Atmospheric flux calculations and LHC input

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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.

Atmospheric neutrino fluxes

$CR + Air$ interactions:
- AA' interaction approximated as $A\ NA'$ interactions (super position);
- 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:

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

Flavour Number Schemes for heavy-flavour production

$m_l = m_u,\ m_d,\ m_s < \Lambda_{QCD}$ → assumed massless always,
$m_{HQ} = m_c,\ m_b,\ m_t > \Lambda_{QCD}$ treatment depends on scheme
and, depending on the kinematics and $\sqrt{s}$, it may happen $p_{T,HQ} >> m_Q$ or $Q >> m_Q$

∗ **Decoupling scheme with a fixed flavour number** (FFNS):
- The mass of at least one (or more) HQ is retained at all scales
- HQ can be produced as final states and circulate in loops.
- They are excluded from initial states.
- Divergences due to light quark loops contributing to α_S renormalization are subtracted at zero mass (like in the $\overline{\mathrm{MS}}$ scheme), those due to heavy-quark loops are subtracted at zero momentum.
- **issue** at high p_T or Q: $\log\,(p^2_{T,HQ}/m^2_{HQ})$ or $\log\,(Q^2/m^2_{HQ})$ may become so big that they may spoil the convergence of the perturbative series!

∗ **Zero-mass variable flavour number scheme** (ZM-VFNS):
- HQ massless quarks at all scales in all components of the calculation.
- These quarks are present in the initial state above fixed thresholds.
- They contribute to α_S running (in the $\overline{\mathrm{MS}}$ scheme) above the same thresholds.
- **issue** at low p_T or Q: powers of $(m^2_{HQ}/p^2_{T,HQ})$ or of (m^2_{HQ}/Q^2_{HQ}) missing!

∗ **General-mass variable flavour number schemes** (GM-VFNS):
- HQ mass retained in part of the calculation; meant to combine optimal features of FFNS and ZM-VFNS at different p_T or Q.
- **advantage**: logs resummed and powers (at least the leading ones) present.
- **problem**: some arbitrariness in the combination (different variants possible)

QCD factorization

for 1-particle inclusive heavy-hadron hadroproduction

$$d\sigma(N_1 N_2 \to H + X) = \sum_{abc} PDF_a^{N_1}(x_a, \mu_{F,i}) PDF_b^{N_2}(x_b, \mu_{F,i}) \otimes$$
$$\otimes\; d\hat{\sigma}_{ab\to cX'}(x_a, x_b, z, \mu_{F,i}, \mu_{F,f}, \mu_R) \otimes\; FF_c^H(z, \mu_{F,f})$$

d$\hat{\sigma}$: differential perturbative partonic cross-section,
its m_h dependence, neglected in ZM-VFNS, is instead kept in GM-VFNS.

μ_F, μ_R reabsorb IR and UV divergences (truncation of P.T. series).

PDFs: perturbative evolution with factorization scale $\mu_{F,i}$,
non-perturbative dependence on $x{=}p^+/P_N^+$.

FFs: perturbative evolution with factorization scale $\mu_{F,f}$,
non perturbative parameterization in terms of $z = P_H^+/p_c^+$ frequently used.

QCD uncertainties

* $\mu_{F,i}$, $\mu_{F,f}$ and μ_R choice: no univocal recipe.
* Approximate knowledge of heavy-quark mass values m_h (SM input parameters).
* Choice of Variable Flavour Number Scheme (several possibilities!)
* PDF (+ $\alpha_S(M_Z)$) fits to experimental data
* Fits to experimental data of the non-perturbative parameters of the FF

GM-VFNS partonic and hadronic pp cross-sections

∗ Taking the limit $m \to 0$ of the massive cross-section does not reduce to the masslese one obtained in dimensional regularization for $\epsilon \to 0$ (finite mass regulators and dimensional regularization of collinear divergences yield different finite terms):

$$d\hat{\sigma}^{sub} = \lim_{m\to 0}\, d\hat{\sigma}^{FFNS}(m) \text{ - } d\hat{\sigma}^{ZM-VFNS}$$

∗ Subtraction of overlapping terms:

$$d\hat{\sigma}^{GM-VFNS}(m) = d\hat{\sigma}^{FFNS}(m) \text{ - } a\, d\hat{\sigma}^{sub}$$

with $a = 1$ in the S-ACOT scheme,
$a = a(p_T, m, ...)$ for other schemes (e.g. FONLL).

