Prompt atmospheric neutrino flux from perturbative QCD

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Outline

The goal: to evaluate the prompt component of the atmospheric neutrino flux taking into account information from collider experiments and QCD theory

- Atmospheric neutrinos: conventional and prompt
- Cross section for charm production: comparison with hadronic data
- Nuclear effects
- Forward charm production
- Prompt neutrino fluxes

A. Bhattacharya, R. Enberg, M. H. Reno, I. Sarcevic, AS

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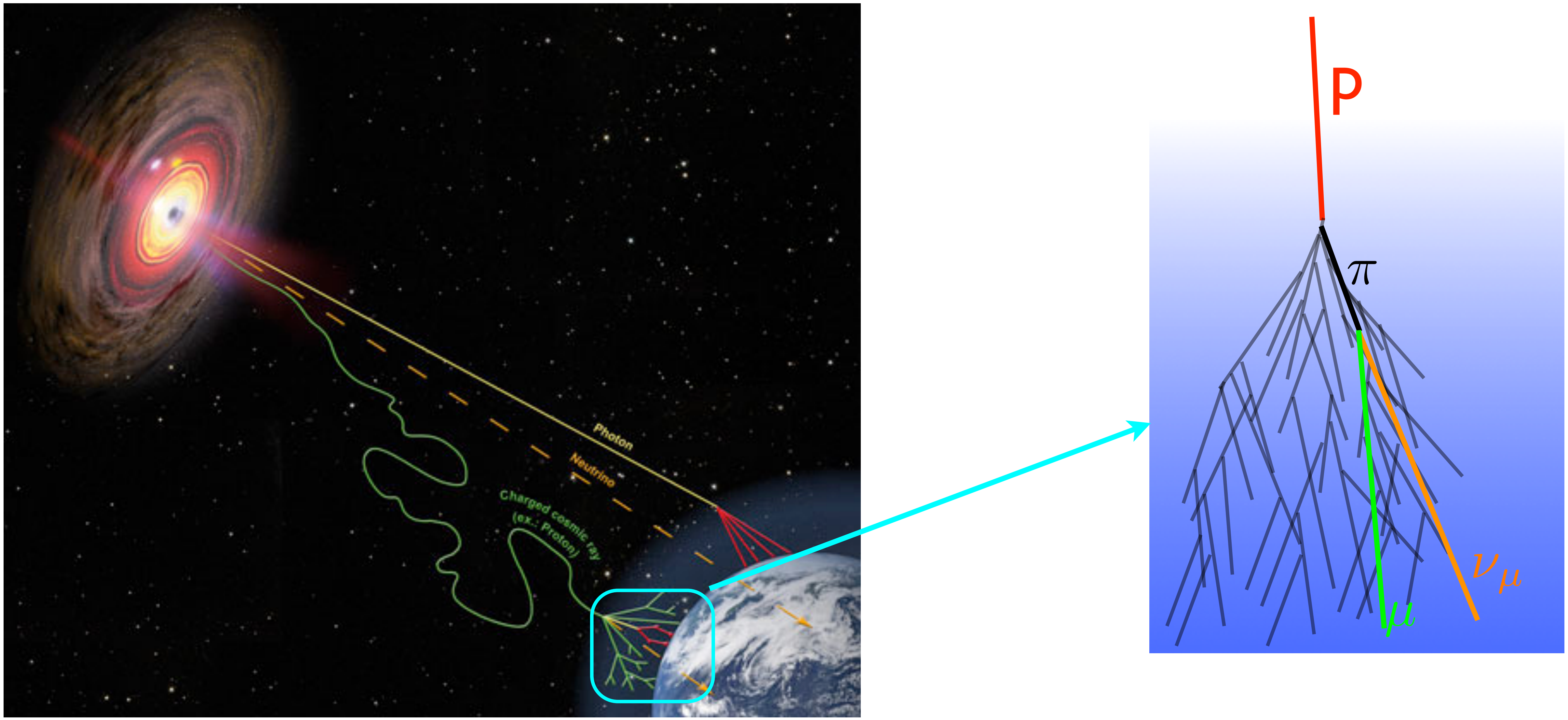
Atmospheric neutrinos



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

$p + \text{Air}$

interaction ↓

π, K

decay ↓

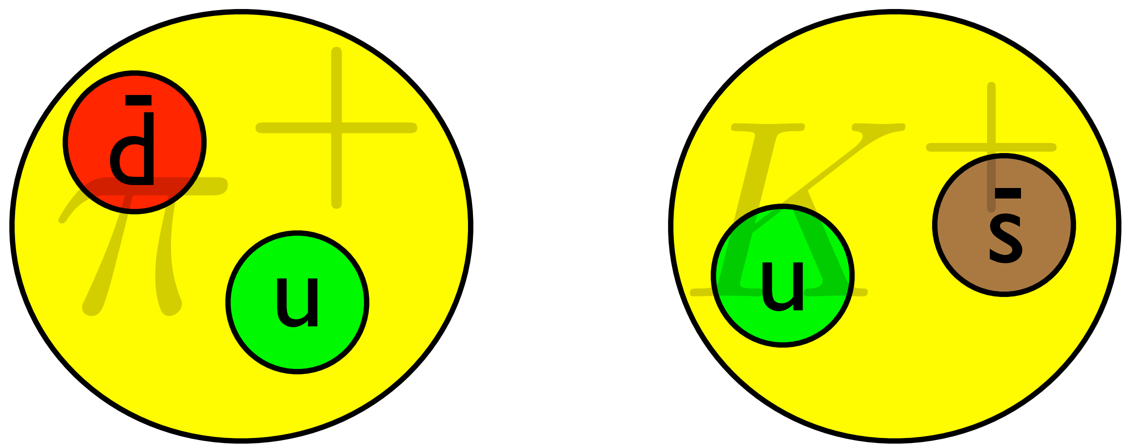
μ, ν_μ

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

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

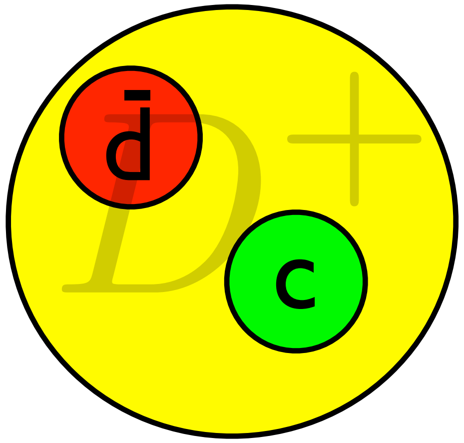
Long-lived mesons loose energy → Steeply falling flux of neutrinos $\Phi_\nu \sim E_\nu^{-3.7}$

