Summary of recent top results presented at the Aspen Winter Conference by M. Kruse, R. Wallny, R. Erbacher, Y. Cadou, L. Wang as well as E. Aguilo and F. Deliot. Thanks for their transparencies!
What Everyone Knows about Top

**discovered in 1995 by CDF and D0:**
- it completes the 3 generations of quarks
- its mass is \( \sim 172 \text{ GeV} \pm 1.5\% \)

And...
- the top is very heavy: \( b/t \sim 40 \)
- only quark to decay before hadronisation
- Yukawa coupling to the Higgs \( \sim 1 \)

\( \Rightarrow \) Does the top quark play a special role in EWSB? Or may we see new physics associated with the top?

**The Tevatron is currently the only place where the top quark can be studied!**
New Physics associated to the top at the EW-scale?

- **Supersymmetry:**
  - Top Yukawa coupling is modified w.r.t. its SM value
  - Mass scale of top partners must be low (not true of other superpartners)
  - New physics associated with top may be first to be seen

- **Little Higgs models:**
  - New vector-like top-partner $T$, $m \sim 1–2$ TeV
  - Mixes with top, decays to $th, tZ, bW$

- **Strongly-coupled models:** Technicolor and its descendents
  - If mass dynamically generated, top is special because of its large mass: extra interactions (topcolor…)
  - Resonances in $tt, tb$ (single top in s-channel)

- **Modified spacetime:** Extra dimensions
  - Not such a special role for top, but can have $\bar{t}t$ production through KK resonances
What We Want to Know Better!

- Single top production
- Top mass
- Top lifetime
- Top charge
- Production cross-section
- Production mechanism
- Resonant production
- Top Branching fractions
- CKM matrix element $|V_{tb}|$
- Rare top decays: FCNC
- W helicity
The Tevatron

- **Run II (2001-200x)**
  - $\sqrt{s} = 1.96$ TeV
  - Current peak luminosity $\sim 25.0 \times 10^{31}$ cm$^{-2}$s$^{-1}$
  - Both experiments have now $> 1.7$ fb$^{-1}$ on tape.
  - Aim for 4-9 fb$^{-1}$ int. luminosity in Run II

- **World’s highest energy collider (until LHC...)**
  - Proton-antiproton Synchrotron
  - Experiments CDF and DØ

  - $\sqrt{s} = 1.8$ TeV
  - 100 pb$^{-1}$ int. luminosity

- **Major upgrade to accelerator complex**
  - Main Injector (x5)
  - Pbar Recycler (x2)

- January 2007: $> 2$ fb$^{-1}$!
...and Its Experiments

Both experiments:
New tracking systems
Upgraded electronics, trigger, DAQ

Excellent tracking
New forward calorimeters

Excellent muon coverage
New magnet, pre-shower detectors
…and brand new Si L0

All crucial for top physics!
Top Pair Production

- Production cross-section
- Production mechanism
- Resonant production
- Single top production
- Top Branching fractions
- CKM matrix element $|V_{tb}|$
- Rare top decays: FCNC
- Top mass
- Top lifetime
- Top charge
- W helicity

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Top Pair Production at the Tevatron

SM Decay:

Three different final states:

**All-hadronic** (BR~46%)
- Huge bkgd

**Lepton+jets** (BR~30%)
- Moderate bkgd

**Dilepton** (BR~5%)
- Low bkgd
How Many Tops Do We Have?

In 1 fb⁻¹ of integrated luminosity:

- 7000 tt events produced
- BR + trigger
- 200 dilepton
- 1000 lepton + jets
- 2000 all-hadronic

Event selection:
- 50 dilepton
- 200 lepton + jets (with b-tag)
- 300 all-hadronic (with b-tag)

Main backgrounds:
- W+jets, WW, WZ, DY
- mistag, W+hf, VV, non-W
- QCD multijets

To first order these are the samples of top events with which we make measurements.
Production Cross-section

- Tests QCD in very high $Q^2$ regime
- Measurements across all decay channels and topologies have different sensitivities to new physics possibilities
- Provides important sample composition for all other top property measurements

