# *Charm hadroproduction in the atmosphere, QCD and neutrino astronomy*

**S. Moch**

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DESY Workshop *Loops and Legs in Quantum Field Theory*, Leipzig, April 28, 2016

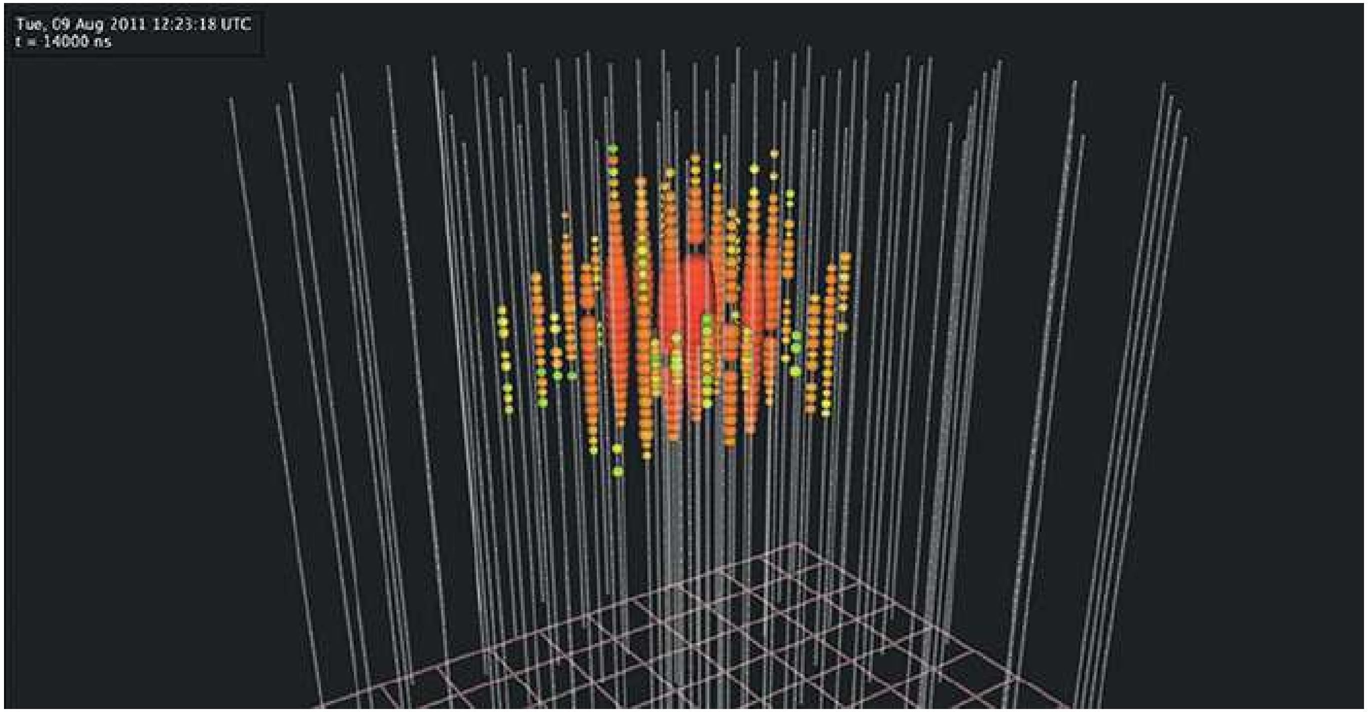
## *Based on work done in collaboration with:*

- *Lepton fluxes from atmospheric charm revisited*
  M.V. Garzelli, S. M. and G. Sigl arXiv:1507.01570
- *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
- *Impact of heavy-flavour production cross sections measured by the LHCb experiment on parton distribution functions at low x*
  PROSA Collaboration: O. Zenaiev, A. Geiser, K. Lipka, J. Blümlein, A. Cooper-Sarkar, M.V. Garzelli, M. Guzzi, O. Kuprash, S. M. P. Nadolsky, R. Plačakytė, K. Rabbertz, I. Schienbein, P. Starovoitov arXiv:1503.04581

# *Neutrino astronomy (I)*

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

Cern Courier Dec. 2014 (title cover)

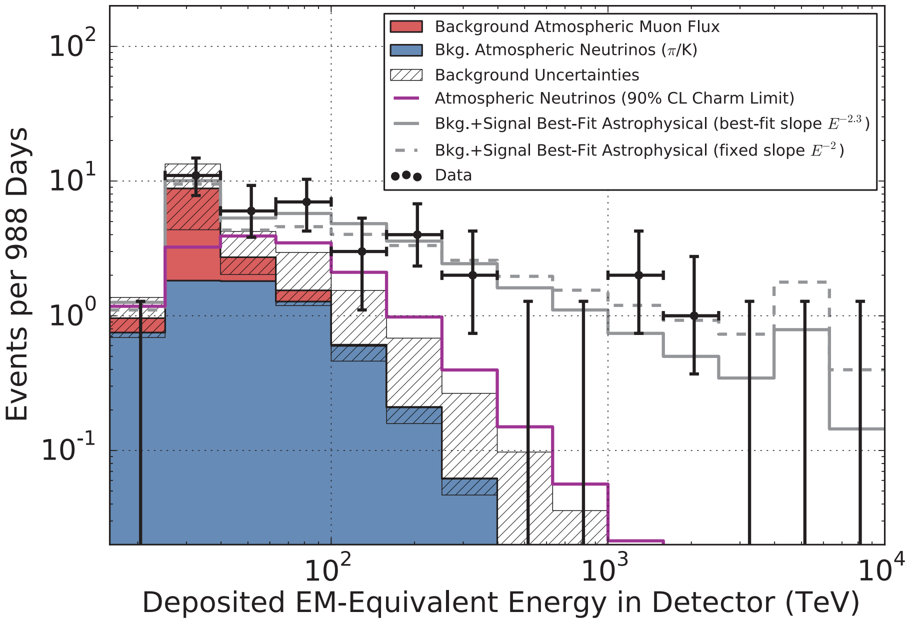


# *Neutrino astronomy (II)*

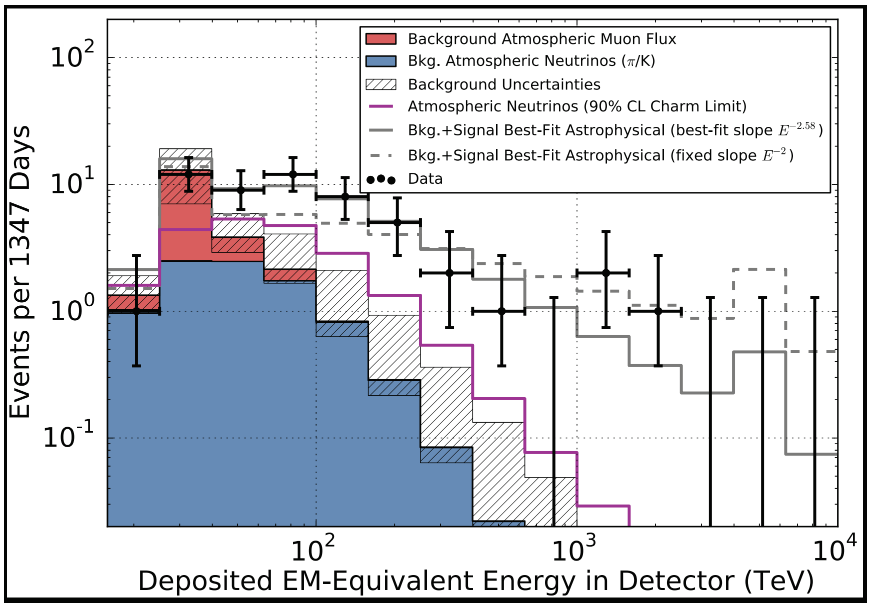
## *IceCube high-energy events* [arXiv:1405.5303] + ICRC 2015

- *2013*: 662-day analysis; 28 candidates in energy range [50 TeV - 2 PeV] (4.1 $\sigma$ excess over the expected atmospheric background)
- *2014*: 988-day analysis; total of 37 events with energy [30 TeV - 2 PeV] (5.7 $\sigma$ 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 $\sigma$ 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 $\nu$-flux from decay of $\pi^\pm$ and $K^\pm$
  - prompt $\nu$-flux from charmed and heavier hadrons $D$'s, $\Lambda_c^\pm$'s, . . .
  - transition point between conventional and prompt $\nu$-flux still subject of investigation . . .
- Precise predictions/measurements of atmospheric $\nu$-fluxes required as background for any astrophysical or BSM hypothesis

