Double Parton Scattering at hadron colliders
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Outline
1) Intro to DPS
2) Review analyses
   ~ 2 $\gamma$ + 2 $j$
   ~ 2 b-jets + 2 light-jets
   ~ 4 jets
   ~ di-quarkonia
   ~ same-sign WW
3) Outlook / Overview
Single Parton Scattering (SPS)
• one hard parton-parton scatter

Double Parton Scattering (DPS)
• two hard scatters within same protons
Why Study DPS?

**Single Parton Scattering (SPS)**
- Probe higher-order diagrams
- Disentangle backgrounds at higher $\sqrt{s}$
- Color Octet vs Singlet models in quarkonia production

**Double Parton Scattering (DPS)**
- Increasingly important at higher $\sqrt{s}$
- Probe transverse profile of proton PDF
- Partonic correlations?
  - color, flavor interference, spin effects?

**Next-to-Leading Order SPS vs Leading Order DPS**

- $\sigma_{\text{SPS}} \sim \text{(parton density)}^2$
- $\sigma_{\text{DPS}} \sim \text{(parton density)}^4$

![Graph showing comparisons between SPS and DPS](chart.png)
**DPS cross section**

- Convolution of PDFs & elementary xsecs summed over all partons

\[
\sigma^{DPS}_{hh'\to ab} = \left( \frac{m}{2} \right) \sum_{i,j,k,l} \int \Gamma_{h}^{ij}(x_1, x_2; b_1, b_2; Q_1^2, Q_2^2) \\
\times \delta_{a}^{ij}(x_1, x_1'; Q_1^2) \delta_{b}^{jl}(x_2, x_2'; Q_2^2) \\
\times \Gamma_{h'}^{kl}(x_1', x_2'; b_1 - b, b_2 - b; Q_1^2, Q_2^2) \, dx_1 \, dx_2 \, dx_1' \, dx_2' \, db_1 \, db_1 \, db_2 \, db_2 \]

- Reduces to ‘pocket formula’ after assumptions:
  - Longitudinal, transverse components factorize
  - Long’tl comps = 2 independent single-PDFs

\[
\sigma^{DPS}_{hh'\to ab} = \left( \frac{m}{2} \right) \frac{\sigma^{SPS}_{(hh'\to a) \cdot \sigma^{SPS}_{(hh'\to b)}}}{\sigma_{eff}}
\]

- Where \( m \) is number of “distinguishable partonic subprocesses”
  - \( m=1 \) for \( J/\psi-J/\psi \), \( m=2 \) for \( J/\psi-Y \)

**What is “\( \sigma_{eff} \)” ?**

- ~effective transverse overlap area
- ~transverse distance btwn partons
- ~partonic density
- ~tells about “conditional prob” to have a second hard scatter
- Theory estimates ~30 mb
- Data says ~5-25 mb
- ~15 mb typically used for calculations
World Data for $\sigma_{\text{eff}}$

**Sigma Effective**

$$\sigma_{\text{eff}} = \left( \frac{m}{2} \right)^2 \frac{\sigma_{\text{SPS}}^{(ab)} \cdot \sigma_{\text{SPS}}^{(a)} \cdot \sigma_{\text{SPS}}^{(b)}}{\sigma_{\text{DPS}}^{(ab)}}$$

When does DPS play a role?

- several particles in final state (typically 4 or more)
- high-energy hadron collisions (probing low-$x$)

A few examples:

- multi-jets (4 jets, 3 jets + $\gamma$, etc)
- di-quarkonia
- double open-charm/beauty
- $Z/W + (\text{jets} / \text{quarkonia} / \text{etc})$
- double same-sign $W$

addressed in this talk
D0 – Tevatron 1.96 TeV

- Key discriminant: azimuthal angle between di-photon & di-jet

\[ \Delta S \equiv \Delta \phi \left( \vec{q}_T^1, \vec{q}_T^2 \right) \]

\[ \vec{q}_T^1 = p_T^{\gamma 1} + p_T^{\gamma 2} \]

\[ \vec{q}_T^2 = p_T^{jet 1} + p_T^{jet 2} \]

