# QCD opportunities by heavy-flavour production in fixed-target experiments at the LHC

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*with input from*

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Meeting of the Forschergruppe For2926
Universität Regensburg, Regensburg, 16 - 17 February, 2023

# Light flavour vs. heavy flavour

$*$ Light-flavoured hadrons include only light quarks as valence quarks in their composition.

$* \; m_u, \;\; m_d, \;\; m_s << \Lambda_{QCD}$

$\Rightarrow \alpha_S(m_u), \;\; \alpha_S(m_d), \;\; \alpha_S(m_s) \;\; > 1$

$\Rightarrow$ Light hadron production at low $p_T$ is dominated by non-perturbative QCD effects.

$*$ Heavy-flavoured hadrons include at least one heavy-quark as valence quark in their composition.

$* \; m_c, \;\; m_b >> \Lambda_{QCD}$

$\Rightarrow \alpha_s(m_c), \;\; \alpha_s(m_b), \;\; << 1$

$\Rightarrow$ At a scale $\sim m_Q$, QCD is still perturbative. At the LHC, charm is produced perturbatively even at low $p_T$, but non-perturbative effects at such low scales may also play important roles.

$* \; m_c, \;\; m_b <<$ LHC energies

$\Rightarrow$ Multiscale issues, appearence of large logs.

# Heavy-quark production in hadronic collisions

* Heavy quarks are mostly produced in pairs in the Standard Model.
  This process is dominated by QCD effects.

* Collinear factorization theorem is assumed:

$$d\sigma(N_1 N_2 \to Q\bar{Q} + X) = \sum_{ab} PDF_a^{N_1}(x_a, \mu_F) PDF_b^{N_2}(x_b, \mu_F) \otimes$$
$$\otimes \; d\hat{\sigma}_{ab \to Q\bar{Q}X'}(x_a, x_b, \mu_F, \mu_R, m_Q) \quad + \quad \text{P.C.}$$

$d\hat{\sigma}$: differential perturbative partonic hard-scattering cross-section,

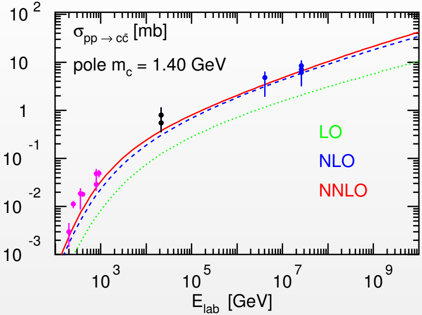
$\mu_F$, $\mu_R$ reabsorb IR and UV divergences,

PDFs: perturbative evolution with factorization scale $\mu_F$,
non-perturbative dependence on $x = p^+/P_N^+$.

QCD uncertainties

* $\mu_F$ and $\mu_R$ choice: no univocal recipe.
* Approximate knowledge of heavy-quark mass values $m_Q$ (SM input parameters).
* Choice of the Flavour Number Scheme (several possibilities).
* PDF ($+ \alpha_S(M_Z)$) fits to experimental data.

# Total $\sigma(pp \to c\bar{c}(+X))$ at LO, NLO, NNLO QCD




$(E_{lab} \simeq 400 \text{ GeV} \sim E_{cm} = 27 \text{ GeV})$

$(E_{lab} \simeq 7000 \text{ GeV} \sim E_{cm} = 114.6 \text{ GeV})$

$(E_{lab} = 10^6 \text{ GeV} \sim E_{cm} = 1.37 \text{ TeV})$
$(E_{lab} = 10^8 \text{ GeV} \sim E_{cm} = 13.7 \text{ TeV})$
$(E_{lab} = 10^{10} \text{ GeV} \sim E_{cm} = 137 \text{ TeV})$

data from fixed target exp (E769, LEBC-EHS, LEBC-MPS, HERA-B)
+ colliders (STAR, PHENIX, ALICE, ATLAS, LHCb)
are extrapolated from fiducial measurements.

- ∗ LHC fixed-target program make measurements in the region between old fixed-target experiments and RHIC (not yet covered).
- ∗ Sizable QCD uncertainty bands not included in the figure.
- ∗ Leading order is not accurate enough for this process!

# From parton production at NLO to heavy-flavour hadrons

Different descriptions of the transition are possible:

1) fixed-order QCD + Parton Shower + hadronization:
match the fixed-order calculation with a parton-shower algorithm (resummation of part of the logarithms related to soft and collinear emissions on top of the hard-scattering process), followed by hadronization (phenomenological model).

