QCD elements in the computation of prompt neutrino fluxes

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Prompt neutrino flux hadroproduction in the atmosphere: theoretical predictions in literature

∗ Long non-exhaustive list of papers, including, among the others:

- Lipari, Astropart. Phys. 1 (1993) 195
- Battistoni, Bloise, Forti et al., Astropart. Phys. 4 (1996) 351
- Gondolo, Ingelman, Thunman, Astropart. Phys. 5 (1996) 309
- Bugaev, Misaki, Naumov et al., Phys. Rev. D 58 (1998) 054001
- Pasquali, Reno, Sarcevic, Phys. Rev. D 59 (1999) 034020
- Enberg, Reno, Sarcevic, Phys. Rev. D 78 (2008) 043005

∗ Updates and recently renewed interest:

- Bhattacharya, Enberg, et al., JHEP 1506 (2015) 110, arXiv:1607.00193
- Fedynitch, Riehn, Engel, Gaisser et al. ICRC 2015, TAUP 2015...
- Garzelli, Moch, Sigl, JHEP 1510 (2015) 115 → **updates in this talk**
- Gauld, Rojo, Sarkar, Rottoli, Talbert, JHEP 1602 (2016) 130
- Halzen, Wille, arXiv:1601.03044, arXiv:1605.01409
- Laha, Brodsky, arXiv:1607.08240

motived by new results from VLVνT's
and updated theory and new results from LHC

Prompt lepton fluxes at VLVνT's

- Background for ν's from astrophysical sources

- Background veto techniques:
  correlations between atmospheric ν's and atmospheric μ's.

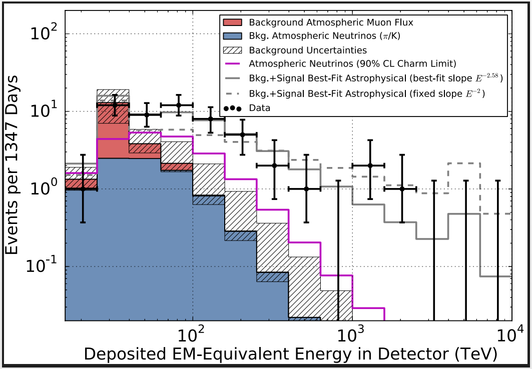


figure from C. Kopper, ICRC2015

Atmospheric neutrino fluxes

∗ conventional neutrino flux:

$$NN \quad \rightarrow \quad \pi^{\pm}, K^{\pm} + \mathrm{X} \quad \rightarrow \quad \nu_\mu(\bar{\nu}_\mu) + \mu^{\pm} + \mathrm{X}$$

∗ prompt neutrino flux:

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

expected to dominate above $E_{lab,\nu} > 5 \cdot 10^5$ GeV

heavy-quarks (c, b, $\bar{c}$, $\bar{b}$) produced through:
1) hard-scattering processes
2) already in the nucleon PDFs.

QCD collinear factorization

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

$\hat{\sigma}$: perturbative partonic cross-section,

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 $x_a = p_a / P_{N_1}$, $x_b = p_b / P_{N_2}$.

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.

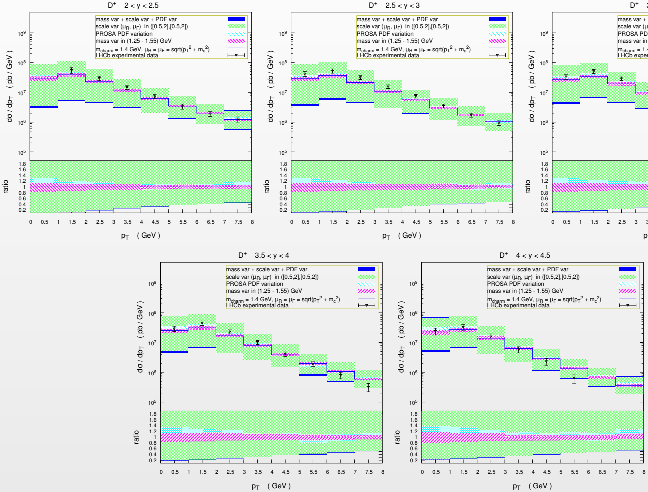
∗ Approximate knowledge of charm and bottom masses.

