D-mesons at the LHC

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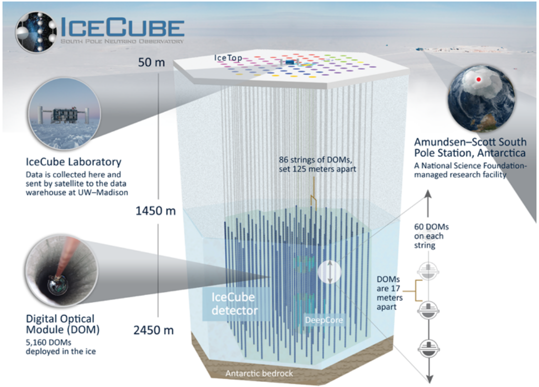
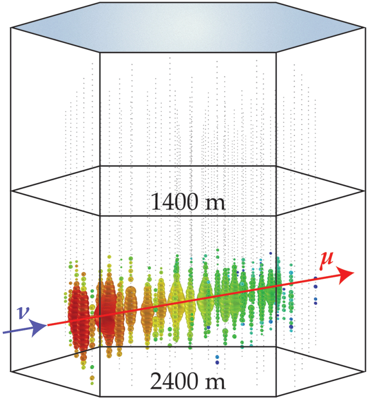
Hitupäivä, November 7th 2019

Prelude

- Neutrino telescopes opening a **new window to the Universe**

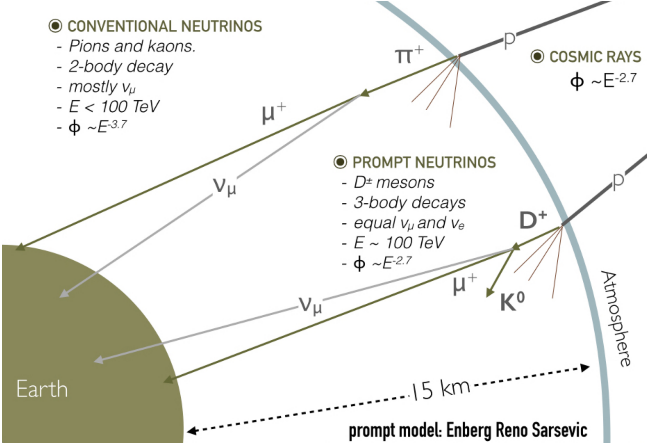




Prelude

- Background created by D-mesons from **cosmic-proton - air** collisions

[JUAN ROJO, DIS'17]



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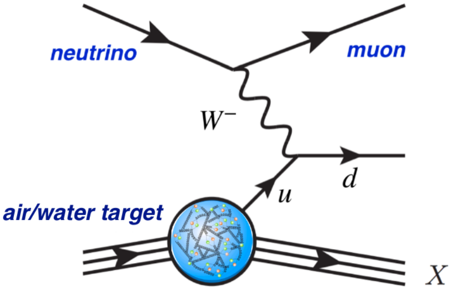
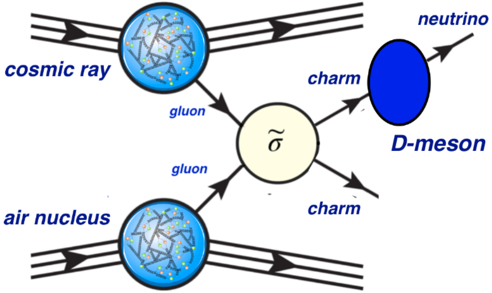
[JUAN ROJO, DIS'17]

***signal**: cosmic neutrino - nucleus scattering*



***background**: prompt charm production*



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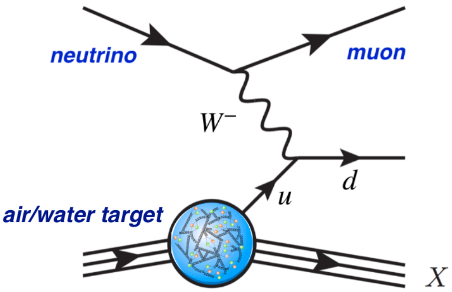

