

The Charm of Colour Octet Fields

A Study of Quark Production in Fragmentation Processes

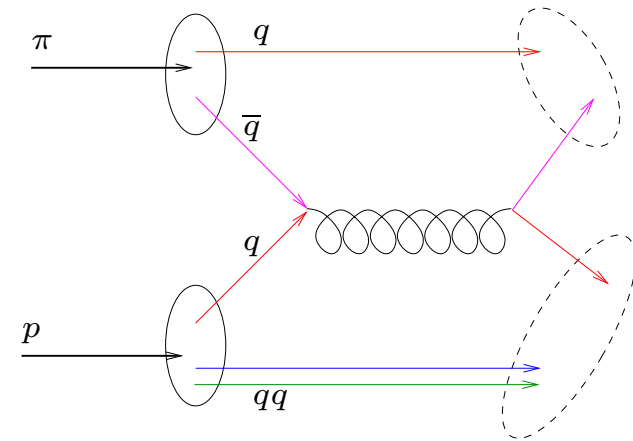
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Outline

- QCD Reminder
- Lund string model
- Our model for colour octet fields \rightarrow soft charm production
- Effects of soft charm: Atmospheric lepton fluxes
- Experimental limits on the octet model: D meson production in π^-p collisions
- Conclusions and Outlook

Quantum Chromo Dynamics (QCD)

- The strong force affects quarks and gluons
- Gauge symmetry of the strong force: $SU(3)_C$
- Quarks: triplet (**3**) colour charge
(red, green, blue)
- Gluons: octet (**8**) colour charge
(colour+anticolour)

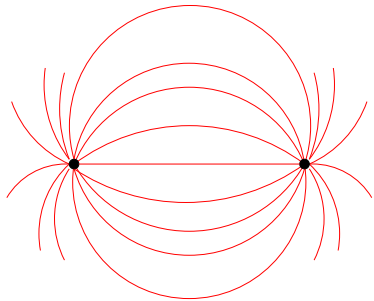


The strong coupling constant is energy dependent:

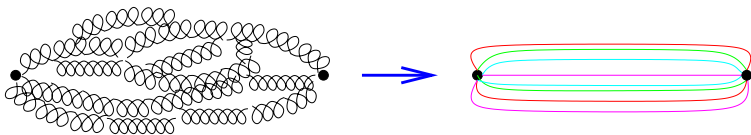
$$\alpha_s(Q^2) \sim \frac{1}{\ln(Q^2/\Lambda^2)} \Rightarrow$$

- **Asymptotic Freedom**: Hard processes can be calculated perturbatively
- **Confinement**: No free coloured particles (e.g. quarks)
- Quarks are produced both in hard and soft processes

Lund String Fragmentation



EM: dipole \Rightarrow field $\rightarrow \infty$



QCD: $q\bar{q}$ colour dipole,
gluon self-interaction \Rightarrow flux tube



Lund string fragmentation:
 $q\bar{q}$ pairs from field energy

Colour field between quarks \approx string

String potential: $V_3(r) = \kappa_3 r$, $\kappa_3 \approx 1\text{GeV/fm}$

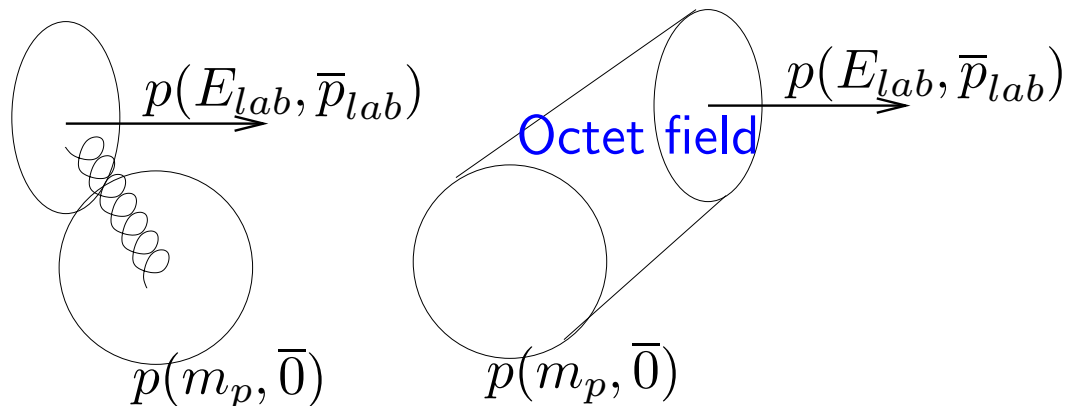
- Fragmentation by e.g. $q\bar{q}$ formation
- Flavour conservation: $q\bar{q}$ produced in a point
- Energy conservation (classically): $q\bar{q}$ produced at a distance

