Neutrinos from charm production in the atmosphere

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Based on RE, M.H. Reno & I. Sarcevic, arXiv:0806.0418
+ work in progress
(RE, Reno, Sarcevic + K. Kutak, A. Szczurek)

Main message

QCD is crucial for some astrophysical processes:

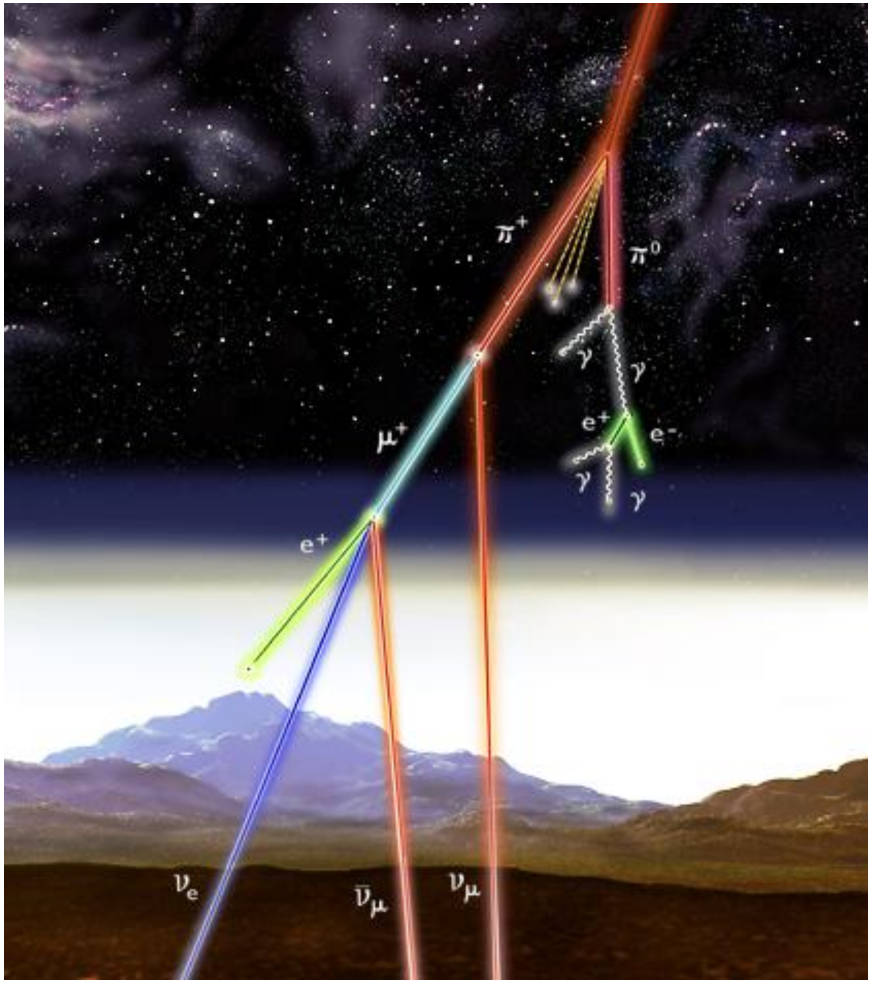
- Atmospheric neutrinos
- Neutrino-nucleon cross-section at high energy
- Interactions in astrophysical sources

For example:

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

Atmospheric neutrinos

- Cosmic rays bombard upper atmosphere and collide with air nuclei
- Hadron production:
  pions, kaons, D-mesons ...
- Interaction & decay
  $\Rightarrow$ cascade of particles
- Semileptonic decays
  $\Rightarrow$ neutrino flux



INFN-Notizie No.1 June 1999

Conventional neutrino flux

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

- π^+ always decay to neutrinos ($\pi^+ \rightarrow \mu^+ \nu_\mu$ is 99.98 %)

- *But π, K are long-lived* ($c\tau \sim 8$ meters for π^+)
  $\Rightarrow$ lose energy through collisions before decaying
  $\Rightarrow$ 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 much energy

