Double Parton Interactions: Recent DZero measurements and Prospects

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University of California, Davis, High Energy Physics Seminar

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Outline

- History and experimental tests
- Double Parton interactions in $\gamma + 2$ and $\gamma + 3$-jet events
- Double Parton interaction as a background to rare processes
- Prospects and Summary
QCD in Hadron-Hadron Collisions

Object reconstruction in the hadron-hadron collisions
Goal is to reconstruct the initial “building”

Sometimes the reality is even more complicated

from P. Skands talk, 2009
Hadron-Hadron Collision

proton

anti-proton

hadron interaction

outgoing parton(s) (quark, gluon, $\gamma$, $Z^0$, $W^\pm$)

high $p_T$
Hadron-Hadron Collision

hadronization, fragmentation

proton

outgoing parton(s)

anti-proton

Hard radiation

outgoing parton(s)
Hadron-Hadron Collision: from Single to Double parton interactions

Double parton interactions
Some history

- Simple models of double di-jet, double Drell-Yan productions
  P.V. Landshoff and J.C. Polkinghorne - 1978
  C. Goebel et al - 1980
  E. Takagi (MPI in pN interactions) - 1979 (MPI ≡ Multiple Parton Interactions)

- ... with extension to perturbative QCD
  B. Humpert et al - 1983-85
  L. Ametller, N. Paver, D. Treleani - 1982-1986
  ....

- First real, software-implemented MPI model (aka “Tune A”, updated by R. Field).
  Description of many “puzzling features” in jet productions in UA1-UA5.

- 2002-today: 20-30 new MPI tunes appeared:
  http://mpi11.desy.de : 3rd MPI workshop (DESY, November, 2011)

- Most features of MPI events are studied experimentally.
  Current emphasis is detailed aspects: parton transverse structure,
  long. and trans. momentum distributions, correlations, etc.

- Amount of theor.&exp. publications is rapidly growing last years:
  - 2011: >20 papers (>50% on the LHCb double J/psi result)
Experimental tests

Charged multiplicity

Hard scattering only; +ISR/FSR

MPI models (fixed and varying impact parameter)

\[ \frac{\sigma_n}{\sum \sigma_n} \]

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

"Poissonian hadronization" of the string model does not work!

UA5, 540 GeV, ppbar

Single string =>
~Poissonian multiplicity

Only additional parton interactions can describe the shape
Experimental tests

Jet pedestal effect

- Presence of high pT 1st interaction biases events towards smaller p-pbar impact parameters and hence leads to a higher additional activity but saturates at $\sigma(pT_{jet}) \ll \sigma_{nd}$ ("nd" = non-diffractive).
- The height of the pedestal depends on the overlap, i.e. on the parton matter distribution function.

CDF (Run 2)

ETsum Density: $dE_T/d\eta d\phi$

- "Toward"
- "Transverse"
- "Away"

CDF Run 2 Preliminary data corrected pyA generator level

"Leading Jet" MidPoint R=0.7 $|\eta_{(jet\#1)}|<2$

Stable Particles ($|\eta|<1.0$, all PT)

- With MPI
- No MPI

UA1 540 GeV

L_{eff}(\Delta) = \int D(r)D(r')dV_{\text{overlap}}

Jet direction

Effective parton Luminosity:

Jet pT>35 GeV

Δφ

Jet #1 Direction

Apply

10-15 GeV
- In case of no MPI events, $\langle p_T \rangle$ grows too rapidly.
- MPI lead to larger Nch that are harder than the beam remnants but not as hard in pT as for the primary hard 2->2 scattering.
- The larger #MPIs the more trend to higher Nch and smaller $\langle p_T \rangle$.
- The details (fit to data) are regulated by the string “drawing” e.g. “minimal” to the nearest neighbor vs. “maximal” across the whole event (A-CR vs No-CR is an example of two extreme cases).
Experimental tests

Charged multiplicity

E735, 200-1800 GeV, ppbar minimum bias events

\(<N_1>\) is the average (KNO) multiplicity for a simple single-parton scattering process

- Most probable ratio \(N/\langle N_1 \rangle\) is close to 2 (a bit larger)
- Width is close to \(\sqrt{2} \times \) SP width

\[\Rightarrow\] strong indication to 2 distinct parton scattering processes occurring at the same ppbar collision

Photon+2 jets study

The difference in azimuthal angle between the transverse momentum vector sum of (photon + lead. jet) and 2\textsuperscript{nd} jet

- Conservation of momentum biases the distribution towards $\pi$.
- Tail at small angles determines the amount of double parton interaction in data.
Double Parton Interactions in $\gamma + 3$ (and 2) jet events: from low $p_T$ to high $p_T$ in MPI studies

- New motivations and prospects
- New effects
Overview

• Tevatron
• Motivations
• Event topology
• Discriminating variables
• Fraction of double parton events
• Effective cross-section
• Interpretations
• Prospects
Fermilab Tevatron Run II

Run II ended on Sep 30, 2011
Typical data collection efficiency is 90-92%
Peak Luminosity: $4.3 \times 10^{32}$ cm$^{-2}$s$^{-1}$
Delivered about 12 fb$^{-1}$
To compare: Run I delivered 120 pb$^{-1}$

Since March 2001: 12 fb$^{-1}$
Double parton and effective cross sections

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

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

→ contains information on the spatial distribution of partons.
  - Uniform: \( \sigma_{\text{eff}} \) is large and \( \sigma_{DP} \) is small
  - Clumpy: \( \sigma_{\text{eff}} \) is small and \( \sigma_{DP} \) is large

→ \( \sigma_A \) and \( \sigma_B \) grow with \( \sqrt{s} \), \( \Rightarrow \sigma_{DP} \) should grow even faster!
→ \( \sigma_{\text{eff}} \) (on top of pure QCD motivations) is needed for precise estimates of background to many rare processes (especially with multi-jet final state)
→ Being phenomenological, it should be measured in experiment !!
Effective cross section

\[ \sigma_{dp} = \sum_{q/g} \int \frac{\sigma_{12}\sigma_{34}}{2\sigma_{\text{eff}}} D_p(x_1, x_3) D_{\bar{p}}(x_2, x_4) dx_1 dx_2 dx_3 dx_4 \]

Double parton cross section

Effective cross section

\[ \sigma_{eff}^{-1} = \int d^2 \beta \left[ F(\beta) \right]^2, \quad \beta \text{ is impact parameter} \]

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

where \( f(b) \) is the density of partons in transverse space.