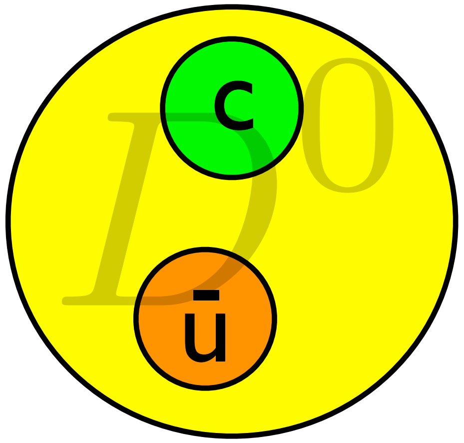
Prompt neutrinos

- *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

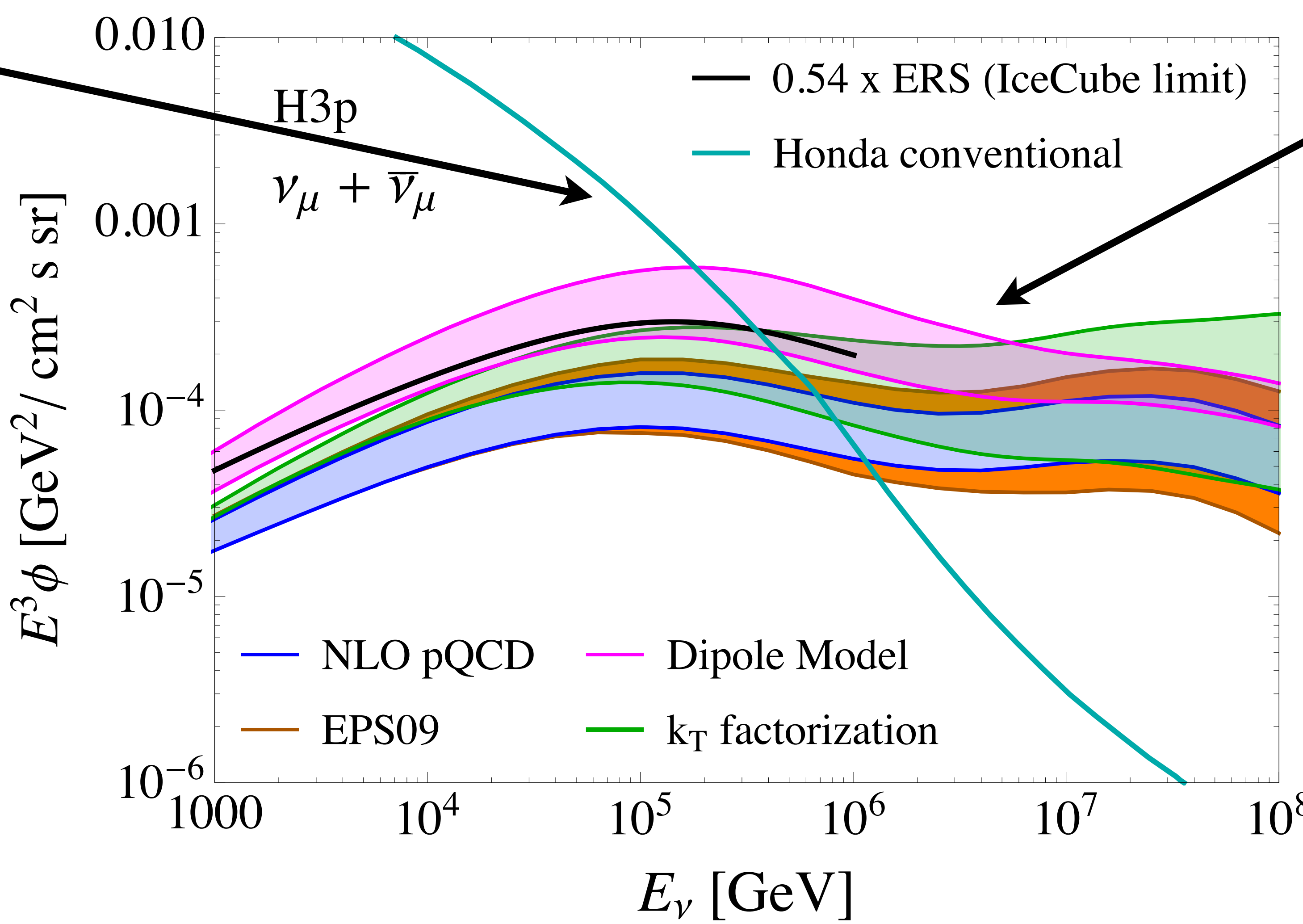
$$\Phi_\nu \sim E_\nu^{-2.7}$$

Prompt vs conventional flux

High energy atmospheric neutrino flux as a function of energy

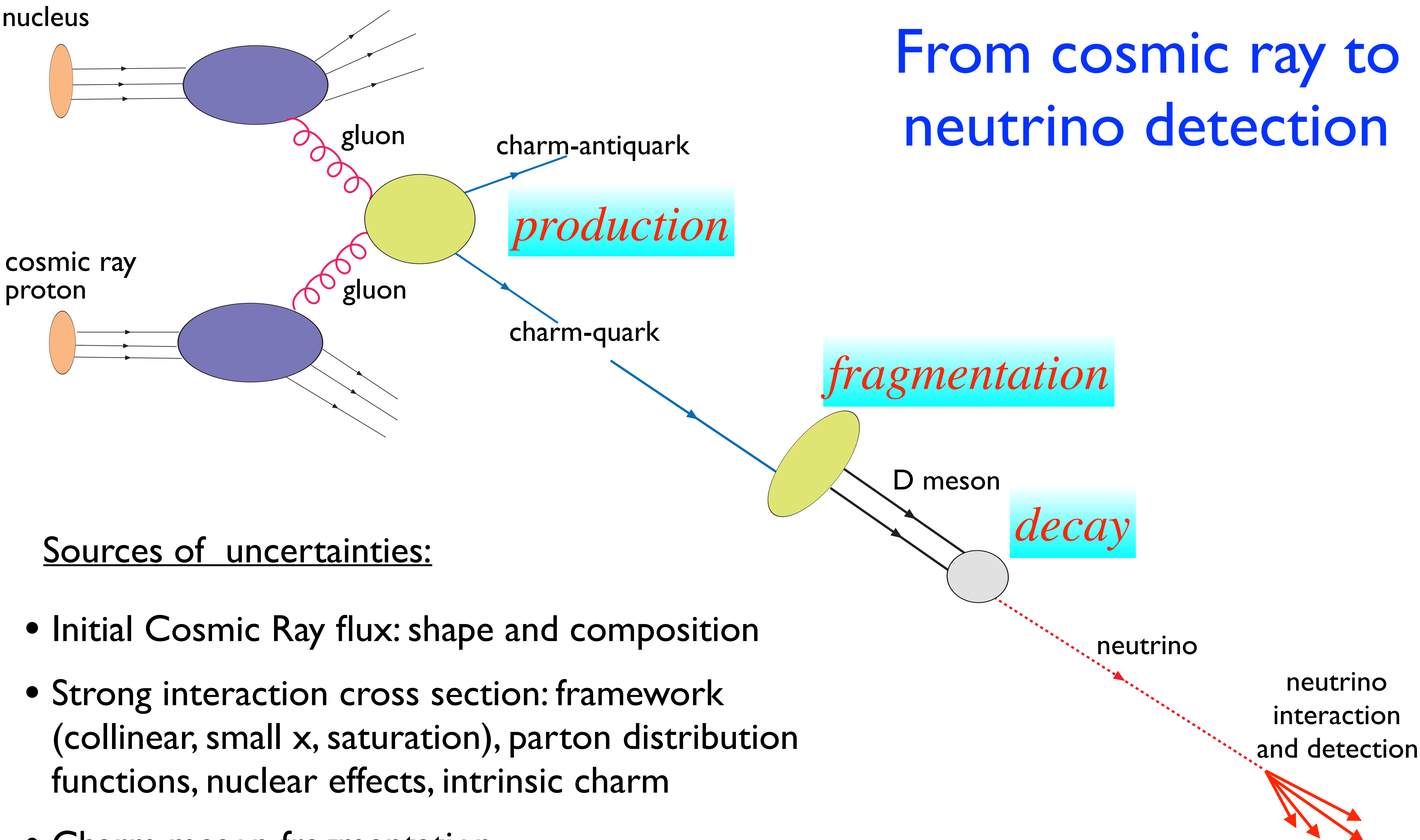
conventional: decay of long lived pions and kaons: loose energy. Soft spectrum.

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

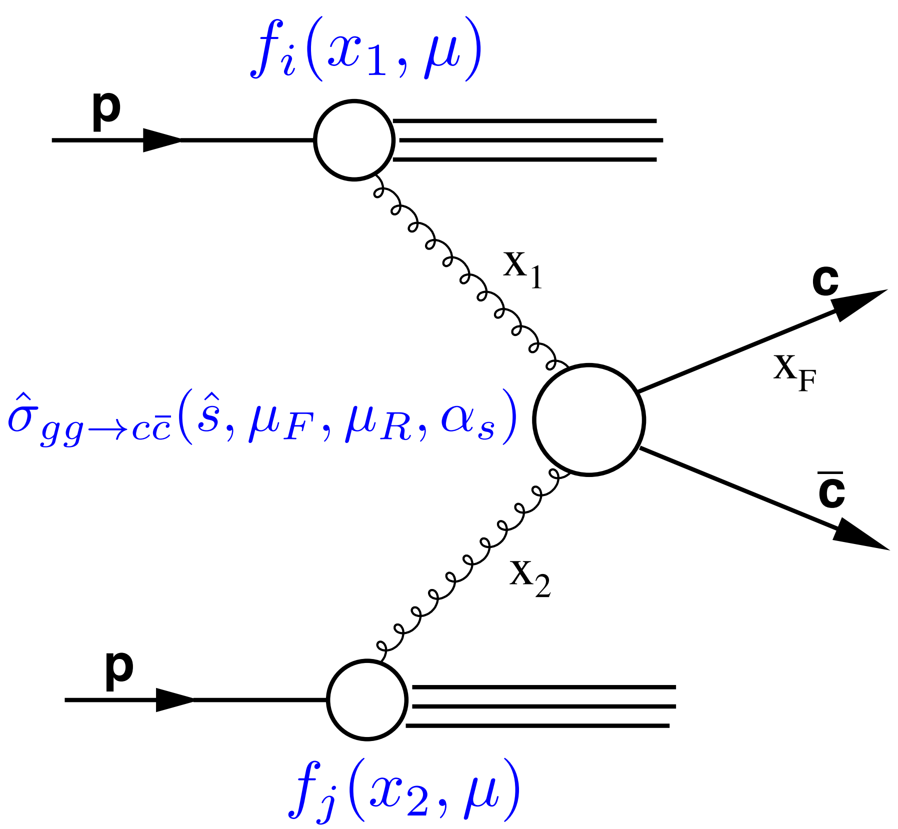
Heavy quark production in hadron collisions

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:

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

Low x parton density

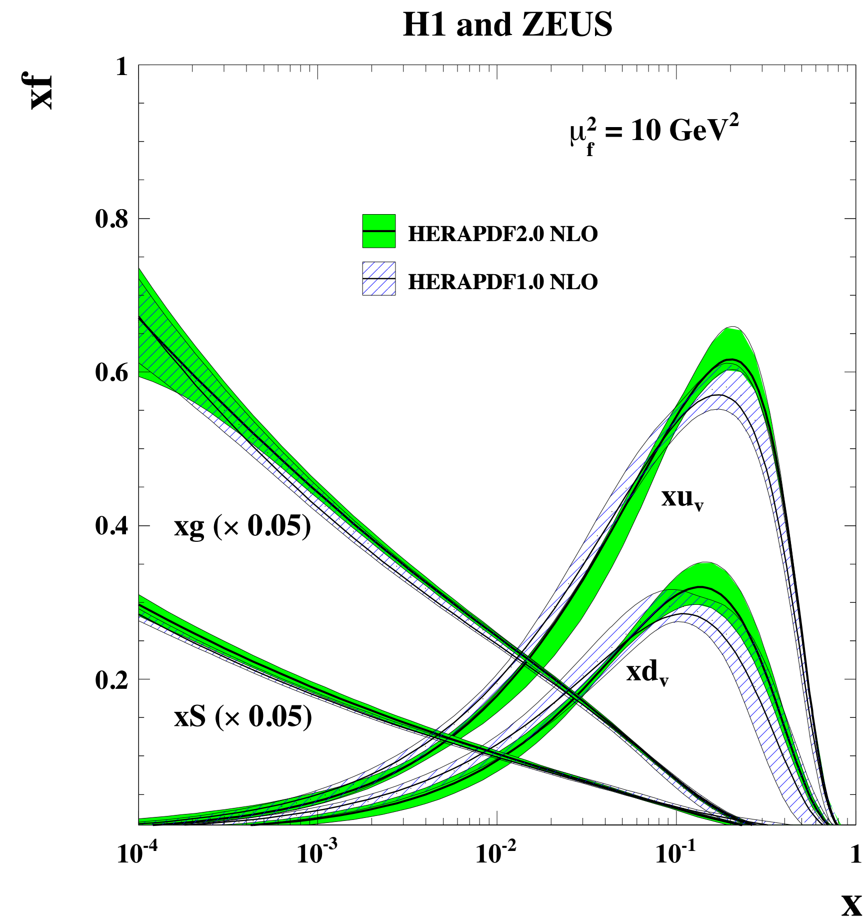
$$\frac{d\sigma^{pp\to c+X}}{dx_F} = \sum_{i,j} f_i(x_1,\mu_F) \otimes \hat{\sigma}_{gg\to c\bar{c}}(\hat{s}, m_c, \mu_F, \mu_R) \otimes f_j(x_2,\mu_F)$$

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:

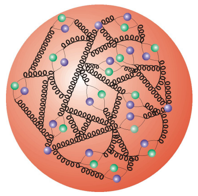
$$x_F \simeq \frac{E_c}{E_p} \qquad x_F \gg x_2 \qquad x_2 \sim \frac{M^2_{c\bar{c}}}{x_F s}$$

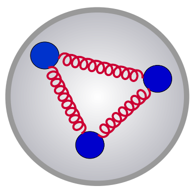
$$s \gg M^2_{c\bar{c}}$$

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



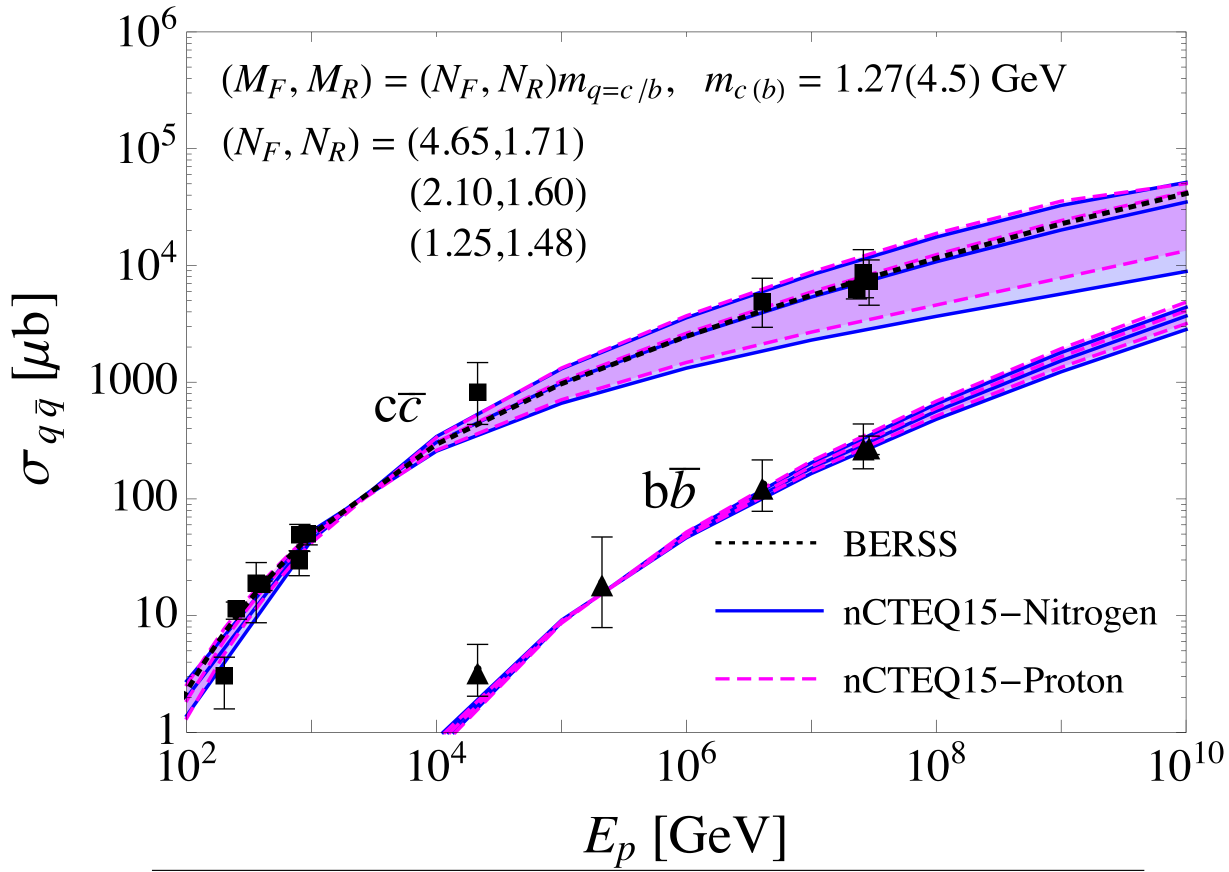
<u>Other approaches tested:</u>
Small x resummation + high energy factorization
Dipole model





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 $m_c = 1.27$ 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.

