Recent Results from CDF on Soft QCD and Diffraction

Christina Mesropian
The Rockefeller University
What Happens when hadrons collide?
Proton-(anti)Proton Collisions

Elastic Scattering

\[ \begin{align*}
\text{p} & \quad \rightarrow \\
\text{t} & \quad \leftarrow
\end{align*} \]
Proton-(anti)Proton Collisions

Elastic Scattering

Single Diffraction

\[ M_X \]

\[ X (M_X) \]
Proton-(anti)Proton Collisions

Elastic Scattering

Single Diffraction

Double Diffraction

\[ M_X \]

\[ M_Y \]
Proton-(anti)Proton Collisions

Elastic Scattering

Single Diffraction

Double Diffraction

“Inelastic Non-Diffractive Component”

\[ M_x \]

\[ M_y \]
The Inelastic Non-Diffractive Cross-Section
The Inelastic Non-Diffractive Cross-Section

“Semi-hard” parton-parton collision ($p_T < \approx 2 \text{ GeV/c}$)
The Inelastic Non-Diffractive Cross-Section

"Semi-hard" parton-parton collision ($p_T < \approx 2 \text{ GeV/c}$)
The Inelastic Non-Diffractive Cross-Section

“Semi-hard” parton-parton collision ($p_T < \approx 2 \text{ GeV/c}$)

Multiple-parton interactions (MPI)
The Inelastic Non-Diffractive Cross-Section

Majority of “min-bias” events!

“Semi-hard” parton-parton collision ($p_T \approx 2$ GeV/c)

Multiple-parton interactions (MPI)
The Inelastic Non-Diffractive Cross-Section

Occasionally one of the parton-parton collisions is hard ($p_T > \approx 2$ GeV/c)

“Semi-hard” parton-parton collision ($p_T < \approx 2$ GeV/c)

Majority of “min-bias” events!

Multiple-parton interactions (MPI)
Proton-(anti)Proton Collisions

Elastic Scattering

Single Diffraction

Double Diffraction

\[ \sigma_{\text{Total}} = \sigma_{\text{EL}} + \sigma_{\text{SD}} + \sigma_{\text{DD}} + \sigma_{\text{ND}} \]

“Inelastic Non-Diffractive Component”

Non-Diffractive

Single Diffractive

Double Diffractive

Elastic Scattering
Proton-(anti)Proton Collisions

much harder to calculate this than this
Proton-(anti)Proton Collisions

Comparison of recent TOTEM results on the total cross section with several theoretical models.
Soft Processes

It’s complicated:

- data often ahead of phenomenology
- non-perturbative contributions important even for hard-scattering studies

*visualization of “minimum bias” event in pp √s=7 TeV collisions in PYTHIA8 with MCViz*
Dissecting Minimum-Bias

Inelastic, Non-Diffractive

slide from talk by Peter Scands at “MB & UE Workshop” at CERN, March 2010
Motivation

Why Study soft QCD:

Dominate strong interaction processes fundamental to our basic understanding of the Standard Model.

“Big” questions:

- confinement
- hadronic mass generation
- non-perturbative degrees of freedom
- strong coupling and super-Gravity...

Practical aspects:

- UE modeling at LHC
- Pile-up modeling at LHC
- Cosmic ray showers modeling
Tevatron $p\bar{p}$ Collider at FNAL
Tevatron $p\bar{p}$ Collider at FNAL

- Superconducting storage ring
  1 km radius, 1 beam-pipe
- Collisions 1985-2011
- Run II: Mar 2001-Sept 2011
- Produced $p\bar{p}$ collisions at 1.96 TeV
  - 36x36 bunches
  - $\sim$E10-E11 particles per bunch
The Collider Detector at Fermilab (CDF)

- Top performance (>85% data taking efficiency)
- ~10 fb\(^{-1}\) good for analysis data
Tevatron energy scan

Study s-dependence of high cross-sections physics
...mostly non-pQCD

1. Study of MB events:
2. Study of UE events
3. Gap-X Gap events
Tevatron energy scan - data

September 8 – 16, 2011
• 3x3 bunches
• Special trigger
• 1 interaction per crossing (no pile-up)