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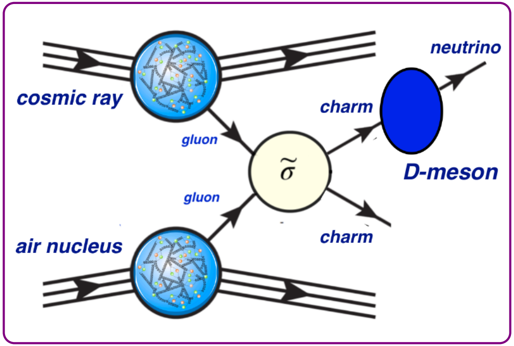
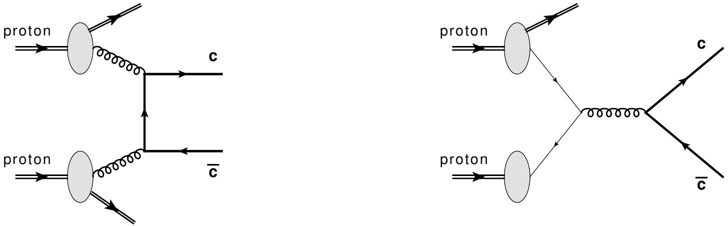


This talk!

Inclusive heavy-quark & D-meson production

Heavy-quark production @ hadron colliders

- To leading order, the heavy quarks Q are produced in two partonic processes



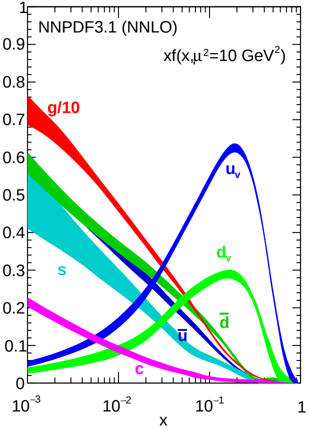
$$\frac{d\sigma^{\rm pp}}{dp_{\rm T}dy} = \sum_{ij} \int dx_1 \int dx_2 \, f_i^p(x_1, \mu^2_{\rm fact}) \, \frac{d\hat{\sigma}^{ij\rightarrow {\rm Q}+X}(x_1,x_2,m^2,\mu^2_{\rm ren},\mu^2_{\rm fact})}{dp_{\rm T}dy} \, f_j^p(x_2, \mu^2_{\rm fact})$$

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

- NLO coefficient functions known since the 80's (Nason, Dawson, Ellis)
- NNLO results also basically known, e.g. **Top++** (Czakon, Mitov)

- Parton distributions $f_i^p(x, \mu^2_{\rm fact})$ "known" from global fits (HERA, Tevatron, LHC)

[NNPDF coll. EPJC 77, 663]



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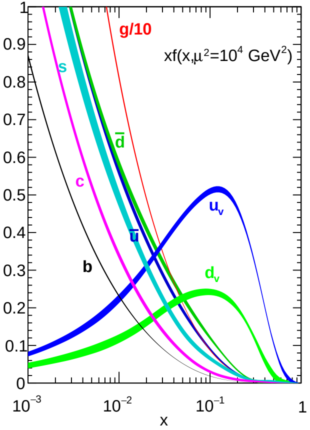
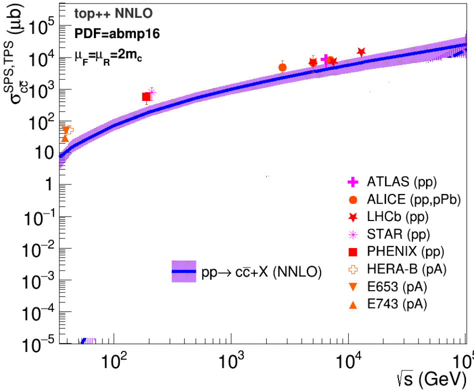
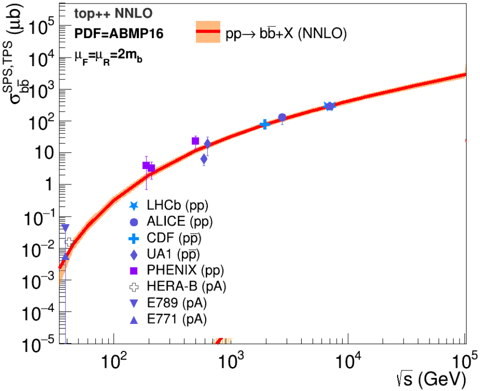


