Atmospheric prompt neutrino flux

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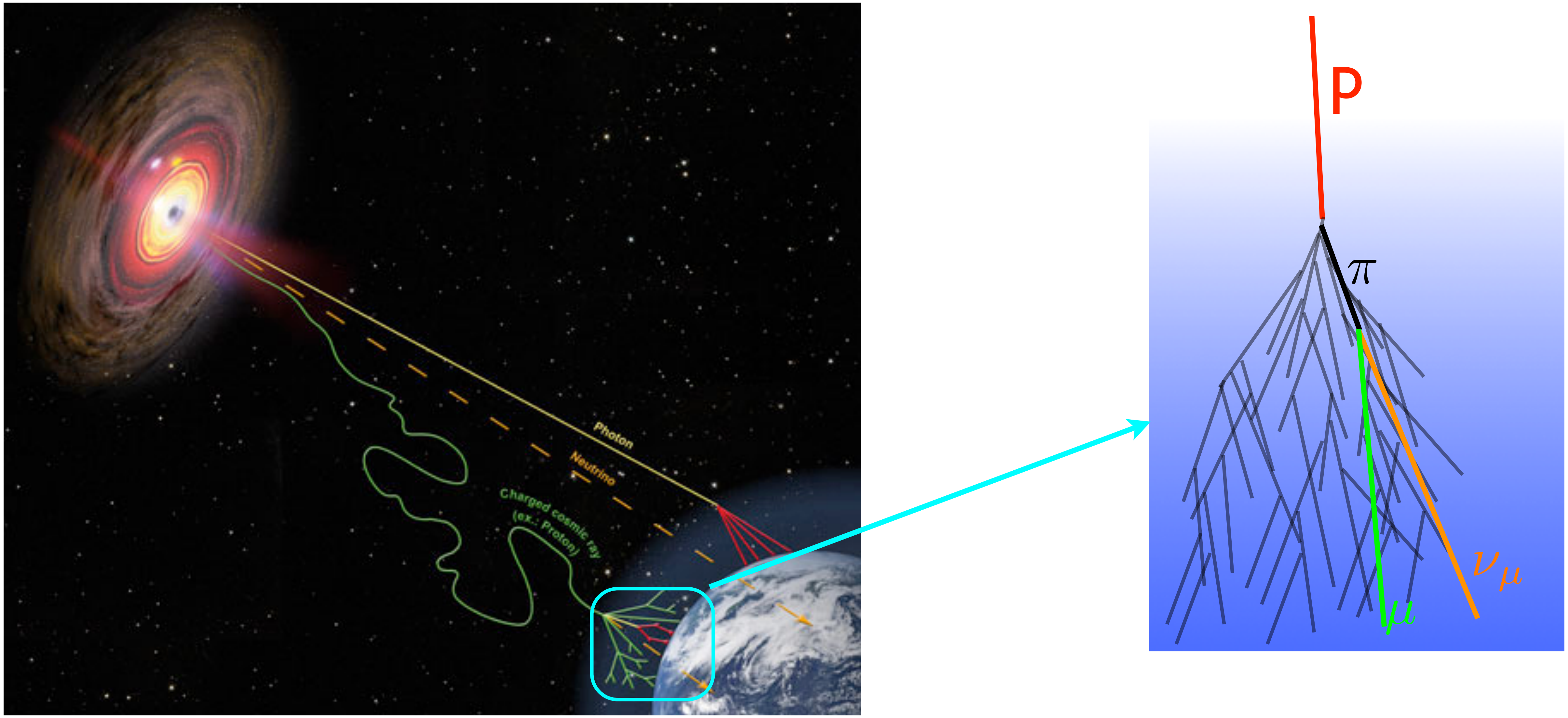
Outline

- Atmospheric neutrinos: conventional and prompt
- Cross section for charm production at forward rapidities: collinear, dipole and k_T factorization calculations
- Prompt neutrino fluxes

Work in collaboration with

A. Bhattacharya, R. Enberg, Y. S. Jeong, C. S. Kim, M. H. Reno, I. Sarcevic

Atmospheric neutrinos



(credit: www.hap-astroparticle.org/ A. Chantelauze)

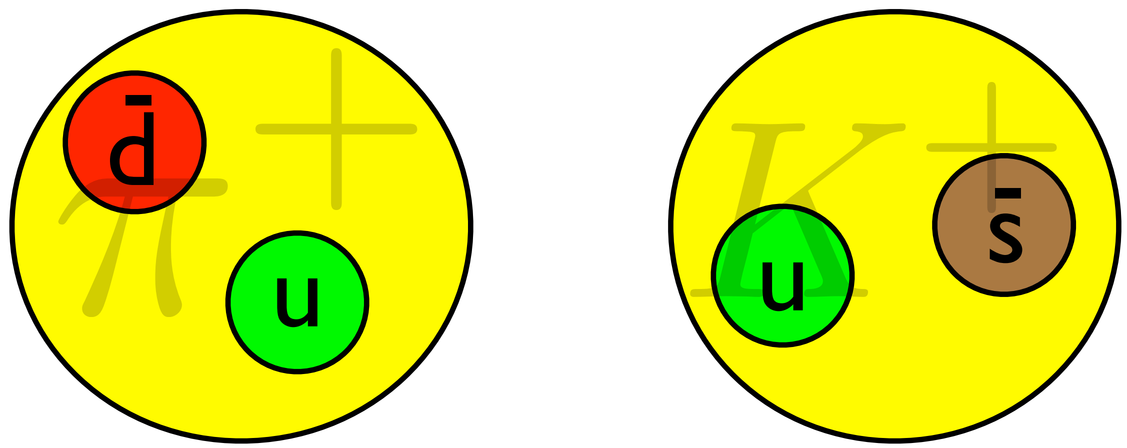
$$p + \text{Air} \xrightarrow{\textit{interaction}} \pi, K \xrightarrow{\textit{decay}} \mu, \nu_\mu$$

Neutrinos in the atmosphere originate from the interactions of cosmic rays (etc. protons) with nuclei.

Atmospheric neutrinos

- *Conventional*: decays of lighter mesons

$\pi^{\pm}, K^{\pm}$



Mean lifetime: $\tau \sim 10^{-8}\ s$

Long lifetime: interaction occurs before decay

$$\mathcal{L}_{\rm int} < \mathcal{L}_{\rm dec}$$

Long-lived mesons loose energy → Steeply falling flux of neutrinos

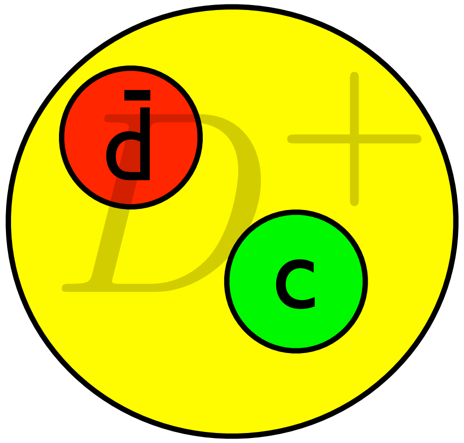
$\Phi_\nu \sim E_\nu^{-3.7}$

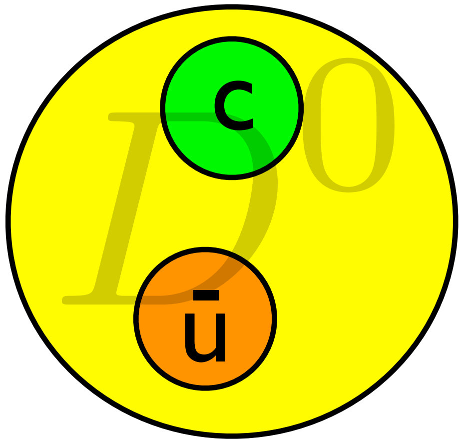
Prompt neutrinos

- *Prompt*: decays of heavier, charmed or bottom mesons

$D^{\pm}, D^{0}, D_s$

baryon Λ_c





Mean lifetime: $\tau \sim 10^{-12}\ s$

Short lifetime: decay, no interaction

$$\mathcal{L}_{\rm int} > \mathcal{L}_{\rm dec}$$

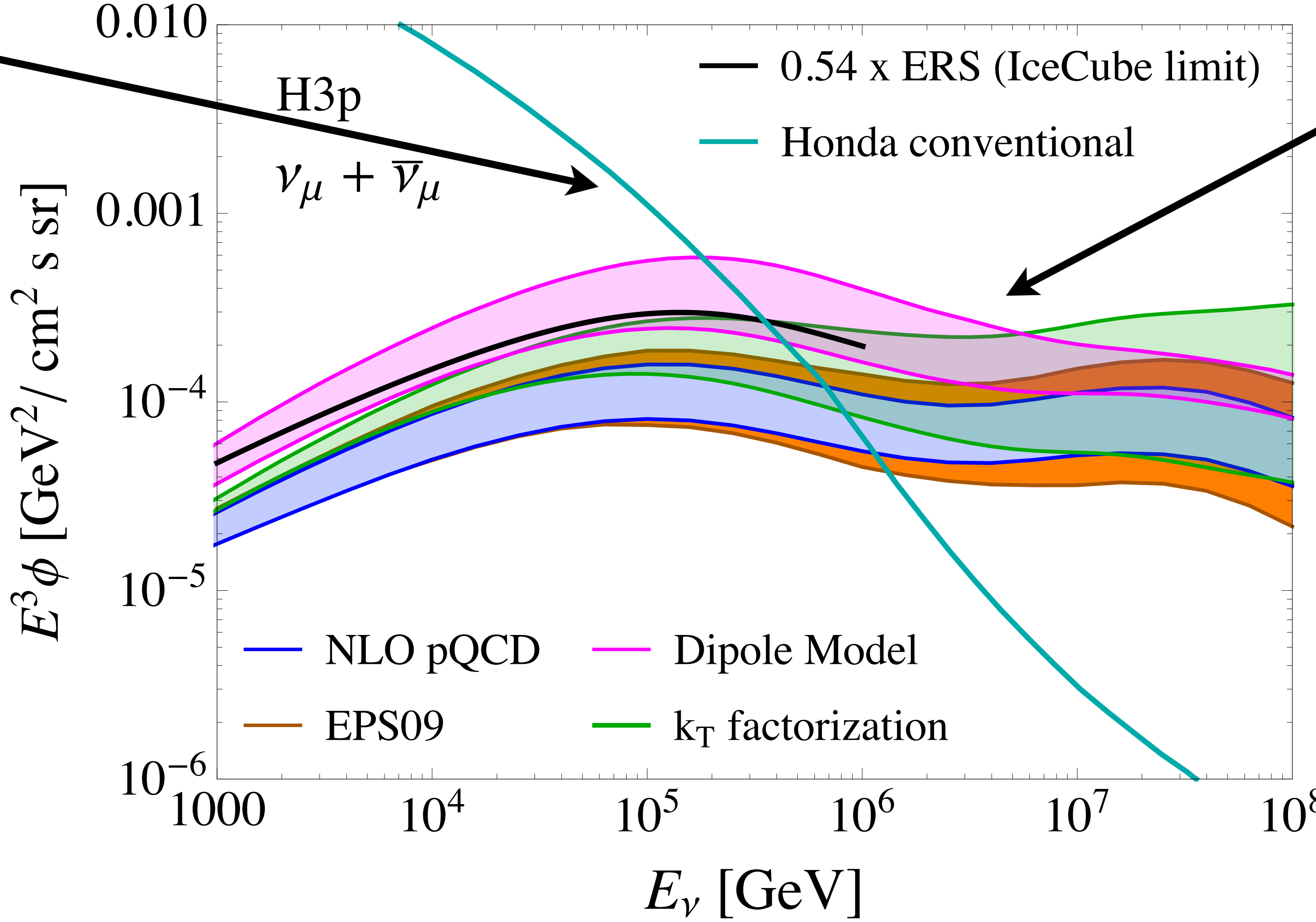
Flat flux, more energy transferred to neutrino

$$\Phi_{\nu} \sim E_{\nu}^{-2.7}$$

Prompt vs conventional flux

High energy atmospheric neutrino flux as a function of energy

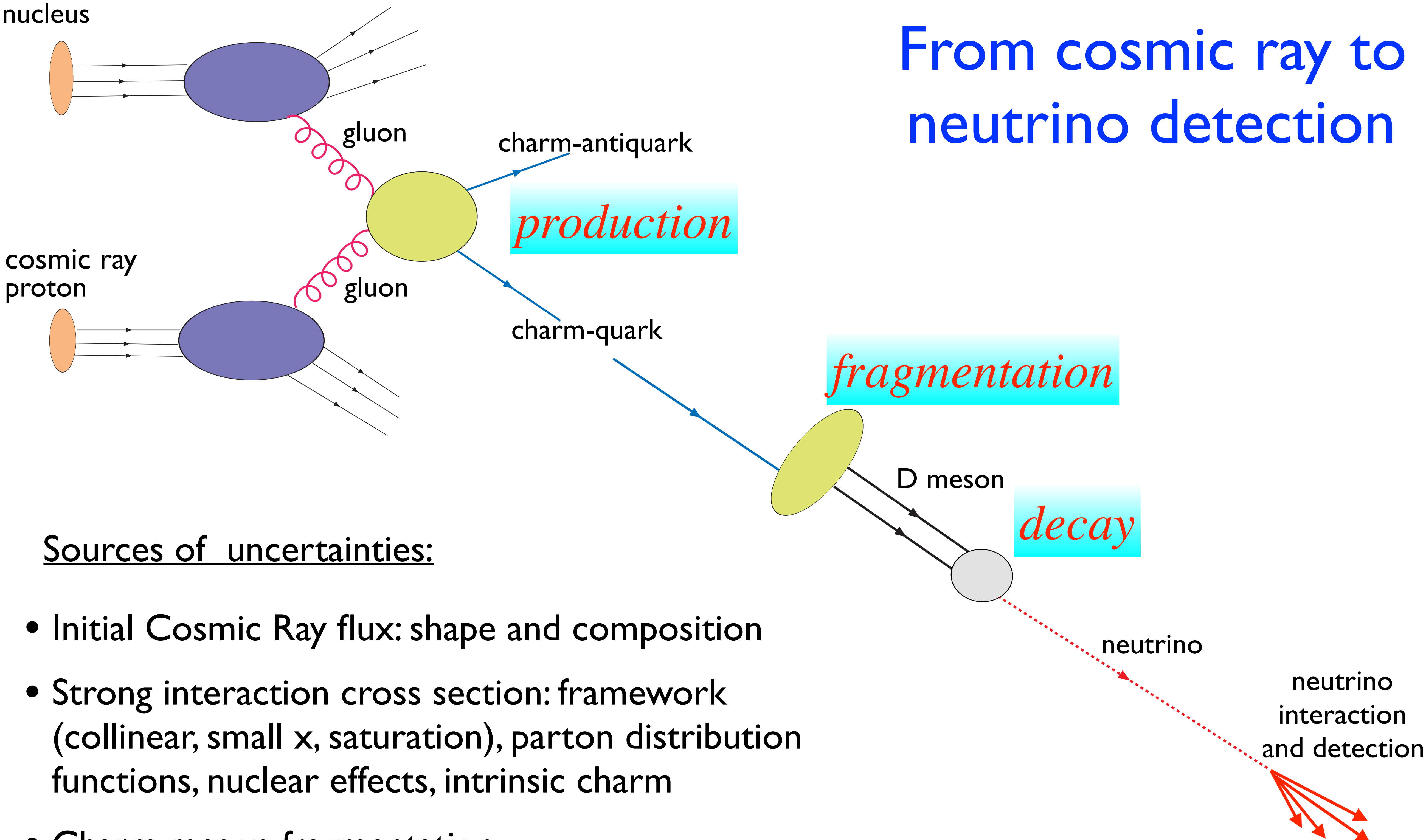
conventional: decay of long lived pions and kaons: loose energy. Soft spectrum.



prompt: decay of short lived charmed mesons: do not loose energy. Hard spectrum.

