Theory predictions for charmed meson production in fixed-target experiments at the LHC and connections with astrophysical applications

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in collaboration with

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Fixed target experiments at LHC - strong2020 workshop
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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 (if one neglects possible intrinsic charm contributions) 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:

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

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

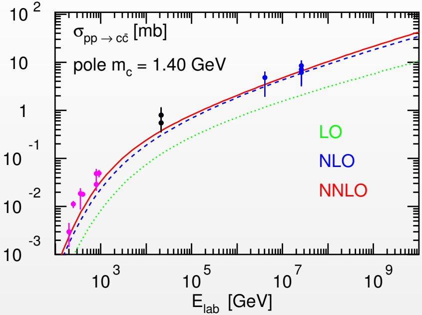
μ_F, μ_R reabsorb IR and UV divergences,

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

<u>QCD uncertainties</u>

* μ_F and μ_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



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

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

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

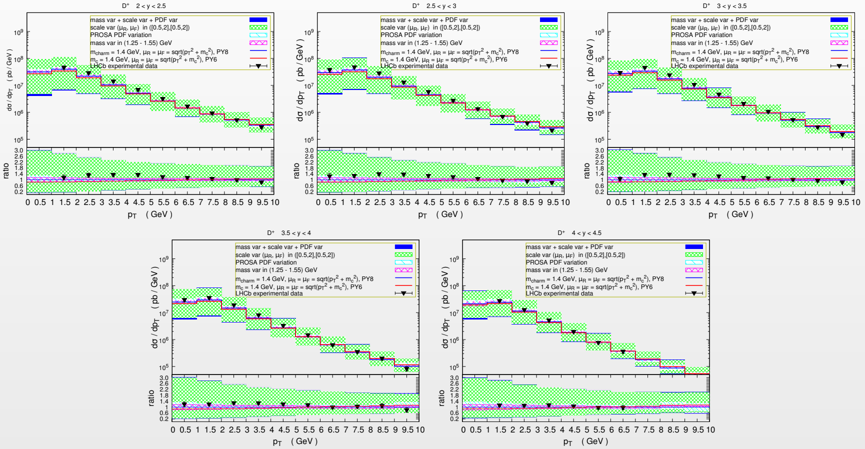
Problem: accuracy not exactly known, differently from the case of conventional analytical resummation procedures to all orders in P. T.

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

Both methods 1) and 2) are used, with compatible results.

NLO+PS differential σ vs experimental data

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

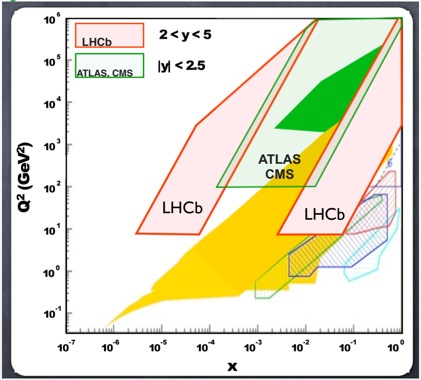


* agreement theory/experiment within large (μ_R, μ_F) uncertainty bands.
* theory uncertainties much larger than the experimental ones.

