The prompt atmospheric neutrino flux

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PAHEN, Naples, Sept 24, 2017

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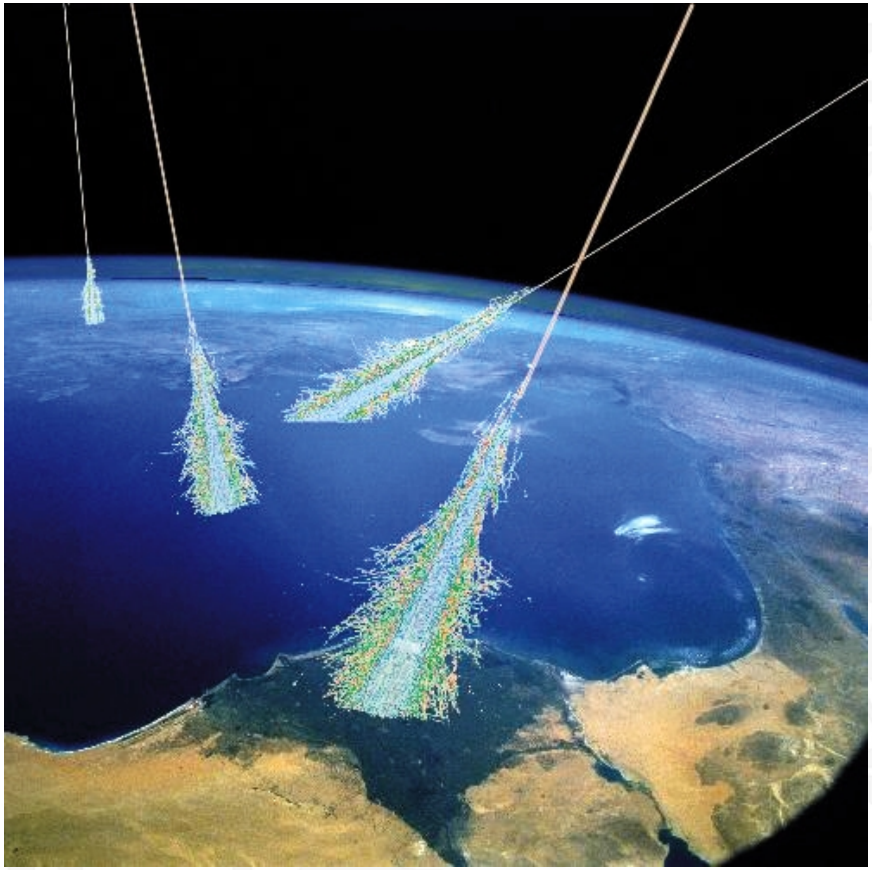
Atmospheric neutrinos

- Cosmic rays bombard upper atmosphere and collide with air nuclei
- Very large CMS energy → Hadron production: pions, kaons, D-mesons …
- Interaction & decay
  ⇒ cascade of particles
- Semileptonic decays
  ⇒ neutrino flux



Credit: Astropic of the day, 060814

Conventional neutrino flux

- Pions (and kaons) are produced in more or less every inelastic collision

- π^+ always decay to neutrinos: BR($\pi^+ \to \mu^+ \nu_\mu$) = 99.98 %

- *But $\pi^\pm$, $K^\pm$ are long-lived* ($c\tau$ ~ 8 meters for π^+)
  ⇒ lose energy through collisions before decaying
  ⇒ neutrino energies are degraded

- This is called the *conventional neutrino flux*

Prompt neutrino flux

- Hadrons containing heavy quarks *(charm or bottom)* are extremely short-lived:
  - ⇒ decay before losing energy
  - ⇒ harder neutrino energy spectrum

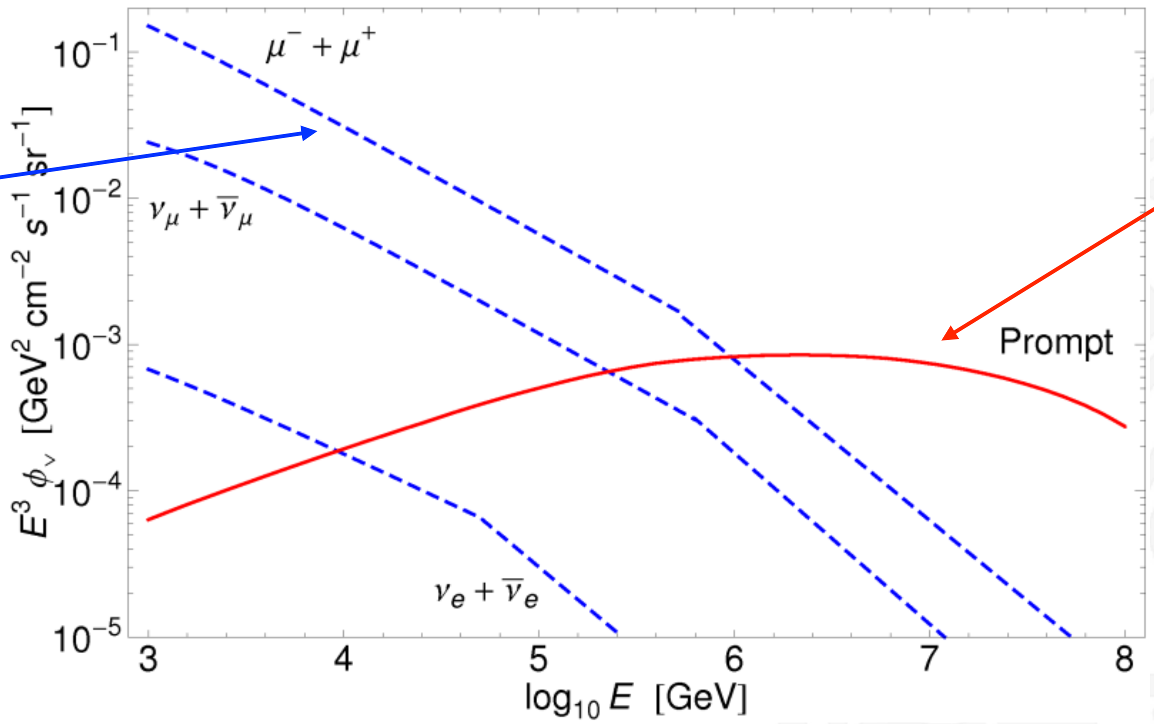
- However, production cross-section is much smaller

- There is a cross-over energy above which prompt neutrinos dominate over the conventional flux

- This is called the *prompt neutrino flux*

Prompt vs conventional fluxes of atmospheric neutrinos

Pions & kaons: long-lived ⇒ lose energy before decay



Charmed mesons: short-lived ⇒ don't lose energy ⇒ harder spectrum

Prompt flux: Enberg, Reno, Sarcevic, arXiv:0806.0418 **(ERS)**
Conventional: Gaisser & Honda, Ann. Rev. Nucl. Part. Sci. **52,** 153 (2002)

Why are we interested?

- Atmospheric neutrinos are a background to extragalactic neutrinos
- Test beam for neutrino experiments
- Learn about cascades and the underlying production mechanism
- Higher energy pp collisions than in LHC:
  can maybe even learn something about QCD?

Calculations of the prompt flux

Recent:

A. Bhattacharya, RE, M.H. Reno, I. Sarcevic, A. Stasto, arXiv:1502.01076 **(BERSS)**

M.V. Garzelli, S. Moch, G. Sigl, arXiv:1507.01570 **(GMS)**

R. Gauld, J. Rojo, L. Rottoli, S. Sarkar, J.Talbert, arXiv:1511.06346 **(GRRST)**

A. Bhattacharya, RE, Y.S. Jeong, C.S. Kim, M.H. Reno, I. Sarcevic, A. Stasto, arXiv:1607.00193 **(BEJKRSS)**

PROSA Collaboration (Garzelli et al), arXiv:1611.03815

M. Benzke, M. V. Garzelli, *et al.*, arXiv:1705.10386

Older but widely used:

M. Thunman, G. Ingelman, P. Gondolo, hep-ph/9505417

L. Pasquali, M.H. Reno, I. Sarcevic, hep-ph/9806428

A.D. Martin, M.G. Ryskin, A. Stasto, hep-ph/0302140 **(MRS)**

RE, M.H. Reno, I. Sarcevic, arXiv:0806.0418 [hep-ph] **(ERS)**

Calculations of the prompt flux

Compare with

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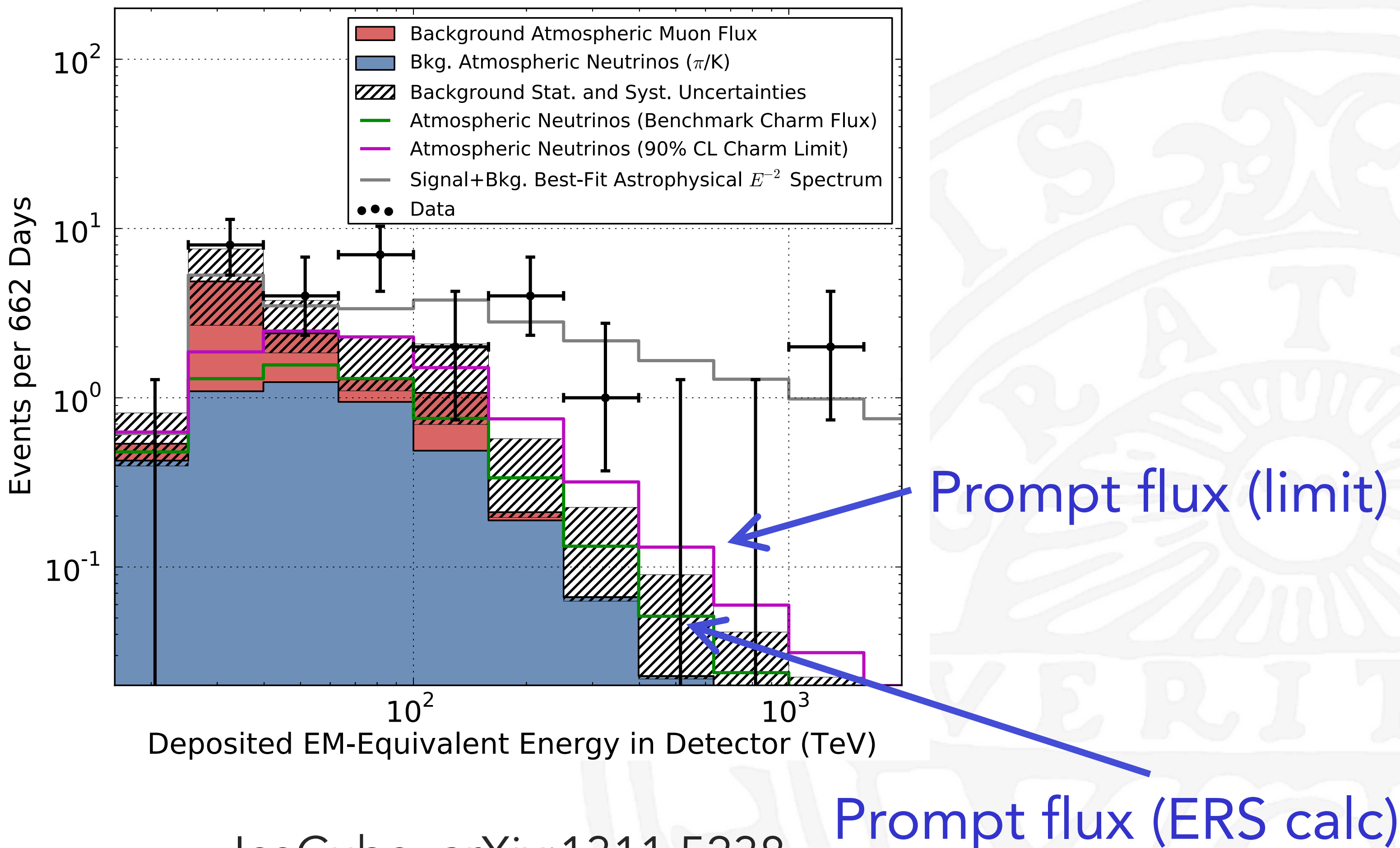
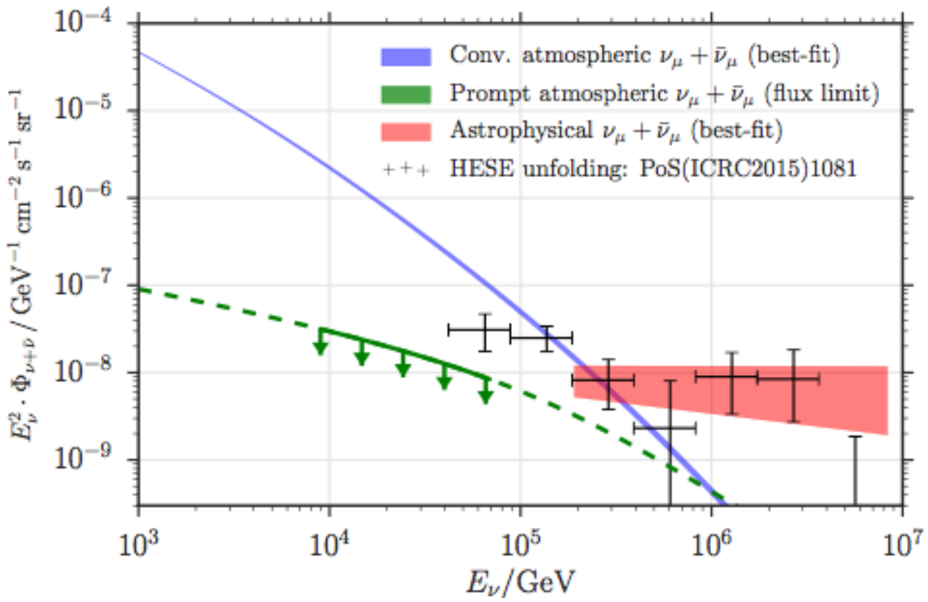
The IceCube events

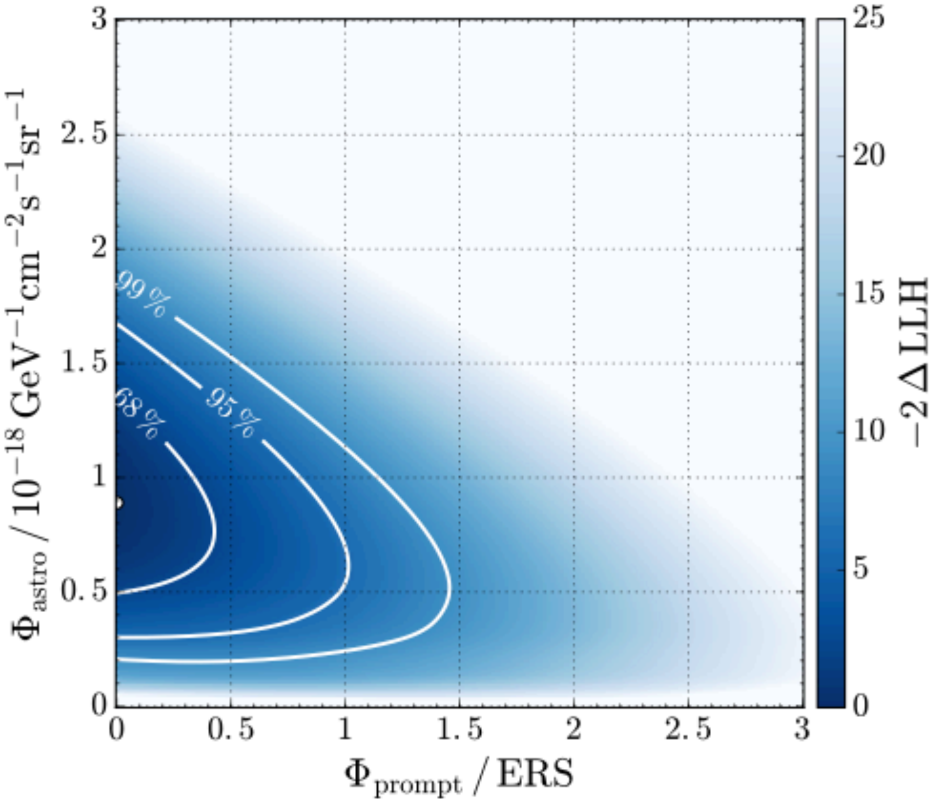
The significance is sensitive to the prompt flux prediction



IceCube, arXiv:1311.5238

IceCube are using ERS





The shape of the ERS flux is used with overall normalization a free parameter

M.G. Aartsen et al., arXiv:1607.08006

Important message

QCD is crucial for some astrophysical processes:

- Atmospheric neutrinos
- Neutrino-nucleon cross-section @ high energy
- (Interactions in astrophysical sources?)

For example:

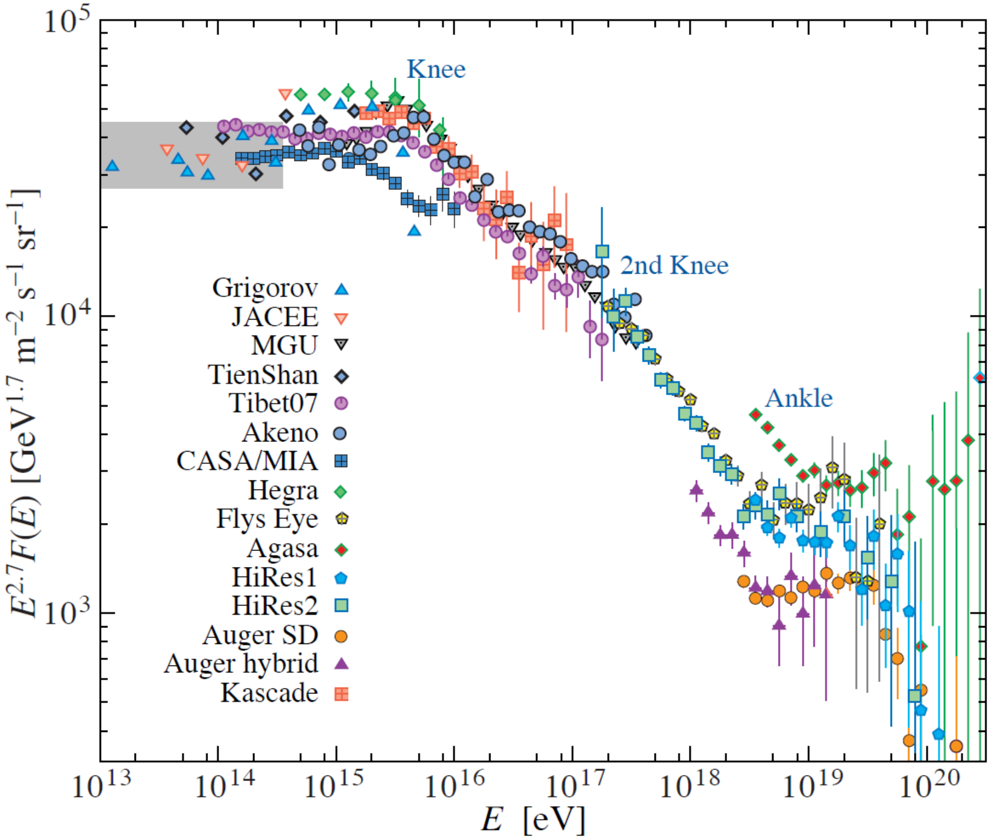
- What happens at **small Bjorken-x**? (Need very small x)
- Forward region (Hard to measure at colliders)
- Fragmentation of quarks → hadrons
- Nuclear effects in pA hard interactions

The calculation has many ingredients

- *Incident cosmic ray flux*
- Atmospheric density
- *Cross section for heavy quarks in pp/pA collisions at extremely high energy (perturbative QCD)*
- Rescattering of nucleons, hadrons (hadronic xsecs) (scattering lengths)
- Decay spectra of charmed mesons & baryons (decay lengths)
- Cascade equations and their solution (Semi-analytic: spectrum-weighted Z-moments)

