The prompt atmospheric neutrino flux

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PPNT19, Uppsala, Oct 9, 2019

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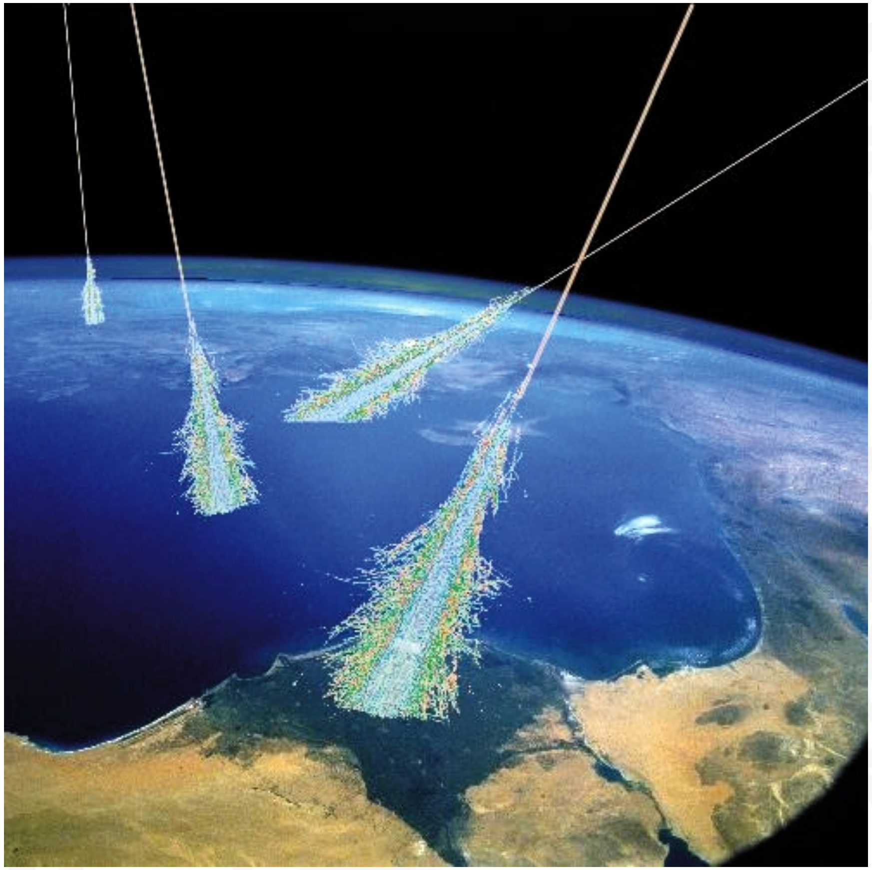
Atmospheric neutrinos

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



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($\pi^+ \rightarrow \mu^+ \nu_\mu$) = 99.98 %

- *But $\pi^\pm$, $K^\pm$ are long-lived* ($c\tau$ ~ 8 meters for π^+)

  $\Rightarrow$ lose energy through collisions before decay

  $\Rightarrow$ 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

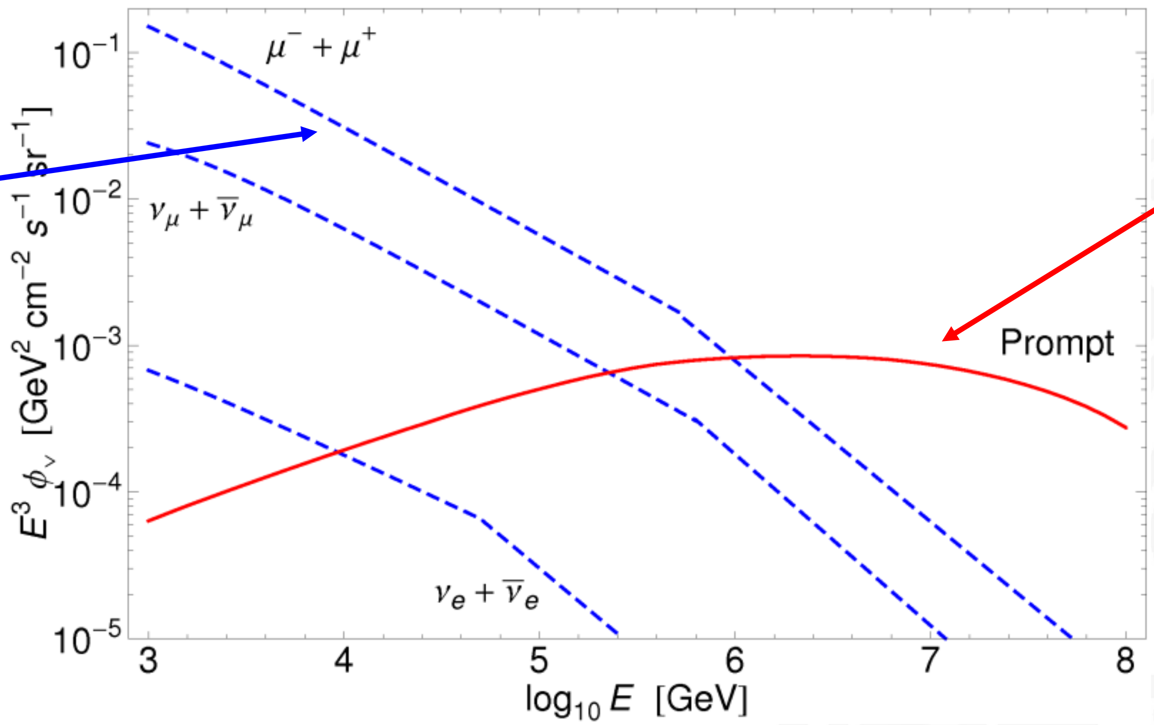
- However, production cross-section is much smaller

- 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

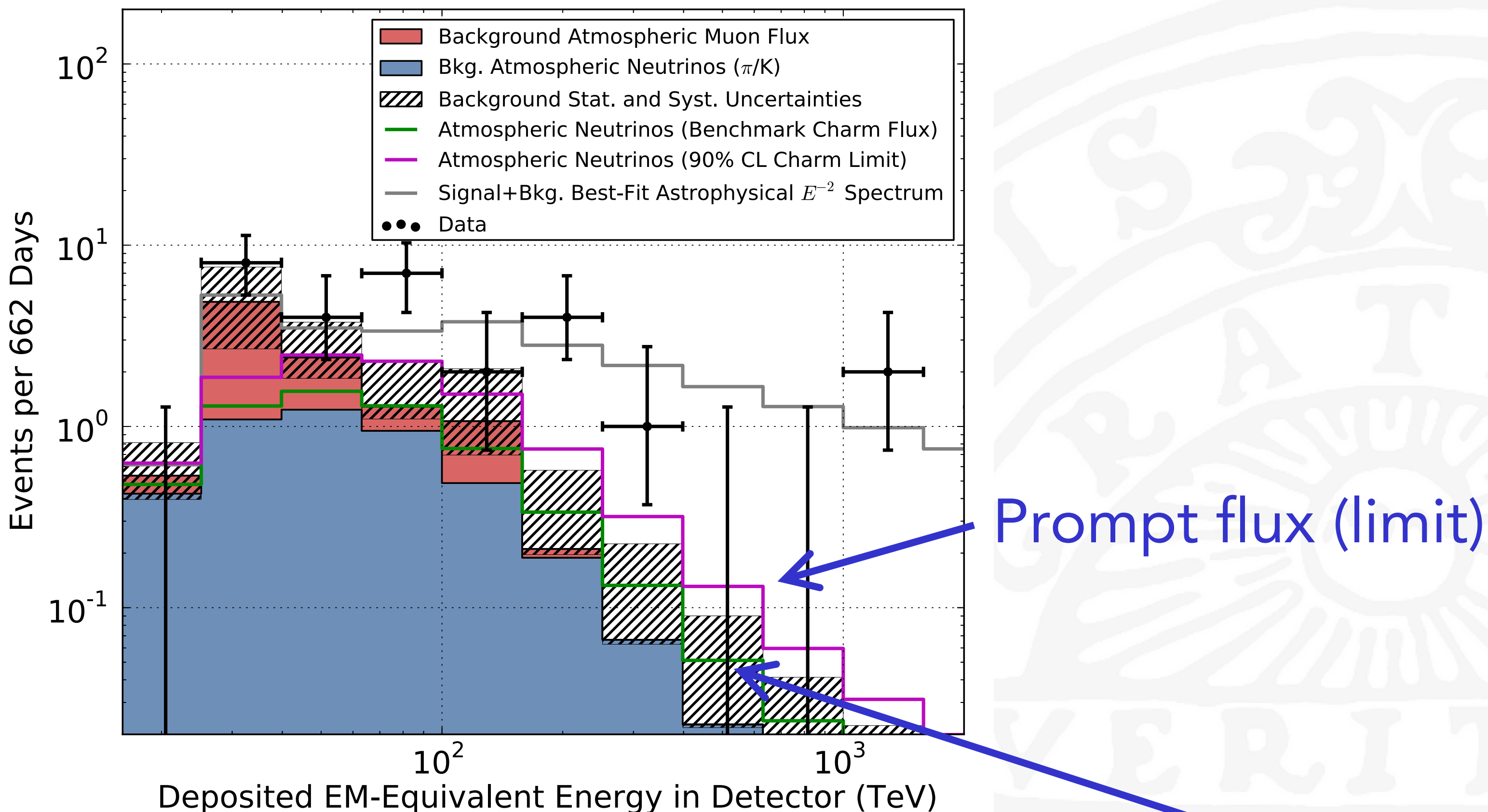
Prompt flux: Enberg, Reno, Sarcevic, arXiv:0806.0418 **(ERS)**
Conventional: Gaisser & Honda, Ann. Rev. Nucl. Part. Sci. **52,** 153 (2002)