Adding data from other experiments

- ∗ 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

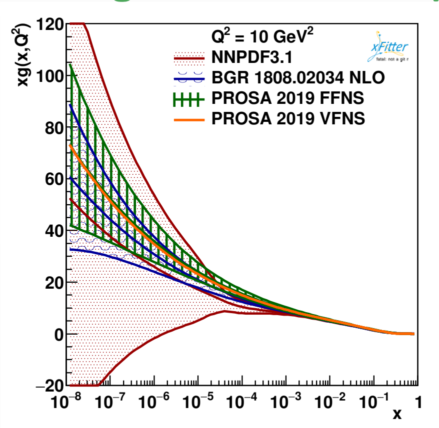


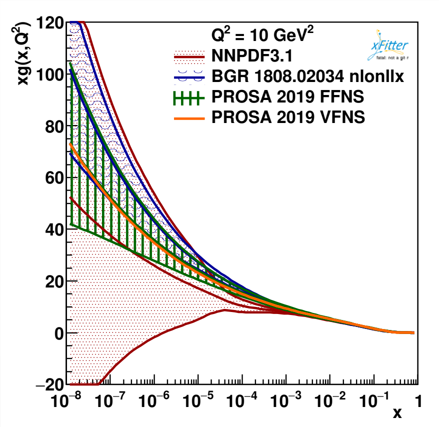
Different experiments span (Q^2, x) regions partially overlapping: good for verifying their compatibility and for cross-checking their theoretical description.

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.

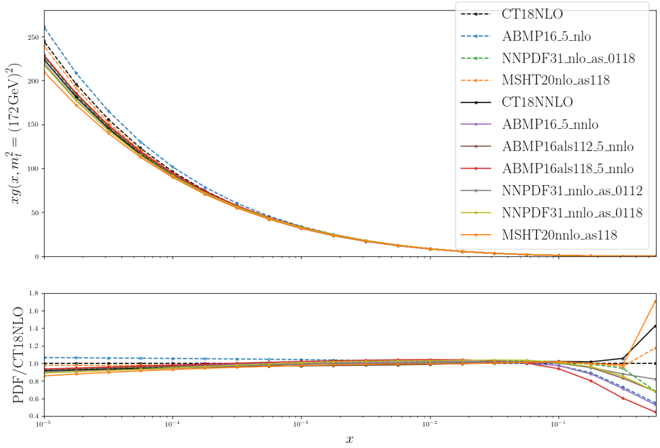
gluon PDF: comparison between different PDF fits including LHCb *D*-meson production data





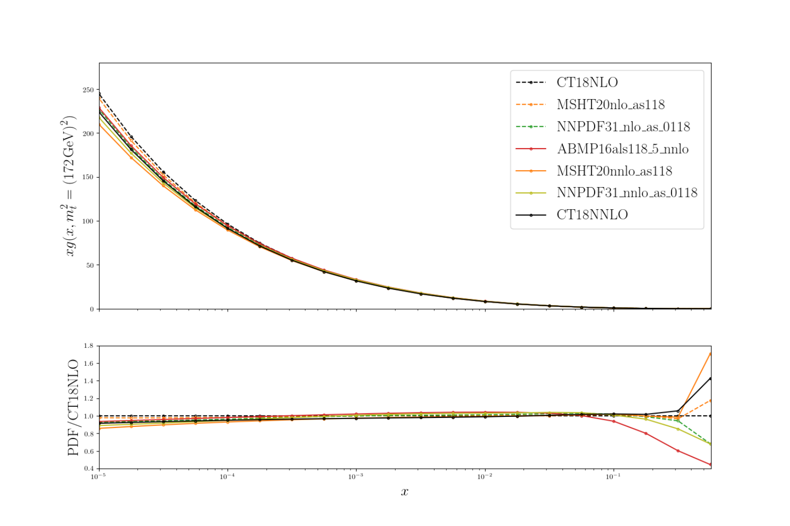
- LHCb *D*-meson data (collider modality) constrain PDFs at small x.
- Compatibility of indipendent PDF fits including *D*-meson data: PROSA central gluon lies in the interval between central NNPDF3.1+LHCb NLO and NNPDF3.1+LHCb NLO+(small-x)NLL.

