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- understand the fundamental physics of hadron collisions
- precision tests of QCD, uncovering new physics

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Today will focus on the latest results in “hard” QCD
Tevatron performing very well:
- 10.3 fb\(^{-1}\) delivered per experiment
- 50 pb\(^{-1}\) per week
- experiment efficiency ~90%
- peak: \(3.5 \times 10^{32}\) cm\(^{-2}\)s\(^{-1}\)

Results today use 0.7 – 6.2 fb\(^{-1}\)

Expect 12 fb\(^{-1}\) delivered by end of FY11
Two general purpose detectors: CDF and D0
- central tracking in a solenoid
- electromagnetic and hadronic calorimeters
- muon tracking (D0: with toroidal magnets)

Competitive advantages
- CDF: better track momentum resolution & displaced track trigger at Level 1
- D0: finer calorimeter segmentation, and muon coverage to $|\eta| < 2.0$
Jets
- searches, precision measurements
- 3 jets, jet substructure
Jet Production

Fundamental process at a hadron collider!

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

Fundamental process at a hadron collider!

Any signs of new interactions?
- dijet angular distributions
- dijet mass resonances

No discovery, limits set
- limits depend on model, in 1-3 TeV range
- hard to compete with LHC!
Precision Measurements

Precision test of QCD!

Benchmark: measurements of jet cross sections
- driven by precise jet energy scale:
  1-2 % (D0)
  2-3 % (CDF)
- into forward region (|η| < 2.4)
- also testing different jet algorithms
  - kT instead of cone: PRD 75, 092006 (2007)

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Use inclusive jet data:
- constrain PDFs, particularly high-x gluon

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G. Hesketh

**PDFs and $\alpha_s$**

Use inclusive jet data:
- constrain PDFs, particularly high-$x$ gluon
- and $\alpha_s$

Legacy measurements from the Tevatron!

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

$\alpha_s(M_Z) = 0.1173^{+0.0041}_{-0.0049}$

Further information in the di-jet mass distribution:
- probe masses > 1.2 TeV!
- still shows some tension with latest PDF fits

See also: PRD.79.112002
Preliminary results on 3 jet mass:
- leading jet $p_T > 150$ GeV
- three rapidity ranges, three $p_T$ selections
- test NLO in more complex events
- systematics limited: 20-30%, JES dominates
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Also look at R3/2:
- cancels many experimental systematics
  - JES still dominates, at 3-5%
- and much of the PDF dependence in theory
- test QCD, and event generators
  - next: extract $\alpha_s$
Test QCD and parton shower models
- using high energy jets (>400 GeV)
- also benchmark boosted objects

Jet mass
- E-scheme sum of tower 4-vectors)
- ~80% of jets originate from quarks

Angularity and planar flow
- better resolution
- less algorithm dependence
2) Bosons
- diphotons
- photon + jets
- Z + jets
- heavy flavour
Use the well-understood bosons as a colourless probe of QCD process!
- properties and interactions of the bosons well understood
- kinematics determined by hadronic recoil
Use electron and muon decay modes of the $Z$ - clear experimental signature

Inclusive $Z$ pT: soft and hard recoil - see J. Sekaric on Electroweak, Thursday

Identified jets: - complex events: recent NLO $W/Z+3$jets - test QCD, understand search background!

$W$: - higher cross section - neutrino adds complication
Photons, Z, W

Use electron and muon decay modes of the Z
- clear experimental signature

Inclusive Z pT: soft and hard recoil
- see J. Sekarić on Electroweak, Thursday

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W:
- higher cross section
- neutrino adds complication

Photons:
- higher production cross section
- purity falls at low pT (>~70%)
- isolation cuts reject fragmentation
Extensive results from CDF and D0
- photon $p_T > 15-20$ GeV, $|\eta| < 1.0$
- diphoton mass, $p_T$, angles

**Theoretical predictions:**
DIPHOX: NLO, gg fusion @ LO
RESBOS: NLO + soft-gluon resummation
PYTHIA: LO + parton shower
Di-photon Production

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Theoretical predictions:
DIPHOX: NLO, gg fusion @ LO
RESBOS: NLO + soft-gluon resummation
PYTHIA: LO + parton shower
Good agreement at high mass

But, no model describes full range:
- low pT, mass regions difficult
  - double differential!
- large contribution from g-g
  - and fragmentation
- g-g more important at the LHC!

