Prompt Atmospheric Neutrino Flux and its theoretical uncertainties

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based on the part of arXiv:1607.00193

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Outline

- Introduction
- Essential ingredients
  - Models for heavy quark production
  - Cosmic ray spectrum
- Formalism for evaluating the atmospheric neutrino flux
- Results of prompt fluxes
- Summary

Atmospheric neutrinos

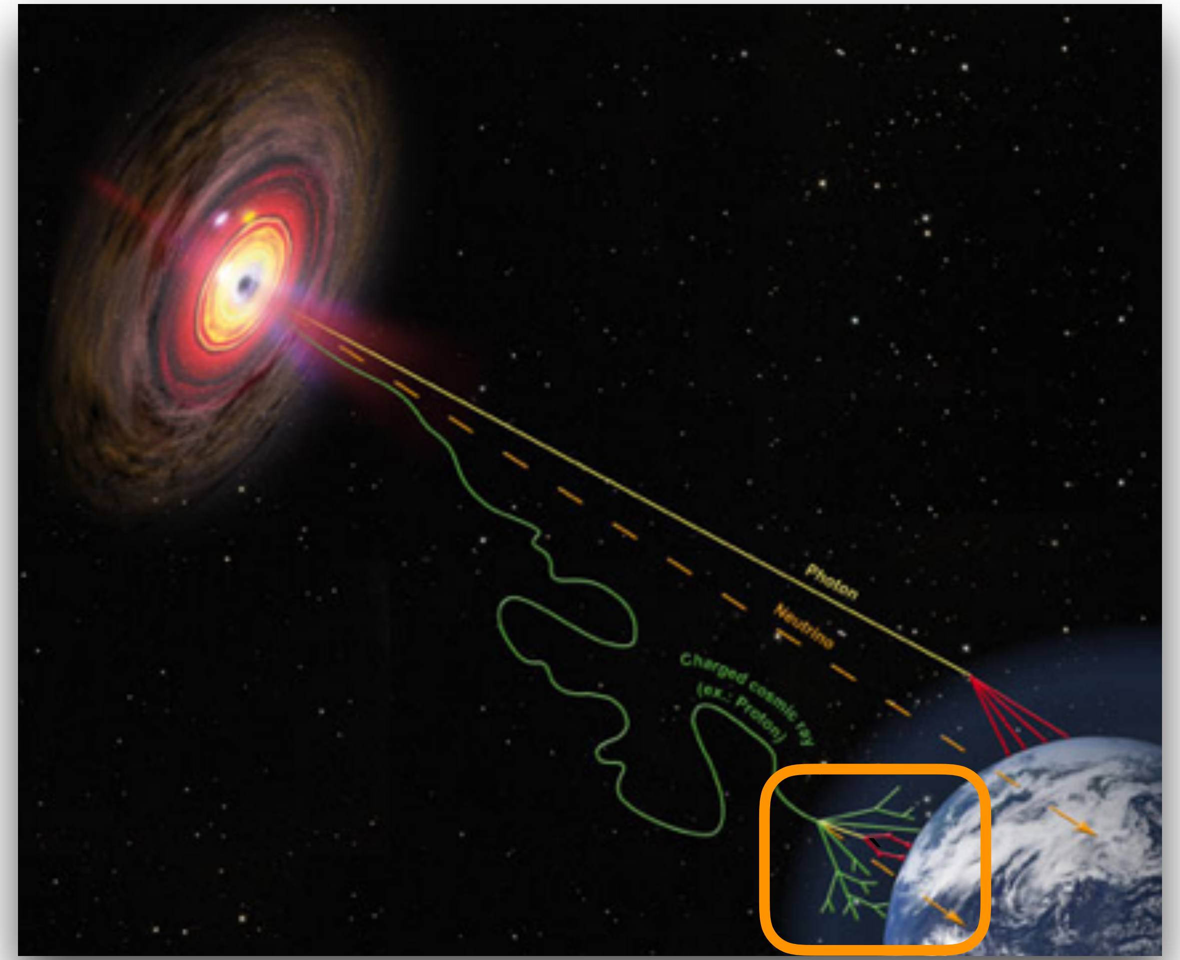


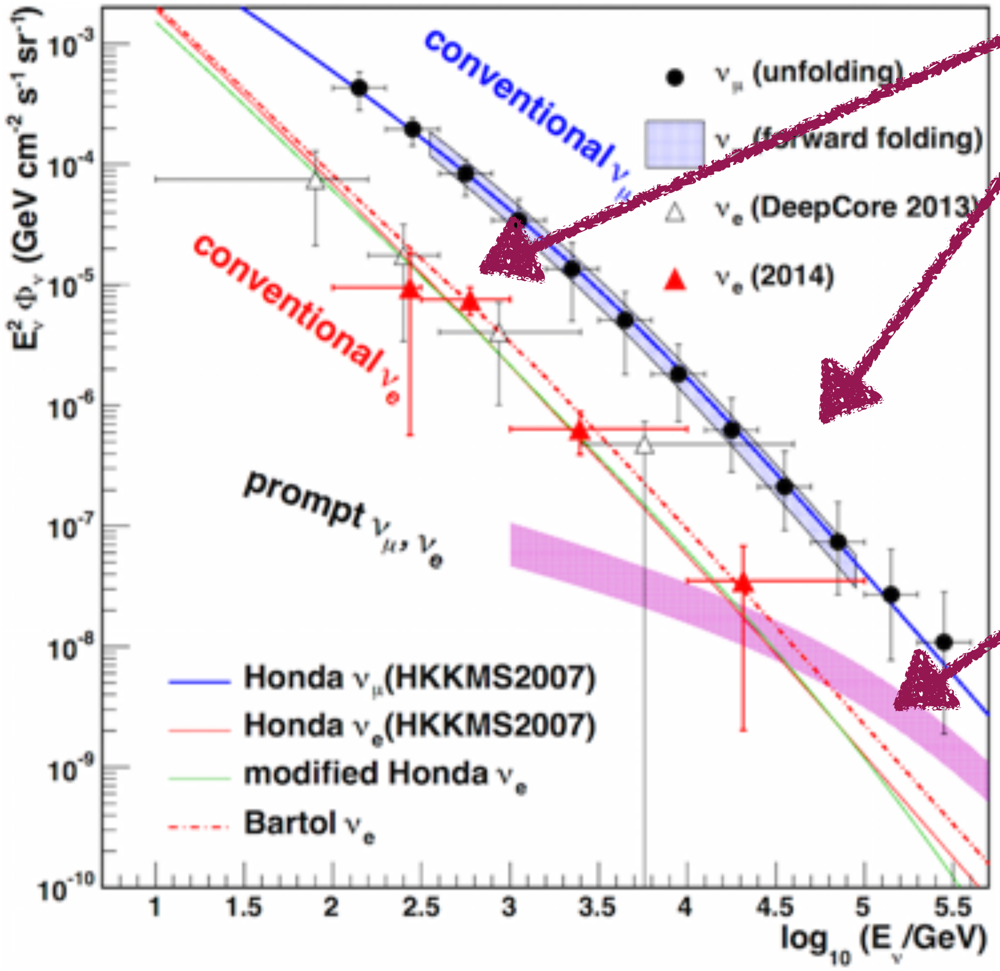
Figure from http://www.hap-astroparticle.org

- From outer space, cosmic rays are incident on the Earth and collide with nuclei in the atmosphere.
- The interaction of cosmic rays and air nuclei produce various hadrons.

  e.g.) pions, kaons, D-mesons etc.
- These secondary hadrons subsequently decay and produce neutrinos

  → Atmospheric neutrinos.

