Diffractive results at the Tevatron

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✓ Introduction
✓ Soft and hard diffraction
✓ Run II diffractive program
✓ Exclusive production (Higgs etc.)
Tevatron Collider

- Tevatron and detector upgrades
  - C.M. energy 1.96 TeV
  - 396 nsec bunch spacing
  - 600 pb⁻¹ delivered (as of Aug. 2004)

- high (low ?) inst. luminosity
  \[ L \sim 2-3 \times 10^{31} \text{ cm}^{-2}\text{sec}^{-1} \]

- multiple interactions

Michele Gallinaro - "Diffractive Physics at the Tevatron", Frascati 2004
Tevatron Experiments

- Peak luminosity
  - x2 increase since 2003
  - reached $L = 10^{32} \text{cm}^{-2}\text{s}^{-1}$
- Future
  - run until 2009
  - deliver 4-9 fb$^{-1}$

Over 200 pb$^{-1}$ more this year
Winter 2005 results,
~400 pb$^{-1}$

Summer 2004 results
~200 pb$^{-1}$
Hadronic Diffraction

Small transferred momentum

Elastic and diffractive processes: leading hadron emitted at small angle

Rapidity gap: the exchange ("pomeron") is colorless
Diffraction and Rapidity Gaps

- Rapidity gaps are regions of rapidity devoid of particles

Non-diffractive interactions:
- Rapidity gaps are formed by multiplicity fluctuations

From Poisson statistics:

\[ P(\Delta \eta) = e^{-\rho \Delta y} \left( \rho = \frac{dn}{dy} \right) \]

(\( \rho \) = particle density in rapidity space)

Gaps are exponentially suppressed

Diffractive interactions:
- Rapidity gaps survive unaltered

\[ \Delta y \approx \ln(1/\xi) = \ln s - \ln M^2 \]

- Large rapidity gaps are signatures for diffraction

\[ \frac{d\sigma}{dM^2} \sim \frac{1}{M^2} \rightarrow \frac{d\sigma}{d\Delta y} \sim \text{constant} \]
Energy flow in MB events

- Most particles are in the central region (|y|<3)

- All particles on average have the same $p_T$

However,
- Most of the energy is carried by a few forward particles
Energy flow in SD events

Diffractive events are “asymmetric”
Soft diffraction

unitarity problem

\[ \sigma_{SD} \sim S^{2\epsilon} \quad \sigma_T \sim S^{\epsilon} \]

\( \Rightarrow \sigma_{SD} \) exceeds \( \sigma_T \) at \( \sim 2 \) TeV

Renormalization
(normalize flux to 1)

\[ \frac{d^2 \sigma_{SD}}{dt d\xi} = f(t, \xi) \cdot \sigma(M_X^2) \]

\( \equiv 1 \)

K. Goulianos, PLB 358 (1995) 379

measurement is suppressed by a factor of \( \sim 10 \) to Regge theory and agrees with renormalization model

PRD 50 (1994) 5518, 5535, 5550
Diffraction in Run I

- Large rapidity gaps are signatures for diffraction

**Soft diffraction**

- Non-Diffractive (ND)
- Single-Diffractive (SD)
- Double Diffractive (DD)
- Double Pomeron Exchange (DPE)
- Single + Double Diffractive (SDD)

**Hard diffraction**

- Methods: large rapidity gaps or leading anti-proton tag
Detectors in Run I

CDF Detector

- Tag rapidity gaps
- Tag antiproton

Acceptance: $0 < |t| < 1$, $0.03 < \xi < 0.1$

Scintillator fiber xy-tracker
270 \( \mu \)m pitch, 2 m lever arm

Diagrams showing CDF detector components and acceptance regions.
Rapidity gaps

\[ \eta = 3.2 < \eta < 5.9 \]

\[ \eta = 2.4 < \eta < 4.2 \]

Rapidity gaps seen as zero multiplicity in both forward calorimeter and beam-beam counters.
Diffractive rates

\[ p\bar{p} \rightarrow X + \text{gap} \]

Measure SD/ND fractions at 1800 GeV

<table>
<thead>
<tr>
<th>process</th>
<th>fraction [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>W(eν)</td>
<td>1.15 (0.55)</td>
</tr>
<tr>
<td>Z</td>
<td>1.44 (0.60)</td>
</tr>
<tr>
<td>jet-jet</td>
<td>0.75 (0.10)</td>
</tr>
<tr>
<td>b</td>
<td>0.62 (0.25)</td>
</tr>
<tr>
<td>J/ψ</td>
<td>1.45 (0.25)</td>
</tr>
</tbody>
</table>

