Prompt Atmospheric Neutrino Fluxes

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with input from and/or after discussion with:
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Atmospheric neutrino fluxes

$CR + Air$ interactions:
- AA' interaction approximated as $A\ NA'$ interactions (superposition);
- NA' approximated as $A'\ NN$ interactions: up to which extent is this valid ?

$*$ conventional neutrino flux:

$$NN \rightarrow \pi^{\pm}, K^{\pm} + \mathrm{X} \rightarrow \nu_{\mu}(\bar{\nu}_{\mu}) + \mu^{\pm} + X,$$
$$NN \rightarrow K_S,\ K_L + \mathrm{X} \rightarrow \pi^0 + \mathrm{e} + \nu + \mathrm{X}$$

$*$ prompt neutrino flux:

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

$c\tau_{0,\,\pi^{\pm}} = 780$ cm, $c\tau_{0,\,K^{\pm}} = 371$ cm, $c\tau_{0,\,D^{\pm}} = 0.031$ cm

Critical energy $\epsilon_h = \mathrm{m}_h c^2 h_0/(c\tau_{0,h}\cos(\theta))$, above which hadron decay probability is suppressed with respect to its interaction probability:

$\epsilon_{\pi}^{\pm} < \epsilon_{K}^{\pm} << \epsilon_D \Rightarrow$ conventional flux is suppressed with respect to prompt one, for energies high enough.

Conventional $\rightarrow$ prompt transition

Prompt fluxes expected to dominate above $E_{lab,\nu} > 10^5$ - 10^6 GeV, depending of the flavour and zenith angle.

Investigating the transition requires accurate computation of both fluxes:

– predictions for conventional fluxes at high energies are more uncertain than at lower ones.

– same applies to prompt fluxes.

– characterizing the transition point is important for an explicit detection of prompt fluxes.

– Possible computation of both fluxes in a consistent framework. But the physics of the interactions at the core of the two fluxes differs.

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, Reno, et al., JHEP 1506 (2015) 110,
  JHEP 1611 (2016) 167
- Fedynitch, Riehn, Engel, Gaisser et al., presented at many conferences
- Garzelli, Moch, Sigl, JHEP 1510 (2015) 115
- Gauld, Rojo, Rottoli, Sarkar, Talbert, JHEP 1602 (2016) 130
- Halzen, Wille, arXiv:1601.03044, PRD 94 (2016) 014014
- Laha, Brodsky, PRD 96 (2017) 123002
- PROSA Collaboration, JHEP 1712 (2017) 021 $\rightarrow$ **updates in this talk**
- Benzke, Garzelli, Kniehl, Kramer, Moch, Sigl, JHEP 1712 (2017) 021
- ......

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

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 available for $E_j >> E_{crit,j}$ and for $E_j << E_{crit,j}$, respectively, are interpolated geometrically.

Z-moments for prompt fluxes: Z_{ph} definition

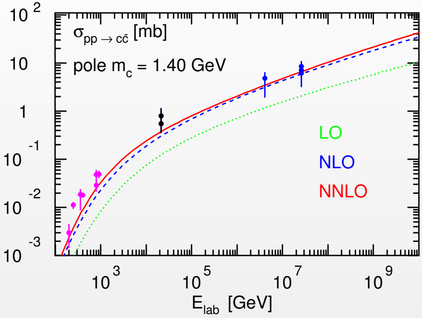
$$Z_{ph}(E_h) = \int_{E_h}^{+\infty} dE'_p \frac{\phi_p(E'_p,0)}{\phi_p(E_h,0)} \frac{\lambda_{p,int}(E_h)}{\lambda_{p,int}(E'_p)} \frac{1}{\sigma_{p-Air}^{tot,inel}(E'_p)} \frac{d\sigma_{p-Air\to c+X\to h+X'}}{dE_h}(E'_p, E_h)$$

* Z_{ph} (as well as the other Z-moments) are energy dependent.

* Z_{ph} at a fixed E_h, depends on charm production cross-section $\sigma(pA \to c + X)$ over a range of proton energies $E_h < E'_p < +\infty$.