$\Delta \sigma_{tt}/\sigma_{tt} \sim 12\%$

same order than theory, but statistics dominated

$\Rightarrow$ updates for winter-conferences with whole Run IIa statistics

$\Rightarrow$ improved analysis techniques!
Lepton+jets channel

**Analysis with b-tagging**

**Signal:** lepton+ ≥3 jets, MET, ≥1 b-tag

\[ \sigma(tt) = 8.2 \pm 0.6 \text{(stat)} \pm 1.0 \text{(sys)} \text{ pb} \]

156 events, 103±18.2 signal

Syst. uncert: b-tagging 6.5%

**Analysis using kinematics**

**Signal:** lepton+ ≥3 jets, MET

\[ \sigma(tt) = 6.0 \pm 0.6 \text{(stat)} \pm 1.1 \text{(sys)} \text{ pb} \]

2102 events, 324.6±31.6 signal

Syst. uncert NN: 10%

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Global di-lepton Analysis

Global technique to extract dilepton cross sections

- Likelihood fit performed on the data to SM templates in the missing-$E_T$ - $N_{jet}$ space:
  - $\sigma(tt)$, $\sigma(WW)$, $\sigma(Z \rightarrow \tau\tau)$ float
  - Extract $tt$, $WW$, and $Z \rightarrow \tau\tau$ cross sections simultaneously
- Provides different test of the SM than single cross section measurements
- Utilizes full statistical power of the data

Results:

<table>
<thead>
<tr>
<th>Process</th>
<th>$e\mu$</th>
<th>$ee + \mu\mu + e\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma(tt)$</td>
<td>9.3 pb</td>
<td>8.5 pb +2.6 +0.7 -2.2 -0.3 pb</td>
</tr>
<tr>
<td>$\sigma(W^+W^-)$</td>
<td>11.4 pb</td>
<td>16.3 pb +5.1 +0.8 -4.4 -0.2 pb</td>
</tr>
<tr>
<td>$\sigma(Z^0 \rightarrow \tau^+\tau^-)$</td>
<td>291 pb $^{+50}_{-46}$ pb</td>
<td>251 ± 5 pb</td>
</tr>
</tbody>
</table>

SM prediction

$6.7 \pm 0.9$ pb
$12.4 \pm 0.8$ pb
$251 \pm 5$ pb

preliminary

$e\mu$ data (103 events)
Cross-section in the SM

Evolution of cross-section with center of mass energy \( \sigma(\sqrt{s}) \) limited by errors of Run I measurement

\[ \Rightarrow \text{QCD challenged with LHC} \]
Top production mechanism

- $gg \rightarrow tt$ versus $qq \rightarrow tt$: tests pQCD and sensitive to new production mechanisms
- Discrimination is tough, but can use # of tracks in underlying event:
  - $gg$ initial state tends to have greater underlying event activity

$\Rightarrow$ establish correlation between number of low $p_T$ tracks (Data) and ME-gluons (MC)

$\Rightarrow$ create templates for gluon-rich and non-gluon samples

$\Rightarrow$ fit to tagged lepton+jets sample

\[
\frac{\sigma(gg \rightarrow tt)}{\sigma(qq \rightarrow tt)} = 0.25 \pm 0.24^{\text{(stat)}} \pm 0.10^{\text{(syst)}}
\]

(SM predicts 0.18)
Resonant top production?

- Particles from New Physics could decay into $t\bar{t}$-pairs ($Z'$, $t'$, MSSM Higgs, RS gravtions...)
  \[ p\bar{p} \rightarrow X \rightarrow t\bar{t} \]
  \(\Rightarrow\) deviations in $m_{tt}$ spectra: resonances or differences in the slope

- reconstruct $m_{tt}$ from b-tagged $l+jets$ sample
- no significant deviations observed
Single Top Production

- Top Branching fractions
- CKM matrix element $|V_{tb}|$
- Rare top decays: FCNC

- Top mass
- Top lifetime
- Top charge

- Single top production
- Production cross-section
- Production mechanism
- Resonant production

