Implications of heavy-quark hadroproduction

M.V. Garzelli, S.-O. Moch and G. Sigl

II Institute for Theoretical Physics, University of Hamburg, Germany

Universität Hamburg
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Implications of heavy-quark hadroproduction

This is a huge subject.....
At the incoming run of LHC, expected cross-sections amount to:

$$\sigma(pp \to t\bar{t}, m_t^{pole} = 172.5 GeV) \sim 716 \text{ pb} \quad \text{at} \quad E_{CM} = 13 \text{ TeV}$$
$$\sigma(pp \to b\bar{b}, m_b^{\bar{M}\bar{S}}(m_b) = 4.2 GeV) \sim 628.4 \,\mu\text{b} \quad \text{at} \quad E_{CM} = 13 \text{ TeV}$$
$$\sigma(pp \to c\bar{c}, m_c^{\bar{M}S}(m_c) = 1.27 GeV)) \sim 13.4 \text{ mb} \quad \text{at} \quad E_{CM} = 13 \text{ TeV}$$

$$\sigma(c\bar{c}) = 21.3 * \sigma(b\bar{b}) = 21.3 * 877.7 * \sigma(t\bar{t})$$

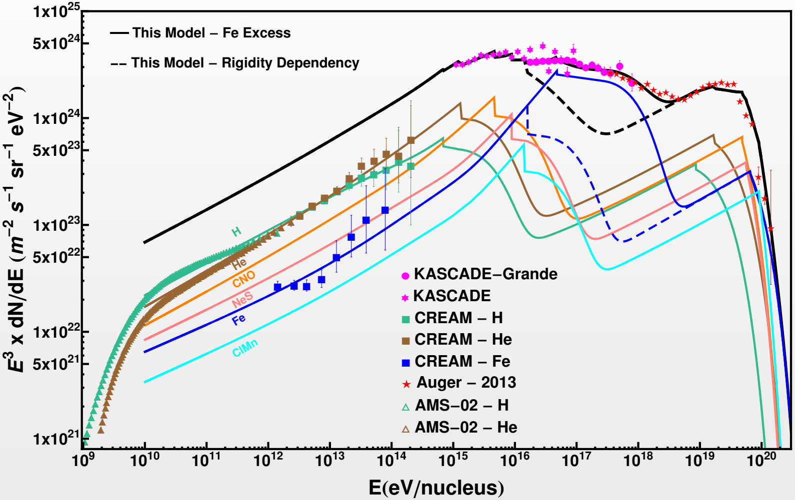
....we concentrate here on
Astrophysical implications of heavy-quark hadroproduction:
we study pp collisions using p of astrophysical origin.....

$\Rightarrow$ this covers a more extended energy range with respect to colliders......
however the ratio between the heavy-quark cross-sections above is expected to decrease relatively slowly.... (in absence of new physics):

$$\sigma(pp \to t\bar{t}, m_t^{pole} = 172.5 GeV) \sim 33624.6 \text{ pb} \quad \text{at} \quad E_{CM} = 100 \text{ TeV}$$
$$\sigma(pp \to b\bar{b}, m_b^{\bar{M}\bar{S}}(m_b) = 4.2 GeV) \sim 3374.5 \,\mu\text{b} \quad \text{at} \quad E_{CM} = 100 \text{ TeV}$$
$$\sigma(pp \to c\bar{c}, m_c^{\bar{M}\bar{S}}(m_c) = 1.27 GeV) \sim 38.2 \text{ mb} \quad \text{at} \quad E_{CM} = 100 \text{ TeV}$$

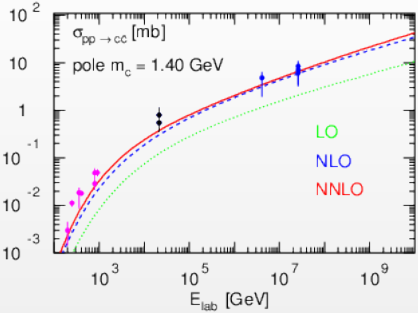
$$\sigma(c\bar{c}) = 11.3 * \sigma(b\bar{b}) = 11.3 * 100.3 * \sigma(t\bar{t})$$

All-particle Cosmic Ray flux [Todero et al., arXiv:1502.00305]

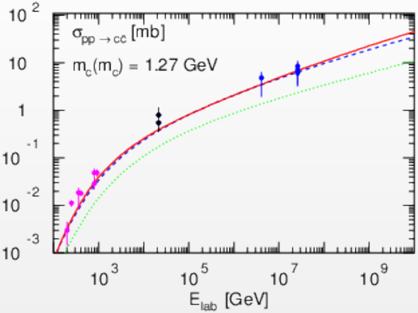


Experimental data cover lab energies up to $E_{lab} \sim 10^{20}$ eV (although with a suppressed flux)