* Crucial inputs: all.
  Differences among predictions of different authors can come from:
  - differences in the calculation of $\sigma_{p-Air}^{tot,inel}$,
  - nuclear treatment of pA interactions: relation between pA and pp,
  - theory and input parameters in $\sigma(pp \to c + X)$.

$\sigma(pp \to c\bar{c}(+X))$ at LO, NLO, NNLO QCD



$(E_{lab} = 10^6 \text{ GeV} \sim E_{cm} = 1.37 \text{ TeV})$
$(E_{lab} = 10^8 \text{ GeV} \sim E_{cm} = 13.7 \text{ TeV})$
$(E_{lab} = 10^{10} \text{ GeV} \sim E_{cm} = 137 \text{ TeV})$

data from fixed target exp (E769, LEBC-EHS, LEBC-MPS, HERA-B)
+ colliders (STAR, PHENIX, ALICE, ATLAS, LHCb).

∗ Assumption: collinear factorization valid on the whole energy range.

∗ Sizable QCD uncertainty bands not included in the figure.

Different computations of $\sigma(pp \to c + X)$ used in prompt neutrino flux estimates

* Dipole model(s): ERS 2008, updated in BEJRSS 2016

* Computations with a pQCD core (collinear or k_T factorization): the post-LHC ones are BERSS 2015, GMS 2016, GRSST 2015, BERSS 2016, PROSA 2016, GM-VFNS 2017

  Why is pQCD applicable on the whole kinematics space ?

  The crucial reason is that the charm quark is massive.

  No divergence of $\mathrm{d}\sigma/\mathrm{d}p_T$ for $p_T \to 0$:

  $\Rightarrow$ No strict need of a description in terms of soft physics for $p_T \to 0$.

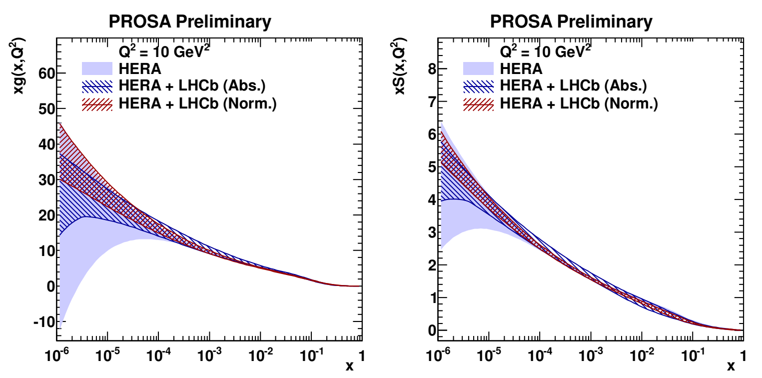
  $\Rightarrow$ Situation radically different from π and K hadroproduction !!!

Where do non-perturbative physics enter in the so-called pQCD computations ?

* it enters in Parton Distribution Functions $\mathrm{PDF}_{i/A}\ (x_i,\ Q^2)$ of partons in protons and nuclei
* it enters in Fragmentation Functions $F_{c,q,g \rightarrow H}(z,\mathrm{Q}^2)$ / hadronization
* it can enter in soft multiple parton interactions (in those calculations where these interactions are accounted for).

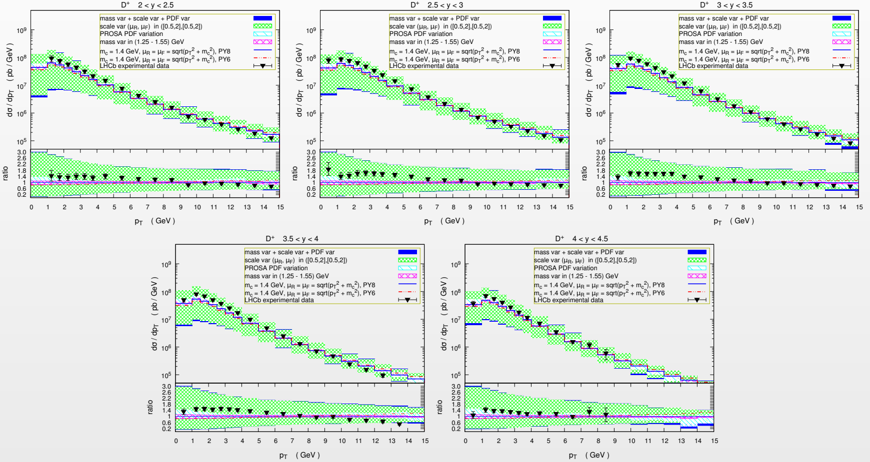
PROSA PDF fit [arXiv:1503.04581]

