Charm hadroproduction in the atmosphere, QCD and neutrino astronomy

S. Moch

Universität Hamburg

24th International Workshop on Deep-Inelastic Scattering and Related Subjects, Hamburg, April 12, 2016

Based on work done in collaboration with:

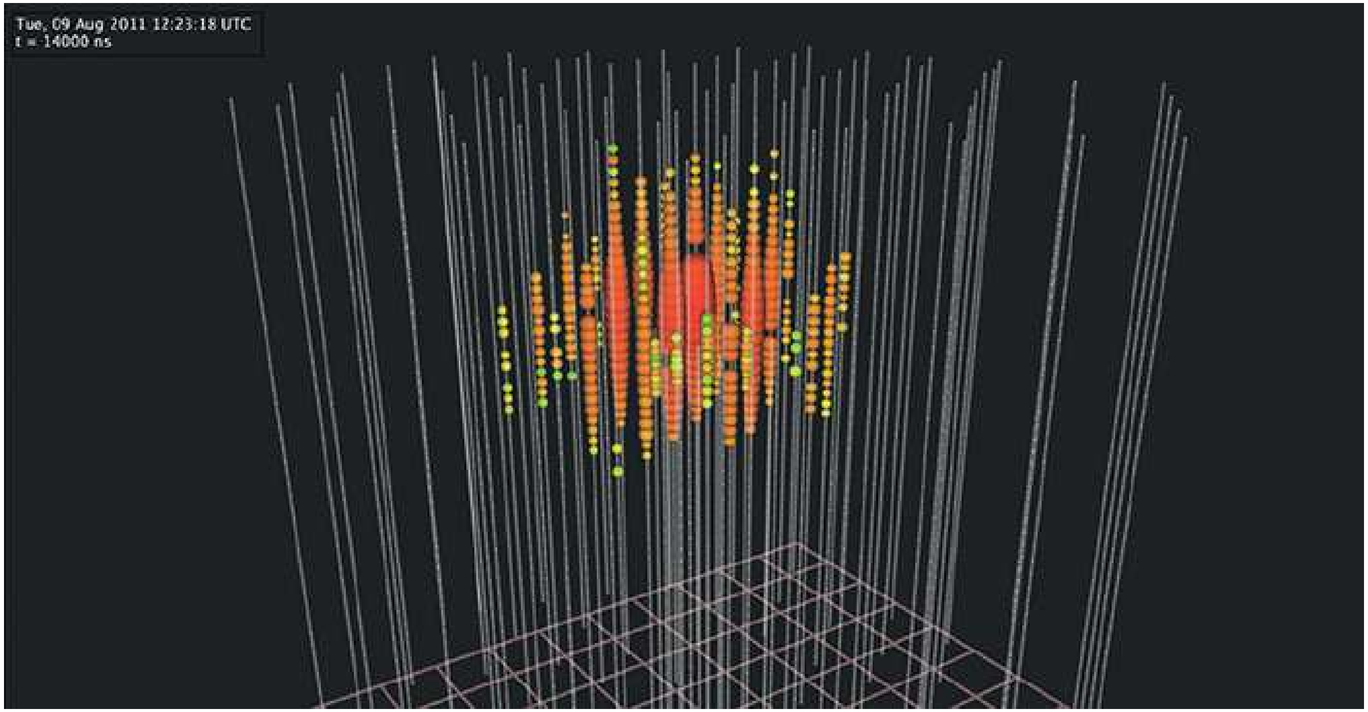
- *Recommendations for PDF usage in LHC predictions*
  A. Accardi, S. Alekhin, J. Blümlein, M.V. Garzelli, K. Lipka, W. Melnitchouk, S. M., J.F. Owens, R. Plačakytė, E. Reya, N. Sato, A. Vogt and O. Zenaiev arXiv:1603.08906

- *Lepton fluxes from atmospheric charm revisited*
  M.V. Garzelli, S. M. and G. Sigl arXiv:1507.01570

Neutrino astronomy (I)

- Observation of astrophysical neutrinos in IceCube
  - neutrino events (significant excess extending to the PeV region)

Cern Courier Dec. 2014 (title cover)

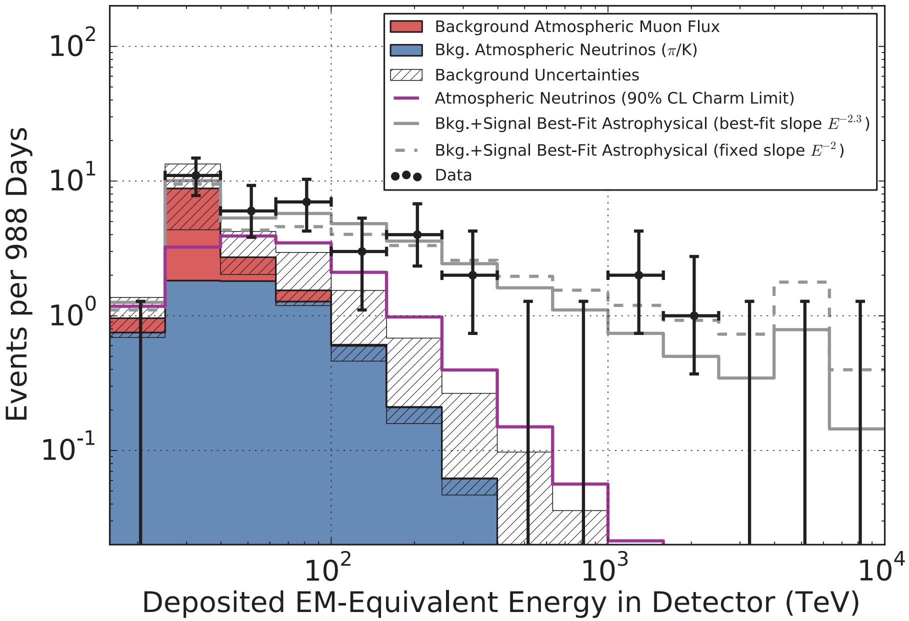


Neutrino astronomy (II)