∗ Flavour Number Scheme

∗ PDF fits to experimental data

∗ FF fits to experimental data

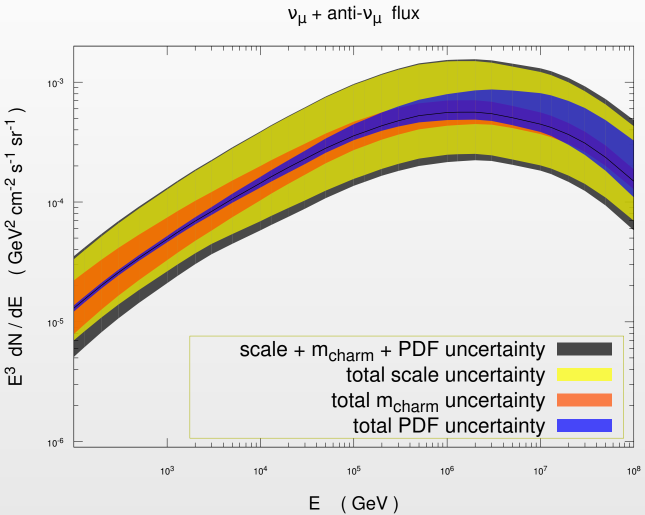
PROSA PDFs and LHCb experimental data (heavy H)



Predictions: NLO QCD hard scattering + Parton Shower + Hadronization, using as input PROSA PDFs.

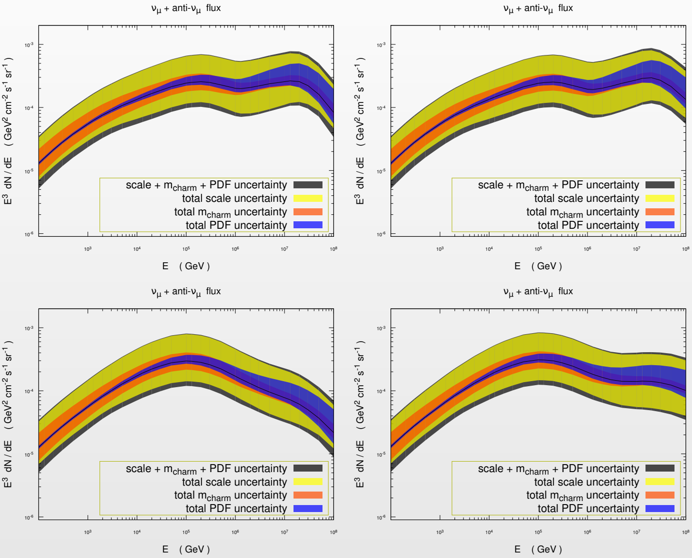
LHCb coverage: $2 < |y| < 4.5$, but astrophysical data cover larger $|y|$ as well.....

Prompt neutrino fluxes: QCD scale, mass and PDF uncertainties



∗ PDF uncertainty evaluated by using PROSA PDFs, which fit LHCb data to determine x dependence of PDFs.

QCD Scale, mass and PDF uncertainties for different CR compositions



Input CR primary spectra from Gaisser et al.: GST-3, GST-4, H3a, H3p

Flavour Number Schemes

$m_c^{pole} \sim 1.4$ GeV, $m_b^{pole} \sim 4.8$ GeV
m_c, $m_b >> \Lambda_{QCD}$
But, depending on the kinematics and E_{cm}, it may happen that $p_{T,c} >> m_c$, m_b

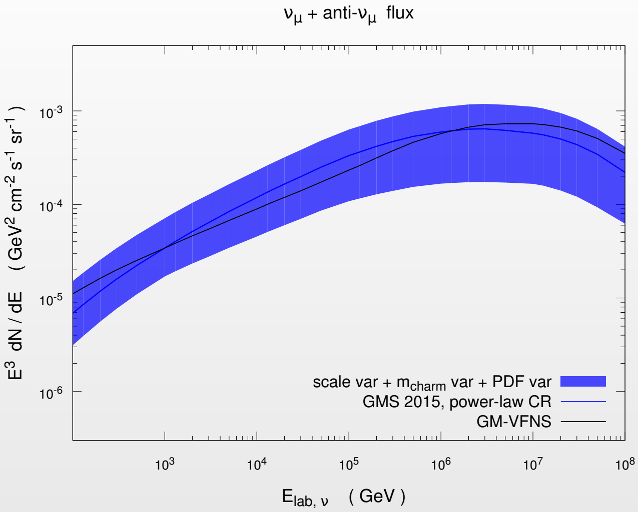
$*$ Fixed flavour number scheme (FFNS):
- c (b) as massive quark in $\hat{\sigma}$, c (b) excluded from initial states.
- problem: $\log\,(m_c^2/p_{T,c}^2)$ ($\log\,(m_b^2/p_{T,b}^2)$) may become so big that they may spoil the convergence of the perturbative series.

