Recent QCD results from the Tevatron

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Hard QCD Processes

high $p_T \rightarrow$ hard partonic scattering

Sensitive to:

- dynamics of interaction
  - validity of approximations (NLO, LLA, ...)
  - QCD vs. new physical phenomena
- proton’s parton content
  $\rightarrow$ unique sensitivity to high-$x$ gluon
- strong coupling constant

CTEQ6.1 gluon uncertainty
Physics Objects

Jets
(all flavors)

Heavy Flavor
Physics Objects

Jets (all flavors)

W/Z Bosons

Photons

Heavy Flavor
Physics Objects

Jets (all flavors)

W/Z Bosons

Photons

Heavy Flavor

Multi-Parton Interactions / Underlying Event
Outline

• Photon Production (+ Jet)
• Vector Boson + Jet(s)
• Event Shapes
• Jet Production
• Determination of $\alpha_s$
Fermilab Tevatron – Run II

- 36x36 bunches
- bunch crossing 396 ns
- Run II: March 2001 – Sept 2011
- Peak Luminosity: $4.2 \times 10^{32}$ cm$^{-2}$ sec$^{-1}$
- Run II total delivered: 12 fb$^{-1}$

Two more days running!!
Integrated Luminosity in One Store: $12150.17 \pm 12048.1$ [1/nb], April 17, 2010, Store #7748. For CDF and D0, respectively

Integrated Luminosity in a Week: $73.070$ [1/pb], April 13 - April 20 2009. Average integrated Luminosity of CDF and D0.

Integrated Luminosity in a Month to CDF: $273.423$ [1/pb], March 2010. D0 also set a record this month (avg 272.720 1/pb)

Maximum number of PBars at Low Beta: $3326E9$, February 10, 2008, Store #5899. From the Recycler

Maximum number of Protons at Low Beta: $18236. E9$, July 14, 2002, Store #1526.

Store Duration: 53.75 Hours, 29-31 July 2006, Store #4862

Integrated Luminosity in a Floating Week: $81.98$ [1/pb], June 14, 2011.
Run II Detectors

- Silicon tracking detectors
- Central Outer Tracker (drift chambers, COT)
- Solenoid Coil
- EM calorimeter
- Hadronic calorimeter
- Muon scintillator counters
- Muon drift chambers
- Steel shielding

- vertexing
- precision tracking
- calorimetry
- muon system
- (hermetic → missing ET)
Photons

test theory
fixed order: NLO
resummation

PDF constraints?
Direct Photon Production

Direct photons emerge unaltered from the hard subprocess → direct probe of the hard scattering dynamics → sensitivity to PDFs (gluon!) ...but only if theory works.

inclusive photon cross section \( 0 < |\eta| < 0.9 \) partonic subprocesses

\[
\begin{align*}
\text{fractional contribution} & \geq 1 \\
\text{fractional contribution} & \geq 0.9 \\
\text{fractional contribution} & \geq 0.8 \\
\text{fractional contribution} & \geq 0.7 \\
\text{fractional contribution} & \geq 0.6 \\
\text{fractional contribution} & \geq 0.5 \\
\text{fractional contribution} & \geq 0.4 \\
\text{fractional contribution} & \geq 0.3 \\
\text{fractional contribution} & \geq 0.2 \\
\text{fractional contribution} & \geq 0.1 \\
\end{align*}
\]

\( gg \) (all quark/anti-quark subprocesses)

also fragmentation contributions:

\[ q g \]

suppress by isolation criterion → observable: isolated photons
Incl. Isolated Photons

CDF and D0 measurements: 20 < $p_T$ < 400GeV → agreement

theory vs. data: disagreement in low $p_T$ shape

experimental and theory uncertainties > PDF uncertainty
→ no PDF sensitivity yet

first: need to understand discrepancies in shape

Isolated Photon + Jet

investigate source for disagreement
→ measure more differential:
  • tag photon and jet
    → reconstruct full event kinematics
  • measure in 4 regions of \( y_\gamma / y_{\text{jet}} \)
    - photon: central
    - jet: central / forward
    - \( \gamma, \text{jet}: \text{same side} / \text{opposite side} \)

L = 1 fb

discrepancies in data/theory
→ figure out what is missing...
  • higher orders, resummation, ... ?

