D-meson duos in p-p and p-Pb collisions

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D mesons

- D-mesons are charm + light quark bound states

- The charm mass $m_{\text{charm}} \sim 1.5\, \text{GeV}$ allows to extend perturbative QCD calculations down to $p_T = 0$.

  $\Rightarrow$ e.g. constraints for (nuclear) parton distributions at low interaction scales [JHEP 05 (2020) 037, PRL 121 (2018) 5, 052004, JHEP 11 (2015) 009, EPJC 75 (2015) 8, 396]

- The large production cross sections at low $p_T$ make the D mesons as good candidates to study double parton scattering (DPS)

<table>
<thead>
<tr>
<th>type</th>
<th>content</th>
<th>mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^+$</td>
<td>$c\bar{d}$</td>
<td>1.870 GeV</td>
</tr>
<tr>
<td>$D^-$</td>
<td>$c\bar{d}$</td>
<td>1.870 GeV</td>
</tr>
<tr>
<td>$D^0$</td>
<td>$c\bar{u}$</td>
<td>1.865 GeV</td>
</tr>
<tr>
<td>$\bar{D}^0$</td>
<td>$\bar{c}u$</td>
<td>1.865 GeV</td>
</tr>
<tr>
<td>$D^+_s$</td>
<td>$c\bar{s}$</td>
<td>1.970 GeV</td>
</tr>
<tr>
<td>$D^-_s$</td>
<td>$\bar{c}s$</td>
<td>1.970 GeV</td>
</tr>
</tbody>
</table>
Heavy-quark production @ hadron colliders

- Heavy quarks $Q$ produced in partonic processes

\[
\frac{d\sigma^{pp}}{dp_T dy} = \sum_{ij} \int dx_1 \int dx_2 \frac{f^p_i(x_1, \mu^2_{\text{fact}})}{d\sigma^{ij\rightarrow Q+X}(x_1, x_2, m^2, \mu_{\text{ren}}^2, \mu^2_{\text{fact}})} \frac{f^p_j(x_2, \mu^2_{\text{fact}})}{dp_T dy}
\]

- NLO coefficient functions known since the 80’s [NPB 327 (1989) 49-92]
- NNLO results also basically known (e.g. Top++) [PRL 110 (2013) 252004, arXiv:2010.11906]
Heavy-quark production @ hadron colliders

- Integrated cross sections at **NNLO** vs. world data [Enterria & Snigirev, PRL 118, 122001]

- Charm production somewhat underestimated – bottom production looks OK
D-meson production @ hadron colliders

- Partonic cross sections folded with charm-to-D fragmentation functions (FFs), $D_c \rightarrow D(z)$

$$\frac{d\sigma_{pp}}{dP_T dY} = \sum_{ij} \int \frac{dz}{z} \int dx_1 \int dx_2 \ f^p_i(x_1, \mu^2_{\text{fact}}) \ f^c_j(x_2, \mu^2_{\text{fact}}) \ \hat{\sigma}_{ij} \rightarrow c^+ X(d\sigma/dP_T dy) \ D_{c \rightarrow D(z)}$$

- FFs can be fitted to $e^+ e^- \rightarrow D + X$ data

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D-meson duos in p-p and p-Pb collisions

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D-meson production @ hadron colliders

- Calculations [Zenaiev EPJ C77, 151; Gauld et.al. JHEP 11 (2015), 009] compared with LHCb data
- Tendency to underestimate the LHCb data – still within the large QCD scale uncertainties
Resummation of final-state $\log(p_T/m_c)$ terms

- Collinear splittings lead to large logarithms $\sim \log(p_T/m_c)$ at $p_T \gg m_c$

These can be resummed via **scale-dependent FFs** $D_i \rightarrow D(z, \mu_{\text{frag}}^2)$

$$D_{g \rightarrow D}(x, \mu_{\text{frag}}^2) = \left[ \left( \frac{\alpha_s}{2\pi} \right) \log \left( \frac{\mu_{\text{frag}}^2}{m_c^2} \right) P_{qg} + \frac{1}{2!} \left( \frac{\alpha_s}{2\pi} \right)^2 \log^2 \left( \frac{\mu_{\text{frag}}^2}{m_c^2} \right) P_{qg} \otimes P_{gg} + \cdots \right] \otimes D_{Q \rightarrow D}$$

- We use the KKKS08 [Kneesch et.al. Nucl.Phys.B 799 (2008) 34] set of scale-dependent FFs
Resummation of final-state $\log(p_T/m_c)$ terms

