The atmospheric neutrino flux and prompt neutrinos

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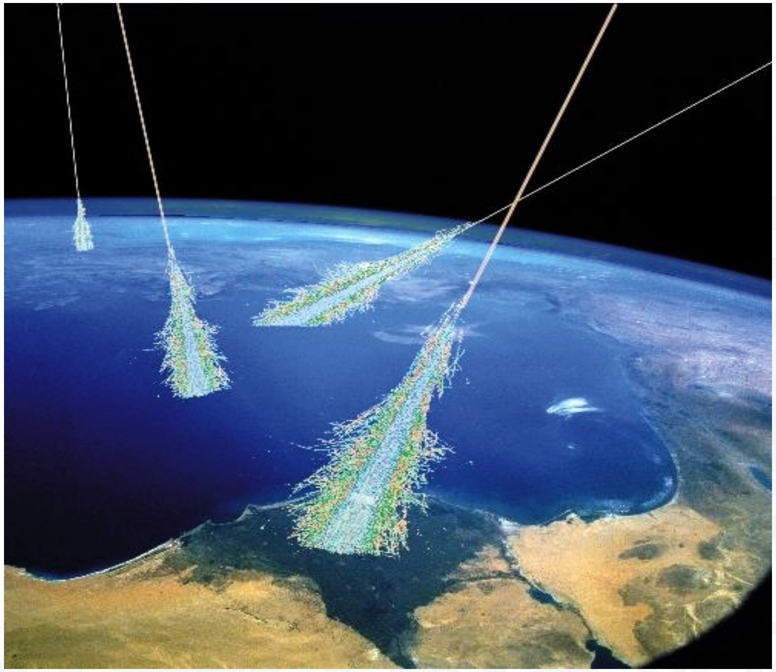
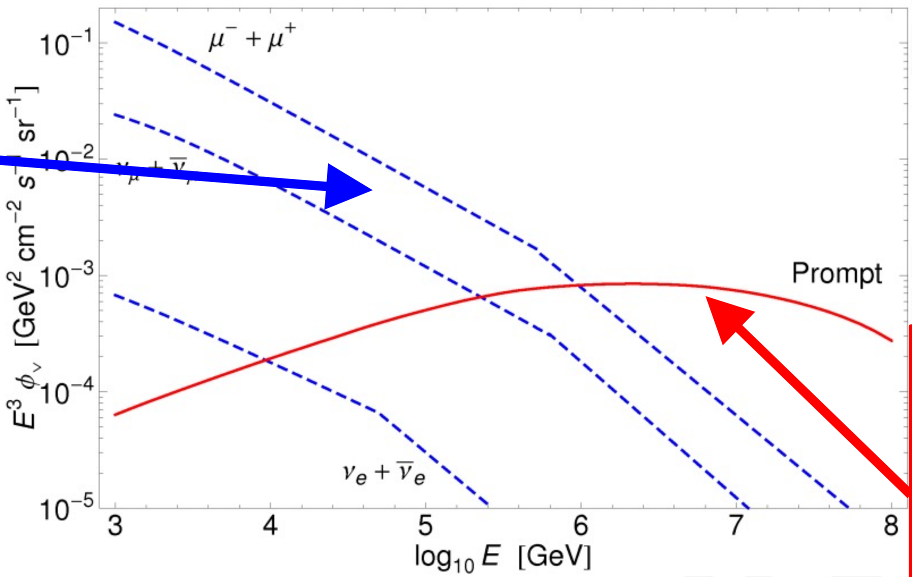
Atmospheric neutrinos

- Cosmic rays hit upper atmosphere, collide with air
- Very large energy → hadron production: pions, kaons, charm
- Semileptonic decays
  ⇒ neutrino flux



Astropic of the day, 060814

Pions: long-lived
⇒ lose energy
⇒ **conventional flux**



Charm: short-lived
⇒ don't lose energy
⇒ **prompt flux**

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:
  $\Rightarrow$ decay before losing energy
  $\Rightarrow$ 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***

Why are we interested?

- Atmospheric neutrinos are a large background to cosmic neutrinos at very high energies

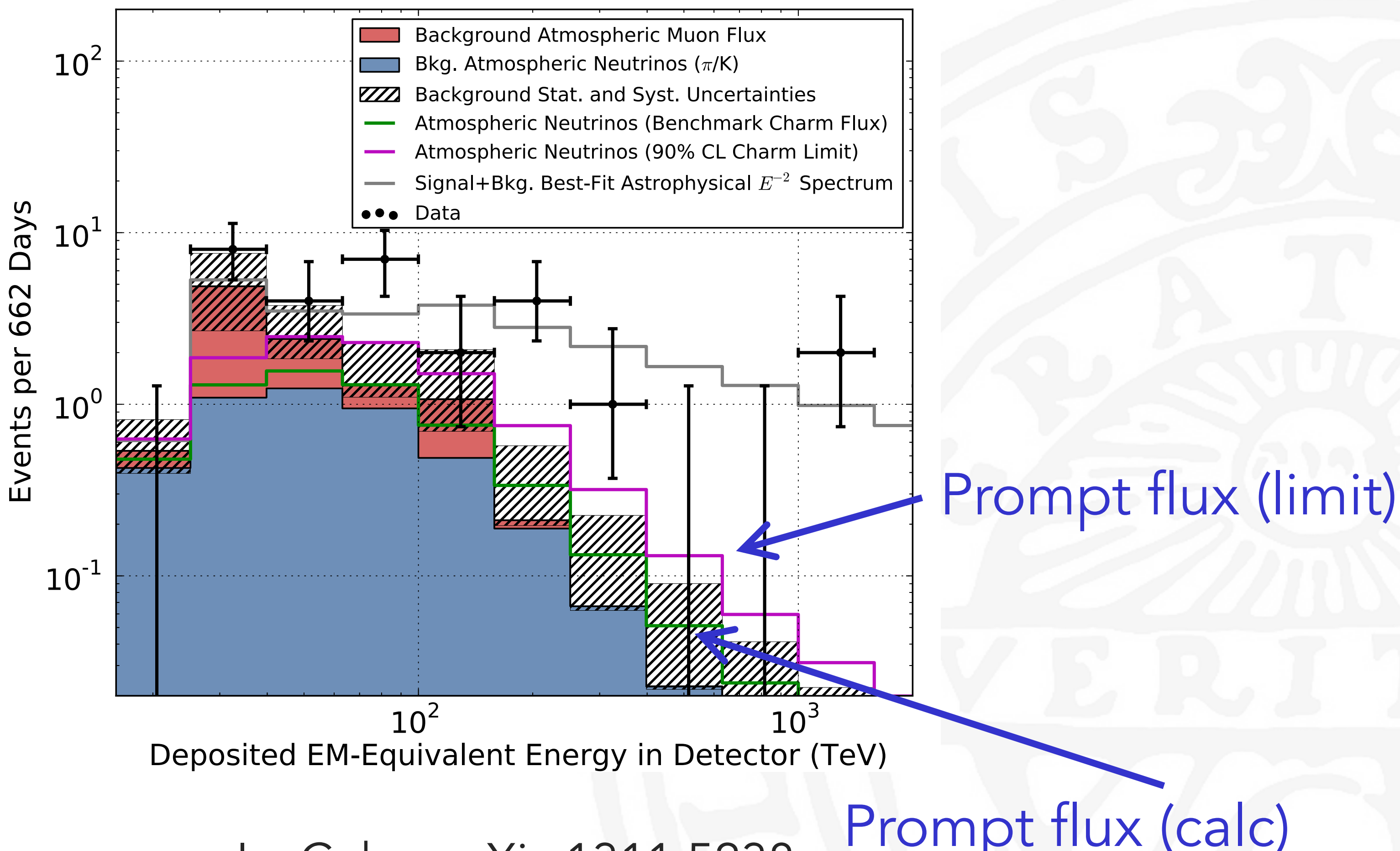
- Thus need to understand atmospheric neutrinos in order to study astrophysical sources

- Learn about atmospheric cascades and the underlying production mechanism

- Higher energy pp collisions than in LHC:
  can maybe even learn something about QCD?