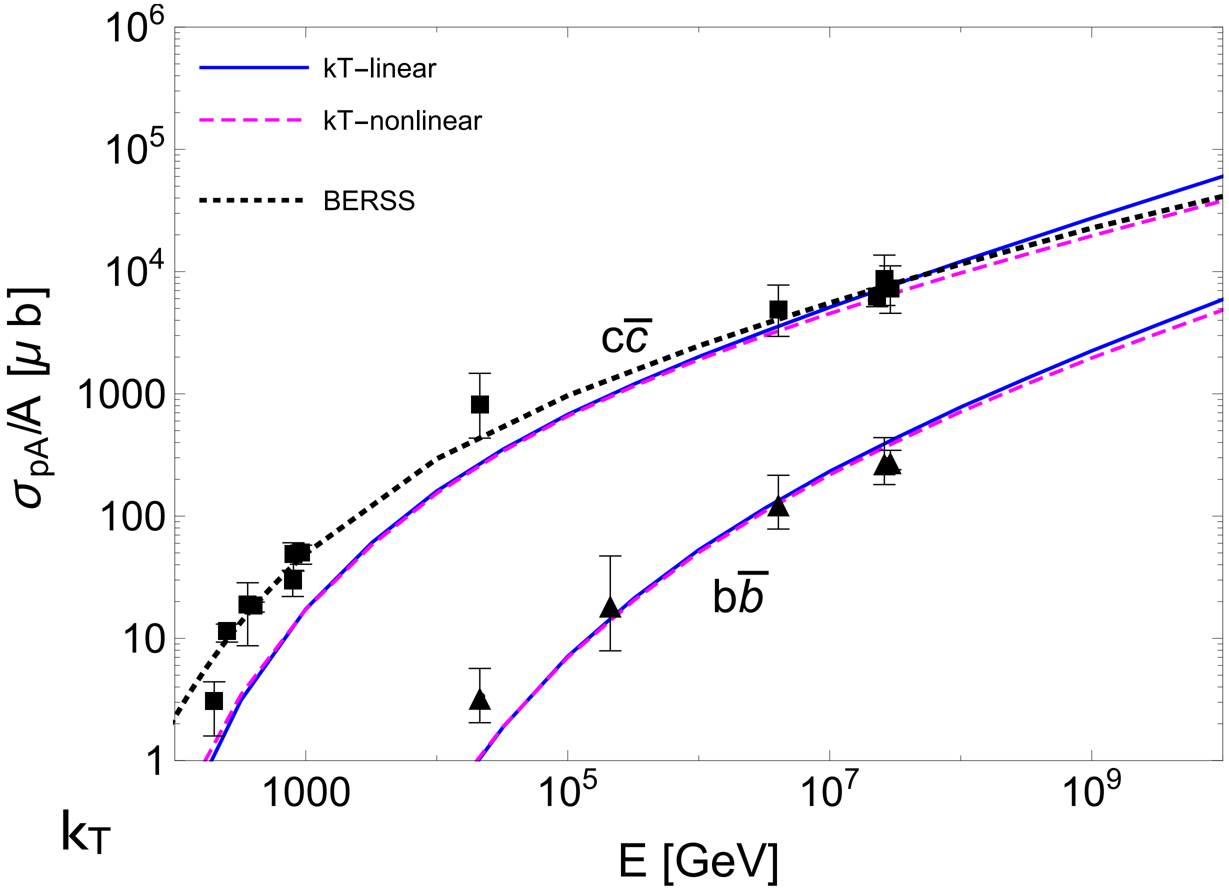


Expt.	$\sqrt{s}$ [TeV]	σ [mb]
PHENIX [31]	0.20	$\mathbf{0.551}^{+0.203}_{-0.231}$ (sys)
STAR [32]	0.20	$\mathbf{0.797} \pm 0.210$ (stat)$^{+0.208}_{-0.295}$ (sys)
ALICE [27]	2.76	$\mathbf{4.8} \pm 0.8$ (stat)$^{+1.0}_{-1.3}$ (sys) ± 0.06 (BR) ± 0.1(frag) ± 0.1 (lum)$^{+2.6}_{-0.4}$ (extrap)
ALICE [27]	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	$\mathbf{6.100} \pm 0.930$

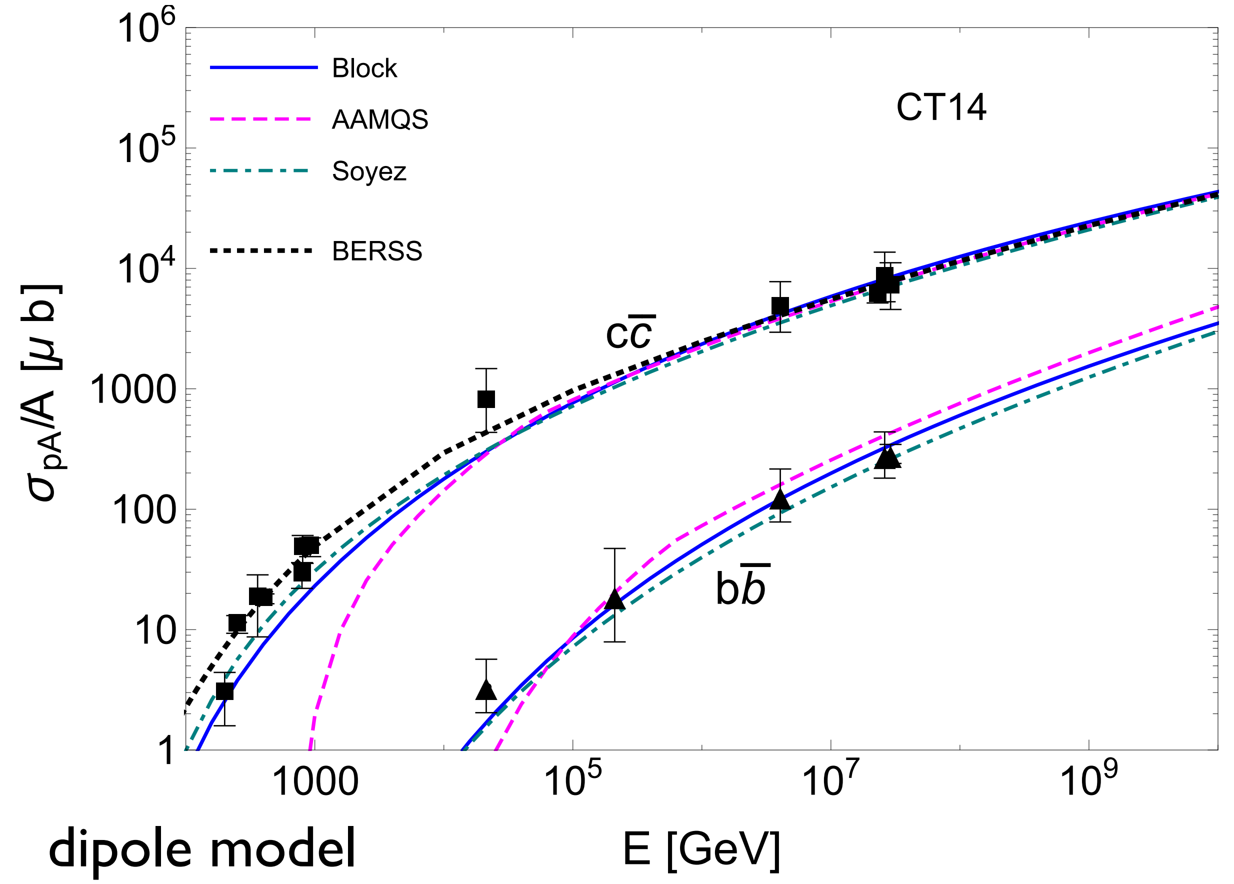
Table 1: Total cross-section for $pp(pN) \to c\bar{c}X$ in hadronic collisions, extrapolated based on NLO QCD by the experimental collaborations from charmed hadron production measurements in a limited phase space region.

Total charm production cross section

Comparison with other models: small x resummation-k_T factorization and dipole model



k_T



dipole model

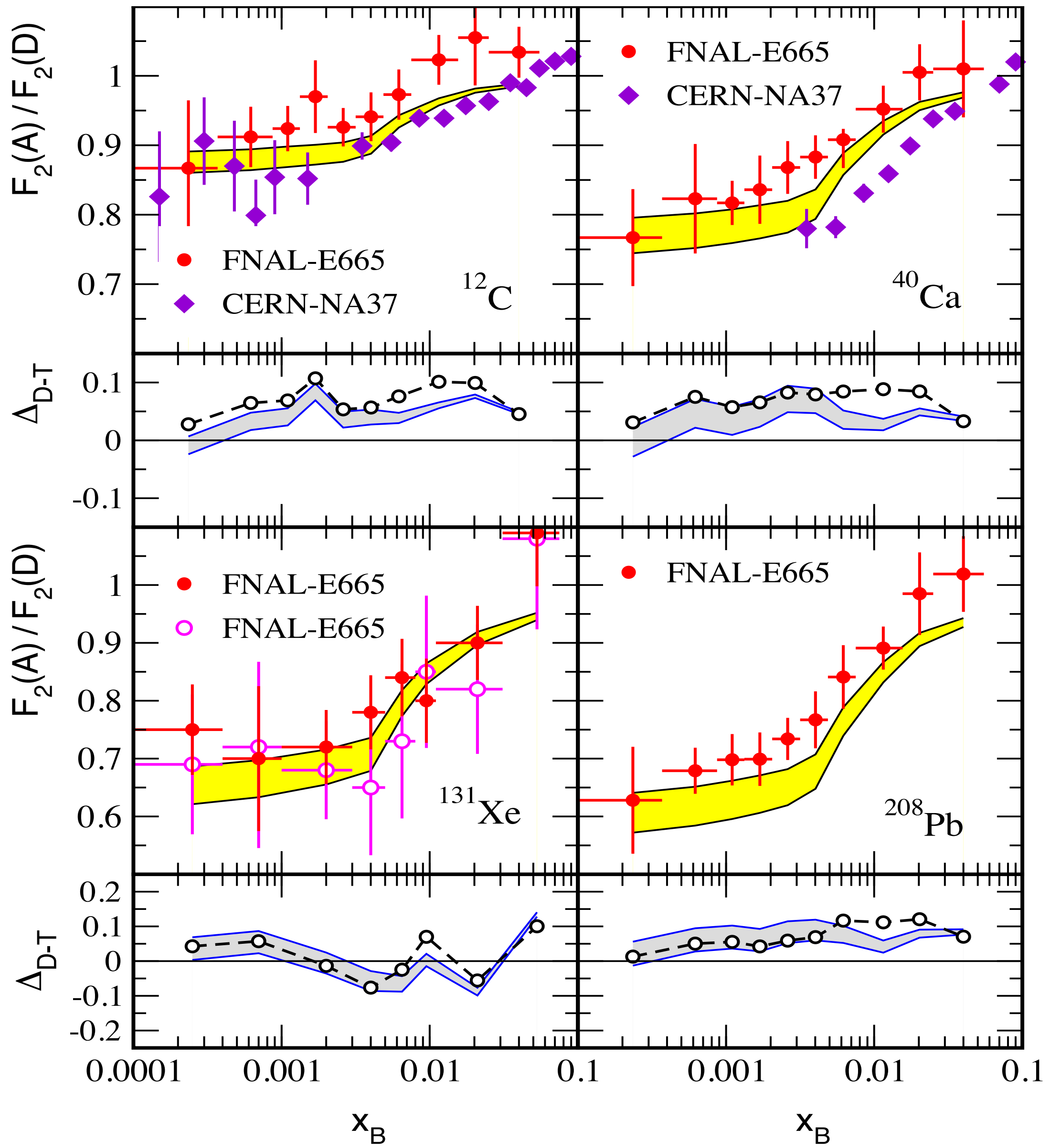
- BERSS: *Bhattacharya, Enberg,Reno,Stasto,Sarcevic*: previous NLO calculation
- AAMQS,*Albacete, Armesto,Milhano,Quiroga-Arias,Salgado:* rcBK
- Soyez: based on *Iancu,Itakura,Munier* parametrization inspired by BK solution
- Block: phenomenological parametrization of the structure function
- k_T calculation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

