Low x physics and prompt neutrino production

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Outline

- Motivation: ultrahigh energy neutrino astronomy
- Atmospheric neutrinos: conventional and prompt
- Cross section for charm production at forward rapidities: collinear, dipole and k_T factorization calculations
- Calculation of prompt neutrino fluxes

Work in collaboration with

A. Bhattacharya, R. Enberg, Y. S. Jeong, C. S. Kim, M. H. Reno, I. Sarcevic
arXiv:1502.01076, arXiv:1607.00193

Neutrino astronomy

- Universe not transparent to extragalactic photons with energy > 10 TeV

- Weakly interacting: neutrinos can travel large distances without distortion

Interaction lengths (at 1 TeV):

$$\mathcal{L}_{\text{int}}^{\gamma} \sim 100\,\text{g}/\text{cm}^2$$

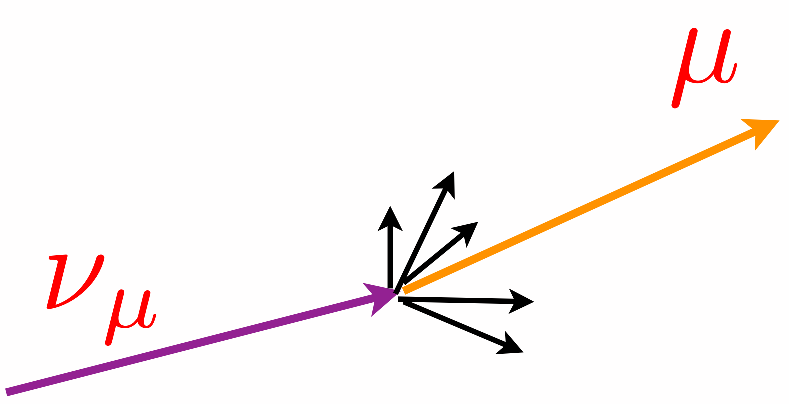
$$\mathcal{L}_{\text{int}}^{\nu} \sim 250 \times 10^9\,\text{g}/\text{cm}^2$$

- Trajectories of protons and nuclei are distorted by the magnetic fields

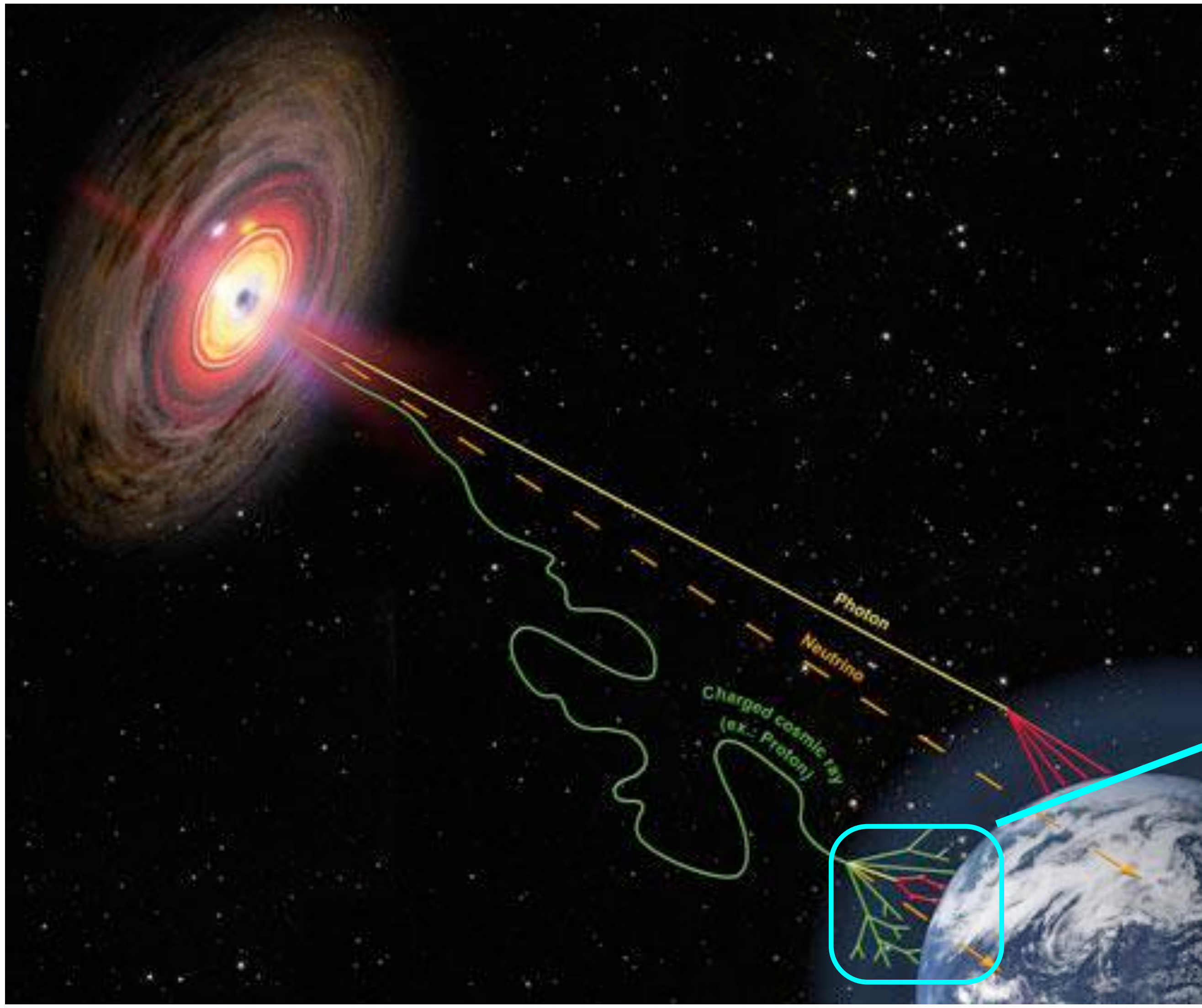
- Neutrinos can point back to their sources

Angular distortion

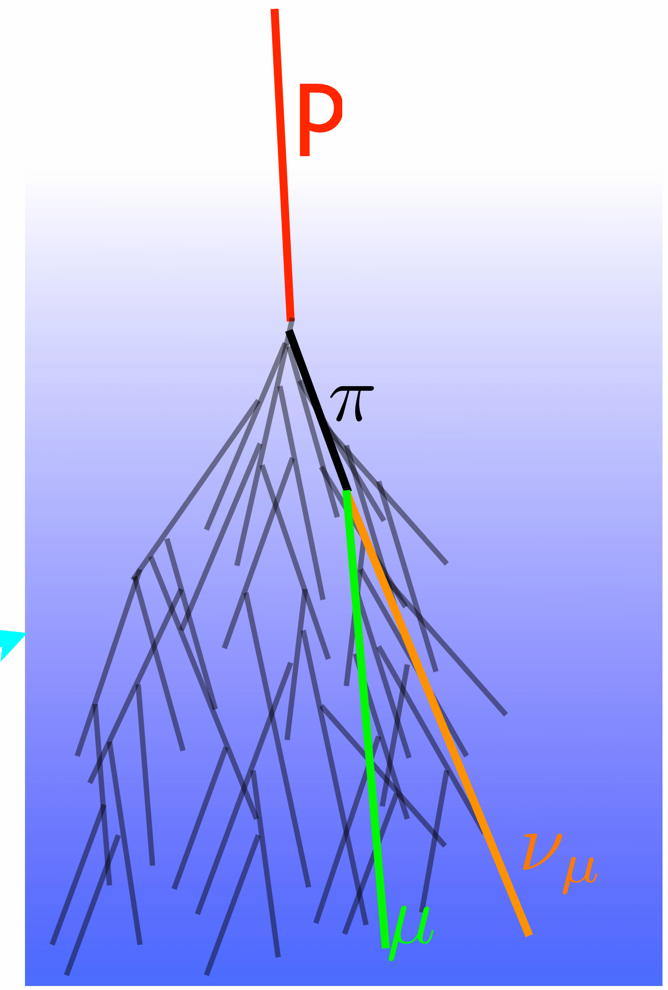
$$\delta\phi \simeq \frac{0.7^o}{(E_\nu/\text{TeV})^{0.7}}$$



Atmospheric neutrinos



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



$p + \text{Air}$

interaction

π, K

decay

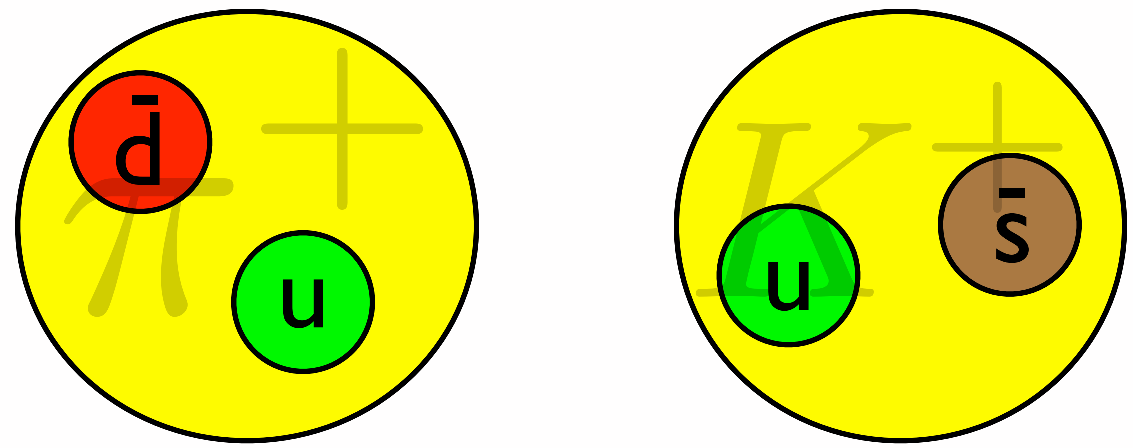
μ, ν_μ

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

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

Long-lived mesons loose energy

Steeply falling flux of neutrinos

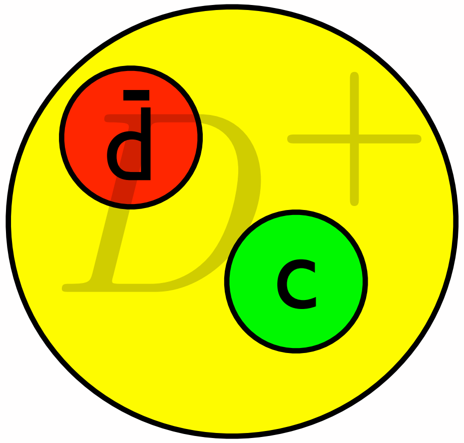
$\Phi_\nu \sim E_\nu^{-3.7}$

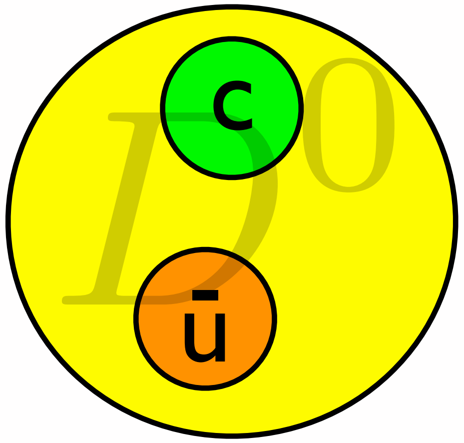
Prompt neutrinos

- *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

$$\boxed{\mathcal{L}_{\text{int}} > \mathcal{L}_{\text{dec}}}$$

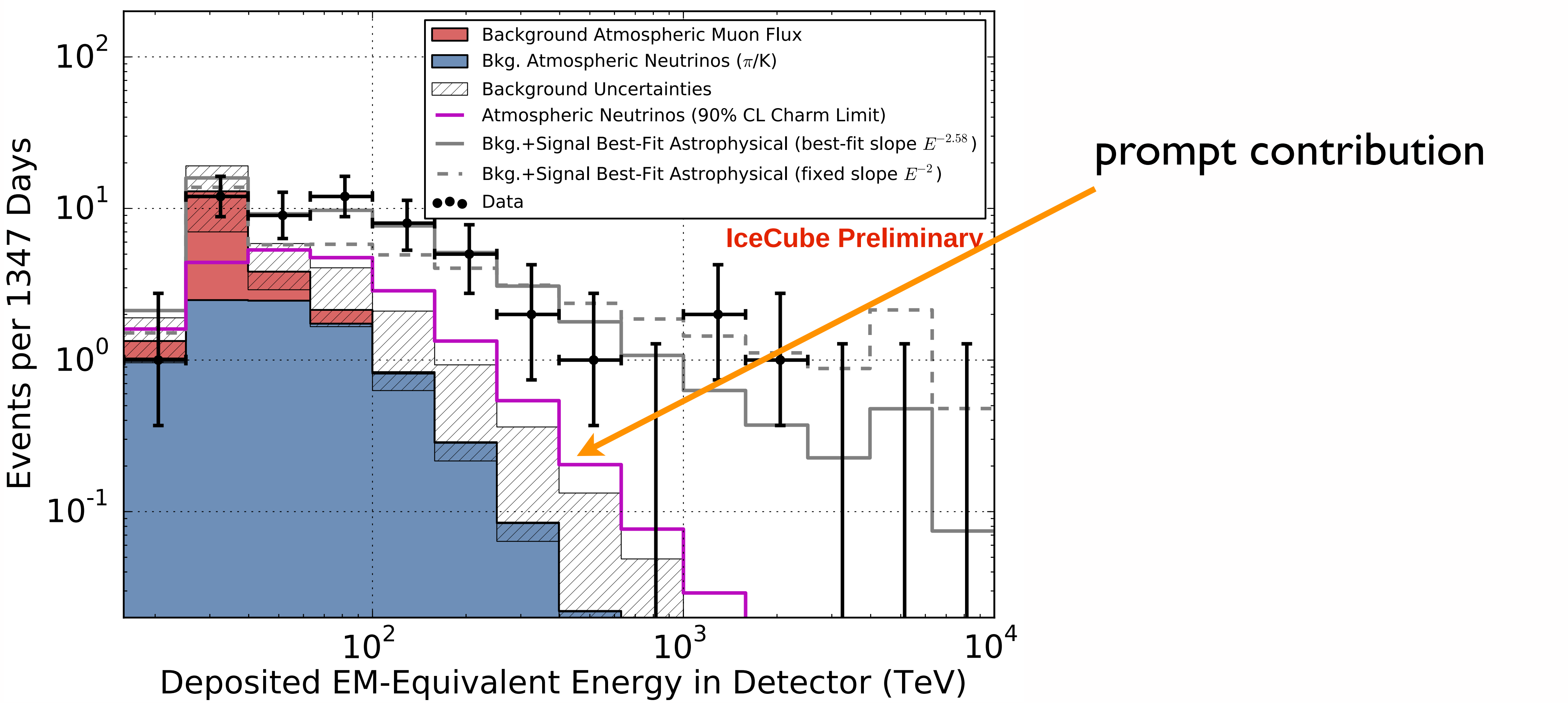
Flat flux, more energy transferred to neutrino