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



pole mass scheme



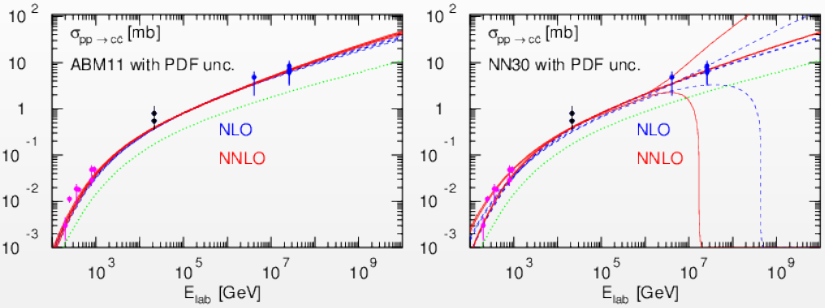
running mass scheme

exp data from fixed target exp + colliders (STAR, PHENIX, ALICE, ATLAS, LHCb).

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

$*$ Assumption: pQCD in DGLAP formalism valid on the whole energy range.

$\sigma(pp \to c\bar{c})$: PDFs and their behaviour at low Bjorken x



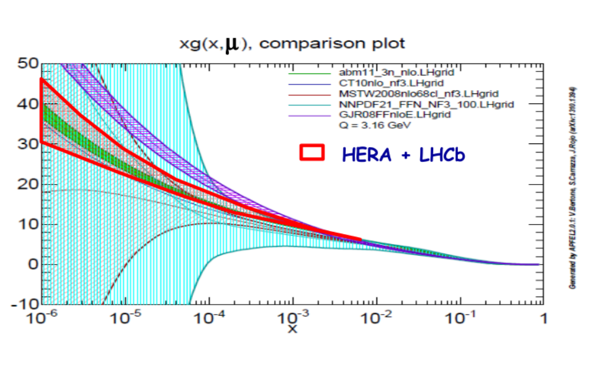
* Probing higher astrophysical energies allows to probe smaller x region, down to values where no data constrain PDFs yet (at least at present).

* $f(x, Q^2)$: Q^2 evolution fixed by DGLAP equations, x dependence non-perturbative: ansatz + extraction from experimental data.

* Different behaviour of different PDF parameterizations:
  - ABM parameterization constrains PDFs at low x;
  - NNPDF parameterization reflects the absence of constraints from experimental data at low x.

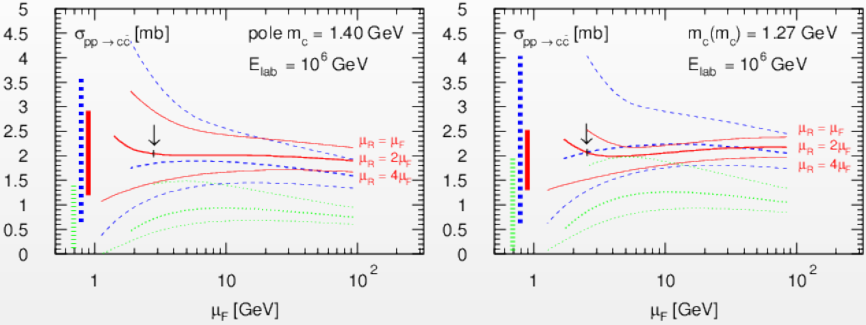
PROSA PDF fit [O. Zenaiev, A. Geiser et al. [arXiv:1503.04585]]

First (and so far only) fit already including some LHCb data (charm and bottom) appeared in arXiv so far:



* ABM PDFs, although non including any info from LHCb, in agreement with PROSA fit → good candidates for ultra-high-energy applications
* CT10 PDFs in marginal agreement with PROSA fit.
* NNPDF PDFs: the largest uncertainties, they are working to try to incorporate PROSA idea in their fit as well.

$\sigma(pp \to c\bar{c})$: scale dependence



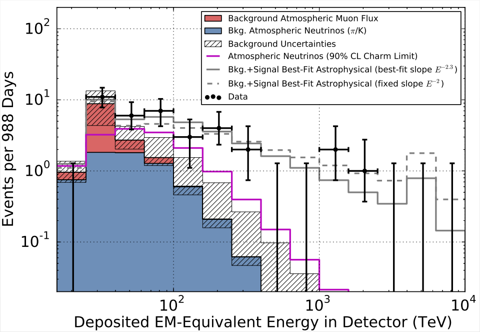
* Perturbative convergence in running mass scheme is reached faster than in pole mass scheme.

* Minimal sensitivity to radiative corrections is reached at a scale $\mu_F \sim 2m_{charm}$.

The astrophysical problem:

IceCube high-energy ν excess [arXiv:1405.5303]

* 2013: 28 neutrino candidates in the energy range [50 TeV - 2 PeV]. (4.1 σ excess over the expected atmospheric background).
* 2014: 988-day analysis, with a total of 37 neutrino events with energy [30 TeV - 2 PeV] (5.7 σ excess).
* no events in the energy range [400 TeV - 1 PeV].