- W helicity
Single top production

$s$-channel
$\sigma_s \sim 0.9 \text{ pb}$

$t$-channel
$\sigma_t \sim 2.0 \text{ pb}$

$\Rightarrow$ new charged particles

$\Rightarrow$ anomalous couplings, FCNC

• Single top quarks produced by weak interaction are a direct probe of top quark’s weak couplings.
  - Measure $V_{tb}$ without assuming three-generation unitarity.
  - Important background for Higgs search
  - Spin correlation measurable in decay products
Single top event yields

- Cross section in SM is close to top quark pair production cross section (2.9 pb vs. 7.5 pb), but: signal/background is much worse
  - fewer jets, softer kinematics, lower acceptance
  - signature: isolated lepton, missing $E_T$, jets$\geq$2
  - s-channel: 1 b-tag
  - t-channel: 2 b-tags

Expected single top signal is smaller than background uncertainties
→ no counting experiment
→ requires advanced analysis techniques
Single top: multivariant techniques

**Methods:**
- **Likelihood:**
  - determine likelihood from various input variables
- **Neural Nets:**
  - use several neural nets to determine signal and background probability
  - **Bayesian:** find a posteriori the probability density for all possible weights in NN

**Matrix element:**
- compute Matrix Elements from reconstructed 4-vectors of leptons and jets for signal and background hypotheses to determine an event probability density for each event

**Boosted Decision Trees:**
- select recursively the best cut for passed and failed events
Single top search: CDF

Likelihood:
- 8 variables for t-channel
- 6 variables for s-channel

Neural Network:
- 3 layers
- 26 input variables

Matrix element:
\[ EPD = \frac{b \cdot P_{\text{signal}}}{b \cdot P_{\text{signal}} + b \cdot P_{\text{Wbb}} + (1 - b)P_{\text{Wcc}} + (1 - b)P_{\text{Wj}}} \]

no evidence of signal
\( \sigma < 2.7 \text{ pb} @ 95\% \text{ CL} \)
From s and t likelihoods

no evidence of signal
\( \sigma < 2.6 \text{ pb} @ 95\% \text{ CL} \)

\[ \sigma = 2.7^{+1.5}_{-1.3} \text{ pb} \]
p-value = 1.0\% (2.3\( \sigma \))

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Single top: DØ

**Bayesian NN**
- 24 input variables
- $\sigma_{s+t} = 3.0 \pm 1.9 \text{ pb}$
- p-value = 0.885% (2.4$\sigma$)

**Matrix Element**
- $D_s(\bar{x}) = P(S|\bar{x}) = \frac{P_{\text{signal}}(\bar{x})}{P_{\text{signal}}(\bar{x}) + P_{\text{bkg}}(\bar{x})}$
- $\sigma_{s+t} = 4.6^{+1.8}_{-1.5} \text{ pb}$
- p-value = 0.21% (2.9$\sigma$)

**Decision Tree**
- 49 input variables
- 36 separate trees
- $\sigma = 4.9 \pm 1.4 \text{ pb}$
- p-value = 0.035% (3.4$\sigma$)
- SM compatibility: 11% (1.1$\sigma$)
Top Quark Properties

Production cross-section
Production mechanism
Resonant production

Single top production

Top Branching fractions
CKM matrix element $|V_{tb}|$
Rare top decays: FCNC

Top mass
Top lifetime
Top charge

W helicity
Top Quark Mass

- allows for prediction of the mass of the Higgs boson via loop correction
- consistency check of the Standard Model

⇒ constraint on Higgs can point to physics beyond the standard model

⇒ actual limits:
  \[ \Delta m_{\text{top}} = 2 \text{GeV}, \Delta m_{W} = 25 \text{MeV} \]
  \[ m_{H} = 80 \pm 31 \text{ GeV} \]

⇒ Future: with \( \Delta m_{\text{top}} = 1 \text{GeV} \),
  \[ \Delta m_{W} = 15 \text{ MeV} \text{ and } m_{\text{top}} = 175 \text{ GeV} \]
  \[ m_{H} = 63 \pm 20 \text{ GeV} \]
Robust program of complementary measurements:

- Many measurements in all the different channels
  => consistency
- Different methods of extraction with different sensitivity
  => confidence
- Combine all channels and all methods
  => precision
Measurement Methods