- Integrated cross sections at **NNLO** vs. world data [ENTERRIA, SNIGIREV, PRL 118, 122001]





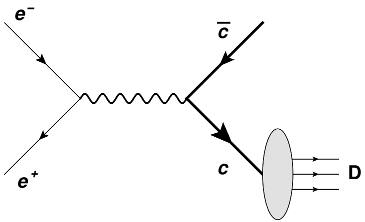
- Charm production somewhat underestimated – bottom production looks OK

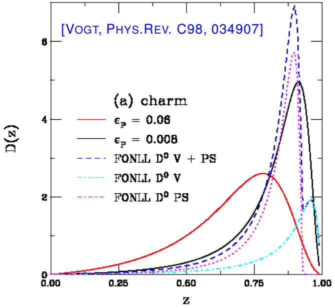
D-meson production @ hadron colliders

- Parton-level calculations folded with $\mathrm{charm} \to \mathrm{D}$ **fragmentation functions** (FFs), $D_{Q\to D}(z)$

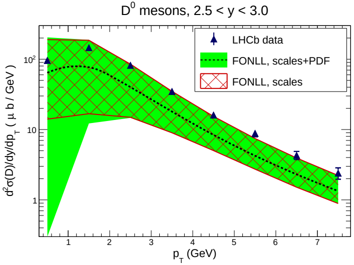
$$\frac{d\sigma^{\mathrm{pp}}}{dP_{\mathrm{T}}dY} = \sum_{ij} \int \frac{dz}{z} \int dx_1 \int dx_2 \underbrace{f_i^p(x_1, \mu^2_{\mathrm{fact}})}_{\text{Parton distributions}} \underbrace{\frac{d\hat{\sigma}^{ij\to \mathrm{Q}+X}(x_1,x_2,m^2,\mu^2_{\mathrm{ren}},\mu^2_{\mathrm{fact}})}{dp_{\mathrm{T}}dy}}_{\text{Coefficient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

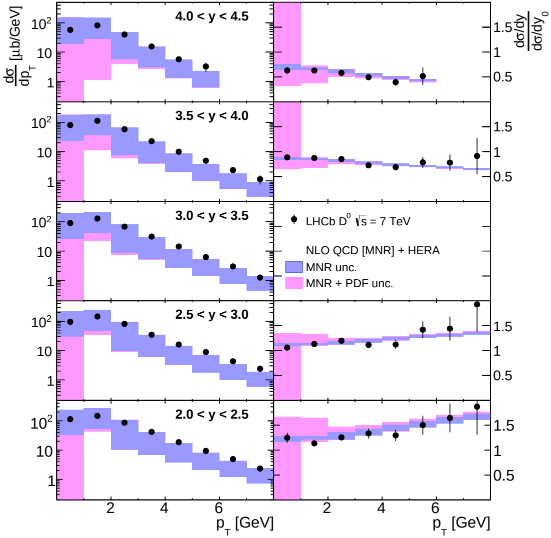
- FFs can be fitted to $e^+e^- \to \mathrm{D} + X$ data





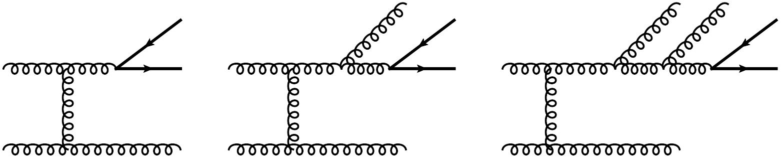
- Calculations [ZENAIEV EPJ C77, 151, GAULD ET.AL. JHEP 1511] compared with LHCb data
- Tendency to underestimate the LHCb data – still within the large QCD scale uncertainties





Resummation of final-state $\log(p_{\mathrm{T}}^2/m^2)$ terms

- Cross section $d\sigma \sim \log(p_{\mathrm{T}}^2/m_{\mathrm{charm}}^2)$ at $p_{\mathrm{T}} \gg m_{\mathrm{charm}}$ due to collinear splittings



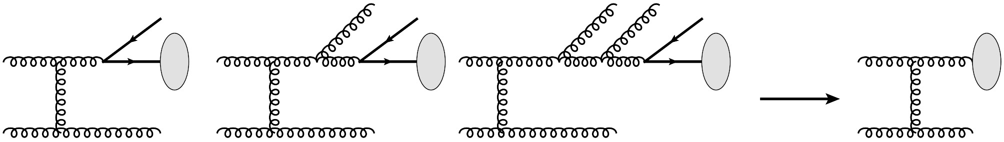
- These can be formally resummed via **scale-dependent FFs** $D_{i\to D}(z, \mu_{\mathrm{frag}}^2)$