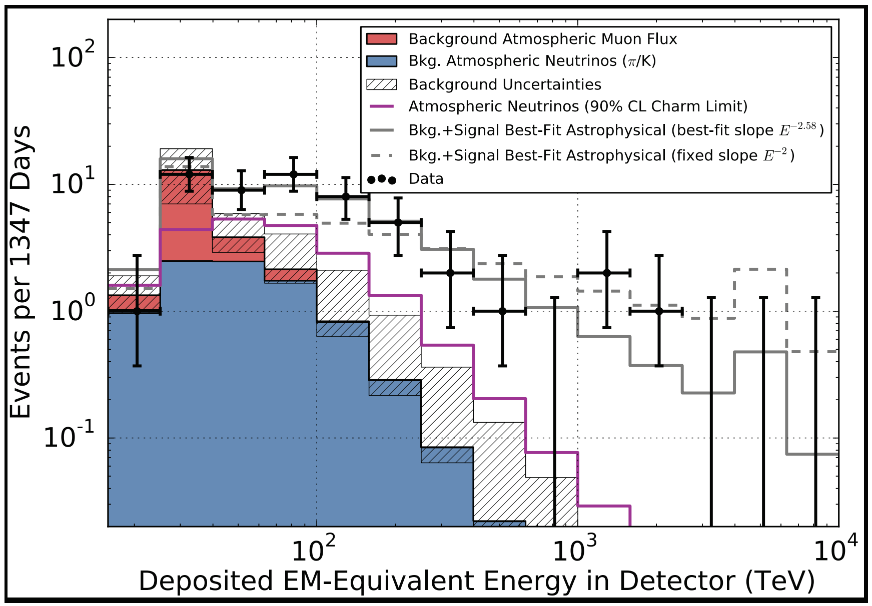
IceCube high-energy events [arXiv:1405.5303] + ICRC 2015

- *2013*: 662-day analysis; 28 candidates in energy range [50 TeV - 2 PeV] (4.1 σ excess over the expected atmospheric background)
- *2014*: 988-day analysis; 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; total of 53 + 1 events, previous energy gap partially filled, (7 σ excess)

figures: C. Kopper @ ICRC2015



2014



2015

Candidate sources

- Various candidate sources for high-energy starting events considered so far in literature

Astrophysical sources

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

Dark matter

- Heavy DM decay, DM-DM annihilation, . . .

Atmospheric leptons

- Cosmic rays + atmospheric nuclei $\to$ hadrons $\to$ neutrinos + X
- Two mechanisms contribute (two different power-law regimes)
  - conventional ν-flux from decay of $\pi^\pm$ and $K^\pm$
  - prompt ν-flux from charmed and heavier hadrons D's, $\Lambda_c^\pm$'s, . . .
  - transition point between conventional and prompt ν-flux still subject of investigation . . .
- Precise predictions/measurements of atmospheric ν-fluxes required as background for any astrophysical or BSM hypothesis

Cascade equations

- Particle evolution through air column of depth X in Earth's atmosphere
  - cascade equations (transport and interaction model for leptons)
  - particle fluxes $\phi_j(E_j, X)$

$$\frac{d\phi_j(E_j,X)}{dX} = -\frac{\phi_j(E_j,X)}{\lambda_{j,\mathrm{int}}(E_j)} - \frac{\phi_j(E_j,X)}{\lambda_{j,\mathrm{dec}}(E_j)} + \sum_{k\neq j} S^{k\to j}_{\mathrm{prod}} + \sum_{k\neq j} S^{k\to j}_{\mathrm{decay}} + S^{k\to j}_{\mathrm{reg}}$$

- System of coupled differential equations regulating particle evolution in atmosphere (interaction/decay/(re)generation) reviews in Gaisser '90; Lipari '93
- Z-moments for approximate analytical solutions
  - assume X dependence of fluxes factorizes from E dependence
  - particle production:

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

  - particle decay:

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

Z-moments

Heavy hadron production

- Z-moments for intermediate hadron production
  - cosmic ray + Air interactions producing heavy hadrons (including charm) described with pp-collisions
  - integration variable: $x_E = E_h/E_p$

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

charm quark hadro-production

Heavy hadron decay

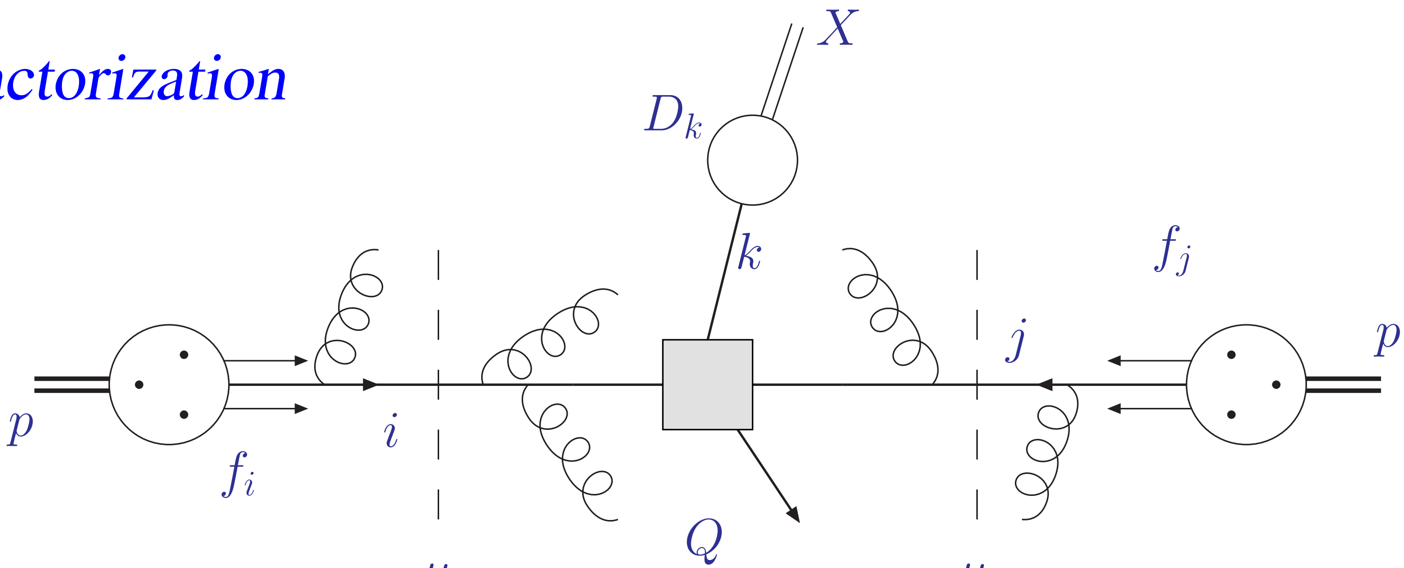
- Z-moments for intermediate hadron decay
  - hadrons in cascade decay semileptonically $h \to \nu_l + l + X$
  - integration variable: $x'_E = E_l/E_h$