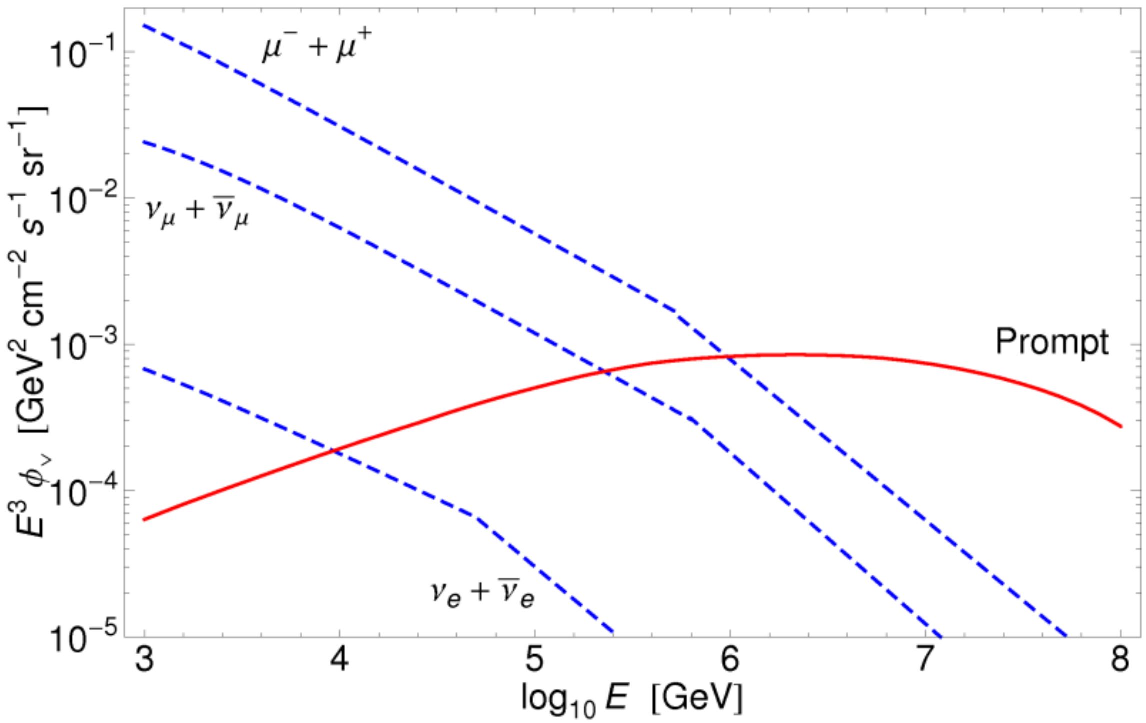
  ⇒ neutrino energy spectrum is harder

- 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*

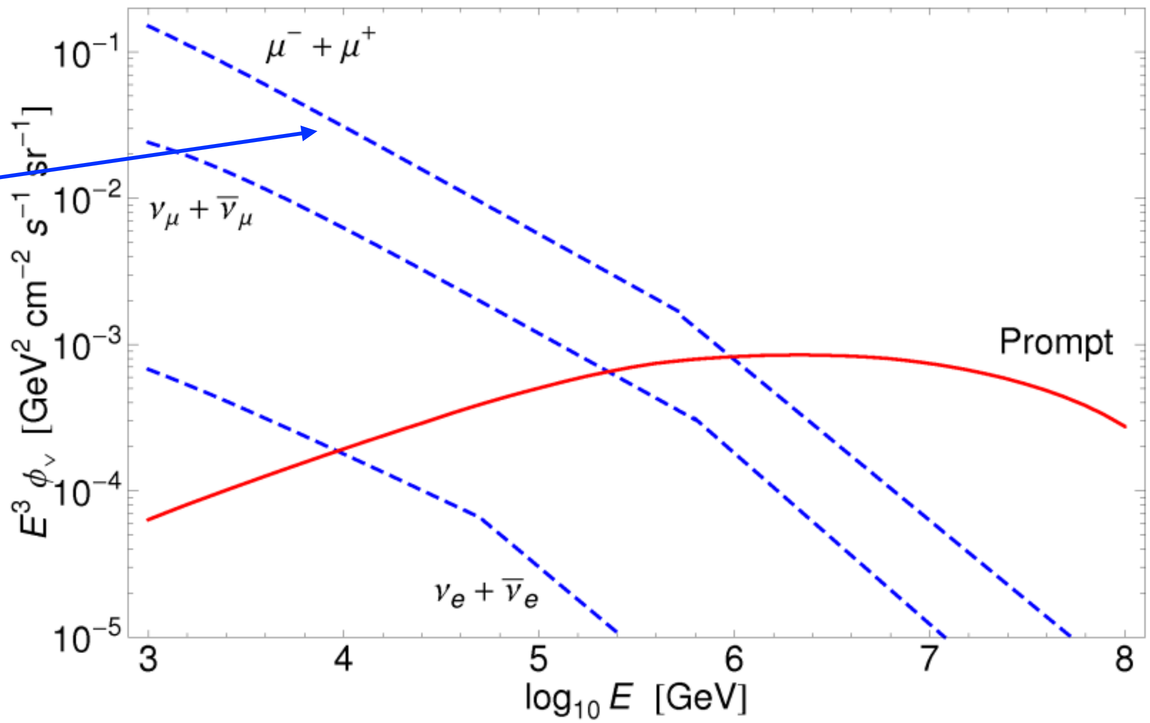
Prompt vs conventional fluxes of atmospheric neutrinos



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

Prompt vs conventional fluxes of atmospheric neutrinos

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



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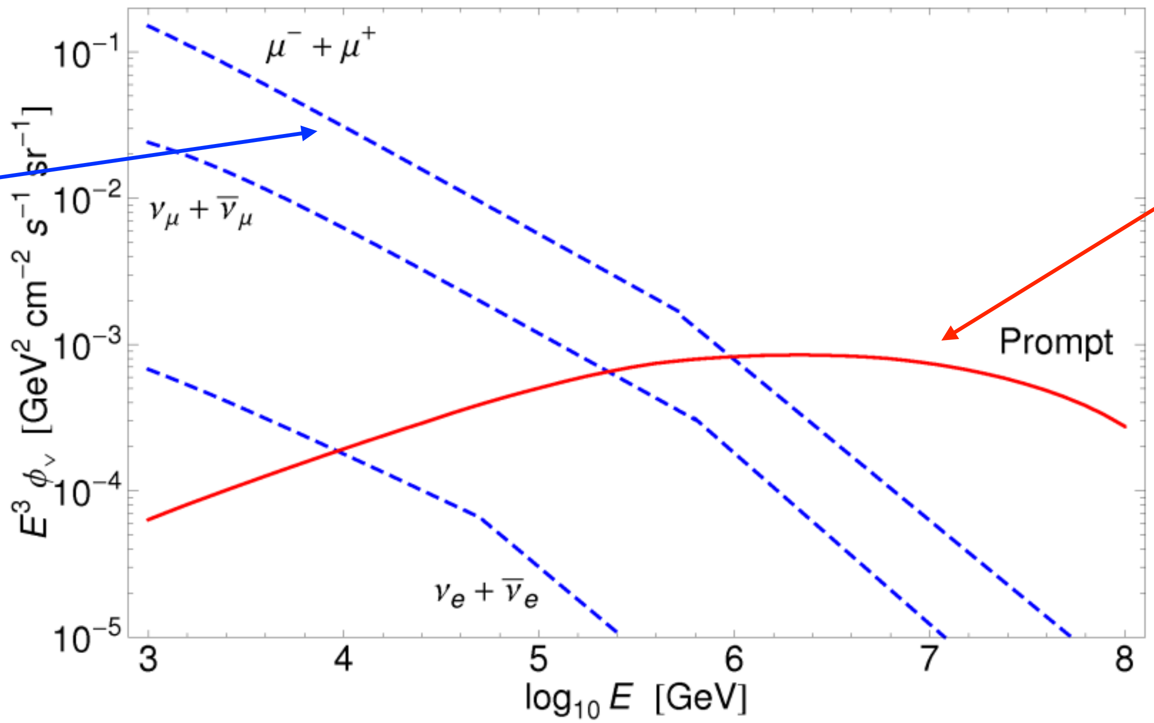

Charmed mesons: short-lived ⇒ don't lose energy ⇒ harder spectrum

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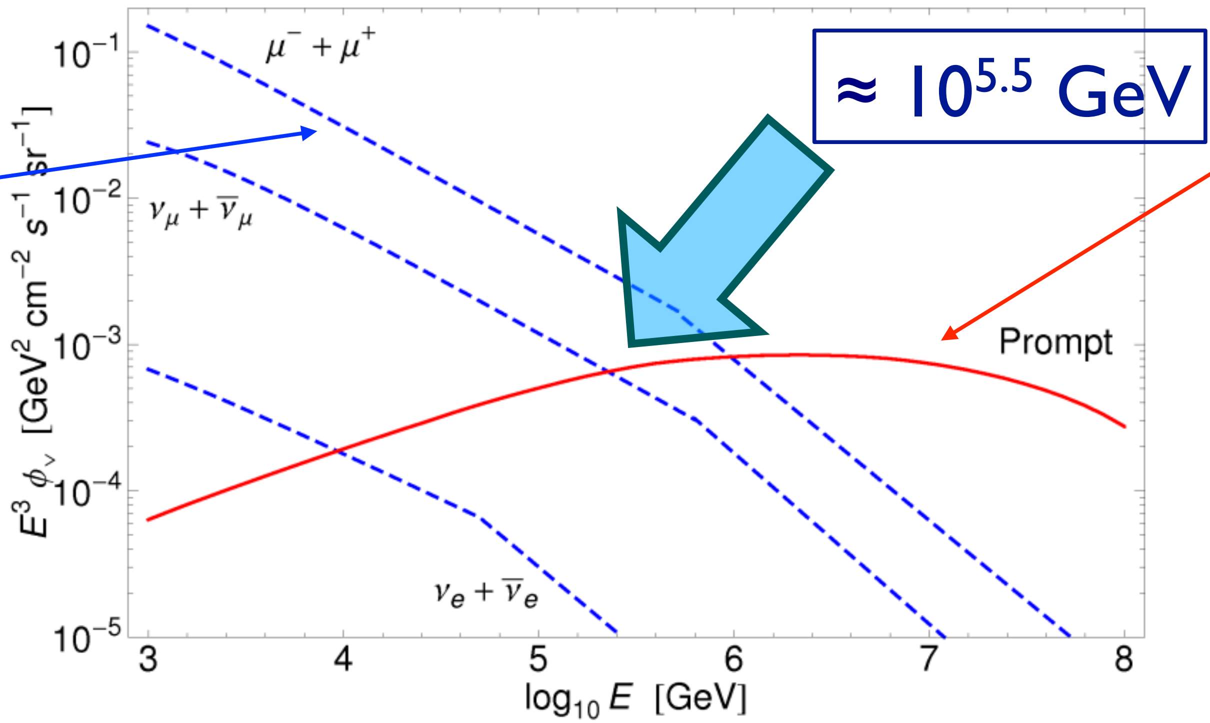