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

- Leads to a DGLAP renormalization-group equation for FFs

Resummation of final-state $\log(p_{\rm T}^2/m^2)$ terms

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



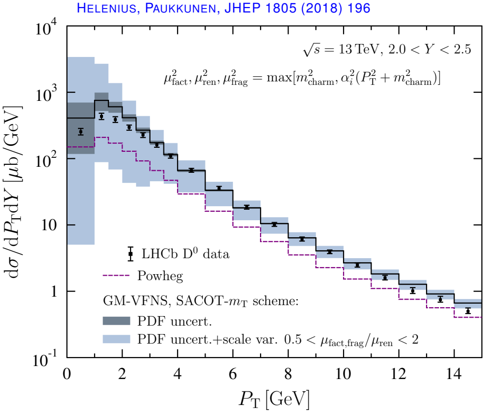
$$\int \frac{dz}{z} dx_1 dx_2 \; f_g^p(x_1, \mu^2_{\rm fact}) \; \frac{d\hat{\sigma}^{gg\rightarrow g+X}(x_1,x_2)}{dp_{\rm T}\, dy} \; f_g^p(x_2, \mu^2_{\rm fact}) \; D_{g\rightarrow D}(z, \mu^2_{\rm frag})$$

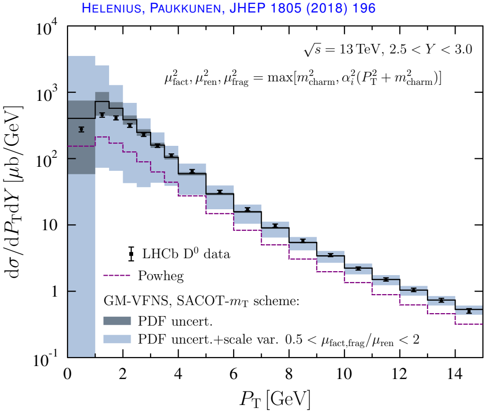
- The heavy-quark implicitly regulates e.g. here the t-channel divergence towards $p_{\rm T} \rightarrow 0$.

- Kinematic constraint worked out in [Helenius, Paukkunen, JHEP 1805, 196] – ignored in the early implementations [Kniehl et.al. PRD 71 (2005) 014018] & [Cacciari et.al. JHEP 9805, 007, FONLL]

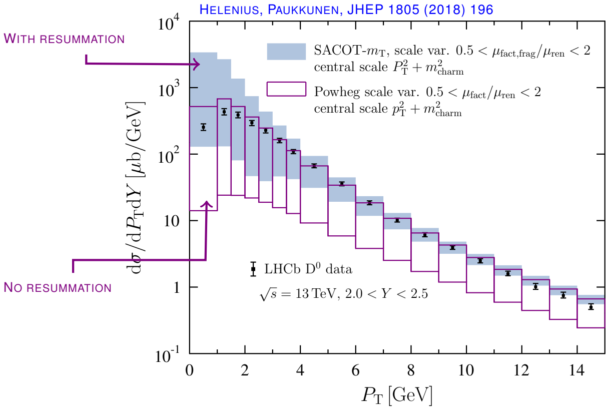
Comparison with the LHCb 13 TeV data

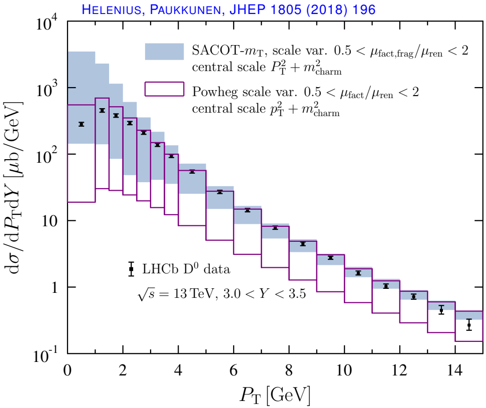
- LHCb p-p cross sections well reproduced by the resummed approach at NLO





