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

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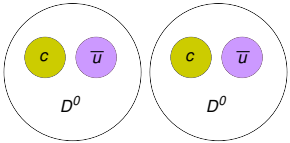
D mesons

- D-mesons are charm + light quark bound states
- The charm mass $m_{\mathrm{charm}} \sim 1.5\,\mathrm{GeV}$ allows to extend perturbative QCD calculations down to $p_{\mathrm{T}} = 0$.

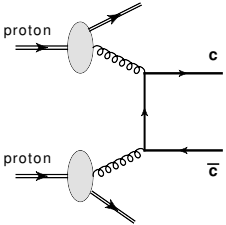
  $\Longrightarrow$ e.g. constraints for (nuclear) parton distributions at low interaction scales [JHEP 05 (2020) 037, PRL 121 (2018) 5, 052004, JHEP 11 (2015) 009, EPJC 75 (2015) 8, 396]
- The large production cross sections at low p_{T} make the D mesons as good candidates to study **double parton scattering (DPS)**

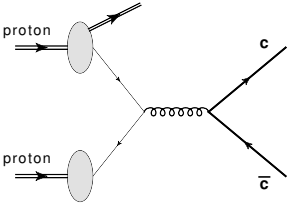
type	content	mass
D^+	$\mathrm{c\bar{d}}$	$1.870\,\mathrm{GeV}$
D^-	$\mathrm{\bar{c}d}$	$1.870\,\mathrm{GeV}$
D^0	$\mathrm{c\bar{u}}$	$1.865\,\mathrm{GeV}$
$\overline{D^0}$	$\mathrm{\bar{c}u}$	$1.865\,\mathrm{GeV}$
D_s^+	$\mathrm{c\bar{s}}$	$1.970\,\mathrm{GeV}$
D_s^-	$\mathrm{\bar{c}s}$	$1.970\,\mathrm{GeV}$



Heavy-quark production @ hadron colliders

- Heavy quarks Q produced in partonic processes





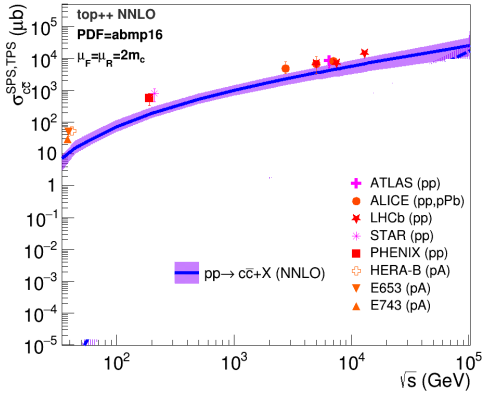
$$\frac{d\sigma^{\mathrm{PP}}}{dp_{\mathrm{T}}dy} = \sum_{ij} \int dx_1 \int dx_2 \; f_i^p(x_1, \mu^2_{\mathrm{fact}}) \; \frac{d\hat{\sigma}^{ij\to \mathrm{Q}+X}(x_1, x_2, m^2, \mu^2_{\mathrm{ren}}, \mu^2_{\mathrm{fact}})}{dp_{\mathrm{T}}dy} \; f_j^p(x_2, \mu^2_{\mathrm{fact}})$$

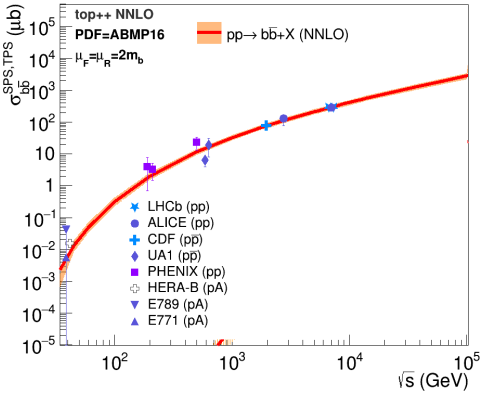
Parton distributions (PDFs) — Partonic coefficient functions — Parton distributions (PDFs)

- 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

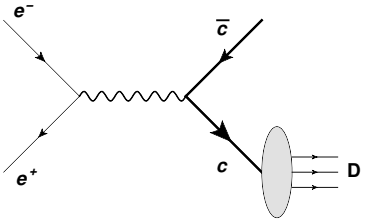
D-meson production @ hadron colliders

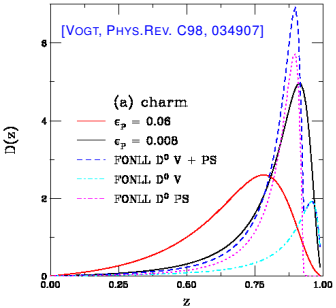
- Partonic cross sections folded with charm-to-D **fragmentation functions** (FFs), $D_{\mathrm{c}\to\mathrm{D}}(z)$

$$\frac{d\sigma^{\mathrm{pp}}}{dP_{\mathrm{T}}dY} = \sum_{ij} \int \frac{dz}{z} \int dx_1 \int dx_2 \; f_i^p(x_1, \mu^2_{\mathrm{fact}}) \; \frac{d\hat{\sigma}^{ij\to\mathrm{c}+X}(x_1, x_2, m^2, \mu^2_{\mathrm{ren}}, \mu^2_{\mathrm{fact}})}{dp_{\mathrm{T}}dy} \; f_j^p(x_2, \mu^2_{\mathrm{fact}}) \; D_{\mathrm{c}\to\mathrm{D}}(z)$$

