Atmospheric neutrinos from charm decays

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QCD at Cosmic Energies, May 16, 2016

Outline

- Motivation: ultrahigh energy neutrino astronomy
- Atmospheric neutrinos: conventional and prompt
- Calculation of prompt neutrino fluxes: uncertainties
- Comparison with IceCube observations

Work in collaboration with

Atri Bhattacharya, Rikard Enberg, Yu Seon Jeong, Mary Hall Reno, Ina Sarcevic
arXiv:1502:01076, also work in progress

Note: I will also show comparisons with calculation by Garzelli, Moch and Sigl: arXiv:1507:01570

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):

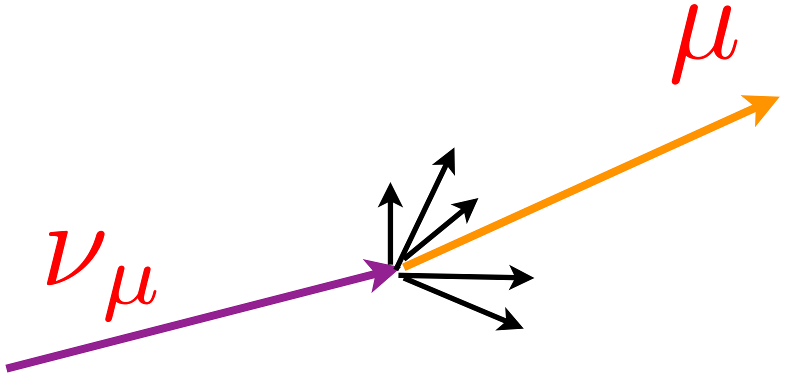
$$\mathcal{L}_{\rm int}^{\gamma} \sim 100\,{\rm g/cm^2}$$

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

- Protons and nuclei get bent by the magnetic fields
- Neutrinos can point back to their sources

Angular distortion

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



Sources of high energy neutrinos

- Atmospheric: interactions of cosmic rays with nuclei in the atmosphere. This talk.

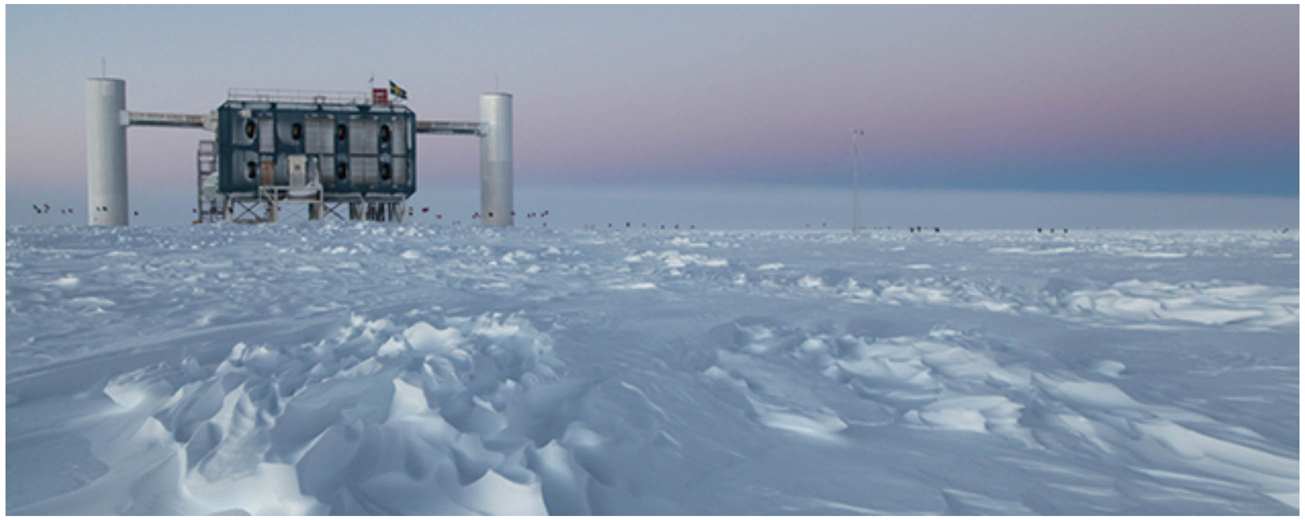
- Interactions of cosmic rays with gas, for example around supernova remnants. Interaction with microwave background (GZK neutrinos).

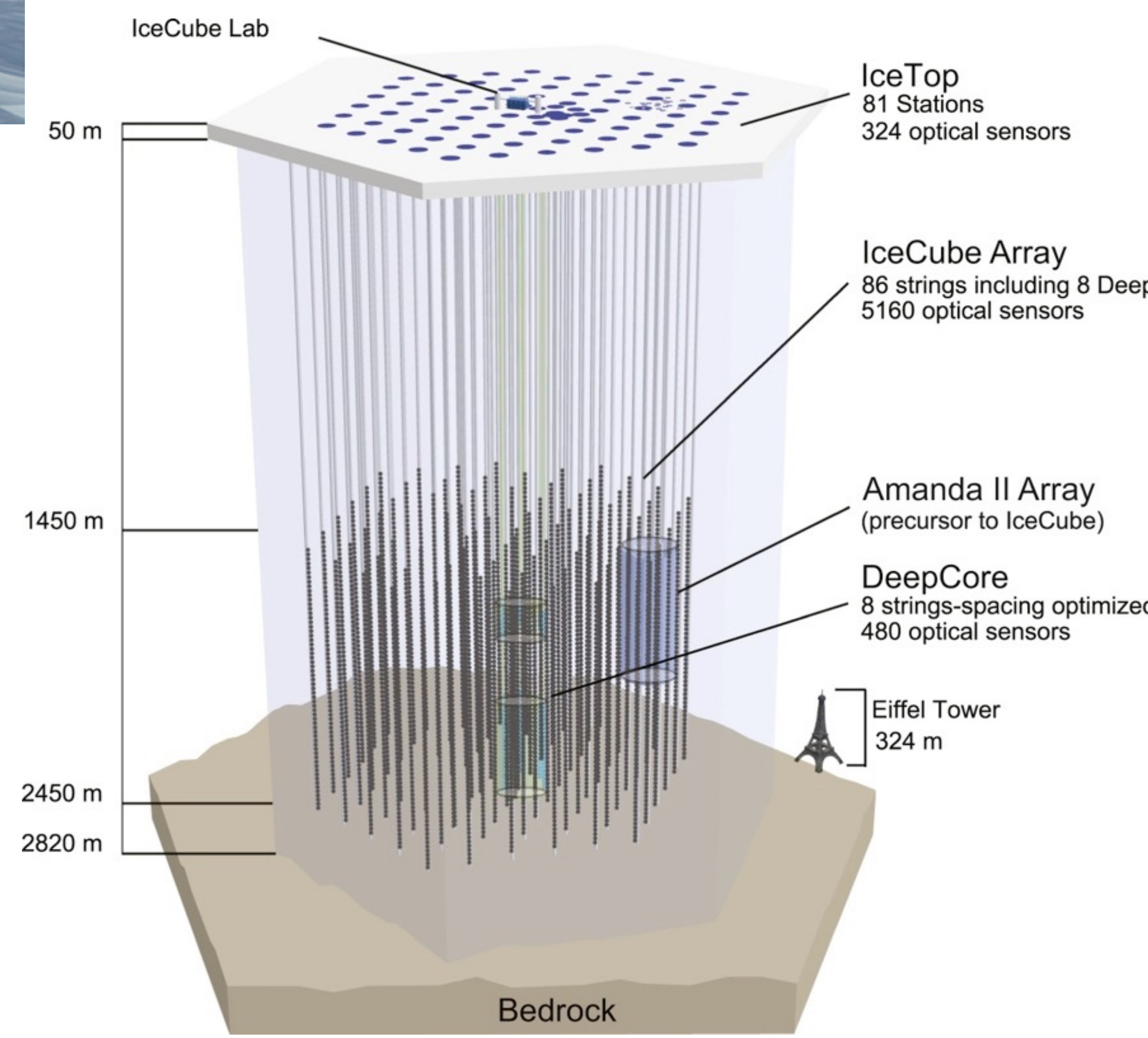
- Production at some source: Active Galactic Nuclei, Gamma Ray bursts.

- More exotic scenarios: WIMP annihilation (in the center of Sun or Earth), decays of metastable relic particles,...

See talk by Kohta Murase on Thursday

IceCube





- UHE neutrinos measured in IceCube Antarctic detector
- Neutrinos detected using Cherenkov light produced by charged particles after neutrinos interact
- Sensitivity to high energy >100 GeV neutrinos (>10 GeV with Deep Core)

IceCube results

Two classes of events:

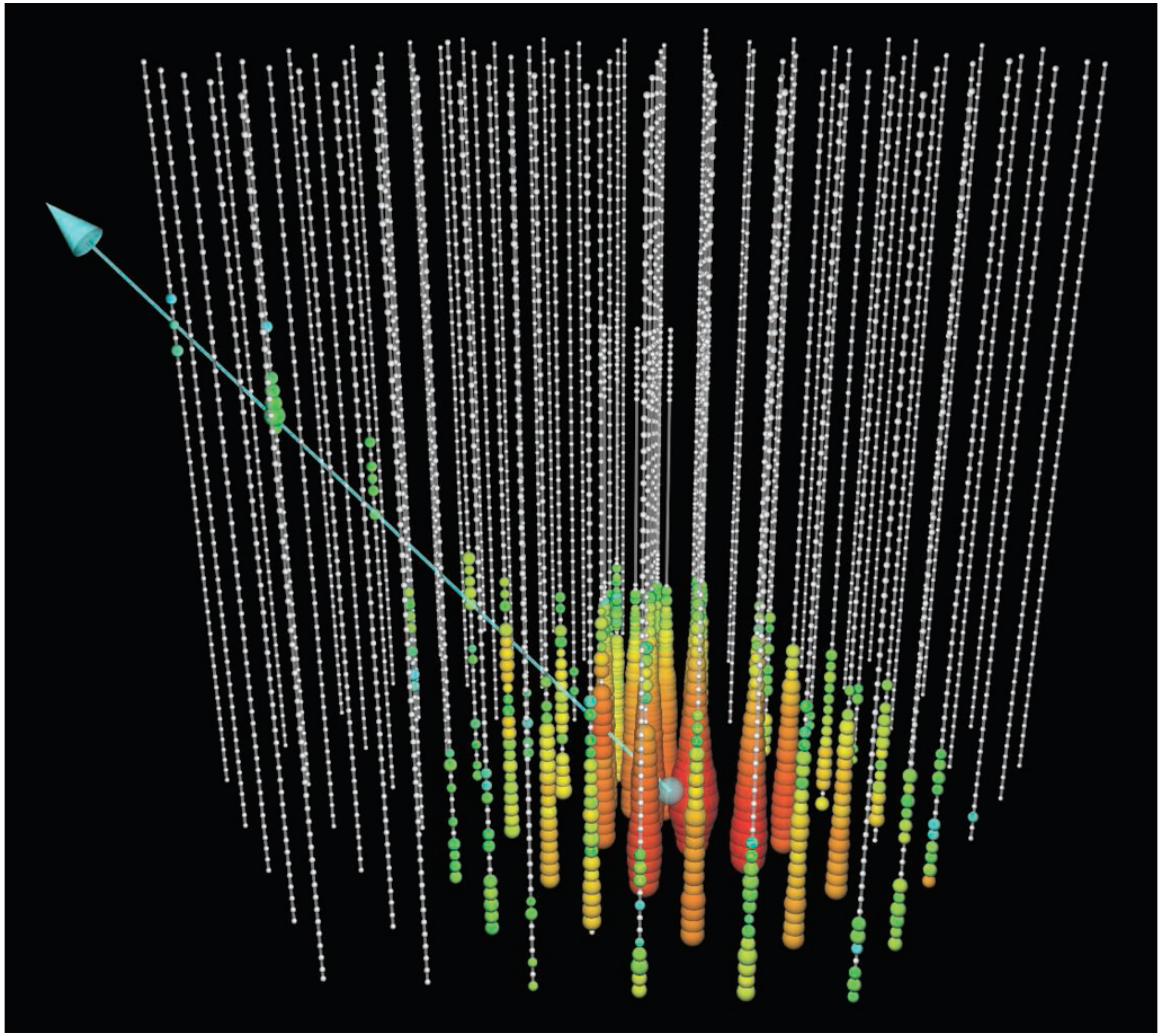
Showers: from secondary charged leptons and hadron dissociation

Tracks: events accompanied by an energetic muon (CC events with incoming ν_μ)

Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector

IceCube Collaboration*

SCIENCE VOL 342 22 NOVEMBER 2013

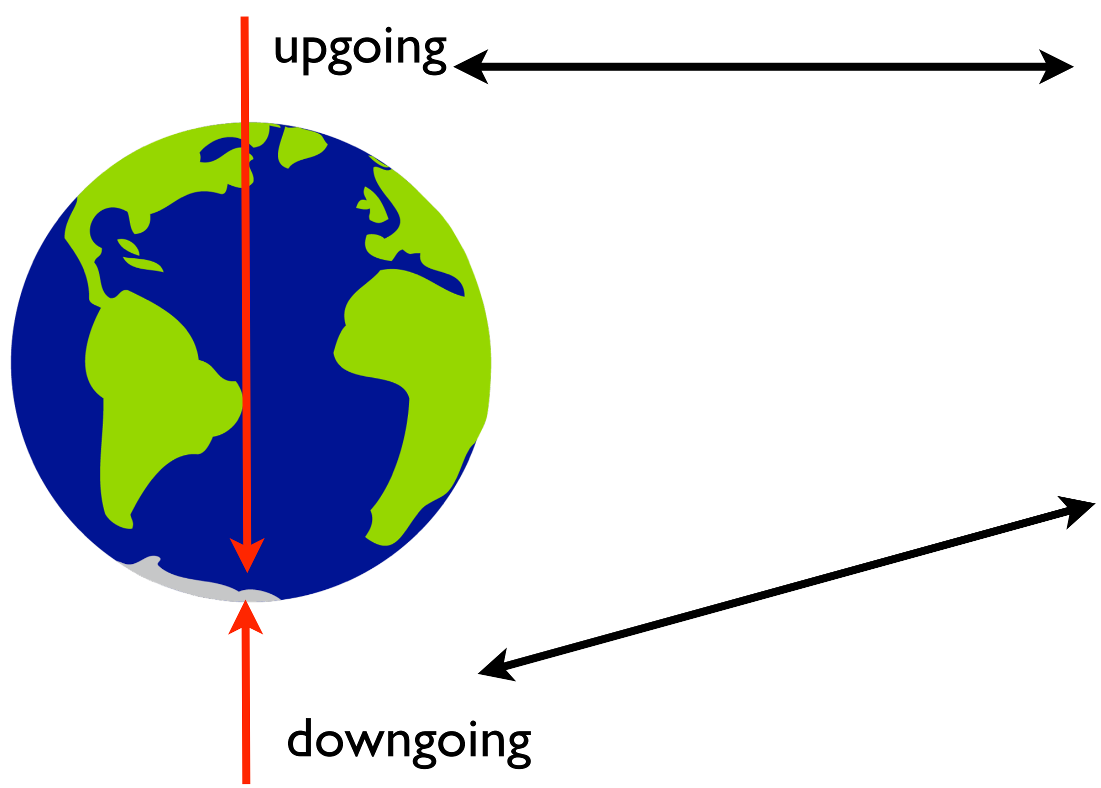


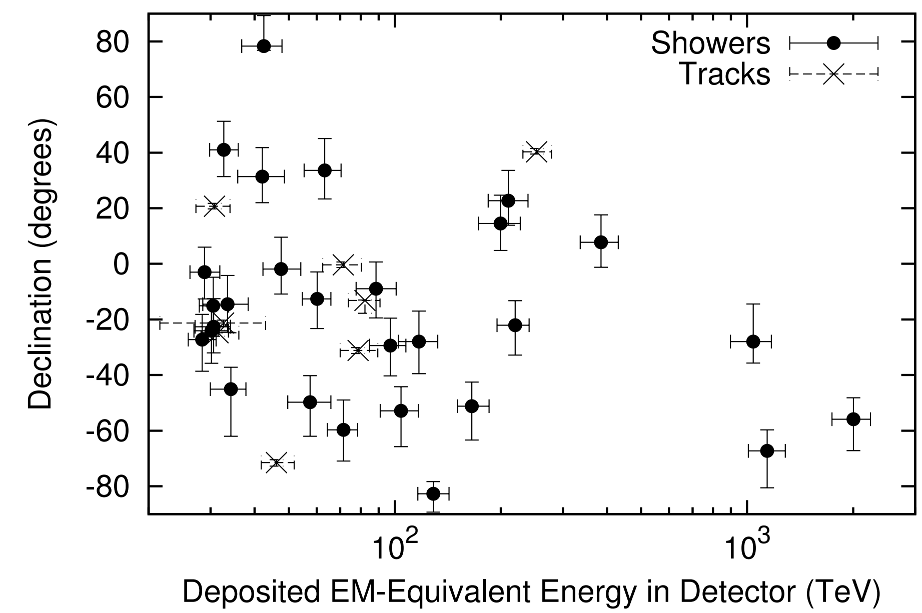
A 250 TeV neutrino interaction in IceCube. At the neutrino interaction point (bottom), a large particle shower is visible, with a muon produced in the interaction leaving up and to the left. The direction of the muon indicates the direction of the original neutrino.

IceCube results

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

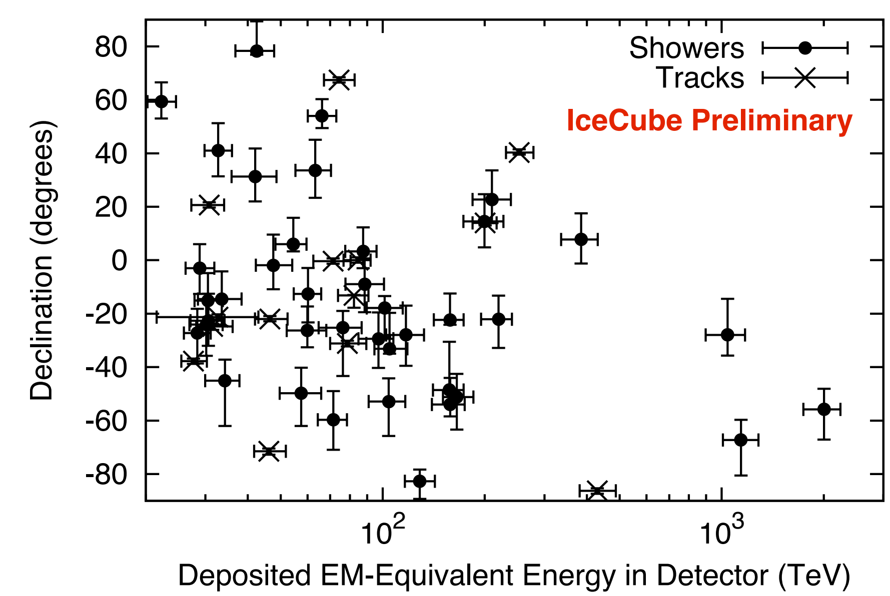
988 day sample, 37 events observed (after selection with entering muon veto) with energies between 30-2000 TeV



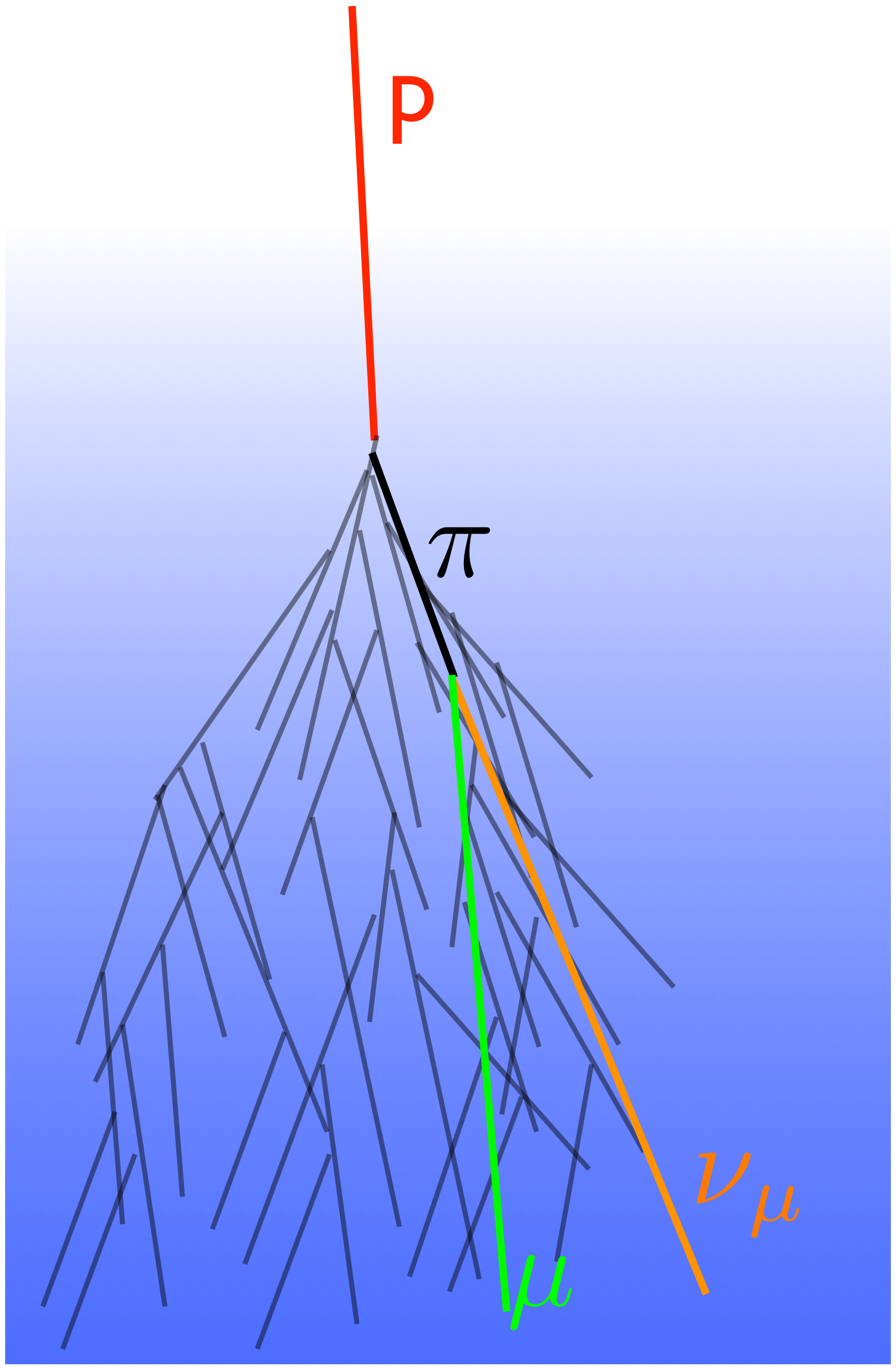


New 4-year data, ICRC2015, arxiv:1510.05223.

1347 day sample, 54 events observed.



Atmospheric neutrinos



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

$$p + \text{Air}$$

interaction

$$\pi, K$$

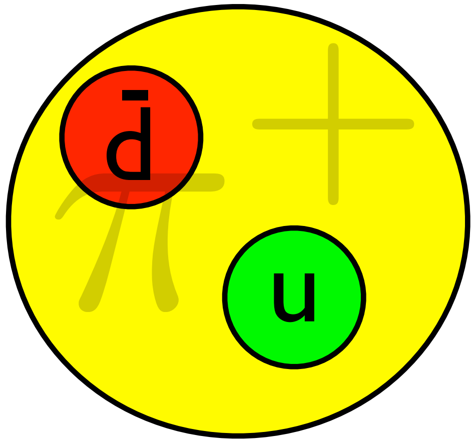
decay

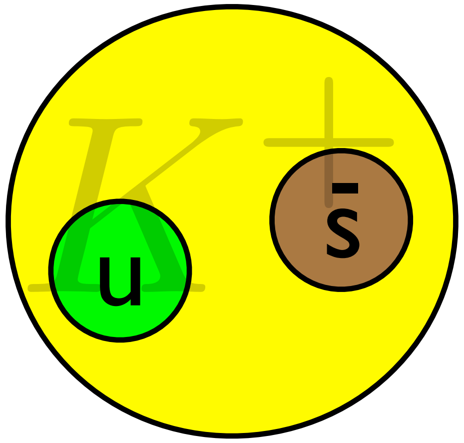
$$\mu, \nu_\mu$$

Atmospheric neutrinos

- *Conventional*: decays of lighter mesons

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





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

Long lifetime: interaction occurs before decay

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

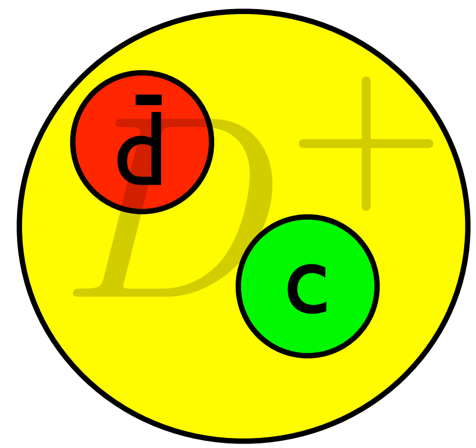
Long-lived mesons loose energy → Steeply falling flux of neutrinos $\Phi_\nu \sim E_\nu^{-3.7}$