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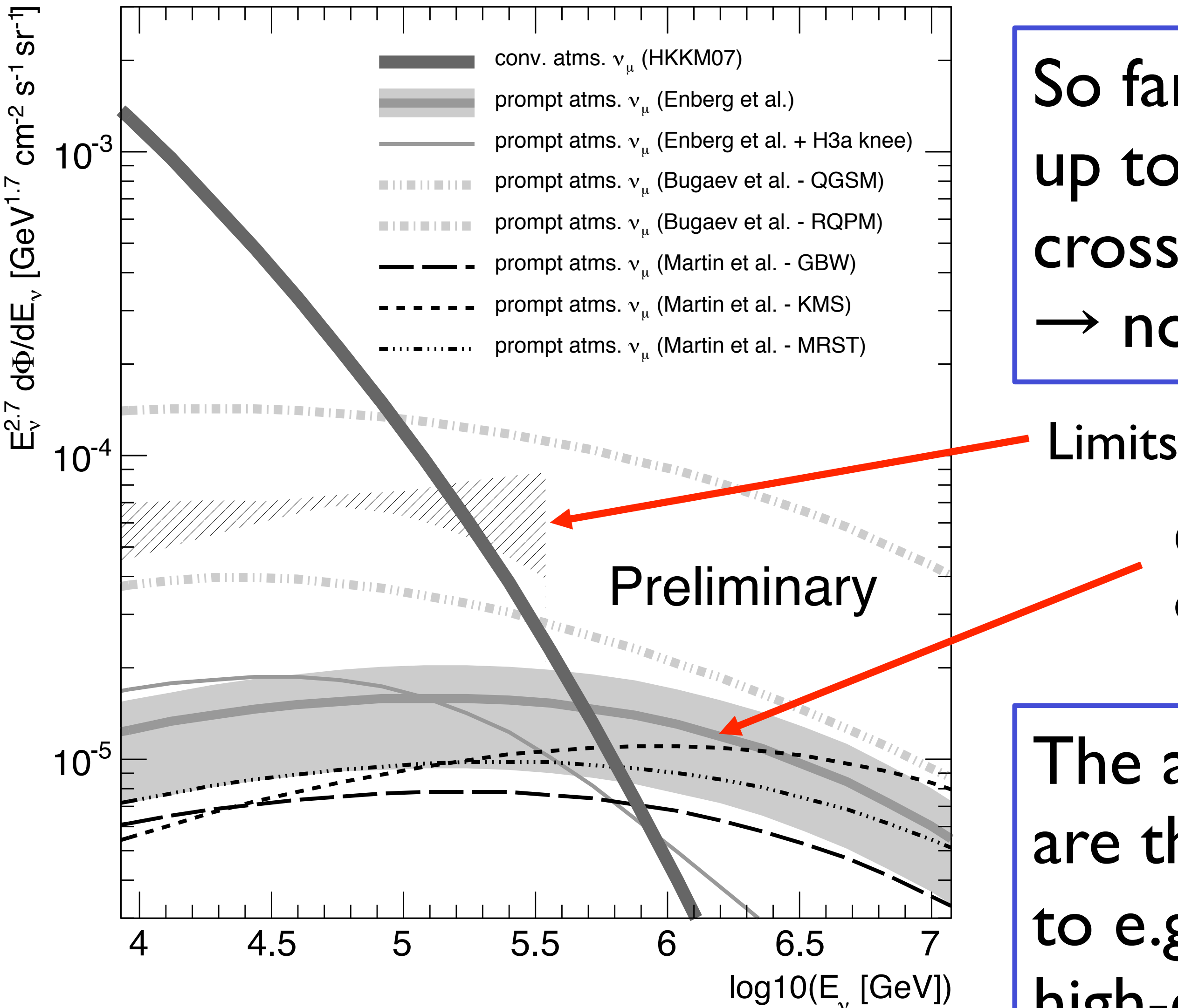
IceCube



A. Schukraft for IceCube, arXiv:1302.0127

So far the limits only reach up to roughly the predicted cross-over point
→ no sign of prompt flux

The atmospheric neutrinos are the major background to e.g. the recent observed high-energy events

Calculating the flux

- To find the neutrino flux we must solve a set of cascade equations given the incoming cosmic ray 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"
  ρd_M is the decay length, with ρ the density of air
  λ_M is the interaction length for hadronic energy loss

Z-moments

- We solve the cascade equations by introducing Z-moments:

$$Z_{kh} = \int_E^\infty dE' \frac{\phi_k(E',X,\theta)}{\phi_k(E,X,\theta)} \frac{\lambda_k(E)}{\lambda_k(E')} \frac{dn(kA \to hY; E', E)}{dE}$$

- Then

$$\frac{d\phi_M}{dX} = -\frac{\phi_M}{\rho d_M} - \frac{\phi_M}{\lambda_M} + Z_{MM}\frac{\phi_M}{\lambda_M} + Z_{NM}\frac{\phi_N}{\lambda_N}$$

- Solve equations separately in low- and high-energy regimes where attenuation is dominated by decay and energy loss, respectively, and interpolate

Particle production

The particle physics inputs are the energy distributions for decay or production

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

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

along with the interaction lengths, or cooling lengths

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

We thus 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**:	$E=10^5 \to x \sim 6\cdot 10^{-3}$
	$E=10^6 \to x \sim 4\cdot 10^{-6}$		$E=10^6 \to x \sim 2\cdot 10^{-3}$
	$E=10^7 \to x \sim 4\cdot 10^{-7}$		$E=10^7 \to x \sim 6\cdot 10^{-4}$

