Six-jet production as a probe of triple parton scattering at the LHC

Marina Maneyro (University of Liverpool)
In collaboration with David d'Enterria (CERN)

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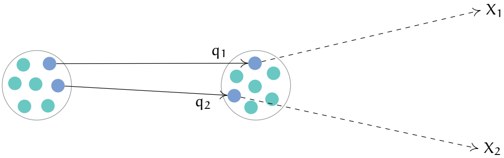
Motivation and Objectives

- Why 6j?
  - multijets used for DPS studies
    - 4j by AFS (1987), UA2 (1991), CDF (1993)
    - $\gamma + 3j$ by CDF (1997), D0 (2020)
  - Large dijet cross sections for low to mid p_T
- Hard Triple Parton Scattering (TPS) studied for the 6-jet production case for the first time
- Focusing on current experimental capabilities at the LHC, for proton-proton and proton-nucleus collisions. Collision energies set at $\sqrt{s} = 14$ TeV for pp and $\sqrt{s} = 8.8$ TeV for pPb

Theoretical Setup

Double Parton Scattering



- If the probabilities of producing X_1 and X_2 are independent:

  Pocket formula: $\sigma_{\mathrm{DPS}}^{pp\to X_1 X_2} = \left(\frac{m}{2}\right) \dfrac{\sigma_{\mathrm{SPS}}^{pp\to X_1}\ \sigma_{\mathrm{SPS}}^{pp\to X_2}}{\sigma_{\mathrm{eff,DPS}}}$

- m: combinatorial factor to avoid double counting

  $m = 1\,(2)$ if $X_1 = X_2$ $(X_1 \neq X_2)$

Theoretical Setup
Double Parton Scattering

- Purely geometric estimation: $\sigma_{\text{eff,DPS}} = \left[\int d^2b\, T^2(\mathbf{b})\right]^{-1}$
  Transverse overlap function for pp $\left(\int d^2b T(\mathbf{b}) = 1\right)$
  $T(\mathbf{b}) = \int \rho(\mathbf{b_1})\rho(\mathbf{b_1} - \mathbf{b}) d^2b_1$
  where $\rho(\mathbf{b_1})$ is the transverse parton density of the proton
- Doesn't take into account correlations between partons $\rightarrow$
  Hereafter, we will use experimental "average"
  $\sigma_{\text{eff,DPS}} \approx 15$ mb

Theoretical Setup

Triple Parton Scattering

- $\sigma_{\mathrm{TPS}}^{pp \to X_1 X_2 X_3} = \left(\frac{m}{3!}\right) \frac{\sigma_{\mathrm{SPS}}^{pp \to X_1} \, \sigma_{\mathrm{SPS}}^{pp \to X_2} \, \sigma_{\mathrm{SPS}}^{pp \to X_3}}{\sigma_{\mathrm{eff,TPS}}^2}$
  - $m = 1$ if $X_1 = X_2 = X_3$
  - $m = 3$ for two different particles (i.e. $X_1 = X_2 \neq X_3$)
  - $m = 6$ if all particles are different
- $\sigma_{\mathrm{eff,TPS}} = \left[\int d^2b \, T^3(\mathbf{b})\right]^{-1/2} = \kappa \, \sigma_{\mathrm{eff,DPS}}$ with $\kappa = (0.82 \pm 0.11)$, obtained by studying transverse parton overlaps (hard sphere, Gaussian, exponential, dipole fit). Then, $\sigma_{\mathrm{eff,TPS}} = 12.5 \pm 4.5$ mb (d'Enterria & Snigirev (2017))

Theoretical Setup

For pA collisions

- We're also interested in studying TPS for hadron-Nucleus interactions, in particular proton-lead
- Cross sections $\rightarrow$ proton-nucleon SPS $+$ scaling procedure
- Single Parton Scattering:

  $\sigma^{\text{SPS}}_{pA\rightarrow X} = \sigma^{\text{SPS}}_{pN\rightarrow X} \int d^2b\, T_{pA}(\mathbf{b}) = A \cdot \sigma^{\text{SPS}}_{pN\rightarrow X}$
- $T_{pA}(\mathbf{r})$: Standard nuclear thickness function
- Defined from nuclear density function $\rho_A(\mathbf{r})$