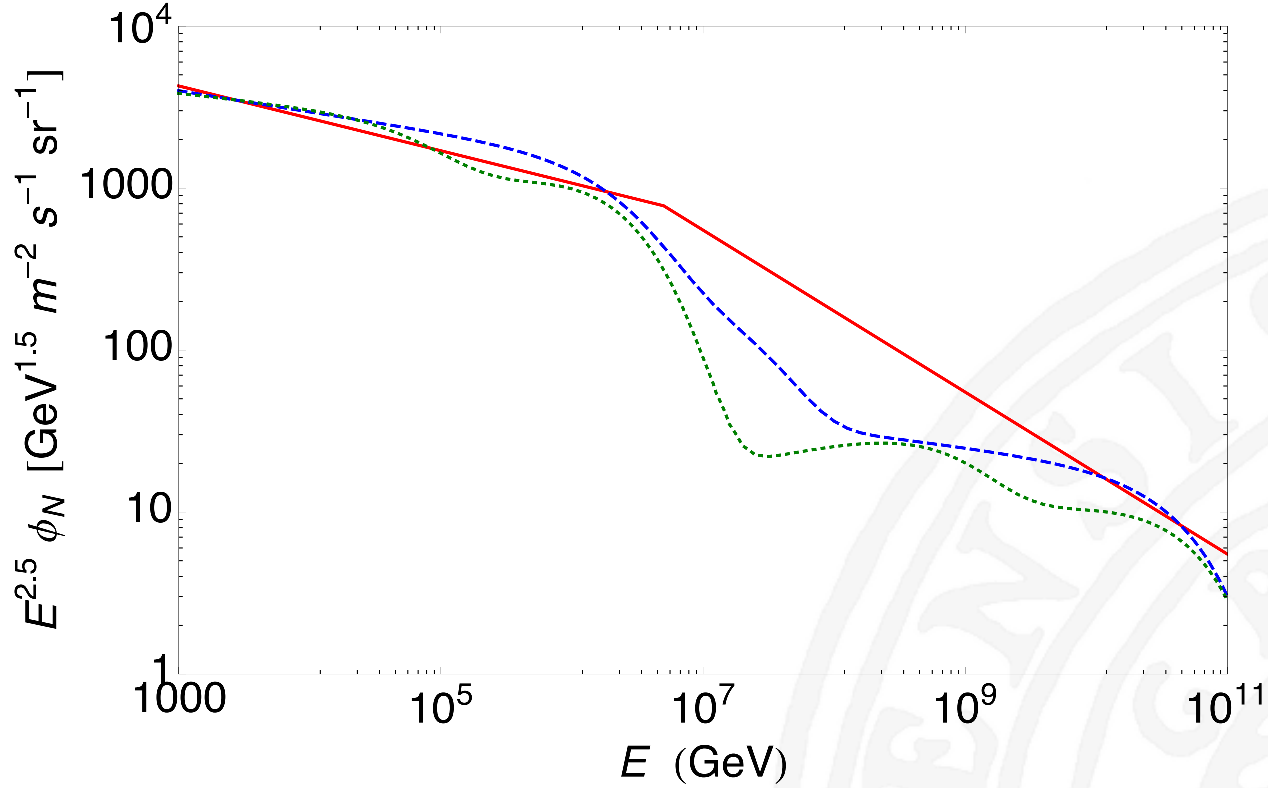
Cosmic rays (CR)

Plot from Particle Data Group



- Knees and ankles → seems natural to associate different sources with different energy ranges of the CR flux
- Highest energies: Extragalactic origin?
  → GRBs, AGNs, or more exotic
- Lower energies: Galactic origin?
  →SNRs etc

Incident cosmic ray flux: nucleons



Solid red = Broken power law (old standard)
Dashed blue = Gaisser all proton (H3p)
Dotted green = Gaisser, Stanev, Tilav (GST4)

Calculating the neutrino flux

- To find the neutrino flux we must **either solve a set of cascade equations** given an incoming CR flux:

$$\frac{d\phi_N}{dX} = -\frac{\phi_N}{\lambda_N} + S(NA \to NY)$$

$$\frac{d\phi_M}{dX} = S(NA \to MY) - \frac{\phi_M}{\rho d_M(E)} - \frac{\phi_M}{\lambda_M} + S(MA \to MY)$$

$$\frac{d\phi_\ell}{dX} = \sum_M S(M \to \ell Y)$$

  - X is the slant depth: "amount of atmosphere"
    $\rho\, d_M$ is the decay length, with ρ the density of air
    λ_M is the interaction length for hadronic energy loss
  - Here: semi-analytic solution (e.g. **MCEq** does it numerically)

- … **or Monte Carlo simulate** the cascade (e.g. **SIBYLL**)

Particle production

Particle physics inputs: energy distributions

$$\frac{dn(k \to j; E_k, E_j)}{dE_j} = \frac{1}{\sigma_{kA}(E_k)} \frac{d\sigma(kA \to jY, E_k, E_j)}{dE_j}$$

$$\frac{dn(k \to j; E_k, E_j)}{dE_j} = \frac{1}{\Gamma_k} \frac{d\Gamma(k \to jY; E_j)}{dE_j}$$

along with interaction lengths, or cooling lengths

$$\lambda_N(E) = \frac{\rho(h)}{\sigma_{NA}(E) n_A(h)}$$

→ Need the charm production cross section $d\sigma/dx_F$

Problem with QCD in this process

Charm cross section in LO QCD:

$$\frac{d\sigma_{\rm LO}}{dx_F} = \int \frac{dM^2_{c\bar{c}}}{(x_1+x_2)s}\sigma_{gg\to c\bar{c}}(\hat{s})G(x_1,\mu^2)G(x_2,\mu^2)$$

where
$$x_{1,2} = \frac{1}{2}\left(\sqrt{x_F^2 + \frac{4M^2_{c\bar{c}}}{s}} \pm x_F\right)$$

CMS energy is large: $s = 2E_p m_p$ so $x_1 \sim x_F$ $x_2 \ll 1$

$x_F=1$:	$E=10^5 \to x \sim 4\cdot 10^{-5}$	$x_F=0$:	$E=10^5 \to x \sim 6\cdot 10^{-3}$
	$E=10^6 \to x \sim 4\cdot 10^{-6}$		$E=10^6 \to x \sim 2\cdot 10^{-3}$
	$E=10^7 \to x \sim 4\cdot 10^{-7}$		$E=10^7 \to x \sim 6\cdot 10^{-4}$

Very small x is needed for forward processes (large x_F)!

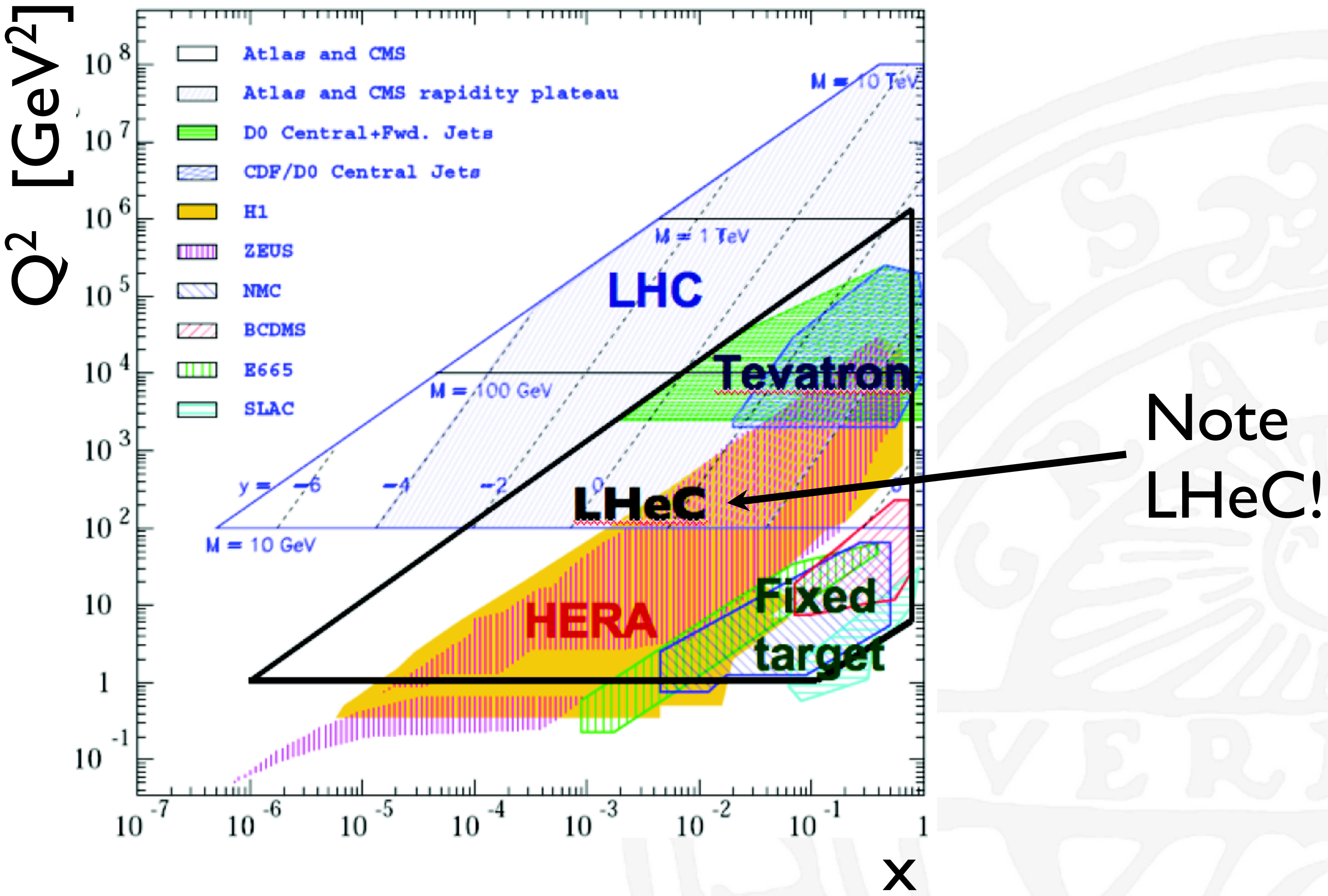
Problem with QCD at small x

- Parton distribution functions poorly known at small x
- At small x, must resum large logs: $\alpha_s \ln(1/x)$
- If logs are resummed *(BFKL)*:
  power growth ~ $x^{-\lambda}$ of gluon distribution as $x \to 0$
- Unitarity would be violated (T-matrix > 1)

How small x do we know?

