Testing QCD at the LHC and the Implications of HERA

DIS 2004

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Jon Butterworth

- Impact of the LHC on QCD
- Impact of QCD (and HERA data) at the LHC
Impact of the LHC on QCD

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QCD will provide the beams, the background, the beauty... we had better understand it.
Impact of QCD at the LHC

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HERA is a precision QCD machine, as well as a QCD “discovery” machine. Data from HERA are needed to fully exploit the LHC.

The focus of this talk.
Areas of Impact

• Precision measurement of QCD inputs
  – $\alpha_s$: from jet rates, jet substructure, event shapes, PDF fits, fragmentation fits...
  – Parton distributions from structure functions, jets and charm.
  – Fragmentation parameters: strange, charm, beauty, leading particles.
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- Testing ground for non- or semi-perturbative models
  - Underlying events; minijets, multiparton interactions, saturation
  - Soft underlying events, rescattering, forward neutrons & protons.
  - Diffractive structure functions, gaps between jets, survival probability.
Areas of Impact

- Testing ground for calculational techniques
  - Very forward jets, low x.
  - Multijets, matrix element/parton showers.
  - Evaluation of theoretical uncertainties.
  - Beauty & charm production cross sections and dynamics.
  - DIS/photoproduction transition; multiscale QCD
  - “Intrinsic” transverse momentum, $k_T$ factorization
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Gain a *quantitative* understanding of hadronic production mechanisms at high energies.

Only time for a few examples.
Precision jet physics in a hadronic environment

Inclusive jet cross sections in \( \gamma \) (ZEUS (Phys Lett B 560 (2003))

Subjet multiplicity in CC DIS (ZEUS (Eur Phys Jour C 31 (2001))

Subjet multiplicity in NC DIS (ZEUS (Phys Lett B 558 (2003))

Jet shapes in NC DIS (ZEUS (DESY 04-xx))

NLO QCD fit (H1 (Eur Phys J C 21 (2001)) 33)

NLO QCD fit (ZEUS (Phys Rev D 67 (2003)) 0)

Inclusive jet cross sections in \( N \) (H1 (Eur Phys J C 19 (2001)) 28)

Inclusive jet cross sections in \( N \) (ZEUS (Phys Lett B 547 (2002))

Dijet cross sections in NC DIS (ZEUS (Phys Lett B 507 (2001))

World average (S. Bethke, hep-ex/0211012)
Parton Distributions in Proton

- HERA data drives the global fits.
Parton Distributions in Proton

- Small overlap with LHC region
- Use DGLAP to evolve up in $Q^2$
Parton Distributions in Proton

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- Use DGLAP to evolve up in $Q^2$
- LHC will be able to measure parton luminosities using $W$, $Z$ production
- Cannot do high $x$ at intermediate $Q^2$.
- Badly need high $x$ information from elsewhere.
PDFs versus new physics...

- Example: Absolute level and shape of cross sections approaching kinematic limit (new physics or just PDFs?)

Ferrag et al: Dijet cross section potential sensitivity to compactification scale of extra dimensions ($M_c$) reduced from $\sim 5$ TeV to 2 TeV.
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- Statistically limited at high $E_T = \text{high } x$
- Cross sections not optimised for sensitivity to high $x$ gluon.
- Can do much better with the rest of HERA I + HERA II
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500 pb$^{-1}$. C. Targett-Adams
Fragmentation Parameters

- e.g. Measure charm fragmentation function in hadronic events.
- Needed for beauty jet rates; minimise extrapolation uncertainties.
- Should be more precise after upgrade (CST, MVD).
- Should also be done for beauty.
- Also measured fragmentation fractions.
Testing Models and Calculational Techniques

- HERA as a 'hadron-hadron' collider
  - Almost on-shell photons come along with the electron beam & collide with protons.
  - These photons can fluctuate to acquire a hadron-like structure.

