Neutrinos from charm production in the atmosphere

Rikard Enberg
(Uppsala University)

Forward physics meeting, CERN, Feb 12, 2013

Work with Mary Hall Reno & Ina Sarcevic,
Phys. Rev. D **78**, 043005 (2008)
+ work in progress

Main message

QCD issues crucial in astrophysical processes such as

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

For example:

- What happens at **small 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 and extragalactic

- Processes that generate high energy neutrinos:
  - Atmospheric interactions of cosmic rays
  - Astrophysical sources (SN, GRB, AGN, etc.)
- Common theme:
  - Hadronic or photo-hadronic collisions produce hadrons, some of which decay to neutrinos
- Example: $pp \to \pi^+ + X$

$$\pi^+ \to \mu^+\nu_\mu$$

$$\mu^+ \to \nu_\mu\nu_e e^+$$

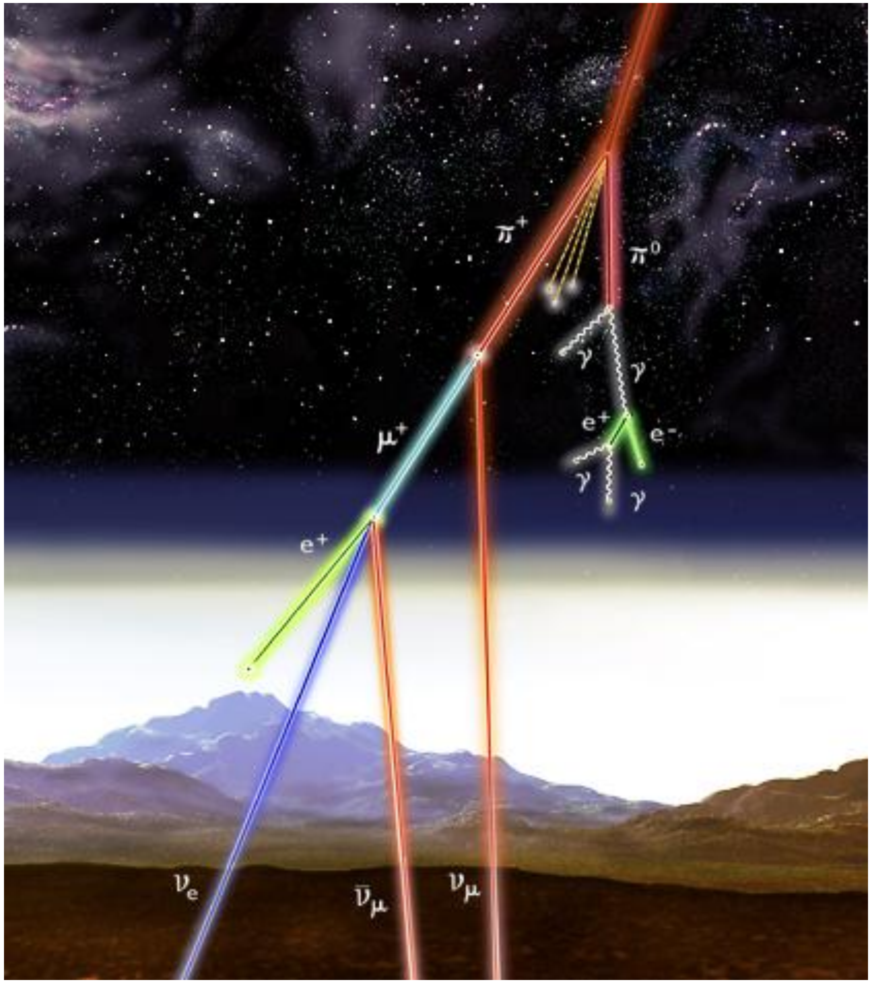
Atmospheric neutrinos

- Cosmic rays bombard upper atmosphere and collide with air nuclei

- Hadron production:
  pions, kaons, D-mesons ...

- Interaction & decay
  ⇒ cascade of particles

- Semileptonic decays
  ⇒ neutrino flux



INFN-Notizie No.1 June 1999

Conventional neutrino flux

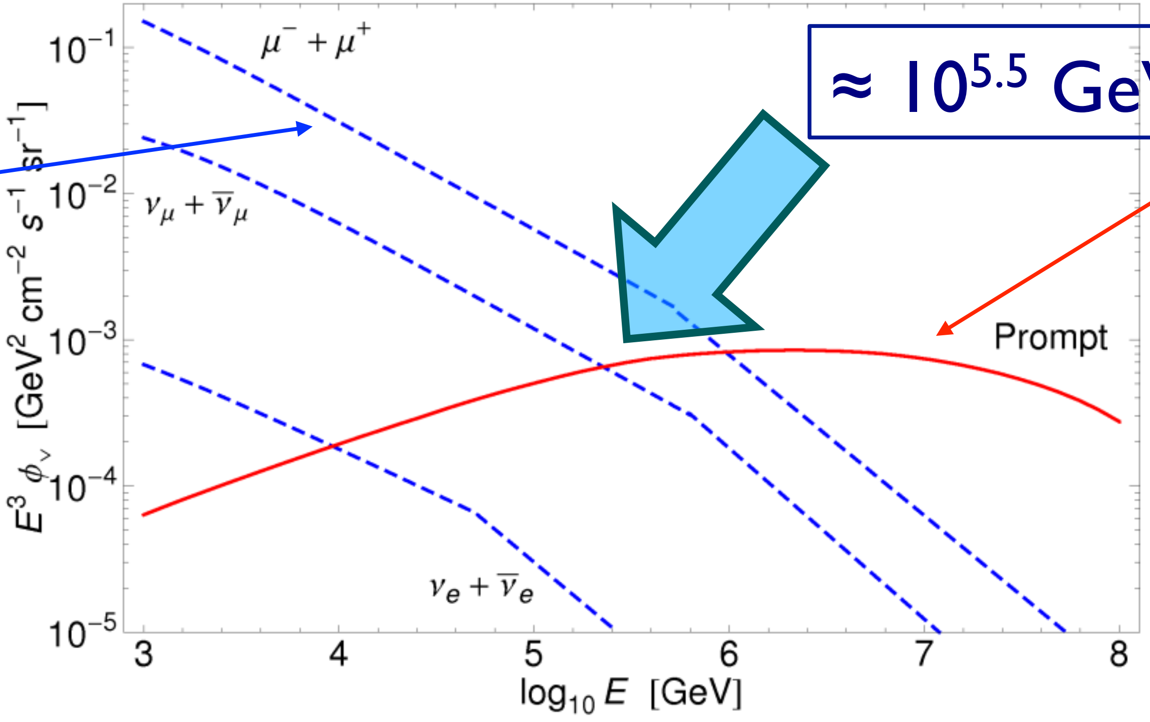
- Pions and kaons are produced in more or less every inelastic collision
- π^+ always decay to neutrinos ($\pi^+ \to \mu^+\nu_\mu$ is 99.98 %)
- *But π, K are long-lived* ($c\tau \sim 8$ meters for π^+)
  ⇒ lose energy through collisions before decaying
  ⇒ neutrino energies are degraded
- This is called the *conventional neutrino flux*