* Are these ν produced and accelerated in astrophysical sources (e.g. Core-Collapsing SN) ?
* Do they come from Dark Matter self-annihilation, or from other BSM mechanisms ?

.....a lot of hypotheses have been formulated.....

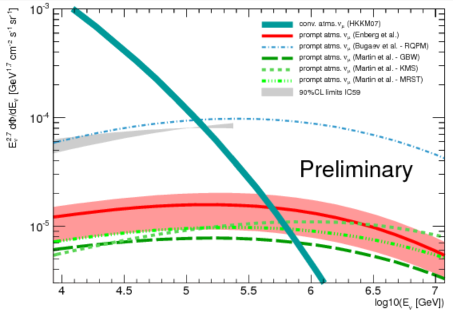
The "background": atmospheric ν

* To assess the entity of an IceCube diffuse signal of purely astrophysical origin an accurate estimation of the background is mandatory.

* Atmospheric neutrinos are a source of background:

Cosmic Rays + Atmospheric Nuclei $\rightarrow$ hadrons $\rightarrow$ neutrinos

* 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 havier hadrons (D's, B's.....)



Transition point: still subject of investigation ([IceCube collab., [arXiv:1302.0127]]).

Transition from conventional to prompt ν: the hadronic critical energy

Approximate energy above which the particle decay probability is suppressed with respect to its interaction probability.

* $\pi^{\pm}$ and $K^{\pm}$ have relatively low critical energies

$$E_{\pi^\pm}^{crit} = 115 \text{ GeV}, \quad E_{K^\pm}^{crit} = 850 \text{ GeV}$$

$\Rightarrow$ the conventional ν flux is cut-off at relatively low energy.....

* D-hadrons have larger critical energies

$$E_{D^0}^{crit} = 9.71 \cdot 10^7 \text{ GeV}, \quad E_{D^+}^{crit} = 3.84 \cdot 10^7 \text{ GeV},$$
$$E_{D_s^+}^{crit} = 8.40 \cdot 10^7 \text{ GeV}, \quad E_{\Lambda_c}^{crit} = 24.4 \cdot 10^7 \text{ GeV}$$

$\Rightarrow$ the prompt flux is expected to dominate over the conventional for energies large enough.

From cascade equations to Z-moments

Particle evolution in the atmosphere (production/interaction/decay) is regulated by a set of coupled differential equations:

$$\frac{d\phi_j}{dX} = -\frac{\phi_j}{\lambda_{j,int}} - \frac{\phi_j}{\lambda_{j,dec}} + \sum_k S_{prod}(k \to j) + \sum_k S_{decay}(k \to j)$$

Under assumption that X dependence of fluxes factorizes from E dependence, analytical approximated solutions in terms of Z-moments:

– Particle Production:

$$S_{prod}(k \to j) = \int_{E_j}^{\infty} dE_k \frac{\phi_k(E_k, X)}{\lambda_k(E_k)} \frac{1}{\sigma_k} \frac{d\sigma_{k\to j}}{dE_j}(E_k, E_j) \sim \frac{\phi_k(E_j, X)}{\lambda_k(E_j)} Z_{kj}(E_j)$$

– Particle Decay:

$$S_{decay}(j \to l) = \int_{E_l}^{\infty} dE_j \frac{\phi_j(E_j, X)}{\lambda_j(E_j)} \frac{1}{\Gamma_j} \frac{d\Gamma_{j\to l}}{dE_l}(E_j, E_l) \sim \frac{\phi_j(E_l, X)}{\lambda_j(E_l)} Z_{jl}(E_l)$$

Solutions available for high E_j and low E_j are interpolated geometrically.

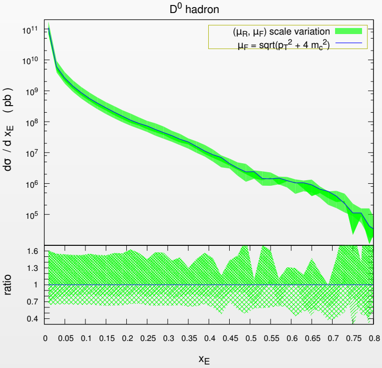
The QCD core of the Z-moments for prompt fluxes: $d\sigma(pp \to charmed\ hadrons)/dx_E$

