New developments in the PROSA PDF fit

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on the basis of
O. Zenaiev, M.V. Garzelli, K. Lipka et al., DESY-19-211
arXiv:1912.XXXX

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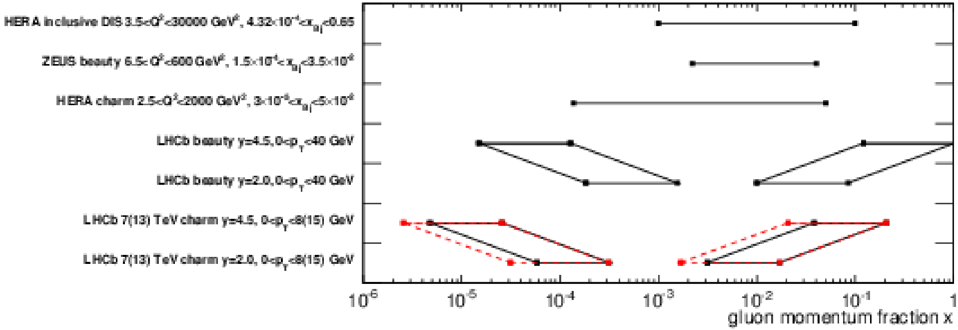
x coverage of HERA and LHCb experiments



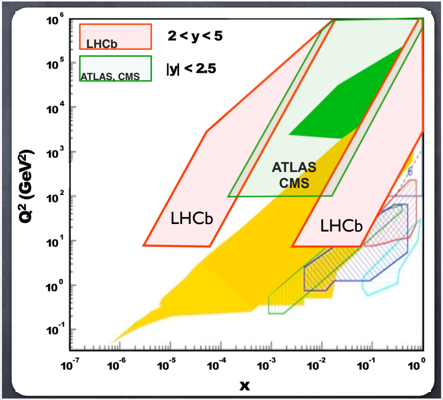
LHCb data allows to cover x regions uncovered by HERA data,
both at low x's (especially open charm data)
and at large x's (especially open bottom data).

Larger rapidities of the emitted quark and/or larger collision energies correspond to more extreme x's

Open heavy-flavour data from further 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.

The PROSA 2015 PDF fit

The PROSA PDF fit [EPJC 75 (2015) 471] is the first one appeared in the literature which has proposed the following
basic idea: use the data on D-meson and B-meson hadroproduction at LHCb to constrain PDFs (especially gluon PDFs) at low x's.

Data sets:

Open charm data at 7 TeV: D-meson p_T distributions in the range [0, 8] GeV, in five equal-size rapidity bins between $2 < y < 4.5$. [arXiv:1302.2864]

Open bottom data at 7 TeV: B-meson p_T distributions in the range [0, 40] GeV, in five equal-size rapidity bins between $2 < y < 4.5$ [arXiv:1306.3663]

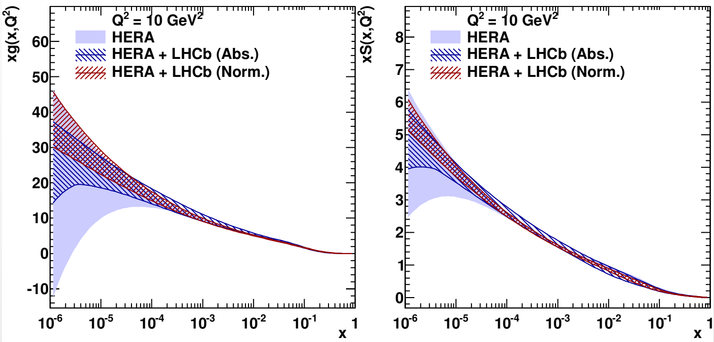
These data are considered together with all HERA data used for the HERAPDF1.0 PDF fit:
– NC and CC inclusive DIS combined HERA-I data,
– $c\bar{c}$ DIS combined HERA data and $b\bar{b}$ DIS ZEUS data.

Follow-up fits (made by reweighting recent NNPDF PDF fits):
- R. Gauld, J. Rojo, L. Rottoli, J. Talbert, JHEP 1511 (2015) 009
- R. Gauld, J. Rojo, PRL 118 (2017) 072001
- V. Bertone, R. Gauld and J. Rojo, arXiv:1808.02034

The last two use even LHCb data at $\sqrt{s} = 5$ and 13 TeV.