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

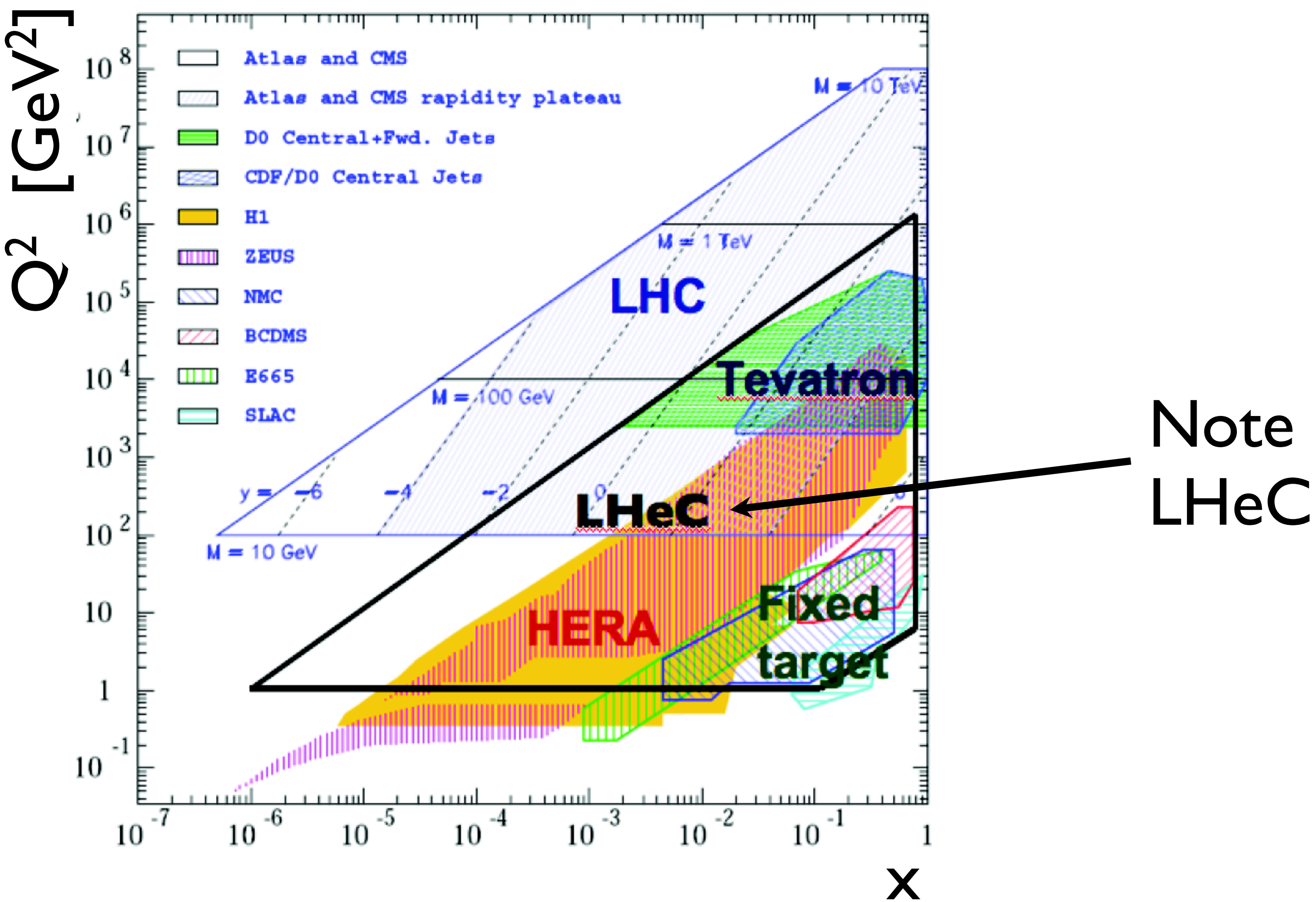
Problem with QCD at small x

- Parton distribution functions poorly known at small *x*
- At small x, large logs must be resummed: $[\alpha_s \log(1/x)]^n$
- If logs are resummed ***(BFKL)***:
  power growth 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 $x > 10^{-4}$!