$$Z_{hl}(E_l) = \int dx'_E \frac{\phi_h(E_l/x_{E'})}{\phi_h(E_l)} F_{h\to l}(x'_E)$$

Charm quark hadro-production

- Perturbative charm production contributes to prompt atmospheric neutrino flux

QCD factorization

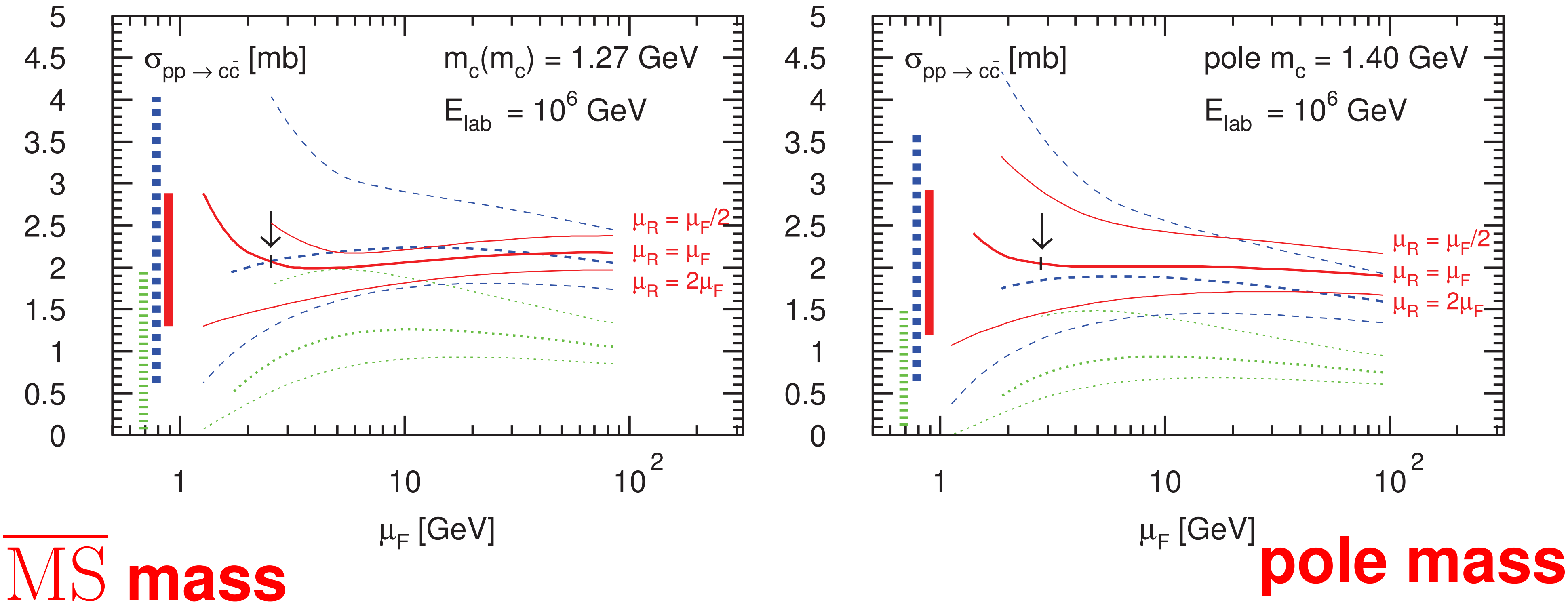


$$\sigma_{pp\to X} = \sum_{ij} f_i(\mu^2) \overset{\mu}{\otimes} f_j(\mu^2) \otimes \hat{\sigma}_{ij\to X}\left(\alpha_s(\mu^2), Q^2, \mu^2, m_X^2\right)$$

- Hard parton cross section $\hat{\sigma}_{ij\to X}$ calculable in perturbation theory
  - cross section $\hat{\sigma}_{ij\to k}$ for parton types i, j and hadronic final state X
- Non-perturbative parameters: parton distribution functions f_i, strong coupling α_s, particle masses m_X