∗ S-ACOT GM-VFNS hadronic σ for single inclusive heavy-hadron production obeys a factorization formula which generalizes the CSS factorization theorem in the ZM-VFNS:

$$d\sigma^{ZM}_{pp\to hX}(P,S) = F_{i/p}(x_1,\mu_i)F_{j/p}(x_2,\mu_i) \otimes d\hat{\sigma}_{ij\to kX}(p,s,\mu_r,\mu_i,\mu_f) \otimes D_{h/k}(z,\mu_f)$$

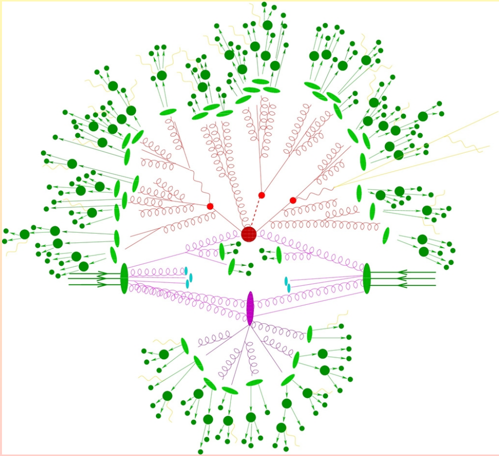
$$\frac{1}{p_T}\frac{d\sigma^{ZM}_{pp\to hX}}{dp_T dy}(S,p_T,y) = \frac{2}{S}\sum_{i,j,k}\int_{1-V+VW}^{1}\frac{dz}{z^2}\int_{\frac{VW}{z}}^{1-\frac{1-V}{z}}\frac{dv}{1-v}\int_{\frac{VW}{vz}}^{1}\frac{dw}{w}$$

$$F_{i/p}(x_1,\mu_i)F_{j/p}(x_2,\mu_i)\,\frac{1}{v}\,\frac{d\hat{\sigma}^{\mathrm{ZM}}_{ij\to kX}}{dv dw}(s,v,w,z,\mu_r,\mu_i,\mu_f)\,D_{h/k}(z,\mu_f)\,,$$

with proper replacement of massless kinematics and integration limits with massive kinematics and integration limits where needed.

Alternative: NLO matched to PS in SMC

p-p and p-$\bar{p}$ collision overview (LHC and Tevatron)



$Q = a\ few\ TeV$

- hard scattering
- parton shower
- QED shower

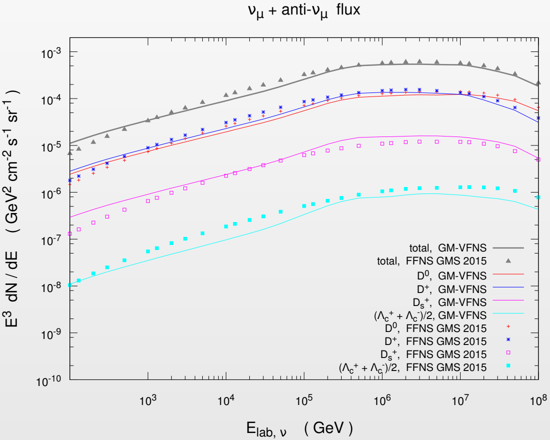
$\Lambda_{QCD} = 200\ MeV$

- hadronization
- hadron decay
- underlying event
- pile-up (overlap of different collisions).

