The PROSA PDF fit and prompt neutrino fluxes

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on behalf of the PROSA collaboration

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mainly on the basis of
[arXiv:1503.04581], [arXiv:1611.03815], [arXiv:1705.10386]

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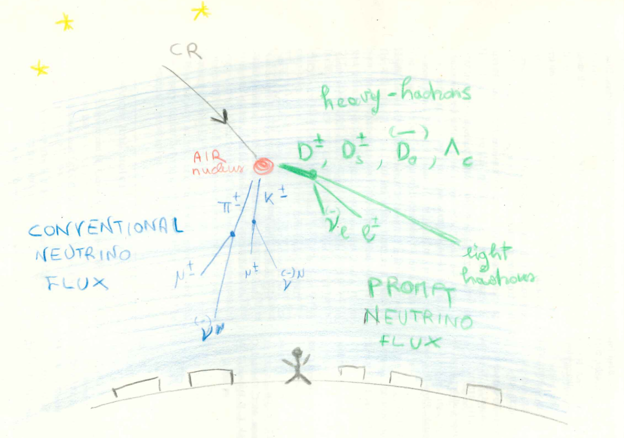
Atmospheric ($\nu + \bar{\nu}$) flux:

conventional and prompt components



Cosmic Rays + Atmospheric Nuclei → hadrons → neutrinos + X

$*$ Two contributing mechanisms, following two different power-law regimes:

- **conventional** ν flux from the decay of $\pi^{\pm}$ and $K^{\pm}$
- **prompt** ν flux from charmed and heavier hadrons (D's, $\Lambda_c^{\pm}$'s.....)

Prompt ν fluxes: ingredients of the computation

QCD and astrophysical input:

* primary CR flux and composition
* Earth atmospheric profile (density and composition)
* *N*-Air total inelastic cross-section
* *NN* hadroproduction cross-sections for charmed mesons/baryons
* cold nuclear matter/QGP effects vs. superposition approximation

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

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

Charmed-hadron hadroproduction: ingredients

* hard-scattering perturbative partonic cross-sections

* PDFs

* fragmentation functions / parton shower + hadronization

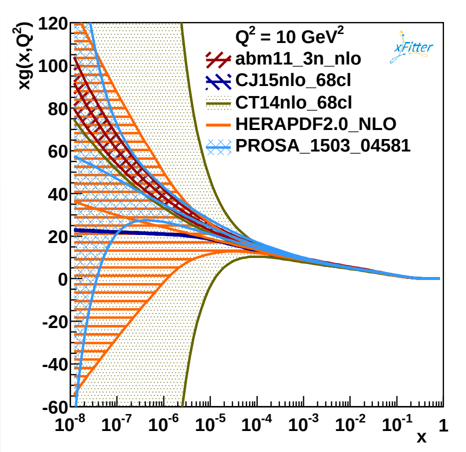
* further perturbative and non-perturbative QCD contributions

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

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

$x_a = p_a/P_{N_1}$, $x_b = p_b/P_{N_2}$, $z = P_H/p_c$ = longitudinal momentum fractions

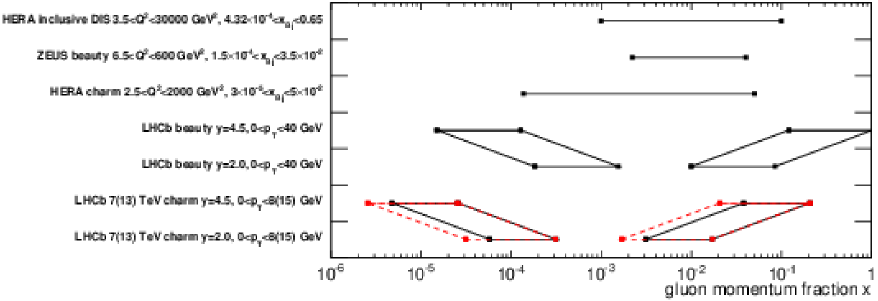
gluon PDF: comparison between different PDF fits



∗ PDF non-perturbative dependence on x: fit to experimental data

∗ The higher are E_{CM} and y_H (forward scattering),
the lower are the x values probed.