- templates based on Sherpa (&S) Pythia
- \( \sigma_{SPS} \cdot \sigma_{SPS} \) estimated via PU evts with 2 vertices and \( \gamma\gamma + \) jet-jet

\[ \sigma_{eff} = 19.3 \pm 1.4\text{(stat)} \pm 7.8\text{(syst)} \text{mb} \]
CMS – LHC 7 TeV

- Key discriminant: azimuthal angle between b-jets and light jets
  \[ \Delta S \equiv \Delta \phi \left( \vec{q}_T^1, \vec{q}_T^2 \right) \]

- addt’nl handle via relative \( p_T \) balance btwn two lighter jets

- without Multi Parton Interactions included, MC cannot reproduce data (~60% low!)
2 b-jets + 2 jets

CMS – LHC 7 TeV

- Key discriminant: azimuthal angle between b-jets and light jets
  \[ \Delta S \equiv \Delta \phi \left( \vec{q}_T^1, \vec{q}_T^2 \right) \]
- addt’nl handle via relative \( p_T \) balance btwn two lighter jets
- without Multi Parton Interactions included, MC cannot reproduce data
- with MPI, MC agrees with data!
- no \( \sigma_{eff} \) estimation… stay tuned?
- note: MPI models tuned at soft scales (~3-5 GeV) but still work when extended to DPS regime

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CMS – LHC 7 TeV

• Key discriminant: azimuthal angle between hard- and light-jet pairs

\[ \Delta S \equiv \Delta \phi (\vec{q}_T^1, \vec{q}_T^2) \]

• without MPI included, MC cannot reproduce data (~50% low)
• with MPI, MC still ~20% low (except Sherpa)

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- Key discriminant: azimuthal angle between hard- and light-jet pairs
  \[ \Delta S \equiv \Delta \phi (\vec{q}_T^1, \vec{q}_T^2) \]

- Some sensitivity via relative \( p_T \) balance between 2 softer jets

- Without MPI included, MC has some trouble at low \( \Delta_{\text{soft}} p_T \)

- 4 jets less sensitive to DPS than 2 b-jets + 2 jets
- Needs more kinematic study of MPI with UE data

\[ \rightarrow \text{no } \sigma_{\text{eff}} \text{ estimation} \]

**ATLAS – LHC 7 TeV**

- **Neural Nets:**
  - input kinematic variables

- **SPS**
  - determined from MC (Alpgen+Herwig+Jimmy)

- **cDPS – complete DPS** (2 jets +2 jets)
  - determined from data (overlaying 2 evts)

- **sDPS – semi DPS** (3 jets + 1 jet)
  - determined from data (overlaying 2 evts)

- **NN outputs in slices of $\xi$**
Inclusive 4 jets

ATLAS – LHC 7 TeV

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- NN outputs in slices of $\xi$

**Equations**

\[
\Delta p_T^{ij} = \frac{p_T^i + p_T^j}{p_T^i + p_T^j}
\]

\[
\Delta \phi_{ij} = |\phi_i - \phi_j|
\]

\[
\Delta y_{ij} = |y_i - y_j|
\]

\[
|\phi_{1+2} - \phi_{3+4}|
\]

\[
|\phi_{1+3} - \phi_{2+4}|
\]

\[
|\phi_{1+4} - \phi_{2+3}|
\]

**Graphs**

- Data 2010
- SPS (AHJ)
- cDPS (data, overlay)
- sDPS (data, overlay)

**Sum of contributions**

- (stat. uncertainty)
- (stat. + sys. uncertainty)

**Anti-$k_t$, jets, $R = 0.6$**

- $p_T^1 \geq 42.5$ GeV
- $p_T^{2,3,4} \geq 20$ GeV
- $|\eta_{1,2,3,4}| \leq 4.4$
**Inclusive 4 jets**

**ATLAS – LHC 7 TeV**

- Neural Nets:
  - input kinematic variables

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    - determined from MC (Alpgen+Herwig+Jimmy)

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  - **sDPS – semi DPS** (3 jets + 1 jet)
    - determined from data (overlaying 2 evts)

