Top Quark Measurements at the Tevatron

- Experimental setup
- Top quark pair production and decay
- Top quark pair cross section
- Top quark mass measurements
- Single top quark measurements
- Conclusion and outlook

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The Tevatron Accelerator

**Tevatron Collider**
- Proton-antiproton collider with $\sqrt{s}=1.96$ TeV
- 36x36 bunches with 396ns between crossings
- ~5 collisions per bunch crossing
- $L_{\text{pInst}} \sim 4 \times 10^{32} \text{cm}^{-2}\text{s}^{-1}$

**Run I 1992-1995**
- Top quark discovered!

**Run II 2001-2011**
- Single Top quark discovered!
- Many more exciting physics results

Tevatron collected significant amount of data
- ~12 fb$^{-1}$ delivered, ~11 fb$^{-1}$ recorded, ~10 fb$^{-1}$ after data quality per experiment
• **Tracking**
  - Momentum measurement of charged particles
  - Vertex and b-jet identification

• **Calorimeter**
  - Energy measurement of jets, electrons and neutrinos

• **Muon system**
  - Momentum measurement of muons

• **Three level trigger system**
Top Quark Physics

Top Quark is unique

- Heaviest fundamental particle now
  - Mass = 173.2 ± 0.9 GeV
  - ~40 times heavier than bottom quark
- Strong coupling to the Higgs

\[ g_{Ht} = \sqrt{2} \frac{m_t}{VEV} = \sqrt{2} \cdot 173.1 \text{ GeV}/246 \text{ GeV} \approx 1 \]

- Very short lifetime (~ \(5 \times 10^{-25}\) s)
  - Decays before hadronization and makes it the only “bare quark” to study
  - Decays almost 100% of the time to \(Wb\)

Top Quark Physics is a rich field

- Production rates and properties
- Precise test of SM and search for new phenomena
- Study top pair and single top separately
Discovered in 1995 at the Tevatron:

- Very few events at the beginning
- Thousands of events now
- Era of precision measurements
- Some area difficult for LHC to catch up
Top Quark Physics at Tevatron

Top (Rare) Decay $|V_{tb}|$, Anomalous Coupling

Top Mass

Top Charge

Top Production

Top Width, Lifetime

W Helicity

Charge Asymmetry

New Particles Resonances

Single Top

Tevatron legacy:

• Top quark mass, production $x_s$, kinematics
• Charge asymmetry, spin correlation complementary to LHC
Top Pair Production and Decay

Pair production via strong production
- Discovery mode (1995)
- Main production mode at Tevatron

\( \sigma_{\text{NNLO+NNLL}} = 7.24^{+0.24}_{-0.27} \) [arXiv:1204.5201]

\( M_t = 172.5 \text{ GeV} \)

\( \sigma_{\text{LHC}} \approx 187 \text{ pb (7 TeV)} \)

85% 15%

Top Pair Branching Fractions

"alljets" 46%
\( \tau + \text{jets} \) 15%
\( \mu + \text{jets} \) 15%
\( e + \text{jets} \) 15%
"lepton+jets"
Signal and Background

**lepton+jets**

- Dominant background: W+jet
- Isolated, energetic leptons

**dilepton**

- Dominant background: Z+jet
- Large missing Energy (neutrino)

**pure hadronic**

- Dominant background: Multijet
- High momentum (b-)jets
Jet Energy Scale (JES)

- Important instrument in experimental particle physics
- Determine the energy of the quarks produced in the hard scattering
- “Correct” back to particle jet energy

Major systematic for many top quark analyses (top mass, cross section etc.)

