Double Parton Interaction with leptonic final state at the LHC

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Double Parton Interaction

- The Double Parton Interaction (DPI) is a form of Multi Parton Interactions which assumes that 2 hard parton-parton interactions can simultaneously appear at the same hadron-hadron interaction.
- Double Drell-Yan Process describes the creation of a neutral vector boson pair via the DPI mechanism.
- Useful process for further information about proton structure.
- Background source for many processes of Run 2 (Higgs / SUSY)

4 leptons final state from DPI will be examined
DPI phenomenology

- The cross-section of the DPI can be expressed as function of the double PDFs: \( \Gamma(x_1, x_2; b) \rightarrow \) factorized by standard PDFs, \( f(x_1), f(x_2) \), convoluted with the overlap function \( F(b) \).
- \( x \): momentum fractions of interacting partons.
- \( b \): relative transverse distance of the partons.

\[
\sigma_D = \frac{m}{2} \int_{p_T} \Gamma(x_i, x_j; b)\hat{\sigma}(x_i, x_k)\hat{\sigma}(x_j, x_l)\Gamma(x_k, x_l; b) \times dx_idx_jdx_kdx_l
\]

Generic form for cross-section

Simpler form for DPI cross-section

\[
\sigma_D = \frac{m}{2} \sum_{ijkl} \int \sigma_s^{ij} \times \sigma_s^{kl} \times F_k^i(b) \times F_l^j(b)d^2b
\]

The spatial correlations in the transverse plane are approximated by the factor \( \sigma_{\text{eff}} \)

\[
\sigma_{\text{eff}}^{-1} = \int [F(b)]^2 d^2b
\]
DPI phenomenology

- With the inclusion of $\sigma_{\text{eff}}$, and assuming 2 uncorrelated hard scatterers, the cross-section for DPI (here: Double Drell-Yan process), can be expressed as:

\[ \sigma_{\text{DPI}} = \frac{1}{2} \frac{\sigma_{\text{SPI}}^2}{\sigma_{\text{eff}}} \]

The purely phenomenological parameter $\sigma_{\text{eff}}$ is useful for the description of multi-parton interactions:
- Effective area parameter.
- Related to the transverse plane of the interaction region.
- Defined in parton level.
- Dependence with fraction of momentum of scatters.
Effective cross-section measurements

- The measurement of the $\sigma_{\text{eff}}$ has been of a great interest for many analyses in the past.

- The measured values of $\sigma_{\text{eff}}$ are quite well localized with relatively small uncertainties. Most of them used Jets.

- Recently ATLAS and D0 used $(Z + J/\psi)$ and double $J/\psi$ with leptonic final state.

- Leptonic final state $\rightarrow$ Less reconstruction uncertainties than jets.

- How about a DPI measurement stemming from 2 $Z$ boson decays to 4 leptons?

Double Drell-Yan process

arXiv:1412.6428
Why 4 leptons?

• A DPI measurement containing 4 leptons has a very strong potential!
• Leptons uncertainties are well known and small. 
  ( < 2% impact in $H \rightarrow ZZ \rightarrow 4l$ mass search)
• Many analyses at various experiments worked with 4 leptons as final state (ATLAS: $H \rightarrow ZZ \rightarrow 4l$, $qq/gg \rightarrow ZZ \rightarrow 4l$, $qq \rightarrow Z \rightarrow 4l$)
• The “golden channel” of Higgs searches with very good S/B
• A Double Drell-Yan process could be background at $H \rightarrow ZZ \rightarrow 4l$

Starting point for present work!
• Actual effort has started in order to study DPI effects on \( H \rightarrow ZZ \rightarrow 4l \) signal with expected negligible contribution.

• Based on this study, we developed a method aiming to measure \( \sigma_{\text{DPI}} \) and the effective cross-section, \( \sigma_{\text{eff}} \), exploiting the clear 4-leptons final state.

• Aim to look on 8 TeV data for potential DPI measurement and \( \sigma_{\text{eff}} \) calculation.

• **Limits on \( \sigma_{\text{eff}} \) from Double Drell-Yan**

• Extending for **LHC future (Run 2 and beyond)**.

• **Potential measurement in HL-LHC ?**
Analysis method

- The proposed analysis is similar to Higgs → ZZ → 4l mass (arXiv:1408.5191) measurement object/event selection (leptons = e/mu):
  - Select events with two same-flavour, opposite-sign dilepton (e/μ) pairs;
  - pT 1,2,3,4 lepton = 20, 15, 10, 7(6) GeV for e (μ);
  - Tracking and calorimeter isolation;
  - Impact parameter significance cuts;
  - Both dilepton masses: 50 GeV < m_{12}(m_{34}) < 106 GeV.

- **Signal**: PowHeg+Pythia 8 (including a 2nd hard process), DPI sample of Z+Z → 4l.

- **Background**: PowHeg+Pythia 8, qq → ZZ → 4l and gg → ZZ → 4l sample.