- As a result, also other partons than charm can fragment into a D meson

\[
\frac{d\sigma^{pp}}{dP_T dY} = \sum_{i,j,k} \int \frac{dz}{z} dx_1 dx_2 f_i(x_1, \mu^2_{\text{fact}}) \frac{d\hat{\sigma}^{ij \to k+X}(x_1, x_2)}{dP_T dy} f_j(x_2, \mu^2_{\text{fact}}) D_k \to D(z, \mu^2_{\text{frag}})
\]

- Framework known as **general-mass variable-flavour-number scheme (GM-VFNS)**
  
  [Helenius, Paukkunen, JHEP 1805, 196; Kniehl et.al. PRD 71 (2005) 014018; Cacciari et.al. JHEP 9805, 007]
Comparison with the LHCb 13 TeV data

- LHCb p-p cross sections well reproduced by the resummed approach at NLO

$$\sqrt{s} = 13 \text{ TeV}, \ 2.0 < Y < 2.5$$

$$\mu_\text{fact}^2, \mu_\text{ren}^2, \mu_\text{frag}^2 = \max[m_{\text{charm}}^2, \alpha_i^2(P_T^2 + m_{\text{charm}}^2)]$$

HELENIUS, PAUKKUNEN, JHEP 1805 (2018) 196

$$\sqrt{s} = 13 \text{ TeV}, \ 2.5 < Y < 3.0$$

$$\mu_\text{fact}^2, \mu_\text{ren}^2, \mu_\text{frag}^2 = \max[m_{\text{charm}}^2, \alpha_i^2(P_T^2 + m_{\text{charm}}^2)]$$

HELENIUS, PAUKKUNEN, JHEP 1805 (2018) 196

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D-meson duos in p-p and p-Pb collisions

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Double-D production

- Simultaneous production of two D mesons from single- (SPS) and double-parton scattering (DPS)

The cross section is of the form

\[
\frac{d\sigma_{AB \to a+b+X}}{d^3p^a d^3p^b} = \sigma_{AB}^{sps} + \sigma_{AB}^{dps} = AB \frac{d\sigma_{nn \to a+b+X}}{d^3p^a d^3p^b} + m \frac{AB}{\sigma_{\text{eff}}^{AB}} \frac{d\sigma_{nn \to a+X}}{d^3p^a} + \frac{d\sigma_{nn \to b+X}}{d^3p^b}
\]

- Nucleon-nucleon cross sections calculated in NLO GM-VFNS (zero-mass approximation for SPS)
Double-D production

- Measurements indicate $10 \text{ mb} < \sigma_{\text{eff}}^{\text{pp}} < 25 \text{ mb}$ [e.g. PLB 790 (2019) 595]

\[
\frac{1}{\sigma_{\text{eff}}^{AB}} \approx \frac{1}{\sigma_{\text{eff}}^{\text{pp}}} + \frac{(B-1)}{B^2} \int d^2 B \left[ T_B(\vec{B}) \right]^2 + \frac{(A-1)}{A^2} \int d^2 B \left[ T_A(\vec{B}) \right]^2 \\
+ \frac{(A-1)(B-1)}{(AB)^2} \int d^2 B \left[ T_{AB}(\vec{B}) \right]^2,
\]

where $T_A(\vec{B})$ and $T_{AB}(\vec{B})$ are the standard nuclear thickness and overlap functions.

\[\Rightarrow \text{ In p-Pb collisions, an enhanced DPS signal theoretically expected, } \frac{\sigma_{\text{eff}}^{\text{pp}}}{\sigma_{\text{eff}}^{\text{pPb}}} \approx 2.5 \ldots 4.8\]
Application to double-D production – p-p case

- SPS dominates the **opposite-sign pairs**

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[Data: JHEP 06 (2012) 141]

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**D-meson duos in p-p and p-Pb collisions**

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Application to double-D production – p-p case

- SPS dominates the opposite-sign pairs

\[ \text{integrated cross section [nb]} \]

\[ \begin{align*}
&\text{D}^0\text{D}^0, D^0\text{D}^-, \\
&\text{D}^0\Lambda_c^-, \text{D}^+\text{D}^-, \\
&\text{D}^+\Lambda_c^-, \text{D}^+\text{D}^- \\
\end{align*} \]

\[ \begin{align*}
&\text{pythia (monash)} \\
&\text{LHCb p-p} \\
&\sqrt{s} = 7 \text{ TeV} \\
&2 < y < 4 \\
&3 < p_T < 12 \text{ GeV} \\
\end{align*} \]

\[ \text{DPS contribution subleading} \]

\[ \text{data: JHEP 06 (2012) 141} \]
Application to double-D production – p-p case