Heavy-flavour hadroproduction at LHCb vs. HERA:



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).

For LHCb, LO formula $x = exp(\pm y \sqrt{p_T^2 + m_Q^2}/E_p\ ) \Rightarrow$

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

PROSA PDF fit: basics

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:

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

Bottom Data at 7 TeV: B-meson p_T distributions in the range [0, 40] GeV, in five 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 data,
– $c\bar{c}$ DIS combined HERA data and $b\bar{b}$ DIS ZEUS data.

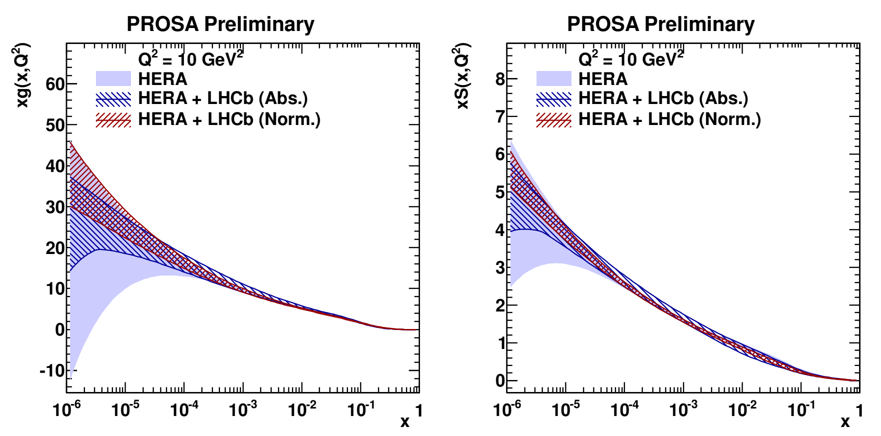
Three variants of the PDF fit:

1) one only with HERA data;

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

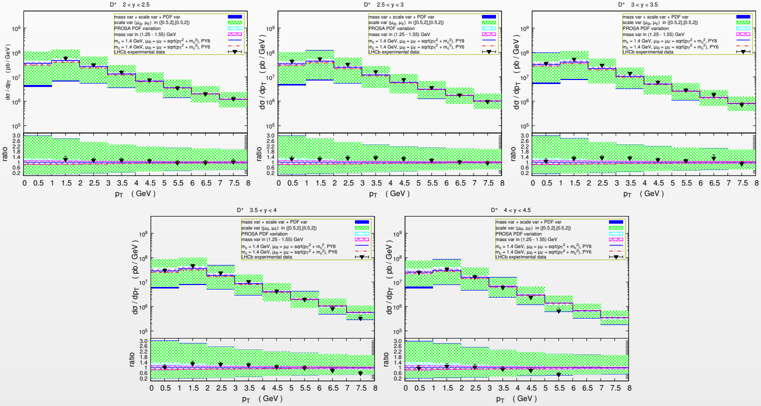
3) another one with reduced uncertainties: for each fixed LHCb p_T bin, use the ratios of distributions $(d\sigma/dy)/(d\sigma/dy_0)$ in different rapidity bis (i.e. normalized to the central bin $3 < y_0 < 3.5$): in the ratios theoretical uncertainties partly cancel.

PROSA PDF fits: comparison between the three variants of the fit



∗ The gluon and the sea quark distributions are correlated:
a reduction on the uncertainty of the former propagates to the latter.

