The atmospheric prompt neutrino flux *revisited*

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Gauld, Rojo, LR, Talbert, arXiv:1506.08025, Gauld, Rojo, LR, Talbert, Sarkar arXiv:1511.06346

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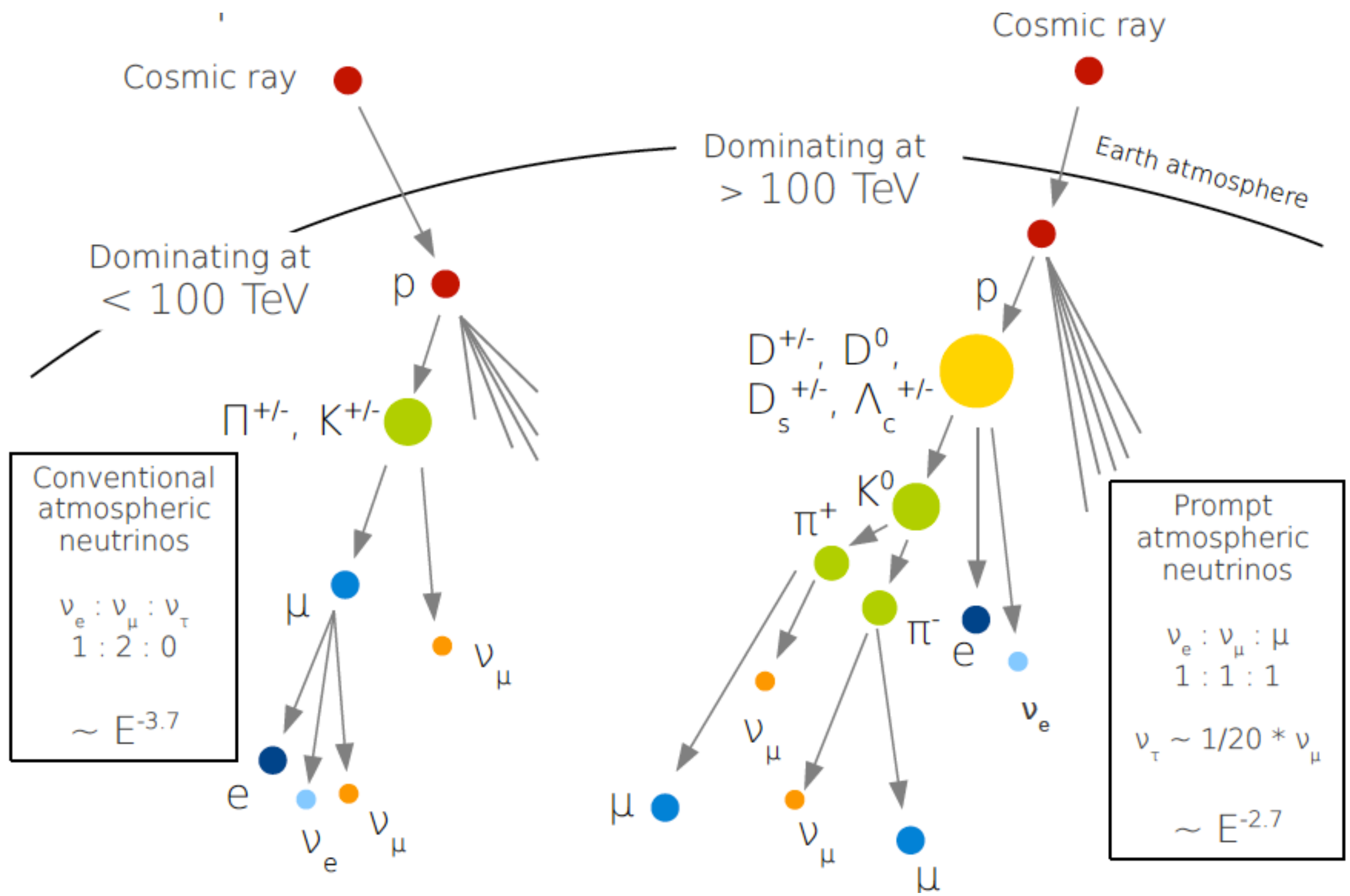
Prompt vs. conventional flux

The energy spectrum from semi-leptonic decay products depends on a hadronic '**critical energy**', *below* which the **decay probability** is > **interaction probability**



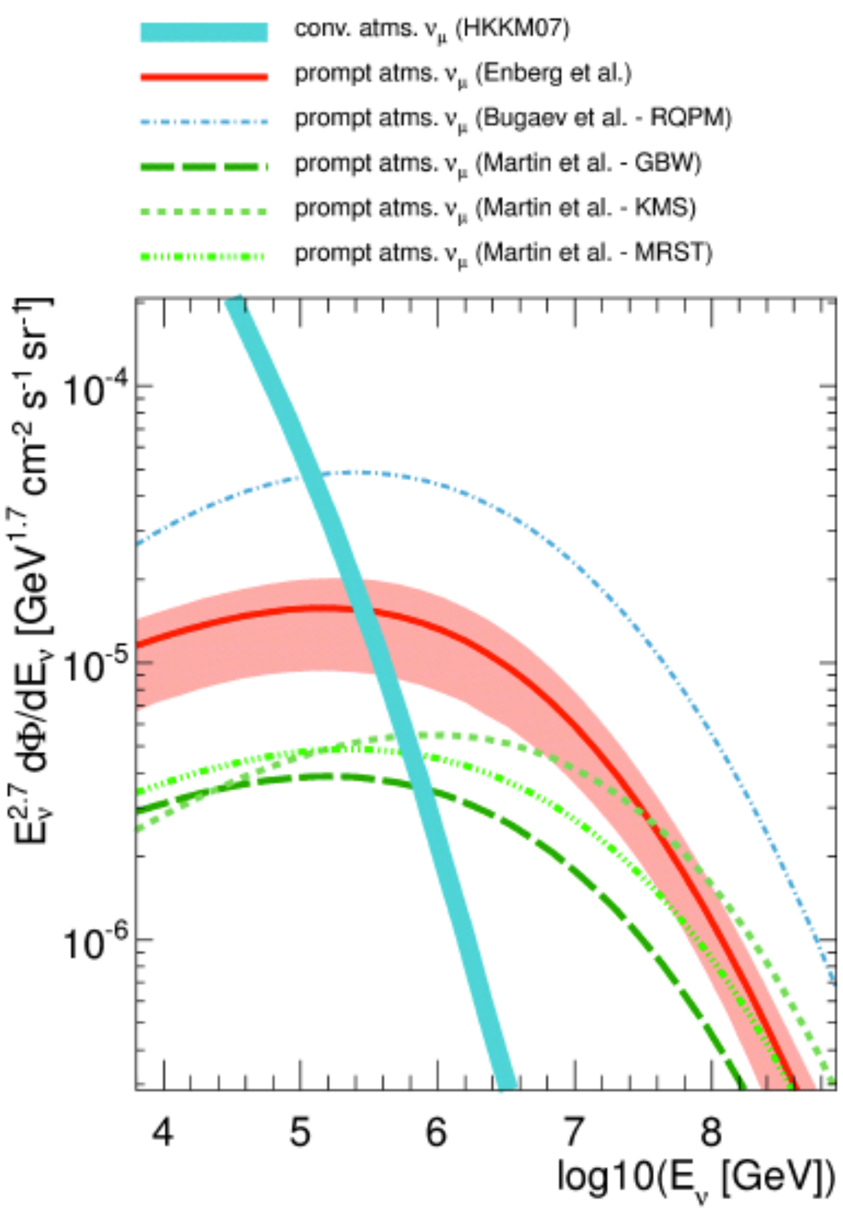
Courtesy: Anne Schukraft

For **pions & kaons**, this critical energy is low (decay length is long) hence the leptonic energy spectrum is soft. For **charmed mesons**, the critical energy is high … they **decay** *promptly* to highly energetic leptons

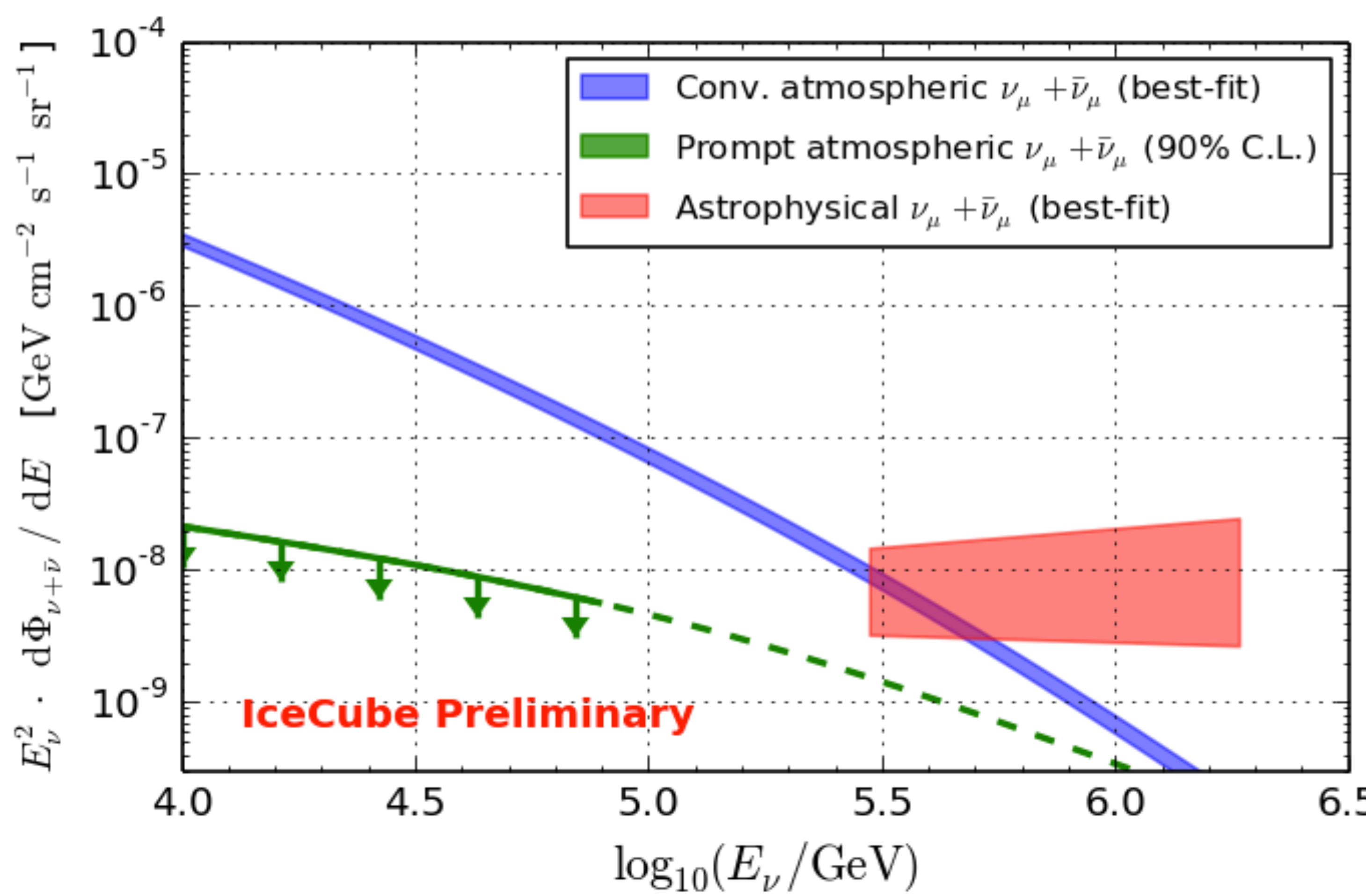
The atmospheric neutrino flux from the decay of pions & kaons is the '**conventional flux**,' whereas that from charm decay is called the '**prompt flux**'

Where are the prompt neutrinos?

The flux of prompt neutrinos is *harder* than that of conventional neutrinos, and was predicted to *dominate* the total atmospheric flux at energies above ~10^{5-6} GeV



No prompt flux seen so far … but an astrophysical signal with similar spectrum has been discovered!



(Sebastian Schonen, IPA 2015)

The conventional background is well understood as it has been calibrated against many observations … uncertainties in charm production make the prompt flux less so but it is the most important background for the expected astrophysical flux!

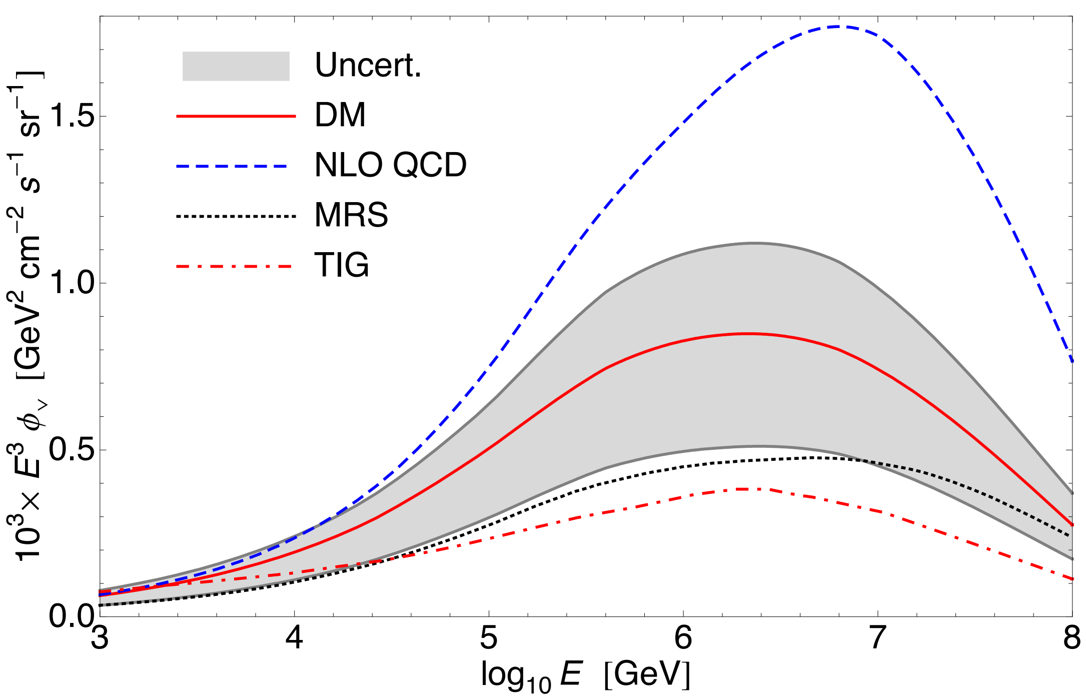
Previous calculations

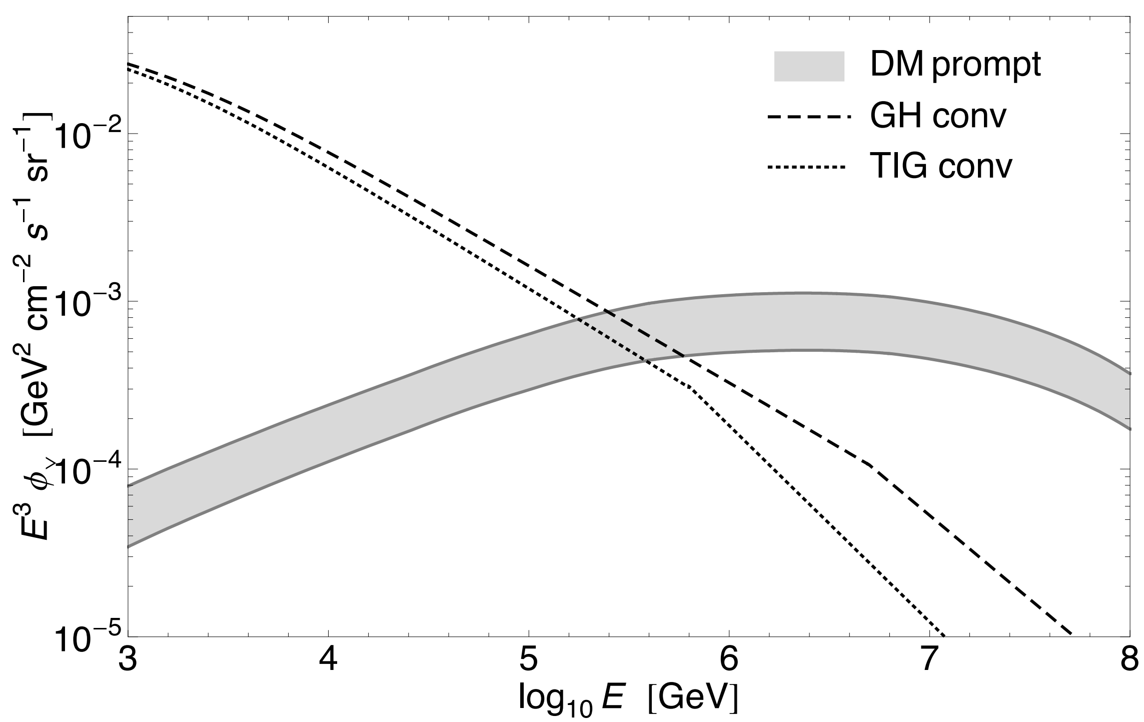
- **Volkova**, Sov. J. Nucl. Physics 12 (1980) 784
- **Bugaev, Naumov, Sinegovksy, Zaslavskaya**, Il Nuovo Cimento C 12 (1989) 41
- **Lipari**, Astroparticle Physics 1 (1993) 195
- **Thunman, Ingelman, Gondolo** (TIG), Astroparticle Physics 5 (1993) 309
- **Pasquali, Reno, Sarcevic** (PRS), Physical Review D59 (1999) 034020
- **Gelmini, Gondolo, Varieschi** (GGV1), Physical Review D61 (2000) 036005
- **Gelmini, Gondolo, Varieschi** (GGV2), Physical Review D61 (2000) 056011
- **Martin, Ryskin, Stasto** (MRS), Acta Physica Polonica B34 (2003) 3273
- **Enberg, Reno, Sarcevic** (ERS), Physical Review D78 (2008) 043005
- **Bhattacharya, Enberg, Reno, Sarcevic, Stasto** (BERSS), arXiv:1502.01076
- **Garzelli, Moch, Sigl** (GMS), arXiv:1507.01570

Calculating the prompt flux of atmospheric neutrinos requires a synthesis of QCD, atmospheric physics, and neutrino physics

Tension with ERS benchmark

arXiv:astro-ph/1410.1749
arXiv:hep-ph/0806.0418





Recent data put an **upper limit** on the prompt flux above 1 TeV, which is *less than* ~1.5 x the benchmark ERS 2008 calculation

Parameter	Best-fit value	No. of events
Penetrating μ flux	$1.73 \pm 0.40\,\Phi_{\rm SIBYLL+DPMJET}$	30 ± 7
Conventional ν flux	$0.97^{+0.10}_{-0.03}\,\Phi_{\rm HKKMS}$	280^{+28}_{-8}
Prompt ν flux	$< 1.52\,\Phi_{\rm ERS}$ (90% CL)	< 23
Astrophysical Φ_0	$2.06^{+0.35}_{-0.26} \times 10^{-18}$ GeV^{-1} cm^{-2} sr^{-1} s^{-1}	87^{+14}_{-10}
Astrophysical γ	2.46 ± 0.12	

Even stronger limit of 0.54×ERS @ 90% C.L. from combined IC59 + IC79 + IC86 data

(Sebastian Schonen, IPA 2015)

But were the uncertainties in the predicted flux calculated conservatively?