**Advantage:** fully exclusive event generation, correlations between final state particles/hadrons are kept.

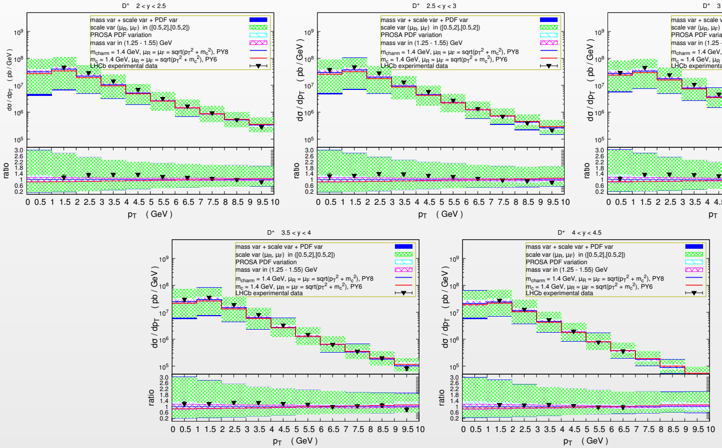
**Problem:** accuracy not exactly known, differently from the case of conventional analytical resummation procedures to all orders in P. T.

2) Convolution of partonic cross-sections with Fragmentation Functions (see the following).

Both methods 1) and 2) are used in the following.

# NLO+PS differential $\sigma$ vs experimental data

## for differential cross-sections for $pp \to D^{\pm} + X$ at LHCb at 5 TeV

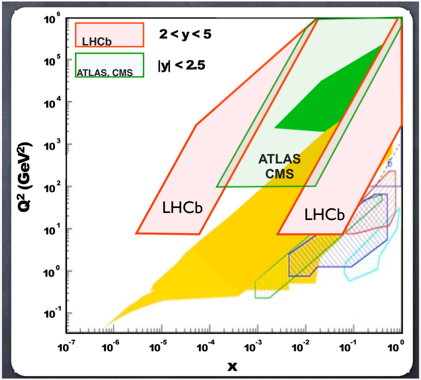



* agreement theory/experiment within large ($\mu_R$, $\mu_F$) uncertainty bands.
* theory uncertainties much larger than the experimental ones.

# Coverage of heavy-flavour data for PDF fits

- ∗ LHCb open-charm data ($2 < y < 4.5$)
- ∗ ATLAS (and CMS) open-charm data ($|y| < 2.5$)
- ∗ CDF open-charm data ($|y| < 1$)
- ∗ ALICE open-charm data ($|y| < 0.5$)

\+ further open-bottom data

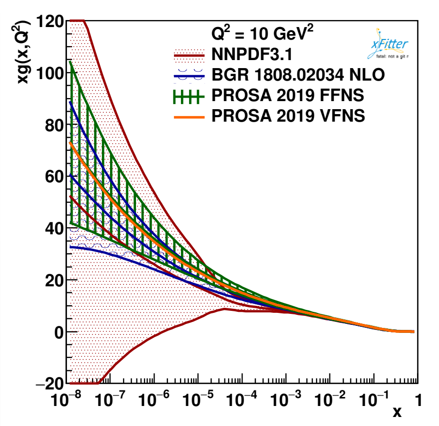


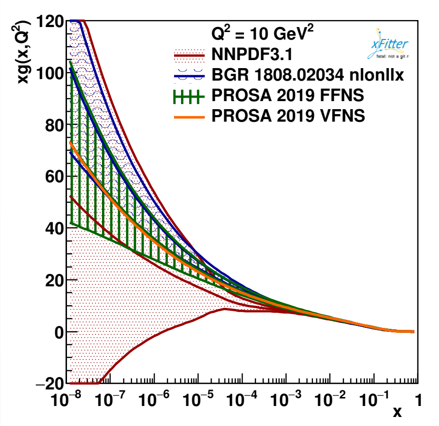

Different experiments span ($Q^2$, $x$) regions partially overlapping: good for verifying their compatibility and for cross-checking their theoretical description.

Description of similar quality for all these data so far.

These data are very useful for constraining gluon PDFs at small $x$: see e.g. various versions of PROSA PDFs and NNPDF+LHCb PDFs.

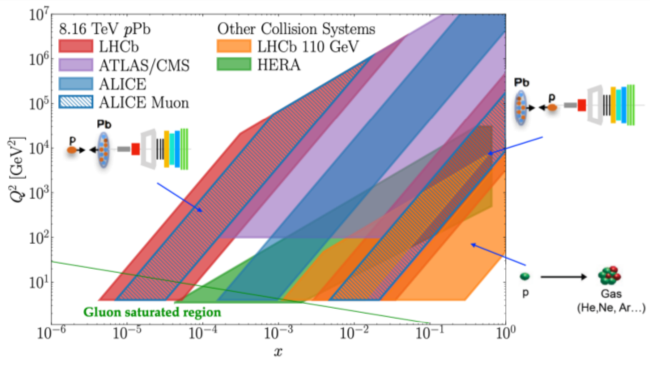
# gluon PDF: comparison between different PDF fits including LHCb *D*-meson production data




- LHCb *D*-meson data (collider modality) constrain PDFs at small x.
- Compatibility of indipendent PDF fits including *D*-meson data: PROSA central gluon lies in the interval between central NNPDF3.1+LHCb NLO and NNPDF3.1+LHCb NLO+(small-$x$)NLL.