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

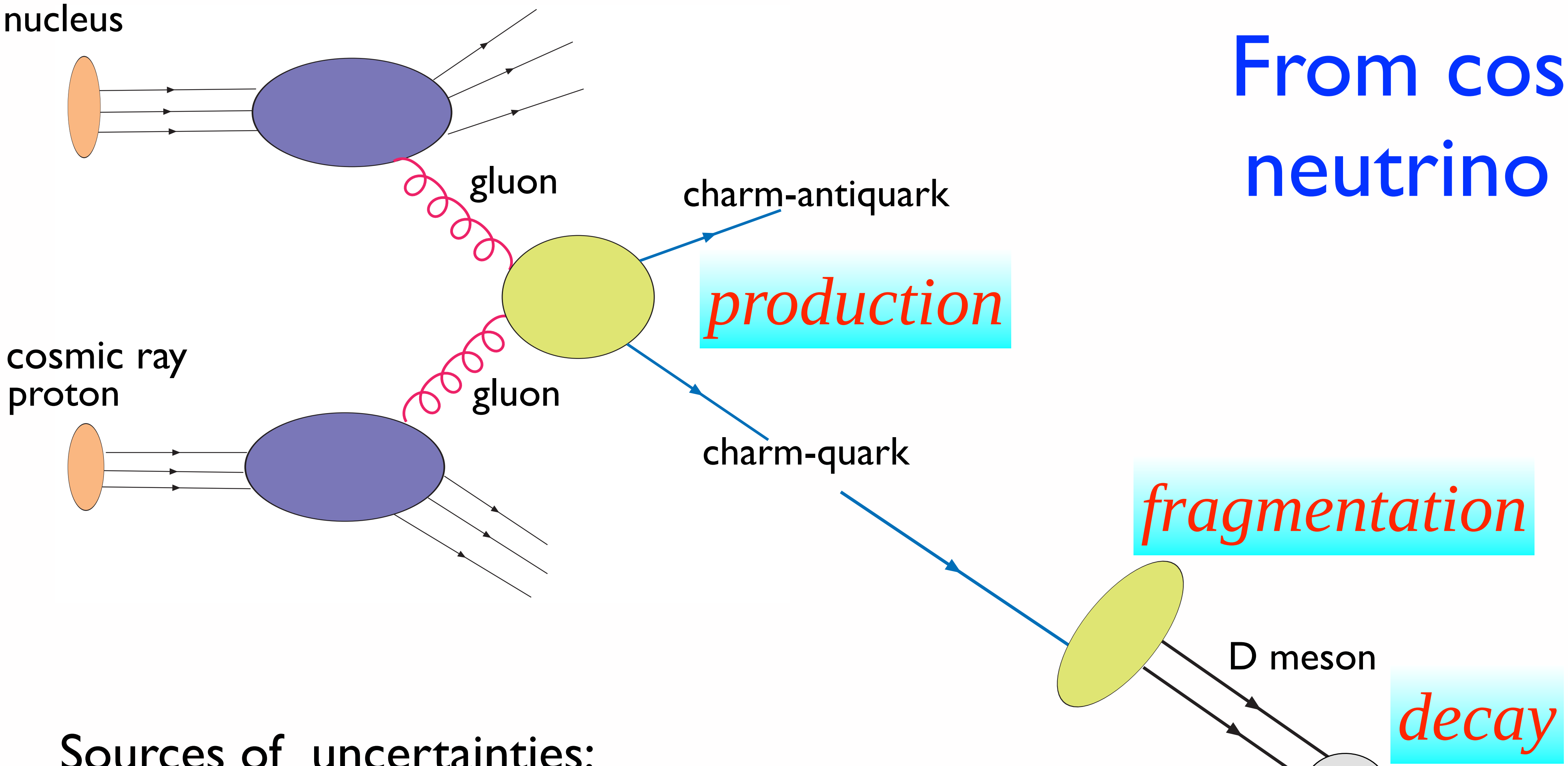
Motivation

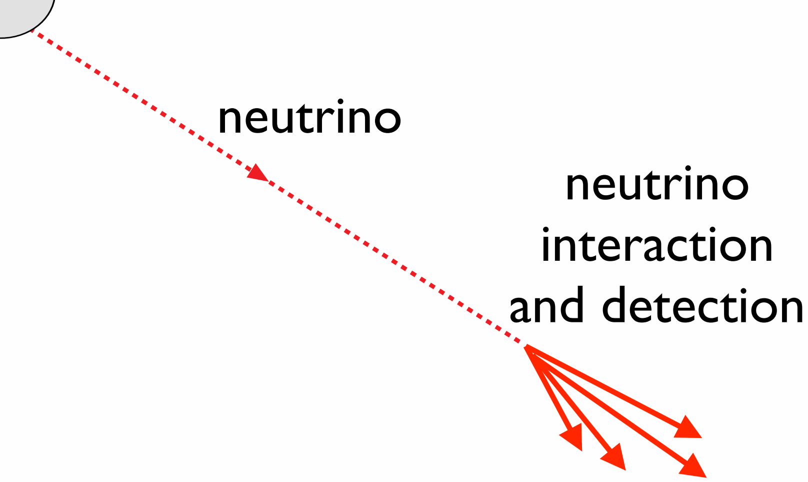
- Prompt neutrino is the background for the astrophysical flux of neutrinos.
- 4 year IceCube data, 1347 days, 54 events, 9 events expected from the background.
- Atmospheric origin excluded with 7 sigma.
- Neutrino production at these range of energies is sensitive to small x physics.

C. Kopper (ICRC2015, arXiv:1510.05223)



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

pQCD collinear calculation

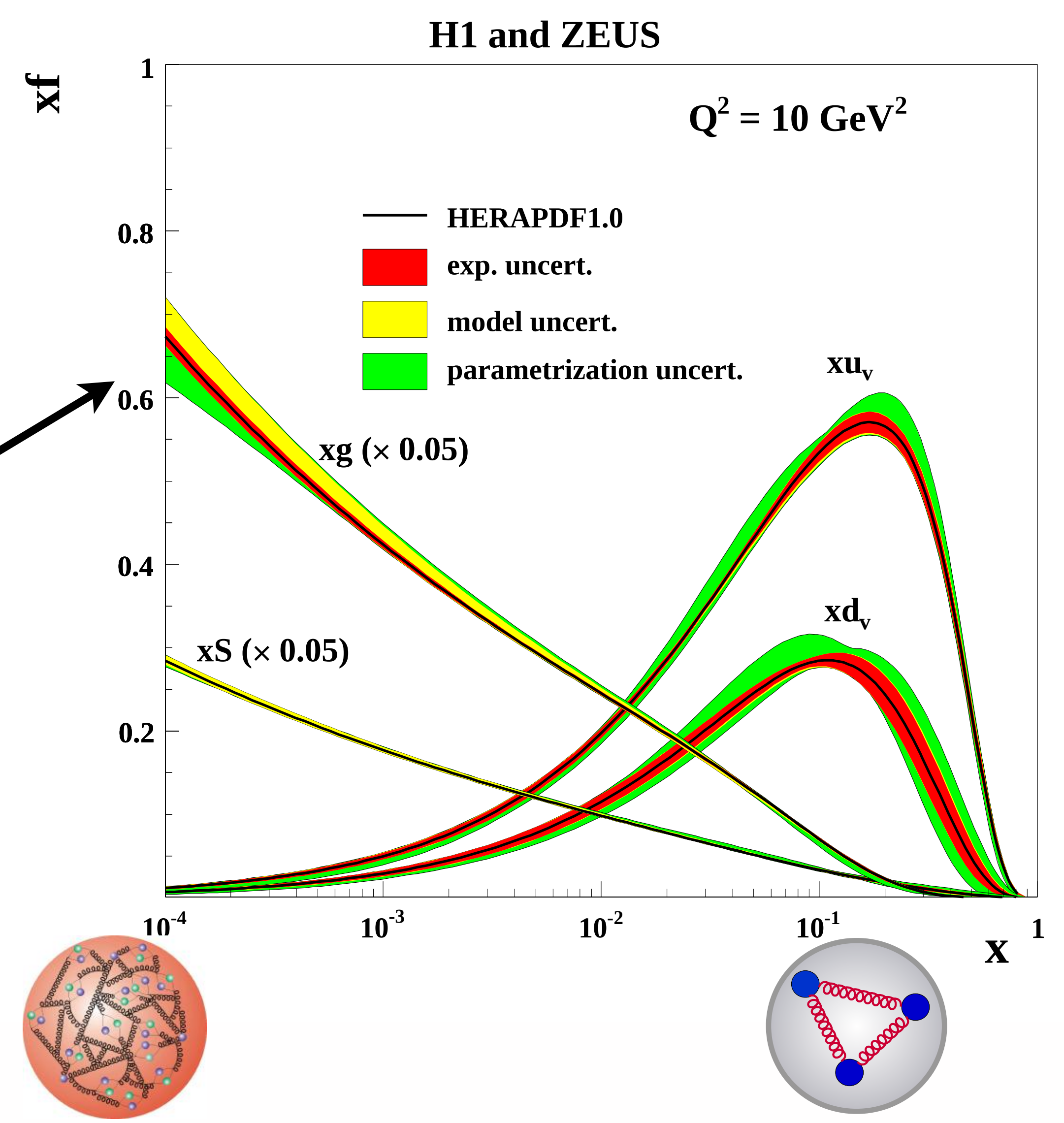
$$\frac{d\sigma^{pp\to c+X}}{dx_F} = \sum_{i,j} f_i(x_1,\mu_F) \otimes \hat{\sigma}_{gg\to c\bar{c}}(\hat{s}, m_c, \mu_F, \mu_R) \otimes f_j(x_2,\mu_F)$$

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:

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

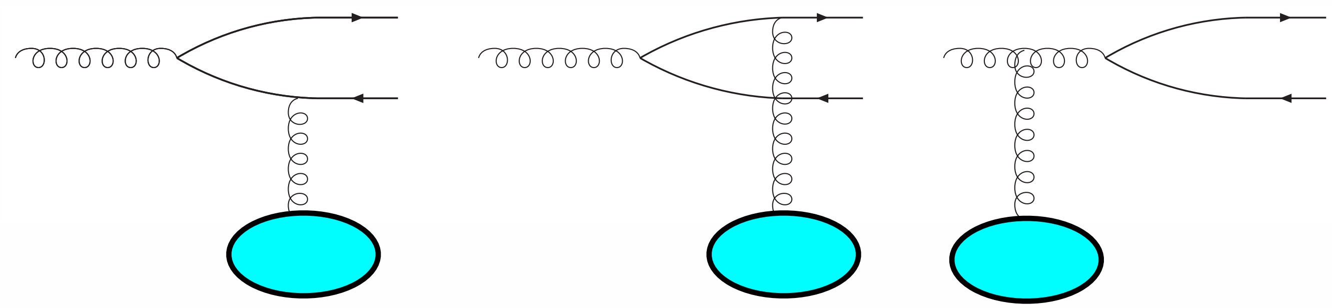
$$s \gg M^2_{c\bar{c}}$$

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



Dipole model calculation

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.

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:

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

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

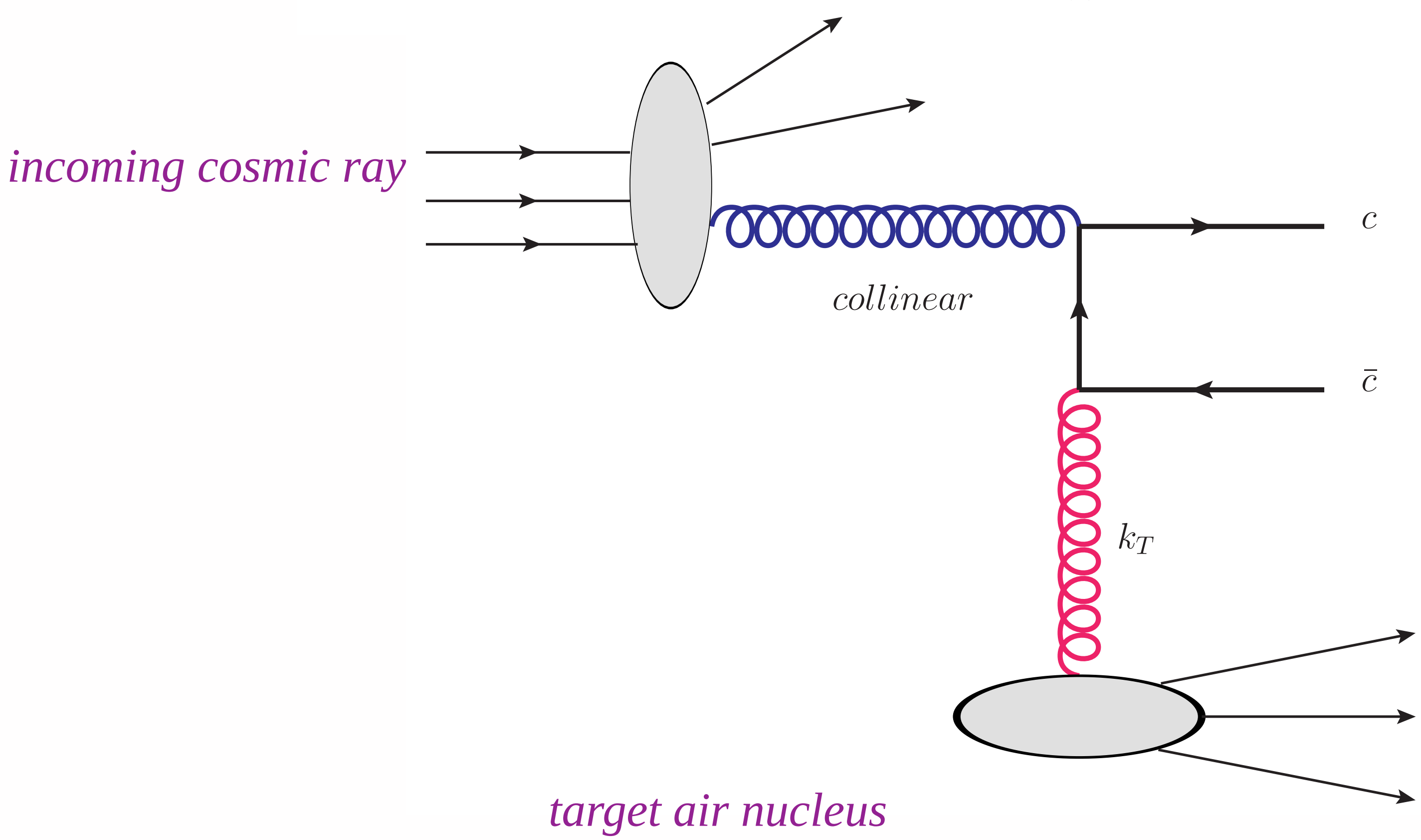
Hybrid k_T factorization calculation

- Use k_T factorization with off-shell gluon and unintegrated parton density.
- Suitable for the high energy - low x regime.
- 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 with small x effects
- Can also include saturation