IceCube discovery of cosmic neutrinos from 2013

Significance was sensitive to the prompt flux prediction



IceCube, arXiv:1311.5238

Important message

QCD is crucial for prompt neutrinos:

- **Small Bjorken-x** (Need very small x)
- **Forward** region (Hard to measure at colliders)
- **Fragmentation** of quarks $\rightarrow$ hadrons (Non-perturbative, hard to measure)
- **Nuclear effects** in pA hard interactions

FPF may help with some of these!

The calculation has many ingredients

- Incident cosmic ray flux
- ***Forward cross section for heavy quarks in pp/pA collisions at extremely high energy (pQCD)***
- ***Fragmentation of heavy quarks into hadrons***
- 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)

Calculations of the prompt flux

ERS: RE, Reno, Sarcevic, arXiv:0806.0418

Bhattacharya, RE, Reno, Sarcevic, Stasto, arXiv:1502.01076

Fedynitch, Engel, Gaisser, Riehn, Stanev, arXiv:1503.00544

Garzelli, Moch, Sigl, arXiv:1507.01570

Gauld, Rojo, Rottoli, Sarkar, Talbert, arXiv:1506.08025, 1511.06346

Halzen and Wille, arXiv:1605.01409

Bhattacharya, RE, Jeong, Kim, Reno, Sarcevic, Stasto, arXiv:1607.00193

PROSA Collaboration (Garzelli et al), arXiv:1611.03815, 1911.13164

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

Goncalves, Maciula, Szczurek, arXiv:2103.05503

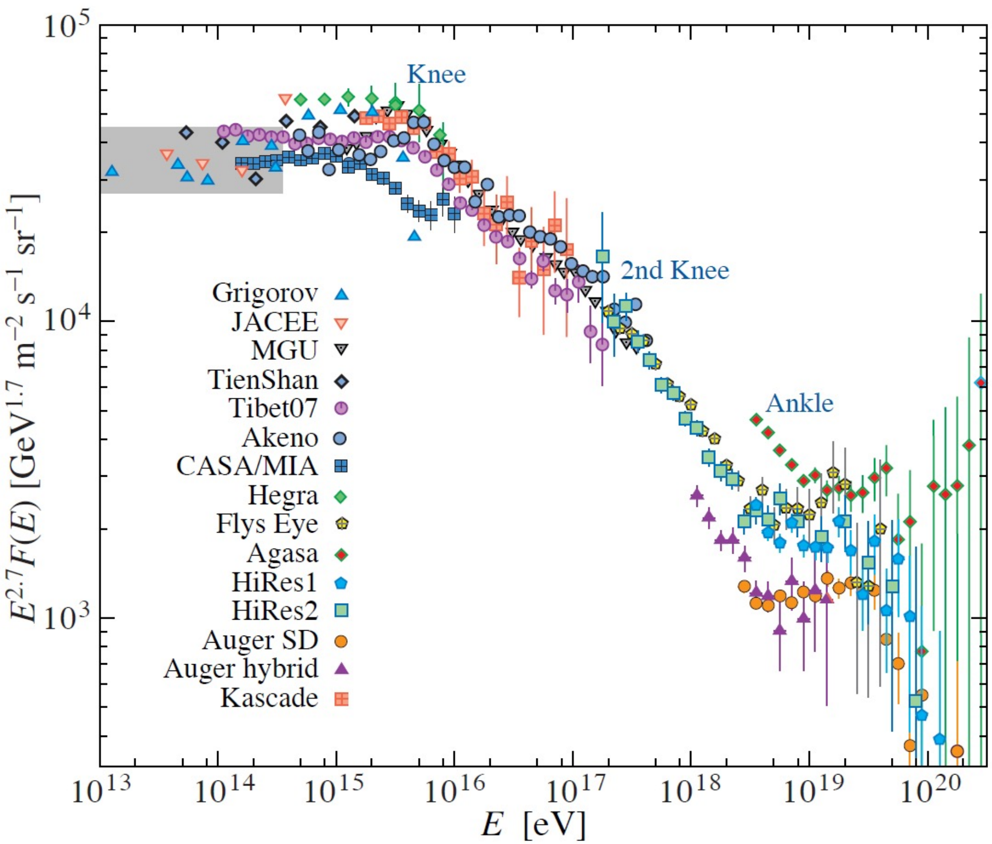
Jeong, Bai, Diwan, Garzelli, Kumar, Reno, arXiv:2107.01178

Arleo, Jackson, Peigné, arXiv:2112.10791

⋮

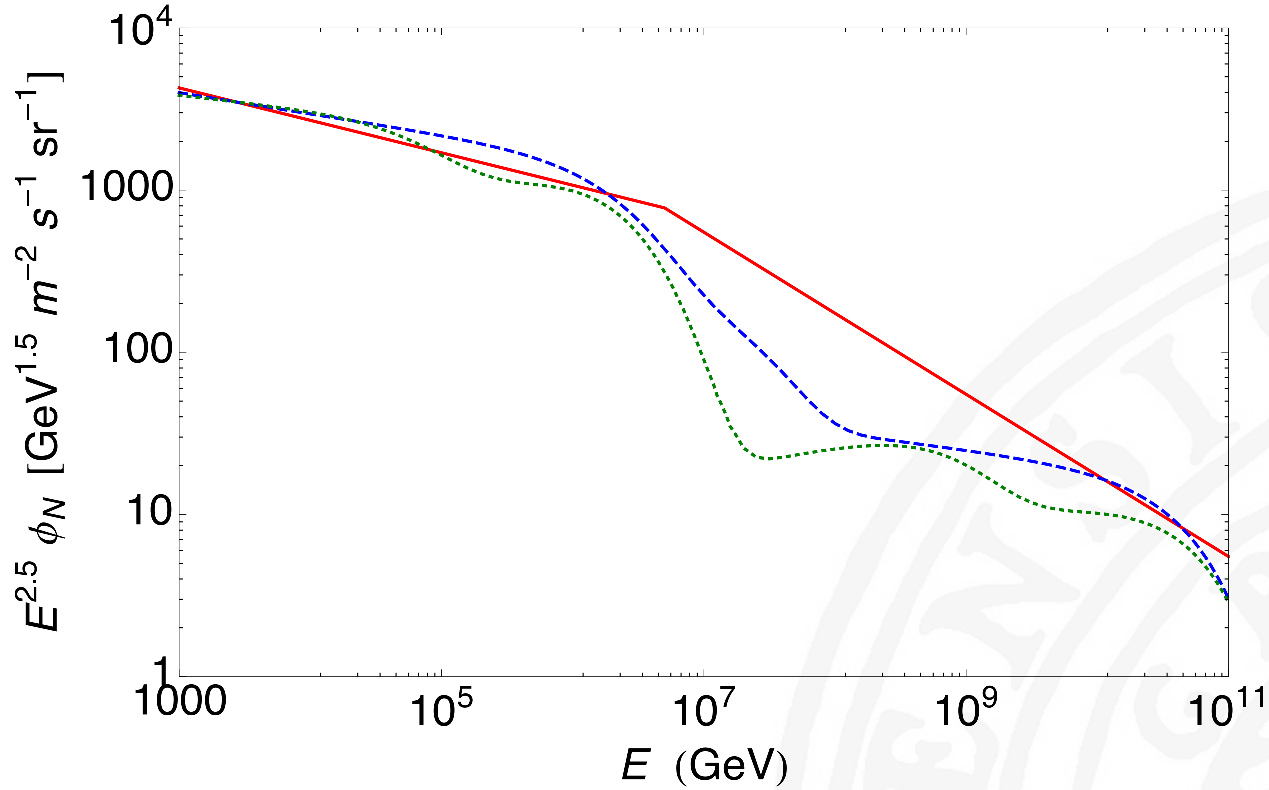
Cosmic rays (CR)