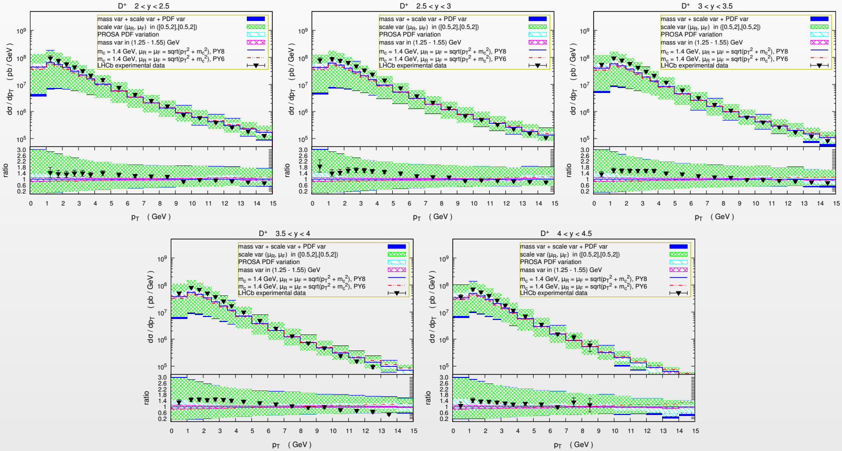
Theory predictions vs. LHCb experimental data on $pp \to D^{\pm} + X$ at $\sqrt{S} = 7$ TeV



* Here we compare theoretical absolute cross-sections to experimental data, whereas the PROSA PDF fit variant using LHCb data ratios is employed in the predictions.

* Big uncertainties on the theoretical predictions, dominated by μ_R and μ_F scale variations.

Theory predictions vs. LHCb experimental data on $pp \rightarrow D^{\pm} + X$ at $\sqrt{S} = 13$ TeV



These data are not included in the PROSA PDF fit:
experimental data always within the theory uncertainty bands.

Comparison between theoretical and experimental uncertainties

* For charm hadroproduction, present theory uncertainties look far larger than the experimental ones.

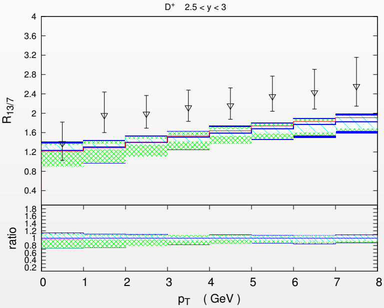
* **Why do not we limit our uncertainty bands to the experimental uncertainty bands ?**

  – Degeneracy: many different modifications in the theory input (charm mass, PDFs, etc....) can lead to a "good agreement" with data. But which modification is the "correct" one ?

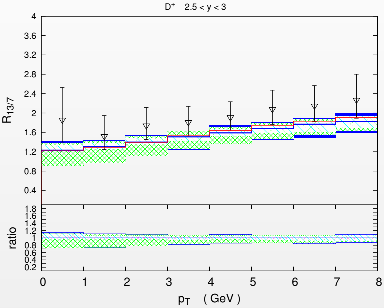
  – QCD theory is not a phenomenological model: predictions coming from first principles as much as possible. The use of phenomenological models is a consequence of our imperfect knowledge of the theory.

  – (Sometimes not only Theories but even) Data can be wrong !

Ratios of theory predictions at different energies vs. LHCb 13/7 experimental data



old (wrong) experimental data



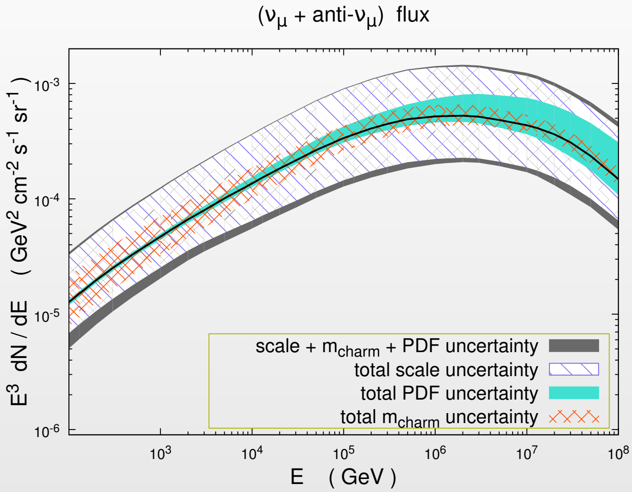
new revised experimental data

∗ Agreement of theory predictions and experimental data improved after last data revision (May 2017).

