High $E_T$ jet physics at the Tevatron

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High $E_T$ jet production at hadron colliders

- **test** perturbative QCD
- **constrain** structure of the proton
  - $\rightarrow$ parton distribution functions (PDFs)
  - gluon ($\leftarrow$ incl. jets)
  - heavy flavor ($\leftarrow W/Z/\gamma^{*}+HF$)
- **measure** important backgrounds to searches for Higgs, Supersymmetry, and other new physics
  - processes with large jet multiplicities only calc. to LO $\rightarrow$ large uncert.
  - provide data to constrain models, to tune event generators to be used at Tevatron and LHC
  - especially important: $W/Z+$jets
- search for new phenomena in signatures with jets (e.g. resonances)
Outline

- jet reconstruction and energy scale calibration
- measurements of jet production
  - inclusive jets, dijets, trijets
  - $\alpha_s$ and PDF extraction
  - searches for physics beyond the standard model
- measurements of $W/Z/\gamma^* +$ jet production
  - jets of any flavor
  - $b$ and $c$ quark jets
Jet reconstruction

ET scale: 190 GeV

Jet reconstruction
Jet reconstruction

- standard jet reconstruction algorithm at Run II: seeded, iterative, **midpoint cone algorithm**
  - use particles (calorimeter tower) as seeds
  - add particles within cone using 4-vectors (\(E\)-scheme)
  - iterate until stable
  - use mid-points between jets as additional seeds
  → improved infrared stability
- split/merge jets with overlapping cones
Jet production and measurements

▶ unfold measurements to the hadron (particle) level
  ▶ need jet energy scale calibration and energy resolution

⇓ data-theory comparison at hadron (particle) level

⇑

▶ correct parton-level theory for non-perturbative effects
  ▶ fragmentation/hadronization, underlying event
Jet energy scale (JES) calibration

\[ E_{\text{particle}} = \frac{E_{\text{cal}} - O}{R \cdot S} \]

- \( E_{\text{cal}} \): measured energy (calorimeter, at EM scale)
- \( O \): offset energy: noise from electronics, uranium, pileup, multiple collisions
- \( R \): calorimeter response: determined from \( E_T \)-balance in \( \gamma \)+jet events
- \( S \): showering correction: net flow of energy in and out of cone

**DO:** JES uncertainties as low as 1.2% for central jets with \( p_T \sim 100 \) GeV

\[ \rightarrow 7 \text{ years of work!} \]
Inclusive jet production

- Kinematic reach in $(x, Q^2)$ compared to HERA and fixed target exp.: sensitive to PDFs at large momentum fractions $x$ and scales $Q^2$
- Sensitive to gluon content of the proton

$Q^2 (\text{GeV}^2)$ vs. $x$

$x_T = 2p_T/\sqrt{s}$
Inclusive jet $p_T$ cross sections

- measurements of $\frac{d^2\sigma}{dp_T dy}$: tests of pQCD over 8 decades
- sensitive to new physics at high $p_T$(jet)
  - benefits from increased Run II energy ($\sqrt{s} = 1.8 \rightarrow 1.96$ TeV), e.g. cross section $\times 5$ at $p_T$(jet) = 600 GeV

$\sqrt{s} = 1.96$ TeV

L = 0.70 fb^{-1}

$R_{\text{cone}} = 0.7$

NLO pQCD

+non-perturbative corrections

CTEQ6.5M $\mu_R = \mu_F = p_T$


Inclusive jet $p_T$: data/theory, uncertainties

- both measurements are in agreement with NLO pQCD
  - both data sets favor smaller gluon densities
- exp. systematics (dominated by JES uncertainty) $<\text{theory uncert. (mostly PDF)}$
  - thanks to precise JES
- PDF sensitivity: $x \propto 2p_T/\sqrt{s}$
PDF influence of Tevatron data

- MSTW2008 and CT10 (also CT09) PDF fits include Tevatron Run II inclusive jets
  - Run II data lead to softer high-$x$ gluons and provide more precise constraints
  - no visible reduction in PDF uncertainty due to new fit procedures
  - Run II data more consistent with DIS measurements than Run I