Basic idea: use the data on *D*-meson and *B*-meson hadroproduction at LHCb to constrain PDFs (especially gluon PDFs) at low $x = p_{z,\,parton}/p_{z,\,proton}$ values.



* The gluon and the sea quark distributions are correlated: a reduction on the uncertainty of the former propagates to the latter.
* good at "low" x's, but how low shall we go for high-energy astroparticle physics ?
* LHCb data constrains down to $x \sim 10^{-6}$. This is not enough for prompt fluxes at extremely high energies.....

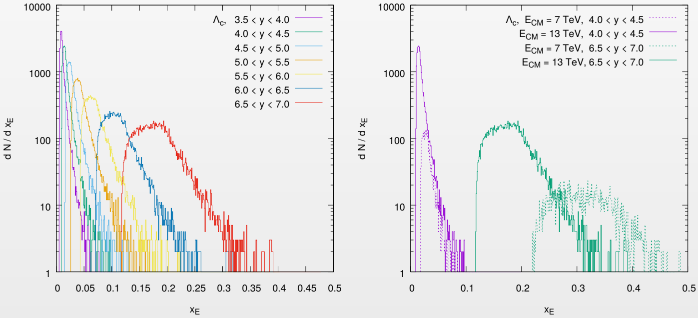
Performances of PROSA PDF fit with respect to LHCb data non included in the fit



* $d^2\sigma/(dp_T dy)$ measured for $pp \to D^{\pm} + X$ at $\sqrt{s} = 13$ TeV.
* Experimental data always within the theory uncertainty bands.

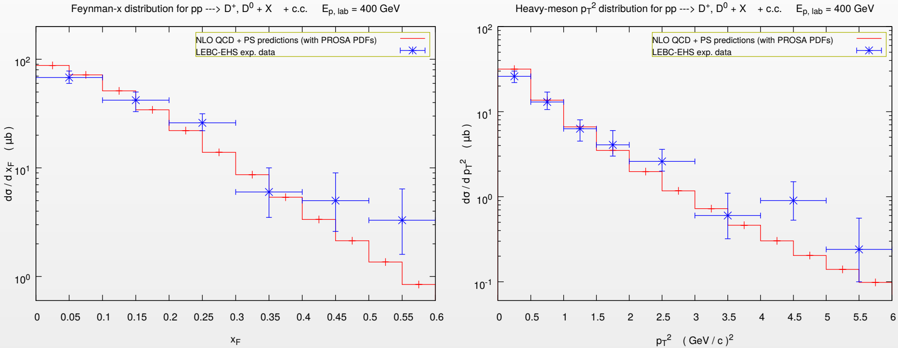
LHCb experimental data coverage for charm hadroproduction in astrophysical applications:

$x_E = E_{h,LAB} \,/\, E_{p,LAB}$ spectra (of interest for prompt fluxes) at different rapidities y (of interest at colliders)



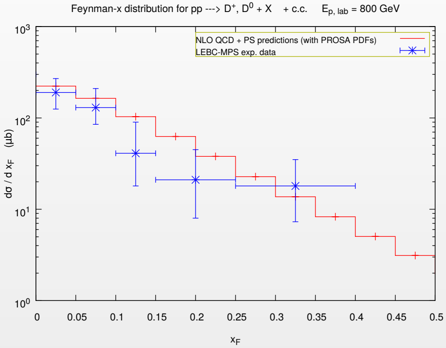
- ∗ case of Λ_c considered here,
  qualitatively similar behaviour for charmed mesons.
- ∗ high x_E corresponds to high y (forward particles)
- ∗ maximum rapidities y probed at LHCb corresponds to $x_E < 0.15$.

