LUND UNIVERSITY

IPPP Workshop on
Multiparticle Production
in QCD Jets
14 December 2001

Production and hadronization of heavy quarks

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Introduction
Production: the shower approach
Hadronization: beam drag effects
Summary

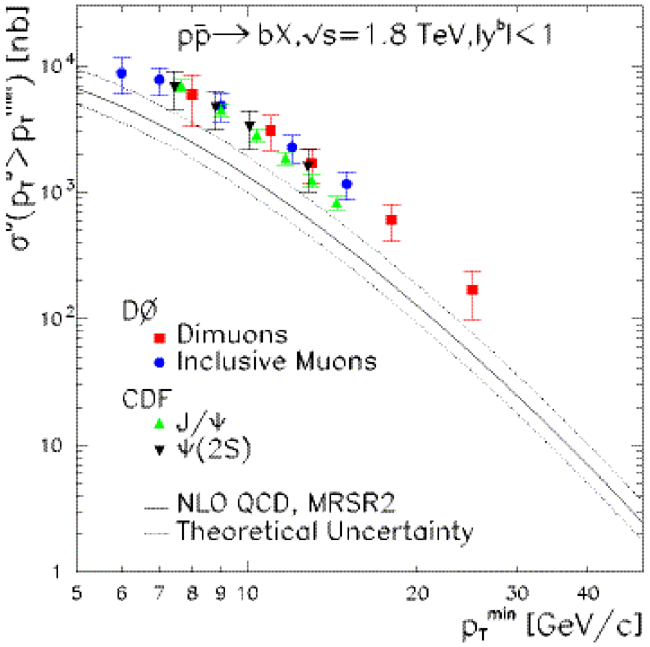
based on E. Norrbin & TS,
Phys. Lett. **B442** (1998) 407,
Eur. Phys. J. **C17** (2000) 137

From: The CTEQ List of Challenges in Perturbative QCD

Calculating b-quark production cross sections at colliders

Fred Olness, Southern Methodist University

Large momentum transfer production of particles and jets provided some of the early tests of QCD. Indeed, by taking into account quark and gluon initiated scattering processes, QCD was able to explain the relatively large cross sections observed at the CERN ISR. However, as the precision of the experiments increased, there was a corresponding need for increased theoretical precision. Discrepancies now exist between theory and data for several large momentum transfer processes. One such long-standing problem in QCD is the calculation of the cross section for the production of b-quarks at high energy hadron colliders. The state of this problem is easily surmised by examining the figure shown below (taken from the 1999 CERN LHC Workshop) which shows the integrated transverse momentum spectrum for b production at the Tevatron vs. p_T. Clearly, the Tevatron data are approximately a factor of 2 above the theoretical bands. Another unsettling feature of this plot is that there is large theoretical uncertainty, despite the fact that this is a NLO calculation. This problem has existed (in various forms) for more than 10 years; a similar discrepancy is also observed in UA1 data.



A recent paper (Berger, et al) demonstrates that pair production of low-mass gluinos that decay into bottom quarks and bottom squarks provides a good description of the b-cross section and reproduces the measured ratio of like-sign to opposite-sign leptons with assumptions consistent with experimental constraints on SUSY particle masses.

Please feel free to send any solutions to this puzzle to PRL and the NY Times. Comments on this entry may be sent to Fred Olness.

ME vs. PS

ME : Matrix Elements

- \+ systematic expansion in α_s (‘exact’)
- – loop calculations very tough
- – may miss logarithmically enhanced contributions
- – negative cross section in collinear regions $\Rightarrow$ unpredictive jet/event structure
- – *no easy match to hadronization*

PS : Parton Showers

- – approximate
- \+ resums large logarithms
- \+ process-generic $\Rightarrow$ simple multiparton
- \+ Sudakov form factors/resummation $\Rightarrow$ sensible jet/event structure
- \+ *easy to match to hadronization*