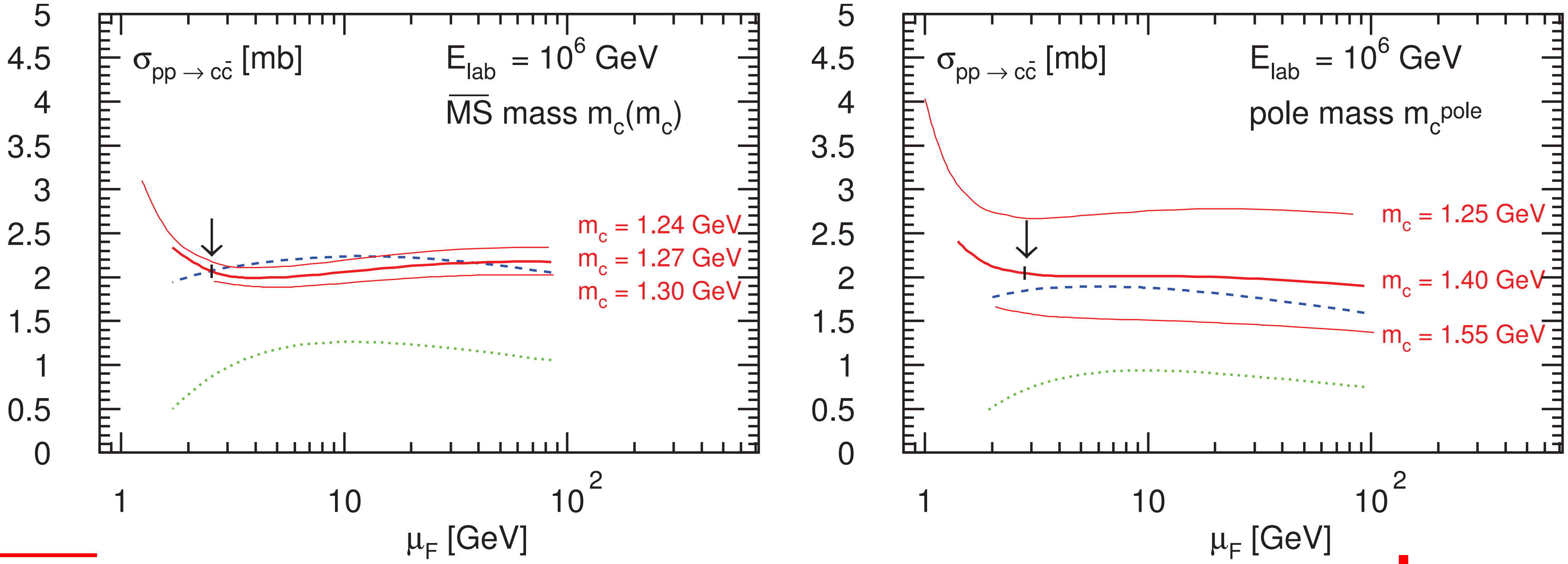
Charm quark hadro-production (I)

- Theory predictions for charm hadro-production
- NNLO cross section with running charm mass $m_c(m_c)$ significantly improved
  - good apparent convergence of perturbative expansion
  - small theoretical uncertainity from scale variation



Charm quark hadro-production (II)

- Scale choice by comparison of NLO and NNLO cross sections
  - minimal sensitivity at renormalization and factorization scale
    $\mu_R, \mu_F = 2m_c(m_c)$