gluon PDF: global comparison



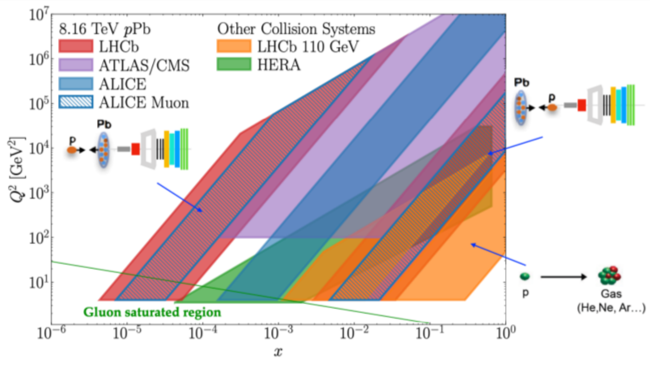
$10^{-5} < x < 0.5$ - uncertainties on each set not plotted

gluon PDF: global comparison of PDFs with $\alpha_S(M_Z) = 0.118$



* Central PDFs exhibits several ten percent differences at $x \sim 0.5$

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

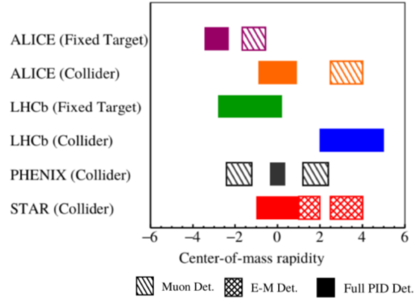
∗ LHCb-FT coverage: $2 \cdot 10^{-4} \lesssim x \lesssim 4 \cdot 10^{-1}$ ⇒ gluon, sea quarks and intrinsic charm

∗ 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): heavy-flavour center-of-mass rapidity $-2.29 < y^* < 0$ 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 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 projectile x

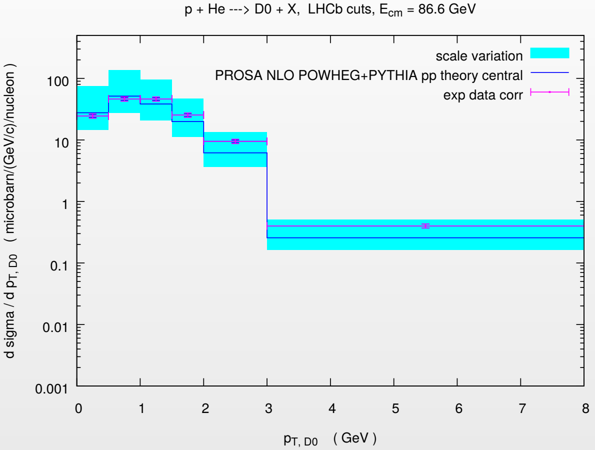
$*$ Most recent results on D^0 production at $\sqrt{s_{NN}} = 68.5$ GeV from LHCb

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

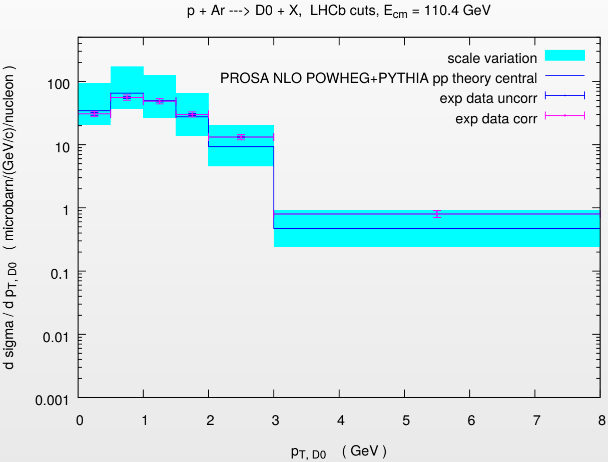
* Total cross-sections per nucleon for $D_0 + \bar{D}_0$ inclusive:
  Theory: $\sigma = 148.7 + 229$ (scale) - 83 (scale) microbarn/n
  LHCb: $\sigma = 156.0 \pm 13$ microbarn/n

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



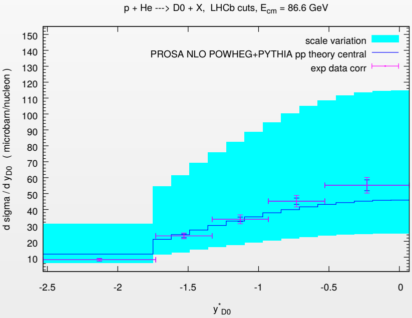
- $*$ *pA* effects might broaden the distribution
- $*$ *pp* central theory predictions slightly underestimate the high p_T tails, but still compatible with data considering scale uncertainties