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?

The IceCube events from 2013

The significance is sensitive to the prompt flux prediction



IceCube, arXiv:1311.5238

Calculations of the prompt flux

More recent:

Bhattacharya, RE, Reno, Sarcevic, Stasto, arXiv:1502.01076 **(BERSS)**

Garzelli, Moch, Sigl, arXiv:1507.01570 **(GMS)**

Gauld, Rojo, Rottoli, Sarkar, Talbert, arXiv:1511.06346 **(GRRST)**

Bhattacharya, RE, Jeong, Kim, Reno, Sarcevic, Stasto, arXiv:1607.00193 **(BEJKRSS)**

PROSA Collaboration (Garzelli et al), arXiv:1611.03815

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

Older but widely used:

Thunman, Ingelman, Gondolo, hep-ph/9505417

Pasquali, Reno, Sarcevic, hep-ph/9806428

Martin, Ryskin, Stasto, hep-ph/0302140 **(MRS)**

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

Calculations of the prompt flux

Compare with

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Important message

QCD is crucial for some astrophysical processes:

- Atmospheric neutrinos
- Neutrino-nucleon cross-section @ high energy
- (Interactions in astrophysical sources?
  See arXiv:0808.2807 and arXiv:1407.2985)

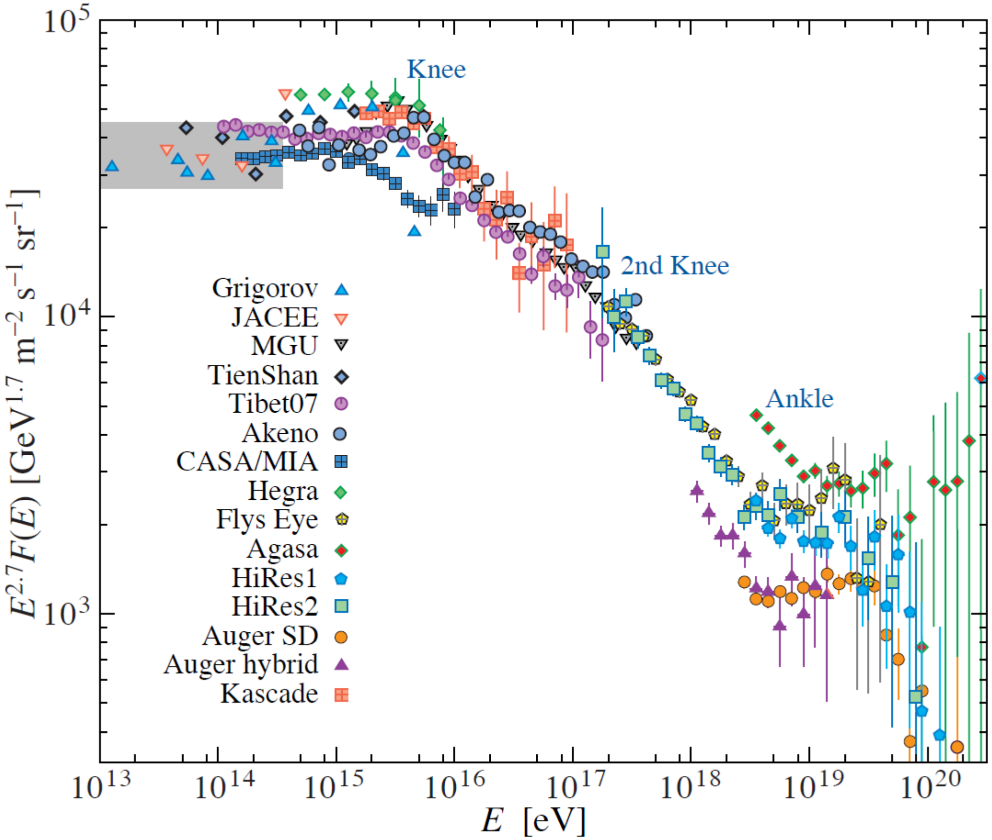
For example:

- What happens at **small Bjorken-x**? (Need very small x)
- **Forward** region (Hard to measure at colliders)
- **Fragmentation** of quarks → hadrons (Non-perturbative, hard meas.)
- **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)

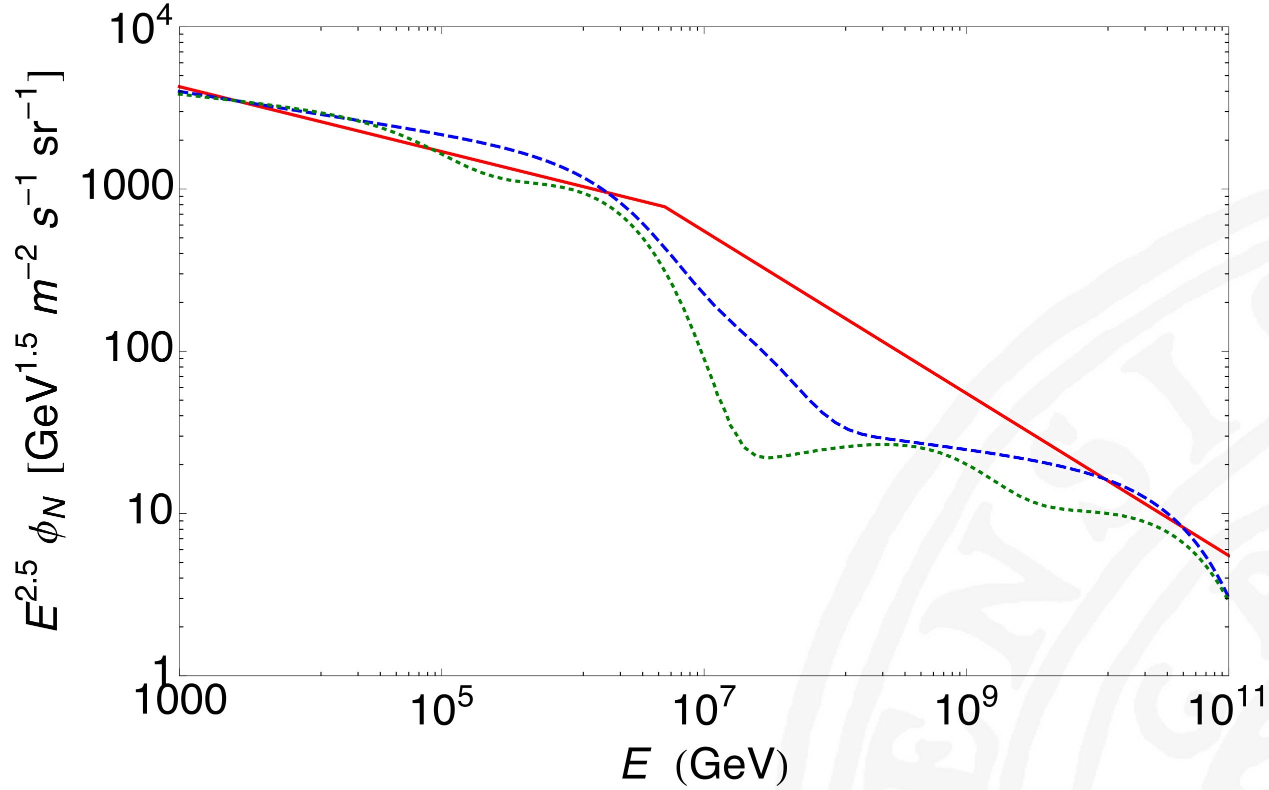
Cosmic rays (CR)