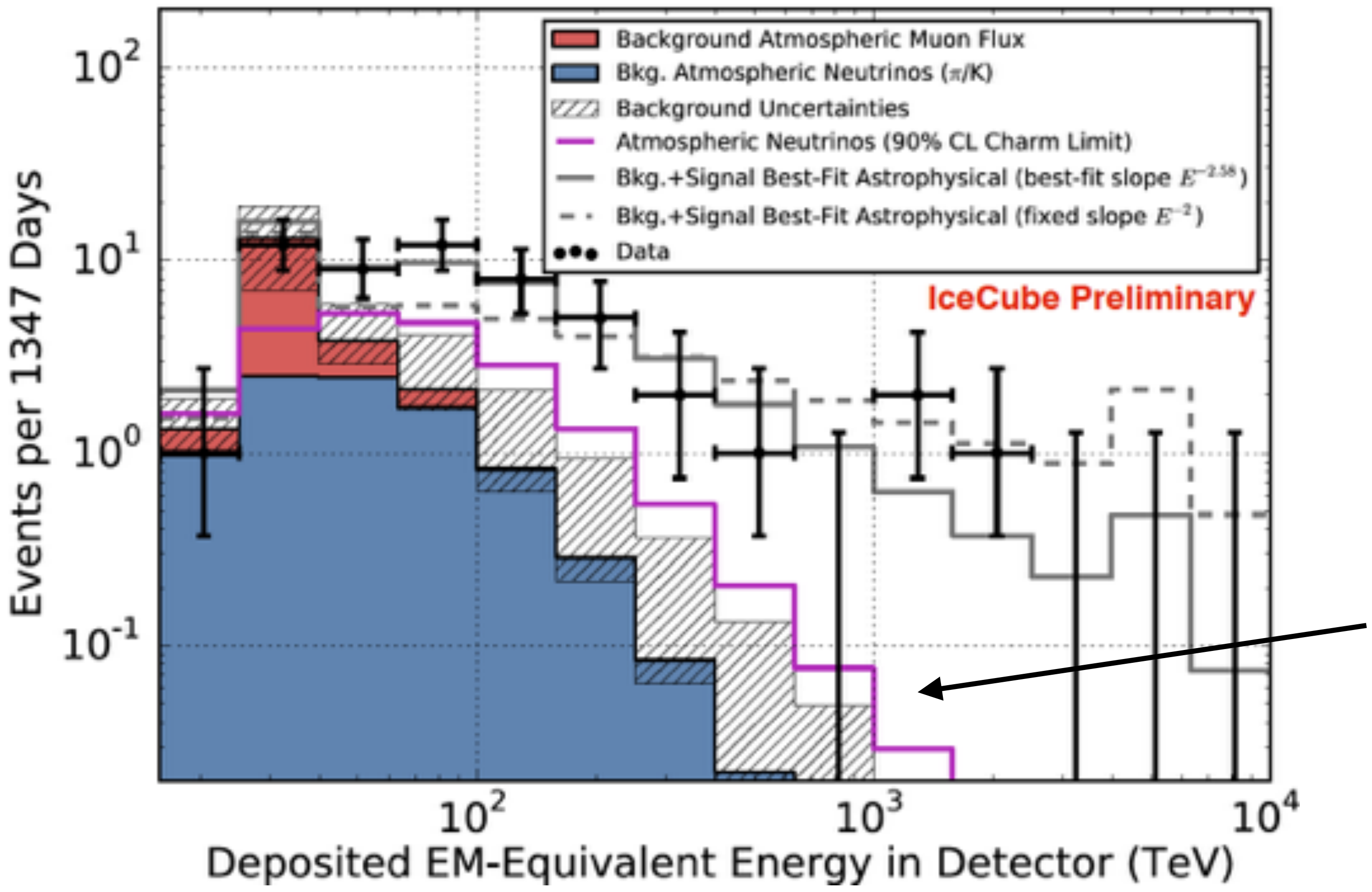
Conventional / Prompt Neutrinos



- ■ Conventional neutrino flux
  - produced from the pion/kaon decay
  - dominates at low energy
  - rapidly decrease with energy
- ■ Prompt neutrino flux
  - produced from the heavy hadron decay
  - less depends on energy (due to short lifetime of heavy hadrons)
  - dominates over the conventional flux at high energy (~1 PeV or higher)

Motivation

- Atmospheric neutrinos are the background to astrophysical neutrinos.