# *Atmospheric leptons*

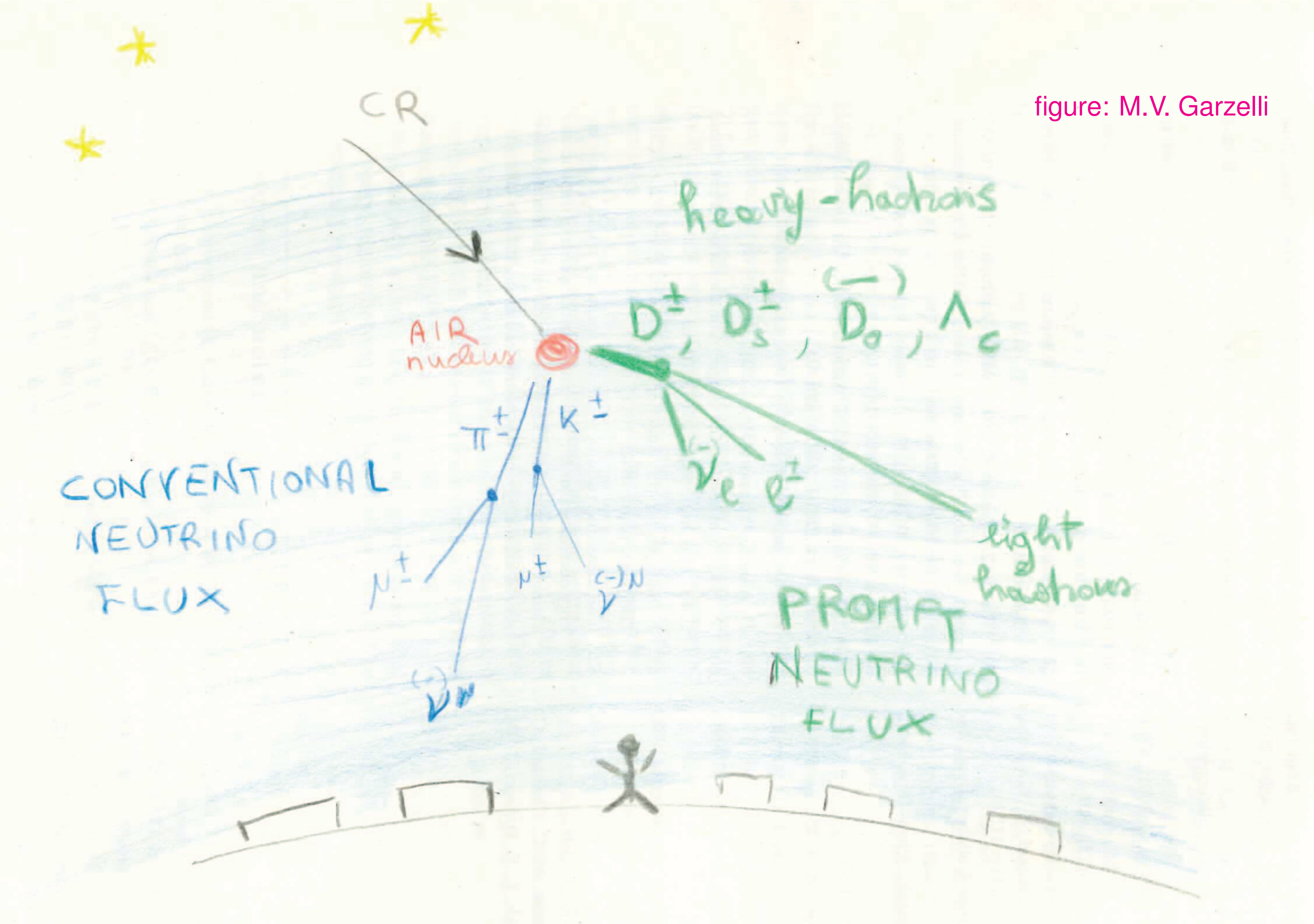



figure: M.V. Garzelli

# *Cascade equations*

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

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

- System of coupled differential equations regulating particle evolution in atmosphere (interaction/decay/(re)generation) reviews in Gaisser '90; Lipari '93
- Energy spectrum from semi-leptonic decay products depends on hadronic critical energy $E_{\mathrm{crit}}$
  - below $E_{\mathrm{crit}}$ decay probability is bigger than interaction probability
- Approximate analytical solutions in terms of $Z$-moments
  - assume $X$ dependence of fluxes factorizes from $E$ dependence
  - particle production:

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

# Cascade equations

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

# $Z$-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: $x_E = E_h/E_p$

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

*charm quark hadro-production*

## Heavy hadron decay

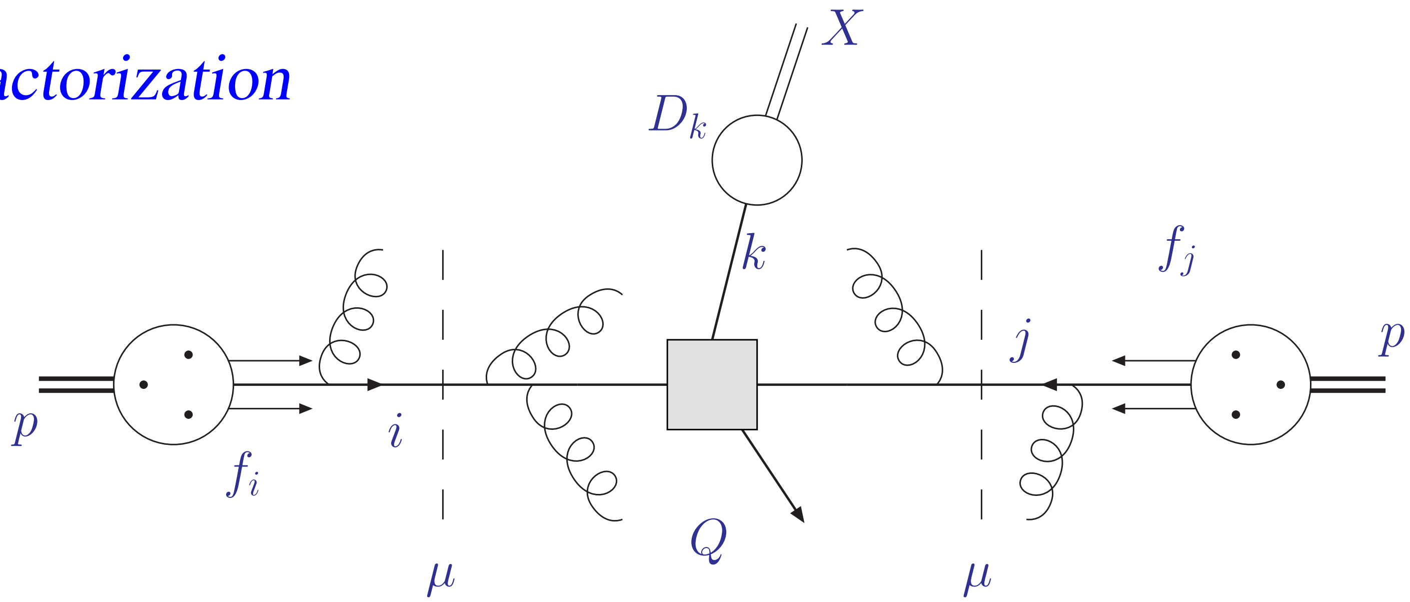
- $Z$-moments for intermediate hadron decay
  - hadrons in cascade may decay semileptonically $h \to \nu_l + l + X$
  - integration variable: $x'_E = E_l/E_h$