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

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

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

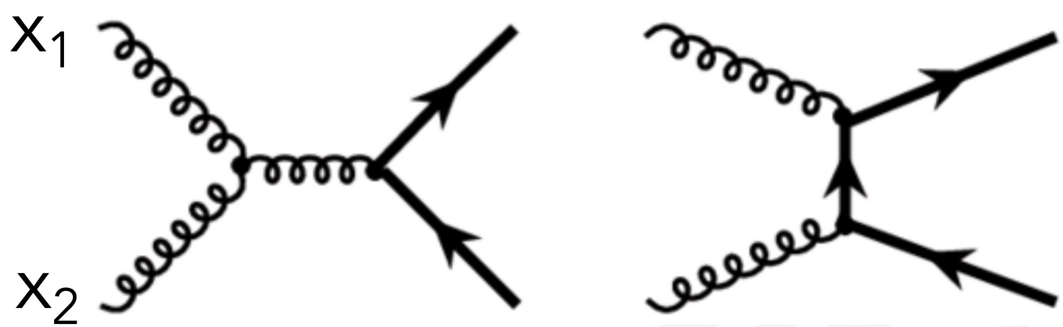
along with interaction lengths, or cooling lengths

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

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

Problem with QCD

Charm production:



x_F = Feynman-x
≃ momentum fraction of charm quark

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

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

→ We need extremely small Bjorken-x, in the range 10^{-7} to 10^{-4}

→ Very asymmetric, x_F is very large

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 $\sim x^{-\lambda}$ of gluon distribution as $x \to 0$

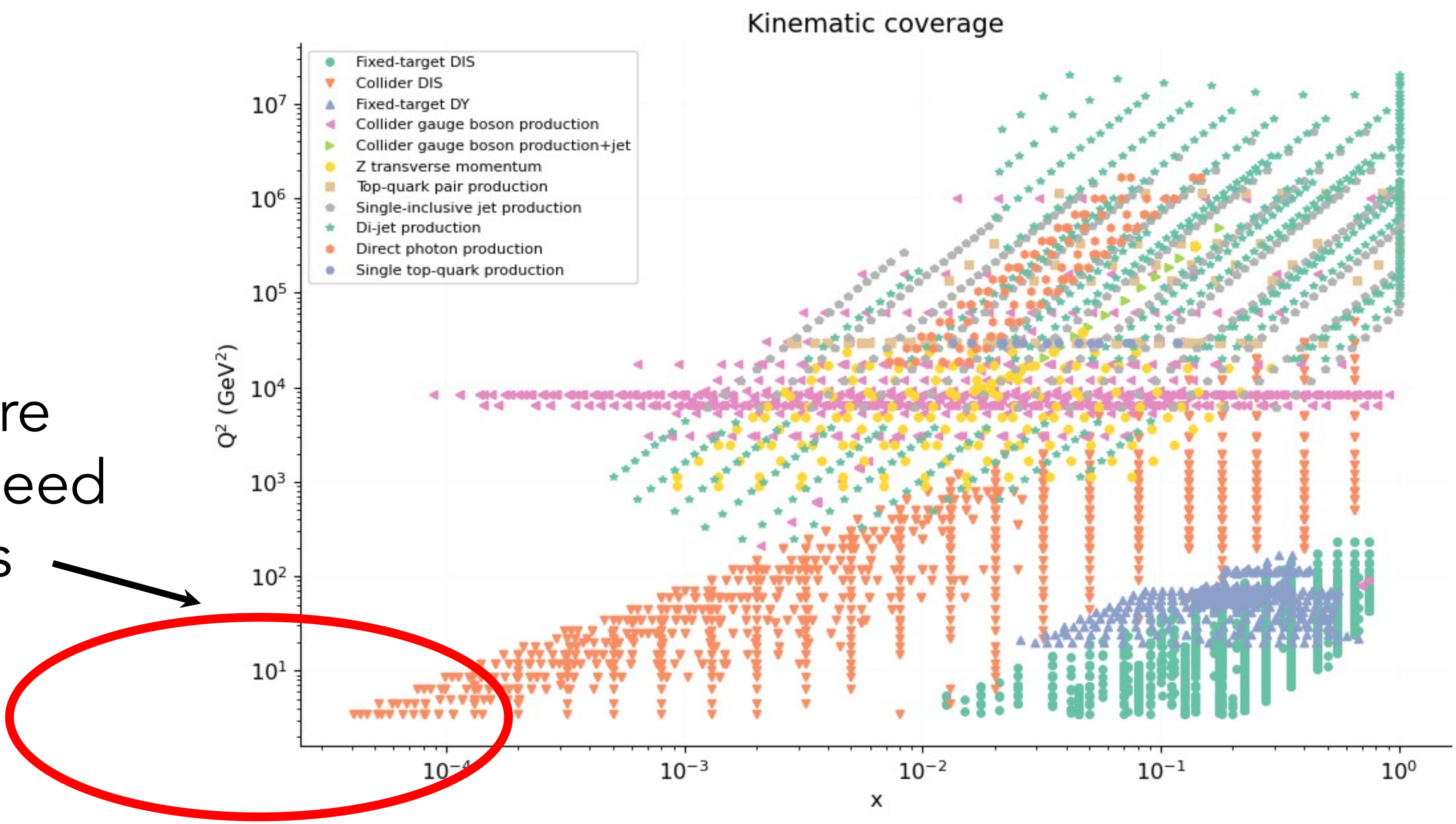
- Unitarity might even be violated (T-matrix > 1)

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: $Q^2 > 3.5\ \text{GeV}^2$ and $x > 10^{-4}$
- See Gao, Harland-Lang, Rojo, arXiv:1709.04922 for more on pdfs