- Due to energetic decay products
- Count for difference between data and Monte Carlo simulation
- Mostly measured by independent (photon+jet and dijet) samples
Separate b-jets from light quark and gluon jets

- B-hadron travels some millimeter before decay
- Use a Neural Network algorithm with input variables based on track impact parameters and reconstructed secondary vertex
  - Displaced tracks & vertex
  - NN discriminant output
- Reject most $W/Z+$jets background
- Require single-tag or double-tag

Multivariate Method (MVA)

- Inputs from multiple variables to build on discriminants
- Optimizes sensitivity to signal
- Takes into account correlations and extract full information
Two Analysis Methods

- Use b-tagging to suppress background
  - Form binned likelihood from data, \( \tt \) cross section and predicted background, maximize it as function of \( \sigma_{\tt} \) and nuisance parameters
    - D0: \( \sigma_{\tt} = 8.13 \pm 0.25 \) \( \text{(stat)} +0.99_{-0.86} \) \( \text{(syst)} \) pb
    - CDF: \( \sigma_{\tt} = 7.22 \pm 0.35 \) \( \text{(stat)} \pm 0.56 \) \( \text{(syst)} \pm 0.44 \) \( \text{(lumi)} \) pb
- Use kinematic discriminant to distinguish signal from background
  - Topological method (no b-tagging)
  - Fit discriminant output to data in all channels to extract cross section
    - D0: \( \sigma_{\tt} = 7.68 \pm 0.31 \) \( \text{(stat)} +0.64_{-0.56} \) \( \text{(syst)} \) pb
    - CDF: \( \sigma_{\tt} = 7.71 \pm 0.37 \) \( \text{(stat)} \pm 0.36 \) \( \text{(syst)} \pm 0.45 \) \( \text{(lumi)} \) pb
Top Pair Cross Section: Lepton+jets Channel

D0 Combination

- Use both kinematic information and b-tagging information
- Construct discriminant for channels dominated by backgrounds, otherwise use b-tagging method; multiply likelihood functions in each channel and fit to data
- \( \sigma = 7.78^{+0.77}_{-0.64} \) (sta + sys + lumi) pb

CDF Combination

- Measure ratio of \( \bar{t}t \) to \( Z/\gamma^* \rightarrow ll \) cross sections to reduce luminosity uncertainty, \( \sigma_{\text{theo} \ Z/\gamma^* \rightarrow ll} = 251.3 \pm 5.0 \) pb
- B-tagging: \( \sigma = 7.32 \pm 0.36 \) (sta) \( \pm 0.59 \) (sys) \( \pm 0.14 \) (theo) pb
- Topological: \( \sigma = 7.82 \pm 0.38 \) (sta) \( \pm 0.37 \) (sys) \( \pm 0.15 \) (theo) pb
- Combined using BLUE method (best linear unbiased estimate)
  - \( \sigma = 7.70 \pm 0.52 \) (sta + sys + theo) pb
  - Total uncertainty: 6.8%
Top Pair Cross Section: Dilepton Channel

Counting method

- Two high pT isolated leptons with two jets
- Clean signal with low yields, only channel with favorable S/B
- Subtract expected background from data
- Pretag (not requiring b-tagging):
  \[ \sigma_{tt} = 7.66 \pm 0.46 \text{ (stat)} \pm 0.66 \text{ (syst)} \pm 0.47 \text{ (lumi)} \text{ pb} \] (625 signal events)
- B-tagged (at least one b-tagged jet):
  \[ \sigma_{tt} = 7.47 \pm 0.50 \text{ (stat)} \pm 0.53 \text{ (syst)} \pm 0.46 \text{ (lumi)} \text{ pb} \] (254 signal events)
Summary of Top Pair Production Cross Section

New Result: September, 2012

- Tested many other channels: all hadronic, tau+lepton, tau+jets, missing $E_T$ + jets
  - Important to measure different channels
  - Different sensitivity to new physics
  - All measurements consistent with Standard Model
- Combined uncertainty 5.5%, working on full data set...
Motivation

- Free parameter of the Standard Model
- Most fundamental and best known top quark property!

Measurement

- Combinatorics: assign jets to partons
- Need to calibrate jet energies to particle level (JES)
- Many methods: template, matrix element, ideogram, lepton momenta etc.