DECREASING ENERGY SCALE

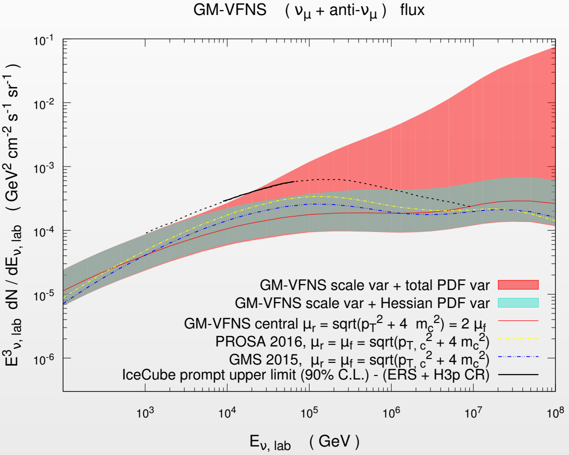
PERTURBATIVE AND NON-PERTURBATIVE COMPONENTS

Prompt ($\nu_\mu + \bar{\nu}_\mu$) fluxes in the GM-VFNS and in GMS (i.e. NLO + PYTHIA) approach: contribution of different charmed hadrons



Prompt neutrino fluxes with GM-VFNS:

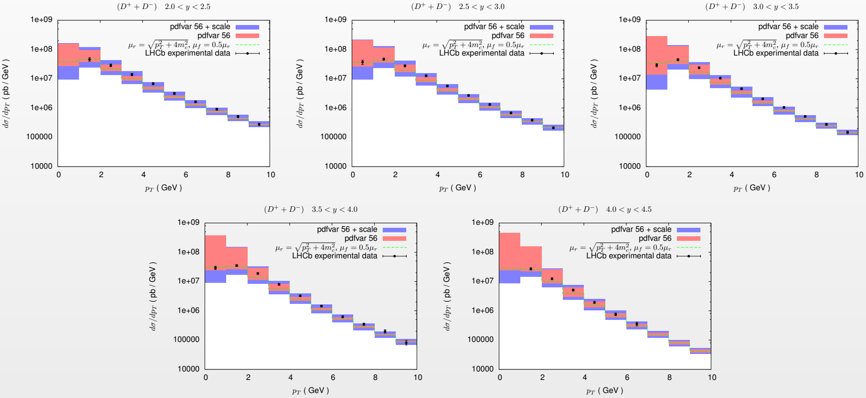
theoretical predictions from [arXiv:1705.10386] vs. IceCube upper limits



The extrapolation to high energy of IceCube results suggest that the CT14nlo gluon PDF uncertainty band at low x's is too large!

GM-VFNS predictions vs experimental data

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



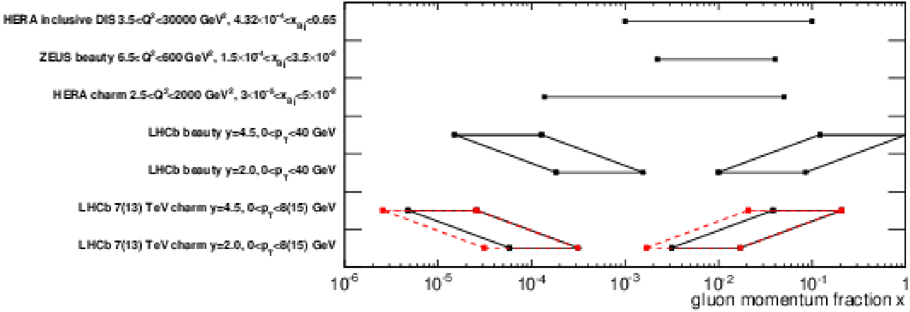
∗ Scale uncertainties larger than experimental ones.

∗ Large PDF uncertainties (CT14nlo), increasing at low p_T / large y, can be mitigated by using other PDF fits.