Gluon distribution at $Q^2 = 10^4$ GeV$^2$


CT10: arXiv:1007.2241
**First LHC results**

- inclusive jet cross sections based on first ATLAS and CMS data
- see Wednesday’s talks by Nadia Pastrone and Brian Peterson and poster session
- both ATLAS and CMS use anti-$k_T$ jets (default algorithm)
LHC: PDF sensitivity

- jet energy scale uncertainty largely dominates exp. systematics
  - conservative estimates: ATLAS: 7%, CMS (particle flow): 5%
  - expect significant improvements soon, but remember long process at Tevatron
- theory: NLO pQCD, uncert. dominated by
  - low $p_T$: non-perturbative corrections
  - high $p_T$: PDF uncertainty
- for central rapidities, cross section for fixed $x_T = 2p_T/\sqrt{s} \propto x$: $\sigma(\text{LHC}) \ll \sigma(\text{Tevatron})$
- Tevatron will still be more sensitive to high-$x$ gluon for several years.
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**$\alpha_s$ from inclusive jets**

- inclusive jet cross section directly related to $\alpha_s$ measurement:
  \[
  \sigma_{\text{theory}}(\alpha_s) = \sigma_{\text{pert}}(\alpha_s) \cdot c_{\text{nonpert}}
  \]
  \[
  \sigma_{\text{pert}}(\alpha_s) = \left( \sum_n \alpha_s^n c_n \right) \otimes f_1(\alpha_s) \otimes f_2(\alpha_s)
  \]
- $c_n$: NLO pQCD + 2-loop corr.
- $f_{1,2}(\alpha_s)$: MSTW2008NNLO $\alpha_s$ dependent fits:
  $\alpha_s(M_Z) = 0.110 - 0.130$
- keep only 22 (of 110) data points in kinematic region where PDF fit is not dominated by Tevatron: $x_{\text{max}} \lesssim 0.25$
**$\alpha_s$ from inclusive jets**

- Measurement of running $\alpha_s$ at highest $p_T$ (together with CDF Run I)
- Most precise determination of $\alpha_s$ from hadron collider

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

- Uncertainties:
  - Experimental: $+0.0034 - 0.0033$
  - Theory: $+0.0023 - 0.0035$

($\mu_r/f$ variation, non-perturbative corrections, PDF)

**Graph:**

- Plot of $\alpha_s(p_T)$ versus $p_T$ (GeV)
- Data points from H1, ZEUS, DØ
- Fit line with $\alpha_s(M_Z) = 0.1161^{+0.0041}_{-0.0048}$ (DØ combined fit)

**References:**

Dijet mass cross section

- measurement of \( \frac{d^2\sigma}{dM_{JJ}d|y|_{\text{max}}} \) in 6 rapidity bins up to \( M_{JJ} \sim 1.3 \text{ TeV} \)

\( M_{JJ} \): dijet mass, \( |y|_{\text{max}} = \text{max}(|y_1|, |y_2|) \), \( p_{T1,2} > 40 \text{ GeV} \)

- central rapidities: data well described by pQCD
- forward region: data below prediction
  - reminder: MSTW2008 includes Run II incl. jets
  - discrepancy w.r.t. CTEQ6.6 even larger

\( \Delta \sigma \) vs \( M_{JJ} \) at \( \sqrt{s} = 1.96 \text{ TeV} \), \( R_{\text{cone}} = 0.7 \)

- NLO pQCD + non-perturbative corrections
- \( \mu_F = \mu_R = (p_{T1} + p_{T2})/2 \)

\( \text{arXiv:1002.4594} \)
Dijet mass: searches for resonances

- dijet mass distribution for jet rapidities $|y| < 1$
- sensitive to new particles decaying into dijets: $q^*$, $W'$, $Z'$, $\rho_T$, axigluon, Randall-Sundrum-graviton, etc.
  - mostly produced more centrally
- search for narrow mass resonance as signal of physics beyond the Standard Model (BSM), lower mass bounds, e.g.:
  - $M(q^*) > 870$ GeV
  - $M$(axigluon) $> 1.25$ TeV