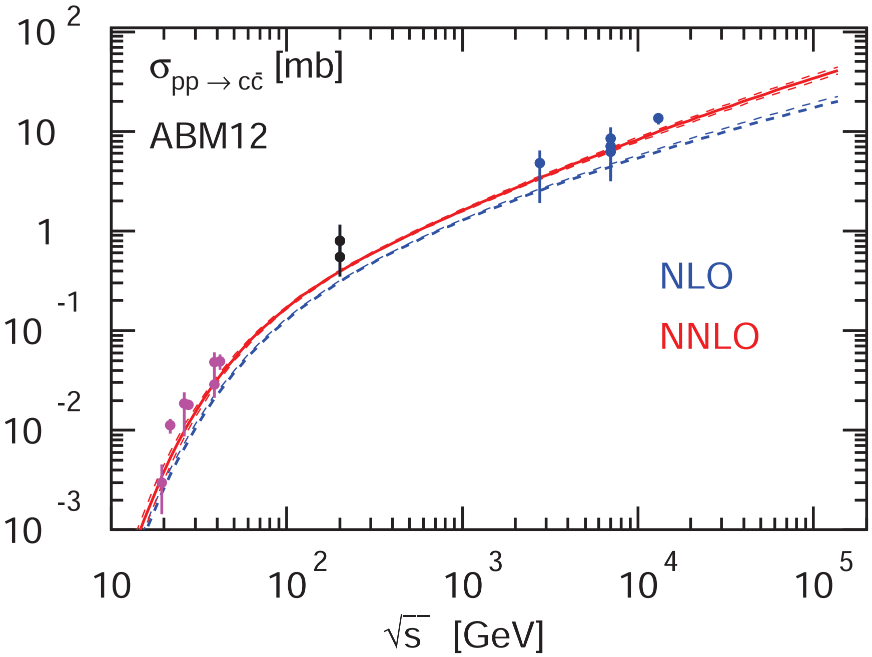


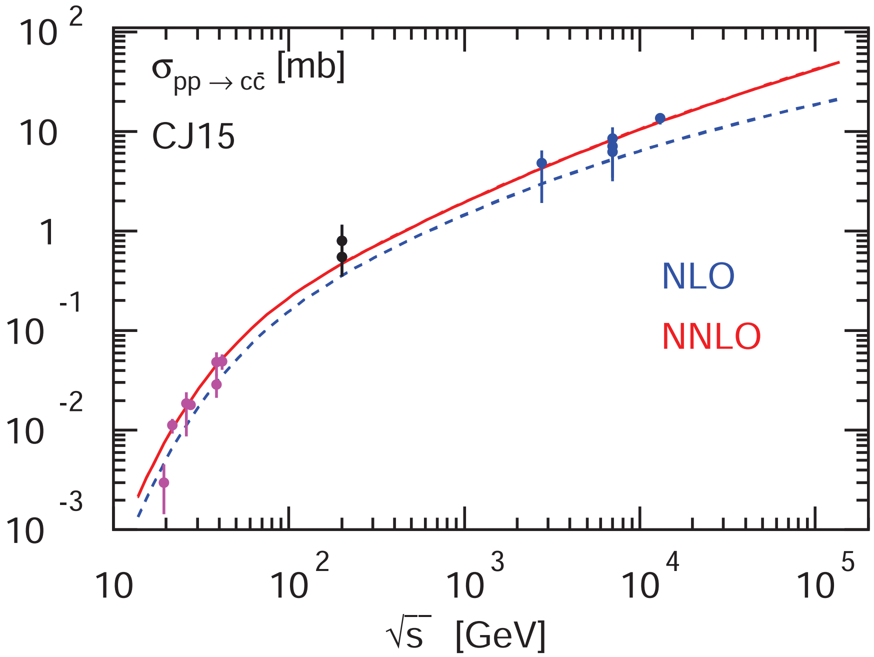
$\overline{\text{MS}}$ **mass**

pole mass

Parton distribution functions (I)

- Charm-quark hadro-production at high energies
  - quark-gluon parton luminositiy dominates
- Gluon PDF at small-x
  - fits yield $xg(x) \simeq x^a$ with $a \simeq -0.2$
  - kinematic coverage of data down to $x \simeq 10^{-5}$
- Predictions compatible with LHC measurements (Alice, ATLAS, LHCb)

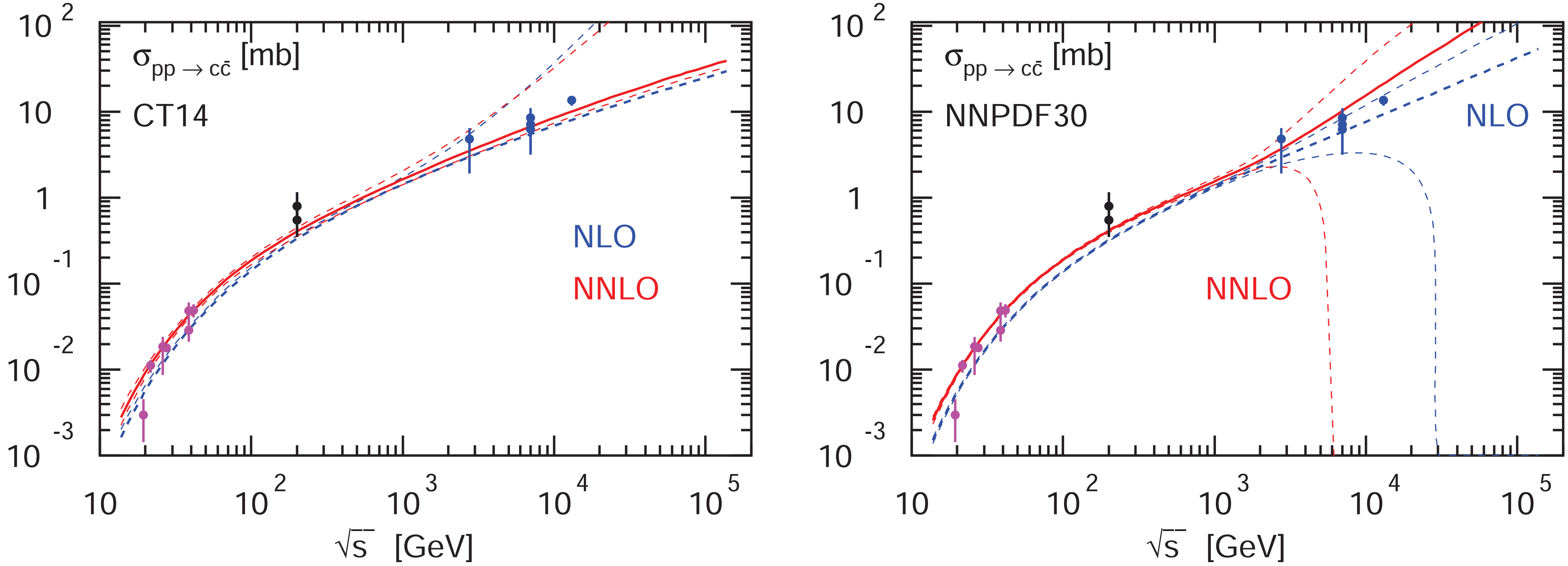




Parton distribution functions (II)