- Scale uncertainties dramatically reduced at $p_T \gtrsim 3\,\text{GeV}$

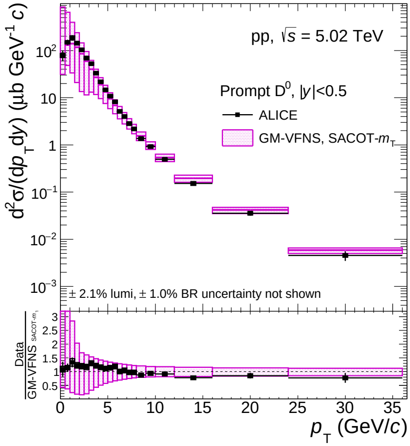




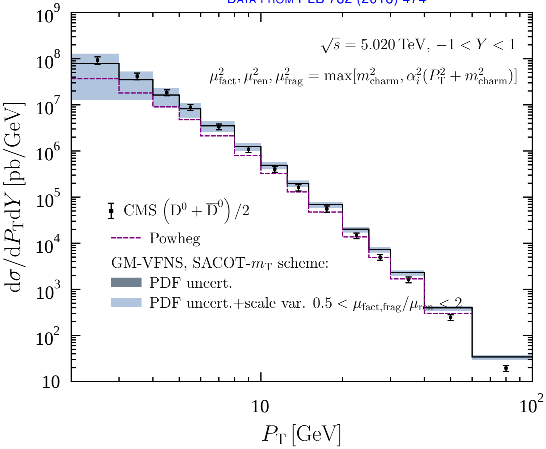
Comparison with the ALICE & CMS 5 TeV data

- ALICE & CMS p-p cross sections vs. resummed NLO calculation

ALICE coll. Eur.Phys.J. C79, 388



Data from PLB 782 (2018) 474



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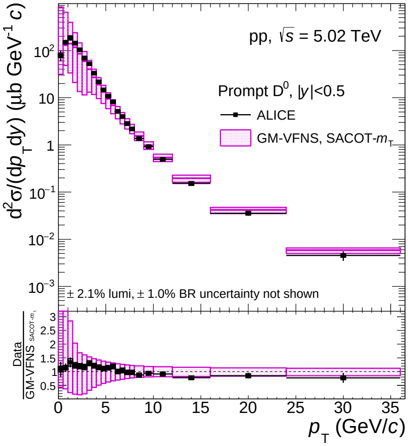

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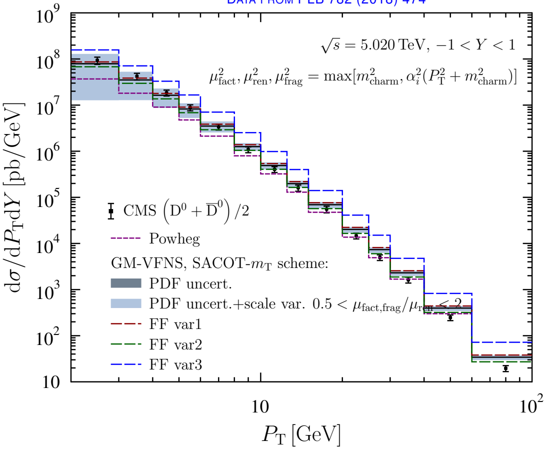
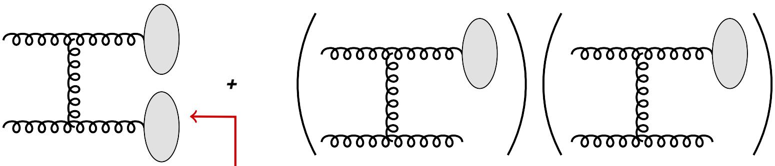


