton+jets channel)
Search for the SM Higgs boson

D0 Run II 2.1 fb⁻¹ Preliminary

≥5 jets, ≥3 tag

Number of events vs. \( H_T \) (GeV)

- **data**
- 100×\( t\bar{t}H \rightarrow t\bar{t}b\bar{b} \)
- \( t\bar{t} \)
- W+jets
- Z+jets
- diboson
- single top
- multijets

Diagram:

- \( q \rightarrow Wq \)
- \( \bar{q} \rightarrow W\bar{q} \)
- \( t \rightarrow Wb \)
- \( \bar{t} \rightarrow W\bar{b} \)
- \( H \)
- MET
Limits for the SM Higgs boson

- only the beginning...
- optimize selection
- analyse more variables as e.g. invariant $b\bar{b}$ mass

$→$ included in the Tevatron Higgs combination
b-tagging at DØ

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

form a 7-variable neural network
event tagging efficiency 54% (with fake rate of 1%)

SVT/SVX
Search for Z' production

**l+jets selection**

**ttbar resonances**

**Z' search**

**FB asymmetry**

**Z' search**

![Graph showing observed limit 95% CL, topcolor Z' (CTEQ6L1), and expected limit 95% CL for DØ RunII, L=3.6 fb⁻¹, Preliminary.](image)

![Graph showing upper limit on f versus Z' mass [GeV].](image)