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

DGLAP with non-singular splitting

non-linear term

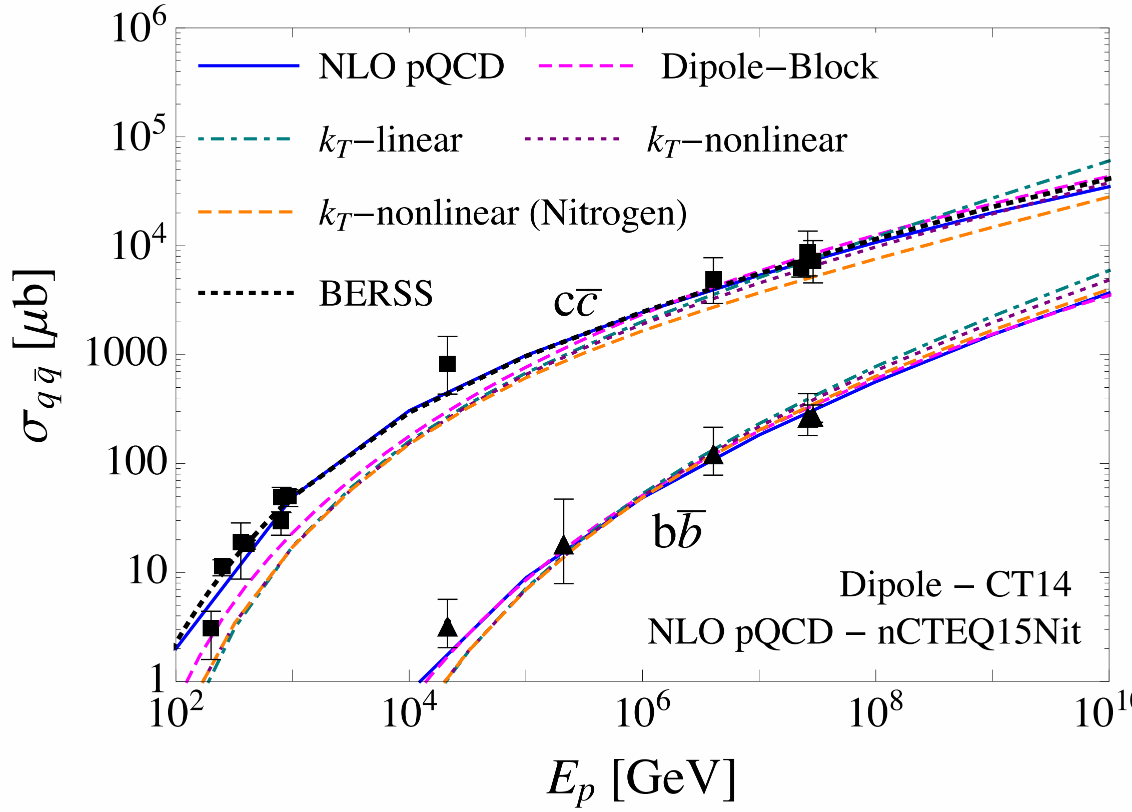
$$
\begin{aligned}
f(x,k^2) \;=\;& \tilde{f}^{(0)}(x,k^2)+ \\
&+ \boxed{\frac{\alpha_s(k^2)N_c}{\pi}k^2\int_x^1\frac{dz}{z}\int_{k_0^2}\frac{dk'^2}{k'^2}\left\{\frac{f(\frac{x}{z},k'^2)\,\Theta(\frac{k^2}{z}-k'^2)\;-\;f(\frac{x}{z},k^2)}{|k'^2-k^2|}+\frac{f(\frac{x}{z},k^2)}{|4k'^4+k^4|^{\frac{1}{2}}}\right\}}+ \\
&\boxed{+\frac{\alpha_s(k^2)N_c}{\pi}\int_x^1 dz\,\bar{P}_{gg}(z)\int_{k_0^2}^{k^2}\frac{dk'^2}{k'^2}\,f(\frac{x}{z},k'^2)-} \\
&\boxed{-\left(1-k^2\frac{d}{dk^2}\right)^2\frac{k^2}{R^2}\int_x^1\frac{dz}{z}\left[\int_{k^2}^{\infty}\frac{dk'^2}{k'^4}\alpha_s(k'^2)\ln\left(\frac{k'^2}{k^2}\right)f(z,k'^2)\right]^2}
\end{aligned}
$$

Nonlinear term responsible for taming the growth of the gluon density

Unintegrated parton density fitted to the inclusive structure function data (*Kutak-Stasto, Kutak-Sapeta*)

Total charm production cross section

- For pQCD calculation using NLO code by Cacciari, Frixione, Greco, Nason.
- Charm quark mass $m_c = 1.27\ \text{GeV}$
- Comparison with RHIC and LHC data. Data are extrapolated with NLO QCD from measurements in the limited phase space region.
- All models describe the data very well at high energies.
- Nuclear effects are very small for the total cross section
- k_T factorization suitable for the description at high energy; underestimates the data at lower energy; need additional diagrams there to match to NLO pQCD

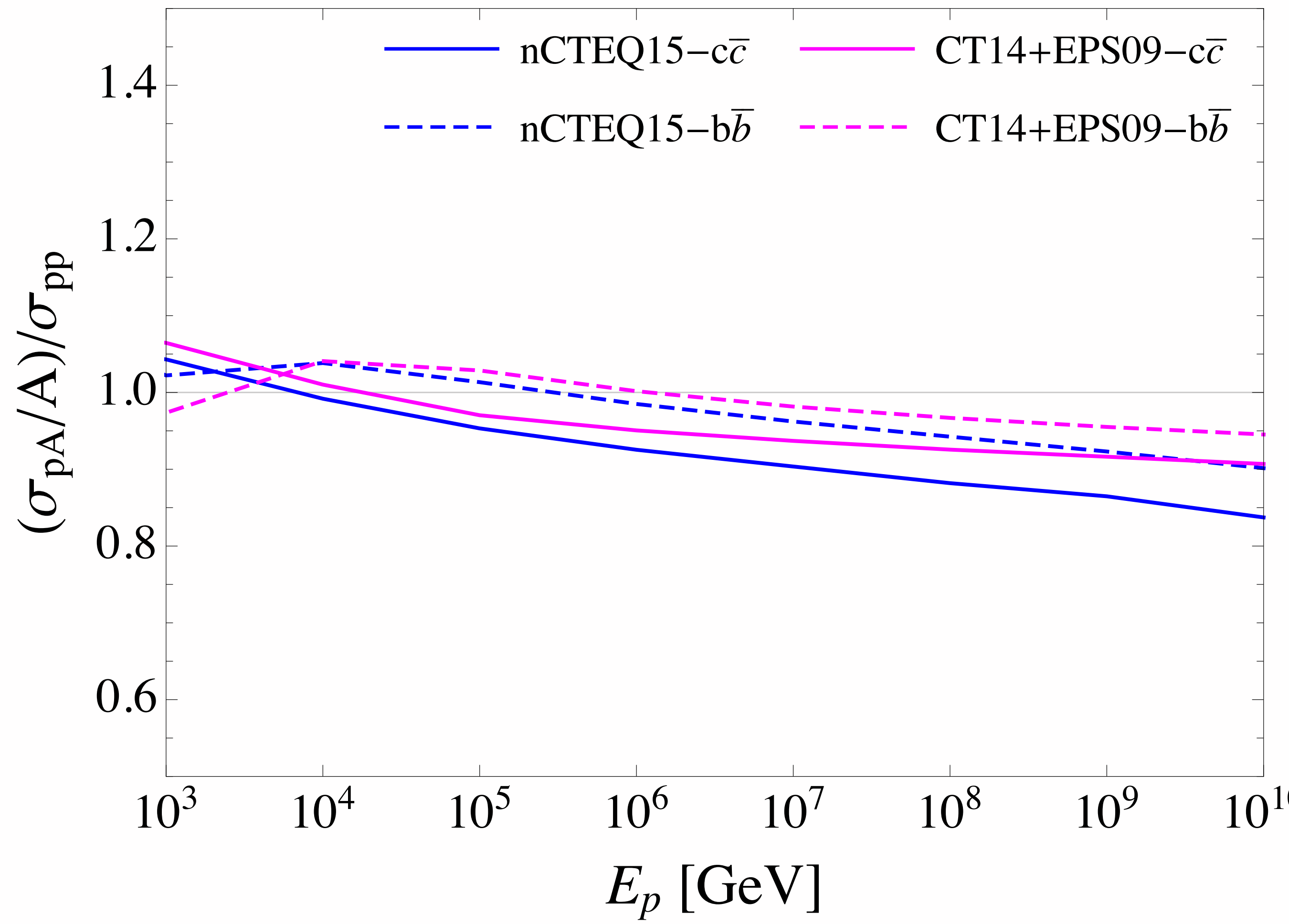


Expt.	$\sqrt{s}$ [TeV]	σ [mb]
PHENIX [31]	0.20	$\mathbf{0.551}^{+0.203}_{-0.231}$ (sys)
STAR [32]	0.20	$\mathbf{0.797} \pm 0.210$ (stat)$^{+0.208}_{-0.295}$ (sys)
ALICE [27]	2.76	$\mathbf{4.8} \pm 0.8$ (stat)$^{+1.0}_{-1.3}$ (sys) ± 0.06 (BR) ± 0.1(frag) ± 0.1 (lum)$^{+2.6}_{-0.4}$ (extrap)
ALICE [27]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

Nuclear corrections

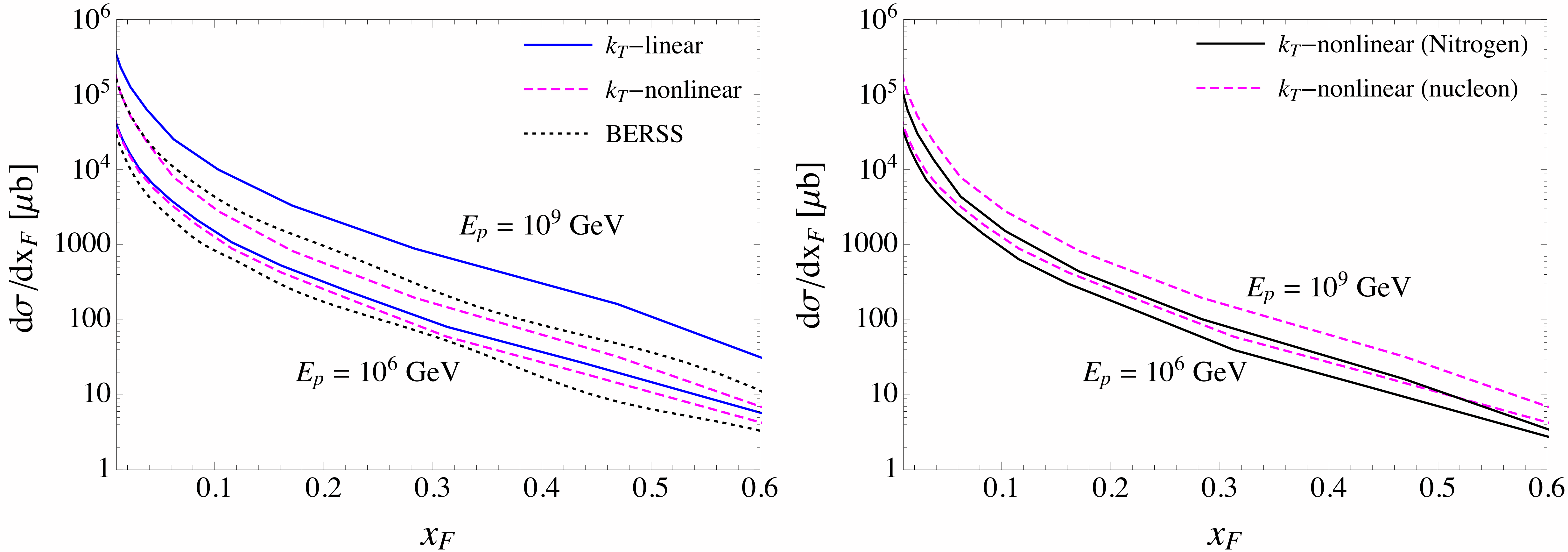
Nuclear modifications to the total charm production cross section are small 5-15%



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.



- 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.