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

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

$x_F=1$:	$E=10^5 \rightarrow x \sim 4\cdot10^{-5}$	$x_F=0$:	$E=10^5 \rightarrow x \sim 6\cdot10^{-3}$
	$E=10^6 \rightarrow x \sim 4\cdot10^{-6}$		$E=10^6 \rightarrow x \sim 2\cdot10^{-3}$
	$E=10^7 \rightarrow x \sim 4\cdot10^{-7}$		$E=10^7 \rightarrow x \sim 6\cdot10^{-4}$

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

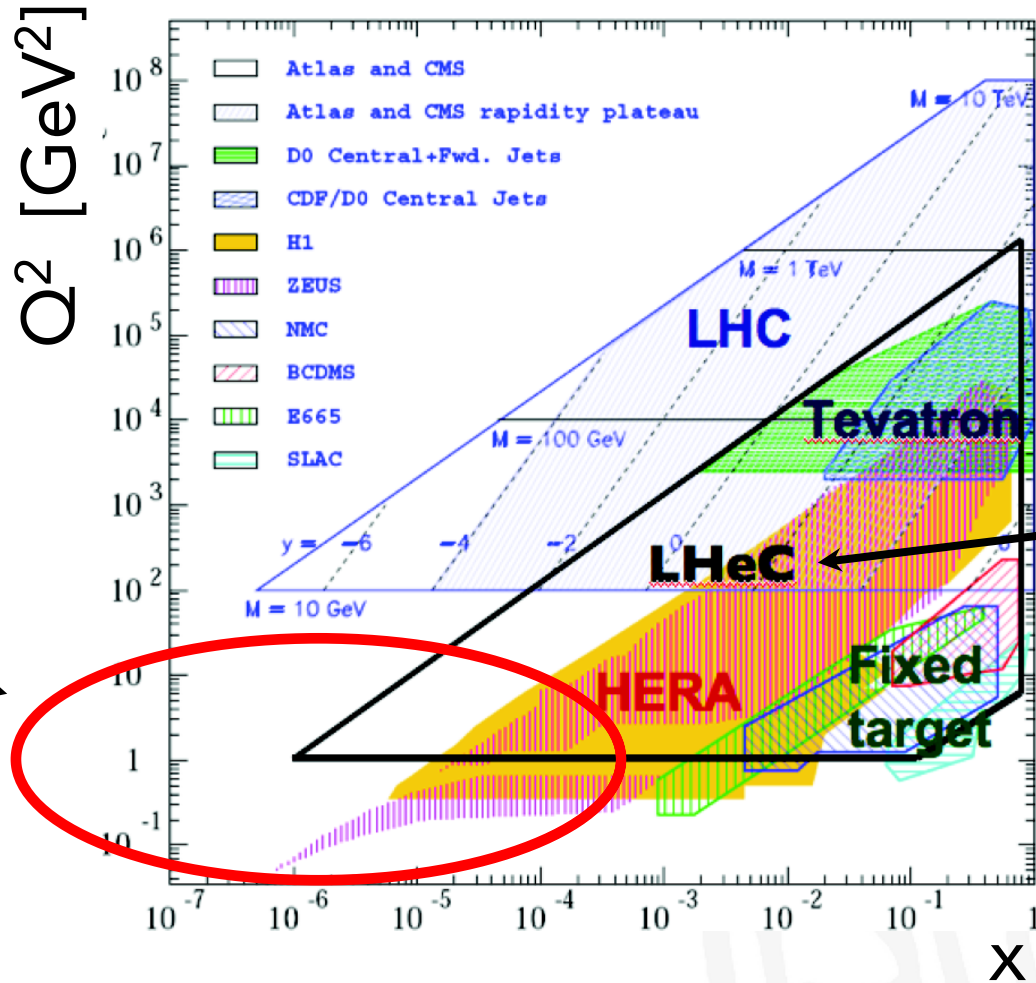
Problem with QCD at small x

- 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

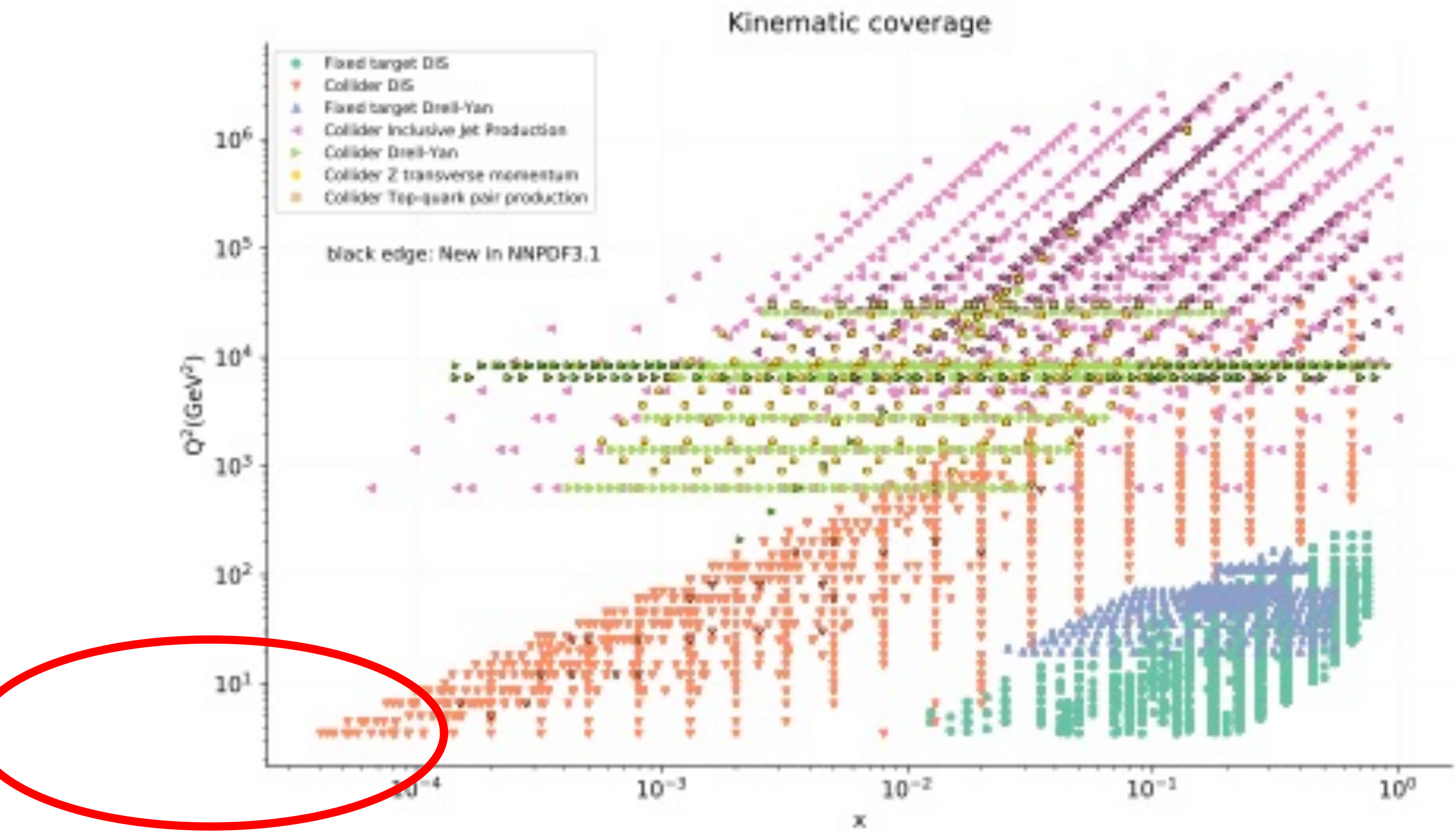


Where we need pdfs

Note LHeC!