Issues

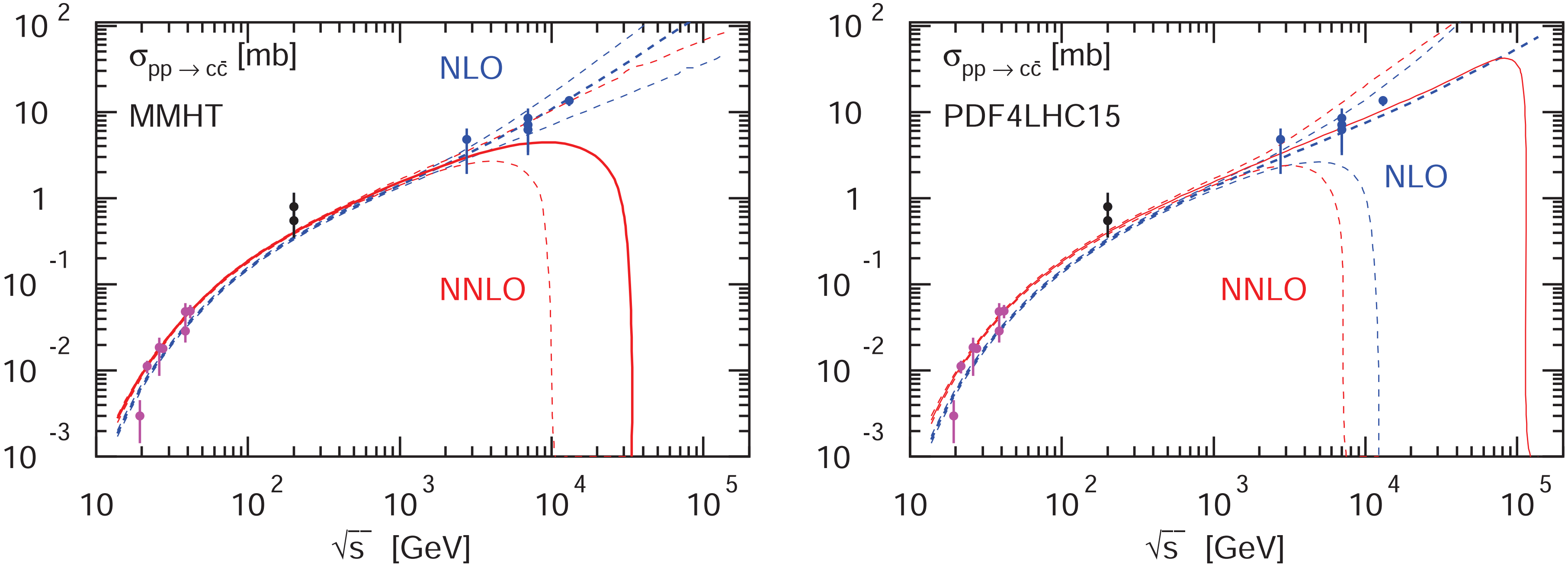
- Extrapolation of gluon PDF towards smaller x
  - some PDFs feature large uncertainities for extrapolation to unmeasured regions $\longrightarrow$ this invalidates predictive potential



Parton distribution functions (III)

More issues

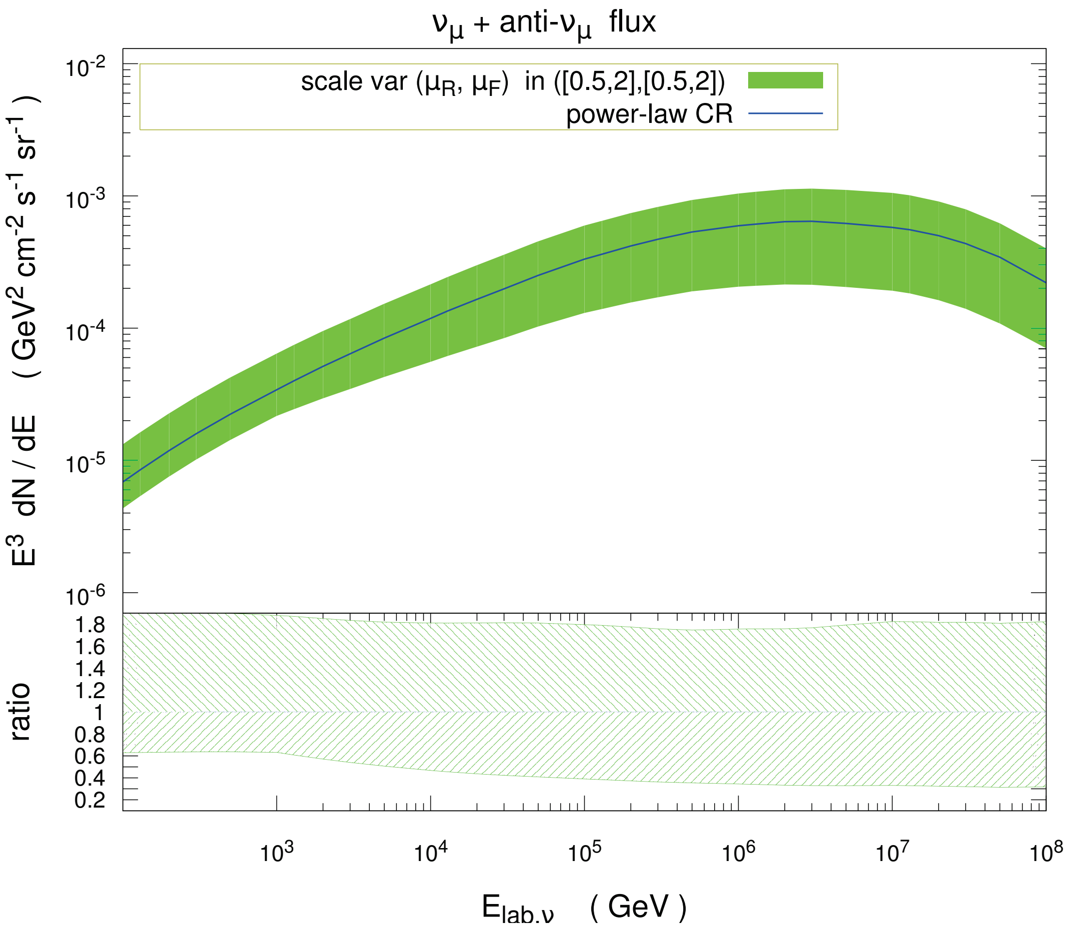
- Some PDFs predict negative gluon PDF at small-x and low scales
  - unphysical feature as consequence of modelling in variable flavor number schemes applied
  - large differences between gluon PDFs fitted at NLO and NNLO



Neutrino flux (I)