- Conventional flux: constrained by the low energy neutrino data.
- Prompt flux: poorly known, large uncertainties. Essential to evaluate as it can dominate the background for searches for extraterrestrial high energy neutrinos.

From cosmic ray to neutrino detection



Sources of uncertainties:

- Initial Cosmic Ray flux: shape and composition
- Strong interaction cross section: framework (collinear, small x, saturation), parton distribution functions, nuclear effects, intrinsic charm
- Charm meson fragmentation
- Decay
- Interaction cross section of neutrino

Frameworks for heavy quark production

- Standard NLO perturbative QCD collinear calculation.

- High-energy factorization with small x BFKL/DGLAP resummed evolution, including saturation effects (through nonlinear evolution equation).

- Small x dipole model with saturation.

Also:

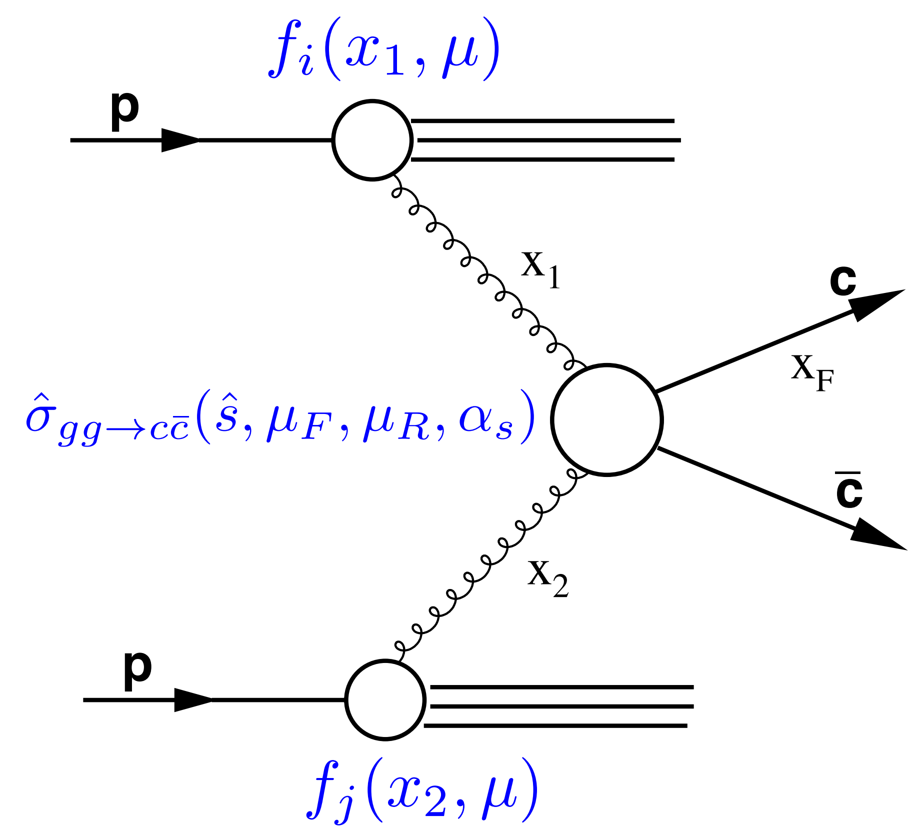
Nuclear corrections.

b quark contribution.

Heavy quark production in hadron collisions

Schematic representation of charm production in pp scattering:

$f_i(x, \mu)$ parton distribution function at scale μ
parametrized at scale μ_0
evolved to higher scales with QCD evolution equations



x_1, x_2 longitudinal momentum fractions (of a proton momentum) of gluons participating in a scattering process

$\hat{\sigma}_{gg\to c\bar{c}}(\hat{s}, \mu_F, \mu_R, \alpha_s)$ partonic cross section calculable in a perturbative way in QCD

Factorization formula for cross section:

$$\frac{d\sigma^{pp\to c+X}}{dx_F} = \sum_{i,j} f_i(x_1, \mu_F) \otimes \hat{\sigma}_{gg\to c\bar{c}}(\hat{s}, m_c, \mu_F, \mu_R) \otimes f_j(x_2, \mu_F)$$

pQCD collinear calculation

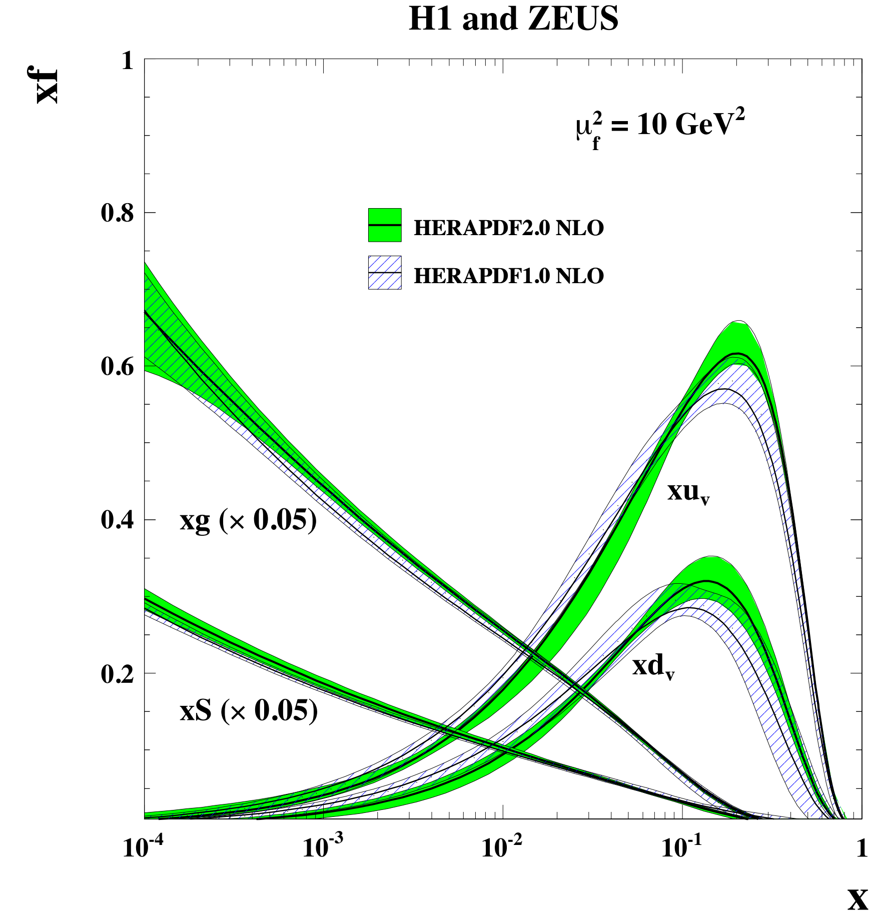
$$\frac{d\sigma^{pp\to c+X}}{dx_F} = \sum_{i,j} f_i(x_1,\mu_F)\otimes\hat{\sigma}_{gg\to c\bar{c}}(\hat{s},m_c,\mu_F,\mu_R)\otimes f_j(x_2,\mu_F)$$

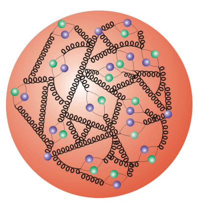
For the cosmic ray interactions we are interested in the forward production: charm quark is produced with very high fraction of the momentum of the incoming cosmic ray projectile. Other participating gluon will have very small fraction of longitudinal momentum:

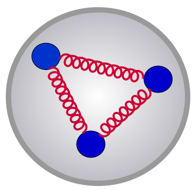
$$x_F \simeq \frac{E_c}{E_p} \qquad x_F \gg x_2 \qquad x_2 \sim \frac{M^2_{c\bar{c}}}{x_F s}$$

$$s \gg M^2_{c\bar{c}}$$

The cross section is sensitive to the domain of parton densities which are at very small values of x. This is poorly constrained region.







Hybrid k_T factorization calculation

Use k_T factorization for heavy quarks with off-shell gluon and unintegrated parton density.
Suitable for the high energy - low x regime.

Catani,Ciafaloni,Hautmann; Collins,Ellis; Levin,Ryskin,Shabelski,Shuvaev

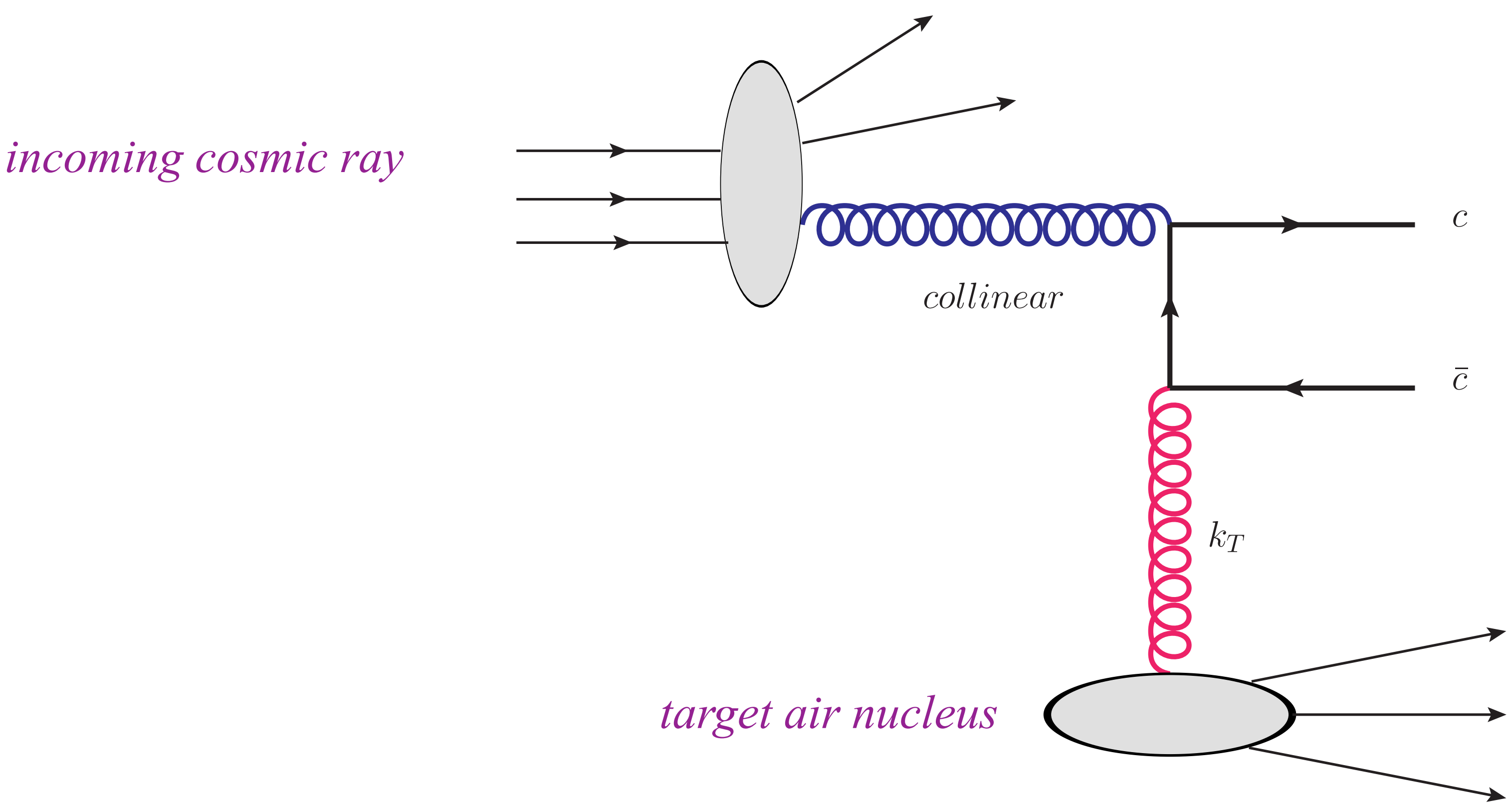
Since it is forward production, use 'hybrid' calculation: treat large x gluon as collinear, and small x gluon as off-shell.

collinear gluon

$$\sigma(pp \to q\bar{q}X) = \int \frac{dx_1}{x_1}\frac{dx_2}{x_2}\, dz\, dx_F\, \delta(zx_1 - x_F)\boxed{x_1 g(x_1, M_F)}$$

$$\times \int \frac{dk_T^2}{k_T^2}\hat{\sigma}^{\rm off}(z,\hat{s},k_T)\boxed{f(x_2,k_T^2)}$$

off-shell gluon with k_T dependence



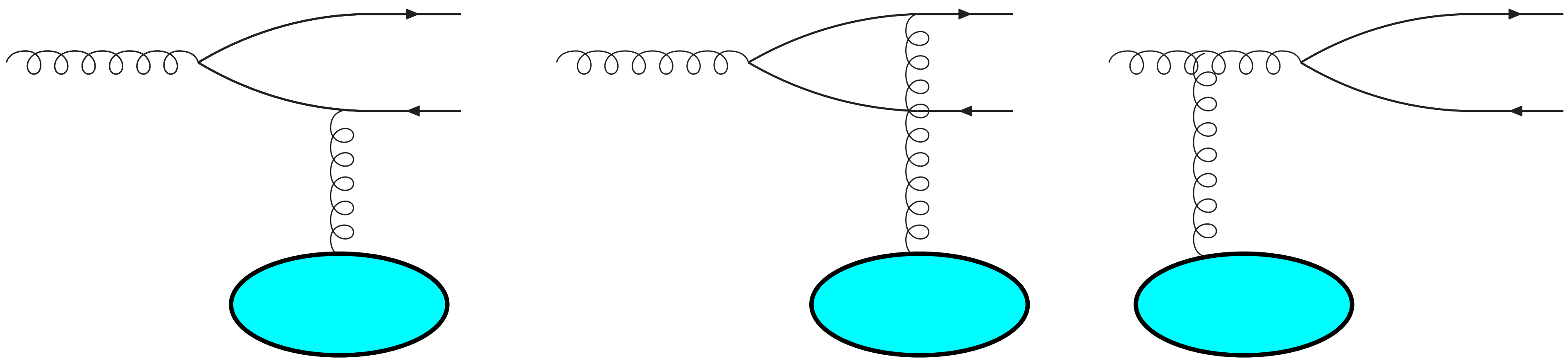
Unintegrated gluon density obtained from the resummed small x evolution equation with non-linear term

Kutak,Sapeta;
based on KMS (Kwiecinski,Martin,AS)

Dipole model calculation

Mueller;Nikolaev,Zakharov; Kopeliovich,Tarasov; Raufeisen,Peng

At high energy the production of the heavy quark pair is viewed as interaction of color dipole:



Gluon fluctuation into heavy quark-antiquark pair : color dipole

Interaction of the color dipole with the hadronic target.

