Top and QCD at the Tevatron

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Outline

- Fermilab and Tevatron
- Top Quark Physics
  - Ttbar cross section
  - Top quark mass
  - Forward-backward asymmetry
  - Single top quark production
- QCD Measurements
  - Jet production
  - W+jets/HF production
  - Z+Jets/HF and Photon+HF production
  - Energy scan
- Summary & Remarks
The Fermilab Tevatron
The Fermilab Tevatron

Run II at the Tevatron

- Proton-antiproton collisions at 1.96 TeV
- March 2001 - September 2011
- Peak luminosity $4.3 \times 10^{32}$ cm$^{-2}$s$^{-1}$
- Delivered integrated luminosity $\sim 12$ fb$^{-1}$

Up to about 10 fb$^{-1}$ of data are available for each experiment

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The CDF and D0 Experiments

The CDF and D0 Experiments are two multi-purpose detectors.

- e, μ, and τ identification
- jet and missing energy measurement
- heavy-flavor tagging through displaced vertices and soft leptons

The data-taking efficiency for both experiments was high (> 90%).
Top Quark Physics
Why Study Top at the Tevatron?

- Predicted by the SM and discovered by CDF&D0 in 1995
- Very unique:
  - \( m_t \sim 170 \text{ GeV} \) vs \( m_b \sim 5 \text{ GeV} \)
  - Top-Higgs Yukawa coupling \( \lambda_t \approx 1 \)
    - may help identify the mechanism of EWSB and mass generation.
    - may serve as a window to new physics that couple preferentially to top.
- Successful Tevatron top quark program
  - Only place we could study the top quark until 2010
  - High precision measurements of top quark mass, top pair production cross section, decay properties
  - Basic properties/kinematics still not known precisely: forward-backward asymmetry, spin, width, charge, lifetime, etc

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Top Quark Production at the Tevatron

- Top quark is mainly produced in pairs (~7 pb)

- Can be also produced singly (~3 pb). Single top quark production discussed later.

- According to SM: $\Gamma(t \rightarrow Wb) \sim 100\%$

Channels:
- $l+$jets: 30%
- Dileptons: ~5% ($l=e$ or $\mu$)
Ttbar Cross Section Measurements

- Ttbar cross section prediction computed at NNLO+NNLL accuracy
  \[ \sigma_{t\bar{t}} = 7.24^{+0.15}_{-0.24} \text{(scale)}^{+0.18}_{-0.12} \text{(PDF)} \text{[pb]} \]
  depends on its mass (~3%/GeV)

- Measurement basics:
  \[ \sigma = \frac{N_{\text{data}} - N_{\text{BG}}}{BR \cdot A \cdot L} \]
  - \( L(\sigma) = P(N_{\text{data}}, N_{\text{pred}}) \) maximized w.r.t. \( \sigma \) where \( P(x, \mu) \) is the Poisson probability dist.
  - Fit a predicted binned distribution to data
  - Actual likelihood is more complicated due to systematics
Ttbar Cross Section Measurements

- The first measurements with the complete Tevatron dataset have started coming.
- Measurements consistent amongst various channels.
- Limitation from systematic uncertainties (JES, b-tag, W+jets).

Combination:
\[ \sigma(p\bar{p} \rightarrow t\bar{t} @ 1.96\,\text{TeV}) = 7.65 \pm 0.20(\text{stat}) \pm 0.29(\text{syst}) \pm 0.22(\text{lumi})\,\text{pb} \]
reaching to the NNLO prediction accuracy.

NNLO+NNLL: \[ \sigma(p\bar{p} \rightarrow t\bar{t}) = 7.24^{+0.15}_{-0.24}(\text{scale})^{+0.18}_{-0.12}(\text{PDF})[\text{pb}] \]

(Barneruther, Czakon, Mitov)
Top Quark Mass in the l+jets Channel

- Top mass close to the scale of EWSB
  - Special role in EWSB?
- Huge mass gives importance to QCD corrections for top quark
  ... $M_{\text{top}}$ with $M_{\text{higgs}}$ & $M_W$ provides a fundamental tests of SM