**LHC takes over...**

- with just $0.0003 \text{ fb}^{-1}$ LHC exceeds Tevatron sensitivity
  - $M(q^*) > 1.26 \text{ TeV}$
- see Wednesday’s talk by Brian Peterson
Dijet angular distribution

- measurement of
  \[ \frac{1}{\sigma_{\text{dijet}}} \cdot \frac{d\sigma}{d\chi_{\text{dijet}}} \] in bins of \( M_{jj} \)
  - \( \chi_{\text{dijet}} = \exp(|y_1 - y_2|) \)
  - massless \( 2 \rightarrow 2 \) scattering:
    \[ \chi_{\text{dijet}} = \frac{(1+\cos \theta^*)}{(1-\cos \theta^*)} \]
  - BSM: excess at large \( M_{jj} \) and small \( \chi_{\text{dijet}} \)

- consistent with NLO QCD

- limits on BSM mass scales:
  - quark compositeness: \( \sim 2.9 \) TeV
  - large extra dimensions (ADD (GRW) and TeV\(^{-1}\)): \( \sim 1.6 \) TeV
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\[ \chi_{\text{dijet}} = \exp(|y_1 - y_2|) \]

Three jet mass

- 3-jet mass distribution $d\sigma/dM_{3\text{jet}}$ with $p_T^{T_1} > 150$ GeV, $p_T^{T_3} > 40$ GeV, reaching $M_{3\text{jet}} > 1.1$ TeV
- compared to NLO pQCD with MSTW2008 PDF
  - reasonable description, but again: data prefer lower bound on theory prediction

D0 Note 6043-CONF (2010)
**$R_{3/2}$**: ratio of inclusive 3-jet to 2-jet production

- Test of QCD, less dependent on PDFs, probes $\alpha_s$
- Well described by SHERPA v1.1.3
- CKKW matching of matrix elements and parton shower
- Here: MEs up to 4 partons
- **Pythia**: large dependence on tunes, generally too many 3-jets (except for BW)
  - Both for $Q^2$ and $p_T$ ordered parton shower
  - Tune BW cannot describe e.g. dijet azimuthal decorrelation
  → hampers $\alpha_s$ extraction

**Pythia**: $Q^2$-ordered shower

**Pythia**: $p_T$-ordered shower

*D0 Note 6032-CONF (2010)*
Jet shape measurements

- jet shape is dictated by multi-gluon emission from primary outgoing parton
  - plus contributions from initial state radiation and underlying event
- allows to distinguish quark/gluon jets
- sensitive to generator tunes

\[
\Psi(r) = \frac{1}{N_{\text{jets}}} \sum_{\text{jets}} \frac{P_T(0,r)}{P_T(0,R)}
\]

\[
1 - \Psi(r)
\]

\[
\begin{align*}
\Psi(r) & > 0.7 \\
P_T^{\text{jet}} & > 277 \text{ GeV/c} \\
P_T^{\text{jet}} & < 304 \text{ GeV/c}
\end{align*}
\]

Substructure of high $E_T$ jets

- massive boosted jets comprise important background for high-$p_T$ top, Higgs and various BSM searches
- standard $E$-scheme for mass calculation: vector sum over $(E, p_x, p_y, p_z)$ of towers (with $m = 0$) in jets
- data in agreement with Pythia prediction
- data between quark and gluon prediction (80% quarks from jet shapes)
- also other jet shapes measured: angularity, planar flow

CDF Run II Preliminary

Midpoint R=0.4, $400 < p_T < 900$ GeV/c, $0.1 < m^{jj} < 0.7$, $p_T^{jj} > 100$ GeV/c, $m^{jj} > 100$ GeV/c, $S_{jet} = 4$

$L_{int} = 5.95$ fb$^{-1}$

CDF/PUB/JET/PUBLIC/10199 (2010)
**W/Z + jets production**

▶ W/Z + jets: critical background at Tevatron and LHC for top, Higgs, Supersymmetry, many BSM scenarios
  ▶ in particular: W/Z + b\bar{b}
  → correct modelling essential

▶ Matrix-Element calculations (ME) for each parton multiplicity
  ▶ works well for large angles and p_T
  ▶ NLO calculations available up to 3 jets