Cascade Formalism

1. $$\frac{d\phi_p}{dX} = -\frac{\phi_p}{\lambda_p} + Z_{pp}\frac{\phi_p}{\lambda_p}$$

2. $$\frac{d\phi_h}{dX} = -\frac{\phi_h}{\rho d_h(E)} - \frac{\phi_h}{\lambda_h} + Z_{hh}\frac{\phi_h}{\lambda_h} + Z_{ph}\frac{\phi_p}{\lambda_p}$$

3. $$\frac{d\phi_l}{dX} = \sum_h Z_{h\to l}\frac{\phi_h}{\rho d_h}$$

Full series of **cascade equations**, from incoming cosmic ray nucleons to final state leptons

Asymptotic solutions

$$\phi_l|_{low} = \phi_p(E)\ Z_{h\to l}^{low}\ \frac{Z_{ph}}{(1-Z_{pp})}$$

$$\phi_l|_{high} = \frac{Z_{h\to l}\epsilon_h}{E}\frac{Z_{ph}\phi_p(E)}{(1-Z_{pp})(1-\frac{\Lambda_p}{\Lambda_h})}\ln\frac{\Lambda_h}{\Lambda_p}$$

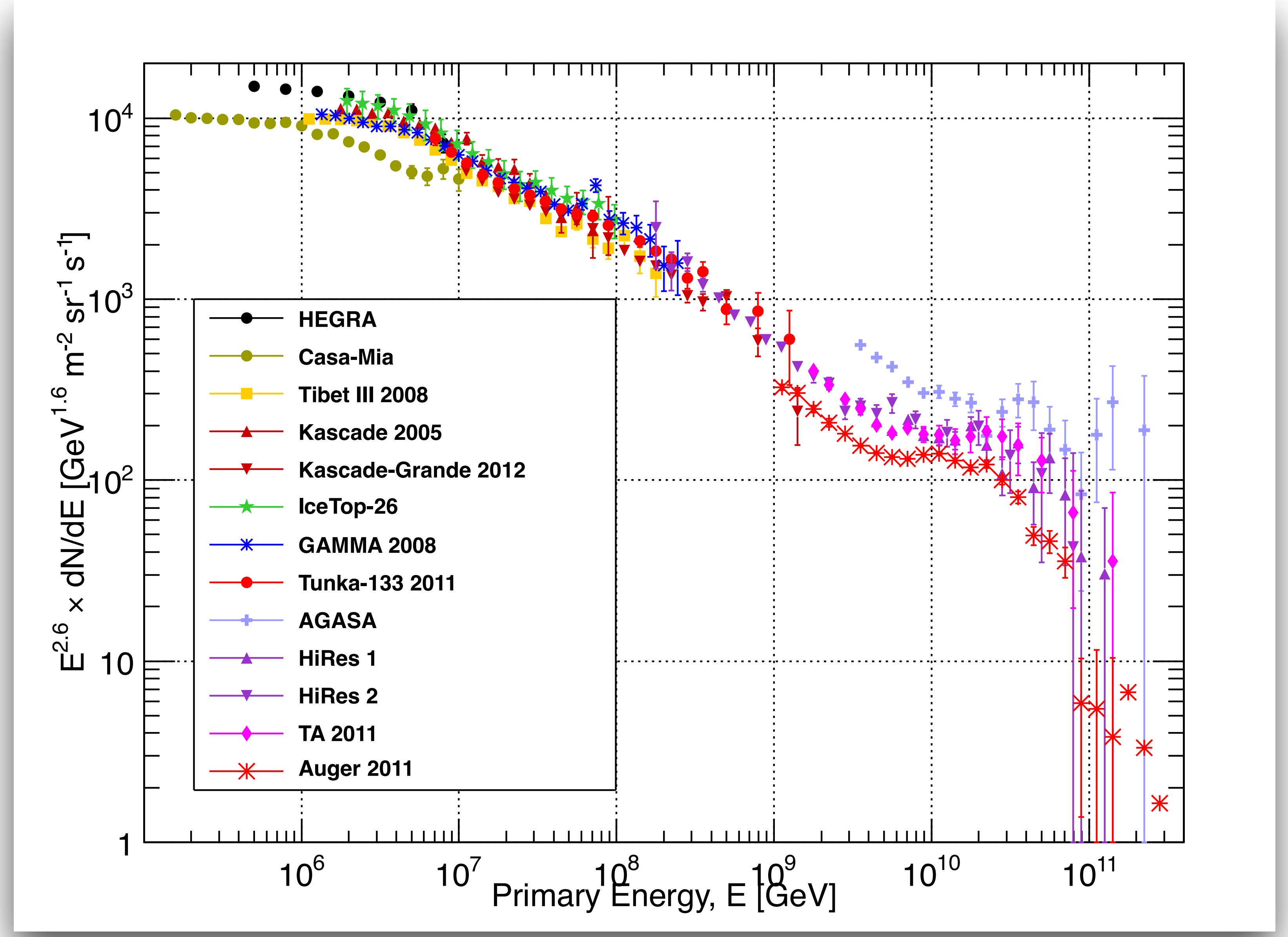
Geometric Interpolation

$$\phi_l = \sum_h \frac{\phi_l^{low}\phi_l^{high}}{\phi_l^{low}+\phi_l^{high}}$$

Our final flux includes all (interpolated) contributions from **charmed hadrons**

Incident Cosmic Ray Fluxes: $\phi_N^0(E)$

Cosmic ray spectrum constrained ~up to 10^5 GeV by balloon and space experiments, e.g. **AMS** and **CREAM**



Higher energies rely on air shower arrays, e.g. **Kascade**, **Auger** & **TA**… *many* uncertainties regarding CR composition

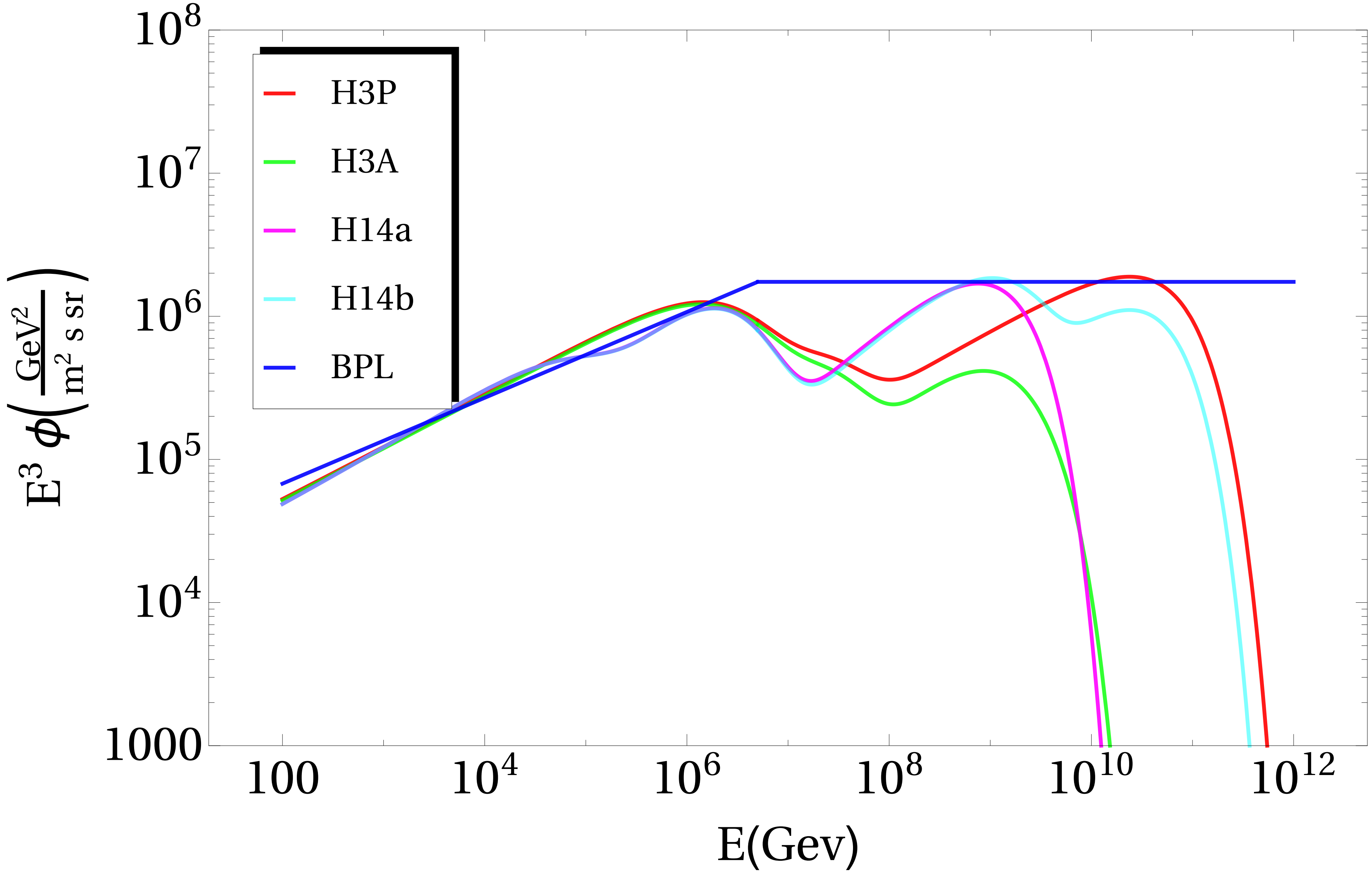
Does a 'Broken-Power-Law' (BPL) fit the data?

$$\phi_N^0(E) = \begin{cases} 1.7\ E^{-2.7} & for\ E < 5 \times 10^6\ \ GeV \\ 174\ E^{-3} & for\ E > 5 \times 10^6\ \ GeV \end{cases}$$

Gaisser *et al.* fluxes: $\phi_N^0(E)$

arXiv:astro-ph/1111.6675
arXiv:astro-ph/1303.3565

$$\phi_i(E) \ = \ \Sigma_{j=1}^{3}\, a_{i,j}\, E^{-\gamma_{i,j}} \times \exp\left[-\frac{E}{Z_i R_{c,j}}\right]$$



The effect of the new parameterisations is **significant above** ~10^6 GeV, and we are interested in making predictions up to ~10^8 GeV…

The QCD input: Z_{ph}

$$Z_{ph} = \int_E^\infty dE' \frac{\phi_p(E')}{\phi_p(E)} \frac{A}{\sigma_{pA}(E)} \frac{d\sigma(pp \to c\bar{c}Y; E', E)}{dE}$$

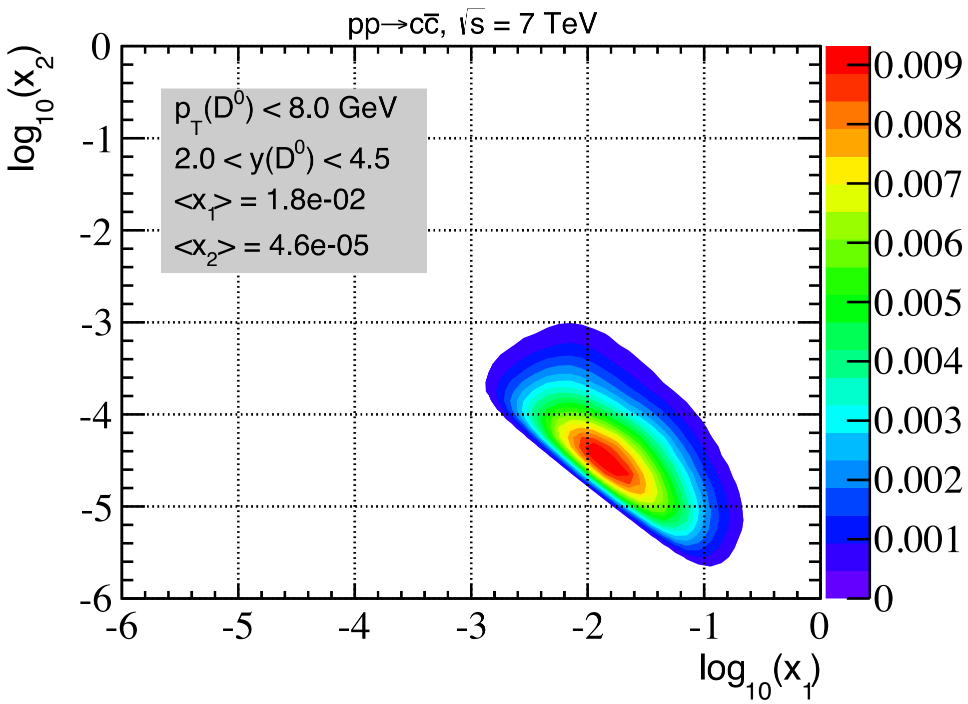
- The **differential cross-section** can be calculated in a variety of formalisms, e.g. the 'colour dipole model' of ERS which is empirical (hard to estimate uncertainties)
- However, there is no evidence that **perturbative QCD** (with DGLAP evolution) *cannot* describe charm production data for the entire kinematical region of interest, hence our calculation is performed with **NLO+PS Monte-Carlo event generators**
- Boosting from CM to the rest frame of the (atmospheric) fixed target, one finds:

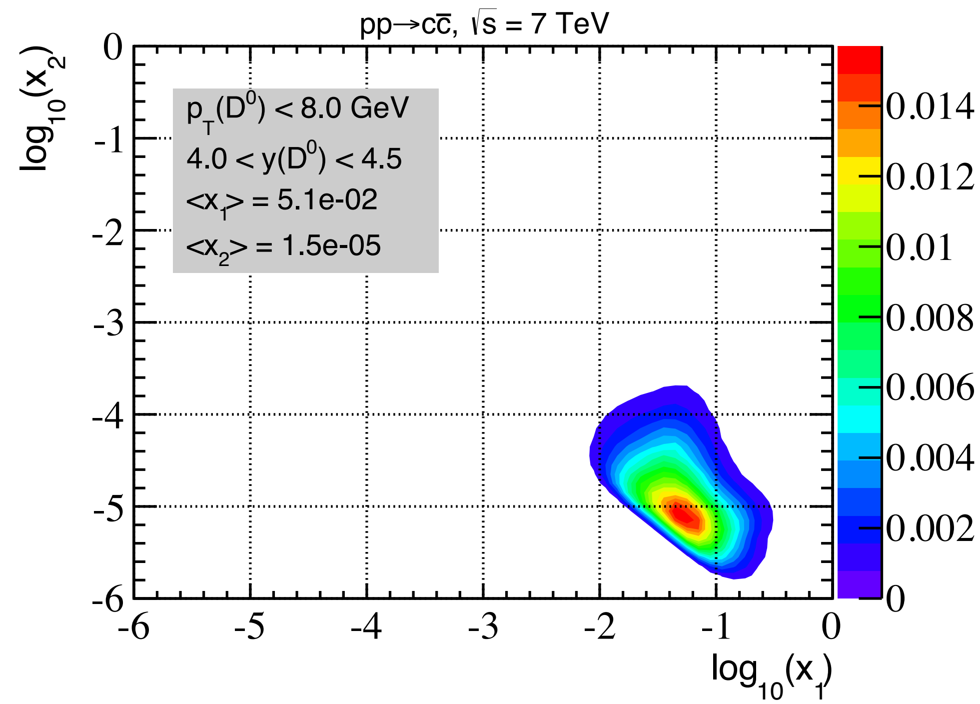
$$\sqrt{s} = 7\ [TeV] \quad \longleftrightarrow \quad E_b = 2.6 \times 10^7\ [GeV]$$

