Multiple Parton Interaction Studies at DØ

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Big ideas and history

Double Parton interactions in $\gamma\gamma + \text{dijet}$

Double Parton interaction in $J/\psi + \Upsilon$ events

Summary / interpretation
Hadron-Hadron collision: simplified

proton

high $p_T$

anti-proton

hard interaction

outgoing parton(s) (quark, gluon, $\gamma$, $Z^0$, $W^\pm$)
Hadron-Hadron collision: traditional

hadronization, fragmentation

proton

anti-proton

outgoing parton(s)

Hard radiation

outgoing parton(s)
Hadron-Hadron Collision: Double parton interactions

Double parton interactions

proton

anti-proton

outgoing parton(s)

outgoing parton(s)

Signal is not too messy
Historical data #1

Charged particle multiplicity

Hard scattering only; +ISR/FSR

\[ \sigma_n \] is a cross section to produce a final state with \( n \) tracks (Nch).

UA5, 540 GeV, ppbar

Multiple Parton Interaction models

Hadronization based on single hard scattering does not work!

Only additional parton interactions can describe the shape.
Jet pedestal effect

ET density distribution inside and around jet can only be described if MPI contribution is taken into account.

ET density and charge particle multiplicities allowed T. Sjostrand and M. van Zijl to build first real, software-implemented MPI model (aka “Tune A”) and describe many “puzzling features” in jet productions in UA1-UA5: PRD36 (1987) 2019
Motivation

Most MPI processes are non-perturbative implemented in models of hadron structure and fragmentation.

Being phenomenological, experimental input crucial. [mainly minbias]
Tevatron (0.63, 1.8, 1.96 TeV; + recent 0.3, 0.9 runs)
SPS (0.2, 0.54, 0.9 TeV),
LHC (7 & 8 TeV data)
Tevatron DY and similar LHC data.

MPI can be tested in higher pT regime [e.g. pT(jet) > 15 GeV]

In the energy regime of perturbative QCD!
MPI events can mimic a signature of a new physics processes

Having measured MPI observable and reliably calculable partonic cross section, one can limit MPI phenomenological models.
Double Parton events: Higgs production background

Many Higgs production channels can be mimicked by a Double Parton event!
Same is true for many other rare (especially multijet) processes
\[ \sigma_{DP} \] - double parton cross section for processes A and B

\[ \sigma_{eff} \] - characterizes size of effective interaction region

\[ \rightarrow \] information on the spatial distribution of partons.

Uniform: \( \sigma_{eff} \) is large and \( \sigma_{DP} \) is small

Compact: \( \sigma_{eff} \) is small and \( \sigma_{DP} \) is large

\[ \rightarrow \] \( \sigma_{eff} \) is phenomenological parameter

\[ \Rightarrow \] should be measured in experiment!

Effective cross section \( \sigma_{eff} \) is directly related with parton spatial density:

\[ \sigma_{eff} = \left[ \int d^2 \beta [F(\beta)]^2 \right]^{-1} \]

\[ F(\beta) = \int f(b)f(1-b)d^2b \]

\( \beta \) is impact parameter
Double Parton Interactions in $\gamma\gamma +$ dijet events:

- Extraction of DP events
- Measurement of effective cross section

Basic approach:
- Determine photon purity
- Determine photon + jet acceptance
- Determine double parton fractions

Count events, divide by luminosity
- Calculate DP cross-section
- Calculate $\sigma_{\text{eff}}$
- The usual.

Kinematic cuts:

Diphotons
- $P_{T\gamma 1} > 16$ GeV, $P_{T\gamma 2} > 15$ GeV
- $|y| < 1.0$

Dijets
- $15 < P_{T\text{jet}} < 40$ GeV
- $|y| < 3.5$

Number events
- $N_{1\text{vtx}} = 401$
- $N_{2\text{vtx}} = 442$
Double Parton Interactions in $\gamma \gamma +$ dijet events:

- Double parton origins

Note that the jet cross section is dominated by $gg \rightarrow gg$ in this kinematic regime.