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

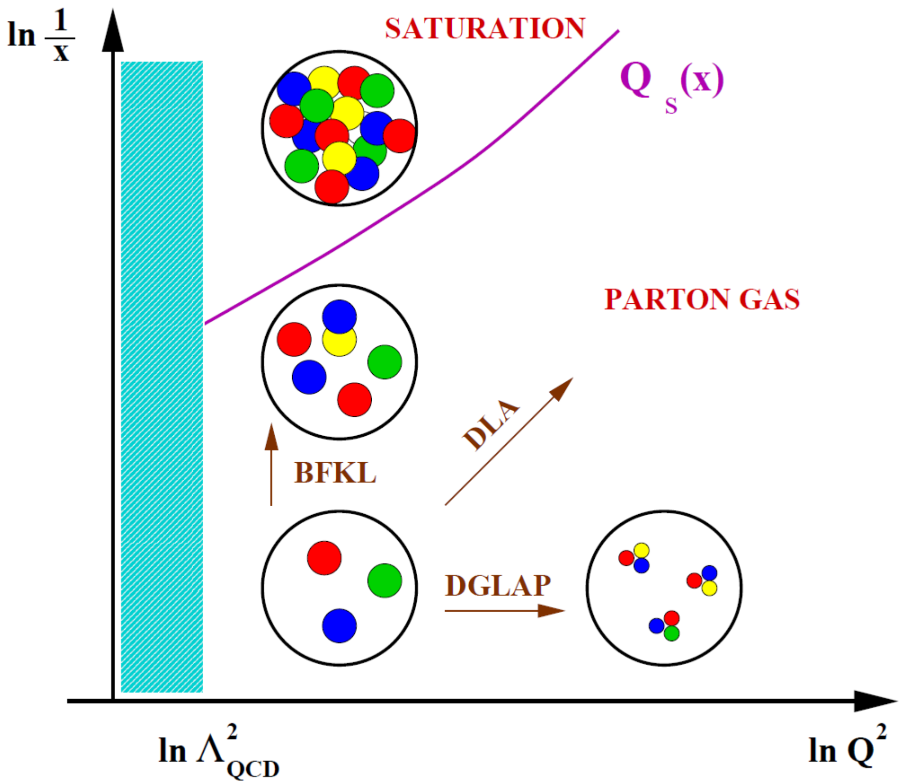
Kinematic plane of NNPDF3.1



R.D. Ball et al, arXiv:1706.00428

Parton saturation

- *Saturation* at small x:
  - 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 many ways

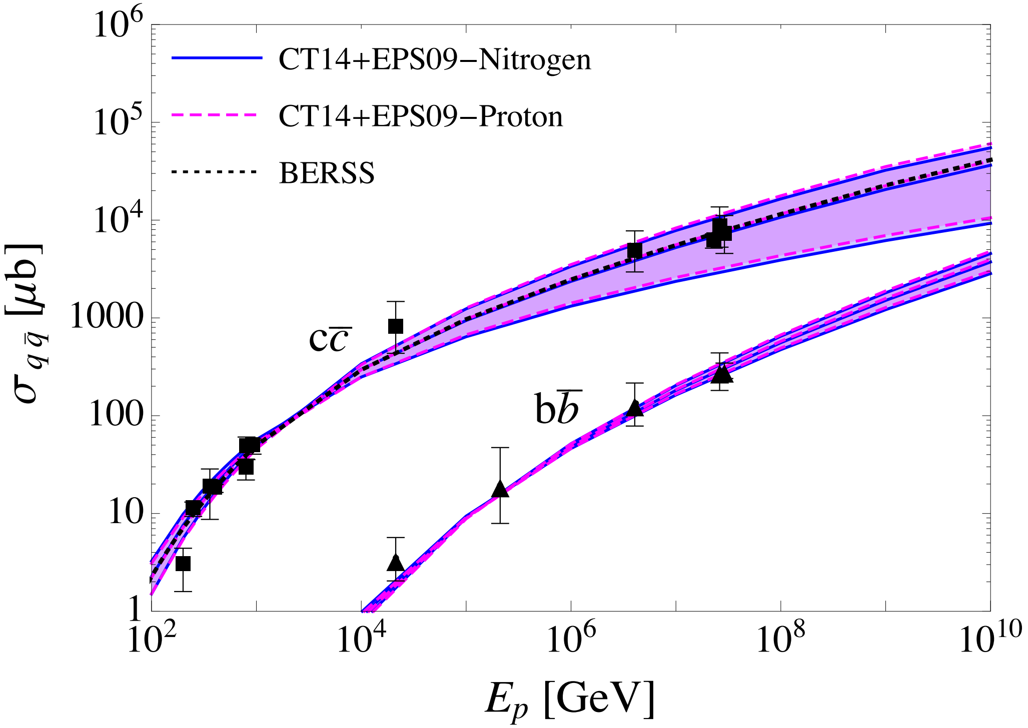
- ***Standard NLO QCD with newest PDFs***
  - BERSS updated with RHIC/LHCb input, uses Nason, Dawson, Ellis and Mangano, Nason, Ridolfi
- ***Dipole picture with saturation***
  - Approximate solution of Balitsky-Kovchegov equation
  - Update of ERS calc with new HERA fits + other dipoles
- ***kT factorization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

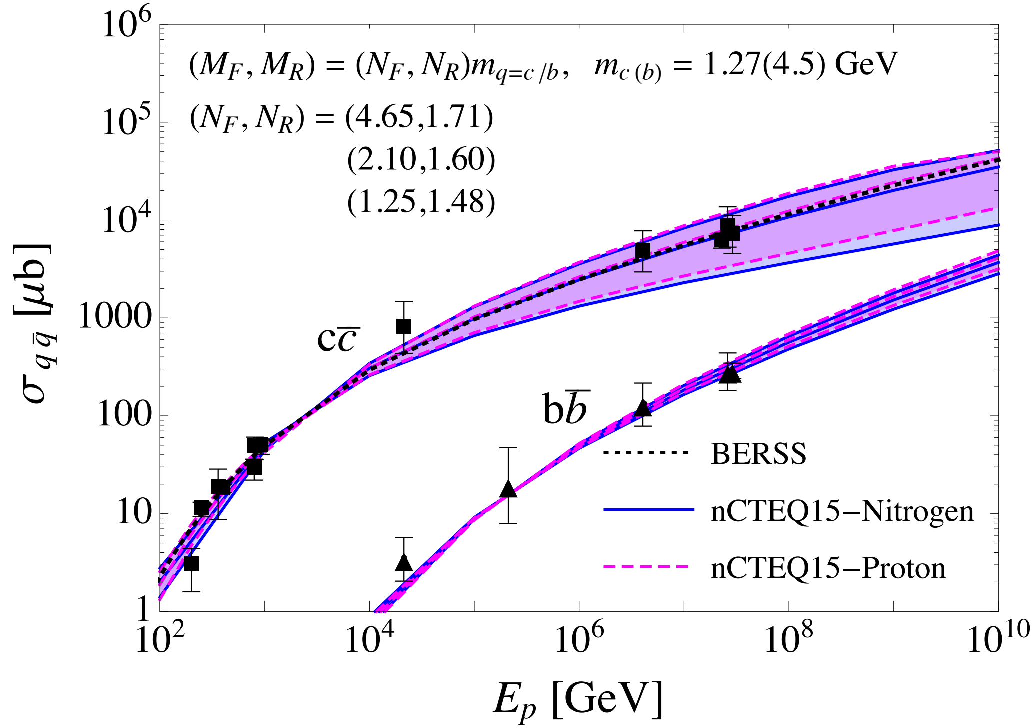
Include scale variations, PDF errors, charm mass, etc
→ Plausible upper and lower limits on xsec

Also include nuclear shadowing

- Partons are not in a free nucleon, but in a nucleus!
- Estimate shadowing with nuclear PDFs (nCTEQ15 and EPS09)
- Reduces flux by 10–30% at the highest energies
- Larger effect 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)

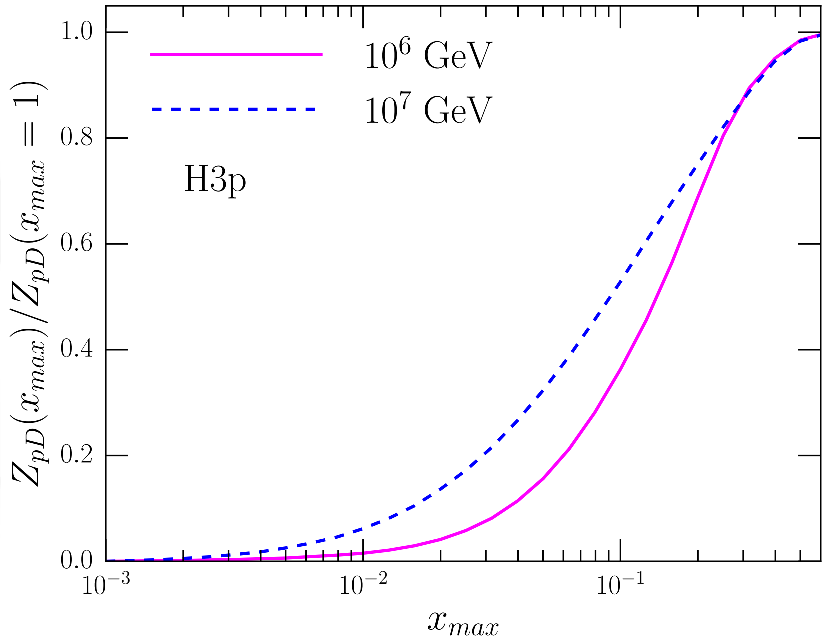
Differential cross sections (LHCb)

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***.

