Double parton scattering measurements at CMS

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Multiple parton interactions

- Theoretical idea dates back to the parton model
- Double parton scattering signatures: 4 jets, 2 jets and W, 3 jets and photon, etc...
- LHC is especially abundant in MPI
  - high energy final states
- Complicated correlation effects are still unexplored
- The effective cross section: overlap of the spatial distributions of partons in the transverse plane
- Experimental challenges:
  - DPS final states can also be produced by SPS
  - Sometimes complicated multivariate analyses
2 jets + 2 b-jets in pp collisions at 7 TeV

- Kinematical distributions between 2 b-jets and 2 light jets
- Data well described by pQCD @NLO with PS and MPI
- Jet correlations do not agree with no-MPI models
2 jets + 2 b-jets in pp collisions at 7 TeV

- $\sigma(pp \rightarrow bb+jj+X) = 69\pm3(st)\pm24(sy)\text{nb}$ for $p_T > 20$ GeV and $|\eta_{b(j)}| < 2.4(4.7)$
- $\Delta S$: azimuthal angle between two dijet pairs
DPS in W+2jets in pp collisions at 7 TeV

- $W \rightarrow \mu\nu$ decay with two associated jets, 5 fb$^{-1}$ data, template fit
- Fraction of $W$ from DPS: $0.055 \pm 0.002$ (stat) $\pm 0.014$ (syst)
- MadGraph5+PYTHIA8 and POWHEG2 + PYTHIA6: MPI is needed
- From that, $\sigma_{\text{eff}} = 20.7 \pm 0.8$ (stat) $\pm 6.6$ (syst) mb
DPS in same-sign WW events at 13 TeV

- $W^\pm W^\pm$ studied in the $\mu^\pm \mu^\pm$ and $e^\pm \mu^\pm$ final states. 2016 data
- Single parton scattering (SPS): 2 jets in the final state!
DPS in same-sign WW events at 13 TeV

• $W^\pm W^\pm$ studied in the $\mu^\pm \mu^\pm$ and $e^\pm \mu^\pm$ final states. 2016 data
• Single parton scattering (SPS): 2 jets in the final state!
• Therefore, the event selection uses a jet veto:

\begin{align*}
\text{two leptons: } e^\pm \mu^\pm \text{ or } \mu^\pm \mu^\pm \\
p_T^{\ell_1} > 25 \text{ GeV}, \ p_T^{\ell_2} > 20 \text{ GeV} \\
|\eta_e| < 2.5, \ |\eta_\mu| < 2.4 \\
E_T^{\text{miss}} > 15 \text{ GeV} \\
N_{\text{jets}} < 2 \ (p_T > 30 \text{ GeV}) \\
N_{\text{b-jets}} = 0 \ (p_T > 25 \text{ GeV}) \\
veto on additional leptons \\
veto on hadronic $\tau$ lepton decays
\end{align*}
DPS in same-sign WW events at 13 TeV

- A multivariate classifier is used to distinguish signal and bkgd
DPS in same-sign WW events at 13 TeV

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DPS in same-sign WW events at 13 TeV

- BDT classifier output for $e^-\mu^-$ and $e^+\mu^+$
DPS in same-sign WW events at 13 TeV

- BDT classifier output for $\mu^-\mu^-$ and $\mu^+\mu^+$
DPS in same-sign WW events at 13 TeV

- Expected background and signal yields, and observed number of data events in 35.9 fb\(^{-1}\):

<table>
<thead>
<tr>
<th>Source</th>
<th>(\mu^+\mu^+)</th>
<th>(\mu^-\mu^-)</th>
<th>(e^+\mu^+)</th>
<th>(e^-\mu^-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fakes</td>
<td>151.1 (\pm) 26.6</td>
<td>132.7 (\pm) 23.4</td>
<td>412.7 (\pm) 47.2</td>
<td>341.4 (\pm) 39.0</td>
</tr>
<tr>
<td>WZ</td>
<td>277.2 (\pm) 28.1</td>
<td>164.5 (\pm) 16.7</td>
<td>355.9 (\pm) 36.1</td>
<td>228.1 (\pm) 23.2</td>
</tr>
<tr>
<td>ZZ</td>
<td>24.8 (\pm) 7.0</td>
<td>18.7 (\pm) 5.3</td>
<td>57.8 (\pm) 16.4</td>
<td>55.8 (\pm) 15.8</td>
</tr>
<tr>
<td>W(\gamma^*)</td>
<td>85.9 (\pm) 27.5</td>
<td>73.1 (\pm) 23.4</td>
<td>142.8 (\pm) 45.7</td>
<td>127.7 (\pm) 40.9</td>
</tr>
<tr>
<td>Other rare</td>
<td>39.7 (\pm) 15.0</td>
<td>20.2 (\pm) 7.7</td>
<td>83.7 (\pm) 31.7</td>
<td>49.4 (\pm) 18.8</td>
</tr>
<tr>
<td>Charge flips</td>
<td>—</td>
<td>—</td>
<td>20.4 (\pm) 0.0</td>
<td>21.5 (\pm) 0.0</td>
</tr>
<tr>
<td>Background</td>
<td>578.6 (\pm) 50.3</td>
<td>409.2 (\pm) 38.2</td>
<td>1073.3 (\pm) 83.0</td>
<td>824.0 (\pm) 65.8</td>
</tr>
<tr>
<td>DPS WW</td>
<td>41.1 (\pm) 1.0</td>
<td>20.6 (\pm) 0.5</td>
<td>48.7 (\pm) 1.2</td>
<td>24.1 (\pm) 0.6</td>
</tr>
<tr>
<td>Observed</td>
<td>604</td>
<td>411</td>
<td>1091</td>
<td>869</td>
</tr>
</tbody>
</table>
DPS in same-sign WW events at 13 TeV