Mass extraction methods:
1. Select signal-like events.
2. Reduce backgrounds (b-tagging, cuts, likelihoods).
3. Reconstruct the final state (combinatorics, fit).
4. Use sophisticated technique to extract top mass:

Template, Idiogram

Matrix element, Neutrino weighting
Most Precise: Lepton+Jets

- Branching fraction: 30% (lepton = e or $\mu$)
- Final state: 2 light quark jets, 2 b quarks, 1 lepton, 1 neutrino
- S:B = 1:4 to 11:1 depending on the b-tagging requirement
- Jet-parton assignment ambiguity: 12 (0 b tag), 6 (1 b tag), and 2 (2 b tags)
- Can infer neutrino energy from $E_T$
- Provides an in-situ calibration candle $W\rightarrow qq$ to determine JES
- Most precise $M_{top}$ measurements
Lepton+Jets Mass

- CDF: 940 pb\(^{-1}\), with 166 candidates with at least one b-tagged jet

\[ M_{\text{top}} = 170.9 \pm 1.6 \text{(stat.)} \pm 1.4 \text{(JES)} \pm 1.4 \text{(syst.) GeV / c}^2 \quad 1.5\% \]

**World’s most precise measurement!**

- DØ: 380 pb\(^{-1}\), with 175 candidates with and without b-tagging requirement

\[ M_{\text{top}} = 170.3 \pm 2.5 \text{(stat.)} \pm 3.5 \text{(JES)} \pm 1.5 \text{(syst.) GeV / c}^2 \quad 2.6\% \]

- Update from DØ coming soon.
Consistency?

• Are the channels consistent?

\[
\begin{align*}
M_{\text{top}}(\text{All Jets}) & = 173.4 \pm 4.3 \text{ GeV/c}^2 \\
M_{\text{top}}(\text{Dilepton}) & = 167.0 \pm 4.3 \text{ GeV/c}^2 \\
M_{\text{top}}(\text{Lepton+Jets}) & = 171.3 \pm 2.2 \text{ GeV/c}^2
\end{align*}
\]

• We compare them taking into account their correlated systematic uncertainties

\[\Rightarrow \text{Determination of } M_{\text{top}} \text{ from the 3 different channels is consistent with one another}\]
Heavy Top $t'$?

- Could a heavy $t'$ exist and mimic top?
- Generic 4th chiral generation is consistent with EWK data; can accommodate a heavy Higgs (500 GeV) without any other new physics
- Several SUSY models provide for a 4th generation $t'$ or mimic top-like signatures
- Little Higgs models predict a heavy $t'$-like particle

**Exclude with 95%CL region of $t'$ masses below 258 GeV**
However...

- 4 events high mass event in $H_T$ tail

... presence of $t'$ could distort $m_t$ measurement.
Long Live the Top Quark?

- Under the SM assumption of a V-A \( tWb \) coupling, and \( |V_{tb}| \approx 1 \), the partial width for \( t \rightarrow Wb \) is \( \Gamma \approx 1.5 \) GeV giving \( \tau \approx 10^{-25} \) s (\( c\tau \approx 10^{-10} \) \( \mu m \))

- Deviations from these assumptions can give very different predictions

- **Using lepton + 3-jet data:**
  - require 1 b-tag
  - measure impact parameter \( (d_0) \) of lepton tracks
  - determine resolution from lepton trigger data

- Obtain:
  - \( c\tau < 52.5 \mu m \) (95% CL)
Top Quark Charge

- In the SM top is +2/3 partner to the -1/3 bottom
- But how do we know that this is what we’ve been measuring?