\Rightarrow QM tunnelling: $P(q) \propto e^{-\frac{\pi}{\kappa} m_q^2}$ (OK for u, d, s)

$\Rightarrow \frac{P(c)}{P(u)} \approx 10^{-11}$ ($m_c = 1.3 \text{ GeV}$)

Our Model: Octet String Creation

- Octet string created by gluon exchange between two protons



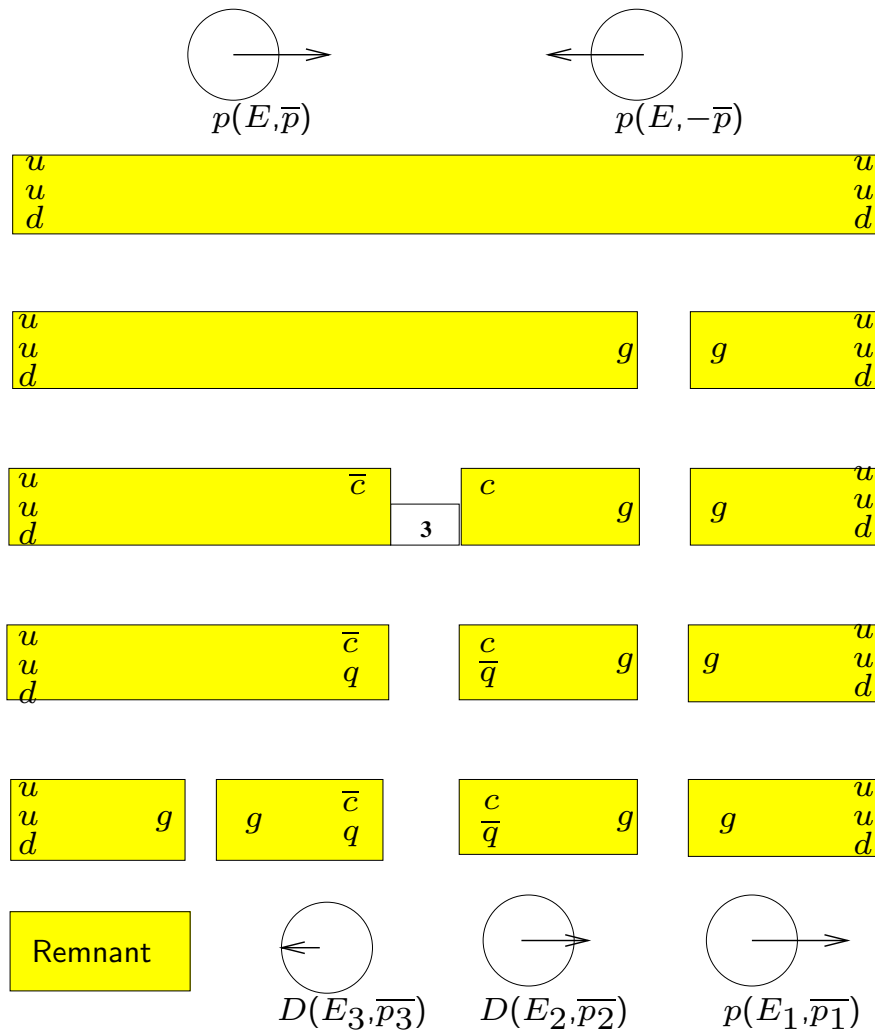
Group theory: $V_D(r) \propto C_D \Rightarrow \kappa_D \propto C_D$ ($D = 3, 8, \dots$)

- Higher order representations have larger C_D
- The energy density of the string is $\kappa_8 = 9\kappa_3/4$

$$\Rightarrow \frac{P(c)}{P(u)} \approx 10^{-5}$$

- Large probability for gluon exchange if protons overlap

Our Model: Octet String Fragmentation 1.