- Fit to the constrained BDT classifier
- Result: $1.09^{+0.50}_{-0.49}$ pb ($2.23\sigma$), PYTHIA 8 prediction: 1.64 pb

<table>
<thead>
<tr>
<th></th>
<th>expected</th>
<th>observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{\text{DPSWW}}^{\text{pythia}}$</td>
<td>1.64 pb</td>
<td>$1.09^{+0.50}_{-0.49}$ pb</td>
</tr>
<tr>
<td>$\sigma_{\text{DPSWW}}^{\text{factorized}}$</td>
<td>0.87 pb</td>
<td></td>
</tr>
<tr>
<td>significance for $\sigma_{\text{DPSWW}}^{\text{pythia}}$</td>
<td>3.27 $\sigma$</td>
<td>2.23 $\sigma$</td>
</tr>
<tr>
<td>significance for $\sigma_{\text{DPSWW}}^{\text{factorized}}$</td>
<td>1.81 $\sigma$</td>
<td></td>
</tr>
<tr>
<td>UL in the absence of signal</td>
<td>$&lt; 0.97$ pb</td>
<td>$&lt; 1.94$ pb</td>
</tr>
</tbody>
</table>
DPS in same-sign WW events at 8 TeV

- $W^\pm W^\pm$ events in 19.7 fb$^{-1}$ of data at 8 TeV
- Our first search for same-sign WW production via DPS
- Event selection:

<table>
<thead>
<tr>
<th>Dimuon channel</th>
<th>Electron-muon channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pair of same-sign leptons</td>
<td></td>
</tr>
<tr>
<td>Leading lepton $p_T &gt; 20$ GeV</td>
<td></td>
</tr>
<tr>
<td>Subleading lepton $p_T &gt; 10$ GeV</td>
<td></td>
</tr>
<tr>
<td>No third isolated and identified lepton with $p_T &gt; 10$ GeV</td>
<td></td>
</tr>
<tr>
<td>$p_T^{\text{miss}} &gt; 20$ GeV</td>
<td></td>
</tr>
<tr>
<td>$m_{\ell\ell} &gt; 20$ GeV</td>
<td></td>
</tr>
<tr>
<td>$m_{\ell\ell} \notin [75, 105]$ GeV</td>
<td>No b-tagged jet with $p_T &gt; 30$ GeV and $</td>
</tr>
<tr>
<td>$</td>
<td>p_{T_{\mu_1}}</td>
</tr>
</tbody>
</table>

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DPS in same-sign WW events at 8 TeV

- Distribution of the BDT discriminant in the $\mu^\pm\mu^\pm$ and $e^\pm e^\pm$ events
DPS in same-sign WW events at 8 TeV

- No significant excess observed above the SPS process
- 0.32 pb is the upper limit (95% CL) for DPS
- Therefore a **lower limit of 12.2 mb** is set for the effective DPS cross section parameter (95% CL)
Effective cross section compilation

- Summary of the effective DPS cross section measurements

\[ \sigma_{\text{eff}} \text{ extractions (vector boson final states)} \]

- CDF $\gamma+3\text{jets (1.8 TeV)}$
PRL 79 (1997) 584
- D0 $\gamma+3\text{jets (1.96 TeV)}$
PRD 89 (2014) 072006
- D0 $\gamma+b/c+2\text{jets (1.96 TeV)}$
PRD 89 (2014) 072006
- D0 $2\gamma+2\text{jets (1.96 TeV)}$
PRD 93 (2016) 052008
- ATLAS $W+2\text{jets (7 TeV)}$
New J. P. 15 (2013) 033038
- CMS $W+2\text{jets (7 TeV)}$
JHEP 03 (2014) 032
- ATLAS $Z+J/\psi (8 \text{ TeV})$
EPJC 75 (2015) 229
- CMS $WW\text{ DPS (8 TeV)}$
JHEP 02 (2018) 032
- CMS $W^\pm W^\pm (13 \text{ TeV})$
PAS FSQ-16-009 (2017)
Summary

• **Multi Parton Interactions** can be studied in many ways, in various channels
  – Multiple jets
  – Vector bosons and multijets
  – vector boson pairs...

• **Challenges**:
  – Complicated **multivariate** analysis methods
  – Finding appropriate and sensitive **observables** is nontrivial
  – High **luminosity** is often essential

• **Very active field and important new observations**:
  – Tiny cross sections, extreme **tests** of the Standard Model,...

*With more date collected, new opportunities!*
The CMS experiment

- Muon Chambers
- Inner Tracker
- Crystal ECAL.
- Very Forward Calorimeter
- HCAL
- Superconducting Coil
- Return Yoke

Total Weight: 14,500 t.
Overall diameter: 14.60 m
Overall length: 21.60 m
Magnetic field: 4 Tesla
The CMS Experiment
DPS in $\gamma + 3$ jets in pp collisions at 7 TeV

- 36 pb$^{-1}$ of data in 2010
- The photon and the leading jet are required to have $p_T > 75$ GeV
- Two other jets are in the $p_T > 20$ GeV range
DPS in $\gamma$+3 jets in pp collisions at 7 TeV

- Many kinematical distributions are compared to MC predictions
- For example, $\Delta S$ distributions are sensitive to DPS in the low $\Delta S$ region
- Higher order, parton showers affect the SPS contributions
- MC with and without MPI do not differ significantly
- Conclusion on DPS component is not possible within this given precision

- Let us look at other observables!

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