Total data taking time:
10 h at 300 GeV and 39 h at 900 GeV

<table>
<thead>
<tr>
<th>√s</th>
<th>0-bias</th>
<th>Minbias</th>
<th>Gap-X-Gap</th>
<th>Jets</th>
<th>e,μ,ν</th>
<th>Total # events</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>1.89 M</td>
<td>12.1 M</td>
<td>9.2 M</td>
<td>8.3 K</td>
<td>352</td>
<td>23.2 M</td>
</tr>
<tr>
<td>900</td>
<td>8.0 M</td>
<td>54.3 M</td>
<td>21.8 M</td>
<td>550 K</td>
<td>16 K</td>
<td>84.7 M</td>
</tr>
</tbody>
</table>
Definitions: MB and UE

Minimum Bias (MB) – is the name of trigger data sample is defined by trigger implementation

Underlying Event (UE) – is defined on event by event basis everything else except 2->2 hard scatter

MB is background to high luminosity pile-up events

UE is background to high $p_T$ observables (jets etc...)

11/27/2012

Christina Mesropian, SLAC Seminar
The Underlying Event

**Underlying Event** is

- Beam Beam Remnants (BBR)
- Final State Radiation (FSR)
- Initial State Radiation (ISR)
- Multi-Parton Interactions (MPI)

**Jet #1 or Z Boson Direction Leading $p_T$ Particle**

- $\Delta \phi$ relative to the leading calorimeter jet (or the Z-boson, or leading $p_T$ particle)
  - $|\Delta \phi| < 60^\circ$ as **Toward**
  - $60^\circ < |\Delta \phi| < 120^\circ$ as **Transverse**
  - $|\Delta \phi| > 120^\circ$ as **Away**

- TransMAX (MIN) - “Transverse” region with largest (smallest) number of charged particles

**Data corrected to the particle level:**

- Tracks $p_T > 0.5$ GeV/s; $|\eta|<1$
- Jets with $|\eta|<2$
- Drell-Yan: $ll = ee, \mu\mu$
- $p_T > 20$ GeV/c; $|\eta|<1$
- $70$ GeV/c$^2 < M_{\text{pair}} < 110$ GeV/c$^2$

---

Christina Mesropian, SLAC Seminar 25

PRD 65, 092002 (2002)
PRD 70, 072002 (2004)
PRD 82, 034001 (2010)
The Underlying Event

Underlying Event is
Beam Beam Remnants (BBR)
Final State Radiation (FSR)
Initial State Radiation (ISR)
Multi-Parton Interactions (MPI)

Different regions sensitive to different contributions:

- TransMIN – BBR+MPI
- TransMAX – BBR+MPI+ISR+FSR

Data corrected to the particle level:
Tracks $p_T > 0.5 \text{ GeV/s}; \ |\eta| < 1$
Jets with $|\eta| < 2$
Drell-Yan: $ll = ee, \mu\mu$
$p_T > 20 \text{ GeV/c}; \ |\eta| < 1$
$70 \text{ GeV/c}^2 < M_{\text{pair}} < 110 \text{ GeV/c}^2$
UE in Drell-Yan and incl. jet events

Event topologies:
- Leading Jet
- Drell-Yan

at high leading jet $p_T$ – “toward”-side and “away”-side jets

away side jet

no FSR!
exclude leptons “towards”=“Trans”
MB studies: MPI contributions

\[ \langle p_T \rangle \text{ vs charged particle multiplicity} \]

- A measure of the amount of \textbf{hard} vs \textbf{soft} processes contributing to minimum-bias collisions;
- Variable sensitive to simulation of multi parton interactions (MPI)

If only hard-scatter would contribute:

- Flat dependence if only soft beam remnants would contribute.
MB studies: MPI contributions

\(<p_T>\text{ vs charged particle multiplicity – a measure of the amount of hard vs soft processes contributing to minimum-bias collisions; variable sensitive to simulation of multi parton interactions (MPI)}\)

very similar behavior
use “Tevatron energy scan” data at 300 GeV, 900 GeV, 1960 GeV

studying charged particles ($p_T > 0.5$ GeV, $|\eta| < 0.8(1.0)$) produced in association with the leading charged particle $P_{T_{\text{max}}}$

good agreement with PYTHIA Tune Z1
Energy Dependence of MB

use “Tevatron energy scan” data at 300 GeV, 900 GeV, 1960 GeV

studying pseudo-rapidity distribution, \( dN/d\eta \), for charged particles (\( p_T > 0.5 \) GeV, \(|\eta| < 0.8(1.0)\))

\[
N_{chg} = \int_{-0.8}^{0.8} \frac{dN}{d\eta} d\eta
\]