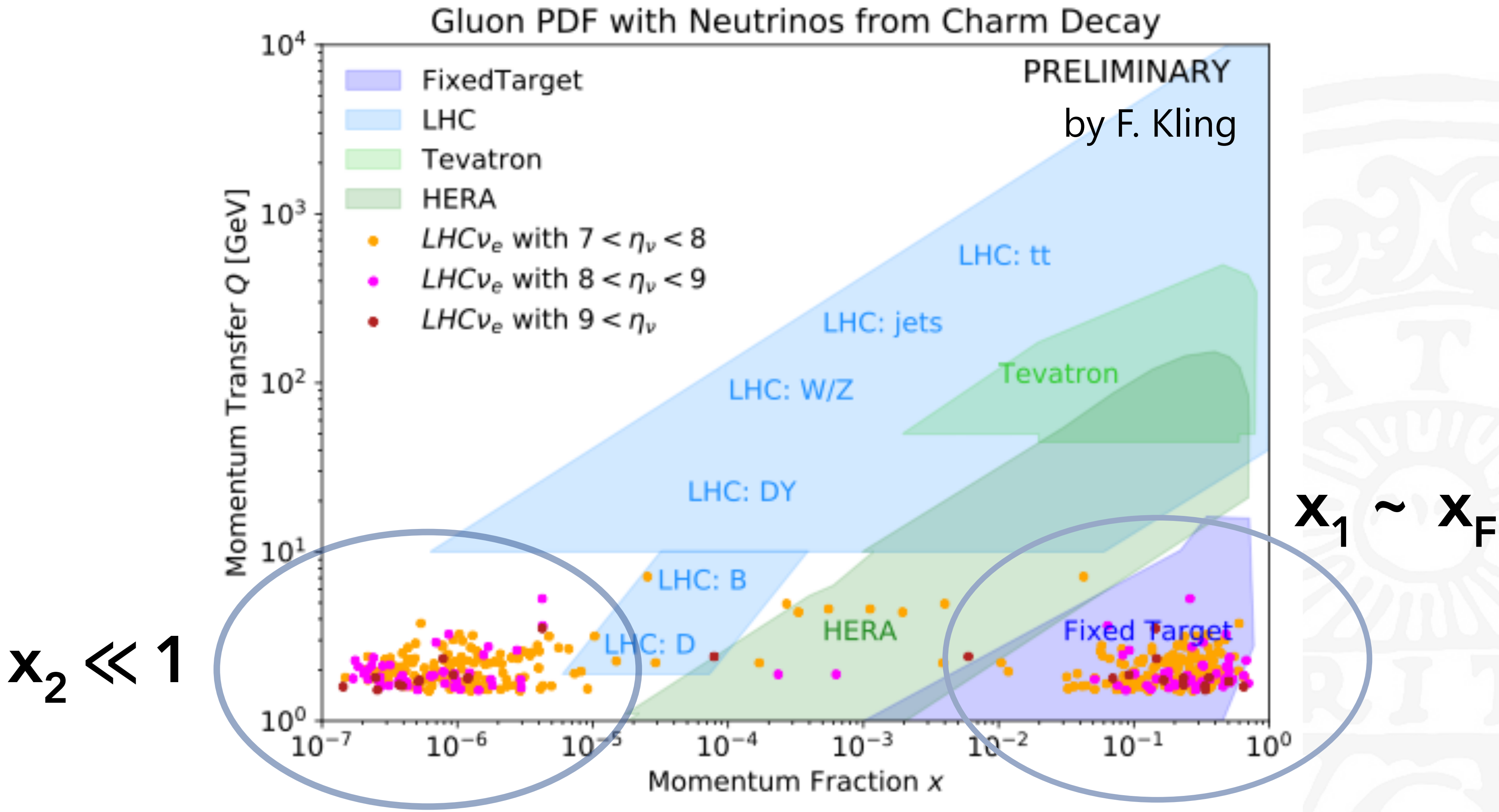
Kinematic plane of NNPDF

Where we need PDFs



NNPDF collaboration, https://nnpdf.mi.infn.it/research/data/
Also talk today by E. Nocera

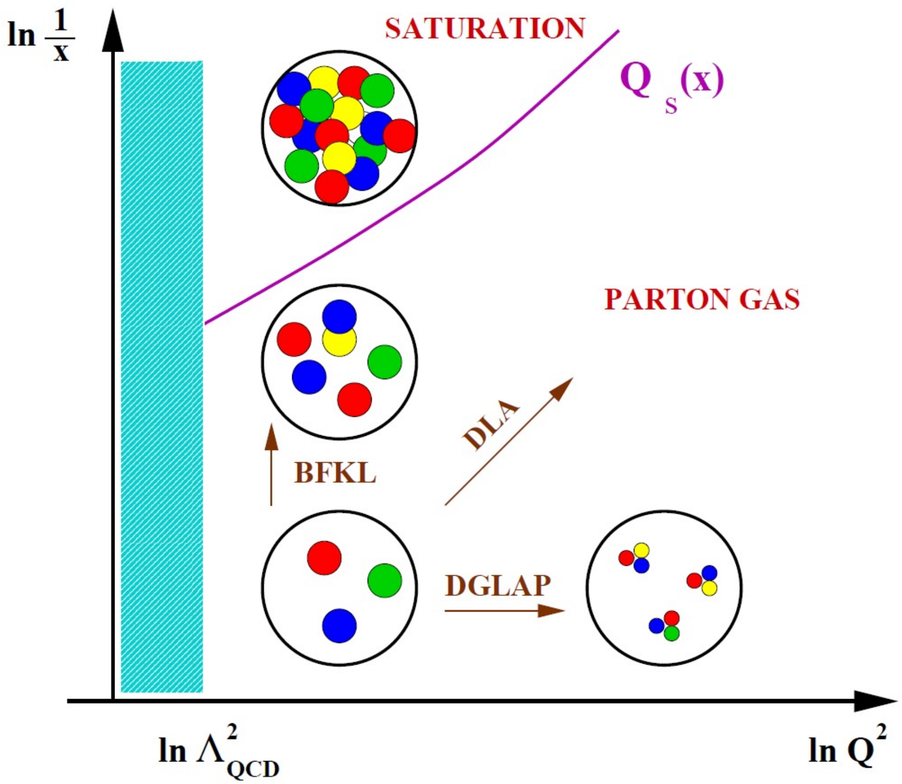
What can be done?



By F. Kling, from talks by T. Ariga and L. Harland-Lang

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 (2016): Redo QCD calculations in many ways

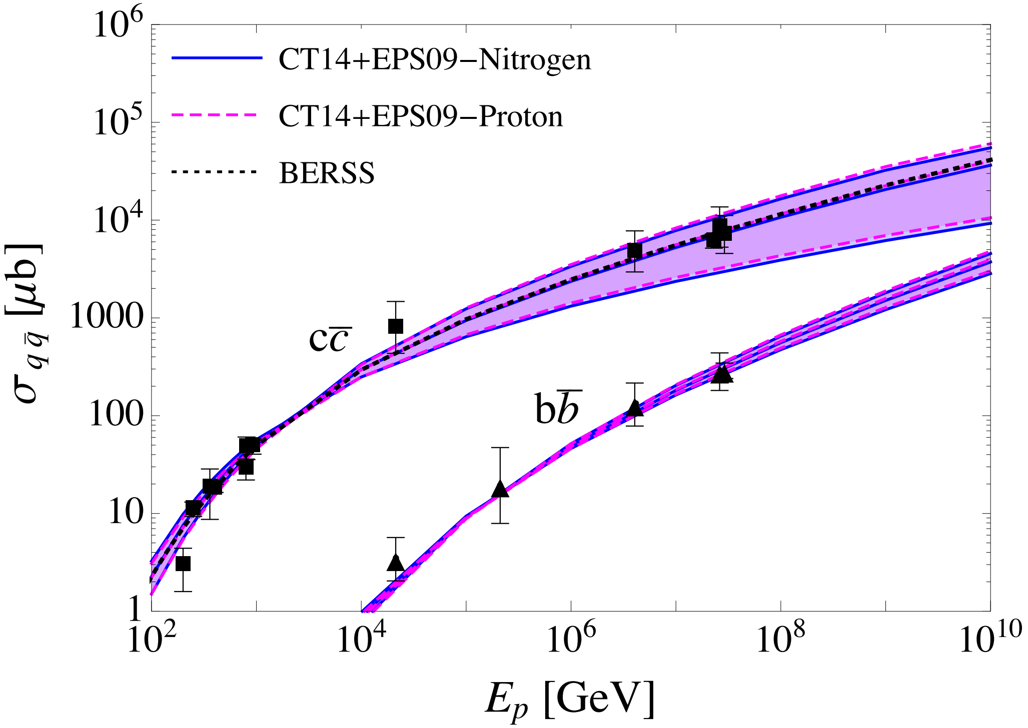
- ***Standard NLO QCD with newer PDFs***
  - Earlier calc updated with RHIC/LHCb input, uses Nason, Dawson, Ellis and Mangano, Nason, Ridolfi
- ***Dipole picture with saturation***
  - Approximate solution of Balitsky-Kovchegov equation
  - Update of ERS calc with new HERA fits + other dipoles
- ***kT 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)