All models agree with data at high energies

Nuclear corrections

Need to take into account the fact that the target is not a proton but nitrogen/oxygen. Possible nuclear corrections: shadowing

$$R^A = \frac{\sigma^A}{A\,\sigma^p} \neq 1$$



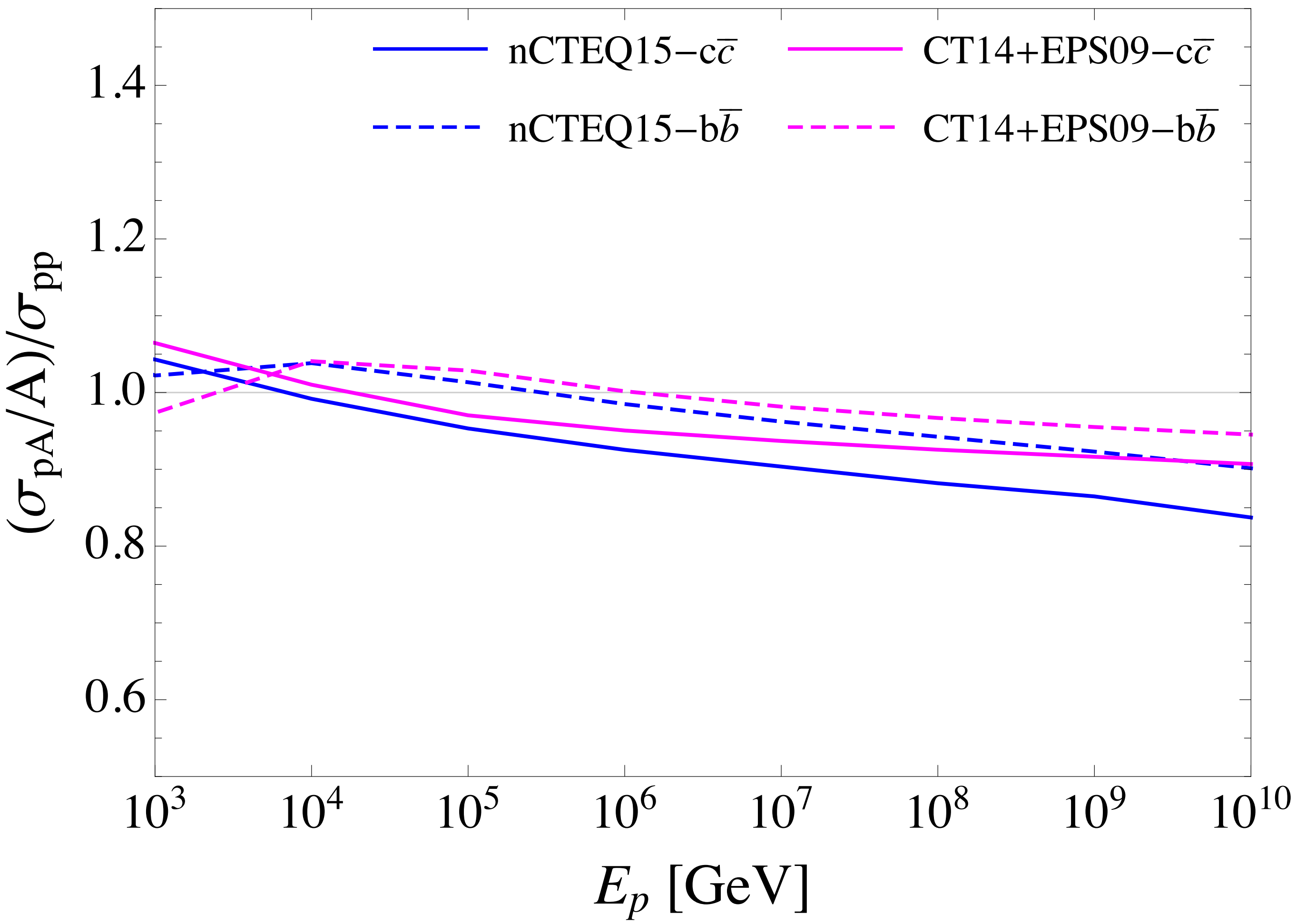
Cross section on nucleus is not a simple superposition of cross sections on nucleons.

Complicated dependence on the kinematical variables as well as mass number.

Nuclear corrections

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

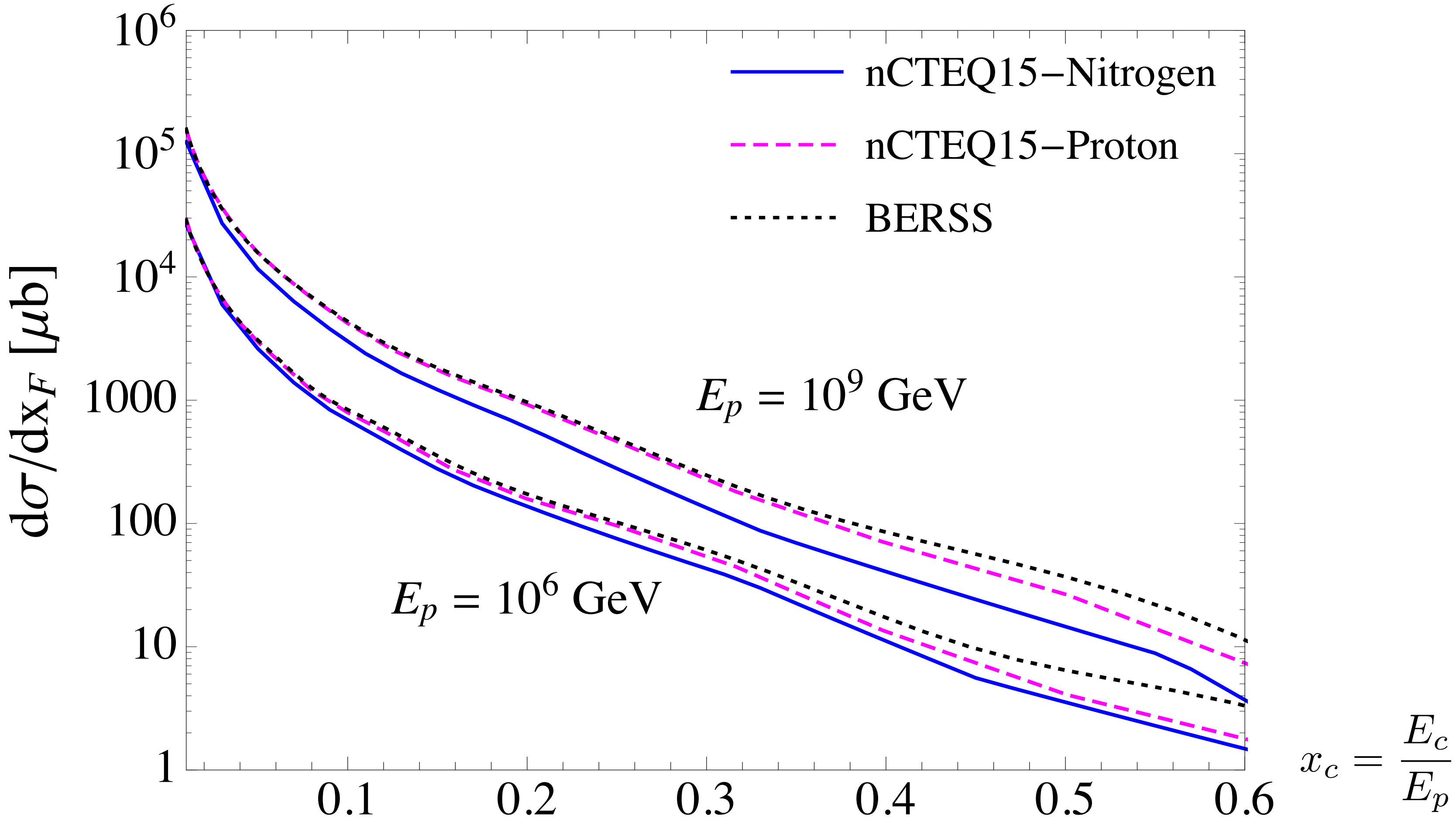
10%-15% for charm
5%-10% for bottom



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.



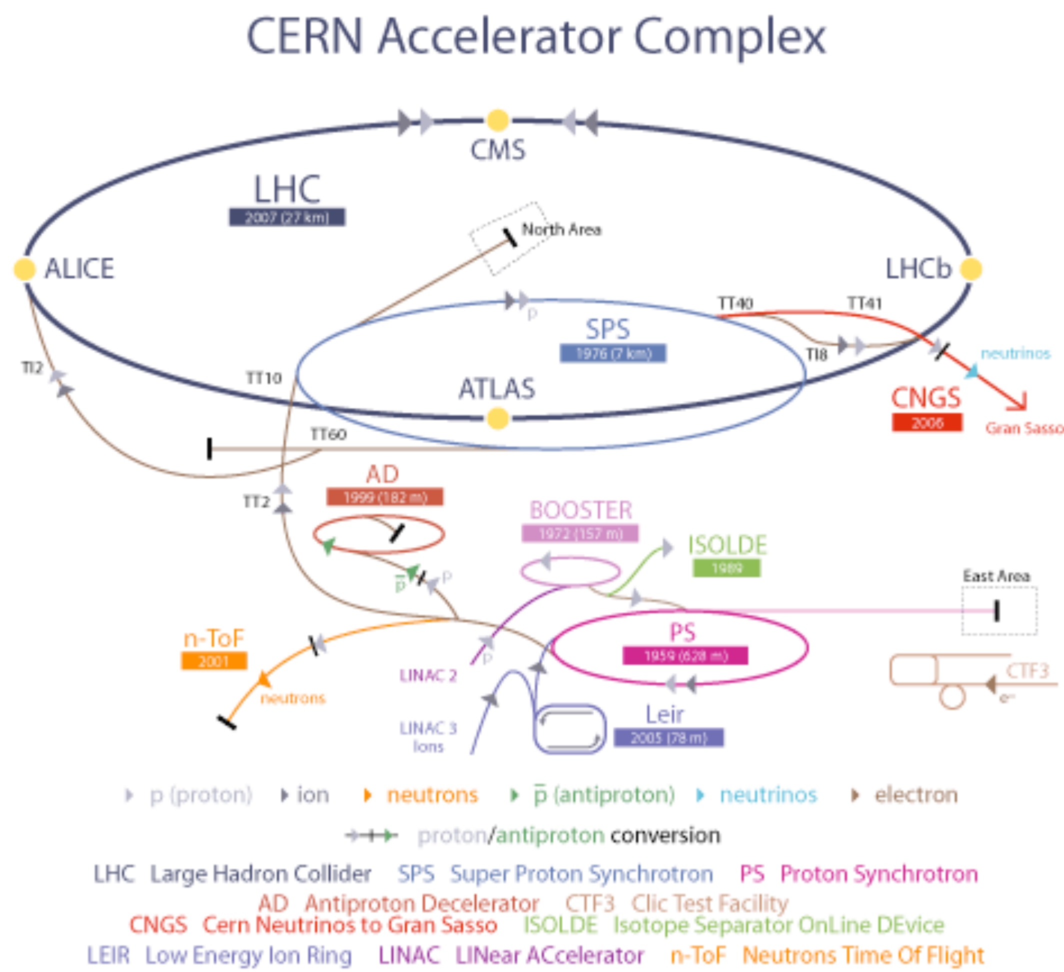
Differential charmed hadron cross section as a function of the energy: need to convolute with the fragmentation function

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

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

Using Kniehl, Kramer fragmentation functions.

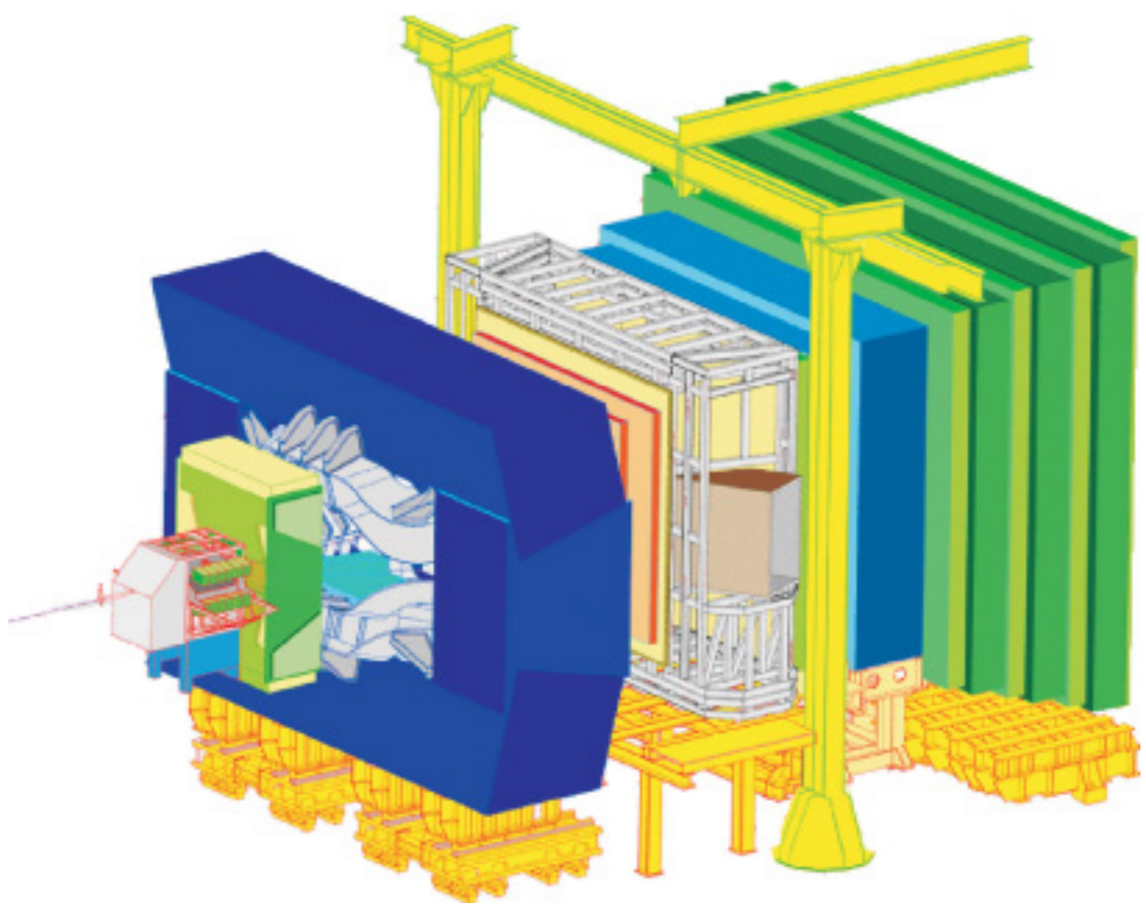
Comparison with LHCb data



Specialized detector on the LHC ring.