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

# Charm quark hadro-production

- Perturbative charm production contributes to prompt atmospheric neutrino flux

## QCD factorization

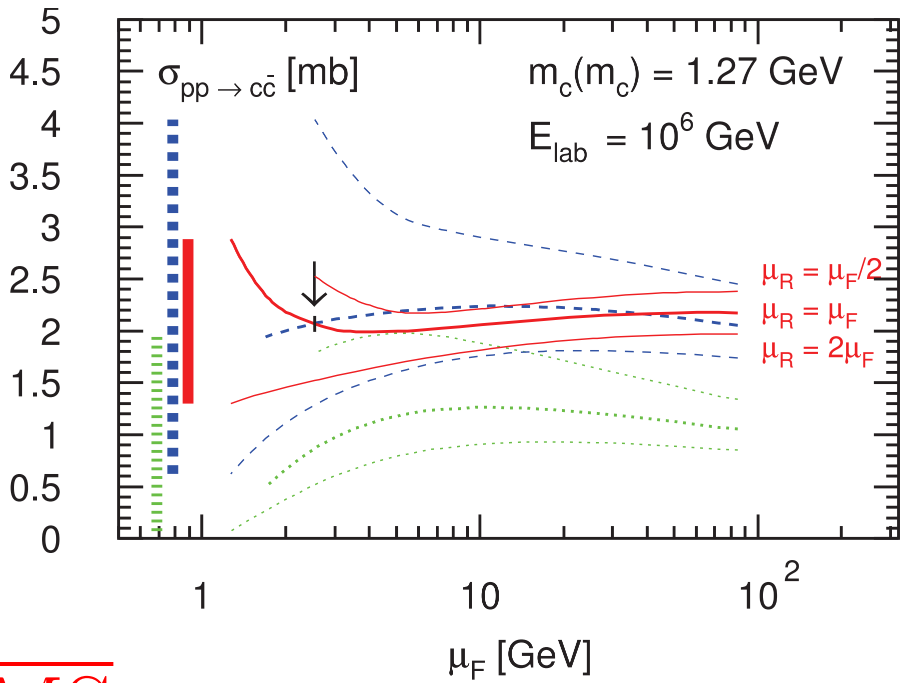



$$\sigma_{pp \to X} = \sum_{ij} f_i(\mu^2) \otimes f_j(\mu^2) \otimes \hat{\sigma}_{ij \to X}\left(\alpha_s(\mu^2), Q^2, \mu^2, m_X^2\right)$$

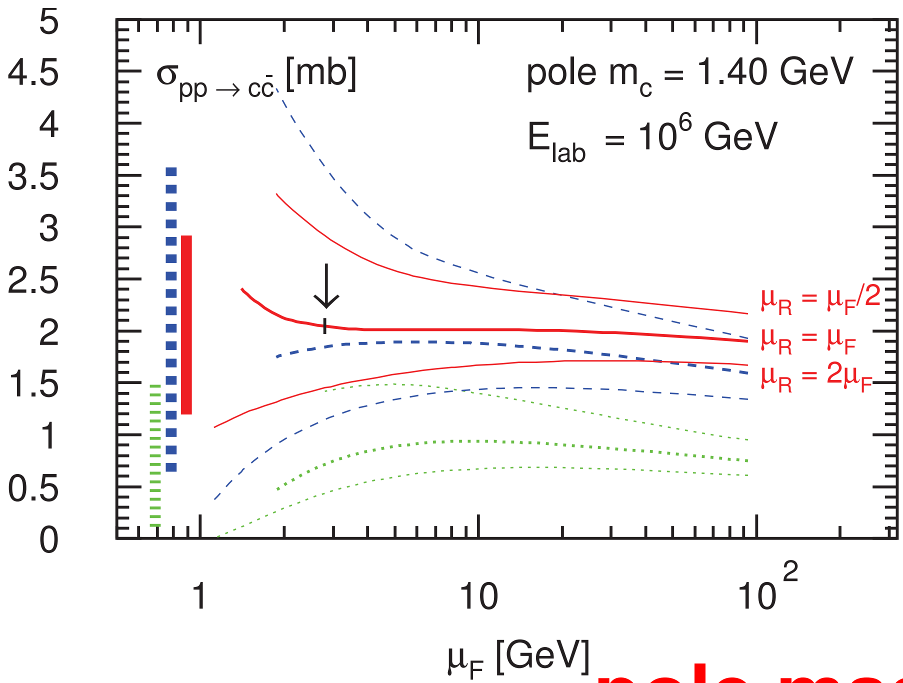
- Hard parton cross section $\hat{\sigma}_{ij \to X}$ calculable in perturbation theory
  - cross section $\hat{\sigma}_{ij \to k}$ for parton types $i$, $j$ and hadronic final state $X$
- Non-perturbative parameters: parton distribution functions $f_i$, fragmentation functions $D_k$, strong coupling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