PROSA 2015 PDF fit: comparison between three variants

from PROSA collab., EPJC 75 (2015) 471



Three variants of the PDF fit:

1) one only with HERA data;

2) one also including LHCb absolute differential cross-sections;

3) another one with reduced uncertainties: for each fixed LHCb p_T bin, use the ratios of distributions $(d\sigma/dy)/(d\sigma/dy)_0$ considering different rapidity intervals (i.e. normalized to the central bin $3 < y_0 < 3.5$):
in the ratios theoretical uncertainties partly cancel.

Main differences of the PROSA 2019 PDF fit

(w.r.t. PROSA 2015)

* We used the HERA I + HERA II combined inclusive DIS data [arXiv:1506.06042] (instead of the HERA I ones)

* We used the HERA I + HERA II combined charm and bottom DIS data [arXiv:1804.01019]

* We used additional LHCb data:
  - open charm data at $\sqrt{s} = 5$ TeV [arXiv:1610.02230],
  - open charm data at $\sqrt{s} = 13$ TeV [arXiv:1510.01707].

* We included recent ALICE data:
  - open charm data at $\sqrt{s} = 5$ TeV [arXiv:1702.00766],
  - open charm data at $\sqrt{s} = 7$ TeV [arXiv:1901.07979].

Main differences of the PROSA 2019 PDF fit

(w.r.t. PROSA 2015)

* (μ_R, μ_F) scale choices

* Together with the PDF dependence on x, we fit the values of $m_c(m_c)$ and $m_b(m_b)$ in the MSbar scheme, consistently used for all theoretical predictions at NLO in the FFNS.

* PDF parameterization modified/extended with additional terms.

* FFNS and VFNS versions: the latter exploits the possibility now present in xFitter to select μ_c, $\mu_b > m_c$, m_b.

PROSA 2019 PDF parameterization

∗ Most general parameterization considered:

$$xf(x) = Ax^B(1-x)^C(1+D\,x+E\,x^2+F\log x), \quad f=g$$
$$xf(x) = Ax^B(1-x)^C(1+D\,x+E\,x^2), \quad f=u_{\rm v}, d_{\rm v}, \overline{\rm U}, \overline{\rm D}$$

- D, E, F parameters initially set to zero and then included one at a time, monitoring the improvment of the χ^2.
- F from [1902.11125] fitted value small (0.068 ± 0.024), F variation affects the fit uncertainties.

∗ Final parameterization:

$$xg(x) = A_g x^{B_g}\,(1-x)^{C_g}\,(1+F_g\log x),$$
$$xu_{\rm v}(x) = A_{u_{\rm v}} x^{B_{u_{\rm v}}}\,(1-x)^{C_{u_{\rm v}}}\,(1+E_{u_{\rm v}}x^2),$$
$$xd_{\rm v}(x) = A_{d_{\rm v}} x^{B_{d_{\rm v}}}\,(1-x)^{C_{d_{\rm v}}},$$
$$x\overline{\rm U}(x) = x\bar{u}(x) = A_{\overline{\rm U}} x^{B_{\overline{\rm U}}}\,(1-x)^{C_{\overline{\rm U}}}\,(1+D_{\overline{\rm U}}x),$$
$$x\overline{\rm D}(x) = x\bar{d}(x)+x\bar{s}(x) = A_{\overline{\rm D}} x^{B_{\overline{\rm D}}}\,(1-x)^{C_{\overline{\rm D}}}.$$

∗ Constraints reduce the number of free parameters

Alternative gluon PDF parameterizations

PROSA19:

$$xg(x) = A_g x^{B_g} (1-x)^{C_g} (1 + F_g \log x),$$

ABMP16:

$$xg(x) = A(1-x)^b x^{a(1+\gamma_1 x)},$$

CT14:

$$xg(x) = Ax^{a_1}(1-x)^{a_2}(e_0(1-y)^2 + e_1(2y(1-y)) + y^2), y = 2\sqrt{x} - x,$$