![Pseudo-Rapidity Distribution: dN/d\(\eta\)](image)

CDF Preliminary

Corrected Data

1.96 TeV

300 GeV

900 GeV

At least 1 charged particle

Charged Particles (\(|\eta| < 0.8, p_T > 0.5 \text{ GeV/c}\))
Energy Dependence of MB

use “Tevatron energy scan” data at 300 GeV, 900 GeV, 1960 GeV

studying pseudo-rapidity distribution, \( dN/d\eta \), for charged particles (\( p_T > 0.5 \) GeV, \( |\eta| < 0.8(1.0) \))

\[
N_{chg} = \int_{-0.8}^{0.8} dN / d\eta \text{d}\eta
\]

Pseudo-Rapidity Distribution: \( dN/d\eta(\eta=0) \)

At least 1 charged particle
Charged Particles (\( |\eta| < 0.8, p_T > 0.5 \) GeV/c)
Energy Dependence of MB

use “Tevatron energy scan” data at 300 GeV, 900 GeV, 1960 GeV

studying pseudo-rapidity distribution, $dN/d\eta$, for charged particles ($p_T>0.5$ GeV, $|\eta|<0.8(1.0)$)

$$N_{chg} = \int_{-0.8}^{0.8} \frac{dN}{d\eta} d\eta$$

comparison of CDF and CMS points
Comparing MB and UE different √ s

**“Transverse” Charged Particle Density: dN/dηdφ**

- **MB**: overall charged particle density, dN/dη
- **UE**: “transverse” charged particle density, dN/dη

1. **900 GeV**
   - CDF Preliminary
   - Corrected Data
   - PTmax (GeV/c) from 0 to 25
   - Overall density

2. **300 GeV**
   - CDF Preliminary
   - Corrected Data
   - PTmax (GeV/c) from 0 to 14
   - Overall density

3. **1.96 TeV**
   - CDF Preliminary
   - Corrected Data
   - PTmax (GeV/c) from 0 to 35
   - Overall density

Christina Mesropian, SLAC Seminar
Comparing MB and UE different √'s

"Transverse" Charged Particle Density: dN/dηdφ

CDF Preliminary
Corrected Data

Overall density

900 GeV
Charged Particles (|η|<0.8, PT>0.5 GeV/c)

0.0 0.2 0.4 0.6
"Transverse" Charged Density
PTmax (GeV/c)

0 5 10 15 20

"Transverse" Charged Particle Density: dN/dηdφ

CDF Preliminary
Corrected Data

Overall density

1.96 TeV
Charged Particles (|η|<0.8, PT>0.5 GeV/c)

0.0 0.3 0.6 0.9
"Transverse" Charged Density
PTmax (GeV/c)

0 5 10 15 20

"Transverse" Charged Particle Density: dN/dηdφ

CDF Preliminary
Corrected Data

Overall density

300 GeV
Charged Particles (|η|<0.8, PT>0.5 GeV/c)

0.0 0.2 0.4 0.6
"Transverse" Charged Density
PTmax (GeV/c)

0 2 4 6 8 10 12

"Transverse" Charged Particle Density: dN/dηdφ

RDF Preliminary
Corrected Data

"Transverse" Charged Density

5 < PTmax < 6 GeV/c

CMS squares
CDF dots

UE

MB

Center-of-Mass Energy (TeV)

0.1 1.0 10.0

At least 1 charged particle
Charged Particles (|η|<0.8, PT>0.5 GeV/c)
Comparing MB and UE different √'s

"Transverse" Charged Particle Density: dN/dηdφ

CDF Preliminary
Corrected Data

Overall density

900 GeV
Charged Particles (|η|<0.8, PT>0.5 GeV/c)

0.0  0.2  0.4  0.6
"Transverse" Charged Density

PTmax (GeV/c)

1.96 TeV
Charged Particles (|η|<0.8, PT>0.5 GeV/c)

0.0  0.3  0.6  0.9
"Transverse" Charged Density

"Transverse" Charged Particle Density: dN/dηdφ

CDF Preliminary
Corrected Data

Overall density

300 GeV
Charged Particles (|η|<0.8, PT>0.5 GeV/c)

0.0  0.2  0.4
"Transverse" Charged Density

PTmax (GeV/c)

Charged Particle Density

RDF Preliminary
Corrected Data
Tune Z1 Generator Level

"Transverse" UE
5 < PTmax < 6 GeV/c

CMS squares
CDF dots

PYTHIA Tune Z1
At least 1 charged particle

Overall
Charged Particles (|η|<0.8, PT>0.5 GeV/c)

Center-of-Mass Energy (TeV)

plateau values
Definitions: Diffraction

- Diffractive reactions at hadron colliders are defined as reactions in which no quantum numbers are exchanged between colliding particles.