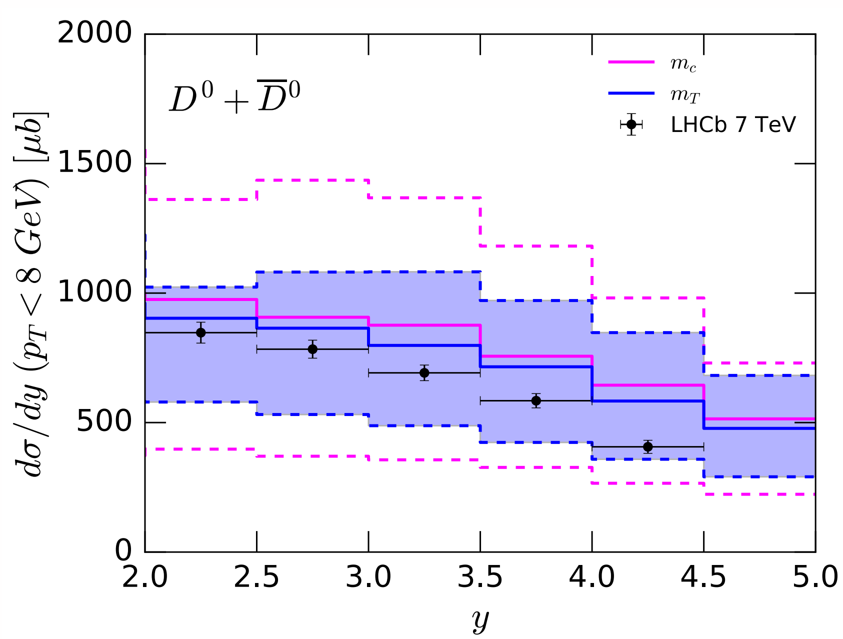
Comparison with LHCb 7 and 13 TeV

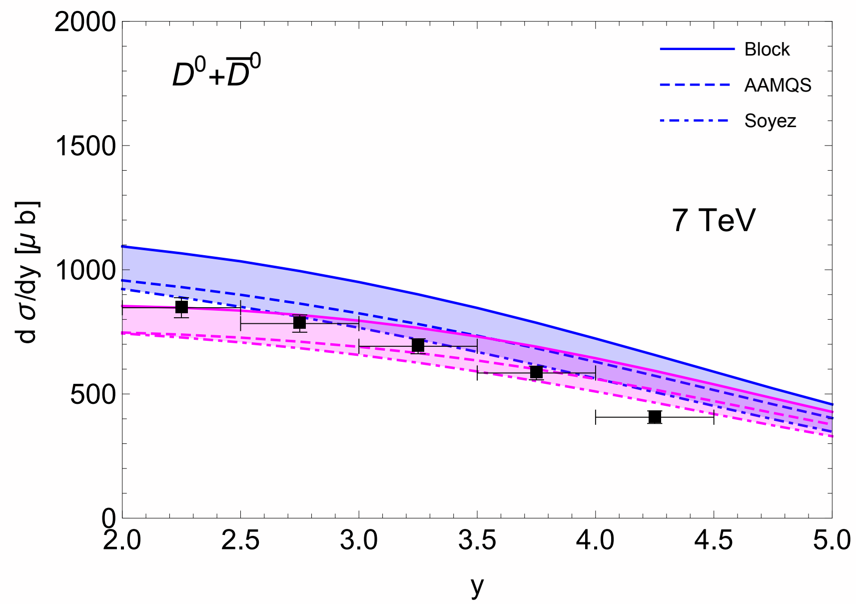
Rapidity distributions

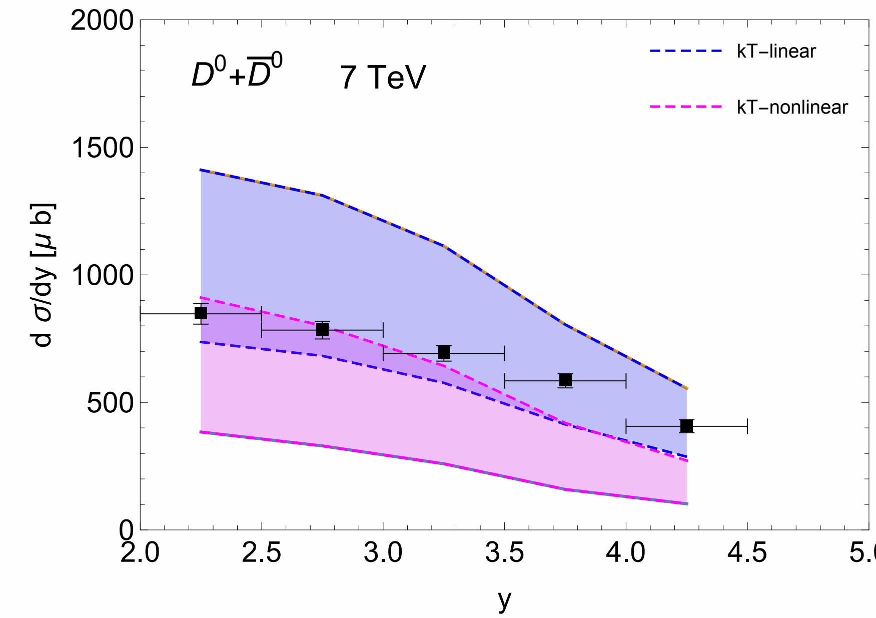
NLO

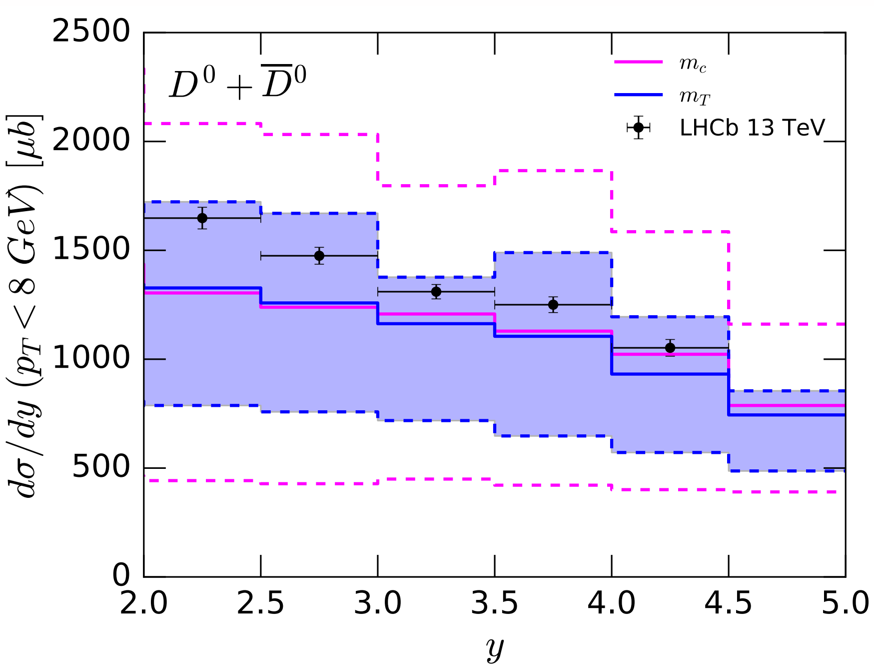
dipole

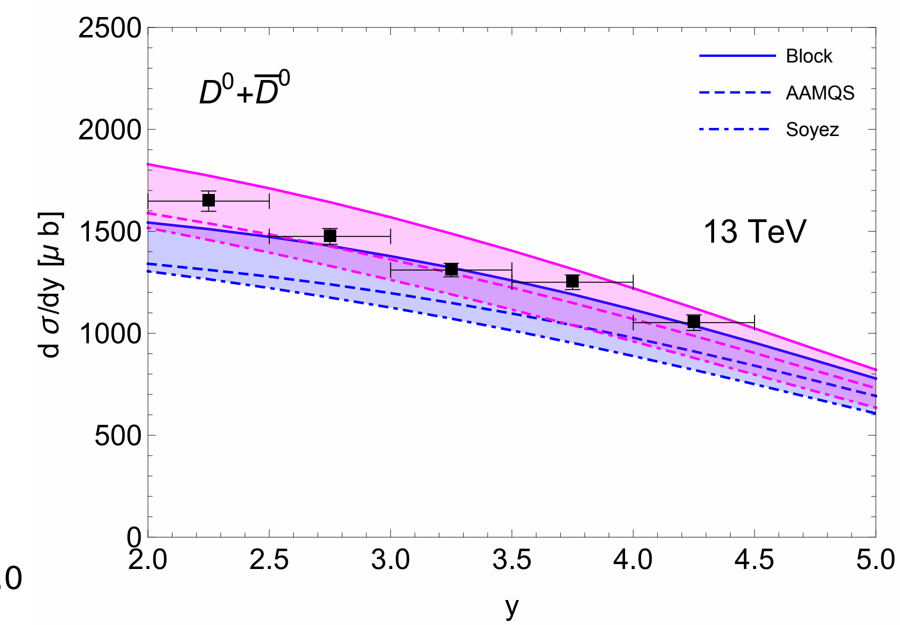
kT

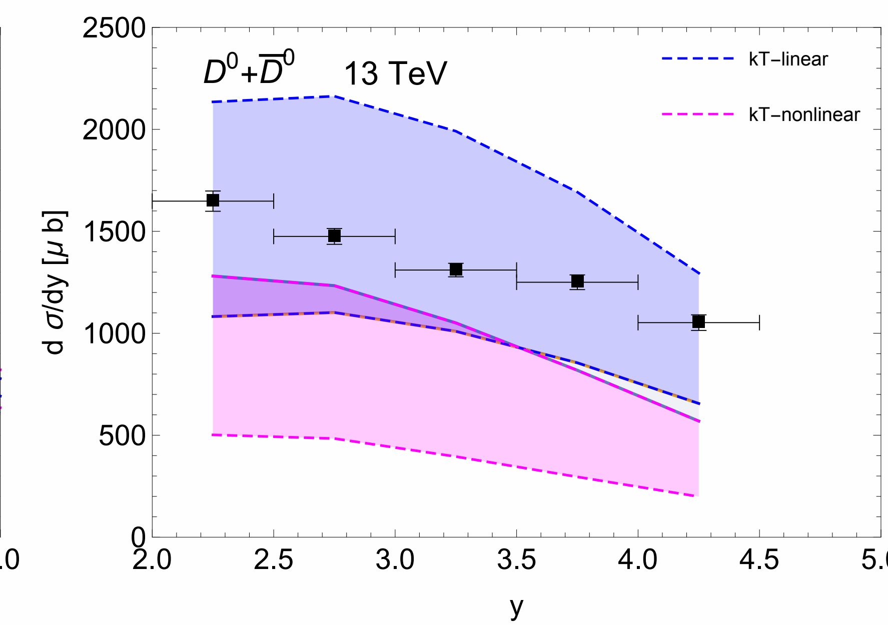








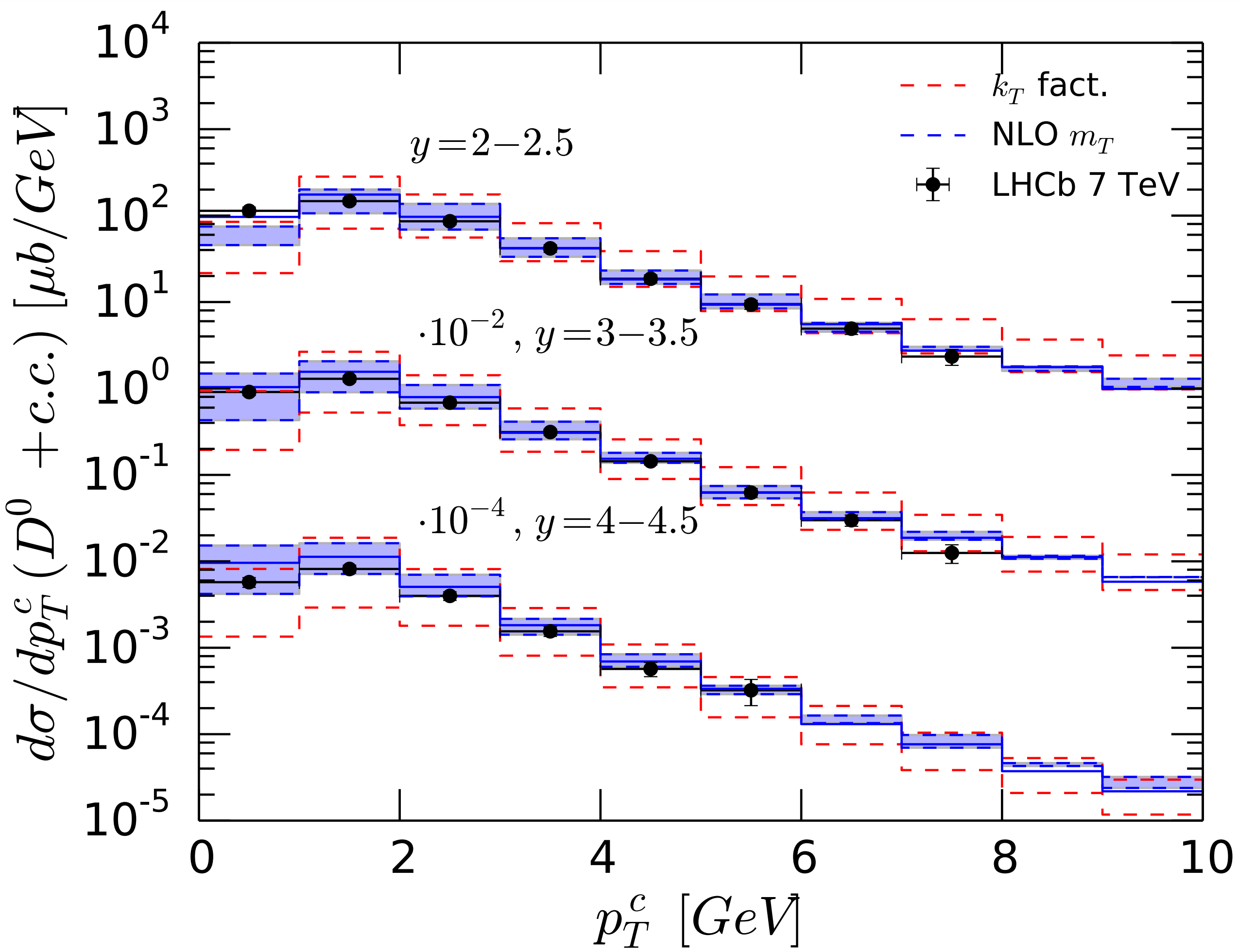


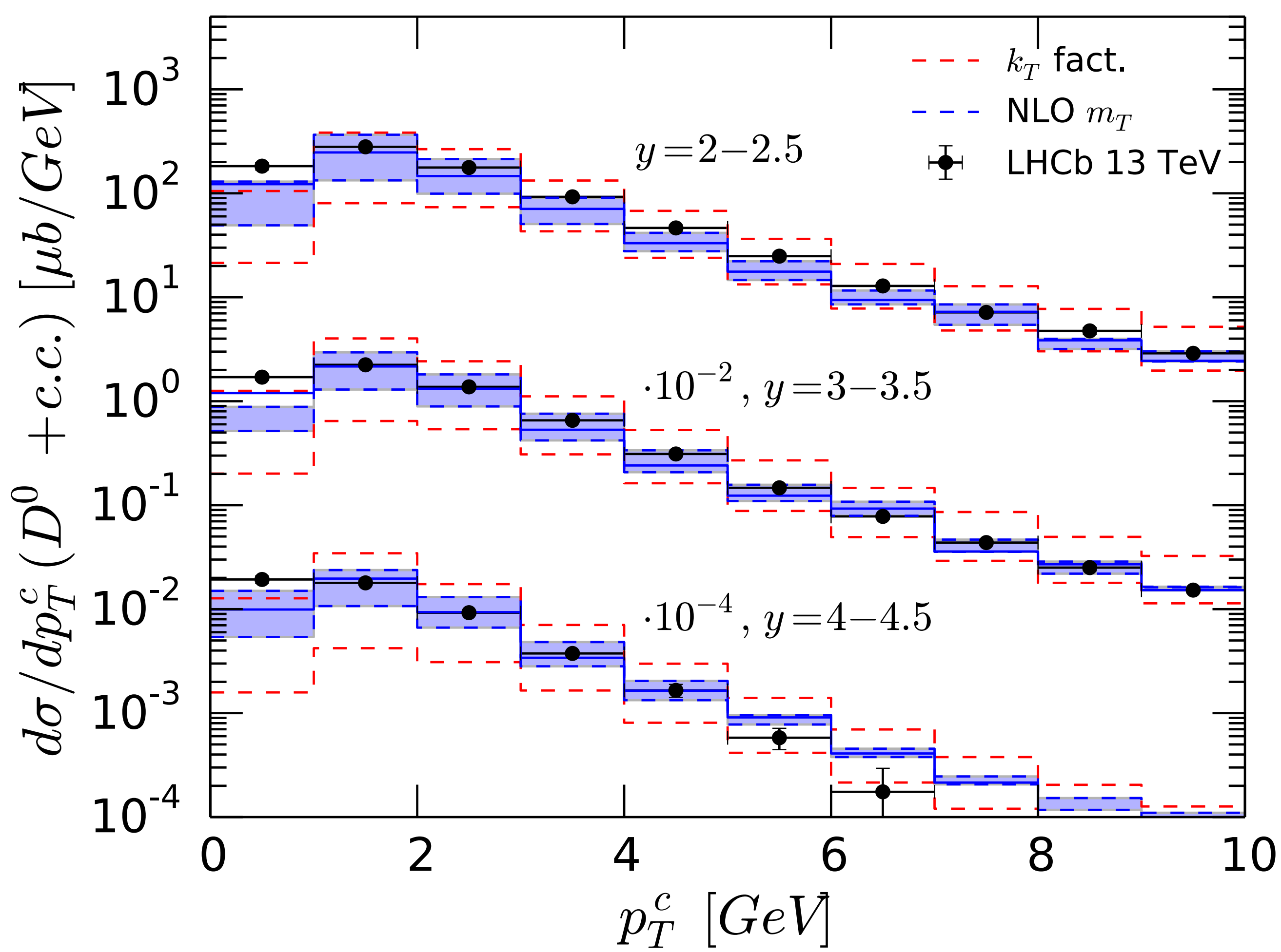


All approaches describe the LHCb data well within the error bands

Comparison with LHCb 7 and 13 TeV

Transverse momentum distributions



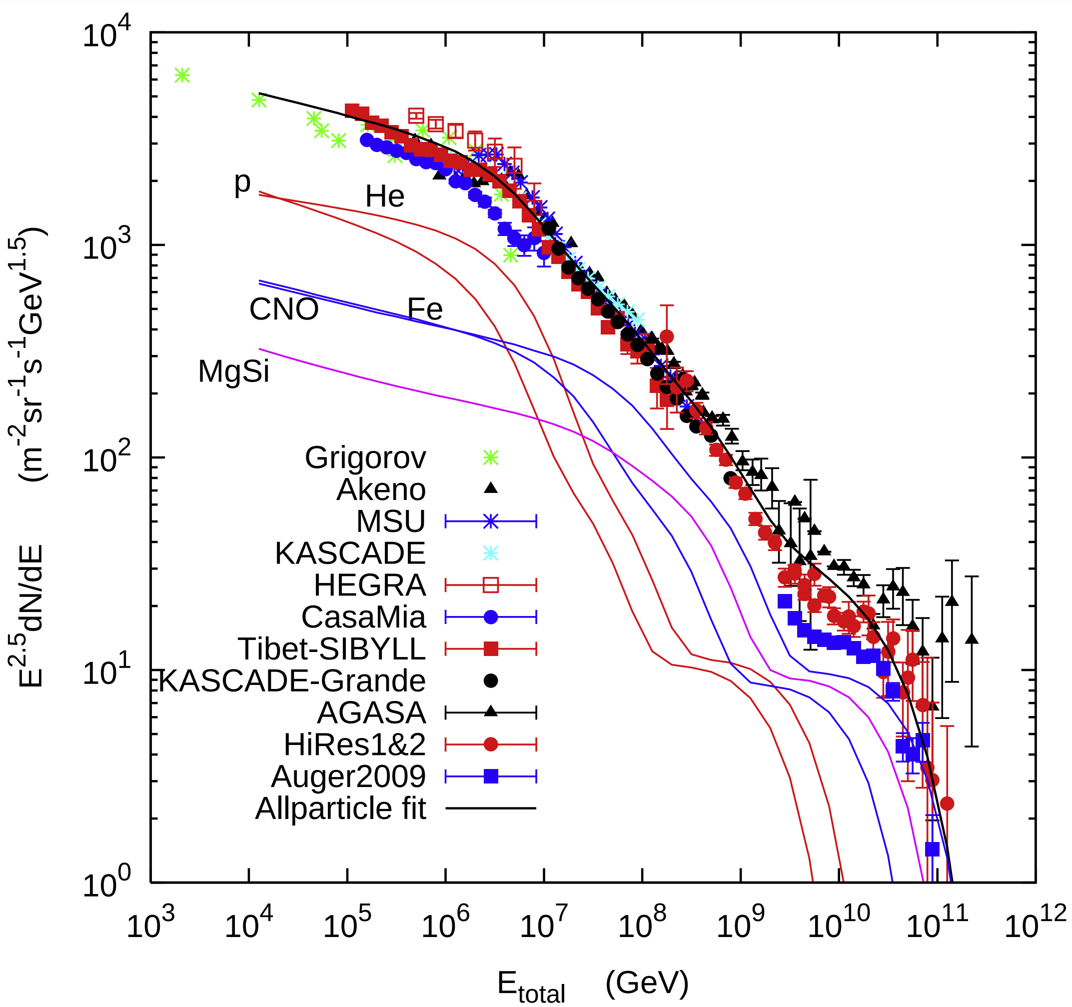


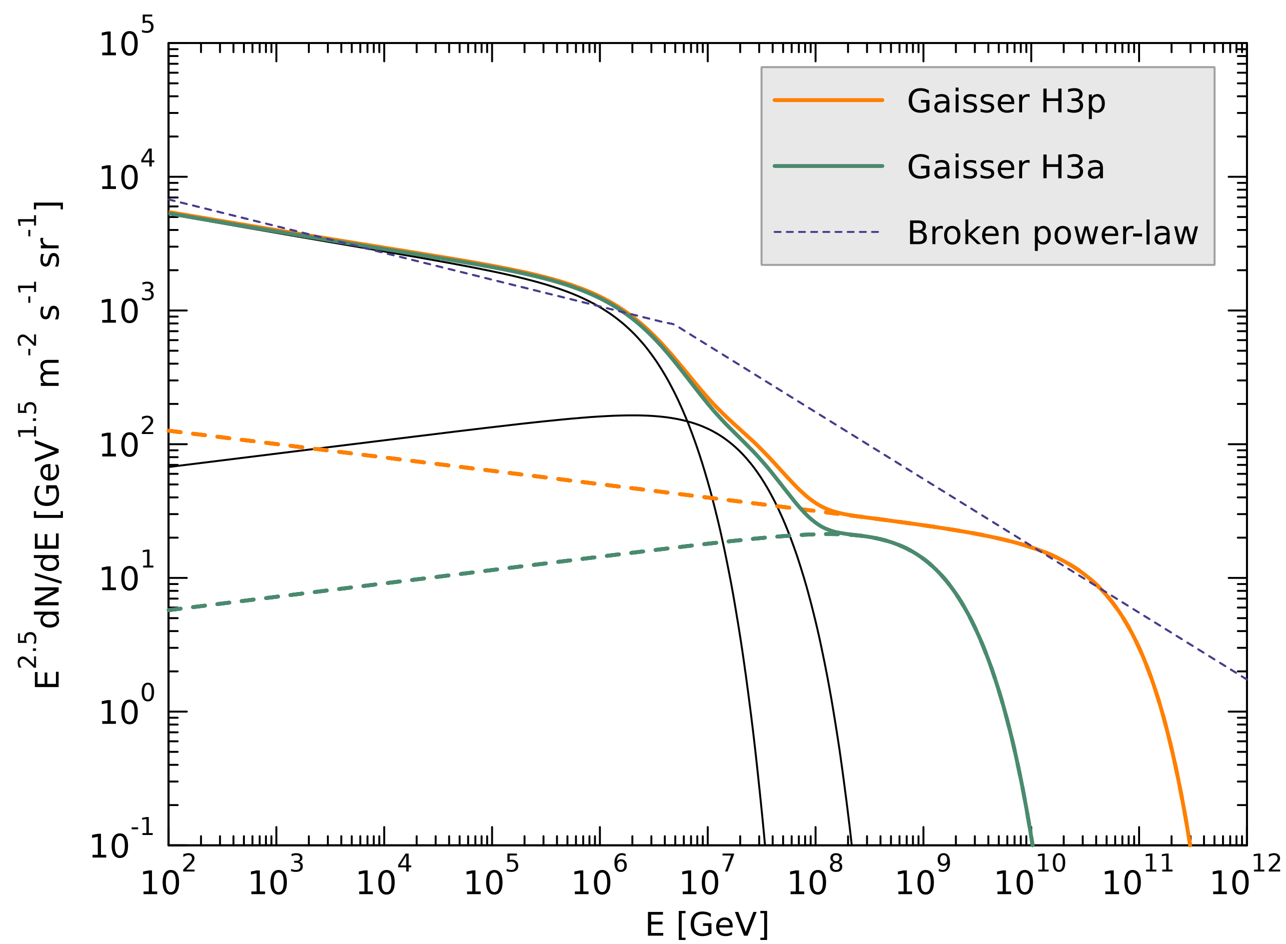
- NLO pQCD and k_T factorization consistent with each other.
- Bands on NLO pQCD calculation correspond to scale variation.
- Two lines in k_T factorization correspond to the saturation/no-saturation calculation.

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

Development of air shower: cascade equations

Production of prompt neutrinos:

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