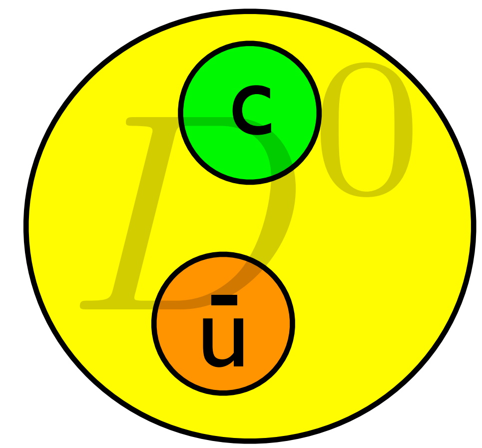
Prompt neutrinos

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

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

baryon Λ_c





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

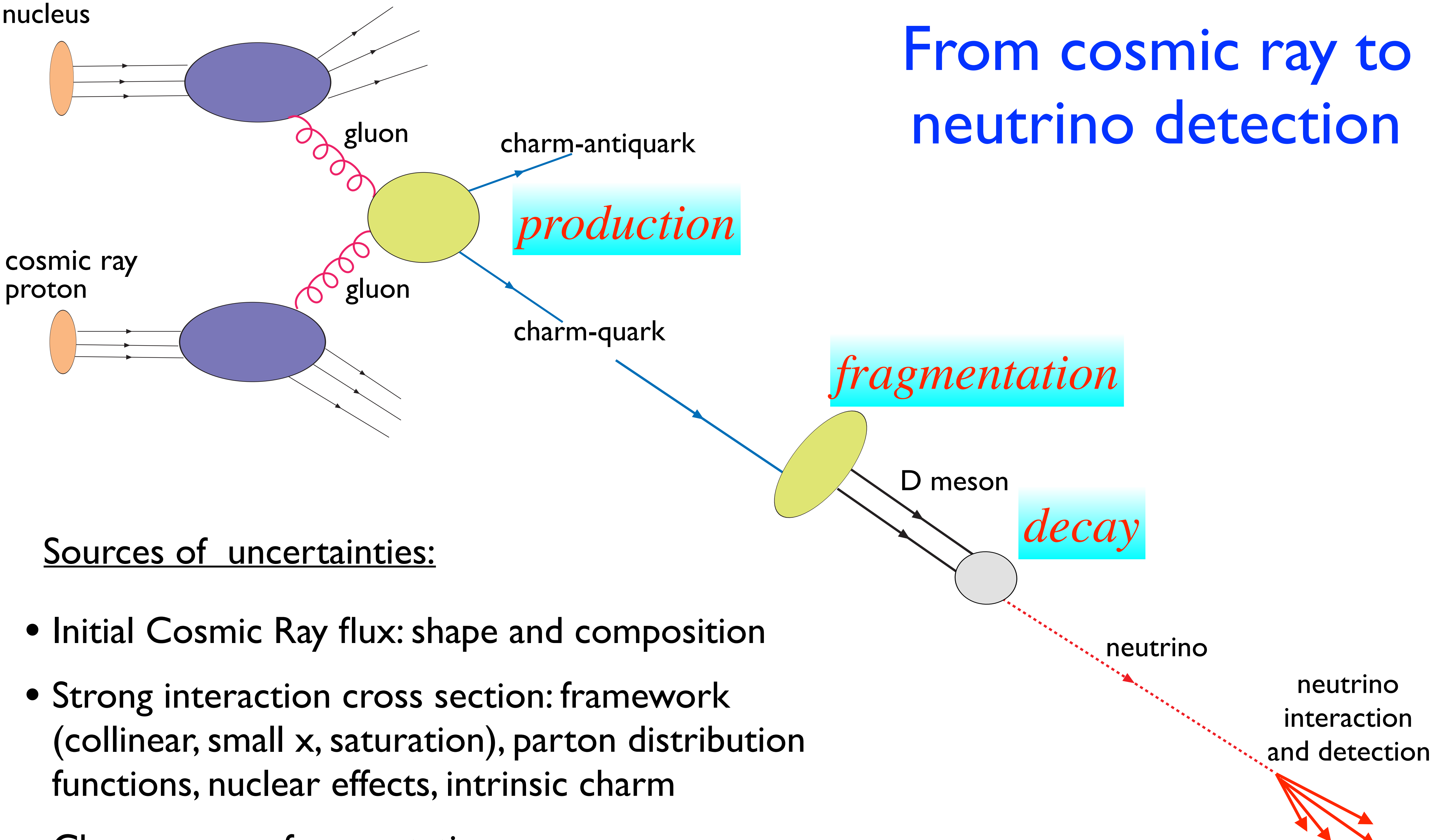
Short lifetime: decay, no interaction

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

Flat flux, more energy transferred to neutrino

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

From cosmic ray to neutrino detection

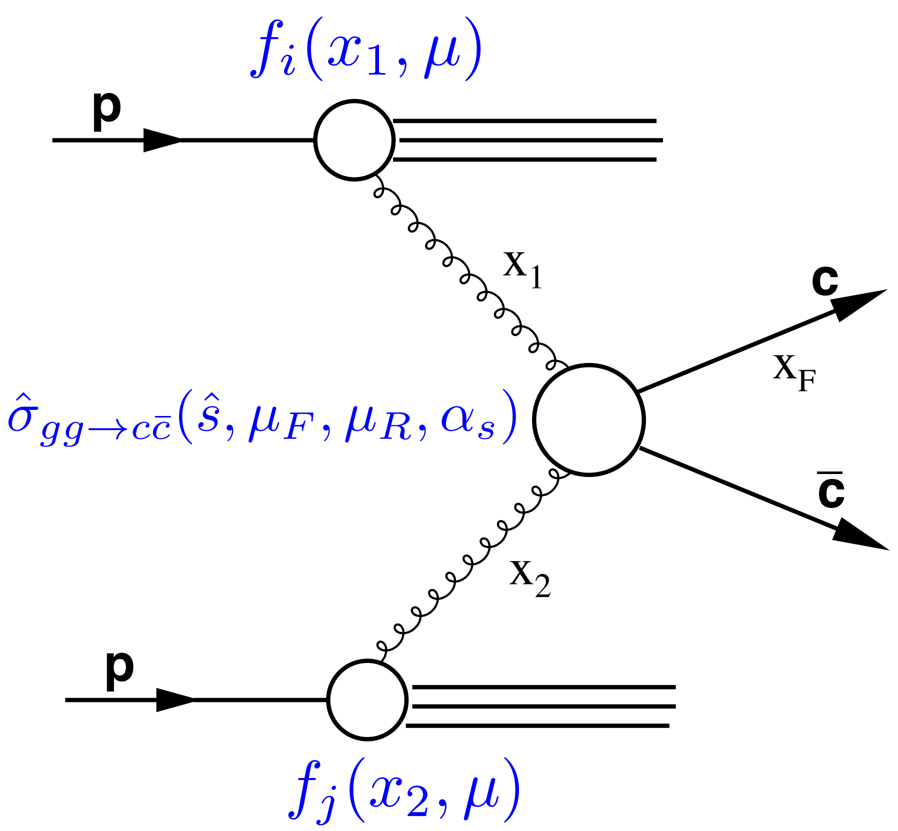


Sources of uncertainties:

- 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

Charm 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:

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

Charm production in hadron collisions

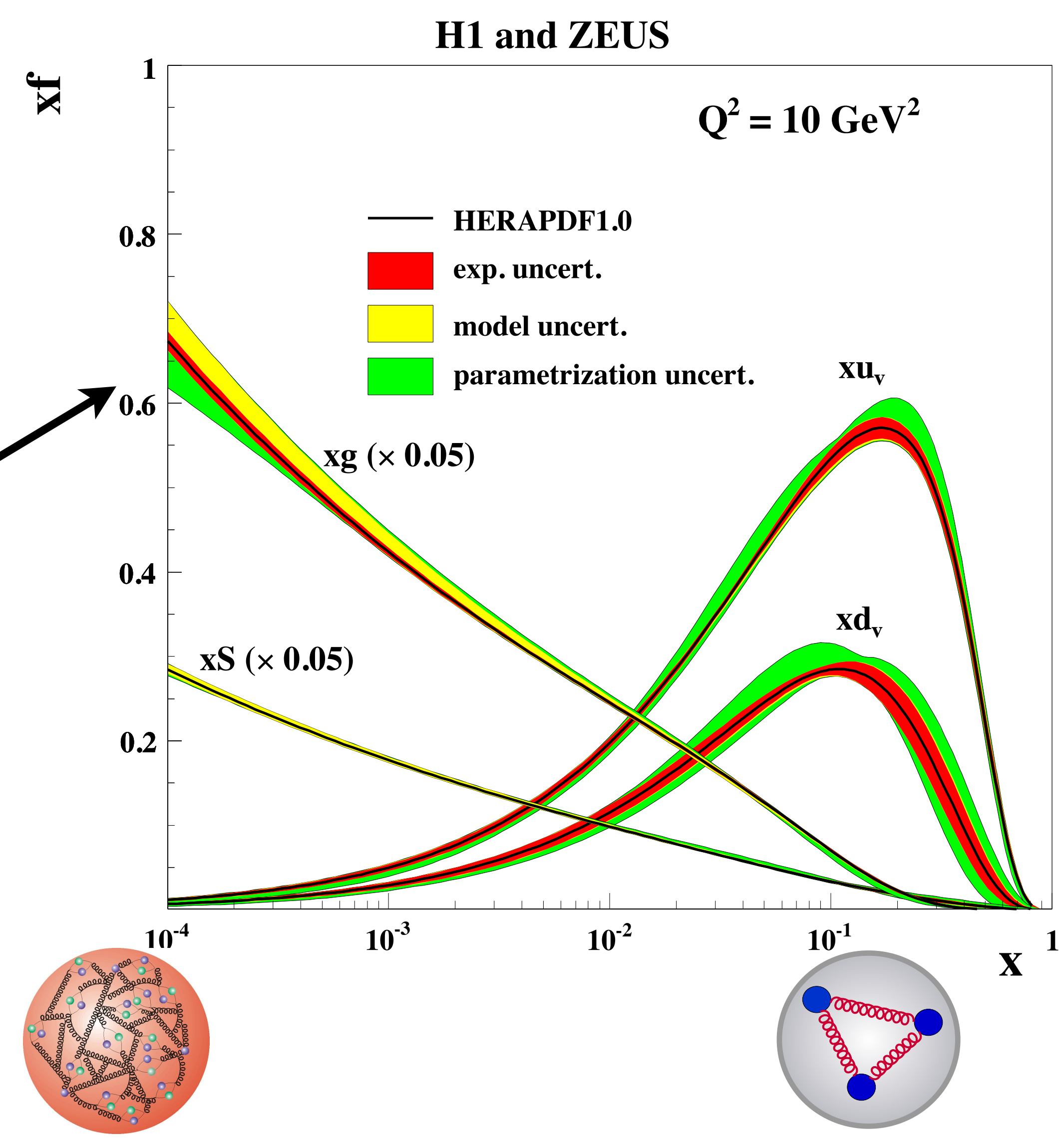
$$\frac{d\sigma^{pp\to c+X}}{dx_F} = \sum_{i,j} f_i(x_1,\mu_F) \otimes \hat{\sigma}_{gg\to c\bar{c}}(\hat{s}, m_c, \mu_F, \mu_R) \otimes f_j(x_2,\mu_F)$$

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.



Frameworks for calculation of charm production

Standard LO/NLO collinear calculation: *Thunman, Ingelman, Gondolo; Gelmini, Gondolo, Varieschi; Pasquali, Reno, Sarcevic; Bhattacharya, Enberg, Reno, Sarcevic, Stasto; Garzelli, Moch, Siegl; Gauld, Rojo, Rottoli, Sarkar, Talbert;*

High-energy factorization with small x BFKL/DGLAP resummed evolution and saturation model: *Martin, Ryskin, AS*.

Small x dipole model with saturation: *Enberg, Reno, Sarcevic*

This talk:

BERSS (1502.01076): NLO calculation with latest parton densities distributions including constraints from charm measurements at RHIC and LHC.

Also:

Preliminary calculations from updated calculation (BEJRSS): dipole model with nonlinear QCD evolution evolution, high energy factorization with unintegrated parton densities, nuclear effects.

Total charm production cross section

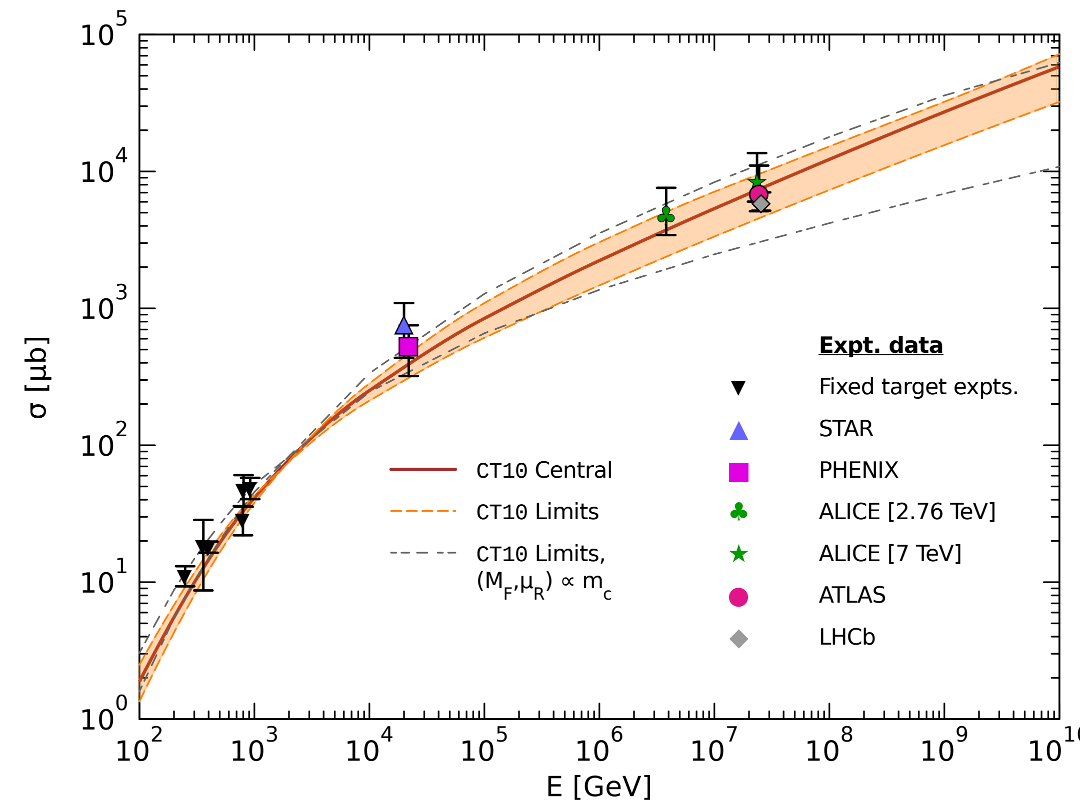
- Using NLO code by Cacciari,Frixione,Greco,Nason.
- Default parton distribution set is CT10 Central.
- Charm quark mass $m_c = 1.27 \ \ \mathrm{GeV}$
- Variation of factorization and renormalization scales with respect to transverse mass $m_T^2 = m_c^2 + p_T^2$
- Comparison with RHIC and LHC data. Data are extrapolated with NLO QCD from measurements in the limited phase space region.