Identified by presence of:
- intact leading particle
- or
- large rapidity gap

Non-Diffractive (ND)

Single Diffraction (SD)

Double Diffraction (DD)

Double Pomeron Exchange (DPE)
Diffractive Processes

Hadronic processes can be characterized by an energy scale:

**soft processes** - energy scale of the order of the hadron size (~ 1 fm)  
pQCD is inadequate to describe these processes

**hard processes** – “hard” energy scale ( > 1 GeV^2 )  
can use pQCD,  
“factorization theorems” - can separate perturbative part  
from non-perturbative

Diffractive processes mostly belong to “soft processes”, however  
discovery of **hard diffraction** - jet production in ppbar collisions  
with a leading proton in the final state (1988 UA8)

**Hard diffractive processes allow to study diffraction in the pQCD framework.**

**At the Tevatron we study both soft and hard diffractive processes.**
Diffraction: definitions

\( y \) - rapidity
\( \eta \) - pseudorapidity
\[ y = \frac{1}{2} \ln \left( \frac{(E+p_z)}{(E-p_z)} \right) \]
\( \eta = y \mid_{m=0} = -\ln \tan(\vartheta/2) \)
\( t \) - four-momentum transfer squared
\( \xi \) - fractional momentum loss of pbar
\( M_X \) - mass of diffractive system X

\[ \xi = M_X^2 / s \]
\[ \Delta \eta \approx \ln(s/M_X^2) \]
 Definitions: Diffraction

Diffractive events at CDF are identified by presence of:

intact leading particle or large rapidity gap

---

**Diagram:**

- **CDF II**
- **DIPOLEs**
- **QUADs**
- **RPS**
- **BSC**
- **MPCAL**
- **CCAL**
- **PCAL**
- **CLC**

**Definitions:**

- **Diffraction**
- **RPS** – Roman Pot Spectrometers
- **BSC** – Beam Shower Counters
- **MPCAL** – MiniPlug Calorimeters

**Tracking System:**

- **Tracking**
- **Tracking Detectors**
  - $|\eta| < 2.0$
- **CCAL, PCAL**
  - Calorimeters
  - $|\eta| < 3.6$
- **RPS**
- **BSC**
- **MPCAL**

**Ranges:**

- **5.4 < $|\eta| < 7.4$**
- **3.5 < $|\eta| < 5.1$**
Forward Detectors at CDFII: Roman Pot Spectrometers (RPS)

Fiber Tracker
- 3 stations
- 57 meters from IP

- 3 trigger counters
- 240 channels

position resolution ±80µm

typical resolutions
in $\xi$ $\delta\xi = \pm 0.001$; in $t$ $\delta t = \pm 0.07$ GeV$^2$

Scintillator fiber xy-tracker
270 µm pitch, 2 m lever arm

Acceptance: $0 < |t| < 2, \ 0.03 < \xi < 0.1$

MIPs (>1000 counts)
Forward Detectors at CDFII: Beam Shower Counters (BSCs)

BSCs are located along beam pipe used for triggering events with forward rapidity gaps.
Forward Detectors at CDFII: MiniPlug Calorimeters (MPs)


designed to measure the energy and lateral position of both electromagnetic and hadronic showers “towerless” geometry – no dead regions
Methodologies were developed to get around the challenges:

Results are mostly MC free

\( \xi \) variable can be determined in two ways

\( \checkmark \) Determine \( \xi \) using Roman Pots tracking

\( \checkmark \) Also can determine \( \xi \) from \( E_T \) in calorimeters

**important to have MiniPlugs**

\( \xi^{\text{cal}} = \sum_{\text{towers}} \frac{E_T}{\sqrt{s}} e^{-\eta} \)

Main challenge: multiple interactions spoiling diffractive signatures

use \( \xi^{\text{cal}} < 0.1 \) to reject overlap events → non-diffractive contributions
Challenges and Methods: $\xi$ distributions

Flat part at $\xi < 0.1$

$$\frac{d\sigma}{d\xi} \sim \frac{1}{\xi} \to \frac{d\sigma}{d(\log \xi)} = \text{const}$$