(Slide 76 shows an extended version)
**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>$</td>
<td>\eta^{jet}</td>
</tr>
<tr>
<td>UA2 ($p\bar{p}$), 1991</td>
<td>630</td>
<td>4 jets</td>
<td>$p_T^{jet} &gt; 15$</td>
<td>$</td>
<td>\eta^{jet}</td>
</tr>
<tr>
<td>CDF ($p\bar{p}$), 1993</td>
<td>1800</td>
<td>4 jets</td>
<td>$p_T^{jet} &gt; 25$</td>
<td>$</td>
<td>\eta^{jet}</td>
</tr>
<tr>
<td>CDF ($p\bar{p}$), 1997</td>
<td>1800</td>
<td>$\gamma + 3$ jets</td>
<td>$p_T^{jet} &gt; 6$</td>
<td>$</td>
<td>\eta^{jet}</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$p_T^{\gamma} &gt; 16$</td>
<td>$</td>
<td>\eta^{\gamma}</td>
</tr>
<tr>
<td>DØ ($p\bar{p}$), 2010</td>
<td>1960</td>
<td>$\gamma + 3$ jets</td>
<td>$60 &lt; p_T^{\gamma} &lt; 80$</td>
<td>$</td>
<td>\eta^{\gamma}</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$</td>
<td>\eta^{jet}</td>
<td>&lt; 2.5$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\sigma_{eff} = 16.4\pm0.3$ (stat)$\pm2.3$ (syst) mb</td>
</tr>
</tbody>
</table>

**DØ, Phys.Rev.D81, 052012(2010)**

**AFS'86, UA2'91 and CDF'93**
4-jet samples, motivated by a large dijet cross section (but low DP fractions)

**CDF’97, DØ’10**
$\gamma + 3$ jets events, data-driven method: use rates of Double Interaction events (two separate ppbar collisions) and Double Parton (single ppbar collision) events to extract $\sigma_{eff}$ from their ratio.

$=>$ reduces dependence on Monte-Carlo and NLO QCD theory predictions.
Measurement of $\sigma_{\text{eff}}$

For two hard scattering events (two separate $p\overline{p}$ collisions):

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

The number of Double Interaction events:

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

For 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:

$$\sigma_{\text{eff}} = \frac{N_{DI}}{N_{DP}} \frac{N_C(1)}{2N_C(2)} \frac{A_{DP}}{A_{DI}} \frac{\epsilon_{DP}}{\epsilon_{DI}} \frac{\epsilon_{1\text{vtx}}}{\epsilon_{2\text{vtx}}} \sigma_{\text{hard}}$$
Built from D0 data. Samples:

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

**B:** ≥1 jets from MinBias events:
- 1-vertex 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 following jet pT re-ordering
- Events should satisfy photon+≥3 jets requirement.
- △R(photon, jet1, jet2, jet3)>0.9

⇒ Two parton scatterings are independent by construction!
Jet PT: jet from dijets vs. radiation jet from $\gamma$+jet events

- Jet pT from dijets falls much faster than that for radiation jets, 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
In the signal DP sample most likely (>94%) S-variables are minimized by pairing photon with the leading jet.

Discriminating variables

\[ \Delta S = \Delta \phi(p_{T}^{\gamma}, jet, p_{T}^{\text{jet}_i, \text{jet}_k}) \]

- \( \Delta \phi \) angle between two best pT-balancing pairs
- The pairs should correspond to a minimum S value:

\[ S_{\phi} = \frac{1}{\sqrt{2}} \sqrt{ \left( \frac{\Delta \phi(\gamma, i)}{\delta \phi(\gamma, i)} \right)^2 + \left( \frac{\Delta \phi(j, k)}{\delta \phi(j, k)} \right)^2 } \]

\[ S_{p_T} = \frac{1}{\sqrt{2}} \sqrt{ \left( \frac{|p_{T}^{\gamma}(\gamma, i)|}{\delta p_{T}(\gamma, i)} \right)^2 + \left( \frac{|p_{T}(j, k)|}{\delta p_{T}(j, k)} \right)^2 } \]
For “γ+3-jet” events from Single Parton scattering we expect ΔS to peak at $\pi$, while it should be flat for “ideal” Double Parton interaction ($2^{nd}$ and $3^{rd}$ jets are both from dijet production).
The fraction of DP events: the two datasets method

Since dijet pT cross section drops faster than that of radiation jets the different DP fractions in various (2\textsuperscript{nd}) jet pT intervals are expected. The larger 2\textsuperscript{nd} jet pT the smaller DP fraction.

Dataset 1 - “DP-rich”, smaller 2\textsuperscript{nd} jet pT bin, e.g. 15-20 GeV
Dataset 2 - “DP-poor”, larger 2\textsuperscript{nd} jet pT bin, e.g. 20-25 GeV

Each distribution can be expressed as a sum of DP and SP:

\[ D_i = f_i M_i + (1 - f_i) B_i \]

where

\[ D_i \] - data distribution
\[ M_i \] - MIXDP distribution
\[ B_i \] - background distribution
\[ f_i \] - fraction of DP events
\[ (1 - f_i) \] - fraction of SP events

\[ D_1 - f_1 M_1 = (1 - f_1) B_1 \]
\[ D_2 - f_2 M_2 = (1 - f_2) B_2 \]

\[ D_1 - \lambda K D_2 = f_1 M_1 - \lambda K C \cdot f_1 M_2 \]

where

\[ \lambda = \frac{B_1}{B_2} \]
\[ K = \frac{(1 - f_1)}{(1 - f_2)} \]
\[ C = \frac{f_2}{f_1} \]

\( f_1 \) is the only unknown, --> get from minimization
The two datasets method

Dataset (a): 2\textsuperscript{nd} jet pT: 15-20 GeV
Dataset (b): 2\textsuperscript{nd} jet pT: 20-25 GeV

✓ Fraction of Double Parton in bin 15-20 GeV ($f_1$) is the only unknown → get from minimization.