Kinematic plane



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

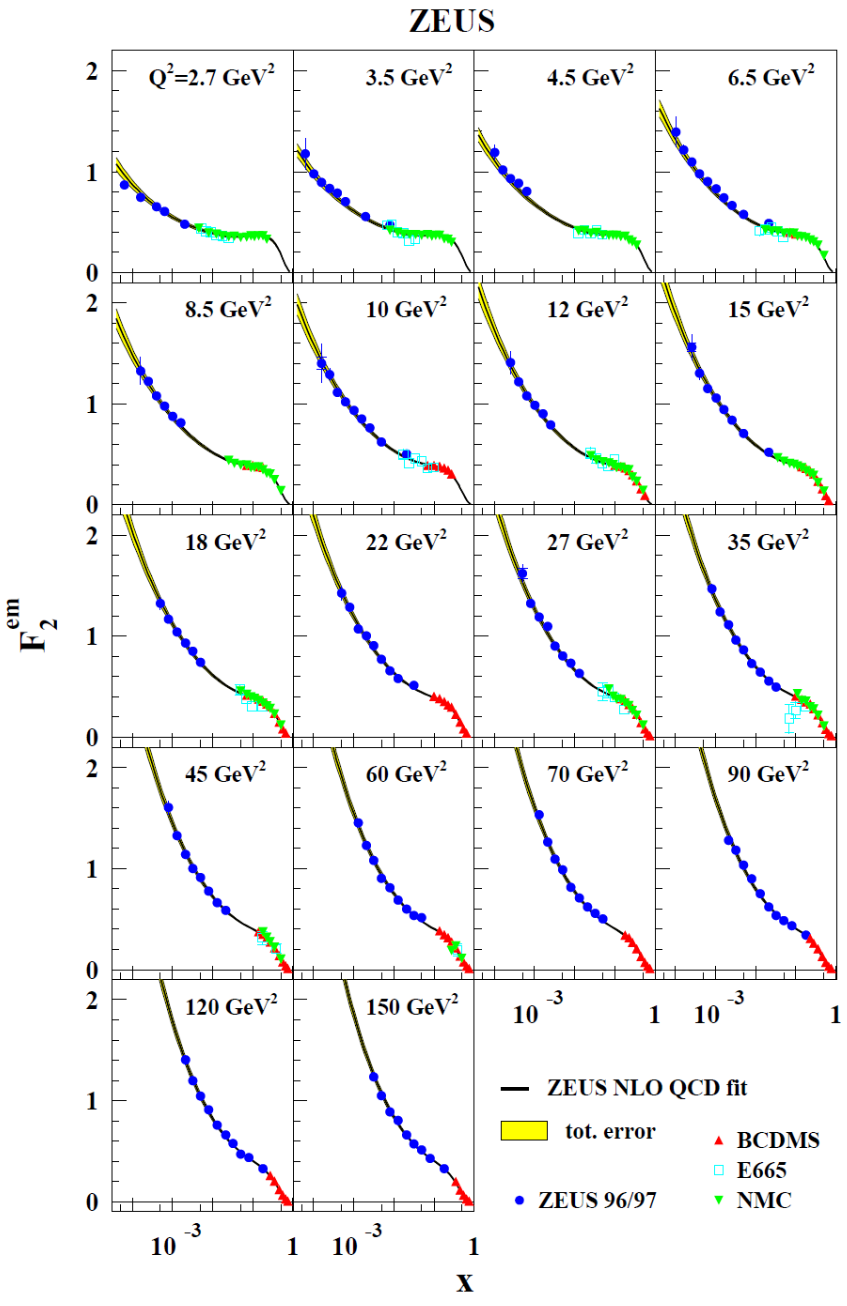
Small x

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

Note the steep power-law rise

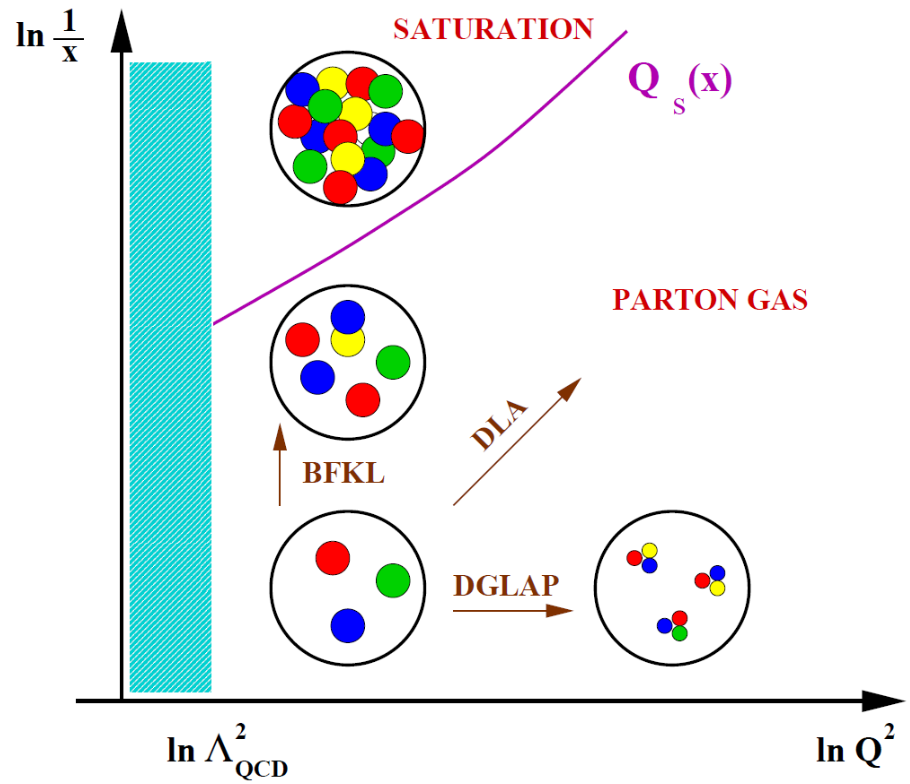
Can this rise continue?

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

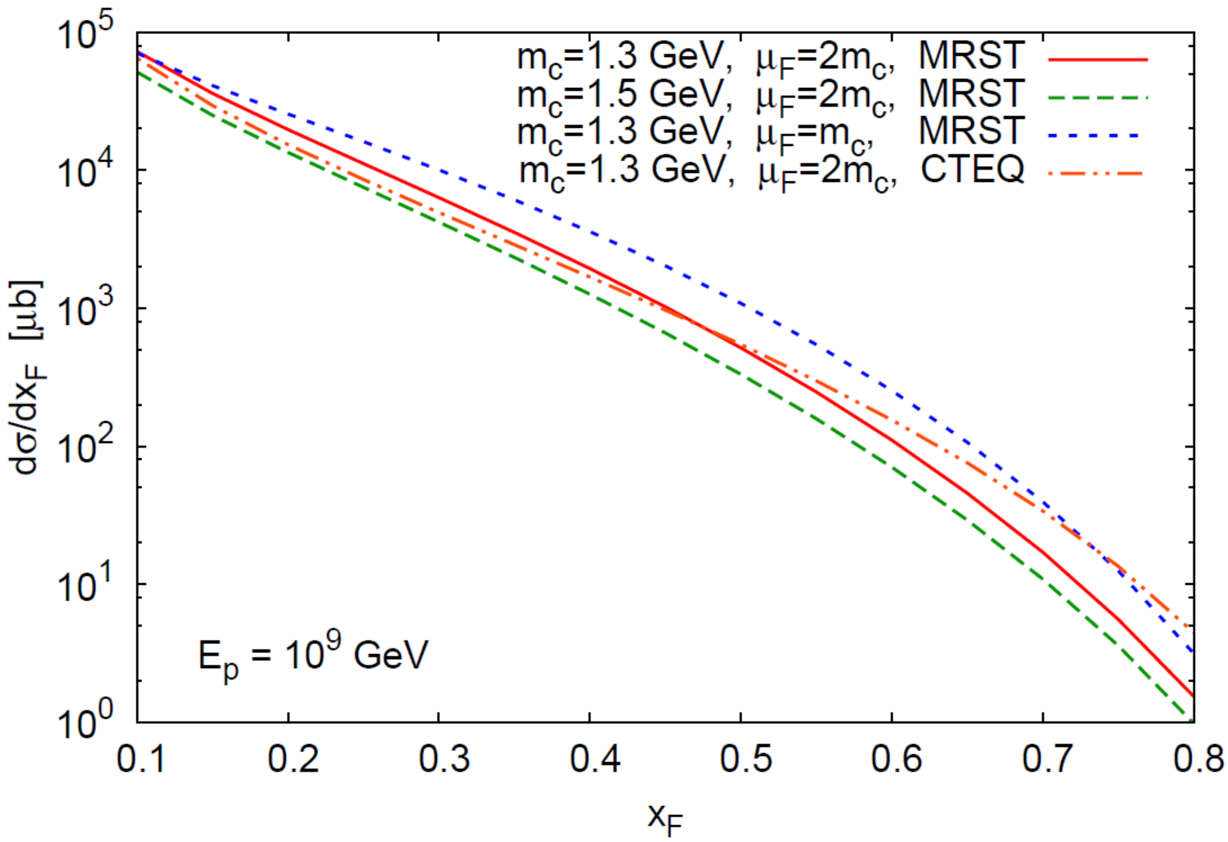
Saturation: theoretical description

- Gribov-Levin-Ryskin and Mueller-Qiu
- Phenomenological saturation model:
  Golec-Biernat and Wüsthoff
- **Color Glass Condensate:**
  McLerran-Venugopalan, JIMWLK, Balitsky
  (Functional integro-differential eqs. or infinite system of nonlinear integro-differential eqs.)
- **Balitsky-Kovchegov equation:**
  Mean field approximation of the above
  (The simplest description: can be more easily used for phenomenology — one nonlinear integro-differential eqn.)