Use photon + jet production:
- look for multiple interactions

Divide event into two systems:
- photon + jet
- additional jets in event
- check for balance/correlation

Data / Theory

$|\sigma_{\gamma j}/d\Delta\phi|$

- Data
- PYTHIA, tune A
- PYTHIA, tune DW
- PYTHIA, tune S0
- PYTHIA, tune P0
- SHERPA, with MPI
- PYTHIA, no MPI
- SHERPA, no MPI

Total uncertainty

DØ, $L_{\text{int}} = 1.0 \text{ fb}^{-1}$
$50 < p_T^\gamma < 90 \text{ GeV}$
$p_T^{\text{jet1}} > 30 \text{ GeV}$
$15 < p_T^{\text{jet2}} < 20 \text{ GeV}$

Accepted by PRD
arXiv:1101.1509
Updated result from CDF:
- electron and muon channels, now with 6.2 fb$^{-1}$
- leading and second jet $p_T$, rapidity
- compared to LO and NLO pQCD
- theory describes data well!

Update to PRL 100, 102001 (2008)
Another way to access higher jet multiplicities:

- $\Delta\phi(Z, \text{leading jet})$, measured for the first time
- compared to pQCD and several event generators


See also:
PLB 669, 278 (2008)
PLB 678, 45 (2009)

$1^{st}$, $2^{nd}$, $3^{rd}$ jet $p_T$
$Z$ $p_T$ and rapidity ($\geq 1$ jet)
$1^{st}$ jet rapidity
$\Delta y(Z,jet)$
$y_{\text{boost}}(Z,jet)$
Much progress with Z+light flavour
- also need to understand heavy flavour
- THE low mass Higgs background!
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Heavy flavour tagging:
- based on many variables in a NN
- cut on discriminant output

Extract flavour fractions:
- fit templates to jet lifetime, vertex mass
- templates from MC (heavy flavour) data (light flavour).
- both experiments require $p_T > 20 \text{ GeV}$
CDF results, based on 2 fb\(^{-1}\):

- **W+b jets**: 2.74 ± 0.27 ± 0.42 pb
  - NLO: 1.22 ± 0.14 pb

- **Z+b / Z**: 0.332 ± 0.053 ± 0.042 %
  - NLO: 0.23% (0.28%)

- **Z+b / Z+jet**: 2.08 ± 0.33(stat) ± 0.34 (syst) %
  - NLO 1.8% (2.2%)

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**PRL** 104, 131801 (2010)
**PRD** 79:052008 (2009)
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New D0 result, using 4.2 fb⁻¹:

- electron and muon channels
- jet \(|\eta| < 2.5\) (1.5 for CDF)

- **Z+b/Z+jet**: \(1.93 \pm 0.22\text{ (stat)} \pm 0.15\text{ (syst)} \%\)
  - NLO: \(1.85 \pm 0.22\text{ \% (}Q^2 = m_Z^2\text{)}\)

Additional references:
- PRL 104, 131801 (2010)
- PRD 79:052008 (2009)
- PRD 83, 031105(R) (2011)
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**Previous results for photon + heavy flavour:**

- theory matches photon + b
- but underestimates photon + c

Probe strange PDF at high $Q^2 \sim M_W$

*Background* to top, Higgs, SUSY

**Strategy:**
- select high pT e, $\mu$ & soft lepton tagged jet
- for W+c, opposite sign (OS) > same sign (SS)
  - multijet, DY, W+bb/cc, OS~SS
- count N(OS) - N(SS)

**Good agreement between NLO & data:**

\[
\sigma_{W+c} \cdot BR = 9.8 \pm 2.8 \text{ (stat)} \pm 1.4 \text{ (syst)} \text{ pb}
\]

NLO pQCD: $11.0^{+1.4}_{-3.0}$ pb

New Preliminary result using soft-e tag:

\[
\sigma \times BR = 33.7 \pm 11.4 \text{ (stat)} \pm 4.7 \text{ (syst)} \text{ pb}
\]

NLO: $17.8 \pm 1.7$ pb

And analysis from D0:
- PLB 666, 23 (2008)
Also consistent with NLO.
Other New Results

Other new results in:
- diffractive W and Z production
- elastic scattering
- underlying event
- strangeness production in min-bias
... and many more published results
Jet results build on the precise JES:
- legacy measurements from the Tevatron
  - improving knowledge of PDFs
  - new measurement of $\alpha_s$
- will remain competitive for years to come

Boson (+ jet) production:
- excellent test of QCD predictions, essential for discoveries!
- extensive study of photons and Z+jets
- interesting new results on Z/W + heavy flavour

Analyses today used up to half of the Tevatron data set
- lots more to come from the Tevatron QCD programme!

http://www-cdf.fnal.gov/physics/new/qcd/QCD.html
http://www-d0.fnal.gov/Run2Physics/qcd/
Backup
The D0 RunII seeded, iterative, midpoint cone algorithm.