Range of scale variation:

$(M_F, \mu_R) = (1.25, 1.48) m_T$

$(M_F, \mu_R) = (4.65, 1.71) m_T$

BERSS



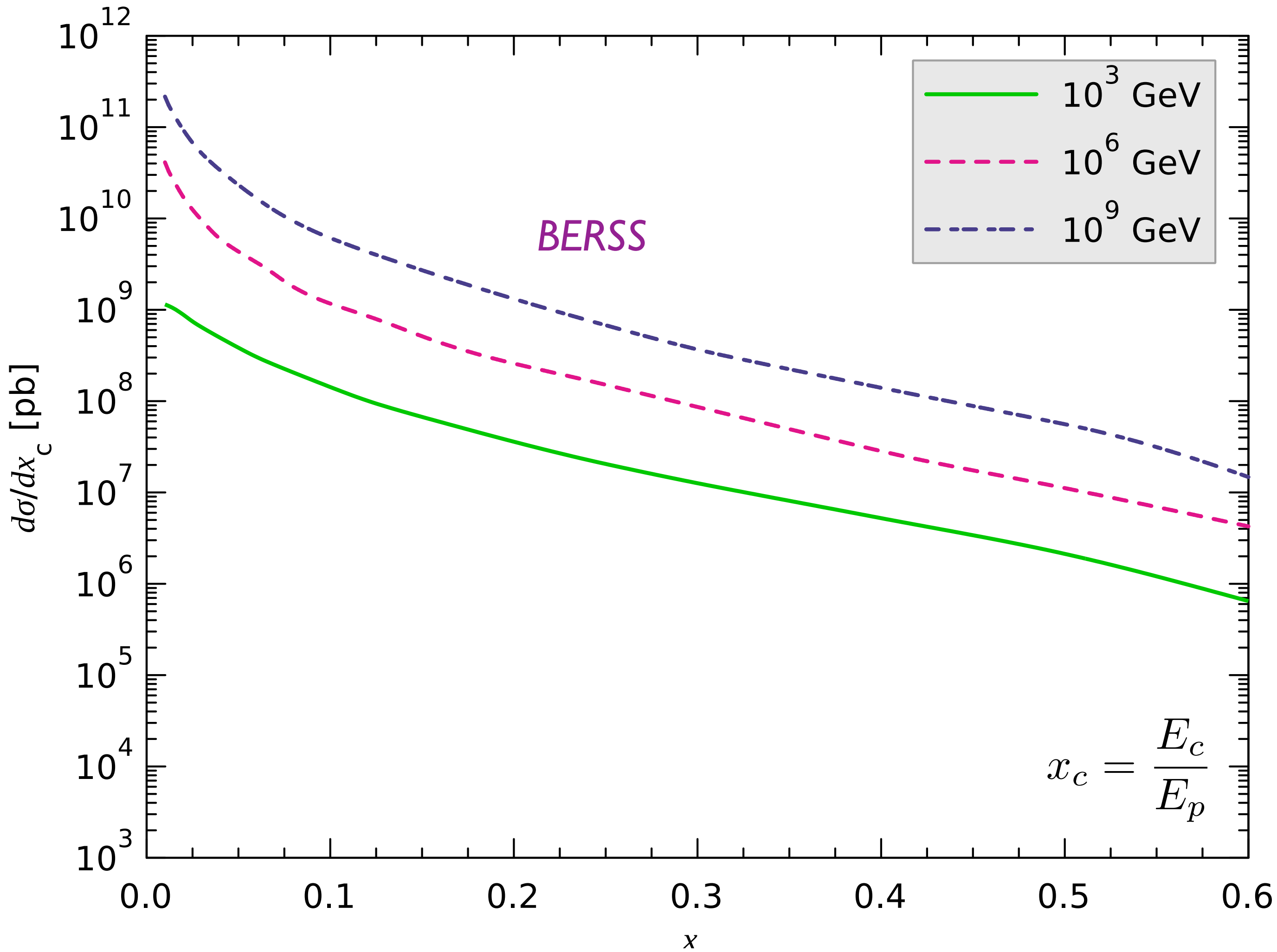
Expt.	$\sqrt{s}$ [TeV]	σ [mb]
PHENIX [31]	0.20	$\mathbf{0.551}^{+0.203}_{-0.231}$ (sys)
STAR [32]	0.20	$\mathbf{0.797} \pm 0.210$ (stat)$^{+0.208}_{-0.295}$ (sys)
ALICE [27]	2.76	$\mathbf{4.8} \pm 0.8$ (stat)$^{+1.0}_{-1.3}$ (sys) ± 0.06 (BR) ± 0.1(frag) ± 0.1 (lum)$^{+2.6}_{-0.4}$ (extrap)
ALICE [27]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

Need to extrapolate CT10 parton distribution functions down to very low x.
PDF uncertainties not included in this plot.

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

$$\frac{d\sigma}{dE_h} = \sum_k \int \frac{d\sigma}{dE_k}(AB \to kX) D_k^h\left(\frac{E_h}{E_k}\right)\frac{dE_k}{E_k} \qquad h = D^\pm, D^0(\bar{D}^0), D_s^\pm, \Lambda_c^\pm$$

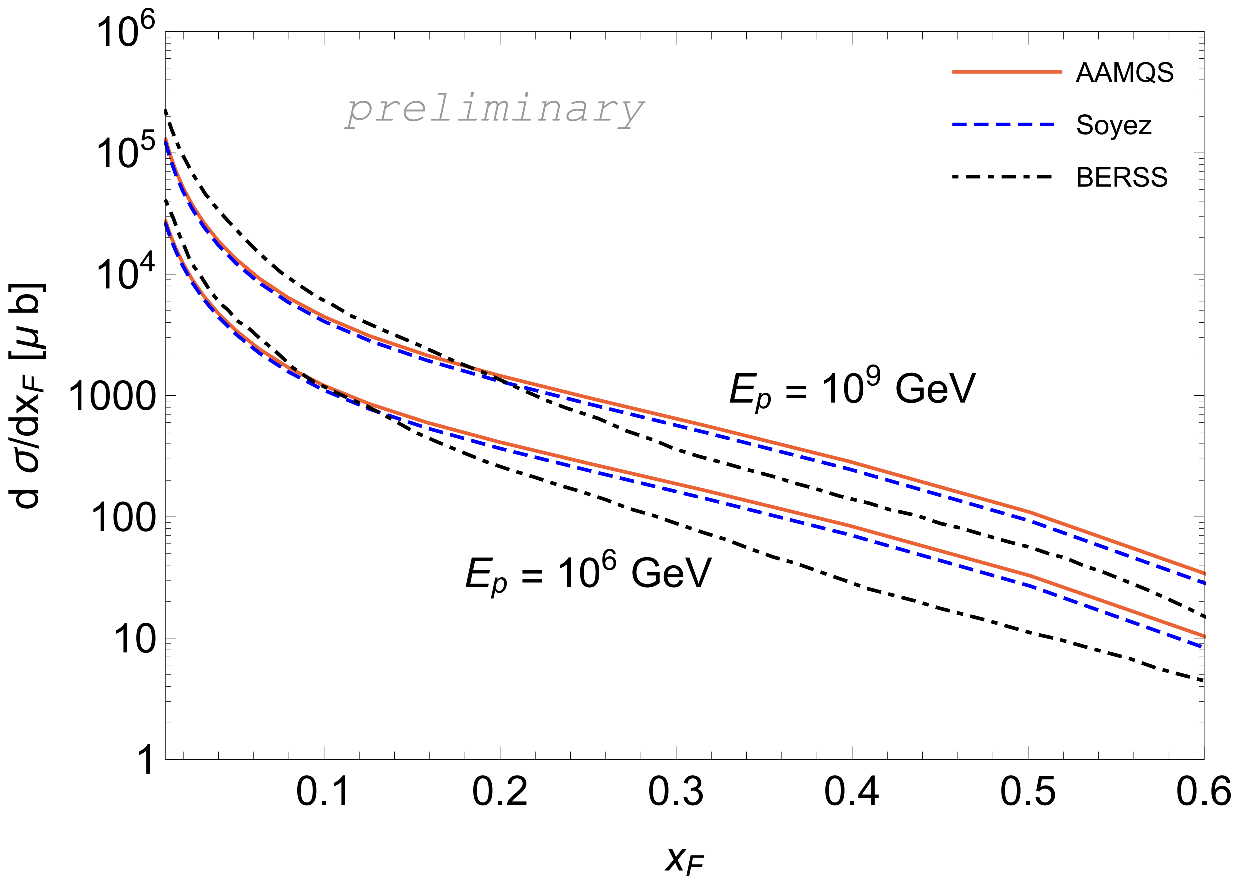
Using Kniehl, Kramer fragmentation functions.

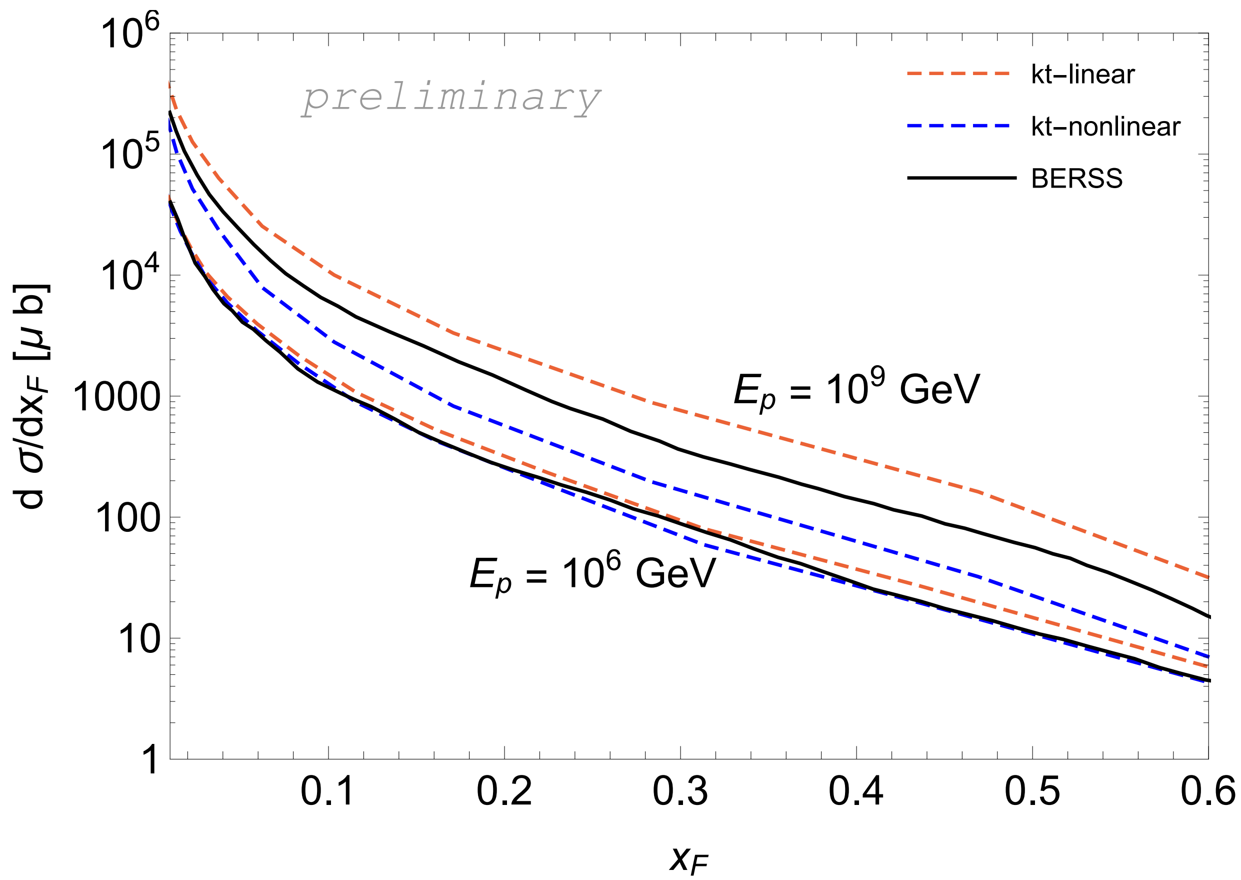
Differential charm cross section

Alternative calculations with low x resummation: kT factorization and dipole model, compared with NLO calculation

<u>kT factorization</u>: two versions of unintegrated gluons used, with and without saturation (Kutak-Sapeta model)

<u>dipole</u>: two versions of dipole cross sections used (AAMQS and Soyez)





Modifications at large xF as expected. NLO calculation in between the kT linear and nonlinear calculation.