Prompt neutrino flux

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

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

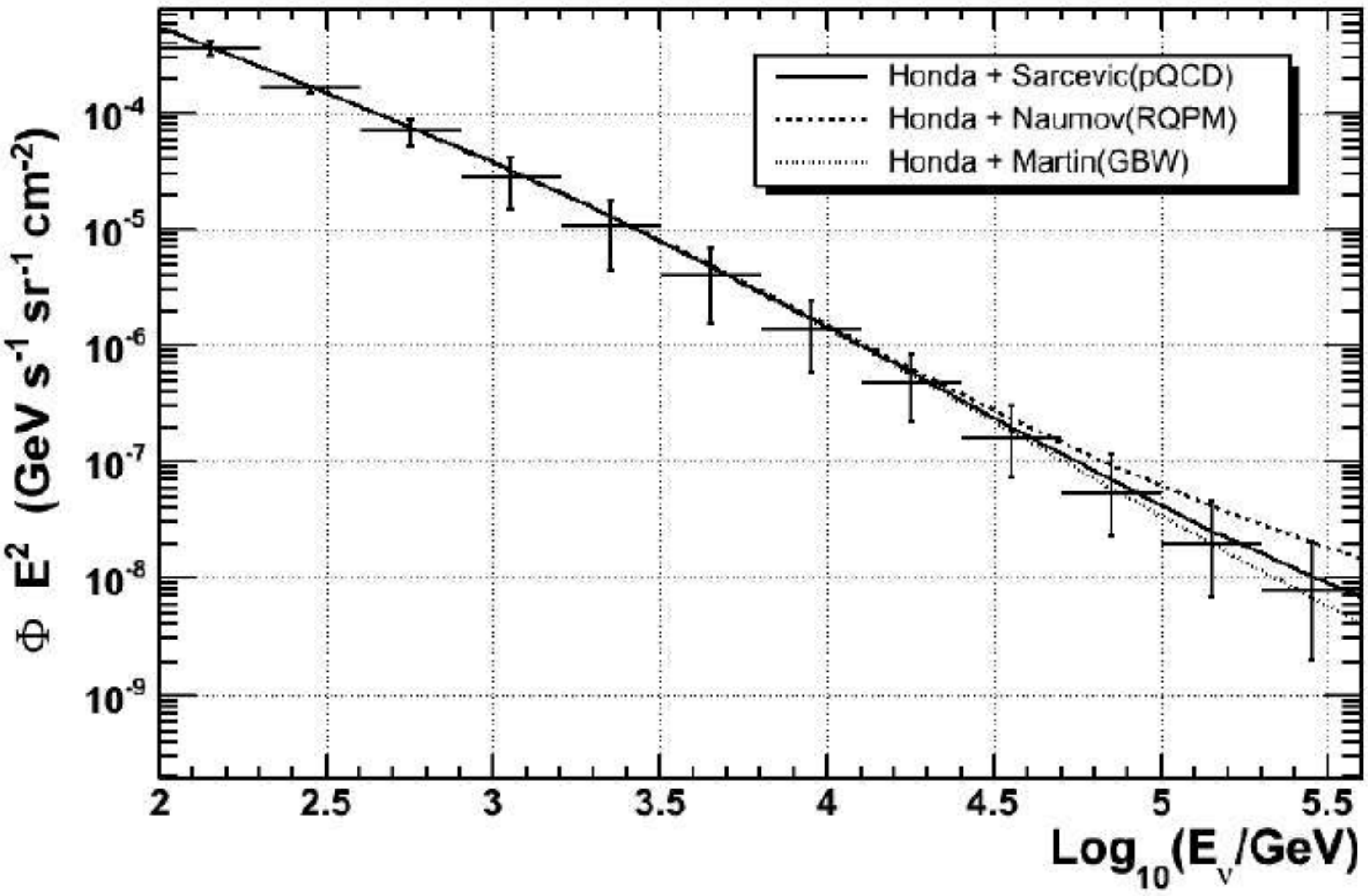


≈ $10^{5.5}$ GeV

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

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

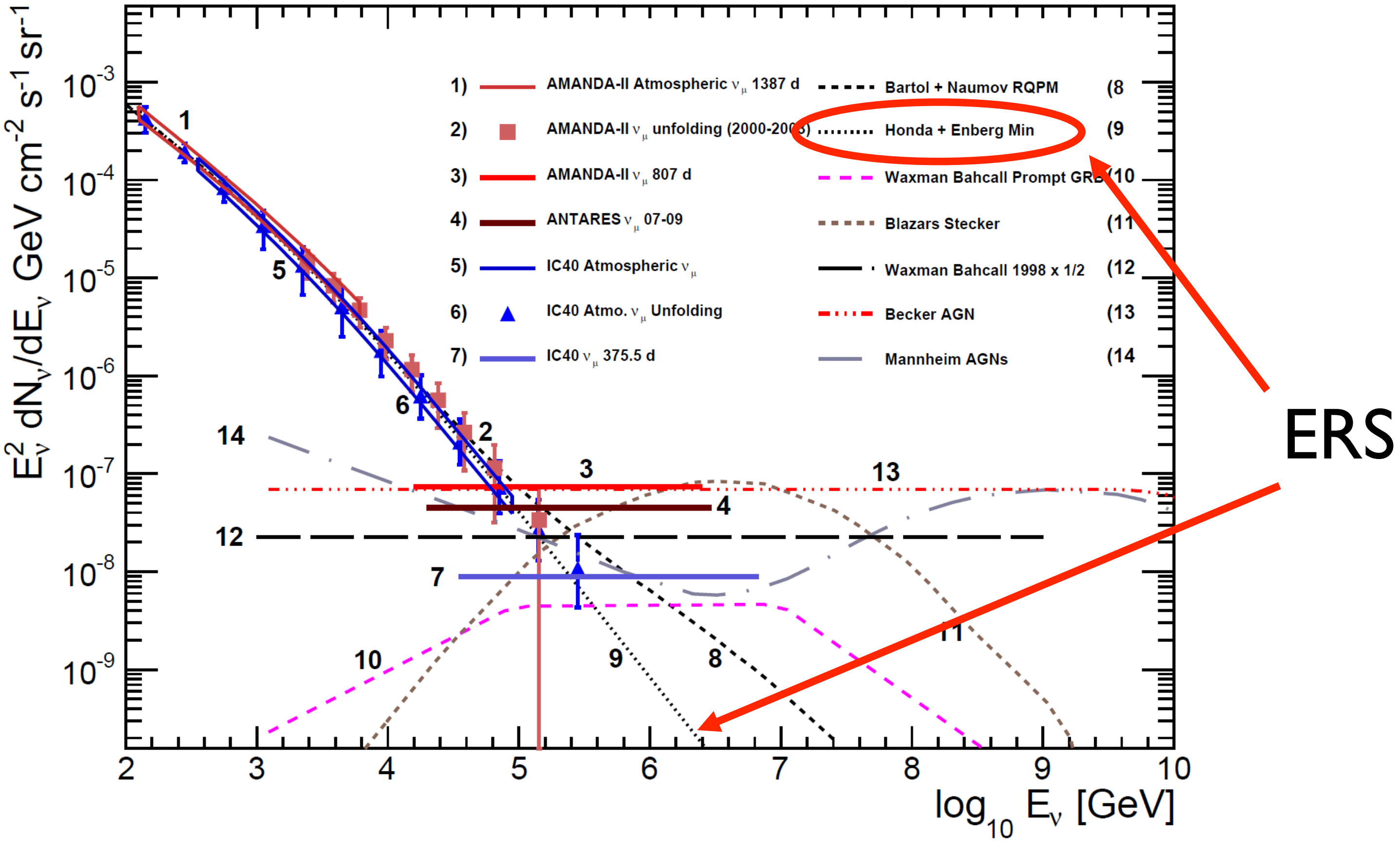
IceCube measurement (2011)