Instrumentation in the forward region.

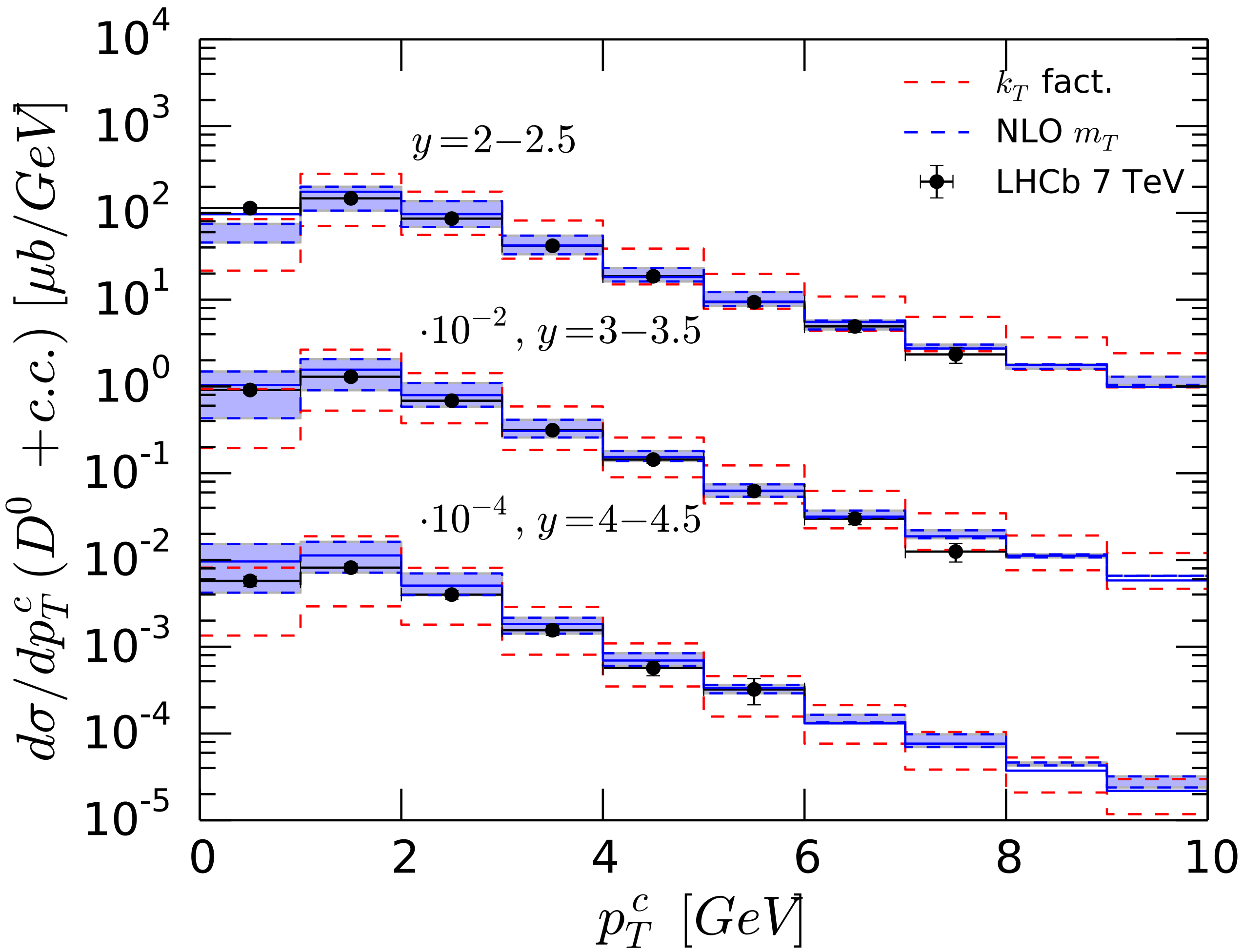
Sophisticated instrumentation to detect heavy particles.

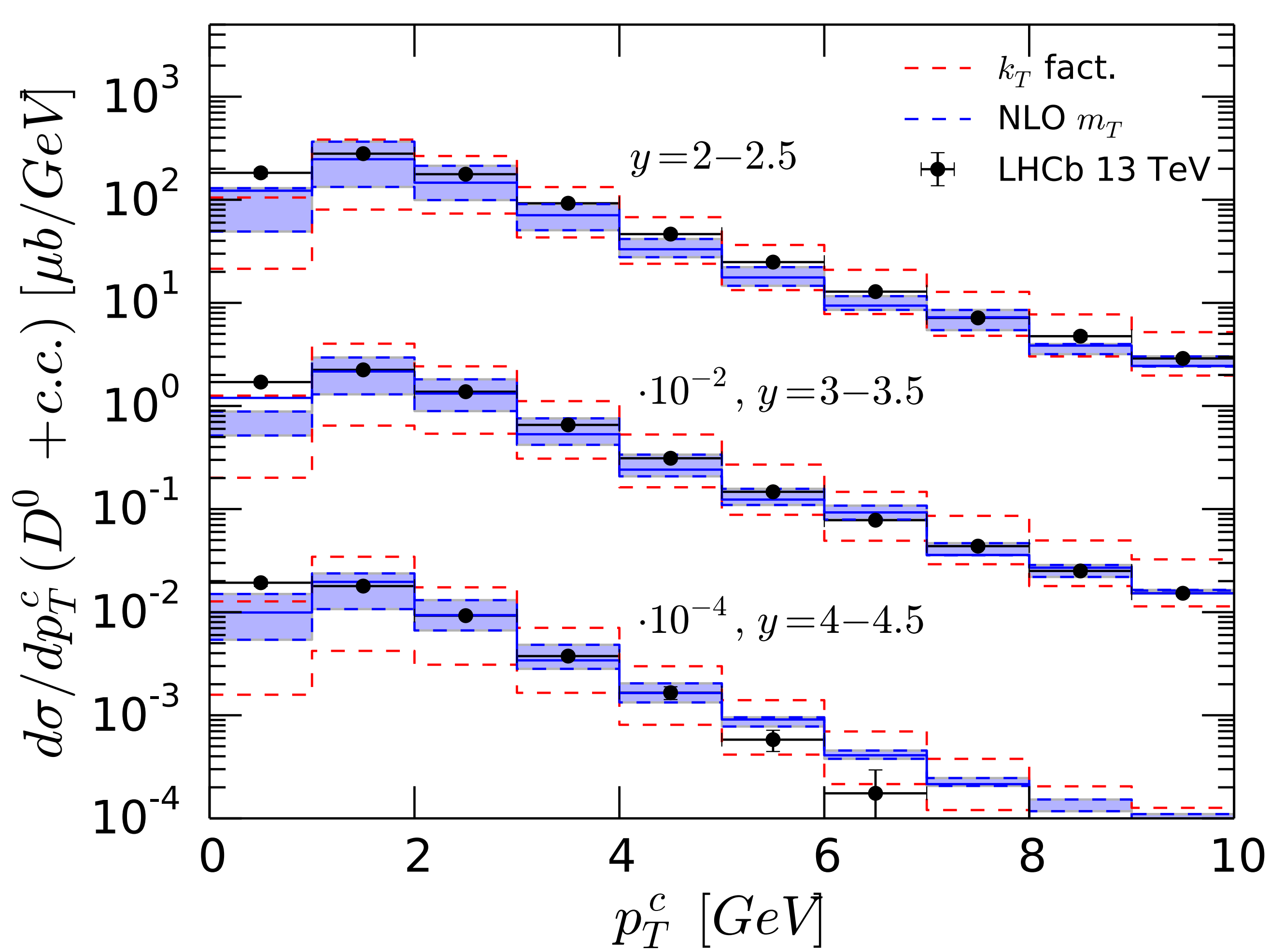


Compare with measurements on D mesons as a function of transverse momenta and rapidity.

Comparison with LHCb 7 and 13 TeV

Transverse momentum distributions at *forward rapidities*



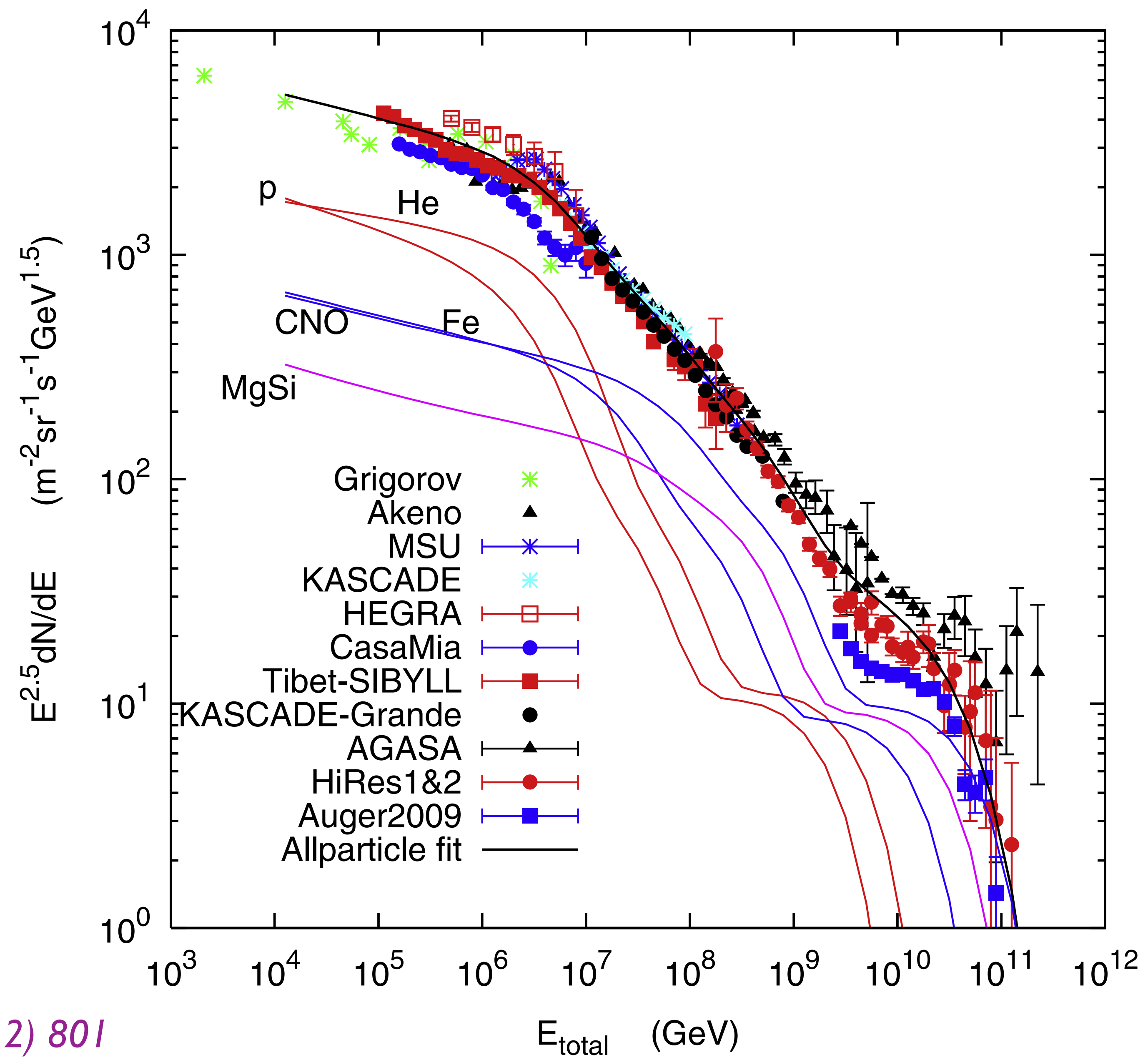


- NLO pQCD and k_T factorization consistent with each other.
- Bands on NLO pQCD calculation correspond to scale variation.
- Two lines in k_T factorization correspond to the saturation/no-saturation calculation.