- Exploit observables which can show clear separation between signal and background.
Analysis method

- The 2 Z bosons for this particular analysis are required to be “on-shell” (50 – 106 GeV).
- The invariant 4-leptons mass is required to be > 170 GeV to exclude any Z+jets bkg.
- The azimuthal angle ($\phi$) between the 2 Z bosons can provide a reduced background contamination, since it has flat distribution for DPI, but peaks on $\pi$ (back-to-back) for background.

$\Delta \phi$ $Z_1(Z_2)$

- Zs with $\Delta \phi < 2.1$ are considered for the analysis
Theoretical expectation

• Production cross-section (ZZ from DPI):

\[ \sigma_{DPI(ZZ)} = \frac{1}{2} \frac{\sigma_Z\sigma_Z}{\sigma_{eff}} \]

• For each channel: (4e, 2e2mu, 2mu2e, 4mu):
  (Separate 2e2mu / 2mu2e due to different acceptances)

\[ N_i = \mathcal{L} \times \sigma_{DPI(ZZ)} \times A_i \times C_i = \mathcal{L} \times \frac{1}{2} \frac{\sigma_Z\sigma_Z}{\sigma_{eff}} \times A_i \times C_i \]

• Summing all the channels together:

\[ N_{TOT} = \frac{2 \times \mathcal{L} \times \sigma_Z\sigma_Z \times A \times C}{\sigma_{eff}} \]
Fiducial Volume

- Pre-selection on MC generation (on transverse momentum ($p_T$) and pseudorapidity ($\eta$))
  $p_T(\text{lepton}) > 3 \text{ GeV}$ and $|\eta| < 5$

<table>
<thead>
<tr>
<th>Lepton selection</th>
<th>Event selection</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Muons</strong></td>
<td></td>
</tr>
<tr>
<td>$p_T &gt; 6 \text{ GeV}$, $</td>
<td>\eta</td>
</tr>
<tr>
<td><strong>Electrons</strong></td>
<td></td>
</tr>
<tr>
<td>$p_T &gt; 7 \text{ GeV}$, $</td>
<td>\eta</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Lepton pairing</th>
<th>DPI related cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Leading pair (Z1)</strong></td>
<td><strong>Mass requirement</strong></td>
</tr>
<tr>
<td>Dilepton pair with closest to the $Z$ mass</td>
<td><strong>Z separation</strong></td>
</tr>
<tr>
<td><strong>Subleading pair (Z2)</strong></td>
<td><strong>Mass window</strong></td>
</tr>
</tbody>
</table>
Acceptance (A, C)

\[
A = \frac{N_{MC\rightarrow Fid.Vol}^{Gen.ZZ}}{N_{MC\rightarrow All}^{Gen.ZZ}}
\]

\[
C = \frac{N_{MC\rightarrow Cuts}^{Reco.ZZ}}{N_{MC\rightarrow Fid.Vol}^{Gen.ZZ}} \times SF
\]

- “A” (Acceptance of the fiducial volume)
- “C” (Detection efficiency and resolution effects correction), SF denotes all the analysis weights

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>A</th>
</tr>
</thead>
<tbody>
<tr>
<td>4mu</td>
<td>0.766 +/- 0.033</td>
<td>0.366 +/- 0.012</td>
</tr>
<tr>
<td>4e</td>
<td>0.514 +/- 0.028</td>
<td>0.283 +/- 0.010</td>
</tr>
<tr>
<td>2e2mu</td>
<td>0.616 +/- 0.029</td>
<td>0.326 +/- 0.011</td>
</tr>
<tr>
<td>2mu2e</td>
<td>0.741 +/- 0.033</td>
<td>0.336 +/- 0.011</td>
</tr>
<tr>
<td>Combined</td>
<td>0.696 +/- 0.016</td>
<td>0.328 +/- 0.006</td>
</tr>
</tbody>
</table>

Work in Progress
Event expectation

• Having defined the Signal Region of the analysis, the event expectation is calculated for Integrated Luminosity = 20.3fb$^{-1}$
• The cross-sections used were corresponding to $\sqrt{s} = 8$ TeV.
• For the DPI expectation, $\sigma_{\text{eff}} = 15$ mb was assumed
• Signal Region:

\[
50 < Z_1/Z_2 < 106 \text{ GeV}, \ M_{4l} > 170 \text{ GeV}, \ |\Delta\phi(Z_1,Z_2)| < 2.1
\]

<table>
<thead>
<tr>
<th>Channel</th>
<th>$qq \rightarrow ZZ$</th>
<th>$gg \rightarrow ZZ$</th>
<th>DPI $\rightarrow Z_Z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4e</td>
<td>7.14</td>
<td>1.15</td>
<td>0.11</td>
</tr>
<tr>
<td>4mu</td>
<td>12.3</td>
<td>1.89</td>
<td>0.21</td>
</tr>
<tr>
<td>2e2mu</td>
<td>8.98</td>
<td>1.45</td>
<td>0.15</td>
</tr>
<tr>
<td>2mu2e</td>
<td>9.85</td>
<td>1.56</td>
<td>0.18</td>
</tr>
<tr>
<td>TOTAL</td>
<td>38.27</td>
<td>6.05</td>
<td>0.65</td>
</tr>
</tbody>
</table>

Work in Progress

Expected number of events

Dimitris Kyriazopoulos (University of Sheffield) – IOP 2015, Manchester, 1/4/2015
• An observable with good discrimination power between DPI and background is needed, which can drive the fit.