ERS
(2008)

Measurements in progress.
IceCube collaboration, Phys. Rev. D83, 012001 (2011)

IceCube diffuse flux search (2011)



IceCube collaboration, Phys. Rev. D 84, 082001 (2011)

So far the data reach up to roughly the predicted cross-over point → no sign of prompt contribution (or diffuse flux)

Cascade equations

- To find the neutrino flux we must solve a set of cascade equations, starting from the incoming proton 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
  λ_M is the interaction length for hadronic energy loss

Particle production

The **particle physics** inputs are the energy distributions

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

along with the interaction lengths, or cooling lengths

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

First and foremost: need differential charm cross sec **d*σ*/d*E***
(or actually charmed hadron cross section)

This of course is where perturbative QCD comes in

Prompt flux calculations

Prompt fluxes have been previously calculated using various models for the charm production mechanism

- E.g. Volkova et al, RQPM (Bugaev et al.) and QGSM (Kaidalov, Piskunova): non-perturbative models
- Thunman, Ingelman, Gondolo [Astropart. Phys. **5**, 309 (1996)] did the first real pQCD calculation (LO QCD in PYTHIA)
- NLO QCD calc. by Pasquali, Reno, Sarcevic [Phys.Rev. D59 (1999) 034020]
- Saturation model calc. by Martin, Ryskin, Stasto [Acta Phys. Polon. B34, 3273-3304 (2003)]

Problem with QCD in this process

Charm cross section in QCD (collinear factorization):

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

$$x_F = x_1 - x_2 \qquad x_{1,2} = \frac{1}{2}\left(\sqrt{x_F^2 + \frac{4M^2_{c\bar{c}}}{s}} \pm x_F\right)$$

$$x_F \simeq x_E = E/E'$$

CMS energy is large: $s = 2\,E_p m_p$ ⇒ $x_1 \sim x_F \sim 0.1\,,\;\; x_2 \ll 1$

xF=1: $E=10^5 \to x \sim 4\cdot 10^{-5}$

$E=10^6 \to x \sim 4\cdot 10^{-6}$

$E=10^7 \to x \sim 4\cdot 10^{-7}$

xF=0: $E=10^5 \to x \sim 6\cdot 10^{-3}$

$E=10^6 \to x \sim 2\cdot 10^{-3}$

$E=10^7 \to x \sim 6\cdot 10^{-4}$

Very small x is needed at **small Q^2** in **forward** process!

Forward processes

- As we saw this morning (e.g. J. Knapp's talk),
  very forward soft processes hard to measure at colliders
- This also holds for forward charm production,
  where there is a hard forward process
- Longitudinal distribution of charm (x_F) needed at small p_T

How small x do we know?

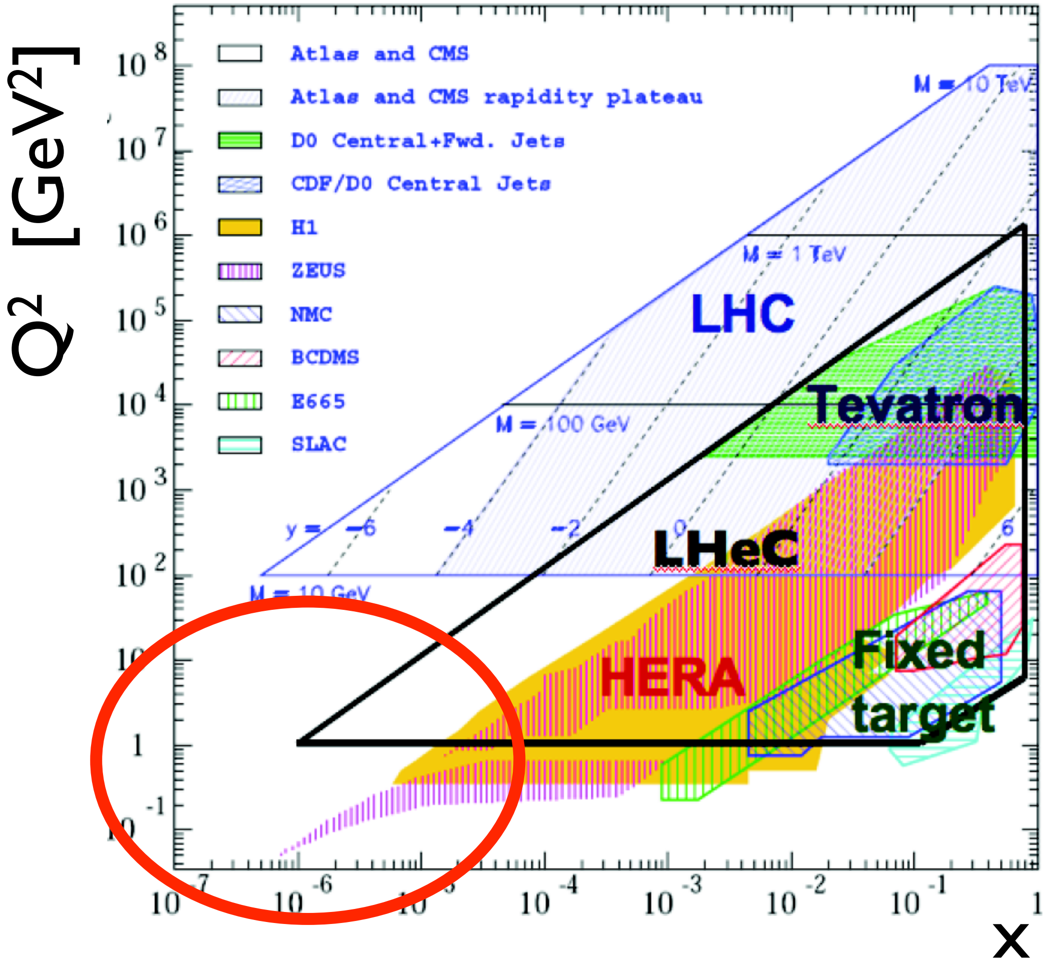
- In fact we have not measured anything at such small x

- E.g. the MSTW pdf has $x_{min}=10^{-6}$
  GJR has $x_{min}=10^{-9}$

- **But these are extrapolations!**

- 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)

Problem with QCD at small x

- For small x fixed order QCD (LO or NLO) does not work well — there are large logarithms that must be resummed:
  $$[\alpha_s \log(1/x)]^n$$
- PDFs poorly known at small *x*
- If logs are resummed ***(BFKL equation)*** one finds power growth of gluon distribution as $x \to 0$
- It grows so large that ultimately unitarity would be violated (T-matrix > 1)