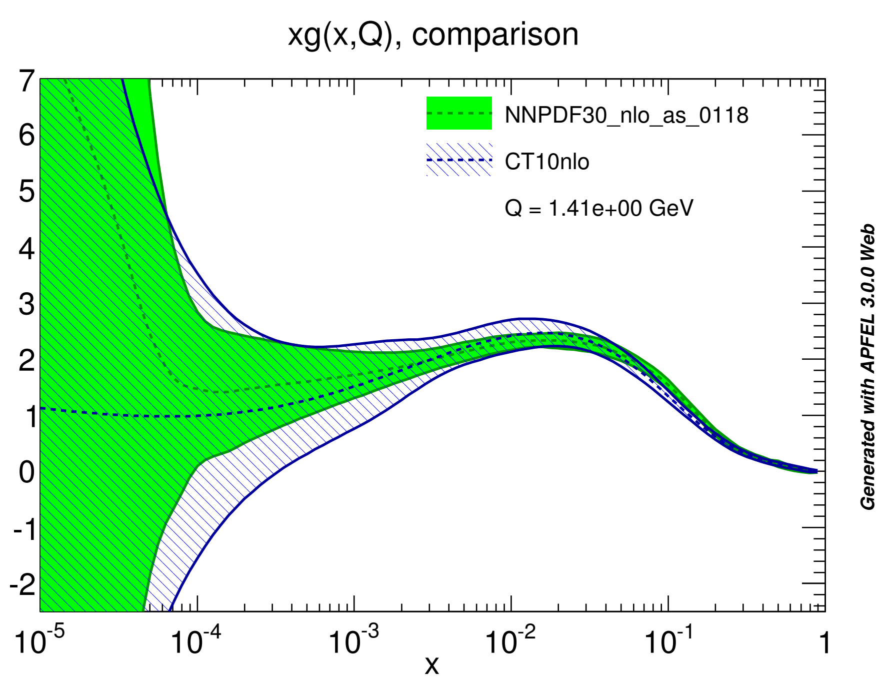
- Thus there is **complementarity with LHC physics**. We will predict the prompt neutrino flux at energies **up to 10^8 GeV** … at these energies, the charm production cross section is dominated by **gluon fusion**, hence we are sensitive to the behaviour of the **gluon PDF** (parton distribution function) **at small-x**

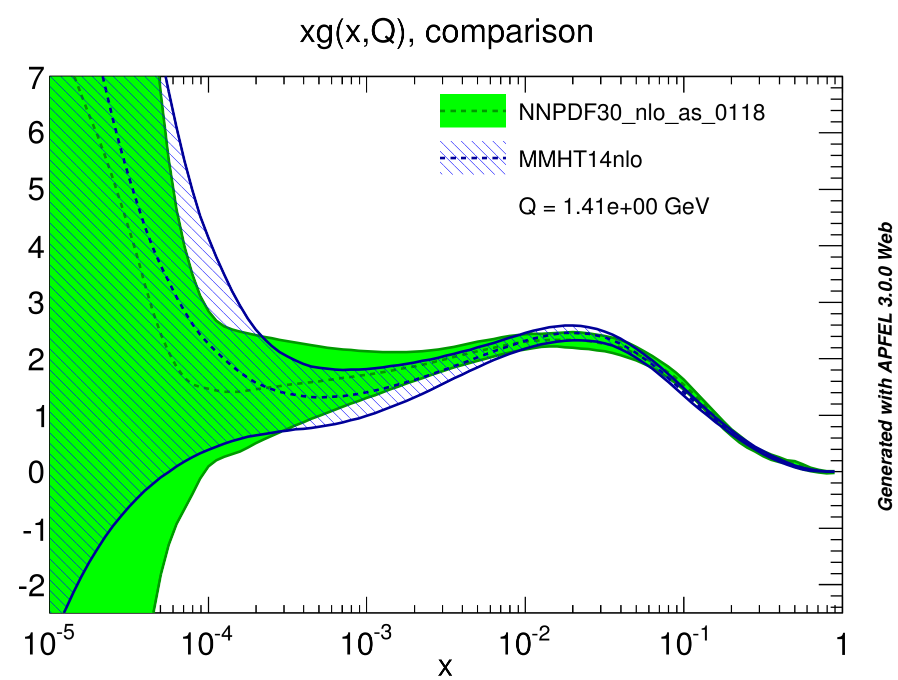
Gluon PDF Sensitivities

arXiv: 1506.08025





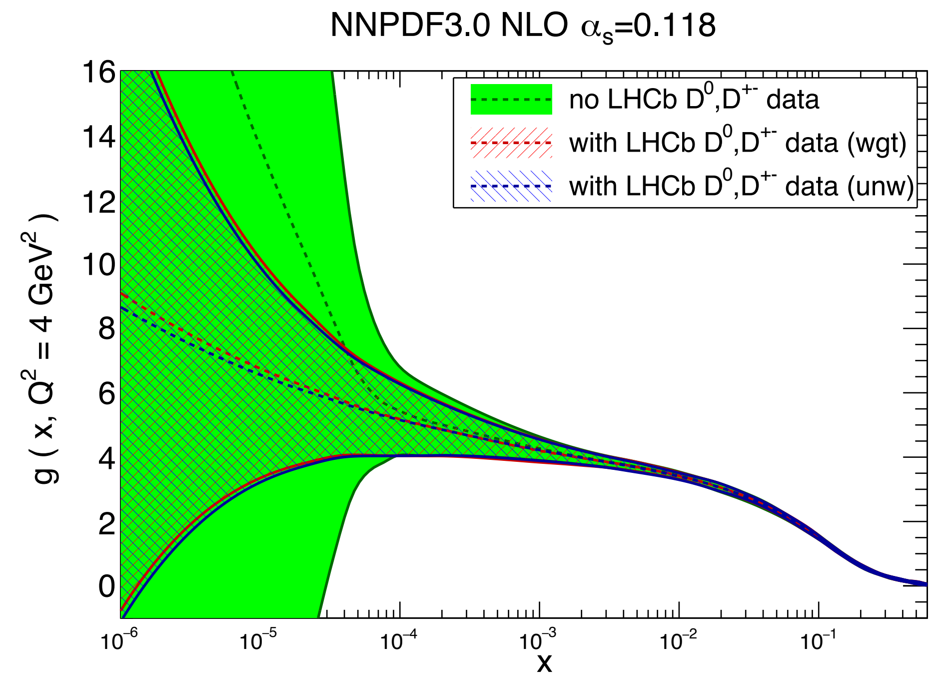


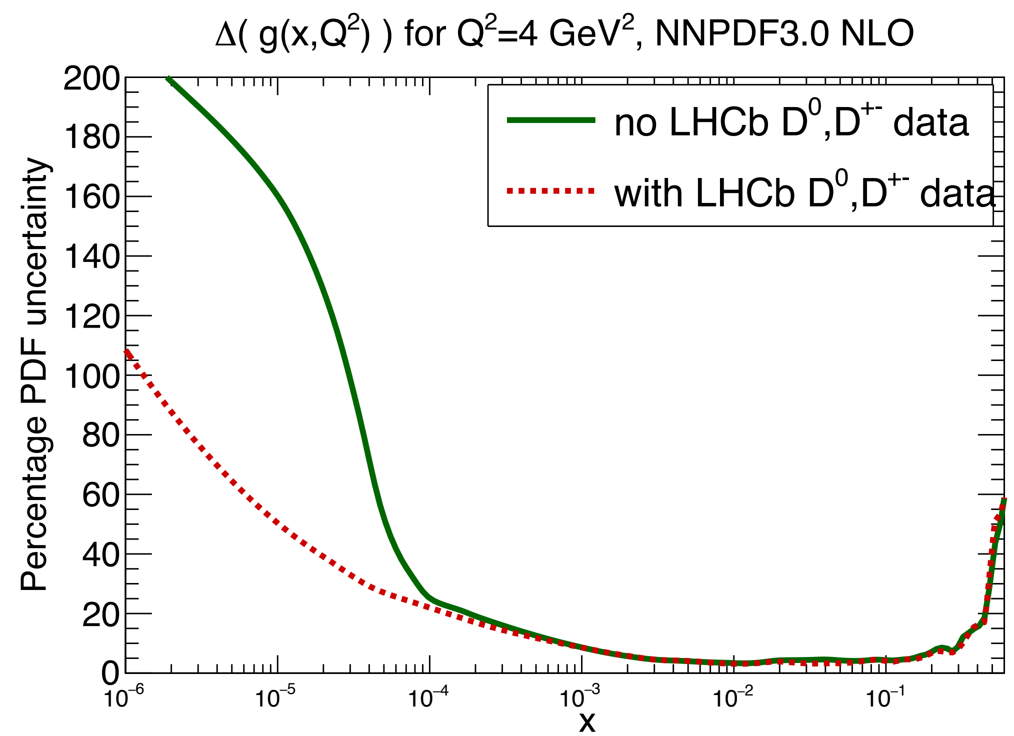


arXiv: 1506.08025

Small-x Gluon NNPDF: LHCb constraints

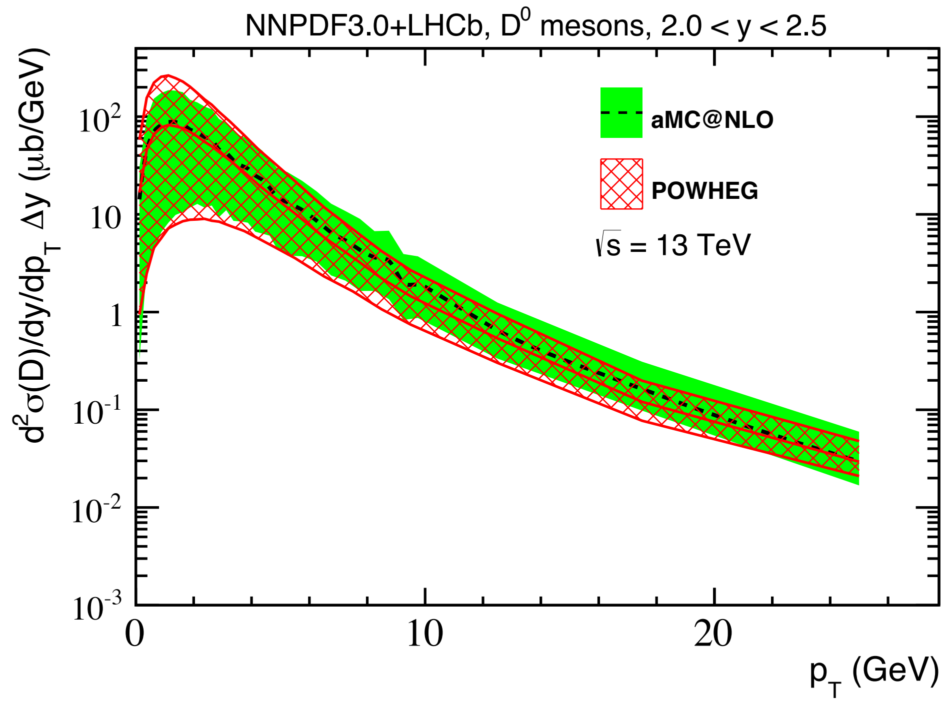
- We utilise charm production data from LHCb to **reduce the uncertainties in the small-x gluon PDF**
- By implementing a Bayesian **reweighting technique**, the impact of the new data is estimated. 75 data points added to NNPDF3.0 analysis
- The impact is negligible for $x > 10^{-4}$, but substantive in the smaller-x region where data was previously unavailable. At $x \sim 10^{-5}$, we achieve a **3x reduction in uncertainty**
- We utilise these improved PDFs to make **predictions for 13 TeV** physics

