STUDIES OF MULTI-PARTON INTERACTIONS IN PHOTON+JETS EVENTS AT DØ

Dmitry Bandurin

Florida State University

DPF 2011, August 12, Brown University
Outline

- Motivations
- Event topology
- Discriminating variables
- Fraction of the events with Double Parton interactions
- Effective cross-section measurement
- Comparison/tuning to MPI models
- Summary
Motivations

- Most of the processes that cause MPI production are non-perturbative and implemented in some phenomenological models of a hadron structure and parton-to-hadron fragmentation.
  
  \( \Rightarrow \) Being phenomenological, the models strongly need experimental inputs.

- The provided experimental inputs have been based so far mainly on the minbias Tevatron (0.63, 1.8, 1.96 TeV), SPS (0.2, 0.54, 0.9 TeV) and Tevatron DY data.

- However, there is a quite small amount of tests of MPI events in high pT regime, specifically with events having jet pT > 15 GeV,
  
  \( \Rightarrow \) i.e. right in the region used in many measurements (e.g. top-quark mass) and most important for searches of rare processes, especially with multi-jet final state.

  \( \Rightarrow \) MPI events can mimic a signature of a new physics processes and thus be a significant background to them.
Double Parton events as a background to Higgs production


- Many Higgs production channels can be mimicked by Double Parton events!
- Some of them can be significant even after signal selections.
- Dedicated cuts are required to increase sensitivity to the Higgs signal (same is true for many other rare processes)!
Double parton and effective cross sections

\[ \sigma_{DP} = \frac{\sigma_A \sigma_B}{\sigma_{eff}} \]

- \( \sigma_{DP} \) - double parton cross section for processes A and B
- \( \sigma_{eff} \) - factor characterizing a size of effective interaction region

→ can be directly related to the spatial distribution of partons \( f(b) \).
  
  Uniform: \( \sigma_{eff} \) is large and \( \sigma_{DP} \) is small
  Clumpy: \( \sigma_{eff} \) is small and \( \sigma_{DP} \) is large

=> Having \( \sigma_{eff} \) measured we can estimate \( f(b) \)

→ **Should be measured in experiment !!**
  Just 4 measurements existed up to recent time: AFS, UA2, 2 CDF [Run 1]
AFS'86, UA2'91 and CDF'93
4-jet samples, motivated by a large dijet cross section (but low DP fractions)

CDF’97, D0’10
γ+3jets events, data-driven method: use rates of Double Interaction (two separate ppbar collisions) and Double Parton (single ppbar collision) to extract $\sigma_{eff}$ from their ratio.
=> reduces dependence on Monte-Carlo and NLO QCD theory predictions.

---

**History of the measurements**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$\sqrt{s}$ (GeV)</th>
<th>Final state</th>
<th>$p_T^{min}$ (GeV)</th>
<th>$\eta$ range</th>
<th>$\sigma_{eff}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>AFS (pp), 1986</td>
<td>63</td>
<td>4 jets</td>
<td>$p_T^{jet} &gt; 4$</td>
<td>$</td>
<td>\eta^{jet}</td>
</tr>
<tr>
<td>UA2 (pp), 1991</td>
<td>630</td>
<td>4 jets</td>
<td>$p_T^{jet} &gt; 15$</td>
<td>$</td>
<td>\eta^{jet}</td>
</tr>
<tr>
<td>CDF (pp), 1993</td>
<td>1800</td>
<td>4 jets</td>
<td>$p_T^{jet} &gt; 25$</td>
<td>$</td>
<td>\eta^{jet}</td>
</tr>
<tr>
<td>CDF (pp), 1997</td>
<td>1800</td>
<td>$\gamma + 3$ jets</td>
<td>$p_T^{jet} &gt; 6$</td>
<td>$</td>
<td>\eta^{jet}</td>
</tr>
<tr>
<td>$p_T^{\gamma} &gt; 16$</td>
<td>$</td>
<td>\eta^{\gamma}</td>
<td>&lt; 0.9$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DØ (pp), 2010</td>
<td>1960</td>
<td>$\gamma + 3$ jets</td>
<td>$60 &lt; p_T^{\gamma} &lt; 80$</td>
<td>$</td>
<td>\eta^{\gamma}</td>
</tr>
<tr>
<td>$15 &lt; p_T^{jet2} &lt; 30$</td>
<td>$1.5 &lt;</td>
<td>\eta^{jet}</td>
<td>&lt; 2.5$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$</td>
<td>\eta^{jet}</td>
<td>&lt; 3.0$</td>
<td>$\sigma_{eff} = 16.4_{-2.3}^{+0.3}$ (stat)$\pm2.3$ (syst) mb</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**DØ, Phys.Rev.D81, 052012(2010)**
Jet pT from dijets falls much faster than that for a radiation jet, i.e.
Fraction of dijet (Double Parton) events should drop with increasing jet pT

