Neutrinos from charm production in the atmosphere

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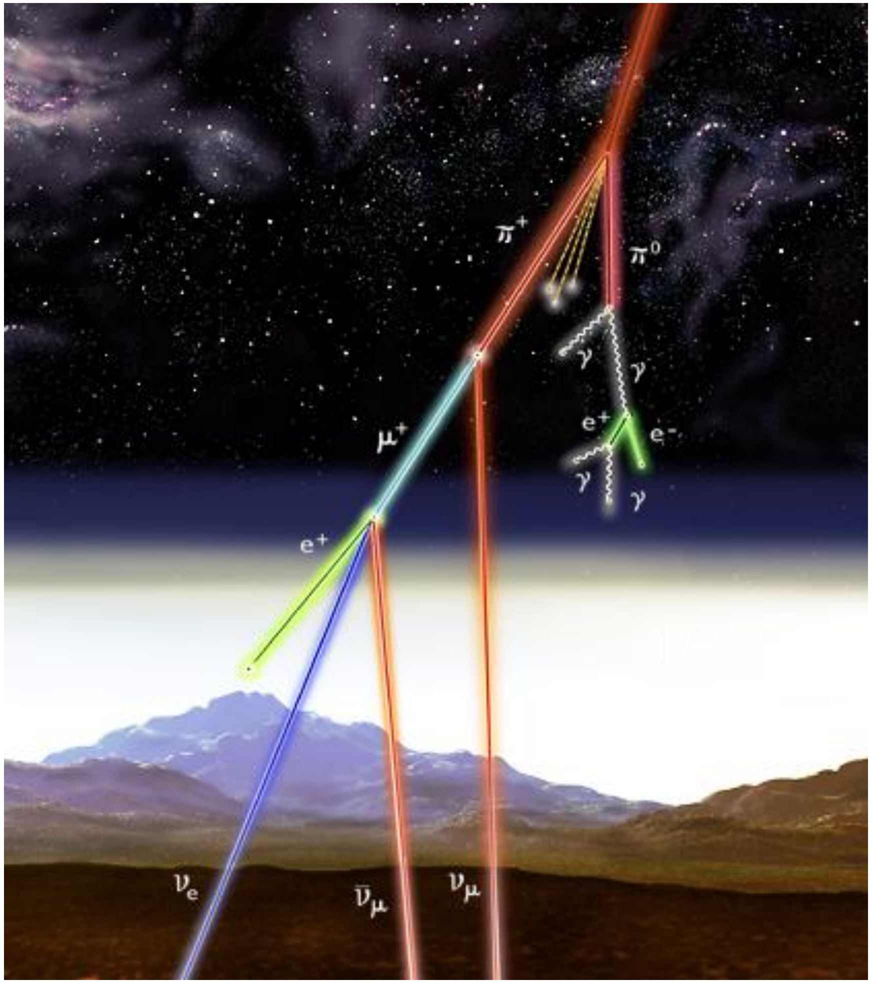
EPS HEP 2013
Stockholm, July 18, 2013

Based on
RE, M.H. Reno & I. Sarcevic, arXiv:0806.0418
+ work in progress w/ Reno, Sarcevic, & K. Kutak