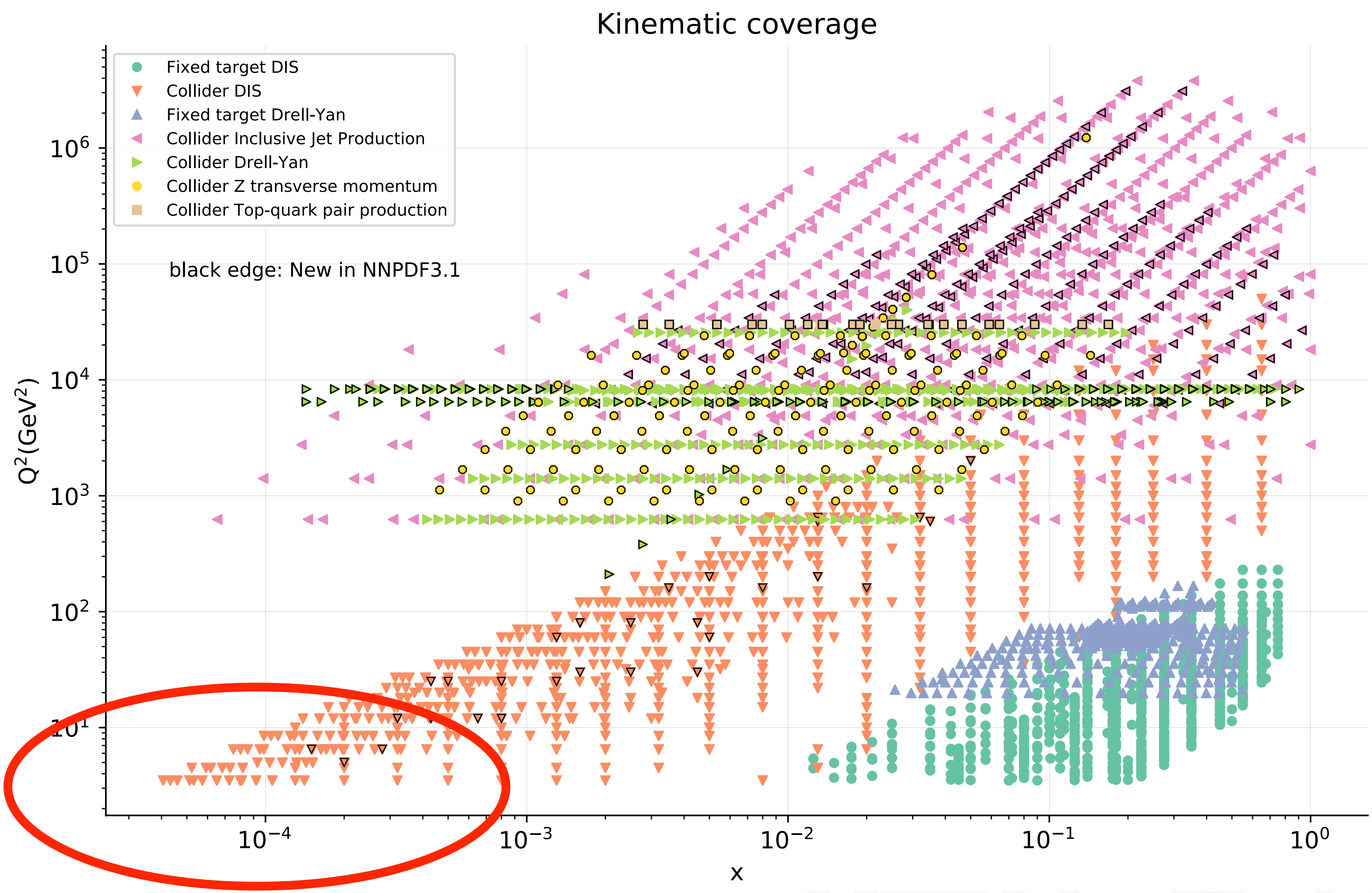
- We haven't measured anything at such small x
- E.g. the MSTW pdf has $x_{min}=10^{-6}$
- But that is an extrapolation!
- HERA pdf fits: $Q^2 > 3.5$ GeV^2 and $x > 10^{-4}$!
- See Gao, Harland-Lang, Rojo, arXiv:1709.04922 for more on pdfs

Kinematic plane



HERA: $x_{min} \sim 10^{-4}$ used for PDF fits ($Q^2 \sim 3.5$ GeV^2)

Kinematic plane of NNPDF3.1



R.D. Ball et al, arXiv:1706.00428

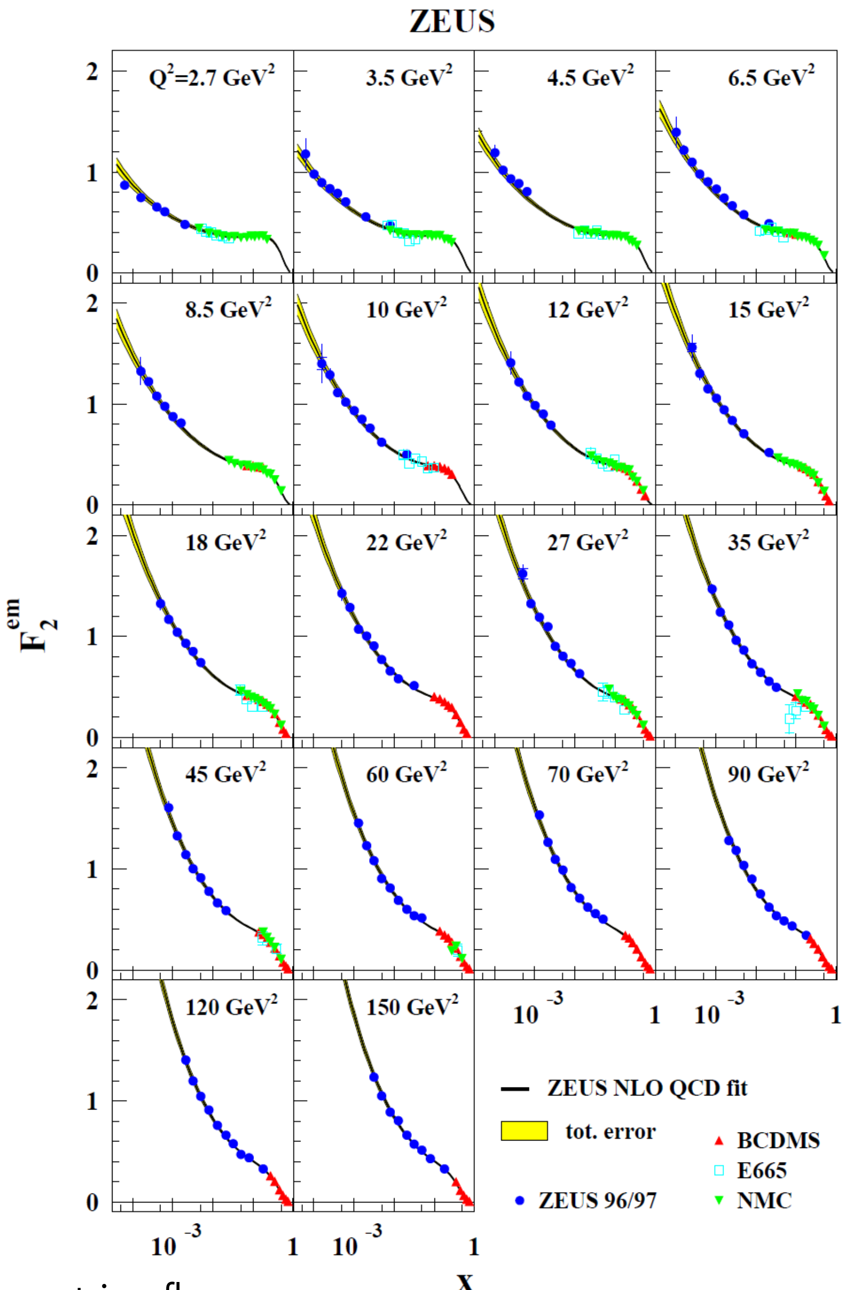
Small x

F2 measured at HERA (ZEUS) as a function of Bjorken-x.

Note the steep power-law rise

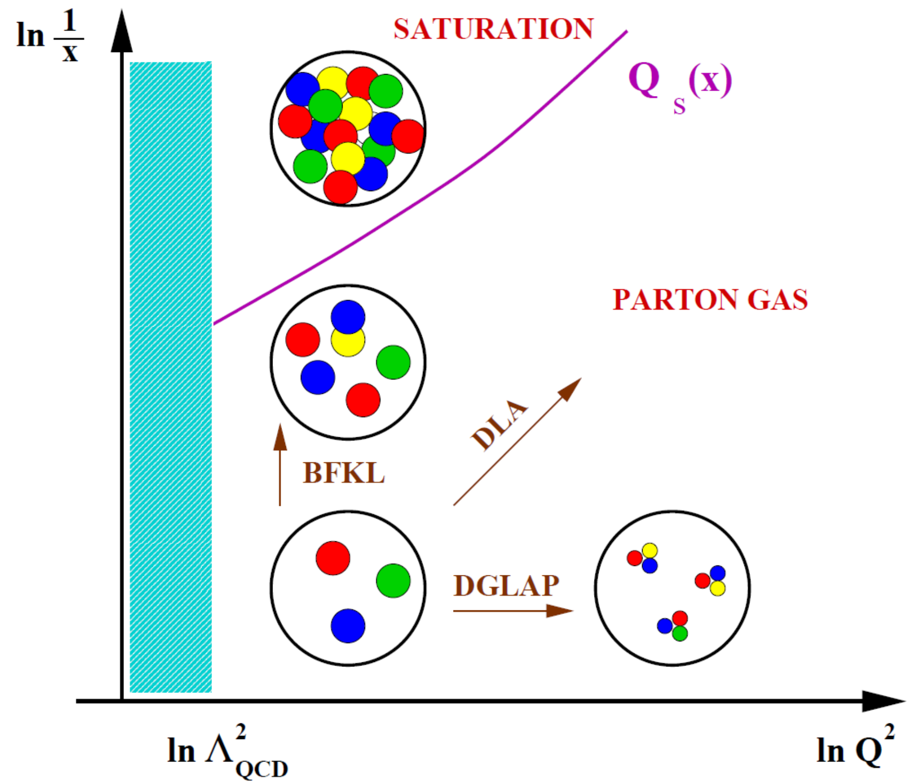
Can this rise continue?