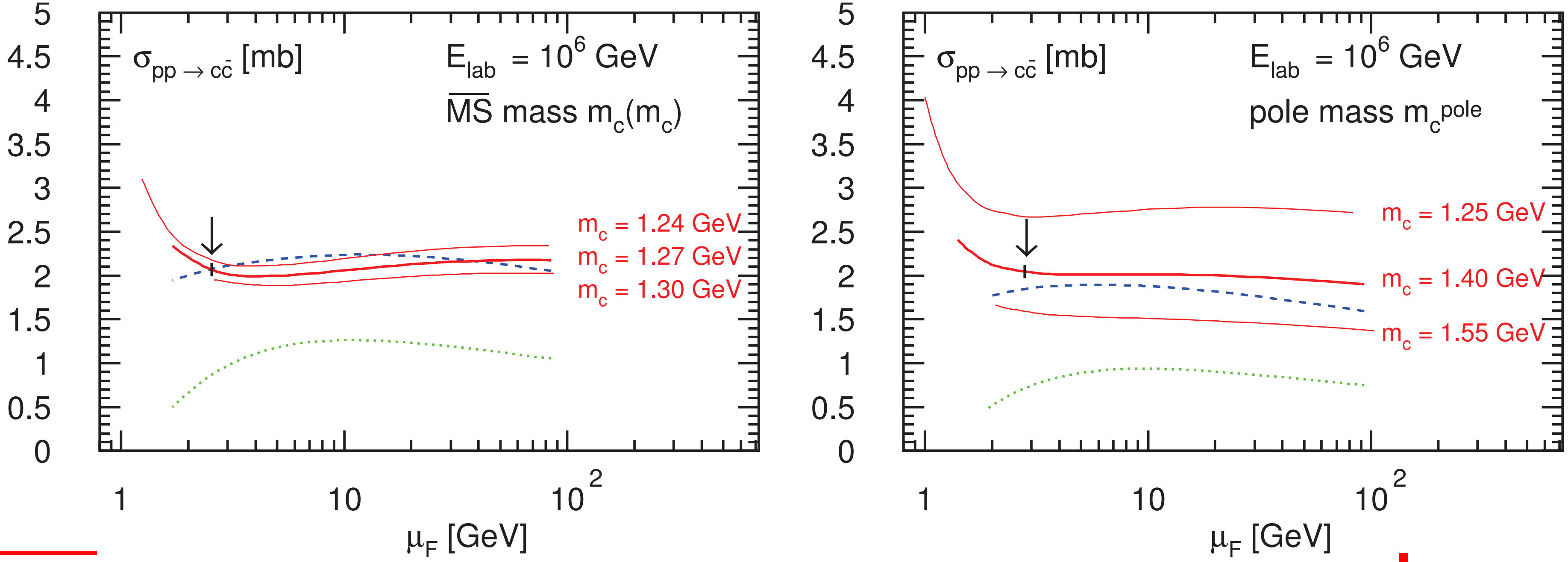

$\overline{\text{MS}}$ **mass**




**pole mass**

# *Charm quark hadro-production (II)*

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

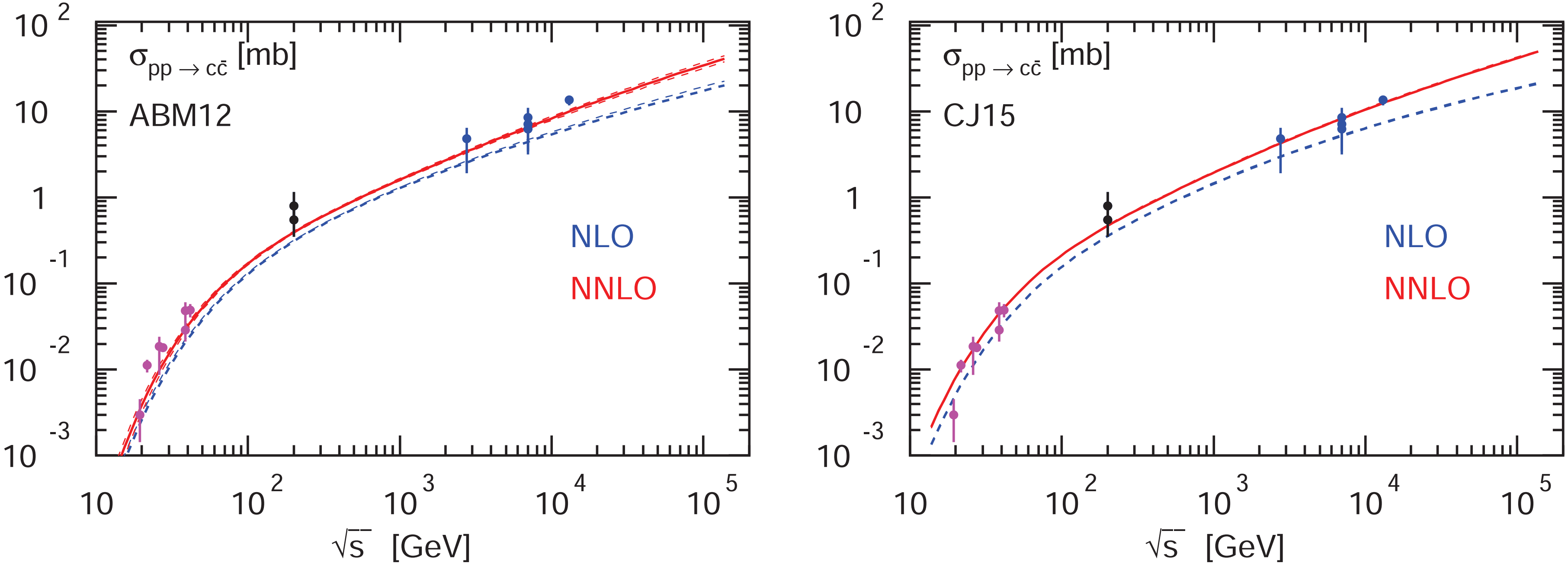



$\overline{\rm MS}$ **mass**

**pole mass**

# *Parton distribution functions (I)*

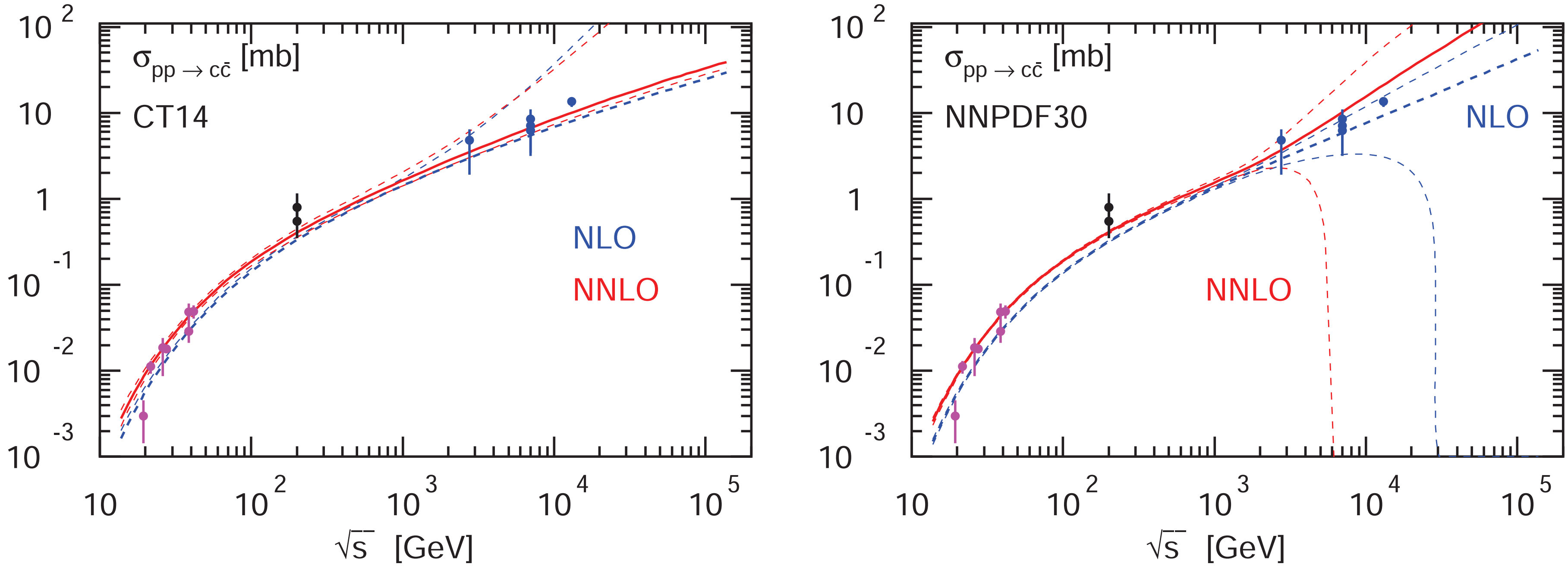
- Charm-quark hadro-production at high energies
  - quark-gluon parton luminosity dominates
- Gluon PDF at small-$x$
  - fits yield $xg(x) \simeq x^a$; e.g. $a \simeq -0.2$ in ABM12
  - kinematic coverage of data down to $x \simeq 10^{-5}$ (DIS structure function $F_L$)
- Predictions compatible with LHC measurements (Alice, ATLAS, LHCb)



# *Parton distribution functions (II)*

## *Issues*

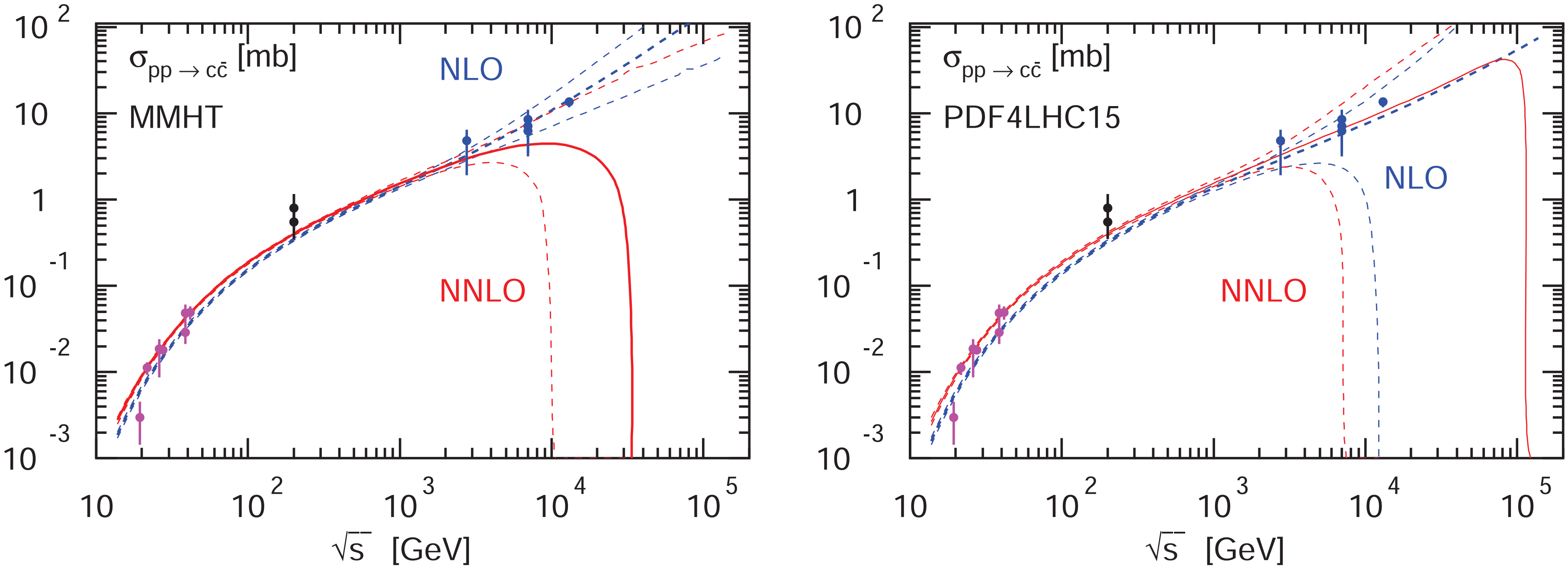
- Extrapolation of gluon PDF towards smaller $x$
  - some PDFs feature large uncertainities for extrapolation to unmeasured regions $\longrightarrow$ this invalidates predictive potential