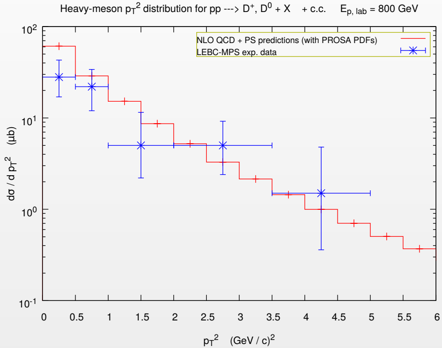
Performances of the PROSA QCD computation of D-meson production w.r.t. LEBC-EHS exp. data



- Fixed target experiment with $E_{p,\,lab} = 400$ GeV.
- Measure relatively large $x_F = p_{z,D}/p_{z,D}^{max}$ (up to $x_F \sim 0.6$) and p_T^2.
- Sizable QCD uncertainty band not included in the plot.

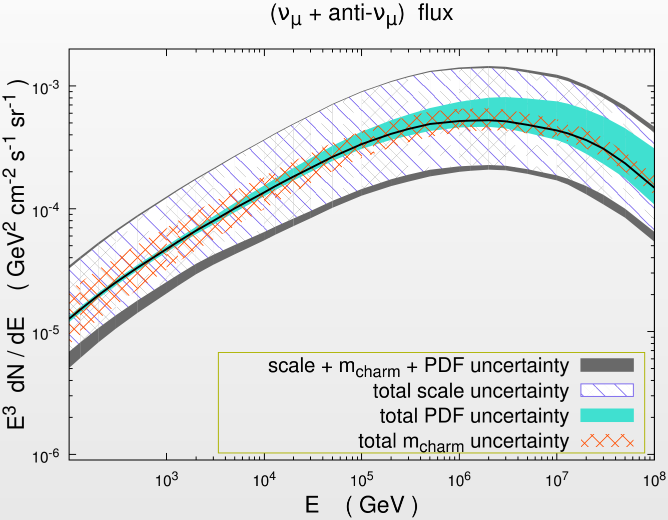
Performances of the PROSA QCD computation of D-meson production w.r.t. LEBC-MPS exp. data





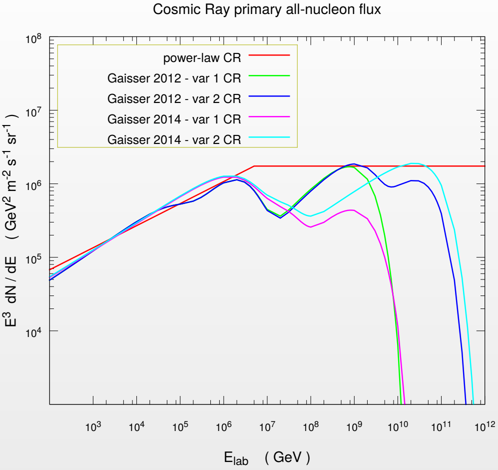
- ∗ Fixed target experiment with $E_{lab} = 800$ GeV.
- ∗ Measure relatively large x_F (up to $x_F \sim 0.4$).
- ∗ Sizable QCD uncertainty band not included in the plot.

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



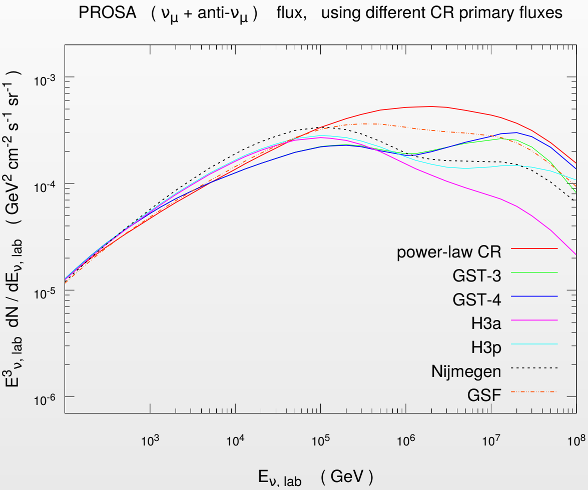
from [arXiv:1611.03815]