HERAPDF2.0 flex. g:

$$xg(x) = A_g x^{B_g}(1-x)^{C_g} - A'_g x^{B'_g}(1-x)^{25},$$

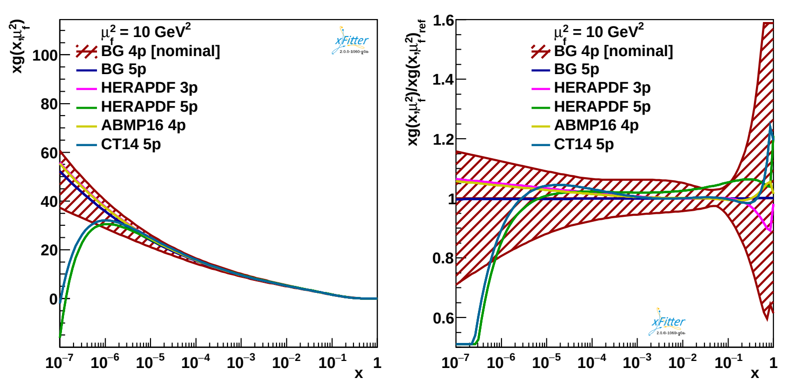
HERAPDF2.0 no flex. g:

$$xg(x) = A_g x^{B_g}(1-x)^{C_g},$$

BG:

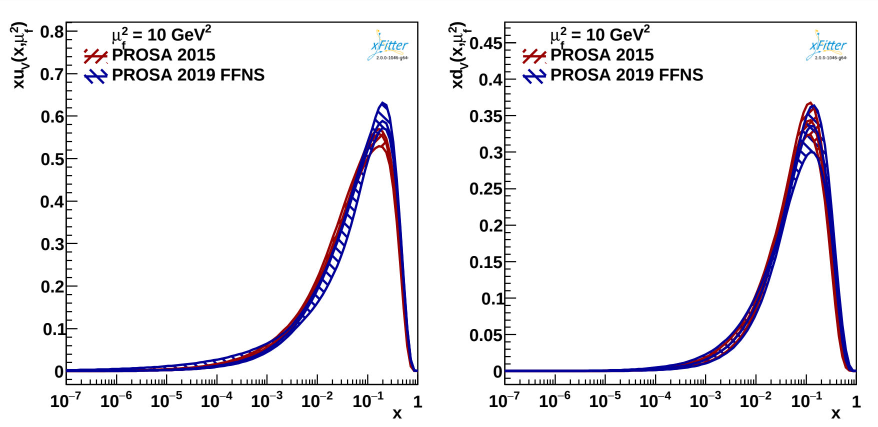
$$xg(x) = A_g x^{B_g} (1-x)^{C_g} (1 + F_g \log x + G_g \log^2 x)$$

Sensitivity of the low-x gluon to the PDF parameterization employed



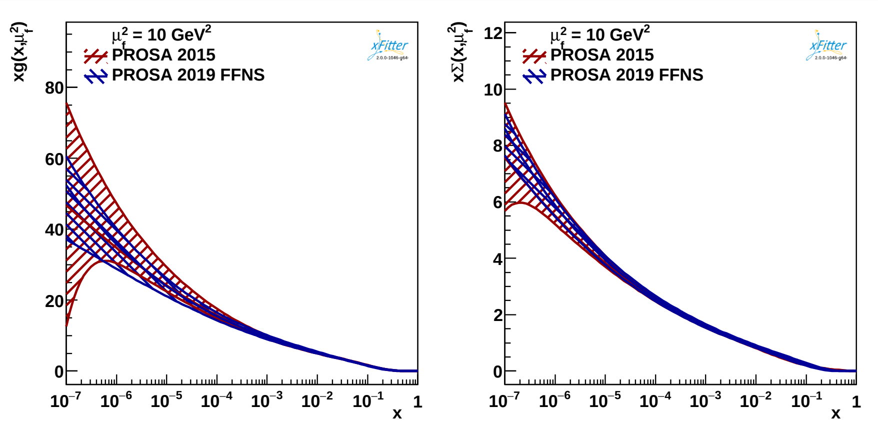
* CT14 and HERAPDF flex gluon yield a gluon distribution with a sharp turnover to negative values at the edge of the kinematic reach of the measurements used in the fit ($x \sim 10^{-6}$)
* They provide a slightly better χ^2 but negative $\sigma_{c\bar{c}}$ for $\sqrt{s} > 20$ TeV

PROSA 2019 vs PROSA 2015: valence quarks



* approximatively consistent results,
* differences mainly driven by the use of different sets of inclusive DIS data.