- Measurement uses a “template” method:
  - $m^\text{reco}_t$ from a kinematic fitter:
    $$
    \chi^2 = \sum_{i=\ell,4j} \frac{(p_{T,i}^{i,\text{fit}} - p_{T,i}^{i,\text{meas}})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(U_j^{\text{fit}} - U_j^{\text{meas}})^2}{\sigma_j^2}
    + \frac{(M_{jj} - M_W)^2}{\Gamma_W^2} + \frac{(M_{t\nu} - M_W)^2}{\Gamma_W^2} + \frac{(M_{bt\nu} - m^\text{reco}_t)^2}{\Gamma_t^2} + \frac{(M_{btt\nu} - m^\text{reco}_t)^2}{\Gamma_t^2}
    $$

- Three $M_{\text{top}}$ sensitive variables:
  - $m^\text{reco}_t$, $m^\text{reco}(2)_t$, $m_{jj}$
  Mapped to $M_{\text{top}}$ and $\Delta\text{JES}$ by a likelihood fit & signal (bkg) probability density function

$$m_t = 172.85 \pm 0.71 \text{ (stat)} \pm 0.84 \text{ (syst) } \text{GeV/c}^2 = 172.85 \pm 1.10 \text{ GeV/c}^2$$

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Top Quark Mass in Dilepton Channel

- Based on neutrino weighting technique (matrix element method)
- Jet calibration (and JES systematic reduction) is achieved by using the energy scale derived from in lepton+jets measurements: $k_{\text{JES}} = 1.013 \pm 0.008$ (stat)
- Neutrino weighting technique
  - The kinematics underconstrained due to two neutrinos
  - Probability density function depends on $\eta$ of neutrinos
    \[ W \propto \int P(\eta_1|m_t)P(\eta_2|m_t)\rho_{\eta_1}\rho_{\eta_2}d\eta_1d\eta_2 \]
  - Binned likelihood fit is used for final mass determination

Combined with other 1fb$^{-1}$ dataset (total 5.3 fb$^{-1}$)

\[ m_t = 174.0 \pm 2.4 \text{ (stat)} \pm 1.4 \text{ (syst)} \text{ GeV}/c^2 \]
\[ = 174.0 \pm 2.8 \text{ GeV}/c^2 \]
Top Quark Mass Combination

Uncertainty below 1%!

Mass of the Top Quark [GeV]

Tevatron Combination 2012

173.00 ± 0.65 ± 1.06 GeV
174.94 ± 0.83 ± 1.24 GeV
176.1 ± 5.1 ± 5.3 GeV
180.1 ± 3.6 ± 3.9 GeV
172.47 ± 1.43 ± 1.40 GeV
186.0 ± 10.0 ± 5.7 GeV
170.28 ± 1.95 ± 3.13 GeV
174.00 ± 2.36 ± 1.44 GeV
167.4 ± 10.3 ± 4.9 GeV
168.4 ± 12.3 ± 3.6 GeV
172.32 ± 1.80 ± 1.82 GeV
166.90 ± 9.00 ± 2.82 GeV

173.18 ± 0.56 ± 0.75 GeV

$\chi^2 / \text{dof} = 8.3 / 11$
Forward-Backward Asymmetry ($A_{FB}$)

- Do tops have a preference to travel along the proton or antiproton direction?
- Measure “asymmetry” in $\Delta y$
  \[ A_{FB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)} \]
- Leading-order: SM predicts no asymmetry
- Next-to-leading-order: small positive asymmetry $A_{FB} = 6.6\%$
- BSM ideas:
  - Massive chiral color octets, RS gluon, $W'$, $Z'$, etc

POWHEG: JHEP 0709, 126 (2007)

PRD84, 112005 (2011), arXiv:1107.4995
**A_{FB} in l+jets Channel**

- Measurement based on 8.7 fb$^{-1}$ of l + MET + $\geq$4jets + btag events
  - 2498 events, bkg = 505 ± 123
- Full ttbar reconstruction
  - $M_W$, $M_{top}$ constraints, best $\chi^2$

- Differential xsec in $\Delta y$
  - Unfolded to the parton level
  - Integrated AFB:
    $$A_{FB}(\text{measured}) = (16.2 \pm 4.7)\%$$

CDF Run II Preliminary $L = 8.7$ fb$^{-1}$

CDF Conf. Note 10807, Also Amidei@TOP2012
A_{FB}: \Delta y & Pt (ttbar) Dependence

- Rapidity dependence
  \[ A_{FB}(|\Delta y|) = \frac{N(|\Delta y|) - N(-|\Delta y|)}{N(|\Delta y|) + N(-|\Delta y|)} \]
  - Line fit measures correlated significance:
    - slope > 3\sigma from 0 (2.4 \sigma from SM)