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.

Development of air shower: cascade equations

Can solve equations numerically or semi-analytically
(assuming factorization of X and E dependence) via Z-moment method

$$\int_E^\infty \mathrm{d}\, E_k \frac{\phi_k(E_k, X)}{\lambda_k(E_k)} \frac{\mathrm{d}n_{k\to j}(E; E_k)}{\mathrm{d}E} \quad \simeq \quad \frac{\phi_k(E, X)}{\lambda_k(E)} Z_{kj}(E)$$

where

$$\boxed{Z_{kj}(E) = \int_0^1 \frac{\mathrm{d}x_E}{x_E} \frac{\phi_k(E/x_E, 0)}{\phi_k(E, 0)} \frac{\lambda_k(E)}{\lambda_k(E/x_E)} \frac{\mathrm{d}n_{k\to j}(E/x_E)}{\mathrm{d}x_E}} \qquad x_E = \frac{E}{E_k}$$

Then fluxes can be expressed via closed analytical expressions in terms of Z moments.

For example proton flux is:

$$\phi_p(E, X) \simeq \phi_p^0(E) \exp(-X/\Lambda_p) = (dN/dE) \exp(-X/\Lambda_p)$$

$$\Lambda_p = \lambda_p(E)/(1 - Z_{pp}(E))$$

Semi-analytical solutions to lepton fluxes

Lepton fluxes from the decays of the hadrons.
Characteristics of solution depends on the energy range and competition between decay and interactions.

