Adroproduzione di quark pesanti e flusso di neutrini prompt nell'atmosfera

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mainly on the basis of JHEP 1510 (2015) 115 [arXiv:1507.01570]

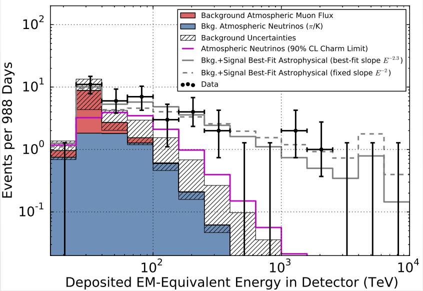
INFN Workshop "What Next. Sezioni d'urto dei neutrini."

Bologna, November 9 - 10 th, 2015

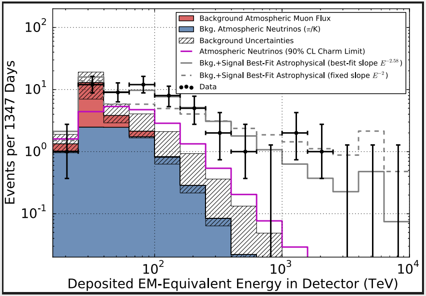
The astrophysical case:

IceCube high-energy events ([arXiv:1405.5303] + ICRC 2015)

* **2013**: 662-day analysis, with **28** 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** events with energy [30 TeV - 2 PeV] (5.7 σ excess), no events in the energy range [400 TeV - 1 PeV].
* **2015**: 1347-day analysis, with a total of **53 + 1** events, previous energy gap partially filled.



2014



2015

figures from the presentation of C. Kopper, ICRC2015

* high-energy diffuse flux further testable by KM3Net/ARCA

Candidate sources for HESE considered so far in literature

1) Astrophysical Sources:

extragalactic: AGNs, GRBs, Starburst galaxies, galaxy clusters...
galactic: SNRs, pulsars, microquasars, Fermi bubbles, Galactic halo

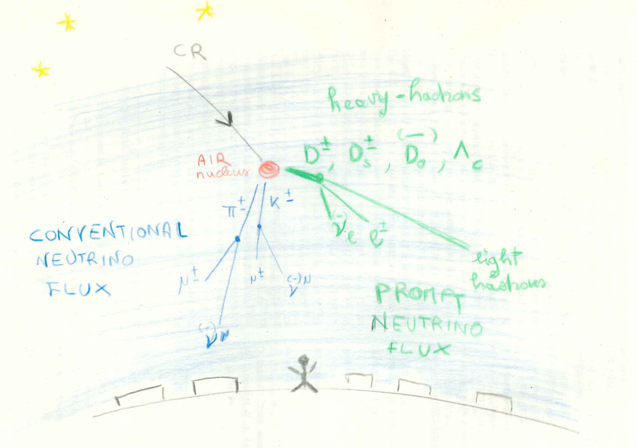
2) Heavy DM decay, DM-DM annihilation

3) Atmospheric leptons

May be a combination of some of the previous ones ?

For sure, precise predictions/measurements of the atmospheric ν fluxes have to be taken into account in the analyses, because they represent a "background" for any astrophysical or BSM hypothesis.

Atmospheric ν 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 haevier hadrons (D's, $\Lambda_c^{\pm}$'s.....)
* **Transition point**: still subject of investigation......

Standard procedure to get 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):

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

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

– Particle Production:

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

– Particle Decay:

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

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

Z-moments for heavy hadron production and decay

* CR + Air interactions producing heavy hadrons (in particular including charm) parameterized in terms of p-p collisions
* Integration variable: $x_E = E_h/E_p$
* Z-moments for intermediate hadron production:

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

* These hadrons are then decayed semileptonically, producing leptons (+ X)
* Integration variable: $x'_E = E_l/E_h$
* Z-moments for intermediate hadron decay:

$$Z_{hl}(E_l) = \int_0^{1-\frac{s^{eff}_{X,h}}{m_h^2}} \frac{dx'_E}{x'_E} \frac{\phi_h(E_l/x_{E'})}{\phi_h(E_l)} F_{h\to l}(x'_E)$$