- Pt(ttbar) dependence
  - Due to color coherence
  - Noted first by a D0 study
    - [PRD 84, 112005 (2011)]
  - The “trend” is as expected
  - Data above predictions

- Other studies:
  - Lepton asymmetries, lepton-top asymmetry ratio, etc
  - A_c measurement at the LHC

CDF Run II Preliminary L = 8.7 fb^{-1}

CDF Data - Bkg, 9.4fb^{-1}

\[ CDF \text{ Data} \]

\[ \text{Powheg} \]

\[ \text{Pythia} \]

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Single Top Quark Production

**Motivation:**
- Direct measurement of CKM matrix element $|V_{tb}|$ ($\sigma_{s+t} \sim |V_{tb}|^2$)
- Sensitive to New Physics (FCNC, $W'$...) and CP violation
- Additional channel for top quark properties study

**Experimental challenge:**
- Extract small signal out of a large background with large uncertainty

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<tr>
<th></th>
<th>$tb$ [pb]</th>
<th>$tqb$ [pb]</th>
<th>$tW$ [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tevatron</strong></td>
<td>1.04 x4.4</td>
<td>2.26 x28</td>
<td>0.3 x26</td>
</tr>
<tr>
<td>(1.96 TeV)</td>
<td></td>
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<tr>
<td><strong>LHC</strong></td>
<td>4.59</td>
<td>64.2</td>
<td>7.8</td>
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<tr>
<td>(7 TeV)</td>
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References:
- PRD 74, 114012 (2006)
- PRD 81, 054028 (2010)
- PRD 85, 091505 (2011)
Observation by D0 & CDF

- Observed by CDF and D0 in 2009
  - D0: [PRL103, 092001](https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.103.092001)

  - CDF: Four multivariate analyses in lepton+jets with 3.2 fb\(^{-1}\) data.
  - CDF: MET+Jets with 2.1 fb\(^{-1}\) data
  - D0: Three multivariate analysis in lepton+jets with 2.3 fb\(^{-1}\) data.
Recent Analyses in Lepton+Jets

- **D0 with 5.4 fb⁻¹:**
  - Three multivariate (MVA) methods to extract signal: Boosted decision tree, neural network, neuro-evolution of augmented topologies

- **CDF with 7.5 fb⁻¹:**
  - Neural network discriminant
  - High quality, high \(P_T\) isolated track: ~15% gain in single top acceptance

- **Measured cross section:**
  - \(\sigma_{s+t} = 3.43^{+0.73}_{-0.74} \text{ pb} \) (D0)
  - \(\sigma_{s+t} = 3.04^{+0.57}_{-0.53} \text{ pb} \) (CDF)

- **Limits on \(|V_{tb}|\):**
  - \(|V_{tb}| > 0.79\) at 95% CL (D0)
  - \(|V_{tb}| > 0.79\) at 95% CL (CDF)
Simultaneous $\sigma_s - \sigma_t$ Measurements

New physics may affect s- and t-channels differently

Remove the s/t channel constraint

- **CDF:**
  - $\sigma_s = 1.81 \pm 0.63 - 0.58$ pb ($\pm\sim 33\%$)
  - $\sigma_t = 1.49 \pm 0.47 - 0.42$ pb

- **D0:**
  - $\sigma_s = 0.98 \pm 0.63$ pb
  - $\sigma_t = 2.90 \pm 0.59$ pb ($\pm\sim 20\%$)

- **SM prediction:**
  - $\sigma_s = 1.04 \pm 0.04$ pb
  - $\sigma_t = 2.26 \pm 0.12$ pb

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Jet Production at the Tevatron

\[ d\sigma_{jet} = \sum_a \sum_b f_{a/p}(x_p, \mu_F^2) f_{b/p}(x_{\bar{p}} , \mu_F^2) \otimes \hat{\sigma}_{a,b}(x_p, x_{\bar{p}}, \alpha_s, \mu_R^2) \]

- Test pQCD
- Based on pQCD: extract PDFs and \( \alpha_s \). Study/test matrix element calculations.

- Underlying event makes the measurement complicated
- Good place to study nature of underlying event
Inclusive Jet Cross Section

- Test pQCD over 8 order of magnitude in $d\sigma^2/dp_Tdy$
- Highest $p_T^{\text{jet}} > 600 \text{ GeV/c}$

PRD 78, 052006 (2008)
PRD 85, 052006 (2012)

PRL 101, 062001 (2008)
Both CDF and D0 measurements are in agreement with NLO predictions:
• Both in favor of somewhat softer gluons at high-\(x\)

Experimental uncertainties: smaller than PDF uncertainties
Tevatron Run II data lead to softer high-\(x\) gluons (more consistent with DIS data than Run I) and help reducing uncertainties.