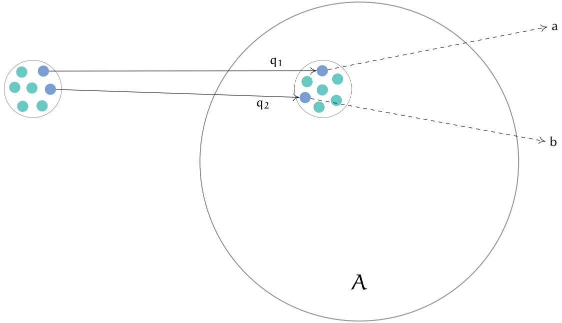
  $T_{pA}(\mathbf{r}) = \int \rho_A\left(\sqrt{r^2+z^2}\right) dz$, with $\int T_{pA}(\mathbf{r})\, d^2r = A$

Theoretical Setup

For pA collisions

- For the DPS case: $\sigma_{pA}^{\text{DPS}} = \sigma_{pA}^{\text{DPS,1}} + \sigma_{pA}^{\text{DPS,2}}$
- Interactions between partons in the same nucleon:

$$\sigma_{pA \to ab}^{\text{DPS,1}} = A \cdot \sigma_{pN \to ab}^{\text{DPS}}$$

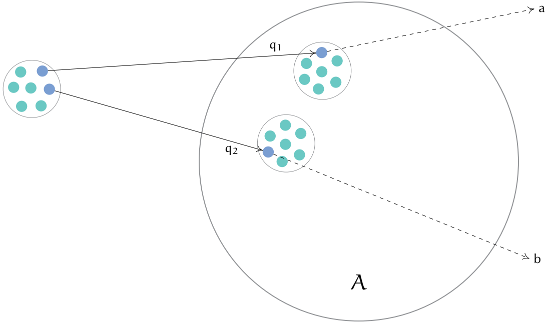


Theoretical Setup

For pA collisions

- Partons from two different nucelons

$$\sigma^{\mathrm{DPS},2}_{pA\to ab} = \sigma^{\mathrm{DPS}}_{pN\to ab} \cdot \sigma_{\mathrm{eff,DPS}} \cdot F_{pA}$$



Theoretical Setup

For pA collisions

- $F_{pA} = \frac{A-1}{A} \int T^2_{pA}(\mathbf{r})\, d^2r$
- $\frac{A-1}{A}$ takes into account the number of pairs of nucleons vs. the number of pairs that are different
- For Lead $A = 208$, F_{pA} derived from Glauber Monte Carlo model with realistic Pb density profile $F_{pA} \approx\ 29.5\ \text{mb}^{-1}$

Theoretical Setup

For pA collisions

- To summarize, total DPS cross section:

  $$\sigma^{\text{DPS}}_{pA\to ab} = \left(\frac{m}{2}\right)\frac{\sigma^{\text{SPS}}_{pN\to a}\cdot\sigma^{\text{SPS}}_{pN\to b}}{\sigma_{\text{eff},\text{DPS},pA}}$$

  $\sigma_{\text{eff},\text{DPS},pA}$ includes the pN DPS effective factor, geometry of F_{pA} and dependence in A

- For Lead, and for $\sigma_{\text{eff},\text{DPS}} \approx 15$ mb, then $\sigma_{\text{eff},\text{DPS},pA} = 22.5 \pm 2.3\ \mu\text{b} \to$ larger DPS cross sections than pp case

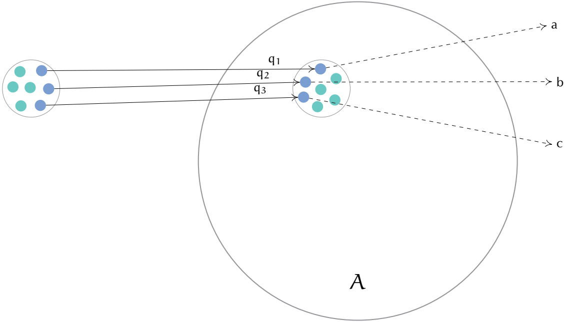
Theoretical Setup

For pA collisions

- Fot TPS there are three different terms:

$$\sigma_{pA}^{\mathrm{TPS}} = \sigma_{pA}^{\mathrm{TPS},1} + \sigma_{pA}^{\mathrm{TPS},2} + \sigma_{pA}^{\mathrm{TPS},3}$$