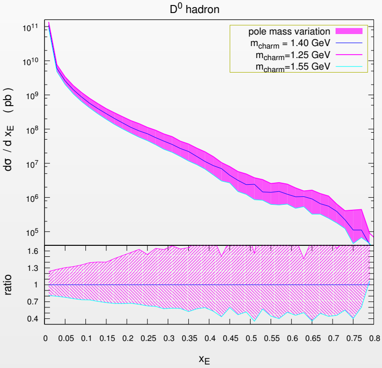
$$Z_{ph}(E_h) = \int_0^1 \frac{dx_E}{x_E} \frac{\phi_p(E_h/x_E, 0)}{\phi_p(E_h, 0)} \frac{\lambda_p(E_h)}{\lambda_p(E_h/x_E)} \frac{A_{air}}{\sigma^{tot,inel}_{p-Air}(E_h)} \frac{d\sigma_{pp \to c\bar{c} \to h+X}}{dx_E}(E_h/x_E)$$

We used a (NLO QCD + Parton Shower + Hadronization) approach, with central scale, PDF and m_{charm} choices driven by previous considerations (see LO/NLO/NNLO plots) and variations in the following intervals:

- central scale $(\mu_R, \mu_F) = \mu_0 = \sqrt{p^2_{T,charm} + 4 m^2_{charm}}$,
  with independent variations of $\mu_R \in (0.5, 2)\mu_0$ and $\mu_F \in (0.5, 2)\mu_0$, excluding extremes (2,0.5)μ_0 and (0.5,2)μ_0.
- m^{pole}_{charm}= 1.40 GeV, with variation in [1.25,1.55] GeV
- PDFs:
  * ABM11-NLO-3fl full set (central + 28 variations)
  * CT10-nlo-3fl (central)
  * NNPDF3.0-3fl (central)

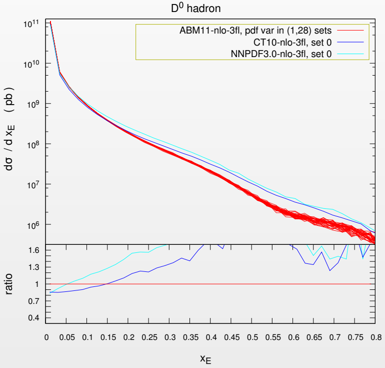
$d\sigma(pp \to c\bar{c} \to D^0 + X)/dx_E$: scale and mass uncertainties

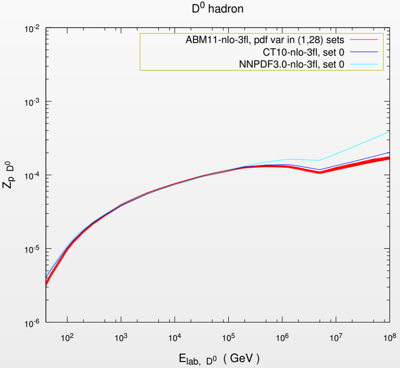




∗ Here plots for *pp* collisions at $E_{lab} = 10^7$ GeV, shape remains similar at different energies.

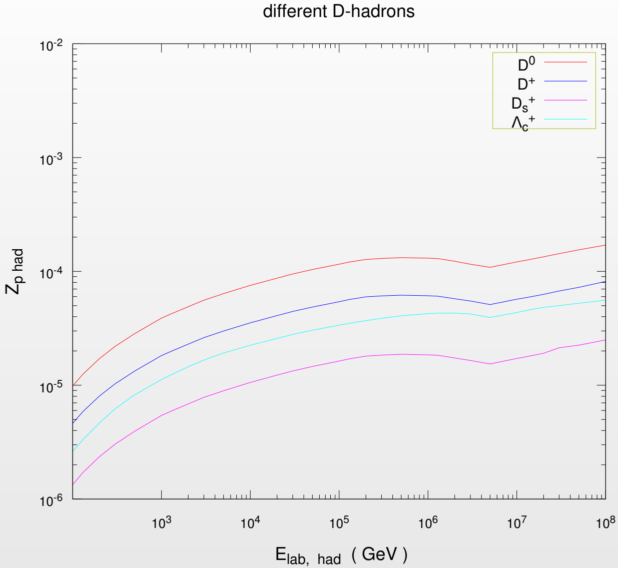
$d\sigma(pp \to c\bar{c} \to D^0 + X)/dx_E$: PDF uncertainties and how do they propagate to the Z-moments





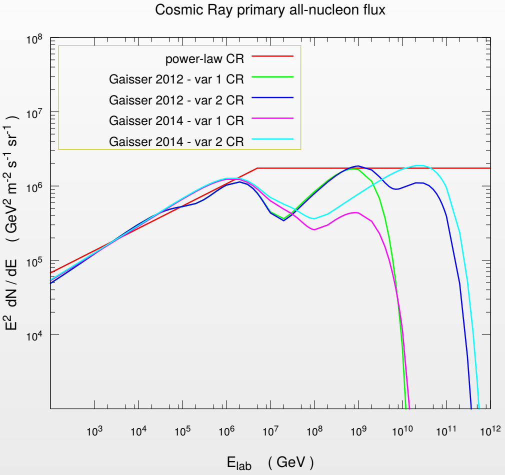
* Significant dependence of observables on choice of PDF set

Z-moments of different D-hadrons, all contributing to ϕ_ν



$*$ On top of this one has to superimpose the uncertainties.....