Peak at $\xi = 1$
-overlap events from multiple interactions

MP calorimeters allow to separate diffractive and non-diffractive parts
Methods and Challenges:
\( \xi \) with RPS and calorimeter info

- Pile-up events
- Calibration of \( \xi \) from calorimeter with \( \xi \) from RPS
Hard Single Diffraction

Diffractive signature:
- large rapidity gap
- intact $p\bar{p}$ detected in RPS

Can study diffractive production of high $p_T$ objects: jets, $W$, $J/\Psi$, $b$

different insight into the nature of Pomeron

Method: measure ratio of diffractive to non-diffractive production
Hard Single Diffraction

Diffractive signature:
large rapidity gap –
slightly different
gap definitions

Fraction: R ≡ SD/ND ratio
@ 1800 GeV

<table>
<thead>
<tr>
<th>Hard component</th>
<th>Fraction (R) %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dijet</td>
<td>0.75 ± 0.10</td>
</tr>
<tr>
<td>W</td>
<td>1.15 ± 0.55</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 fractions ~ 1%
(differences due to kinematics)
➤ ~ uniform suppression

method used as a model for LHC analyses
Diffractive Structure Function

Diffractive dijet cross section

\[ \sigma(\bar{p}p \rightarrow \bar{p}X) \approx F_{jj} \otimes F_{jj}^D \otimes \hat{\sigma}(ab \rightarrow jj) \]

Study the diffractive structure function

\[ F_{jj}^D = F_{jj}^D(x, Q^2, t, \xi) \]

Experimentally determine diffractive structure function \( F_{jj}^D \)

at LO

\[ R_{SD \over ND}^{SD} (x, \xi) = \frac{\sigma (SD_{jj})}{\sigma (ND_{jj})} = \frac{F_{jj}^D(x, Q^2, \xi)}{F_{jj}(x, Q^2)} \]

\( F_{jj} \) from known PDF

\( \hat{\sigma} \) from CDF data

\( \xi \) is the momentum fraction of parton in pomeron

\( |t| < 1.0 \text{ GeV}^2 \) and \( (Q^2 = 75 \text{ GeV}^2) \)

0.035 < \( \xi < 0.095 \)
The Diffractive Structure Function

PRD 86, 032009 (2012)

\[ \sqrt{s} = 1.96 \text{ TeV} \]

same behavior for different \( \xi \) values

same behavior for different \( Q^2 \)
Kinematic Distributions for SD dijets

SD and ND dijets have similar $E_T$ distributions

SD dijets are shifted in $\eta$

The multiplicity distributions in MP

SD dijets are more back to back
Fit to double exponential function:
\[ \frac{d\sigma}{dt} \propto 0.9 e^{b_1 t} + 0.1 e^{b_2 t} \]

antiproton $|t|$ distribution

- no diffractive dips
- no $Q^2$ dependence
  in slope from inclusive to $Q^2 \sim 10^4$ GeV$^2$

PRD 86, 032009 (2012)
Search for diffraction minimum around $t$ of 2.5 GeV$^2$?
Diffractive $W/Z$ production probes the quark content of the Pomeron

- to Leading Order the $W/Z$ are produced by a quark in the Pomeron

- production by gluons is suppressed by a factor of $\alpha_s$ and can be distinguished by an associated jet
Identify diffractive events using Roman Pots:
accurate event-by-event $\xi$ measurement
no gap acceptance correction needed
can still calculate $\xi^{\text{cal}}$

$$\xi^{\text{cal}} = \sum_{\text{towers}} \frac{E_T}{\sqrt{s}} e^{-\eta}$$

In W production, the difference between $\xi^{\text{cal}}$ and $\xi^{\text{RP}}$ is related to missing $E_T$ and $\eta_\nu$

$$\xi^{\text{RP}} - \xi^{\text{cal}} = \frac{E_T}{\sqrt{s}} e^{-\eta_\nu}$$

allows to determine:
neutrino and W kinematics
$x_{\text{bj}}$

reconstructed
diffractive W mass

Phys. Rev. D 82, 112004, 2010
Diffractive W Production

\[ \xi_{\text{cal}} < \xi_{\text{RP}} \]

requirement removes most events with multiple p\overline{p}-p interactions

50 < M_W < 120 \text{ GeV/c}^2

requirement on the reconstructed W mass cleans up possible mis-reconstructed events