- The first is again with all partons from the same nucleon

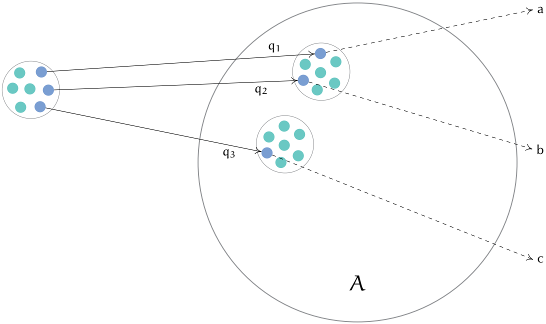


Theoretical Setup

For pA collisions

- Partons from two different nucleons:

$$\sigma^{\mathrm{TPS},2}_{pA\to abc} = \sigma^{\mathrm{TPS}}_{pN\to abc} \cdot 3\,\frac{\sigma^2_{\mathrm{eff,TPS}}}{\sigma_{\mathrm{eff,DPS}}} F_{pA}$$



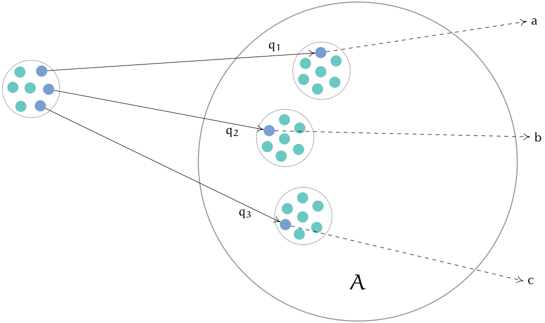
Theoretical Setup

For pA collisions

- Partons from three different nucleons:

$$\sigma^{\mathrm{TPS},3}_{pA\to abc} = \sigma^{\mathrm{TPS}}_{pN\to abc} \cdot \sigma^2_{\mathrm{eff,TPS}} \cdot C_{pA}$$

with $C_{pA} = \frac{(A-1)(A-2)}{A^2} \int d^2b\, T^3_{pA}(\mathbf{b})$



Theoretical Setup

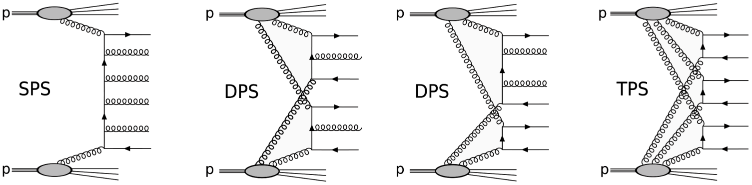
For pA collisions

- Summarizing the terms:

$$\sigma^{\mathrm{TPS}}_{\mathrm{pA}\to abc} = \left(\frac{m}{6}\right) \frac{\sigma^{\mathrm{SPS}}_{\mathrm{pN}\to a} \cdot \sigma^{\mathrm{SPS}}_{\mathrm{pN}\to b} \cdot \sigma^{\mathrm{SPS}}_{\mathrm{pN}\to c}}{\sigma^2_{\mathrm{eff,TPS,pA}}}$$

- F_{pA} and C_{pA} derived from Glauber Monte Carlo. Again $\sigma_{\mathrm{eff,TPS,pA}}$ absorbs the dependence in A, F_{pA} and C_{pA}, and $\sigma_{\mathrm{eff,TPS}}$
- For Lead, and for $\sigma_{\mathrm{eff,DPS}} \approx 15$ mb, $\sigma_{\mathrm{eff,TPS,pA}} = 0.29 \pm 0.04$ mb (also bigger TPS yields than for pp)

Methodology



- To study pp $\rightarrow$ 6j we looked at:
  - SPS: pp $\rightarrow$ 6j (LO)
  - DPS: from pp $\rightarrow$ 2j (SPS, NLO) and pp $\rightarrow$ 4j (SPS, LO), and also pp $\rightarrow$ 3j (SPS,NLO) $\times$ 2
  - TPS: from pp $\rightarrow$ 2j (SPS,NLO) $\times$ 3

Methodology

- Two MC generators used: Madgraph5_aMC@NLO and Alpgen
- Madgraph5: NLO generation for 2j, 3j (can't do 4j, 6j)
- Alpgen: Works for 4j,6j (albeit at LO)
- PDF: NNPDF4.0 NLO (LO for $N \geqslant 4j$)
- Scale variations: dynamical scale ($Q = \hat{H}_T$ or $\hat{H}_T/2$ chosen) & renorm/fact. scale variations: $\mu_{F,R} = Q/2, Q, 2Q$.