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

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

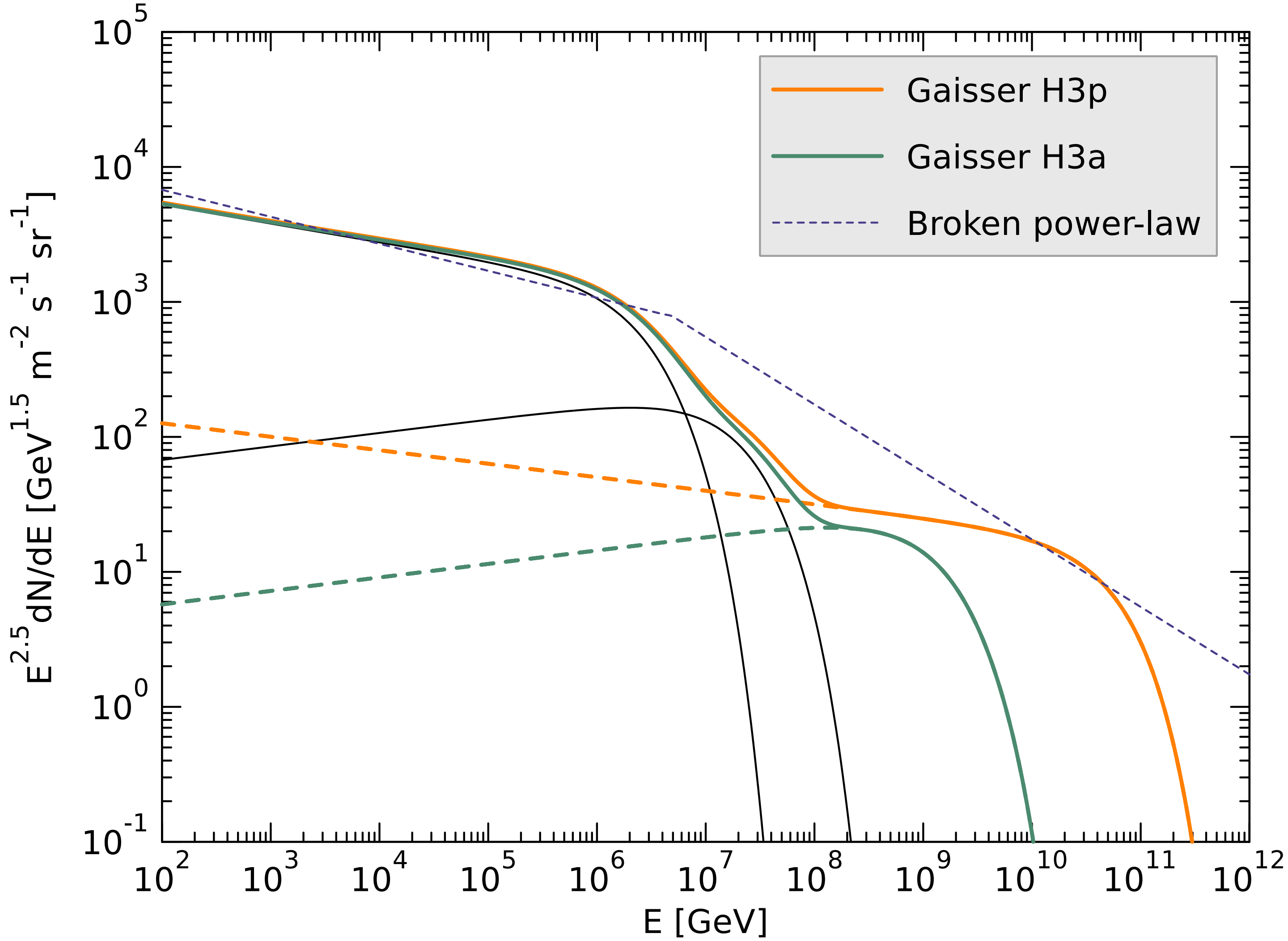
$a_{i,j}$ normalization

$\gamma_{i,j}$ 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

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

Development of air shower: cascade equations

Production of prompt neutrinos:

$$p \xrightarrow{\text{production}} c \xrightarrow{\text{fragmentation}} M \xrightarrow{\text{decay}} \nu$$

where M=$D^{\pm}, D^0, D_s, \Lambda_c$

Use set of cascade equations in depth X

$$X = \int_h^\infty \rho(h')dh'$$

$$\frac{d\Phi_j}{dX} = -\frac{\Phi_j}{\lambda_j} - \frac{\Phi_j}{\lambda_j^{dec}} + \sum_k \int_E^\infty dE_k \frac{\Phi_k(E_k, X)}{\lambda_k(E_k)} \frac{dn_{k\to j}(E; E_k)}{dE}$$

λ_j interaction length and $\lambda_j^{dec} = \gamma c \tau_j \rho(X)$ decay length

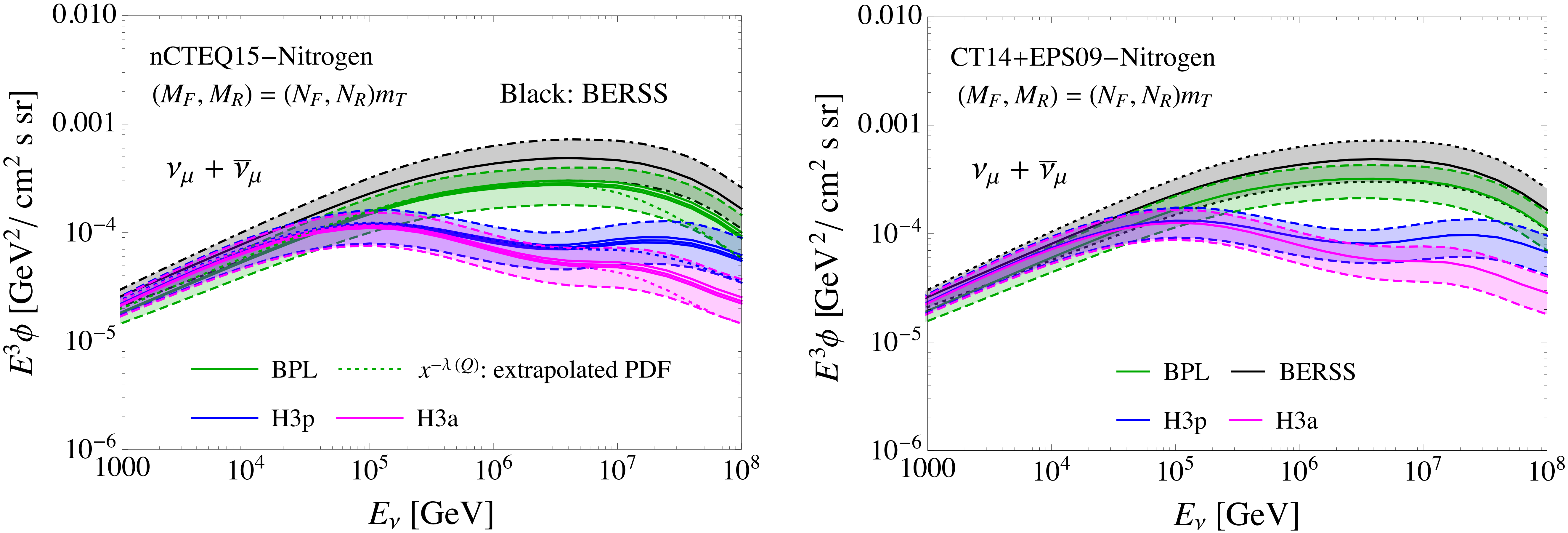
$\frac{dn_{k\to j}}{dE}$ production or decay distribution

$$\frac{1}{\sigma_k}\frac{d\sigma_{k\to j}(E, E_k)}{dE} \qquad \frac{1}{\Gamma_k}\frac{d\Gamma_{k\to j}(E, E_k)}{dE}$$

Need to solve these equations simultaneously assuming non-zero initial proton flux.