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

$*$ We used QCD in the standard collinear factorization formalism.

$$\sigma_{H_1 H_2 \to X} = \sum_{i,j} \int dx_1 dx_2 f_{i/H_1}(x_i, \mu_F^2) f_{j/H_2}(x_j, \mu_F^2) \hat{\sigma}_{ij \to X}(x_i p_1, x_j p_2; \alpha_S, \mu_R^2, \mu_F^2)$$

where

$x_i = p_{z,i}/p_{z,H_1}$ = Bjorken variable

$f_{i/H_1}(x_i, \mu_F^2)$ = PDFs (long-distance physics) reabsorb infrared collinear singularities uncancelled within the hard-scattering and are universal (process independent). At a given scale, they are non-perturbative objects, but their evolution with μ_F is governed by perturbation theory (DGLAP equation).

$\hat{\sigma}_{ij \to X}$ = partonic hard-scattering cross-section (short-distance physics), computable by pQCD.

μ_F = factorization scale: separates long-distance physics (non-perturbative QCD) from short-distance physics (perturbative QCD).

μ_R = renormalization scale: renormalization eliminates UV divergences, by reabsorbing the divergences in renormalized quantities.

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

* We used QCD in the standard collinear factorization formalism.

* So far this has been succesfully employed not only to explain ATLAS and CMS results (central pseudorapidities), but even many observables at LHCb (mid-forward pseudorapidities $2 < \eta < 5$).

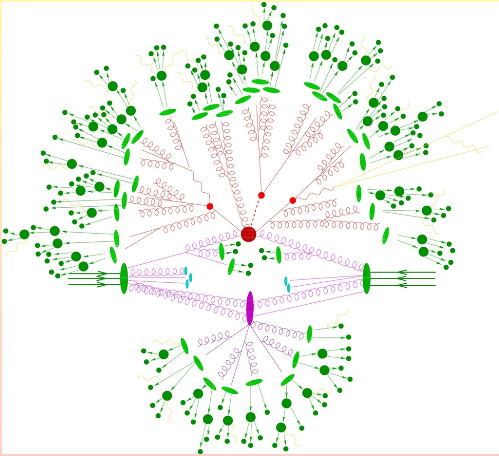
* LHCf is able to investigate in very-forward rapidity regions ($8.4 < \eta < \infty$) the production of γ's, π^0's, neutrons and light neutral hadrons, no charmed charged particles :-(

* total cross-section for $c\bar{c}$ pair hadroproduction using NNLO QCD radiative corrections in pQCD.

* differential cross-section for $c\bar{c}$ pair hadroproduction not yet available at NNLO; use of a NLO QCD + Parton Shower + hadronization + decay approach.

* QCD parameters of computation and uncertainties due to the missing higher orders fixed by looking at the convergence of the perturbative series (LO/NLO/NNLO comparison).

p-p and p-$\bar{\mathrm{p}}$ collision overview (LHC and Tevatron)



$Q = a\ few\ TeV$

- hard scattering
- parton shower
- QED shower

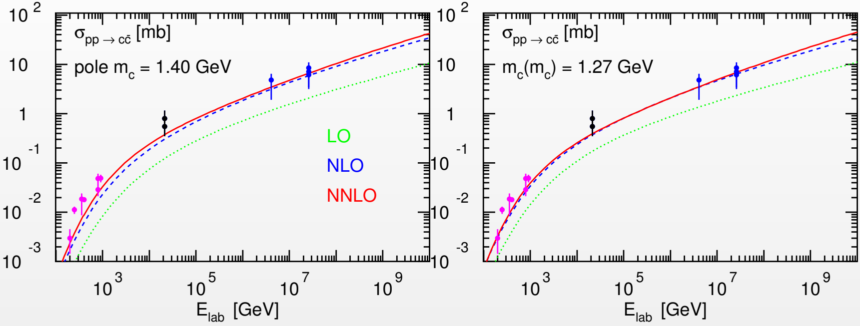
$\Lambda_{QCD} = 200\ \ MeV$

- hadronization
- hadron decay
- underlying event
- pile-up (overlap of different collisions).