▶ parton showers (PS, **Pythia**, **Herwig**)
  ▶ successive radiation \( q \rightarrow qg \) etc.
  ▶ works well for small angles and p_T
  → matching of LO-MEs (up to 6 partons) and PS in **Alpgen**, **Sherpa** event generators
  → validation with data essential
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**Z/γ^*(→ μ^+ μ^-) + jets production**

incl. jet multiplicity

**CDF Run II Preliminary**

- CDF Data \( L = 6.03 \text{ fb}^{-1} \)
- Systematic uncertainties
- LO MCFM CTEQ6.1M
- NLO MCFM CTEQ6.1M
- Corrected to hadron level \( \mu_0 = M_Z^2 + p_T^2(Z), R_{\text{sep}} = 1.3 \)
- \( \mu = 2\mu_0; \mu = \mu_0/2 \)
- PDF uncertainties

**incl. jet \( p_T \) distr. for \( \geq 1 \) jet**

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CDF note 10216

⇒ good agreement with NLO pQCD (MCFM)

▶ scale uncertainties: 10-15%
Z/γ^*(→ μ^+ μ^-) + jets production

incl. jet multiplicity

CDF Run II Preliminary

![Graph](image1)

Z/γ^*(→ μ^+ μ^-) + ≥N jets inclusive
p_T^{jet} ≥ 30 GeV/c, |Y^{jet}| ≤ 2.1

Data / LO

CDF note 10216

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Thomas Nunnemann, LMU Munich

PIC 2010, Karlsruhe, 1.-4.9.2010

24/32
Z/γ∗(→ e⁺e⁻) + jets: jet $p_T$ spectra

1/$σ_{Z/γ∗}$ · $dσ_{Z/γ∗}/dp_T(\text{jet}_i)$ in events with $≥ i$ jets, $i = 1, 2, 3$

e.g. $≥ 2$ jets, $p_T(2^{\text{nd}} \text{jet})$, ratios to NLO QCD

parton shower generators

ME+PS generators

shape of $p_T$ distribution well described by ME+PS generators, but large scale uncertainties (← LO MEs)

parton shower generators predict too soft spectrum
$Z/\gamma^* (\rightarrow \mu^+ \mu^-) + \text{jets}$: angular observables

- observables
  - $\Delta \phi(Z, \text{jet}_1)$, shown ⇒
  - $\Delta y(Z, \text{jet}_1)$
  - $\frac{1}{2}(y_Z + y_{\text{jet}_1})$
- further constrains kinematics
- avoids systematics of jet energy scale
- fixed-order pQCD predictions not valid for small $\Delta \phi$

▸ shape of angular observables well described by Sherpa, but large scale uncertainties


Thomas Nunnemann, LMU Munich

PIC 2010, Karlsruhe, 1.-4.9.2010 26/32
**Z + b jet**

- probes $b$-quark PDF and fragmentation
- $Z + b$ and $Z + b\bar{b}$
  - $b\bar{b}$ from gluon splitting can collapse in one jet
- measurements require $\geq 1$ $b$-jet
- for jets with $E_T > 20$ GeV, $|\eta| < 1.5$
  - $\frac{\sigma(Z+b)}{\sigma(Z+\text{jet})} = (2.08\pm0.33\pm0.34)\%$
  - MCFM (NLO, not complete for $Z + (b\bar{b})_{1\text{jet}}$): 1.8 – 2.2%
- large difference between ALPGEN/PYTHIA
  - different scales
  - only $g \to b\bar{b}/b$-PDF

\[\text{Phys.Rev.D79, 052008 (2009), L=2 fb}^{-1}\]
jet flavor fractions determined from fit to jet lifetime probability tag
- templates: $b, c$: Alpgen+Pythia, light $q, g$: negative tag data
- jet $p_T$ distribution well described
- for jets with $p_T > 20 \text{ GeV}, |\eta| < 1$
  - $\frac{\sigma(Z+b)}{\sigma(Z+jet)} = (1.76 \pm 0.24(\text{stat}) \pm 0.23(\text{syst}))\%$
  - consistent with NLO QCD
$W + b$ jet

- $b$-jet fraction determined from fit to vertex-mass distribution $M_{\text{vert}}$