- HERA can look like a hadron-hadron machine (hadronic photon vs proton)
  - can also do "simpler" measurements with a pointlike photon (in Deep Inelastic Scattering or direct photoproduction).
HERA as a 'hadron-hadron' collider
Parton Showers & Matrix Elements

Matching of (N)NLO Matrix elements to parton showers is important for multijet final states at LHC (See Frixione, Monday: several presentations this week in HFS sessions)

W+jets, WW+jets, top+jets, Higgs+jets....Sophisticated topological cuts to identify signals at LHC.

How well do fixed-order matrix element programs and LL partons shower simulations do compared to current jet data?

ZEUS dijet cross section for hadronic photon events as a function of the leading jet transverse energy.
Data vs Herwig x 1.6.
Matrix Elements & Parton Showers

Dijet cross section defined in terms of highest $E_T$ jet and the rapidities of the two jets.

What happens when we vary the $E_T$ of the second jet?

Shape well modelled by HERWIG, not by fixed order NLO.
Three-Jet Cross Sections

Three-jet cross sections for $M_{jjj}>50$ GeV

Colour Coherence in initial & final state radiation.

Data vs Herwig.

NB: HERWIG normalisation factor of 1.6x, determined by the high $E_T$ dijet data. Parton showers do very well.
Four-jet cross sections

Photoproduction, jet transverse energy > 6 (5) GeV. No mass cut.

Four jet Mass > 50 GeV.
QCD (LO+PS) doing well.

No mass cut. Need something else.
Multiparton interaction models are favoured.
Why care about underlying events

- Inevitable property of hadronic collisions. Impact on jet energies and profiles, energy flow, isolation of photons...

- Natural consequence of eikonalisation of the parton model in high density PDF region. Related to saturation and total cross sections.
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- Responsible for diffractive factorisation breaking/gap survival probability

- Related to absorption/rescattering corrections to forward proton and neutron production.
Vector Boson Fusion at LHC

Commonly used minijet veto in WW events.

Great sensitivity to choice of underlying event model.
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Commonly used minijet veto in WW events.

Great sensitivity to choice of underlying event model.
Also determines 'survival probability' in diffractive events.
Double Pomereron Scattering as a Search Channel at LHC

- An area of increasing interest. Much phenomenological progress in the past year. Several talks in the diffractive sessions this week.
- Possibly the cleanest way see a low-mass Higgs at LHC. Other search channels also possible.
- Requires leading proton tagging, triggered with central detector
- Would also do some excellent diffractive QCD physics
- Predictions require a good understanding of diffractive processes, particularly diffractive PDFs and factorization breaking/ survival probabilities/ rescattering
What might we learn from HERA about underlying events

- Learn about energy dependence and target dependence of models by comparing $\gamma p$, $pp(\text{bar})$ and $\gamma\gamma$.
- Learn about proton PDFs at low $x$ -> input to multiparton interaction models.
- Look at behaviour of jet finding for the same kinematics but with & without an underlying event.
- Test models which predict both minimum bias & underlying event by studying tagged photoproduction.
- Look at forward neutron and proton rates in photoproduction vs DIS.
Four-jet cross sections

Same data: compare absolute cross sections.

HERWIG+JIMMY, as tuned to Tevatron data minimum bias data.

HERWIG default.

NB: Both these options give a decent fit to the high ET data.
Look at leading neutron rates

- Shown to be well described by pion exchange.
- Different rates of forward neutrons for different central events. Modelled by rescattering (absorption) of the neutron in the photon remnant.

Uncorrected rate – real rate is ~8%
Look at leading neutron rates

  - No hard scale; Dominated by hadronic photon;
    Rescattering similar to hadron-hadron (?)

- DIS (same paper):
  - Hard scale; Pointlike photon; No rescattering

- Charm Photoproduction (DESY 03-221):
  - Hard scale; Some hadronic photon, but suppressed
    w.r.t. Inclusive case. No rescattering (rate ~9+/-1%
    agrees with DIS, not inclusive photoproduction).
Look at leading neutron rates

  - Hard scale; can select between pointlike and hadronic photons.
  - Suggestive trend vs $x_{\gamma}$. 