DECREASING ENERGY SCALE

PERTURBATIVE AND NON-PERTURBATIVE COMPONENTS

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



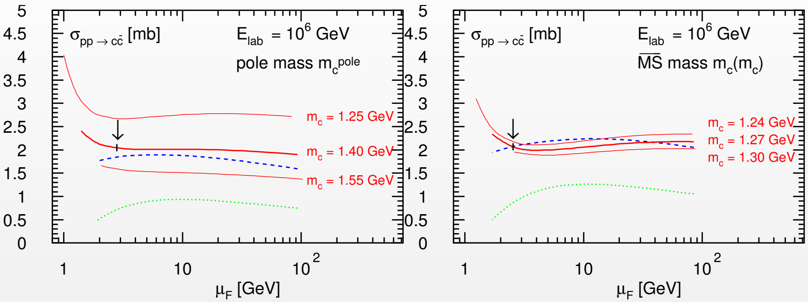
pole mass scheme — running mass scheme

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.

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



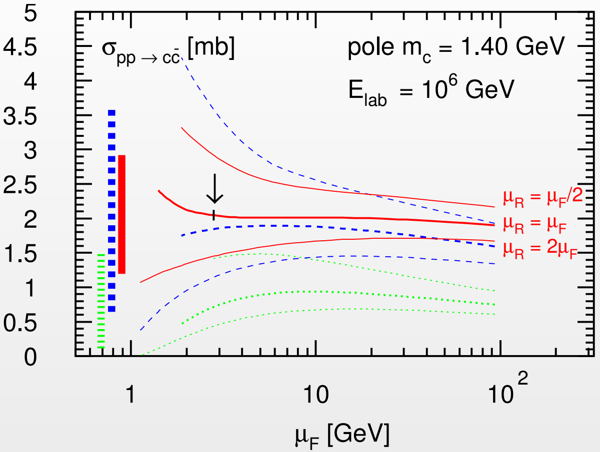
* PDG running mass in the $\bar{MS}$ scheme
  $m_c(m_c) = 1.275 \pm 0.025$ GeV

* Conversion to the pole mass scheme suffers from poor convergence:
  $m_c(m_c) = 1.27 \to m_c^{pole} = 1.48$ at 1-loop
  $m_c(m_c) = 1.27 \to m_c^{pole} = 1.67$ at 2-loop

* Furthermore, accuracy of the pole mass limited to be of the order of $\mathcal{O}(\Lambda_{QCD})$ by the renormalon ambiguity.

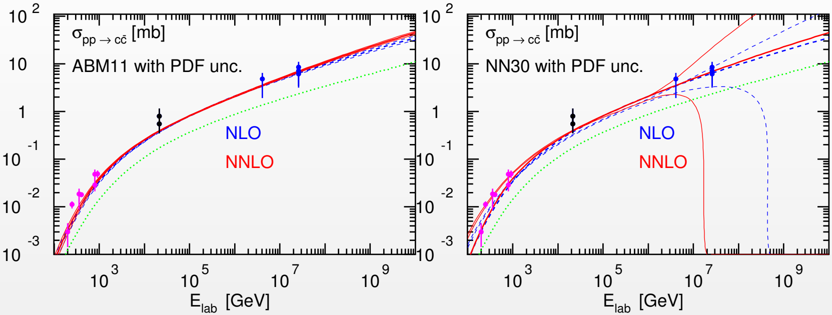
  $\Rightarrow$ We fix $m_c^{pole} = 1.4 \pm 0.15$ GeV. With this choice the cross-section in the pole mass scheme approximately reproduces that in the running mass scheme.

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



- $*$ Minimal sensitivity to radiative corrections is reached at a scale $\mu_R \sim \mu_F \sim 2m_{charm}$.
- $*$ This translates into a dynamical scale $\sqrt{p_{T,charm}^2 + 4m_{charm}^2}$ to better catch dynamics in differential distributions.