Parton distributions — Coefficient functions — Parton distributions — Fragmentation function

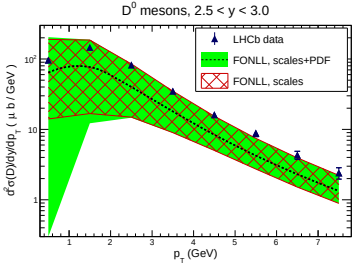
- FFs can be fitted to $e^+e^- \to \mathrm{D} + X$ data

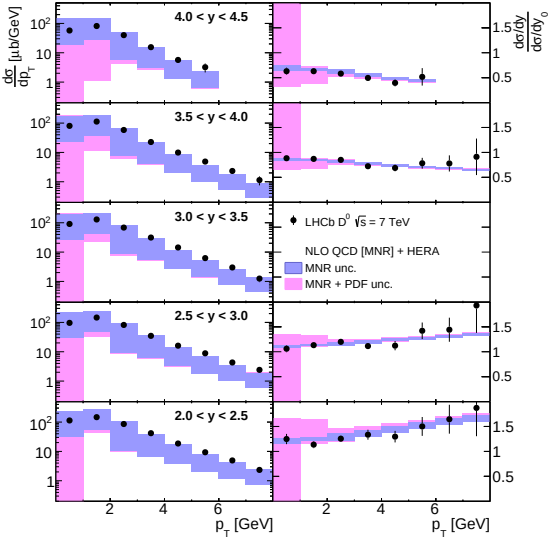




D-meson production @ hadron colliders

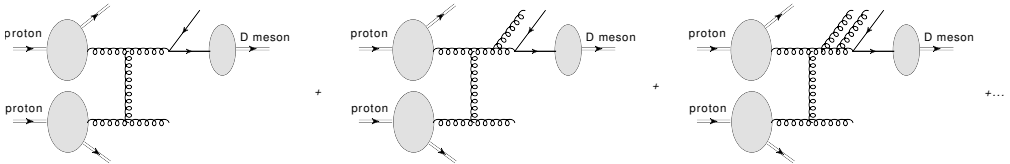
- Calculations [Zenaiev EPJ C77, 151; Gauld et.al. JHEP 11 (2015), 009] compared with LHCb data
- Tendency to underestimate the LHCb data – still within the large QCD scale uncertainties





Resummation of final-state $\log(p_{\mathrm{T}}/m_{\mathrm{c}})$ terms

- Collinear splittings lead to large logarithms $\sim \log(p_{\mathrm{T}}/m_{\mathrm{c}})$ at $p_{\mathrm{T}} \gg m_{\mathrm{c}}$



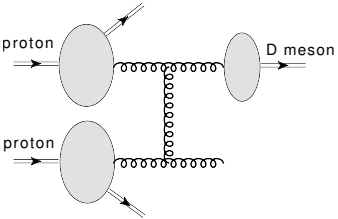
- These can be resummed via **scale-dependent FFs** $D_{i\to D}(z, \mu^2_{\mathrm{frag}})$

$$D_{g\to D}(x, \mu^2_{\mathrm{frag}}) = \left[\left(\frac{\alpha_s}{2\pi}\right) \log\left(\frac{\mu^2_{\mathrm{frag}}}{m_c^2}\right) \underbrace{P_{qg}}_{\text{splitting functions}} + \frac{1}{2!}\left(\frac{\alpha_s}{2\pi}\right)^2 \log^2\left(\frac{\mu^2_{\mathrm{frag}}}{m_c^2}\right) \underbrace{P_{qg} \otimes P_{gg}}_{\text{splitting functions}} + \cdots \right] \otimes D_{Q\to D}$$

- We use the KKKS08 [Kneesch et.al. Nucl.Phys.B 799 (2008) 34] set of scale-dependent FFs