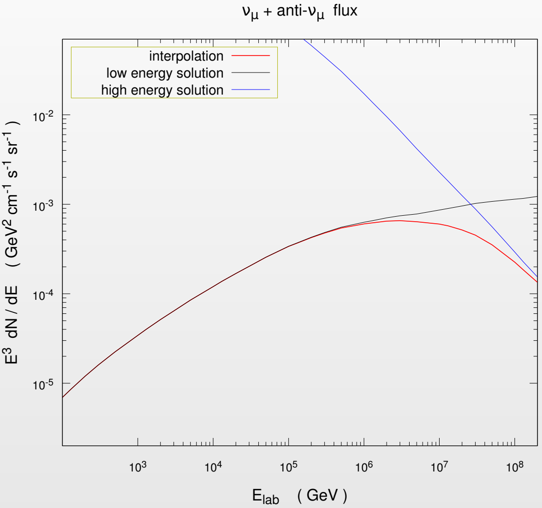
The all nucleon CR spectra: considered hypotheses



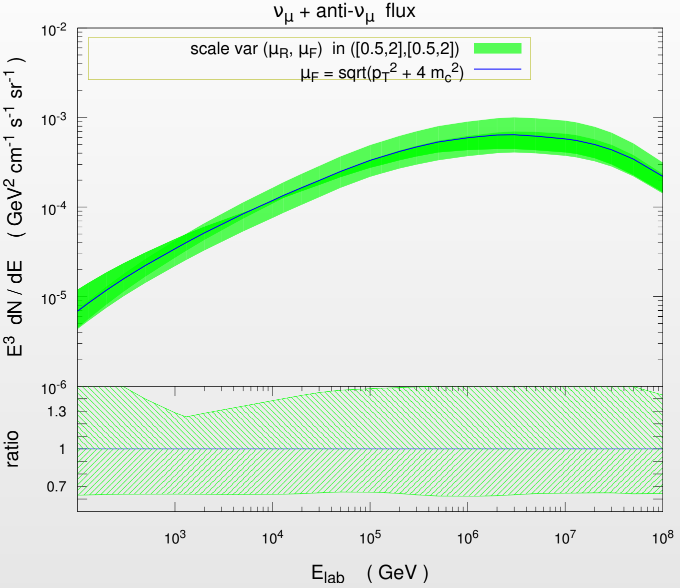
∗ All nucleon spectra obtained from all particles ones under different assumptions as for the CR composition at the highest energies.

∗ Models with 3 or 4 populations are available.

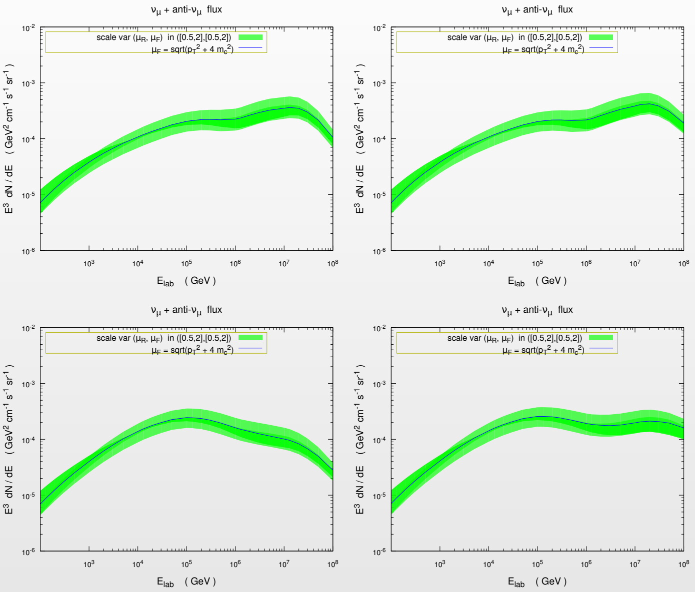
$\nu_\mu + \bar{\nu}_\mu$ fluxes: interpolation between high energy and low energy solutions



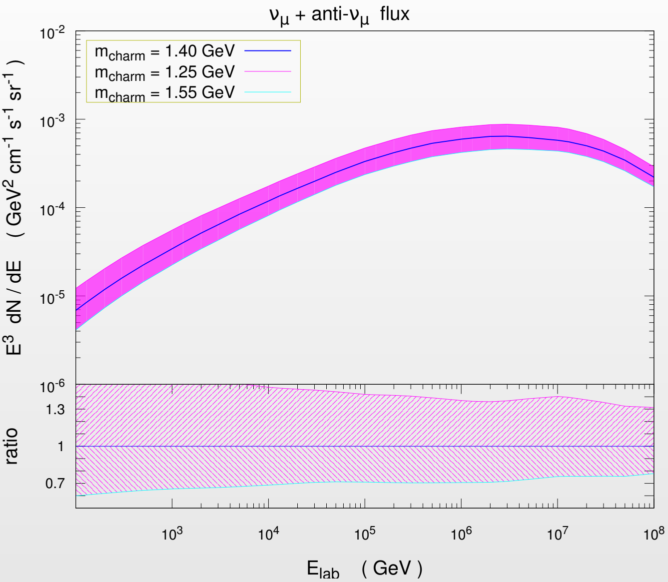
$(\nu_\mu + \bar{\nu}_\mu)$ fluxes: scale variation - power law CR