Result from cascade equations

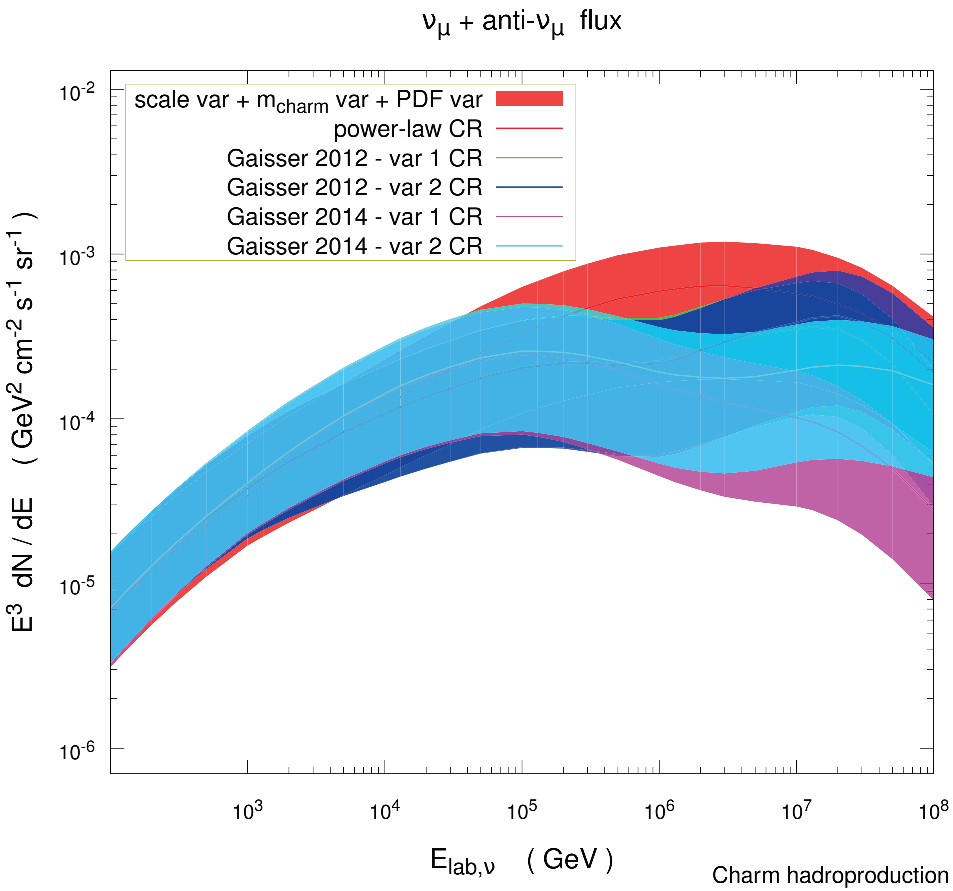
- $\nu_\mu + \bar{\nu}_\mu$-fluxes as function of neutrino energy $E_{lab,\,\nu}$
  - uncertainties from μ_R, μ_F scale variation
  - power law spectrum for initial flux of cosmic rays



Neutrino flux (II)

Summary of main uncertainties for $\nu_\mu + \bar{\nu}_\mu$-fluxes

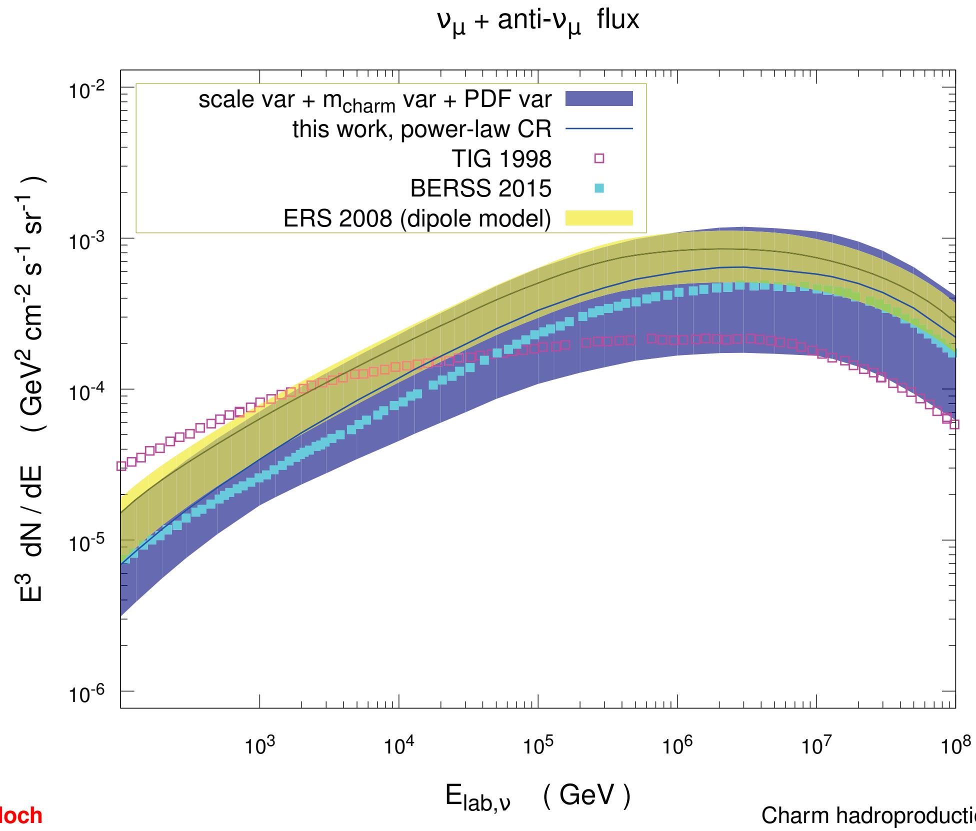
- QCD uncertainties due to μ_R, μ_F scale and charm mass variation
  - PDF and α_s uncertainties from ABM11
- Astrophysical uncertainties illustrated with five primary cosmic ray spectra
  - dominant uncertainty for large neutrino energies $E_{lab,\,\nu}$



Neutrino flux (III)