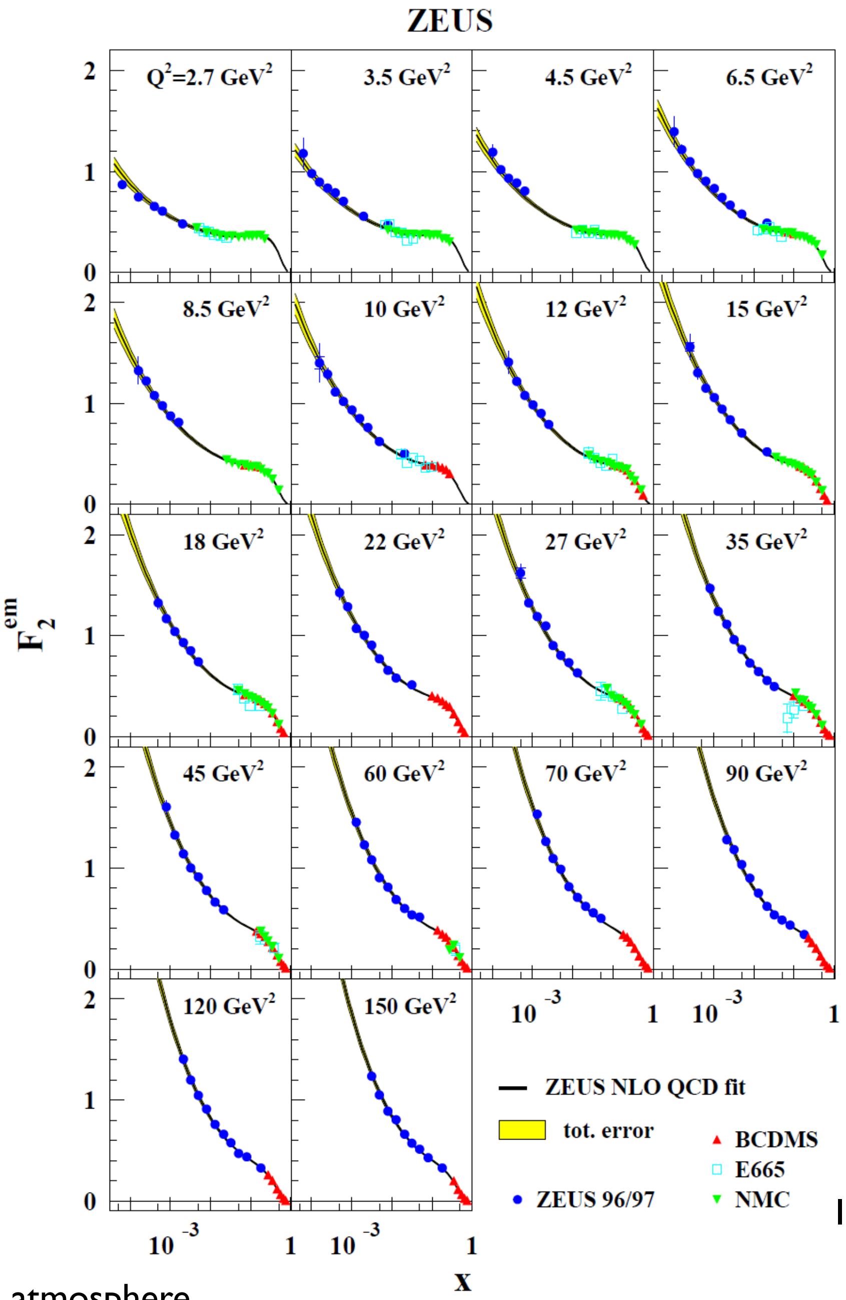
Small x

F_2 measured at HERA (ZEUS) as a function of Bjorken-x.

Note the steep power-law rise

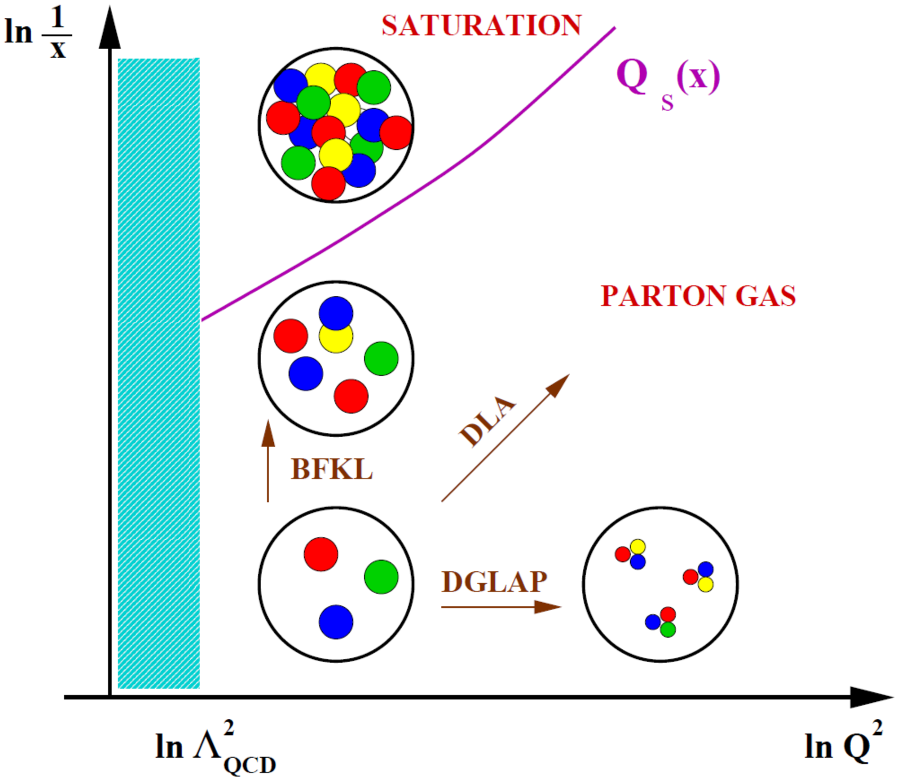
Can this rise continue?

Theoretical answer: no



Parton saturation

- Unitarity saved by ***saturation***:
  - Number of gluons in the nucleon becomes so large that gluons can recombine
  - Reduction in the growth
  - Non-linear evolution eqs.



- This is sometimes called the ***color glass condensate***
- The simplest PQCD evolution equation is the Balitsky-Kovchegov equation: BFKL with non-linear term

Our calculation

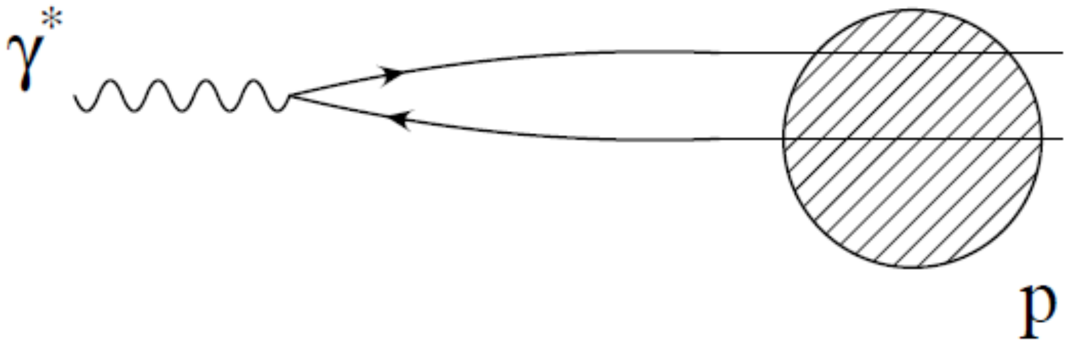
- We need $d\sigma_{\text{charm}}/dx_F$
- To include parton saturation, the calculation is done in the *dipole picture*, using an approximate solution of the Balitsky-Kovchegov equation
- Saturation suppresses the cross section at larger energy relative to NLO QCD