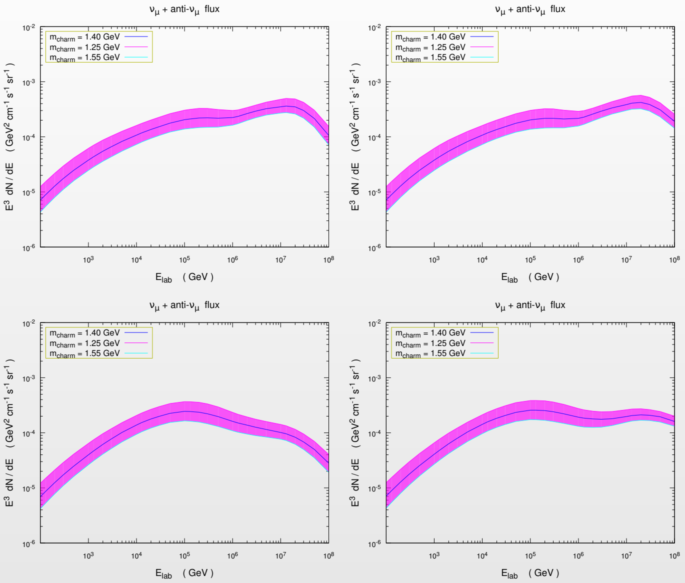
$(\nu_\mu + \bar{\nu}_\mu)$ fluxes: scale variation - different CR spectra



$(\nu_\mu + \bar{\nu}_\mu)$ fluxes: mass variation - power law CR



$(\nu_\mu + \bar{\nu}_\mu)$ fluxes: mass variation - different CR spectra



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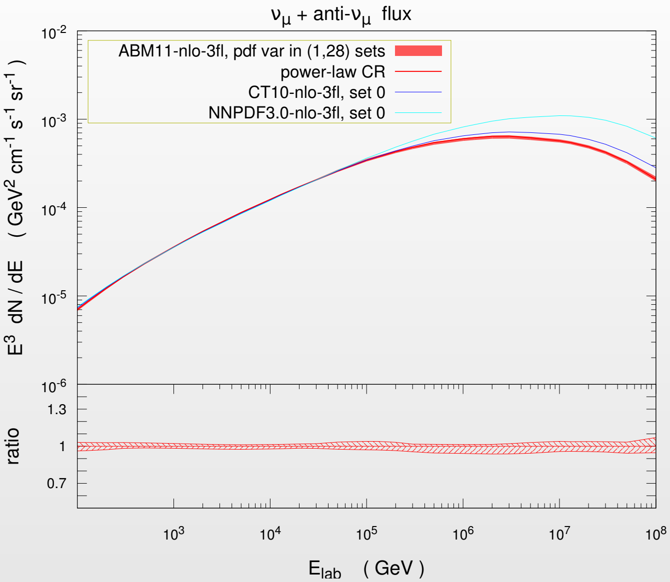
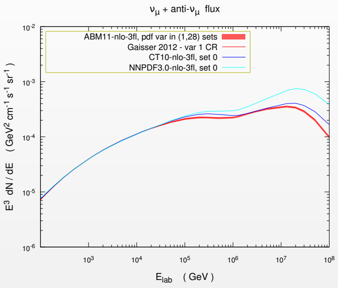
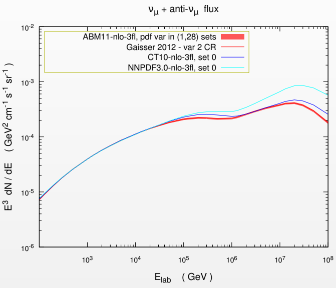
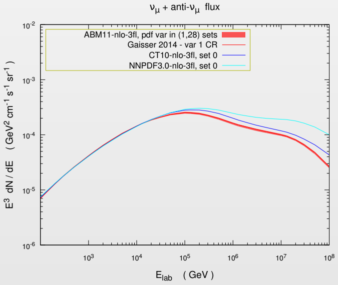
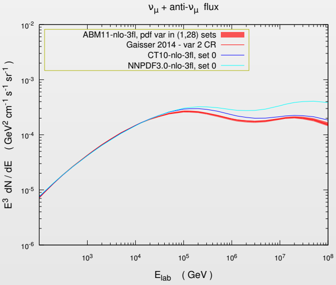