New!!!
Double Parton Interactions in $\gamma \gamma +$ dijet events:

- Double parton origins

For two hard interactions:
- at one pp collision (Double Parton scattering):
  \[ P_{DP} = \left( \frac{\sigma_{\gamma\gamma}}{\sigma_{\text{hard}}} \right) \left( \frac{\sigma_{jj}}{\sigma_{\text{eff}}} \right) \]

For two hard scattering events:
- at two separate pp collisions (Double Interaction):
  \[ P_{DI} = 2 \left( \frac{\sigma_{\gamma\gamma}}{\sigma_{\text{hard}}} \right) \left( \frac{\sigma_{jj}}{\sigma_{\text{hard}}} \right) \]

Same approach as in 1fb$^{-1}$ measurement, PRD81, 052012 (2010)

arXiv:XXXXX
Double Parton Interactions in $\gamma \gamma +$ dijet events:

$N_{DP} = P_{DP} \times N_{1\text{int}} = \left( \frac{\sigma_{\gamma\gamma}}{\sigma_{\text{hard}}} \right) \left( \frac{\sigma_{jj}}{\sigma_{\text{eff}}} \right) N_{1\text{col}} A_{DP} \epsilon_{DP} \epsilon_{1vtx}$

$N_{DI} = P_{DI} \times N_{2\text{int}} = 2 \left( \frac{\sigma_{\gamma\gamma}}{\sigma_{\text{hard}}} \right) \left( \frac{\sigma_{jj}}{\sigma_{\text{hard}}} \right) N_{2\text{col}} A_{DI} \epsilon_{DI} \epsilon_{2vtx}$

$\sigma_{\text{eff}} = \frac{1}{2} \frac{N_{DI}}{N_{DP}} \frac{A_{DP}}{A_{DI}} \frac{\epsilon_{DP}}{\epsilon_{DI}} \frac{\epsilon_{1vtx}}{\epsilon_{2vtx}} \frac{N_{1\text{col}}}{N_{2\text{col}}} \sigma_{\text{hard}}$

Note that
(a) all variables are experimentally derived; or
(b) all variables are in ratios that greatly reduce systematic uncertainties

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Double Parton Interactions in $\gamma \gamma +$ dijet events:

\[
\begin{align*}
\frac{\epsilon_{1\nu tx}}{\epsilon_{2\nu tx}} & \quad 1.021 \pm 0.005 \text{ Determined in data} \\
\frac{A_{DP}}{A_{DI}} & \quad 0.521 \pm 0.015 \text{ Determined in MC [Pythia and Sherpa].} \\
& \quad \text{Difference in acceptance due to variation of energy in jet and photon cones, which vary the chance to pass $p_T$ and $\eta$ cuts.} \\
\frac{\epsilon_{DP}}{\epsilon_{DI}} & \quad 1.372 \pm 0.039 \text{ Determined in MC [Pythia and Sherpa].} \\
& \quad \text{Difference in acceptance due to variation of energy near photons, which affects photon isolation.}
\end{align*}
\]

Note that
(a) all variables are experimentally derived; or
(b) all variables are in ratios that greatly reduce systematic uncertainties.

arXiv:XXXXXX
$N_{DP}$: Single Parton vs Double Parton: $\Delta S$ distribution

DP events have two uncorrelated scattering centers. $\Delta S$ should be flat.

For SP events, $\Delta S$ should peak at $\pi$.

$$\Delta S = \Delta \phi(p_T^\gamma, p_T^{jet,jet})$$

In single vertex events, can use $\Delta S$ distribution to fit to $DS$ determine $N_{DP} = 401 \times f_{DP}$

arXiv:XXXX
$N_{DI}$: Number of Double Interaction Events: Vertex pointing

$\gamma \gamma$ + dijet events must come from two vertices, one with diphoton and one with dijets.

Look at events with two vertices and use tracks associated with jets to determine their vertex of origin.