Dipole frame picture of DIS

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

→ Go to frame where the photon has very large energy (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
Dynamics is in the dipole-target cross section

Charm in dipole picture

- Dipole-target cross section obtained from approximate solution of the Balitsky-Kovchegov equation:
  Good fit to F_2

  Iancu, Itakura and Munier, Phys.Lett. B590 (2004) 199-208

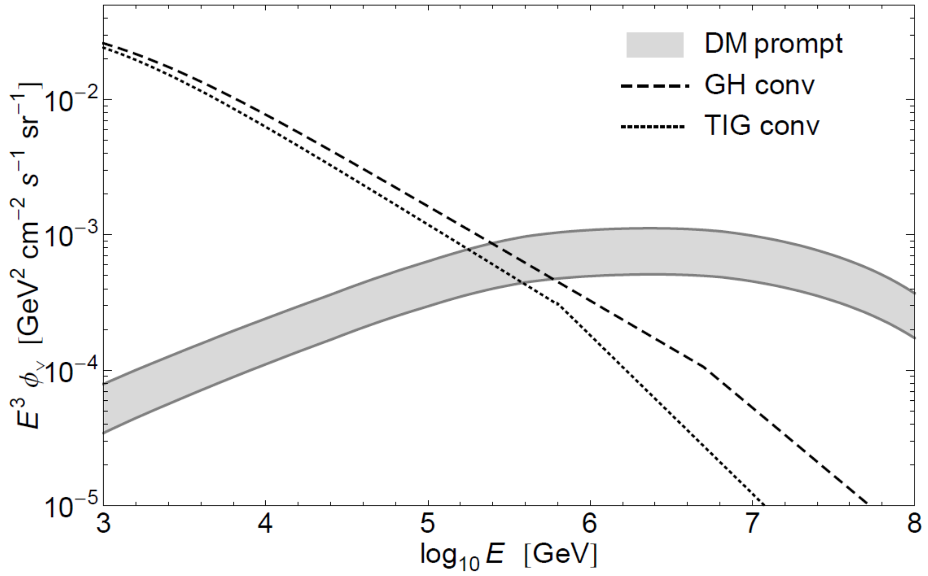
- Updated fit to F_2 with heavy quarks

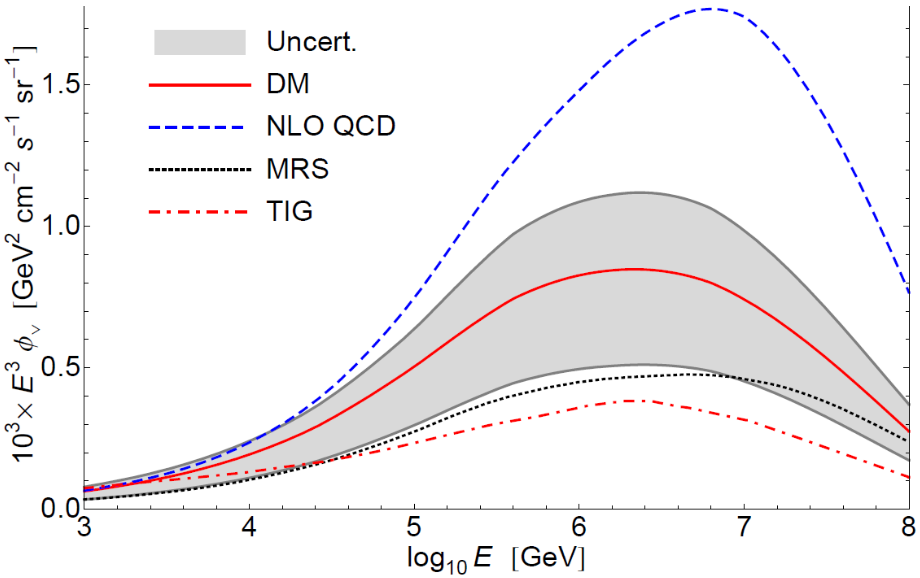
  G. Soyez, Phys.Lett. B655 (2007) 32-38

- Generalized from DIS to hadron-hadron

  (Nikolaev, Piller & Zakharov, Raufeisen & Peng, Kopeliovich & Tarasov, Goncalves & Machado)

Resulting neutrino fluxes

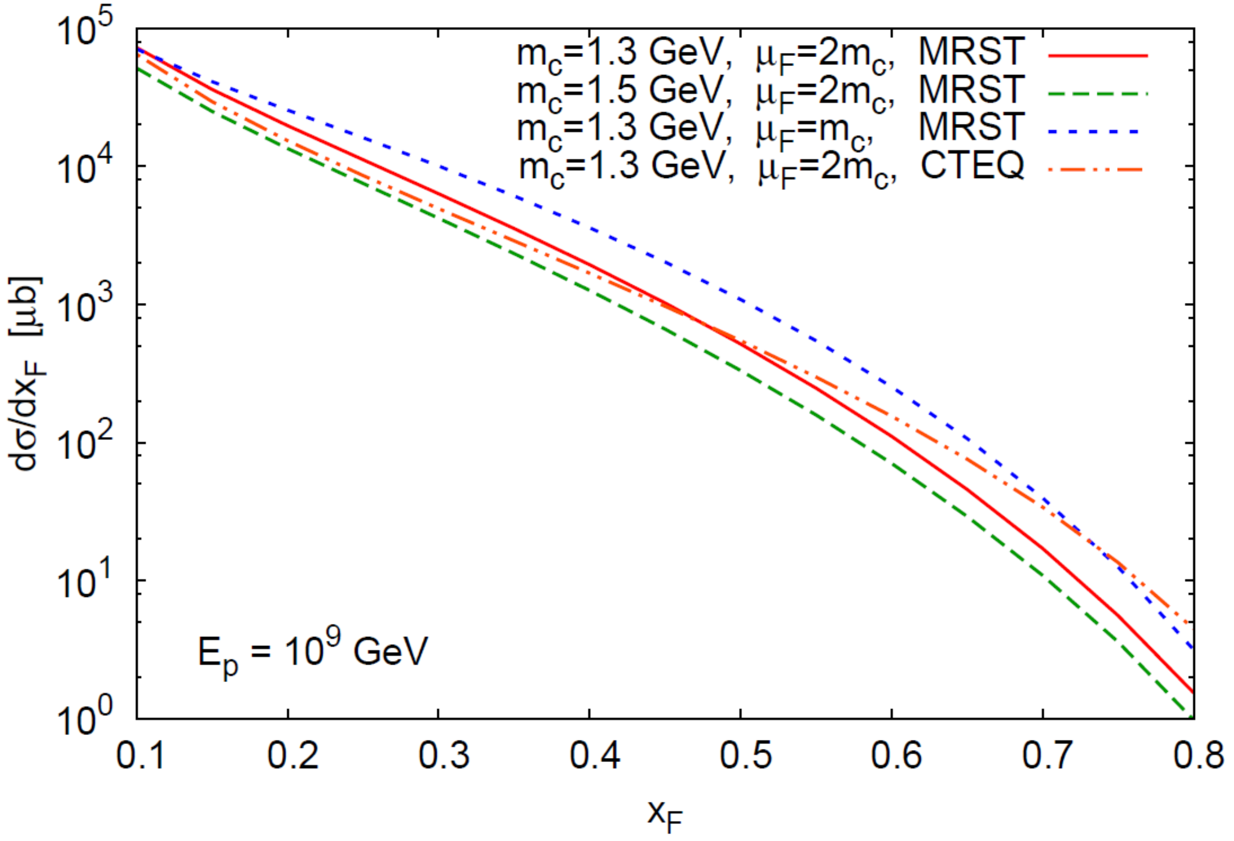




The band shows uncertainty of the dipole calc.