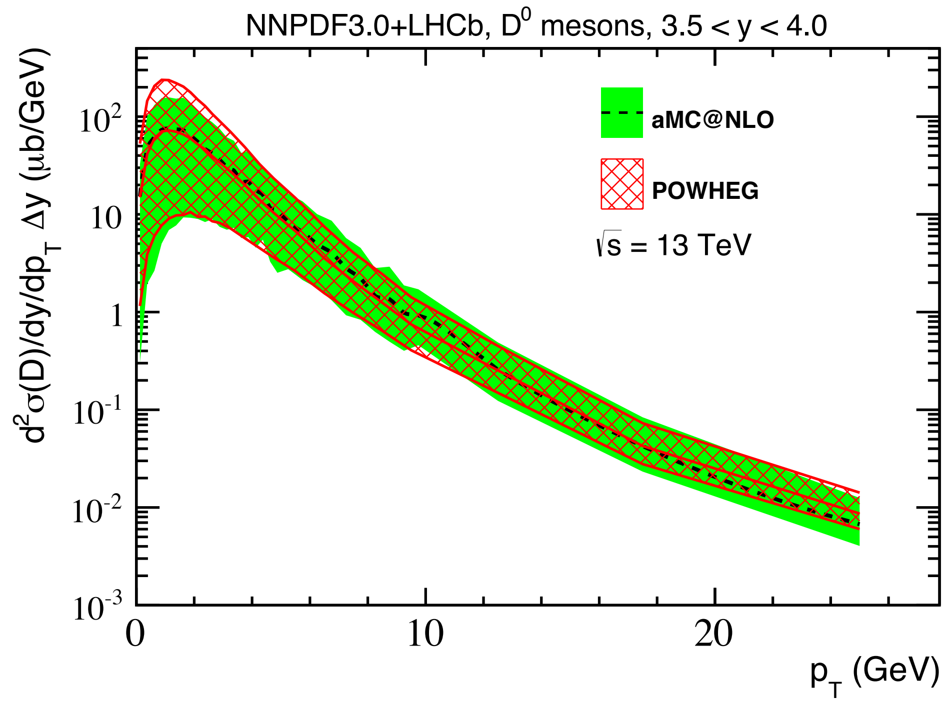


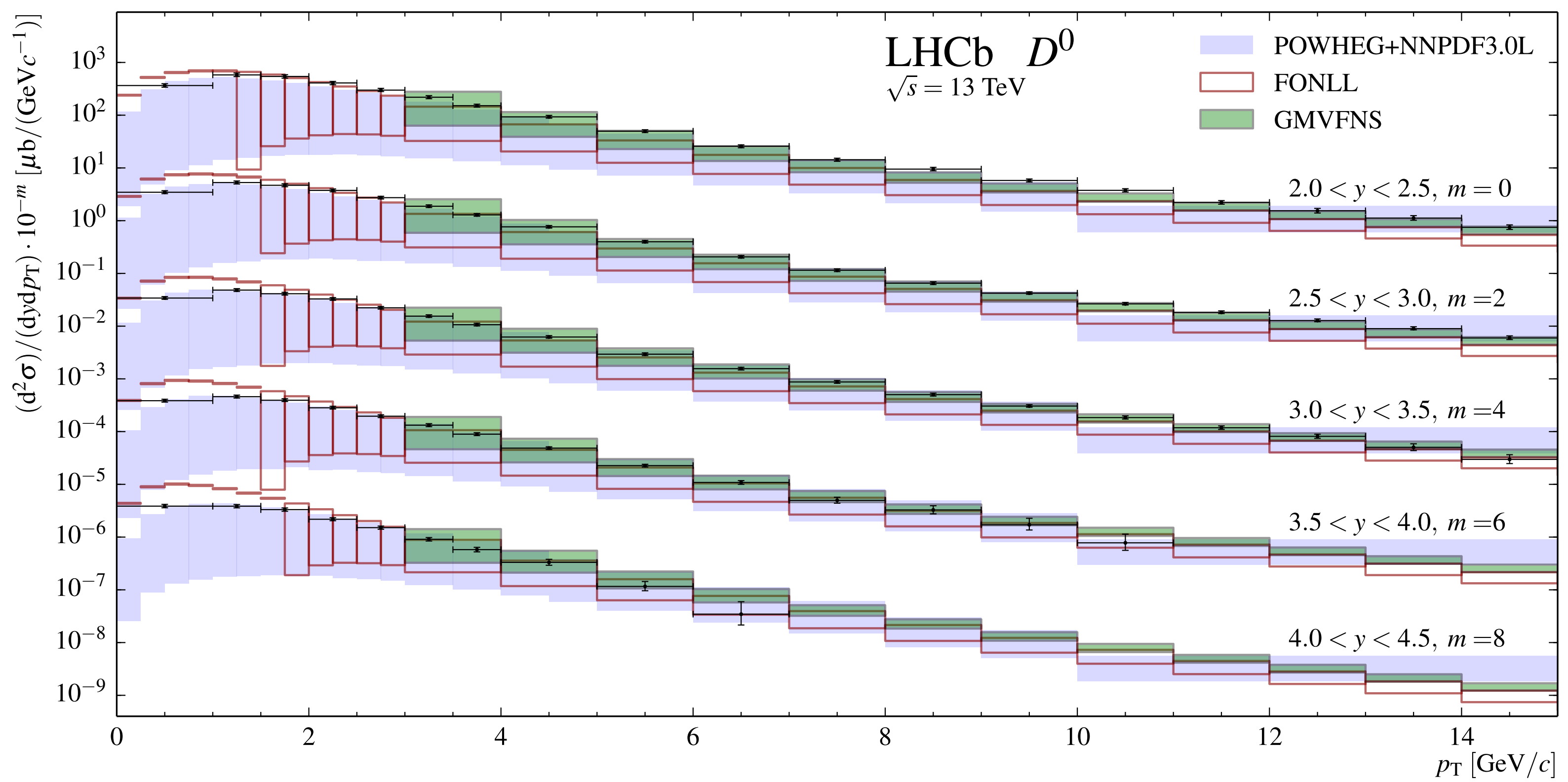


Predictions and validation with LHC data

Due to the improved NNPDF3.0+LHCb, the PDF errors are moderate even @ 13 TeV





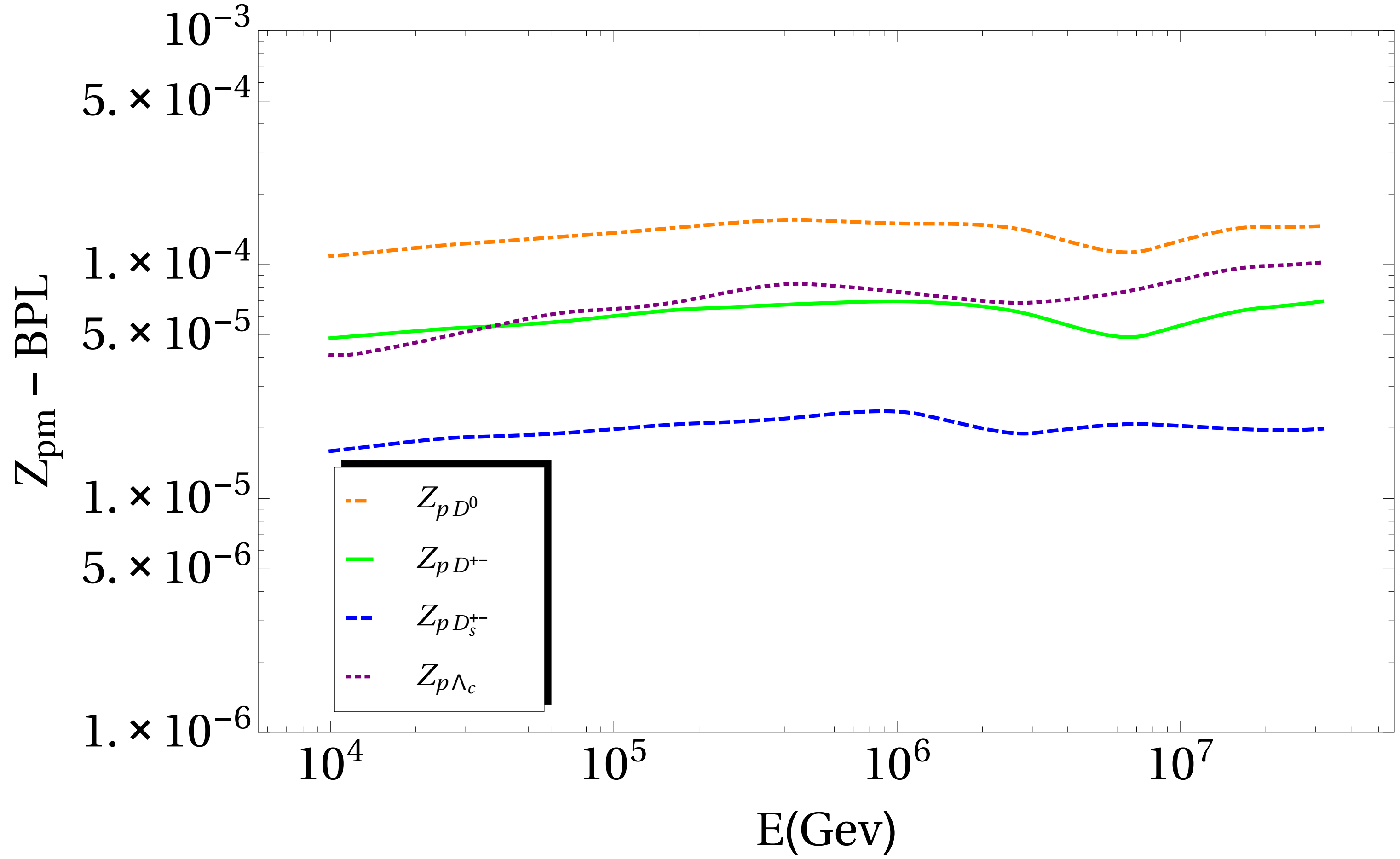


Z_{ph} with NNPDF3.0+LHCb

$$Z_{ph} = \int_E^\infty dE' \frac{\phi_p(E')}{\phi_p(E)} \frac{A}{\sigma_{pA}(E)} \frac{d\sigma(pp \to c\bar{c}Y; E', E)}{dE}$$

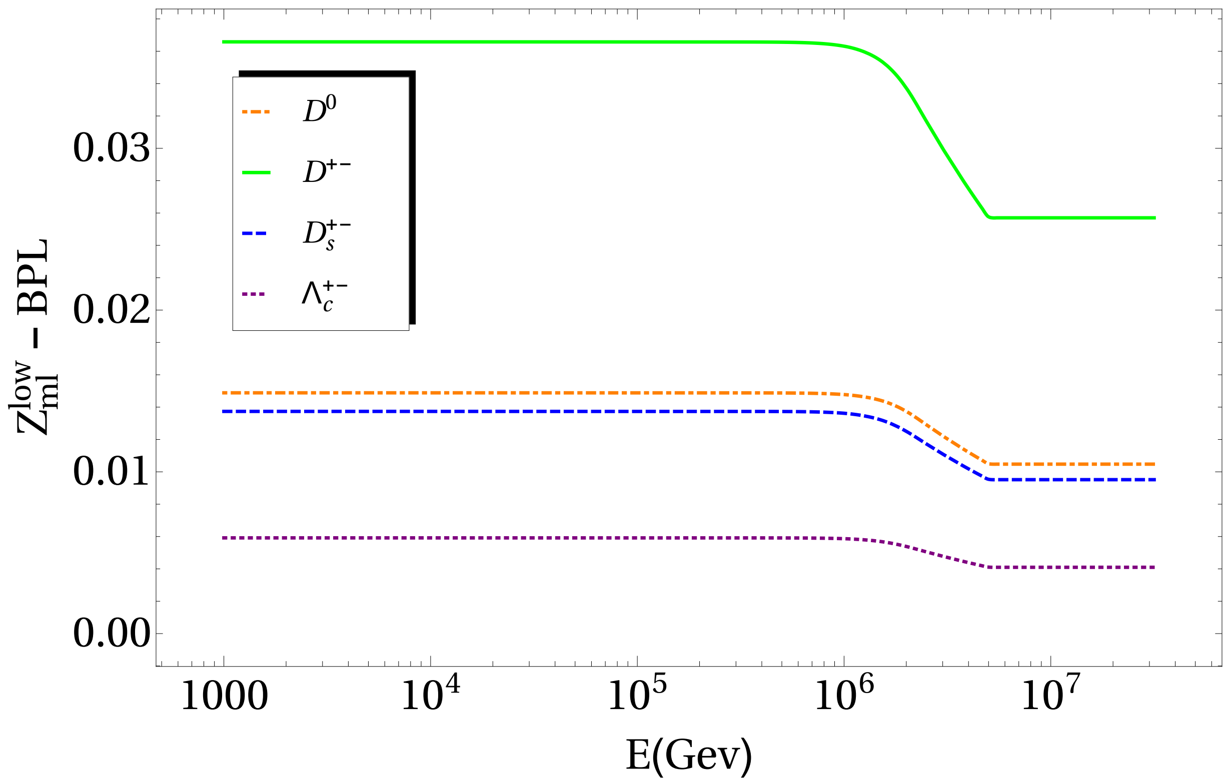
The differential cross-section is generated at various E′ between 10^3 and 10^{10} GeV with **POWHEG+PYTHIA8**, and incorporates our updated **NNPDF3.0+LHCb** … Cross-checks made with **aMC@NLO**

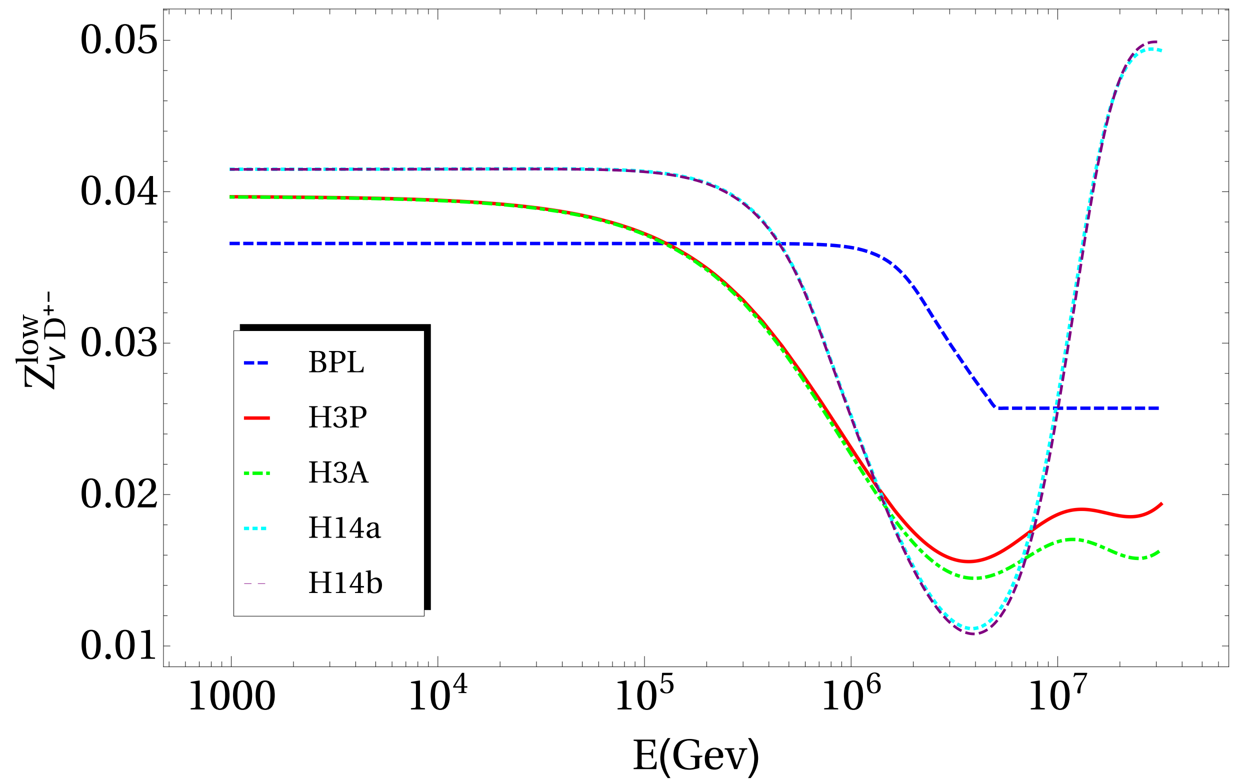
We perform an interpolation over E_{inc} and E_h.



Decay moments: $Z_{h\to l}$

$$Z_{h\to l} = \int_E^\infty dE' \, \frac{\phi_h(E',X)}{\phi_h(E,X)} \frac{d_h(E)}{d_h(E')} \frac{dn(h\to lY;E',E)}{dE}$$

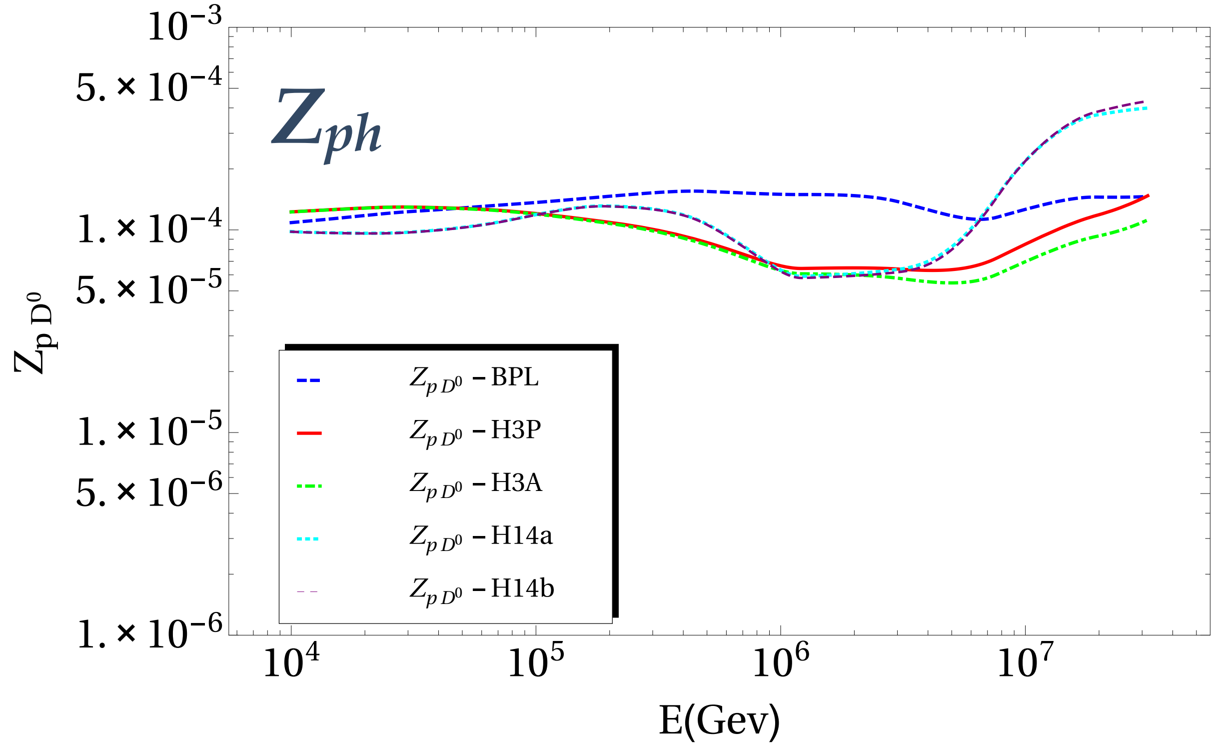


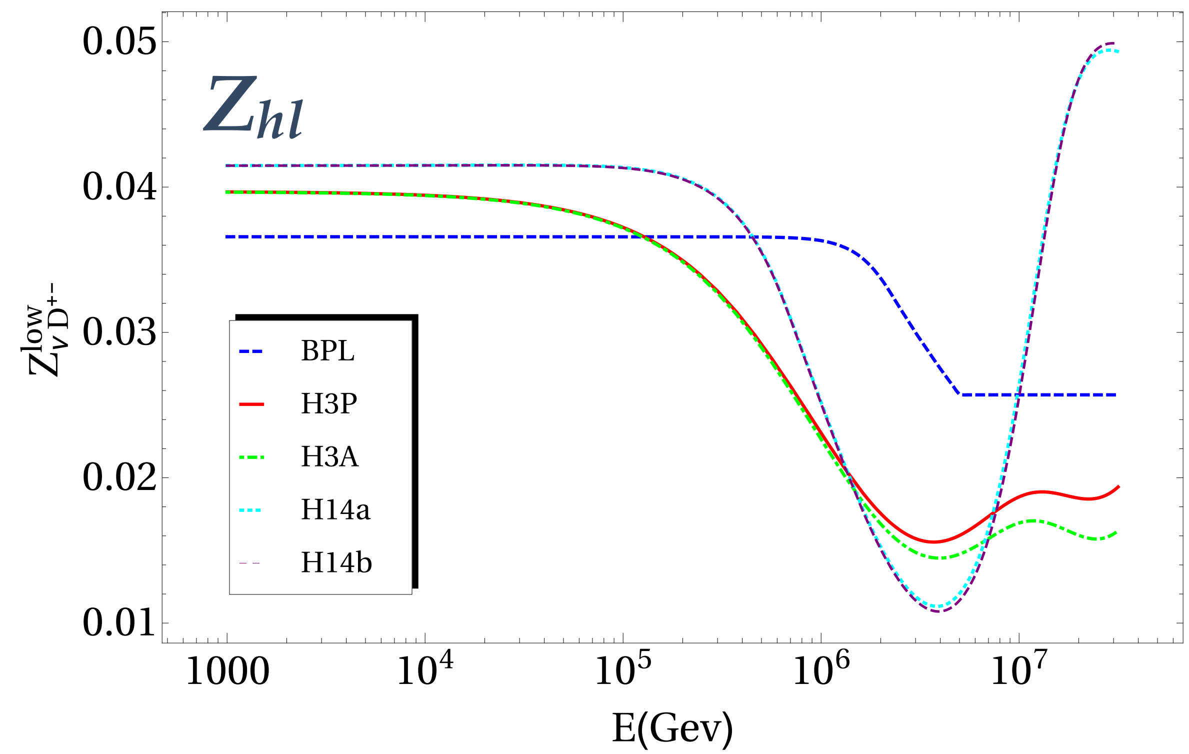


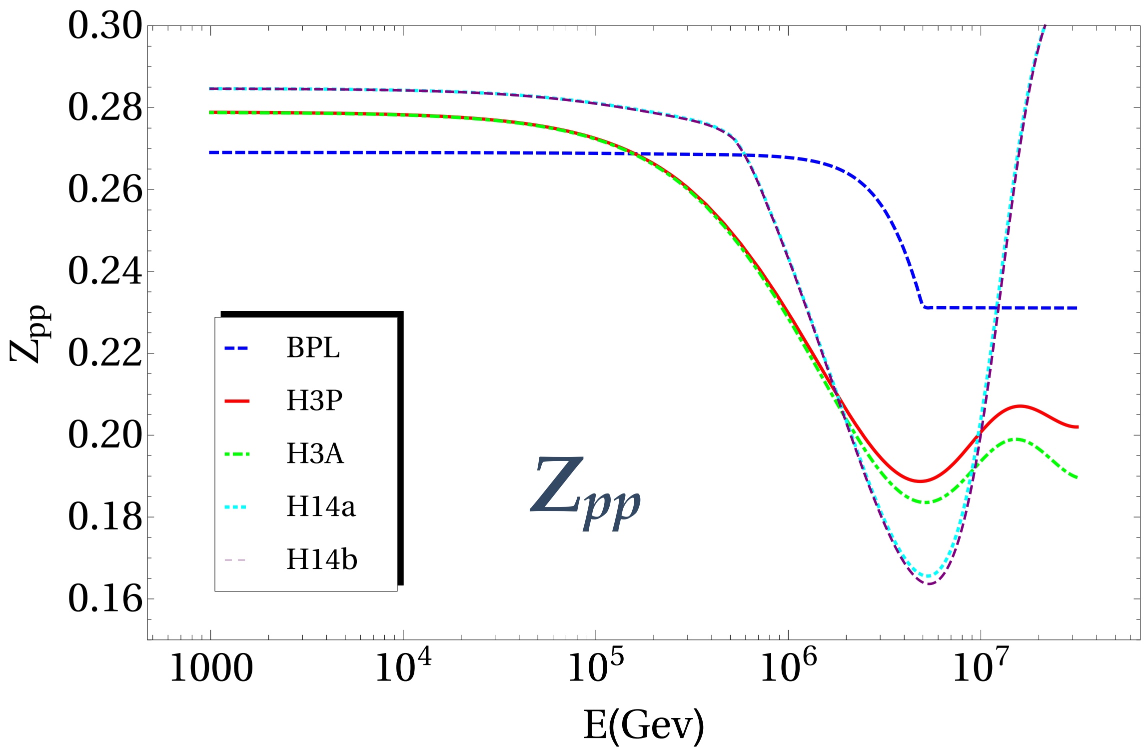
The relative contributions of different species in the BPL cosmic ray scenario.