Advantage of this framework: saturation and nuclear effects can be easily included as multiple scattering of the color dipole off the target.

Dipole model calculation

Heavy quark cross section in the dipole model:

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

Partonic cross section:

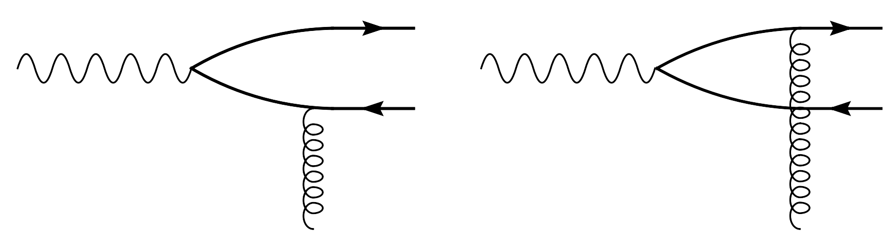
$$\sigma^{gp\to q\bar{q}X}(x, M_R, Q^2) = \int dz\, d^2\vec{r}\, |\Psi_g^q(z, \vec{r}, M_R, Q^2)|^2 \sigma_d(x, \vec{r})$$

Dipole cross section:

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

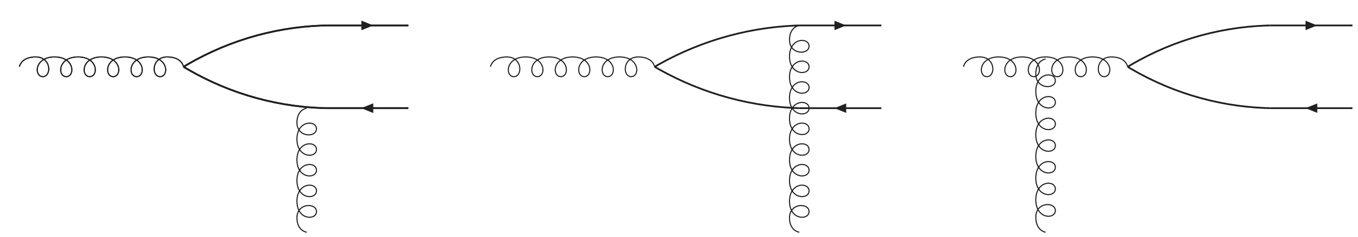
$\sigma_d(x, \vec{r})$

gluon dipole



$\sigma_{d,em}(x, \vec{r})$

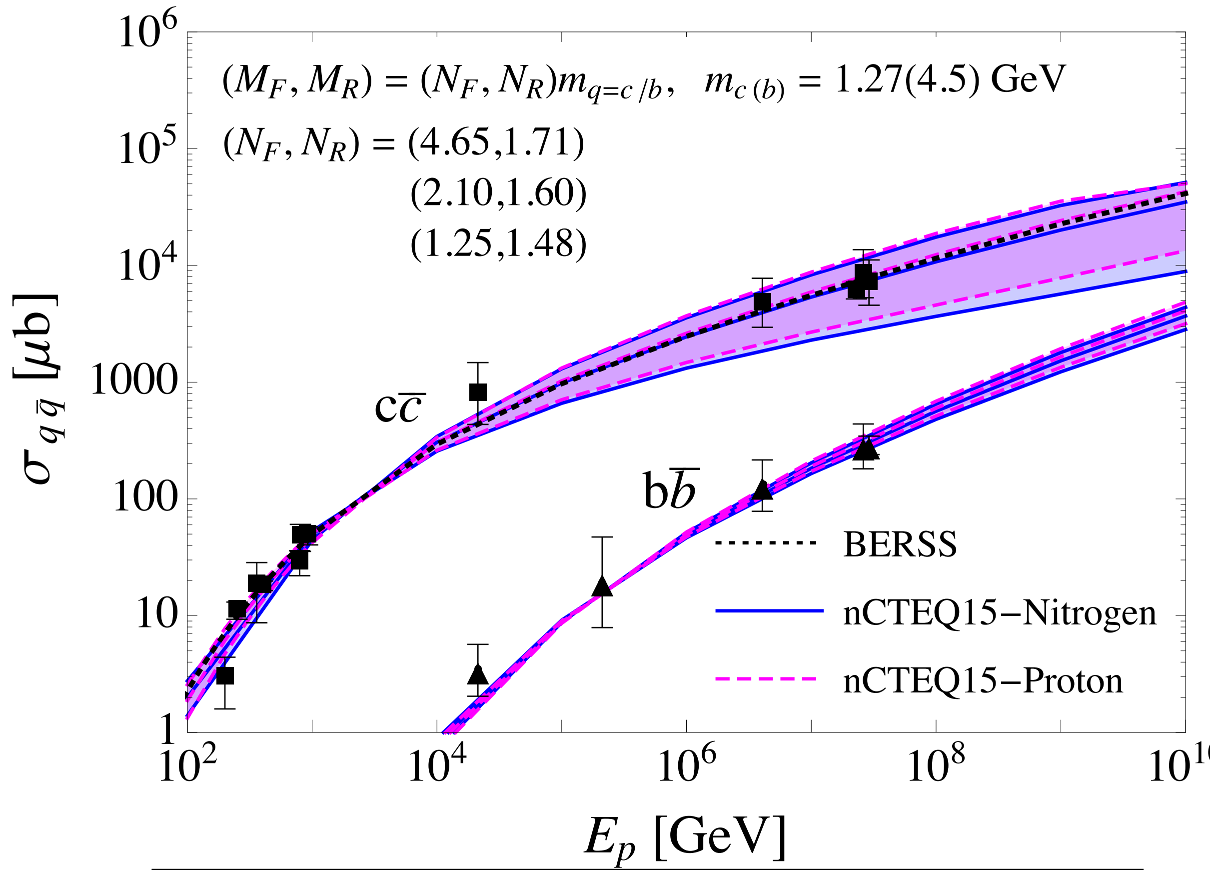
color singlet dipole



Dipole xsection constrained by collider data

Total charm production cross section

- NLO collinear calculation, HVQ, *Nason, Dawson,Ellis; Mangano, Nason, Ridolfi*
- Default parton distribution set is CT15 Central.
- Charm quark mass $m_c = 1.27\ \text{GeV}$
- Variation of factorization and renormalization scales with respect to charm quark mass. Using range provided by Nelson,Vogt,Frawley
- Magenta-free nucleons, blue-nitrogen
- Comparison with RHIC and LHC data. Data are extrapolated with NLO QCD from measurements in the limited phase space region.

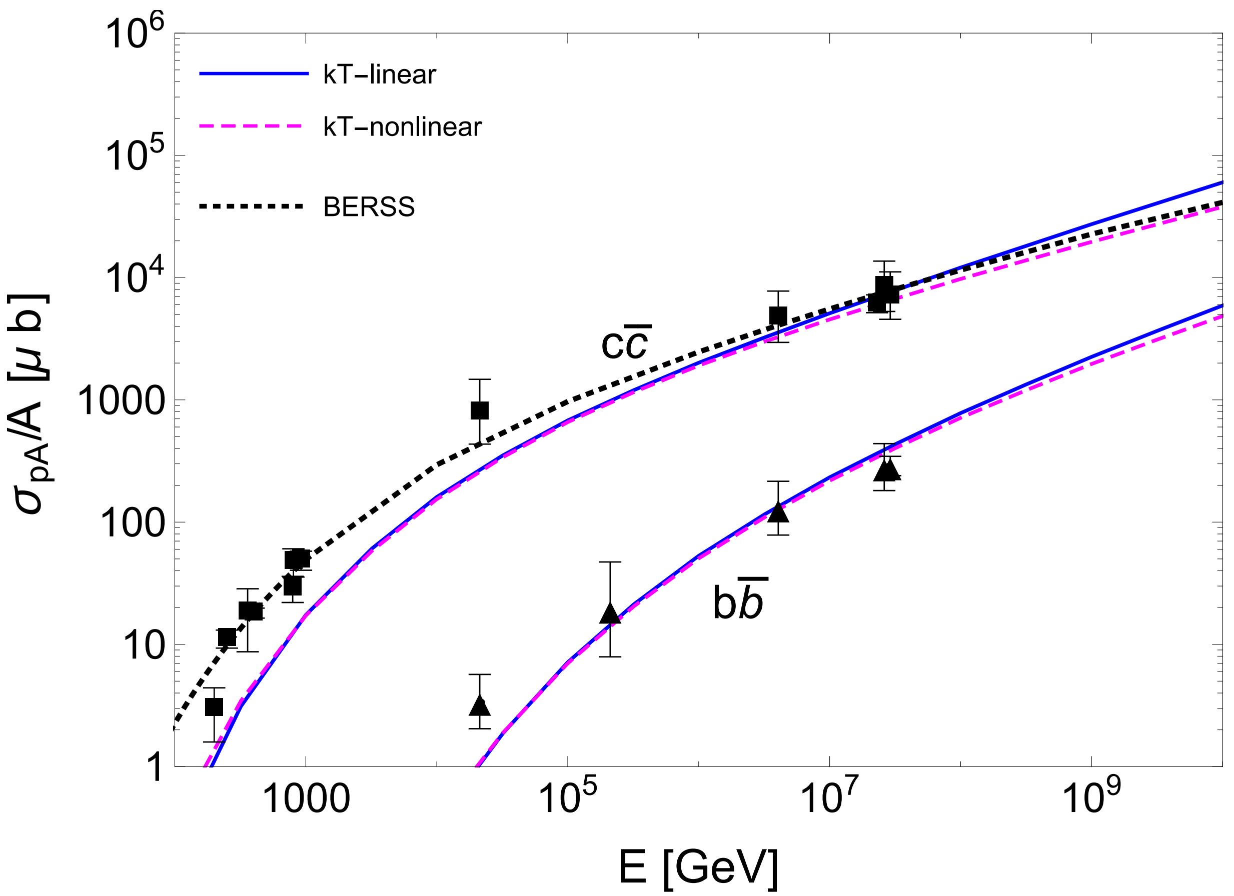


Expt.	$\sqrt{s}$ [TeV]	σ [mb]
PHENIX [31]	0.20	$\mathbf{0.551}^{+0.203}_{-0.231}$ (sys)
STAR [32]	0.20	$\mathbf{0.797} \pm 0.210$ (stat)$^{+0.208}_{-0.295}$ (sys)
ALICE [27]	2.76	$\mathbf{4.8} \pm 0.8$ (stat)$^{+1.0}_{-1.3}$ (sys) ± 0.06 (BR) ± 0.1(frag) ± 0.1 (lum)$^{+2.6}_{-0.4}$ (extrap)
ALICE [27]	7.00	$\mathbf{8.5} \pm 0.5$ (stat)$^{+1.0}_{-2.4}$ (sys) ± 0.1 (BR) ± 0.2(frag) ± 0.3 (lum)$^{+5.0}_{-0.4}$ (extrap)
ATLAS [28]	7.00	$\mathbf{7.13} \pm 0.28$ (stat)$^{+0.90}_{-0.66}$ (sys) ± 0.78 (lum)$^{+3.82}_{-1.90}$ (extrap)
LHCb [30]	7.00	$\mathbf{6.100} \pm 0.930$

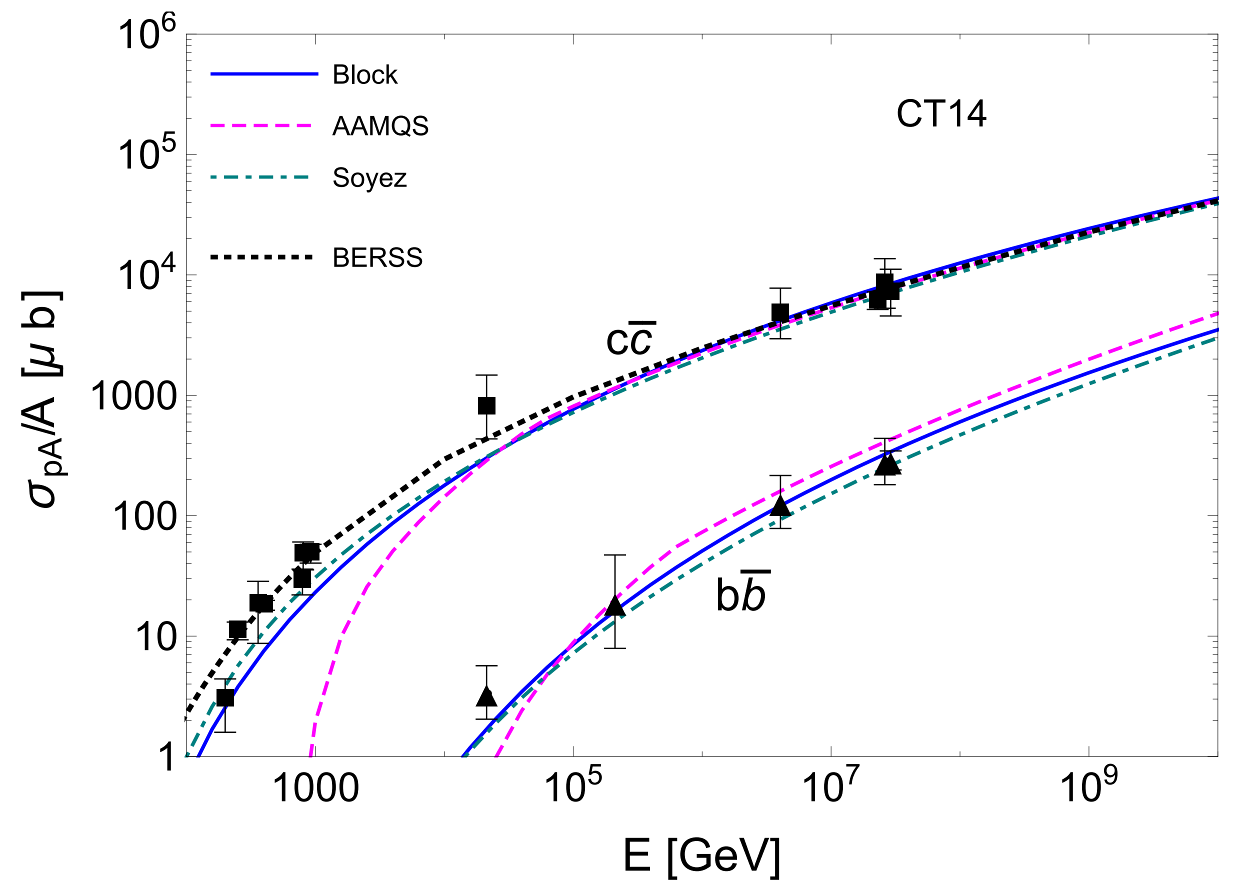
Table 1: Total cross-section for $pp(pN) \to c\bar{c}X$ in hadronic collisions, extrapolated based on NLO QCD by the experimental collaborations from charmed hadron production measurements in a limited phase space region.