- Upper line in right plot: NLO QCD (Pasquali et al.)
- Lowest line: LO QCD (Thunman et al.)
- MRS line: GBW saturation (Martin, Ryskin, Stasto) (phenomenological dipole model)

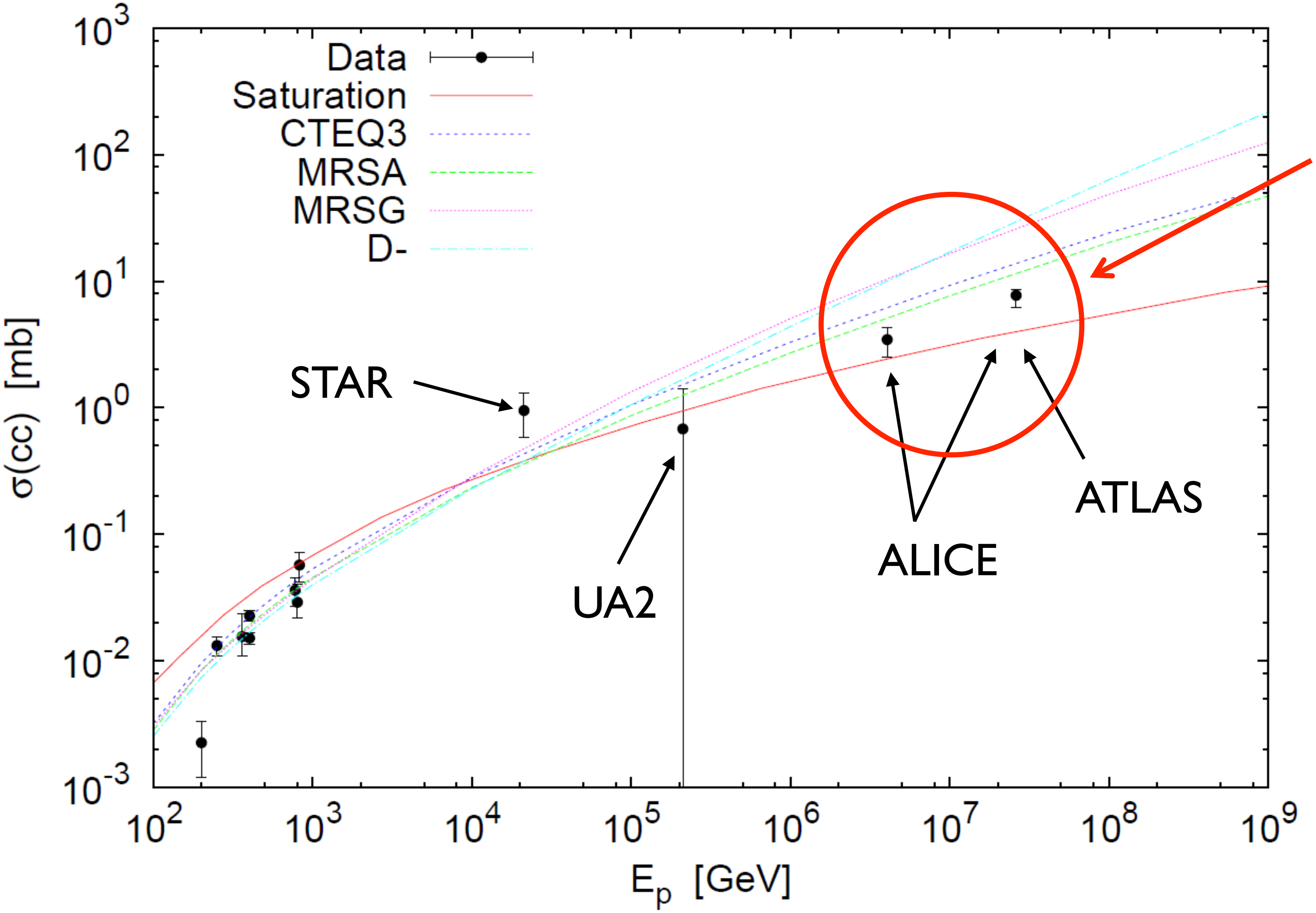
Uncertainties in charm cross section



Different charm mass, factorization scale, pdf choice

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

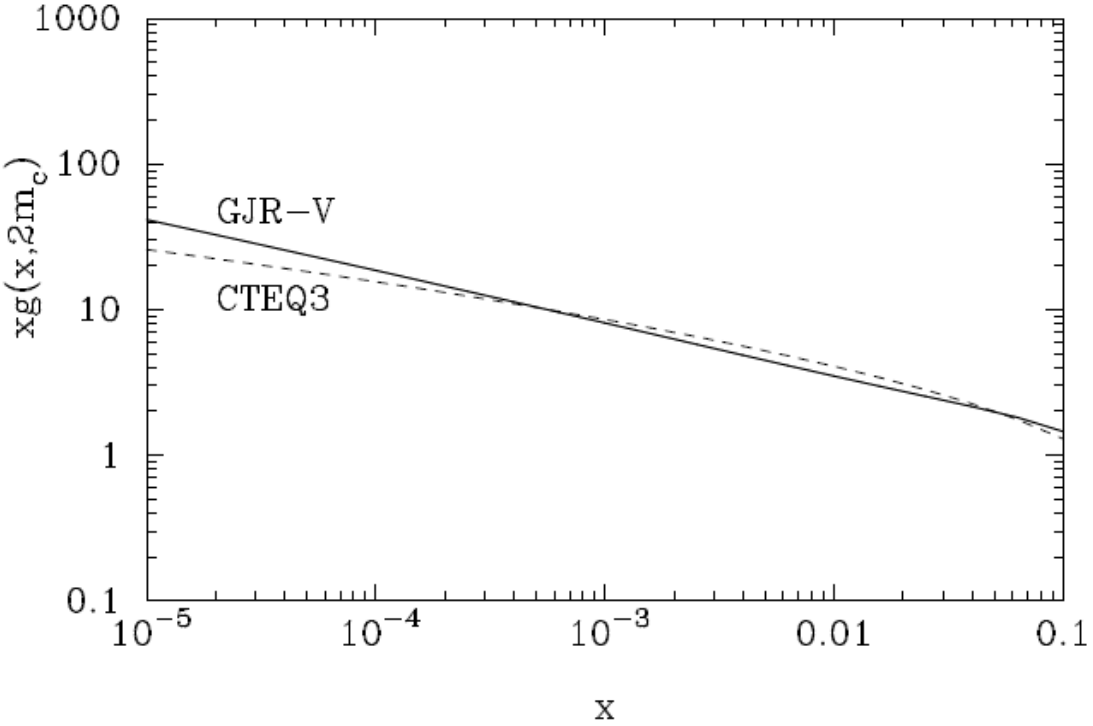
Total charm cross section pp → cc



New
data
since
2011

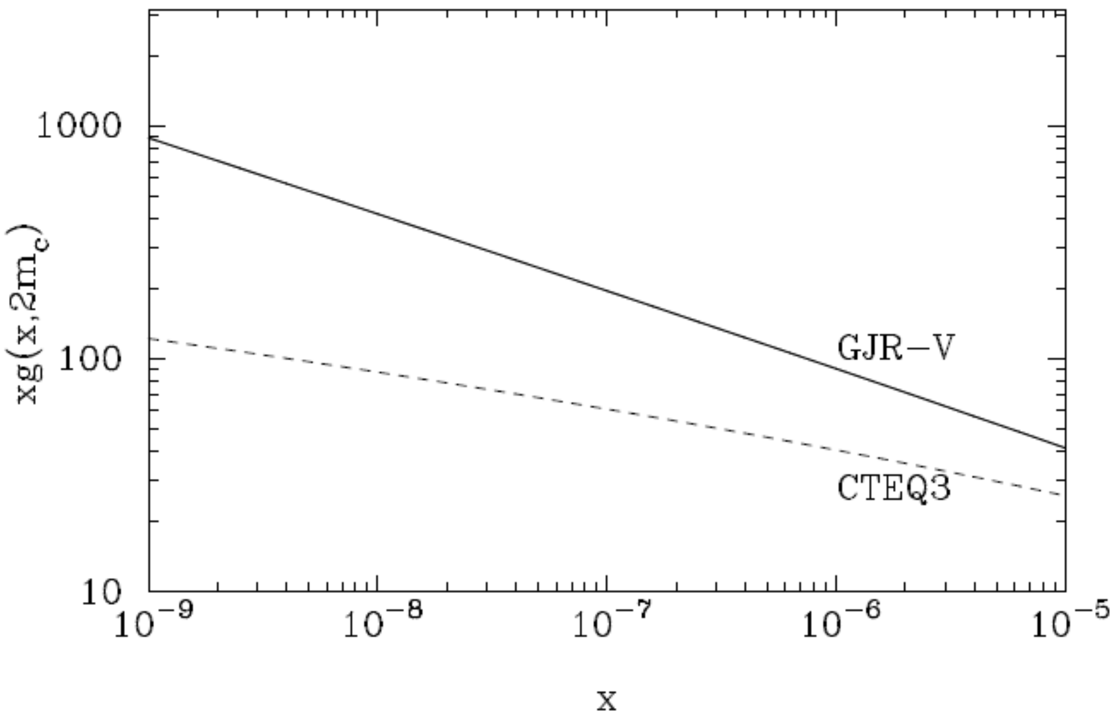
Very different energy dependence of calculations!

Gluon pdfs: medium small x



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

Gluon pdfs: very small x



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