# Fixed-target experiments at the LHC: increased large $x$ coverage and sensitivity to nuclear matter effects



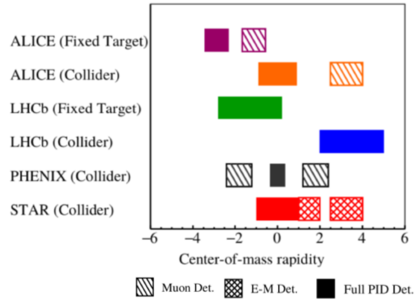

*from K. Mattioli (LHCb), talk at QCD@LHC, December 2022*

* LHCb-FT coverage at scale $Q^2 \sim 4$ GeV$^2$:

  $2 \cdot 10^{-4} \lesssim x \lesssim 4 \cdot 10^{-1} \Rightarrow$ gluon, sea quarks and intrinsic charm
* Light targets: probe NM effects in $pA$ collisions in $A$ range different from Pb
* Cold and Hot Nuclear Matter effects (at small $x$) can be compared by using $p$ or Pb beams impinging on the nuclear targets (He, Ne, Ar, ......).

# Fixed-target experiments at the LHC: $y^*$ coverage

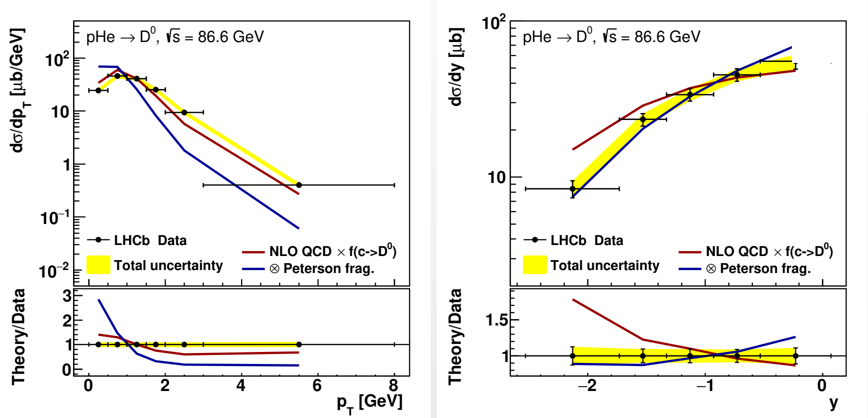
* LHCb SMOG (Run 2): center-of-mass rapidity of heavy-flavour: $-2.29 < y^* < 0$, corresponding to rapidity $2.0 < y < 4.29$
* LHCb SMOG2 (Run 3): $-2.8 < y^* < 0.2$
* ALICE FT extension (Run 4): $-3.6 < y^* < -2.6$




*from FTP4LHC community support document for FT program at LHC*

* Different experiments span $y^*$ regions partially overlapping: good for verifying their compatibility and for cross-checking their results.
* But different materials: $H_2$, $D_2$, Ar, Kr, Xe, He, Ne, $N_2$, $O_2$ (SMOG2) vs. C, Ti, W (ALICE-FT)
* ALICE more backward than LHCb $\Rightarrow$ larger target $x$
* Most recent results on $D^0$ production at $\sqrt{s_{NN}} = 68.5$ GeV from LHCb

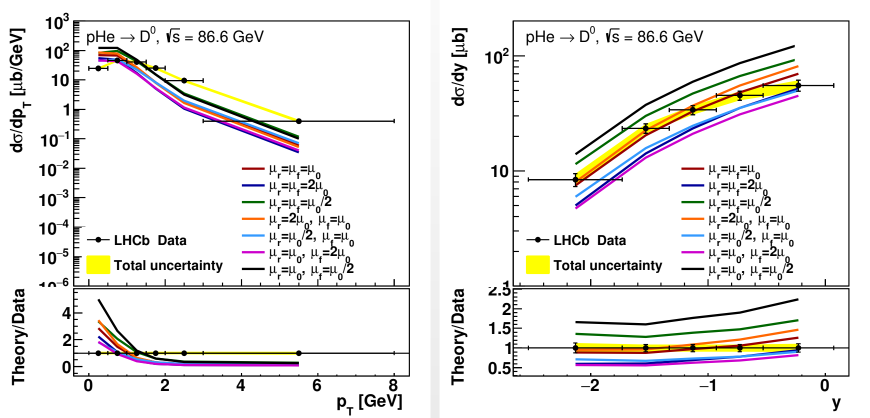
# PROSA (NLO QCD + phenomenological FF) computation of $D^0$-meson production w.r.t. LHCb fixed-target data on pHe in [arXiv:1810.07907]




*

The same NLO + phenomenological FF setup capable to reproduce LHCb $pp \to D_0 + X$ data at $\sqrt{s} = 5, 7$ and 13 TeV, fails to reproduce data at LHC in fixed-target mode → inadequacy/non univ. of the FF approach

# PROSA (NLO QCD + phenomenological FF) computation of $D^0$-meson production w.r.t. LHCb fixed-target data on pHe in [arXiv:1810.07907]