Theoretical answer: no



Parton saturation

- *Saturation* to the rescue:
  - Number of gluons in the nucleon becomes so large that gluons recombine
  - Reduction in the growth



- This is sometimes called the *color glass condensate*
- Non-linear QCD evolution: Balitsky-Kovchegov equation

Bhattacharya et al (BEJKRSS, 2016): Redo QCD calculations in 3 ways

- ***Standard NLO QCD with newest PDFs***
  - BERSS updated with RHIC/LHCb input,
    uses Nason, Dawson, Ellis and Mangano, Nason, Ridolfi
- ***Dipole picture with saturation***
  - Approximate solution of Balitsky-Kovchegov equation
  - Update of ERS calc with new HERA fits + other dipoles
- ***kT factorization with and without saturation***
  - Resums large logs, $\alpha_s \log(1/x)$ with BFKL
  - Off-shell gluons, unintegrated PDFs (+ subleading…)
  - Kutak, Kwiecinski, Martin, Sapeta, Stasto (permutations)

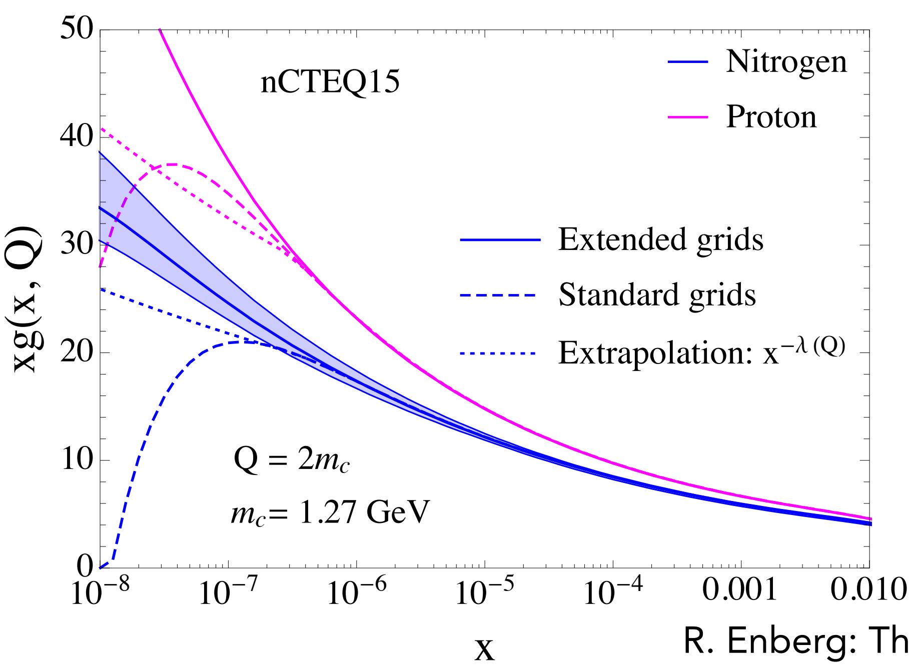
Include scale variations, PDF errors, charm mass, etc
→ Plausible upper and lower limits on xsec

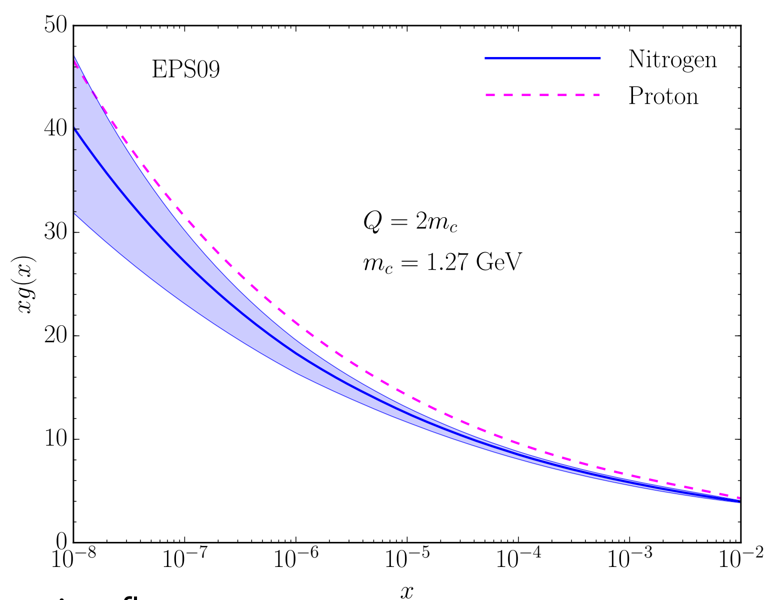
Also include nuclear shadowing

Partons are not in a free nucleon, but in a nucleus!

To estimate shadowing, we use PDFs:

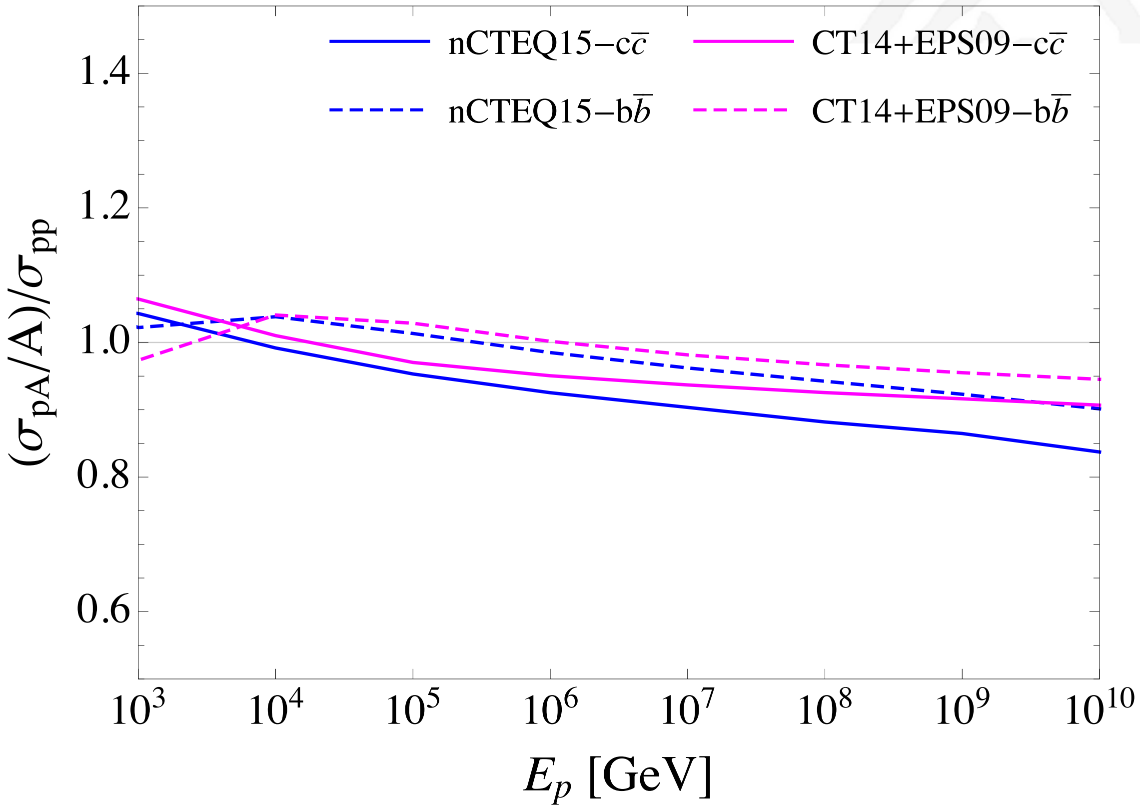
- Eskola, Paukkunen, Salgado (EPS) for ^{16}O
- nCTEQ15 for ^{14}N
- CT14 for free protons