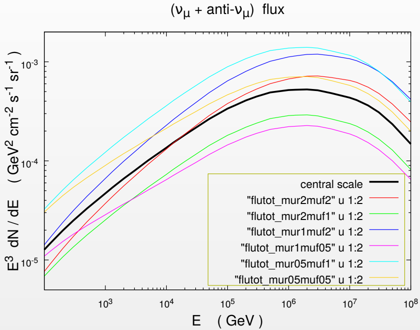
∗ Reduced uncertainties in ratios (compared to the absolute case)

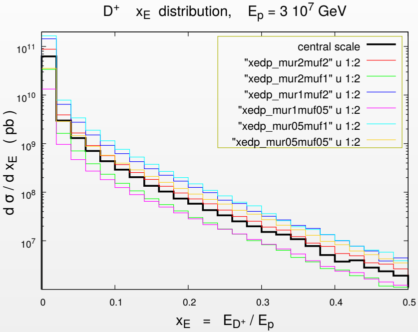
∗ Theory predictions from two different independent computations and PDF sets are considered (red line: NLO QCD + NLL GM-VFNS with CT14nlo PDFs, green/blue bands: NLO QCD FFNS + LL with PROSA PDFs).

Prompt neutrino fluxes: QCD scale, mass and PDF uncertainties



μ_R and μ_F scale uncertainties

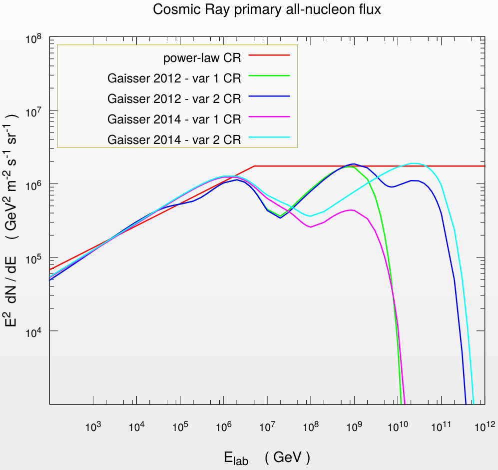




∗ Scale uncertainties are evaluated by making an envelope over different variations.

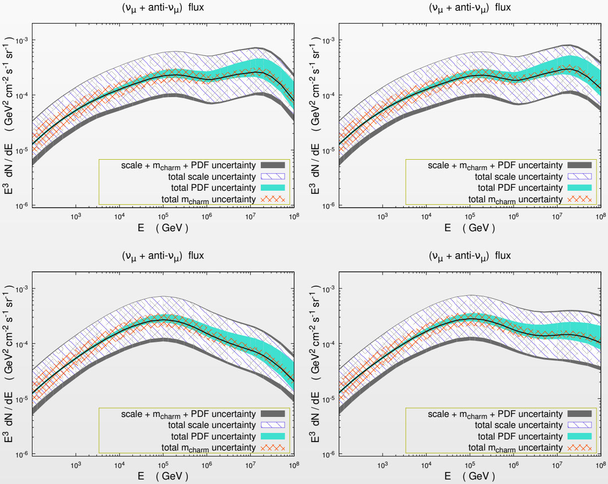
∗ Predictions have a shape uncertainty, not only a normalization uncertainty!