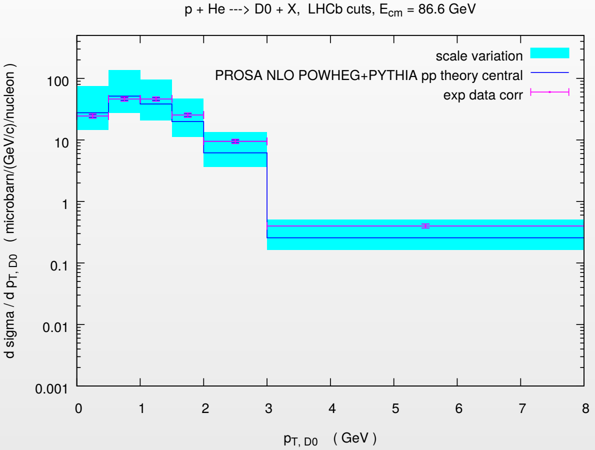

* Scale variation uncertainties are not enough to reconcile theory with data on $p_{T,D_0}$ distribution.
* $y_{D_0}$ distribution well in agreement with exp. data, within scale uncer.

# PROSA NLO+PS computation of $D^0$-meson production w.r.t. LHCb fixed-target data on pHe in [arXiv:1810.07907]

∗ Total cross-sections per nucleon for $D_0 + \bar{D}_0$ after LHCb rapidity cuts:
Theory: $\sigma = 76.1 + 116$ (scale) - 35 (scale) microbarn/n
LHCb: $\sigma = 80.8 \pm 2.4 \pm 6.3$ microbarn/n

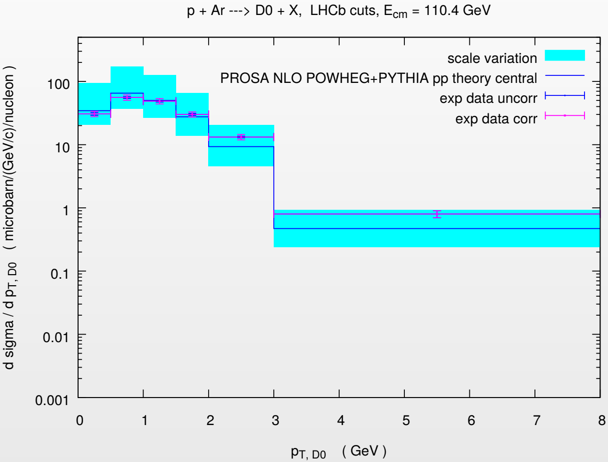
∗ Total cross-sections per nucleon for $D_0 + \bar{D}_0$ inclusive:
Theory: $\sigma = 148.7 + 229$ (scale) - 83 (scale) microbarn/n
LHCb: $\sigma = 156.0 \pm 13$ microbarn/n

# PROSA NLO+PS computation of $D^0$-meson production w.r.t. LHCb fixed-target data on pHe



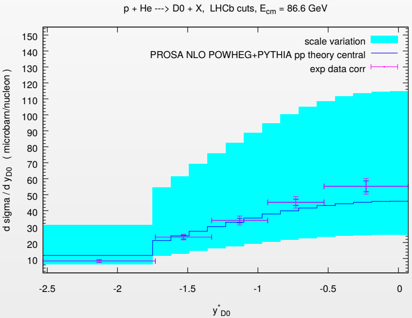

- $pA$ effects might broaden the distribution
- $pp$ central theory predictions slightly underestimate the high $p_T$ tails, but still compatible with data considering scale uncertainties

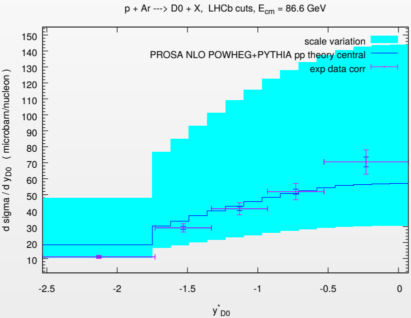
# PROSA NLO+PS computation of $D^0$-meson production w.r.t. LHCb fixed-target data on pAr




∗ exp. ($p$+He) and ($p$+Ar) data similarly enhanced with respect to theory at large $p_T$: final state effects ?

# PROSA NLO+PS computation of $D^0$-meson production w.r.t. LHCb fixed-target data on pHe and pAr



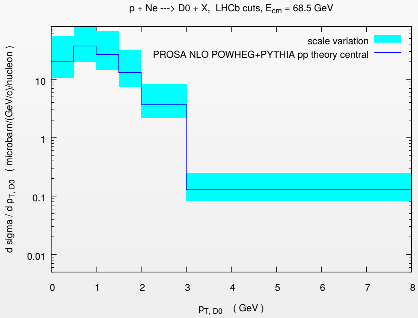

- Big scale uncertainties.
- Before discussing intrinsic charm, one has to disentangle *pA* effects: they can impact on the shapes of the distributions.