✓ Good agreement of the $\Delta S$ Single Parton distribution extracted in data and in MC (see slide 24) → another confirmation for the found DP fractions.

Data are corrected for the DP fractions

✓ Good agreement of Data and DP model
Found DP fractions are pretty sizable: they drop from $\sim$46-48% at 2\textsuperscript{nd} jet $p_T$ 15-20 GeV to $\sim$22-23% at 2\textsuperscript{nd} jet 25-30 GeV with relative uncertainties $\sim$7-12%.

CDF Run I: 53\(\pm\)3\% at 5-7 GeV of uncorr. jet $p_T$. 

Fractions of Double Parton $\gamma$+3-jet events

![Graph showing fraction of DP events vs $p_T^{jet2}$]
Fractions of Double Parton events: MPI models and D0 data

- Pythia MPI tunes A and S0 are considered.
- Data are in between the model predictions.
- Results are preliminary: data should be corrected to the particle level.
- Will be done later to find the best MPI Tune
Calculation of $\sigma_{\text{eff}}$

- $\sigma_{\text{eff}}$ values in different jet $p_T$ bins agree with each other within their uncertainties (also compatible with a slow decrease with $p_T$).

- Uncertainties have very small correlations between 2$^{\text{nd}}$ jet $p_T$ bins.

- One can calculate the averaged (weighted by uncertainties) values over the $p_T$ bins:

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

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>$\delta_{\text{syst}}$</th>
<th>$\delta_{\text{stat}}$</th>
<th>$\delta_{\text{total}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$f_{\text{DP}}$</td>
<td>$f_{\text{DI}}$</td>
<td>$\varepsilon_{\text{DP}} / \varepsilon_{\text{DI}}$</td>
<td>JES</td>
</tr>
<tr>
<td>15 – 20</td>
<td>7.9</td>
<td>17.1</td>
<td>5.6</td>
<td>5.5</td>
</tr>
<tr>
<td>20 – 25</td>
<td>6.0</td>
<td>20.9</td>
<td>6.2</td>
<td>2.0</td>
</tr>
<tr>
<td>25 – 30</td>
<td>10.9</td>
<td>29.4</td>
<td>6.5</td>
<td>3.0</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 VI: Parameters of parton spatial density models calculated from measured $\sigma_{\text{eff}}$.

<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, $r &lt; r_p$</td>
<td>$4\pi r_p^2/2.2$</td>
<td>$\sqrt{3/5}r_p$</td>
<td>0.53 ± 0.06</td>
<td>0.41 ± 0.05</td>
</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-radia 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-radia from some other source, one can estimate the size of the spatial correlations (larger corr. $\leftrightarrow$ larger rms-radius with a fixed $\sigma_{\text{eff}}$).
• Strictly speaking, the PDF factorization assumption (used in our meas.) is wrong!
If at any given scale $\mu_0$ one assumes the factorized form
\[ D(x_1, x_2, \mu_0) = D(x_1, \mu_0) \times D(x_2, \mu_0) \times \theta(1 - x_1 - x_2) \]
then \textit{dPDF evolution} violates this factorization \textit{inevitably} at any different scale $\mu \neq \mu_0$:
\[ D(x_1, x_2, \mu) = D(x_1, \mu) \times D(x_2, \mu) + R(x_1, x_2, \mu), \]
where $R(x_1, x_2, \mu)$ is a (positive) correlation term.

Correlations for 2 gluon PDFs as an example:

V.L. Korotkikh, A.M. Snigirev, hep-ph/0404155

\[ R(x, t) = \frac{D^{gg}_{p(QCD, corr)}(x_1, x_2, t)}{D^{g}_{p}(x_1, t) D^{g}_{p}(x_2, t)(1 - x_1 - x_2)^2} \bigg|_{x_1 = x_2 = x} \]

Ratio of the PDFs correlation term, induced by the evolution to the factorization component (both PDFs are at one scale)

Size of the correlations should also depend on the types of PDFs used in the product: e.g. they will be different for $qg$ and $qq$ processes and depend on the quark species.
Possible manifestation of PDF correlations

Following paper of A.M. Snigirev, http://arxiv.org/abs/1001.0104 appeared as an interpretation the D0 measurement. ... right in 4-5 days after submission!

DP cross section \[\sigma_{dp} = \sum_{q/g} \int \frac{\sigma_{12}\sigma_{34}}{2\sigma_{\text{eff}}} D_p(x_1, x_3) D_p(x_2, x_4) dx_1 dx_2 dx_3 dx_4\]

Possible manifestation of PDF correlations

Same general conclusions should be true for the two different photon pT scales!
FIG. 1: Effective cross section $\sigma_{\text{eff}}^{\text{exp}}$ measured in the three $p_T^{\text{jet}^2}$ bins at the D0 experiment [5]. The solid ($k = 0.5$) and dashed ($k = 0.1$) lines are the results from Eq. (11) at $p_T^{\text{jet}^2} = 22.5$ GeV and $\sigma_{\text{eff}}^0 = 16.3$ mb.
dPDF evolution

Direct account of double PDFs: J.Gaunt and J.Stirling, 0910.4347 [hep-ph].

--> **first software implemented evolution equations for dPDF!!**

--> LO dPDF grid files for $10^{-6} < x_1, x_2 < 1.0$ and two scales $Q_1, Q_2$

- The evolution strongly depends on the process (parton species, kinematics).
- The correlations are estimated using simulated kinematics of $\gamma$+jet events and the G&S evolution code.