Resummation of final-state $\log(p_{\mathrm{T}}/m_{\mathrm{c}})$ terms

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

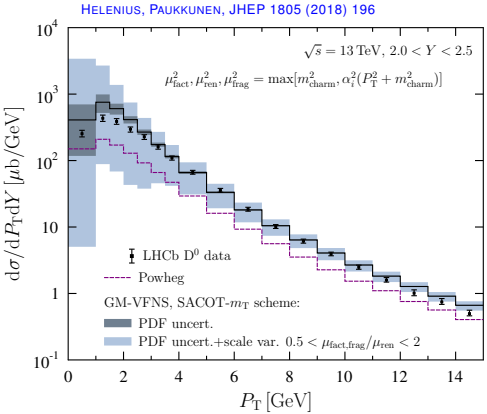


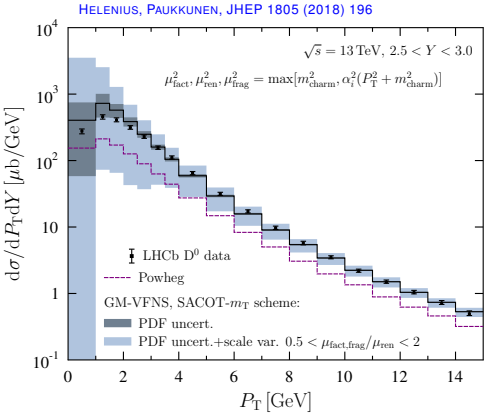
$$\frac{d\sigma^{\mathrm{pp}}}{dP_{\mathrm{T}}dY} = \sum_{i,j,k} \int \frac{dz}{z} dx_1 dx_2 \; f_i^p(x_1, \mu_{\mathrm{fact}}^2) \; \frac{d\hat{\sigma}^{ij\to k+X}(x_1, x_2)}{dp_{\mathrm{T}}dy} \; f_j^p(x_2, \mu_{\mathrm{fact}}^2) \; D_{k\to D}(z, \mu_{\mathrm{frag}}^2)$$

- 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

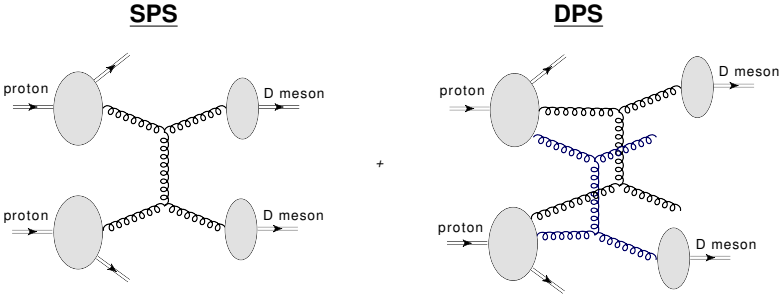
- LHCb p-p cross sections well reproduced by the resummed approach at NLO





Double-D production

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



- The cross section is of the form

$$\frac{\mathrm{d}\sigma_{AB\to a+b+X}}{\mathrm{d}^3\vec{p}^{\,a}\mathrm{d}^3\vec{p}^{\,b}} = \sigma_{AB}^{\mathrm{sps}} + \sigma_{AB}^{\mathrm{dps}} = AB\frac{\mathrm{d}\sigma_{nn\to a+b+X}^{\mathrm{sps}}}{\mathrm{d}^3\vec{p}^{\,a}\mathrm{d}^3\vec{p}^{\,b}} + m\frac{AB}{\sigma_{\mathrm{eff}}^{AB}}\frac{\mathrm{d}\sigma_{nn\to a+X}^{\mathrm{sps}}}{\mathrm{d}^3\vec{p}^{\,a}}\frac{\mathrm{d}\sigma_{nn\to b+X}^{\mathrm{sps}}}{\mathrm{d}^3\vec{p}^{\,b}}$$

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

Double-D production

- Measurements indicate 10 mb $< \sigma_{\rm eff}^{\rm pp} < 25$ mb [e.g. PLB 790 (2019) 595]
- For larger nuclei, one can derive [Adv.Ser.Direct.High Energy Phys. 29 (2018) 159, PLB 800 (2020) 135084]

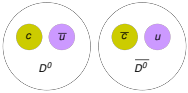
$$\frac{1}{\sigma_{\rm eff}^{AB}} \approx \frac{1}{\sigma_{\rm eff}^{\rm pp}} + \frac{(B-1)}{B^2}\int {\rm d}^2\vec{B}\left[T_B(\vec{B})\right]^2 + \frac{(A-1)}{A^2}\int {\rm d}^2\vec{B}\left[T_A(\vec{B})\right]^2 + \frac{(A-1)(B-1)}{(AB)^2}\int {\rm d}^2\vec{B}\left[T_{AB}(\vec{B})\right]^2 ,$$