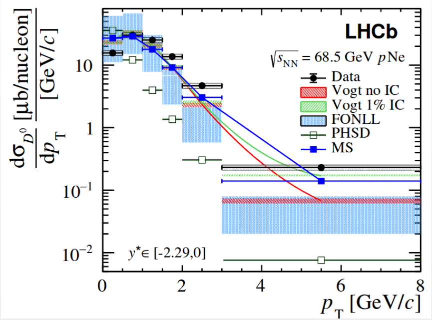
# PROSA NLO+PS computation of $D^0$-meson production w.r.t. LHCb fixed-target data on pNe in [arXiv:2211.11633]

* Total cross-sections per nucleon for $D_0 + \bar{D}_0$ after LHCb rapidity cuts:
  Theory: $\sigma = 53 + 81$ (scale) - 24 (scale) microbarn/n
  LHCb: $\sigma = 48.2 \pm 0.3 \pm 4.3$ microbarn/n

* Total cross-sections per nucleon for $D_0 + \bar{D}_0$ inclusive:
  Theory: $\sigma = 109 + 167$ (scale) - 50 (scale) microbarn/n
  LHCb: $\sigma = 97.6 \pm 0.7 \pm 9.1$ microbarn/n

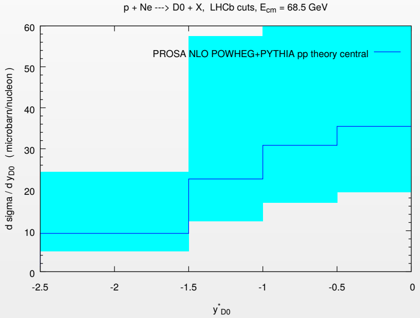
# PROSA NLO+PS computation of $D^0$-meson production w.r.t. LHCb fixed-target data on pNe

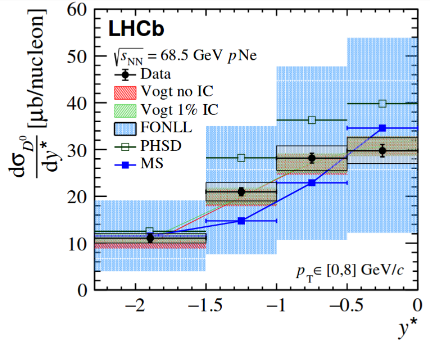



* *pA* effects might broaden the distribution
* *pp* central theory predictions slightly underestimate the high $p_T$ tails, but still compatible with data considering scale uncertainties.
* No need for IC to explain the high $p_T$ tail.

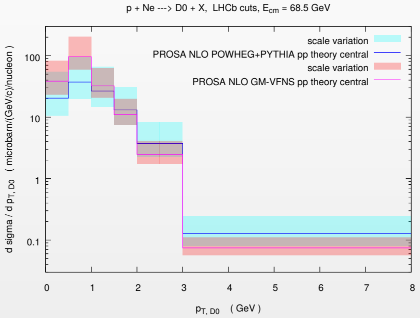
# PROSA NLO+PS computation of $D^0$-meson production w.r.t. LHCb fixed-target data on pNe

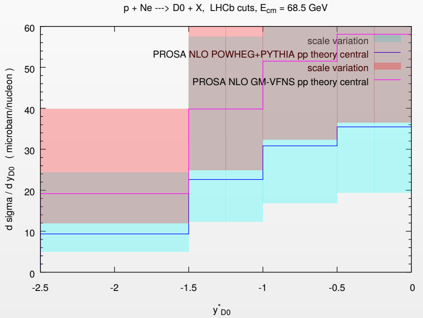



* *pp* central theory predictions slightly overestimate the high *y* tails, but still compatible with data considering scale uncertainties.
* No need for IC to explain this distribution as well.

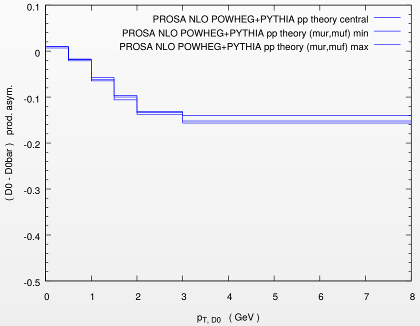
# PROSA NLO+PS computation of $D^0$-meson production in $p$Ne w.r.t. GM-VFNS NLO + FF

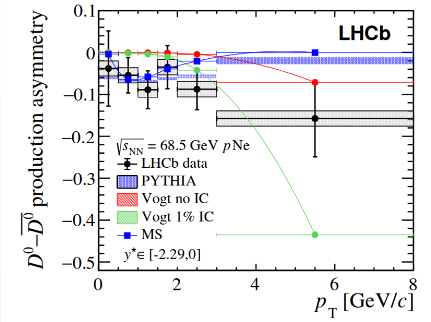



* GM-VFNS predictions compatible with NLO+PS predictions, if one accounts for the scale uncertainty bands of both.
* GM-VFNS predictions however not in agreement with the LHCb data.
* GM-VFNS $y_{D^0}$-distribution spoiled by the low $p_{T,D^0}$ behaviour.