$N_{DI} = 442 \times f_{DI}$
Number of one and two vertex collisions

Determined by world average Tevatron

\[ \sigma_{\text{hard}} = 44.76 \pm 2.89 \text{ mb} \]

The number of events with one and two collisions determined by integrating \( \sigma_{\text{hard}} \) and the known instantaneous luminosity profiles, plus Poissonian statistics.

\[ \frac{1}{2} \frac{N_{1\text{col}}}{N_{2\text{col}}} \sigma_{\text{hard}} = 18.92 \pm 0.49 \text{ mb} \]
Effective cross section

- Having measured number of DP events and corresponding acceptances and efficiencies one can calculate $\sigma_{\text{eff}}$.

- Measured $\sigma_{\text{eff}}$ is in agreement with all Tevatron and LHC measurements.

### Possible initial state dependence?

| $\sigma_{\text{eff}}$ (mb) | $\gamma\gamma + 2 \text{ jet}$ |
|---------------------------|-------------------------------|
| $21.3 \pm 1.5$ (stat) $\pm 4.5$ (syst) |

DP Fraction $0.193 \pm 0.037$

arXiv:XXXXXX
Double Parton Interactions in $J/\psi + \Upsilon$ production

- Almost 100% DP
  - 97% [Estimated: arXiv:1504.06531]

- If highly-DP, excellent laboratory in which to study the phenomenon.

- However, dominantly gluonic initial state.

- Study only $J/\psi + \Upsilon \rightarrow \mu^+\mu^-$
Data selection

- $L = 8.1 \text{ fb}^{-1}$ statistics

- Logical OR of low $p_T$ unprescaled di-muon triggers

- $p_T(\mu) > 2 \text{ GeV}$ if $|\eta| < 2$
  - exclude muons having hits just outside of toroid
  - veto cosmic muons by timing cut

- muon track segment is matched to the central tracker

- track with at least 3 hits

- opposite charge $\mu$

- $r$-DCA (transverse distance of closest approach of the track to the primary vertex point) $< 0.5 \text{ cm}$; $z$-DCA $< 2 \text{ cm}$

- Muon pair is in
  - $2.88 < M_{\mu\mu} < 3.32 \text{ GeV}$
  - $9.1 < M_{\mu\mu} < 10.2 \text{ GeV}$

- 21 events
Results

\[ D\phi, L = 8.1 \text{ fb}^{-1} \]

\[ \text{2D fit. } J/\psi + \Upsilon(1S, 2S, 3S) \]

\[ N_{\text{sig}} = 14.5 \pm 4.6 \text{ (stat)} \pm 3.4 \text{ (syst)} \]

\[ \text{P(accidental) } = 2.5 \times 10^{-4} \]

(3.5 \sigma)
Studies of MPI events are important → lead to a knowledge of fundamental hadron structure.

Provide a better description of complex final states in hadron-hadron collisions.

Double parton production in $\gamma \gamma + \text{2-jet}$ final states using ($L = 8.1 \text{ fb}^{-1}$):

|                      | $\gamma \gamma + \text{dijet}$ |
|----------------------|---------------------------------|
| Fraction DP events   | 0.193 ± 0.037                   |
| $\sigma_{\text{eff}}$ (mb) | 21.3 ± 1.5 (stat) ± 4.5 (syst) |

We have also studied production of $J/\psi + \Upsilon$ production and found that

|                      | $J/\psi + \Upsilon$ |
|----------------------|----------------------|
| Evidence for $J/\psi + \Upsilon$ | 3.5 $\sigma$ |

A simple study in $\Delta \phi(J/\psi, \Upsilon)$ supports DP-dominance claim.

Studies of the $J/\psi + \Upsilon$ final state are ongoing. Should be available soon, including $\sigma_{\text{eff}}$. 
D0 detector

- Tracking in magnetic field of 2T:
  - Silicon microstrip and central fiber tracker
  - Calorimeter: Liquid argon sampling calorimeter
    - Central and Endcap, coverage: |η|<4.2
  - Muon system: Drift chambers and scintillation counters; 1.8 T toroid
    Wide muon system coverage (|η|<2); thick shielding suppresses background.