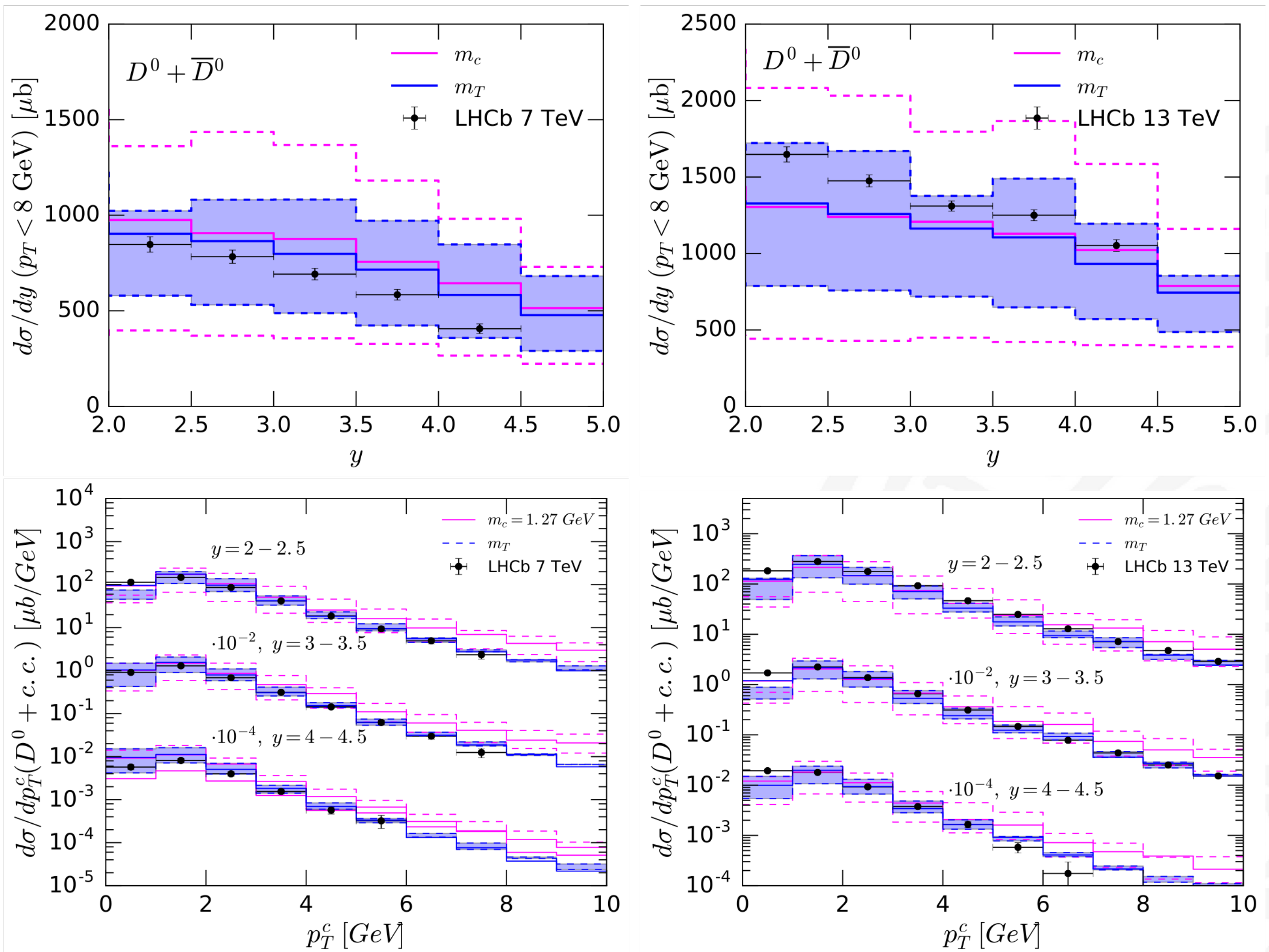
Cumulative fraction of Z-moment as function of xF:



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 ($=\nu_e=\mu$) fluxes

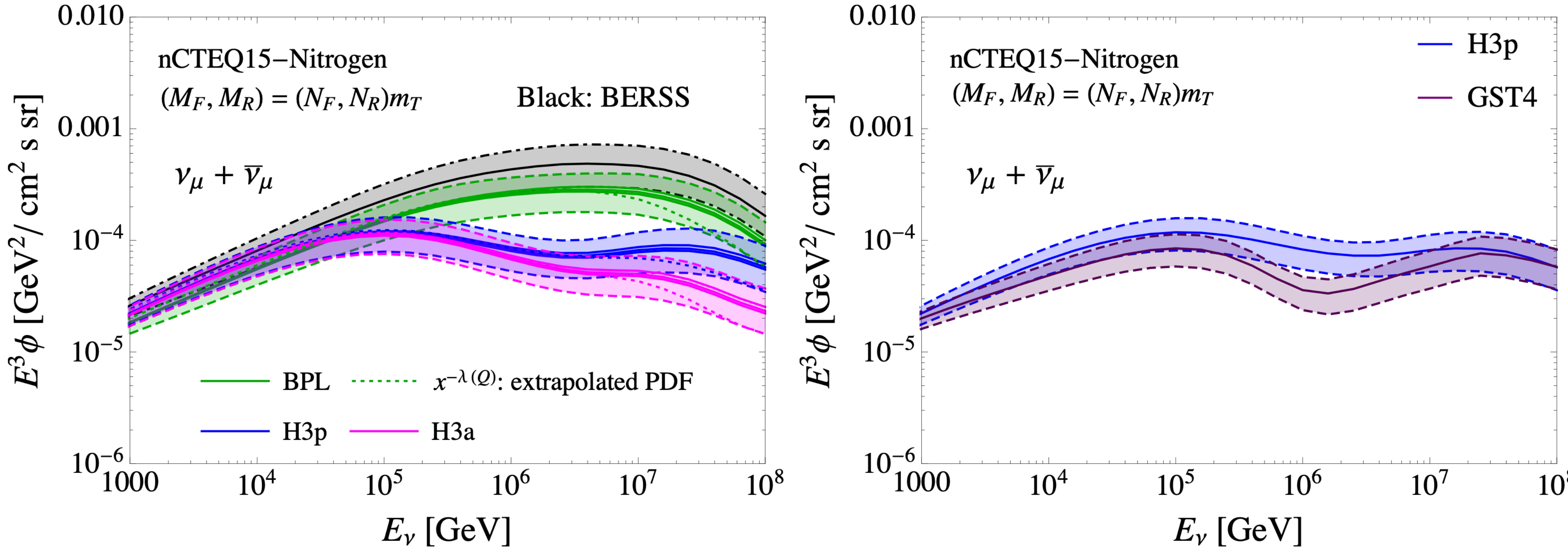
We have calculated prompt neutrino fluxes using all these variations in QCD, nuclear effects, cosmic ray fluxes.