- Proton-proton collision, gluon exchange \Rightarrow octet string between proton remnants
 - String fragmentation by octet charges (gluons or $q\bar{q}$ pairs)
 - Gluons absorbed in formed hadrons (no glueballs)
 - $q\bar{q}$ break-ups made in two steps

$$e^{-\frac{\pi}{\kappa}(m_{q1}+m_{q2})^2} \lll e^{-\frac{\pi}{\kappa}m_{q1}^2} e^{-\frac{\pi}{\kappa}m_{q2}^2}$$
- \Rightarrow a leading proton, two charmed mesons and a remnant system (low-energetic particles) are created

Our Model: Energy and Momentum Distribution

Each fragmentation step: fraction of string energy \rightarrow particle energy

New particle gets energy and momentum $E + p_z = z(E + p_z)_{string}$

$$E = \frac{1}{2} \left(z(E + p_z)_{string} + \frac{m^2}{z(E + p_z)_{string}} \right)$$

$$p_z = \frac{1}{2} \left(z(E + p_z)_{string} - \frac{m^2}{z(E + p_z)_{string}} \right)$$

z Monte Carlo'd from

$$f(z) = \frac{1}{z} (1 - z)^a e^{-bm_T^2/z} \Rightarrow \langle z \rangle \approx 1 - \frac{a+1}{bm_T^2}$$

heavier particle \rightarrow larger z

$$(E + p_z)_1 = (1 - z_0)(E + p_z)_0$$

$$z_0(E + p_z)_0$$

$$(1 - z_1)(E + p_z)_1$$

$$z_1(E + p_z)_1$$

$$z_0(E + p_z)_0$$

Remnant string's energy scaled down:

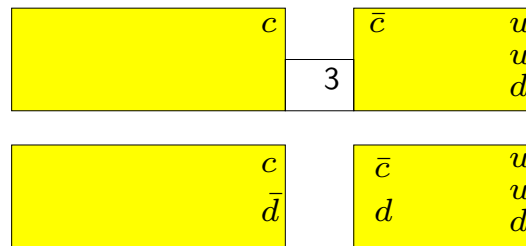
$$(E + p_z)_{new} = (1 - z)(E + p_z)_{old}$$

\Rightarrow Leading particles from string ends

Fragmentation continues while $M_{string}^{inv} = (E + p_z)(E - p_z)_{string}$ big enough

Our Model: Octet String Fragmentation 2: Pentaquarks

- Hypothetic pentaquark $\Theta_c = udud\bar{c}$ (cf. $\Theta^+ = udud\bar{s}$)
- A leading Θ_c formed if the first break-up is made by quarks
- No leading proton \Rightarrow more string energy available for charmed hadron



Θ_c mass \rightarrow weak or strong decay

- $m_{\Theta_c} = 2710$ MeV \rightarrow weak decay: $\Theta_c \rightarrow l\nu_l\Theta^+$, BR=20%, lifetime?
- $m_{\Theta_c} = 2895$ MeV \rightarrow strong decay: $\Theta_c \rightarrow D^-p/\bar{D}^0n$
 $\hookrightarrow D^-/\bar{D}^0 \rightarrow l\nu_l X$

Neutrino Astronomy and Charm

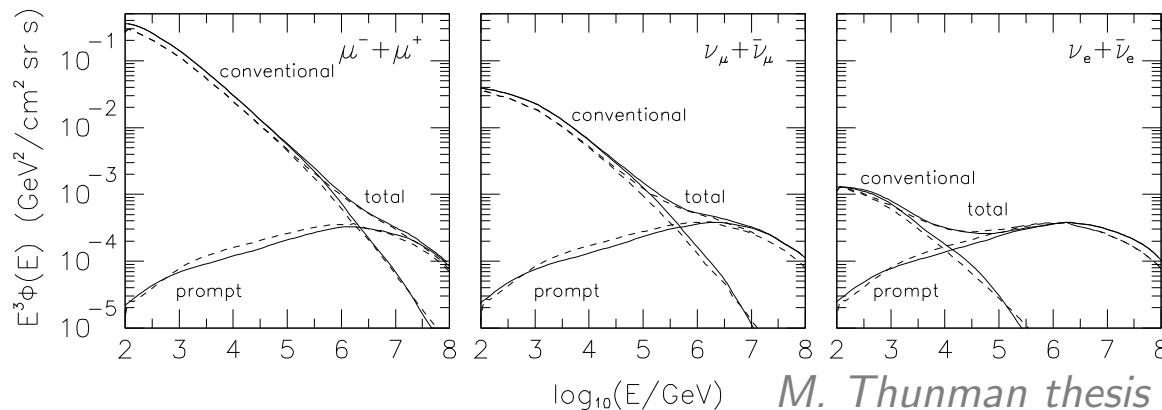
- Detecting cosmic neutrinos extend our knowledge of the Universe
- Atmospheric leptons obscure cosmic neutrino measurements