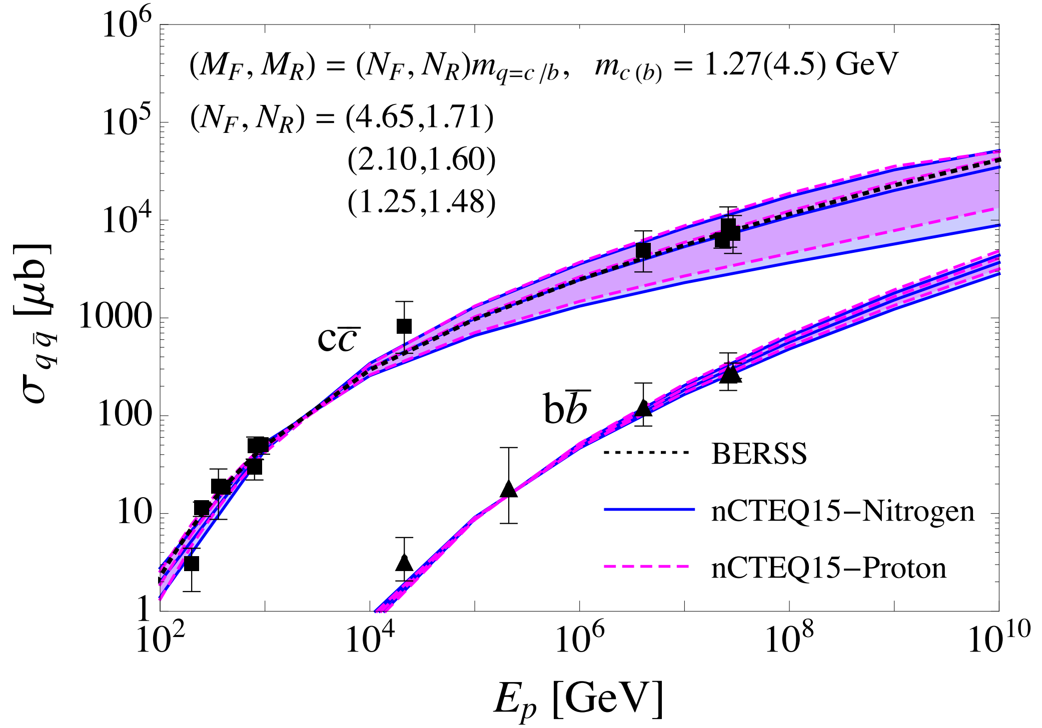
Include scale variations, PDF errors, charm mass, etc
→ Plausible upper and lower limits on xsec

Also include nuclear shadowing

- Partons are not in a free nucleon, but in a nucleus!
- 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 $\sigma(cc)$ due to asymmetric $x_{1,2}$

σ(cc) and σ(bb)

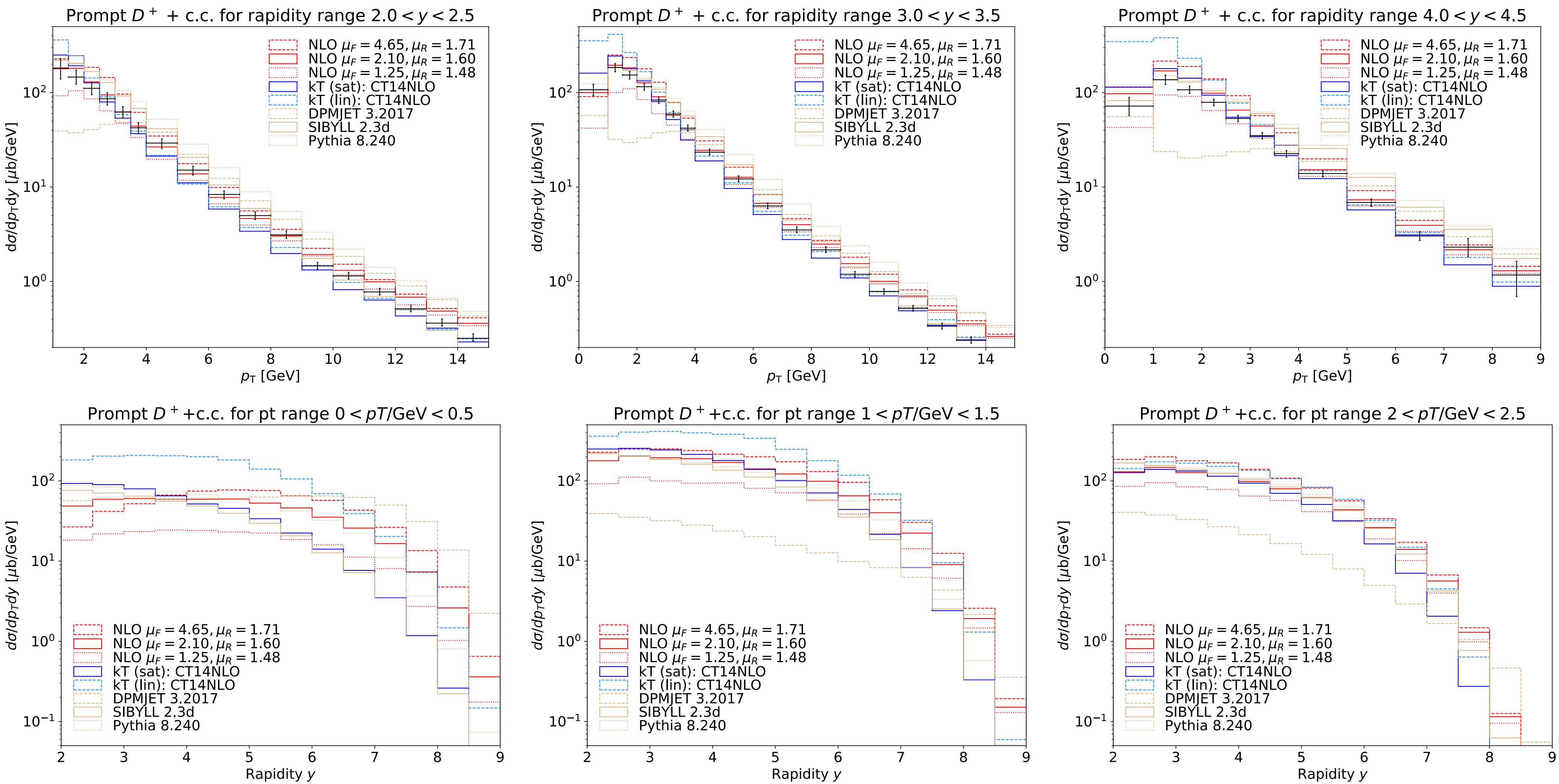




Data from RHIC, LHC and lower energies
Total cross sections well described by all calculations (at high energies), nuclear shadowing small

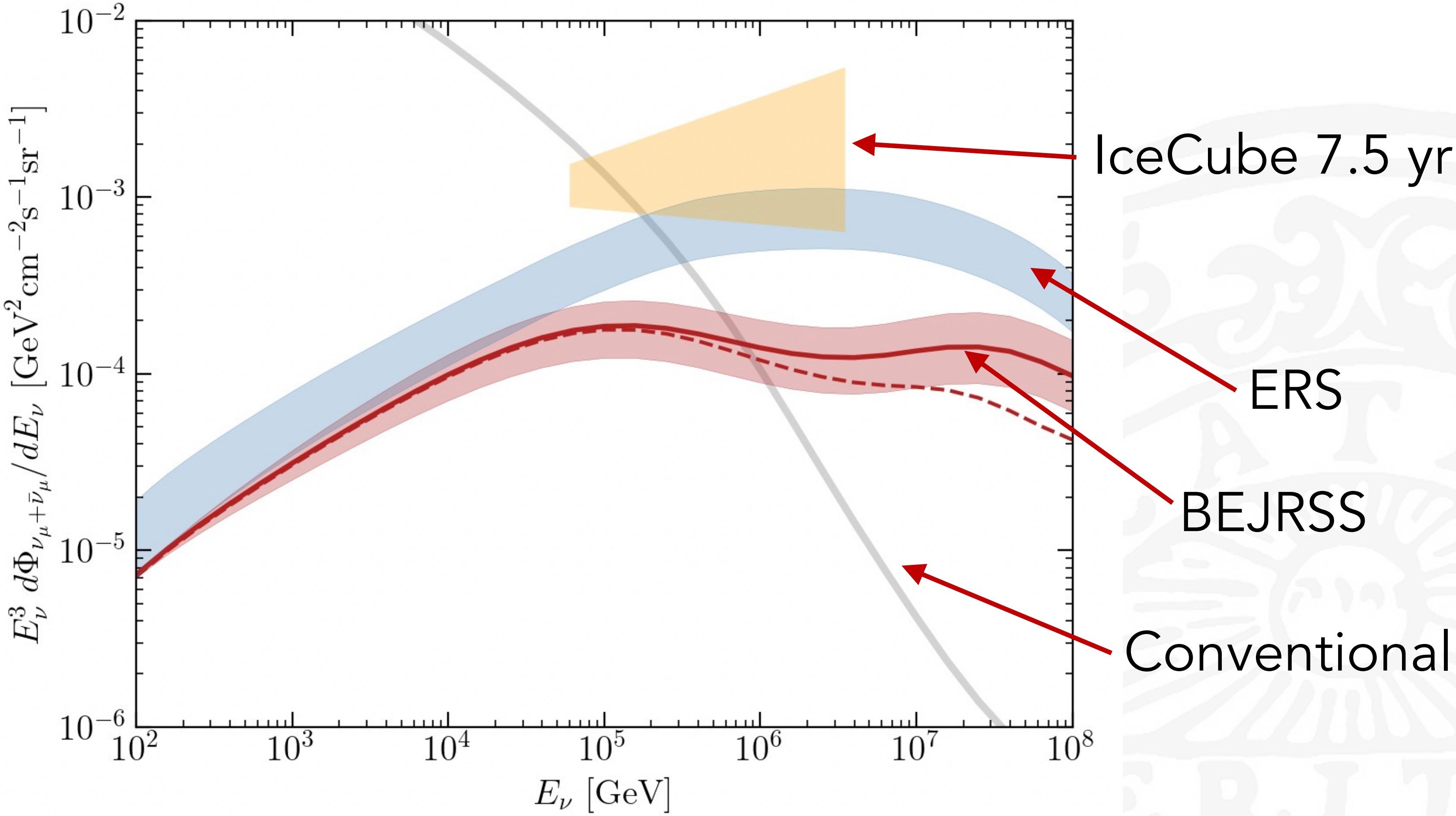
(Error bands=scale variations and PDF uncertainties)