Comparison to previous estimates

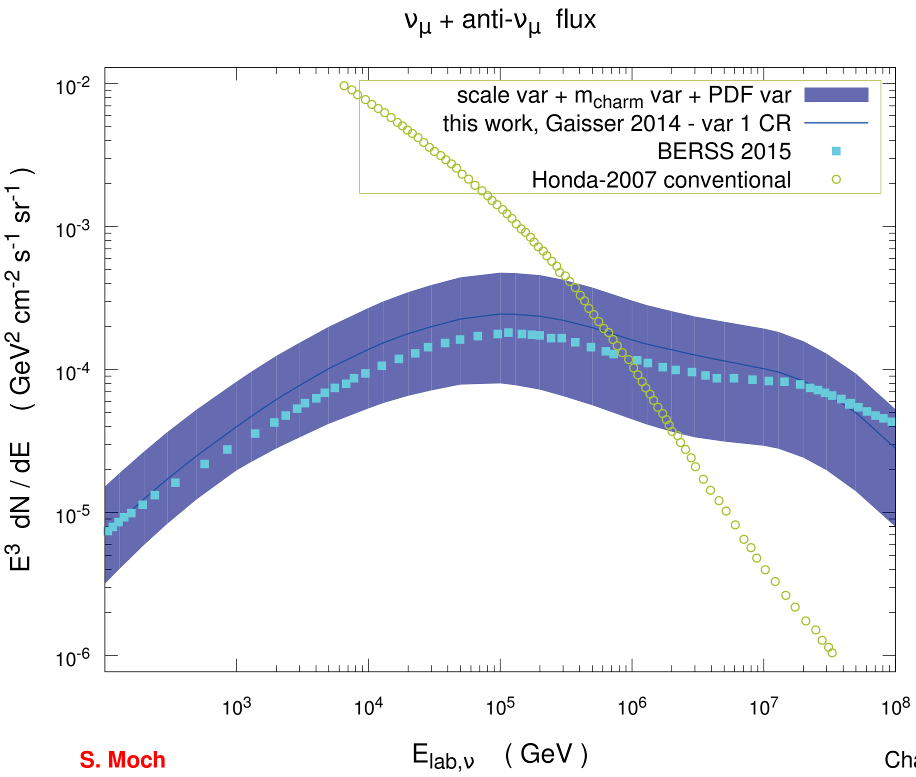
- Power-law primary cosmic ray spectrum for prompt $\nu_\mu + \bar{\nu}_\mu$-fluxes
- Comparison with
  - TIG flux Gondolo, Ingelman, Thunman '95
  - ERS central flux Enberg, Reno, Sarcevic '08 and uncertainties
  - BERSS flux Bhattacharya, Enberg, Reno, Sarcevic, Stasto '15

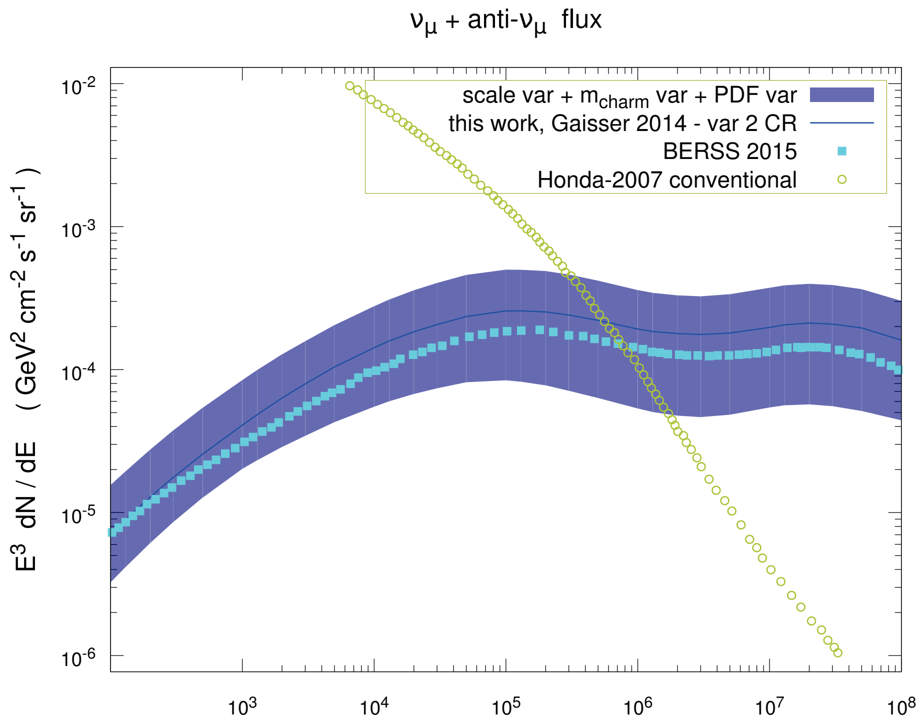


Neutrino flux (IV)

Conventional and prompt $\nu_\mu + \bar{\nu}_\mu$-fluxes

- Recent primary cosmic ray spectra
  Gaisser-2014-variant 1 (left) and Gaisser-2014-variant 2 (right)
- Comparison of prompt $\nu_\mu + \bar{\nu}_\mu$-fluxes with BERSS flux Bhattacharya, Enberg, Reno, Sarcevic, Stasto '15
- Conventional neutrino flux Honda, Kajita, Kasahara, Midorikawa, Sanuki'06
  (reweighted to account for the cosmic ray spectrum of Gaisser-2014-variant 1)





Summary

- Neutrino fluxes are several tens percent larger than previous predictions
  - increase of prompt $\nu_\mu + \bar{\nu}_\mu$-flux amounts to some 40% at IceCube energies
- QCD uncertainties dominate at low neutrino energies
  - sizeable uncertainties due to renormalization and factorization scale variation
  - charm quark mass dependence significant
  - not all PDF sets are appropriate for extrapolations to high energies
- astrophysical uncertainties (primary cosmic ray flux) important for increasing energies $E_{lab,\,\nu} \gtrsim 10^5 - 10^6$ GeV