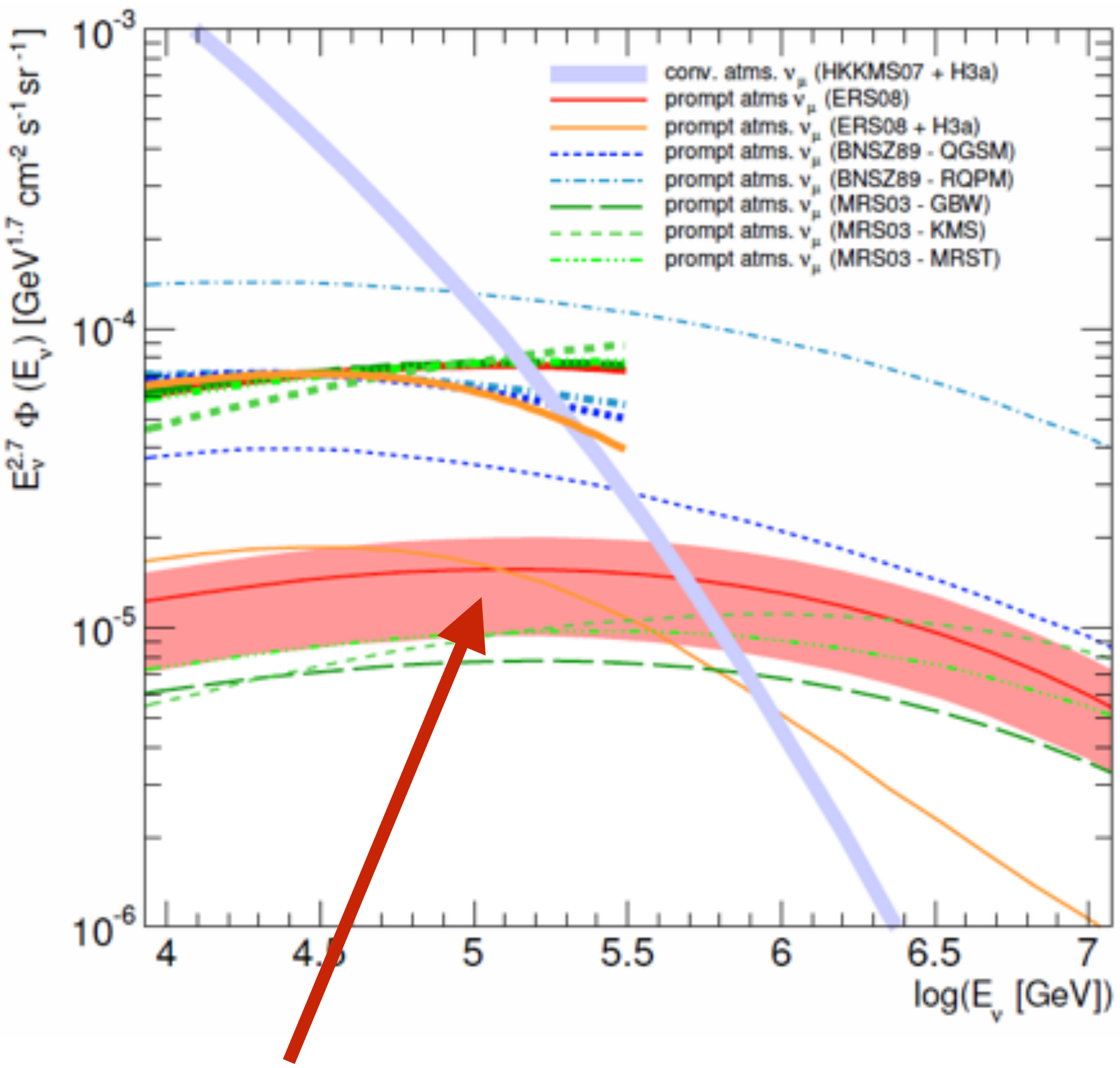
Prompt flux limit

C. Kopper (ICRC2015, arXiv:1510.05223)

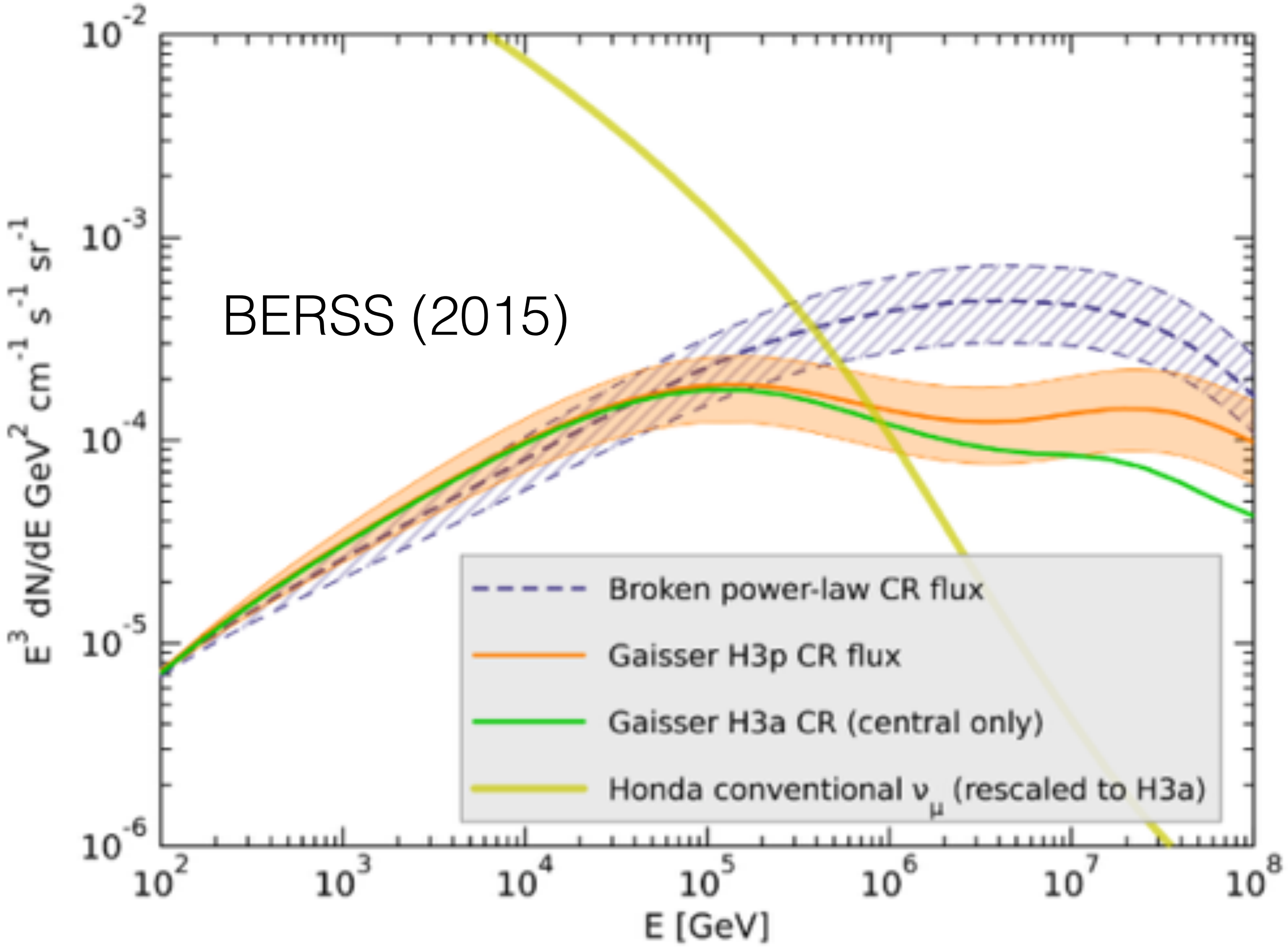
- 54 events from 1347 day observation
- Pure atmospheric origin is rejected with ~ 7 sigma.

- The study of heavy quark production is helpful to explore the QCD at low x region.

Some earlier works



Enberg, Reno and Sarcevic (ERS, 2008)
In the dipole model for HQ production



BERSS (2015)

- with the NLO pQCD approach
- more developed PDF (CT10) and cosmic ray fluxes etc.
- reduces the ERS flux by a factor of 1.5

Main updates in this work

- Heavy quark production with different frameworks
  - Standard NLO pQCD
  - Dipole model

    → Nuclear corrected
  - kT factorization → evaluated for the first time
- Contributions from b quark

Essential Ingredients

- Heavy quark production in hadron collisions
- Cosmic rays - energy spectrum and composition

Heavy quark production

- Perturbative QCD with collinear approximation
  - The HQ production cross section:

$$\sigma(pp \to c\bar{c}X) = \int dx_1 dx_2 \sigma_{gg\to c\bar{c}}(\hat{s}) g(x_1, \mu^2) g(x_2, \mu^2)$$

$$x_{1,2} = \frac{1}{2}\left(\sqrt{x_F^2 + \frac{4M_{c\bar{c}}^2}{s}} \pm x_F\right) \qquad x_F = x_1 - x_2$$

- At high energy, $x_1 \sim x_F$ and x_2 is very small.
- Need the small x gluon PDF, which is currently not well known.
- It is important to investigate other possible approaches, which can constrain the gluon PDF at small x region.