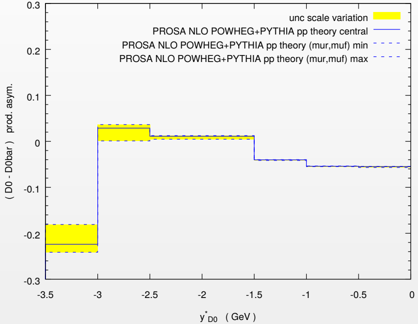
# PROSA NLO+PS computation of $D^0$-meson production w.r.t. LHCb fixed-target data on pNe

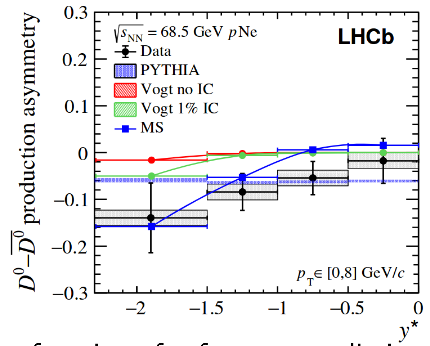



* $D^0 - \bar{D}^0$ pruduction asymmetry as a function of $p_T$ from $pp$ predictions compatible with data, considering uncertainty on the latter.
* Most theory uncertainties cancel in ratios.
* Reduction in data uncorrelated (systematical + statistical) uncertainty is needed for more conclusive remarks.

# PROSA NLO+PS computation of $D^0$-meson production w.r.t. LHCb fixed-target data on pNe




- ∗ $D^0 - \bar{D}^0$ pruduction asymmetry as a function of $y$ from $pp$ predictions compatible with data only for central rapidity $(-1 < y^* < 0)$ , considering uncertainty on the latter.
- ∗ for $-2.5 < y^* < -1$, theory predictions not compatible with data.
- ∗ Theory predictions lead to a very negative asymmetry only at rapidities $y < -3$ (effect of recombination with $p$ remnant: $\bar{D}^0 = \bar{c}u$ ).

# PROSA NLO+PS computation of $D^0$-meson production in fixed-target experiments at HL-LHC

$*$ Total cross-sections per nucleon for $D_0 + \bar{D}_0$ after LHCb-SMOG2 rapidity cuts:

Theory: $\sigma = 114 + 186$ (scale) - 52 (scale) microbarn/n

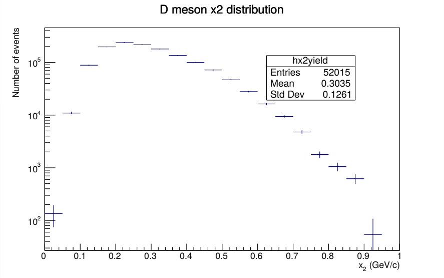
$*$ Total cross-sections per nucleon for $D_0 + \bar{D}_0$ after ALICE-FT rapidity cuts:

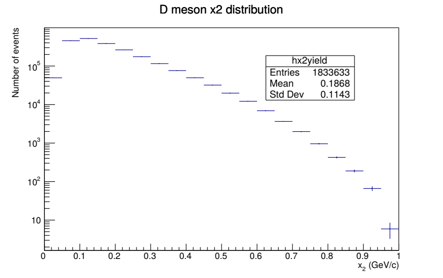
Theory: $\sigma = 3.1 + 5.3$ (scale) - 1.5 (scale) microbarn/n

$*$ Total $c\bar{c}$ cross-section - no cuts :

Theory: $\sigma = 187 + 288$ (scale) - 86 (scale) microbarn/n

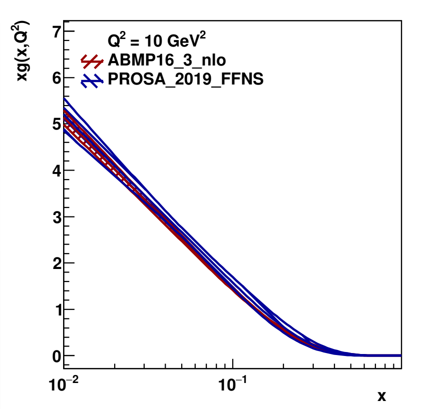
# $x_2$ range probed at ALICE-FT and LHCb-SMOG2 (HL-LHC)

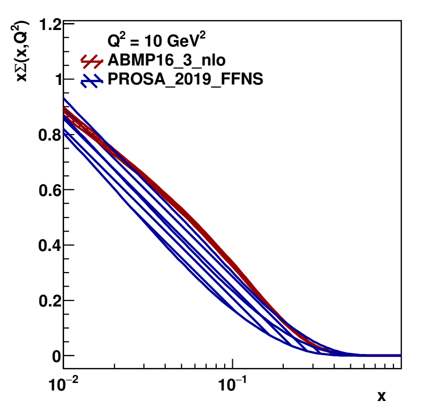



- ALICE-FT $x_2$ distribution peaked in the [0.2 - 0.25] bin
- LHCb-SMOG2 $x_2$ distribution peaked in the [0.1 - 0.15] bin