- Size of PDF correlation caused by the dPDF evolution (scaling violation) should be about 25% for photon pT varied as $25 \rightarrow 120$ GeV.
- **Planned** as a next D0 measurement at the full data set!
Angular decorrelations in $\gamma+2$ and $\gamma+3$ jet events

**Motivations:**

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

- 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:

- $\Delta \phi(\gamma+jet1, jet2)$ in 3 bins of 2$^{nd}$ jet pT: 15-20, 20-25 and 25-30 GeV

- $\Delta S(\gamma+jet1, jet2+jet3)$ for 2$^{nd}$ jet pT 15-30 GeV
Another motivation

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.

**ΔS and Δφ cross sections**

- 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!
\( \Delta \phi \) cross sections

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 \( 0.0 \leq \Delta S (\Delta \phi) \leq \pi \) rad. Values are \( \chi^2 / ndf \).

<table>
<thead>
<tr>
<th>Variable</th>
<th>( p_{\text{T}}^{\text{jet}2} ) (GeV)</th>
<th>SP model</th>
<th>MPI model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>15 - 30</td>
<td>PYTHIA</td>
<td>P-soft</td>
</tr>
<tr>
<td>( \Delta S )</td>
<td>15 - 20</td>
<td>SHERPA</td>
<td>P-hard</td>
</tr>
<tr>
<td>( \Delta \phi )</td>
<td>20 - 25</td>
<td>A</td>
<td>P-6</td>
</tr>
<tr>
<td>( \Delta \phi )</td>
<td>25 - 30</td>
<td>DW</td>
<td>P-X</td>
</tr>
<tr>
<td></td>
<td>0.4</td>
<td>0.5</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>16.6</td>
<td>11.7</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td>4.0</td>
<td>1.6</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>7.2</td>
<td>3.5</td>
<td>0.2</td>
</tr>
</tbody>
</table>

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DP fractions in $\gamma + 2$ jet events

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

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

<table>
<thead>
<tr>
<th>$p_T^{\text{jet2}}$ (GeV)</th>
<th>$\left&lt; p_T^{\text{jet2}} \right&gt;$ (GeV)</th>
<th>$f_{\gamma 2j}^{DP}$ (%)</th>
<th>Uncertainties (in %)</th>
<th>Fit</th>
<th>$\delta_{tot}$</th>
<th>SP model</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 – 20</td>
<td>17.6</td>
<td>11.6 ± 1.0</td>
<td>5.2</td>
<td>8.3</td>
<td>6.7</td>
<td></td>
</tr>
<tr>
<td>20 – 25</td>
<td>22.3</td>
<td>5.0 ± 1.2</td>
<td>4.0</td>
<td>20.3</td>
<td>11.0</td>
<td></td>
</tr>
<tr>
<td>25 – 30</td>
<td>27.3</td>
<td>2.2 ± 0.8</td>
<td>27.8</td>
<td>21.0</td>
<td>17.9</td>
<td></td>
</tr>
</tbody>
</table>

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 in smaller $\Delta\phi$ regions.

DP fit for 2\textsuperscript{nd} jet pT bin 15 – 20 GeV

$0 < \Delta\phi < 2.15$

$\frac{1}{\sigma_{\gamma+2\text{jet}}} \frac{d\sigma_{\gamma+2\text{jet}}}{d\Delta\phi}$

$15 < p_{T,\text{jet2}} < 20$ GeV

$\Delta\phi = 0.450 \pm 0.024$

DP fractions vs $\Delta\phi$ bin for 3 bins of 2\textsuperscript{nd} jet pT

$\Delta\phi_{\text{max}}$ (rad)

$\Rightarrow$ DP fractions are larger at smaller angles and smaller 2\textsuperscript{nd} jet pT
γ+3jet final state can also 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 Type I (II) events found in our previous measurement (p.27). TP in γ+3jet data is calculated as:

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

The fraction of TP in MixDP can be found as:

\[ f_{\gamma 3j}^{dp+tp} = F_{\text{type II}} \cdot f_{dp}^{\gamma 2j} + F_{\text{type I}} \cdot f_{dp}^{jj} \]

\[ f_{dp}^{\gamma 3j} \] - measured in previous DP analysis;

\[ f_{dp}^{jj} \] - measured;

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

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

<table>
<thead>
<tr>
<th>( p_T^{jet2} ) (GeV)</th>
<th>( f_{tp}^{\gamma 3j} ) (%)</th>
<th>( f_{tp}^{\gamma 3j}/f_{dp}^{\gamma 3j} ) (%)</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>
Double Parton Interactions
As Background to Rare Processes
Double Parton events as a background to Higgs production

Many Higgs production channel can be mimicked by Double Parton event!
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)!

=> see example of possible variables below (and also 0911.5348[hep-ph])

Several estimates for LHC: PRD 61 077502; PRD 66 074012; arXiv:0710.0203
- Kinematic selections are same as in actual D0 analyses.
- Dijet $d\sigma/dM$ and $W(Z)$ cross sections are normalized to D0 measurements.
- DP background can be significant for both the Higgs productions channels!
DP as background to p+p\bar{p}→WH at Tevatron (2)

**Fast MC based on Pythia-8 (detector smearing+TRF)**

**HW, H→bb: DP and SP cross sections**

With bID selections (TRFs)

- Kinematic + bID selections are same as in actual D0 analyses.
- Dijet d\sigma/dM and W(Z) cross sections are normalized to D0 measurements.
- DP background can be significant for both the Higgs productions channels!
DP as background to p+pbar→WH at Tevatron (3)

HW(Z) / DP cross sections with account of jet E smearing and b-tagging efficiencies for light/c/b jets.