Charm production

- We calculate the charm production cross section $d\sigma/dx_F$
- We use the **dipole picture** *(see backup slides)*, and a solution of the **Balitsky-Kovchegov equation**
- Cross section at large energy suppressed relative to NLO QCD

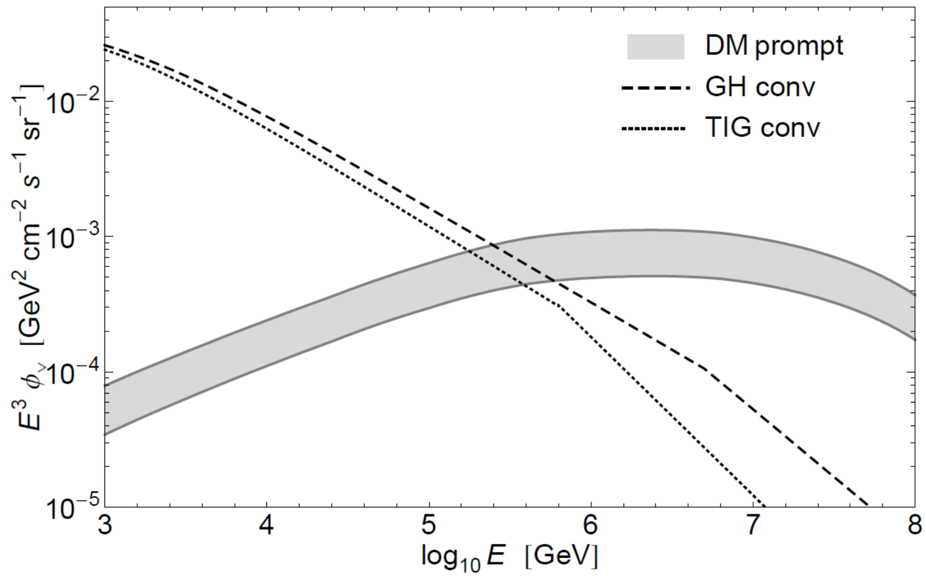
Uncertainties in charm cross section

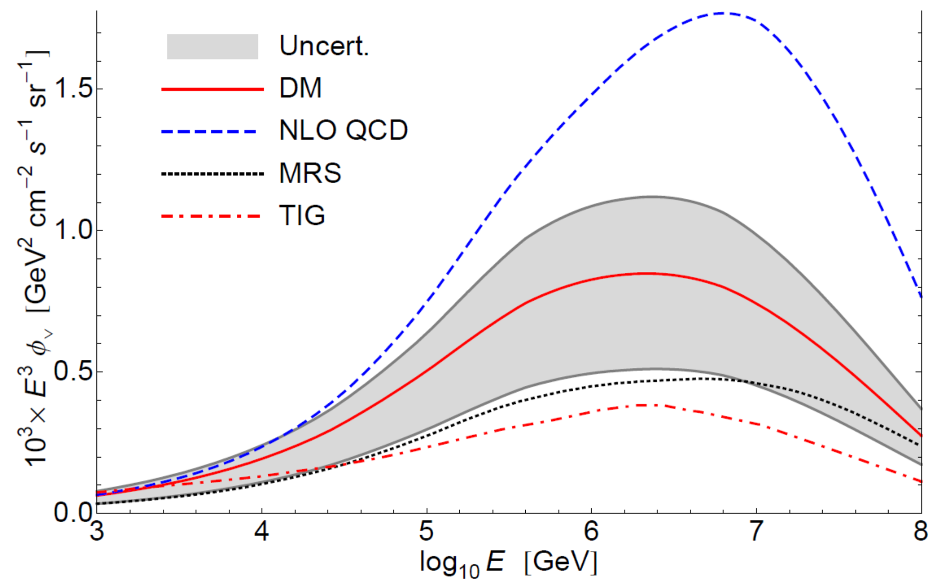


Different charm mass, factorization scale, pdf choice

[R. Enberg, M.H. Reno, I. Sarcevic, arXiv:0806.0418 (in PRD)]

Resulting neutrino fluxes





The band shows uncertainty of the dipole calc.
Upper line in right plot: old NLO QCD

[R. Enberg, M.H. Reno, I. Sarcevic, arXiv:0806.0418 (in PRD)]

Fixed order calc at small x

- At x << 10^{-4} a power-law extrapolation of parton distributions is not warranted if there is saturation
- We can take this as an upper limit on the cross section **if** there is no saturation: use modern PDFs
- Improve calc with FONLL:
  NLO QCD with NLL resummation of $\log(p_T/m)$
- Saturation could in principle be included in pdf fit with data at higher energies

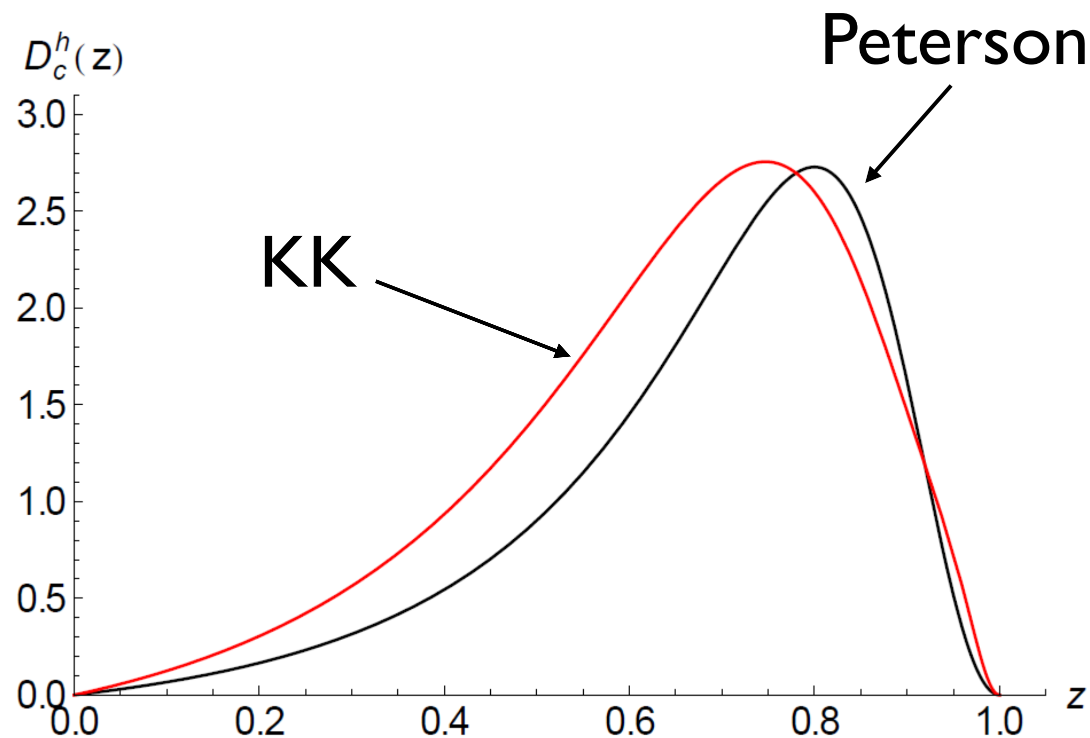
Quark fragmentation to hadrons

Hadronization degrades energy of quark compared to hadron:
Use fragmentation functions fitted to data