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

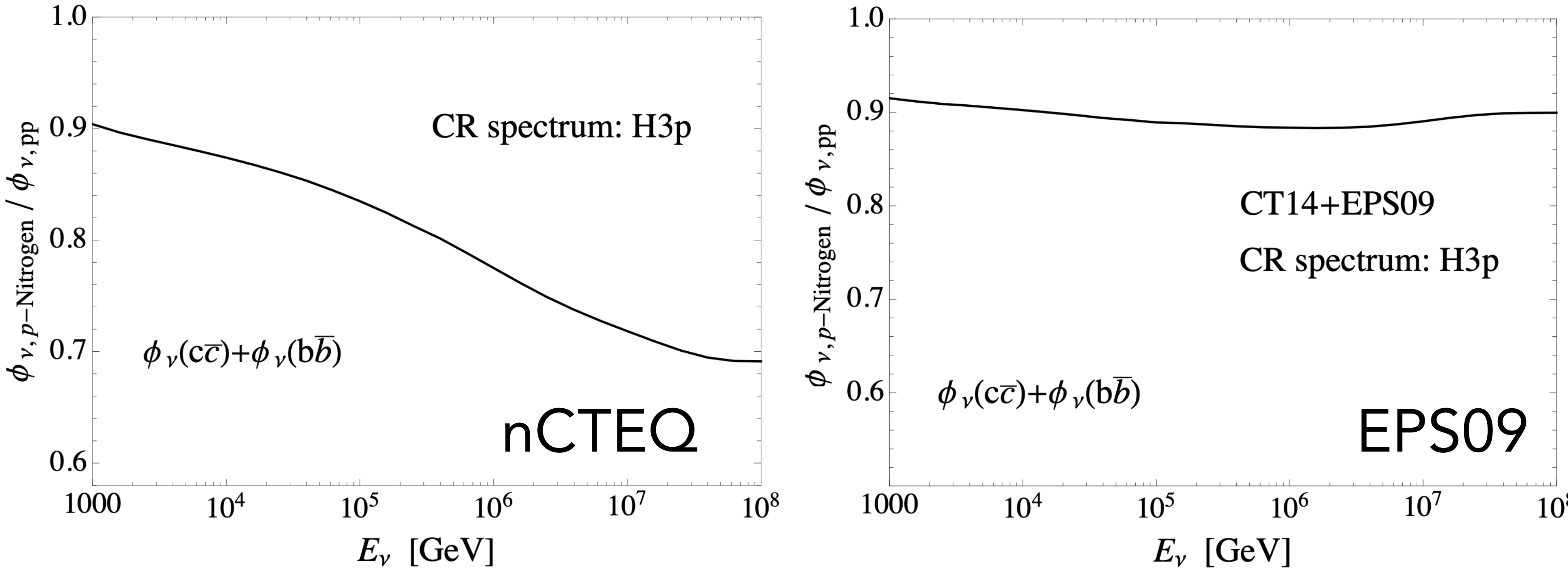


Compare with our BERSS NLO QCD and different cosmic ray fluxes

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



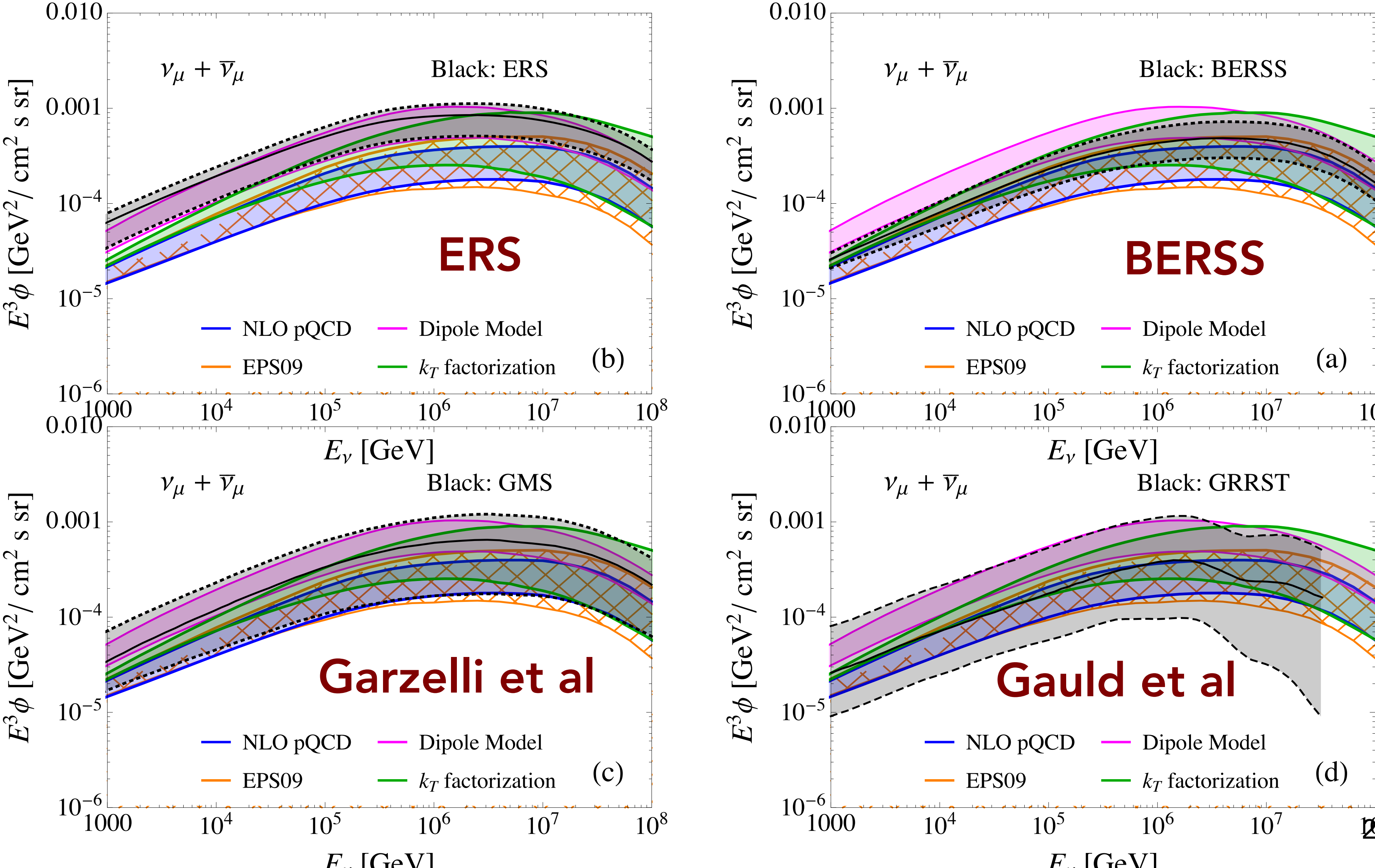
Ratio of NLO QCD flux with and without nuclear effects

→ 20–30% suppression from 10^5 to 10^8 GeV for nCTEQ

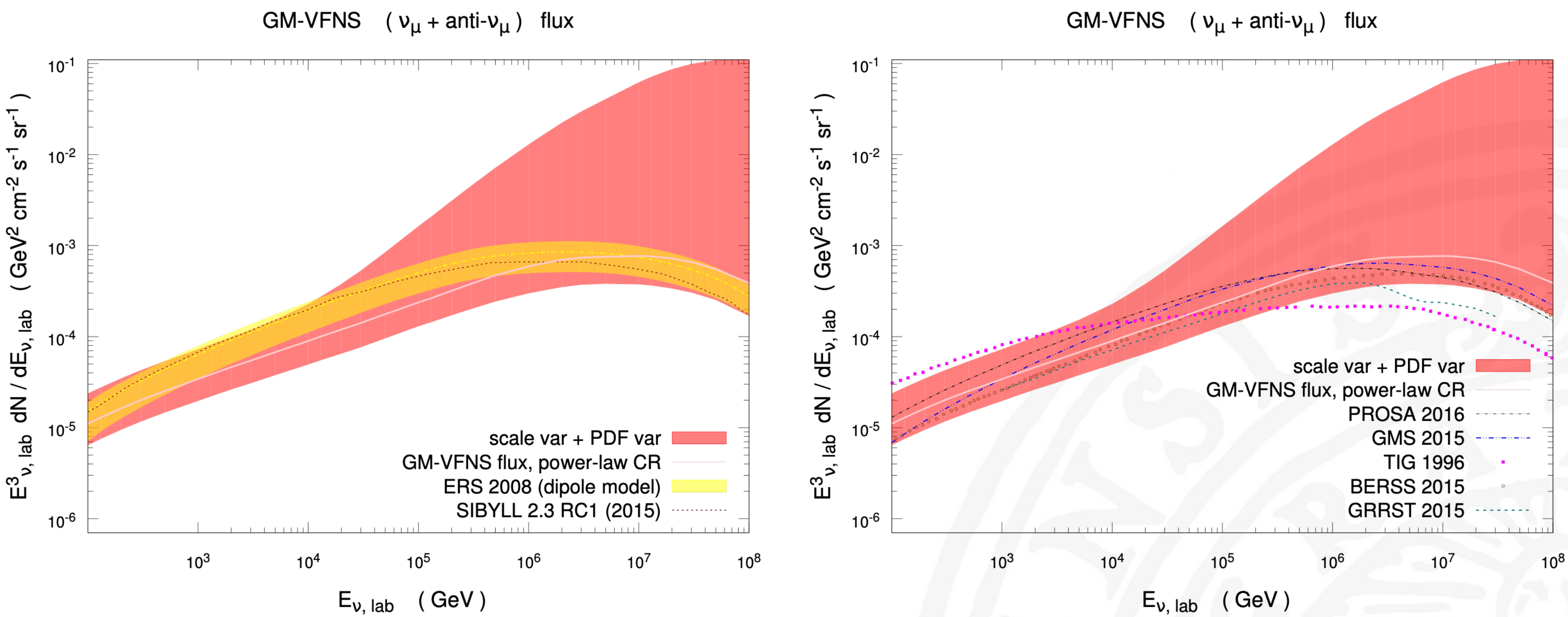
(only 4–13% for total cross section)