- Higgs signal is suppressed even in the peak by a factor 2.5-5

Let's try to improve it:

⇒ Discriminator (ANN based) is built using all the variables sensitive to kinematics of HW /DP productions

The uncertainties are caused by K-factors (~10%) and $\sigma_{\text{eff}}$ (~15%)

Fractions of events with single jet b-tagging and double b-tagging are chosen as in data/full reco for WH
DP as background to $p+p\bar{p} \rightarrow W(Z)H$ at Tevatron (3)

Input ANN variables

Red is WH
Black is DP
... and with account of a cut on the output value of the dedicated ANN
The cut is chosen to have 90% of signal HW events
The 85% cut gives another factor 1.5-1.8 of the S/B increase
Some more ongoing studies
Photon+HF+2jet DP events

Goal: Measurement of $\sigma_{\text{eff}}$ in the events with initial b or c quark
$\Rightarrow$ sensitivity to HF (sea) quark spatial distribution

- Main scattering is caused by photon+HF production with dominating contribution from $Qg \rightarrow Q\gamma$ ($Q$=c,b) scattering

- At least one HF-jet is required (a jet passed Tight b-ID) $\Rightarrow$ estimated HF fraction is 75-80%

- Photon $p_T$$>$$30$ GeV
  Two 2$^{nd}$ jet $p_T$ bins: 15-23 and 23-35 GeV

- Use of data-driven method to calculate $\sigma_{\text{eff}}$
Double J/psi production

Goal: Meas. of double J/psi cross sections in SP and DP events

=> extraction of $\sigma_{\text{eff}}$ at low pT (!)

=> test of $\sigma_{\text{eff}}$ energy dependence: see slide 34

hep-ph/9706293

- Expected DP fractions at pT(Jpsi)>5 GeV: 10-20% at Tevatron and 70-80% at LHC (gluon-gluon luminosity are higher at LHC)

- The measurements of the cross sections are at the full speed in D0, CMS and Atlas experiments (about similar statistics of the selected events, $O(100)$, in the three experiments for now)

- Main background: b+b$\bar{b}$ events with semileptonic B-meson decays into J/psi+X

- DP and SP events should be separated by using $\Delta \eta$ & $\Delta \Phi$ distributions.

arXiv:1105.4186
Di-photon+dijet and di-lepton+dijet events

- Two parton scatterings that can be separated kinematically and in ID space
- Initial state (mainly $q\bar{q}$) differs from the photon+3jet and 4-jet events
  => new and independent test of $\sigma_{\text{eff}}$ and MPI models

- Expected DP fractions are higher than in photon+3jet events

Cross sections (pb) of DP and SP events for various cuts on pT-imbalance

$$||p_T(i)|-|p_T(j)|| \leq c_{ij}\sqrt{\delta^2[p_T(i)] + \delta^2[p_T(j)]}.$$  

<table>
<thead>
<tr>
<th></th>
<th>$c_1 = c_2 = 5$</th>
<th>$c_1 = c_2 = 2$</th>
<th>$c_1 = 1, c_2 = 2$</th>
<th>$c_1 = c_2 = 1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma(jj\gamma\gamma)(S)$</td>
<td>1.86</td>
<td>0.96</td>
<td>0.71</td>
<td>0.59</td>
</tr>
<tr>
<td>$\sigma(jj\gamma\gamma)(B)$</td>
<td>20.8</td>
<td>2.34</td>
<td>1.16</td>
<td>0.94</td>
</tr>
<tr>
<td>$\sigma(jj\gamma\gamma)(S)$</td>
<td>0.089</td>
<td>0.41</td>
<td>0.61</td>
<td>0.63</td>
</tr>
<tr>
<td>$\sigma(jj\gamma\gamma)(B)$</td>
<td>3.45</td>
<td>2.01</td>
<td>1.42</td>
<td>1.07</td>
</tr>
<tr>
<td>$\sigma(jj\gamma\gamma)(S)$</td>
<td>19.0</td>
<td>1.94</td>
<td>1.00</td>
<td>0.70</td>
</tr>
<tr>
<td>$\sigma(jj\gamma\gamma)(B)$</td>
<td>0.18</td>
<td>1.04</td>
<td>1.42</td>
<td>1.53</td>
</tr>
</tbody>
</table>

- The measurement with $\gamma\gamma$+jj events is started recently.

- By analogy to photon+3j, the events are split into jet pT bins.
  About 3,000 of 1-vertex events with photon pT>18 and jet pT>15 GeV are selected at $\sim$7.5 fb-1.
In D0 we have been studying DP production events and measured recently:

- Fraction of DP events in $\gamma + 3$-jet events in three $p_T$ bins of 2nd jet: 15-20, 20-25, 25-30 GeV. It varies from $\sim 47\%$ at 15-20 GeV to $\sim 23\%$ at 25-30 GeV.

- Effective cross section (process-independent, defines rate of DP events) $\sigma_{eff}$ in the same jet $p_T$ bins with average value:
  \[ \sigma_{eff}^{ave} = 16.4 \pm 0.3(\text{stat}) \pm 2.3(\text{syst}) \text{mb} \]

- 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 2nd jet $p_T$, they drop from $\sim 5.5\%$ at 15-20 GeV, to $\sim 0.9\%$ 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 $p_T$-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.
Studies of MPI events (esp at high pTs) 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 dPDFs. Plus $\sigma_{\text{eff}}$ should drop due to the dPDF evolution. Thus, MPI can be important background to many 'new physics' processes at LHC.
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 (e.g. valence vs. sea quarks / gluons)?
  What observables could be used to improve understanding of transverse structure?