Results ($pp \to 6j + X$ at $\sqrt{s}$ =14 TeV)

- MadGraph5 ($|\eta| < 5$, $p_{T,j} > 35$GeV)

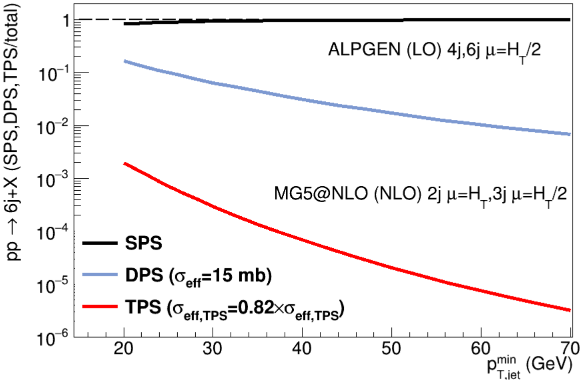
Process	σ^{LO}	σ^{NLO}
$pp \to jj$ (SPS) at $\sqrt{s} = 14$ TeV ($\hat{H}_T$)	66.7 μb $^{+28.6\% +1.34\%}_{-21.9\% -1.34\%}$	11.7 μb $^{+95.7\%}_{-205.5\%}$
$pp \to 3j$ (SPS) at $\sqrt{s} = 14$ TeV ($\hat{H}_T/2$)	4.30 μb $^{+38.4\%}_{-26\%}$ $^{+0.746\%}_{-0.746\%}$	3.78 μb $^{+2.7\%}_{-27.2\%}$
$pp \to 4j$ (SPS) at $\sqrt{s} = 14$ TeV ($\hat{H}_T/2$)	0.71 μb $^{+55.9\%}_{-33.5\%}$ $^{+1.1\%}_{-1.1\%}$	
$pp \to 4j + 2j$ (DPS) at $\sqrt{s} = 14$ TeV	3.85 nb	
$pp \to 3j + 3j$ (DPS) at $\sqrt{s} = 14$ TeV	751 pb	581 pb
$pp \to 6j$ (TPS) at $\sqrt{s} = 14$ TeV	486 pb	2.62 pb

- Alpgen ($|\eta| < 5$, $p_{T,j} > 35$GeV)

Process	σ^{LO}
$pp \to jj$ (SPS) at $\sqrt{s} = 14$ TeV ($\hat{H}_T$)	73.8 ± 0.023 μb
$pp \to 3j$ (SPS) at $\sqrt{s} = 14$ TeV ($\hat{H}_T/2$)	5.05± 0.013 μb
$pp \to 4j$ (SPS) at $\sqrt{s} = 14$ TeV ($\hat{H}_T/2$)	0.92± 0.002 μb
$pp \to 6j$ (SPS) at $\sqrt{s} = 14$ TeV ($\hat{H}_T/2$)	31.5± 0.094 nb

LO and NLO results are consistent within scale uncertainties, except for the 2j case due to jets going below the $p_{T,jet}^{min}$ threshold

Results (pp $\to$ 6j + X at $\sqrt{s}$ =14 TeV)



Can we experimentally observe TPS contributions amounting to $\approx 10^{-3}$ (at $p_{T,jet}^{min} = 20$ GeV), 10^{-5} (at $p_{T,jet}^{min} = 50$ GeV)? Discriminating kinematic cuts can improve this. Moreover, values of $N_{evts} = \sigma L$ are very large, so the Signal counts are very large (relatively small statistical fluctuations)

Results ($pPb \to 6j + X$ at $\sqrt{s}$ =8.8 TeV)

- MadGraph5 ($|\eta| < 5$, $p_{T,j} > 35 GeV$)

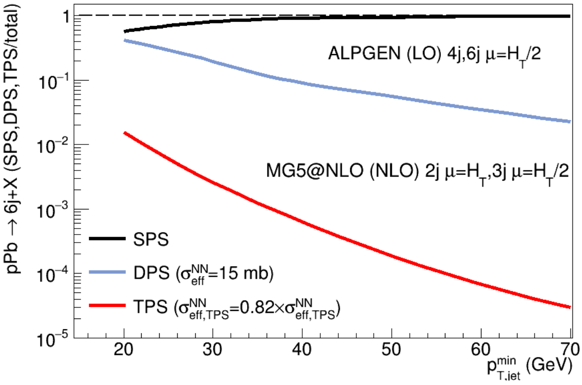
Process	σ^{LO}	σ^{NLO}
$pN \to jj$ (SPS) at $\sqrt{s} = 14$ TeV ($\hat{H}_T$)	31.1 μb $^{+25.6\%}_{-19.7\%}$ $^{+1.03\%}_{-1.03\%}$	8.41 μb $^{+73.2\%}_{-140.0\%}$
$pN \to 3j$ (SPS) at $\sqrt{s} = 14$ TeV ($\hat{H}_T/2$)	1.69 μb $^{+42.1\%}_{-27.7\%}$ $^{+0.84\%}_{-0.84\%}$	1.54 μb $^{1.7\%}_{-27.2\%}$
$pN \to 4j$ (SPS) at $\sqrt{s} = 14$ TeV ($\hat{H}_T/2$)	235 nb $^{+59.6\%}_{-34.9\%}$ $^{+1.41\%}_{-1.41\%}$	
$p - Pb \to 4j + 2j$ (DPS) at $\sqrt{s} = 14$ TeV	323 nb	
$p - Pb \to 3j + 3j$ (DPS) at $\sqrt{s} = 14$ TeV	632 nb	559 nb
$p - Pb \to 6j$ (TPS) at $\sqrt{s} = 14$ TeV	596 nb	1.18 nb