Cosmic rays (protons) + atmospheric nuclei \rightarrow pions, kaons, charmed hadrons

$$p + X \rightarrow M + Y$$

$$\hookrightarrow l^{+/-} + \nu_l(\bar{\nu}_l) + X \quad l = \mu, e$$

- Pions, kaons \rightarrow 'conventional' leptons, charmed hadrons \rightarrow 'prompt' leptons
- Prompt leptons dominate high-energy atmospheric lepton fluxes



M. Thunman thesis 1996

How big is the lepton flux from the octet model?

Calculation of Lepton Fluxes

- Conventional charm production processes

$$gg \rightarrow c\bar{c}, q\bar{q} \rightarrow c\bar{c}$$

simulated with Lund Monte Carlo PYTHIA

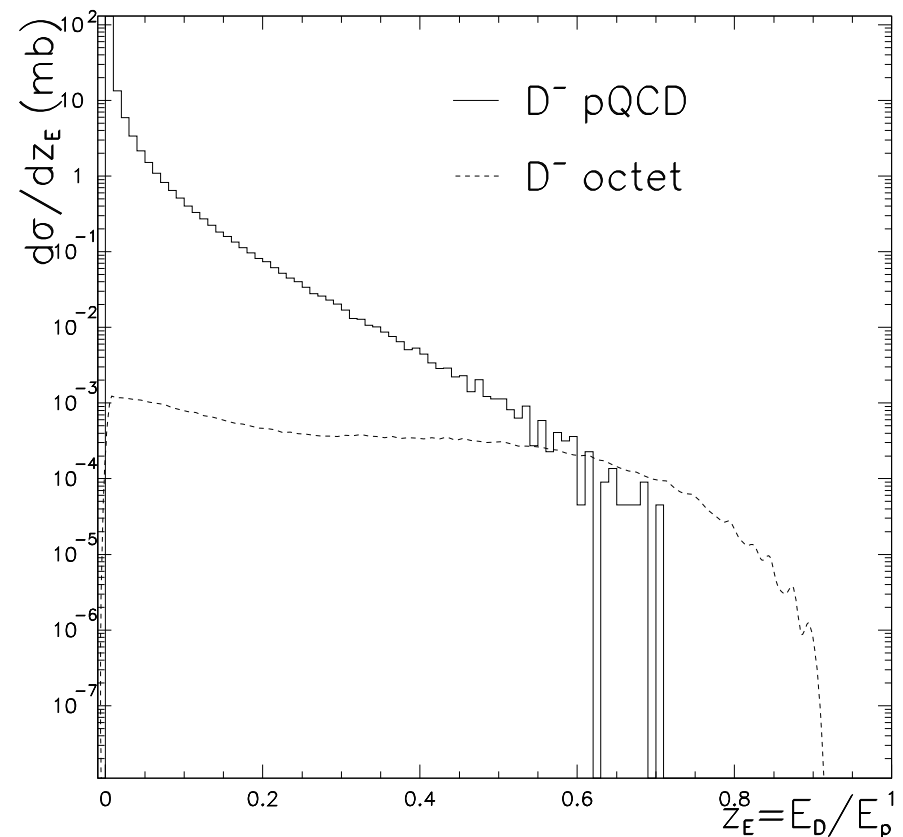
- Charm production in octet strings:

$$\sigma(pp \rightarrow c\bar{c}...) \approx 10^{-5} \sigma_{pp}$$

Differential cross sections $\frac{d\sigma}{dz_E}$ compared at different energies

Octet model: harder $z_E = E_D/E_p$ spectra

e.g. D^- from 10^9 GeV protons



⇒ non-vanishing contribution at large energies?