Template method

- Compare data to MC with different mass hypothesis
- Take info from W mass to constrain JES: $\chi^2$ fit with $m_t$, $m_W$
- CDF all-hadronic: $m_t = 172.5 \pm 1.4$ (stat) $\pm 1.4$ (syst) GeV

CDF Conf. Note 10456

CDF Run II Preliminary (5.8 fb$^{-1}$)
Top Quark Mass: Matrix Element Method

- Probability density functions for an event characterized by a set of measurements $x$, given parameter(s) $\alpha$

$$P(x \mid \alpha)$$

- Sum over all (signal) states that can lead to the measurements

$$P(x \mid \alpha) = \sum_{states} c_s \, P_s(x \mid \alpha)$$

- For an ideal detector we have

$$P_s(x \mid \alpha) \, dx = \frac{d\sigma_s(x \mid \alpha)}{\sigma(\alpha)}$$

- In reality, we have

$$P_s(x \mid \alpha) = \frac{1}{\sigma_s(\alpha)} \int d\sigma_s(y \mid \alpha) W(y, x \mid \alpha)$$

measured variables

parameters

partonic variables

mapping between partonic and measured variables

LO Matrix Element X phase space
**Top Quark Mass: Matrix Element Method**

- Extract parameter(s) $\alpha$ by maximizing the overall event likelihood ($C_s$ is the signal fraction)

$$L(\alpha) = \prod_{i=1}^{N} (C_s P_s(x_i | \alpha) + (1-C_s) P_b(x_i | \alpha))$$

- In case of one parameter: $M_{\text{top}}$

- In case of two parameters: $M_{\text{top}}$ & JES
  - in-situ JES fit
  - Most precise measurement method
  - CDF lepton + jets:

  $$m_t = 173.0 \pm 0.9 \text{ (stat+JES)} \pm 0.9 \text{ (syst)} \text{ GeV}$$

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PRL 105 252001 (2010)
Top Quark Mass: Pole Mass

Quark mass definition

- Pole mass: classic definition, four-momentum squared
  - Quarks cannot exist as free particles and this definition becomes ambiguous; in perturbation theory only on order by order
  
  - Different definitions based on different orders and other renormalization schemes (\(\overline{MS}\)-mass)

Extract \(M_{top}\) from cross section

- Different assumptions: pole mass or \(\overline{MS}\)-mass, extract separately
  
  - Compare measurement with high-order theoretical predictions
    
    \[
    m_t^{\text{pole}}(\text{NNLO}_{\text{approx}}) = 167.5^{+5.4}_{-4.9} \text{GeV} \\
    m_t^{\overline{MS}}(\text{NNLO}_{\text{approx}}) = 160.0^{+5.1}_{-4.5} \text{GeV}
    \]

  - Only pole mass value consistent with direct measurement
Summary of Top Quark Mass

- 0.54% relative uncertainty!
- All channels, methods consistent
- Detailed study on systematics!
- Main sources: JES, statistics, signal modeling
- Improving results with 10fb⁻¹ data
Single Top Quark Production

Not $W^+ (W', H^+?)$

FCNC ($g\to tu, g\to tc$)

Width

Lifetime

Tau decay

Separate $t$-channel, $s$-channel cross sections

Anomalous $Wtb$ couplings

CKM matrix element $V_{tb}$
Single Top Quark Event Selection

Event Topology:
- High energy isolated lepton (e or mu from $W$) $p_T$(lepton) > 15 GeV
- Missing $E_T$ (ν from $W$) Missing $E_T$ > 20 GeV
- One b-quark jet (from $t$) and a light flavor jet and/or another b-jet
  2–4 jets with $p_T$ > 15 GeV, $|\eta| < 3.4$
- Leading jet $p_T$ > 25 GeV

Parton distributions

$\sigma_{SM} = 1.04 \pm 0.04$ pb

$M_t = 172.5$ GeV

$\sigma_{SM} = 2.26 \pm 0.12$ pb

PRD 74, 114012 (2006)
Single Top Quark Cross Section

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**DØ e/μ+jets 2.3 fb⁻¹**
- $3.94_{-0.88}^{+0.88}$ pb