Isolated Photon + HF Jet

Photon + (b/c) jet + X
Photon $p_T$: 30-150 GeV

0.01 < x < 0.3 $\rightarrow$ b, c, gluon PDF
$\rightarrow$ test gluon splitting contribution

**tag photon and jet**

Rapidities: $|y^\gamma| < 1.0$  $|y^{\text{jet}}| < 0.8$

$\rightarrow$ triple differential $d^3\sigma/(dp_T^\gamma dy^\gamma dy^{\text{jet}})$
→ photon+b: agreement over full $p_T$ range: 30-150 GeV → no PDF sensitivity

→ photon+c: - agree only at $p_T < 50$ GeV - disagreement increases with photon $p_T$ - using PDF including intrinsic charm (IC) improves the theory $p_T$ dependence

Di-photon production

- Di-Photon final state: one of main discovery channels for Higgs at the LHC
- Possible signatures of new physics, such as large Extra Dimensions

Leading order diagram: dominant at high di-photon mass (Higgs background at LHC)

Next-to-next-to leading order contribution → suppressed by factor $\alpha_s^2$
But important at low mass → large gluon density

- **ResBos:**
  - NLO prompt di-photons
  - LO fragmentation contribution
  - Resummed initial state gluon radiation (important for qT)

- **DIPHOX:**
  - NLO prompt di-photons
  - NLO fragmentation (1 or 2 $\gamma$)
  - NNLO $gg \rightarrow \gamma\gamma$ diagram

- **PYTHIA**

- **SHERPA**
agreement between CDF and D0 data
theory describes data at high mass (> 50 GeV)
at low mass: theory too high
→ between 20-50 GeV: theory does not describe data
→ RESBOS (resummed gluon contributions) describes $p_T < 20$ GeV
→ no theory describes data over whole $\Delta \phi$ range  
→ RESBOS (resummed gluon contributions) describes $\Delta \phi \to \pi$
Vector Boson + Jets

Fixed-order: NLO
LO + Parton Shower
Matched Tree-Level + PS
Backgrounds to New Physics
Vector Boson + Jet

- relevant to other high-multiplicity processes
- background to Higgs
- test “matched” predictions → critical to Tevatron / LHC physics

Provide detailed measurements of $p_T$ and angular distributions of vector boson and jet
→ test perturbative QCD calculations
→ testing and tuning of phenomenological models
Z + jets $\rightarrow p_T$ - jet

Measurement of 1st, 2nd and 3rd jet $p_T$ in Z events:
$\rightarrow$ normalize to inclusive Z production (cancel some uncertainties)
compare to pQCD @ LO / NLO


**Leading jet in Z + jet + X**

**Second jet in Z + 2jet + X**

**Third jet in Z + 3jet + X**

NLO describes data within scale range

LO not too bad
Z + jets (angular distrib.)

Angular variables:  \( \Delta \phi(Z, \text{jet}) \)  \[ | \Delta y |(Z, \text{jet}) \]  \[ | y_{\text{boost}} |(Z, \text{jet}) \]

Overall: decent agreement
new preliminary CDF result \((8.2 \text{fb}^{-1})\) \(Z(\rightarrow \ell\ell) + n\) jets \(n=1-4\), \(l=e,\mu\)

Measure comprehensive set of differential distributions

\(\rightarrow\) detailed test of LO / NLO pQCD predictions (Blackhat+SHERPA)

\(\rightarrow\) NLO for \(n=1-3\)

\(\rightarrow\) LO for \(n=4\)

Here: cross section vs. jet multiplicity

\(\rightarrow\) described for \(n=1,2,3\) (NLO)
brand new preliminary CDF result (8.2 fb$^{-1}$) \( Z(\rightarrow \ell\ell) + n \text{ jets} \quad n=1-4, \ell=e,\mu \)