- NN outputs in slices of $\xi$

\[
\Delta p_T^{ij} = \frac{|p_T^i + p_T^j|}{p_T^i + p_T^j} \\
\Delta \phi_{ij} = |\phi_i - \phi_j| \\
\Delta y_{ij} = |y_i - y_j| \\
\phi_{1+2} - \phi_{3+4} \\
\phi_{1+3} - \phi_{2+4} \\
\phi_{1+4} - \phi_{2+3}
\]

\[
\Delta p_T^{ij} = |p_T^i + p_T^j| (\text{stat. uncertainty}) \\
\sum \Delta p_T^{ij} (\text{stat. + sys. uncertainty})
\]

Anti-$k_t$ jets, $R = 0.6$

- $p_T^1 \geq 42.5 \text{ GeV}$
- $p_T^{2,3,4} \geq 20 \text{ GeV}$
- $|\eta_{1,2,3,4}| \leq 4.4$

---

**ATLAS-STDMD-2015-08**

\[
\frac{1}{3} \xi_{sDPS} + \frac{2}{3} \xi_{cDPS}
\]
**ATLAS – LHC 7 TeV**

- Neural Nets:
  input kinematic variables

- **SPS**
  determined from MC (Alpgen+Herwig+Jimmy)

- **cDPS – complete DPS** (2 jets + 2 jets)
  determined from data (overlaying 2 evts)

- **sDPS – semi DPS** (3 jets + 1 jet)
  determined from data (overlaying 2 evts)

- NN outputs in slices of $\xi$

\[
\Delta p_T^{ij} = \frac{p_T^i + p_T^j}{p_T^i + p_T^j}
\]
\[
\Delta \phi_{ij} = |\phi_i - \phi_j|
\]
\[
\Delta y_{ij} = |y_i - y_j|
\]
\[
\phi_{1+2} - \phi_{3+4}
\]
\[
\phi_{1+3} - \phi_{2+4}
\]
\[
\phi_{1+4} - \phi_{2+3}
\]

**Graphical Representation**

- Data 2010
- SPS (AHJ)
- cDPS (data, overlay)
- sDPS (data, overlay)
- Sum of contributions (stat. uncertainty)
- Sum of contributions (stat. + sys. uncertainty)

Anti-$k_t$ jets, $R = 0.6$

- $p_T^1 \geq 42.5$ GeV
- $p_T^{2,3,4} \geq 20$ GeV
- $|n_{1,2,3,4}| \leq 4.4$

\[
\frac{1}{\sqrt{3}} \xi_{sDPS} + \frac{2}{\sqrt{3}} \xi_{cDPS}
\]

**ATLAS-STD-2015-08**
ATLAS – LHC 7 TeV

- Neural Net – cross-check of sensitive variables
  - Focus on correlations between two lightest jets
    \[ \Delta p_T^{ij} = \frac{|\vec{p}_T^i + \vec{p}_T^j|}{p_T^i + p_T^j} \quad \Delta \phi_{ij} = |\phi_i - \phi_j| \]

- cDPS – complete DPS (2 jets + 2 jets) determined from data (overlaying 2 events)
- sDPS – semi DPS (3 jets + 1 jet) determined from MC (Alpgen+Herwig+Jimmy)

- NN returns robust results
- estimate ~8% of 4-jet events originate from DPS

- \( \sigma_{\text{eff}} = 16.1^{+2.0}_{-1.5} \, \text{(stat.)}^{+6.1}_{-6.8} \, \text{(syst.)} \, \text{mb} \)
Clean Signature via Mass

Types of Events

- Sig: prompt J/ψ + J/ψ
- Bkg: non-prompt J/ψ (B decays)
- Bkg: prompt J/ψ + unassoct’d μμ
- Bkg: unassoct’d μμ + unassoct’d μμ

Main Observables

- $\Delta \eta_{\psi \psi}$, $\Delta \phi_{\psi \psi}$, $M_{\psi \psi}$, $p_T^{\psi \psi}$
Clean Signature via Mass

Types of Events

General Cuts
- Sig: prompt J/ψ + J/ψ mass cut (x2)
- Bkg: non-prompt J/ψ (B decays) di-muon decay vertex cuts
- J/ψ – J/ψ separation distance
- Bkg: prompt J/ψ + unasscoct’d μμ
- Bkg: unasscoct’d μμ + unasscoct’d μμ mass cut (x2), fit combinatorial/bkg

Main Observables
- $\Delta \eta_{\psi \psi}$, $\Delta \phi_{\psi \psi}$, $M_{\psi \psi}$, $p_T^{\psi \psi}$

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How to separate SPS from DPS?