Heavy quark production

■ Dipole Model

- the partonic interaction has two step process:
  - Gluon fluctuation into the quark-antiquark pair (color dipole) → $|\Psi_g^q|^2$
  - Interaction of the color-dipole with the target particle → σ_d
- The partonic interaction cross section:

$$\sigma^{gp\to q\bar{q}X}(x, M_R, Q^2) = \int dz\, d^2\vec{r}\,|\Psi_g^q(z, \vec{r}, M_R, Q^2)|^2 \sigma_d(x, \vec{r})$$

$$\sigma_d(x, \vec{r}) = \frac{9}{8}\left[\sigma_{d,em}(x, z\vec{r}) + \sigma_{d,em}(x, (1-z)\vec{r})\right] - \frac{1}{8}\sigma_{d,em}(x, \vec{r})$$

- The HQ pair production cross section in dipole model:

$$\sigma(pp \to q\bar{q}X) \simeq \int dy\, x_1 g(x_1, M_F)\sigma^{gp\to q\bar{q}X}(x_2, M_R, Q^2 = 0)$$

Heavy quark production

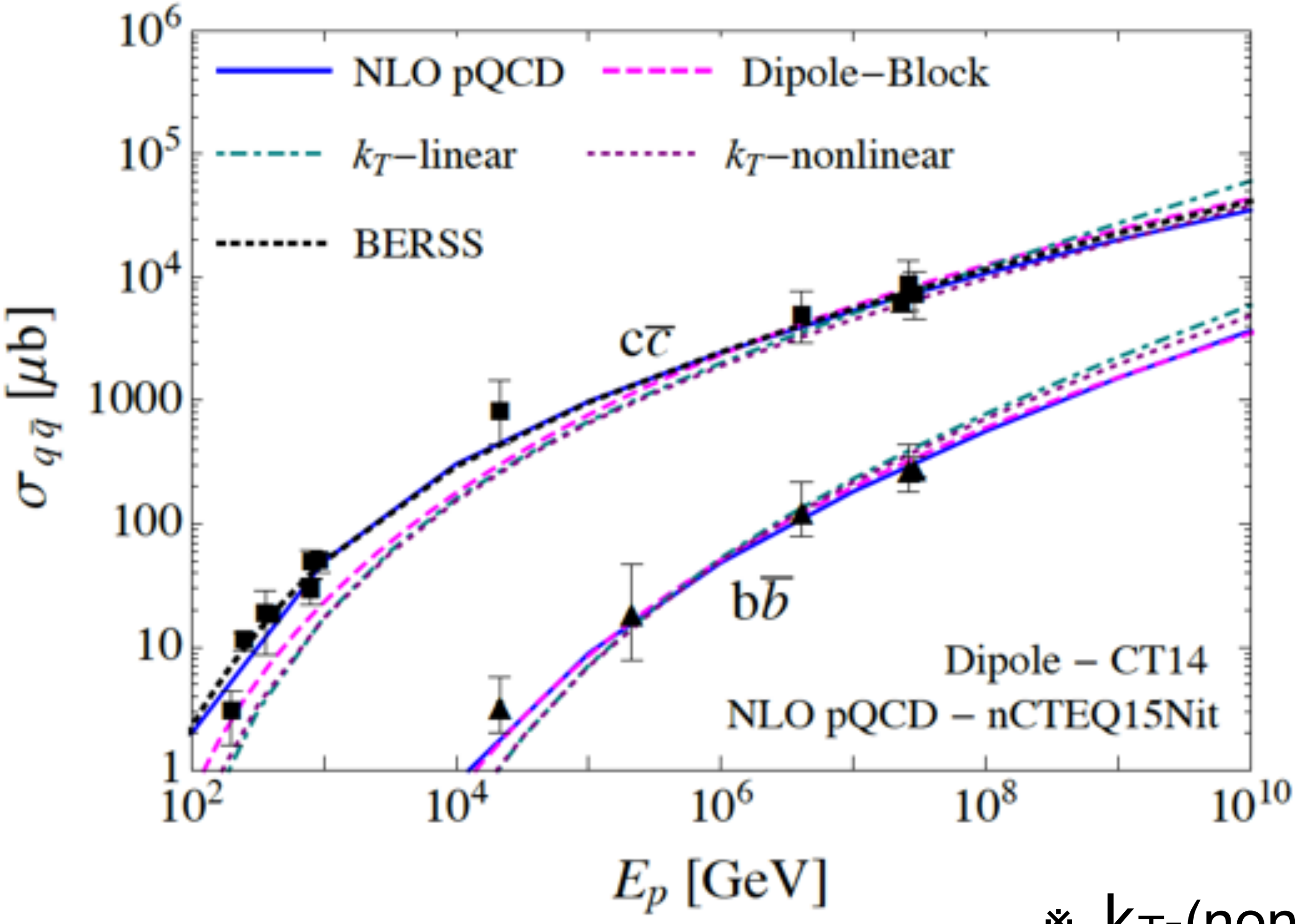
- k_T-factorization
  - The HQ pair production cross section in hybrid formalism:

$$\sigma(pp \to q\bar{q}X) = \int \frac{dx_1}{x_1}\frac{dx_2}{x_2}\, dz\, dx_F\, \delta(zx_1 - x_F)\, x_1 g(x_1, M_F)$$
$$\times \int \frac{dk_T^2}{k_T^2} \hat{\sigma}^{\rm off}(z, \hat{s}, k_T)\, f(x_2, k_T^2)$$

    - collinear approximation for the incoming parton from the CR particles.
    - kT factorization for the low x parton from target nucleus

  - The small x resummation is incorporated in the unintegrated PDF.
  - Parton saturation can be included through nonlinear evolution of the unintegrated parton density

Cross sections of HQ production



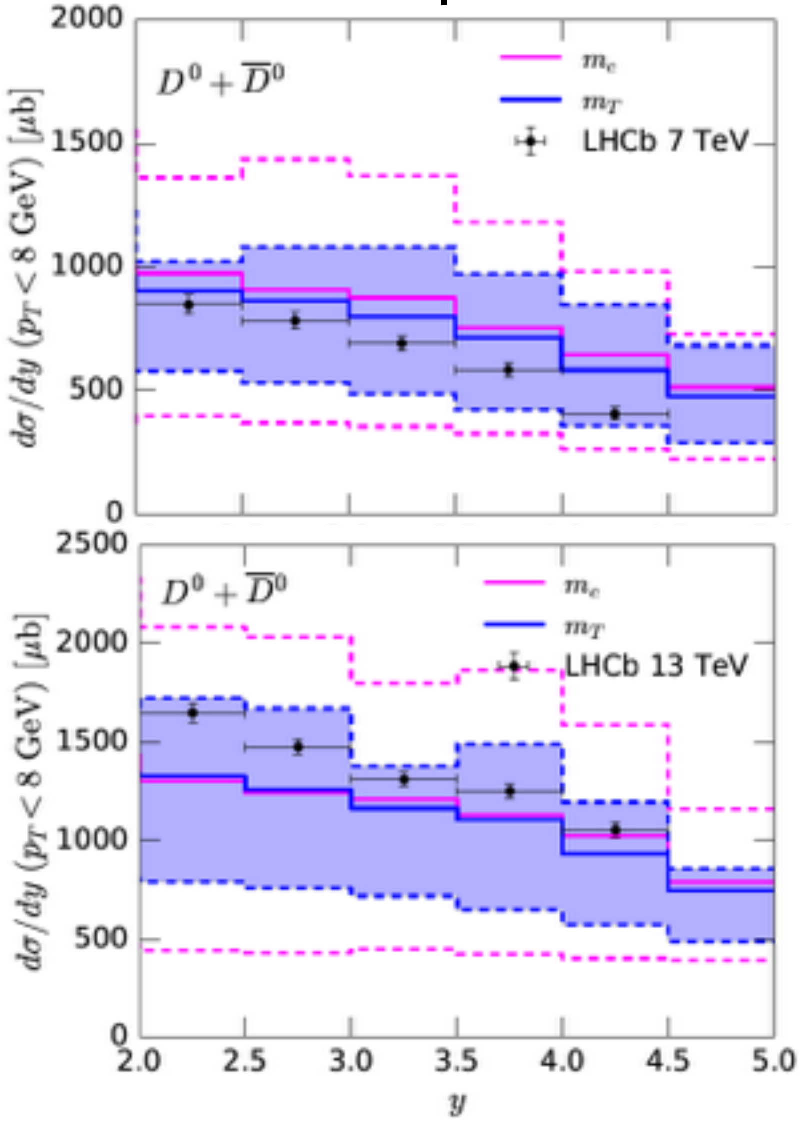
- High energy data
  - RHIC (STAR, PHENIX)
  - LHC (ALICE, ATLAS, LHCb)
- Low energy data
  - Fixed target experiments