Run I algorithm:
- draw cone axis around seed (tower)
- split/merge after proto-jet finding
- recompute axis using $E_T$ weighted mean
- re-draw cone
- iterate until stable.

Algorithm sensitive to soft radiation:
- infra-red problem.

D0 Run II algorithm:
- add additional seeds between jets
- use 4-vectors instead of $E_T$
  - Jets characterised in terms of $p_T$ and $y$.

Improved infra-red stability

Algorithm available in fastjet v2.4
Gluon distribution at $Q^2 = 10^4$ GeV$^2$

- MSTW 2008 NLO (90% C.L.)
- MRST 2004 NLO
- CTEQ6.6 NLO

Fractional contributions:
- inclusive jets: Tevatron Run II
- $qq \rightarrow$ jets
- $gg \rightarrow$ jets

Ratio to MSTW 2008 NLO

Ratio to reference fit

CTEQ6.6
CT10

hep-ph:0901.0002
At the LHC:
- cross section vs $p_T$ obviously much larger

**BUT** cross section vs $x$ significantly smaller!  
e.g. for $|y| < 0.4$, factor of 200 at $x = 0.5$

D0 results with $0.7 \text{ fb}^{-1}$  
→ need $140 \text{ fb}^{-1}$ at LHC

Further, problem of steeply falling spectrum:  
at D0, 1% error on jet energy calibration
→ 5 - 10% error on central $\sigma$  
→10 - 25% error on forward $\sigma$

At LHC:
- need excellent jet energy scale  
- out to very high $p_T$

Expect Tevatron to dominate high-$x$ gluon PDF for some years!
Dominant Systematics:
- photon fraction at low p_T (5%)
- photon energy scale at high p_T (5-15%).

New CDF result (2.5 fb⁻¹)
- extends measured photon p_T range
- agreement within systematics
- shape features at low p_T seen at D0 and CDF
  - similar feature seen in Run I, UA2, ...

![Graph showing data and theory for inclusive photons with a legend indicating various uncertainties and fits.](image)
Investigate further: add a jet
- $p_T > 15$ GeV, $|\eta_{\text{jet}}| < 0.8$, $1.5 < |\eta_{\text{jet}}| < 2.5$

Triple differential:
- in jet $\eta$, photon $\eta$ and photon $p_T$

Something missing in the theory?
- higher orders, resummation, ..?
- LHC measurements will be very interesting!
Gluon splitting contribution
- dominates for high photon $p_T$
- important as background elsewhere

heavy flavour sea contribution
- dominates at low photon $p_T$
- LHC: larger contribution over all $p_T$
- charm PDF has significant uncertainties

CTEQ Up Quark PDF Uncertainties

CTEQ Charm Quark PDF Uncertainties

$\pm \frac{1}{2} \sqrt{\sum_{i=1}^{20} (\sigma_{(2i-1)} - \sigma_{(2i)})^2}$

$\pm \frac{1}{2} \sqrt{\sum_{i=1}^{20} (\sigma_{(2i-1)} - \sigma_{(2i)})^2}$

Ratio of central value to MRST
Similar analysis to photon + jet:
- $p_T^{\gamma} > 15$ GeV, $|\eta_{\gamma}| < 0.8$, $|\eta_j| < 1$

Systematics dominated by flavour fractions
- from template fit to jet lifetime probability

b-jet cross section well modeled

Deficit in c-jet at high $p_T^j$:
- region dominated by gluon splitting

Increased charm sea models:
- move in direction, but not enough

What will the LHC observe?
- more sensitive to heavy flavour sea
hadronization
parton distribution
parton distribution
Jet
Underlying event
Photon, W, Z etc.

Hard process
ISR
FSR
hadronization
Jet

p
p