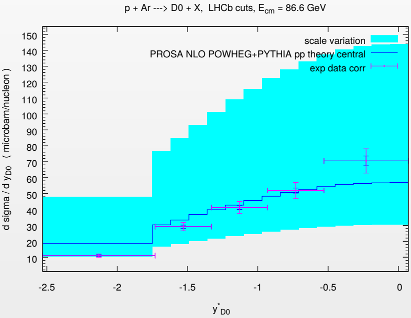
PROSA NLO+PS computation of D^0-meson production w.r.t. LHCb fixed-target data on pAr



$*$ exp. $(p+\text{He})$ and $(p+\text{Ar})$ 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





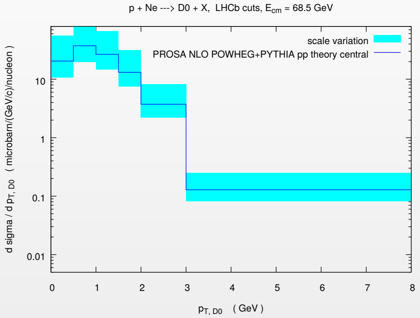
- ∗ Big scale uncertainties, especially at large y
- ∗ Before discussing intrinsic charm, one has to disentangle pA effects: they can impact on the shapes of the distributions.

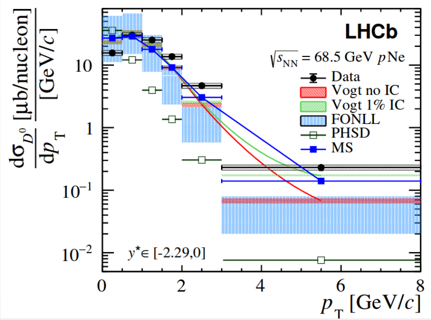
PROSA NLO+PS computation of D^0-meson production w.r.t. LHCb fixed-target data on pNe in [arXiv:2211.11633]

$*$ 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

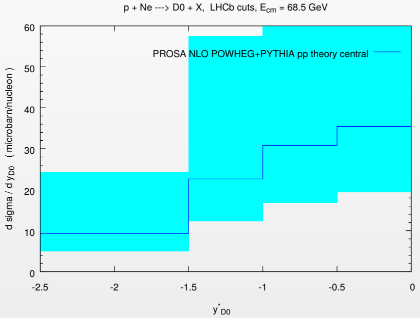
PROSA NLO+PS computation of D^0-meson production w.r.t. LHCb fixed-target data on pNe

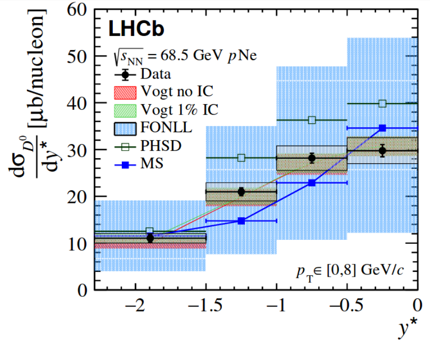




- ∗ *pA* effects might broaden the distribution
- ∗ *pp* central theory predictions slightly underestimate the high p_T tails, but still compatible with data considering scale uncertainties.
- ∗ No need for IC to explain the high p_T tail.