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

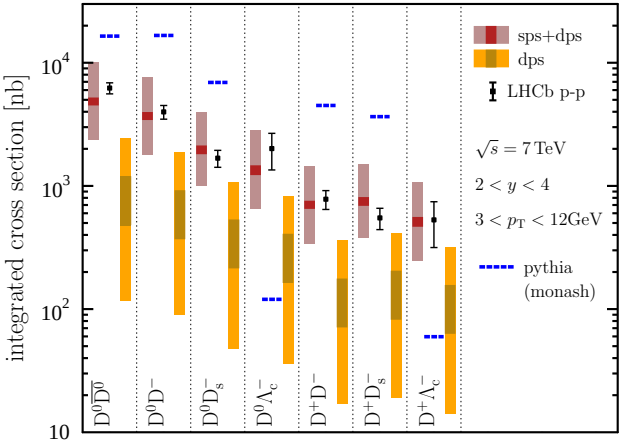
$\Longrightarrow$ In p-Pb collisions, an enhanced DPS signal theoretically expected, $\dfrac{\sigma_{\rm eff}^{\rm pp}}{\sigma_{\rm eff}^{\rm pPb}} \approx 2.5\ldots4.8$

Application to double-D production – p-p case

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



[Helenius, Paukkunen, PLB 800 (2020) 135084]



[data: JHEP 06 (2012) 141]

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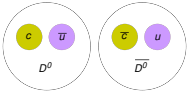

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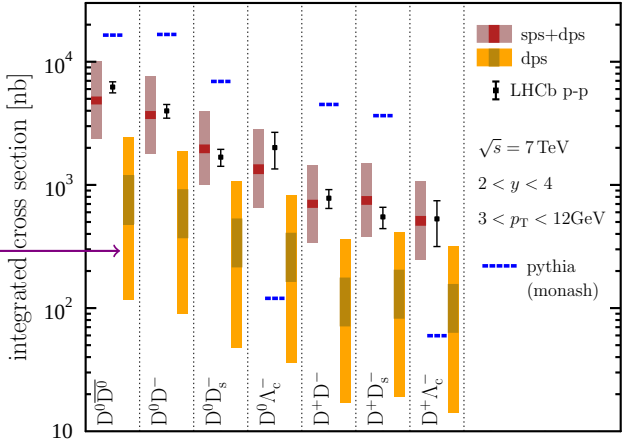
DPS CONTRIBUTION SUBLEADING



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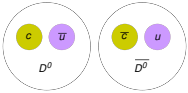

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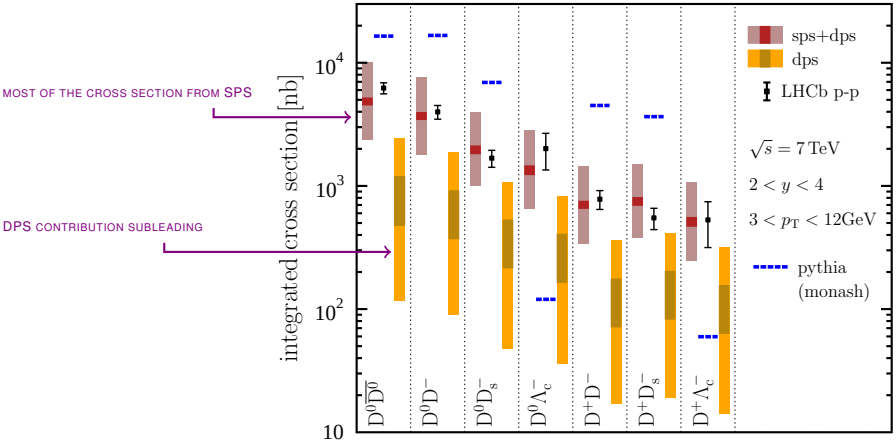

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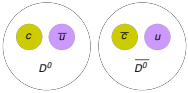

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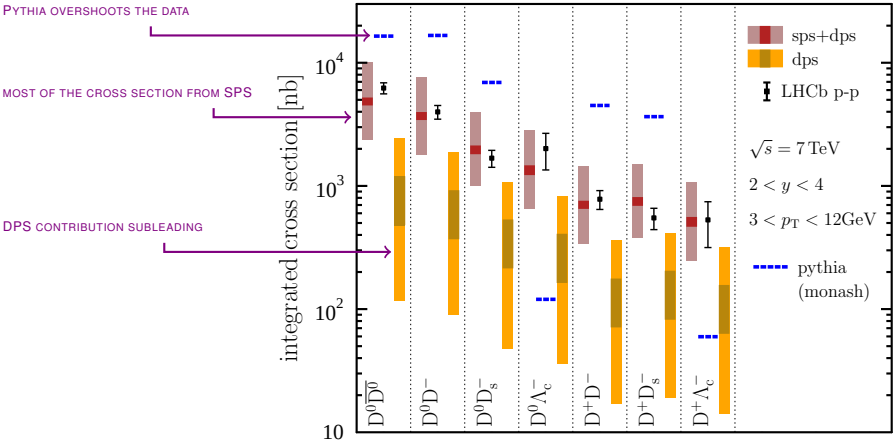