# *Parton distribution functions (III)*

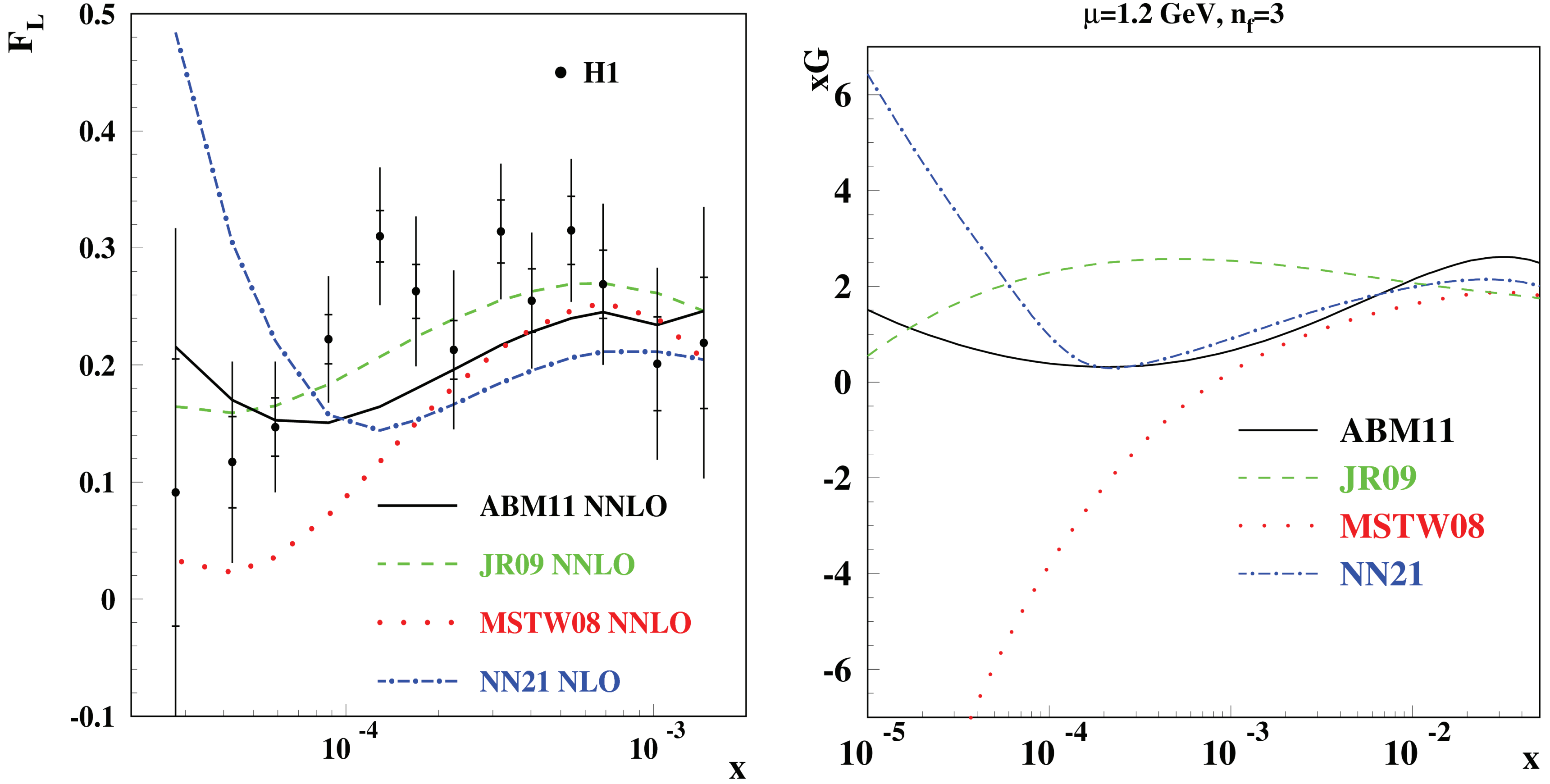
## *More issues*

- Some PDFs predict negative gluon PDF at small-$x$ and low scales $\mu_F \simeq 2m_c$
  - negative cross section is unphysical; consequence of modelling in variable flavor number schemes applied and description of structure function $F_L$ at NNLO
  - large differences between gluon PDFs fitted at NLO and NNLO