Atmospheric neutrinos

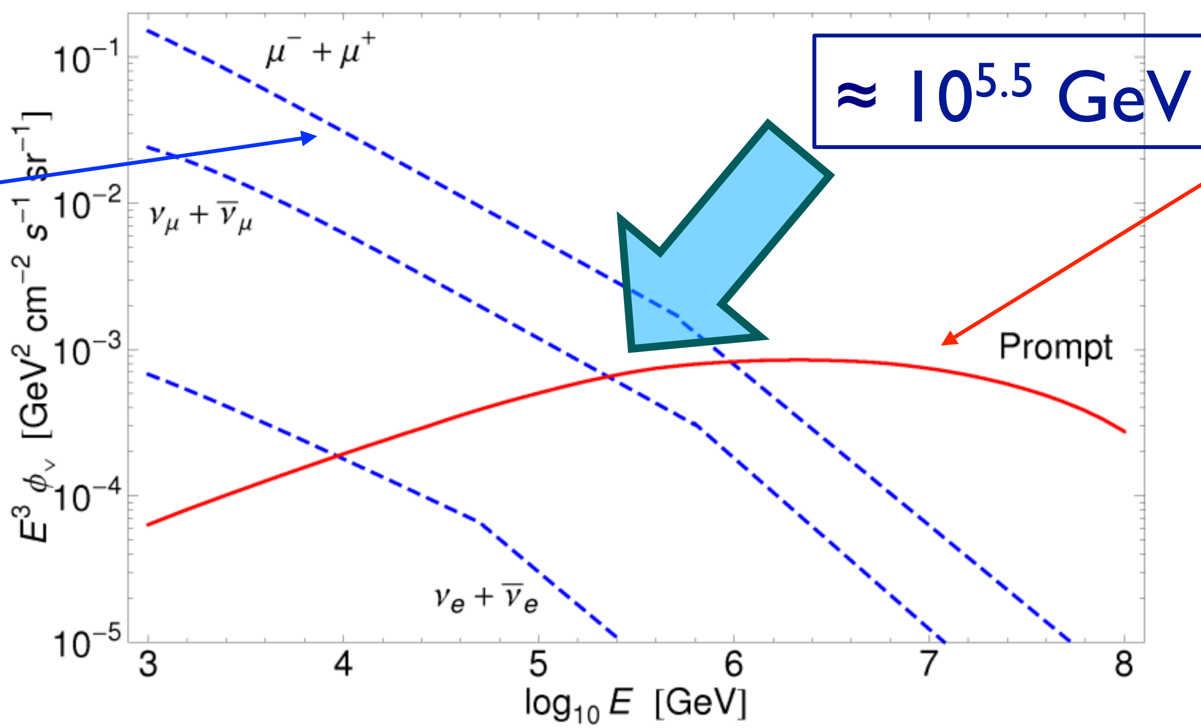
- Cosmic rays bombard upper atmosphere and collide with air nuclei
- Hadron production:
  pions, kaons, D-mesons ...
- Interaction & decay
  $\Rightarrow$ cascade of particles
- Semileptonic decays
  $\Rightarrow$ neutrino flux