Here: \( p_{T\text{jet}} \) distributions for jet #1, 2, 3

→ good agreement for jets #1, #2
brandnew preliminary CDF result \((8.2\text{fb}^{-1})\quad Z(\rightarrow\ell\ell) + n \text{jets}\quad n=1-4, \ell=e,\mu\)

Here: rapidity distributions for jet #1, 2, 3

→ good agreement for jet #1, reasonable for #2, poor for #3 (large k-factor)
Z+ b jet

\[
\frac{\sigma(Z + b\text{jet})}{\sigma(Z + \text{jet})} = 0.0193 \pm 0.0022\text{(stat)} \pm 0.0015\text{(syst)}
\]

NLO MCFM

0.0192 \pm 0.0022

Prediction decreases by 3.6% when the effects from detector response, resolution as well as hadronization and underlying event are taken into account.
W+jets

$p_T^{jet}$ distributions for jet #1, 2, 3, 4 → test NLO (n=1,2,3) LO (n=4)

NLO describes 1st jet well – 3rd jet less well
Event Shapes

Successfully used in e+e- collisions

→ first tests at hadron colliders
Event Shapes

New CDF measurement of transverse thrust and thrust minor
(show uncorrected data)
→ Large underlying event corrections
Define new variable “thrust differential” as a weighted sum of $T_{\text{min}}$ and $\tau$

$$D(\langle \tau \rangle, \langle T_{\text{min}} \rangle) = \gamma_{MC}(\alpha \langle T_{\text{min}} \rangle - \beta \langle \tau \rangle)$$

→ Insensitive to underlying event

Present (corrected) average values of $<D>$ as a function of $E_{T, \text{leading jet}}$
→ Compared to PYTHIA (tune A)
→ and to analytical NLO+NLL calculation (parton-level) in CEASAR

→ See also recent CMS result: events shapes based on jets
SM production well-understood

→ use data for SM and NP phenomenology
→ quantitative results
Jet Production

In the absence of new physics:
theory @NLO is reliable (10%)
→ Precision phenomenology
  - sensitivity to PDFs → high-x gluon
  - sensitive to unique sensitivity to new physics:
    - new particles decaying to jets,
    - quark compositeness,
    - extra dimensions,
    - ...(?)...

largest high pT cross section at a hadron collider
→ highest energy reach

Jet Production

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In the absence of new physics:
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    - ...(?)...
Inclusive Jets

benefit from:
• high luminosity in Run II
• increased Run II cm energy → high $p_T$
• hard work on jet energy calibration

steeply falling $p_T$ spectrum:
1% error in jet energy calibration → 5—10% (10—25%)
central (forward) x-section
Inclusive Jets

- high precision results
- consistency between CDF/D0
- well-described by NLO pQCD
- experimental uncertainties: smaller than PDF uncertainties!!
  \[ \rightarrow \text{sensitive to distinguish between PDFs} \]

Data are used in PDF fits:
- MSTW2008
- NNPDF2.0/2.1
- CT10
Dijet Angular Distribution

\[ \chi_{\text{dijet}} = \exp(|y_1 - y_2|) = \frac{1 + \cos \theta^*}{1 - \cos \theta^*} \]

\[ \frac{1}{\sigma} \frac{d\sigma}{d\chi_{\text{dijet}}} \]

- Redo the Rutherford Experiment

\[ \chi_{\text{dijet}} \]

- small \( \Delta y \)
- large \( \Delta y \)
Dijet Angular Distribution

Measurement for dijet masses from 0.25 TeV to >1.1 TeV

→ First time:
Rutherford experiment above 1 TeV
→ Data described by Standard Model

Constrain models of Spatial Extra Dimensions and quark compositeness:
• Quark Compositeness $\Lambda > 2.9$ TeV
• ADD LED (GRW) $M_s > 1.6$ TeV
• TeV$^{-1}$ ED $M_c > 1.6$ TeV

→ Most stringent pre-LHC limits
central dijet production $|y|<1$

- test pQCD predictions
- sensitive to new particles decaying into dijets: excited quarks, $Z'$, $W'$, Randall-Sundrum gravitons, color-octet, techni-rho, axigluons, colorons
central dijet production \(|y| < 1\)
- test pQCD predictions
- sensitive to new particles decaying into dijets: excited quarks, \(Z', W'\), Randall-Sundrum gravitons, color-octet, techni-rho, axigluons, colorons