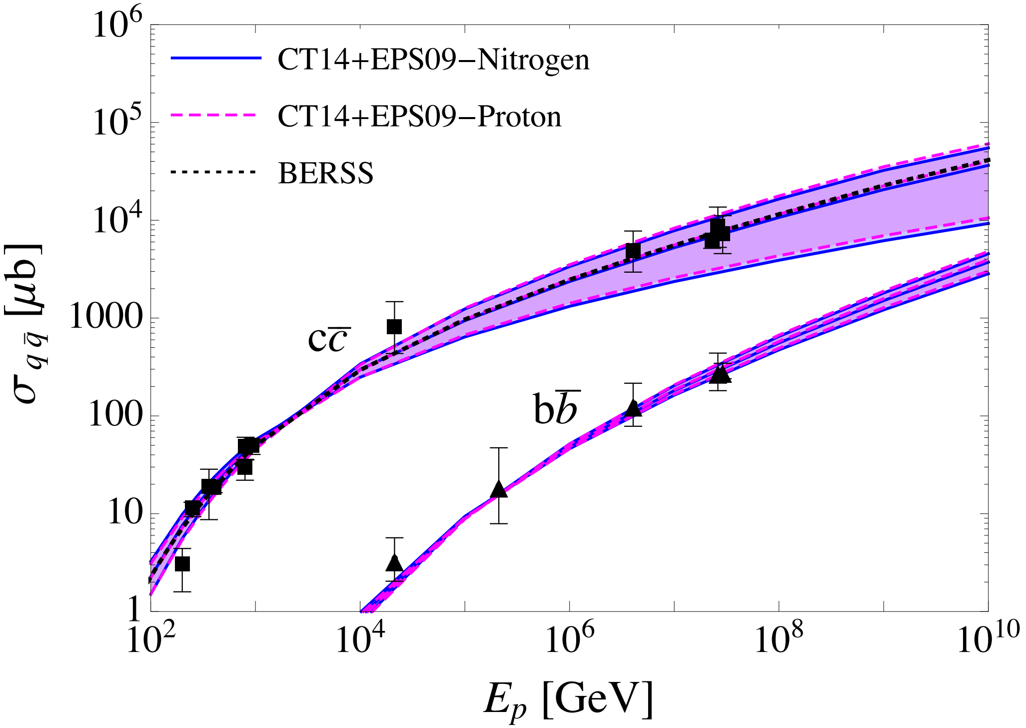


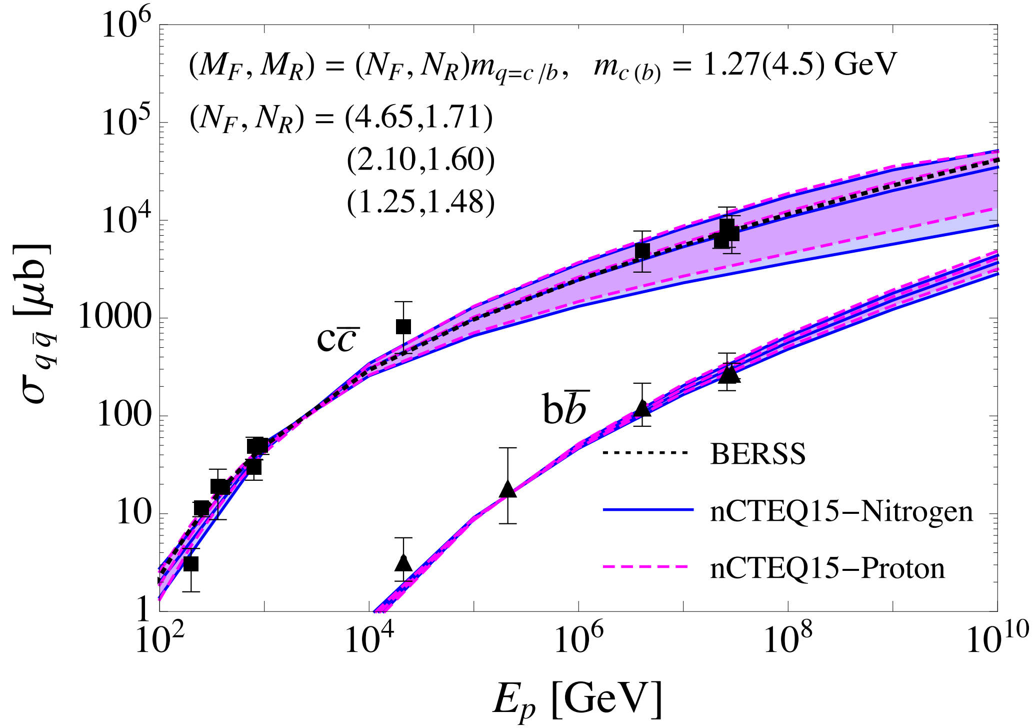
Nuclear effects

- Nuclear shadowing reduces flux by 10–30% at the highest energies
- Effect is larger on the flux than on the total σ(cc) due to asymmetric $x_{1,2}$



σ(cc) and σ(bb)





Data from RHIC, LHC and lower energies
Total cross sections well described by all calculations
(at high energies), nuclear shadowing small

(Error bands=scale variations and PDF uncertainties)

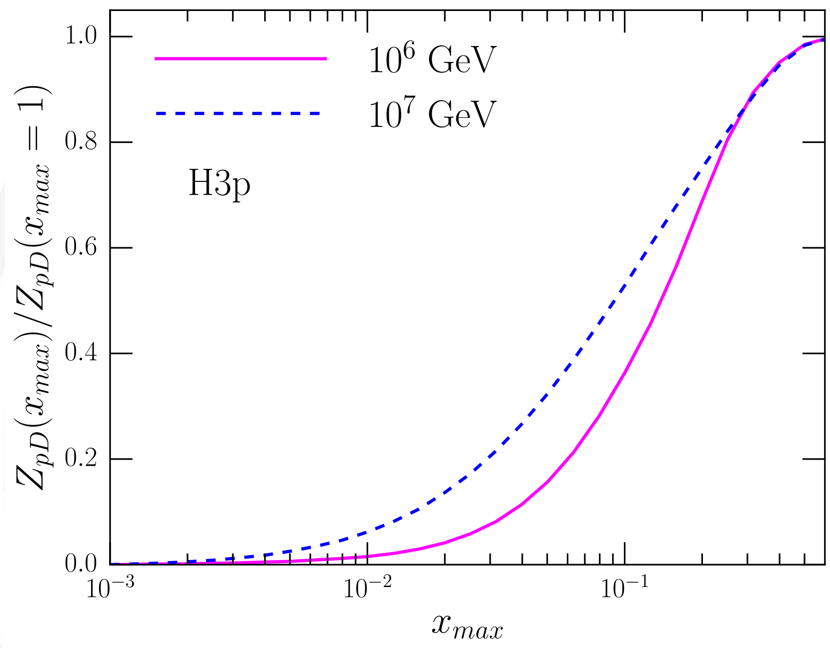
Differential cross sections (LHCb)

LHCb measured D-meson production at 7 and 13 TeV

Kinematical range: pT < 8 GeV, 0 < y < 4.5

The flux is mostly sensitive to ***large y and small pT***.

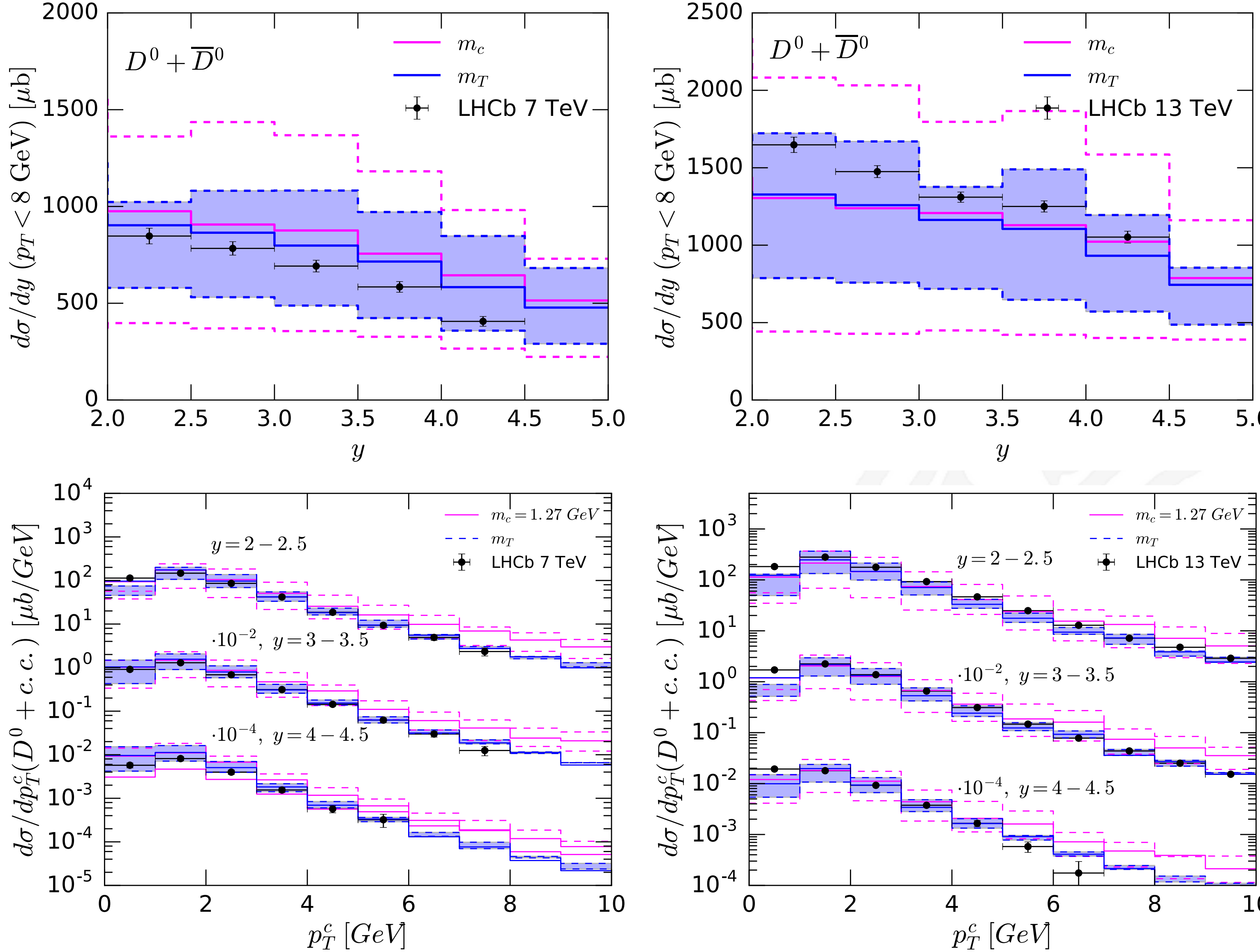
Cumulative fraction of Z-moment as function of xF:



Estimate: 90% of Z_{pD} given by

y > 4.9 for $E_p=10^6$ TeV
y > 5.7 for $E_p=10^7$ TeV

Comparison of NLO QCD



Data from LHCb: arXiv:1302.2864 and arXiv:1510.01707

Prompt ν_μ (=ν_e=μ) fluxes

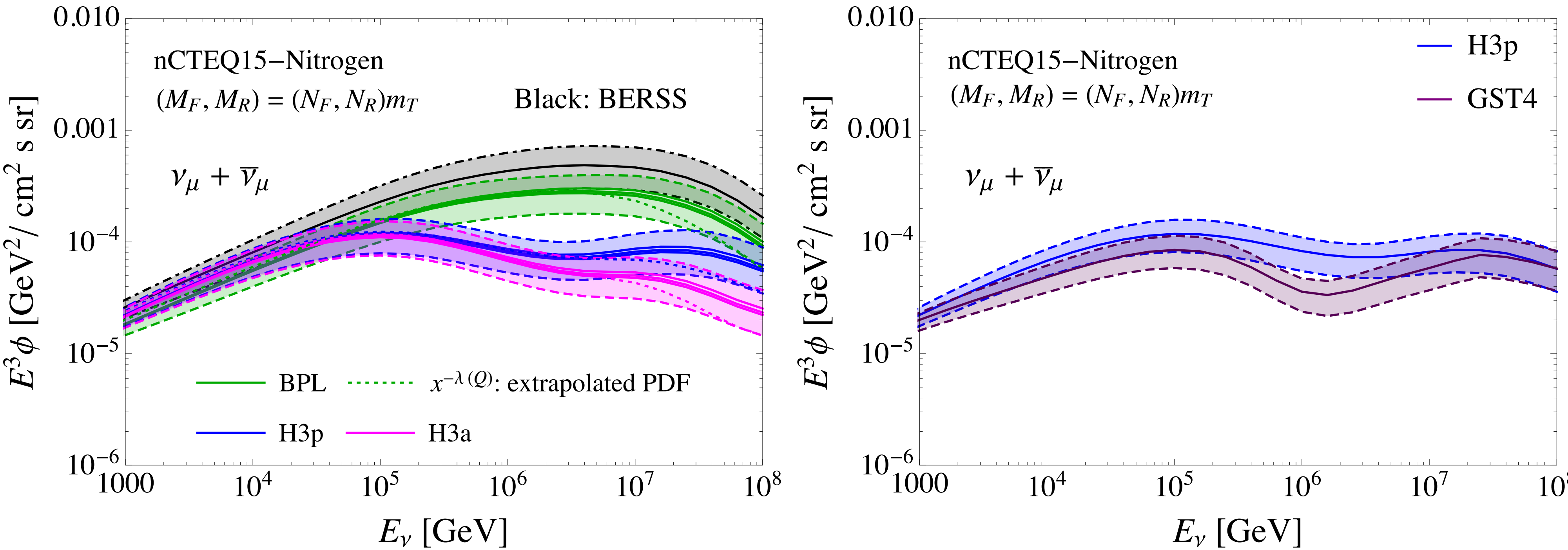
We have calculated prompt neutrino fluxes using all these variations in QCD, nuclear effects, cosmic ray fluxes.

Also compare to other calculations:

- RE, Reno, Sarcevic (ERS) 0806.0418
- Bhattacharya et al (BERSS), 1502.01076
- Garzelli, Moch, Sigl, 1506.08025
- Gauld, Rojo, Rottoli, Sarkar, Talbert, 1511.06346

→ estimate of theoretical uncertainties

NLO QCD

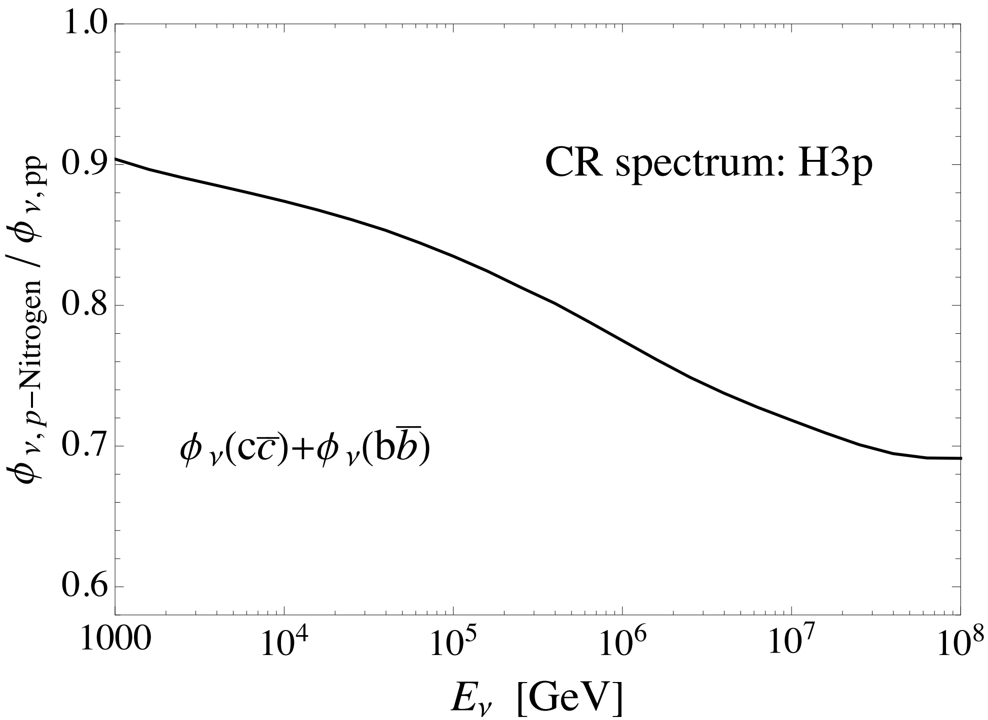


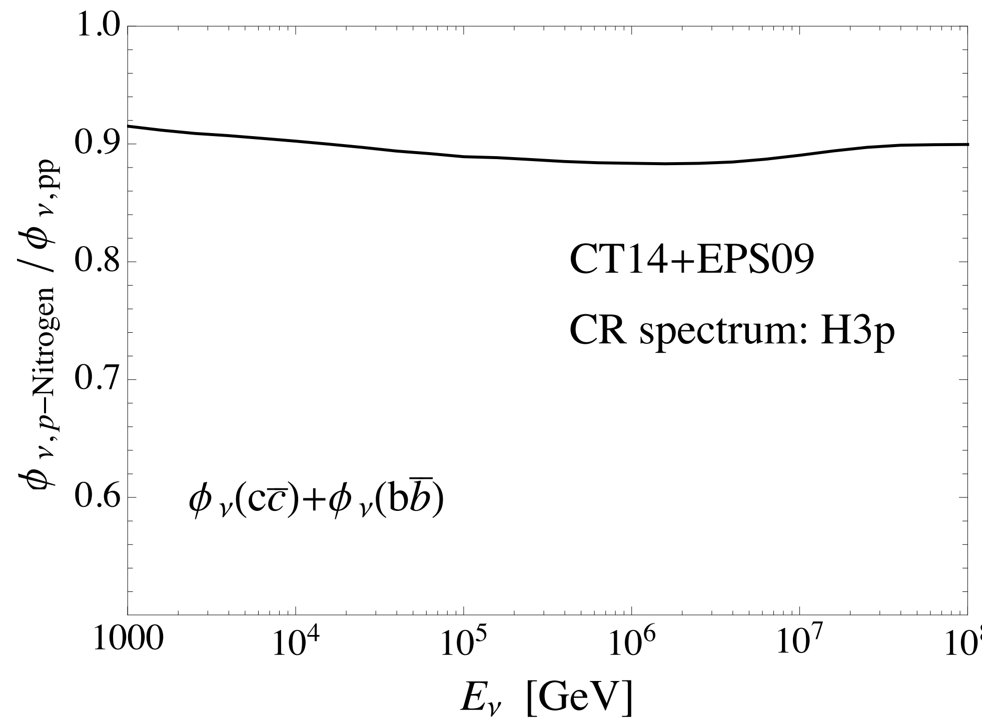
Compare with our BERSS NLO QCD and different cosmic ray fluxes

Difference to BERSS: bb now included, modified fragmentation fractions, nuclear effects (here: nCTEQ15)