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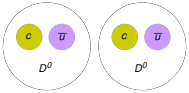
Application to double-D production – p-p case

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



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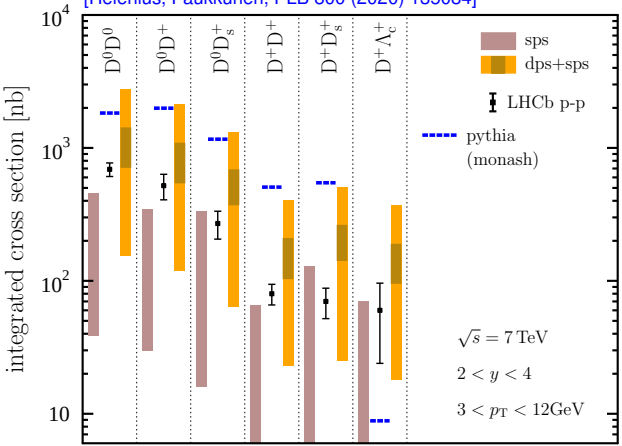

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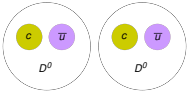

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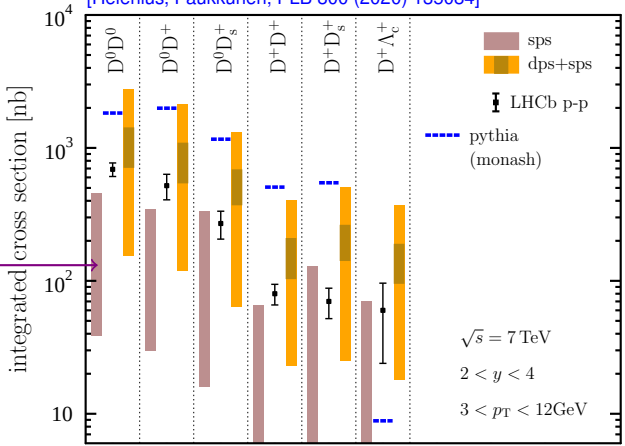

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SPS CONTRIBUTION SUBLEADING NOW

Application to double-D production – p-p case

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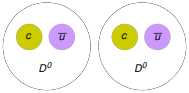

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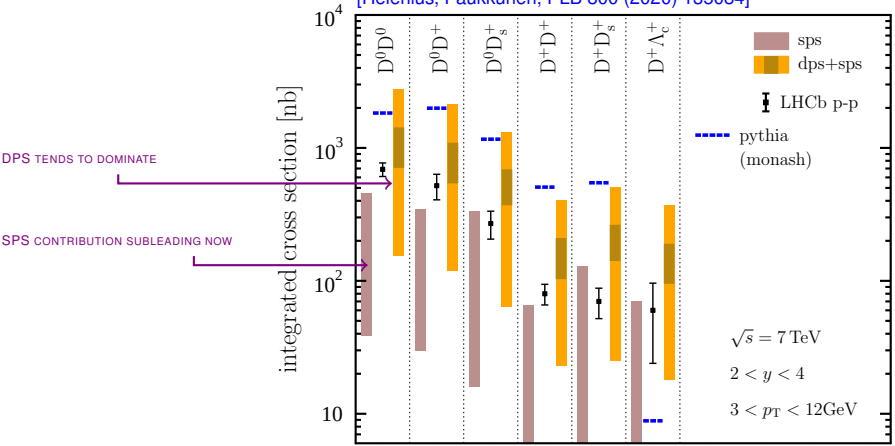

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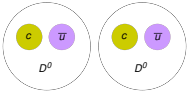
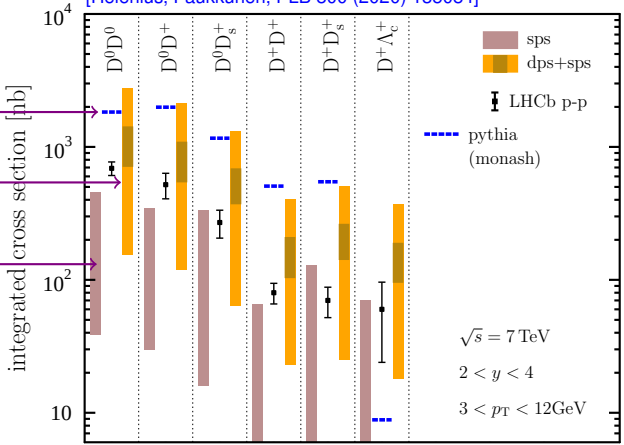


[Helenius, Paukkunen, PLB 800 (2020) 135084]

PYTHIA OVERSHOOTS THE DATA

DPS TENDS TO DOMINATE

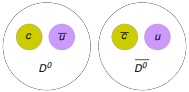
SPS CONTRIBUTION SUBLEADING NOW



[data: JHEP 06 (2012) 141]