New work: $D^{\pm}$ meson production



Some of our calculations compared with MC generators and LHCb data (plots by F. Kling)

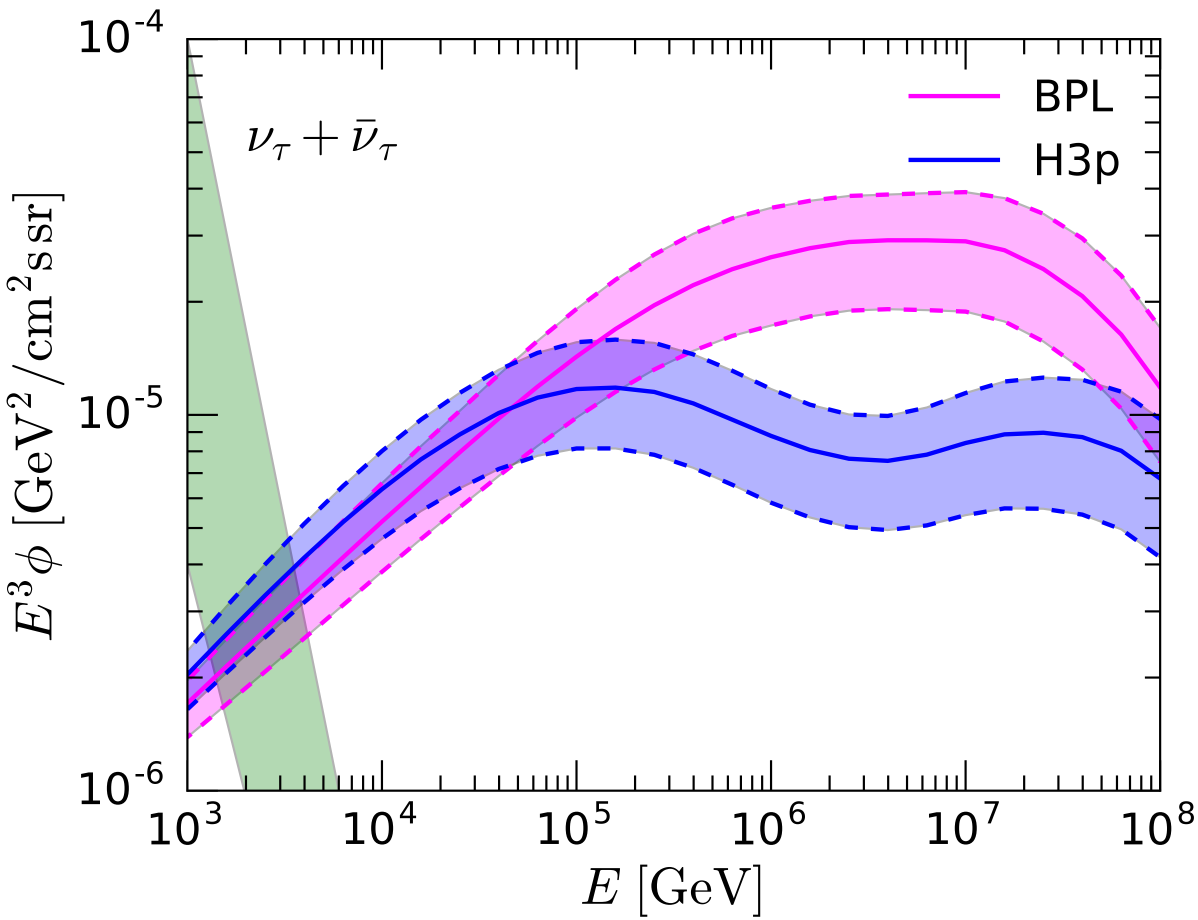
Our recent result on ν_μ



Plot from Atri Bhattacharya's talk yesterday

Note that prompt $\nu_\mu \approx \nu_e$ but conventional $\nu_\mu \gg \nu_e$