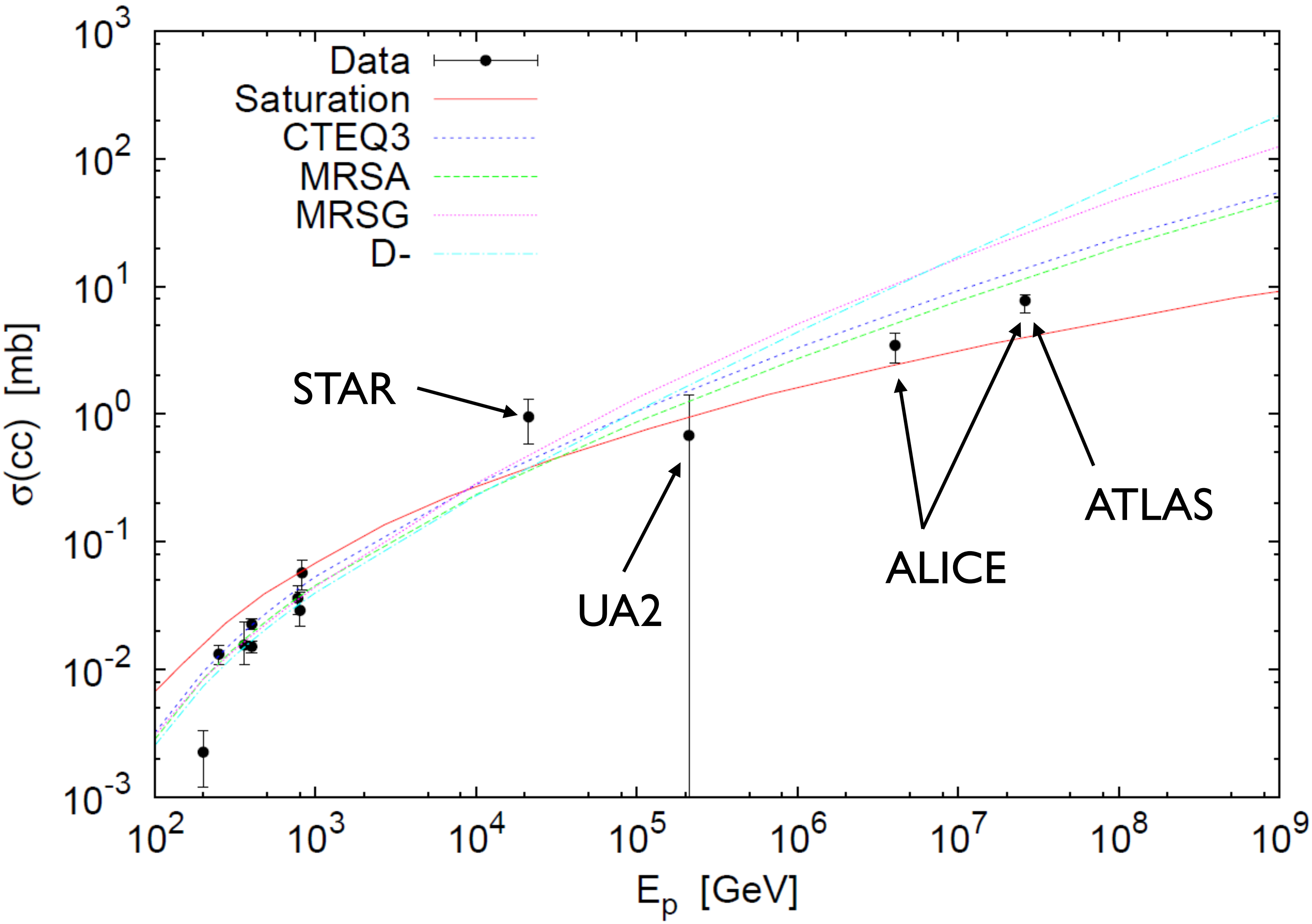
$$\frac{d\sigma(pp \to hX)}{dE_h} = \int_{E_h}^{\infty} \frac{dE_c}{E_c} \frac{d\sigma(pp \to cX)}{dE_c} D_c^h(E_h/E_c)$$

Used Kramer-Kniehl (KK) and Peterson functions

Uncertainty in normalization and average energy fraction

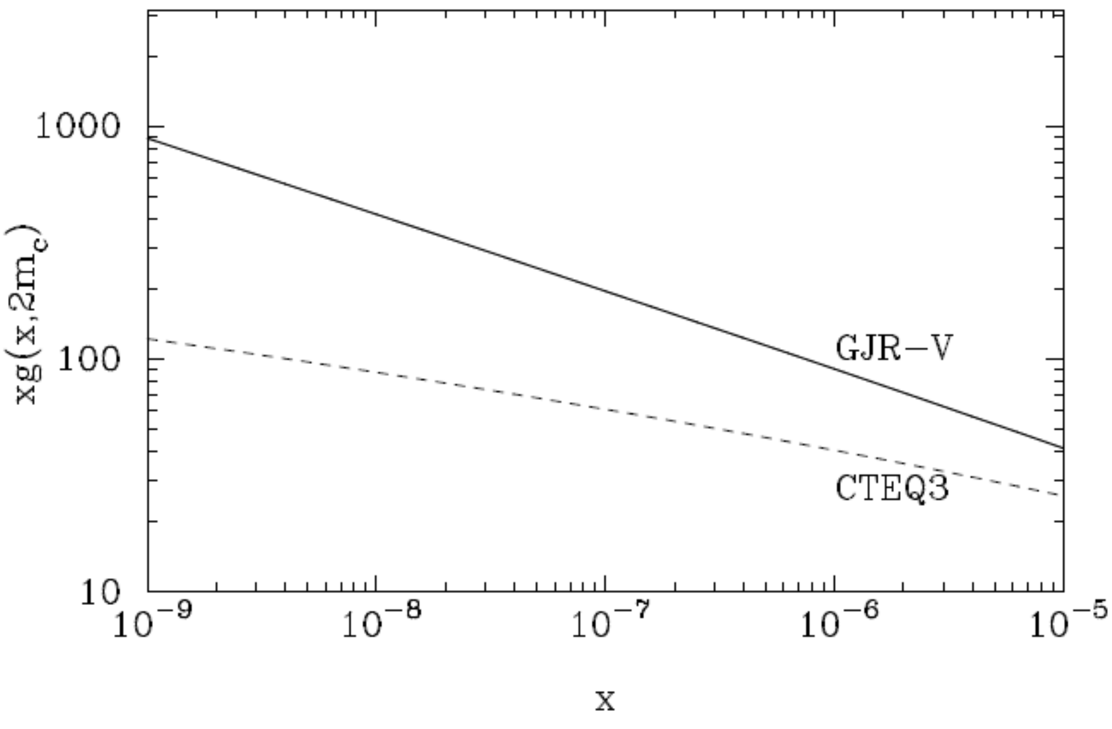


Total cross section, pp → cc



Very different energy dependence!

Gluon pdfs: very small x



GJR-V is a new pdf: **extrapolated** down to $x = 10^{-9}$
CTEQ3 was used in original calculation

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 or Bugaev et al.]

Theoretical uncertainties

Given all these uncertainties, can we get a better handle on how uncertain our prediction is?