Important ingredient of these calculations: PDF fits

* x-dependence of PDFs is fitted to experimental data.
* HERA data (core of all PDF fits) offer good coverage in the range $10^{-4} < x < 10^{-1}$.
* Prompt ν fluxes sensitive to a wider range of x values, due to the fact that
  - The $\sqrt{s}$ for the relevant collisions involve a wide range of energies (from $\sqrt{s} \sim 100$ GeV to $\sqrt{s} \sim 150$ TeV).
  - The relevant rapidities extend to values much larger than those accessible in traditional experiments at human-made colliders.

x coverage of HERA and LHCb experiments

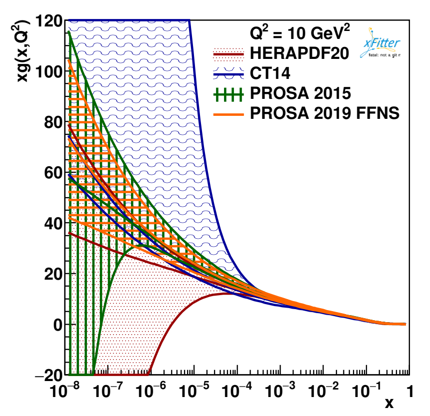


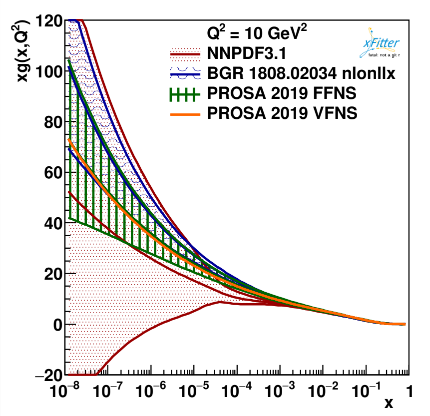
LHCb data allow to cover x regions uncovered by HERA data,
both at low x's (especially open charm data)
and at large x's (especially open bottom data).

For LHCb, LO formula $x_{1,2} = (\sqrt{p_T^2 + m_Q^2}/E_p)\, \exp(\pm y) \Rightarrow$ Larger rapidities of the emitted quark correspond to more extreme x's; large $\sqrt{s} \leftrightarrow$ small x 's

charm production in DIS at EIC extends HERA charm coverage even to $x > 0.1$.

gluon PDF: comparison between different PDF fits

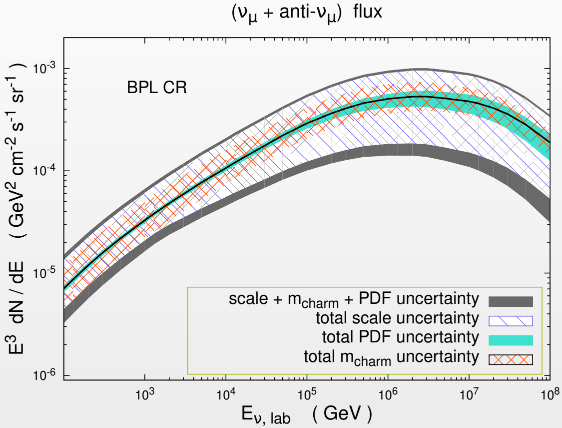




∗ PROSA2019 better constrained than PROSA2015 due to inclusion of data at $\sqrt{s} = 13$ and 5 TeV, besides 7 TeV.

∗ Compatibility between different PDF sets including *D*-meson LHCb data.

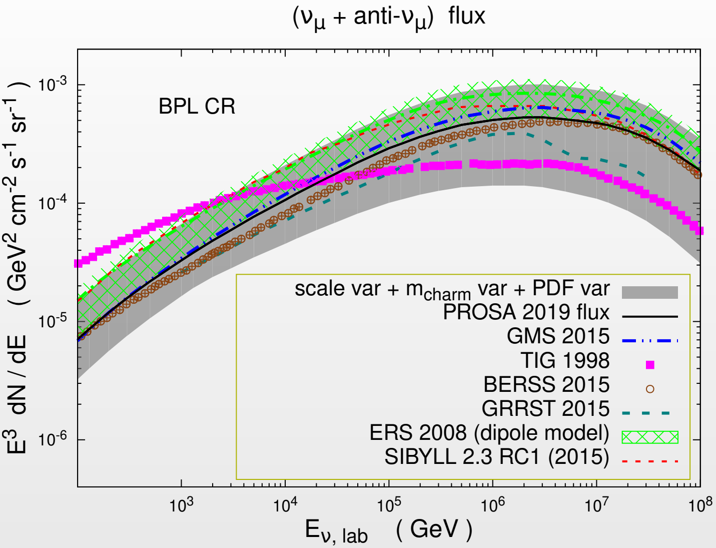
PROSA 2019 atmospheric prompt $(\nu_\mu + \bar{\nu}_\mu)$ flux: QCD scale, mass and PDF uncertainties



from [arXiv:1911.13164]