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



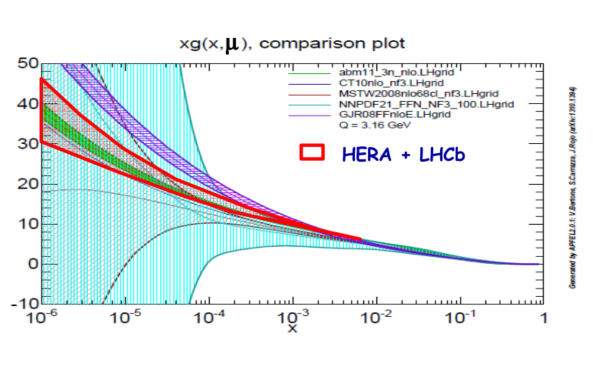
- $*$ Probing higher astrophysical energies allows to probe smaller x region, down to values where no data constrain PDFs yet (at least at present).

- $*$ $f(x, \mu_F^2)$: μ_F^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]]

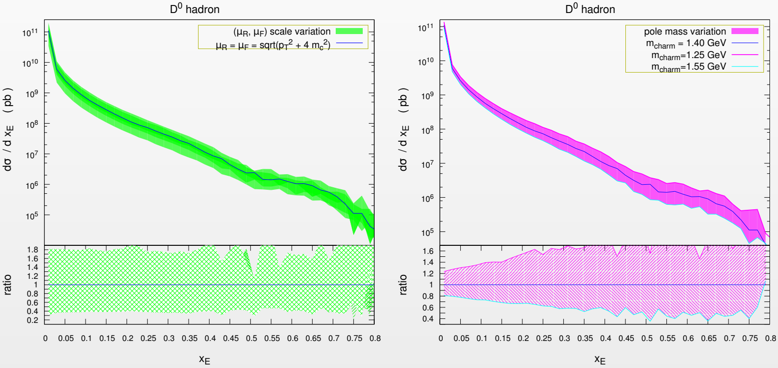
First fit already including some LHCb data (charm and bottom) appeared in arXiv.



* **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: at present still the largest uncertainties, they are working to incorporate PROSA idea in their fit as well (Gauld et al. [arXiv:1506.08025], not yet available in the 3 flavour scheme).

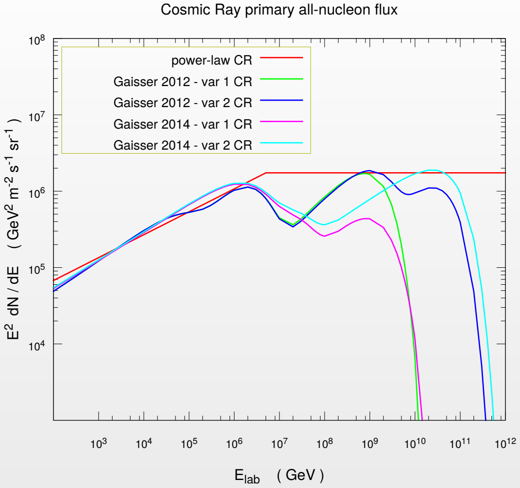
$d\sigma(pp \to c\bar{c} \to D^0 + X)/dx_E$:

scale and mass uncertainties



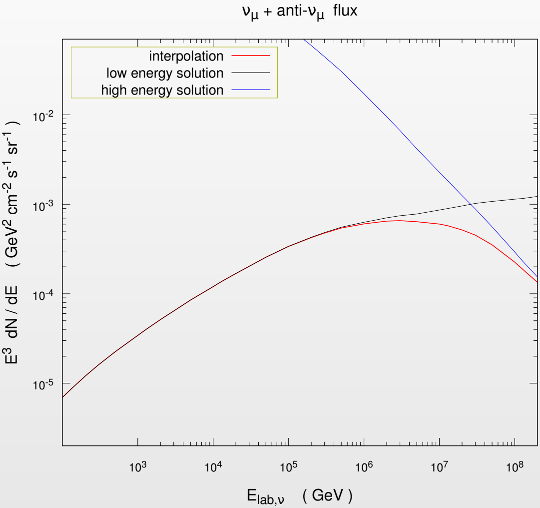
∗ Here plots for *pp* collisions at $E_{p,\,lab} = 10^7$ GeV, shape remains similar at different energies.