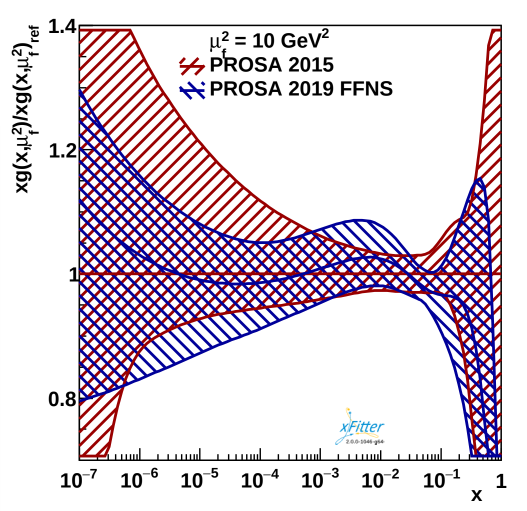
PROSA 2019 vs PROSA 2015: gluons & sea quarks



∗ new gluon and sea quark PDFs consistent with the old ones

∗ reduced uncertainties for $x < 10^{-4}$

PROSA 2019 vs PROSA 2015: gluons



- ∗ new gluon PDFs consistent with the old one
- ∗ reduced uncertainties for $x < 10^{-4}$

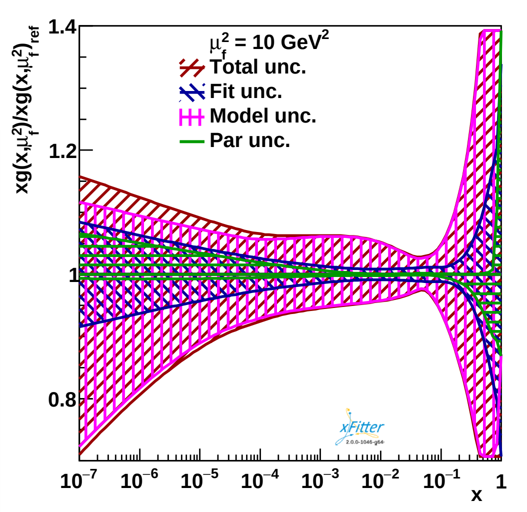
PROSA 2019 PDF fit uncertainties

- **fit** uncertainties: uncertainties in the measurements, estimated by Hessian method woth tolerance criterion $\Delta\chi^2 = 1$ (68% C.L.)

- **model** uncertainties:
  strangeness fraction $f_s = x\bar{s}/(x\bar{d} + x\bar{s})$ with $0.3 < f_s < 0.5$
  $2.5 < Q^2_{min} < 5.0$ GeV^2 cut on HERA I+II data
  $0.105 < \alpha_S^{nf=3}(M_Z) < 0.107$ ($0.117 < \alpha_S^{nf=5}(M_Z) < 0.119$)
  $\alpha_k^c = 4.4 \pm 1.7$, $\alpha_k^b = 11 \pm 3$
  (μ_R, μ_F) 7-point scale variation

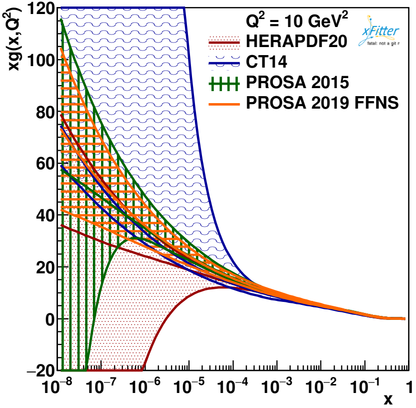
- **parameterization** uncertainties:
  $1.6 < \mu^2_{f0} < 2.2$ GeV^2
  D, E parameters and $G_g log^2 x$ term

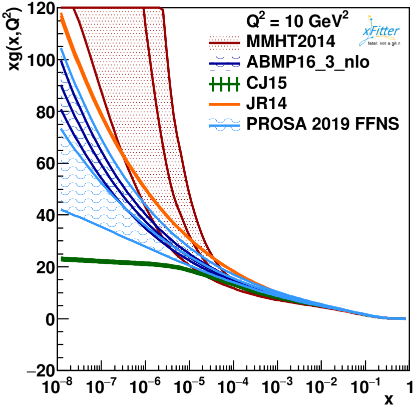
PROSA 2019 vs PROSA 2015: gluon uncertainties