※ k_T-(non)linear : without (with) parton saturation

- All models (NLO pQCD, dipole model and kT factorization) matches well with the experimental data at high energies.

Differential cross section in rapidity

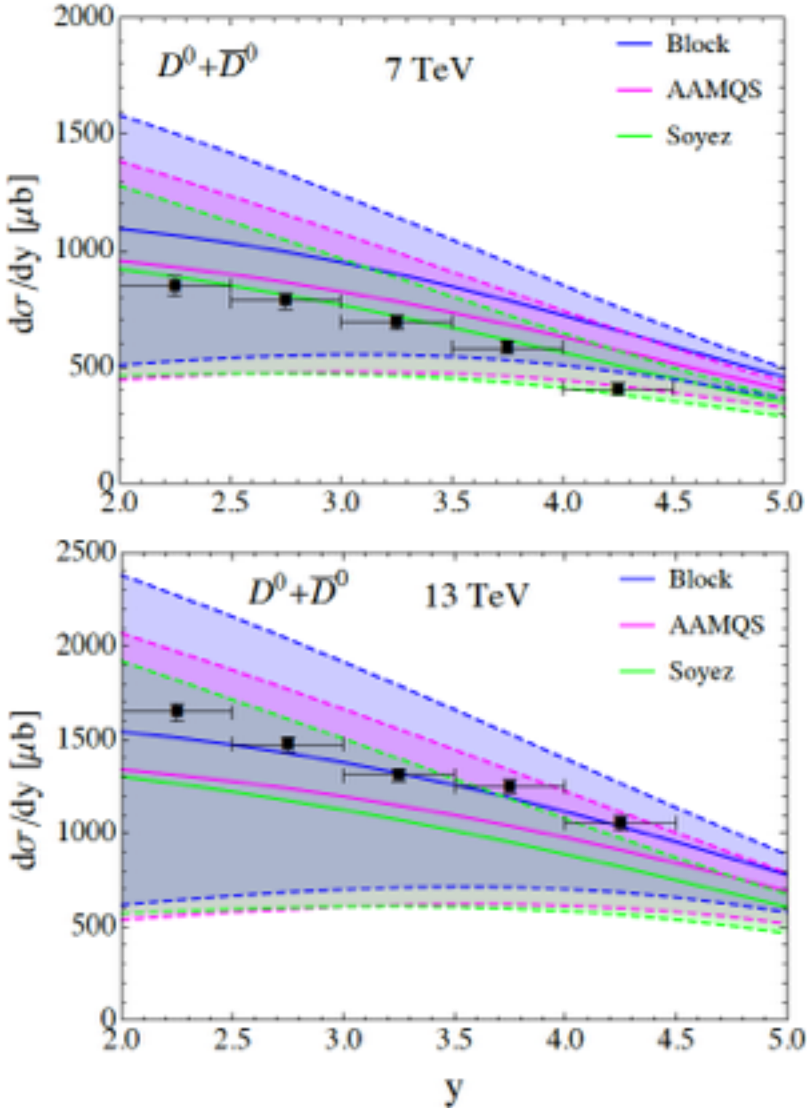
NLO pQCD



$$(M_F, M_R) = (N_F, N_R)m_q$$

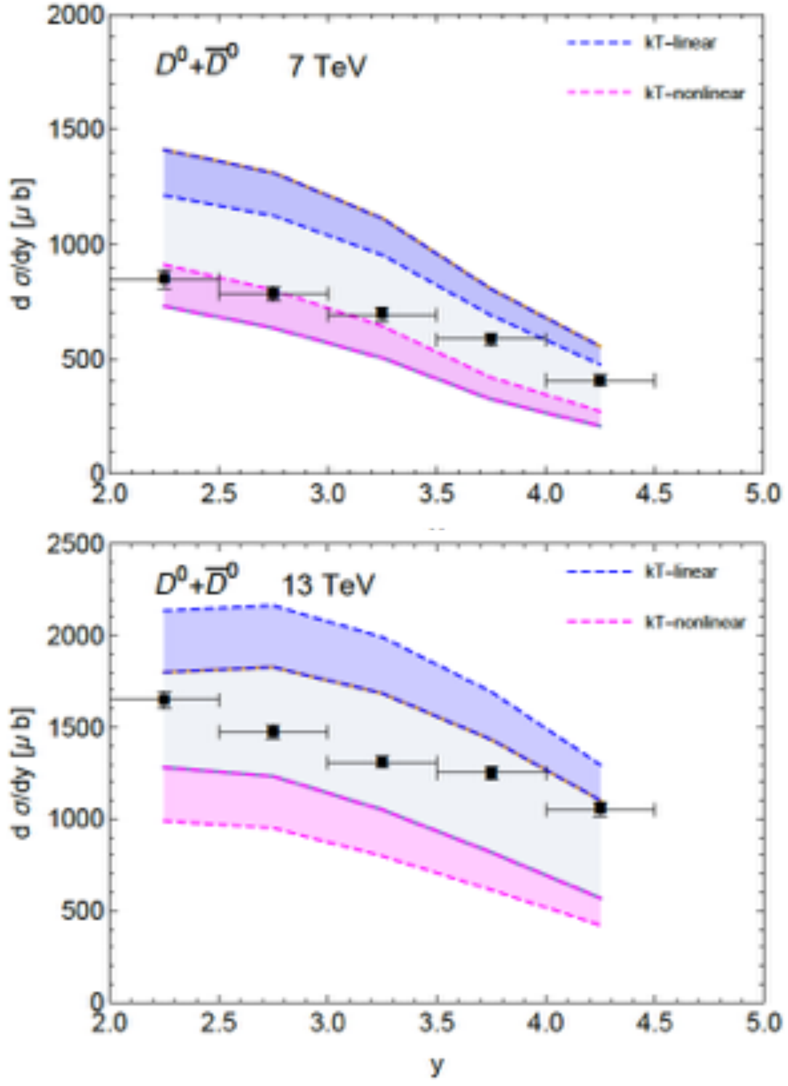
$$(N_F, N_R) = (4.65, 1.71)$$
$$(2.10, 1.60)$$
$$(1.25, 1.48)$$