The all-nucleon CR spectra: considered hypotheses

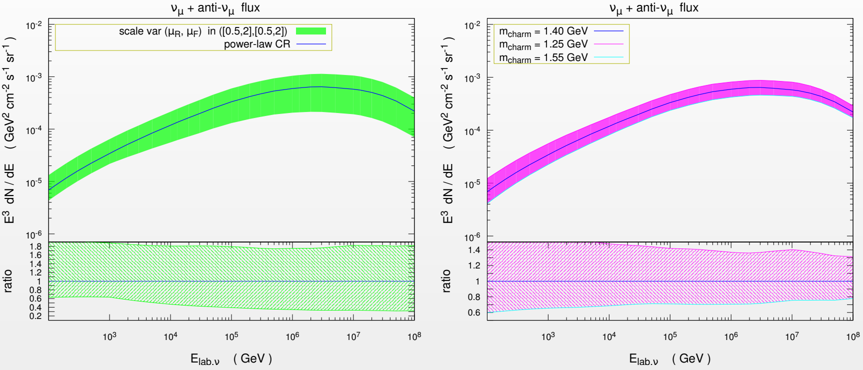


* All-nucleon spectra obtained from all-particles ones under different assumptions as for the CR composition at the highest energies.
* Models with 3 (2 gal + 1 extra-gal) or 4 (2 gal + 2 extra-gal) populations are available.

$(\nu_\mu + \bar{\nu}_\mu)$ fluxes: interpolation between high energy and low energy solutions - power law CR



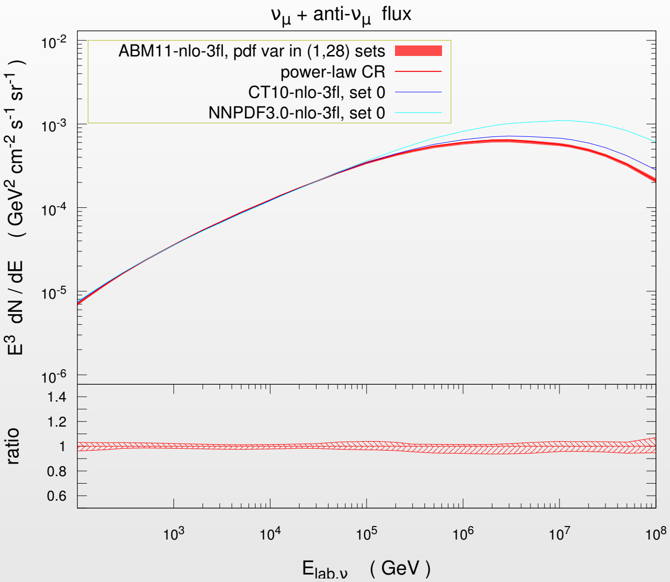
$(\nu_\mu + \bar{\nu}_\mu)$ fluxes: scale and mass variation - power law CR



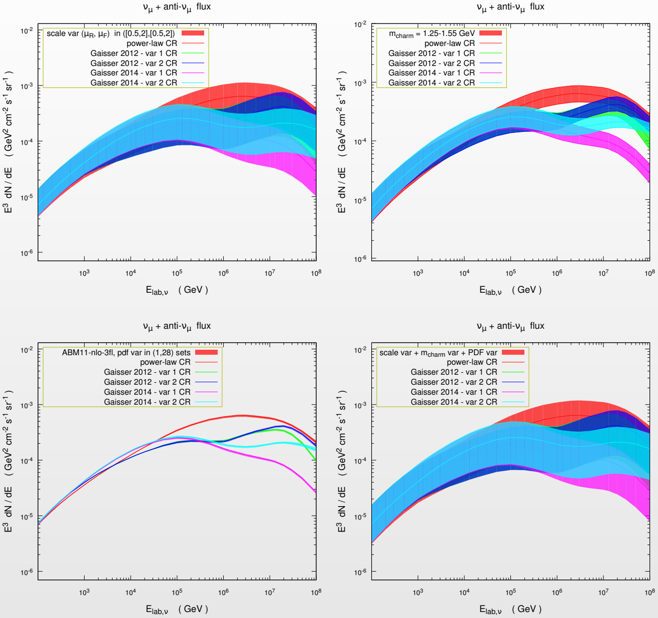
* scale uncertainty slowly changes with $E_{lab,\nu}$,
  it accounts for missing higher orders (pQCD).