 Fraction of diffractive W

\[ R_W(0.03 < \xi < 0.10, \ |t| < 1) = [0.97 \pm 0.05(\text{stat}) \pm 0.10(\text{syst})] \%

consistent with Run I result, extrapolated to all \( \xi \)
Diffractive Z Production

Phys. Rev. D 82, 112004, 2010

37 diffractive $Z \rightarrow ee/\mu\mu$ candidates
(RP track, $\xi_{\text{cal}} < 0.1$)

estimate 11 overlap ND+SD background events based on ND $\xi_{\text{cal}}$ distribution

Fraction of diffractive Z
$R_Z (0.03 < \xi < 0.10, |t| < 1) = [0.85 \pm 0.20(\text{stat}) \pm 0.08(\text{syst})] \%$

37 diffractive $Z \rightarrow ee/\mu\mu$ candidates
(RP track, $\xi_{\text{cal}} < 0.1$)

estimate 11 overlap ND+SD background events based on ND $\xi_{\text{cal}}$ distribution

Fraction of diffractive Z
$R_Z (0.03 < \xi < 0.10, |t| < 1) = [0.85 \pm 0.20(\text{stat}) \pm 0.08(\text{syst})] \%$
W/Z Results

$R^W (0.03 < \xi < 0.10, |t|<1) = [0.97 \pm 0.05\text{(stat)} \pm 0.11\text{(syst)}]\%$

Run I: $R^W (\xi<0.1 ) = [1.15\pm0.55]\% \Rightarrow 0.97\pm0.47\%$ in $0.03 < \xi < 0.10 \& |t|<1$

$R^Z (0.03 < x < 0.10, |t|<1) = [0.85 \pm 0.20\text{(stat)} \pm 0.11\text{(syst)}]\%$

CDF/DØ Comparison – Run I ($\xi < 0.1$)

CDF PRL 78, 2698 (1997)
$R^w=[1.15\pm0.51\text{(stat)}\pm0.20\text{(syst)}]\%$
gap acceptance $A^\text{gap}=0.81$
Uncorrected for $A^\text{gap}$
$R^w=(0.93\pm0.44)\%$

$R^w=[5.1\pm0.51\text{(stat)}\pm0.20\text{(syst)}]\%$
gap acceptance $A^\text{gap}=(0.21\pm4)\%$
Uncorrected for $A^\text{gap}$
$R^w=(0.93\pm0.44)\%$

$R^w=[0.89+0.19-0.17 ]\%$
$R^Z=[1.44+0.61-0.52 ]\%$

This analysis is a good example of agreement between RPS and large rapidity gap identification methods
Exclusive Production

At the Tevatron we use similar processes with larger cross sections to test and calibrate theoretical predictions.

- At the Tevatron we use similar processes with larger cross sections to test and calibrate theoretical predictions.

Suppression at LO of the background sub-processes (J_z=0 selection rule) → “exclusive channel” → clean signal (no underlying event)

- LHC

- CDF

Dijets,

γγ,

χ_c
Observation of Excl. Dijet Production

Reconstruct $R_{jj} = \frac{M_{jj}}{M_X}$, where $M_{jj}$ mass of dijet system, $M_X$ – mass of system $X$

Observe excess over inclusive DPE dijet MC’s at high dijet mass fraction

Signal at $R_{jj}=1$ is smeared due to shower/hadronization effects, NLO $gg\rightarrow ggg,qqg$ contributions

PRD 77, 052004 (2008)
Calculation by KMR is consistent within its factor of 3 uncertainty. 

$d\sigma_{jj}^{\text{excl}}$ vs Dijet Mass

derived from CDF excl. dijet x-sections using ExHuME

- Stat. and syst. errors are propagated from measured cross section uncertainties using $M_{jj}$ distribution shapes of ExHuME generated data.
Exclusive Dimuon Production

\[ \bar{p} + p \rightarrow \bar{p} + \mu^+ \mu^- + p \]

3 GeV/c^2 < M_{\mu\mu} < 4 GeV/c^2

Many Physics Processes in this data:

- Observation of exclusive $\chi_c$ in DPE
- $\gamma + IP \rightarrow J/\psi \rightarrow \mu^+ \mu^-$
- $IP + IP \rightarrow \chi_c \rightarrow (J/\psi + \gamma)$

• Observation of exclusive $\chi_c$ PRL 102 242001 (2009)
Exclusive dimuon production

\[ p + \bar{p} \rightarrow p + \mu^+ \mu^- + \bar{p} \]

\[ 3 \text{ GeV/c}^2 < M_{\mu\mu} < 4 \text{ GeV/c}^2 \]