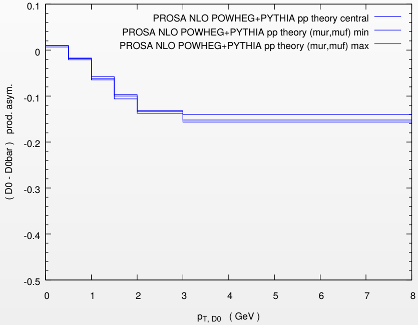
PROSA NLO+PS computation of D^0-meson production w.r.t. LHCb fixed-target data on pNe

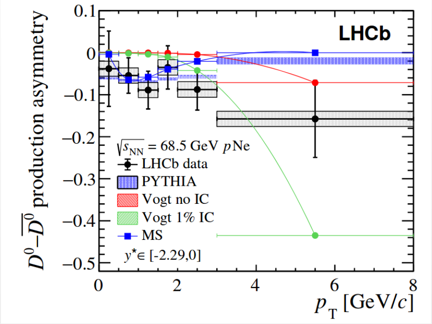




* pp central theory predictions slightly overestimate the high y tails, but still compatible with data considering scale uncertainties.
* No need for IC to explain this distribution as well.

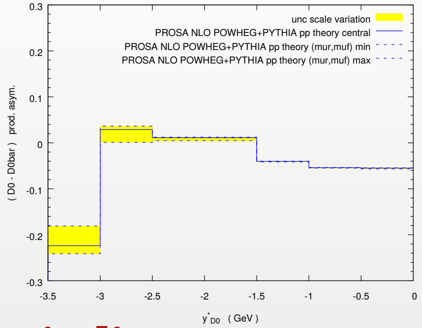
PROSA NLO+PS computation of D^0-meson production w.r.t. LHCb fixed-target data on pNe

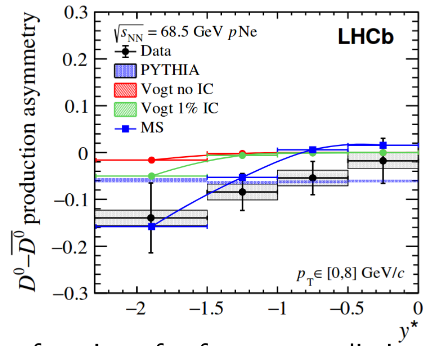




* $D^0 - \bar{D}^0$ pruduction asymmetry as a function of p_T from pp predictions compatible with data, considering uncertainty on the latter.
* Most theory uncertainties cancel in ratios.
* Reduction in data uncorrelated (systematical + statistical) uncertainty is needed for more conclusive remarks.

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: $\bar{D}^0 = \bar{c}u$).

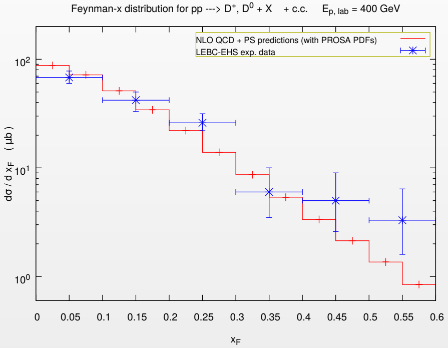
PROSA NLO+PS computation of D^0-meson production in fixed-target experiments at HL-LHC

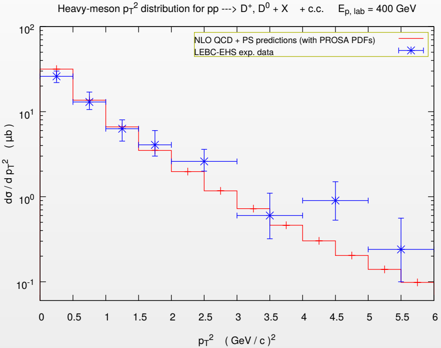
* Total cross-sections per nucleon for $D_0 + \bar{D}_0$ after LHCb-SMOG2 rapidity cuts:
  Theory: $\sigma = 114 + 186$ (scale) - 52 (scale) microbarn/n

* 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

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



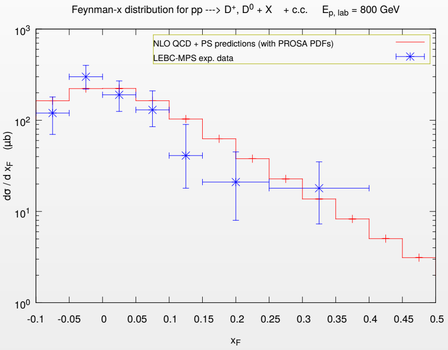


Fixed target experiment with $E_{p,\,lab} = 400$ GeV.