Total charm production cross section

k_T



dipole model

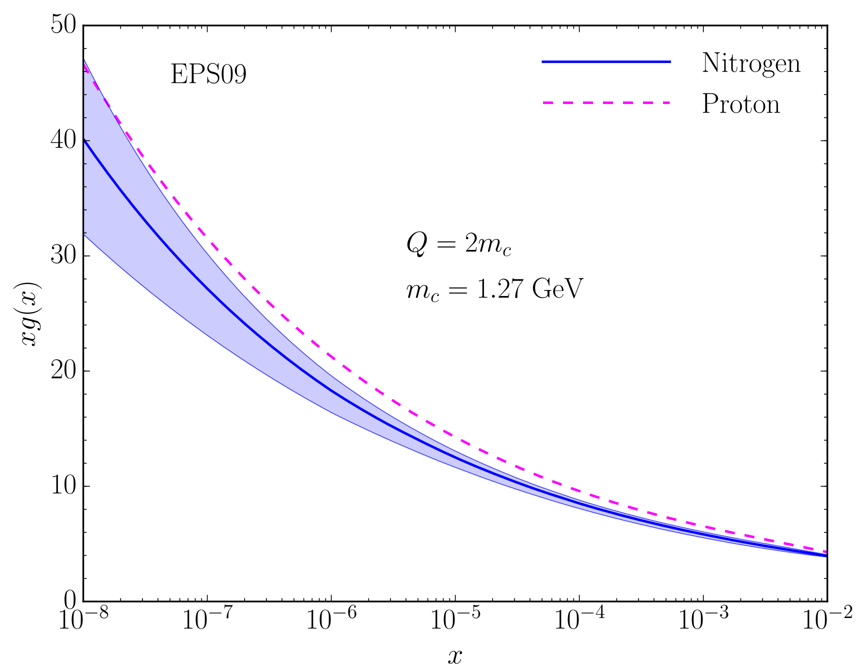


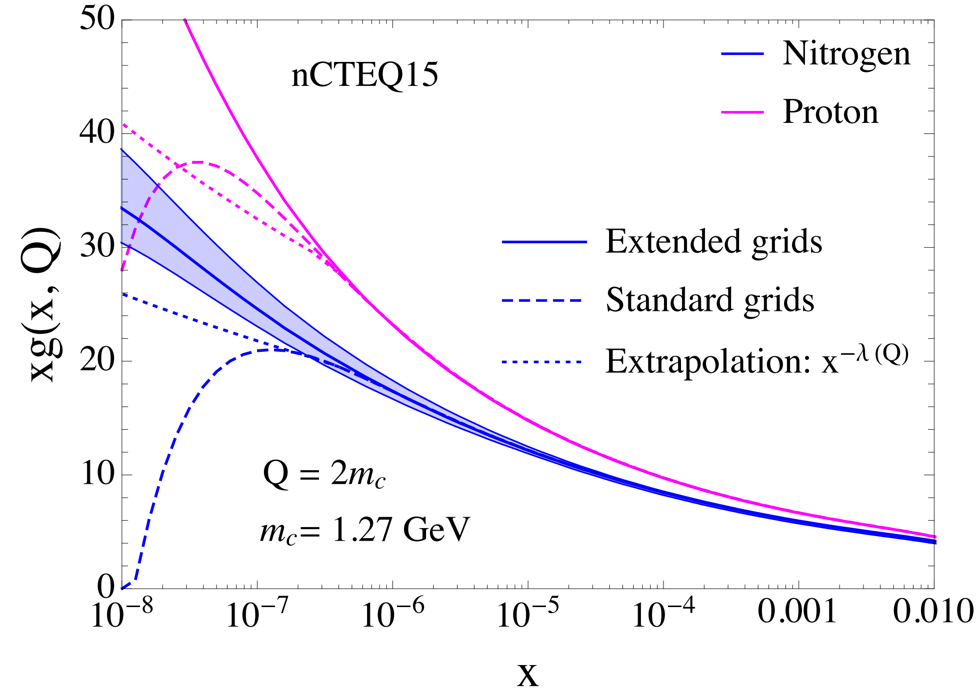
- BERSS: *Bhattacharya, Enberg,Reno,Stasto,Sarcevic*: previous NLO calculation
- AAMQS,*Albacete, Armesto,Milhano,Quiroga-Arias,Salgado:* rcBK
- Soyez: based on *Iancu,Itakura,Munier* parametrization inspired by BK solution
- Block: phenomenological parametrization of the structure function
- k_T calculation underestimates data at low energy.
- Need additional diagrams there (or energy dependent K-factor).

Nuclear corrections

NLO pQCD

Use of nuclear PDFs, nCTEQ and EPS





Dipole model

Glauber-Gribov formalism for nuclear rescattering

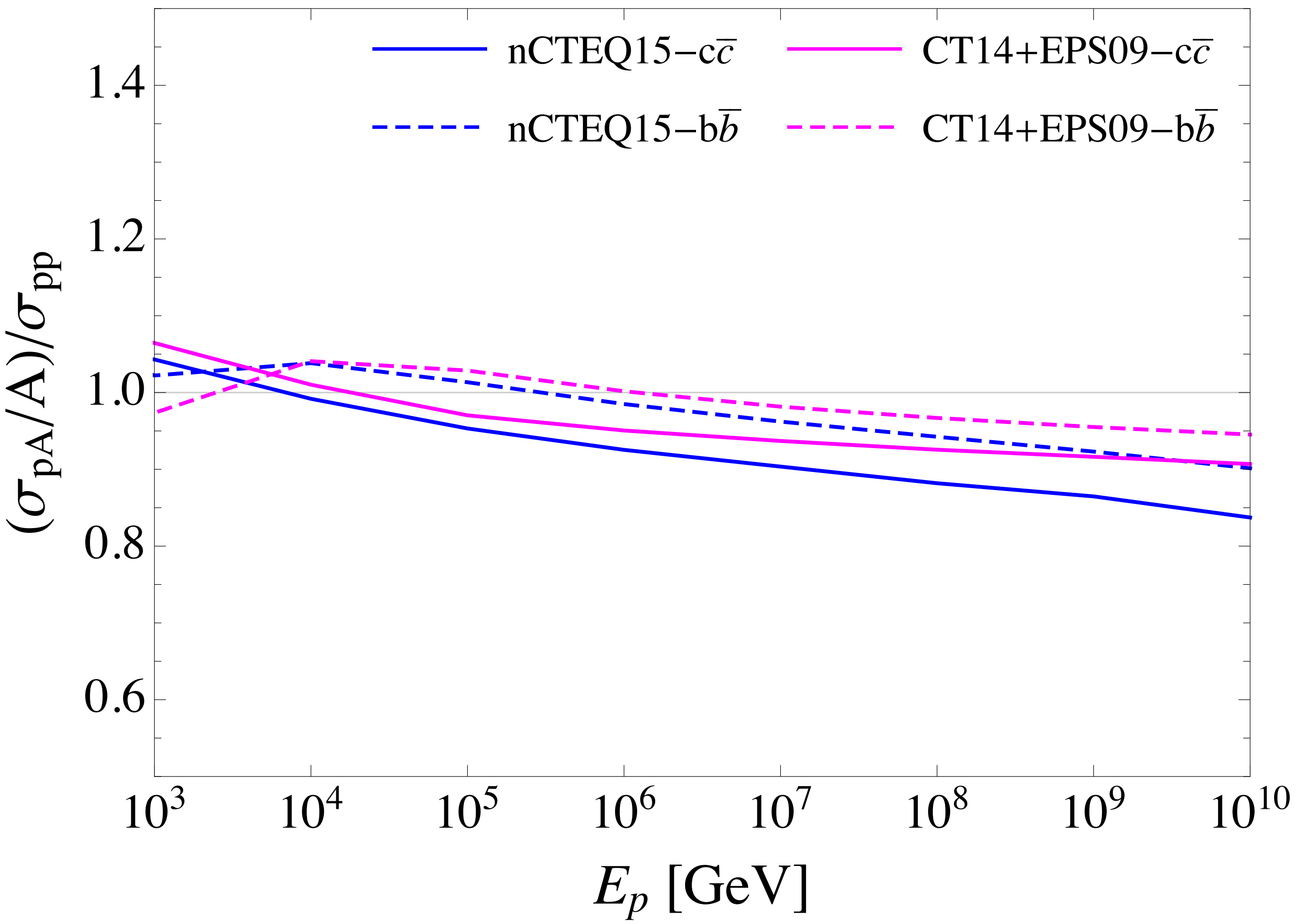
k_T factorization

Small x evolution with the nonlinear density term enhanced by factor proportional to mass number A

Nuclear corrections

Nuclear modifications to the total charm production cross section are small:

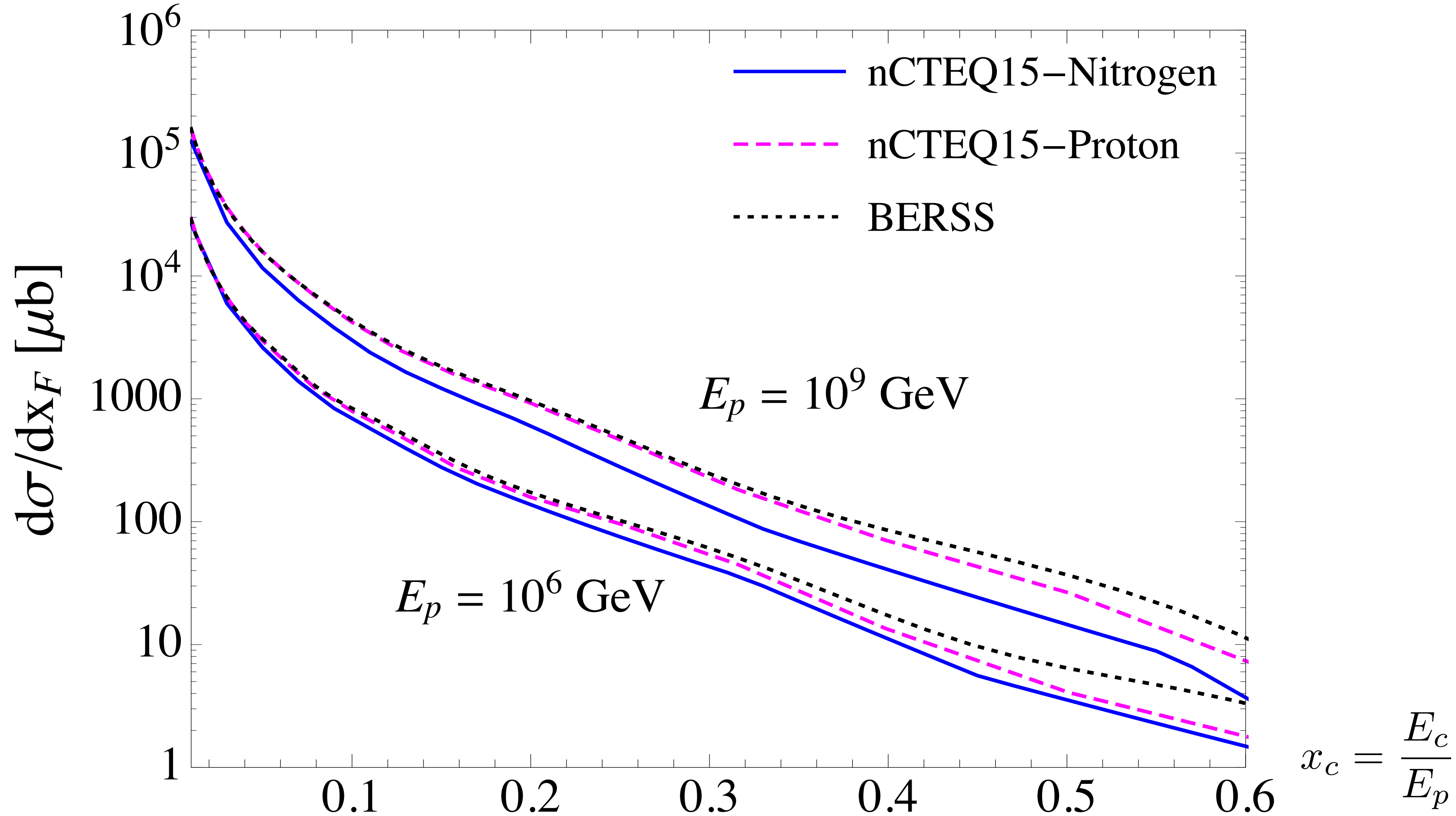
10%-15% for charm
5%-10% for bottom



E_p	$\sigma(pp \to c\bar{c}X)$ [μb]		$\sigma(pA \to c\bar{c}X)/A$ [μb]		$[\sigma_{pA}/A]/[\sigma_{pp}]$	
	$M_{F,R} \propto m_T$	$M_{F,R} \propto m_c$	$M_{F,R} \propto m_T$	$M_{F,R} \propto m_c$	$M_{F,R} \propto m_T$	$M_{F,R} \propto m_c$
10^2	1.51	1.87	1.64	1.99	1.09	1.06
10^3	3.84×10^1	4.72×10^1	4.03×10^1	4.92×10^1	1.05	1.04
10^4	2.52×10^2	3.06×10^2	2.52×10^2	3.03×10^2	1.00	0.99
10^5	8.58×10^2	1.03×10^3	8.22×10^2	9.77×10^2	0.96	0.95
10^6	2.25×10^3	2.63×10^3	2.10×10^3	2.43×10^3	0.93	0.92
10^7	5.36×10^3	5.92×10^3	4.90×10^3	5.35×10^3	0.91	0.90
10^8	1.21×10^4	1.23×10^4	1.08×10^4	1.09×10^4	0.89	0.89
10^9	2.67×10^4	2.44×10^4	2.35×10^4	2.11×10^4	0.88	0.86
10^{10}	5.66×10^4	4.67×10^4	4.94×10^4	3.91×10^4	0.87	0.84

Differential charm cross section

Differential charm cross section in proton-nucleon collision as a function of the fraction of the incident beam energy carried by the charm quark.