Trigger:

muon + track + forward rapidity gaps in BSCs

2 oppositely charged muon tracks with \( p_T > 1.4 \text{ GeV/c}, \ |\eta| < 0.6 \)

\[ \epsilon_{\text{excl}} \sim 0.093 \Rightarrow L = 1.48 \text{ fb}^{-1} \text{ but } L_{\text{eff}} \sim 140 \text{ pb}^{-1} \]
Exclusive J/ψ and ψ(2s)

J/ψ production
243 ± 21 events
\( \frac{d\sigma}{dy}|_{y=0} = 3.92 \pm 0.62 \text{ nb} \)

Theoretical Predictions
2.8 nb [Szczurek07,],
2.7 nb [Klein&Nystrand04],
3.0 nb [Conclaves&Machado05], and
3.4 nb [Motkya&Watt08].

Ψ(2s) production
34±7 events
\( \frac{d\sigma}{dy}|_{y=0} = 0.54 \pm 0.15 \text{ nb} \)
R = ψ(2s)/J/ψ = 0.14 ± 0.05
In agreement with HERA:
R = 0.166 ± 0.012 in a similar kinematic region
Exclusive $\chi_c \rightarrow J/\psi (\rightarrow \mu^+\mu^-) + \gamma$

- Allowing EM towers ($E_T > 80\text{MeV}$) large increase in the $J/\psi$ peak
- Minor change in the $\psi(2s)$ peak

Evidence for $\chi_c \rightarrow J/\psi + \gamma$ production

$\frac{d\sigma}{dy}\big|_{y=0} = 75 \pm 14 \text{ nb}$, compatible with theoretical predictions
- 160 nb (Yuan 01)
- 90 nb (KMR01)
Exclusive $\gamma\gamma$ Production

Requirements: no other particles in the detectors up to $|\eta| < 7.4$

Study noise level by looking at “zero-bias” events:
- “no interaction” class of events
- “interaction” class of events

3 candidates observed, limit set

more data!
adjusted triggers

Exclusive $\gamma\gamma$ Production

Use control sample to understand

$$p + \bar{p} \rightarrow p + e^+e^- + \bar{p} \text{ via } \gamma + \gamma (QED)$$

$$\sigma_{|\eta|<1, E_T>2.5 GeV e^+e^- \text{ excl.}} = 2.88 \pm 0.59 \text{(stat)} \pm 0.62 \text{(sys)} \text{ pb}$$

$$\sigma_{L_{\text{Pair}}} = 3.25 \pm 0.07 \text{ pb}$$

$$\sigma_{|\eta|<1, E_T>5.0 GeV e^+e^- \text{ excl.}} = 0.60 \pm 0.28 \text{(stat)} \pm 0.14 \text{(sys)} \text{ pb}$$

$$\sigma_{I_{\text{Pair}}} = 0.58 \pm 0.003 \text{ pb}$$

Kinematic distributions of photon pair
Observed 43 events >> 5 $\sigma$

$\sigma_{\gamma\gamma_{\text{excl}}} = 2.48 \pm 0.42 \text{(stat)} \pm 0.41 \text{(sys)} \text{ pb}$

Good agreement with the theoretical predictions

*PRL 108, 081801 (2012)*
Conclusions

• We have very extensive program of soft QCD and diffractive studies at the Tevatron – new forward detectors R&D, new methodologies developed, many pioneering measurements performed.

• Working on datasets collected at $\sqrt{s}=300$ and 900 GeV – some results in the process to be published, more in the pipeline

*not shown here – studies of DPS, exclusive studies in Gap – X – Gap at different $\sqrt{s}$
Conclusions

So what is in the future for soft and diffractive studies at the LHC and beyond?