Important given that this is a major background for neutrino telescopes and affects their significance calculations

We are investigating the variation in theoretical predictions using different approaches

Updating the prediction

Three issues:

- Saturation prediction
  - Compare previous calculation with
    - Running-coupling BK (numerical solution, AAMQS)
    - BK/DGLAP matching (numerical solution)
- Fixed order prediction using small-x PDF
  - Use NLO QCD with NLL resummation (FONLL)
- Nuclear dependence of incoming cosmic ray flux
  - Previously used proton flux only. Assess impact of using e.g. polygonato flux with mixture of elements

Work in progress!

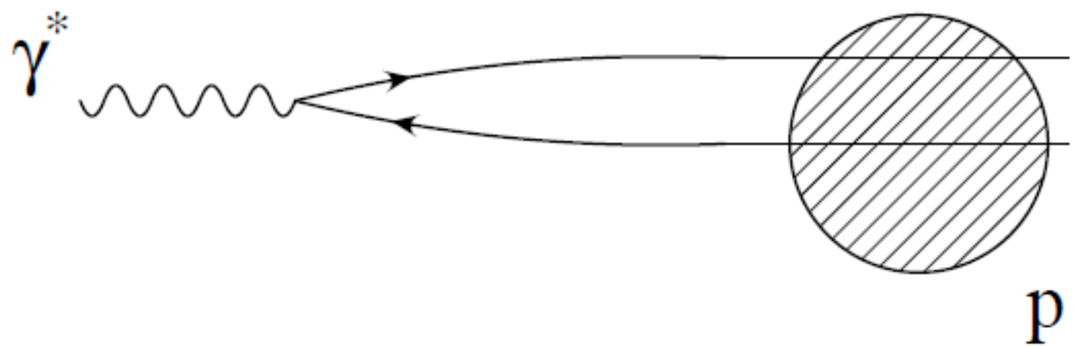
Backup slides

Dipole frame picture of DIS

It is convenient to use the **dipole frame**:

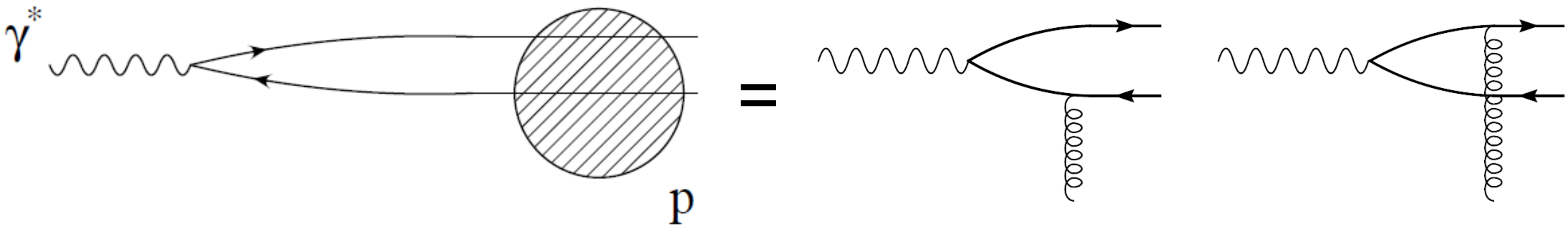
→ Go to frame where the photon has very large lightcone $q+$ momentum (e.g. proton's rest frame)

Then the photon fluctuates into a **color dipole** before hitting the target and the dipole scatters on the proton:



Fluctuation is long-lived at small x:
Very useful in small-x physics

DIS at small x in dipole picture



The factorization is different from "standard" pQCD:

$$\sigma(\gamma^* N) = \int_0^1 dz \int d^2\mathbf{r} |\Psi_T(z, \mathbf{r}, Q^2)|^2 \sigma_{q\bar{q}N}(x, \mathbf{r})$$

Dipole cross section from BK eqn

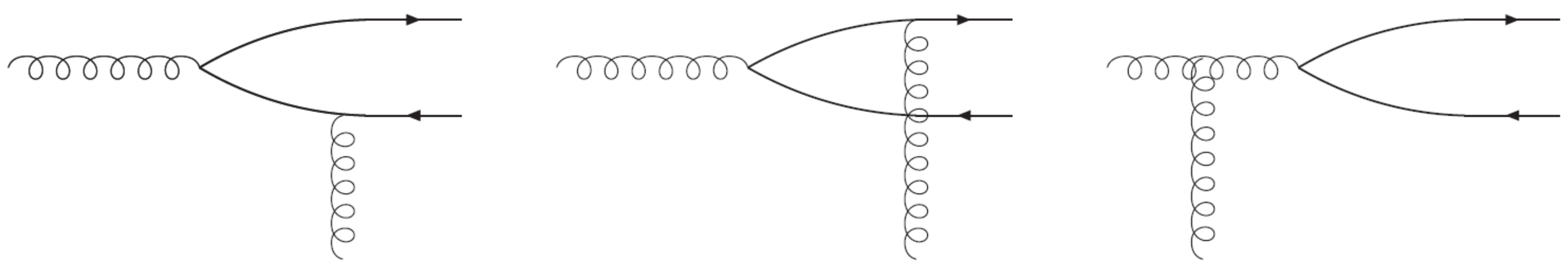
The wave function for the fluctuation is given by:

$$|\Psi_T^f(z, \boldsymbol{r}, Q^2)|^2 =$$

$$e_f^2 \frac{\alpha_{em} N_c}{2\pi^2} \left[\left(z^2 + (1-z)^2\right) \epsilon^2 K_1^2(\epsilon r) + m_f^2 K_0^2(\epsilon r) \right]$$

Generalize to hadron-hadron

Generalized to dipole picture for heavy quark production in hadron-hadron collisions by Nikolaev, Piller & Zakharov; Raufeisen & Peng; Kopeliovich & Tarasov



$$\frac{d\sigma(pp \to Q\bar{Q}X)}{dy} \simeq x_1\, G(x_1, \mu^2)\, \sigma^{Gp \to Q\bar{Q}X}(x_2, \mu^2, Q^2)$$

Gluon distribution of the projectile hadron → gives dipole

Scattering of this dipole on the target hadron

Dipole cross section from BK

Iancu, Itakura and Munier: model for σ_d from the BK equation:
Match two analytic solutions in different regions:

- Saturated region when the amplitude approaches one
- Color transparency region when it approaches BFKL result

$$\mathcal{N}(rQ_s, Y) = \begin{cases} \mathcal{N}_0 \left(\frac{\tau}{2}\right)^{2\gamma_{\rm eff}(x,r)}, & \text{for } \tau < 2 \\ 1 - \exp\left[-a \ln^2(b\tau)\right], & \text{for } \tau > 2 \end{cases}$$

where $\tau = rQ_s,\ Y = \ln(1/x)$ $\qquad \gamma_{\rm eff}(x,r) = \gamma_s + \frac{\ln(2/\tau)}{\kappa\lambda Y}$

Then $\qquad \sigma_d(x, \boldsymbol{r}) = \sigma_0 \mathcal{N}(rQ_s, Y)$

Fitted to HERA data at small x: good description
(we use an update by Soyez for heavy quarks)