Application to double-D production – p-Pb predictions

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



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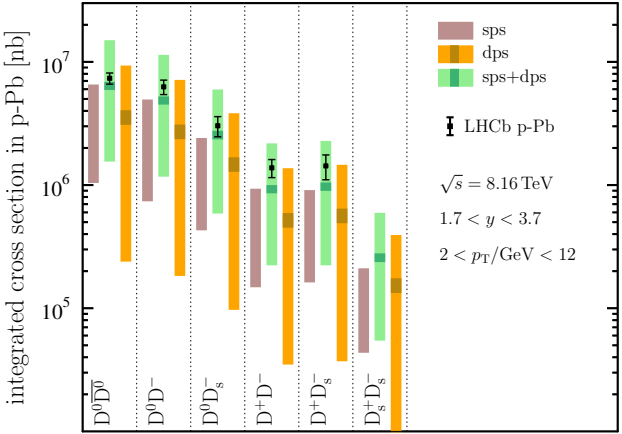

[data: PRL 125 (2020) 21, 212001]

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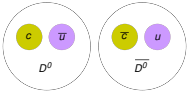

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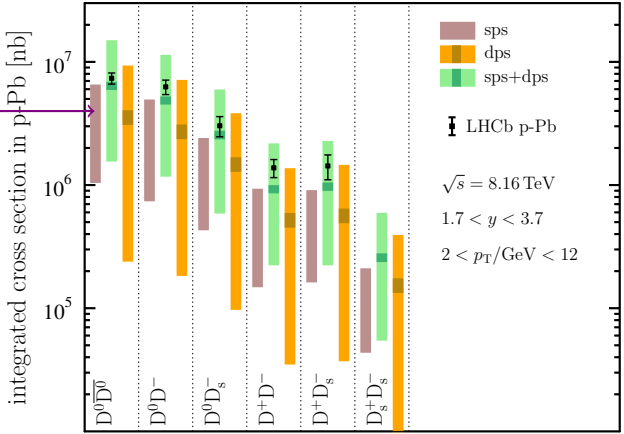
SPS ALONE TENDS TO UNDERSHOOT THE DATA



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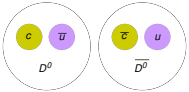

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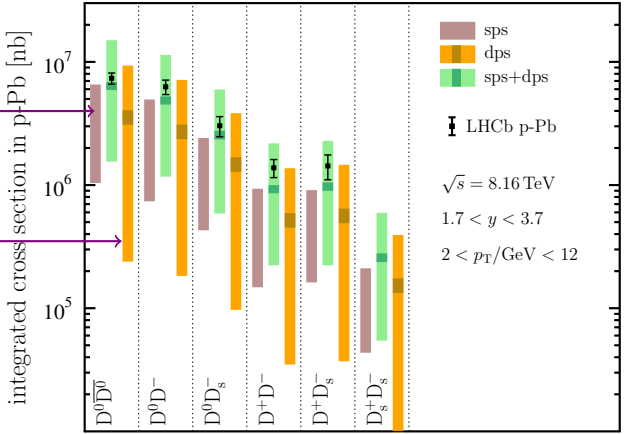
SPS ALONE TENDS TO UNDERSHOOT THE DATA

DPS CONTRIBUTION SIMILAR TO SPS



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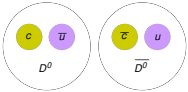
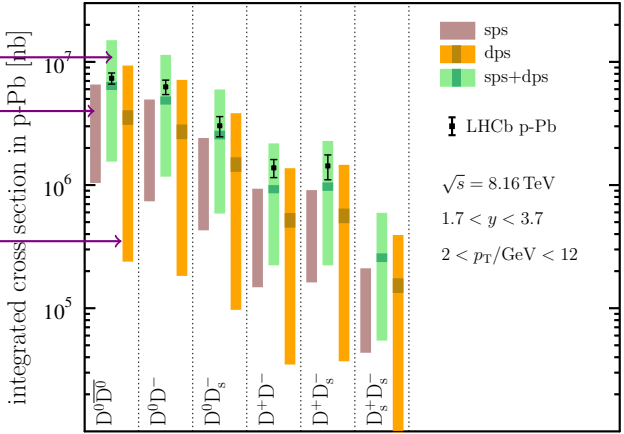


[Helenius & Paukkunen, based on PLB 800 (2020) 135084]