INFN-Notizie No.1 June 1999

Prompt vs conventional fluxes of atmospheric neutrinos

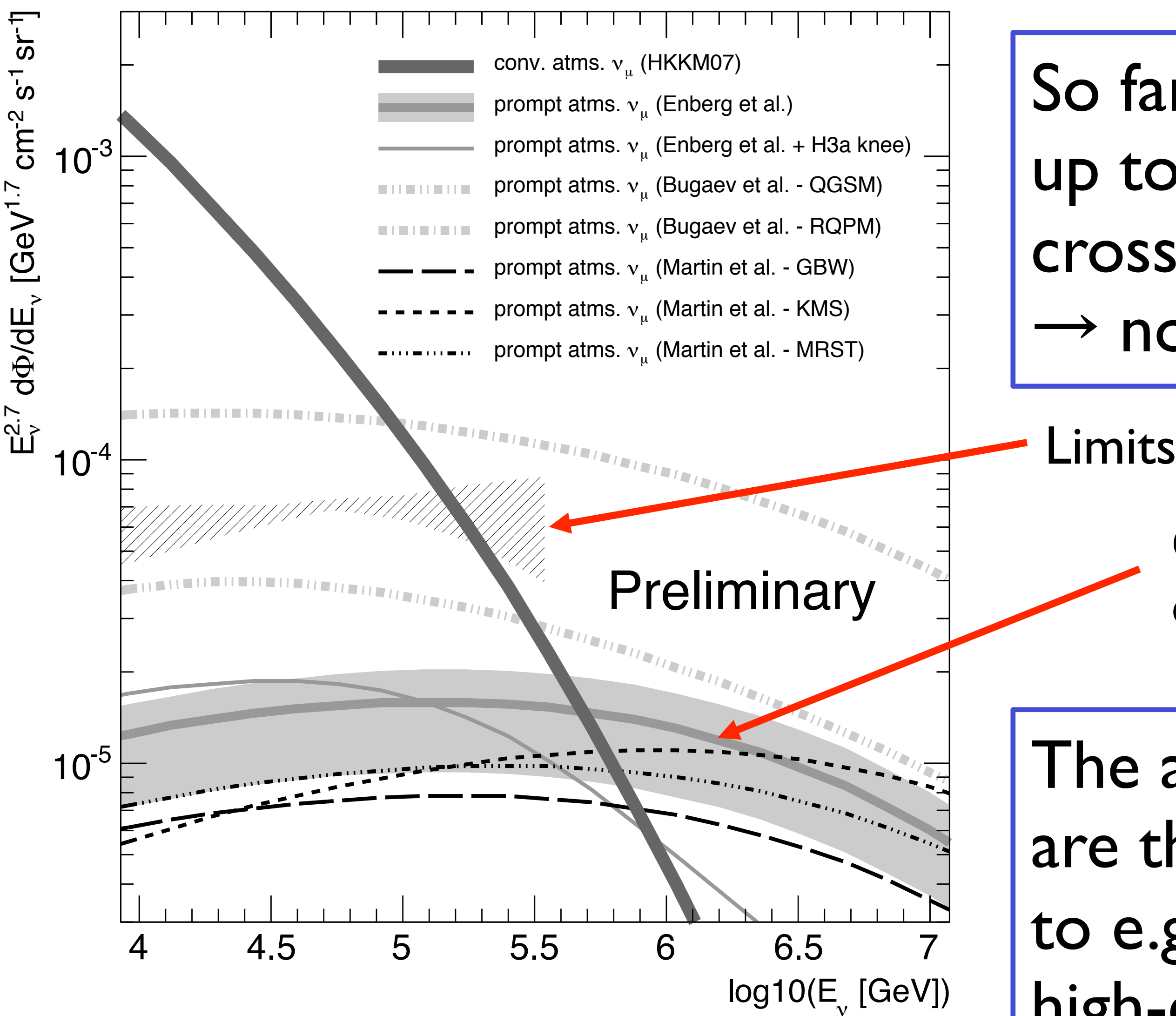
Pions & kaons: long-lived $\Rightarrow$ lose energy before decay



Charmed mesons: short-lived $\Rightarrow$ don't lose energy $\Rightarrow$ harder spectrum

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

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

Problem with QCD in this process

Charm cross section in LO QCD:

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

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

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

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

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: $[\alpha_s \log(1/x)]^n$

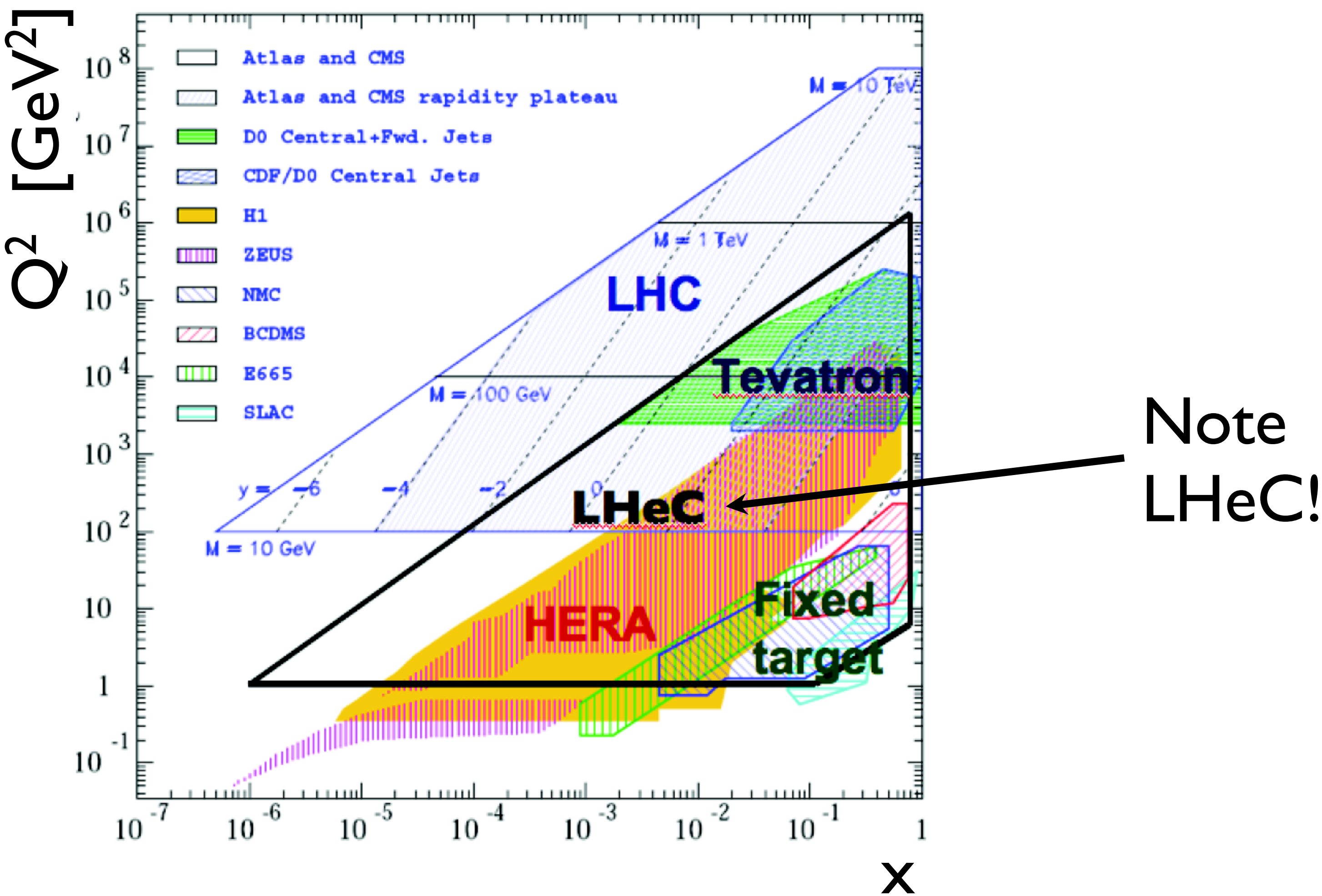
- If logs are resummed ***(BFKL)***:
  power growth of gluon distribution as $x \to 0$

- 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 $x > 10^{-4}$!