PDF with Tevatron Run II Jet Data


Dijet Mass & Angular Distributions

Data well described by pQCD
No significant indication of new physics
Three Jet Cross Section (Ratio)

- Test QCD at \( O(\alpha_s^3) \)
- Decorrelate \( \alpha_s \) and PDFs in \( \sigma_{3\text{-jet}} / \sigma_{2\text{-jet}} \) ratio

- Data well described by pQCD
Angular Correlations of Jets

- Observable: $R_{\Delta R}$
  - average number of neighboring jets for jets from an inclusive jets sample
- It depends on three variables
  - inclusive jet $p_T$
  - distance $\Delta R$ to neighbor jet in ($\Delta \phi$, $\Delta y$)
  - neighbor jet $p_T^{nbr_{min}}$ requirement
- Sensitive to strong coupling constant

Average number of neighboring jets within $\Delta R$ to an inclusive jet

- Uncertainties 2-5%!
- Dependence of $R_{\Delta R}$ on ($p_T$, $\Delta R$, $p_T^{nbr_{min}}$) described by pQCD
Running of Strong Coupling Constant

- Extract $\alpha_s$ from $R_{\Delta R}$ measurement
  - $p_T^{n_{\text{br\, min}}} \geq 50, 70, 90 \text{ GeV}$
  - At each $p_T$, combine all data points with different $p_T^{n_{\text{br\, min}}}$ and $\Delta R$ requirements

- $\alpha_s(p_T)$ measurement up to 400 GeV!

- $\alpha_s(p_T)$ decreases with $p_T$ as predicted by the RGE

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arXiv:1207.4957, Accepted by PLB
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Consistent with other results from jet and event shape data

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- Fundamental test of pQCD, at high momentum scales.
- W+jets are critical for physics at the Tevatron and LHC: top, Higgs, SUSY, and other BSM
  - Large theory uncertainties (30%-40%) on W+HF production limits our physics potentials

W+b+X

$$\sigma(W + b) \cdot B(W \rightarrow \mu \nu) = 1.04 \pm 0.05 \text{ (stat.)} \pm 0.12 \text{ (syst.) pb}.$$  

Theory (MCFM):

$$1.34^{+0.40}_{-0.33} \text{ (scale)} \pm 0.06 \text{ (PDF)}^{+0.09}_{-0.05} (m_b) \text{ pb}$$

Sharpa: 1.21, Madgraph5: 1.52 (pb)

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Z+Jets

Motivation:
- Fundamental test of pQCD, at high momentum scales.
- Background for rare SM processes (top, diboson) and BSM searches

Measurement:
- Full dataset 9.6 fb⁻¹. Z→ll, l=e, µ.

Theory for comparisons:
- MCFM&BLACKHAT+SHERPA: NLO pQCD
- ALPGEN+PYTHIA: Matched LO-ME+PS
- POWHEP+PYTHIA: Merged NLO+PS
- LOOPSIM+MCFM: Approximate nNLO
- arXiv:1103.0914: NLO QCD+NLO EW (EW corr. important at high p_T)

Overall good agreement between data and predictions
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Overall good agreement between data and predictions.
Blackhat+Sherpa NLO for Z+3jets!

LOOPSIM+MCFM scale variation lower than experimental uncertainty
Motivation

- Sensitive to HF-content of proton
- Bkgd for many BSMs

Higher order effects? Gluon splitting? Intrinsic HF?
Just before the shutdown, Tevatron delivered small amount (a few 10 M of events) of data at 300 & 900 GeV

Transverse region sensitive to UE

Measurements will allow for
- Deeper understanding of MPI
- More precise prediction to projections to next LHC energies

Summary

Tremendous effort has been made to advance understanding of top quark and QCD at the Tevatron

- Data taking ended last fall, but still analyses with full dataset are ongoing
- Many areas of studies are competitive and complimentary to results from the LHC
- Ttbar x-section, top quark mass are measured to 5%, 1% accuracy. AFB is rather unique at the Tevatron.
- Tevatron QCD measurements provide important inputs/feedback for PDF determination, QCD modeling, and MC tuning