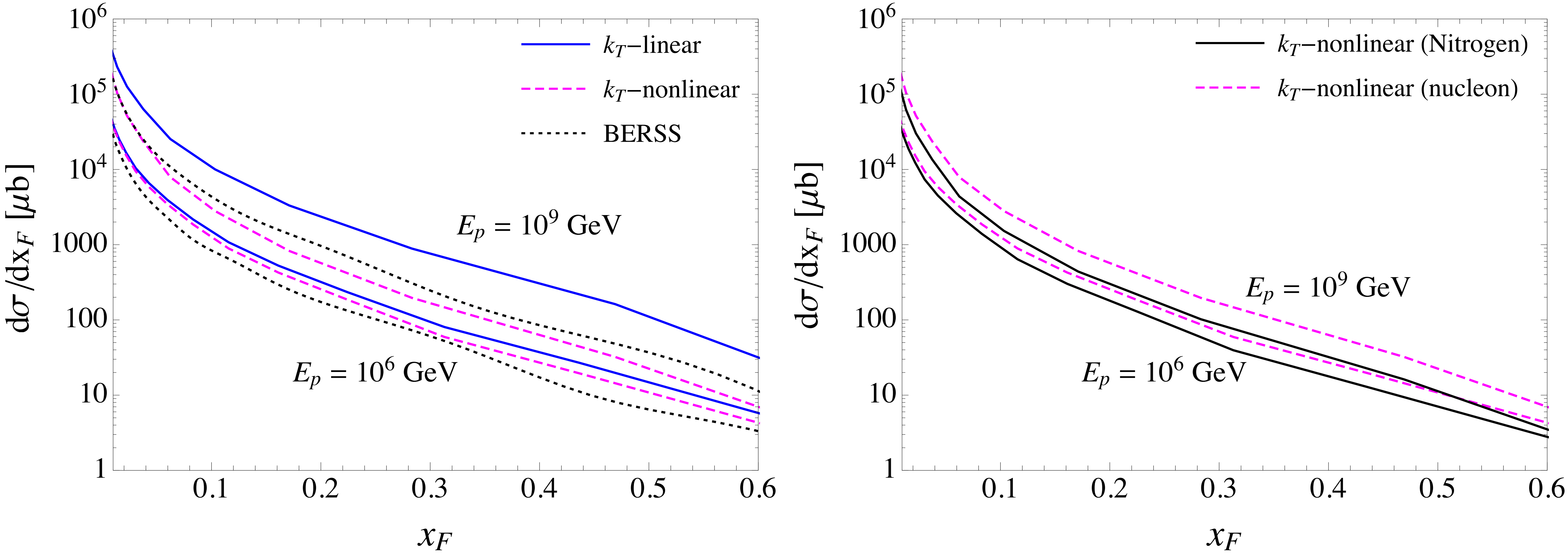
Differential charmed hadron cross section as a function of the energy: need to convolute with the fragmentation function

$$\frac{d\sigma}{dE_h} = \sum_k \int \frac{d\sigma}{dE_k}(AB \to kX) D_k^h\left(\frac{E_h}{E_k}\right)\frac{dE_k}{E_k}$$

$$h = D^\pm, D^0(\bar{D}^0), D_s^\pm, \Lambda_c^\pm$$

Using Kniehl, Kramer fragmentation functions.

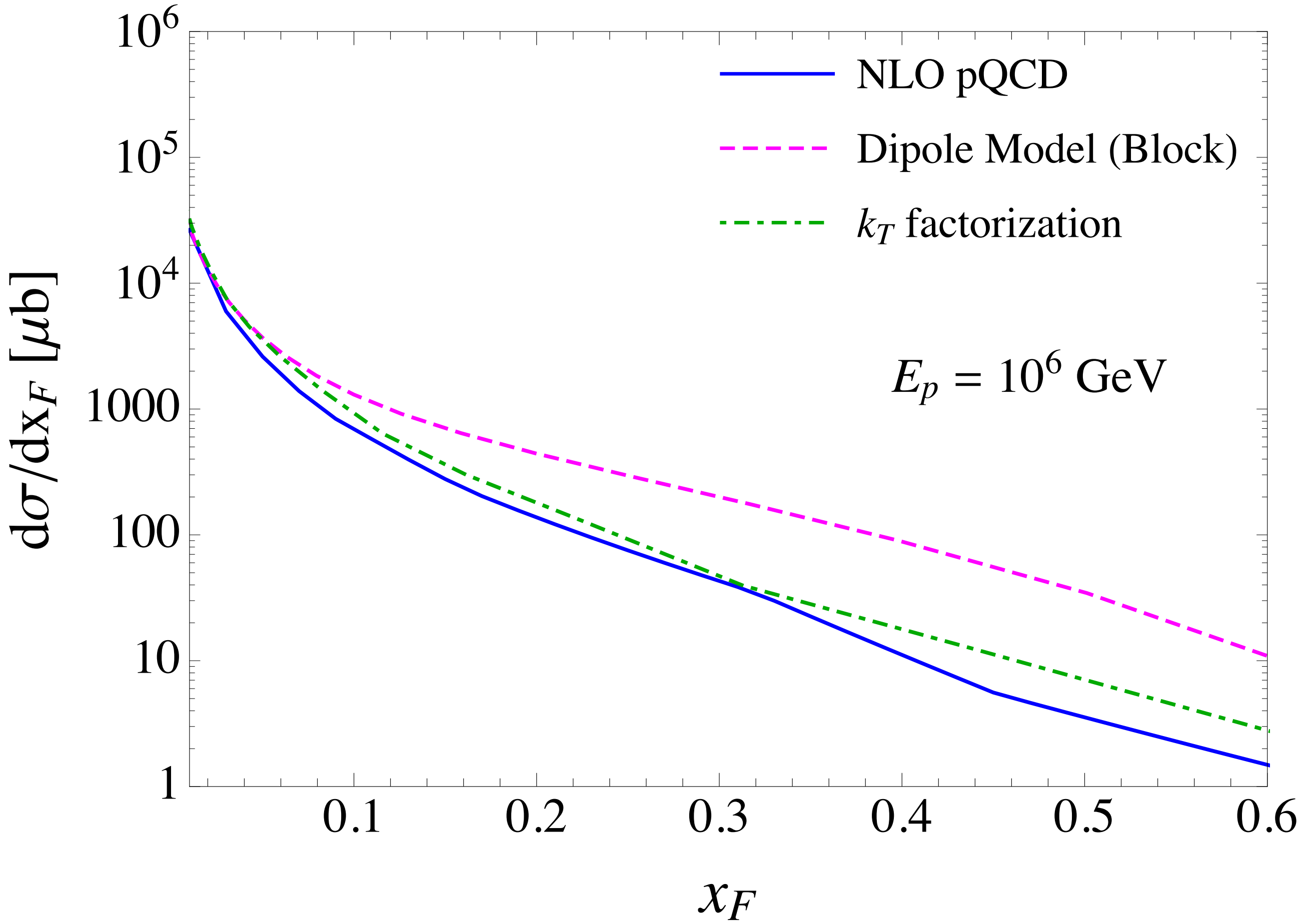
Differential charm cross section

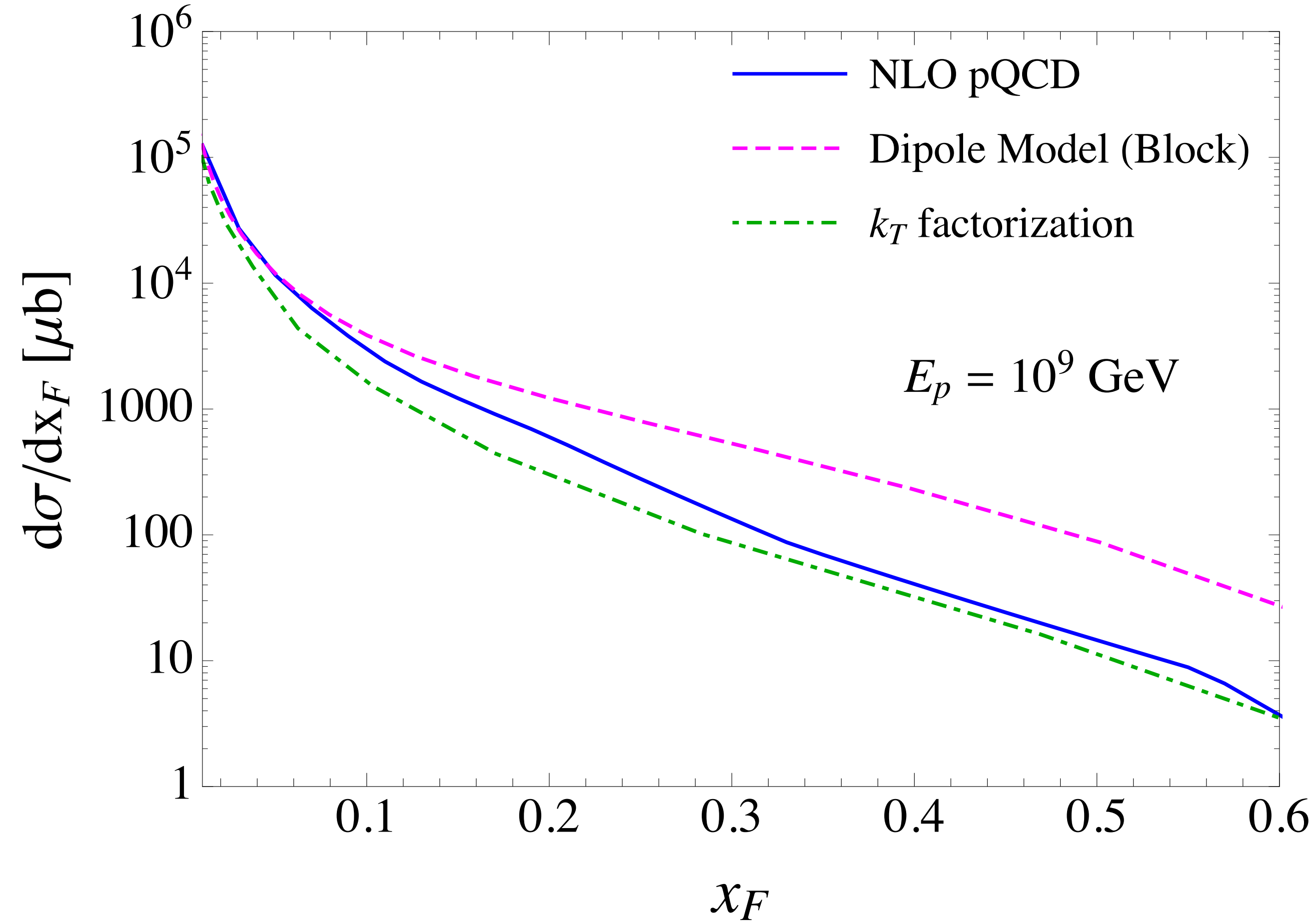


- Parton saturation effects affect the differential cross section more than the integrated cross section.
- Reduction of the cross section, at large energy of the charm quark.
- Nuclear effects in nitrogen are non-negligible at these energies.