* m_{charm} mass uncertainty decreases with increasing $E_{lab,\nu}$,
  because configurations with smaller $x_E = E_{had}/E_p$ become possible.

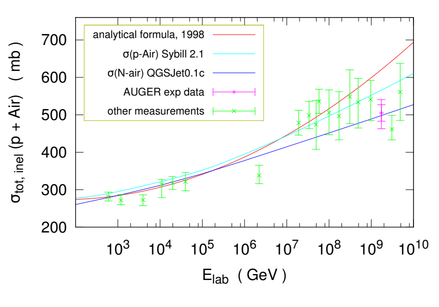
$(\nu_\mu + \bar{\nu}_\mu)$ fluxes: PDF variation - power law CR

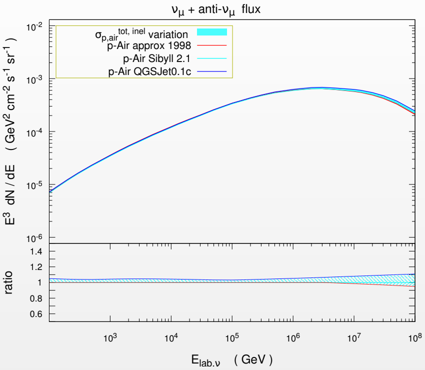


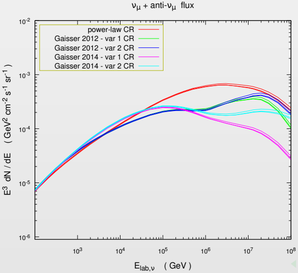
$(\nu_\mu + \bar{\nu}_\mu)$ fluxes: (scale + mass + PDF) variation summary



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





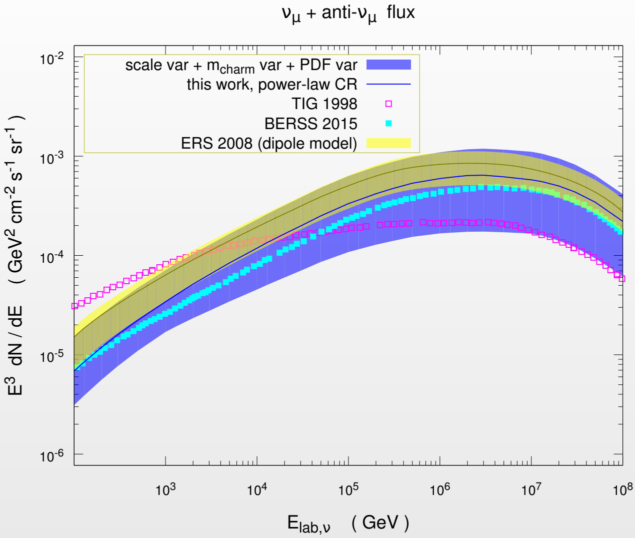


Prompt neutrino flux hadroproduction in the atmosphere: theoretical predictions in literature

* 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

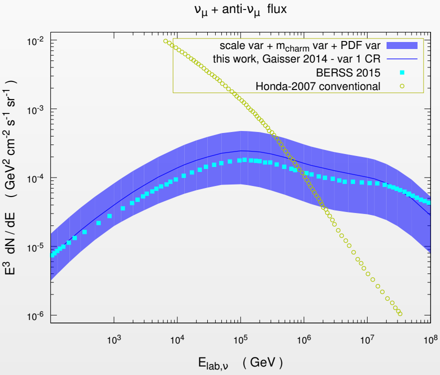
* Updates and recently renewed interest:
  - Bhattacharya, Enberg, Reno et al., JHEP 1506 (2015) 110
  - Fedynitch, Gaisser et al. ICRC 2015, TAUP 2015...
  - Garzelli, Moch, Sigl, JHEP 1510 (2015) 115 $\rightarrow$ **this talk**
  - + other works in preparation......