=> Measurement is done in three bins of 2nd jet pT: 15-20, 20-25, 25-30 GeV
Discriminating variables

► Main one is \( \Delta \phi \) angle between two best pT-balancing pairs

\[
\Delta S = \Delta \phi(p_T^{\gamma, \text{jet}}, p_T^{\text{jet}_1, \text{jet}_k})
\]

For "\( \gamma + 3\)-jet" events from Single Parton scattering we expect \( \Delta S \) to peak at \( \pi \), while it should be flat for "ideal" Double Parton interaction (2\text{nd} and 3\text{rd} jets are both from dijet production) due to a pairwise pT balance.
Built from D0 data. Samples:

**A:** photon + ≥1 jet from γ+jets data events:
- 1 VTX events
- photon pT: 60-80 GeV
- leading jet pT>25 GeV, |η|<3.0.

**B:** ≥1 jets from MinBias events:
- 1 VTX events
- jets with pT's recalculated to the primary vertex of sample A have pT>15 GeV and |η|<3.0.

- ▶ **A & B** samples have been (randomly) mixed with jets pT re-ordering
- ▶ Events should satisfy photon+≥3 jets requirement.
- ▶ △R(photon, jet1, jet2, jet3)>0.7

♫ Two scatterings are independent by construction !
The two datasets method

Dataset 1: 2\textsuperscript{nd} jet p\textsubscript{T}: 15-20 GeV
Dataset 2: 2\textsuperscript{nd} jet p\textsubscript{T}: 20-25 GeV

\checkmark Fraction of Double Parton in bin 15-20 GeV (f\textsubscript{1}) is the only unknown
→ get from minimization.

Data are corrected for the DP fractions
Good agreement of Data and DP model

Good agreement of the $\Delta S$ Single Parton distribution extracted in data and in MC (see previous slide)
→ another confirmation for the found DP fractions.
Found DP fractions are pretty sizable: they drop from $\sim$46-48% at 2$^{nd}$ jet pT 15-20 GeV to $\sim$22-23% at 2$^{nd}$ jet 25-30 GeV with relative uncertainties $\sim$7-12%.

CDF Run I: $53\pm3\%$ at 5-7 GeV of uncorr. jet pT.
Calculation of $\sigma_{\text{eff}}$

- $\sigma_{\text{eff}}$ values in different jet pT bins agree with each other within their uncertainties (also compatible with a slow decrease with pT).
- Uncertainties have very small correlations between 2nd jet pT bins.
- One can calculate the averaged (weighted by uncertainties) values over the pT bins:

$$\sigma_{\text{eff}}^{\text{ave}} = 16.4 \pm 0.3 \, (\text{stat}) \pm 2.3 \, (\text{syst}) \, \text{mb}$$

CDF Run I: $14.5 \pm 1.7^{+1.7}_{-2.3} \, \text{mb}$

Main systematic and statistical uncertainties (in %) for $\sigma_{\text{eff}}$.