- Measurement of

$$\sigma(W + b) \times B(W \rightarrow \ell \nu)$$

- With $p_T^{\ell} > 20$ GeV, $|\eta^{\ell}| < 1.1$, $p_T^{\nu} > 25$ GeV, $E_T^{b-\text{jet}} > 20$ GeV, $|\eta|^{b-\text{jet}} < 2$

- $(2.74 \pm 0.27 \pm 0.42)$ pb

- NLO QCD: $1.22 \pm 0.14$ pb

(Campbell, Febres Cordero, Reina)

$\sim 3\sigma$ smaller

- Alpgen + Pythia: $0.78$ pb

Vertex Mass Fit

CDF Run II Preliminary - 1.9/fb

- Data
- Bottom contribution
- Charm contribution
- LF contribution
- Summed contribution

$\begin{align*}
    b &= 71.3 \pm 4.7(\text{stat}) \pm 6.4(\text{syst})
    
    c &= 15.9 \pm 5.5(\text{stat})
    
    \text{LF} &= 12.6 \pm 3.5(\text{stat})
\end{align*}$

KS Prob = 84.8 %

$W + c$ jet

- $s + g$ fusion: $\sim 90\%$ contribution
  - probes $g$ and $s$ PDFs at high $Q^2$
- $c$-jet identified by soft lepton
- CDF, $4.3 \text{ fb}^{-1}$
  - $c$-jet: $p_T > 12 \text{ GeV}, |\eta| < 1.5$
  - $\sigma(W + c) \times B(W \to \ell \nu) = (33.7 \pm 11.4(\text{stat}) \pm 4.7(\text{syst})) \text{ pb}$
  - NLO: $17.8 \pm 1.7 \text{ pb}$
- D0, $1 \text{ fb}^{-1}$
  - jet: $p_T > 20 \text{ GeV}, |\eta| < 2$
  - $\frac{\sigma(W+c)}{\sigma(W+\text{jet})} = (7.4 \pm 1.9(\text{stat})^{+1.2}_{-1.4}(\text{syst}))\%$
  - Alpgen+Pythia: 4.4\%  

$\Rightarrow$ reasonable agreement
\( \gamma + b/c \text{ jet} \)

\begin{align*}
\text{Phys. Rev. Lett. 102, 192002 (2009)}
\end{align*}

- again: sensitivity to heavy flavor and gluon content of proton
- \( p_T^{\text{jet}} > 15 \text{ GeV}, 30 \text{ GeV} < p_T^{\gamma} < 150 \text{ GeV} \)
- \( \gamma + b \): agreement over full \( p_T^{\gamma} \) range
- \( \gamma + c \): NLO QCD underestimates rate at large \( p_T^{\gamma} \), some improvement for PDF sets with inclusive charm
- CDF: \( \gamma + b \) in agreement with NLO QCD, Phys. Rev. D81, 052006 (2010)
Conclusions

- Understanding of high $E_T$ jet and $W/Z+$jet production significantly advanced over the last years
- Inclusive jet cross section
  - High precision due to precise jet energy scale calibration
  - Precision measurement of running $\alpha_s$
  - Stringent constraints on gluons at high $x$
- Multijets
  - Agreement with NLO QCD, but data prefer lower bound on theory
- Dijet mass and angular distribution
  - Best limits on quark compositeness, extra dimensions, etc.
- $Z/W/\gamma+$jets(s)
  - Test pQCD, help generator modeling/tuning
  - Crucial for SUSY and Higgs searches (in particular for $b$-jets)
  - $W+b$, $\gamma+c$: some tension with theory
- Tevatron expects $12\,\text{fb}^{-1}$ until 2011 (and prospects beyond)
  - Extend measurements to higher $p_T$, $M_{jj}$ and multiplicities
<table>
<thead>
<tr>
<th>incl. jets</th>
<th>dijets</th>
<th>trijets</th>
<th>jet shapes</th>
<th>W/Z + jets</th>
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Inclusive jets: $k_T$ vs. midpoint cone
Inclusive jets: SIS cone vs. midpoint cone

hadron level

parton level

⇒ effect on data/pQCD comparison < 1%
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