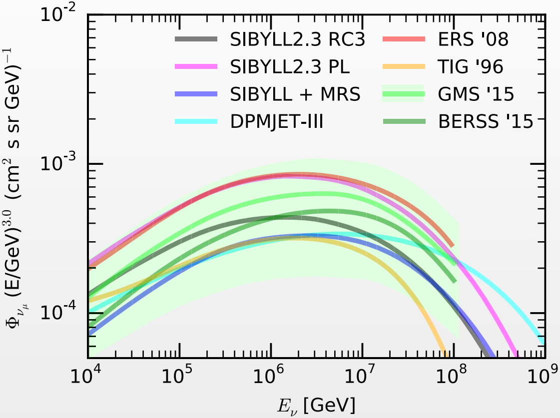
∗ PDF uncertainty subdominant, assuming extrapolation at $x < 10^{-6}$ works.

Comparison of predictions by different groups



Different predictions compatible within the uncertainty band

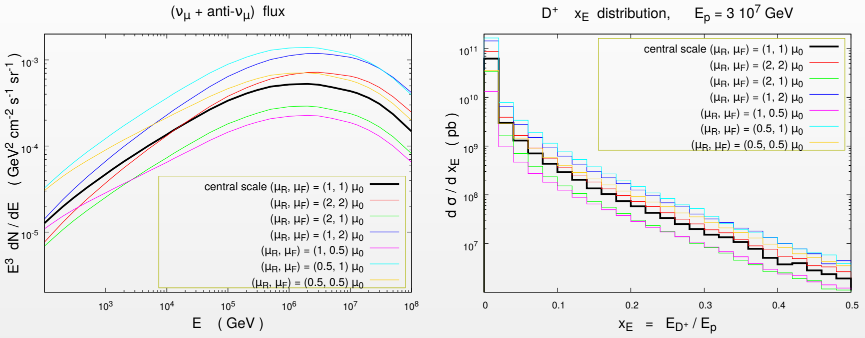
$(\nu_\mu + \bar{\nu}_\mu)$ fluxes: comparison with predictions of hadronic models used in EAS physics



from A. Fedynitch, EPJ Web of Conferences 116, 11010 (2016)

All recent central predictions, both those on the basis of pQCD and those on the basis of hadronic models used in EAS physics (like SIBYLL, DPMJET), turn out to lie within our uncertainty band.

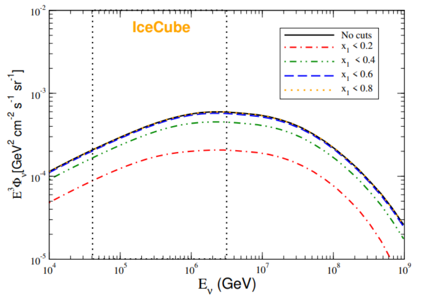
μ_R and μ_F scale uncertainties

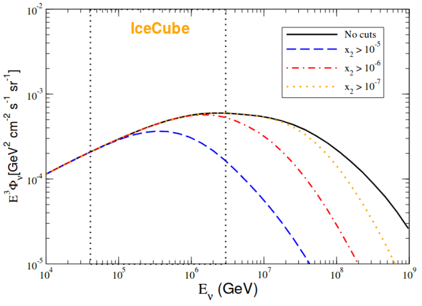


* Scale uncertainties are evaluated by making an envelope over different variations.

* Predictions have a <u>shape</u> uncertainty, not only a <u>normalization</u> uncertainty!