Nuclear corrections

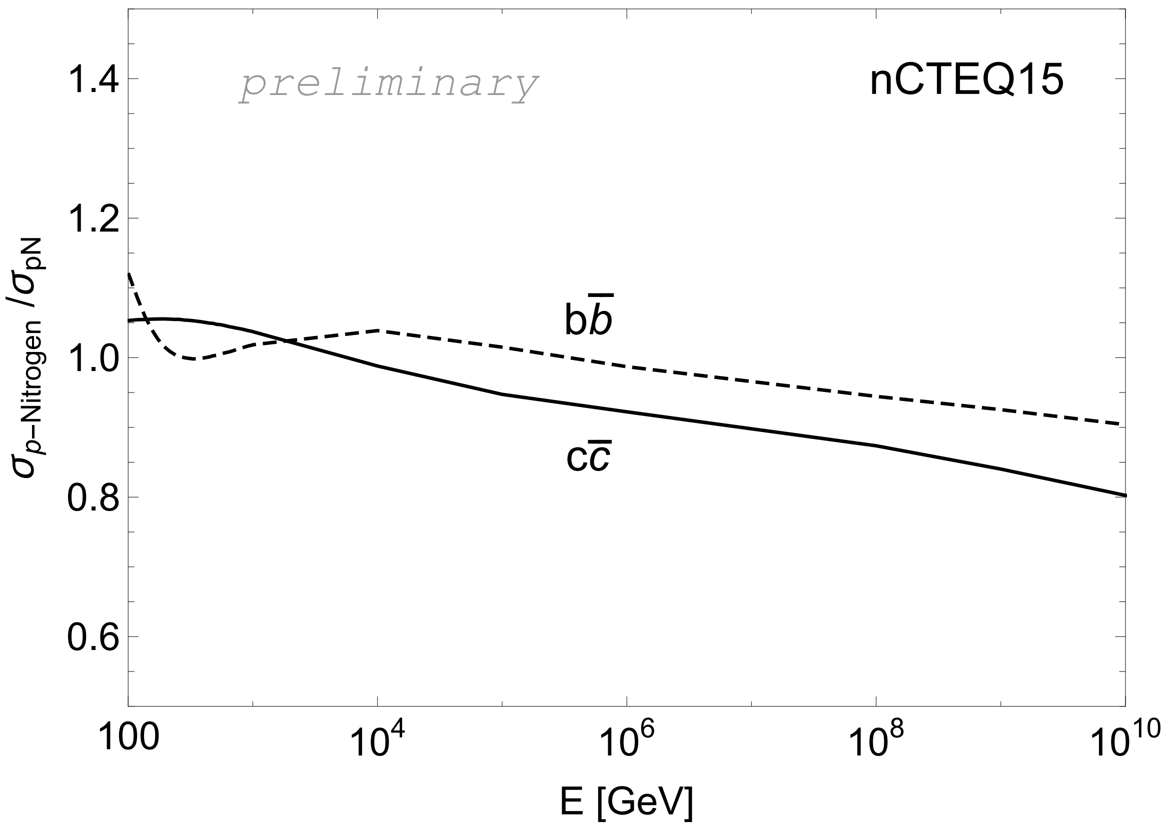
In most calculations simple superposition was used, no nuclear effects: $\sigma(pA \to c\bar{c}X) \simeq A\sigma(pN \to c\bar{c}X)$

For air: $\langle A \rangle = 14.5$.
Used nuclear pdfs: EPS and nCTEQ15

preliminary

	$pp \to c\bar{c}X$		$[pA \to c\bar{c}X]/A$	
Energy	$\sigma_{c\bar{c}}(M_{F,R} \propto m_T)$	$\sigma_{c\bar{c}}(M_{F,R} \propto m_c)$	$\sigma_{c\bar{c}}(M_{F,R} \propto m_T)$	$\sigma_{c\bar{c}}(M_{F,R} \propto m_c)$
10^2	1.51	1.87	1.64	1.99
10^3	3.84×10^1	4.72×10^1	4.03×10^1	4.92×10^1
10^4	2.52×10^2	3.06×10^2	2.52×10^2	3.03×10^2
10^5	8.58×10^2	1.03×10^3	8.22×10^2	9.77×10^2
10^6	2.25×10^3	2.63×10^3	2.10×10^3	2.43×10^3
10^7	5.36×10^3	5.92×10^3	4.90×10^3	5.35×10^3
10^8	1.21×10^4	1.23×10^4	1.08×10^4	1.09×10^4
10^9	2.61×10^4	2.41×10^4	2.27×10^4	2.05×10^4
10^{10}	5.12×10^4	4.28×10^4	4.38×10^4	3.50×10^4

Table 1. The NLO cross section per nucleon [μb] for charm pair production as a function of incident energy [GeV] for scale factors $(N_F, N_R) = (2.1, 1.6)$ (the central values for charm production) for protons incident on isoscalar nucleons. The PDFs are for free nucleons (nCTEQ15-01) and the target nucleons bound in nitrogen (nCTEQ15-14). For these numbers, we use $\Lambda = 226$ MeV, $N_F = 3$ and $m_c = 1.27$ GeV.



20% reduction of integrated charm cross section for highest energies for nCTEQ15 and 30% reduction for EPS

10% reduction of integrated beauty cross section for highest energies for nCTEQ15

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.

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

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

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

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

$E < E_{\rm crit}$

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

$E > E_{\rm crit}$

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

Interpolation:

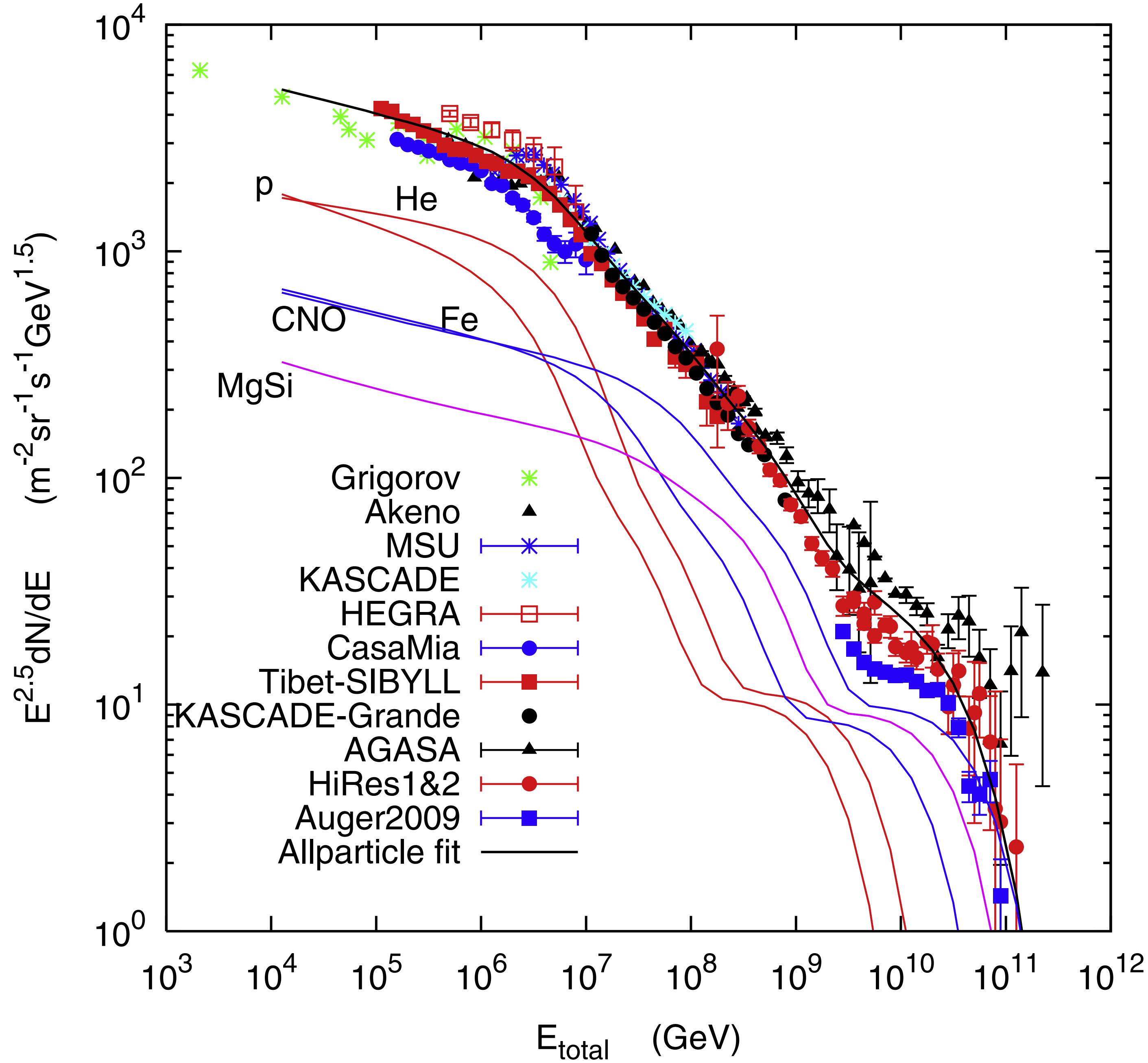
$$\phi_\ell = \sum_h \frac{\phi_\ell^{low}(h)\phi_\ell^{high}(h)}{\phi_\ell^{low}(h) + \phi_\ell^{high}(h)}$$

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

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

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

R_c	γ	p	He	CNO	Mg-Si	Fe
γ for Pop. 1	–	1.66	1.58	1.63	1.67	1.63
Population 1: 4 PV	See line 1	7860	3550	2200	1430	2120
Pop. 2: 30 PV	1.4	20	20	13.4	13.4	13.4
Pop. 3 (mixed): 2 EV	1.4	1.7	1.7	1.14	1.14	1.14
Pop. 3 (Proton only): 60 EV	1.6	200	0	0	0	0

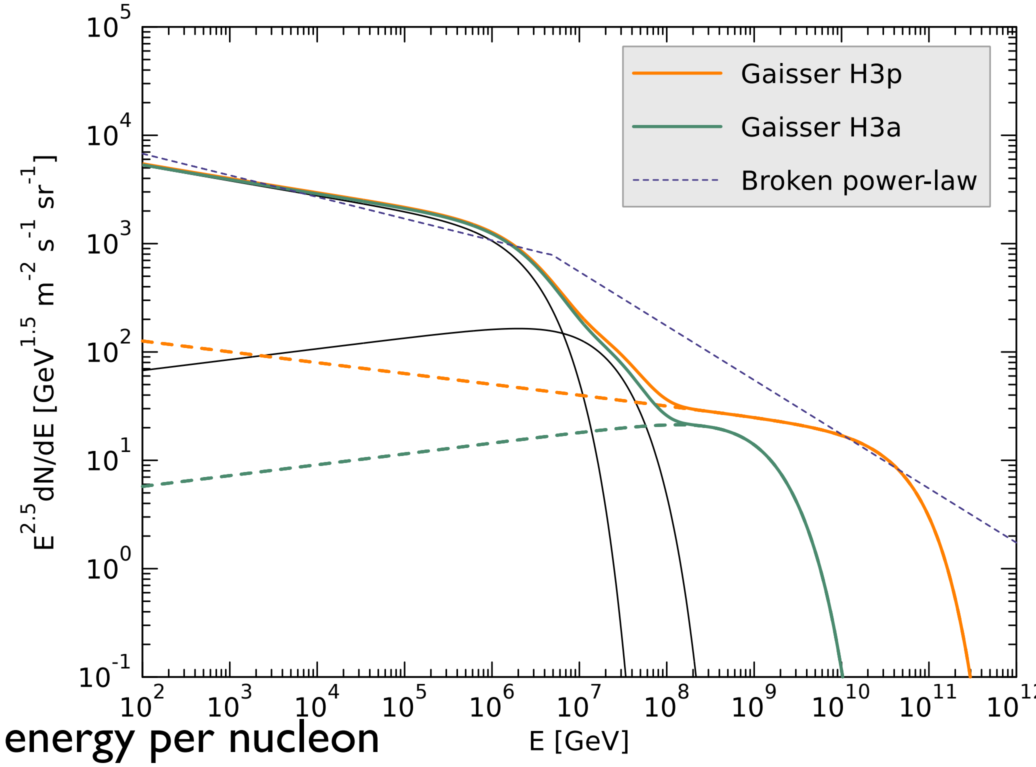
$a_{i,j}$ normalization

$\gamma_{i,j}$ spectral index

$R_{c,j}$ magnetic rigidity

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

$$\phi = dN/d\ln E$$



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

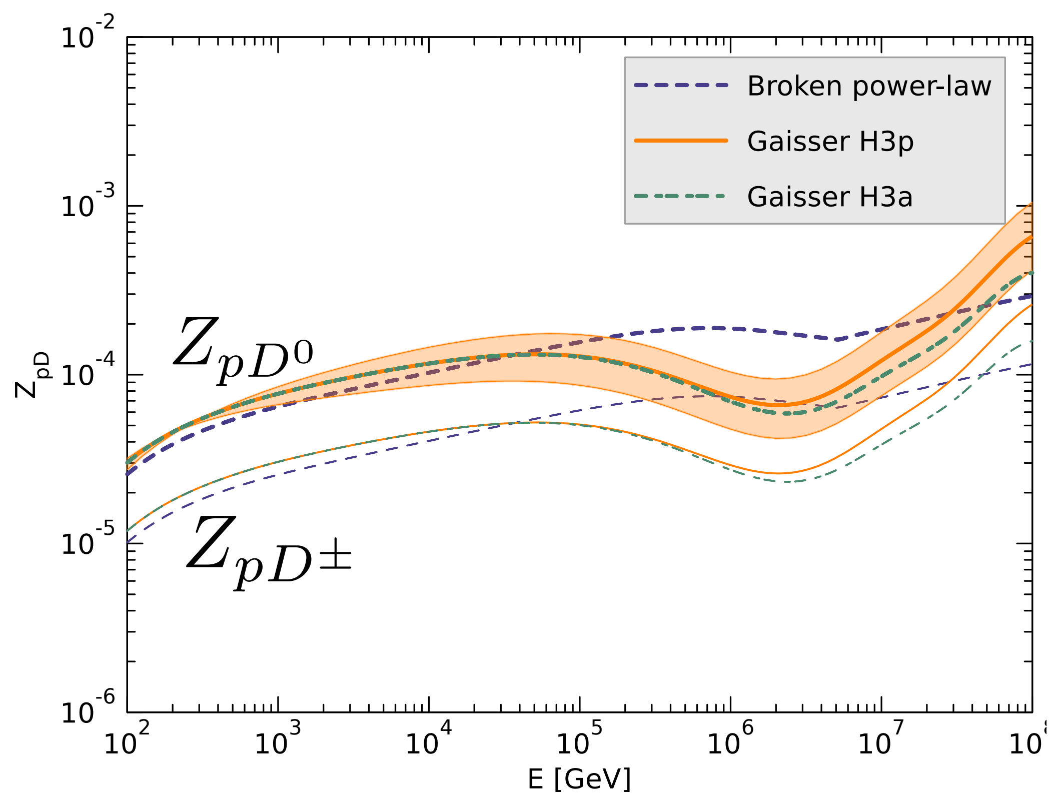
$$\phi^0_p(E) = \begin{cases} 1.7\, E^{-2.7} & \text{for } E < 5 \cdot 10^6 \text{ GeV} \\ 174\, E^{-3} & \text{for } E > 5 \cdot 10^6 \text{ GeV,} \end{cases}$$