$(\nu_\mu + \bar{\nu}_\mu)$ fluxes: PDF variation - different CR spectra

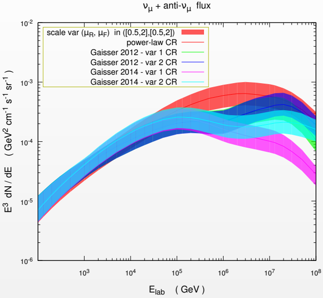


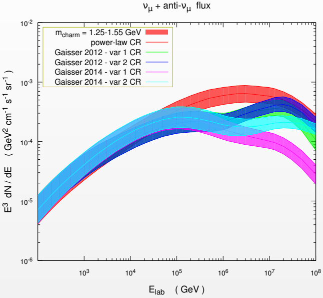


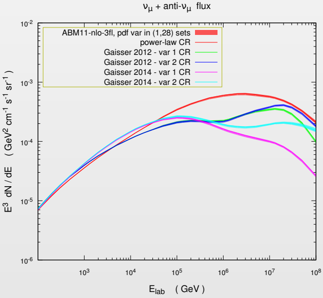


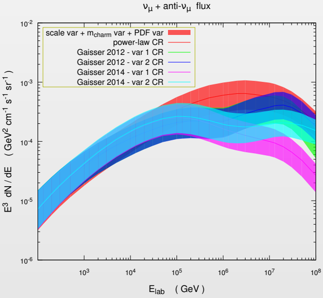


$(\nu_\mu + \bar{\nu}_\mu)$ fluxes: (scale + mass + PDF) variation summary



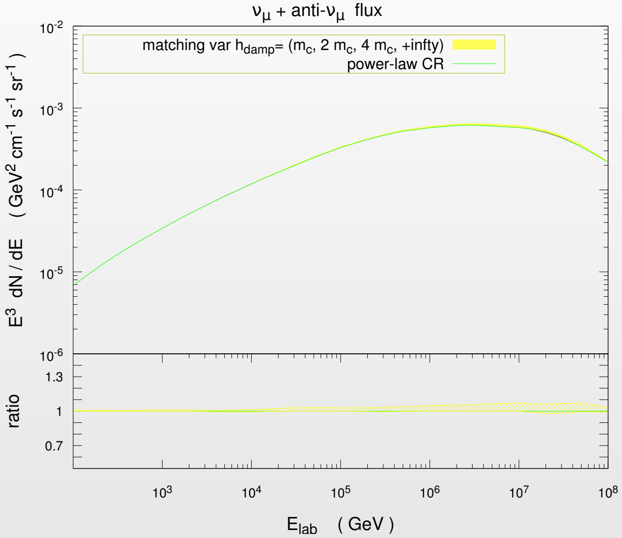






$(\nu_\mu + \bar{\nu}_\mu)$ fluxes: NLO + PS matching uncertainty

(VERY PRELIMINARY)



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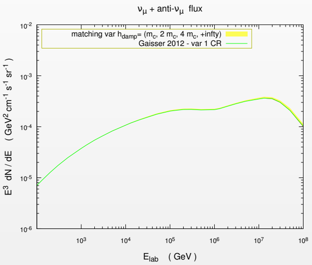
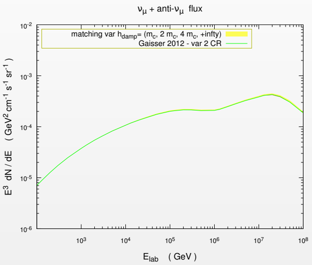
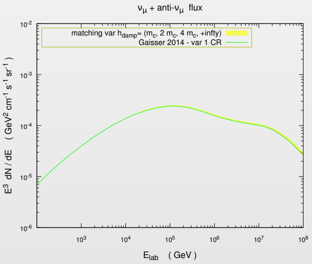
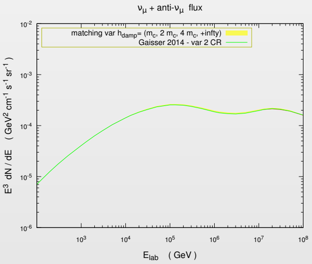
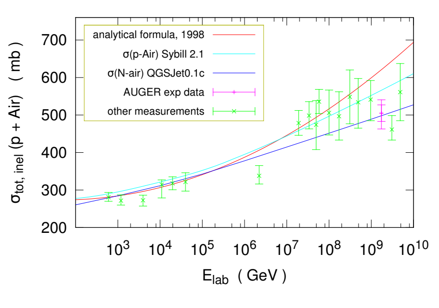