For example:

In lepton + 4-jet sample:
- require 2 b-tags
- use a jet-charge algorithm to discriminate between b and bbar
- pair to charged lepton to infer $Q_{\text{top}}$

$Q_{\text{top}} = 4/3e$ excluded at 94% CL
Top Decays

- Top mass
- Top lifetime
- Top charge

- Single top production
- Production cross-section
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- $W$ helicity
Top Branching Fractions

- In the SM, $R = \frac{BR(t \rightarrow Wb)}{BR(t \rightarrow Wq)} = 0.998 \sim |V_{tb}|^2$
- $R$ determines the fraction of $tt$ events with 0, 1 and 2 b-jets
- Use this to extract $R$ from fits to the 0, 1 and 2 b-tagged samples

Still need a lot more data to really test the SM, but a nice technique for doing so
Direct $|V_{tb}|$ Measurement

Single top production allows for direct $|V_{tb}|$ measurement

- Translate $tb + tqb$ cross section into measurement of the strength of $V-A$ coupling $|V_{tb} f_1^L| \text{ in } Wtb$ vertex ($f_1^L$: arbitrary left-handed form factor)
- Assume $V_{td}^2 + V_{ts}^2 \ll V_{tb}^2$ and pure $V-A$ and CP-conserving $Wtb$ interaction:
  
  $$|V_{tb} f_1^L| = 1.3 \pm 0.2$$

- Also assuming $f_1^L = 1$:
  
  $$0.68 < |V_{tb}| < 1 \text{ @ 95% CL}$$

- No assumption about number of quark families or CKM matrix unitarity
Light charged Higgs?
\( t \rightarrow H^+ b \) affects proportion of various decay channels

- search for inconsistency correlated in four decay channels:
  \[ \Rightarrow \text{Top} \rightarrow \text{dilepton (e\(e\), } \mu\mu, \, e\mu) + \text{jets} \]
  \[ \Rightarrow \text{Top} \rightarrow \text{dilepton (e\(\tau\), } \mu\tau) + \text{jets} \]
  \[ \Rightarrow \text{Top} \rightarrow \text{lepton(e\(\mu\)) + jets + 1 b-tag} \]
  \[ \Rightarrow \text{Top} \rightarrow \text{lepton(e\(\mu\)) + jets + 2 b-tags} \]

parameters change according to model:
- \( BR(t \rightarrow H^+ b) \)
- \( BR(H^+ \rightarrow \tau\nu) \)
- \( BR(H^+ \rightarrow cs) \)
- \( BR(H^+ \rightarrow t^* b) \)
- \( BR(H^+ \rightarrow W^+ h^0) \)
- \( BR(H^+ \rightarrow W^+ A^0) \)

Shown here:
Variations as a function of tan\(\beta\) in a particular set of MSSM parameters
Charged Higgs Search

- Calculate BR($t \rightarrow H^+ b$) and $H^+$ BR's as function of $M_A$ and $\tan\beta$.
- 6 MSSM benchmarks used, #1 is shown below. No evidence.
Flavor Changing Neutral Currents

No FCNCs in SM at tree level
- Allowed in higher order penguins
Light quark penguins observed
- e.g. $b \rightarrow s \gamma$ observed by CLEO in 1995, BR $O(10^{-4})$
Not yet observed for top
- SM BR: $O(10^{-12})$
New Physics models predict BRs up to $O(10^{-2})$

Current limits: 13.7% (LEP), 33% (CDF Run I)
1fb$^{-1}$ analysis underway:
expected limit at 95% C.L. (no signal):
- Anti-tagged sample: 23-30%
- Tagged sample: 18-24%
- Combined: 10-15%
Top Spin: W Helicity

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W Helicity in Top Events

top decay in the SM: (V-A) charged current interaction

helicity states of the W:

- right handed fraction $f_+$
- left handed fraction $f_-$
- fraction of longitudinally polarized W $f_0$

```
f_0 = \frac{m_t^2}{2M_W^2 + m_t^2 + m_b^2}
= (70.1 \pm 1.6)\% 
```

Left handed fraction: $f_- \approx 30\%$

Right handed fraction: $f_+ \approx 0\%$

\[ \frac{-ig}{2\sqrt{2}} t\gamma^\mu (1 - \gamma^5) V_{tb} b W_\mu \]
W polarizations can be disentangled:
• \( \cos \theta^* \) distribution
• lepton \( p_T \) distribution
• invariant \( m_{\ell b} \)

\( \rightarrow \) **Longitudinal W-polarization:**
- leptons are emitted perpendicular
- harder \( p_T \) distribution