**DØ τ+jets 4.8 fb⁻¹**
- $3.4_{-1.8}^{+2.0}$ pb

**CDF e/μ+jets 3.2 fb⁻¹**
- $2.17_{-0.55}^{+0.56}$ pb

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**DØ e/μ+jets 5.4 fb⁻¹**
- $3.70_{-0.80}^{+0.78}$ pb

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**s-channel evidence promising**

**Tevatron result complementary!**

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Kidonakis PRD 74, 114012 (2006)

$m_t = 170$ GeV
Top quark couplings to W boson is a good place to look for deviations from SM

- Effective single top production cross section: \( \sigma = A (L_V)^2 + B (R_V)^2 + C (L_V \cdot L_T) + D (R_V \cdot R_T) + E (L_T)^2 + F (R_T)^2 \)
  - \( L_{V,T} = V_{tb} \cdot f_{LV,T} \)
  - SM (left-handed vector coupling, \( L_V \)): \( L_V = |V_{tb}| \sim 1, \) all other \( =0 \)
  - Non-SM (anomalous couplings): left-handed tensor (\( L_T \)), right-handed vector (\( R_V \)), right-handed tensor (\( R_T \)) couplings

- Single top production directly sensitive to the \( Wtb \) interaction: rate, kinematics and angular distributions
  - Direct constraint on all four couplings
Single Top Quark Physics: Anomalous $Wtb$ Couplings

- Simultaneous limit setting for two signals by calculating two dimensional posterior probability density

**NO evidence for anomalous couplings in single top production**

**Strong direct constraints on non-SM $Wtb$ couplings**

- Improved limits by a factor of 3 to 5 compared to previous $0.9 \text{ fb}^{-1}$ analysis
  - $|V_{tb} \cdot f_{LT}|^2 < 0.06$, $|V_{tb} \cdot f_{RV}|^2 < 0.93$, $|V_{tb} \cdot f_{RT}|^2 < 0.13$ at 95% C.L.
- Further improvement when combining with $W$ helicity measurements
W helicity:

- Three helicity states for $W$ boson from top quark decay
- Standard model precise predictions (right-handed $W$ suppressed)

Left handed $f_-$ $\sim 0.30$
Longitudinal $f_0$ $\sim 0.70$
Right handed $f_+ \sim 1.4 \times 10^{-3}$

• Measure $W$ helicity through $\cos(\theta^*)$ distribution: best-fit using templates
Combined Top Quark Results

- Non-SM $Wtb$ couplings can alter $W$ helicity fractions significantly
- $W$ helicity measurements from top pair production and single top quark measurements provide complementary information
- Combination gives the best limits

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<th>Significant improvement on couplings limits</th>
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Learned a lot from 17 years of study on the top quark:

- \( M_t = 173.2 \pm 0.9 \text{ GeV}, \ \sigma_{tt} = 7.6 \pm 0.4 \text{ pb} \)
- \( \sigma_t = 2.7 \pm 0.6 \text{ pb}, |V_{tb}| = 0.88 \pm 0.07 \)
- Top charge: exclude -4/3 e @ 95% C.L.
- \( \Gamma_t = 2.0 \pm 0.4 \text{ GeV} \) (SM \( \Gamma_t = 1.3 \text{ GeV} \)), \( \tau_t < 4.88 \times 10^{-25} \text{ s} \) @ 95%
- Longitudinally polarized W: \( f_0 = 0.72 \pm 0.08 \) (SM \( f_0 = 0.7 \))
- Spins in top pair are correlated: \( C_F = 0.85 \pm 0.29 \) (>3\( \sigma \) sig.)
- and many more...

Expect (already) stronger results from LHC data

- Adopt similar techniques: e.g. W helicity and t-channel single top quark production
- Many complementary analyses: s-channel single top, spin correlation, charge asymmetry
- Tevatron legacy measurement: top quark mass