<table>
<thead>
<tr>
<th>$p_T^{\text{jet2}}$ (GeV)</th>
<th>Systematic uncertainty sources</th>
<th>$\delta_{\text{sys}}$</th>
<th>$\delta_{\text{stat}}$</th>
<th>$\delta_{\text{total}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 – 20</td>
<td>$f_{\text{DP}}$</td>
<td>7.9</td>
<td>20.5</td>
<td>3.1</td>
</tr>
<tr>
<td></td>
<td>$f_{\text{DI}}$</td>
<td>17.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\varepsilon_{\text{DP}}/\varepsilon_{\text{DI}}$</td>
<td>5.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>JES</td>
<td>5.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$R_{c}\sigma_{\text{hard}}$</td>
<td>2.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20 – 25</td>
<td>$f_{\text{DP}}$</td>
<td>6.0</td>
<td>22.8</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>$f_{\text{DI}}$</td>
<td>20.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\varepsilon_{\text{DP}}/\varepsilon_{\text{DI}}$</td>
<td>6.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>JES</td>
<td>2.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$R_{c}\sigma_{\text{hard}}$</td>
<td>2.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25 – 30</td>
<td>$f_{\text{DP}}$</td>
<td>10.9</td>
<td>32.2</td>
<td>2.7</td>
</tr>
<tr>
<td></td>
<td>$f_{\text{DI}}$</td>
<td>29.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\varepsilon_{\text{DP}}/\varepsilon_{\text{DI}}$</td>
<td>6.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>JES</td>
<td>3.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$R_{c}\sigma_{\text{hard}}$</td>
<td>2.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Models of parton spatial density and $\sigma_{\text{eff}}$

- $\sigma_{\text{eff}}$ is directly related with parameters of models of parton spatial density
- Three models have been considered: Solid sphere, Gaussian and Exponential.

<table>
<thead>
<tr>
<th>Model for density</th>
<th>$\rho(r)$</th>
<th>$\sigma_{\text{eff}}$</th>
<th>$R_{\text{rms}}$</th>
<th>Parameter (fm)</th>
<th>$R_{\text{rms}}$ (fm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid Sphere</td>
<td>Constant, $r &lt; r_p \frac{4\pi r_p^2}{2.2}$</td>
<td>$\sqrt{3/5} r_p$</td>
<td>0.53 ± 0.06</td>
<td>0.41 ± 0.05</td>
<td></td>
</tr>
<tr>
<td>Gaussian</td>
<td>$e^{-r^2/2a^2}$</td>
<td>$8\pi a^2$</td>
<td>$\sqrt{3}a$</td>
<td>0.26 ± 0.03</td>
<td>0.44 ± 0.05</td>
</tr>
<tr>
<td>Exponential</td>
<td>$e^{-r/b}$</td>
<td>$28\pi b^2$</td>
<td>$\sqrt{12}b$</td>
<td>0.14 ± 0.02</td>
<td>0.47 ± 0.06</td>
</tr>
</tbody>
</table>

- The rms-radii above are calculated w/o account of possible parton spatial correlations. For example, for the Gaussian model one can write [Trelelani, Galucci, 0901.3089, hep-ph]:

$$\frac{1}{\sigma_{\text{eff}}} = \frac{3}{8\pi R_{\text{rms}}^2} (1 + \text{Corr.})$$

- If we have rms-radii from some other source, one can estimate the size of the spatial correlations (larger corr. $\leftrightarrow$ larger rms-radius with a fixed $\sigma_{\text{eff}}$)
Angular decorrelations in $\gamma+2$ and $\gamma+3$ jet events

**Motivations:**

- By measuring *differential* cross sections vs. the azimuthal angles in $\gamma+3(2)$ jet events, we can better tune (or even exclude some) MPI models in events with high pT jets.

- Differentiation in jet pT increases sensitivity to the models even further.

Four normalized differential cross sections are measured:

- $\Delta \phi(\gamma+\text{jet1}, \text{jet2})$ in 3 bins of 2nd jet pT: 15-20, 20-25 and 25-30 GeV
- $\Delta S(\gamma+\text{jet1}, \text{jet2+jet3})$ for 2nd jet pT 15-30 GeV (larger for stat. reasons but still has good sensitivity to MPI models)
• MPI models substantially differ from any SP (=single parton scattering) prediction.
• Large difference between SP models and data confirms presence of DP events in data.
• MPI models differ noticeably, especially at small angles
  => we can tune the models or just choose the best one(s)
• Data are close to Perugia (P0), S0 and Sherpa MPI tunes.
  N.B.: the conclusion is valid for both the considered variables and 3 jet pT intervals!
TABLE V: The results of a $\chi^2$ test of the agreement between data points and theory predictions for the $\Delta S (\gamma + 3 \text{ jet})$ and $\Delta \phi (\gamma + 2 \text{ jet})$ distributions for $0.0 \leq \Delta S(\Delta \phi) \leq \pi \text{ rad}$. Values are $\chi^2 / ndf$.
DP fractions in $\gamma+2$ jet events

- In $\gamma+2$ jet events in which 2$^{nd}$ jet is produced in the 2nd parton interaction, $\Delta\phi(\gamma+\text{jet1, jet2})$ distribution should be flat.
- Using this fact and also SP prediction for $\Delta\phi(\gamma+\text{jet1, jet2})$ one can get DP fraction from a maximal likelihood fit to data.