# PROSA 2019 vs. ABMP16 PDFs at large $x$

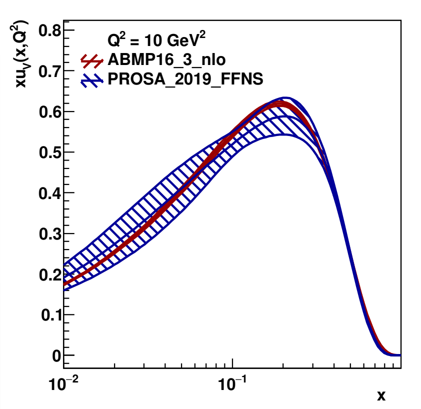


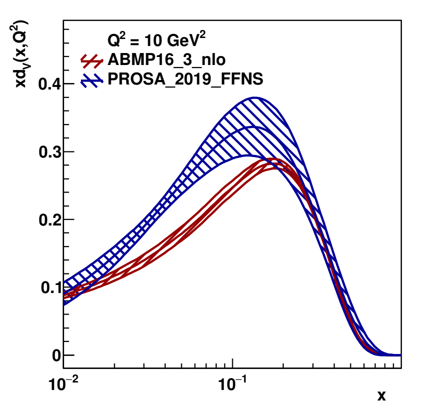




$*$ PROSA 2019 and ABMP16 $g(x)$ turns out to be compatible amomg each other, notwithstanding being constrained by different data sets.

$*$ ABMP16 uncertainties much smaller than PROSA 2019 ones.

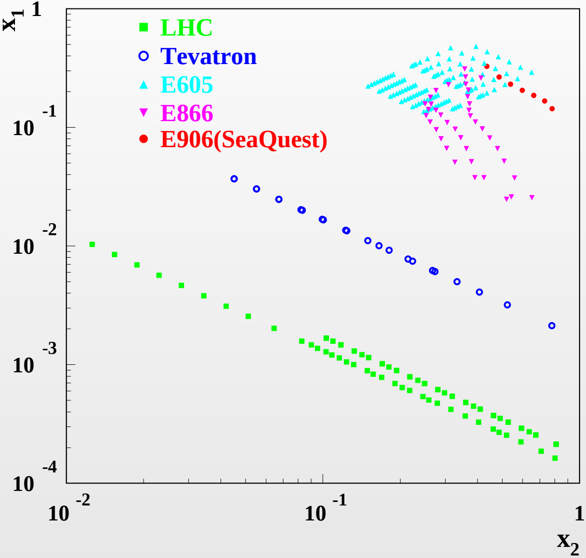
# PROSA 2019 vs. ABMP16 PDFs at large $x$



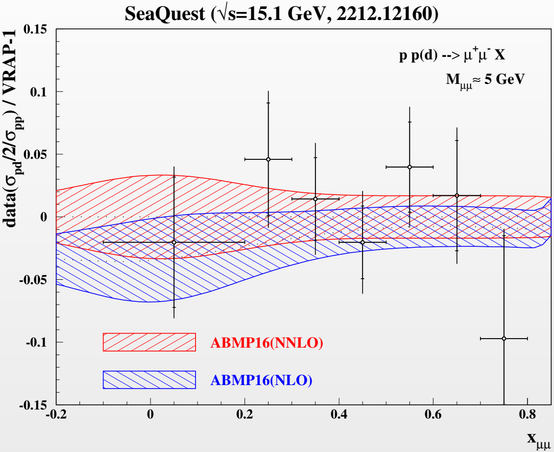

* PROSA 2019 and ABMP16 $u_v(x)$ turns out to be compatible amomg each other (effect of DIS data in both fits).
* Large discrepancies in case of $d_v(x)$ in case of $2 \cdot 10^{-2} < x < 10^{-1}$: ABMP16 are more reliable, including DY data (inclusive and asymmetries), sensitive to light flavour separation.

# $(x_2, x_1)$ coverage of DY at different experiments sensitive to $\bar{d}(x)/\bar{u}(x)$ and $\bar{d}(x) - \bar{u}(x)$



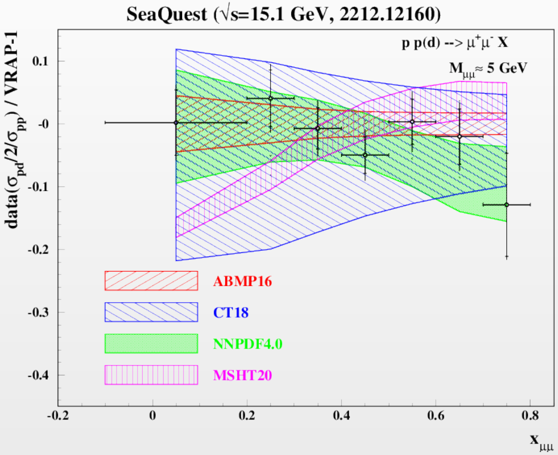

* fixed-target experiments sensitive to large $(x_1, x_2)$

# ABMP16 comparison with recent SeaQuest data



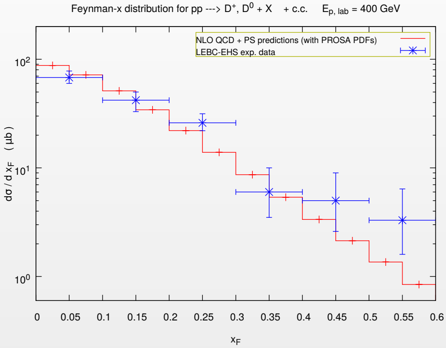

* Data not included in the fit, but well reproduced by the latter.
* Confirm $\bar{d}(x)/\bar{u}(x) > 1$ at large $x$.