Impact of CR flux on Z moments

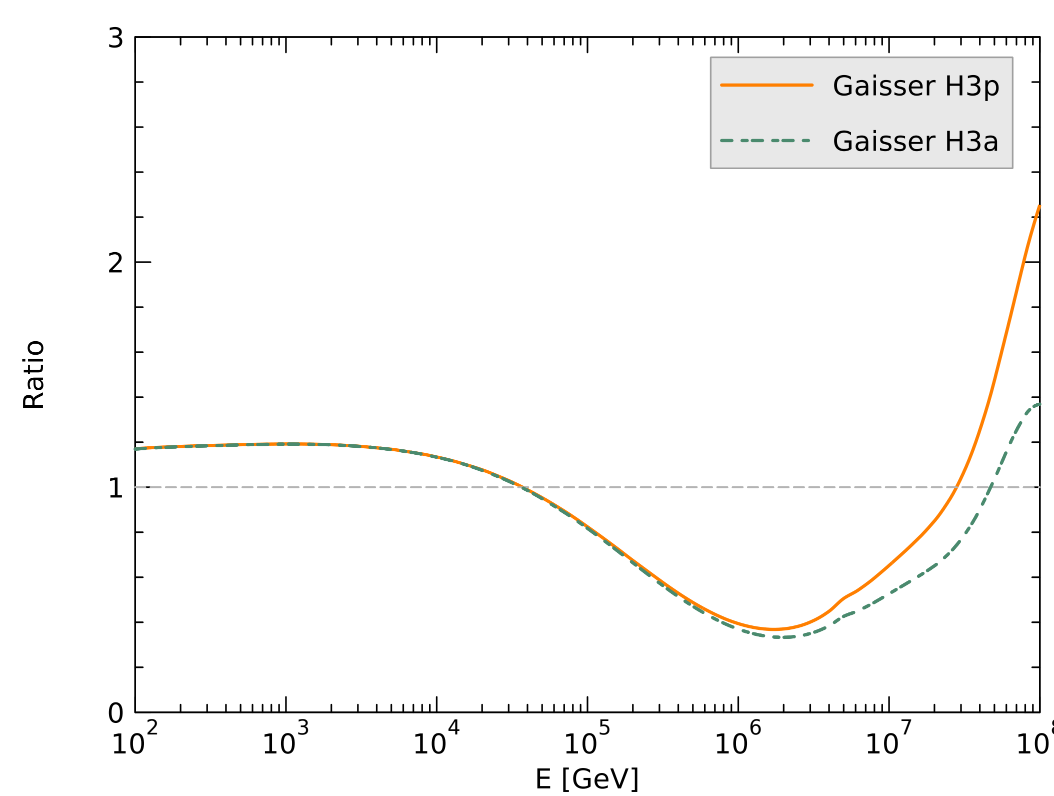
Z moments: $$Z_{ph}(E_h) = \int_{x_{E_{\min}}}^{1} \frac{dx_E}{x_E} \frac{\phi_p^0(E_h/x_E)}{\phi_p^0(E_h)} \frac{1}{\sigma_{pA}(E_h)} \times A \frac{d\sigma}{dx_E}(pN \to hX)$$

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.

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



Ratio to the calculation with power law



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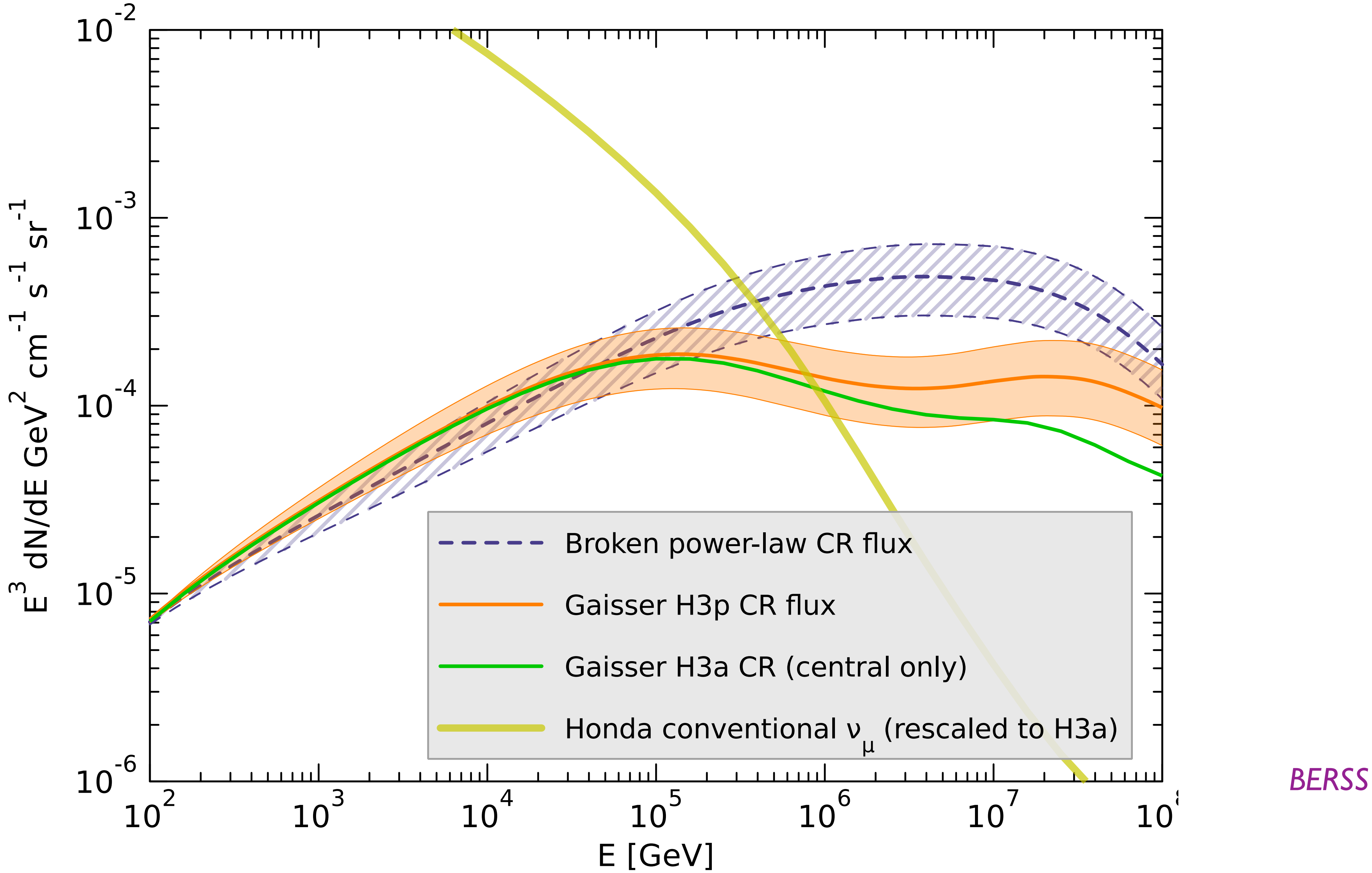
Neutrino fluxes

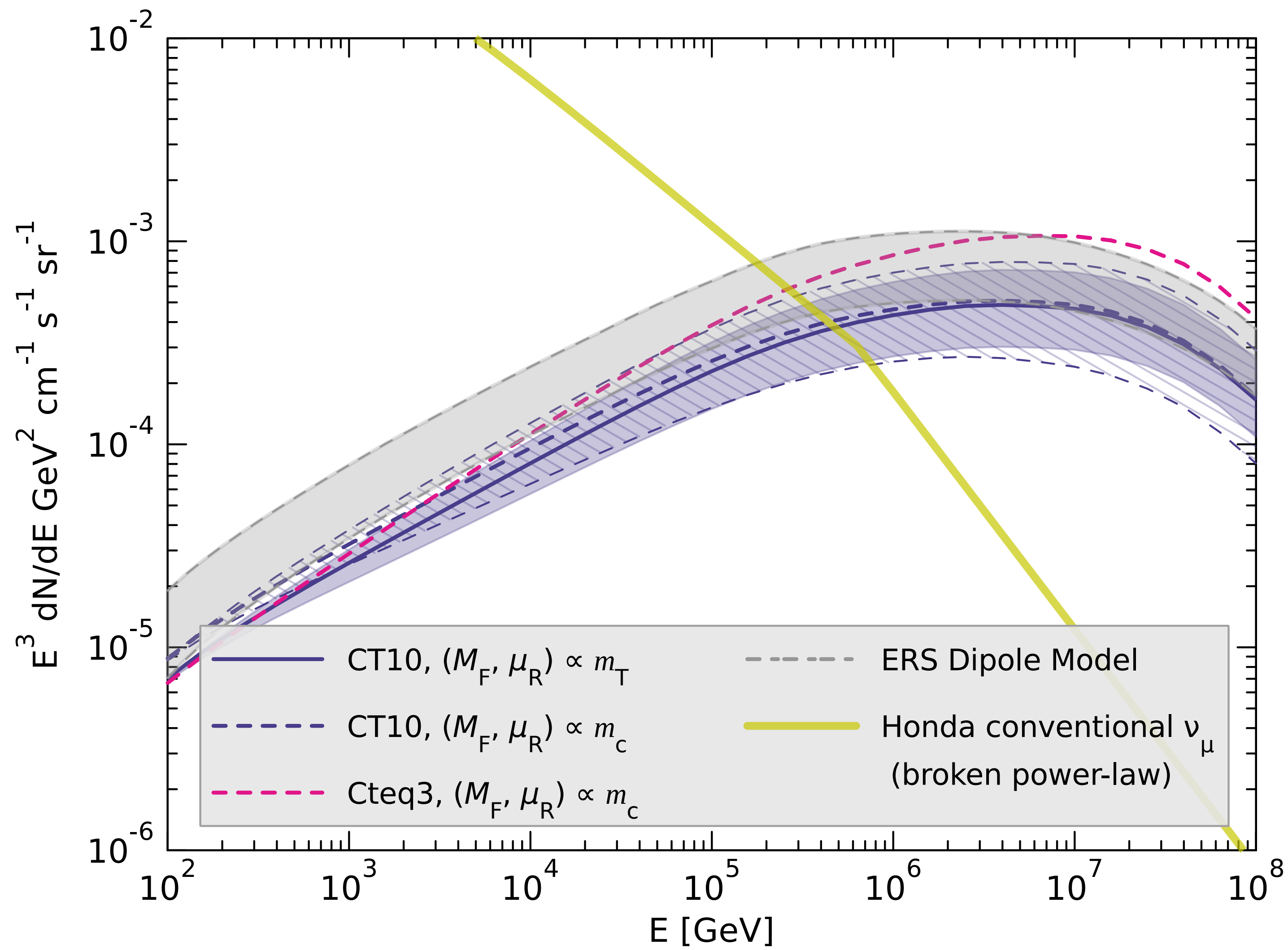
flux of $\nu_\mu + \bar{\nu}_\mu$



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.