All SD/ND fractions ~ 1%
Different sensitivities to quark/gluon
\[ \Rightarrow \text{gluon fraction } f_g = 0.54 (0.15) \]
**Gap between jets**

\[ pp \rightarrow \text{jet} + \text{gap} + \text{jet} \]

**DD/ND fractions**

- 74 (1995) 855
- 80 (1998) 1156
- 81 (1998) 5278
- 72 (1994) 2332
- 76 (1996) 734
- PLB 440 (1998) 189

Extend range in Run II

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Multiple gaps

Determine gap survival probability experimentally in soft diffraction

Gap rates suppressed by:
jet radiation and non-pQCD

Measure the rate of additional gaps in soft diffractive events

\[ R^{2\text{-gap}} \frac{?}{R^{1\text{-gap}}} = R^{0\text{-gap}} \]
Gap survival

\[ S = R_{1\text{-gap}/0\text{-gap}}^{2\text{-gap}/1\text{-gap}} \]

- Survival probability

S(0.63 TeV) = 0.29
S(1.80 TeV) = 0.23

One-gap cross sections suppressed
Two-gap to one-gap ratios not suppressed

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Diffractive dijets

\( \xi \): fraction of anti-proton momentum loss
\( \beta \): fraction of pomeron momentum carried by parton

parton \( x_{Bj} \equiv \beta \cdot \xi \)

Measure SD/ND ratio of dijet rates

\[
\frac{\sigma (SD_{jj})}{\sigma (ND_{jj})} = \frac{F_{jj}^D(x)}{F_{jj}(x)}
\]

(LO QCD)

\[
R_{SD/ND} = R_0 \cdot x^{-0.45}
\]

\( \Rightarrow \) no significant \( \xi \) dependence

\[ \langle \xi \rangle = 0.04, 0.05, 0.06, 0.07, 0.08, 0.09 \]
\[ \Delta \xi = 0.01 \]

\[ E_T^{jet1,2} \geq 7 \text{ GeV} \]
\[ |t| \leq 1.0 \text{ GeV}^2 \]

stat errors only

\( x = 0.5 \times \xi_{\text{min}} \)

PRL 84 (2000) 5043
**Diffractive structure function**

CDF Run I result suppressed by factor of ~10 relative to HERA

⇒ breakdown of QCD factorization (renormalization removes s-dependence)

K. Goulianos, PLB 358 (1995) 379

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Michele Gallinaro - "Diffractive Physics at the Tevatron", Frascati 2004
Goals for Run II

- Diffractive structure function
  - $Q^2$ and $\xi$ dependence
  - Process dependence

- Exclusive production in DPE
  - Dijet, heavy flavor, low-mass

- Jet-Gap-Jet w/large gaps
New Detectors for Run II

- Tracking
  - Silicon
  - Central Outer Tracker
- Time of Flight
- Expanded Muon Coverage
- Endplug Calorimeter
- Forward Detectors
  - Beam Shower Counters
  - Miniplugs
  - Roman Pots (same as Run I)

All detectors are used in the diffractive program!
Run II diffractive program
Beam Shower Counters

Beam Loss vs time

$p$

$p\bar{p}$

BSC1

beam loss

beam rate

Rapidity gap trigger

BSC1+BSC2+BSC3(+BSC4)

rate vs inst. luminosity
MiniPlug Calorimeters

- liquid scintillator + lead
- flexible tower geometry
- full coverage (no dead regions)
- detect charged/neutral

Group fibers to form “towers”
Particles/jets in MP

One PMT channel

One MAPMT

One tower (3 PMT channels)

CDF Run II Preliminary

multiplicity

ND

SD

MP\_p Multiplicity

Events (ND norm to SD)

10^1

10^2

10^3

10^4

10^5

10^6

10^7

10^8

10^9

10^10

10^11

10^12

10^13

10^14

10^15

10^16

10^17

10^18

10^19

10^20

10^21

10^22

10^23

10^24

10^25
MP calibration

“Seed” and neighbor towers in $\phi$

“Seed” tower ADC counts

ADC counts vs $\phi$
before/after calib.