Dipole Model



$$M_F = (m_c,\, 2m_c,\, 4m_c)$$

k$_T$-factorization



$$(2.5m_T, k_{\max})$$

Data - from LHCb

Nuclear correction

- NLO pQCD: by the new PDF set, nCTEQ 15 for the PDF in proton bounded in nucleus.
- Dipole model: by the Glauber and Gribov formalism for the nuclear re-scattering.

$$\sigma_d^A(x,r) = \int d^2\vec{b}\,\sigma_d^A(x,r,b)$$

$$\sigma_d^A(x,r,b) = 2\left[1 - \exp\left(-\frac{1}{2}AT_A(b)\sigma_d^p(x,r)\right)\right]$$

$$T_A(b) = \int dz\rho_A(z,\vec{b})$$

- nuclear profile function

$$\rho_A(z,b) = \frac{1}{\pi^{3/2}a^3}e^{-r^2/a^2} \quad \text{for } r^2 = z^2 + \vec{b}^2$$

Cosmic ray nucleon spectrum

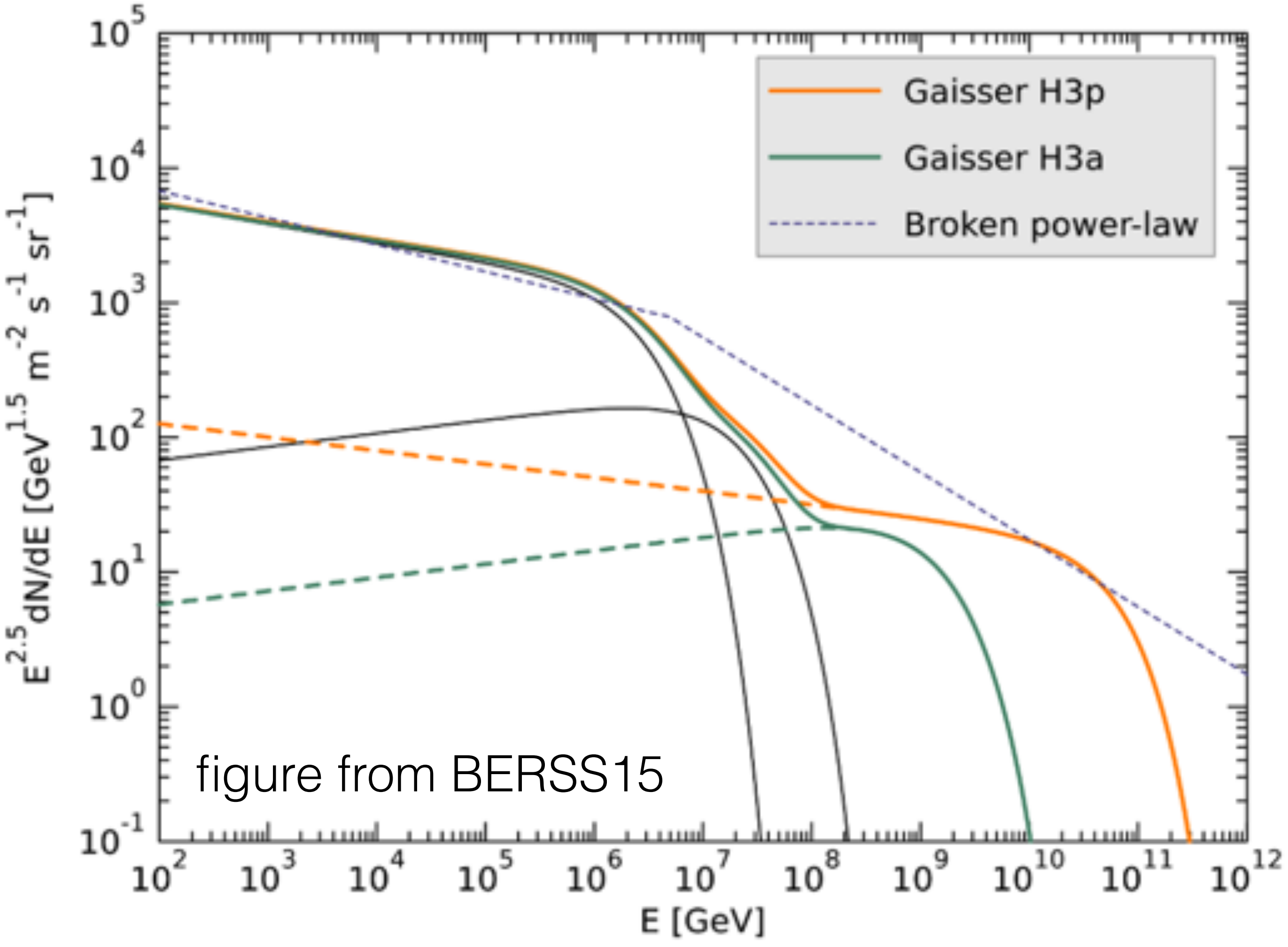


figure from BERSS15

- **BPL** - all CR particles are protons.

$$\phi_N(E) = \begin{cases} 1.7E^{-2.7} & \text{for } E < 5 \cdot 10^6 \text{ GeV} \\ 174E^{-3} & \text{for } E > 5 \cdot 10^6 \text{ GeV} \end{cases}$$

- Gaisser's parameterizations
  - from the 3 source populations (SN remnants, other galactic and extra galactic sources)
  - from the multi nuclear species.

T. K. Gaisser,
Astropart. phys. 35 (2012) 801

- H3p - all protons in extragalactic population.
- H3a - mixed composition in extra galactic pop.

Formalism - cascade equations

- Cascade equation

$$\frac{d\phi_j(E,X)}{dX} = -\frac{\phi_j(E,X)}{\lambda_j(E)} - \frac{\phi_j(E,X)}{\lambda_j^{\rm dec}(E)} + \sum S(k \to j)$$

$$X(\ell,\theta) = \int_\ell^\infty d\ell' \rho(h(\ell',\theta))$$

$$\rho = \rho_0 \exp(-h/h_0)$$

$$h_0 = 6.4\,{\rm km} \quad \rho_0 h_0 = 1300\,{\rm g/cm^2}$$

$$S(k \to j) = \int_E^\infty dE' \frac{\phi_k(E',X)}{\lambda_k(E')} \frac{dn(k \to j; E',E)}{dE}$$

$$\frac{dn(k \to j; E',E)}{dE} = \frac{1}{\sigma_{kA}(E')} \frac{d\sigma(kA \to jY; E',E)}{dE} \quad \text{(production)}$$

$$= \frac{1}{\Gamma_k(E')} \frac{d\Gamma(k \to jY; E',E)}{dE} \quad \text{(decay)}$$

Formalism - Z moments

$$S(k \to j) = \int_E^\infty dE' \, \frac{\phi_k(E', X)}{\lambda_k(E')} \frac{dn(k \to j; E', E)}{dE}$$

$$\simeq Z_{kj}(E) \frac{\phi_k(E, X)}{\lambda_k(E)}$$

$$\phi_k(E, X) = \phi_k^0(E) f(X)$$

$$Z_{kj}(E) = \int_E^\infty dE' \, \frac{\phi_k^0(E')}{\phi_k^0(E)} \frac{\lambda_k(E)}{\lambda_k(E')} \frac{dn(k \to j; E', E)}{dE}$$