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Midpoint, \(R=0.7\), \(|y^{\text{jet}1,2}| < 1\), \(L_{\text{int}} = 1.13\ \text{fb}^{-1}\)
- Data
- NLO: NLOJET++, CTEQ6.1 M corrected to hadron level
  \(\mu = p_T^{\text{near}}(\text{jet1,2})/2, R_{\text{sep}}=1.3\)
- Systematic uncertainties

CDF Run II Preliminary
central dijet production  \(|y|<1\)

- test pQCD predictions
- sensitive to new particles decaying into dijets: excited quarks, \(Z', W'\), Randall-Sundrum gravitons, color-octet, techni-rho, axigluons, colorons

\[\frac{d\sigma}{dM_{jj}} \text{ [pb/(GeV/c)^2]}\]

\[M_{jj} \geq 1.2 \text{ TeV} \]

\[\text{all described by NLO pQCD}\]

\[\text{no indications for resonances}\]

\[\text{set limits on new particles}\]

→ data with \(M_{2\text{-jet}} > 1.2 \text{ TeV}!\)
Dijet Mass Spectrum


First measurement of rapidity dependence of dijet mass spectrum in six $|y|_{\text{max}}$ regions

$0 < |y|_{\text{max}} < 2.4$

extend QCD test to forward region

up to $M_{2\text{-jet}} > 1.2$ TeV

→ good agreement with Standard Model predictions

no hints for:

- dijet mass bumps (resonances, decaying into dijets)
- excess at high masses (indications of new physics at higher energies)
First measurement of rapidity dependence of dijet mass spectrum in six $|y|_{\text{max}}$ regions $0 < |y|_{\text{max}} < 2.4$

→ extend QCD test to forward region
→ up to $M_{2\text{-jet}} > 1.2$ TeV

→ PDF sensitivity at large $|y|_{\text{max}}$
  - MSTW2008 consistent w/ data (but correlation of experimental and PDF uncertainties!)
  - CTEQ6.6 prediction too high (how significant? → CTEQ paper)
  - theory uncertainty at large $|y|_{\text{max}}$

**3-jet Mass Spectrum**

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**2-jet cross section:**
\[ O(\alpha_s^2) \times \text{PDF}^2 \]
(correlation of \( \alpha \) and gluon density)

**3-jet cross section:**
\[ O(\alpha_s^3) \times \text{PDF}^2 \]

analyze 2-jet and 3-jet cross sections:

→ **decorrelate** \( \alpha_s \) and gluon density in PDF fits

---

First Run II measurement of 3-jet cross section vs.

- rapidity \(|y_{1,2,3}|\) (left)
- \( p_T3 \) requirement (right)

→ up to \( M_{3\text{-jet}} > 1.2 \) TeV
→ extend QCD tests to \( O(\alpha_s^3) \) processes
similar to dijet mass result:

- **MSTW2008**: slightly higher than data at all $M_{3\text{-jet}}$ (but consistent)
- **CT10** agrees at low $M_{3\text{-jet}}$ - different shape: too high at high $M_{3\text{-jet}}$
- CT10, MSTW2008 68% CL uncertainty bands: no overlap at high $M_{3\text{-jet}}$
compare all recent PDFs (MSTW2008, CT10, ABKM09, HERA1.0)

- NNPDF2.1 very similar to MSTW2008
- ABKM09 very similar to HERAPDF1.0 (5-20% lower than MSTW)
- CT10 has strong increase for $M_{3\text{-}jet} > 0.6 \text{ TeV}$ ($x > 0.3$)
Agreement between theory and data depends on

- PDF
- Choice of \( \alpha_s(M_Z) \) – especially since \( \sigma_{3\text{-jet}} \) is of \( O(\alpha_s^3) \)
- Choice of scales \( \mu_R, \mu_F \)