Prompt flux important for ν_τ



The conventional flux is much smaller for $\boldsymbol{\nu_\tau}$

Comparison of calculations

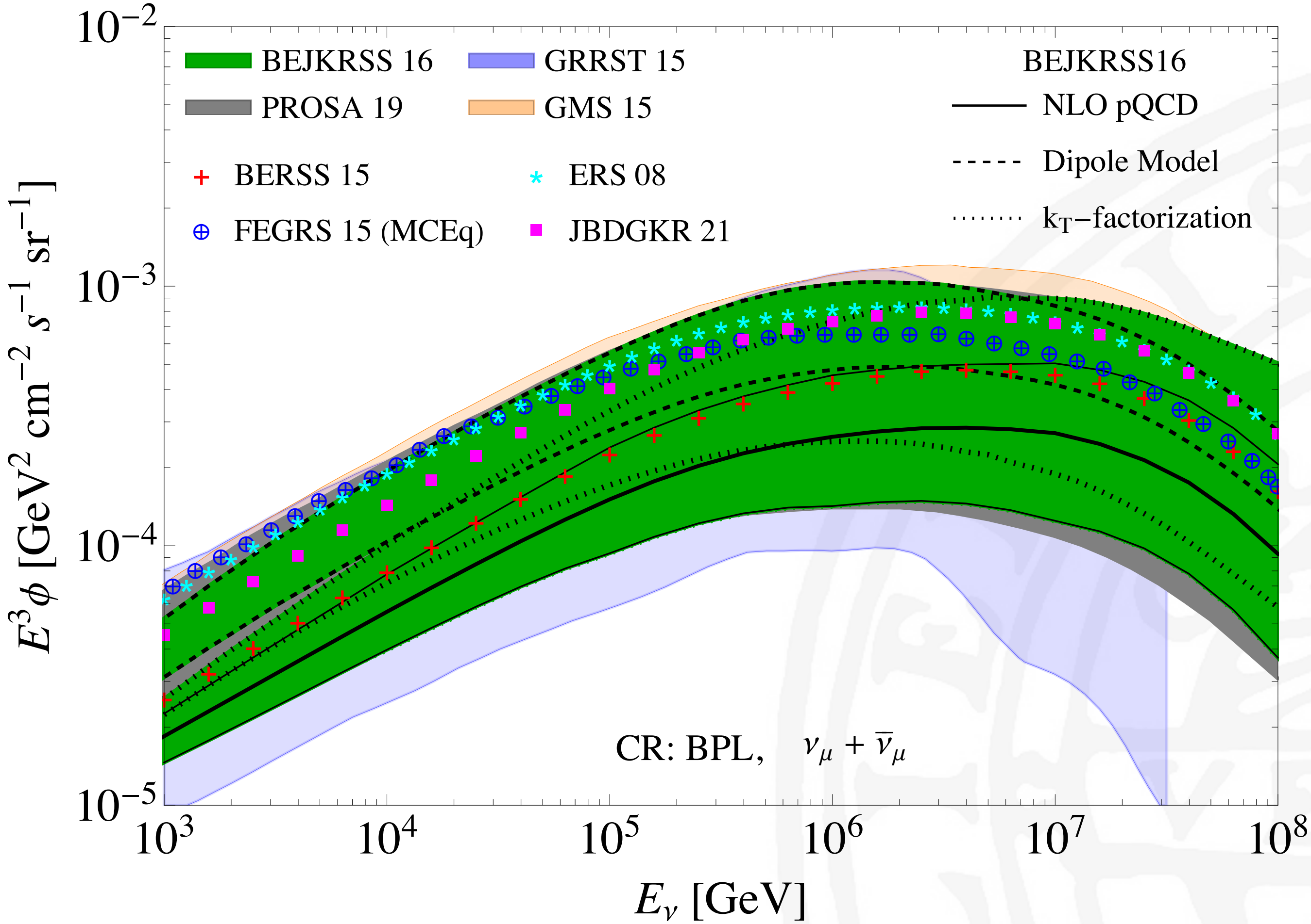
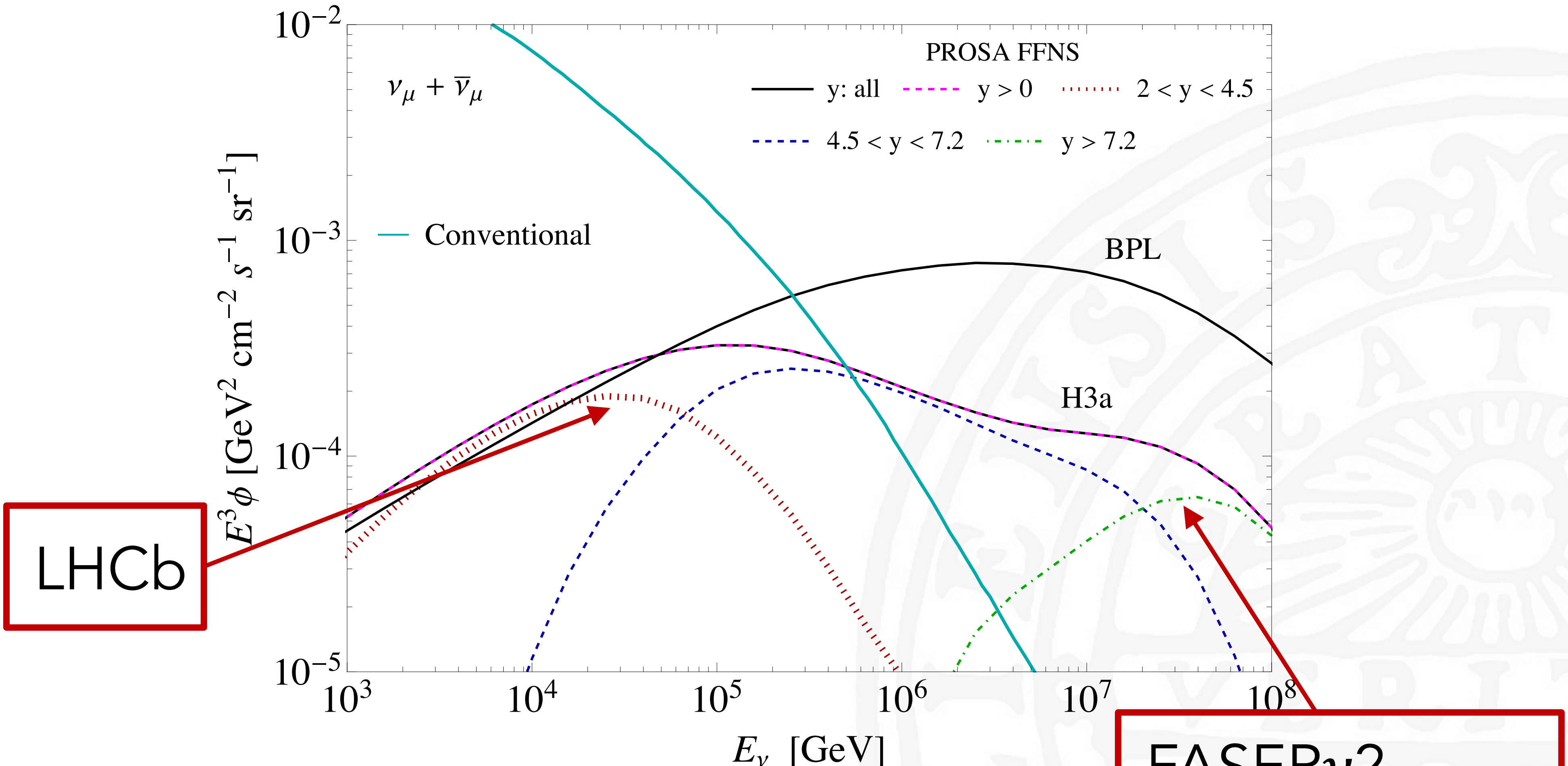


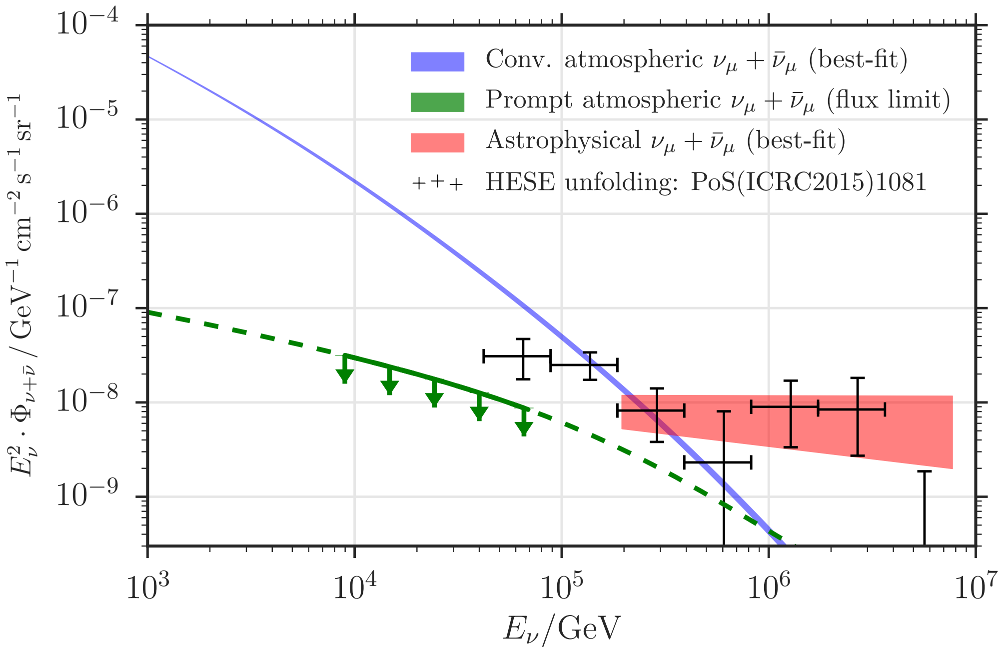
Figure from the FPF Snowmass White Paper draft