$*$ 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.

Why reducing theory and experimental uncertainties on open heavy-flavour hadroproduction in fixed-target experiments matters ?

* Constraints of PDFs at large x's, which in turns is relevant for
  - constraining BSM, already in the LHC era:
  - present and future far-forward LHC experiments: Faserν, SND@LHC, FPF, etc.....
  - future high-energy colliders: FCC-hh, etc.....

* high-energy astroparticle physics applications:
  - High Energy Cosmic Ray physics and prompt neutrino fluxes

* disentangling cold and hot nuclear matter effects (in pA and AA collisions).

* various other applications not discussed in this talk: see the document "Community Support for A Fixed-Target Programme for the LHC"

Atmospheric neutrino fluxes

$CR + Air$ interactions:
- AA' interaction approximated as $A\ NA'$ interactions (superposition);
- NA' approximated as $A'\ NN$ interactions: up to which extent is this valid ?

$*$ conventional neutrino flux:

$$NN \rightarrow u, d, s, \bar{u}, \bar{d}, \bar{s} + \mathrm{X} \rightarrow \pi^{\pm}, K^{\pm} + \mathrm{X}' \rightarrow \nu_{\ell}(\bar{\nu}_{\ell}) + \ell^{\pm} + \mathrm{X}',$$
$$NN \rightarrow u, d, s, \bar{u}, \bar{d}, \bar{s} + \mathrm{X} \rightarrow K^0_S,\ K^0_L + \mathrm{X} \rightarrow \pi^{\pm} + \ell^{\mp} + \overset{(-)}{\nu}_{\ell} + \mathrm{X}$$
$$NN \rightarrow u, d, s, \bar{u}, \bar{d}, \bar{s} + \mathrm{X} \rightarrow light\ hadron + \mathrm{X}' \rightarrow \nu(\bar{\nu}) + \mathrm{X}''$$

$*$ prompt neutrino flux:

$$NN \rightarrow c, b, \bar{c}, \bar{b} + \mathrm{X} \rightarrow heavy\text{-}hadron + \mathrm{X}' \rightarrow \nu(\bar{\nu}) + X'' + X'$$

where the decay to neutrino occurs through semileptonic and leptonic decays:

$D^+ \rightarrow e^+ \nu_e X, \quad D^+ \rightarrow \mu^+ \nu_\mu X,$

$D_s^{\pm} \rightarrow \nu_\tau(\bar{\nu}_\tau) + \tau^{\pm},$ with further decay $\tau^{\pm} \rightarrow \nu_\tau(\bar{\nu}_\tau) + \mathrm{X}$

proper decay lenghts: $c\tau_{0,\pi^{\pm}} = 780$ cm, $c\tau_{0,K^{\pm}} = 371$ cm, $c\tau_{0,D^{\pm}} = 0.031$ cm

Critical energy $\epsilon_h = m_h c^2 h_0\ /\ (\mathrm{c}\ \tau_{0,h} \cos(\theta))$, above which hadron **decay** probability is suppressed with respect to its **interaction** probability:

$\epsilon_{\pi}^{\pm} < \epsilon_{K}^{\pm} << \epsilon_D \Rightarrow$ conventional flux is suppressed with respect to prompt one, for energies high enough, due to finite atmosphere height h_0.