# *Longitudinal structure function*

## Discrimination of the small-x gluons

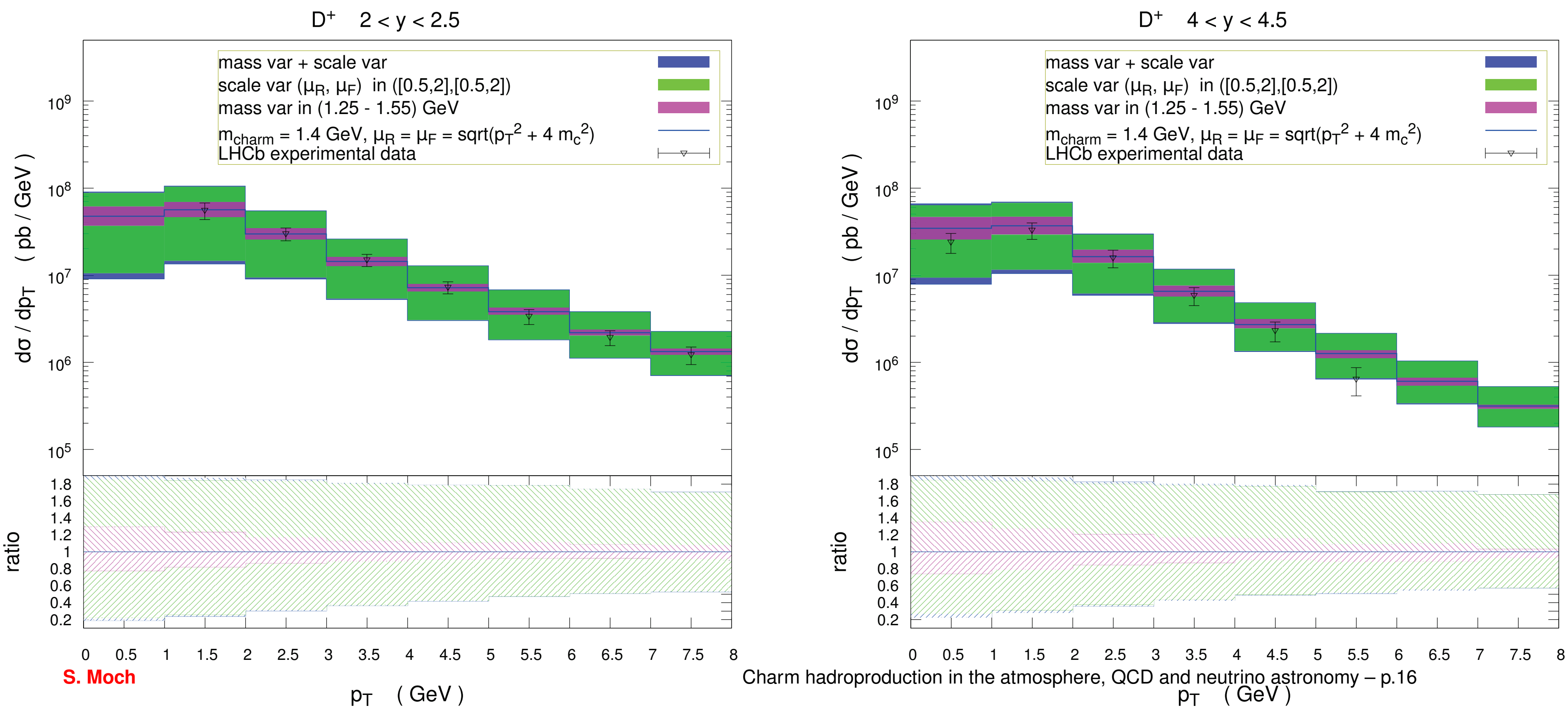



Slide from S. Alekhin

# LHCb data on charmed mesons (I)

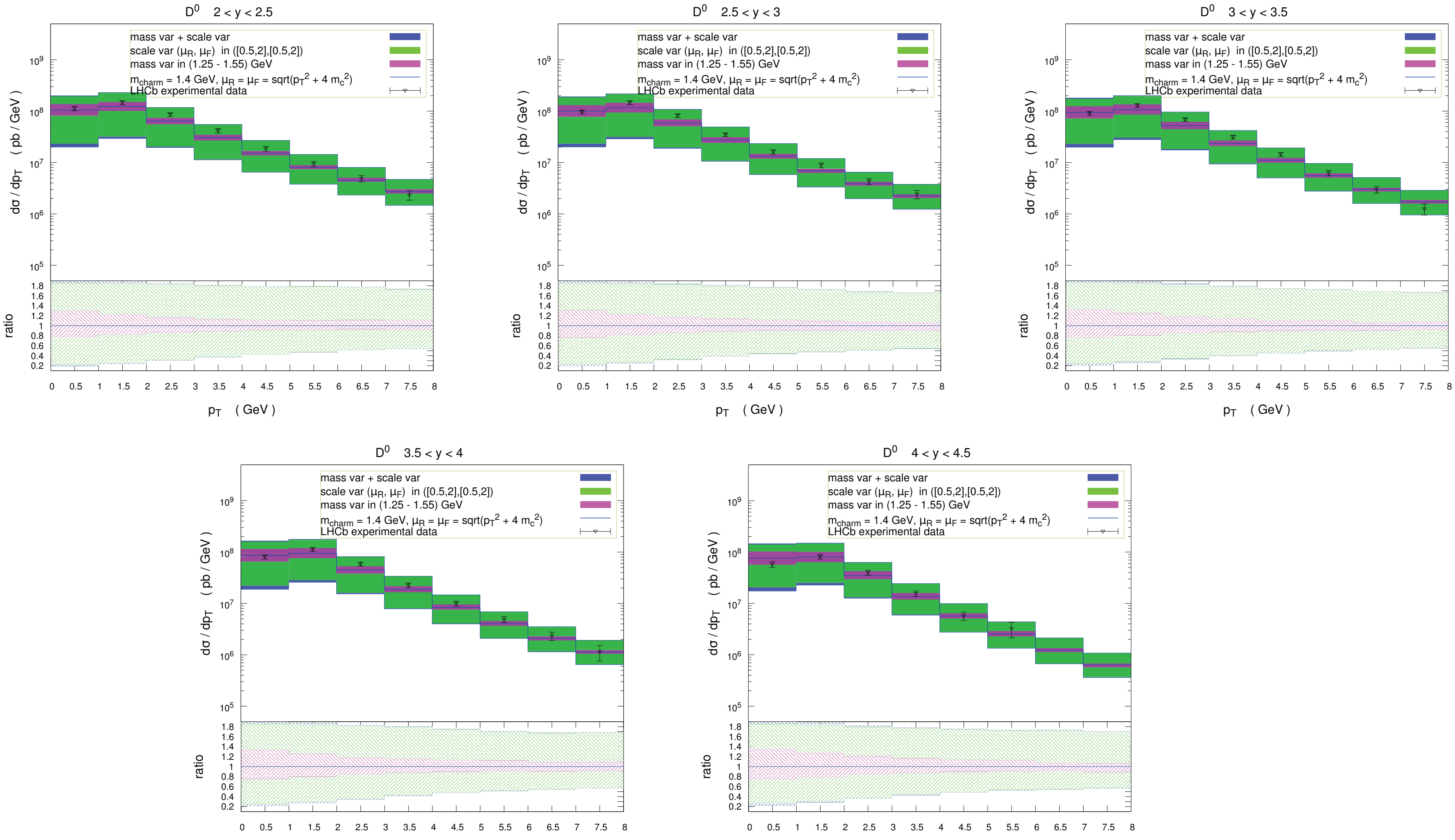
## Comparison of theory predictions with LHCb data

- Charmed meson production $pp \to D^+ + X$ at $\sqrt{s} = 7$ TeV
  - theory predictions to NLO with PowHeg + Pythia and ABM PDFs
  - data within theory uncertainties due to scale and mass variation both for central and for more peripheral collisions
  - theory improvement needed to match accuracy of experimental data



# LHCb data on charmed mesons (II)

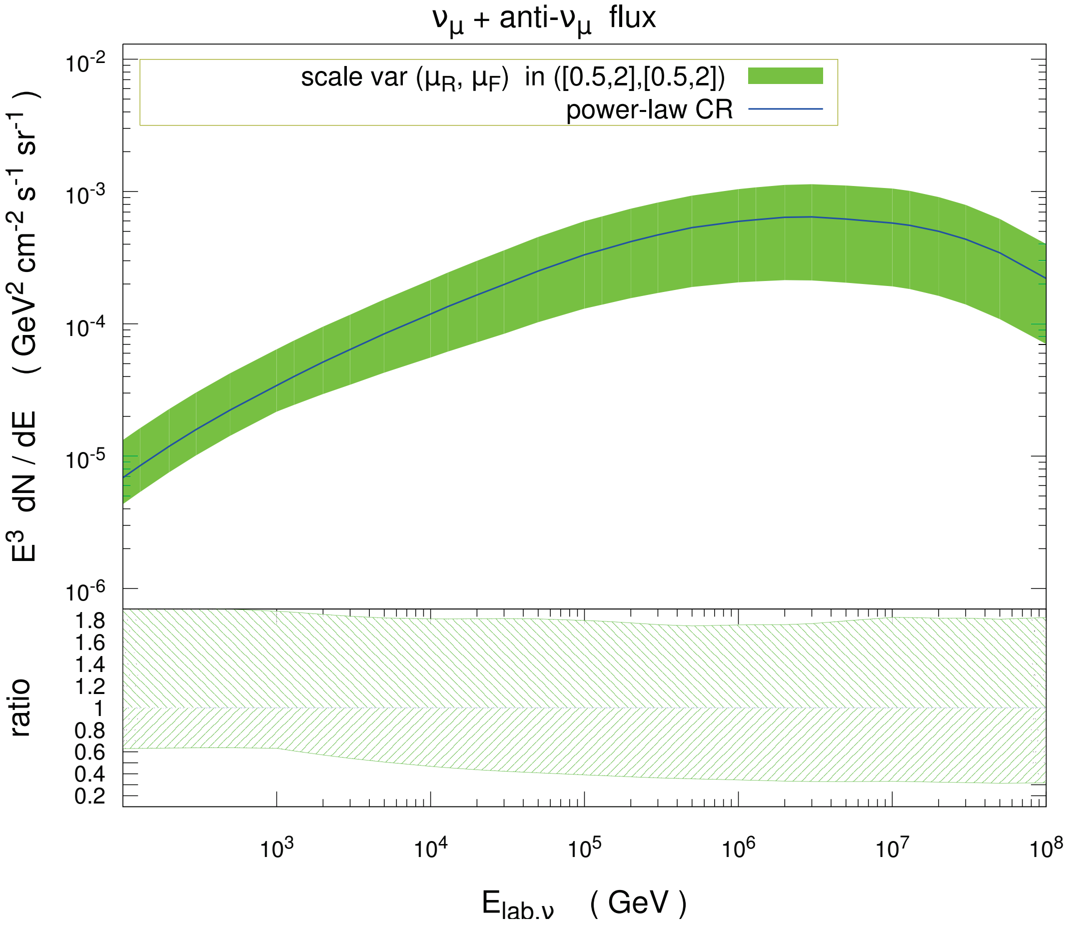
- Charmed meson production $pp \to D^0 + X$
  - data compatible with theory predictions within uncertainties in all measured rapidity bins



# Neutrino flux (I)

## Result from cascade equations

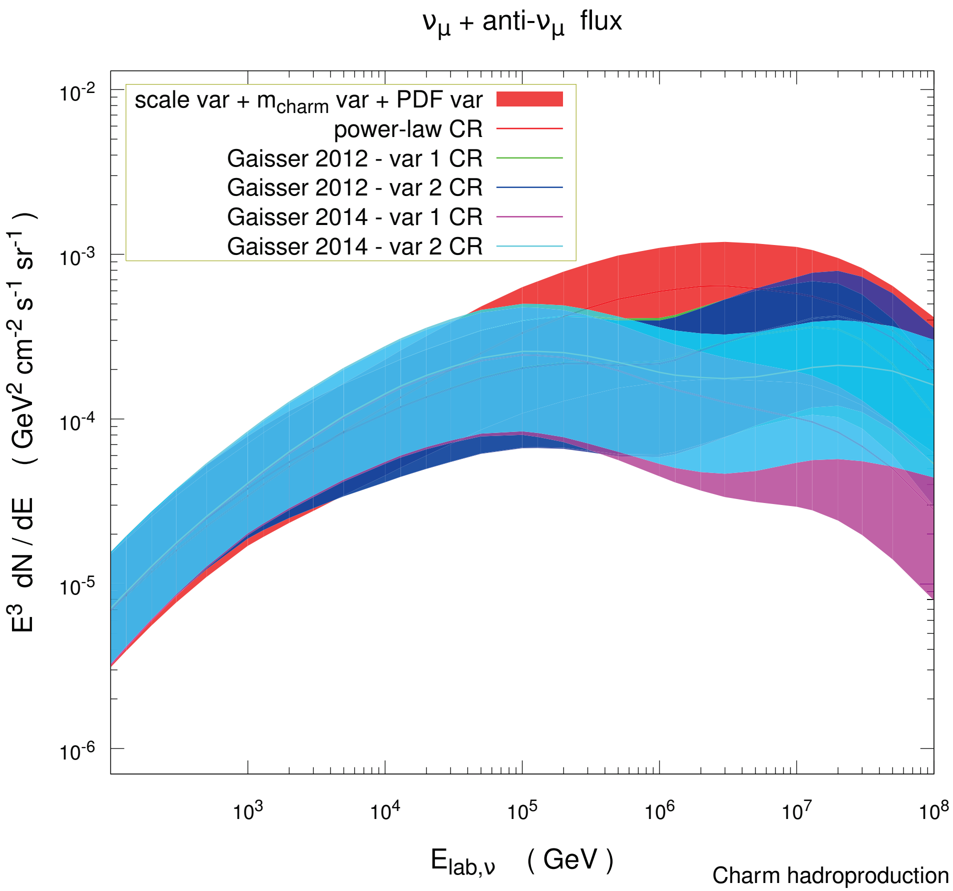
- $\nu_\mu + \bar{\nu}_\mu$-fluxes as function of neutrino energy $E_{lab,\,\nu}$
  - uncertainties from $\mu_R, \mu_F$ scale variation
  - power law spectrum for initial flux of cosmic rays