Calculation of Lepton Fluxes: Cascade Equations

Flux propagating through matter \sim cascade equations

$$\frac{\partial \Phi_N(E, X)}{\partial X} = -\frac{\Phi_N(E, X)}{\lambda_N} + Z_{NN} \frac{\Phi_N(E, X)}{\lambda_N}$$

$$\frac{\partial \Phi_M}{\partial X} = -\frac{\Phi_M}{\rho d_M} - \frac{\Phi_M}{\lambda_M} + Z_{MM} \frac{\Phi_M}{\lambda_M} + Z_{NM} \frac{\Phi_N}{\lambda_N}$$

$$\frac{\partial \Phi_l}{\partial X} = \sum_M Z_{M \rightarrow l, \beta+1} \frac{\Phi_M}{\rho d_M}$$

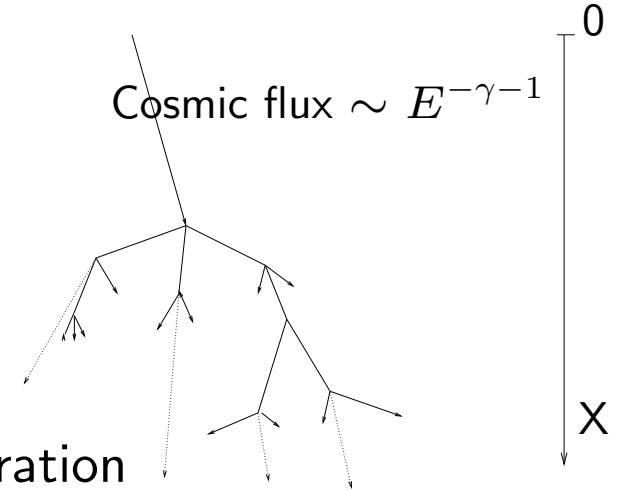
Z moments ($Z_{NN}, Z_{NM} \dots$): particle generation and regeneration

Assuming factorized fluxes: $\Phi_{N,M,l}(E, X) = E^{-\gamma-1} \Phi_{N,M,l}(X) \Rightarrow$

$$Z_{kh}(E) = \int_E^\infty \left(\frac{E_k}{E}\right)^{-\gamma-1} \frac{\sigma_{kA}(E_k) dn(kA \rightarrow hY; E_k, E)}{\sigma_{kA}(E) dE} dE_k$$

Scaling: $\frac{dn(kA \rightarrow hY; E_k, E)}{dE} = \frac{1}{E_k} \frac{dn(kA \rightarrow hY)}{dz}$

$$\Phi_l(E) = \sum_M \frac{\Phi_l^{low} \Phi_l^{high}}{\Phi_l^{low} + \Phi_l^{high}} = \frac{\Phi_N(E, X)}{1 - Z_{NN}} \sum_M \frac{Z_{NM} Z_{M \rightarrow l, \gamma+1}}{1 + AE/\epsilon_M}, \text{ with } A = \frac{Z_{M \rightarrow l, \gamma+1}}{Z_{M \rightarrow l, \gamma+2}} \frac{1 - \frac{\Lambda_N}{\Lambda_M}}{\ln(\frac{\Lambda_M}{\Lambda_N})}$$