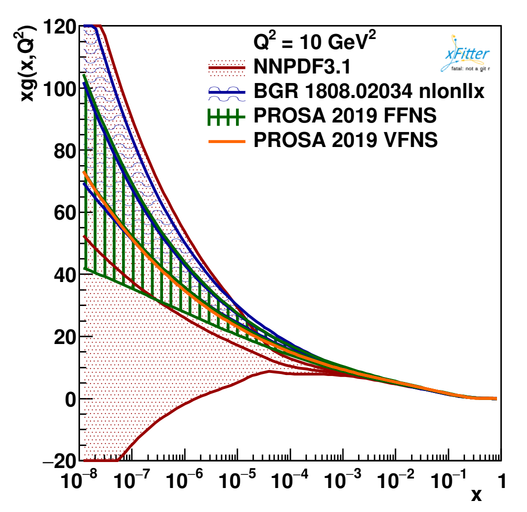
* Model uncertainties dominating over the others. They are mostly driven by (μ_R, μ_F) variation.

gluon PDF: comparison between different PDF fits





gluon PDF: comparison between different PDF fits



∗ Differences between different gluon PDF fits at relatively large x values

∗ Compatibility of the PDF fits including D-meson data.

Why improving the description of heavy-flavour hadroproduction matter ?

∗ Constraints of PDFs at low x's, which in turns is relevant for

- forward physics and multiple parton interactions, already in the LHC era:
  with increasing precision of the LHC data,
  improving the description of these aspects matters!

- future high-energy colliders: FCC-hh, etc.....
  (see the study in the FCC-hh SM report [arXiv:1607.01831]).

∗ 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).

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):

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

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

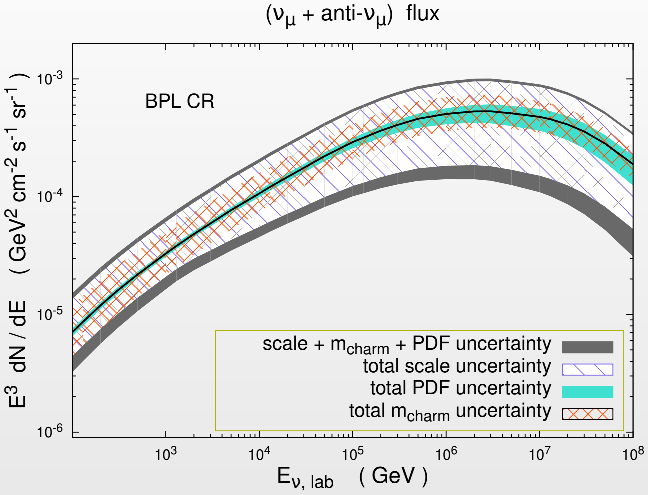
– Particle Production:

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

– Particle Decay:

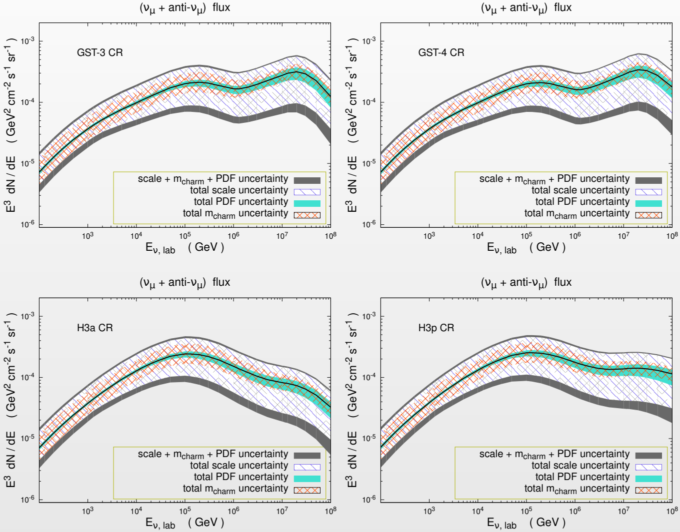
$$S^{j\to l}_{decay}(E_l,X) = \int_{E_l}^{\infty} dE_j \frac{\phi_j(E_j,X)}{\lambda_j(E_j)} \frac{1}{\Gamma_j} \frac{d\Gamma_{j\to l}(E_j,E_l)}{dE_l} \sim \frac{\phi_j(E_l,X)}{\lambda_j(E_l)} Z_{jl}(E_l)$$

PROSA 2019 atmospheric prompt $(\nu_\mu + \bar{\nu}_\mu)$ flux: QCD scale, mass and PDF uncertainties