The all-nucleon CR spectra: considered hypotheses



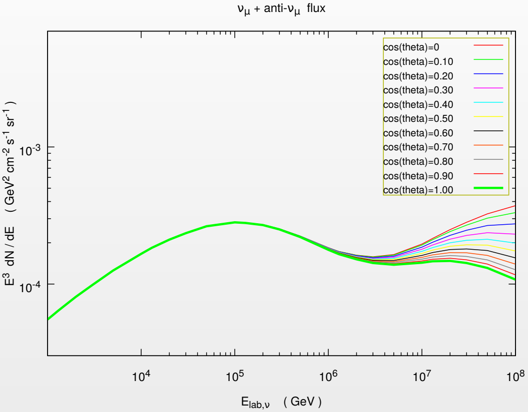
* All-nucleon spectra obtained from all-particles ones under different assumptions as for the CR composition at the highest energies.
* Models with 3 (2 gal + 1 extra-gal) or 4 (2 gal + 2 extra-gal) populations are available.

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



* GSF is the newest CR spectrum available by the Gaisser group (ICRC 2017), leading to results somehow similar to the broken power-law case.

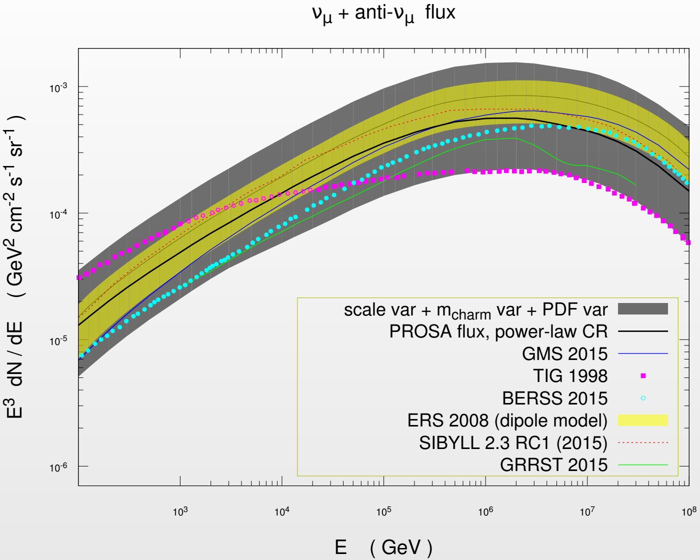
Zenith angle dependence of the PROSA prompt $(\nu_\mu + \bar{\nu}_\mu)$ flux



Flux computed with H3p primary CR spectrum

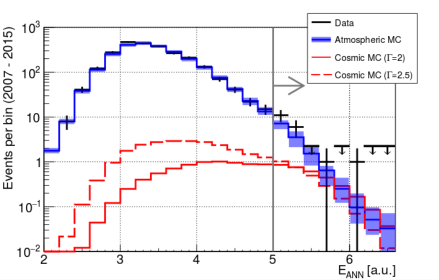
* prompt fluxes are not isotropic
  (although this approximation is good at low energies).
* At high energies, they increase towards the horizon.

Comparison of predictions by different groups

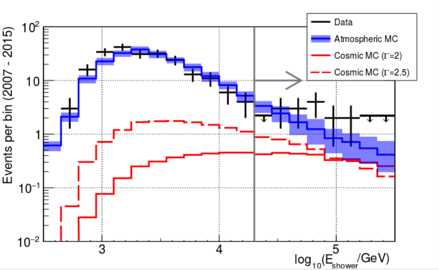


Different predictions compatible within the uncertainty band: accidentally ?

Recent results from ANTARES on tracks and showers [arXiv:1711.07212]



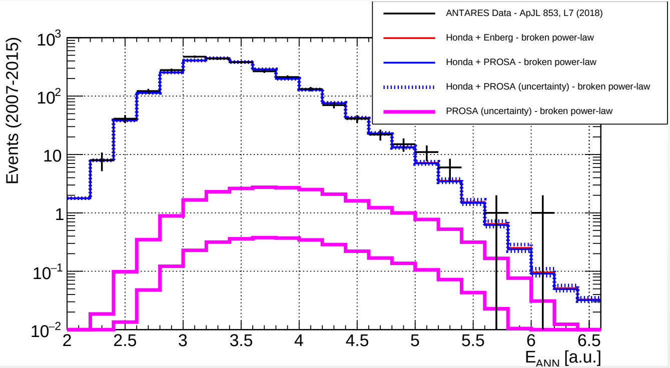
tracks



showers

* theory predictions for atmospheric flux = Honda + ERS
* interesting to extend to more recent predictions
* interesting to compare ANTARES data with IceCube data: warning E_{ANN} is an energy estimator, it is linearly related to the ν reconstructed energy, but it does not coincide with it!.