Neutrino fluxes

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



BERSS

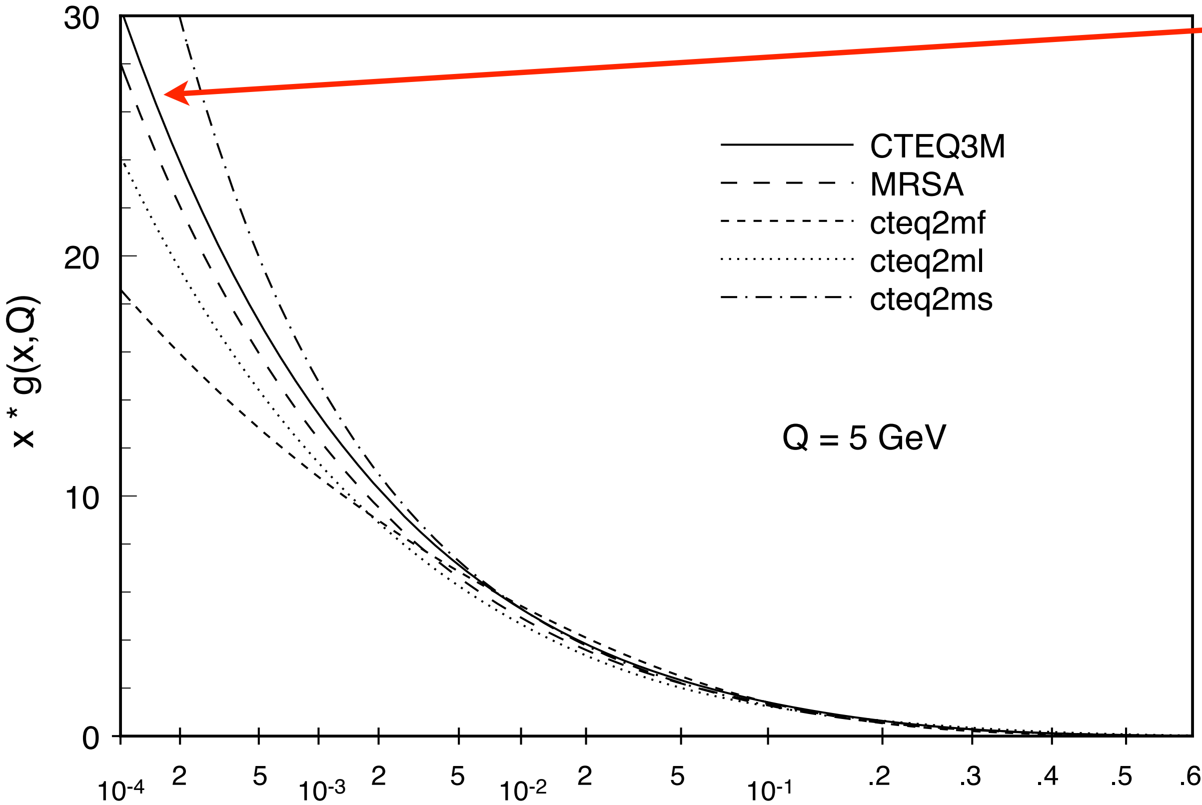
Comparison with earlier calculation based on the dipole model (using the same power law flux for comparison).

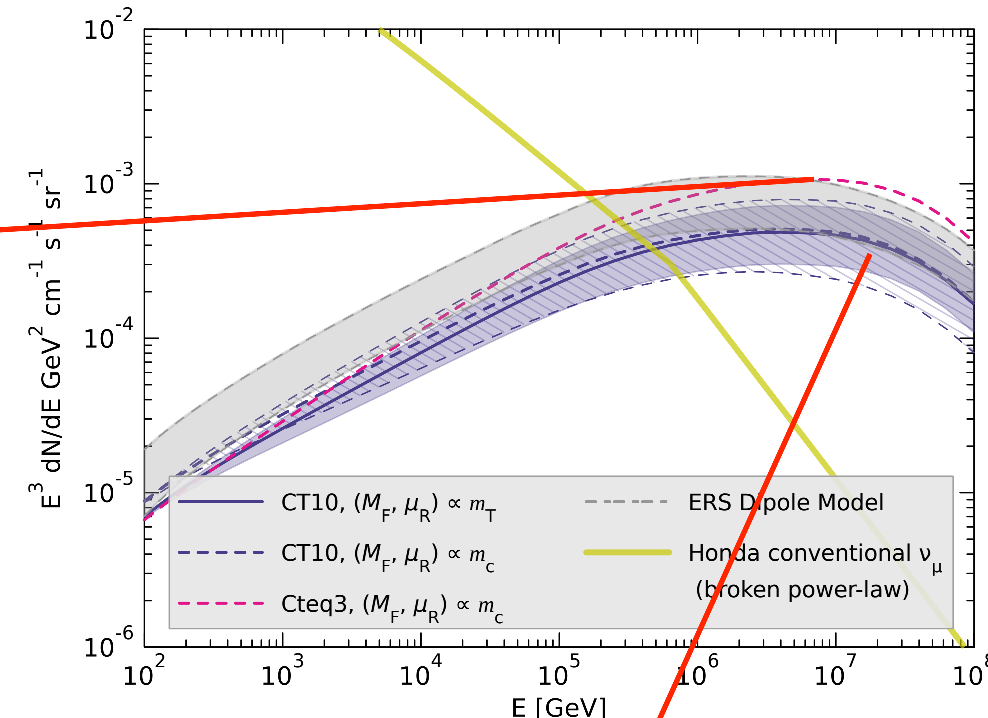
NLO calculation lower than the calculation based on dipole model with parton saturation…different large x partons, CT10 very low at low scales.

Large sensitivity to gluon at low x, CTEQ3 higher than CT10.

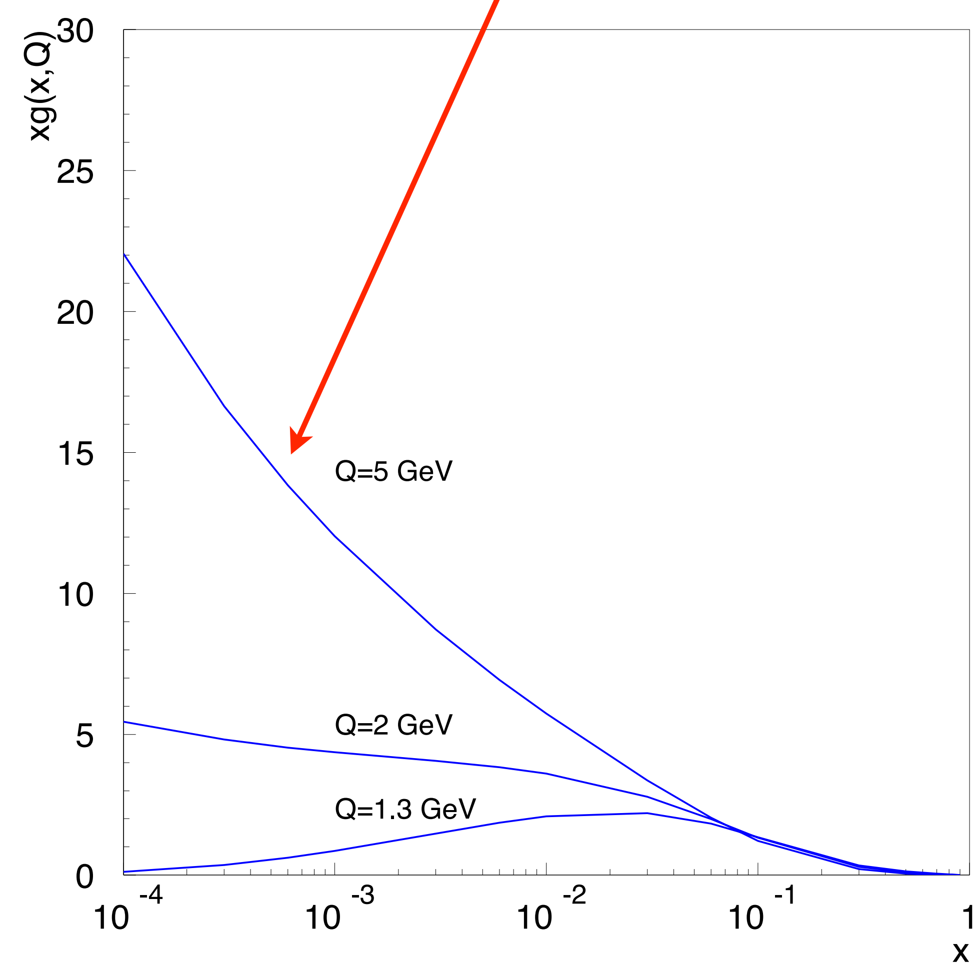
Bands illustrated scale variation in NLO calculation.

PDF differences: CTEQ3 v CT10





CT10



At initial scales:

CTEQ3: gluon rises towards small x

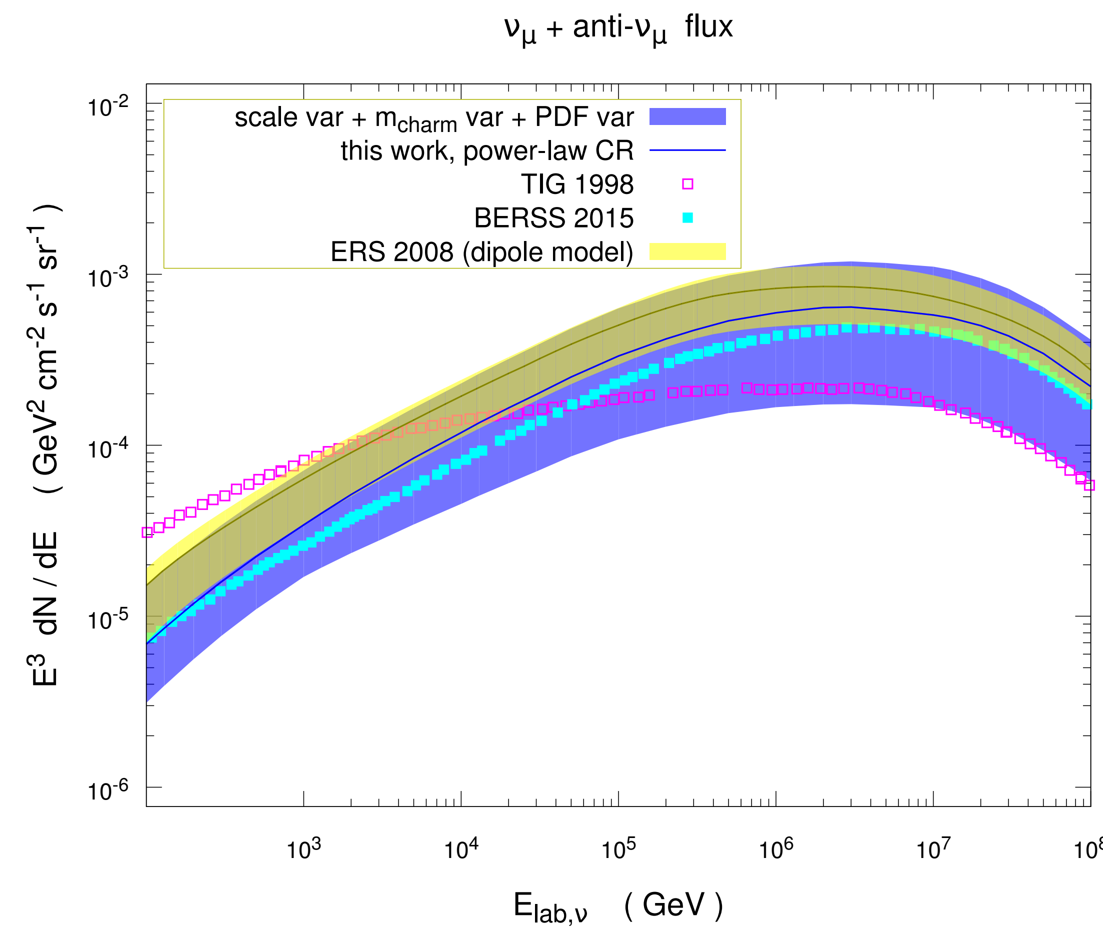
$$xg(x,Q_0) \sim x^{-0.3}$$

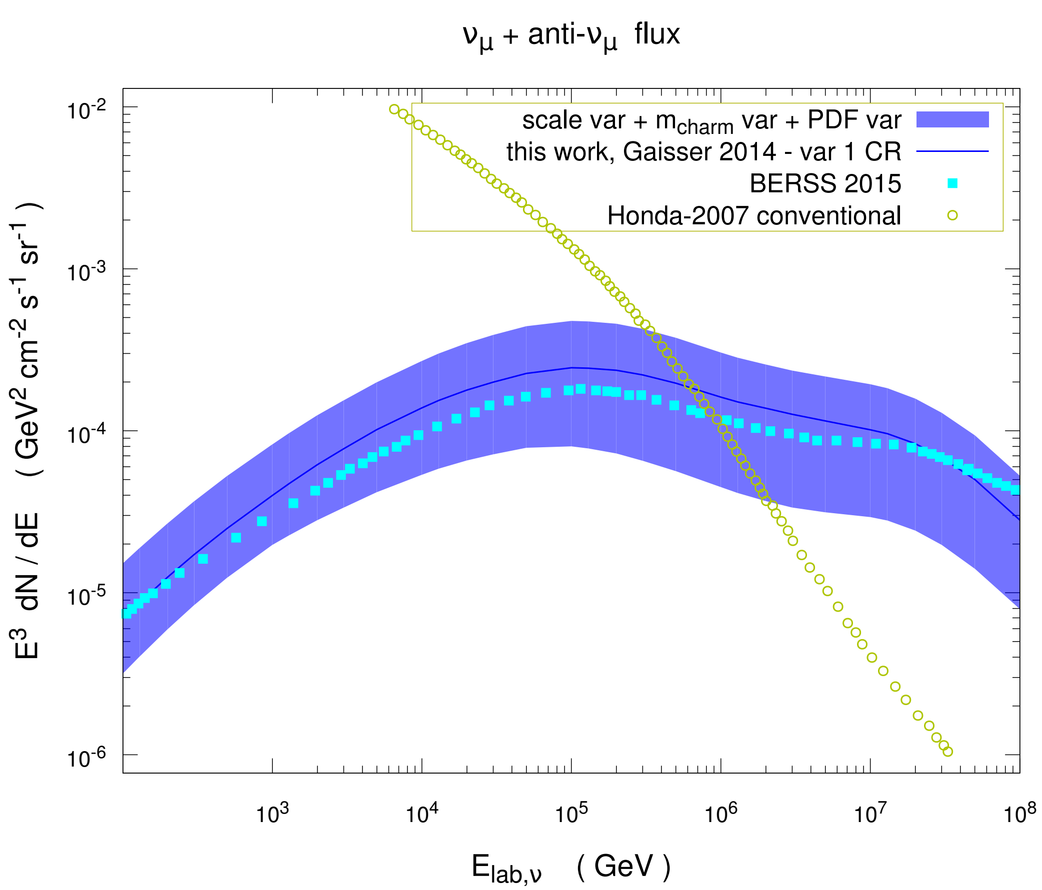
CT10: valence like gluon at low scales.