Critical energy at which hadron decay probability is suppressed with respect to the interaction probability

$$E_{\rm crit} \simeq 3.7 - 9.5 \times 10^7 \ \ {\rm GeV}$$

$E < E_{\rm crit}$

$$\phi_\ell^{low}(h) = Z_{h\ell}^{low} \frac{Z_{ph}}{1 - Z_{pp}} \phi_p^0$$

$E > E_{\rm crit}$

$$\phi_\ell^{high}(h) = Z_{h\ell}^{high} \frac{Z_{ph}}{1 - Z_{pp}} \frac{\ln(\Lambda_h/\Lambda_p)}{1 - \Lambda_p/\Lambda_h} \phi_p^0$$

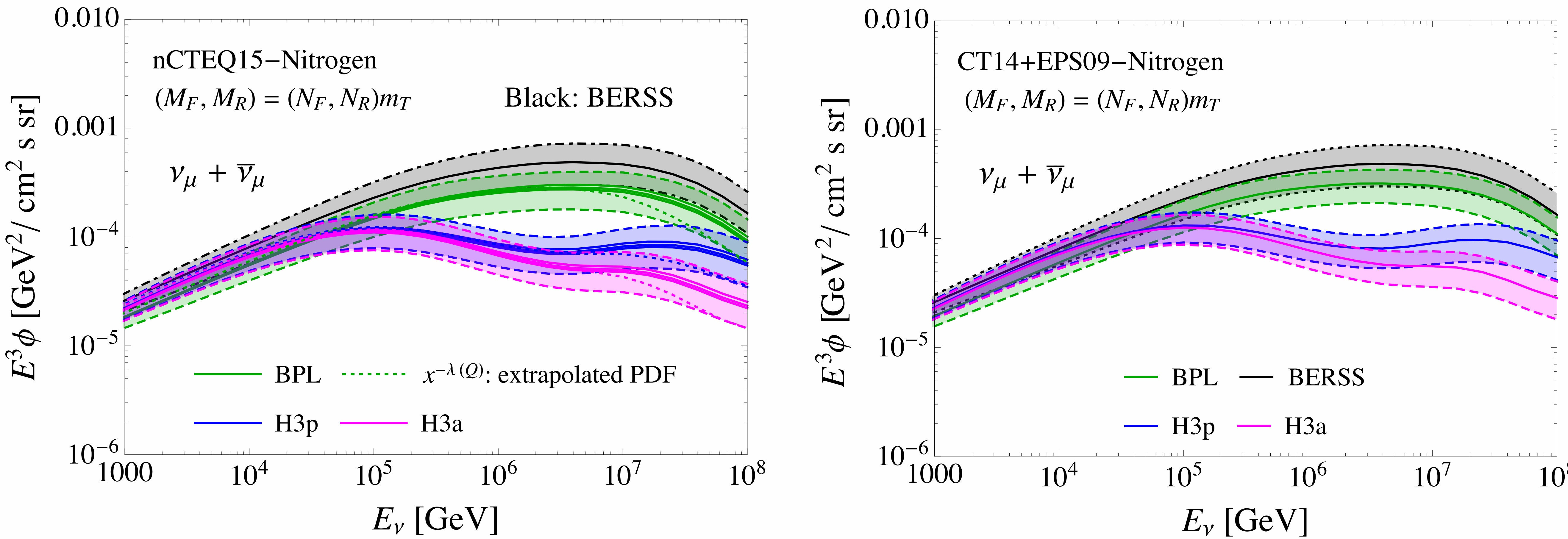
Interpolation:

$$\phi_\ell = \sum_h \frac{\phi_\ell^{low}(h)\phi_\ell^{high}(h)}{\phi_\ell^{low}(h) + \phi_\ell^{high}(h)}$$

Above formulae are good approximation to the exact solution of the cascade equations.

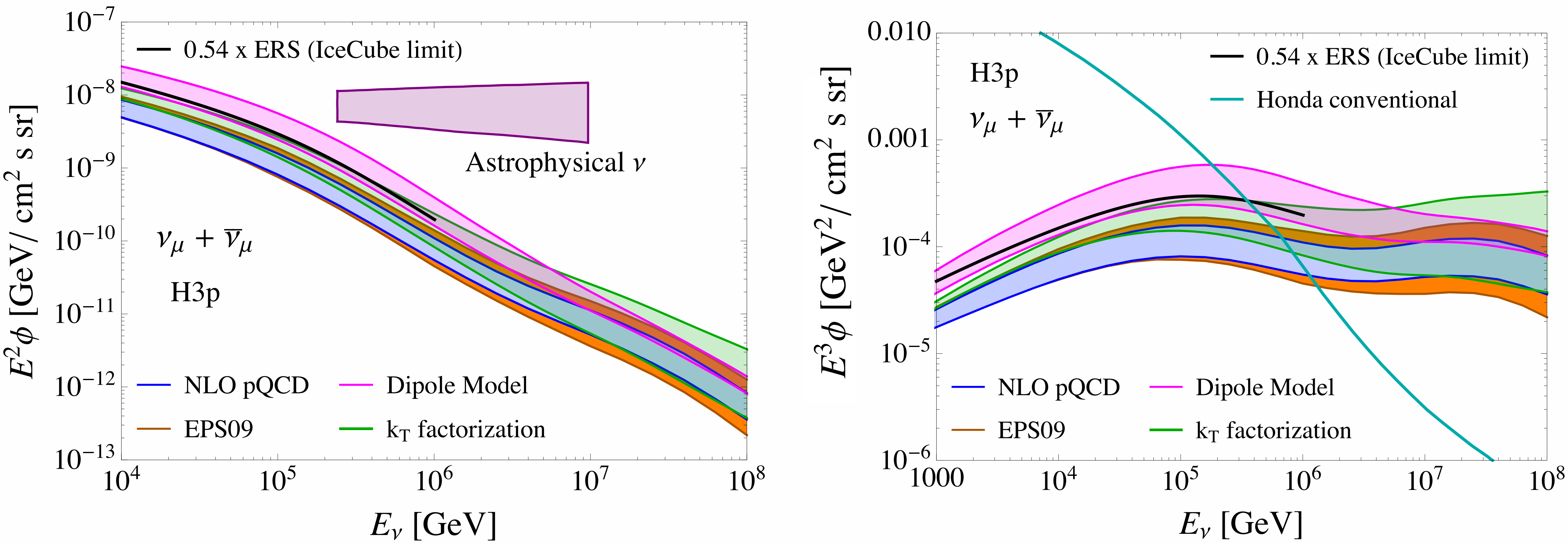
Neutrino fluxes

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. Bands correspond to the scale variation.
- 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



- IceCube limit on prompt neutrino flux (PoS(ICRC2015)1079).
- NLO perturbative and k_T factorization within the limit.
- Dipole model calculation is in 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 pQCD and latest PDFs as well as dipole and k_T factorization. Charm cross section matched to LHC and RHIC data.
- Consistent with LHCb data (rapidity and transverse momentum distributions) on forward charm production.
- Updated cosmic ray flux gives lower values (as compared with earlier ERS and BERSS evaluation) for the atmospheric neutrino flux.
- Prompt neutrino component is rather small. Limit on prompt production from IceCube data constraints dipole calculation.
- 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.
- 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.

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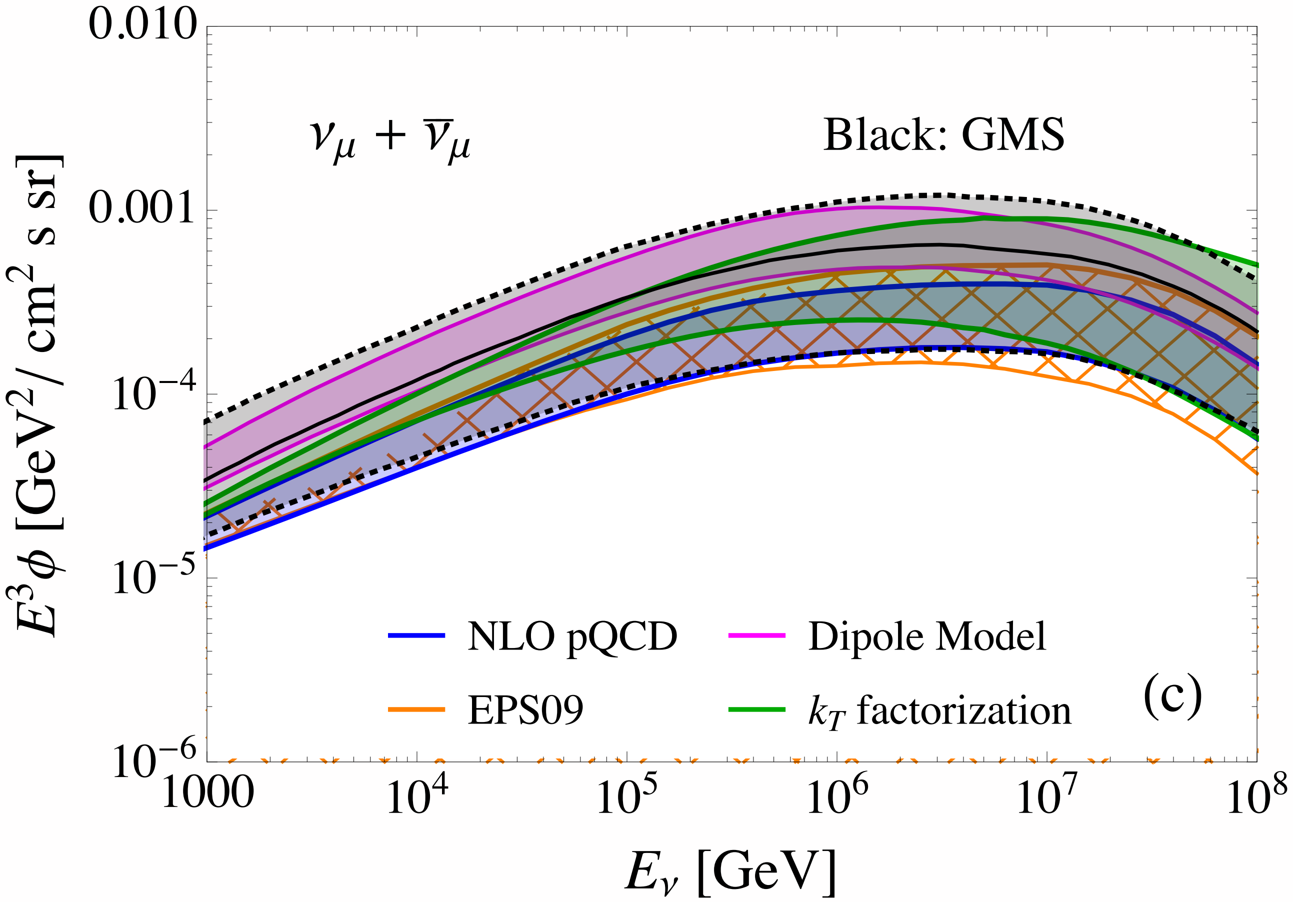
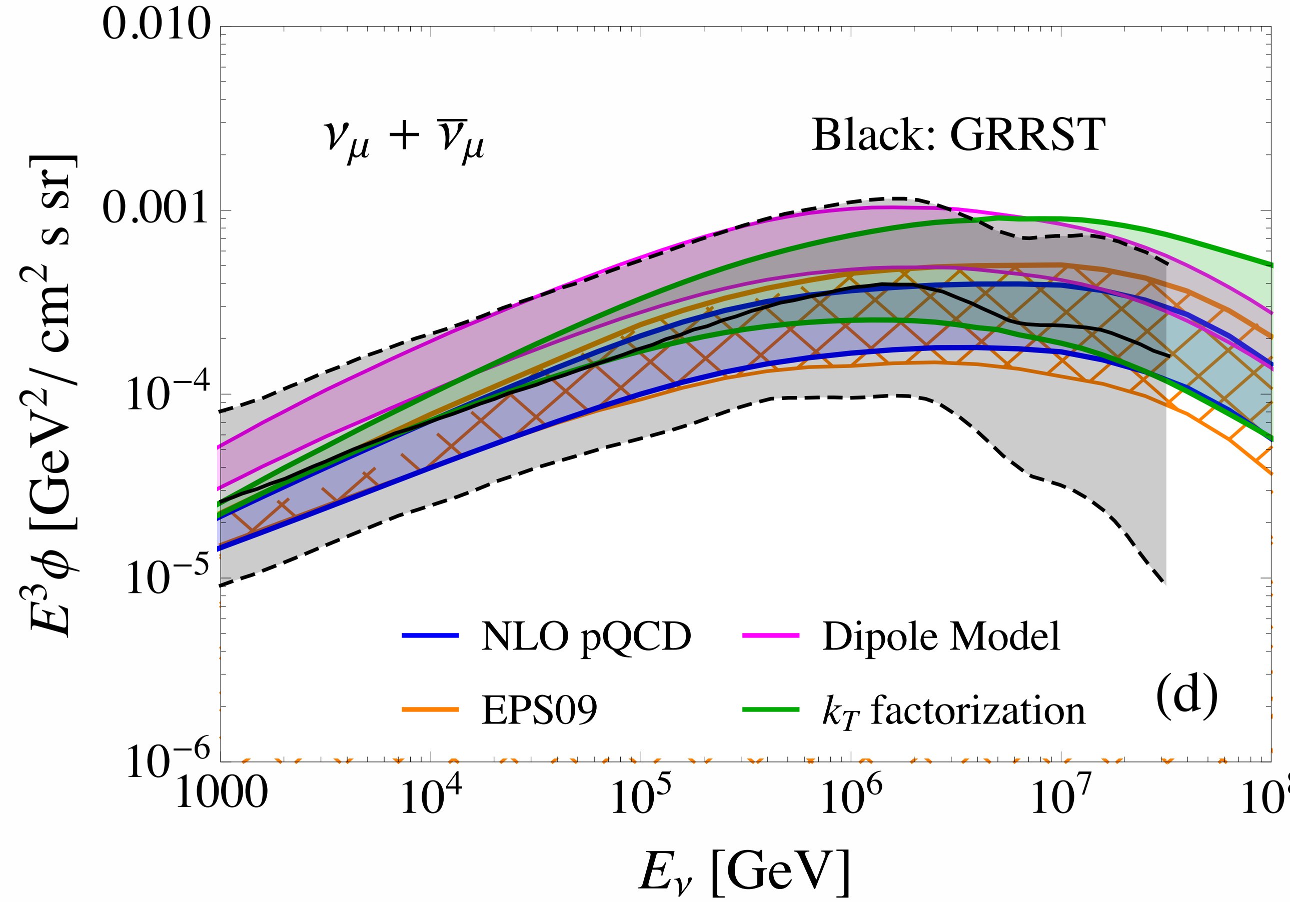
Neutrino fluxes





Comparison with other calculations:

GMS: Garzelli, Moch, Sigl

GRRST: Gauld, Rojo, Rotolli, Sarkar, Talbert

Consistency within the error bands.