Lepton (ν_μ) Flux from Octet String Fragmentation

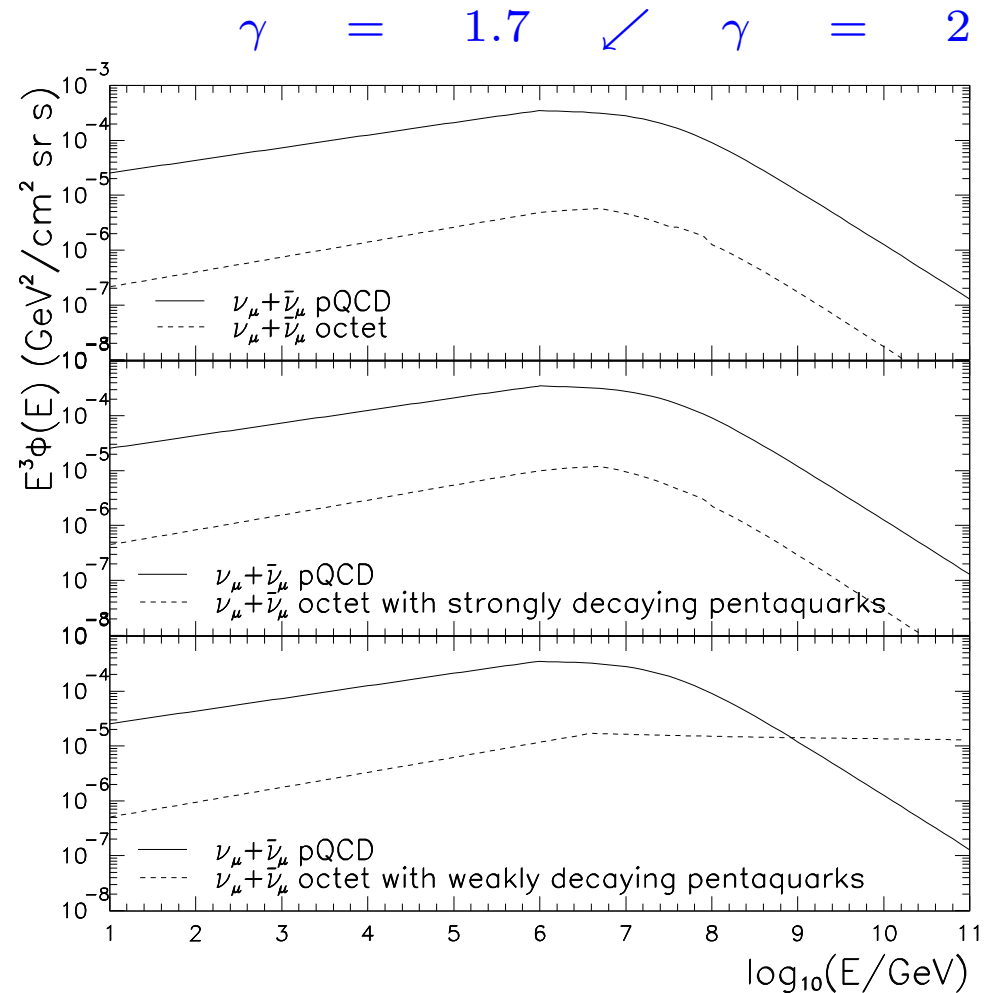
E^3 -weighted ν_μ flux at sea level.

Critical energy $\epsilon_M = \frac{m_M h_0}{\tau_M}$

\Rightarrow slope change ($\gamma + 1 \rightarrow \gamma + 2$)

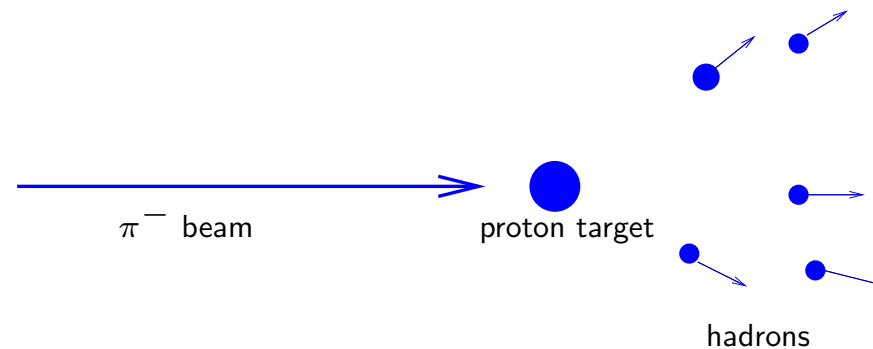
- No $\Theta_c \Rightarrow$ low flux
- Strongly decaying $\Theta_c \Rightarrow$ low flux
- Weakly decaying $\Theta_c \Rightarrow$ eventually dominating if $\tau_{\Theta_c} \leq 10^{-14} s$

Octet model normalization?