# *Neutrino flux (II)*

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

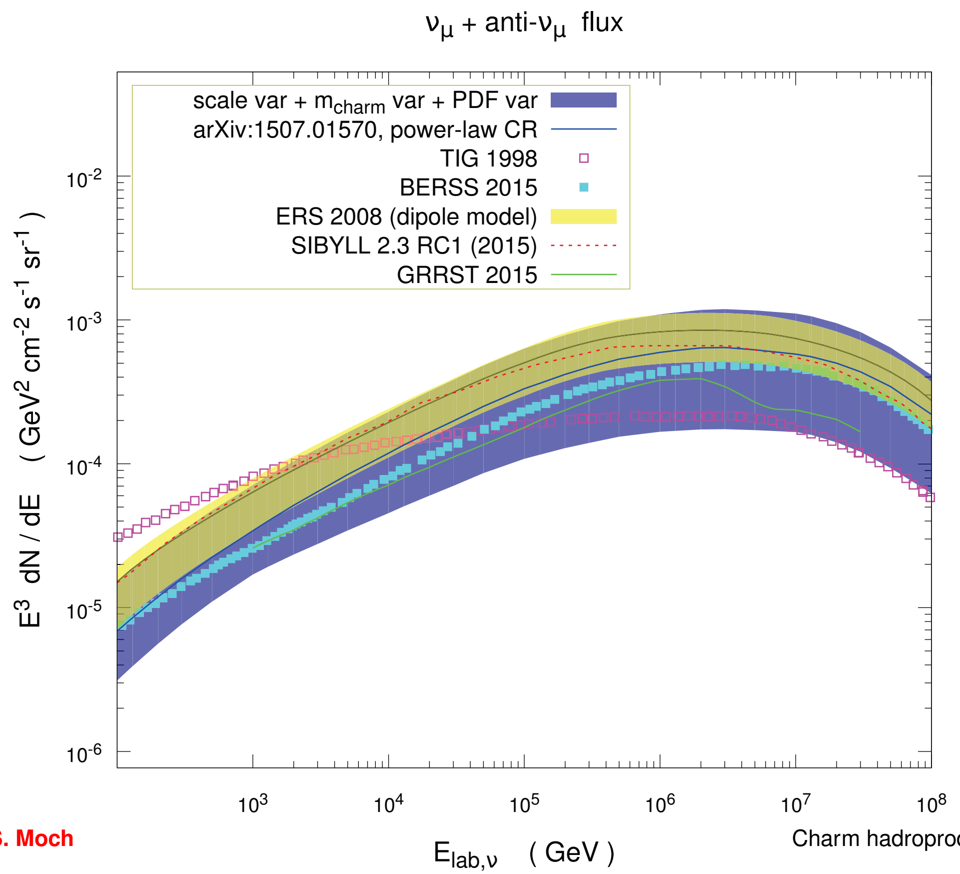
- QCD uncertainties due to $\mu_R, \mu_F$ scale and charm mass variation
  - PDF and $\alpha_s$ uncertainties from ABM11
- Astrophysical uncertainties illustrated with five primary cosmic ray spectra
  - dominant uncertainty for large neutrino energies $E_{lab,\,\nu}$



# *Neutrino flux (III)*

## *Comparison to previous estimates*

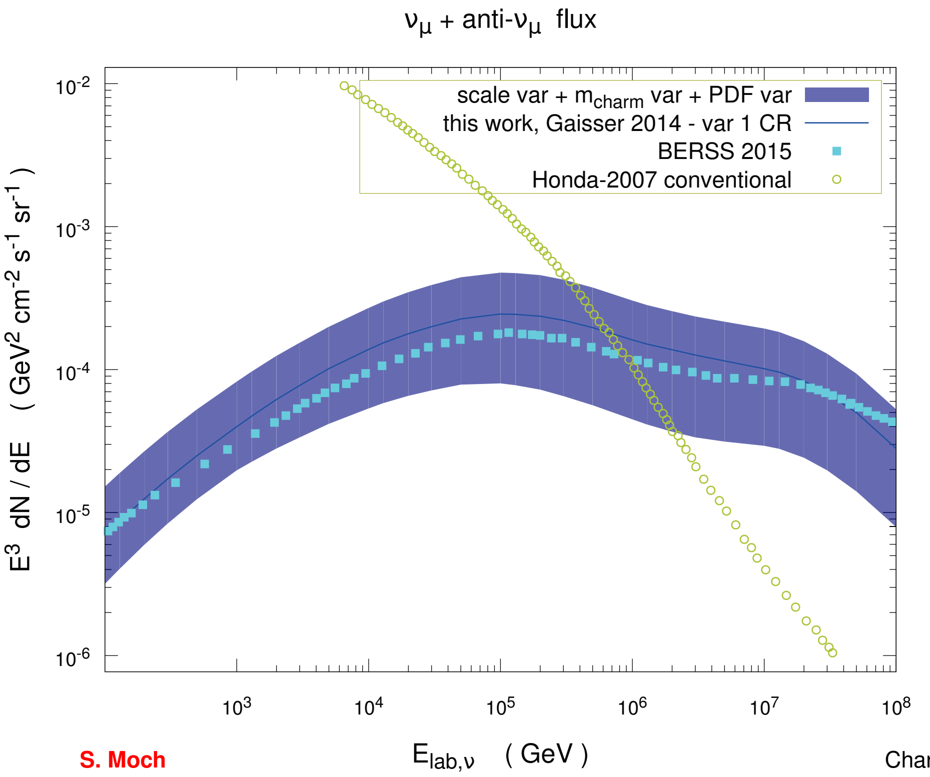
- Power-law primary cosmic ray spectrum for prompt $\nu_\mu + \bar{\nu}_\mu$-fluxes
  - from cascade equations: TIG Gondolo, Ingelman, Thunman ‘95, ERS Enberg, Reno, Sarcevic ‘08, BERSS Bhattacharya, Enberg, Reno, Sarcevic, Stasto ‘15, GRSST Gauld, Rojo, Rottoli, Sarkar, Talbert ‘15
  - from Monte Carlo Sibyll v2.3 RC ‘15