→ But much less for EPS (frozen at $x=10^{-6}$)

And now everything, using broken power law



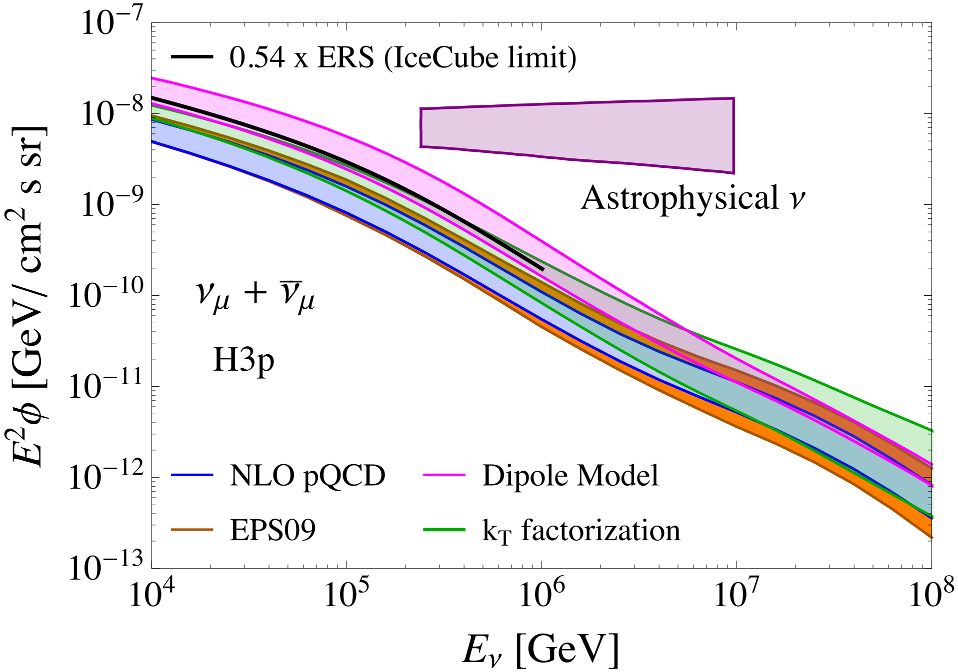
Benzke et al GM-VFNS calculation

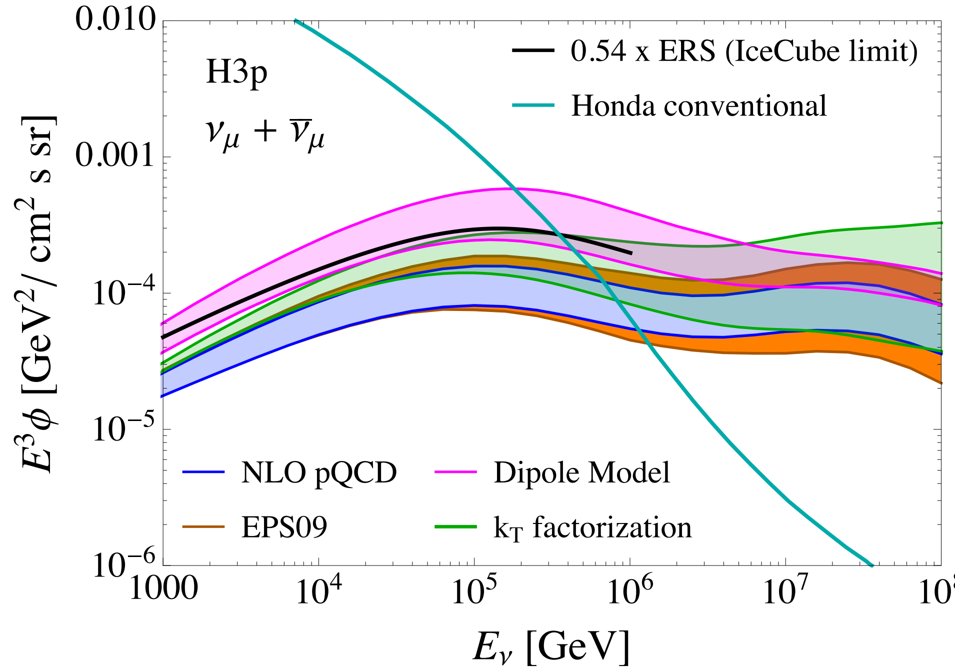


pQCD calculation in “General Mass–Variable Flavor Number Scheme” (GM-VFNS)
M. Benzke, M. V. Garzelli, B. Kniehl, G. Kramer, S. Moch, G. Sigl, arXiv:1705.10386

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

And what does IceCube say?





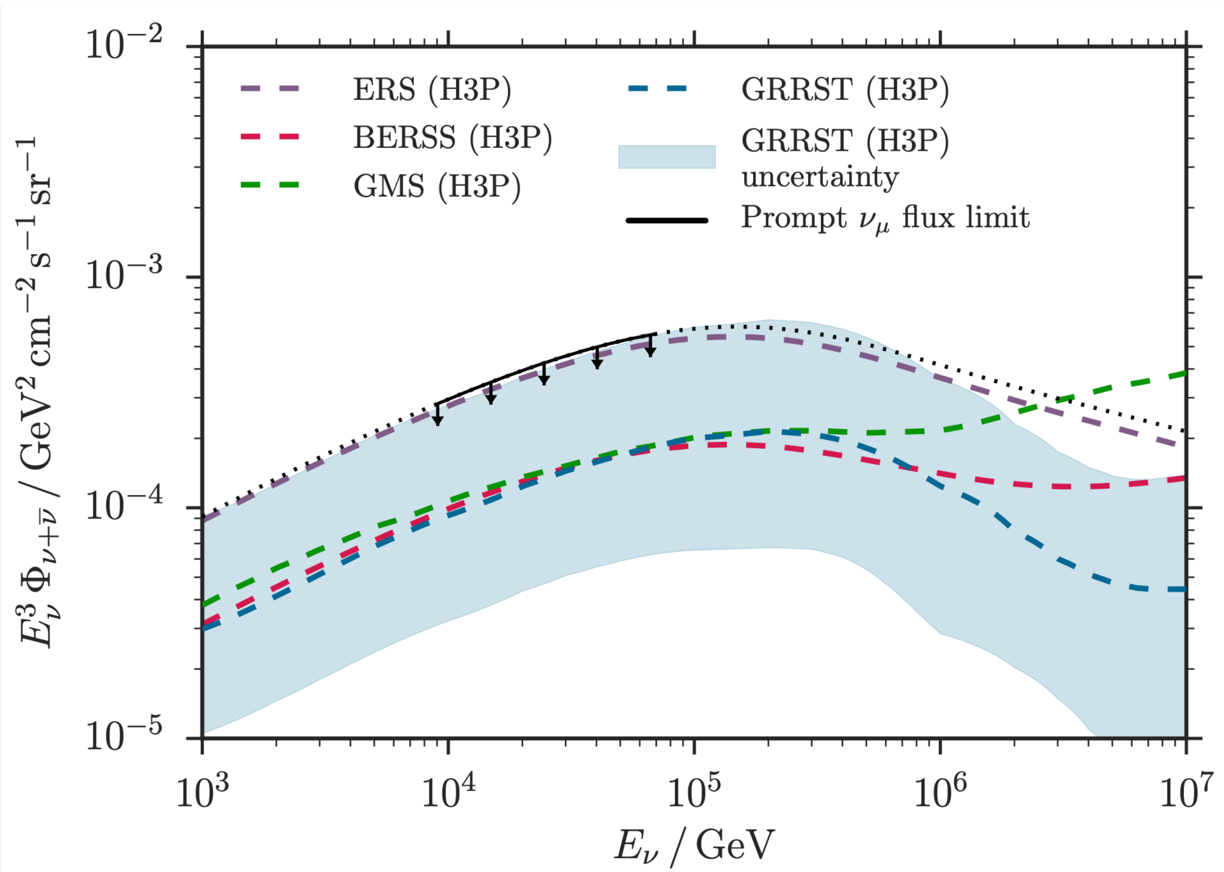
One IceCube limit (3 yr data) on the prompt flux sets a limit at 90% CL of