More results on top and QCD physics from Tevatron can be found on:

- [http://www-d0.fnal.gov/Run2Physics/top/](http://www-d0.fnal.gov/Run2Physics/top/)
- [http://www-d0.fnal.gov/Run2Physics/qcd/](http://www-d0.fnal.gov/Run2Physics/qcd/)
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Spin Correlation

- Top pairs are produced with a definite spin state depending on production mechanism:
  - Quark-Antiquark Annihilation (~85%): Spin 1
  - Gluon Fusion (~15%): Spin 0

- Top decays before hadronization (only known quark to do so!)
  - Spin information passed to decay products - the correlated spins can be measured from decay product angular distributions

- Correlation strength (frame dependent!) is defined as:

  \[ A = \frac{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} - N_{\uparrow\downarrow} - N_{\downarrow\uparrow}}{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} + N_{\uparrow\downarrow} + N_{\downarrow\uparrow}} \]

- Theory prediction: \[ A_{\text{beam}}^{SM} = 0.78^{+0.03}_{-0.04} \]
Spin Correlation

- New matrix element approach
  - Significantly increased sensitivity
  - Likelihood fit based on probabilities that events are signal events and do (or do not) contain SM spin correlation

- 3 sigma evidence for spin correlations!

$$A = 0.66 \pm 0.23 \text{(stat.} \oplus \text{syst.)}$$
Use three multivariate (MVA) methods to extract signal:
- Boosted decision tree, neural network, neuro-evolution of augmented topologies

Six analysis channels:
2, 3 or 4 jets with 1 or 2 b-tags

Cross section measured using Bayesian approach
- Posterior density peak for x-section, with 68% interval as uncertainty.

Since $\sigma_{s+t} \propto |V_{tb}|^2$, directly measure $|V_{tb}|$ from $\sigma_{s+t}$ posterior
- Assuming $|V_{td}|^2 + |V_{ts}|^2 \ll |V_{tb}|^2$
- Pure V-A and CP conserving $W_{tb}$ vertex

| $V_{tb}$ | > 0.79 @ 95% C.L.  

DØ, 5.4 fb$^{-1}$

$\sigma_{\text{expected}} = 3.49^{+0.77}_{-0.71}$ pb

$\sigma_{\text{observed}} = 3.43^{+0.73}_{-0.74}$ pb
Use a neural network discriminant

Add new lepton category: ISOTRK
- High quality, high PT isolated track: ~15% gain in single top acceptance

POWHEP for signal modeling

Assuming $m_{top} = 172.5 \text{ Gev}/c^2$,
- Measured cross section: $\sigma_{s+t} = 3.04^{+0.57-0.53}$ pb
- From the cross section posterior set limit: $|V_{tb}| > 0.78$ at 95% CL
- Extracted $|V_{tb}| = 0.92^{+0.10-0.08}$ (stat.+sys.) $\pm 0.05$(theory)
Jet Production and Measurement

Calorimeter-level jets

Hadronic showers

EM showers

Hadron-level jets

Hadronization

Parton-level jets

Underlying event

Unfold measurements to the hadron (particle) level

Correct parton-level theory for non-perturbative effects (hadronization & underlying event)
Jet Algorithms

Two main categories of jet algorithms

- **Cone Algorithms**
  - E.g. Midpoint Algo.: Extensive use at Tevatron in Run II (as suggested in Run II workshop in 1999, hep-ex/0005012)
  - Cluster objects based on their proximity in $y(\eta)$-$\phi$ space
  - Identify “stable” cones (kinematic direction = geometric center)
  - Pros: simpler for underlying-event and pileup corrections
  - Cons: infrared-unsafe in high order pQCD & overlapping stable cones.

- **Successive Combination Algorithms**
  - E.g. Kt Algorithm: Extensive use at HERA. A few Tevatron analyses.
  - Cluster objects based on a certain metric. Relative Kt for Kt algorithm.
  - Pros: Infrared-safe in all order of perturbative QCD calculations.
  - Cons: Jet geometry can be complicated. Complex corrections.

A lot of developments in recent years.

- SIS Cone, Cambridge-Aachen, Anti-Kt, etc.
- Extensively studied in LHC experiments. Will benefit future studies.
Jet “Definitions” - Jet Algorithms

**Midpoint cone-based algorithm**

- Cluster objects based on their proximity in $y$-$\phi$ space.
- Starting from seeds (calorimeter towers/particles above threshold), find stable cones (kinematic centroid = geometric center).
- Seeds necessary for speed, however source of infrared unsafety.
- In recent QCD studies, we use “Midpoint” algorithm, i.e. look for stable cones from middle points between two adjacent cones.
- Stable cones sometime overlap → merge cones when $p_T$ overlap > 75%.