- Alpgen ($|\eta| < 5$, $p_{T,j} > 35 GeV$)

Process	σ^{LO}
$pN \to jj$ (SPS) at $\sqrt{s} = 14$ TeV ($\hat{H}_T$)	34.8 ± 0.010 μb
$pN \to 3j$ (SPS) at $\sqrt{s} = 14$ TeV ($\hat{H}_T/2$)	1.93± 0.004 μb
$pN \to 4j$ (SPS) at $\sqrt{s} = 14$ TeV ($\hat{H}_T/2$)	282± 0.494 nb
$pN \to 6j$ (SPS) at $\sqrt{s} = 14$ TeV ($\hat{H}_T/2$)	5.56± 0.017 nb

$$\sigma_{p-Pb} = A \times \sigma_{pN}$$

Results (pPb $\to$ 6j + X at $\sqrt{s}$ =8.8 TeV)



6j TPS in pPb amounts to 2% (10^{-4}) at $p_{T,jet}^{min} \sim 20$ GeV (50 GeV). Much larger DPS/TPS contributions than in pp collisions.

MVA for TPS event identification

- MG5/Alpgen events showered using PYTHIA 8
- Jet reconstruction with anti-k_T algorithm and $R = 0.4$ (FastJet)
- Key kinematic variables identified to separate SPS, DPS and TPS events
- Jets ranked by decreasing $p_{T,jet}$ value
- Variables (66 initially):
  - $p_{T,i}$ for $i = 1, ..., 6$
  - $\Delta\eta_{ij}$ for all possible pairs ($|\eta| < 5$)
  - $\Delta\phi_{ij}$ (absolute, between 0 and π)
  - $A^{ij}_{p_T} = |(p_{T,i} - p_{T,j})/(p_{T,i} + p_{T,j})|$, p_T pair asymmetry
  - Invariant mass of the pairs

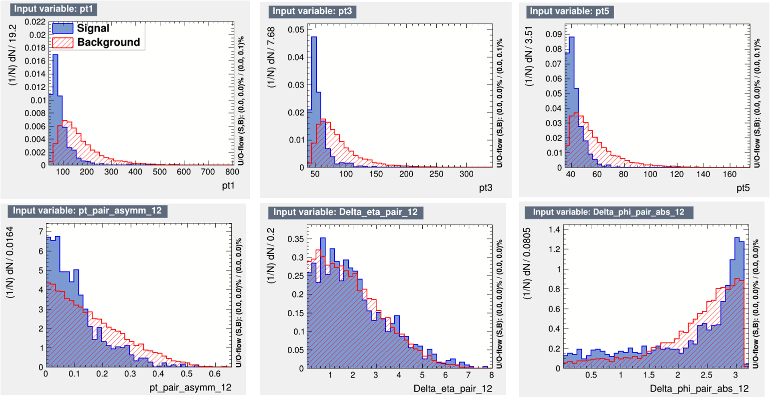
MVA for TPS event identification

- The selected variables and the generated SPS, DPS (background) and TPS (signal) events were used in conjunction with TMVA
- Studied the relevance of the variables for separating background and signal using Boosted Decision Trees
- The MPI events were weighted according to their known proportion of each contribution

MVA for TPS event identification

Relevant discriminating variables include:

$p_{T,1}$, $p_{T,3}$, $p_{T,5}$, $\Delta\phi_{12}$, $\Delta\eta_{12}$, $A^{12}_{p_T}$, $\Delta\phi_{23}$, $\Delta\eta_{13}$, $A^{56}_{p_T}$



Conclusions and Outlook

- Preliminary results indicate BDT output with stat. significance $> 5\sigma$ for $L_{int} = 1fb$. Ongoing MVA training/testing to obtain final significance soon.
- TPS 6-jets yields are large at the LHC: Observing TPS in pp and pPb promising, new σ_{eff} extraction at hand.