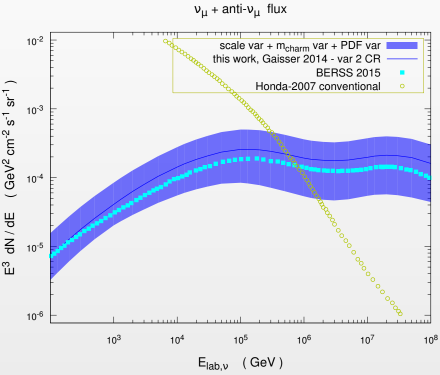
$(\nu_\mu + \bar{\nu}_\mu)$ fluxes: comparison with other predictions



Our uncertainty band is an envelope of theoretical uncertainties, not only normalization but even shape of ν fluxes can change within the envelope.

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





$*$ Our predictions point to a transition energy $E_{trans} = 6^{+12}_{-3} \cdot 10^5$ GeV:

is the last E bin where IceCube have not seen events just filled by prompt ν ?

Conclusions

∗ Prompt lepton fluxes are background for astrophysical high-energy ν seen by in-ice or under-water large volume neutrino telescopes.

∗ We provide a new estimate of the prompt ν component, on the basis of up-to-date QCD theoretical results + recent knowledge in astrophysical CR fluxes.

∗ Our central predictions are in between those recently obtained by pQCD by another group (BERSS 2015) and those previously obtained by the same group (ERS 2008) with a phenomenological dipole model.

∗ We got a sizable uncertainty band, larger than those previously (under)estimated, dominated by QCD renormalization and factorization scale uncertainties very slowly varying with $E_{lab,\nu}$ energy.

∗ At increasing energies above the transition region, the uncertainties on primary cosmic ray origin (galactic/extragalactic) and composition (p/heavy ions) become increasingly more important (and comparable to QCD uncertainty): more investigation is needed from EAS experiments.

∗ A web page with our most recent predictions is available:

http://promptfluxes.desy.de

What Next ? (from the point of view of people providing theoretical predictions for high-energy lepton fluxes)

∗ Further scenarios, on the basis of alternative QCD factorization frameworks, are worth of being explored as well.

∗ Comparisons of predictions from different scenarios are valuable.

∗ Uncertainties on hadronization and on soft and hard multiple particle interactions deserve probably a dedicated study.

∗ Role of nuclear media in modifying properties of the microscopic collisions to be better explored.

∗ Run-I at LHC provided a boost for QCD theory (e.g. NLO QCD revolution, Standard Model confirmed with high precision) and developments will probably continue (e.g. NNLO predictions for hard-scatterings and PDFs, EW effects, new α_S determination, decay properties of heavy-hadrons.....).

∗ Data from Run-I and Run-II at LHC very useful in constraining: PDFs (LHCb, CMS, ATLAS), pp inelastic and elastic cross-sections (TOTEM), role of nuclear media in modifying pp collisions (ALICE), QCD factorization (CMS, ATLAS, LHCb, LHCf).

∗ New hh collider at higher energy (e.g. FCC-hh at $\sqrt{s} = 100\,TeV$) can be necessary as well....: high-energy QCD factorization, low Bjorken-x PDFs, precise determination of heavy-quark masses, New Physics (?).

What Next ? (for CR and ν Telescope experimentalists)

$*$ Provide measurements of cosmic-ray composition, as much as possible independent of the theory, in the energy region above 10^{15} - 10^{16} eV.

$*$ Provide precise measurements of atmospheric lepton fluxes, including the prompt component, independent of the theory.

$*$ In case the uncertainties on these measurements will be smaller than those from theoretical predictions, use astroparticle measurements to constrain QCD and, more generally, the SM: complementarity with respect to collider experiments (LHC and future colliders....).