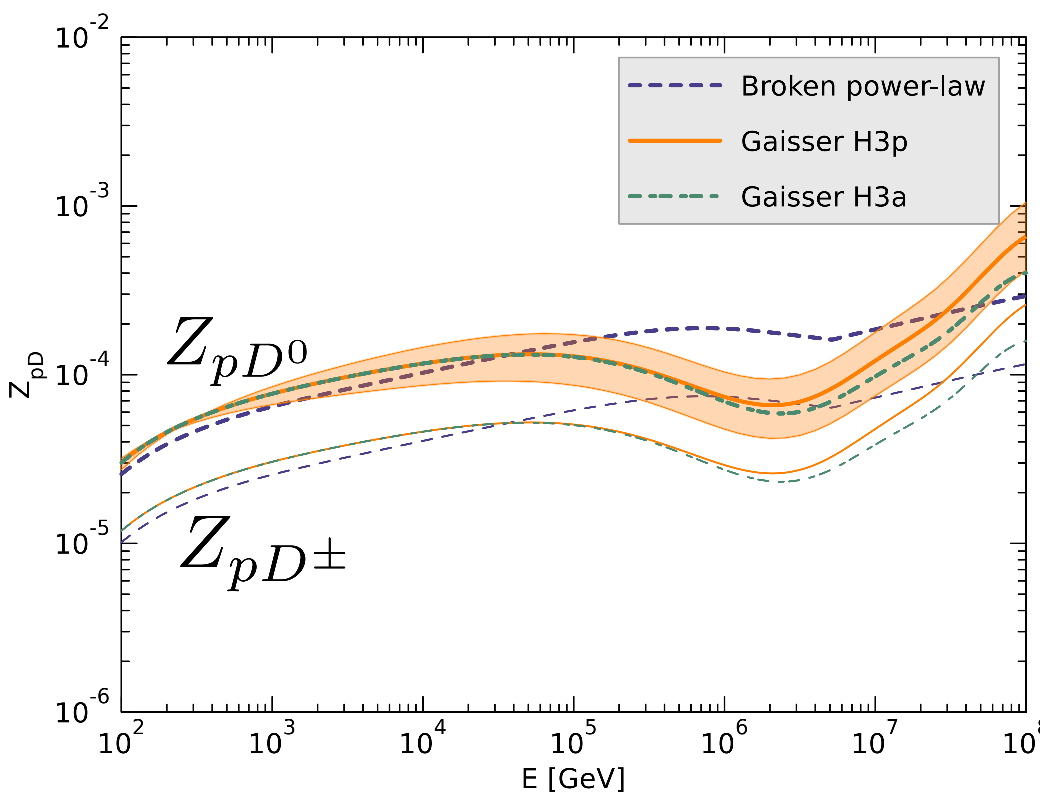
Impact of CR flux on Z moments

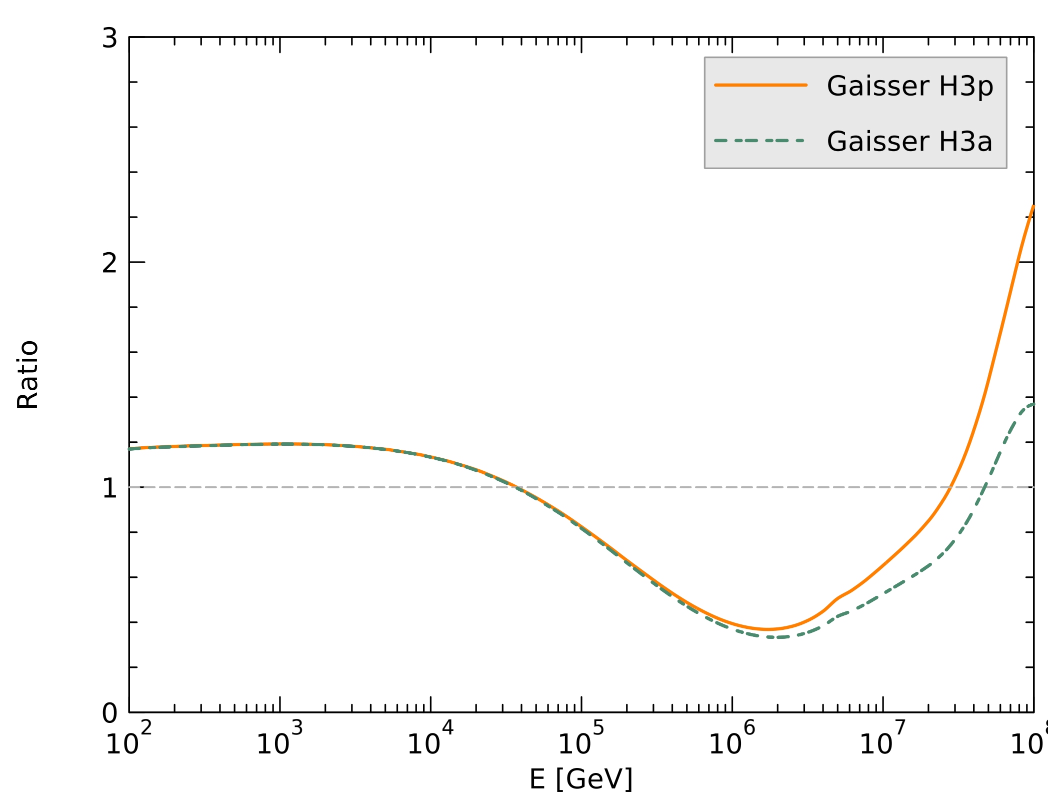
Z moments: $$Z_{ph}(E_h) = \int_{x_{E_{\min}}}^{1} \frac{dx_E}{x_E} \frac{\phi_p^0(E_h/x_E)}{\phi_p^0(E_h)} \frac{1}{\sigma_{pA}(E_h)} \times A \frac{d\sigma}{dx_E}(pN \to hX)$$

Noticeable dip of Z moments as a function of energy. The dip corresponds to the softening of cosmic ray flux due to the change of the population. The energy is reduced because of the inelasticity of the collisions.

$$x_E = \frac{E_{\text{hadron}}}{E_{\text{beam}}}, \quad \langle x_E \rangle \sim 0.1$$