The all-nucleon CR spectra: considered hypotheses



- ∗ All-nucleon spectra obtained from all-particles ones under different assumptions as for the CR composition at the highest energies.
- ∗ Models with 3 (2 gal + 1 extra-gal) or 4 (2 gal + 2 extra-gal) populations are available.

Prompt $(\nu_\mu + \bar{\nu}_\mu)$ fluxes: comparison between theory predictions using different primary CR fluxes



* Each panel corresponds to a different CR primary flux (GST-3, GST-4, H3a, H3p).
* For each panel: μ_R and μ_F scale, PROSA PDF and charm mass uncertainties.

Prompt $(\nu_\mu + \bar{\nu}_\mu)$ fluxes: comparison of PROSA predictions with those of other groups

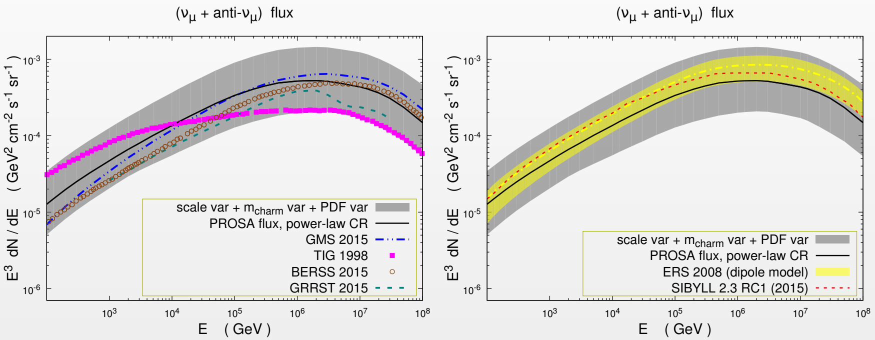
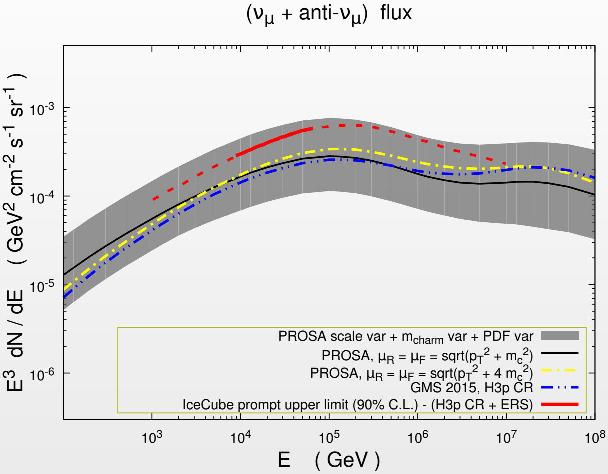


Figure : Prompt neutrino fluxes from the PROSA PDFs with its uncertainties compared to other predictions from the literature. Predictions treating charm hadroproduction at parton-level by means of perturbative QCD are shown on the left. On the right comparisons with predictions using the dipole model (ERS) and a recent version of the SYBILL event generator are shown. The broken power-law CR spectrum is used as input in all predictions.

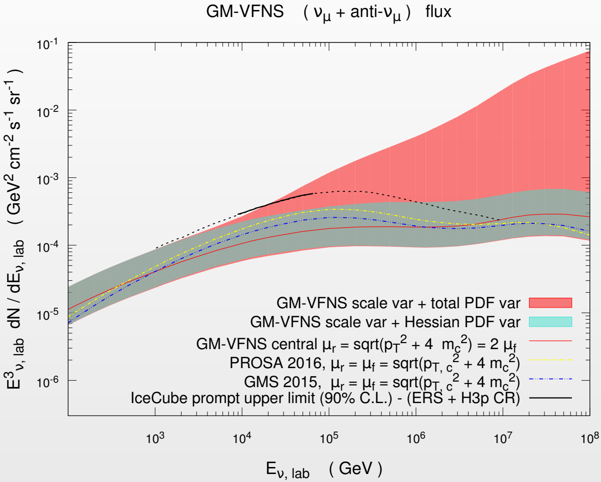
Prompt neutrino fluxes:
theoretical predictions vs. IceCube upper limits



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

Prompt neutrino fluxes:

theoretical predictions vs. IceCube upper limits



∗ IceCube results give clear indication that the CT14nlo gluon PDF uncertainties at low x's (see PDF error sets 53-56) are too large!