Overall: (30%, 40%, 45%) lower than BERSS at (10^3, 10^6, 10^8) GeV

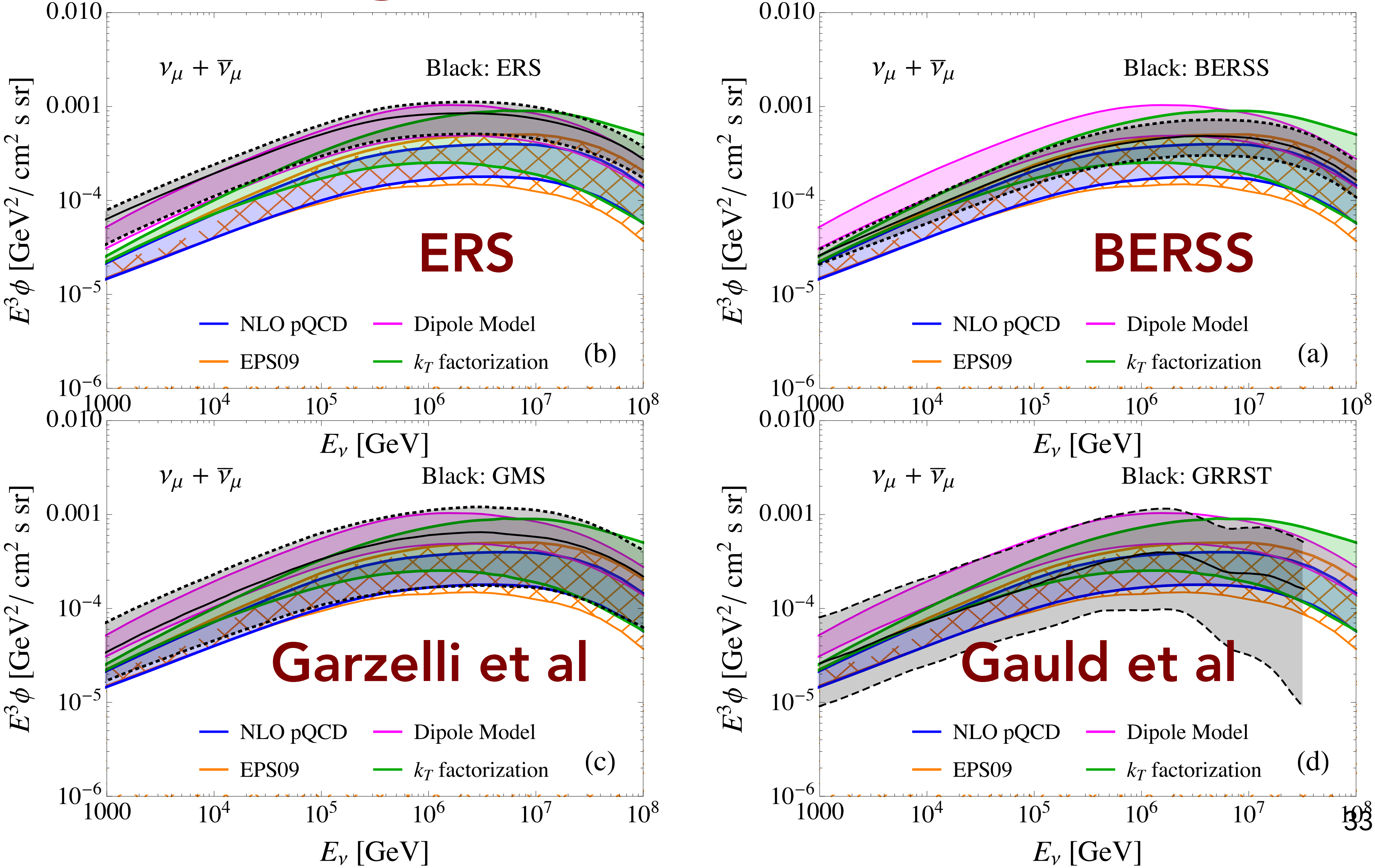
Influence of nuclear shadowing



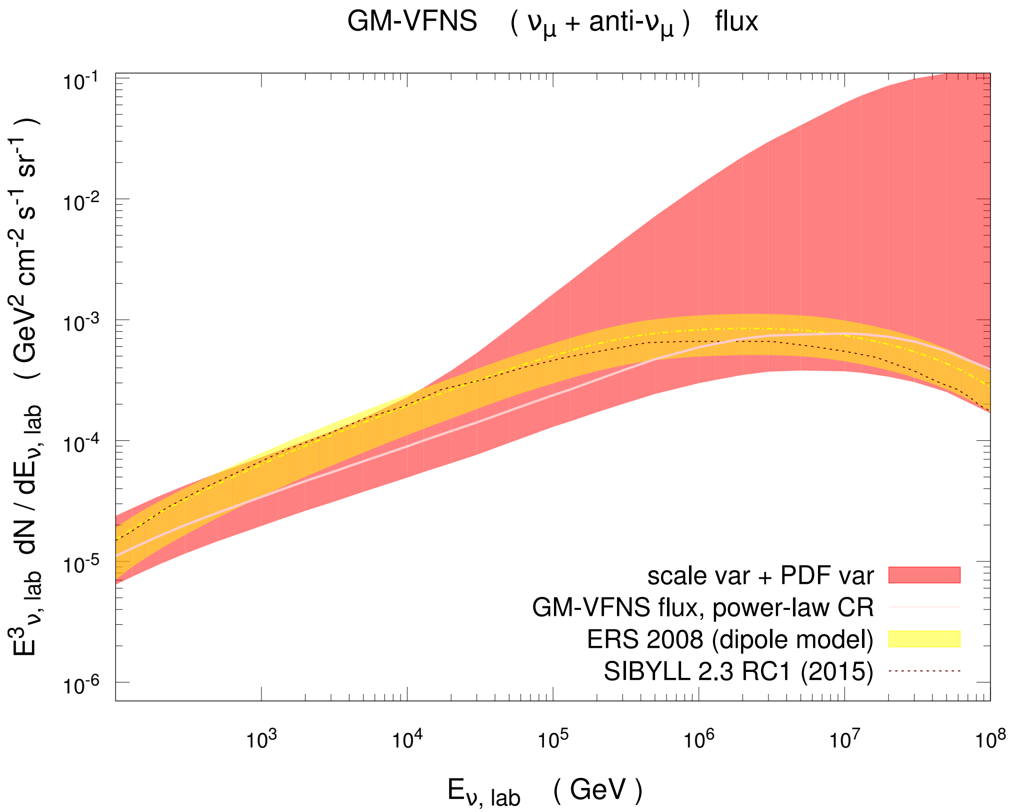


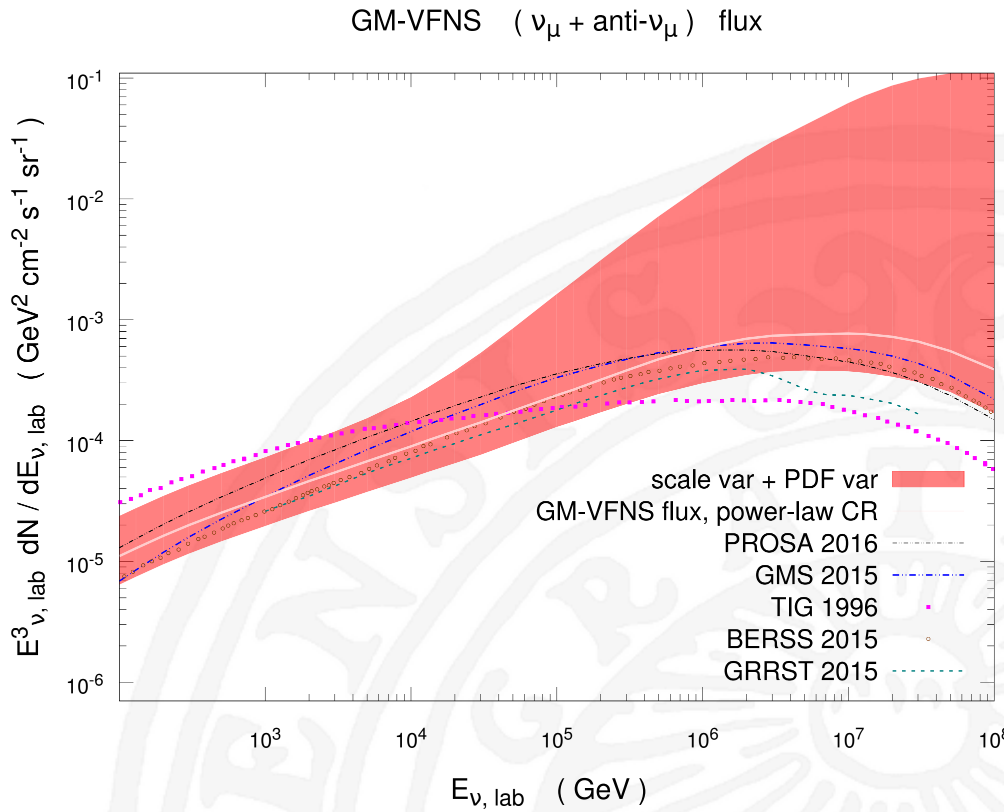
Ratio of NLO QCD flux with and without nuclear effects
→ 20–30% suppression from 10^5 to 10^8 GeV for nCTEQ
(only 4–13% for total cross section)
→ But much less for EPS (frozen at $x=10^{-6}$)

And now everything, using broken power law



Benzke et al GM-VFNS calculation

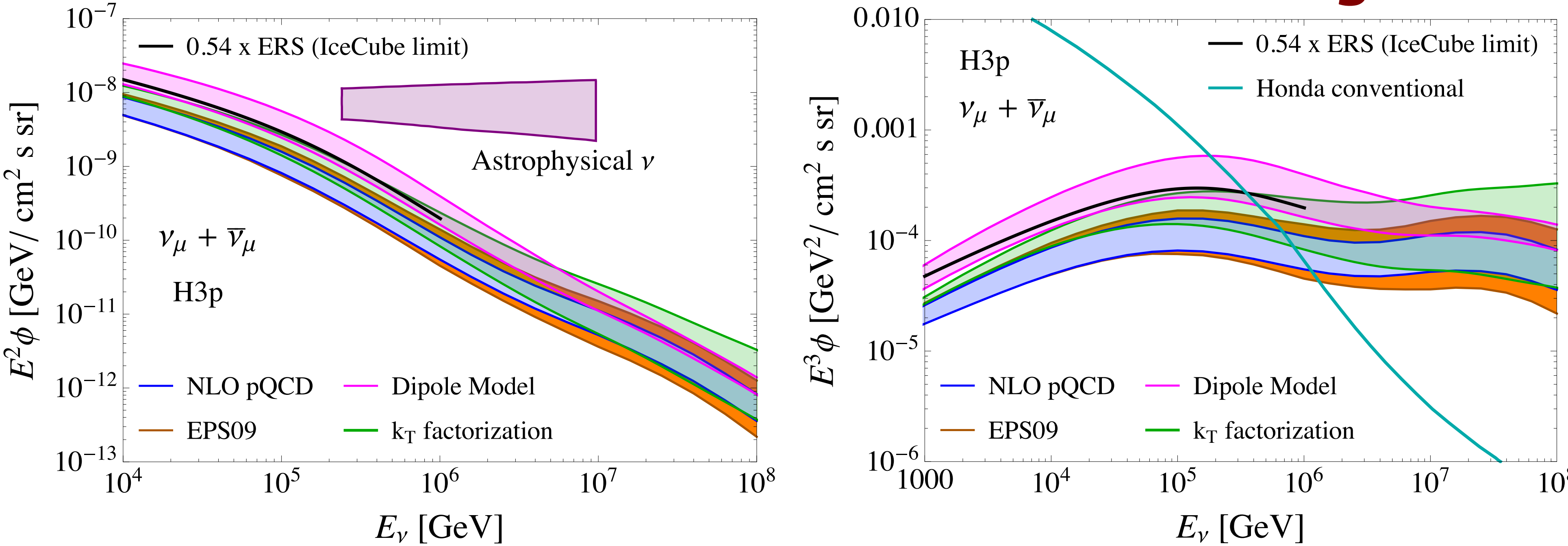




pQCD calculation in "General Mass – Variable Flavor Number Scheme" (GM-VFNS)
M. Benzke, M. V. Garzelli, B. Kniehl, G. Kramer, S. Moch, G. Sigl, arXiv:1705.10386

The large pdf uncertainty at large energy arises from a particular set of CTEQ pdf fits (ct14nlo) – not constrained by data (but other sets do not show this – situation unclear)

And what does IceCube say?



A recent IceCube limit (3 yrs) on the prompt flux sets a limit at 90% CL of

0.54 x (*ERS modified with H3p CR's*)

Best fit is still $\phi_{\text{prompt}} = 0$

L. Rädel & S. Schoenen (IceCube), PoS ICRC2015, 1079

Intrinsic charm

- "Normal" charm parton distribution is generated from gluon splittings
- There may be an "intrinsic" non-perturbative charm component in the nucleon
  [Brodsky, Hoyer, Peterson, Sakai, 1980]
- Would contribute charmed mesons at large xF
  [See e.g. Thunman et al; Bugaev et al.; Halzen and Wille…]

But there is hardly room in the data for that!
Or is there?

Conclusions

- The prompt neutrino flux poses one of the questions in neutrino astroparticle physics
  - How large is the flux?
  - Why hasn't it been discovered?
  - What is the proper way to calculate it?
- We think we know what we don't know – more accelerator and cosmic ray data needed!