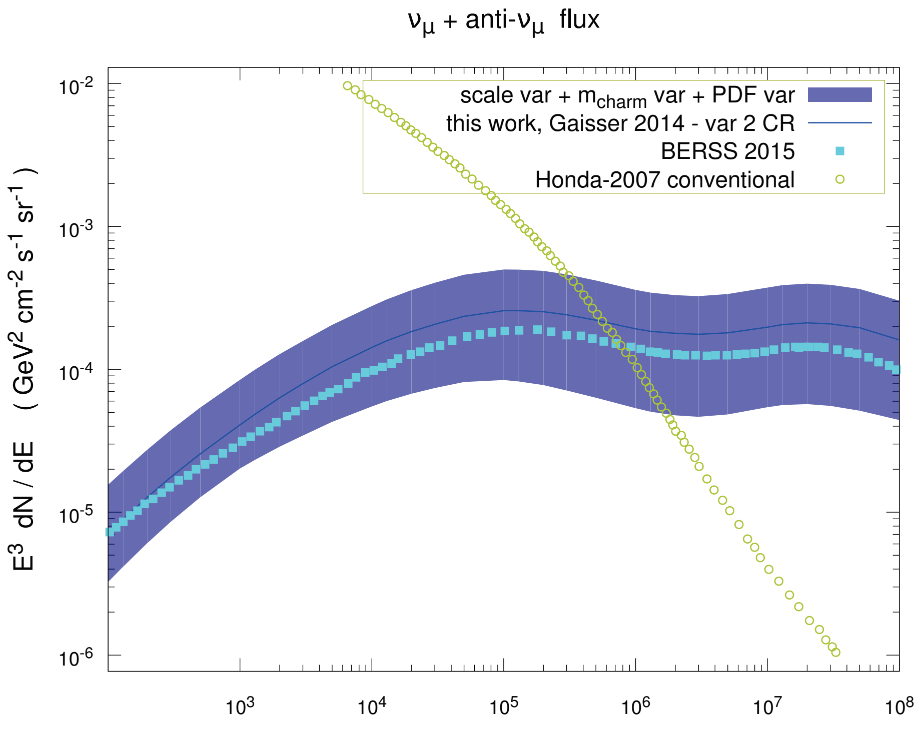


# *Neutrino flux (IV)*

## *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)

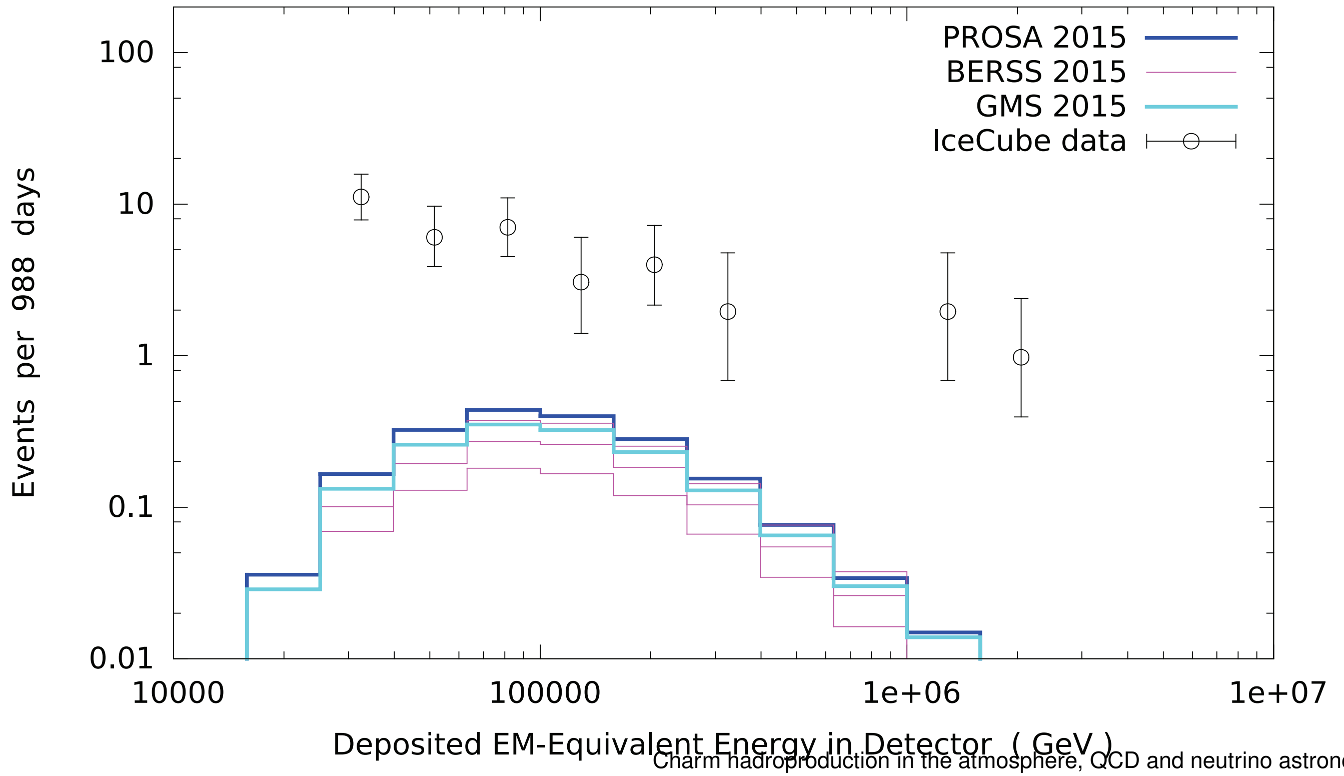


# Expected IceCube events (I)

## Prompt component of $\nu_\mu + \bar{\nu}_\mu$-fluxes

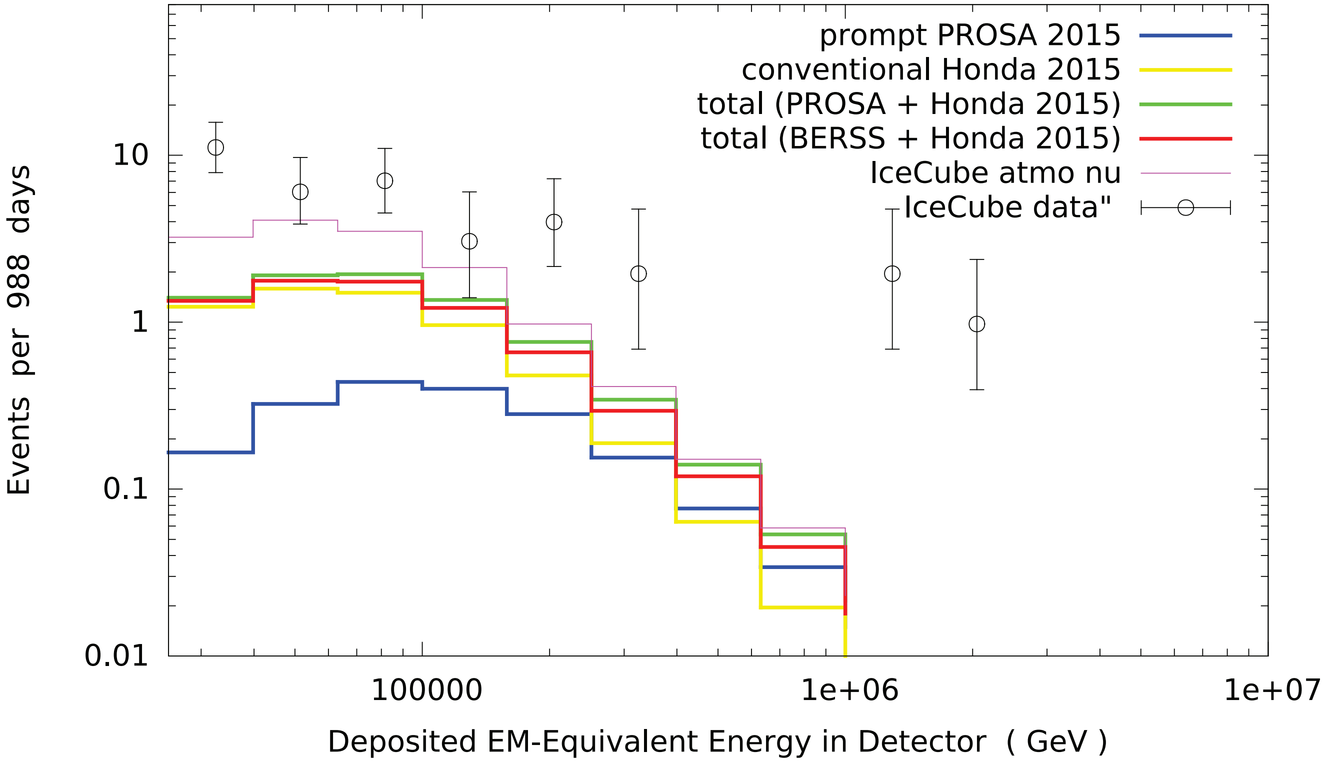
- Central prediction and uncertainty band of BERSS Bhattacharya, Enberg, Reno, Sarcevic, Stasto '15 with primary cosmic ray spectra Gaisser-2014-variant 1
- Comparison with GMS Garzelli, S.M., Sigl '15 and predictions with fluxes based on recent PDFs with LHCb data at small $x$ from PROSA collaboration; in progress



# *Expected IceCube events (II)*

## *Prompt, conventional and total component of $\nu_\mu + \bar{\nu}_\mu$-fluxes*

- Primary cosmic ray spectra Gaisser-2014-variant 1
  - prompt flux overcomes conventional flux around $E = 5 \cdot 10^5$ GeV
  - uncertainties related to scale, $m_c$ and PDF variation not yet included
  - for 988 days expected number of events from prompt neutrinos $N_{prompt}(E > 10^5$ GeV) = 0.89 $\pm$ 1



# *Summary*

- Computation of neutrino fluxes with comprehensive study of uncertainties
  - previously uncertainties in prompt $\nu_\mu + \bar{\nu}_\mu$-flux were largely underestimated
- 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