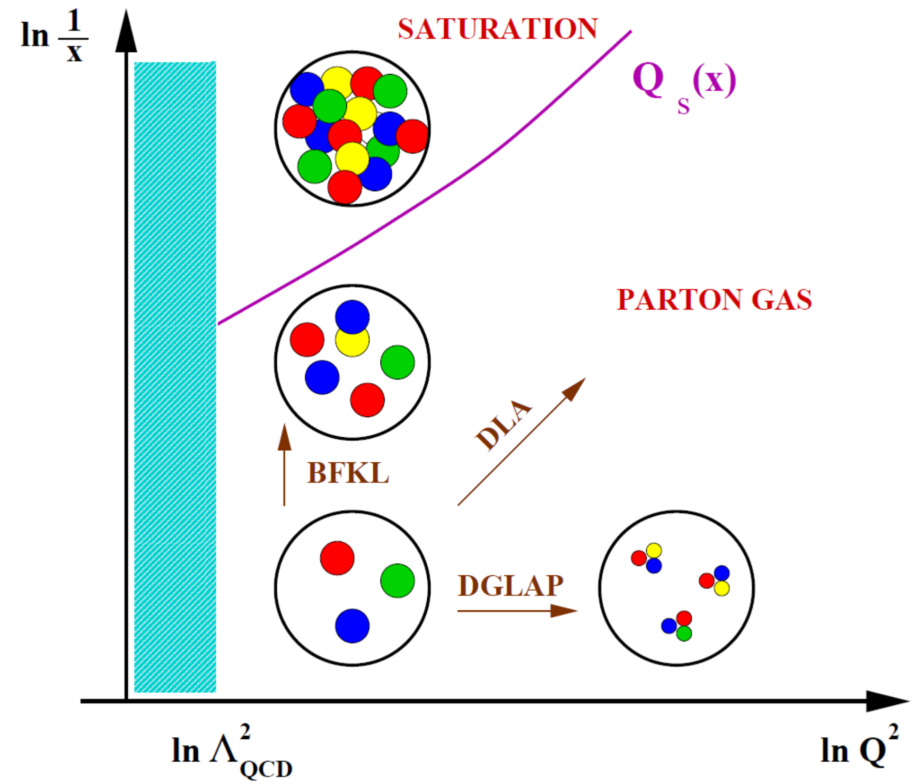
Kinematic plane



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

Parton saturation

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

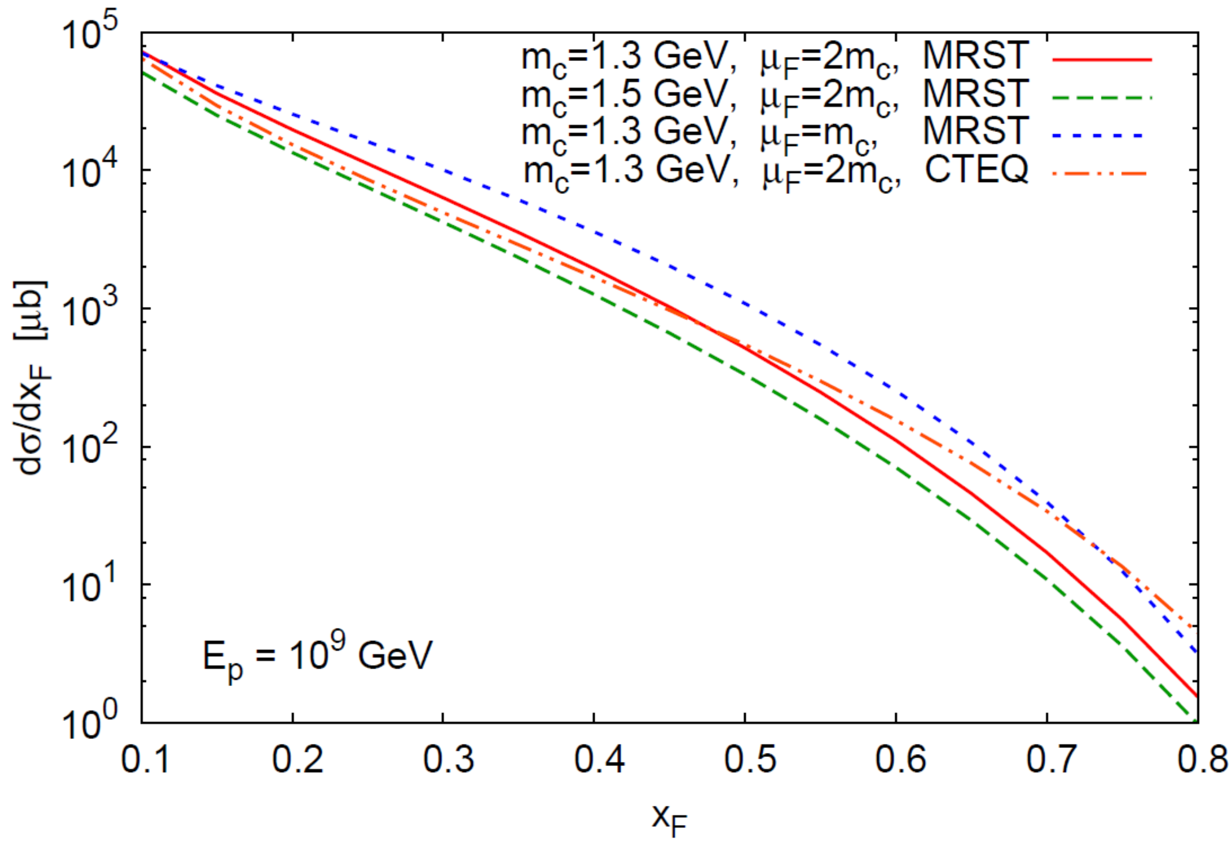


- This is sometimes called the ***color glass condensate***
- Non-linear QCD evolution: Balitsky-Kovchegov equation