Differential charm cross section

Comparison of NLO pQCD, dipole model, and k_T factorization

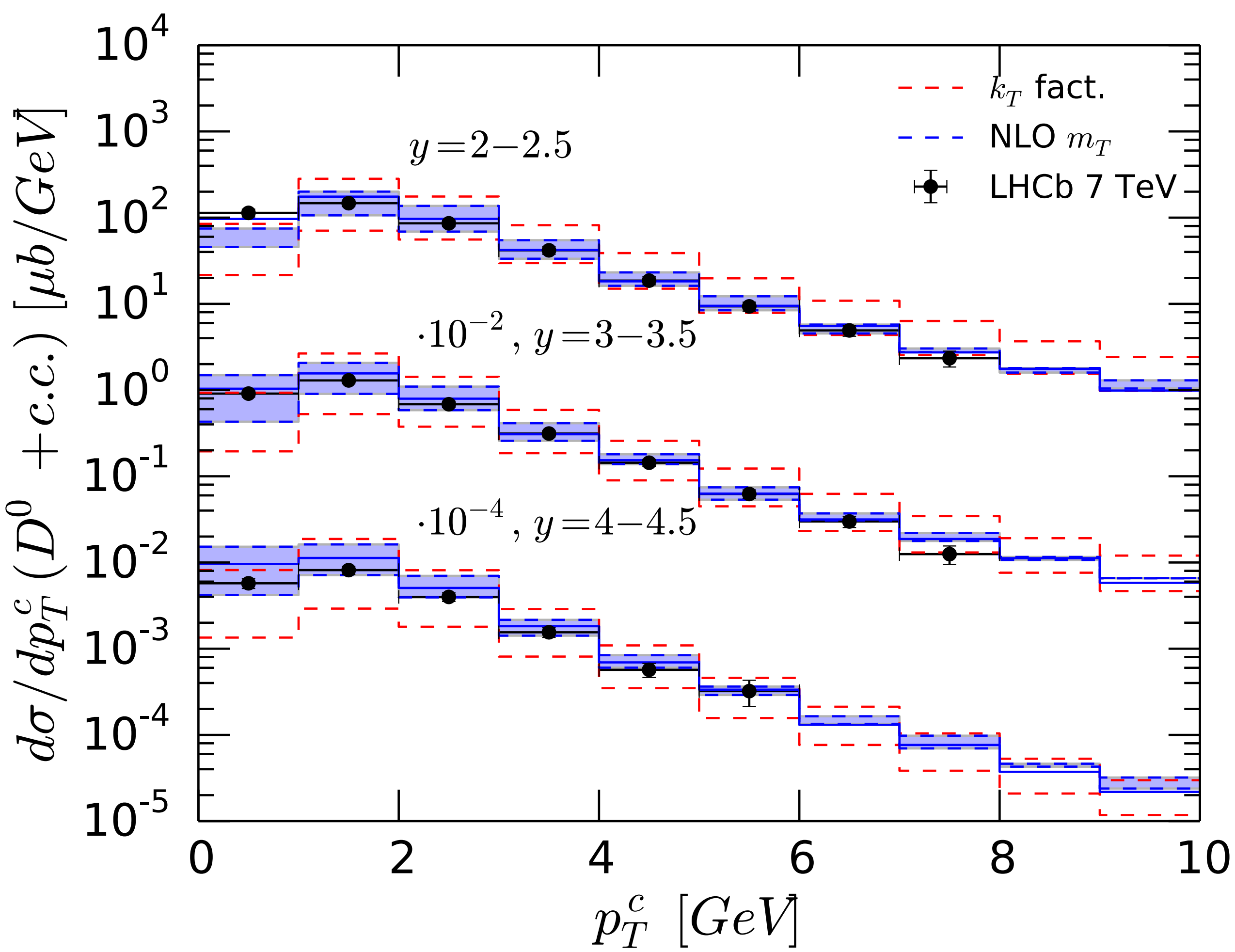


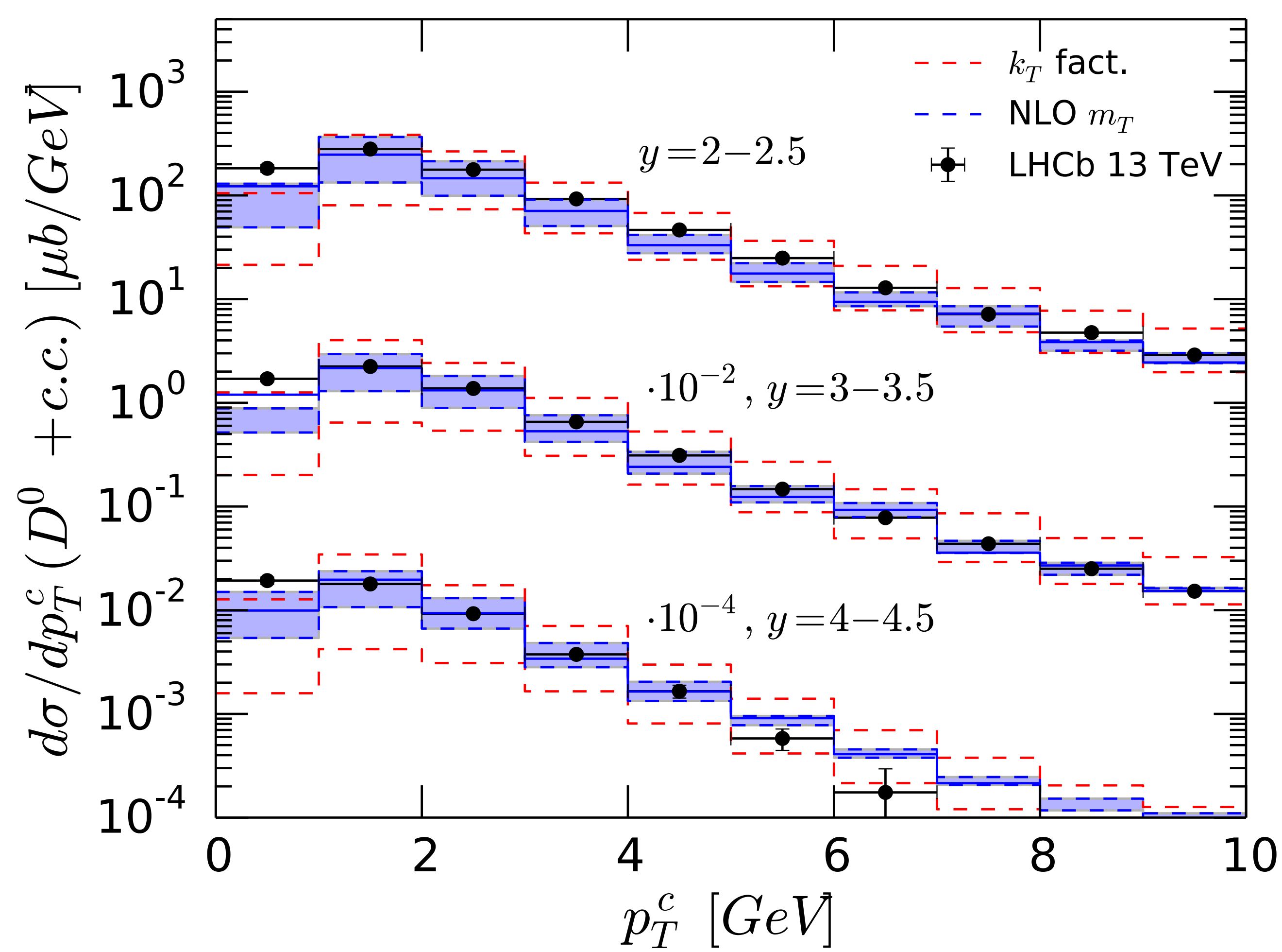


- NLO calculation and k_T factorization calculation consistent with each other.
- Dipole calculation systematically above the other two : need for improvements in this model.

Comparison with LHCb 7 and 13 TeV

Transverse momentum distributions





- NLO pQCD and k_T factorization consistent with each other.
- Bands on NLO pQCD calculation correspond to scale variation.
- Two lines in k_T factorization correspond to the saturation/no-saturation calculation.

Comparison with LHCb 7 and 13 TeV

Integrated cross section for charm-anticharm production at 7 and 13 TeV.

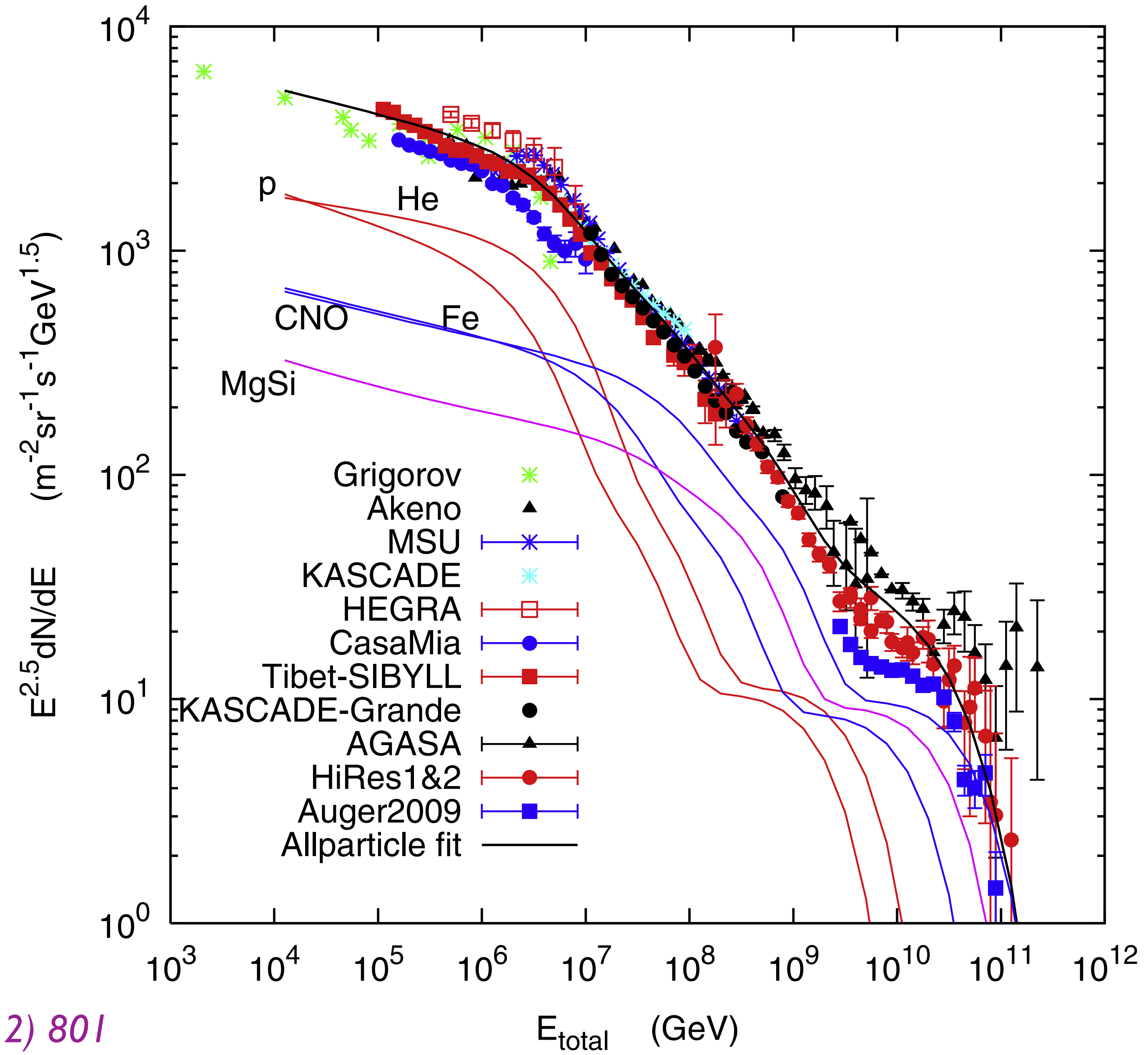
$1 < p_T < 8 \quad \mathrm{GeV/c}$ $\qquad$ $2.0 < y < 4.5$

$\sqrt{s}$	$\sigma(pp \to c\bar{c}X)$ [μb]				
	NLO ($\mu \propto m_T$)	NLO ($\mu \propto m_c$)	DM	k_T	Experiment
7 TeV	1610^{+480}_{-620}	1730^{+900}_{-1020}	1619^{+726}_{-705}	$1347 \div 1961$	1419 ± 134
13 TeV	2410^{+700}_{-960}	2460^{+1440}_{-1560}	2395^{+1276}_{-1176}	$2191 \div 3722$	2369 ± 192

Cosmic ray flux

Important ingredient for lepton fluxes: initial cosmic ray flux.

Parametrization by Gaisser (2012) with three populations and five nuclei groups: H,He,CNO,Fe,MgSi



Gaisser,
Astroparticle Physics 35 (2012) 801

Cosmic ray flux

Multicomponent parametrization by Gaisser (2012) with three populations:

1st population: supernova remnants
2nd population: higher energy galactic component
3nd population: extragalactic component

$$\phi_i(E) = \sum_{j=1}^{3} a_{i,j} E^{-\gamma_{i,j}} \times \exp\left[-\frac{E}{Z_i R_{c,j}}\right]$$