Comments

- Different PDF fits have different preferred \( \alpha_s(M_Z) \) values
- Different PDF fits use a different scale for inclusive Tevatron jets:
  - CT10: \( \mu_R, \mu_F = p_T/2 \)
  - other groups: \( \mu_R, \mu_F = p_T \) (better behaved at large \( |y| \) which gives strong constraints for high-\( x \) PDFs)

For a fair comparison: study theory(PDF)/data agreement

- versus \( \alpha_s(M_Z) \)
- for different scales \( \mu_R, \mu_F = \mu_0, \mu_0/2, 2\mu_0 \)
  - with \( \mu_0 = (p_{T1} + p_{T2} + p_{T3}) / 3 \)
Find that previous conclusions are independent of $\mu_R$, $\mu_F$ and $\alpha_s(M_Z)$ choices

Best agreement for MSTW2008/NNPDF for $\mu_R, \mu_F = \mu_0$ and $\alpha_s(M_Z) = \text{world average}$
inclusive jet cross section is sensitive to $\alpha_s$

$$\sigma_{\text{pert}}(\alpha_s) = \left( \sum_n \alpha_s^n c_n \right) \otimes f_1(\alpha_s) \otimes f_2(\alpha_s)$$

previous CDF result from Run I: PRL88, 042001 (2002)
\( \alpha_s \) and the RGE

- \( \alpha_s(\mu_R) \): depends on renormalization scale \( \rightarrow \) predicted by “RGE”
- Values \( \alpha_s(\mu_R) \) are not predicted
- \( \alpha_s(\mu) \leftarrow \text{RGE} \rightarrow \alpha_s(M_Z) \)
- Agreement: compare \( \alpha_s(M_Z) \)

QCD test (2 aspects):
- Determine \( \alpha_s(M_Z) \) \( \rightarrow \) check process independence
- Test RGE \( \rightarrow \) running \( \alpha_s(\mu_R) \)

\( \alpha_s(M_Z) \) extraction at large \( p_T \) requires high (experimental & theory) precision

\[
\beta(\alpha_s(Q^2)) = -\beta_0 \alpha_s^2(Q^2) - \beta_1 \alpha_s^3(Q^2) - \beta_2 \alpha_s^4(Q^2) - \beta_3 \alpha_s^5(Q^2) + \mathcal{O}(\alpha_s^6)
\]

\[
Q^2 \frac{\partial \alpha_s(Q^2)}{\partial Q^2} = \beta \left( \alpha_s(Q^2) \right)
\]

\( \alpha_s(M_Z) = 0.1184 \pm 0.006 \)
Knowledge of $\alpha_s$ has been tested for momenta up to 209 GeV (LEP $e^+e^-$ data). 

But not yet for larger scales.
Basic principle

Perturbative cross section formula:

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

- pQCD matrix elements: explicit \( \alpha_s \) dependence
- \( f_1, f_2 \) (PDFs): implicit \( \alpha_s \) dependence

Determine \( \alpha_s \) from data:
- Vary \( \alpha_s \) until sigma-theory agrees with sigma-experiment
  - \( \chi^2 \) minimization

For a single bin →

→ Procedure requires PDFs as external input
PDFs and input data

MSTW2008 paper (Fig 52. / see also Figs. 51, 53)

Currently:
Main constraints on high-x gluon density come from Tevatron jet data

Goal:
Minimize correlations between data and PDF uncertainties

→ Restrict $\alpha_s$ analysis to kinematic regions where impact of Tevatron data for PDFs is small.

→ Tevatron jet data don’t affect gluon for $x < 0.2 - 0.3$
Incl. Jets: x-sensitivity

Jet cross section has access to x-values of: (in LO kinematics)

\[ x_a = x_T \frac{e^{y_1} + e^{y_2}}{2}, \quad x_b = x_T \frac{e^{-y_1} + e^{-y_2}}{2} \quad \text{with} \quad x_T = \frac{2p_T}{\sqrt{s}} \]

What is the x-value for a given incl. jet data point @ (p_T, |y|) ?
→ Not completely constrained – unknown kinematics since we integrate over other jet(s)
→ Construct “test-variable” (treat as if other jet was at y=0):

\[ x = x_T \cdot \left( e^{y} + 1 \right) / 2 \]