• Naïve idea –
  J/ψ’s in SPS are mostly back-to-back
  → just cut on $\Delta \varphi_{\psi\psi}$! (à la multi-jets)

• However, only true for high $p_T$ J/ψ

• Meanwhile, DPS/SPS is dropping…
How to separate SPS from DPS?

- Much cleaner separation in $\Delta \eta_{\psi \psi}$

- SPS
  J/$\psi$’s highly correlated in $\Delta \eta$
  one gluon exchange $\times 1000$ (dotted)
  two gluon exchange $\times 25$ (solid)

- DPS
  $\Delta \eta_{\psi \psi}$ much broader

- Kinematically cleaner way to proceed for quarkonia (along with $M_{\psi \psi}$, $p_T^{\psi \psi}$)

Double J/ψ

D0 – Tevatron
- 1.96 TeV pp
- Observable: J/ψ + J/ψ
- Use template fit to $\Delta \eta_{J/\psi, J/\psi}$ (and decay vertex)
- Subtract background

Result
- $\sigma_{DPS}(J/\psi + J/\psi) = 59 \pm 6 \pm 22$ fb
- $\sigma_{SPS}(J/\psi + J/\psi) = 70 \pm 6 \pm 22$ fb
- $\sigma_{\text{eff}} = 4.8 \pm 0.5 \pm 2.5$ mb

Fiducial Acceptance (J/ψ)
- $p_T > 4$ GeV/c
- $|\eta| < 2$
D0 – Tevatron
• 1.96 TeV pp
• Observable: J/ψ + Y
• Baranov et al calculate DPS ~97% of xsec
• D0 assumes it’s all DPS

Result
• \( \sigma(J/\psi) = 28 \pm 7 \text{ nb} \)
• \( \sigma(Y) = 2.1 \pm 0.3 \text{ nb} \)
• \( \sigma_{\text{DPS}}(J/\psi+Y) = 27 \pm 9 \pm 7 \text{ fb} \)
• \( \sigma_{\text{eff}} = 2.2 \pm 0.7 \pm 0.9 \text{ mb} \)

Fiducial Acceptance (\( \mu \))
• \( p_T > 2 \text{ GeV/c} \)
• \( |\eta| < 2.0 \)
D0 – Tevatron

• 1.96 TeV pp
• Observable: J/ψ + Y

• Baranov et al calculate DPS ~97% of xsec
• D0 assumes it’s all DPS
• Consistent with DPS MC

Result

• $\sigma(J/\psi) = 28 \pm 7 \text{ nb}$
• $\sigma(Y) = 2.1 \pm 0.3 \text{ nb}$
• $\sigma_{\text{DPS}}(J/\psi+Y) = 27 \pm 9 \pm 7 \text{ fb}$
• $\sigma_{\text{eff}} = 2.2 \pm 0.7 \pm 0.9 \text{ mb}$

Fiducial Acceptance ($\mu$)

• $p_T > 2 \text{ GeV}/c$
• $|\eta| < 2.0$
CMS – LHC 8 TeV

• DPS/SPS contributions comparable
• W suffers from contamination
• Currently, statistics quite low

BDT input variables:

- leading muon ($\mu_1$) $p_T$
- subleading muon ($\mu_2$) $p_T$
- $E_T^{\text{miss}}$
- $M_T(\mu_1, \mu_2)$ di-muon invariant transverse mass
- $\Delta \phi(\mu_1, \mu_2)$
- $\Delta \phi(\mu_1, E_T^{\text{miss}})$
- $\Delta \phi(\mu_2, E_T^{\text{miss}})$
- $\Delta \phi(\mu_1 + \mu_2, E_T^{\text{miss}})$: where $\mu_1 + \mu_2$ is the vector sum of muon four-momenta
- $m_T(W_{1/2}) = \sqrt{2 \cdot p_T^{\mu_1/2} \cdot E_T^{\text{miss}} \cdot (1 - \cos(\Delta \phi(\mu_1/2, E_T^{\text{miss}})))}$