SPS+DPS WELL IN LINE WITH THE DATA

SPS ALONE TENDS TO UNDERSHOOT THE DATA

DPS CONTRIBUTION SIMILAR TO SPS



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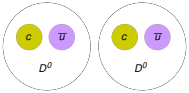
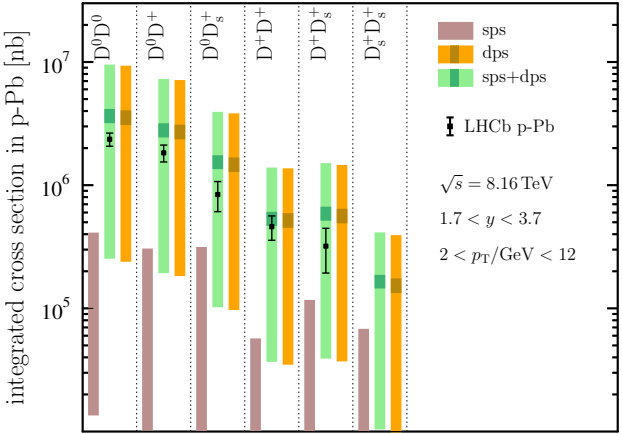
Application to double-D production – p-Pb predictions

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



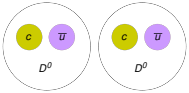
[Helenius & Paukkunen, based on PLB 800 (2020) 135084]



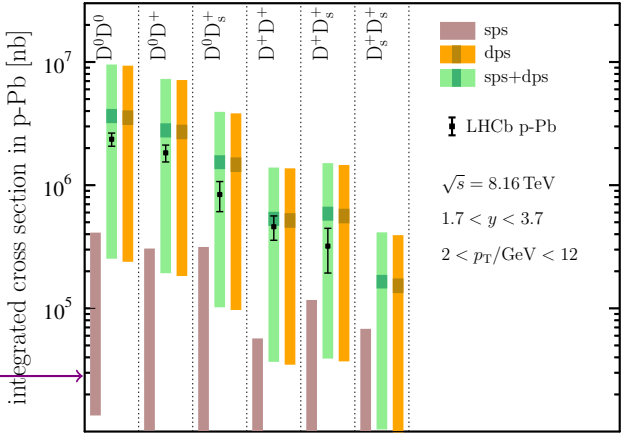
[data: PRL 125 (2020) 21, 212001]

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]



SPS CONTRIBUTION NEGLIGIBLE

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

Application to double-D production – p-Pb predictions

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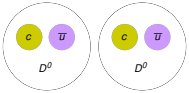
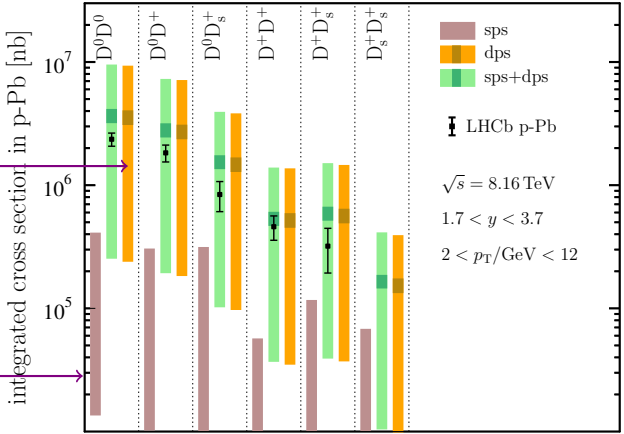


[Helenius & Paukkunen, based on PLB 800 (2020) 135084]

DPS CONTRIBUTION EXPLAINS THE MEASURED CROSS SECTION

SPS CONTRIBUTION NEGLIGIBLE



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

Application to double-D production – p-Pb predictions

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

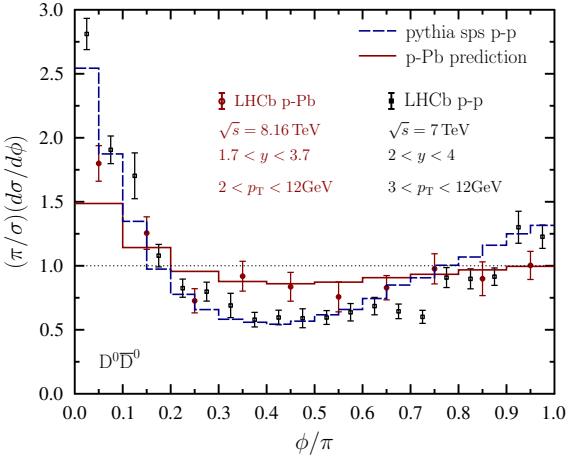
$$\frac{1}{\sigma^{\mathrm{pPb}}}\frac{\mathrm{d}\sigma^{\mathrm{pPb}}}{\mathrm{d}\phi} = \alpha \times \left[\frac{1}{\sigma^{\mathrm{pp}}}\frac{\mathrm{d}\sigma^{\mathrm{pp}}}{\mathrm{d}\phi}\Big|_{\mathrm{pythia\ sps}}\right] + \beta/\pi$$