Charm in Fixed Target Experiments

Fermilab E791 Collaboration: charmed hadron production in collisions of 500 GeV π^- on a fixed p target



In such collisions both standard (pQCD + Lund strings) and octet charm production can take place

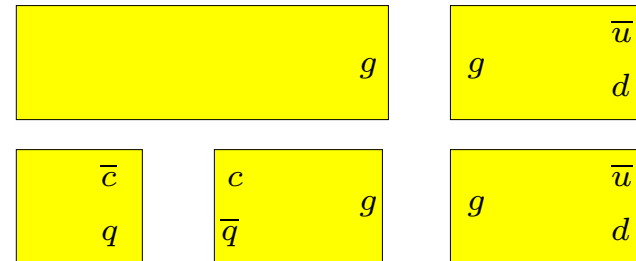
The octet effects could be important for leading particles

\Rightarrow Limits on charm suppression in octet fields

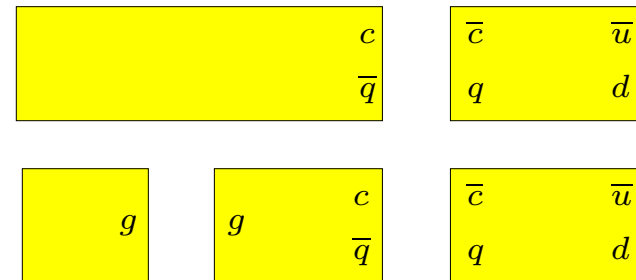
Octet Strings in $\pi^- p$ Collisions

- High-energy charm formed at π^- string end
- Two fragmentation possibilities (as before)

★ a leading pion and two D mesons

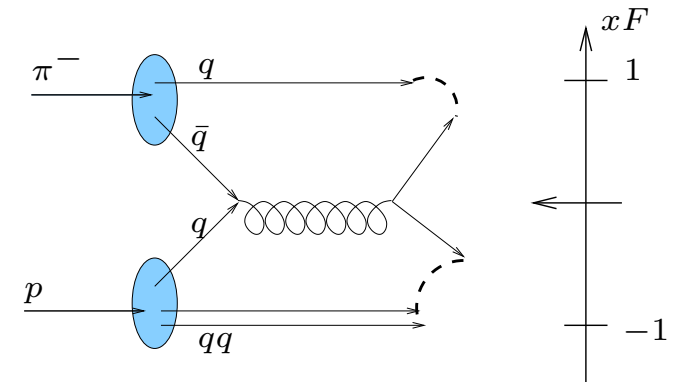
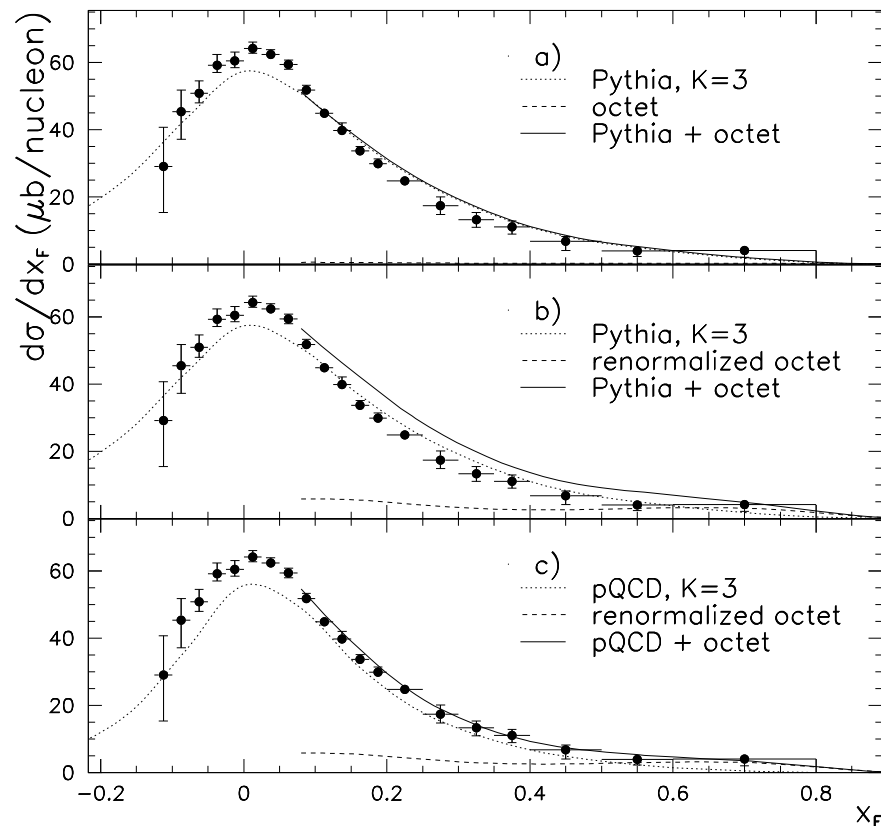