Prompt atmospheric ν fluxes, small-x and large-x PDFs





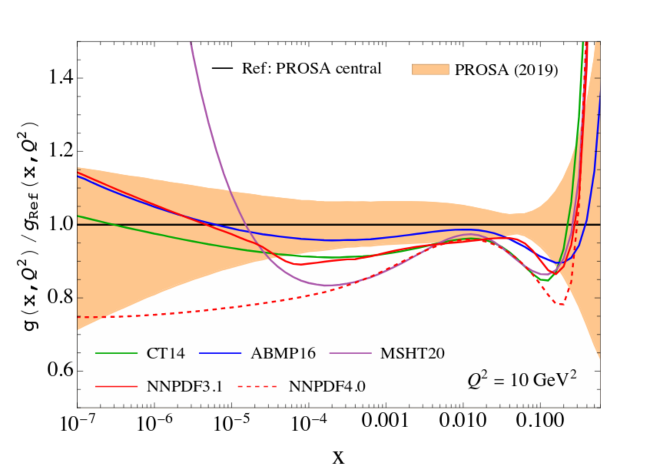
, *from V. Goncalves et al. [arXiv:1708.03775]*

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

$*$ Region particularly relevant: $0.2 < x < 0.6$, partly testable through ν experiments at the LHC.

$*$ On the other hand, for ν at the PeV scale, knowledge of PDF down to $x > 10^{-6}$ is enough.

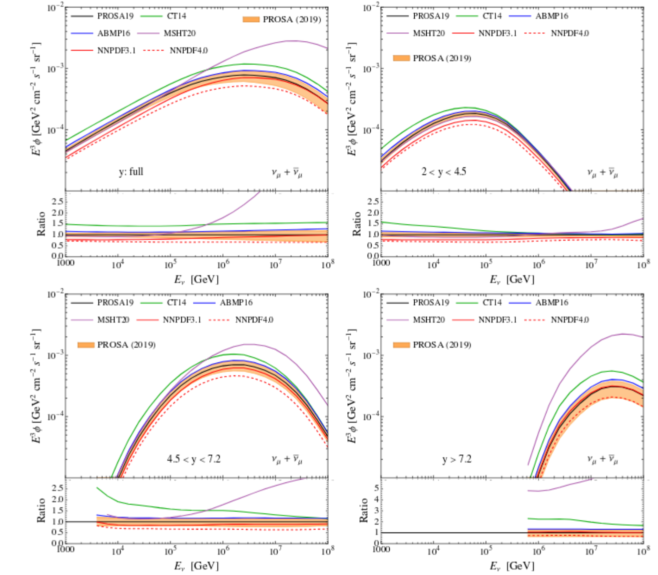
PDFs uncertainties at low and large-x



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

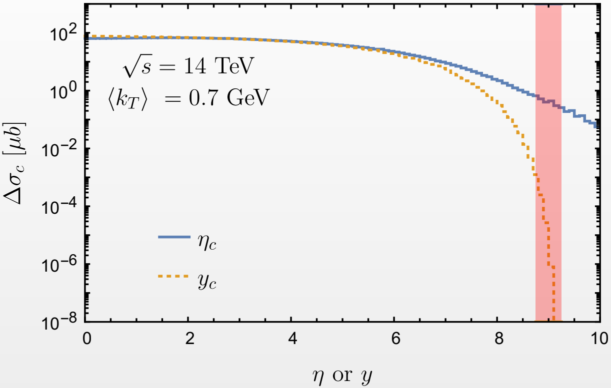
∗ Differences in gluon PDFs at large x are not covered by the uncertainties associated to each single PDF set.

Contribution to prompt $(\nu_\mu+\bar{\nu}_\mu)$ fluxes from different y_c regions



larger E_ν are obtained for larger $\sqrt{s}$, larger y and larger x.

Charm production at large rapidity/pseudorapidity



- $*$ For forward charm production ($\eta_c \gtrsim 6$) rapidity and pseudorapidity distributions increasingly differ.
- $*$ η_ν distribution effectively limited by the fact that y_c distribution is bounded.