- When the assumption $G(x,b) = D(x) F(b)$ is true?
  In general, it is not:
  - $GPD(x_1,x_2,b)$ (e.g. arXiv:1009.2741);
    $F(b)$ should depend on the parton species;
    There is a log-dependence of gluon $F(b)$ on parton $x$
    from excl. $J/\psi$ production in DESY (see Backup)
  - Correlation between different partons in the nucleon (in $x$, spin, flavor)

$\Rightarrow$ More measurements of DP fractions and $\sigma_{\text{eff}}$ are needed
  - in 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 + ≥2 heavy flavour jets,
  diphoton+dijet, mutlijet Drell-Yan events.
BACK-UP SLIDES
Some other possible DP studies

- Measurement of DP and TP x-sections in the same type of events.
- Study of the gluon matter density in SP and DP events

A small–x spectator parton (not involved in main hard parton scattering) from the left proton propagates through the strong gluon field and acquires large pT \((BBL \ pT \gg \Lambda_{QCD})\).

\[ x = \frac{4 p_{\perp}^2}{x_R s} \]

(The small–x parton is then resolved in a collision with a large–xR parton from the right proton):

\[ \Rightarrow \text{results in extensive hadron production with } p_T > 1-2 \text{ GeV in the backward(forward) rapidity region} \]

In D0, the calorimeter can be used for this aim (with SPR corrections)

\[ \Rightarrow \text{Potentially may explain CMS “ridge” structure} \]

\[ \text{(arXiv:1009.4122)} \]

Average impact parameter \( b \) in hard SP, DP and incl. inelastic events

<table>
<thead>
<tr>
<th>Facility</th>
<th>( \sqrt{s}/\text{GeV} )</th>
<th>( \langle b^2 \rangle_{2}/\text{fm}^2 )</th>
<th>( \langle b^2 \rangle_{4}/\text{fm}^2 )</th>
<th>( \langle b^2 \rangle_{\text{in}}/\text{fm}^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHC</td>
<td>14000</td>
<td>0.67</td>
<td>0.26</td>
<td>2.7</td>
</tr>
<tr>
<td>Tevatron</td>
<td>1800</td>
<td>0.63</td>
<td>0.24</td>
<td>1.8</td>
</tr>
<tr>
<td>RHIC</td>
<td>500</td>
<td>0.59</td>
<td>0.23</td>
<td>1.43</td>
</tr>
</tbody>
</table>
From PRD61 (2000) 077502 by Fabbro, Treleani

Example: DP as background to $p+p \rightarrow WH$ at LHC

DP background as a function of H mass: LO and NLO $b\bar{b}$ production ($\mathcal{O}_{\text{eff}} = 14.5$ mb used here)

DP background is 3 orders of magnitude higher than the HW cross section

SP (dotted) and DP (dashed) cross sections after selection cuts

DP background is still very important even after selections
Prospects

Measurements coming soon in D0:

(1) $\gamma + \text{heavy flavor jet} + 2\text{jets events}$:
   Measurements of $\sigma_{\text{eff}}$ in the events with initial b or c quark in the initial state
   $\Rightarrow$ sensitivity to the b&c quark spatial distribution

(2) Study of DP events in $\gamma\gamma + 2\text{jet final state}$
   $\Rightarrow$ New and independent test of $\sigma_{\text{eff}}$ and MPI models

(3) DP events in the double J/psi production
   $\Rightarrow$ Extraction of $\sigma_{\text{eff}}$ at low pT
      Test of $\sigma_{\text{eff}}$ energy dependence
Track angular correlations in minbias events

- Use correlations in $\Delta \phi$ to characterize Minimum Bias Events
- Compare data to various Monte Carlo tunes and models

**Strategy:** Associate all tracks to PVs and then select good quality tracks associated to minbias PVs. Minimize fakes, cosmics, conversions, long-lived resonances, vertex mis-associations
  - $p_T > 0.5$ GeV
  - $|\eta| < 2$

- Trigger on dimuon events
- Require exactly 2 muons with $p_T > 2$ GeV associated with the same vertex
- Then require one or more Minimum Bias PVs
  - At least 5 tracks
  - At least 0.5 cm from triggered PV
  - Within 20 cm of center of detector

Tests with same-sign and opposite-sign events in $\eta$
Δφ comparison to MC

\[
\Delta \phi \text{ subtracted, normalised } |\eta| < 2
\]

**DO Preliminary**
\[\sqrt{s} = 1.96 \text{ TeV}\]

- Data
- Pythia Tune A
- Pythia Tune P0
- Pythia GAL

\[
\frac{(N^T - N^T_{\text{min}})}{(\sigma / 50)}
\]

\[\Delta \phi\]

\[
\Delta \phi \text{ subtracted, normalised } |\eta| < 1
\]

**DO Preliminary**
\[\sqrt{s} = 1.96 \text{ TeV}\]

- Data
- Pythia Tune A
- Pythia Tune P0
- Pythia GAL

\[
\frac{(N^T - N^T_{\text{min}})}{(\sigma / 50)}
\]

\[\Delta \phi\]
Transverse distributions: Gluons from $J/\psi$

- Exclusive process $\gamma^* N \rightarrow J/\psi + N$
  
  Gluon GPD at $x \sim m_{\psi}^2 / W^2$, $Q^2 \sim 3 \text{GeV}^2$

  Reaction mechanism, universality tested at HERA $H1, \text{ZEUS}$

  Transverse profile from relative $t$–dependence

- Transverse gluonic size of nucleon

  Gluons concentrated at center
  
  $\langle \rho^2 \rangle_g (x \sim 10^{-2}) < \langle b^2 \rangle_{\text{charge}}$

  Radius grows slowly with decreasing $x$
  
  $\alpha_g' \ll \alpha_P' = 0.25 \text{GeV}^{-2}$

  Gribov diffusion suppressed by hard scale

  $Q^2$ dependence from DGLAP evolution calculable, weak $FSW, \text{PRL}69 (2004) 114010$
Final states: Underlying event

- Two different sizes

\[ R^2(\text{soft}) \gg R^2(\text{partons } x > 10^{-4}) \]

Hard parton–parton processes require central \( pp \) collisions

Trigger on high–\( p_T \) jet selects central \( pp \) collisions!

- Geometric correlations

High–\( p_T \) trigger \( \rightarrow \) central collisions \( \rightarrow \) event characteristics

Example: Transverse multiplicity
Also: Rapidity dependence, energy flow, . . .