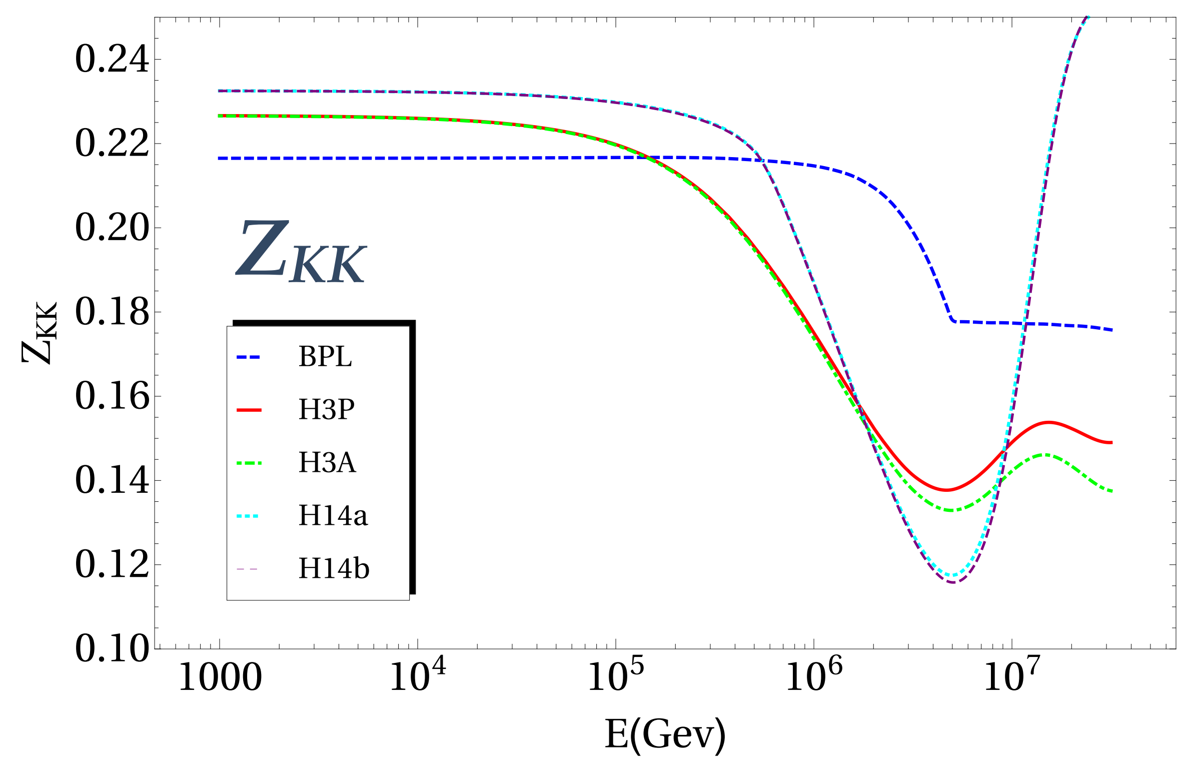
The relative contributions of the D^+ species in varying cosmic ray scenarios.

Stitching things together...



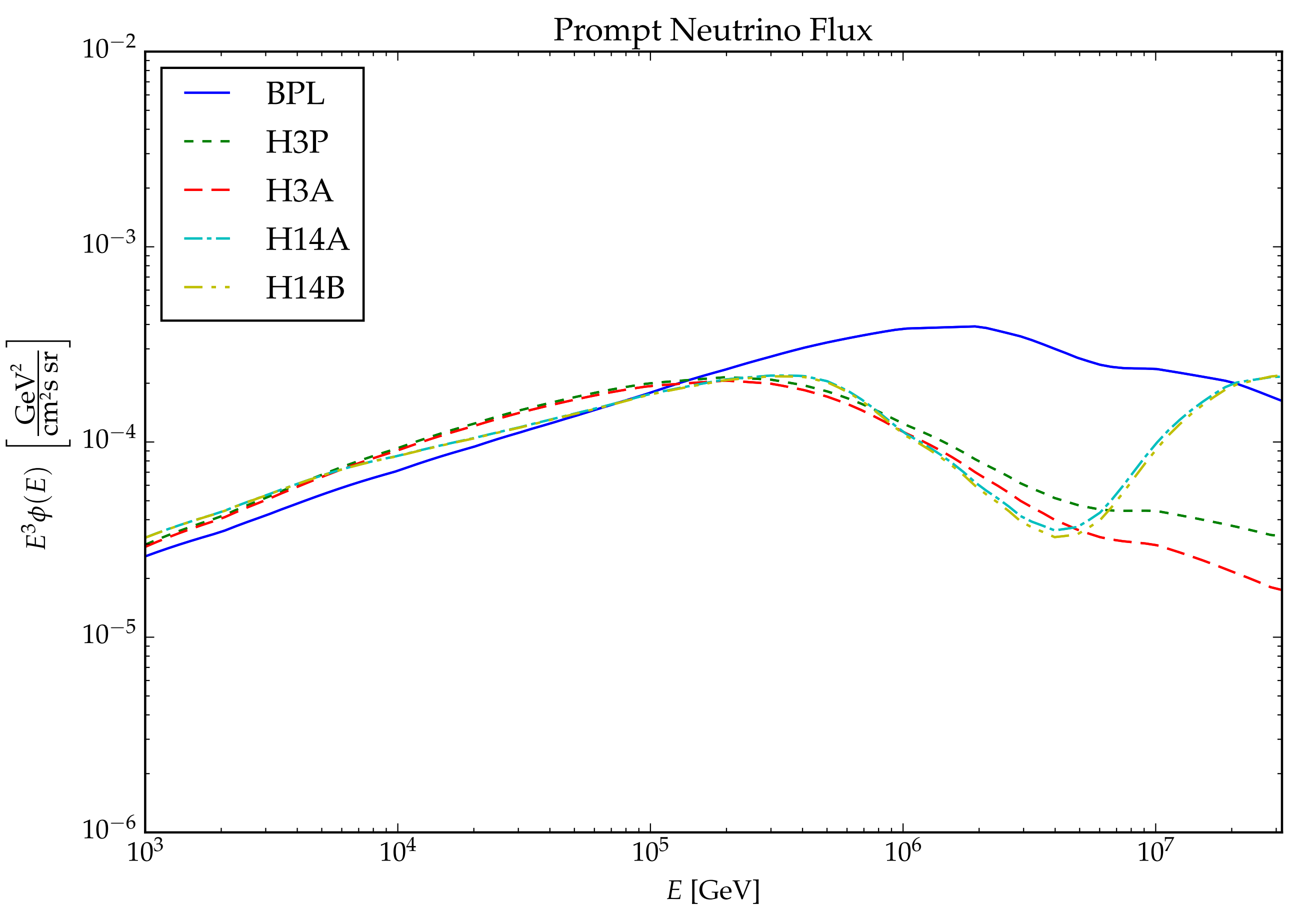


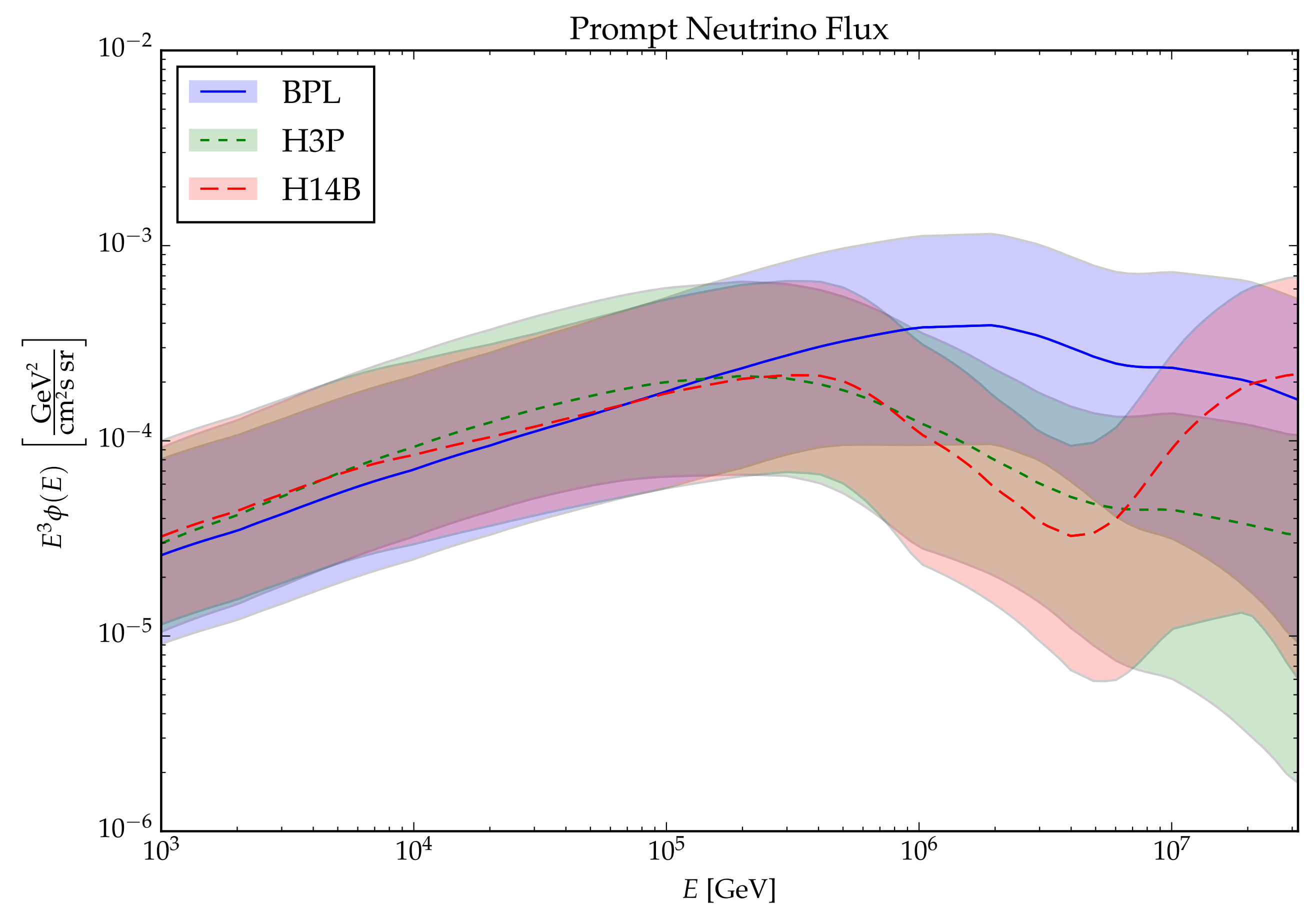




Benchmark NNPDF3.0+LHCb flux

We present the following predictions for **prompt atmospheric neutrino flux** adopting the broken power-law (BPL) as well as H3A and H3P cosmic-ray spectra