: depends only on the energy.

$$\phi_{h\to\nu}^{\text{low}} = \sum_h \frac{Z_{Nh} Z_{h\nu}}{1 - Z_{NN}} \phi_N^0$$

$$\phi_{h\to\nu}^{\text{high}} = \sum_h \frac{Z_{Nh} Z_{h\nu}}{1 - Z_{NN}} \frac{\ln(\Lambda_h/\Lambda_N)}{1 - \Lambda_N/\Lambda_h} \frac{\epsilon_h}{E} \phi_N^0$$

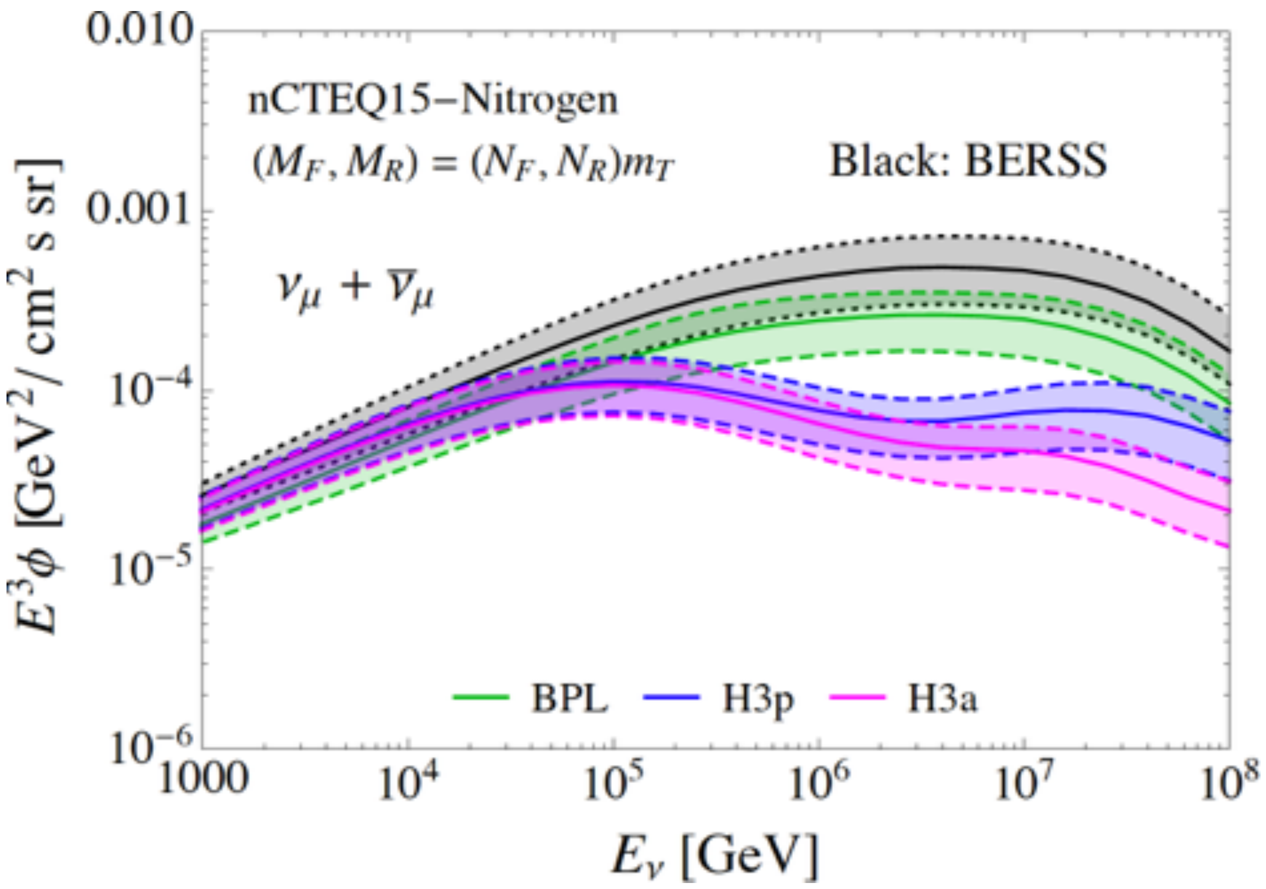
→

$$\phi_\nu = \sum_h \frac{\phi_{h\to\nu}^{\text{low}} \phi_{h\to\nu}^{\text{high}}}{(\phi_{h\to\nu}^{\text{low}} + \phi_{h\to\nu}^{\text{high}})}$$

$\Lambda_k = \lambda_k/(1 - Z_{kk})$

ϵ_k – critical energy, determines the high- and low-energy regimes

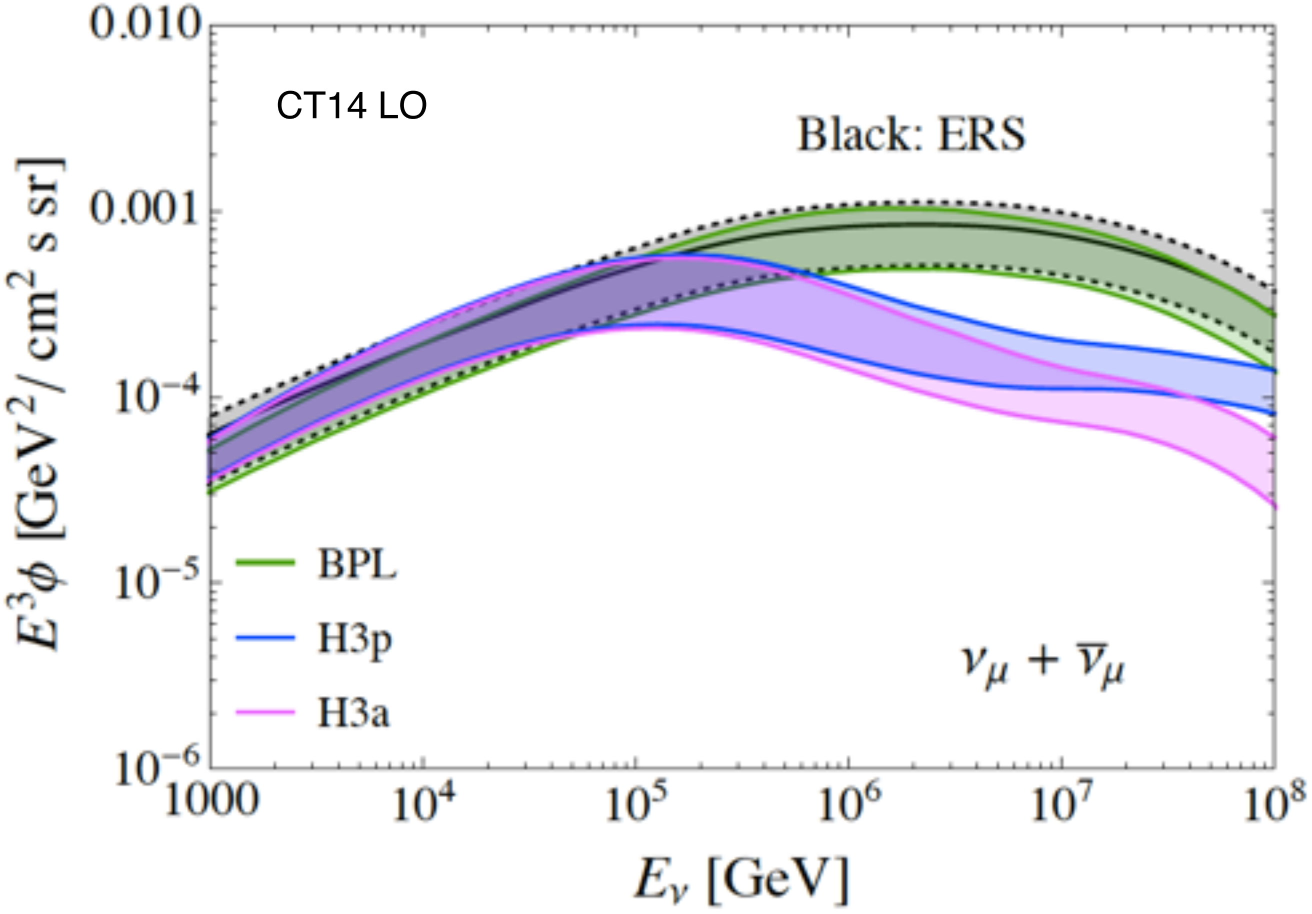
Comparison with earlier work (NLO pQCD)