- SPS dominates the **opposite-sign pairs**

![Graph showing integrated cross section](image)

[SPS dominates the opposite-sign pairs](Helenius, Paukkunen, PLB 800 (2020) 135084)

Most of the cross section from SPS

DPS contribution subleading

**Data:** JHEP 06 (2012) 141

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D-meson duos in p-p and p-Pb collisions

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Application to double-D production – p-p case

- SPS dominates the **opposite-sign pairs**

**Pythia overshoots the data**

**Most of the cross section from SPS**

**DPS contribution subleading**

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**Pythia**

LHCb p-p

√s = 7 TeV

2 < y < 4

3 < p_T < 12 GeV

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D-meson duos in p-p and p-Pb collisions

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Application to double-D production – p-p case

- DPS dominates the like-sign pairs

\[ \text{DPS dominates the like-sign pairs} \]

\[ [\text{Helenius, Paukkunen, PLB 800 (2020) 135084}] \]

\[ \text{integrated cross section [mb]} \]

\[ \text{sps} \]

\[ \text{dps+sps} \]

\[ \text{LHCb p-p} \]

\[ \sqrt{s} = 7 \text{ TeV} \]

\[ 2 < y < 4 \]

\[ 3 < p_T < 12 \text{ GeV} \]

\[ [\text{data: JHEP 06 (2012) 141}] \]
Application to double-D production – p-p case

- DPS dominates the **like-sign pairs**

![Graph showing integrated cross section](image)

**Legend:**
- sps
- dps+sps
- LHCb p-p
- pythia (monash)

**Details:**
- $\sqrt{s} = 7$ TeV
- $2 < y < 4$
- $3 < p_T < 12$ GeV

References:
- [Helenius, Paukkunen, PLB 800 (2020) 135084]
- [data: JHEP 06 (2012) 141]
Application to double-D production – p-p case

- DPS dominates the **like-sign pairs**

![Graph showing integrated cross section for D-meson duos in p-p and p-Pb collisions]

- [Helenius, Paukkunen, PLB 800 (2020) 135084]
- [data: JHEP 06 (2012) 141]
Application to double-D production – p-p case

- DPS dominates the like-sign pairs

\[
\begin{align*}
&D_0^- D_0^+ \\
&D_0^- D^+
\end{align*}
\]

[Pythia overshoots the data]

[DPS tends to dominate]

[SPS contribution subleading now]

[Data: JHEP 06 (2012) 141]

\[
\begin{align*}
&\sqrt{s} = 7 \text{ TeV} \\
&2 < y < 4 \\
&3 < p_T < 12 \text{ GeV}
\end{align*}
\]
Application to double-D production – p-Pb predictions

- SPS and DPS contributions similar in **opposite-sign pairs**

![Chart showing integrated cross section in p-Pb](data: PRL 125 (2020) 21, 212001)

**[Helenius & Paukkunen, based on PLB 800 (2020) 135084]**

- Integrated cross section in p-Pb [nb]

**LHCb p-Pb**

- $\sqrt{s} = 8.16$ TeV
- $1.7 < y < 3.7$
- $2 < p_T/\text{GeV} < 12$

**[data: PRL 125 (2020) 21, 212001]**
Application to double-D production – p-Pb predictions

- SPS and DPS contributions similar in **opposite-sign pairs**

\[ \text{[Helenius & Paukkunen, based on PLB 800 (2020) 135084]} \]

SPS ALONE TENDS TO UNDERSHOOT THE DATA

[Data: PRL 125 (2020) 21, 212001]

\[ \sqrt{s} = 8.16 \text{ TeV} \]

\[ 1.7 < y < 3.7 \]

\[ 2 < p_T/\text{GeV} < 12 \]
Application to double-D production – p-Pb predictions

- SPS and DPS contributions similar in **opposite-sign pairs**

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<td>DPS CONTRIBUTION SIMILAR TO SPS</td>
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[Helenius & Paukkunen, based on PLB 800 (2020) 135084]

- Integrated cross section in p-Pb [nb]
- Data: PRL 125 (2020) 21, 212001
- $\sqrt{s} = 8.16$ TeV
- $1.7 < y < 3.7$
- $2 < p_T/GeV < 12$

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D-meson duos in p-p and p-Pb collisions

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Application to double-D production – p-Pb predictions

- SPS and DPS contributions similar in opposite-sign pairs

\[ \int \text{cross section in p-Pb} \ [\text{nb}] = 10^7 \]

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D-meson duos in p-p and p-Pb collisions