Example of the fit for 2$^{nd}$ jet $p_T$ bin 15 – 20 GeV

CDF Run I: 14$^{+8}_{-7}$% at jet $p_T > 8$ GeV and photon $p_T > 16$ GeV
DP fractions in $\gamma+2$ jet events vs. $\Delta \phi$

- DP fractions should depend on $\Delta \phi(\gamma+\text{jet1, jet2})$: the smaller $\Delta \phi$ angle the larger DP fraction (see, for example, the plot on previous slide).
- We can find this dependence by repeating the same fits at smaller $\Delta \phi$ angles.

$\Rightarrow$ DP fractions are larger at smaller angles and smaller 2$^{nd}$ jet pT.
TP fractions

γ+3jet final state also can be produced by Tripple Parton interaction (TP). In γ+3jet events all 3 jets should stem from 3 different parton scatterings. To estimate the TP fraction the we used results on DP+TP fractions and fractions of TypeI(II) events found in our previous measurement. TP in γ+3jet data is calculated as:

\[ f_{\gamma 3j}^{tp} = f_{dp+tp}^{tp} \cdot f_{dp+tp}^{\gamma 3j} \]

The fraction of TP in MixDP can be found as:

\[ f_{dp+tp}^{\gamma 3j} = F_{typeII}^{dp} \cdot f_{dp}^{\gamma 2j} + F_{typeI}^{dp} \cdot f_{dp}^{jj} \]

- measured in previous DP analysis;
- estimated using dijet cross section;
- measured;

\[ F_{typeI(II)} \] - found from the model (MixDP).

Probability to produce another parton scattering is proportional to \( R=\sigma_{ij}/\sigma_{eff} \), the \( f_{\gamma 3j}^{tp}/f_{\gamma 3j}^{dp} \) ratio should be proportional to \( R \).

<table>
<thead>
<tr>
<th>( p_T^{jet2} ) (GeV)</th>
<th>( f_{\gamma 3j}^{tp} ) (%)</th>
<th>( f_{\gamma 3j}^{dp}/f_{\gamma 3j}^{dp} ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 – 20</td>
<td>5.5 ± 1.1</td>
<td>13.5 ± 3.0</td>
</tr>
<tr>
<td>20 – 25</td>
<td>2.1 ± 0.6</td>
<td>6.6 ± 2.0</td>
</tr>
<tr>
<td>25 – 30</td>
<td>0.9 ± 0.3</td>
<td>3.8 ± 1.4</td>
</tr>
</tbody>
</table>
In D0 we have been studying DP production events and measured recently:

- Fraction of DP events in $\gamma+3$-jet events in three pT bins of 2$^{\text{nd}}$ jet: 15-20, 20-25, 25-30 GeV. It varies from $\sim47\%$ at 15-20 GeV to $\sim23\%$ at 25-30 GeV.

- Effective cross section (process-independent, defines rate of DP events) $\sigma_{\text{eff}}$ in the same jet pT bins with average value:

$$\sigma_{\text{eff}}^{\text{ave}} = 16.4 \pm 0.3(\text{stat})\pm 2.3(\text{syst})\text{mb}$$

- The DP in $\gamma+2$jets: 11.6\% at 15-20 GeV to 2.2\% at 25-30 GeV.

- The TP fractions in $\gamma+3$-jet events are determined for the first time. As a function of 2$^{\text{nd}}$ jet pT, they drop from $\sim5.5\%$ at 15-20 GeV, to $\sim0.9\%$ at 25-30 GeV.

- The $\Delta S$ and $\Delta \phi$ cross sections. They allow to better tune MPI models: Data prefer the Sherpa and Pythia MPI models (P0, P0-X, P0-hard) with pT-ordered showers.

- DP production can be a significant background to many rare processes, especially with multi-jet final state. A set of variables allowing to reduce the DP background is suggested.

Summary
BACK-UP SLIDES
Some still open questions and Prospects

- Is $\sigma_{\text{eff}}$ really stable from small to very big scales $\mu$ of a hard interaction?