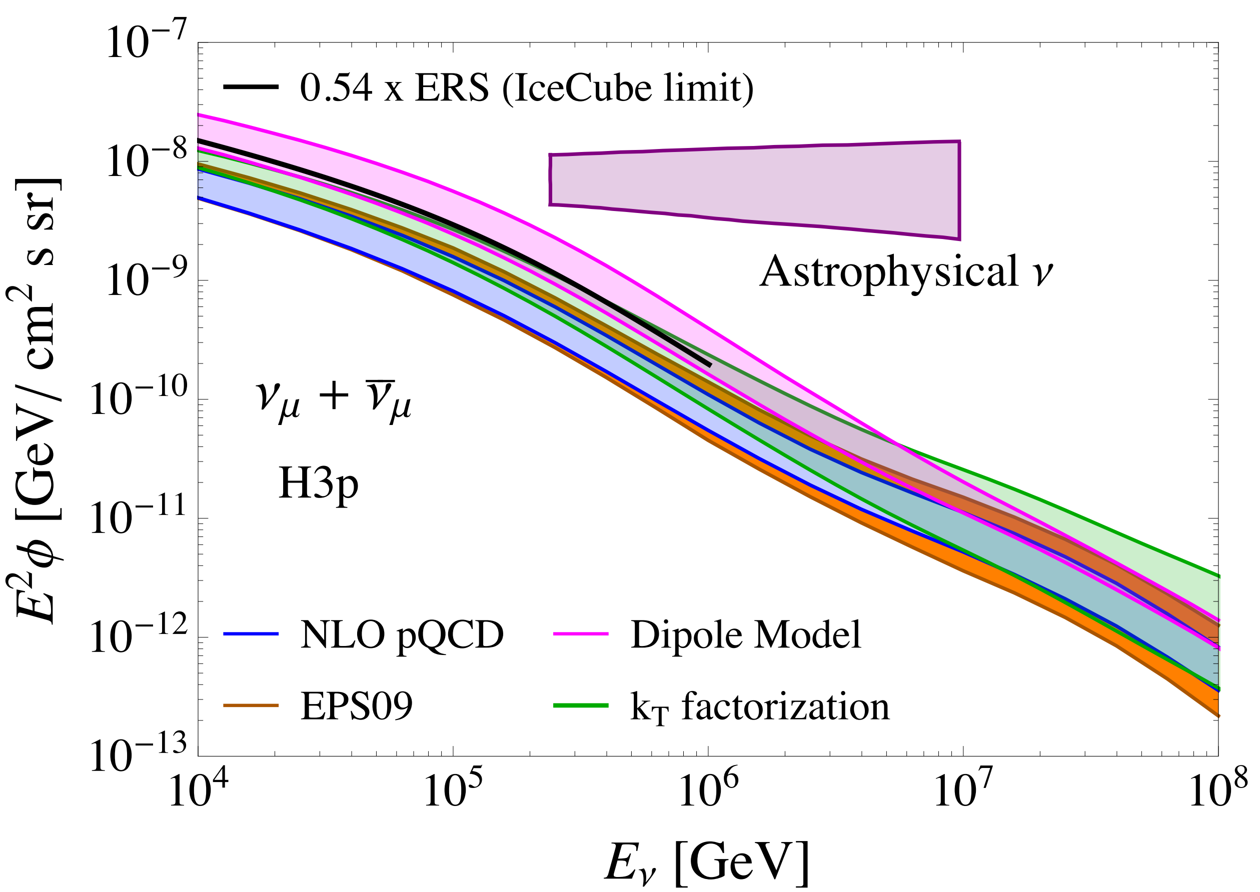
Neutrino fluxes

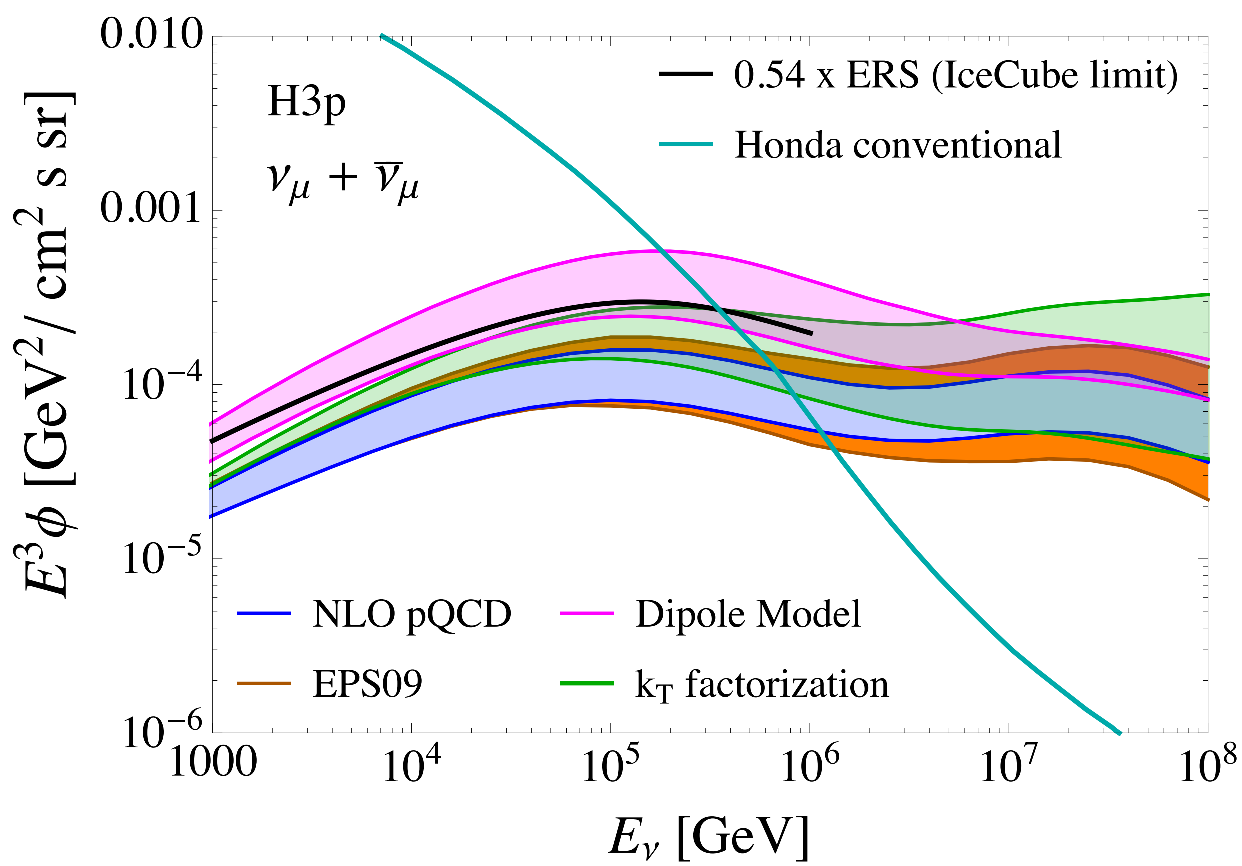
flux of $\nu_\mu + \bar{\nu}_\mu$



- 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.

Predictions and IceCube limit



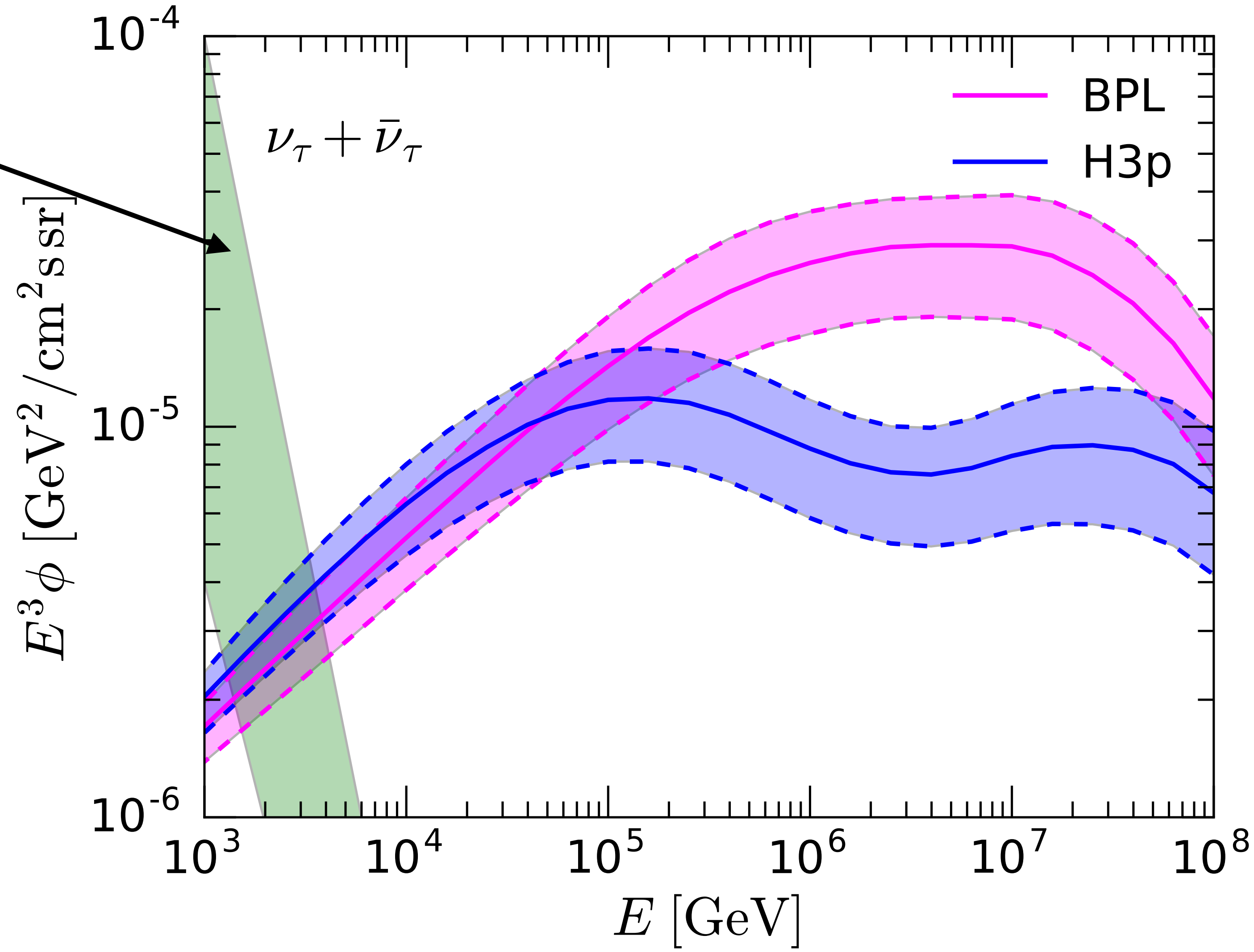


- NLO perturbative and k_T factorization within the limit.
- Dipole model calculation is in slight tension with the IceCube limit.
- Overall the flux is well below the astrophysical flux measured by IceCube.

Prompt tau neutrino flux

From oscillations:

$$\nu_\mu \to \nu_\tau$$



Tau neutrinos can be produced in the decays:

Direct $\quad D_s \to \nu_\tau$

Chain $\quad D_s \to \tau \to \nu_\tau$

Beauty $\quad B^0, B^\pm$

Summary and outlook

- Calculation of the prompt muon 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. Tau neutrino flux from B decays and D_s . Small fraction: 10% of muon neutrino flux.

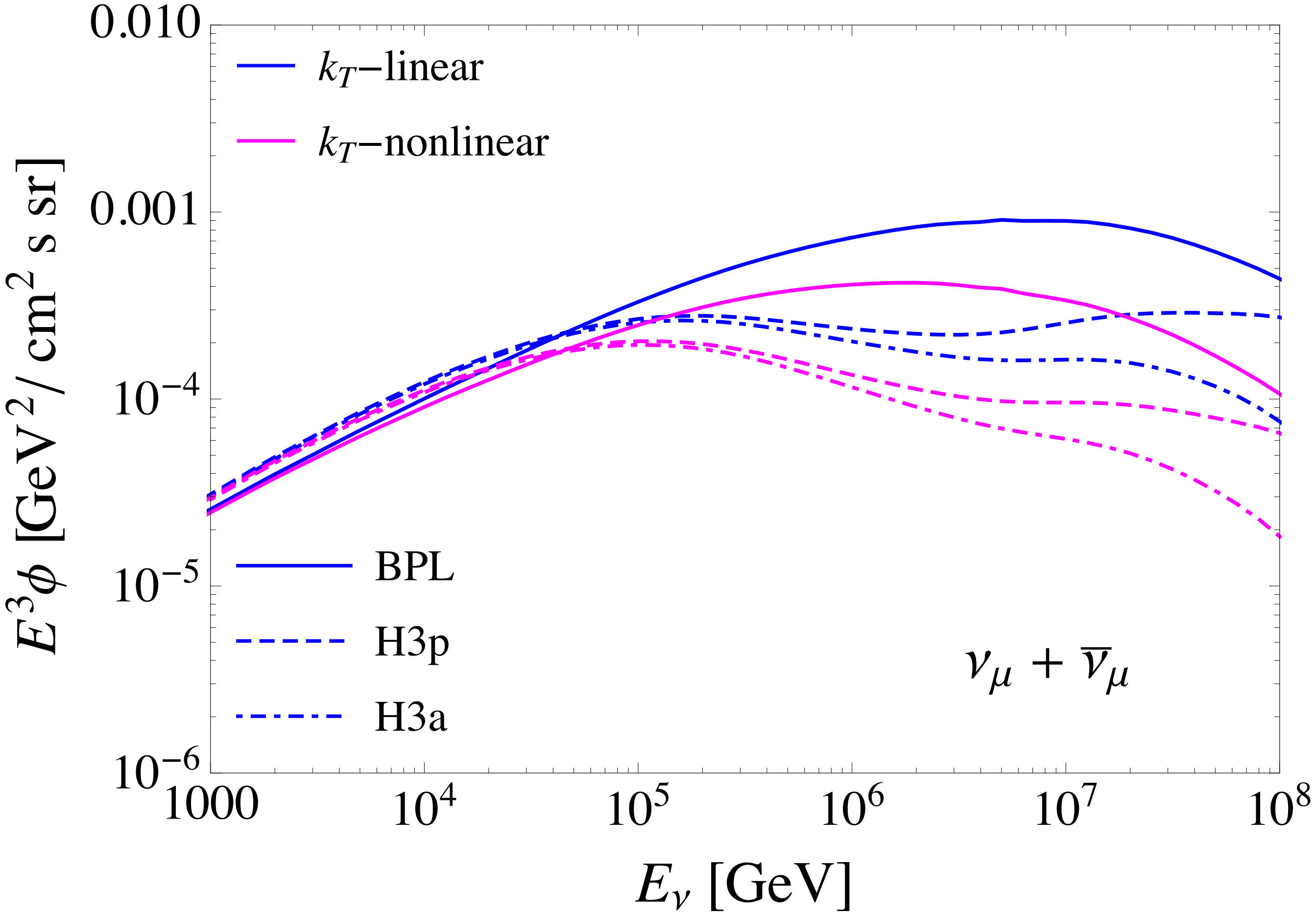
- Nuclear effects in the target. Further reduction of the flux by about 20-35%. Estimate of nuclear corrections within the NLO pQCD consistent with the small x calculation.