SPS + DPS well in line with the data
SPS alone tends to undershoot the data
DPS contribution similar to SPS

\[ \sqrt{s} = 8.16 \text{ TeV} \]
\[ 1.7 < y < 3.7 \]
\[ 2 < p_T/GeV < 12 \]

[SPS ALONE TENDS TO UNDERSHOOT THE DATA]
[DPS CONTRIBUTION SIMILAR TO SPS]

[SPS + DPS WELL IN LINE WITH THE DATA]

[Data: PRL 125 (2020) 21, 212001]
[Helenius & Paukkunen, based on PLB 800 (2020) 135084]
Application to double-D production – p-Pb predictions

- The DPS signal is clean & clear in like-sign pairs

\[ \text{integrated cross section in p-Pb [nb]} \]

\[ D^0D^0, D^0D^+, D^0D^{+\ast}, D^+D^+, D^+D^{+\ast}, D^+D^0 \]

\[ \text{LHCb p-Pb} \]
\[ \sqrt{s} = 8.16 \text{ TeV} \]
\[ 1.7 < y < 3.7 \]
\[ 2 < p_T/\text{GeV} < 12 \]

[Helenius & Paukkunen, based on PLB 800 (2020) 135084]

[data: PRL 125 (2020) 21, 212001]
Application to double-D production – p-Pb predictions

- The DPS signal is clean & clear in **like-sign pairs**

**[Helenius & Paukkunen, based on PLB 800 (2020) 135084]**

![Graph showing integrated cross section in p-Pb](#)

- Integrated cross section in p-Pb [nb]
- \( \sqrt{s} = 8.16 \text{ TeV} \)
- \( 1.7 < y < 3.7 \)
- \( 2 < p_T/\text{GeV} < 12 \)

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D-meson duos in p-p and p-Pb collisions

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Application to double-D production – p-Pb predictions

- The DPS signal is clean & clear in **like-sign pairs**

**Graphical Representation:**

- [Helenius & Paukkunen, based on PLB 800 (2020) 135084]

**Legend:**
- sps
- dps
- sps+dps

**Data:**
- LHCb p-Pb
- $\sqrt{s} = 8.16$ TeV
- $1.7 < y < 3.7$
- $2 < p_T/\text{GeV} < 12$

**Note:**
- DPS contribution explains the measured cross section
- SPS contribution negligible
Application to double-D production – p-Pb predictions

- In p-Pb the enhanced double-parton scattering smears the azimuthal correlations

\[ \frac{1}{\sigma_{pPb}} \frac{d\sigma_{pPb}}{d\phi} = \alpha \times \left[ \frac{1}{\sigma_{pp}} \frac{d\sigma_{pp}}{d\phi} \right]_{\text{pythia sps}} + \beta/\pi \]

- Coefficients \( \alpha \) and \( \beta \) come from NLO calculation

\[ \alpha = \frac{\sigma_{sps}^{pPb}}{\sigma_{sps}^{pPb} + \sigma_{dps}^{pPb}}, \quad \beta = \frac{\sigma_{dps}^{pPb}}{\sigma_{sps}^{pPb} + \sigma_{dps}^{pPb}} \]

- The away side peak essentially disappears due to the enhanced DPS contribution - no signals of saturation here!

[Helenius & Paukkunen, based on PLB 800 (2020) 135084]
Applied a NLO GM-VFNS framework on double D-meson hadroproduction

Good agreement with the recent p-p & p-Pb data from LHCb

⇒ confirms the enhanced double-parton scattering component in p-Pb vs. p-p!

Azimuthal correlations in p-Pb consistent with the enhanced DPS contribution

⇒ no evidence of saturation signatures at this point
Inclusive p-p cross sections $D^0$, $D^\pm$, $D_s^\pm$
Backward cross sections

LHCb p-Pb
$\sqrt{s} = 8.16$ TeV
$-4.7 < y < -2.7$
$2 < p_T/\text{GeV} < 12$

integrated cross section in p-Pb [nb]

D-meson duos in p-p and p-Pb collisions

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Azimuthal correlations in the backward direction

\[
\left( \frac{\pi}{\sigma} \right) \left( \frac{d\sigma}{d\phi} \right)
\]

- LHCb p-Pb
  - \( \sqrt{s} = 8.16\) TeV
  - \(-4.7 < y < -2.7\)
  - \(2 < p_T < 12\) GeV

- LHCb p-p
  - \( \sqrt{s} = 7\) TeV
  - \(2 < y < 4\)
  - \(3 < p_T < 12\) GeV

\( D^0D^0 \)