• Following the example of the ATLAS ($W+2\text{jets}$) DPI analysis we use the $\Delta$ variable which we construct for each dilepton pair. At the end we have the observable $(\Delta 1 \ast \Delta 2)$,

\[
\Delta = \frac{|\vec{p}_{T}^{\text{lep}_i} + \vec{p}_{T}^{\text{lep}_j}|}{|\vec{p}_{T}^{\text{lep}_i}| + |\vec{p}_{T}^{\text{lep}_j}|}
\]

• The momenta of the 2 leptons coming from $Z$ produced through DPI must compensate each other at the transverse plane

\[0.14 \quad 0.16 \quad 0.18\]

\[0.1 \quad 0.12 \quad 0.14\]

\[0.08 \quad 0.06 \quad 0.04\]

\[0.02 \quad 0\]

\[0 \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \quad 1\]

Very good discriminant!
Closure test

- With the previously assumed expectations the Asimov dataset is constructed / (Asimov dataset: Representative simulated event sample, using asymptotic approximations), and a simultaneous fit is performed at the observable.

<table>
<thead>
<tr>
<th>Channel</th>
<th>DPI Expected (20.3/ fb @8TeV)</th>
<th>Fitted (Asimov)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4e</td>
<td>0.11</td>
<td>0.107 +/- 1.883</td>
</tr>
<tr>
<td>4μ</td>
<td>0.21</td>
<td>0.207 +/- 2.531</td>
</tr>
<tr>
<td>2e2μ</td>
<td>0.15</td>
<td>0.148 +/- 2.169</td>
</tr>
<tr>
<td>2μ2e</td>
<td>0.18</td>
<td>0.183 +/- 2.185</td>
</tr>
</tbody>
</table>

σ_eff (mb) | 15 | 15 +/- 2.44 |
Expected limits

- From the fit results on the Asimov dataset, using the Profile Likelihood estimation we set at 95% CL, upper limits on the number of DPI events and lower limits on $\sigma_{\text{eff}}$.

<table>
<thead>
<tr>
<th>Property</th>
<th>Lower / Upper Limit (95% CL)</th>
<th>Expected limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>DPI events</td>
<td>$&lt; 10.92$</td>
<td>10.88 ($+4.85 - 3.17$ 1σ, $+11.37 - 5.12$ 2σ)</td>
</tr>
<tr>
<td>$\sigma_{\text{eff}}$</td>
<td>$&gt; 0.92$ mb</td>
<td>0.93 mb ($+0.38 - 0.29$ 1σ, $+0.82 - 0.47$ 2σ)</td>
</tr>
</tbody>
</table>
HL-LHC projections

- The future proposed High Luminosity – LHC (HL-LHC) will provide excellent conditions for further investigating of the partonic model. The DPI process to 4-leptons will be a very challenging channel to investigate.

- Using the existing framework, the number of expected events is scaled up at 14 TeV and 95% CL limits are reproduced.
Conclusions

• The Double Drell-Yan process is of great interest for further investigating the properties of the partonic model.

• A comparison of the parameter $\sigma_{\text{eff}}$ extracted for DDYP and other processes will provide a better understanding of the proton structure, the form factors and the pertubative QCD properties.

• An alternative method for $\sigma_{\text{eff}}$ measurement is proposed, using 4 leptons (electrons, muons) as final state from Z bosons coming from Double Drell-Yan.

• Using observables related with kinematics at the transverse plane, closure tests were performed. From this MC study, a lower limit on $\sigma_{\text{eff}}$ can be set. Next step will be to look at 8 TeV ATLAS data.

• The prospects for a future measurement at the LHC/ HL-LHC era are presented, demonstrating the big potential of this analysis at higher luminosities.

Thank you!
BACKUP
Production of a $Z$ boson in association with $J/\psi$ allows studies of multiple parton scattering.

The small $\Delta \phi(Z, J/\psi)$ region is sensitive to DPS contributions.

With the assumption that all observed signal in the first bin ($\Delta \phi(Z, J/\psi) < \pi/5$ region) is due to DPS, a lower limit $\sigma_{\text{eff}} > 5.3$ mb (3.7 mb) at 68% (95%) confidence level can be extracted.

arXiv:1412.6428
D0 – J/psi + J/psi

- Doubly produced prompt J/psi
- Estimated 15% of events to be from Double Parton
- Measuring cross-section of DP events, then using sigma_eff formula:

\[ \sigma_{eff} = \frac{\sigma(J/\psi)^2}{\sigma(J/\psi)(J/\psi)} \]

\[ \sigma_{eff} = 4.8 \pm 0.5 \text{ (stat)} \pm 2.5 \text{ (syst)} \text{ mb} \]

arXiv:1406.2380
Closure test - Asimov

ATLAS Work in Progress

ATLAS Work in Progress

ATLAS Work in Progress

ATLAS Work in Progress