How to get atmospheric fluxes? From cascade equations to Z-moments [*review in Gaisser, 1990; Lipari, 1993*]

Solve a system of coupled differential equations regulating particle evolution in the atmosphere (interaction/decay/(re)generation):

$$\frac{d\phi_j(E_j,X)}{dX} = -\frac{\phi_j(E_j,X)}{\lambda_{j,int}(E_j)} - \frac{\phi_j(E_j,X)}{\lambda_{j,dec}(E_j)} + \sum_{k\neq j} S_{prod}^{k\to j}(E_j,X) + \sum_{k\neq j} S_{decay}^{k\to j}(E_j,X) + S_{reg}^{j\to j}(E_j,X)$$

Under assumption that X dependence of fluxes factorizes from E dependence, analytical approximated solutions in terms of Z-moments:

– Particle Production:

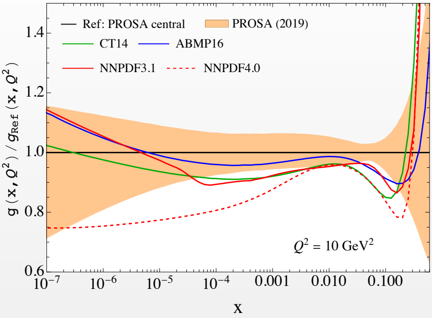
$$S_{prod}^{k\to j}(E_j,X) = \int_{E_j}^{\infty} dE_k \frac{\phi_k(E_k,X)}{\lambda_k(E_k)} \frac{1}{\sigma_k} \frac{d\sigma_{k\to j}(E_k,E_j)}{dE_j} \sim \frac{\phi_k(E_j,X)}{\lambda_k(E_j)} Z_{kj}(E_j)$$

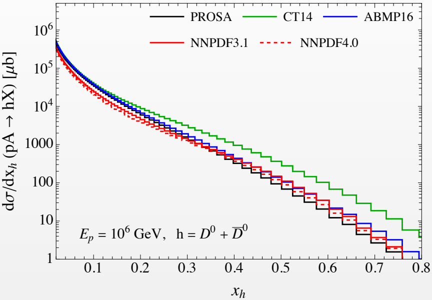
– Particle Decay:

$$S_{decay}^{j\to l}(E_l,X) = \int_{E_l}^{\infty} dE_j \frac{\phi_j(E_j,X)}{\lambda_j(E_j)} \frac{1}{\Gamma_j} \frac{d\Gamma_{j\to l}(E_j,E_l)}{dE_l} \sim \frac{\phi_j(E_l,X)}{\lambda_j(E_l)} Z_{jl}(E_l)$$

Solutions for $E_j >> E_{crit,j}$ and for $E_j << E_{crit,j}$, respectively, are interpolated geometrically.

Z-moments and large-x PDFs effects



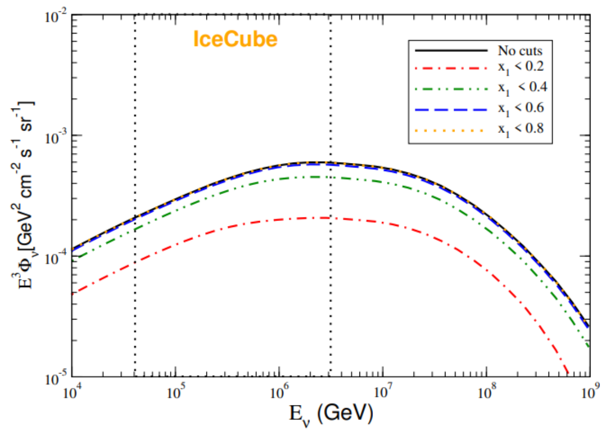


from W. Bai et al., [arXiv:2212.07865]

∗ Differences in gluon PDFs at large x are not covered by the uncertainties associated to each single PDF set.

∗ They translate directly in differences in the $d\sigma/dx_E$ distributions, where $x_E = E_{D,lab}/E_{p,lab}$, fundamental ingredient of the Z-moments used in the computation of prompt neutrino fluxes.