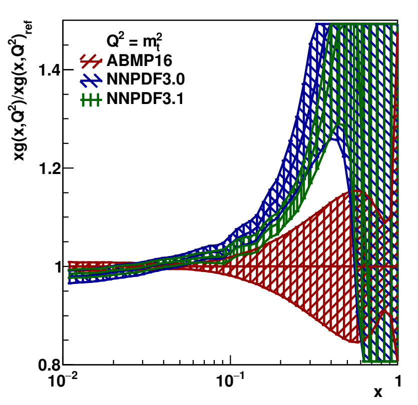
PDF uncertainties at large x

* PDF uncertainties are often estimated by considering a single PDF set.
* However, the differences between different PDF sets might be not covered by the uncertainty of a single set.

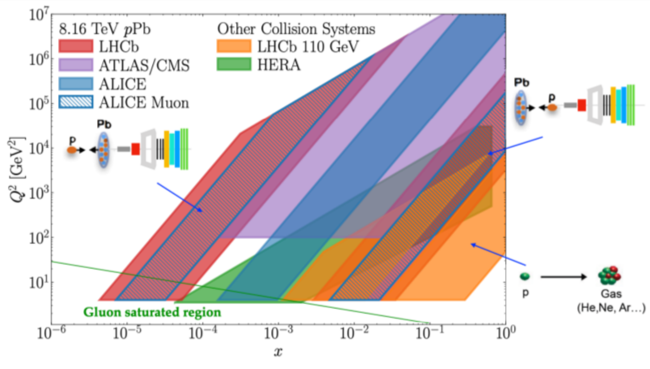
$\Rightarrow$ A more comprehensive estimate would be recommended.

* g PDF at large x play an important role in the predictions.

$\Rightarrow$ data on $t\bar{t} + X$ and jet production at the LHC are important for constraining g PDF in this region.



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



from LHCb collaboration

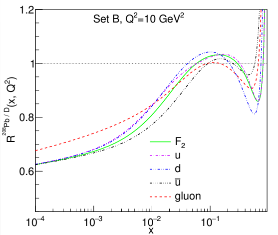
* LHCb-FT coverage at scale $Q^2 \sim 4$ GeV^2:

  $2 \cdot 10^{-4} \lesssim x \lesssim 4 \cdot 10^{-1}$ $\Rightarrow$ gluon, sea quarks
* 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, ...).

Nuclear modification factors R_p^{Pb}

$*$ Shadowing: $R < 1$ for $x \lesssim 0.1$ (a possible explanation: parton r ecombination/fusion process enhanced in nuclear target: partons with large spatial uncertainties (small x), can leak to a neighbor nucleon)

$*$ Antishadowing: $R > 1$ for $0.1 \lesssim x \lesssim 0.3$, related to sha dowing.



from [arXiv:1611.03670]

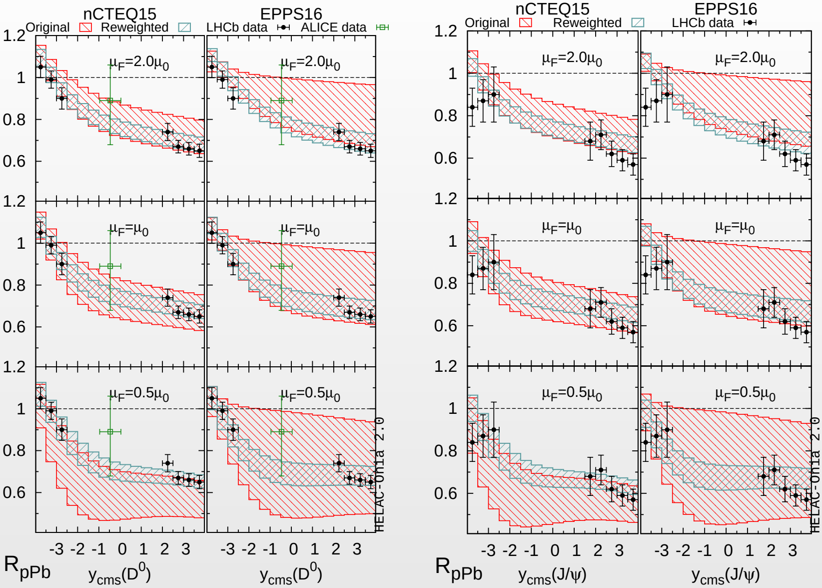
$*$ EMC effect: $R < 1$ for $0.3 \lesssim x \lesssim 0.7$ (attributed to in-m edium nucleon swelling, nucleon-nucleon short range correlations, binding, ...).