• already have new types of data – wide variety of variables for non-diffractive studies,
• more activity in developing MC tools,
  ✓ reliable MC simulations are essential
  ✓ new types of measurements
  ✓ new methods for identification of diffractive events
Ref: Papers on diffraction at CDF

**Soft Diffraction**

**Double Pomeron Exc.**
PRL 93, 141603 (2004)

**Multi-Gap Diffraction**

**Single Diffraction**
PRD 50, 5355 (1994)

**Double Diffraction**
PRL 87, 141802 (2001)

---

**Hard Diffraction**

**Dijets:**
- 1.8 TeV PRL 85, 4217 (2000)
- 1.96 TeV PRD 77, 052004 (2008)

**Di-photons**
- 1.96 TeV PRL 99, 242002 (2007)
- 1.96 TeV PRL 108, 081801 (2012)

**Charmonium**
- 1.96 TeV PRL 102, 242001 (2009)

**Rapidity Gap Tag**
- W: PRL 78, 2696 (1997)
- J/ψ: PRL 87, 241802 (2001)

**Roman Pot Tag**

**Dijets:**
- 1.96 TeV PRD 86, 032009 (2012)
- 1.8 TeV PRL 84, 5043 (2000)

**W/Z:**
- 1.96 TeV PRD 82, 112004 (2010)

**Jet-Gap-Jet**

- 1.8 TeV PRL 74, 855 (1995)
- 1.8 TeV PRL 80, 1156 (1998)
- 630 GeV PRL 81, 5278 (1998)
Elastic Scattering

- The particles after scattering are the same as the incident particles.
  \[ \xi = \Delta p / p = 0 \] for elastic events; \[ t = -(p_i - p_f)^2 \]

- The cross section can be written as:

\[
\frac{d\sigma}{dt} = e^{bt} \approx 1 - b(p\theta)^2
\]

<table>
<thead>
<tr>
<th>( \sqrt{s} )</th>
<th>Exp.</th>
<th>( t )-range [GeV(^2)]</th>
<th>( B [\text{GeV}^{-2}] ), ( \rho )</th>
</tr>
</thead>
<tbody>
<tr>
<td>546 GeV</td>
<td>CDF</td>
<td>0.025 ( \div ) 0.08</td>
<td>( B = 15.28 \pm 0.58 )</td>
</tr>
<tr>
<td>1.8 TeV</td>
<td>CDF</td>
<td>0.04 ( \div ) 0.29</td>
<td>( B = 16.98 \pm 0.25 )</td>
</tr>
<tr>
<td>E710</td>
<td>0.034 ( \div ) 0.65</td>
<td>( B = 16.3 \pm 0.3 )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.001 ( \div ) 0.14</td>
<td>( B = 16.99 \pm 0.25 )</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>( \rho = 0.140 \pm 0.069 )</td>
<td></td>
</tr>
<tr>
<td>E811</td>
<td>0.002 ( \div ) 0.035</td>
<td>using ( \langle B \rangle_{\text{CDF,E710}} )</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>( \rho = 0.132 \pm 0.056 )</td>
<td></td>
</tr>
<tr>
<td>1.96 TeV</td>
<td>DØ</td>
<td>0.9 ( \div ) 1.35</td>
<td>-</td>
</tr>
</tbody>
</table>

![Fig. from TOTEM publications](image)
Event topologies:

- Leading Jet
- Drell-Yan

**Drell-Yan:**
less gluon radiation, easier to reconstruct

\[ l\bar{l} = e^+e^-, \mu^+\mu^- \]

\[ p_T > 20 \text{ GeV/c} \]

\[ |\eta| < 1 \]

70 GeV/c^2 < M_{\text{pair}} < 110 GeV/c^2

\[ |\eta(\text{pair})| < 6 \]

**Transverse Region**

**The Drell-Yan Process**
Dynamic alignment of the RPS

Method: iteratively adjust the RPS X and Y offsets from the nominal beam axis until a maximum in the b-slope is obtained at $t=0$. 

![Graphs showing dynamic alignment](image)
Background evaluation

schematic view of fiber tracker

- tracker’s upper edge: $|t| = 2.3 \, (\text{GeV/c})^2$
- the lower edge is at $|t| = 6.5 \, (\text{GeV/c})^2$ (not shown)
- background level: region of $Y_{\text{track}} > Y_0$ data for $|t| > 2.3 \, (\text{GeV/c})^2$

PRD 86, 032009 (2012)
Proton-(anti)Proton Collisions

Elastic Scattering

\[ t - \text{four-momentum transfer squared} \]

\[ \text{usually } t << 1 \text{ GeV}^2 \]

for fixed \( s \):

\[ \frac{d\sigma}{dt} = \left. \frac{d\sigma}{dt} \right|_{t=0} e^{-B|t|} \]

- \( B \), slope parameter
- "measures" size of interaction region

\[ B = 19.9 \text{ GeV}^2 \]

Statistical uncertainties
Systematic uncertainties
To be published

\[ |t|_{\text{min}} = 0.53 \text{ GeV}^2 \]