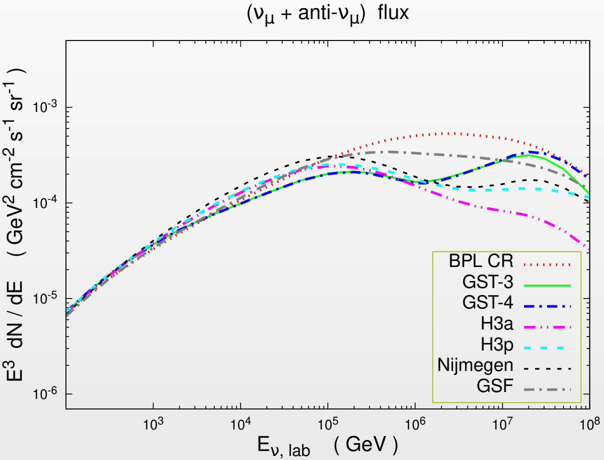
PDF uncertainty subdominant, assuming extrapolation at $x < 10^{-6}$ works.

Prompt neutrino flux uncertainties:



∗ Panels differ for different assumptions in CR composition.

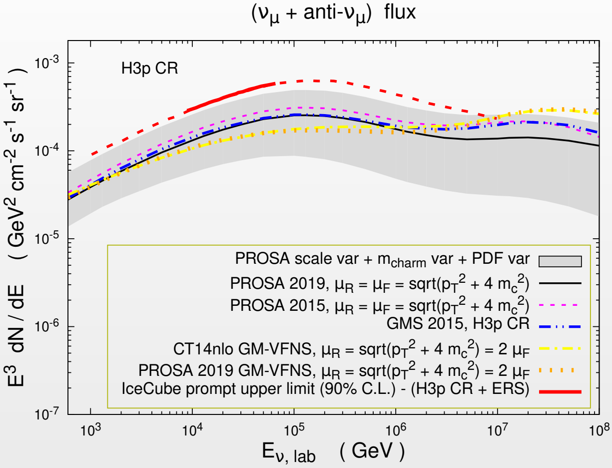
PROSA prompt $(\nu_\mu + \bar{\nu}_\mu)$ fluxes with different CR primary all-nucleon fluxes



* Uncertainty in CR composition turns out to be smaller than QCD scale uncertainties.

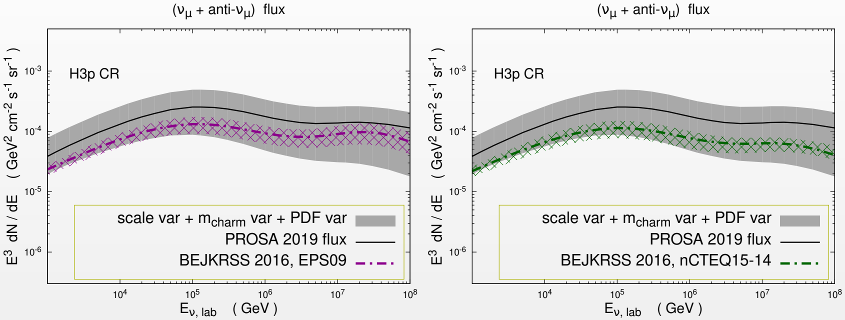
Prompt neutrino fluxes:

theoretical predictions vs. IceCube upper limits



IceCube upper limit on prompt fluxes from the 6-year analysis of thoroughgoing μ tracks from the Northest Hemisphere [arXiv:1607.08006] assumed the ERS flux as a basis for modelling prompt neutrinos (reweighted to the H3p CR flux).

Nuclear PDFs and prompt neutrino fluxes



* Bhattacharya et al. 2016, produce predictions by using nuclear PDFs, instead of nucleon PDFs + superposition model
  → their prompt fluxes look suppressed with respect to their older ones.

* However, still compatible with our predictions on the basis of nucleon PDFs + superposition model.

* Uncertainty on these nuclear PDF fits are probably underestimated.

Conclusions

∗ Open charm and bottom data have the potentiality to constrain gluon and sea quark PDF at various x values.

∗ At present experimental uncertainties smaller than theoretical ones.

∗ Theory predictions (and PDF fits) plagued by large scale uncertainty.

∗ Incorporation in PDF fits so far limited to very few cases (PROSA 15, recent NNPDF variants, PROSA 19, ABMP preliminary, nCTEQ15).

∗ In order to use open charm and bottom data in PDF fits: information on bin-to-bin correlations for each separate measurement as well as between different measurements (charm and beauty, and different center of mass energies) is necessary. Information of correlations between integrated cross-sections is not enough.

∗ Notwithstanding the uncertainties, the compatibility of the gluon distri from the fits including these data is remarkable.