Double D-meson production

Application to double-D production

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



- The cross section is of the form

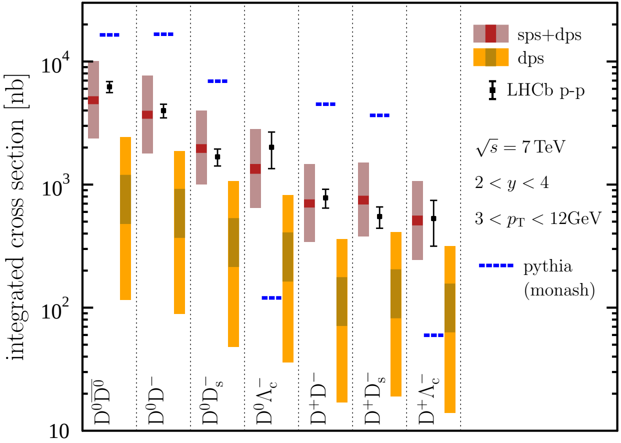
$$\frac{d\sigma_{AB\to a+b+X}}{d^3\vec{p}^a d^3\vec{p}^b} = AB\left[\frac{d\sigma^{\rm sps}_{nn\to a+b+X}}{d^3\vec{p}^a d^3\vec{p}^b} + \frac{1}{\sigma^{AB}_{\rm eff}}\frac{d\sigma^{\rm sps}_{nn\to a+X}}{d^3\vec{p}^a}\frac{d\sigma^{\rm sps}_{nn\to b+X}}{d^3\vec{p}^b}\right]$$

- In p-Pb collisions, an enhanced DPS signal theoretically expected, $\frac{1}{\sigma^{\rm pPb}_{\rm eff}} \approx \frac{2.5\ldots4.8}{\sigma^{pp}_{\rm eff}}$

Application to double-D production – opposite-sign case

- Resummed calculation agrees with the LHCb p-p data – default Pythia fails quite completely

[Helenius, Paukkunen, arXiv:1906.06971]



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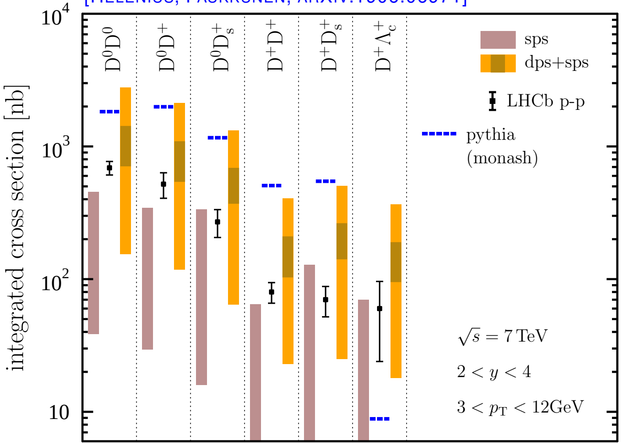
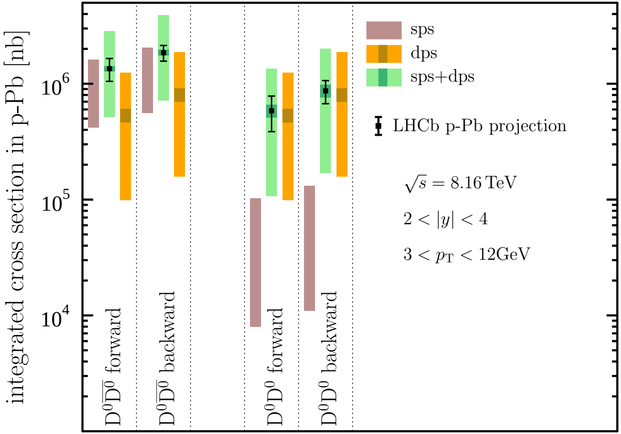


Application to double-D production – p-Pb predictions

- DPS signal in p-Pb should be visible in the $12.2\,\mathrm{nb}^{-1}$(p-Pb) + $18.6\,\mathrm{nb}^{-1}$(Pb-p) Run-II data sample

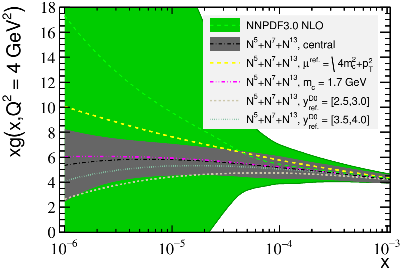
[HELENIUS, PAUKKUNEN, ARXIV:1906.06971]



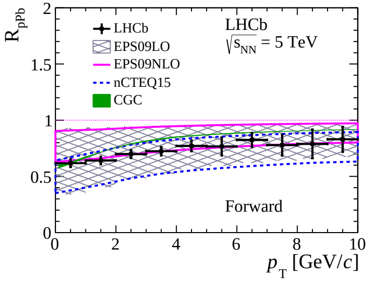
Constraining (nuclear) PDFs with D mesons