Infrared unsafety: soft parton emission changes jet clustering.
Jet “Definitions” - Jet Algorithms

**Midpoint cone-based algorithm**

- Cluster objects based on their proximity in y-\(\phi\) space

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- In recent QCD studies, we use “Midpoint” algorithm, i.e. look for stable cones from middle points between two adjacent cones.

- Stable cones sometime overlap
  - \(\Rightarrow\) merge cones when \(p_T\) overlap > 75%

More advanced algorithm(s) available now, but negligible effects on this measurement.
Jet “Definitions” - Jet Algorithms

**$k_T$ algorithm**

- Cluster objects in order of increasing their relative transverse momentum ($k_T$)
  
  $$d_{ii} = p_{T,i}^2, \quad d_{ij} = \min \left( p_{T,i}^2, p_{T,j}^2 \right) \frac{\Delta R^2}{D^2}$$

  until all objects become part of jets

- $D$ parameter controls merging termination and characterizes size of resulting jets

- No issue of splitting/merging. Infrared and collinear safe to all orders of QCD.

- Every object assigned to a jet: concerns about vacuuming up too many particles.

- Successful at LEP & HERA, but relatively new at the hadron colliders
  
  More difficult environment (underlying event, multiple $pp$ interactions...)

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October 23, 2012
Jet Production at the Tevatron

- Test pQCD at highest $Q^2$.
- Unique sensitivity to new physics
  - Compositeness, new massive particles, extra dimensions, ...
- Constrain PDFs (especially gluons at high-$x$)
- Measure $\alpha_s$
Inclusive Jet Cross Section

Test pQCD over 8 order of magnitude in $d\sigma/dp_T dy$

Highest $p_T^{jet} > 600$ GeV/c

Jet energy scale (JES) is dominant uncertainty: CDF (2-3%), D0 (1-2%)

Spectrum steeply falling: 1% JES error $\rightarrow$ 5–10% (10–25%) central (forward) x-section
I. Inclusive Jets with Kt Algorithm

- Data/theory comparison consistent between measurements with cone and Kt algorithms and with different D values (jet sizes)

use models to study effects of non-perturbative processes (PYTHIA, HERWIG)
- hadronization correction
- underlying event correction

CDF study for cone R=0.7 for central jet cross section

→ apply this correction to the pQCD calculation
→ to be used for future MSTW/CTEQ PDF results
→ first time consistent theoretical treatment of jet data in PDF fits
Midpoint vs SIScone: hadron level

- Differences between the currently-used Midpoint algorithm and the newly developed SIScone algorithm in MC at the hadron-level.
Midpoint vs SIScone: parton level

- Differences between the currently-used Midpoint algorithm and the newly developed SIScone algorithm at the parton-level.

Differences < 1% → negligible effects on data-NLO comparisons
Inclusive Jets: Cone vs Kt Algorithms

Midpoint Cone Algorithm

|y|<0.1

0.1<|y|<0.7

0.7<|y|<1.1

1.1<|y|<1.6

1.6<|y|<2.1

Cross Section Ratio (kT / Midpoint)

pT JET (GeV/c)

pT (GeV/c)

- Data corrected to the hadron level
- Systematic uncertainty on data
- NLO pQCD corrected to the hadron level
- PYTHIA hadron level
Tevatron Run II data lead to softer high-x gluons (more consistent with DIS data) and help reducing uncertainties

MSTW08 does not include Tevatron Run 1 data any longer while CT09 (CTEQ TEA group) still does, which makes MSTW08 high-x even softer (consistent within uncertainty)
Strong Coupling Constant

\[ \sigma_{\text{jet}} = \left( \sum_{n} \alpha_s^n c_n \right) \otimes f_1(\alpha_s) \otimes f_2(\alpha_s) \]

From 22 (out of 110) inclusive jet cross section data points at 50 < \( p_T \) < 145 GeV/c

- NLO + 2-loop threshold corrections
- MSTW2008NNLO PDFs
- Extend HERA results to high \( p_T \)

\[ \alpha_s(M_Z) = 0.1161^{+0.0041}_{-0.0048} \]

3.5-4.1% precision