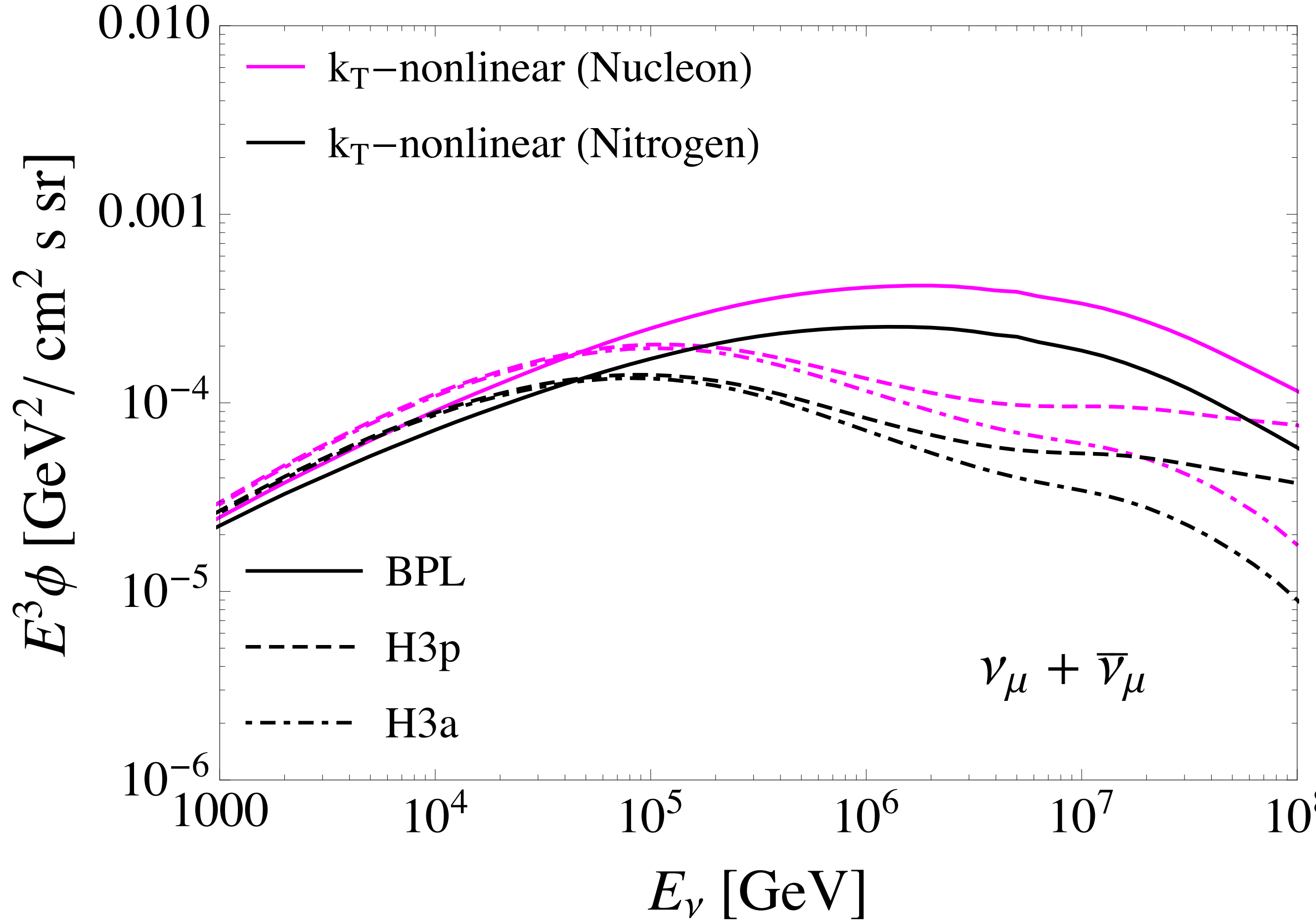
- Other calculations also on the market: consistent but still large uncertainties. Largest uncertainties due to the QCD scale variation, PDF uncertainties and CR flux.

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

Backup

Neutrino fluxes





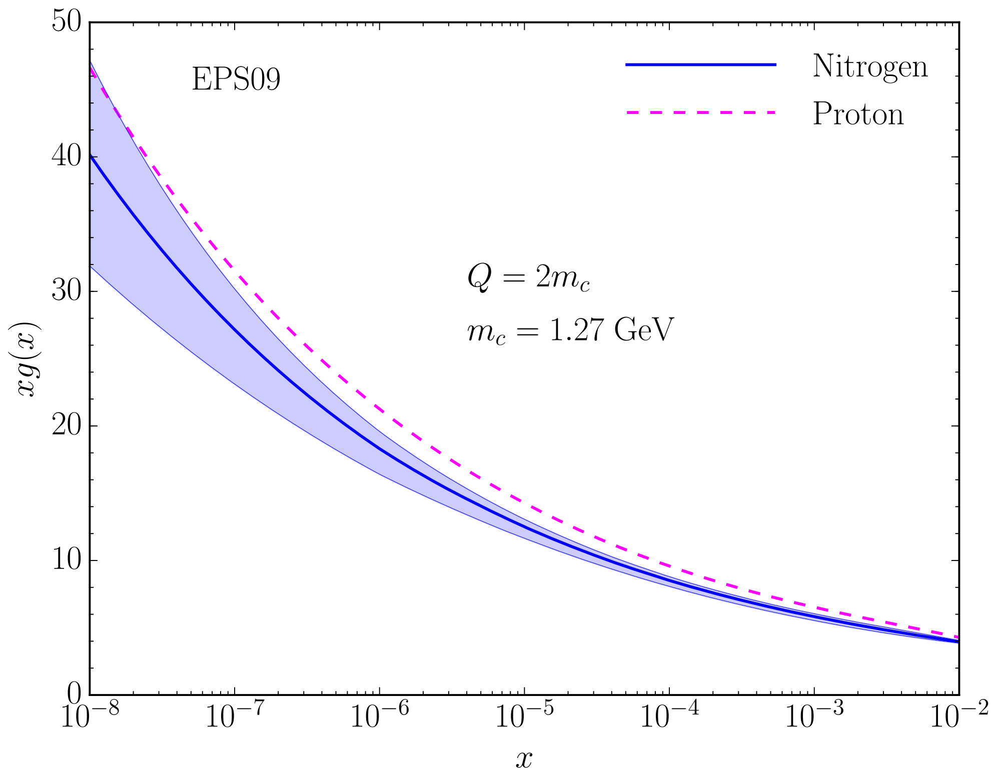
- Sizeable reduction of the flux due to the changes from linear to nonlinear evolution in k_T factorization.
- Further reduction of the flux when nuclear effects in nitrogen are included.

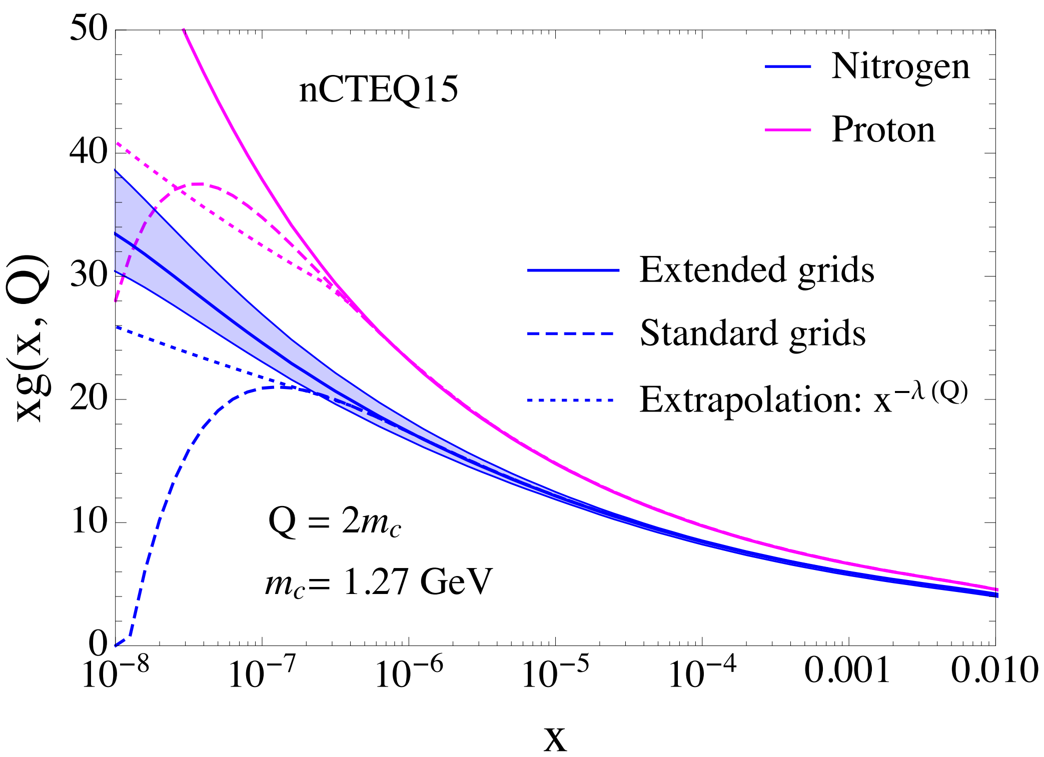
Nuclear corrections

NLO pQCD

Use of nuclear PDFs, nCTEQ and EPS

Large uncertainties in the extrapolations to the unmeasured regime





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

Comparison with LHCb 7 and 13 TeV

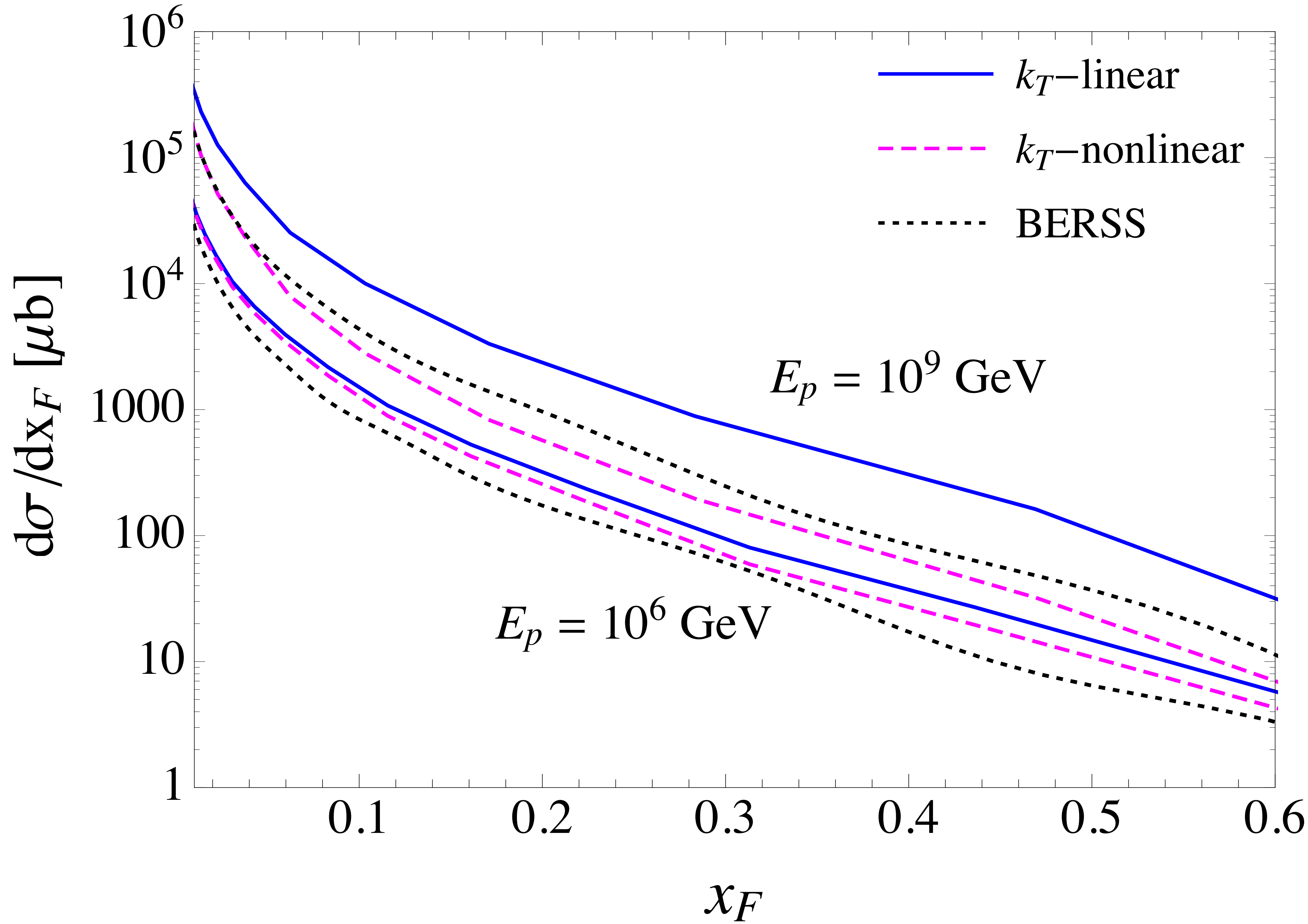
Integrated cross section for charm-anticharm production at 7 and 13 TeV.

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

$\sqrt{s}$	$\sigma(pp \to c\bar{c}X)$ [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

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.



Nuclear effects are non-negligible at these energies.