Conclusions

* Constraining PDFs at low x is important for hadronic interactions at UHE, as probed in astroparticle physics.

* PROSA PDF fit: low x gluon PDF constrained by LHCb data on open charm and bottom hadroproduction at $\sqrt{s} = 7$ TeV.

* Recent revision of LHCb open charm data at $\sqrt{s} = 13$ TeV (May 2017): we plan to incorporate these data in the PROSA PDF fit soon!

* Other PDF fits (e.g. CT14nlo) would definitely benefit from the inclusion of these data. At present big uncertainties, well above IceCube upper limits on prompt neutrino fluxes.

* Once PDF uncertainties are under control, bigger uncertainties on prompt fluxes are related to μ_R and μ_F scale variation.

* IceCube analyses of thoroughgoing muon tracks from the northern hemisphere put strong constraints on prompt fluxes: VLVνTs complementary to colliders in constraining QCD ?

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

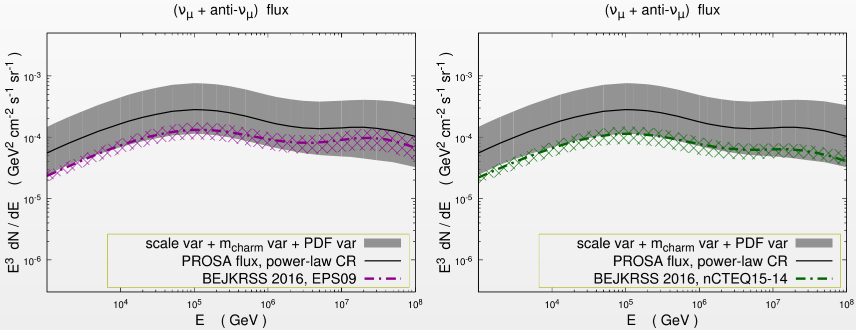
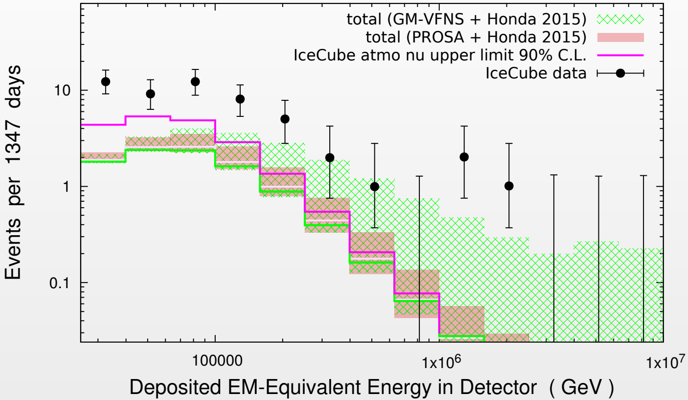


Figure : Comparison of prompt neutrino fluxes with the PROSA proton PDFs and the superposition approximation, to those of Bhattacharya et al. (BEJKRSS 2016) using nuclear PDFs, with their respective uncertainty bands. Uncertainties affecting nuclear PDFs are not accounted for in these plots. The CR primary flux H3p is used in all these predictions.

HESE analysis:

theoretical predictions vs. IceCube experimental data



- ∗ PROSA 2016 predictions vs GM-VFNS 2017 predictions vs IceCube exp. data
- ∗ GM-VFNS 2017 predictions dominated by CT14nlo PDF uncertainties.