$*$ Zero-mass variable flavour number scheme (ZM-VFNS):
- c (b) massless quark in $\hat{\sigma}$, c (b) present in the initial states.
- $\log\,(m_c^2/p_{T,c}^2)$ resummed through PDF evolution
  but powers of $(m_c^2/p_{T,c}^2)$ missing!

$*$ General-mass variable flavour number scheme (GM-VFNS):
- combines massive and massless partonic cross-sections,
  with subtraction terms to avoid double countings.
- meant to combine optimal features of FFNS and ZM-VFNS.

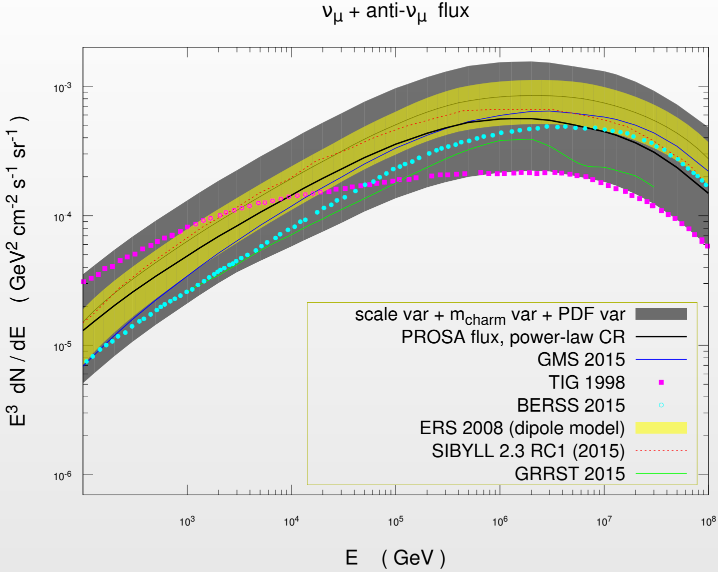
Prompt ν fluxes: GM-VFNS vs. FFNS

(PRELIMINARY)



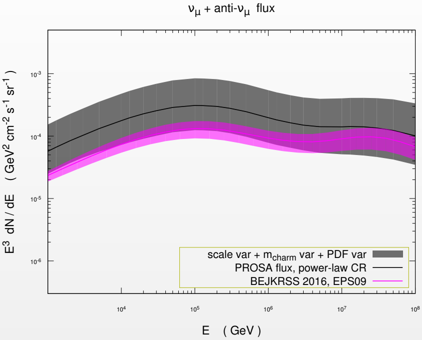
Predictions of GM-VFNS within the uncertainty band of those from FFNS (GMS 2015).

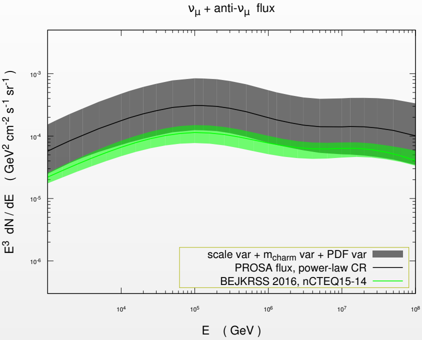
Comparison of predictions by different groups



Different predictions compatible within uncertainty band.

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 the older ones.
- $*$ However, still compatible with our predictions on the basis of nucleon PDFs + superposition model.
- $*$ Uncertainty on nuclear PDF are neglected: however they can be huge!