- The error bands come from the scale variances.
- Differences from BERSS:
  - new fragmentation fraction (FF)
  - B hadron contribution
  - new PDF
  - nuclear effect.

- The updated FF reduces overall fluxes by about 20%.
- B hadron contribution increases the flux by 5-10%.
- Nuclear effect: 20-35%
- Combined effect : ~45% at $10^{6\text{-}8}$ GeV.

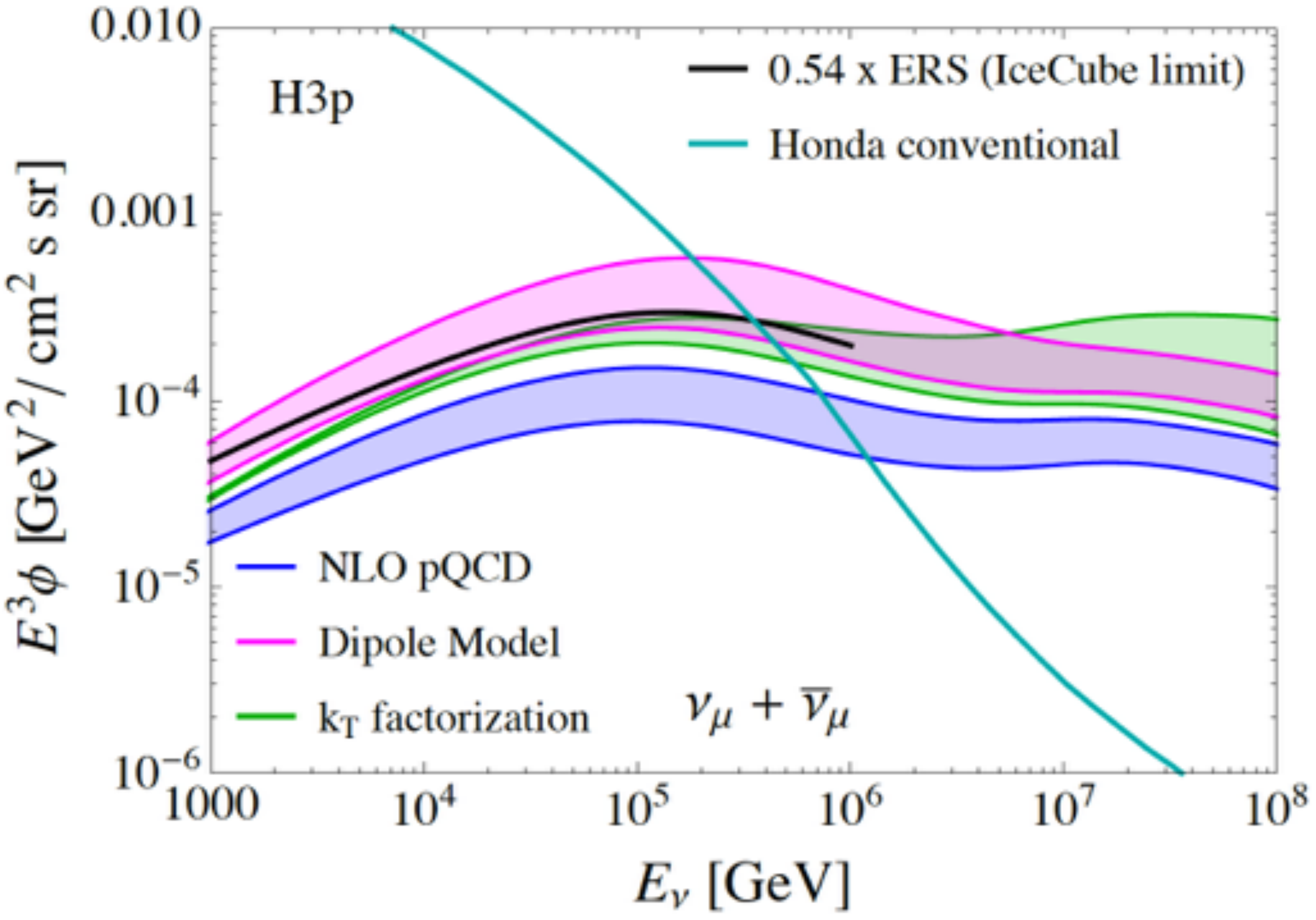
Comparison with earlier work (Dipole Model)



- The error bands come from the three dipole models and the scale variance.
- Differences from ERS:
  - new fragmentation fraction (FF)
  - two other dipole models
  - B hadron contribution
  - recent PDF
  - nuclear effect.
  - updated Z_{pp} and Z_{DD}
  - charm quark mass

- The effect of the updated FF is ~20% reduction .
- The new fluxes with all the theoretical updates listed above are comparable to the old ERS fluxes.

Fluxes from all approaches with H3p and comparison with IceCube limit



IceCube limit from
ICRC2015, 1079

- IceCube limit on the prompt flux = 0.54 x ERS based on the three year data with 90% C.L., (rescaled from BPL to H3p)
- IceCube limit based on the three year data excludes most dipole model predictions and quite constrains the kT factorisation prediction in this work.
- The whole range of NLO pQCD prediction with nuclear correction is lower than the IceCube limit.

Summary

- The prompt neutrino fluxes are investigated in the different frameworks for heavy quark production including the bottom hadron contributions with the recent cosmic ray fluxes.

- The updated CR fluxes give much lower prompt neutrinos flux than that with the BPL spectrum at ~1 PeV or higher.

- Theoretical uncertainties due to PDFs, nuclear effects, and scales constrained from the charm cross section measurements are included in the flux evaluation.
  - The impact by the nuclear effect has larger on the NLO pQCD prediction than on the dipole approach.
  - With the parameters constrained by the exp. data and all the other effects, the NLO pQCD predictions can survive safely from the IC limit from 3 yr data.

- IceCube limit from 3 yr data excludes most of the dipole model results in this work, and strictly constrains the kT factorisation prediction. If included the nuclear correction, the kT factorisation results would be lower.

  ** The recent new IC limit with six year data saves all predictions.