→ Apply cut on this test-variable to restrict accessible x-range
→ Find: requirement x-test < 0.15
   removes most of the contributions with x > 0.2 – 0.3
→ 22 (of 110) data points remaining at 50 < p_T < 145 GeV
$x_{\text{min}} / x_{\text{max}}$ distributions

Every analysis bin $\rightarrow$ one plot
Each plot: $x$-min/$x$-max distributions

Cut on test-variable $x$-test $< 0.15$
$\rightarrow$ 22 (of 110) data points remain

These have small contributions from $x > 0.2 - 0.3$

$\leftarrow$ Only data points above green line are used
22 (out of 110) inclusive jet cross section data points at 50 < $p_T$ < 145 GeV → Input in $\alpha_s$ analysis
→ Use best theory prediction: NLO + 2-loop threshold corrections (Kidonakis/Owens) with MSTW2008NNLO PDFs

\[ \alpha_s(M_Z) = 0.1161 \pm 0.0041 \]

→ Most precise result from a hadron collider

→ Consistent with HERA results and world average

<table>
<thead>
<tr>
<th>$\alpha_s(M_Z)$</th>
<th>from inclusive jet cross section in hadron-induced processes</th>
</tr>
</thead>
<tbody>
<tr>
<td>DØ</td>
<td>$\alpha_s(M_Z) = 0.1161 \pm 0.0041$ (DØ combined fit)</td>
</tr>
</tbody>
</table>

All uncertainties are multiplied by a factor of $10^3$
Theoretical Precision

Main result: use best theory predictions
NLO + 2-loop threshold corrections
(Kidonakis/Owens)
with MSTW2008NNLO PDFs

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

Use only NLO
with MSTW2008NLO PDFs

\[ 0.1202^{+0.0072}_{-0.0059} \]

• Larger value of “NLO-only” result:
  → due to missing \( O(\alpha_s^4) \) contributions

• Larger uncertainty of “NLO-only” result:
  → due to increased scale dependence (main effect)
  → and increased PDF uncertainty (minor effect)

All uncertainties are multiplied by a factor of \( 10^3 \)

<table>
<thead>
<tr>
<th></th>
<th>Total uncertainty</th>
<th>Experimental uncorrelated</th>
<th>Experimental correlated</th>
<th>Nonperturb. correction</th>
<th>PDF uncertainty</th>
<th>( \mu_{r,f} ) variation</th>
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<tbody>
<tr>
<td>( \alpha_s(M_Z) )</td>
<td>0.1161</td>
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<td></td>
<td>( +4.1 ) \text{ (f)}</td>
<td>( \pm 0.1 ) \text{ (f)}</td>
<td>( +3.4 ) \text{ (f)}</td>
<td>( +1.0 ) \text{ (f)}</td>
<td>( +1.1 ) \text{ (f)}</td>
<td>( +2.5 ) \text{ (f)}</td>
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<td></td>
<td>( -4.8 ) \text{ (f)}</td>
<td></td>
<td>( -3.3 ) \text{ (f)}</td>
<td>( -1.6 ) \text{ (f)}</td>
<td>( -1.2 ) \text{ (f)}</td>
<td>( -2.9 ) \text{ (f)}</td>
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</tbody>
</table>
Running of $\alpha_s$ (?)

→ so far tested up to $\mu_r = 209$ GeV (LEP)

Could be modified for scales $\mu_r > \mu_0$ e.g. by extra dimensions

here: $\mu_0 = 200$ GeV and n=1,2,3 extra dim.
(n=0 $\rightarrow$ Standard Model)

But: $\alpha_s$ extraction from inclusive jets uses PDFs which were derived assuming the RGE

→ We cannot use the inclusive jets to test the RGE in yet untested region
Going further …

… towards testing in the RGE in novel energy regimes

→ Cannot rely on PDF information
   (PDF parametrizations already assume RGE in DGLAP evolution)
Goal: test pQCD (and $\alpha_s$) independent of PDFs

Conditional probability:

$R_{3/2} = P(\text{3rd jet} | 2 \text{ jets})$

$= \sigma_{3\text{-jet}} / \sigma_{2\text{-jet}}$

- Probability to find a third jet in an inclusive dijet event
- Sensitive to $\alpha_s$ (3-jets: $\alpha_s^3$ / 2-jets: $\alpha_s^2$)
- (almost) independent of PDFs
\[ R_{3/2} = \frac{\sigma_{3\text{-jet}}}{\sigma_{2\text{-jet}}} \]

**Measure as a function of two momentum scales:**
- \( p_{T\text{max}} \): common scale for both \( \sigma_{2\text{-jet}} \) and \( \sigma_{3\text{-jet}} \)
- \( p_{T\text{min}} \): scale at which 3rd jet is resolved (\( \sigma_{3\text{-jet}} \) only)

Sensitive to \( \alpha_s \) at the scale \( p_{T\text{max}} \) \( \rightarrow \) probe running of \( \alpha_s(p_{T\text{max}}) \)

**Details:**
- inclusive \( n\)-jet samples (\( n=3,2 \)) with \( n \) (or more) jets above \( p_{T\text{min}} \)
- \( |y| < 2.4 \) for all \( n \) leading \( p_T \) jets
- \( \Delta R_{\text{jet,jet}} > 1.4 \) (insensitive to overlapping jet cones)
- study \( p_{T\text{max}} \) dependence for different \( p_{T\text{min}} \) of 50, 70, 90 GeV
  \( \rightarrow \) Measurement of \( R_{3/2}(p_{T\text{max}}; p_{T\text{min}}) \)
\( R_{3/2} \) vs. NLO pQCD

Using \( R_{3/2} \) to test NLO matrix elements

For a given \( \alpha_s(M_Z) = 0.118 \):

\( \rightarrow \) NLO results for MSTW2008NLO, NNPDF v2.1, ABKM09NLO agree

\( \rightarrow \) CT10 slightly higher at high \( p_T \)
Overview

Theory-data comparison for jet cross section data in processes with initial-state hadrons

- RHIC
- HERA 1, 2 (high Q2 only)
- Tevatron Run I, II (central rapidities only)
- First LHC results (central rapidities only)

Highest pT reach by LHC data
Overview: $x_T$ dependence

hadron-hadron collisions only

plot vs. $x_T = 2p_T / \sqrt{s}$

Interpretation:

for $y_1 = y_2 = 0 \rightarrow x_T = x$

demonstrate PDF sensitivity

highest $x$-reach by Tevatron data
Summary

→ **precision measurements** of fundamental observables @2TeV
→ **consistent results** from CDF and D0

- **photon production** (inclusive, plus jet, plus HF jet, diphoton)
  → need to find missing pieces in theory
- **Z/W + jet production** ($p_T$ spectra, angular distributions)
  → many distributions for pQCD tests and for model tuning
  → NLO describes some of the basic variables (not all)
- **event shape variables**
  → interesting new (in pp) testing ground from soft to hard QCD
- **jet production** (inclusive $p_T$, dijet angle and mass, 3-jet mass, ratio $R_{32}$)
  → precision measurements – pQCD very successful
  → constraints on $\alpha_s(M_Z)$ and high-x gluon
In the RGE one performs matching at the flavor thresholds

→ one threshold at $m_{\text{top}}$ (= 170 - 180 GeV) where $n_f$ makes a step from 5 to 6

→ For inclusive jets / dijets at the Tevatron/LHC:
  Do we really want to do that?
  • What $n_f$ should one use for computing single jet inclusive / or inclusive dijet cross sections for $\mu = p_T > m_{\text{top}}$

So far, fastNLO (used in all global PDF fits to compute Tevatron jets) uses $n_f = 5$ everywhere

Reasoning: We do not measure jets from top decays at $p_T > m_{\text{top}}$

→ Make people aware – in that case RGE should also use $n_f = 5$
"soft" ISR does not describe Inclusive dijet $\Delta\phi$ distribution → needs more ISR → tune DW

Different when explicitly requiring a third jet → R32

tune DW much too hard for R32 → Prefers “BW” (original) soft ISR