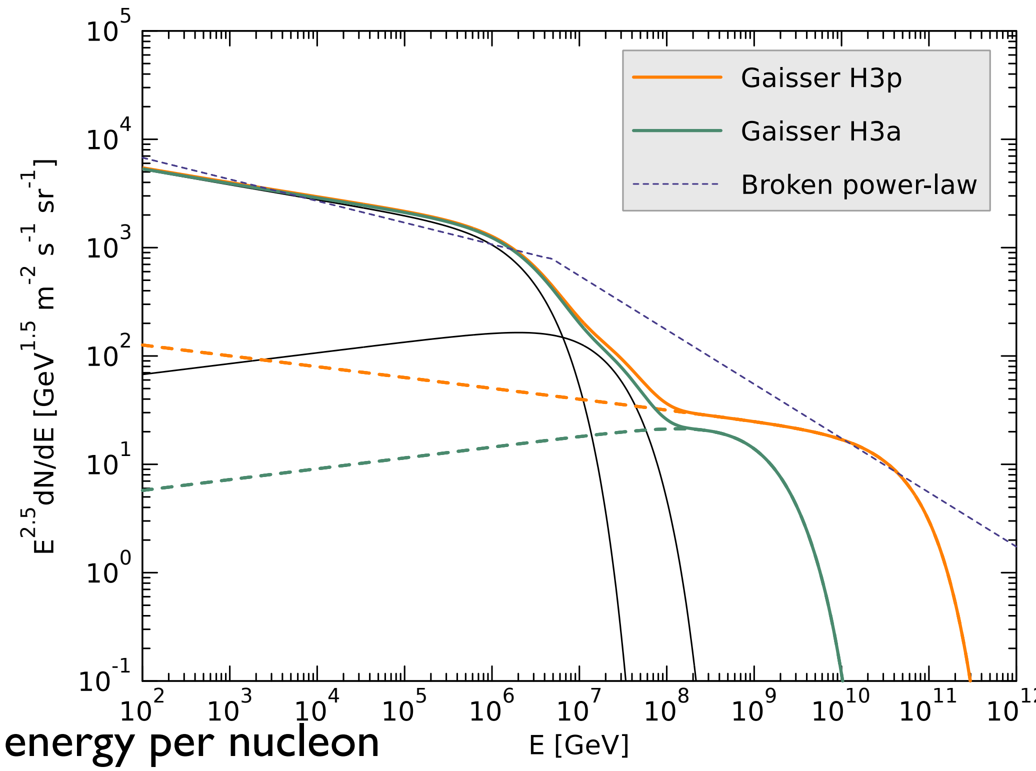
$a_{i,j}$ normalization

$\gamma_{i,j}$ spectral index

$R_{c,j}$ magnetic rigidity

$E^c_{\mathrm{tot}} = Ze \times R_c$

$\phi = dN/d\ln E$



energy per nucleon

Converting to nucleon spectrum

$$\phi_{i,N}(E_N) = A \times \phi_i(AE_N)$$

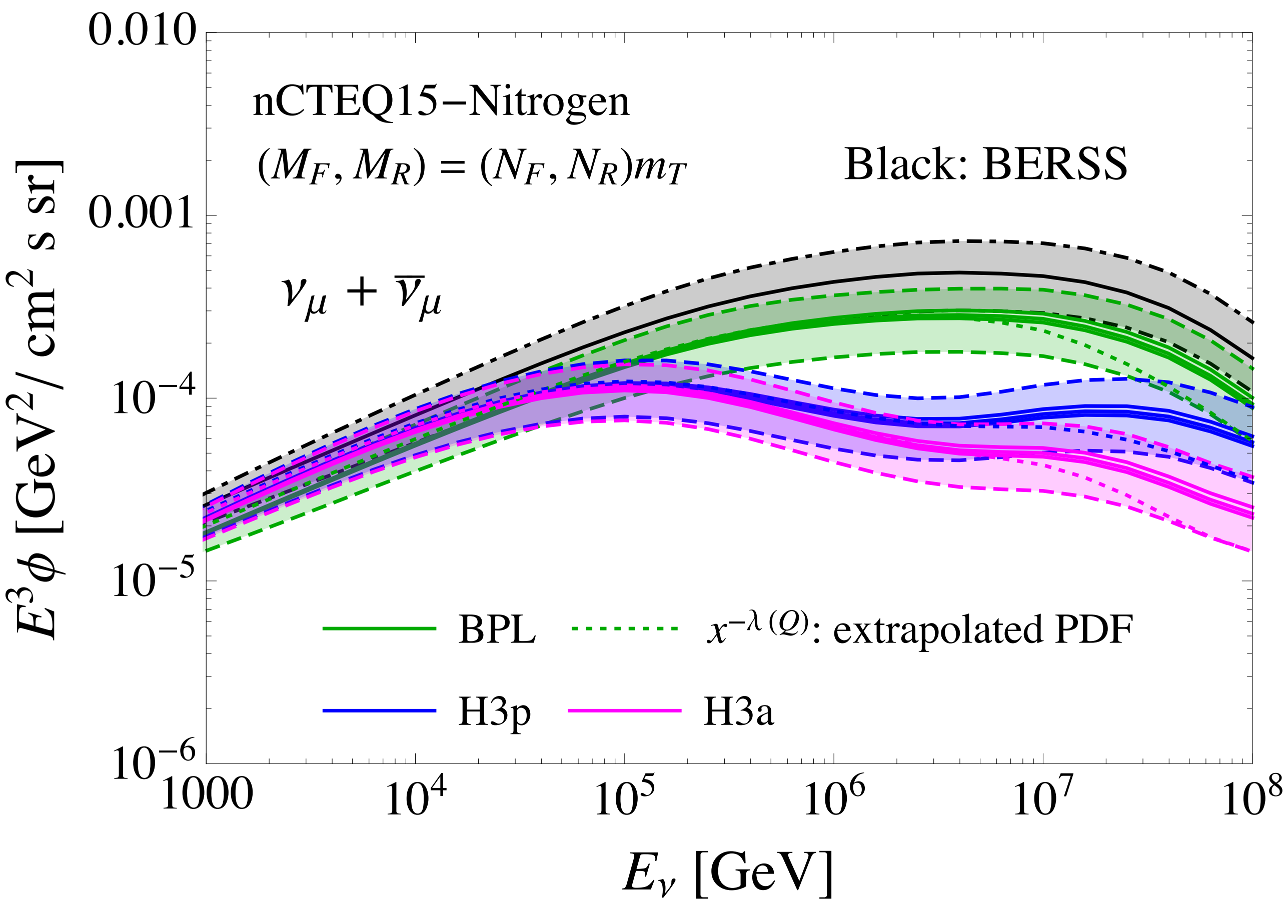
for each component

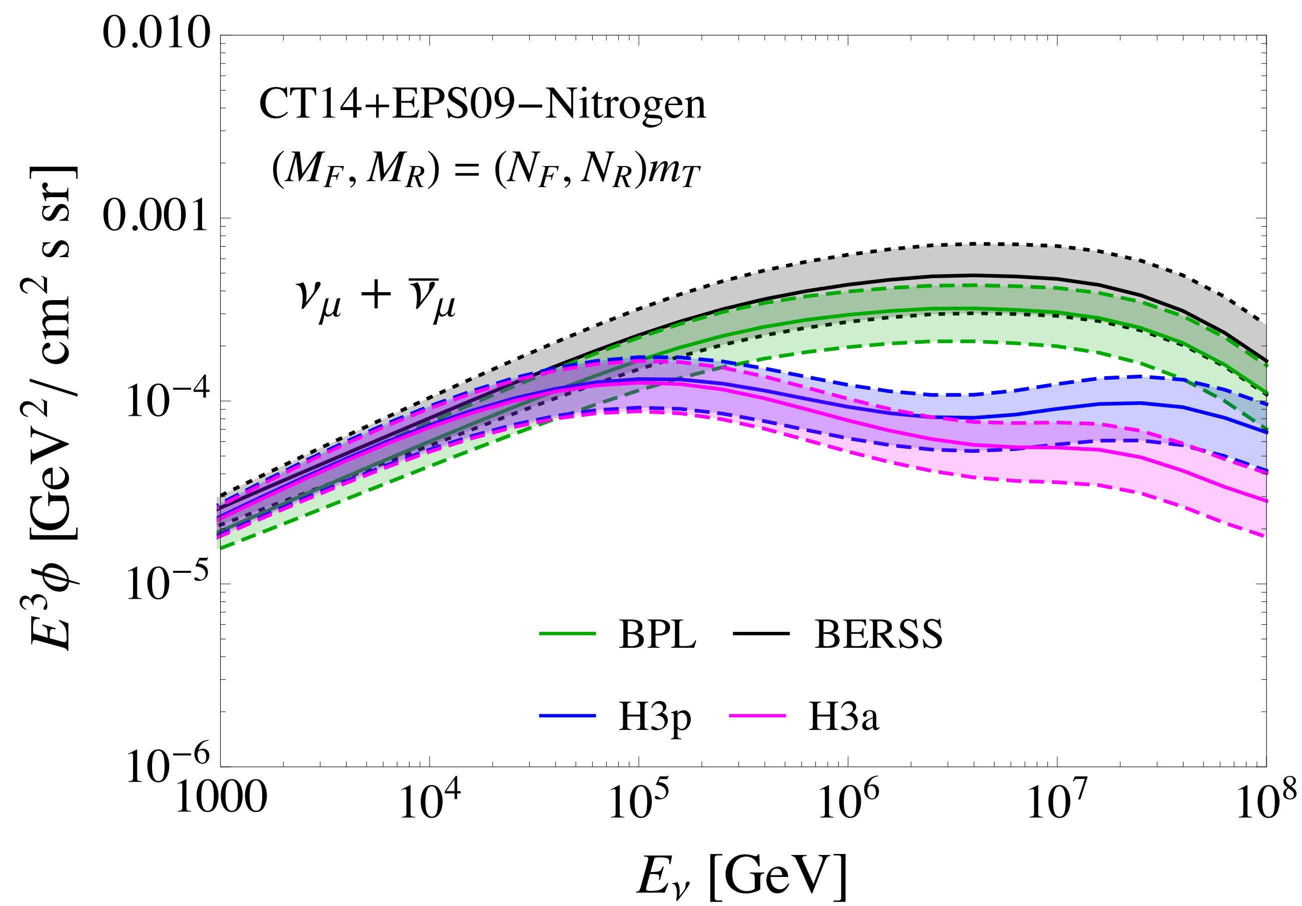
This power law was used widely in previous evaluations of the prompt neutrino flux

$$\phi_p^0(E) = \begin{cases} 1.7\, E^{-2.7} & \text{for } E < 5 \cdot 10^6 \text{ GeV} \\ 174\, E^{-3} & \text{for } E > 5 \cdot 10^6 \text{ GeV}, \end{cases}$$

Neutrino fluxes

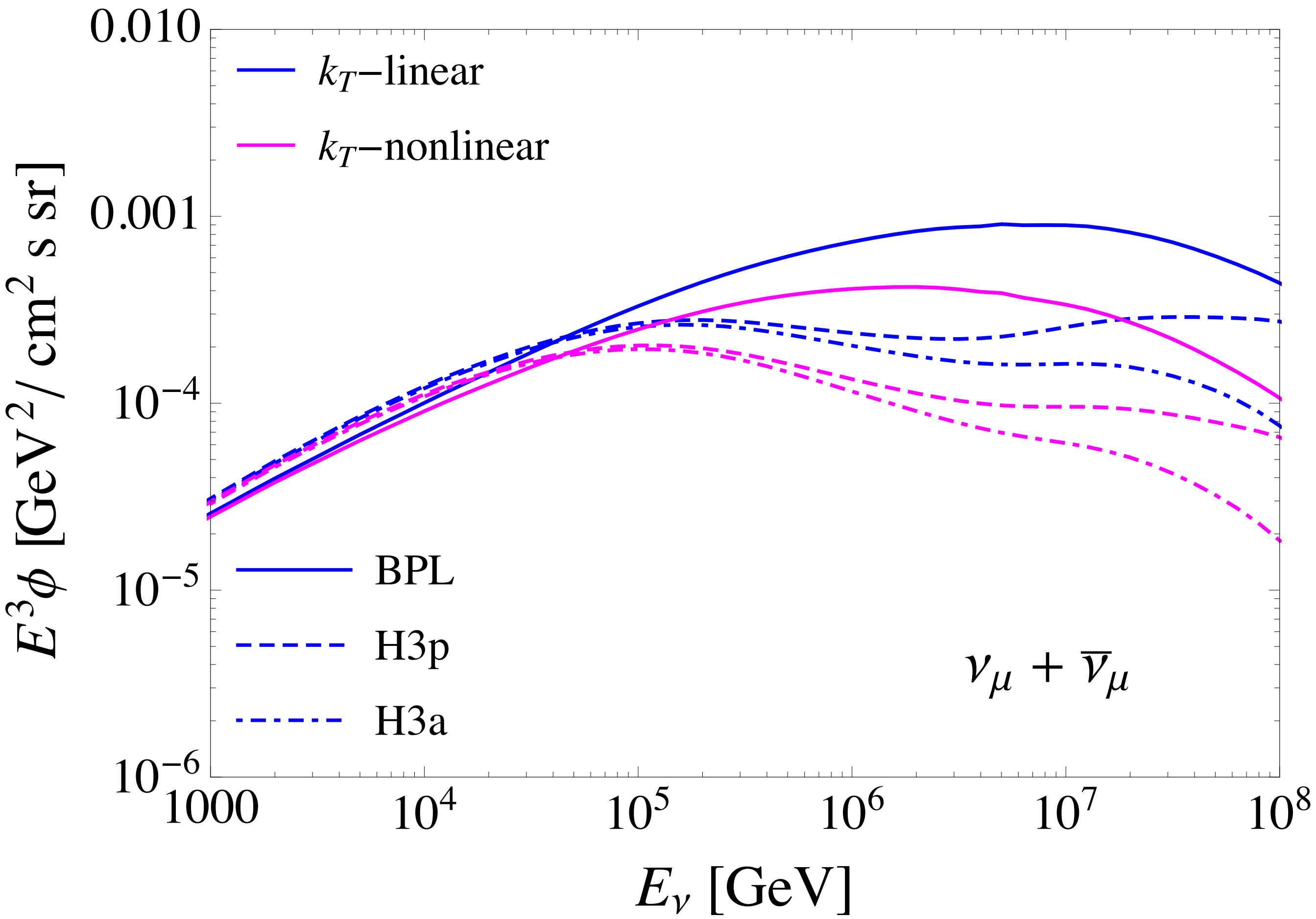
flux of $\nu_\mu + \bar{\nu}_\mu$

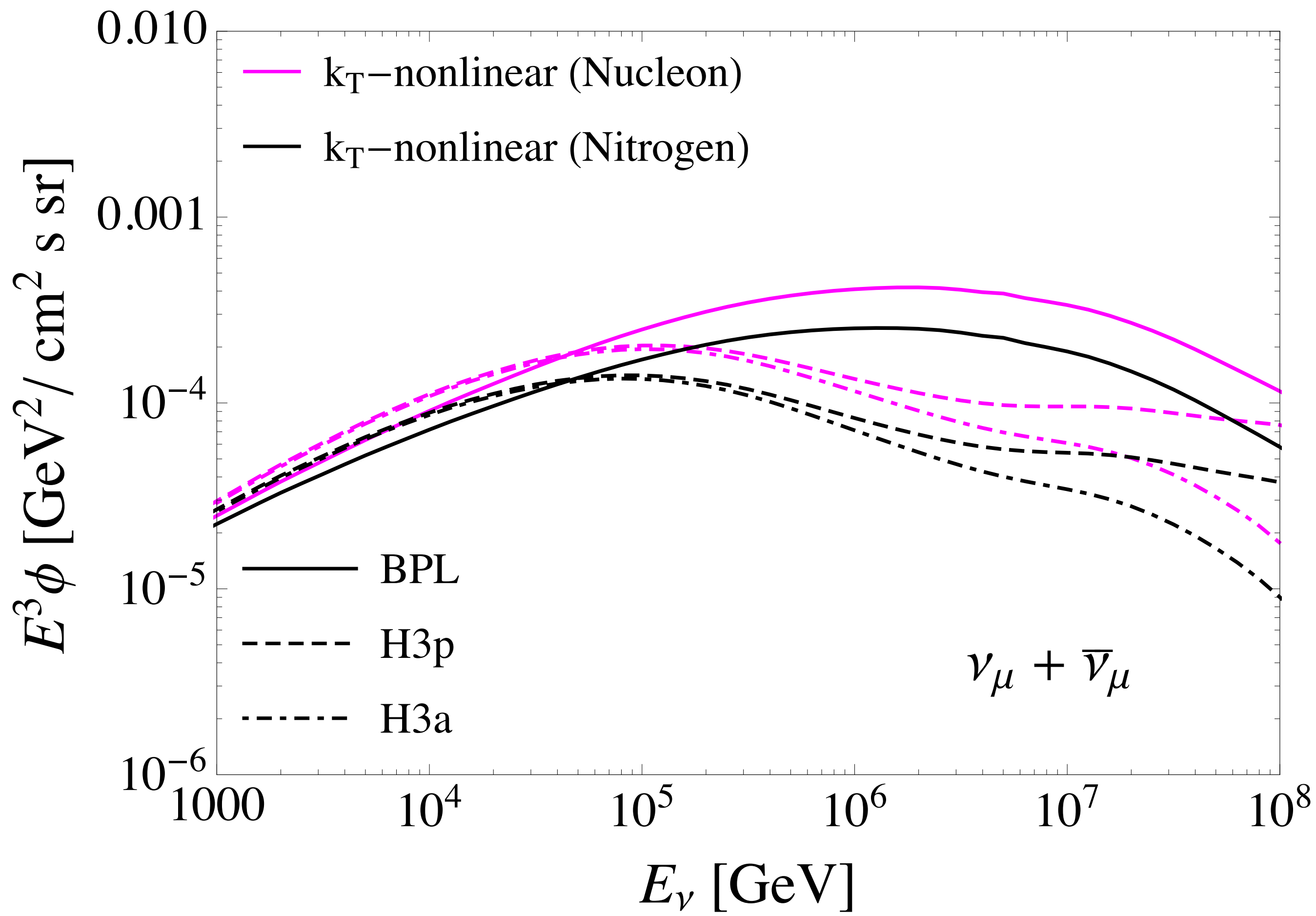




- Significant reduction (factor 2-3) due to the updated cosmic ray spectrum with respect to the broken power law.
- The reduction is in the region of interest, where prompt neutrino component should dominate over the atmospheric one.
- Black band: previous calculation.
- The updated fragmentation function reduces flux by 20%.
- B hadron contribution increases flux by about 5-10%.
- Nuclear effects: 20-35%.
- Combined effects: reduction by 45% at highest energies.