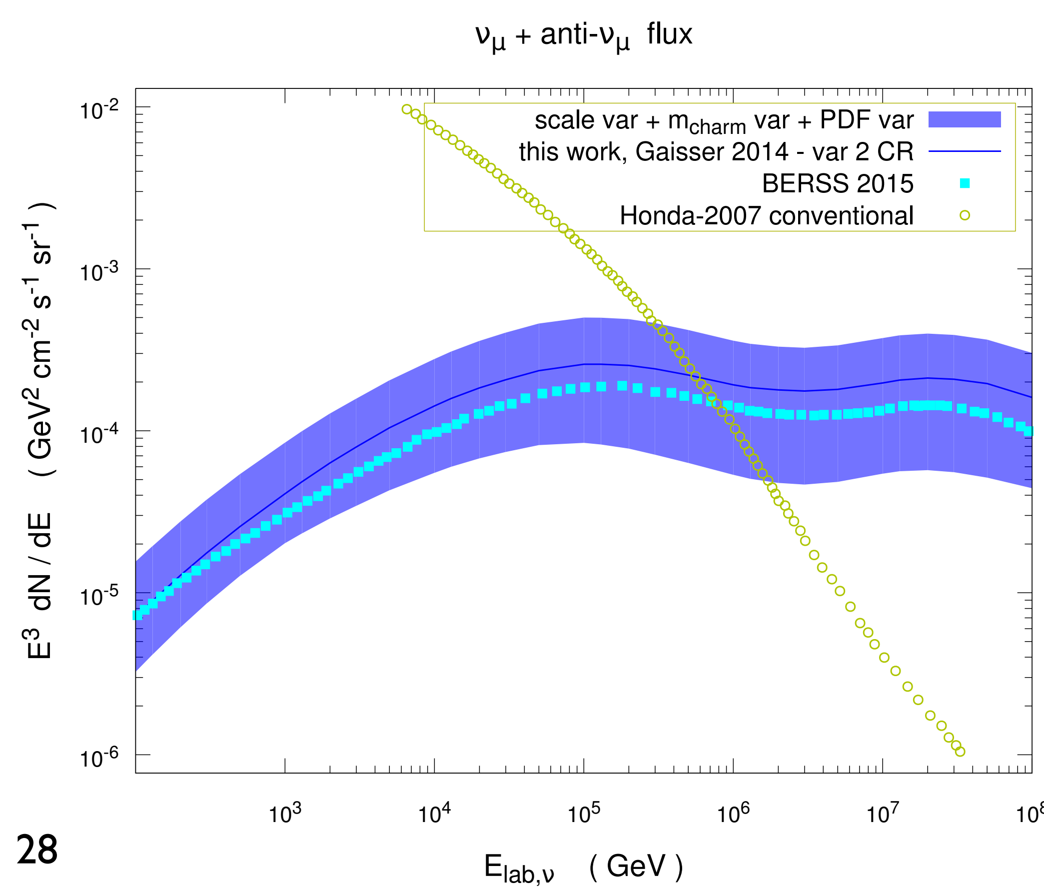
Smaller CT10 gluon vs CTEQ3

Flux differences: BERSS vs GMS

- Our (BERSS) calculation is smaller but consistent with the GMS(Garzelli-Moch-Sigl) calculation within pQCD uncertainties.
- Some differences due to PDF choice and fragmentation.
- GMS closer to the older ERS calculation based on the dipole model with gluon saturation.
- Below: comparison between BERSS and GMS for Gaisser fluxes (note: BERSS uses Gaisser 2012 fluxes whereas GMS Gaisser 2014 fluxes)
- QCD uncertainties dominate for lower energies, astrophysical uncertainties (CR flux) for higher energies. Though PDF uncertainties can be large at high energies as well (not shown on these plots).

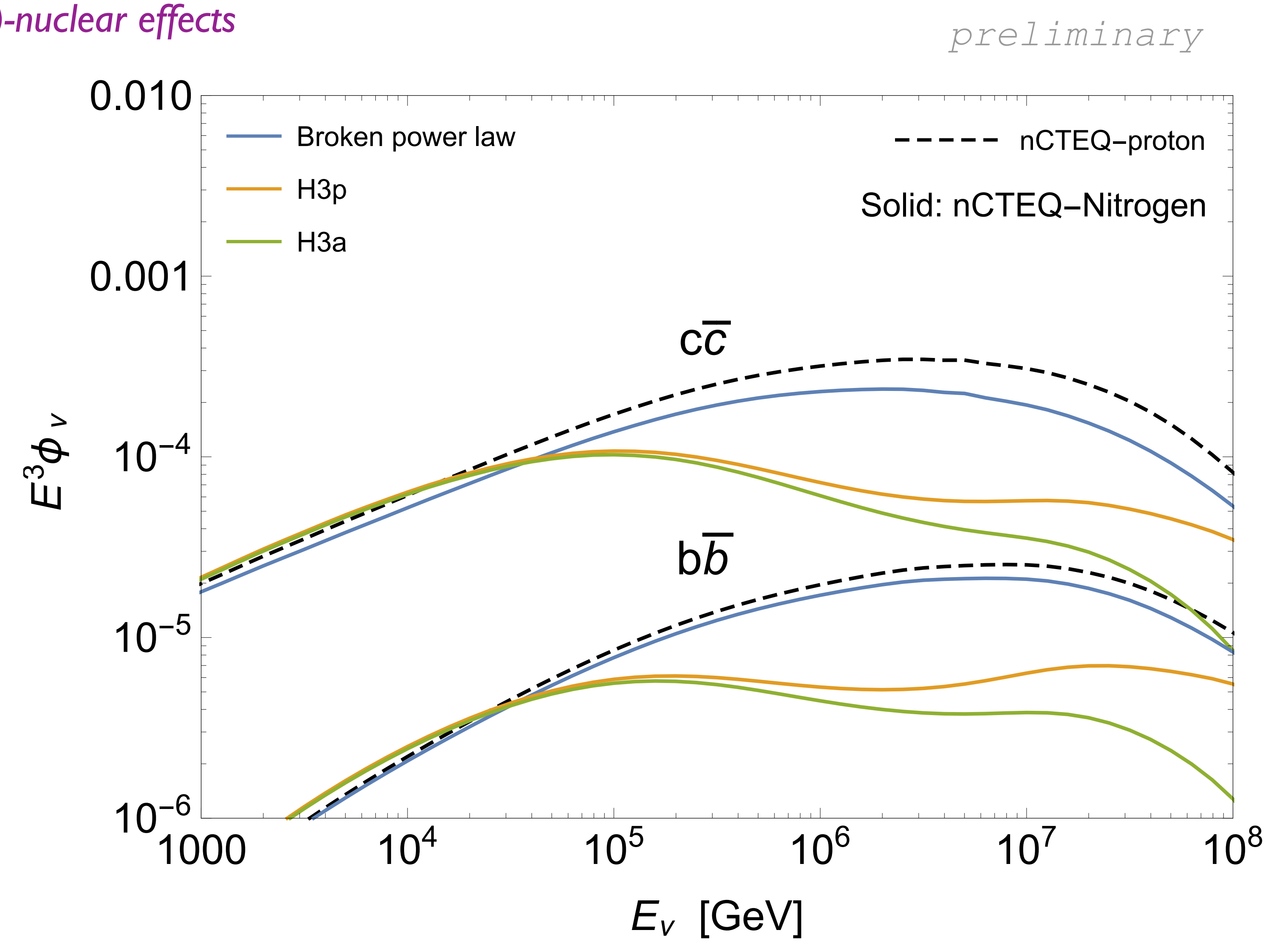






Nuclear corrections

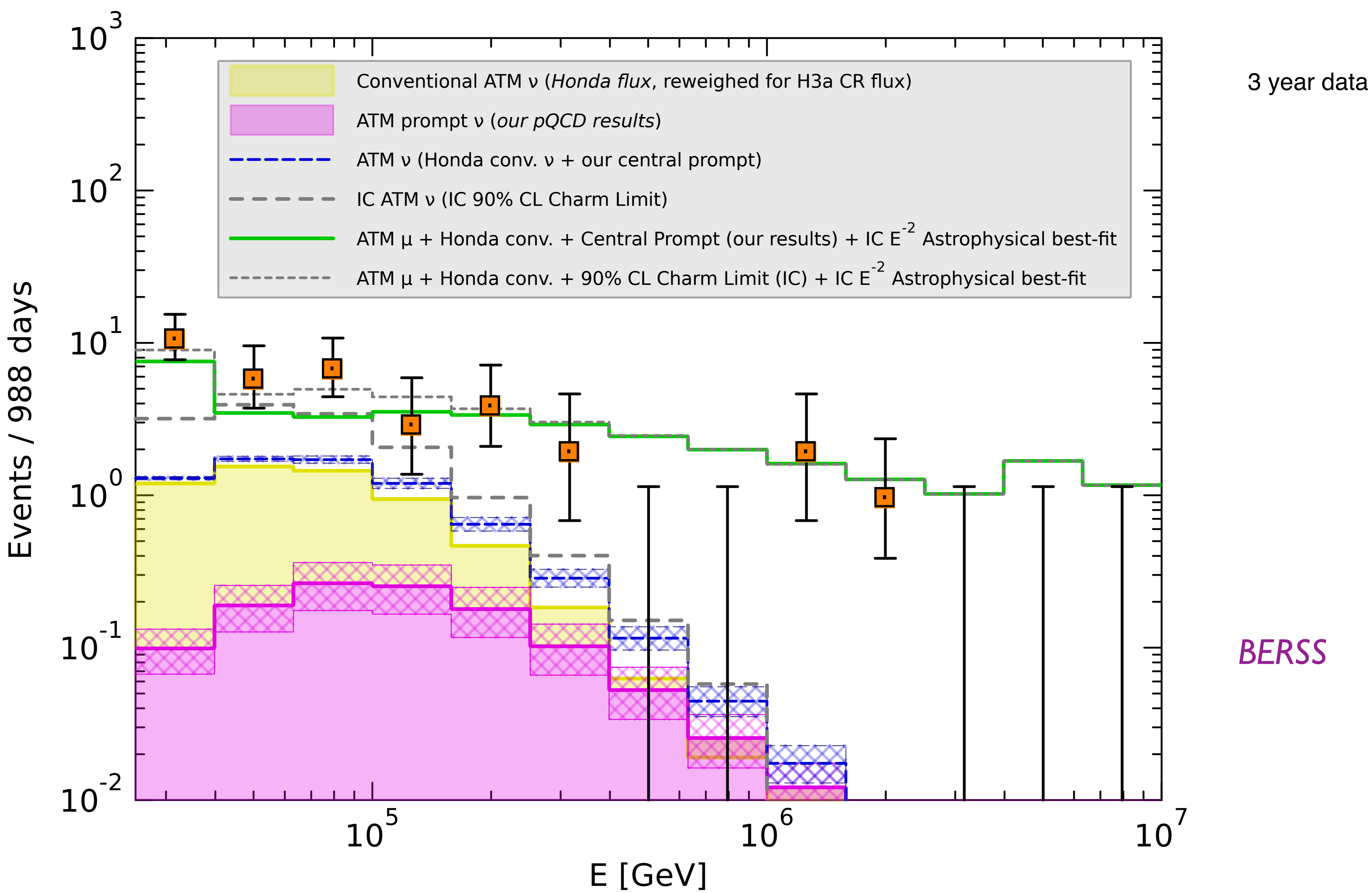
BEJRSS(different PDF)-nuclear effects



- Nuclear effects mostly visible above 100TeV, still within the uncertainties of PDFs and scale uncertainties (not shown here).

Comparison with IceCube 3-year data

- BERSS NLO calculation from charm gives reduced background (with respect to earlier calculations).
- GMS on the other hand would likely not change the current IceCube background estimate.
- Need to redo the analysis with 4-year data



Summary and outlook

- Calculation of the prompt neutrino flux using NLO and new PDFs. Charm cross section matched to LHC and RHIC data.
- Updated cosmic ray flux gives lower values (as compared with earlier ERS evaluation) for the atmospheric neutrino flux.
- Prompt neutrino component is rather small. The data are significantly above, new calculation can change the evaluation of the statistical significance of the astrophysical signal for IC.
- Nuclear effects in the target. Further reduction of the flux by about 20-45%.
- Alternative calculations: dipole and kT factorization. Small x resummation leads to enhancement, saturation to the reduction of the flux.
- Other calculations also on the market: consistent but still large uncertainties. Largest uncertainties due to the QCD scale variation, PDF uncertainties and CR flux.
- Work in progress: fragmentation (forward production, hadronic-nuclear environment, differences between PYTHIA and fragmentation functions), comparison withe LHCb data (NLO is consistent), comparison with 4-year data.