Reveals minimum \( p_T \) for hard production:
Test of production mechanism
FSW, PRD83 (2011) 054012

Model–independent! Benchmarks for detailed MC simulations
FIG. 13. Separation of multiplicity distribution at 540 GeV by number of interactions in event for double-Gaussian matter distribution. Long dashes, double diffractive; dashed-dotted one interaction; thick solid line, two interactions; dashed line, three interactions; dotted line, four or more interactions; thin solid line, sum of everything.

FIG. 15. Average charged multiplicity as a function of the “enhancement factor” $f(b)$. Notation as in Fig. 14.
Like-sign WW boson production

- No branching ratios or cuts are included

- SP process: $\sigma(W^+W^+) \sim \alpha_{sw}^2 \sigma(W^+W^-)$
  
  LHC: $\sigma(W^+W^+) > \sigma(W^-W^-)$
  
  TeV: $\sigma(W^+W^+) = \sigma(W^-W^-)$

Table 1: The expected number of $WW$ events expected for $\mathcal{L} = 10^8$ pb$^{-1}$ at the LHC from single and double scattering, assuming $\sigma_{eff} = 14.5$ mb for the latter.
1\textsuperscript{st} and 2\textsuperscript{nd} interactions: Estimates of possible correlations

... in the momentum space:

1\textsuperscript{st} interaction: photon pT ≃ 70 GeV, ⇒ parton xT ≃ 0.07
2\textsuperscript{nd} interaction: jet pT ≃ 20 GeV, ⇒ parton xT ≃ 0.02

large (almost unlimited) kinematic space for the 2\textsuperscript{nd} interaction

... at the fragmentation stage:

=> Simulate γ+3 jets and di-jets with switched off ISR/FSR; then additional 2 jets in γ+3 jets should be from 2\textsuperscript{nd} parton interaction

=> compare 2\textsuperscript{nd} (3\textsuperscript{rd}) jets pT/Eta in γ+3 jets with 1\textsuperscript{st} (2\textsuperscript{nd}) jet pT/Eta in dijets

=> Tunes tested: A, A-CR, S0

From D.Wicke & P.Skands hep-ph:0807.3248
\( \gamma + 3 \) jets and di-jets, IFSR=OFF: jets pT comparison.

**Tune A**

- pT and Eta distributions are analogous for jets from 2nd interaction in \( \gamma + 3 \)jets and di-jet events
- Analogous results (incl. 3rd jet from \( \gamma + 3 \)jets and 2nd from di-jets) are obtained for Tunes A-CR, S0.
$\gamma + 3$ jets and di-jets, IFSR=OFF: jets pT comparison.

Tune A-CR
**Signal:** Double Parton (DP) production: 1\textsuperscript{st} parton process produces $\gamma$-jet pair, while 2\textsuperscript{nd} process produces dijet pair.

**Background:** Single Parton (SP) production: single hard $\gamma$-jet scattering with 2 radiation jets in 1 vertex events.

**Background:** Single Parton (SP) production: single hard $\gamma$-jet scattering in one vertex with 2 radiation jets and soft unclustered energy in the 2\textsuperscript{nd} vertex.

**Signal:** Double Interaction (DI) production: two separate collisions within the same beam crossing, producing $\gamma$-jet and dijet pairs.
Built from D0 data by analogy to Double Parton model with the only difference: ingredient events ($\gamma$+jets and dijets) are 2-vertex events.

In case of 2 jets, both jets are required to originate from the same vertex using jet track information.

Main difference of Double Parton and Double $p\bar{p}$ Interaction signal events and corresponding SP backgrounds: different amount of soft unclustered energy in 1-vertex vs. 2-vertex events → different photon and jet ID efficiencies.
To calculate $\sigma_{\text{eff}}$, we also need $N_{\text{DI}} = f_{\text{DI}} N_{\text{2vtx}}$.

- Use $\Delta S$ shapes and get $f_{\text{DI}}$ by fitting DI signal and background distributions to 2-vertex data.

**Fractions of Double $p \bar{p}$ Interactions (DI) events**

Total sum of DI signal+bkgd, weighted with DI fractions, is in agreement with data.

Main uncertainties in DI fractions are from building DI signal and background models.
Total numbers of events with 1 and 2 hard $p \bar{p}$ collisions, $N_c(1)$ and $N_c(2)$, are calculated from the expected average number of hard interactions at a given instantaneous luminosity $L_{inst}$:

$$\bar{n} = \left( \frac{L_{inst}}{f_0} \right) \sigma_{hard}$$

using Poisson statistics.

$f_0$ is a frequency of the beam crossings at the Tevatron in RunII. $\sigma_{hard}$ is hard (non-elastic, non-diffractive) $p \bar{p}$ cross section. It is $44.7 \pm 2.9$ mb : from Run I $\rightarrow$ Run II extrapolation.

$$R_c = \frac{N_c(1)}{2N_c(2)} \sigma_{hard} = 52.3 \text{mb}$$

Variation of $\sigma_{hard}$ within uncertainty (2.9 mb) gives the uncertainty for $R_c$ of just about 1.0 mb: increase of $\sigma_{hard}$ leads to decrease of $N_c(1)/N_c(2)$ and vice versa.
Comparison of $\gamma$+3 jets measurements: CDF'97 vs. D0'09

- Center of mass energy: 1.8 $\rightarrow$ 1.96 TeV

- About a factor 60 increase in the integrated luminosity allows to change selections:
  - $\text{photon pT} > 16$ GeV (CDF) $\rightarrow$ 60 < pT < 80 GeV (D0)
  - A better separation of 2 partonic scatterings in the momentum space
  - A higher photon purity (due to also tighter photon ID)
  - A better determination of energy scales of 1$^{\text{st}}$ parton process

- Higher jet pTs and JES correction to the particle level
  - Jet pT (uncorr.) > 6 GeV $\rightarrow$ pT (corr.) > 15 GeV

- Binning in the 2$^{\text{nd}}$ jet pT: 15 - 20; 20 - 25, 25 - 30 GeV
  - A better determination of energy scales of 2$^{\text{nd}}$ process
  - Study of Double Parton fractions and $\sigma_{\text{eff}}$ vs. 2$^{\text{nd}}$ jet pT

- Double Parton fractions and $\sigma_{\text{eff}}$ are inclusive: we do not subtract fractions of events with triple parton (TP) interactions (TP fractions are presented as a separate result)
Type II events (1 jet from dijet and 1 brems. jet) dominate (≥73%): It is caused by jet reco eff-cy and threshold (6 GeV for pT_raw) and difference in jet pT (it is smaller for dijets)

CDF ('97) found at least 75% Type II events: a good agreement.