Charm production

- We need 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

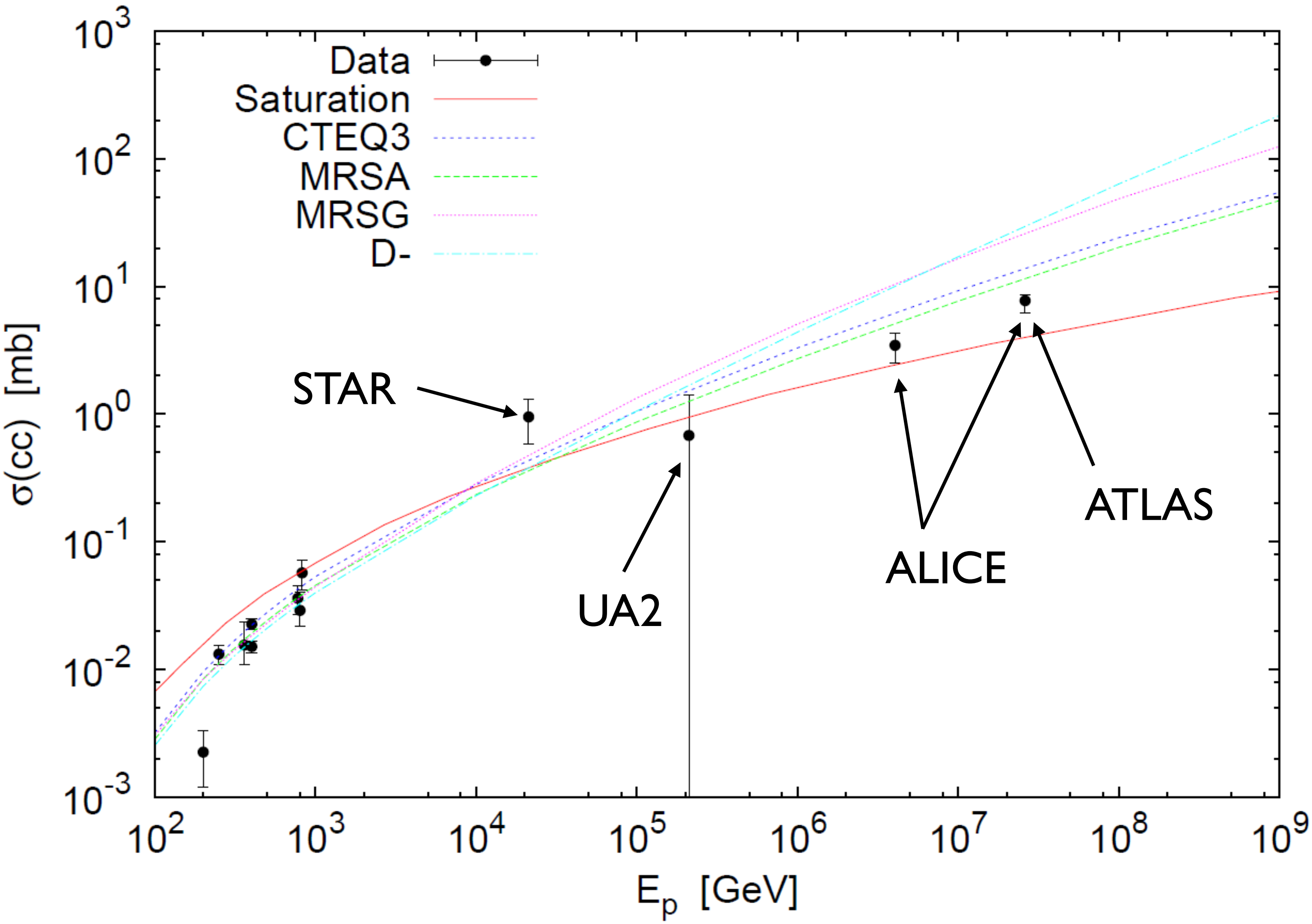
Uncertainties in charm cross section



Different charm mass, factorization scale, pdf choice

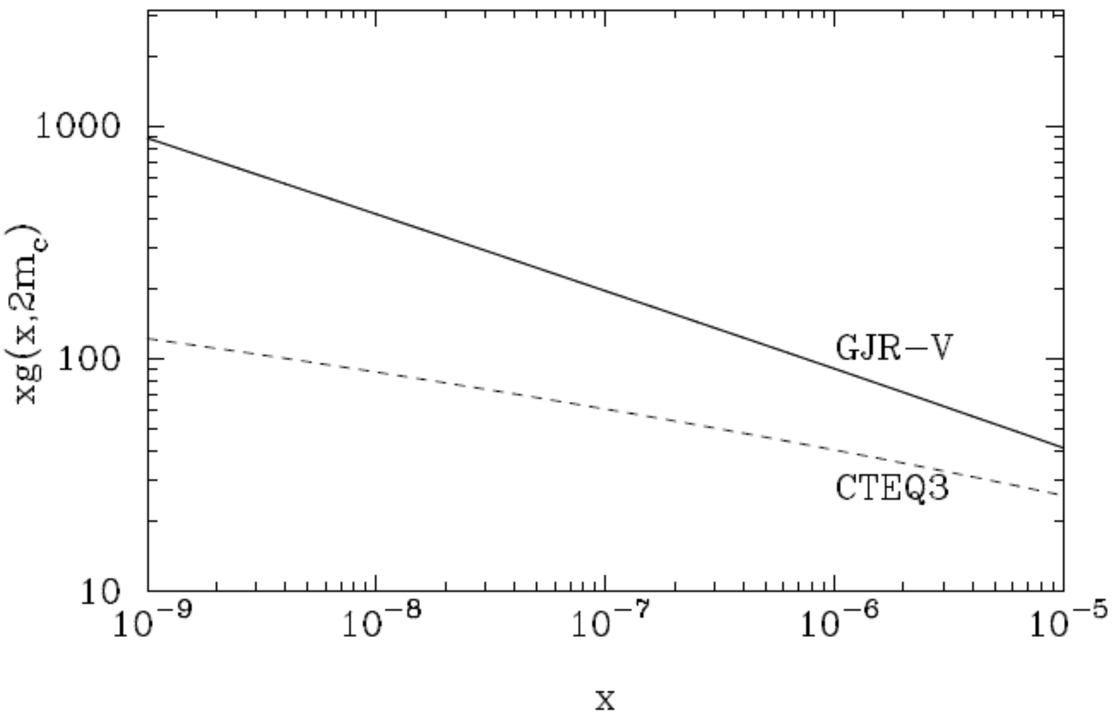
[R. Enberg, M.H. Reno, I. Sarcevic, arXiv:0806.0418 (in PRD)]

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

Theoretical uncertainties

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

Especially important given that this is a major background for IceCube 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 (RE, Reno, Sarcevic, et al.)