$*$ Fermi smearing: $R > 1$ for $0.7 \lesssim x < A$ short range nucleon correlations deform the nuclear structure functions mainly at large x.

No explicit modelization of nuclear effects occurs in most global fits of nPDFs. The modifications of the structure functions by nuclear effects are absorbed into the nPDF themselves.

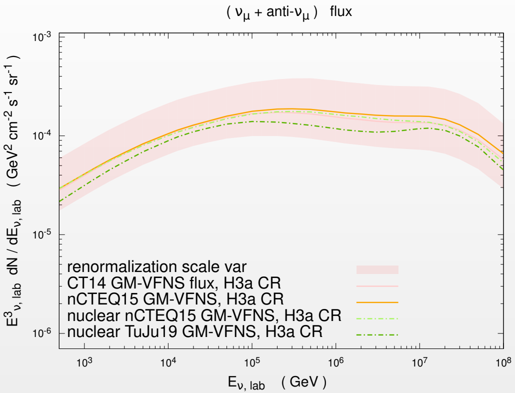
$\Rightarrow$ Evergreen questions: how to write a parameterization for nPDFs ?

nPDF fits and D^0 and J/ψ data in *p*-Pb / *pp* collisions



from A. Kusina, J.-P. Lansberg, I. Schienbein, H.-S. Shao, [arXiv:1712.07024v2]

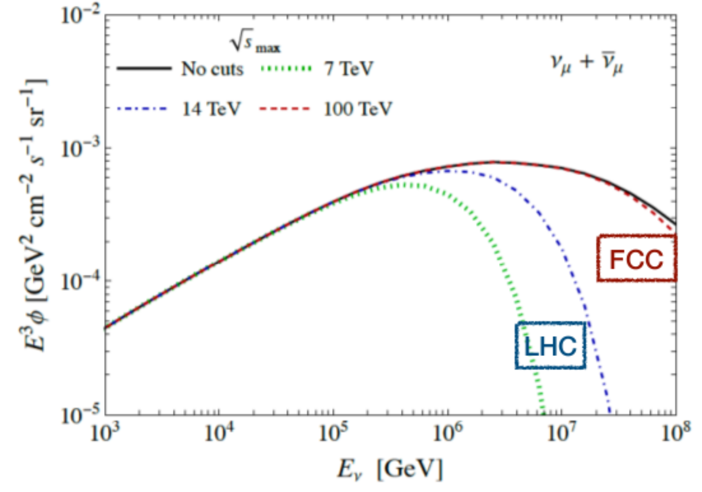
$(\nu_\mu + \bar{\nu}_\mu)$ fluxes: cold nuclear matter effects



* 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

Prompt atmospheric ν fluxes and LHC phase-space coverage



$*$ The $\sqrt{s} = 14$ TeV at LHC is in any case a limitation, FCC would be better (see also analysis in V. Goncalves et al, [arXiv:1708.03775]).

Wishlist useful measurements LHC, especially LHCb

* D-meson and B-meson spectra at 13.6 TeV, 14 TeV.
* if possible, more p_T bins in the region 0 - 5 GeV
* $\Lambda_c^{\pm}$ double-differential spectra in y, p_T.
* Additional focus on $D_s^{\pm}$ (main source of ν_τ and $\bar{\nu}_\tau$).
* Charge asymmetries with better statistics.
* All above in pp, pPb, pO standard collider modality
  $+$ SMOG fxixed-target modality using various light targets.
* LHCb measurements of DY and $t\bar{t}$-pair production in pp.
* Measurements should be accompanied by detailed information concerning systematic uncertainties (correlation matrices).
* Further measurements of correlations between D-mesons from c and $\bar{c}$ help to stress-test theory predictions and to test predictions in factorization schemes beyond collinear one.