Fixed order calc at small x

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

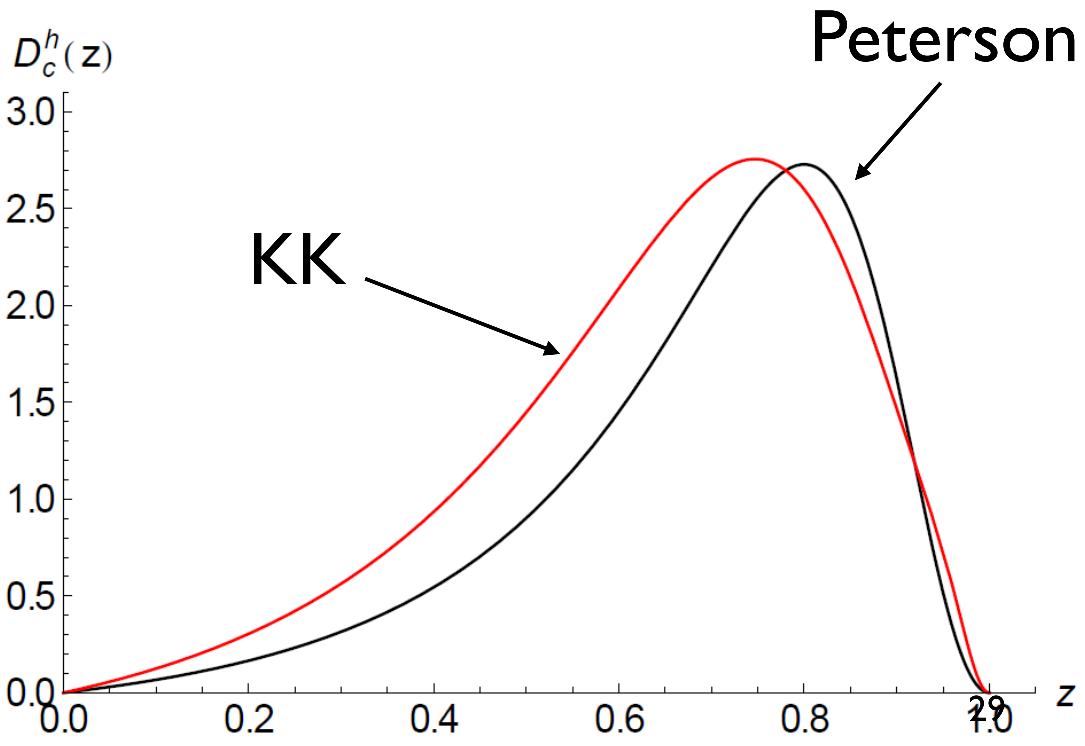
Quark fragmentation to hadrons

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, use also BCFY (Braaten, Cheung, Fleming & Yuan)

Uncertainty in normalization and average energy fraction



Work in progress

Using the **PDF** approach:

- Improve hard scattering with the **FONLL** approach (Fixed Order Next-to-Leading Log), which matches resummed logs $\log(p_T/m_c)$ to fixed order result.
- Need low pT and high rapidity for our case
  (For 10^8 GeV, Y ~ 5-7, pT < 10 GeV)
- Need small-x pdfs

FONLL:
M. Cacciari, M. Greco & P. Nason, JHEP 9805 (1998) 007;
M. Cacciari, S. Frixione & P. Nason, JHEP 0103 (2001) 006