Small fraction of Type III events.

Dominance of Type II naturally reduces a dependence of results (see variable ΔS below) on possible issues with correlations between 1st & 2nd parton interactions.
Pythia MPI Tunes: $\Delta S$ and Njets

Pythia predictions with MPI tunes:
- $\Delta S$ is much broader for events with MPI events and almost flat at $\Delta S < 1.5$
- $\#\text{events}(\text{Njest} \geq 1) / \#\text{events}(\text{Njets} \geq 3)$ is larger by a factor 2(!) for MPI events
SP events (Pythia): $\Delta S$ distributions

$p_T^{jet2}$, GeV

$1/N \frac{dN}{d\Delta S_{p_T}}$

$p_T^{jet2}$, GeV

$1/N \frac{dN}{d\Delta S_{p_T}}$
Introducing the 3D parton density $\Gamma(x, b)$ and making the assumption $\Gamma(x, b) = G(x)f(b)$ one may express the single scattering inclusive cross section as

$$\sigma_S = \int_{p_i^c} G(x)\hat{\sigma}(x, x')G(x')dx dx'$$

$$= \int_{p_i^c} G(x)f(b)\hat{\sigma}(x, x')G(x')f(b - \beta)d^2bdx dx'd^2\beta$$

$$\sigma_D = \frac{1}{2!} \int_{p_i^c} G(x_1)f(b_1)\hat{\sigma}(x_1, x'_1)G(x'_1)f(b_1 - \beta)d^2b_1dx_1 dx'_1 \times$$

$$\times G(x_2)f(b_2)\hat{\sigma}(x_2, x'_2)G(x'_2)f(b_2 - \beta)d^2b_2dx_2 dx'_2 d^2\beta$$

$$= \frac{1}{2!} \int (\int_{p_i^c} G(x)f(b)\hat{\sigma}(x, x')G(x')f(b - \beta)d^2bdx dx')^2 d^2\beta$$

$$= \frac{1}{2} \sigma_S$$

where $$\sigma_{\text{eff}}^{-1} = \int d^2\beta [F(\beta)]^2$$ is effective cross section

$$F(\beta) = \int f(b)f(b - \beta)d^2b,$$

and $f(b)$ is the density of partons in transverse space.
DP cross section:
\[
\sigma_{(A,B)}^D = \frac{m}{2} \sum_{i,j,k,l} \int \Gamma_{ij}(x_1, x_2, b; Q_1^2, Q_2^2) \hat{F}_{ik}(x_1, x_1') \hat{F}_{jl}(x_2, x_2') \\
\times \Gamma_{kl}(x_1', x_2', b; Q_1^2, Q_2^2) dx_1 dx_2 dx_1' dx_2' d^2b.
\]

Generalized 2-parton distributions:
\[
\Gamma_{ij}(x_1, x_2, b; Q_1^2, Q_2^2) = D_{ij}^{(i,j)}(x_1, x_2; Q_1^2, Q_2^2) F_{ij}(b).
\]

\(b\) – distance between two partons in the transverse plane
\(F_{ij}(b)\) – parton spatial density functions

2-parton momentum density function
\[
D_{ij}^{(i,j)}(x_1, x_2; Q_1^2, Q_2^2) = D_{i}^i(x_1, Q_1^2) D_{j}^j(x_2, Q_2^2).
\]

\(\sigma_{(A,B)}^D\) assumption (used in the meas.)

\(F_{ij}(b)\) is also assumed to be same for partons of types i and j

\[
\sigma_{(A,B)} = \frac{m}{2} \frac{\sigma_{(A)} \sigma_{(B)}}{\sigma_{\text{eff}}},
\]

\[
\sigma_{\text{eff}} = \left[ \int d^2b (F(b))^2 \right]^{-1}
\]
Selection criteria for $\gamma + 3\text{jet}$ events

**PHOTON:**
- photons with $|\eta|<1.0$ and $1.5<|\eta|<2.5$
- $60<p_T<80$ GeV (good separation of 1$^{st}$ and 2$^{nd}$ parton interactions)
- Shower shape cuts
- Calo isolation ($0.2<dR<0.4)<0.07$
- Track isolation ($0.05<dR<0.4)<1.5$ GeV
- Track matching probability $<0.001$

**JETS (pT corrected):**
- Midpoint Cone algo with $R=0.7$
- $|\eta|<3.0$
- #jets $\geq 3$
- $p_T$ of any jet $>15$ GeV
- $p_T$ of leading jet $>25$ GeV
- $p_T$ of 2$^{nd}$ jet $\in (15,20), (20,25), (25,30)$ GeV.
- $\Delta R($any objects pair$)>0.9$
A comparison of the cross sections for single and double encounter process with increase in sigma_NSD above its minimum of about 32 mb, as a function of Sqrt(s).
Overview of the calorimeter

- Liquid argon active medium and (mostly) uranium absorber
- Hermetic with full coverage: $|\eta| < 4.2$
- Segmentation (towers): $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ ($0.05 \times 0.05$ in 3rd EM layer)
- Three main subregions: Central ($|\eta|<1.1$), Intercryostat ($1.1<|\eta| <1.5$) and End calorimeters ($1.5 < |\eta| < 4.2$)
- Stable response, good resolution

46000 channels
50 non-working channels