- The potential of D-meson production as a PDF constraint under active investigation
  [Gauld, Rojo, PRL 118, 072001 ; PROSA, EPJ C75, 396 ; Kusina et.al. PRL 121,052004]

reduction of NNPD3.0 gluon uncertainty upon including LHCb D-meson data



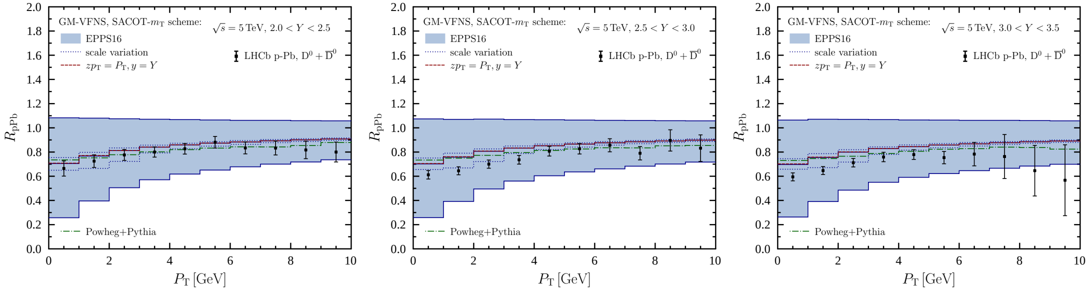
nuclear modification in p-Pb at large rapidity from LHCb



Constraining nuclear PDFs with D mesons

- Cross-section ratios $d\sigma^{\mathrm{pPb}}/d\sigma^{\mathrm{pp}}$ sensitive to the nuclear effects in Pb PDFs
- The LHCb data significantly more precise than the EPPS16 nuclear PDFs

[Eskola, Helenius, Paakkinen, Paukkunen, arXiv:1906.02512]



- Estimate the impact of these data via PDF reweighting [Paukkunen, Zurita, JHEP 1412, 100]

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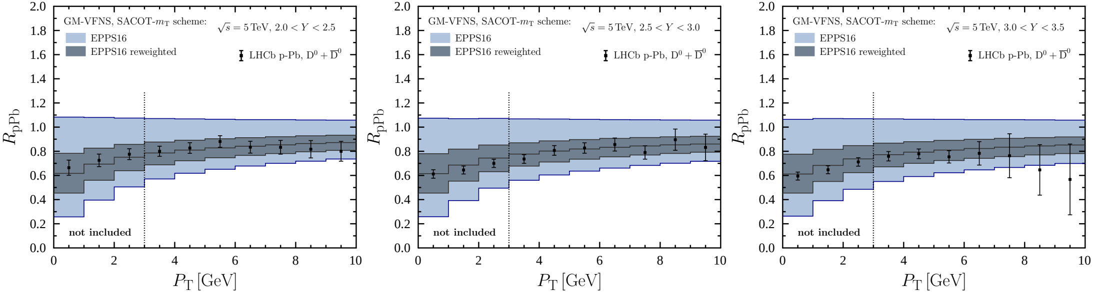


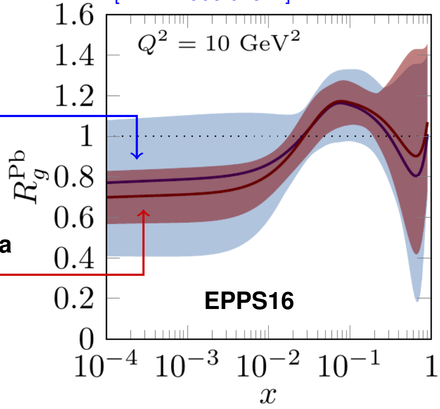
- Can reproduce the data down to $p_T = 0\,\mathrm{GeV}$ – **no signs of non-linear dynamics** (a la CGC)

Constraining nuclear PDFs with D mesons

- Effect for gluon-PDF nuclear modifiction $f_g^{\mathrm{p,Pb}}(x,Q^2)/f_g^{\mathrm{p}}(x,Q^2)$,

Original EPPS16 gluons

[ARXIV:1906.02512]



EPPS16 gluons + LHCb data

- **The world of D mesons at the LHC**