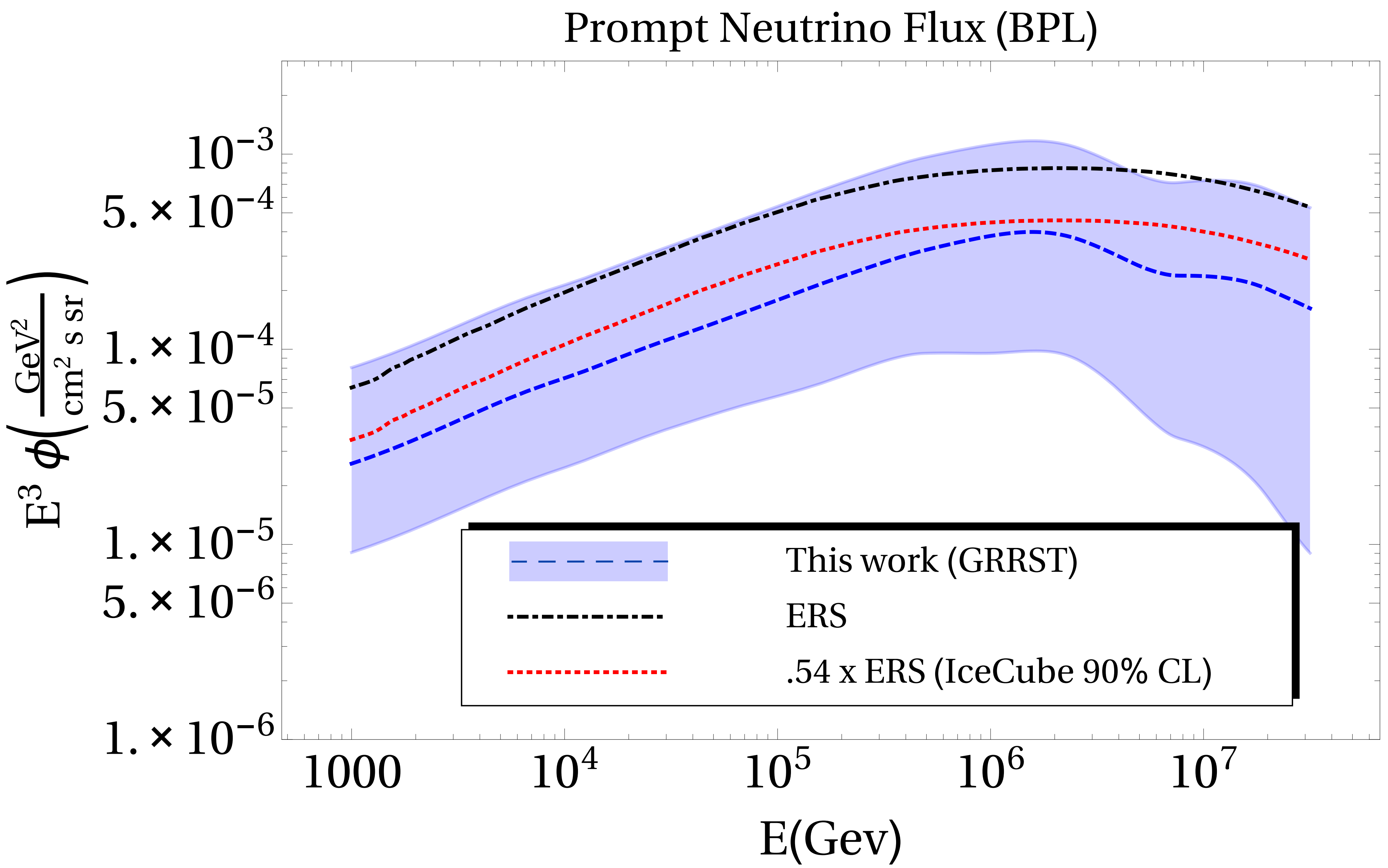


Scale, PDF, and charm mass uncertainty

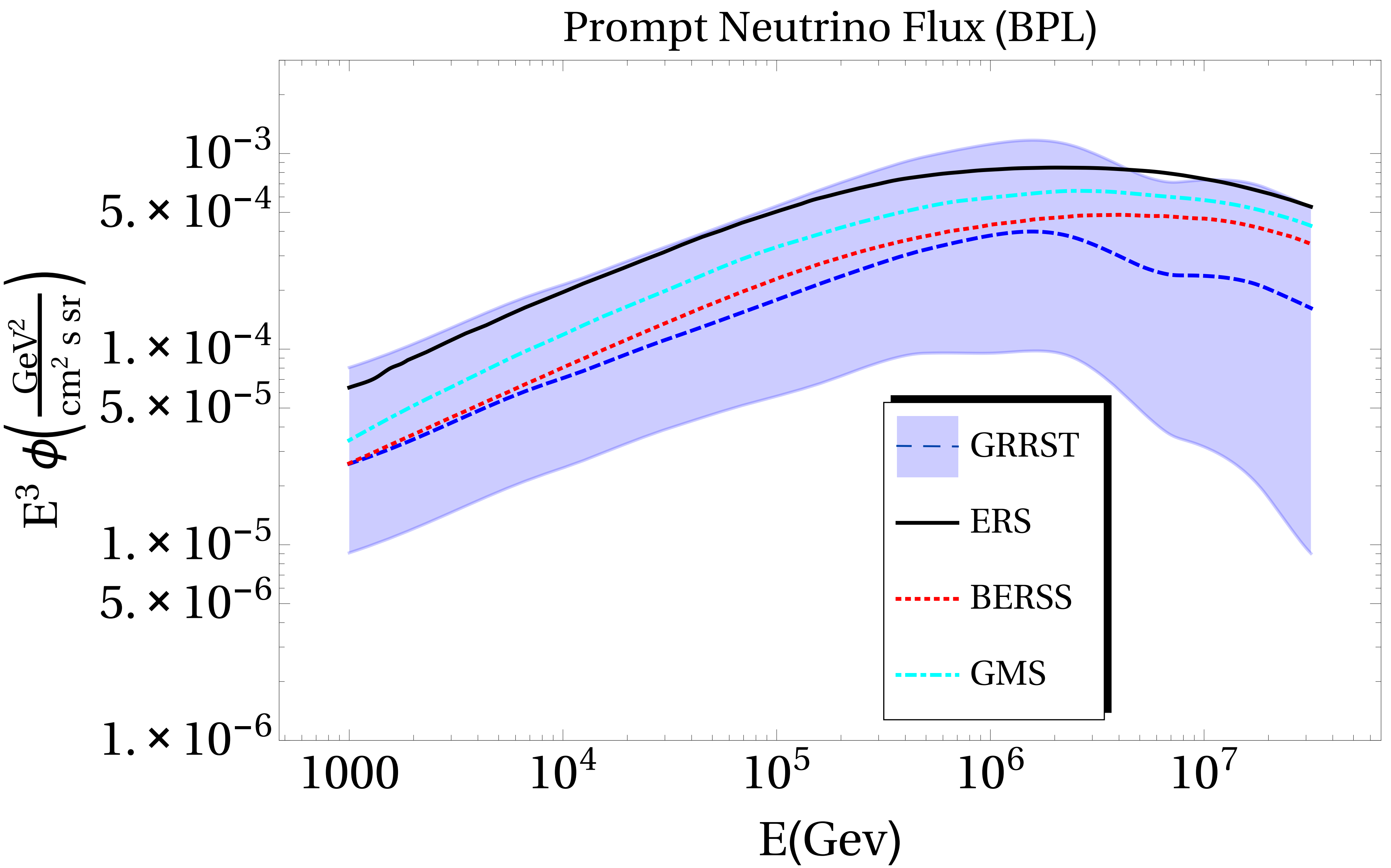
Different cosmic ray spectrum parameterisations

→ **significant differences in the expected flux above ~10^6 GeV**

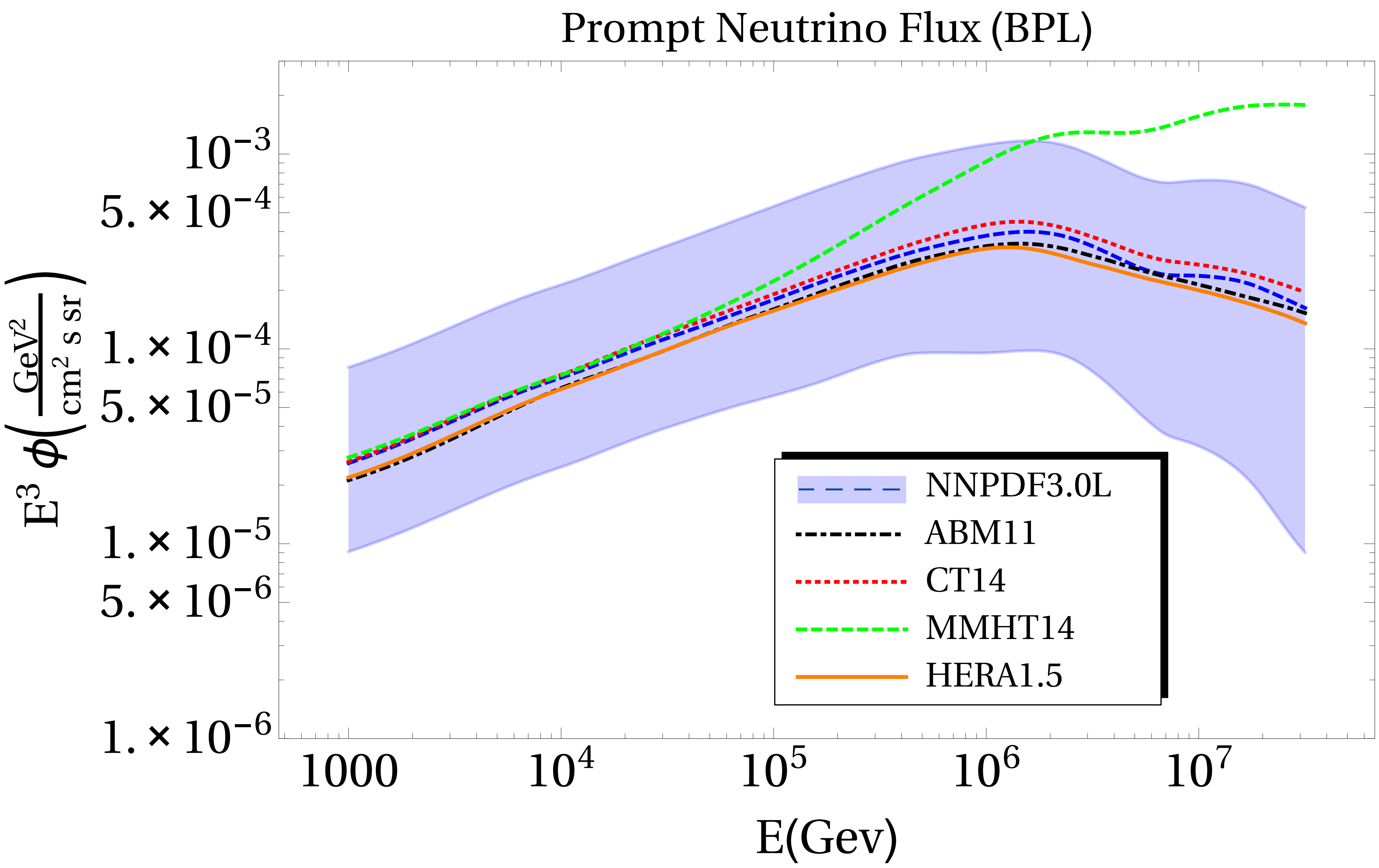
Consistency with IceCube bounds



Consistency with previous calculations



Input PDF dependency



Conclusions

We have presented updated predictions for the flux of **prompt atmospheric neutrinos** at ground-based detectors.

Our approach is grounded in **perturbative QCD**, and incorporates:

1. State-of-the-art calculation of **charmed hadron production** in the **forward region**, validated against recent LHCb measurements

2. A **small-x gluon PDF** which is also constrained by **LHCb data**

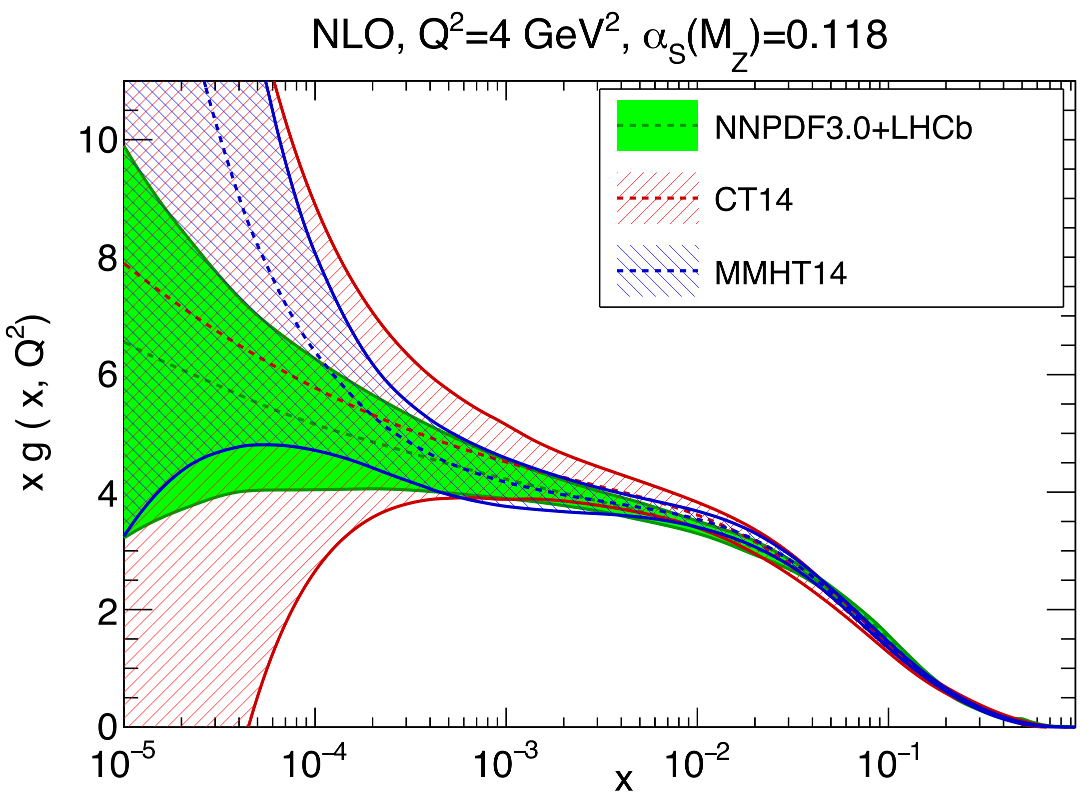
Our estimates are consistent with previous studies but provide a **more reliable estimate of uncertainties** and alleviate the tension between the previous benchmark (ERS) calculation and IceCube data

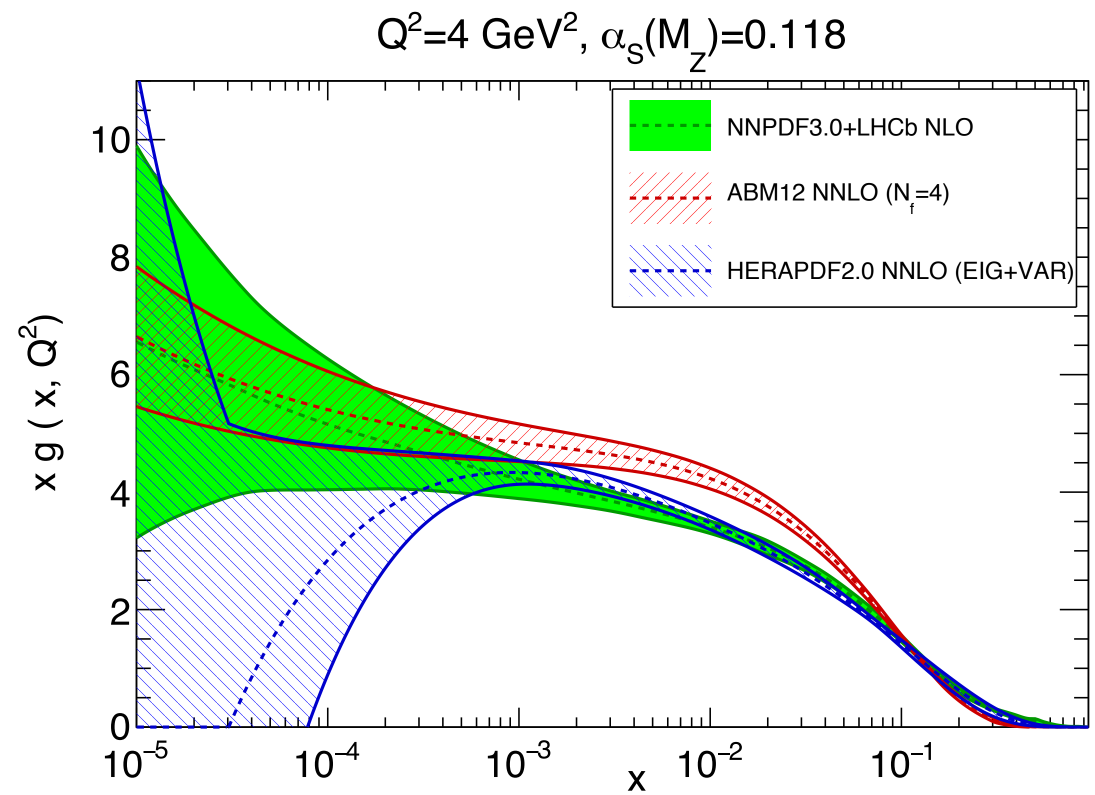
The prompt flux should be seen *soon* (and provide a probe of low-x QCD)

Back-up

Input PDF dependency

arXiv: 1506.08025





Evaluations of charm production utilising multiple input PDFs, including our updated NNPDF3.0+LHCb, indicate **substantive differences in the small-x region**.

This will trace through our calculation of the prompt atmospheric neutrino flux and lead to qualitative differences in the high-energy tail.

We are thus evaluating final uncertainties utilising **multiple input PDFs**.

Prompt vs. conventional flux

The energy spectrum from semi-leptonic decay products depends on a hadronic '**critical energy**', *below* which the **decay probability** is > **interaction probability**:

$$\epsilon_h = \frac{m_h c^2 h_0}{c\tau_h \cos\theta}$$

$$\epsilon_{\pi^\pm} = 115 \; [GeV]$$

$$\epsilon_{K^\pm} = 850 \; [GeV]$$

For **pions & kaons**, this critical energy is low (decay length is long) hence the leptonic energy spectrum is soft. For **charmed mesons**, the critical energy is high ... they **decay** *promptly* to highly energetic leptons:

$$\epsilon_{D^0} = 9.71 \times 10^7 \; [GeV]$$

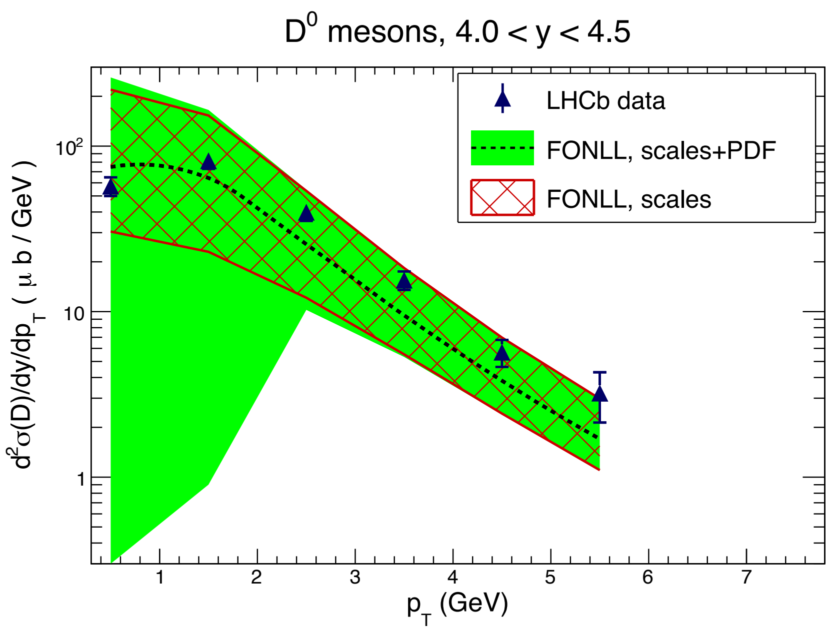
$$\epsilon_{D^\pm} = 3.84 \times 10^7 \; [GeV]$$