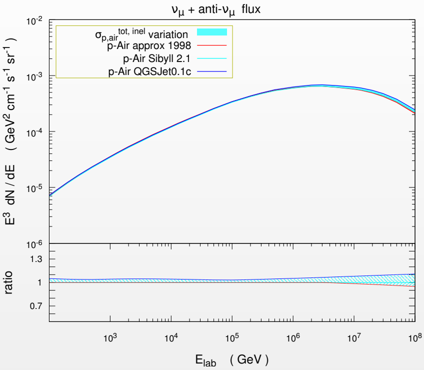


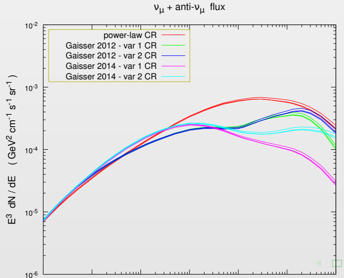




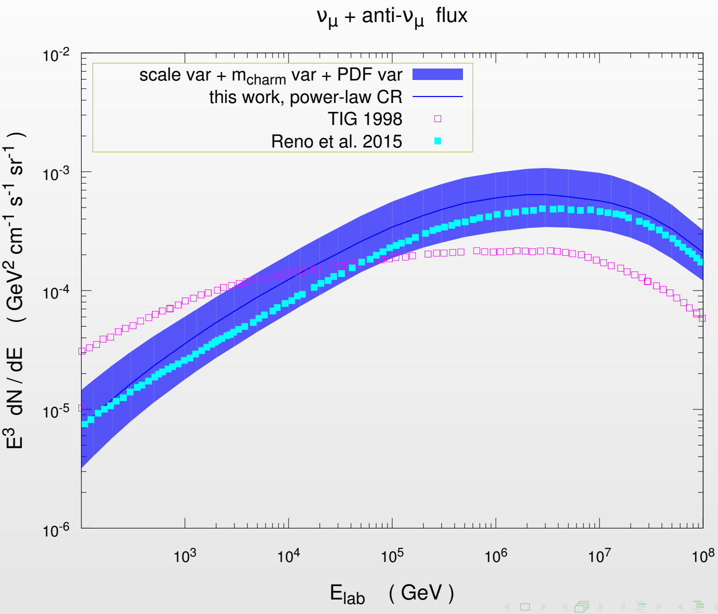
$(\nu_\mu + \bar{\nu}_\mu)$ fluxes: variation in the total inelastic σ_{p-Air}



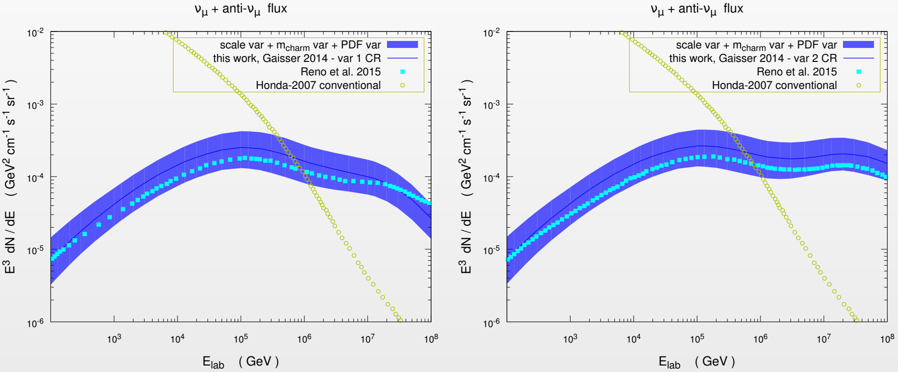




$(\nu_\mu + \bar{\nu}_\mu)$ fluxes: comparison with other predictions



$(\nu_\mu + \bar{\nu}_\mu)$ fluxes: comparisons with other predictions and transition region



* Our predictions point to a transition energy in the interval $3{\cdot}10^5$ - 10^6 GeV: the region where IceCube does not see any event is just filled by prompt ν ?

Conclusions

* Other sources of uncertainties not treated in this talk:
  - fragmentation
  - in-medium effects
  - total and elastic σ_{pD}
  - hadron decay uncertainties
  - contribution of other processes

* Our central predictions for ν fluxes in agreement within 40 % with other recent ones (within theoretical errorbars), although obtained on the basis of a completely independent calculation.

* Precise shape affected by the choice of the PDF set.

* Our estimate of uncertainties is far more conservative: at least (+ 70% - 50%) at $E_\nu = 1$ PeV.

Messages to the pQCD community

In order to shrink our uncertainties from pQCD we need:

* NNLO QCD differential predictions of $pp \to c\bar{c}$:
  this would also improve the description of the small x region.

* gluon PDF fits incorporating NNLO theoretical predictions.

* gluon PDF fits including not only HERA, CMS and ATLAS data
  but also LHCb present and future data,
  capable of constraining small-x region, are important
  for UHECR astrophysical applications (e.g. EAS by CR at 10^{19}-10^{20} eV).

Complementarity
between astroparticle physics measurements and collider physics.