Ratio to the calculation with power law

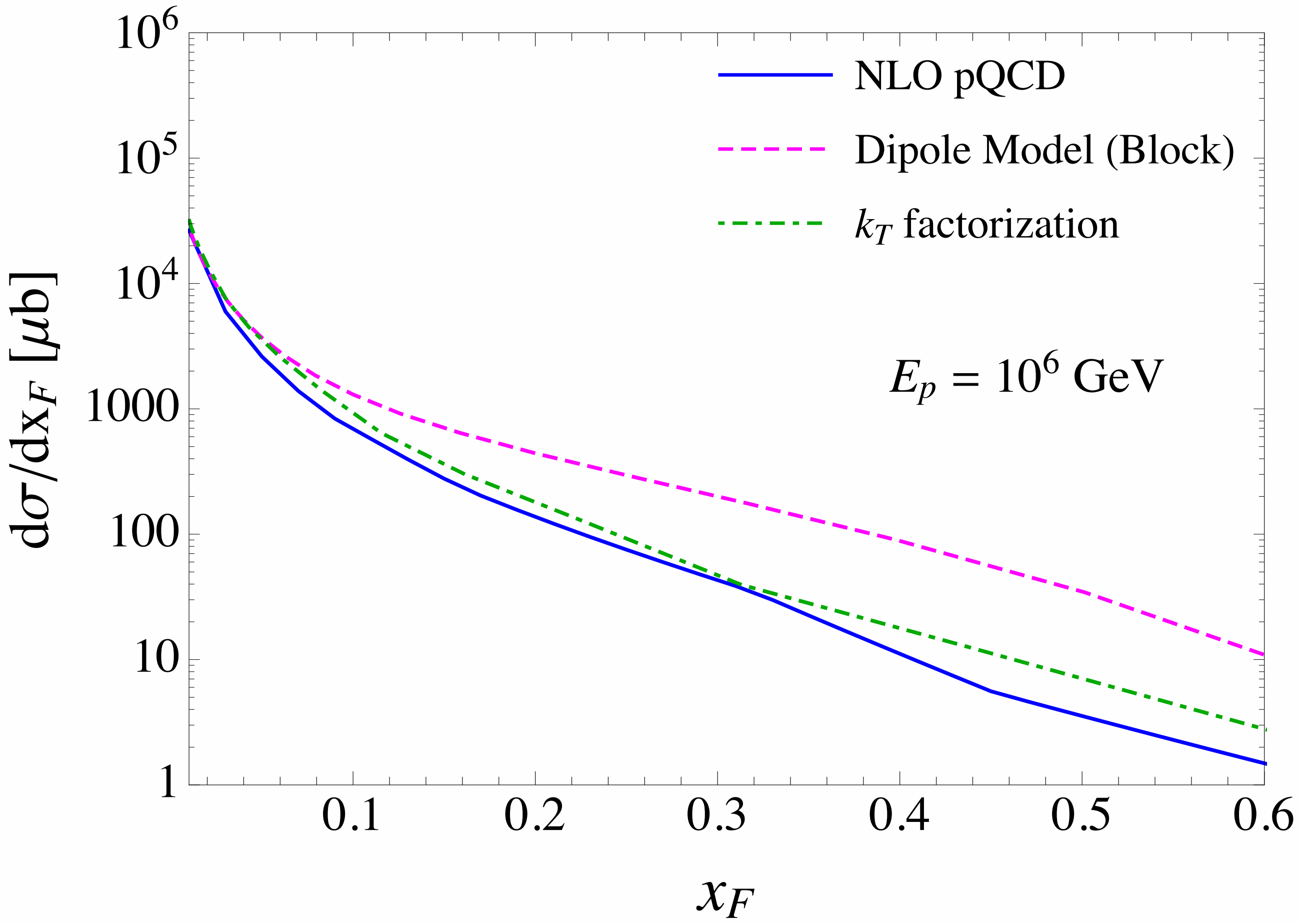


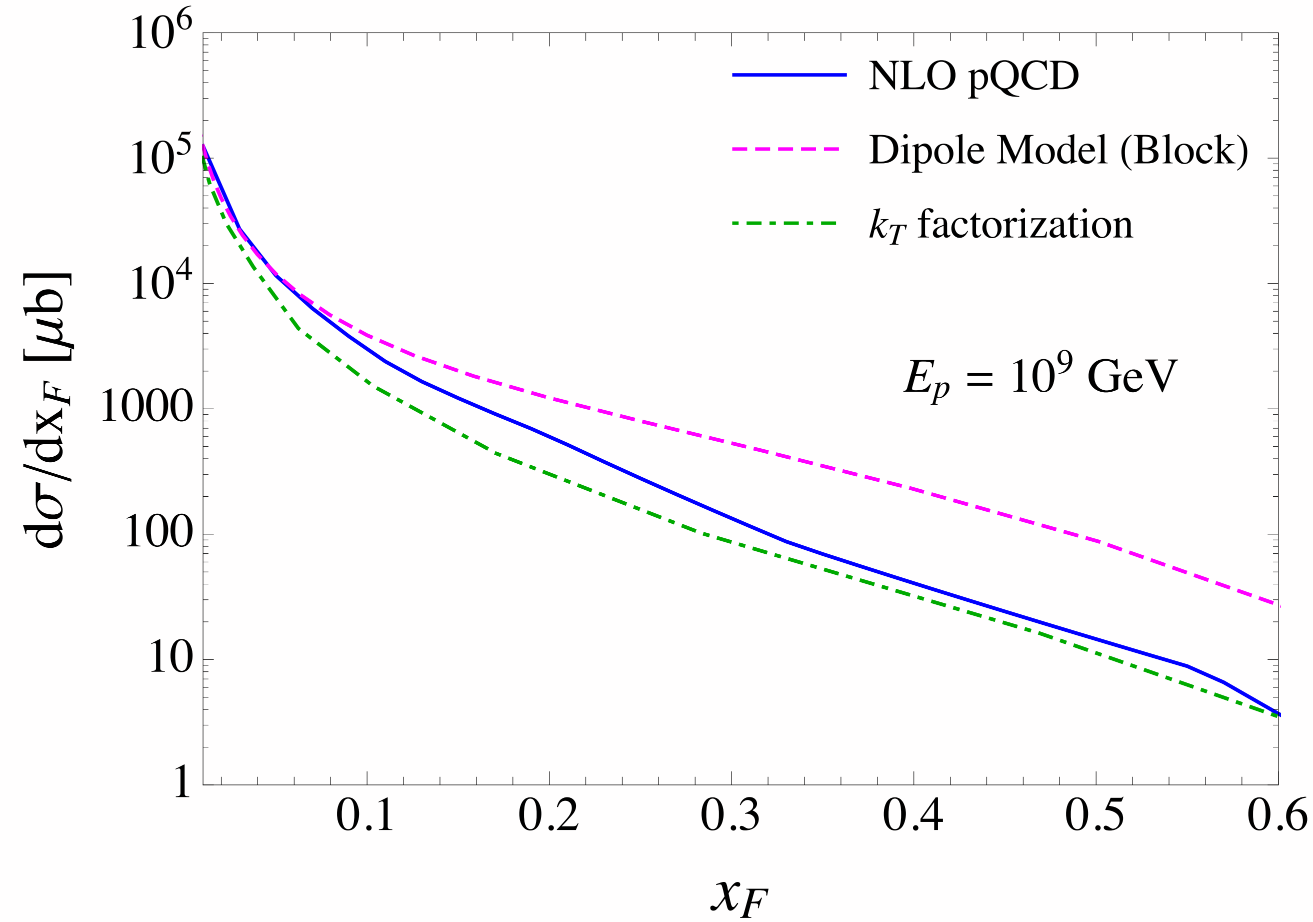


BERSS

Differential charm cross section

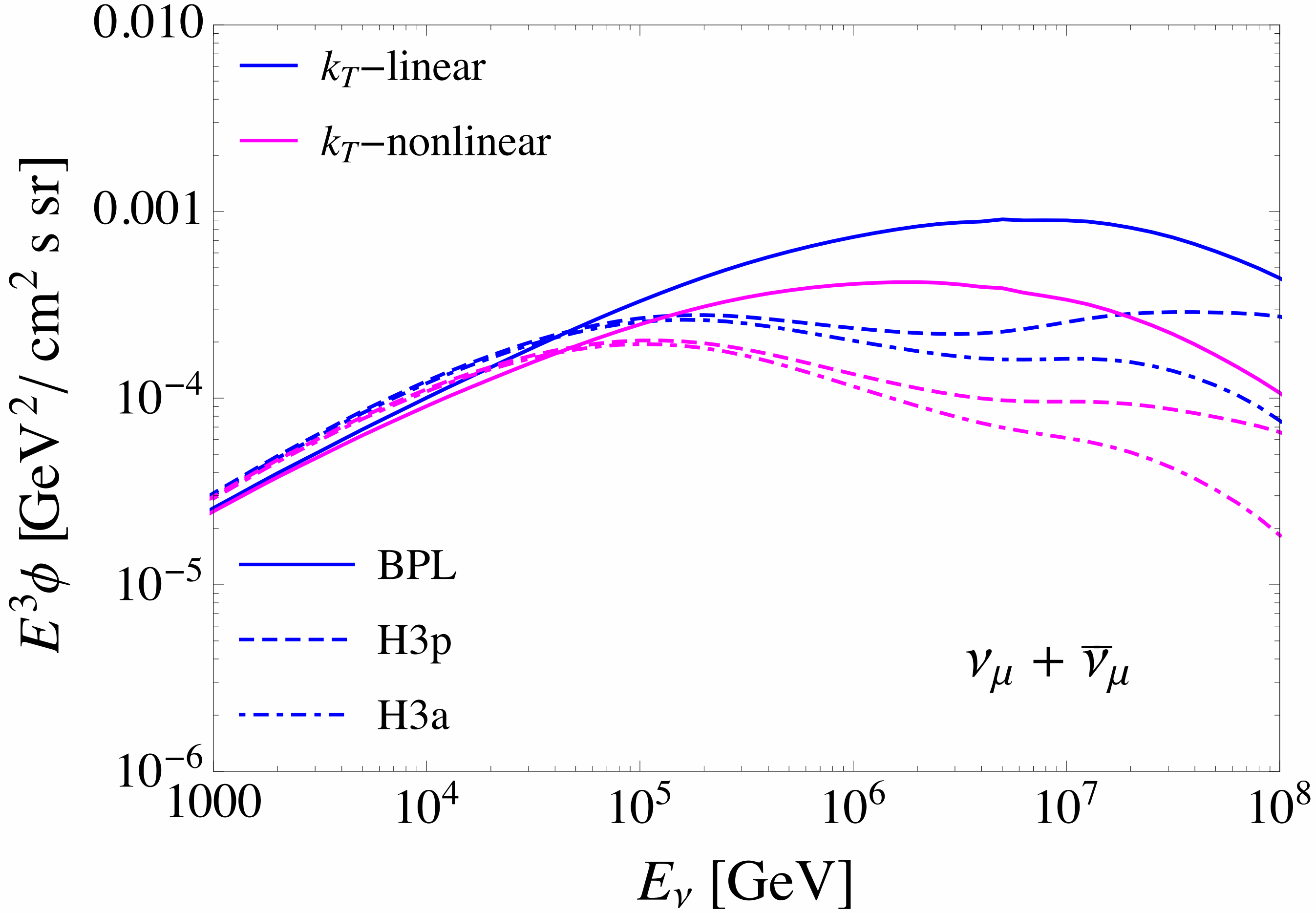
Comparison of NLO pQCD, dipole model, and kT factorization

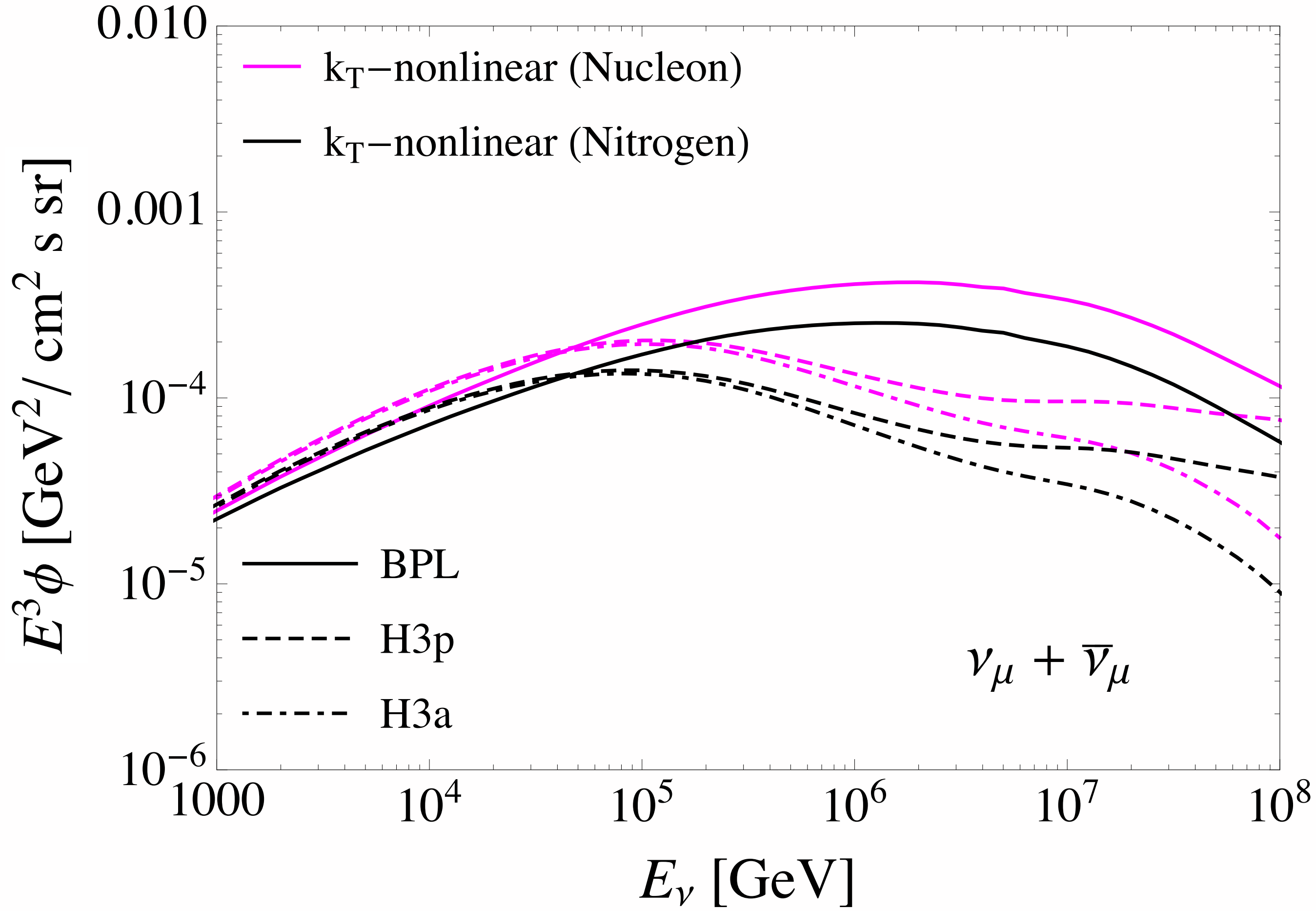




- NLO calculation and kT factorization calculation consistent with each other.
- Dipole calculation systematically above the other two : need for improvements in this model.

Neutrino fluxes



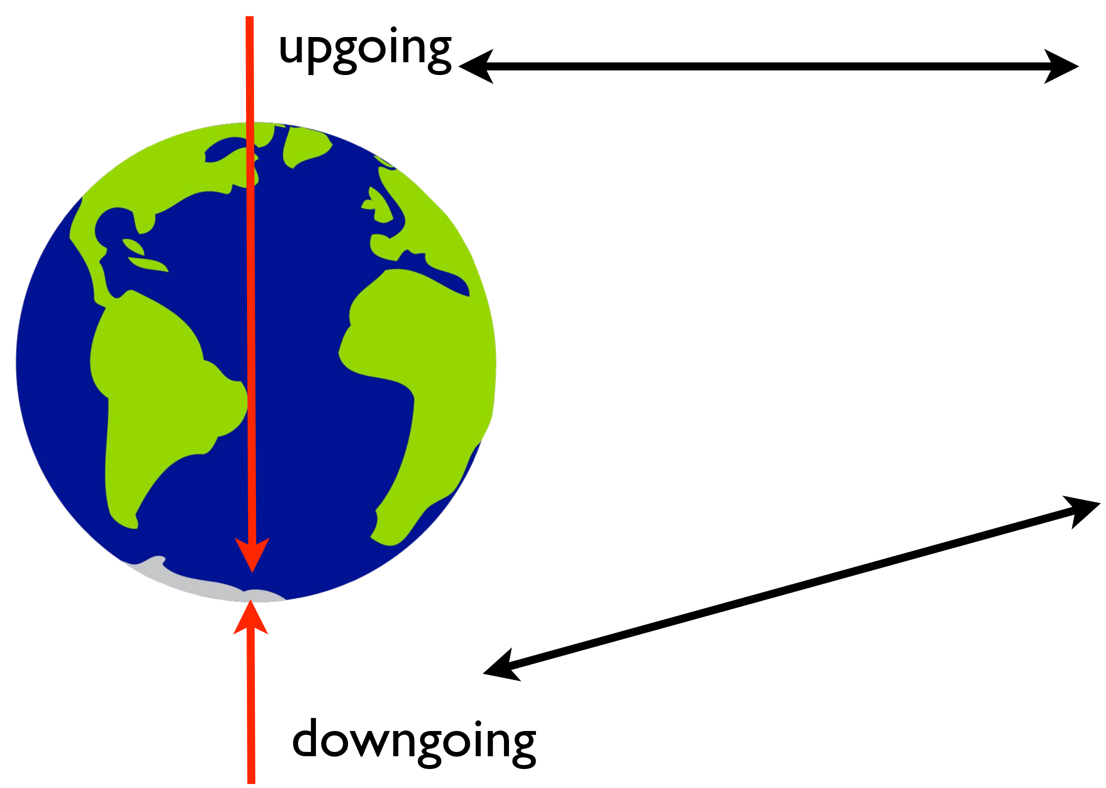


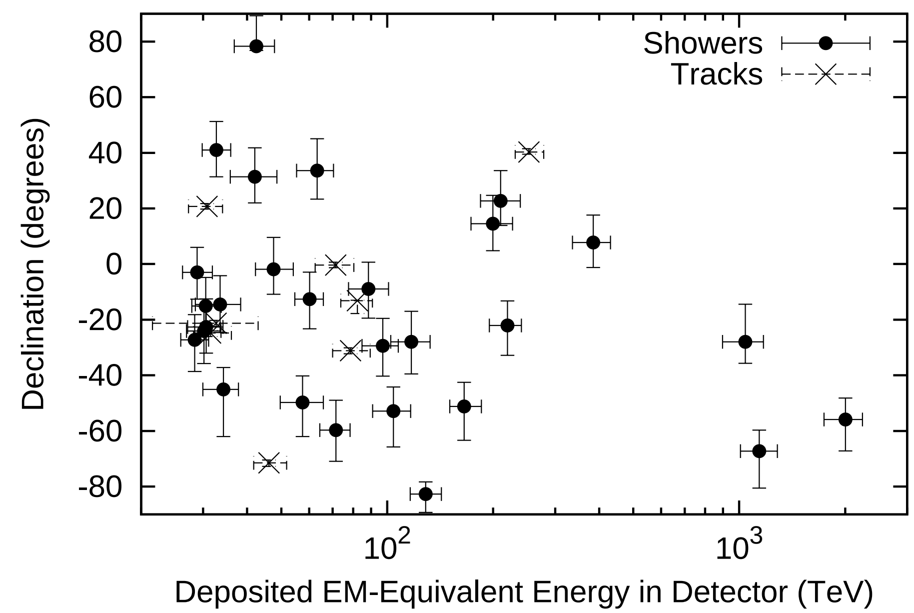
- Sizeable reduction of the flux due to the changes from linear to nonlinear evolution in kT factorization.
- Further reduction of the flux when nuclear effects in nitrogen are included.

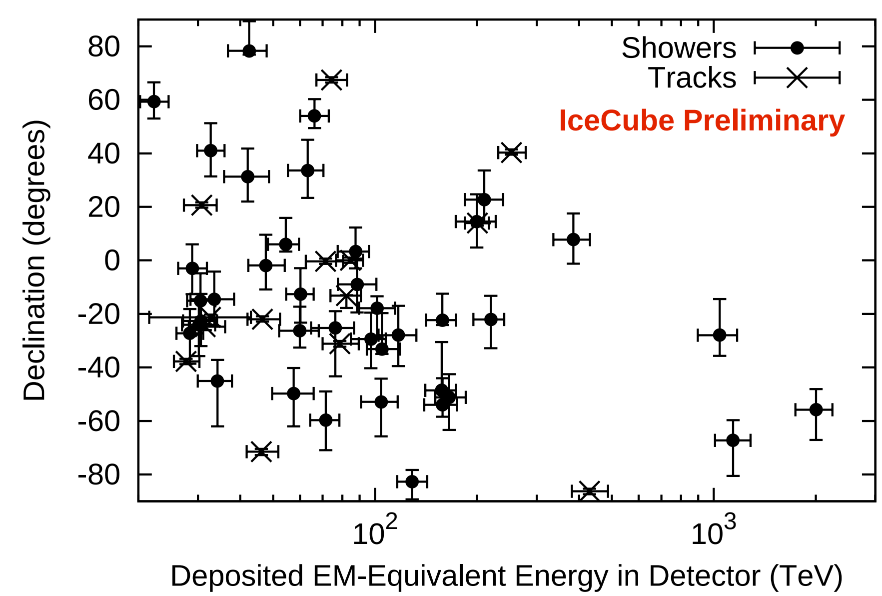
IceCube results

IceCube Coll. Phys.Rev.Lett. 113 (2014) 101101; Observation of High-Energy Astrophysical Neutrinos in Three Years of IceCube Data

988 day sample, 37 events observed (after selection with entering muon veto) with energies between 30-2000 TeV







4-year data, ICRC2015, arxiv:1510.05223.

1347 day sample, 54 events observed.