Prompt ν fluxes and large-x PDFs

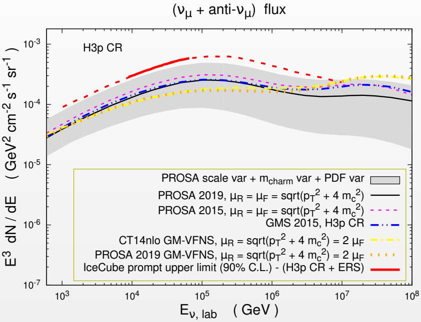


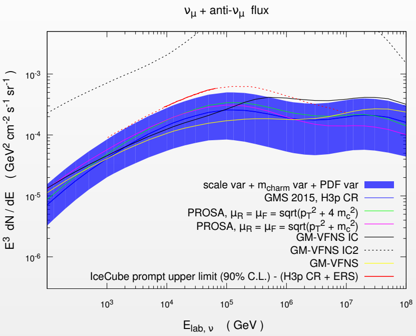
, *from V. Goncalves et al. [arXiv:1708.03775]*

$*$ A robust estimate of large x effects is important for determining the normalization of prompt neutrino fluxes

$*$ Region particularly relevant: $0.2 < x < 0.8$, partly testable through FT experiments at the LHC.

Prompt ν fluxes and IceCube upper limits



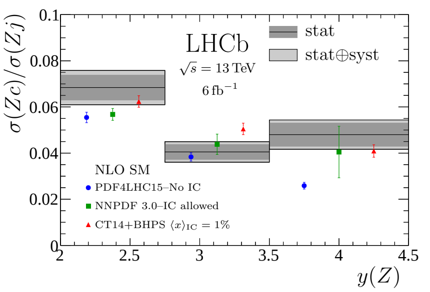


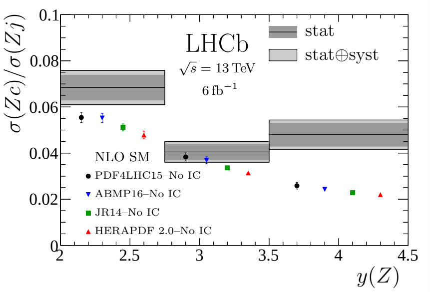
from O. Zenaiev et al. [arXiv:1911.13164]

$*$ IceCube has constrained the normalization of prompt neutrino fluxes through an upper limit.

$*$ Intrinsic charm already constrained by this limit as well, at least at low energy/not so large rapidities.....

$(Z+j_c)/(Z+j)$ and (intrinsic) charm PDFs



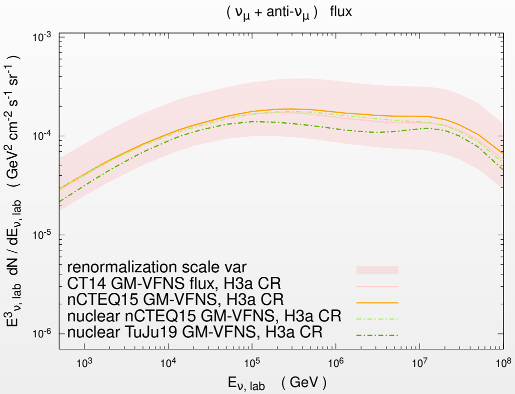


from LHCb collaboration, [arXiv:2109.08084]

* Significant enhancement of the experimental data in the largest rapidity bin, compatible with a non-negligible IC component.

* The atmosphere is a well suitable environment to look for intrinsic charm. This will simply lead to enhanced ν fluxes at large energies.

$(\nu_\mu + \bar{\nu}_\mu)$ fluxes: cold nuclear matter effects



* Predictions using nuclear PDFs within scale uncertainty bands of those with proton PDFs and superposition model.

* Suppression of prompt fluxes due to CNM effects ?
  Large shadowing effects do not emerge for all nuclear PDF fits, especially for low-mass nuclei

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.

$*$ 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 (fragmentation including recombination with beam remnants) in SMC codes.

$*$ Important to add ALICE-FT experiment for enlarging y and A coverage and for cross-checking LHCb-FT results.

$*$ Is it possible to report separate data for both D^0 and $\bar{D}^0$?

$*$ Is it possible to measure different observables (e.g. x_F) ?