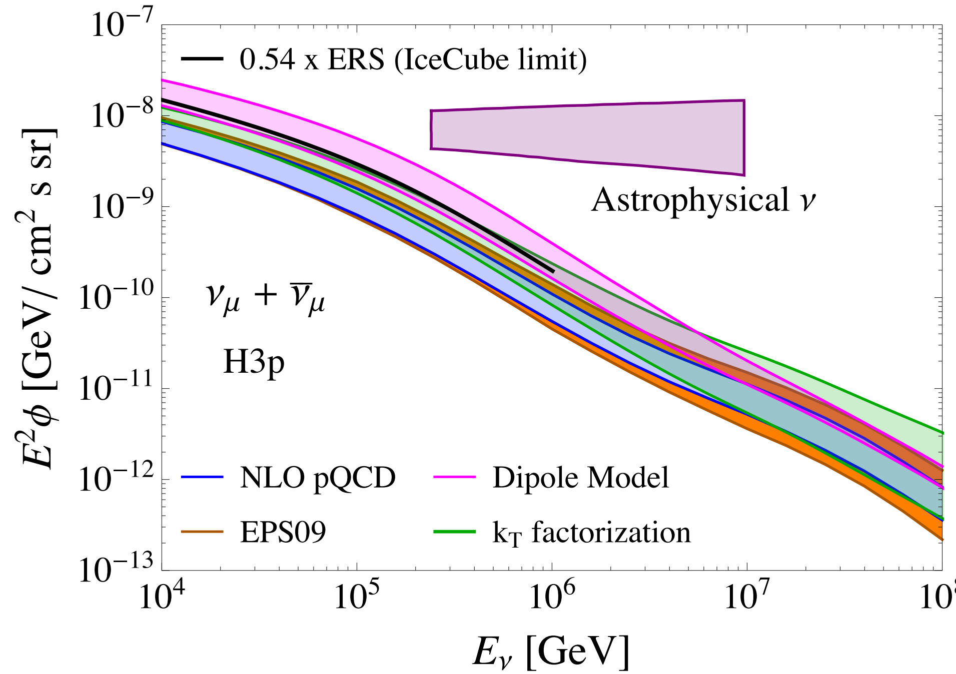
What rapidity ranges?



Where we can hope to see the prompt flux, we have y>4.5, and quite a bit bigger.

IceCube vs prompt flux





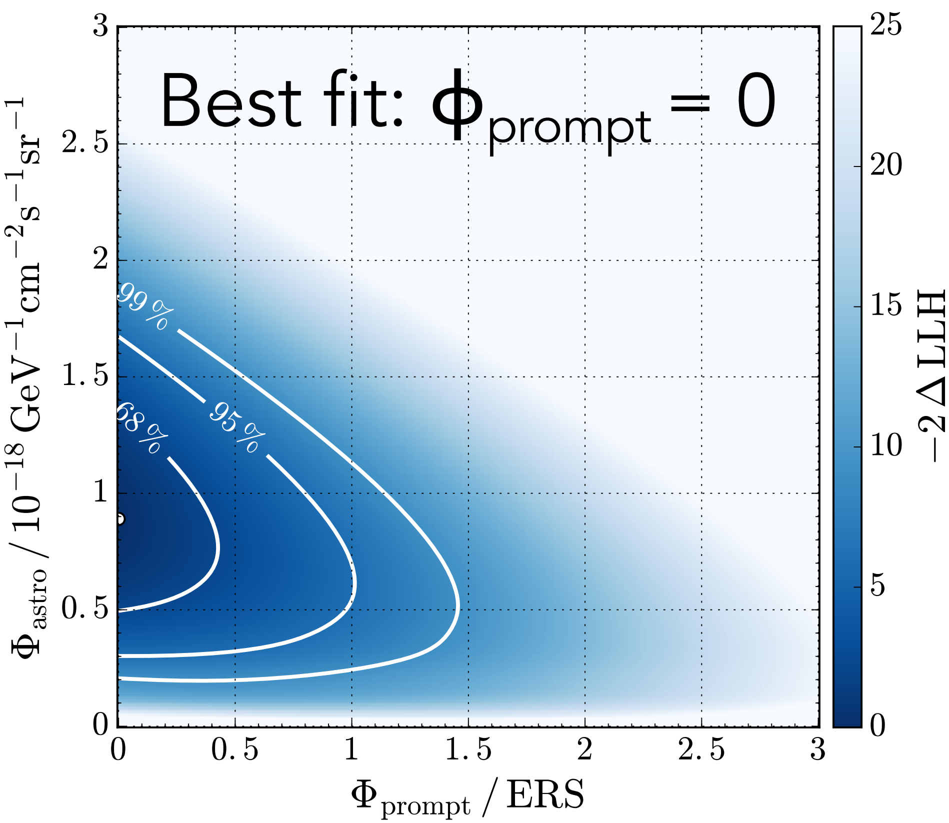
3-year IceCube limit on the prompt flux (at 90% CL):

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

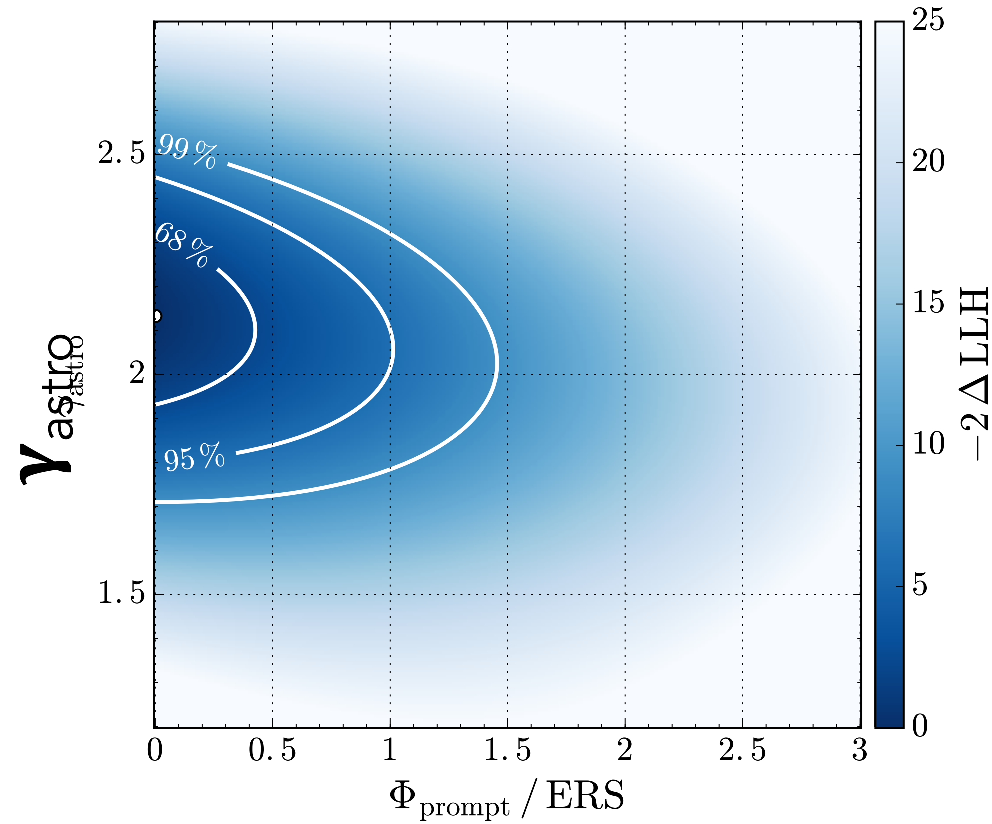
Best fit is $\Phi_{prompt} = 0$

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

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



Φ_{prompt}



Φ_{prompt}

IceCube, arXiv:1607.08006

What can FPF do?

Generally: constrain PDFs at very small **and** very large x

Neutrinos: (see also talk by Hallsie Reno)

✓ FASERν2: neutrinos at $\eta > 8.6$ or 8.8

✓ Advanced SND:

- Neutrinos in far detector at $7.2 < \eta < 8.4$
- Near detector $4 < \eta < 5$
  - Can measure neutrinos from charm here, learn about charm → neutrino fragmentation

✓ FLArE: $\boldsymbol{\nu_\tau}$ flux

Basically, predict neutrinos at FPF and in atmosphere with same underlying QCD calculations