- Coefficients α and β come from NLO calculation

$$\alpha = \frac{\sigma^{\mathrm{sps}}_{\mathrm{pPb}}}{\sigma^{\mathrm{sps}}_{\mathrm{pPb}} + \sigma^{\mathrm{dps}}_{\mathrm{pPb}}}\,, \quad \beta = \frac{\sigma^{\mathrm{dps}}_{\mathrm{pPb}}}{\sigma^{\mathrm{sps}}_{\mathrm{pPb}} + \sigma^{\mathrm{dps}}_{\mathrm{pPb}}}$$

- 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]



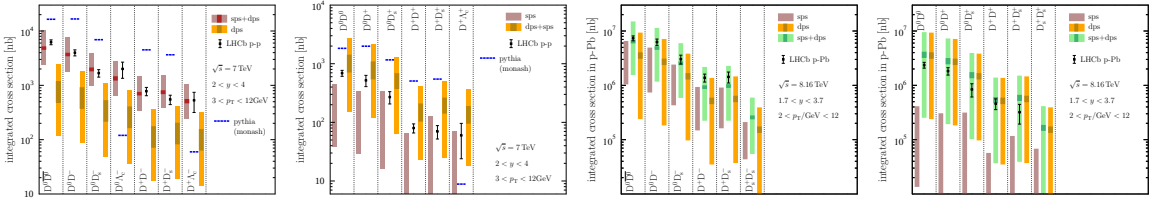
Summary

- Applied a NLO GM-VFNS framework on double D-meson hadroproduction
- Good agreement with the recent p-p & p-Pb data from LHCb

$\Longrightarrow$ confirms the enhanced double-parton scattering component in p-Pb vs. p-p!

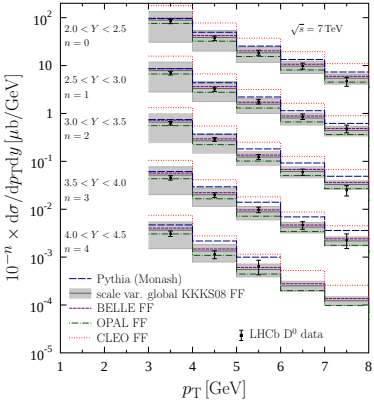
- Azimuthal correlations in p-Pb consistent with the enhanced DPS contribution

$\Longrightarrow$ no evidence of saturation signatures at this point

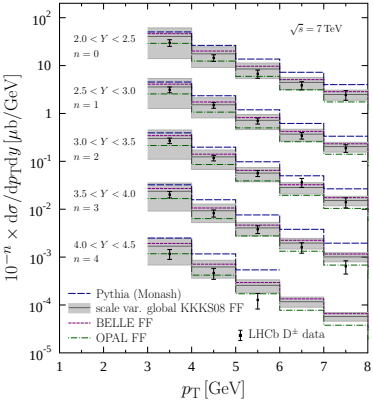


Inclusive p-p cross sections D^0, $D^\pm$, $D_s^\pm$

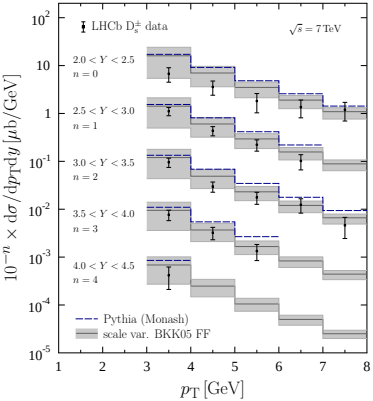
[PLB 800 (2020) 135084]



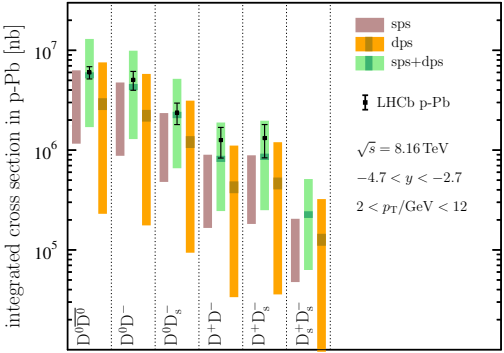
[PLB 800 (2020) 135084]

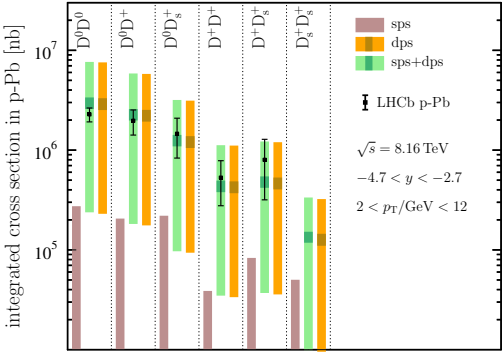


[PLB 800 (2020) 135084]



Backward cross sections





Azimuthal correlations in the backward direction