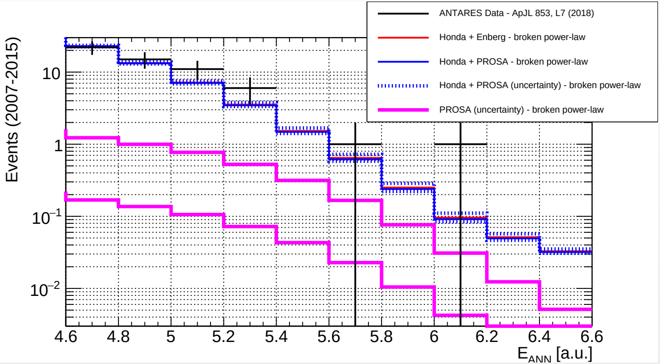
Effects of PROSA prompt flux in the analysis of ANTARES High-Energy Track Events



courtesy of L. Fusco, ANTARES collaboration

- ∗ Broken power-law CR primary spectrum assumption.
- ∗ Only $\sim 1\ \sigma$ excess above the atmospheric only hypothesis: no striking need of astrophysical neutrinos to explain these data

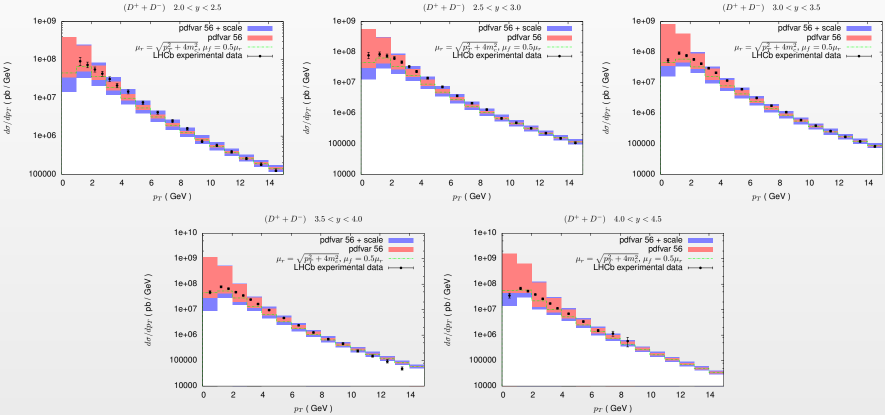
Effects of PROSA prompt flux in the analysis of ANTARES High-Energy Track Events



courtesy of L. Fusco, ANTARES collaboration

- ∗ Effects of different prompt predictions hardly distinguishable.
- ∗ Accurate estimate of the uncertainties on conventional flux needed before reaching any firm conclusion on astrophysical neutrinos.
- ∗ Waiting for more statistics (KM3NeT).

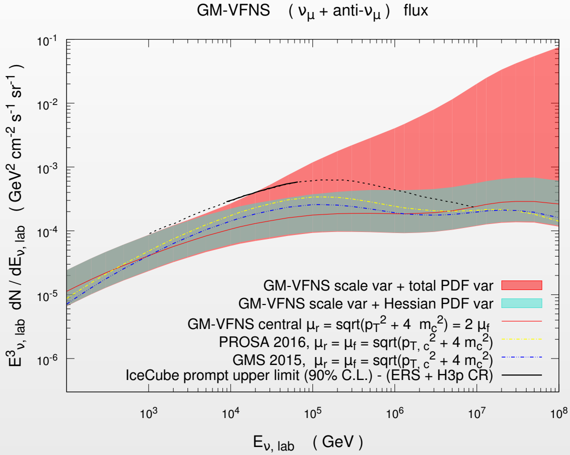
How do other PDF fits (CT14nlo), not including LHCb data, behave ? $pp \to D^{\pm} + X$ at LHCb at 13 TeV



* GM-VFNS predictions using CT14nlo PDFs, constrained only down to $x \sim 10^{-4}$
* Large PDF uncertainties, increasing at low p_T / large y.