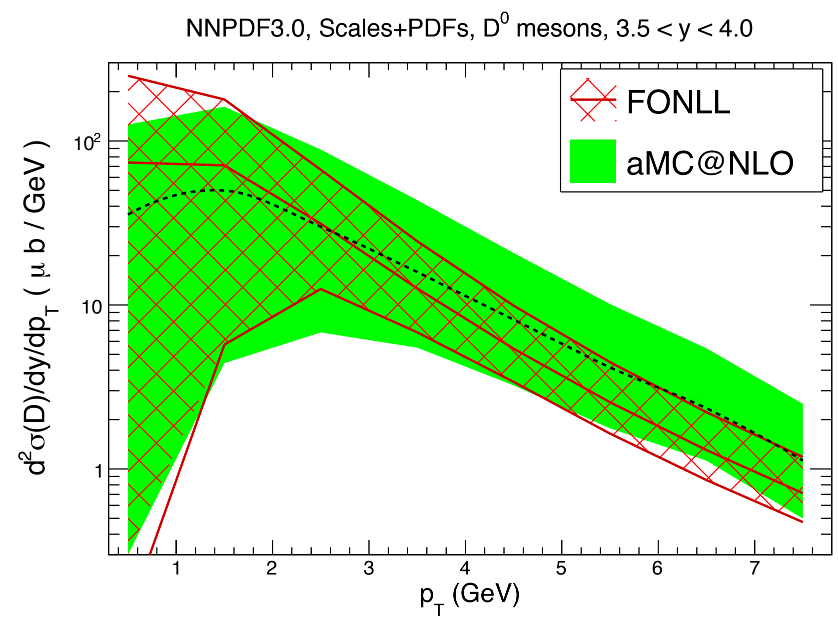
$$\epsilon_{D_s^\pm} = 8.40 \times 10^7 \; [GeV]$$

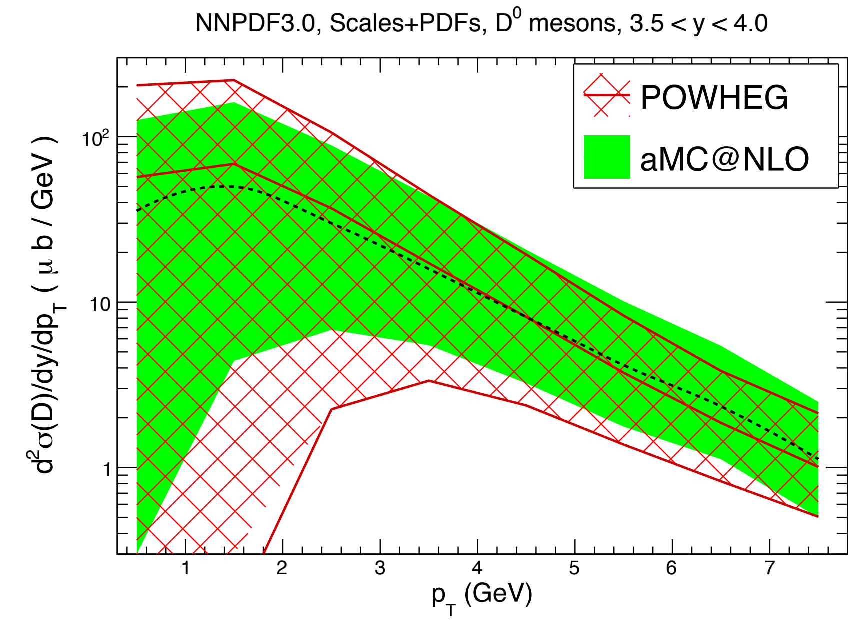
$$\epsilon_{\Lambda_c} = 24.4 \times 10^7 \; [GeV]$$

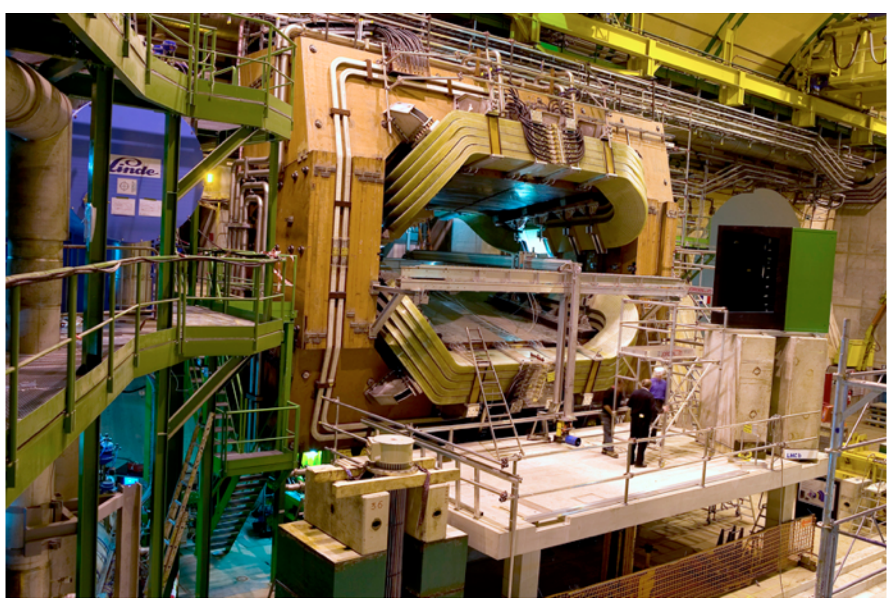
The atmospheric neutrino flux from the decay of pions & kaons is the '**conventional flux**,' whereas that from charm decay is called the '**prompt flux**'

Forward Charm Production & LHCb





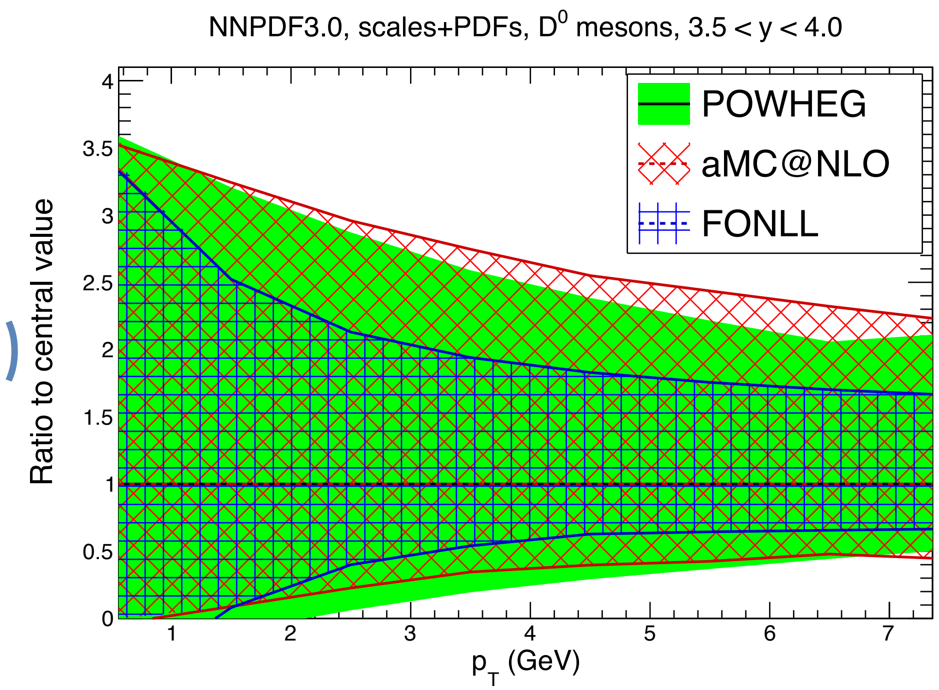




$$\sqrt{s} = 7\ [TeV]$$

arXiv:1506.08025

arXiv:1302.2864 (LHCb)



We first **validate our NLO predictions** for forward charm production against recent LHCb data … finding **good agreement** between the 3 calculation schemes

Tracing a particle through the atmosphere

The flux of particle j can be generically written as:

$$\frac{d\phi_j}{dX} = -\frac{\phi_j}{\lambda_j} - \frac{\phi_j}{\lambda_j^{dec}} + \sum S(k \to j)$$

This depends on the '**slant depth**' X measuring the atmosphere traversed:

$$X(l,\theta) = \int_l^{\infty} \rho(H(l^{'},\theta)dl^{'} \qquad H(l,\theta) \simeq l\cos\theta + \frac{l^2}{2R_0}\sin^2\theta$$

We adopt a simple **isothermal model** of the atmosphere:

$$\rho(H) = \rho_0 e^{-\frac{H}{H_0}}$$

$$\rho_0 = 2.03 \times 10^{-3} \quad [\frac{g}{cm^3}]$$

$$H_0 = 6.4 \quad [km]$$

Such that sample values of X are:

$$X = 0 \; [\frac{g}{cm^2}] \;\; (space) \qquad X = 1300 \; [\frac{g}{cm^2}] \;\; (\theta = 0)$$

$$X = \infty \; [\frac{g}{cm^2}] \;\; (ground) \qquad X = 36000 \; [\frac{g}{cm^2}] \;\; (\theta = \frac{\pi}{2})$$

Cascade Formalism: Sources & Z-moments

$$S(k \to j) = \int_E^\infty \frac{\phi_k(E_k^{'})}{\lambda_k(E_k^{'})} \frac{dn(k \to j; E^{'}, E)}{dE} dE^{'}$$

Under reasonable assumptions, the S-moments simplify:

$$S(k \to j) = \frac{\phi_k}{\lambda_k} \; Z_{kj}$$

For particle **production**:

$$Z_{kh} = \int_E^\infty dE^{'} \frac{\phi_k(E', X, \theta)}{\phi_k(E, X, \theta)} \frac{\lambda_k(E)}{\lambda_k(E')} \frac{dn(kA \to hY; E', E)}{dE}$$

$$\frac{dn(pA \to hY; E', E)}{dE} = \frac{1}{\sigma_{pA}(E')} \frac{d\sigma(pA \to hY; E', E)}{dE}$$

For particle **decay**:

$$Z_{h\to l} = \int_E^\infty dE^{'} \frac{\phi_h(E', X)}{\phi_h(E, X)} \frac{d_h(E)}{d_h(E')} \frac{dn(h \to lY; E', E)}{dE}$$

$$\frac{dn(h \to lY; E', E)}{dE} = \frac{1}{\Gamma} \frac{d\Gamma}{dE}$$

Atmospheric Nucleon Flux

$$\frac{d\phi_N}{dX} = -\frac{\phi_N}{\lambda_N} + S(NA \to NY) = -\frac{\phi_N}{\lambda_N} + Z_{NN}\frac{\phi_N}{\lambda_N}$$

Assume a **factorisation** of fluxes → $\phi_k(E,X) = \phi_k(E)\phi_k(X)$

Define the **interaction** length → $\lambda_N(E) = \frac{A}{N_0\sigma_{pA}(E)}$

Define the **attenuation** length → $\Lambda_N = \frac{\lambda_N}{(1-Z_{NN})}$

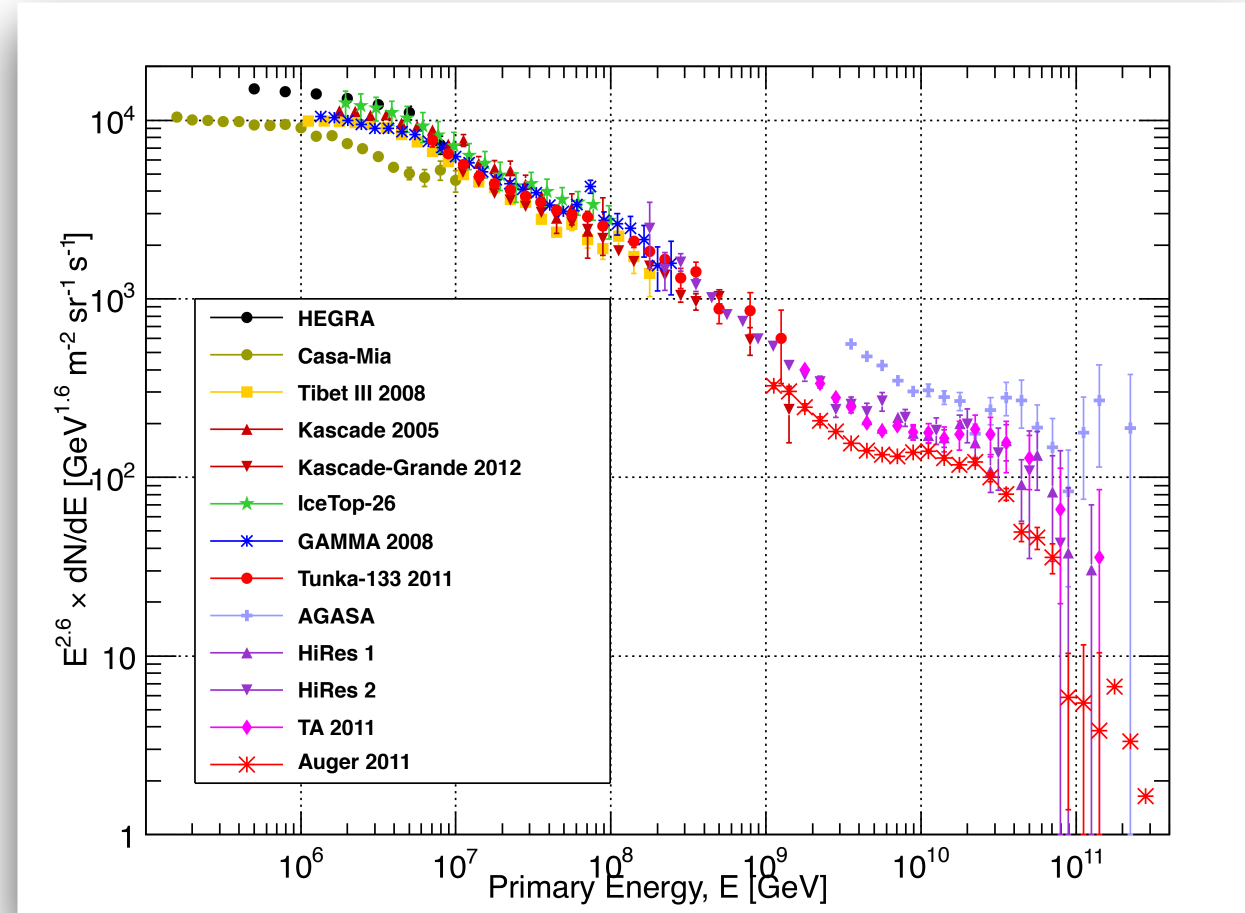
$$\frac{d\phi_N}{dX} = \frac{\phi_N}{\lambda_N}(Z_{NN}-1) \to \frac{d\phi_N}{dX} + \frac{\phi_N}{\lambda_N}(1-Z_{NN}) = 0$$

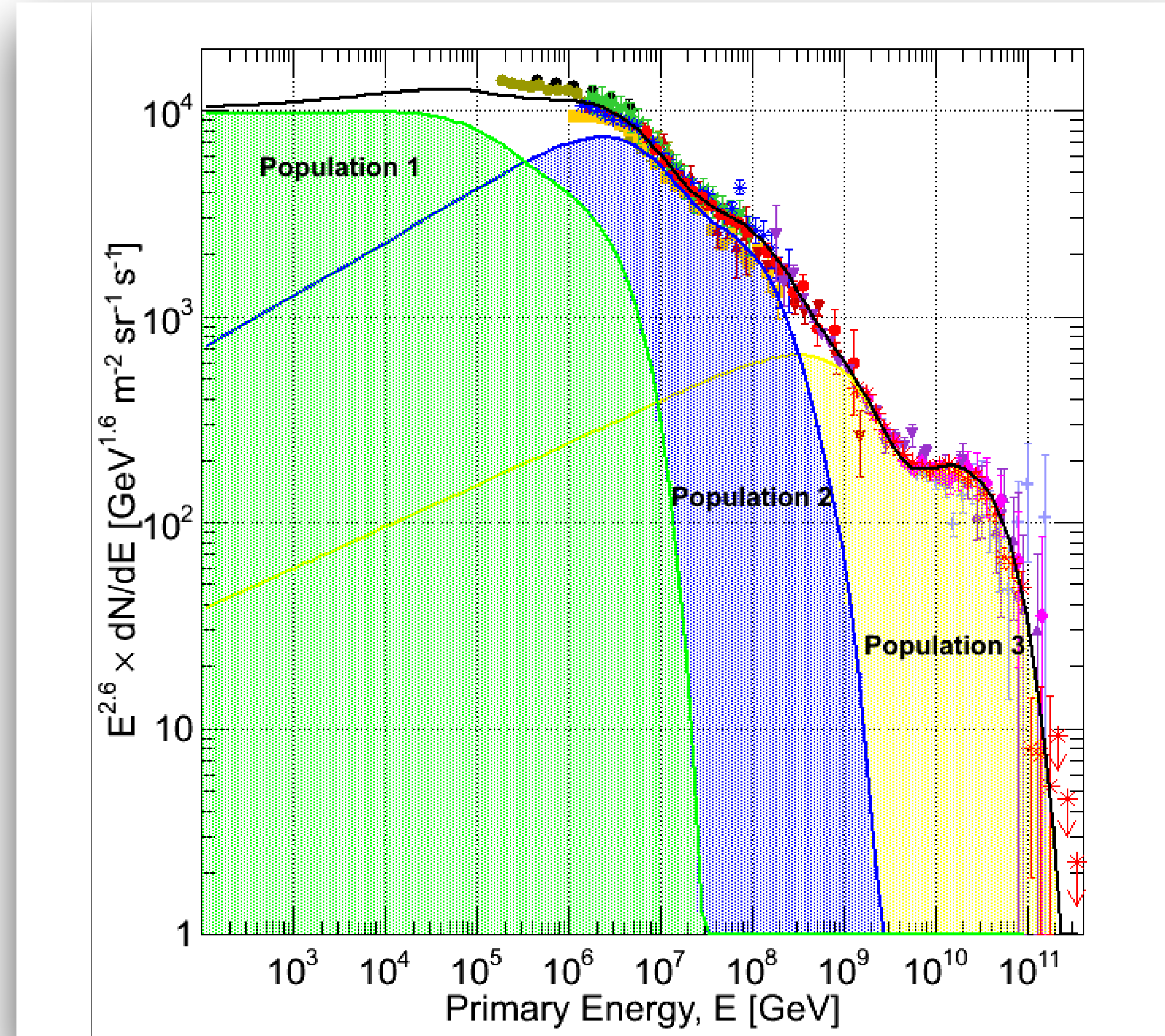
$$\phi_N = \phi_N^0(E)\ e^{-\frac{X}{\Lambda_N}}$$

What constitutes this primary nucleon flux?