- use data for relative calib. of towers at same $\eta$
- use MC for relative calib. vs $\eta$ and overall energy scale
Roman Pot Spectrometer

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Roman Pot Trigger

Use 3-fold coincidence of RP trigger counters

Acceptance: \(0 < |t| < 2, \ 0.03 < \zeta < 0.1\)
Diffractive dijets

\[ \xi : \text{momentum loss fraction of pbar} \]

\[ \xi = \frac{\Sigma_{\text{all towers}} E_T e^{-\eta}}{\sqrt{s}} \]

Approx. flat at \( \xi < 0.1 \)

MP energy scale: \( \pm 25\% \rightarrow \Delta \log \xi = \pm 0.1 \)

RP acceptance (0.03 < \( \xi < 0.1 \)) ~ 80% (Run I)
Kinematic Properties

compare ND and SD
SD/ND ratio in Run II

ratio of SD/ND dijet event rates compared to Run I data

• slope and normalization agree with Run I result
• no $\xi$ dependence observed $0.03 < \xi < 0.1$
  $\Rightarrow$ confirms Run I results

no appreciable $Q^2$ dependence observed within $100 < Q^2 < 1,600 \text{ GeV}^2$

$\Rightarrow$ pomeron evolves similarly to proton
Roman Pot tracking

FIBER TRACKER

Reconstructed track
A bunch of fibers

True Track

Pot 3
Pot 2
Pot 1

\textbf{x} : measured hit position

0.255mm, (0.1 in)

0.8mm

: Scintillating fiber
(KURARAY SCSF81 single clad)

Expected position resolution 80 \mu m
Expected angle resolution 60 \mu rad

Run 175066, Event 517876
POT-X Fiber

POT-1 POT-2 POT-3

POT-Y Fiber

\xi = 0.059

POT-1 POT-2 POT-3
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ξ: RP vs calorimeter

ξ from RP

Overlap events

Signal region

ξ_cal distribution for slice of ξ_RP
DPE Dijet Production

from SD data:

SD: anti-proton side

SD: proton side

SD: anti-proton side

SD: proton side
DPE dijets

\[ R(\text{DPE/SD}) \approx 5 \times R(\text{SD/ND}) \]

\[ \Rightarrow \text{additional gap is not suppressed} \]
**Exclusive production in DPE**

**exclusive**

Khoze, Martin, Ryskin
Eur. Phys. J.
C23, 311 (2002)
C25, 391 (2002)
C26, 229 (2002)

C. Royon, hep-ph/0308283

**inclusive**

**Attractive Higgs discovery channel at the LHC**

$\overline{p}p \rightarrow pH\overline{p}$

Standard Model light Higgs:

- "exclusive" channel $\Rightarrow$ clean signal
- $M_H=\Delta M_{miss}= (s \xi_1 \xi_2)^{1/2}$
- $\sigma_H(\text{LHC}) \sim 3 \text{ fb, signal/background} \sim 3 \text{ (if } \Delta M_{miss} = 1 \text{ GeV)}$

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Exclusive production

Measurement of exclusive processes can be used to calibrate Higgs predictions

Exclusive dijets: $gg \rightarrow gg$
- exclusive $gg \rightarrow q\bar{q}$ is suppressed

Exclusive $\chi_C$:
- small cross section, clean signal
Exclusive Dijets in Run I

- antiproton tag: $0.035 < \xi < 0.095$
- 2 jets, $E_T > 7$ GeV
- proton-side gap ($2.4 < \eta < 5.9$)

⇒ observed 132 events

Mass fraction: $R_{jj} = \frac{M_{jj}}{M_x}$

⇒ $\sigma_{jj}$ (excl.) $< 3.7$ nb (95% CL)

theory expectns $\sim$ 1 nb (Run I kinematics)
DPE Enhanced Sample

- Use Run II dedicated DPE trigger (RP+J5+BSC_Gap_P)

Data presented from 26 pb$^{-1}$:

<table>
<thead>
<tr>
<th>Condition</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Triggers</td>
<td>397 k</td>
</tr>
<tr>
<td>$N_{\text{vertex}} \leq 1$, $</td>
<td>z_{\text{vertex}}</td>
</tr>
<tr>
<td>RP offline cut</td>
<td>309 k</td>
</tr>
<tr>
<td>$N_{\text{jets}} \geq 2$ ($E_T&gt;5$ GeV, $</td>
<td>\eta</td>
</tr>
<tr>
<td>$E_T(jeT2)&gt;10$ GeV</td>
<td>116,473</td>
</tr>
<tr>
<td>SD ($0.01&lt;\xi&lt;0.1$)</td>
<td>54,552</td>
</tr>
<tr>
<td>DPE (MP-East $N_{\text{hit}}=0$)</td>
<td>17,101</td>
</tr>
</tbody>
</table>
DPE: kinematics

Compare ND and SD and DPE
Dijet Mass Fraction

use dedicated DPE trigger (RP+J5+BSC_Gap_P)

rate falls smoothly as $R_{jj} \rightarrow 1$

no excess at large $R_{jj}$

independent of rapidity gap size

<table>
<thead>
<tr>
<th>Minimum $E_T$(Jet1)</th>
<th>Cross section ($R_{jj}&gt;0.8$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 GeV</td>
<td>$970 \pm 65$(stat) $\pm 272$(syst) pb</td>
</tr>
<tr>
<td>25 GeV</td>
<td>$34 \pm 5$(stat) $\pm 10$(syst) pb</td>
</tr>
</tbody>
</table>


~ 60 pb (factor of 2 uncertainty)

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Exclusive Dijet Events?

$R_{jj}=0.81$

$R_{jj}=0.36$
Prospects w/exclusive dijets

Experimental method:
- normalize $R_{jj}$ for all jets to $R_{jj}$ for $qq$
- look for excess of events at large $R_{jj}$

Pros:
- many systematics cancel out
- good HF quarks id
- small $g$ mistag $O(1\%)$

Cons:
- heavy quark mass
- contribution from exclusive b/c

Theory:
- $gg\rightarrow gg$ dominant contribution at LO
- $gg\rightarrow qq$ suppressed when $M_{jj}\gg m_q$

Difference between gluon and quark jet
- charged particle multiplicity in jet
  $N_{g\text{-jet}}=1.6 N_{q\text{-jet}}$ (from Run I)
- study how $N_{\text{jet}}$ behaves as $R_{jj}\rightarrow 1$
- sensitive to light quark jets
- $q/g$ jets are not well separated

P. Gallinaro - "Diffractive Physics at the Tevatron", Frascati 2004
Exclusive low-mass states

\[ p\bar{p} \rightarrow p\chi\bar{p} \rightarrow J/\psi \gamma \rightarrow \mu\mu\gamma \]

(same quantum numbers as Higgs boson)

Event selection:
- start from \( J/\psi \) sample
- exclusive events
- invariant mass (\( \mu\mu + EM \) tower)

Background:
- cosmics
- calorimeter noise
Event Selection

Data sample of 93 pb\(^{-1}\):

- BSC+MP veto: 107
- (calorimeter+CLC+trk+muon) veto: 23
- EM tower: 10

- Mass resolution is poor
- Bkg from multiplicity fluctuations (under threshold)
- Difficult to estimate noise contribution

Cross section upper limit for exclusive production:

\[ \sigma_{\text{excl}}(J/\psi+\gamma) = 49 \pm 18(\text{stat}) \pm 39(\text{syst}) \text{ pb} \]

\(~70\text{ pb}\)

Khoze, Martin, Ryskin, Stirling
Diffractive Higgs Production

Exclusive diffractive Higgs production $pp \rightarrow p\, H\, p$ : 3-10 fb
Inclusive diffractive Higgs production $pp \rightarrow p+X+H+Y+p$ : 50-200 fb

Advantages Exclusive:
- $J_z=0$ suppression of $gg\rightarrow bb$ background
- Mass measurement via missing mass

$M_H^2 = (p + \bar{p} - p' - \bar{p}')^2$

$\Delta M = O(1.0 - 2.0) \text{ GeV}$

Thanks to A. de Roeck: Tev4LHC, Sept 16-18, 2004

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Rapidity Gaps at LHC

Number of overlap events versus LHC luminosity
distribution of number of interactions
Doable at startup luminosity!

Benefit from experience of HERA/Tevatron experiments!!
Summary

Soft and hard diffraction
non suppressed two-gap to one-gap ratios

forward detectors working well
dedicated diffractive triggers

re-established Run I measurements
no significant \( Q^2 \) dependence in SD/ND ratio
no exclusive dijet/low-mass production