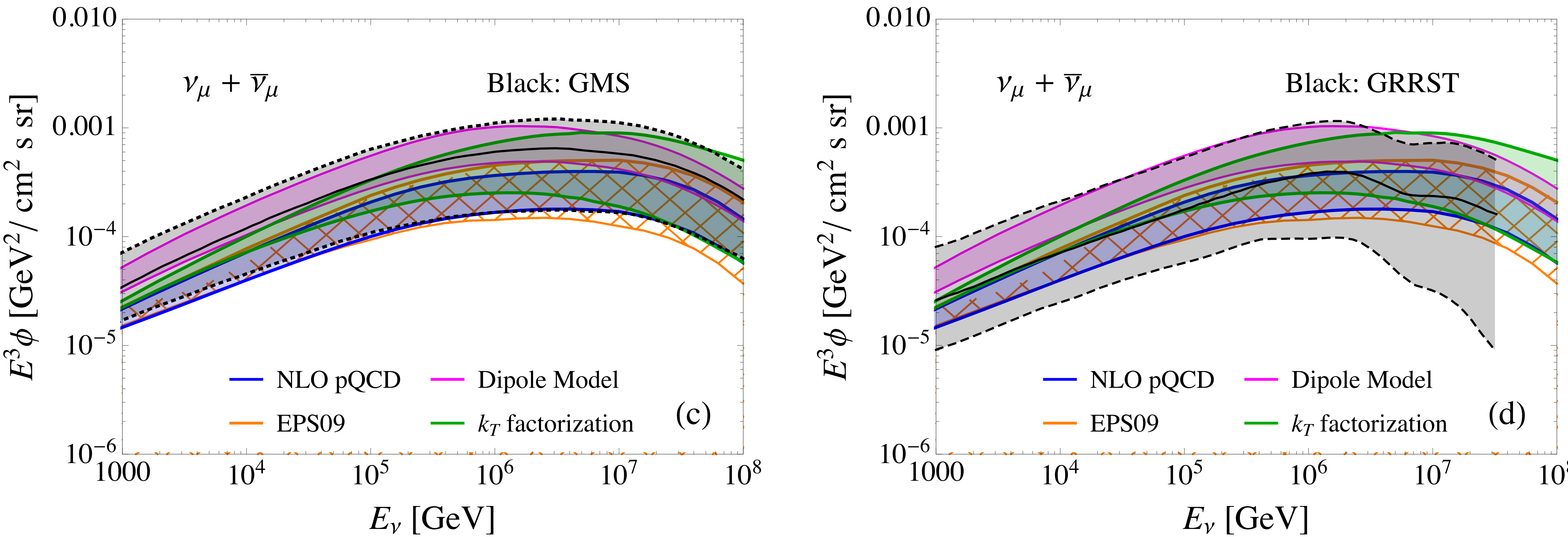
Neutrino fluxes





- Sizeable reduction of the flux due to the changes from linear to nonlinear evolution in k_T factorization.
- Further reduction of the flux when nuclear effects in nitrogen are included.

Neutrino fluxes



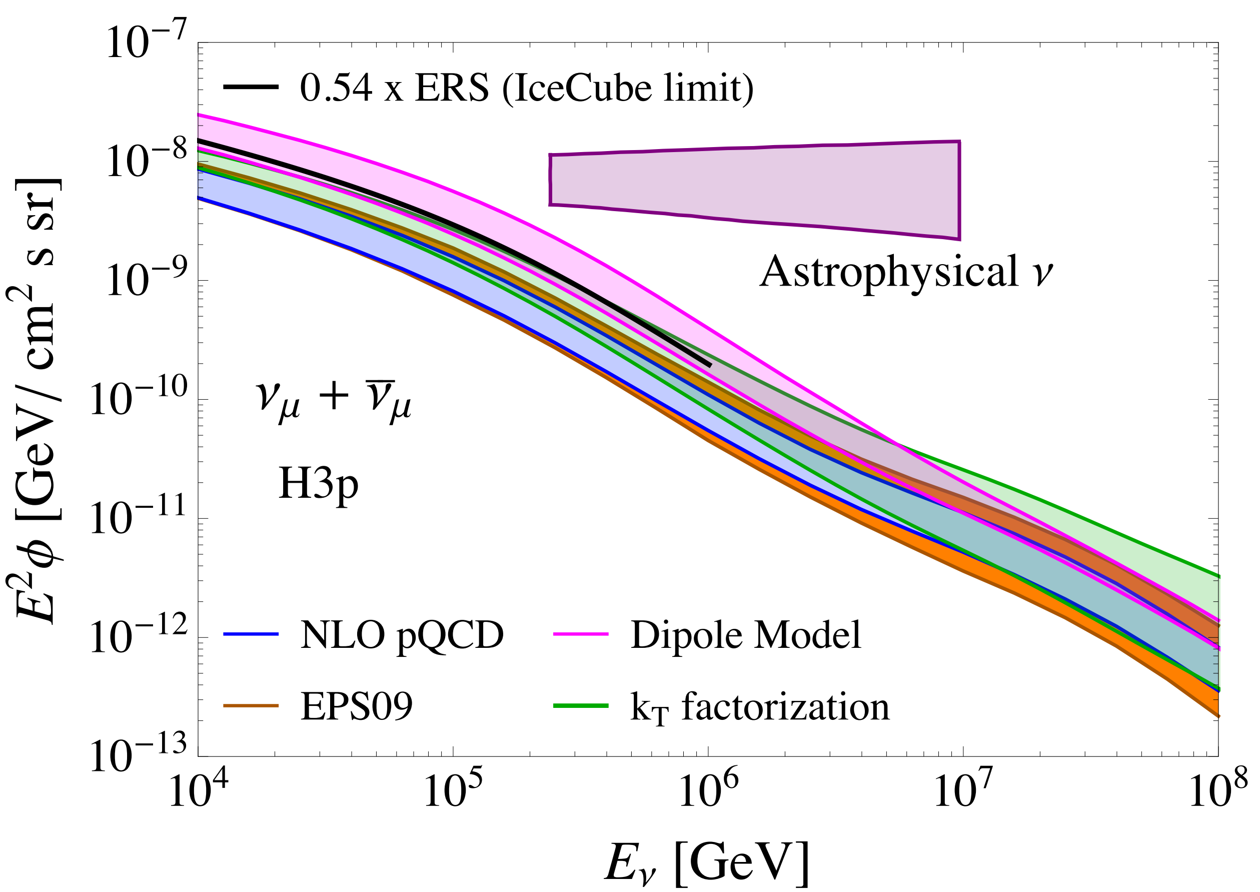
Comparison with other calculations:

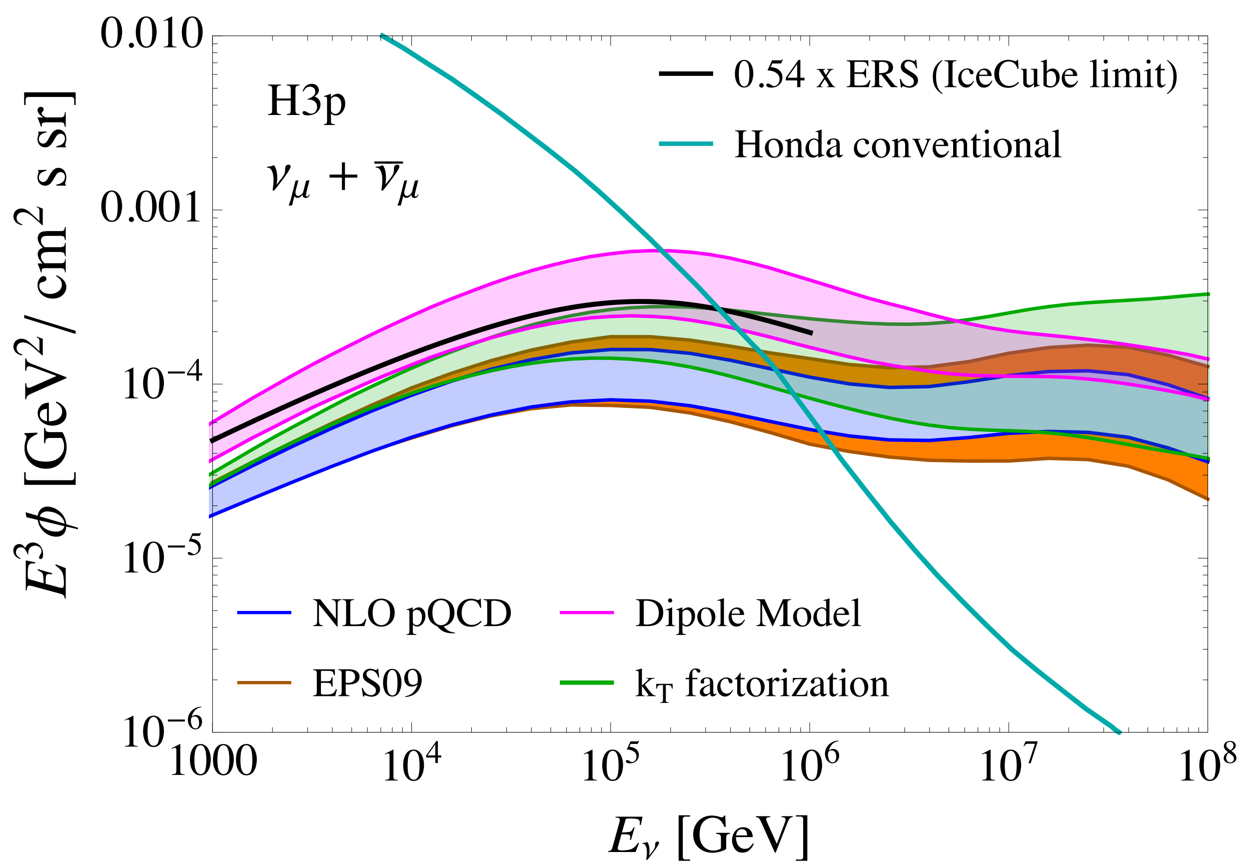
GMS: Garzelli, Moch, Sigl

GRRST: Gauld, Rojo, Rotolli, Sarkar, Talbert

Consistency within the error bands.

Predictions and IceCube limit





- IceCube limit on prompt neutrino flux (PoS(ICRC2015)1079).
- NLO perturbative and k_T factorization within the limit.
- Dipole model calculation is in slight tension with the IceCube limit.
- Overall the flux is well below the astrophysical flux measured by IceCube.

Summary and outlook

- Calculation of the prompt neutrino flux using NLO and new PDFs. Charm cross section matched to LHC and RHIC data. Consistent with LHCb data on forward charm production.

- Updated cosmic ray flux gives lower values (as compared with earlier ERS and BERSS evaluation) for the atmospheric neutrino flux.

- Nuclear effects in the target. Further reduction of the flux by about 20-35%. Estimate of nuclear corrections within the NLO pQCD consistent with the small x calculation.

- Alternative calculations: dipole and k_T factorization. Small x resummation leads to enhancement, saturation to the reduction of the flux. Dipole model larger than other calculations at low energies, needs improvement.

- Other calculations also on the market: consistent but still large uncertainties. Largest uncertainties due to the QCD scale variation, PDF uncertainties and CR flux.

- Outstanding questions: fragmentation (forward production, hadronic-nuclear environment, differences between PYTHIA and fragmentation functions); intrinsic charm.

Backup

Hybrid k_T factorization calculation

Unintegrated gluon density obtained from the resummed small x evolution equation with non-linear term:

BFKL term with kinematical constraint

$$f(x,k^2) = \tilde{f}^{(0)}(x,k^2) +$$

$$+ \frac{\alpha_s(k^2) N_c}{\pi} k^2 \int_x^1 \frac{dz}{z} \int_{k_0^2} \frac{dk'^2}{k'^2} \left\{ \frac{f(\frac{x}{z},k'^2)\,\Theta(\frac{k^2}{z}-k'^2) - f(\frac{x}{z},k^2)}{|k'^2-k^2|} + \frac{f(\frac{x}{z},k^2)}{|4k'^4+k^4|^{\frac{1}{2}}} \right\} +$$

DGLAP with non-singular splitting

$$+ \frac{\alpha_s(k^2) N_c}{\pi} \int_x^1 dz\, \bar{P}_{gg}(z) \int_{k_0^2}^{k^2} \frac{dk'^2}{k'^2} f(\frac{x}{z},k'^2) -$$

$$- \left(1 - k^2 \frac{d}{dk^2}\right)^2 \frac{k^2}{R^2} \int_x^1 \frac{dz}{z} \left[\int_{k^2}^{\infty} \frac{dk'^2}{k'^4} \alpha_s(k'^2) \ln\left(\frac{k'^2}{k^2}\right) f(z,k'^2) \right]^2$$

non-linear term

Nonlinear term responsible for taming the growth of the gluon density
Unintegrated parton density fitted to the inclusive structure function data at HERA
Two scenarios: linear and non-linear. Included A dependence in the nonlinear term.

Kutak,Sapeta; based on KMS (Kwiecinski,Martin,AS)