Gaisser *et al.* fluxes: $\phi^0_N(E)$

arXiv:astro-ph/1111.6675
arXiv:astro-ph/1303.3565





	p	He	CNO	Mg-Si	Fe
Pop. 1:	7860	3550	2200	1430	2120
$R_c = 4$ PV	1.66 1	1.58	1.63	1.67	1.63
Pop. 2:	20	20	13.4	13.4	13.4
$R_c = 30$ PV	1.4	1.4	1.4	1.4	1.4
Pop. 3:	1.7	1.7	1.14	1.14	1.14
$R_c = 2$ EV	1.4	1.4	1.4	1.4	1.4
Pop. 3(*):	200	0.0	0.0	0.0	0.0
$R_c = 60$ EV	1.6				

$$\phi_i(E) \;=\; \Sigma_{j=1}^{3}\, a_{i,j}\, E^{-\gamma_{i,j}} \times \exp\left[-\frac{E}{Z_i R_{c,j}}\right]$$

Atmospheric hadron flux

$$\frac{d\phi_h}{dX} = -\frac{\phi_h}{\rho d_h(E)} - \frac{\phi_h}{\lambda_h} + Z_{hh}\frac{\phi_h}{\lambda_h} + Z_{ph}\frac{\phi_p}{\lambda_p}$$

In the low energy limit, the probability for hadron interaction is minimal, and thus we **neglect the interaction and regeneration terms**:

$$\phi_h|_{low} = \frac{Z_{ph}}{\Lambda_p(1 - Z_{pp})}\rho d_h \phi_p(E) e^{-\frac{X}{\Lambda_p}}$$

At high energies the decay length becomes large, hence we **neglect the decay term**:

$$\phi_h|_{high} = \frac{Z_{ph}\phi_p(E)}{(1 - Z_{pp})} \frac{(e^{-\frac{X}{\Lambda_h}} - e^{-\frac{X}{\Lambda_p}})}{(1 - \frac{\Lambda_p}{\Lambda_h})}$$

These solutions then **feed into asymptotic solutions for the final leptonic flux** (note that the low-energy solution scales with an additional power of E):

$$\begin{aligned} high \quad & \phi_h \propto \phi_p \\ low \quad & \phi_h \propto E\phi_p \end{aligned}$$

Atmospheric Nucleon Flux

$$\frac{d\phi_N}{dX} = -\frac{\phi_N}{\lambda_N} + S(NA \to NY) = -\frac{\phi_N}{\lambda_N} + Z_{NN}\frac{\phi_N}{\lambda_N}$$

Assume a **factorisation** of fluxes → $\phi_k(E, X) = \phi_k(E)\phi_k(X)$

Define the **interaction** length → $\lambda_N(E) = \dfrac{A}{N_0\sigma_{pA}(E)}$

Define the **attenuation** length → $\Lambda_N = \frac{\lambda_N}{(1-Z_{NN})}$

$$\frac{d\phi_N}{dX} = \frac{\phi_N}{\lambda_N}(Z_{NN} - 1) \to \frac{d\phi_N}{dX} + \frac{\phi_N}{\lambda_N}(1 - Z_{NN}) = 0$$

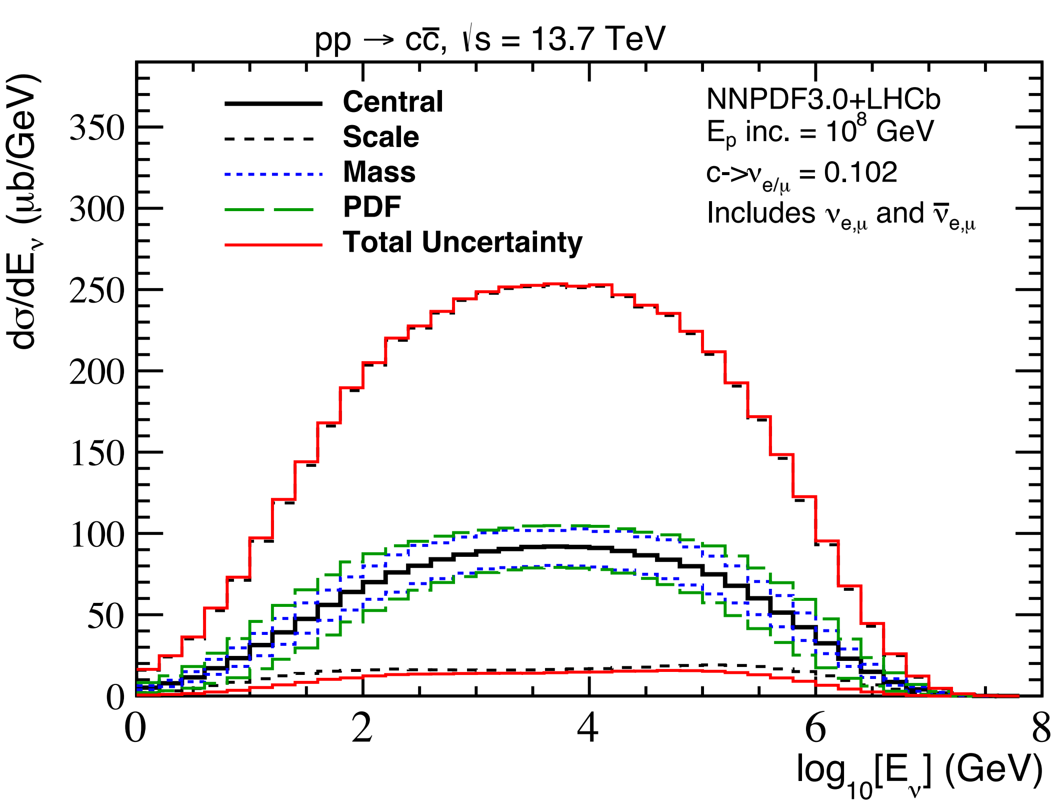
$$\phi_N = \phi_N^0(E)\ e^{-\frac{X}{\Lambda_N}}$$

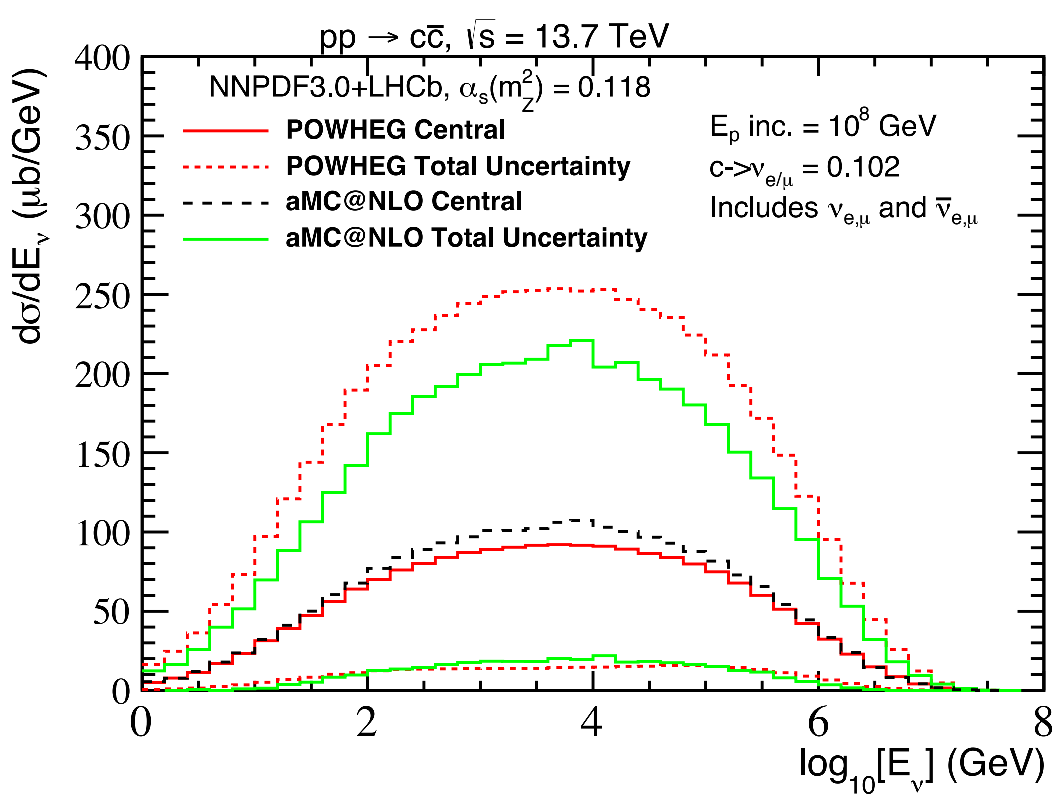
What constitutes this primary nucleon flux?

Our principal new result: Z_{ph}

$$Z_{ph} = \int_E^\infty dE' \frac{\phi_p(E')}{\phi_p(E)} \frac{A}{\sigma_{pA}(E)} \frac{d\sigma(pp \to c\bar{c}Y; E', E)}{dE}$$

The differential cross-section is generated at various E′ between 10^3 and 10^{10} GeV with **POWHEG+PYTHIA8**, and incorporates our updated **NNPDF3.0+LHCb** … Cross-checks made with **aMC@NLO**





arXiv: 1506.08025

Decay moments: $Z_{h\to l}$

$$Z_{h\to l} = \int_E^\infty dE' \frac{\phi_h(E',X)}{\phi_h(E,X)} \frac{d_h(E)}{d_h(E')} \frac{dn(h\to lY;E',E)}{dE}$$

The distribution for leptonic decay is known to obey the simple scaling law:

$$dn(h\to lY;E',E) = F_{h\to l}\left(\frac{E}{E'}\right)\frac{dE}{E'}$$

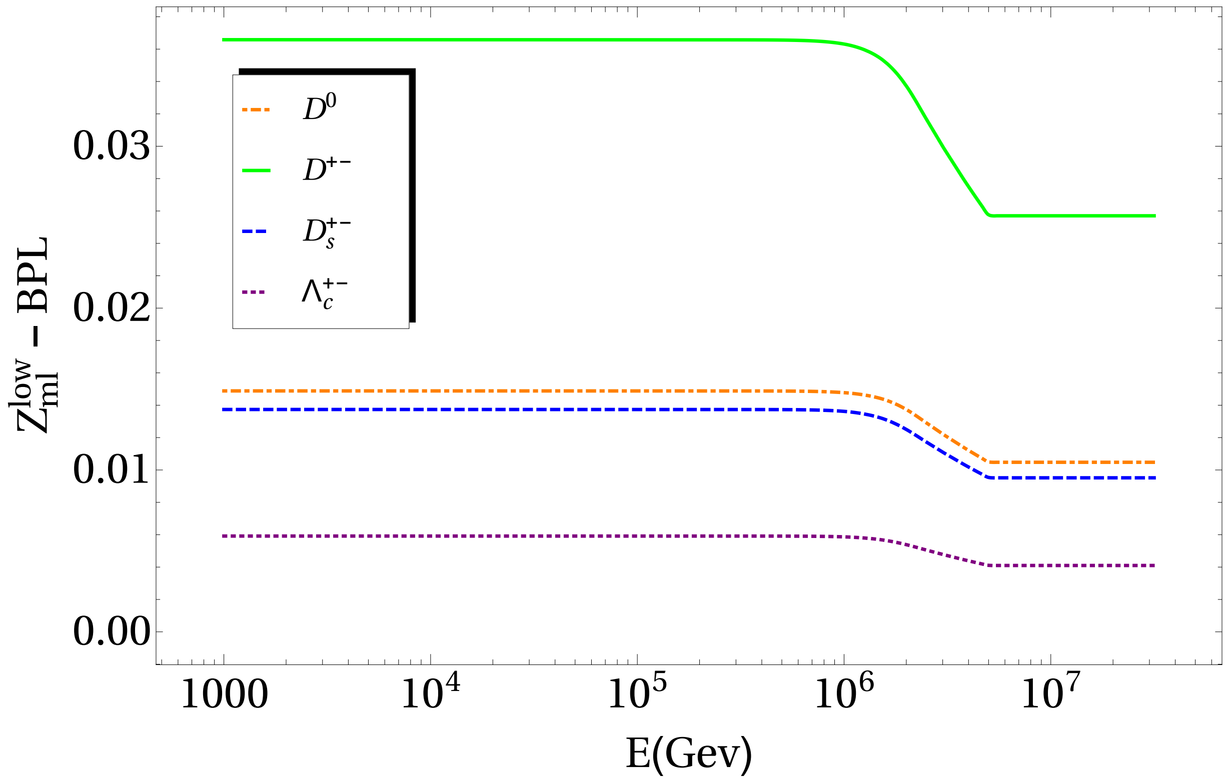
The moment then simplifies, and we generate F with POWHEG:

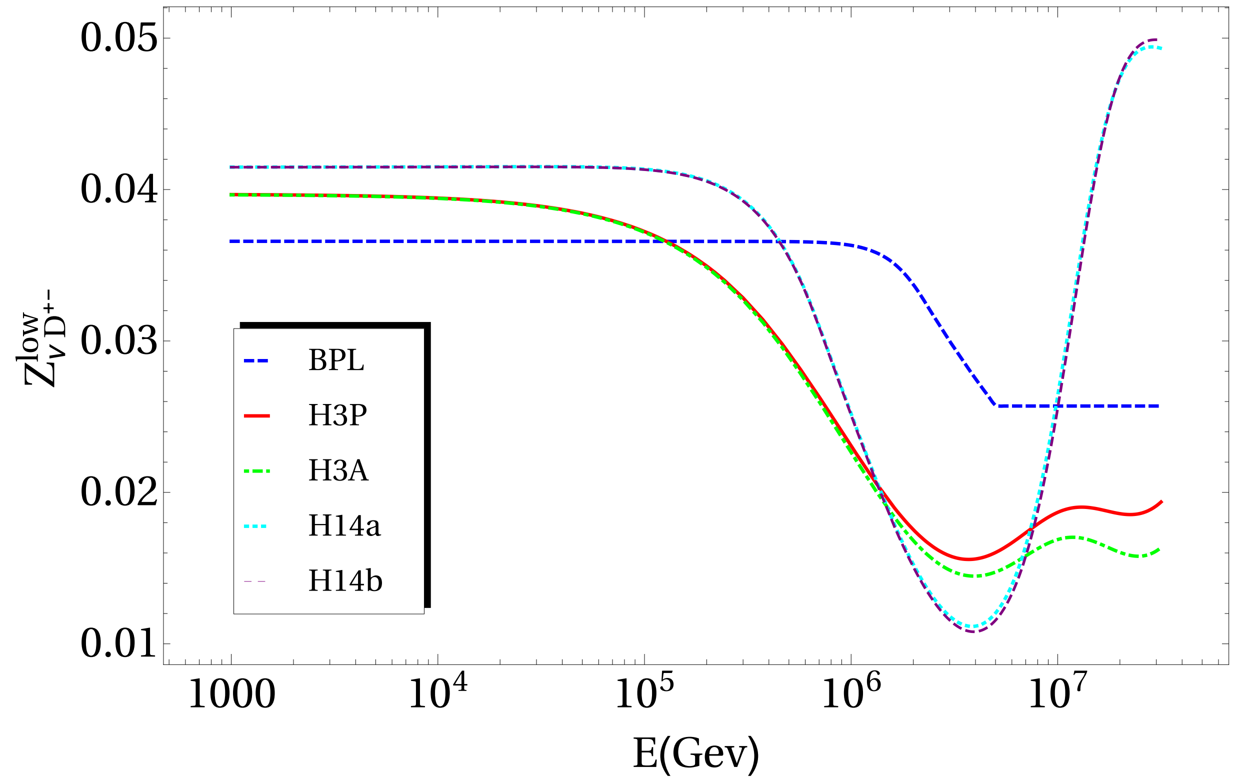
$$Z_{h\to l} = \int_0^1 dx_E \frac{\phi_h(E/x_E)}{\phi_h(E)} F_{h\to l}(x_E)$$

The following branching fractions are built into our decay moments:

$$\mathcal{B}(D^\pm \to \nu_l X) = .153$$
$$\mathcal{B}(D^0 \to \nu_l X) = .101$$
$$\mathcal{B}(D_s^\pm \to \nu_l X) = .06$$
$$\mathcal{B}(\Lambda_c \to \nu_l X) = .02$$

Decay moments: $Z_{h\to l}$





The relative contributions of different species in the BPL cosmic ray scenario.

The relative contributions of the D^+ species in varying cosmic ray scenarios.

$$Z_{h\to l} = \int_0^1 dx_E \; x_E^\beta \; F_{h\to l}(x_E)$$

$$Z_{h\to l} = \int_0^1 dx_E \frac{\phi_h(E/x_E)}{\phi_h(E)} F_{h\to l}(x_E)$$