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

Best fit is $\Phi_{prompt} = 0$

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

Another IceCube analysis (6 yrs)



IceCube, arXiv:1607.08006

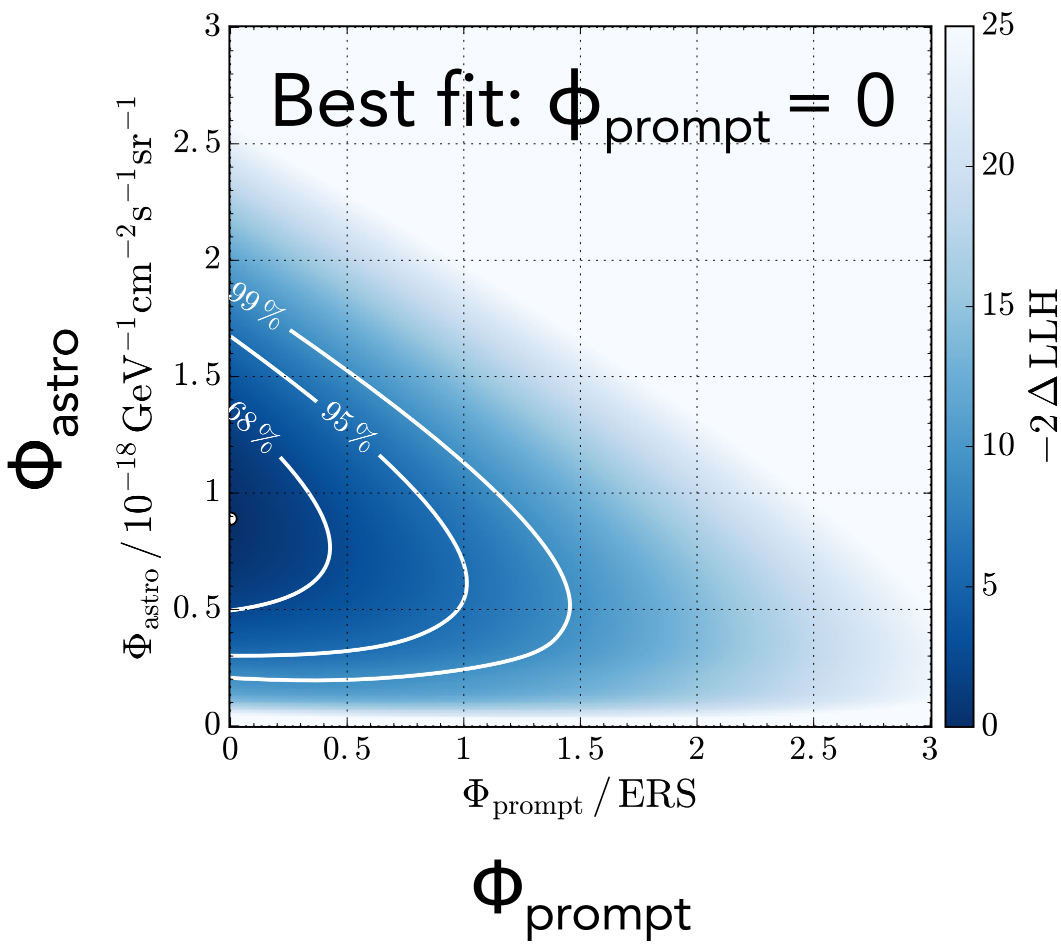
Limits on various calculations:

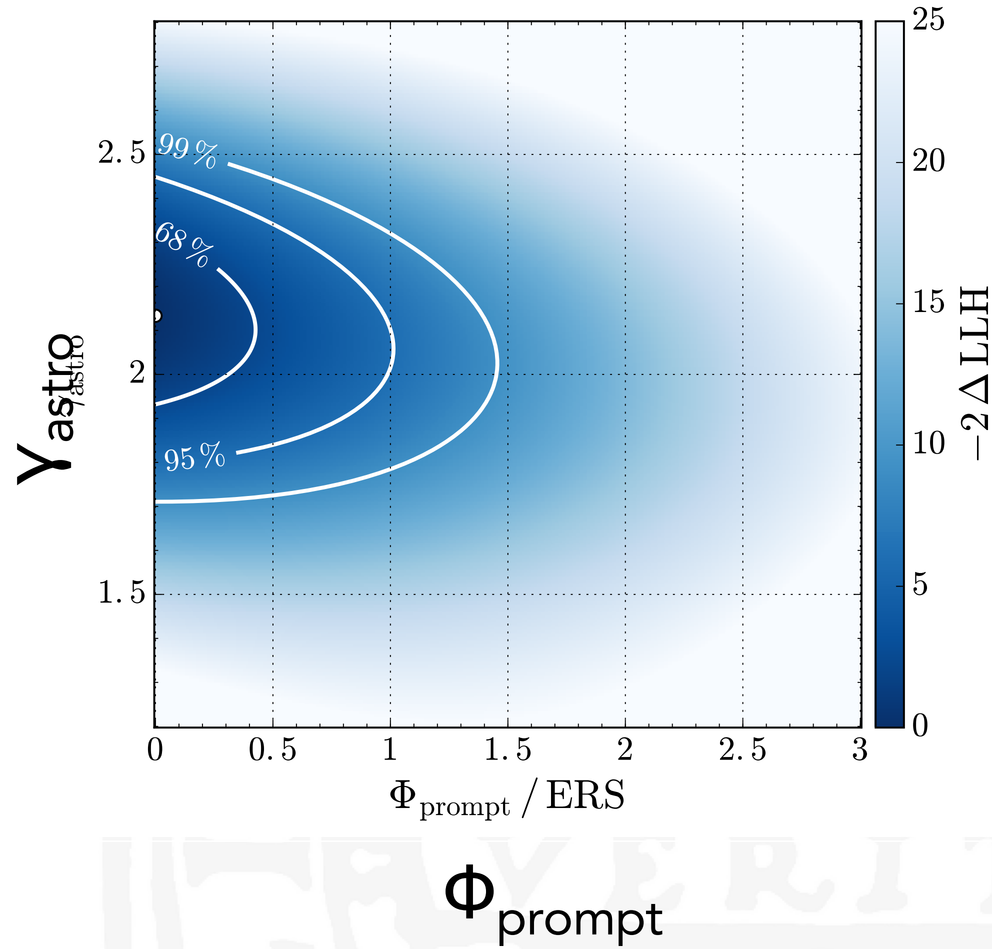
Model	Flux limit
ERS (H3p)	1.06
GMS (H3p)	≈ 2.9
BERSS (H3p)	≈ 3.0
GRRST (H3p)	≈ 3.1

Limit: $1.06 \times$ ERS

Best fit: $\phi_{prompt} = 0$

IceCube fits to Φ_{astro} and Φ_{prompt}





IceCube, arXiv:1607.08006

IceCube angular analysis:

Sample	Best Fit (ERS)	1σ Interval (90% CL)	$\sigma(\Phi_{prompt} > 0)$
Uncorrected	4.93	4.05-5.87 (3.55-6.56)	9.43
Marginalized Ang. Corr.	3.19	1.64-5.48 (0.98-7.26)	3.46

- Best fit $\Phi_{prompt} = 3.19 \times$ ERS
- 0.98–7.26 × ERS @ 90% CL
- $\Phi_{prompt} = 0$ excluded at 3.46σ

IceCube, arXiv:1506.07981

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 about how to calculate it – more accelerator and cosmic ray data needed!