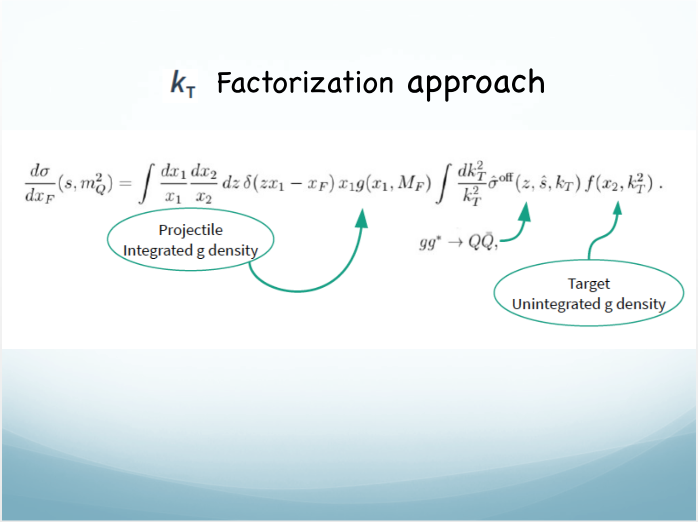
Prompt neutrino fluxes:

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 (see PDF error sets 53-56) is too large!

Prompt neutrinos using QCD k_T factorization



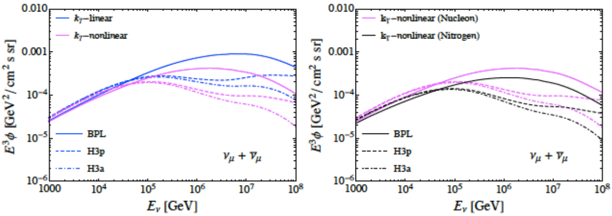
hybrid formalism:

low-x parton from the target and large-x parton from the projectile

slide and calculation by Ina Sarcevic, M. H. Reno, et al.

KT factorization

Bhattacharya et al., JHEP 1611 (2016) 167



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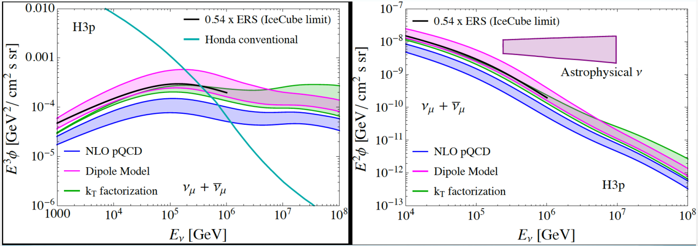
* saturation vs. no-saturation in the uPDF: saturation suppress fluxes
* cold nuclear matter effects likely suppress fluxes
* Large QCD and nuclear uncertainties (not included in these plots)

Prompt Neutrino FLux

A. Bhattacharya, R. Enberg, Y.S. Jeong, M.H. Reno, I. Sarcevic and A. Stasto, JHEP 1611 (2016) 167



comparison between computations in different QCD frameworks: dipole model / k_T factorization / collinear factorization

slide and calculation by I. Sarcevic, M. H. Reno, et al.

Conclusions

* Many theory computations of prompt atmospheric ν fluxes.
* VLVνT results published so far are not enough to rule out, confirm or prefer any of the most recent predictions (but they can rule out very extreme cases).
* Open questions which deserve further investigation in the future:
  - reduction of QCD uncertainties (in both collinear and k_T-factorization)
  - nuclear matter effects
  - transition region: conventional $\rightarrow$ prompt
  - explicit more dedicated searches of prompt fluxes at VLVνTs
  - intrinsic charm ?
  - BSM enhancement of charm production
  - Systematic inclusion of prompt flux contribution when looking for and fitting the "astrophysical" neutrino component.