![Graph showing ratio vs $x_{\gamma}$]
Look at leading neutron rates

- Dijet Photoproduction: H1 preliminary.
  - Hard scale; can select between pointlike and hadronic photons.
  - Suggestive trend vs $x_\gamma$.

- Compare with diffractive dijets- underlying event, survival probability.
Look at leading proton rates

- Dijet Photoproduction: H1, NLO from Klasen & Kramer
  - H1 vs NLO: Agreement if resolved scaled by factor 0.34 (from Kaidalov et al).
Look at leading proton rates

- Dijet Photoproduction:
  - H1 vs NLO: Agreement if resolved scaled by factor 0.34
  - ZEUS (LO PS) agreement without a separate scale factor for resolved (also true for H1 data!).
  - Can we understand what's going on?
Forward Jets and Low $x$

Back to vector boson fusion

Background rates and efficiencies critical. Also possible to use as a trigger at LHCb?

(E.Rodrigues, HERA-LHC wkshp)
Forward Jets and Low x

How well is the rate predicted?

Uncertainties blowing up at high rapidities.
How well is the rate predicted?

Uncertainties blowing up at high rapidities.

Not particularly a low $E_T$ effect.
Charm and Beauty Production

- How are heavy flavours produced in hadronic collisions?
  - Challenging multiscale problem in QCD (Transverse energy, Quark mass, Photon Virtuality).
  - Obviously important to understand these processes for LHC (b-tagging for searches)
Beauty Production

Example: Higgs or A production with bb pairs; H/A -> bb

(ATLAS TDR)
Beauty Production

\[ \frac{d\sigma}{d\eta^\mu}(e+e^{-}\rightarrow \mu^{+}\mu^{-}X) \]

\[ p_{T}^{\mu}>2.5 \text{ GeV} \]

- ZEUS 96-00
- H1 (prel.) 99-00
- NLO QCD x had
- NLO QCD
Beauty Production

See also: New DIS measurements this week from H1; CST
Summary

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  - hadroproduction of jets, photons, rapidity gaps.
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- Systematic efforts to make best use of this data are underway and should intensify.
  - http://www.desy.de/~heralhc/
  - (Thanks to speakers from the opening meeting)
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• Working out what we need to know from current colliders should be a priority for LHC physicists now, while new measurements can still be proposed.
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Parton density functions
Multijet final states and energy flow
Heavy quarks
Diffraction
Monte Carlo tools

Startup Meeting
March 26-27 2004
Midterm Meeting
11-13 October 2004
CERN, Geneva

Final Meeting
January 2005
DESY, Hamburg

www.desy.de/~heralhc
heralhc.workshop@cern.ch
Charm production dynamics

(a) \[ e^- + p \rightarrow c + \bar{c} \]

(b) \[ \gamma + p \rightarrow c + \bar{c} \]

ZEUS

- ZEUS (prel.) 1996-2000
- PYTHIA: \[ e^- p \rightarrow D^{*-} + \text{dijets} + X \]
- HERWIG: \[ M_{jj} > 18 \text{ GeV} ; |\eta| < 0.7 \]
- CASCADE: \[ x_{\gamma}^{\text{obs}} < 0.75 \]
- PYTHIA: Direct
- PYTHIA: Resolved

\[ I/\sigma (\text{all } x_{\gamma}^{\text{obs}}) d\sigma/d\cos(\Theta) \]

\[ \cos(\Theta) \]

JMB UCL

DIS04 17/04/04
Charm Photoproduction


PDFs versus new physics...

- Example: Absolute level and shape of cross sections approaching kinematic limit (new physics or just PDFs?)

S.Ferrag: Dijet cross section potential sensitivity to compactification scale of extra dimensions ($M_c$) reduced from ~5 TeV to 2 TeV.
Charm Production as a function of photon virtuality

• Charm + jets.

Suppression due to photon virtuality and suppression due to charm mass are not independent.

One example of many multiscale problems which have been or will be precisely studied.