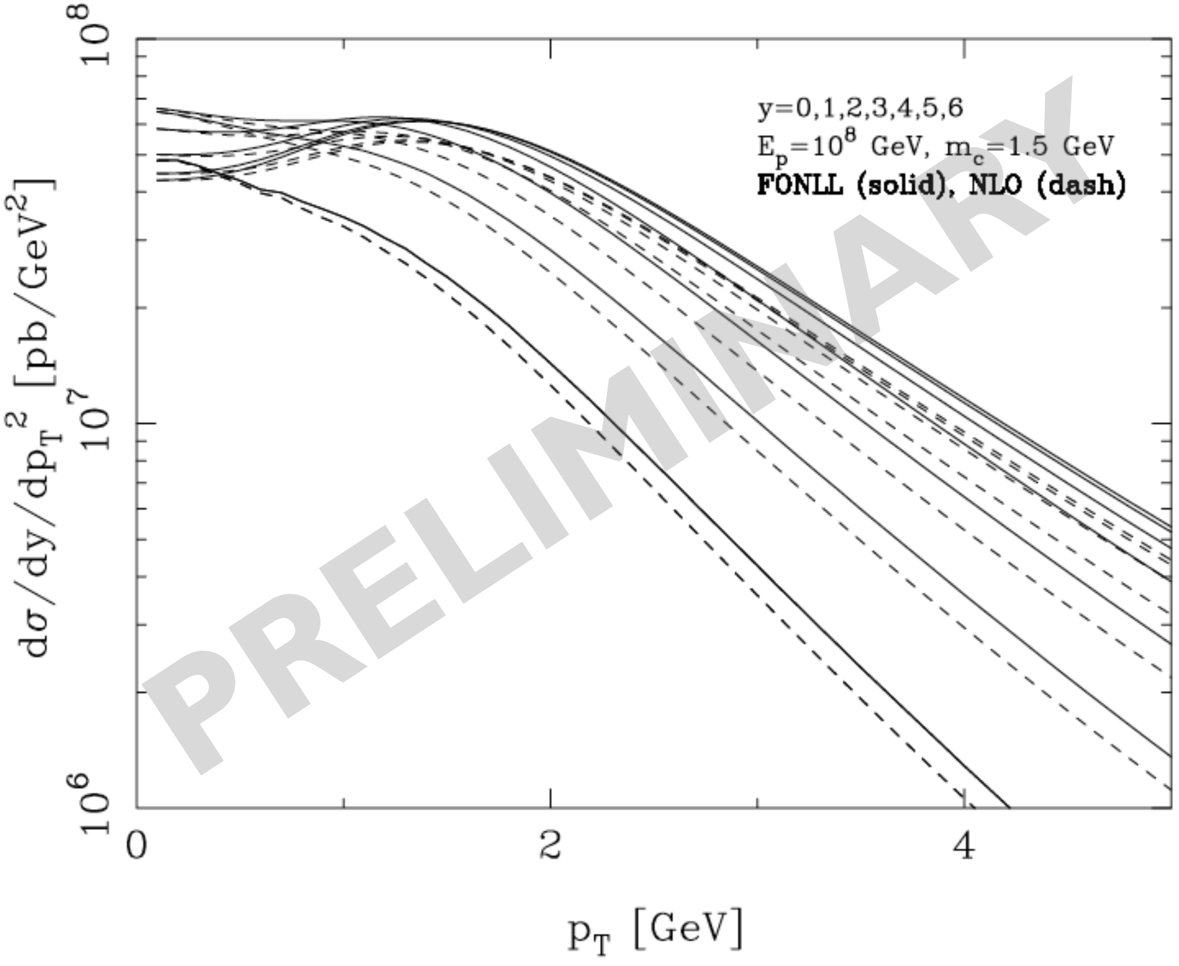
Work in progress

Using the **dipole** approach:

- Use a more recent full numerical solution of the Balitsky-Kovchegov equation including NLL corrections
  [AAMQS, Albacete et al., Eur. Phys. J. C71 (2011) 1705]
- Tested against HERA DIS data at small x

Will compute fluxes with both PDF and saturation approach, compare with LHC data

FONLL cross section



(Enberg, Reno, Sarcevic, work in progress)

High p_T muons from charm

E.g. L. Gerhardt and S. Klein at ICRC 2009, arXiv:0909.0055

- Charm production at **high p_T** (> 6 GeV for 1 TeV muons): lateral separation of muons from charm and from shower
- Muons from conventional flux: **lower p_T**
- Sensitive to the cosmic ray composition.
- Potential to pick out charm contribution at lower energies than the cross-over because of the separation.

- This should be calculated with FONLL

From colliders to astro

- We will need more data at smaller x to constrain neutrino fluxes:
  - Balitsky-Kovchegov calc describes HERA F_2 data
  - But at larger x → we don't know the energy evolution
- **LHC, ALICE, LHCb**
  - New data on cc cross section
- **LHeC ?!** *(Large Hadron–electron Collider)*

From astro to colliders

- Maybe atmospheric neutrino data can give constraints on small-x scattering and saturation at very small x!

- Of course: numerous astrophysical and experimental uncertainties. But one can hope...

- Some non-perturbative charm models are already disfavored by IceCube

Main message

QCD issues crucial in astrophysical processes such as

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

- We need pdfs at **small x**

Z-moments

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

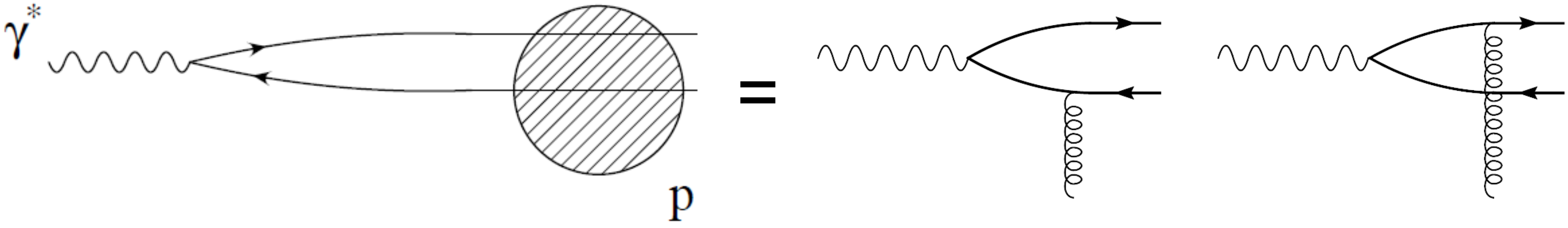
$$Z_{kh} = \int_E^\infty dE' \frac{\phi_k(E',X,\theta)}{\phi_k(E,X,\theta)} \frac{\lambda_k(E)}{\lambda_k(E')} \frac{dn(kA \to hY;E',E)}{dE}$$

- 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

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

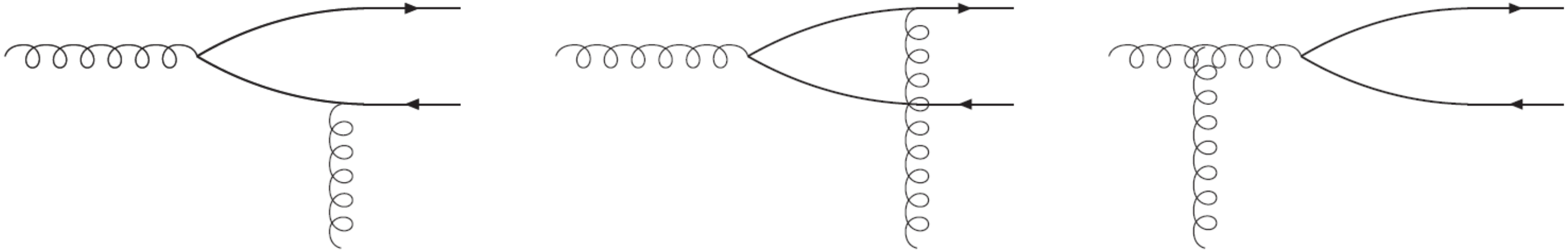
The wave function for the fluctuation is given by:

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

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

Generalize to hadron-hadron

Generalized to dipole picture for heavy quark production in hadron-hadron collisions by Nikolaev, Piller & Zakharov; Raufeisen & Peng; Kopeliovich & Tarasov. Applied to include saturation by Goncalves and Machado.



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

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

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

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

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)