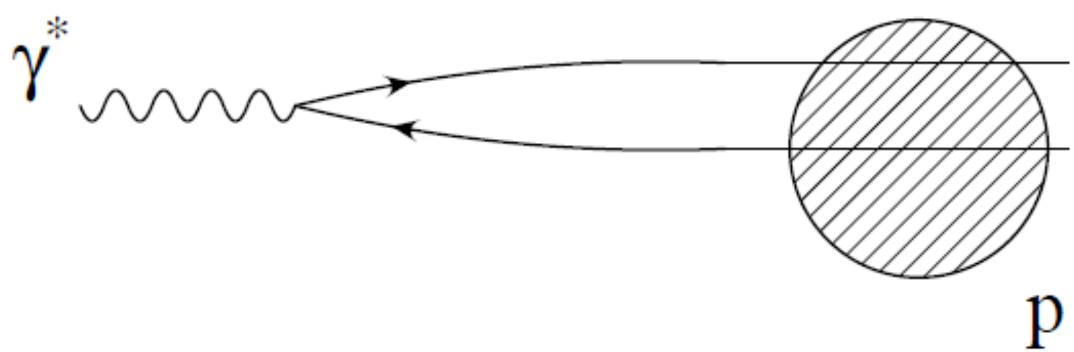
Backup slides

Dipole frame picture of DIS

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

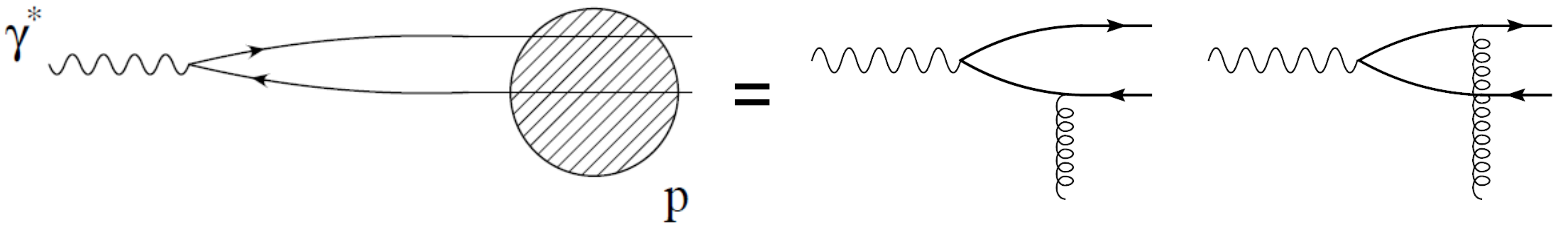
→ Go to frame where the photon has very large lightcone q+ momentum (e.g. proton's rest frame)

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

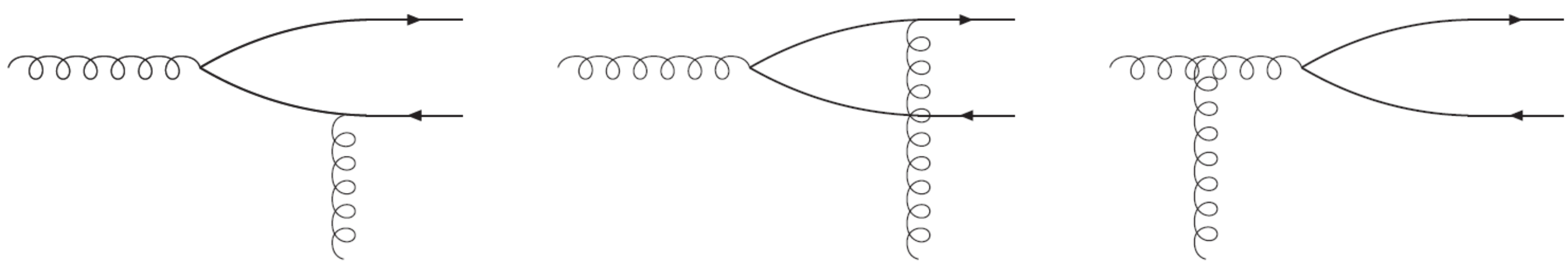
The wave function for the fluctuation is given by:

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

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

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

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

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)