★ a leading, hypothetical dimeson
 $(\widehat{M} : d\bar{u}c\bar{q}, d\bar{u}q\bar{c})$ and one D meson



- The dimeson decays strongly: $\widehat{M} \rightarrow D + \pi$

Differential $D^0 + \bar{D}^0$ Cross Section

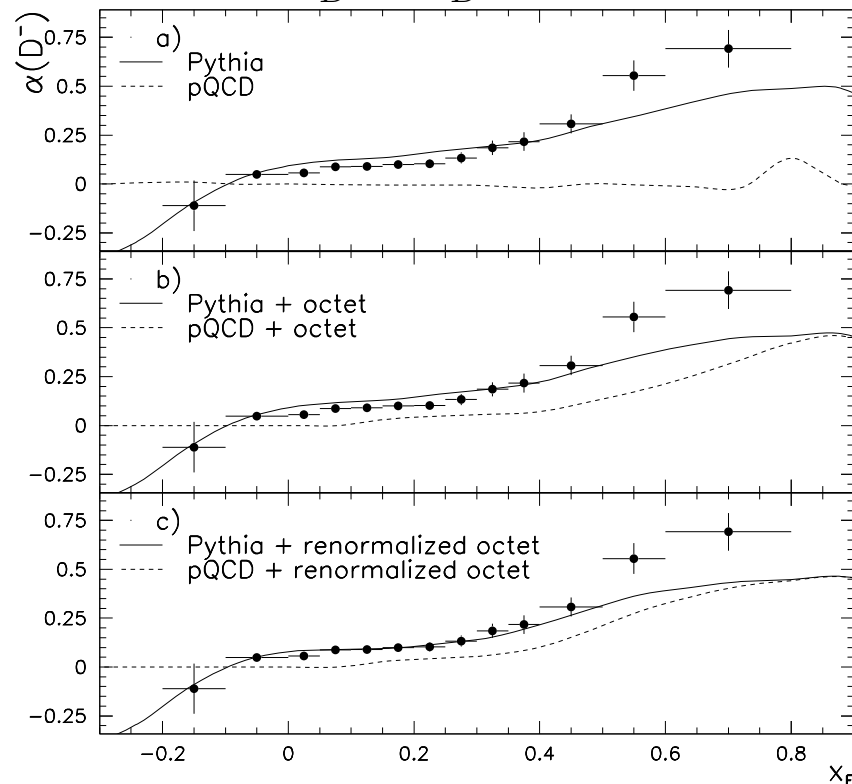


- PYTHIA overshoots data
 \Rightarrow the Lund string drag effects accelerates \bar{D}^0 too much
- Octet model+PYTHIA compatible with data
- 10^{-4} octet charm suppression octet good, if string drag effects are reduced
- $P(c) \leq 10^{-4} P(u)$

$$\sigma_{NLO} \approx K \sigma_{LO}, x_F = \frac{(2p_z)_{CM}}{E_{CM}}$$

Asymmetry in D^+/D^- Production

$$\alpha(D^-) = \frac{N_{D^-} - N_{D^+}}{N_{D^-} + N_{D^+}}$$



- pQCD: no asymmetry
- Lund string drag effect \rightarrow asymmetry

Octet model: dimeson decay?



- Low norm \rightarrow no contribution
- Renormalized octet model works fine

Conclusions and Outlook

Conclusions:

- Octet strings expected at high energies
 - Enhanced charm production probability compared to triplet fields ($10^{-11} \rightarrow 10^{-5}$)
- Octet model effects are typically small
- Atmospheric lepton fluxes: high-energy effect if short-lived, weakly decaying pentaquark is formed.
 - Fixed-target charm: compatible with data when combined with PYTHIA
 - Data fix the charm suppression to $P(c) \leq 10^{-4}P(u)$

Outlook:

Higher order colour strings?

Octet string model \rightarrow properties of exotic states?
(Pentaquark jamboree!)

Colour field	3	6, $\bar{6}$	8	$\frac{10}{\bar{10}}$	15
κ_D	1	10/4	9/4	9/2	4
Charm suppr.	10^{-11}	10^{-4}	10^{-5}	10^{-3}	10^{-3}