Uncertainties in the heavy-quark content of PDFs

∗ Ansatz:
charm and bottom in the nucleon PDFs are radiatively generated:

- for scales $\mu_F \leq m_c$ ($\mu_F < m_b$) no charm (bottom) in PDFs
- for scales $\mu_F > m_c$ ($\mu_F > m_b$) charm (bottom) is produced by QCD evolution through $g \to c\bar{c}$ and $c \to gc$ splittings ($g \to b\bar{b}$ and $b \to gb$ splittings)

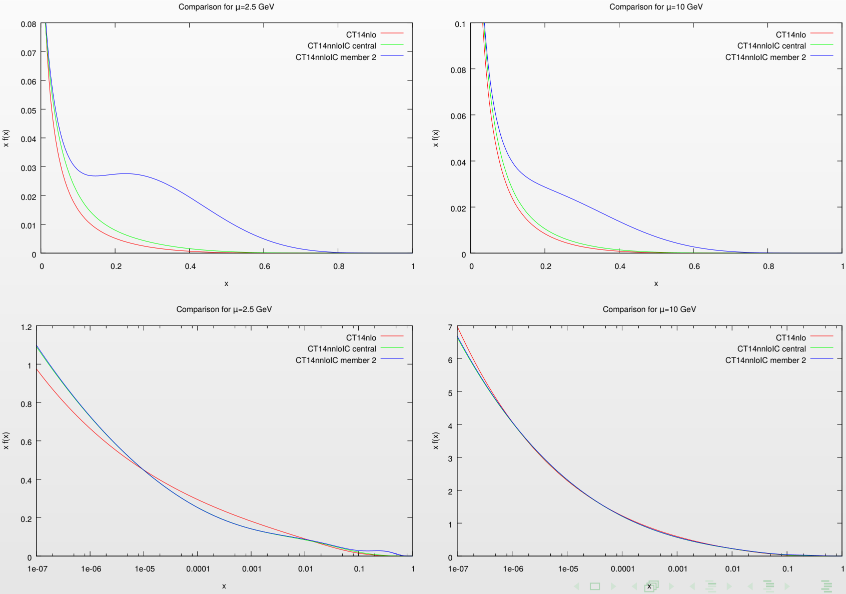
∗ Further possibility:
additional non-perturbative charm and bottom components:
⇒ Models for intrinsic charm/bottom.

Original motivation: old experimental data at large x_F.
But, no need for intrinsic charm/bottom at LHC
(at least for the observables studied so far).
Possible probe of the (non-)existence of intrinsic charm at LHC:
$pp \to Zc, \gamma c$

Charm component in modern PDFs (CT14)

$\mu_F = 2.5$ GeV

$\mu_F = 10$ GeV



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Prompt neutrino fluxes with intrinsic charm

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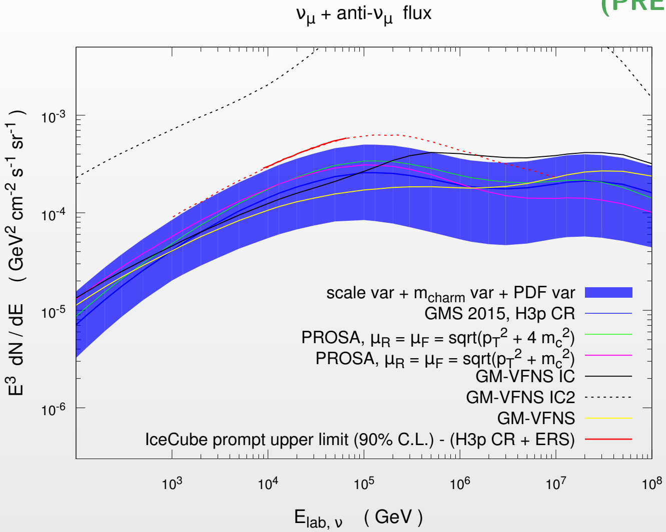

Other calculations:

- Halzen and Wille (upper limit somehow compatible with our IC2)
- Laha and Brodsky (smaller upper limit).

Conclusions

- ∗ Prompt ν fluxes: several new calculations in 2015-2016.

- ∗ Large QCD uncertainties can be mitigated by:
  - resummation of different kinds of logarithms
  - new data from LHC

- ∗ Uncertainties to be better quantified:
  - FFs/hadronization
  - nuclear PDFs

- ∗ In perspective:
  identification of sensitive observables to be studied at future hadron colliders, like the FCC ($\sim$ 2030).
  Proposals for new fixed target experiments ?

- ∗ VLVνT's complementary to colliders in constraining QCD ?
  At this aim, it is important to reduce astrophysical uncertainties,
  in particular those related to CR spectrum composition.