\( \rightarrow \) **Left-handed W:**
- leptons are emitted opposite
- soft \( p_T \) distribution
W Helicity

- Using $\cos(\theta^*)$:
  - $F_+ = 0.06 \pm 0.10$
  - $F_+ < 0.23$ @ 95% CL
  - (370 pb$^{-1}$, dilepton and lepton + jets)

- Using $M_{lb}^2$ (700 pb$^{-1}$, dilepton and lepton + jets):
  - $F_+ = 0.02 \pm 0.07$
  - $F_+ < 0.09$ @ 95% CL
  - (1 fb$^{-1}$, lepton + jets)

Within large errors, consistency observed with SM. New analyses underway.
What We Know Now About Top:

<table>
<thead>
<tr>
<th>Measurement</th>
<th>SM prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{\text{top}}$ (Tevatron combined) (GeV/c$^2$)</td>
<td>171.4 ± 2.1 GeV</td>
</tr>
<tr>
<td>$\sigma_{tt}$ (CDF combined)</td>
<td>7.3 ± 0.9 pb</td>
</tr>
<tr>
<td>$\sigma(gg \to tt) / \sigma(gg + qq \to tt)$</td>
<td>0.25 ± 0.26</td>
</tr>
<tr>
<td>$c\tau_{\text{top}}$</td>
<td>&lt; 53.5 μm (95% CL)</td>
</tr>
<tr>
<td>BR($t \to Wb$) / BR($t \to Wq$)</td>
<td>&gt; 0.61 (95% CL)</td>
</tr>
<tr>
<td>$F_0$</td>
<td>0.59 ± 0.14</td>
</tr>
<tr>
<td>$F_+$</td>
<td>&lt; 0.09 (95% CL)</td>
</tr>
<tr>
<td>charge</td>
<td>Not 4/3 @ 94% CL</td>
</tr>
<tr>
<td>spin</td>
<td>$\frac{1}{2}$</td>
</tr>
<tr>
<td>single top production</td>
<td>4.9±1.4 pb</td>
</tr>
<tr>
<td>$</td>
<td>V_{tb}</td>
</tr>
</tbody>
</table>
Concluding Remarks

top quark physics at the Tevatron is growing out of its infancy!

• the precision measurements which will show us if the top quark is the Standard Model particle we think was discovered in 1995 are starting to come in

• naturally LHC will take over which a huge amount of top events, and ILC allowing for high precision measurement, but until then

... there might be a lot more to come from the Tevatron
Backup
Determine limits on a narrow leptophobic $Z'$ resonance with $\Gamma(Z') = 1.2\% M_{Z'}$.

- **370 pb$^{-1}$**
  - $M_X < 680$ GeV

- **680 pb$^{-1}$**
  - $M_X < 725$ GeV

- **955 pb$^{-1}$**
  - $M_X \sim 725$ GeV!
Extraction technique

- Need to extract $M_{\text{top}}$ from imprecise measurements (jets) and non-measured (neutrino) quantities
- Template analyses:
  - Evaluate a variable strongly correlated with $M_{\text{top}}$
  - Obtain $M_{\text{top}}$ comparing data to Monte Carlo with different $M_{\text{top}}$ input
- Matrix Element analyses:
  - Evaluate $t\bar{t}$ and background probability densities as a function of $M_{\text{top}}$
  - Obtain $M_{\text{top}}$ multiplying event probability densities:

\[
\text{Signal event} \times \text{Background event} = \text{Experiment}
\]
Separate channels

**W helicity** Kruse: D0/CDF consistent with V-A within statistics, still poor. LHC gets $F_+ (F_R)$ to 0.02 with 10 fb-1. However...

- Separate channel fits still look funny!

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Dil+LJ 200 pb$^{-1}$

Dilepton only 200 pb$^{-1}$

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Forward/backward asymmetry

- $A_{fb}$ typically associated with parity-violating weak processes
- Not expected in top, but for BSM.
- Diagram interference at NLO predicts 3.8% effect. (Kuhn, Rodrigo 99)

- Massive neutral gauge boson $Z'$ could produce an asymmetry.
- Look for Moriond results from the Tevatron.