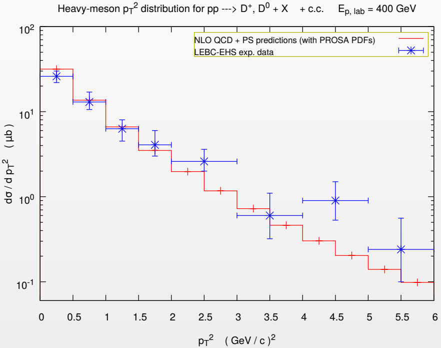
# Comparison of global PDFs with recent Seaquest data




* NNPDF4.0 agrees with them, even because it includes them in the fit.
* (Too) large CT18 bands: these data can be used to constrain them.

# Performances of the PROSA QCD computation of $D$-meson production w.r.t. LEBC-EHS exp. data



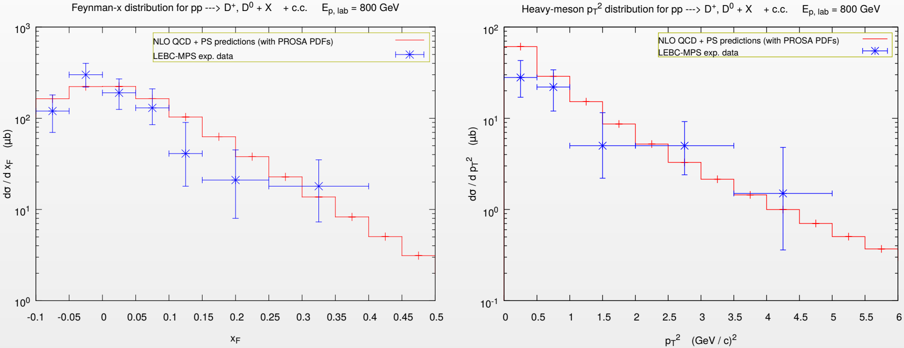




Fixed target experiment with $E_{p,\,lab} = 400$ GeV.

$*$ Measure relatively large $x_F = p_{z,D}/p_{z,D}^{max}$ (up to $x_F \sim 0.6$) and $p_T^2$.

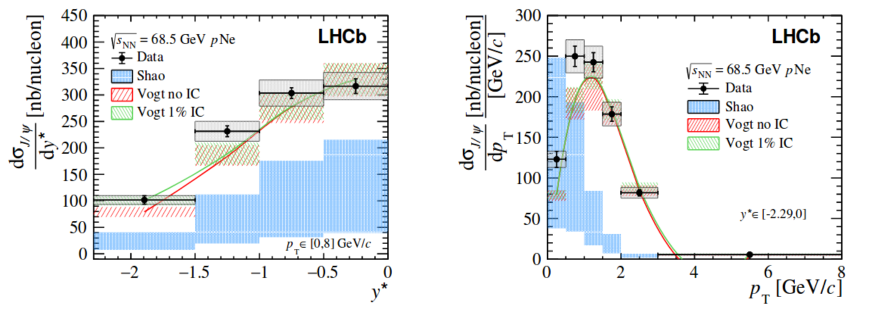
$*$ Sizable QCD uncertainty band not included in the plot.

# Performances of the PROSA QCD computation of $D$-meson production w.r.t. LEBC-MPS exp. data




* Fixed target experiment with $E_{lab} = 800$ GeV.
* Measure relatively large $x_F$ (up to $x_F \sim 0.4$).
* Sizable QCD uncertainty band not included in the plot.

# Another challenge: comparison with data on charmonium production in $p$Ne at $\sqrt{s_{NN}} = 68.5$ GeV at LHCb-SMOG




*from LHCb collaboration, [arxiv:2211.11645]*

∗ Can NRQCD reproduce the experimental $p_{T,J/\psi}$ distribution at least at large enough $p_{T,J/\psi}$ ?

*Work in progress with M. Butenschoen.....*

# Conclusions

* LHC fixed-target program has produced first high-quality data on $D^0$ production, exploring a $\sqrt{s_{NN}}$ region in between old fixed-target experiments and RHIC.

* LHCb has produced first high-quality data, but reduction of statistical and especially systematical uncertainties is important for using them for making strong conclusions. Important to add ALICE-FT experiment for enlarging $y$ and $A$ coverage and for cross-checking LHCb-FT results.

* No evident need for intrinsic charm to explain present data, but $pA$ effects have also to be understood.

* Data on $(D^0 - \bar{D}^0)$ asymmetries particularly interesting. Asymmetry as a function of $y$ can be used to constrain soft physics (hadronization including recombination with beam remnants) in SMC codes.

* Target fragmentation region: standard FF picture does not work for emissions anticollinear w.r.t. to the incoming beam. Fracture functions ? New factorization theorem ?