- How the spatial distribution should depend on the parton species (eg. valence vs. sea quarks / gluons) ?
  What observables could be used to improve understanding of transverse structure?

- Is the assumption $G(x,b) = D(x) F(b)$ true ?
  How to make unambiguous test of this factorization?
  Interesting recent related analysis: 4-jet production in the light of two-parton GPD($x_1, x_2, b$), where $b$ is a transverse distance: arXiv:1009.2741 [hep-ph].

=> More measurements of DP fractions and $\sigma_{\text{eff}}$ are needed in different processes having different initial state, but at similar energy scales as in the studied $\gamma + 3$-jet events.
  For example, di-b-jet+dijet, W/Z/photon + $\geq 2$ heavy flavour jets, diphoton+dijet, mutlijet Drell-Yan events.
Studies of MPI events did not receive a proper attention up to recent time, but currently more people/groups are becoming involved in this business.

Studies of MPI events are important since lead to a knowledge of the fundamental hadron structure.

Rates of DP/MPI events are significant at the Tevatron, but should be much larger at the LHC (about a factor 2) mainly because PDF increase rapidly with $x \to 0$ and DP cross section grows as a product of $2 \times 2$ PDFs. Plus $\sigma_{\text{eff}}$ seems should drop due to dPDF evolution. Thus, they can be important background to many 'new physics' processes at LHC.
Effective cross section $\sigma_{\text{eff}}$ is directly related with parton spatial density:

$$\sigma_{\text{eff}} = \int d^2 \beta [F(\beta)]^2, \quad \beta \text{ is impact parameter}$$

where $F(\beta) = \int f(b)f(b - \beta) d^2b$, $f(b)$ is the density of partons in transverse space.

$=>$ Having $\sigma_{\text{eff}}$ measured we can estimate $f(b)$.
Measurement of $\sigma_{\text{eff}}$

At two hard scattering events:

$$P_{Di} = 2 \left( \frac{\sigma^{\gamma j}}{\sigma_{\text{hard}}} \right) \left( \frac{\sigma^{jj}}{\sigma_{\text{hard}}} \right)$$

The number of Double Interaction events:

$$N_{Di} = 2 \frac{\sigma^{\gamma j}}{\sigma_{\text{hard}}} \frac{\sigma^{jj}}{\sigma_{\text{hard}}} N_C(2) A_{Di} \epsilon_{Di} \epsilon_{2\text{vtx}}$$

At one hard interaction:

$$P_{DP} = \left( \frac{\sigma^{\gamma j}}{\sigma_{\text{hard}}} \right) \left( \frac{\sigma^{jj}}{\sigma_{\text{eff}}} \right)$$

Then the number of Double Parton events:

$$N_{DP} = \frac{\sigma^{\gamma j}}{\sigma_{\text{hard}}} \frac{\sigma^{jj}}{\sigma_{\text{eff}}} N_C(1) A_{DP} \epsilon_{DP} \epsilon_{1\text{vtx}}$$

Therefore one can extract:

$$\sigma_{\text{eff}} = \frac{N_{Di}}{N_{DP}} \frac{N_C(1)}{2N_C(2)} \frac{A_{DP}}{A_{Di}} \frac{\epsilon_{DP}}{\epsilon_{Di}} \frac{\epsilon_{1\text{vtx}}}{\epsilon_{2\text{vtx}}} \sigma_{\text{hard}}$$
Double parton interactions and dPDF evolution


If at any given scale $\mu_0$:
$$D(x_1,x_2,\mu_0) = D(x_1,\mu_0) \cdot D(x_2,\mu_0) \cdot \theta(1-x_1-x_2)$$
the dPDF evolution violates this factorization inevitably at any different scale $\mu \neq \mu_0$:
$$D(x_1,x_2,\mu) = D(x_1,\mu) \cdot D(x_2,\mu) + R(x_1,x_2,\mu)$$
where $R(x_1,x_2,\mu)$ is a correlation term.

Direct account of double PDFs: J.Gaunt and J.Stirling, JHEP 1003:005,2010. First software implemented evolution equations and solutions for dPDF To the large extent, being encouraged by the D0 measurement.
Motivations

Comparison of the top-quark mass offset corrections with a few MPI models


Difference between the two sets of the models leads to about 0.5-1.0 GeV uncertainty to the offset corrections for the top-quark mass.