CMS PAS FSQ-13-001
CMS – LHC 8 TeV

• DPS/SPS contributions comparable
• W suffers from contamination
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BDT input variables:

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- $M_T(\mu_1, \mu_2)$ di-muon invariant transverse mass
- $\Delta \phi(\mu_1, \mu_2)$
- $\Delta \phi(\mu_1, E_T^{\text{miss}})$
- $\Delta \phi(\mu_2, E_T^{\text{miss}})$
- $\Delta \phi(\mu_1 + \mu_2, E_T^{\text{miss}})$: where $\mu_1 + \mu_2$ is the vector sum of muon four-momenta

Set lower limit:

• $\sigma_{\text{eff}} > 5.91$ mb (95% cf)

CMS PAS FSQ-13-001
Compiling Data...

- Can $\sigma_{\text{eff}}$ for some final states be systematically different than others?
- Can we differentiate g dominated processes from q dominated?
  - gluon transverse PDF $\neq$ quark transverse PDF?
Various ways to have two hard scatters in pA collisions

\[ \sigma_{DPS,1}^{pA \rightarrow ab} + \sigma_{DPS,2}^{pA \rightarrow ab} \]

now write

\[ \sigma_{DPS}^{pA \rightarrow ab} = \left( \frac{m}{2} \right) \frac{\sigma_{SPS}^{pN \rightarrow a} \cdot \sigma_{SPS}^{pN \rightarrow b}}{\sigma_{eff,pA}} \]

with \[ \sigma_{eff,pA} = \frac{\sigma_{eff,pp}}{A + \sigma_{eff,pp} F_{pA}} \]

\[ \sigma_{eff,pA} \approx \frac{1}{3A} \sigma_{eff,pp} \]

\[ F_{pA} = \frac{A - 1}{A} \int T_{pA}^2 (r) d^2r \approx 30 \text{ mb}^{-1} \]

- cross sections for DPS go up by x3 compared to SPS
- significance of measurement \((S/\sqrt{B})\) can increase by x40

D’Enterria & Snigirev, PLB 718 (2013)
Various ways to have two hard scatters in AA collisions

\[
\sigma_{DPS}^{(AA\rightarrow ab)} = \sigma_{DPS,1}^{(AA\rightarrow ab)} + \sigma_{DPS,2}^{(AA\rightarrow ab)} + \sigma_{DPS,3}^{(AA\rightarrow ab)}
\]

- Third term is dominant
- “Genuine” DPS only \(\sim 2.5\%\) of two-hard-scatterings

\(\rightarrow \text{not an efficient system to measure DPS}\)

D'Enterria & Snigirev, PLB 727 (2013)
DPS probe transverse parton dist profile as well as illuminate backgrounds for NLO SPS processes

Can give insight to partonic correlations inside proton

Beginning to map $\sqrt{s}$ dependence of $\sigma_{\text{eff}}$
Access to transverse PDFs
Gluon / quark separation?

Higher $\sqrt{s}$… higher luminosities…
larger systems (pA)…
Future is exciting!
CMS – LHC 7 TeV

- Key discriminant: azimuthal angle between $\gamma$-jet & di-jet

\[
\Delta S \equiv \Delta \phi (\vec{p}_T(\gamma,\text{jet1}), \vec{p}_T(\text{jet2, jet3}))
\]

the difference in azimuthal angle between the jets belonging to the di-jet pair,

\[
\Delta \phi_{23} = \phi_{\text{jet2}} - \phi_{\text{jet3}};
\]

the transverse momentum balance of the jets belonging to the di-jet pair,

\[
\Delta^\text{rel} p_T_{23} = \frac{|\vec{p}_T \text{jet2} + \vec{p}_T \text{jet3}|}{|\vec{p}_T \text{jet2}| + |\vec{p}_T \text{jet3}|};
\]
Main Observables
- $\Delta \eta_{\psi \psi}$, $\Delta \varphi_{\psi \psi}$, $M_{\psi \psi}$, $p_T^{\psi \psi}$