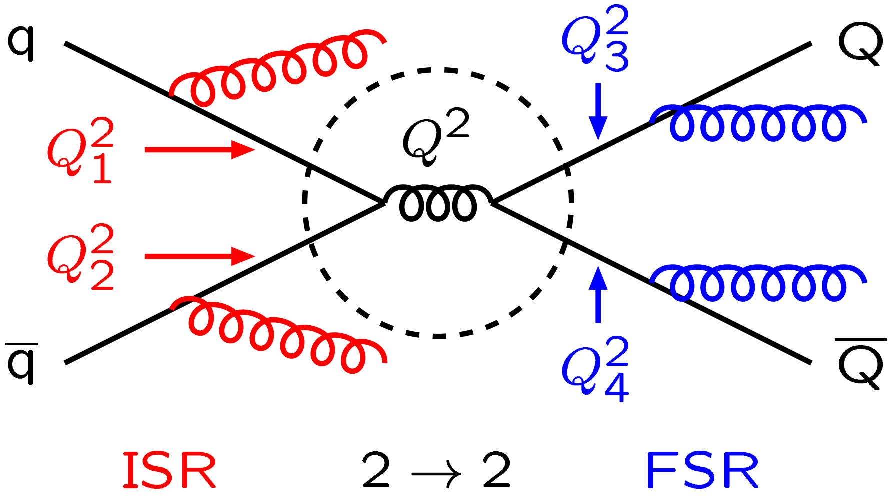
Conventional description: ME

Here: PS, as alternative/check/complement

No claim of ultimate truth!

PS approach

$2 \to n \quad = \quad (2 \to 2) \, \oplus \, \text{ISR} \, \oplus \, \text{FSR}$



$2 \to 2$ = hard scattering

$$\sigma = \iiint \mathrm{d}x_1 \, \mathrm{d}x_2 \, \mathrm{d}\hat{t} \; f_i(x_1, Q^2) \, f_j(x_2, Q^2) \, \frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}\hat{t}}$$

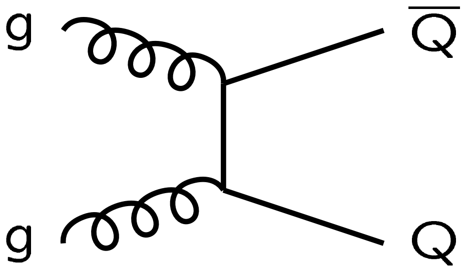
FSR = Final-State Radiation; timelike shower
$Q_i^2 = M^2 > 0$ decreasing + coherence

ISR = Initial-State Radiation; spacelike shower
$Q_i^2 = -M^2 > 0$ increasing + ∼ coherence
backwards evolution: start at hard scattering

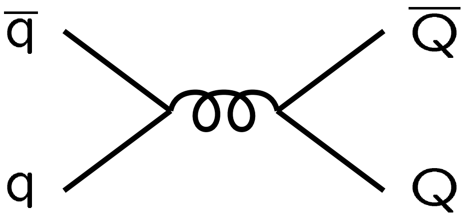
Do not doublecount! $\boxed{Q^2 > Q_1^2, Q_2^2, Q_3^2, Q_4^2}$
$2 \to 2$ = most virtual = shortest distance

Production graphs

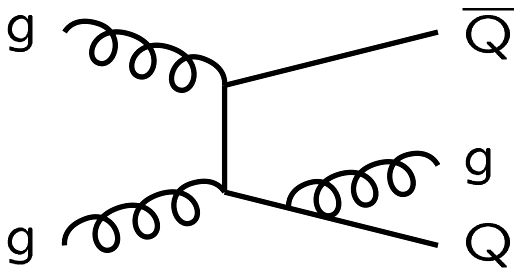
Examples of $Q = c/b$ production diagrams, *not* exhaustive:



Leading order

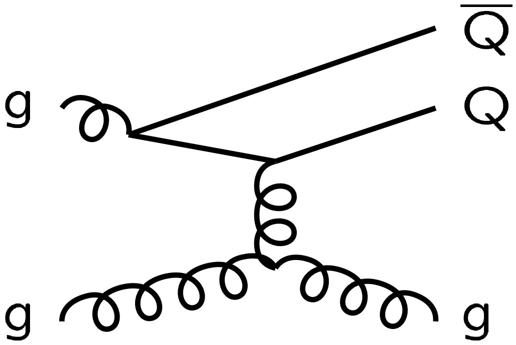


Leading order

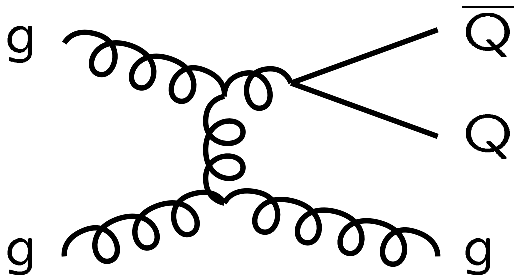


Pair creation

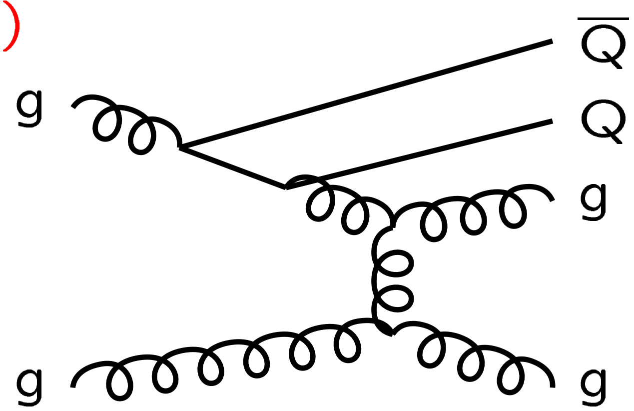
(with gluon emission)



Flavour excitation



Gluon splitting



Gluon splitting

(flavour excitation)

PS approach to heavy quarks

3 main sources (arbitrary names):

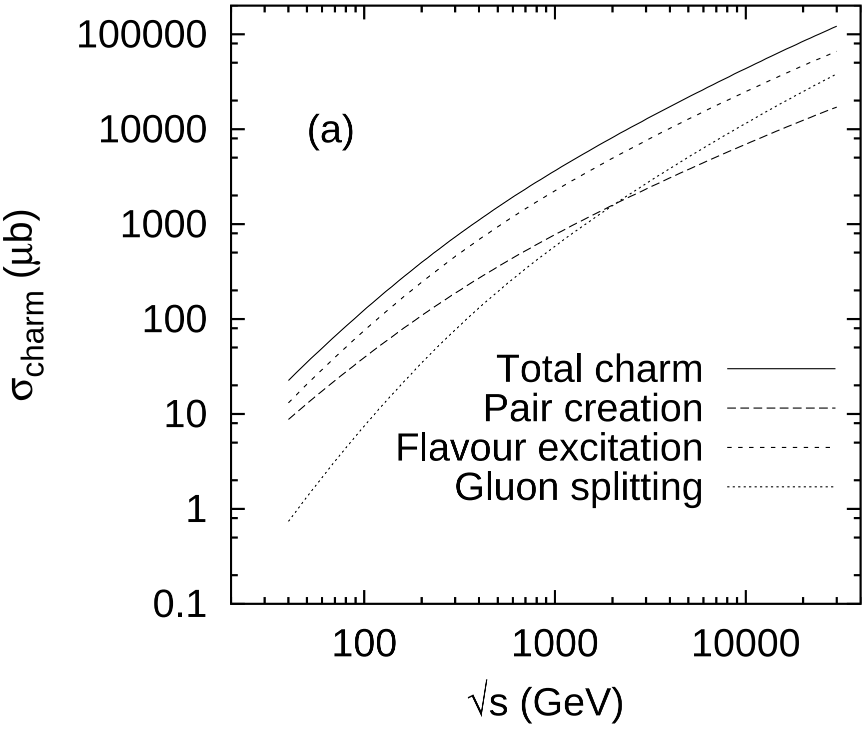
1) pair creation:
based on $\mathrm{gg} \to \mathrm{Q}\overline{\mathrm{Q}}$ and $\mathrm{q}\overline{\mathrm{q}} \to \mathrm{Q}\overline{\mathrm{Q}}$ with masses
+ additional showering

2) flavour excitation:
based on c and b content of standard PDF's
+ $\mathrm{Qg} \to \mathrm{Qg}$ and $\mathrm{Qq} \to \mathrm{Qq}$ ME's;
massive kinematics but massless ME's;
with $Q^2 > m_{\mathrm{Q}}^2$ (so PDF>0) and $Q_i^2 < Q^2$;
$\mathrm{g} \to \mathrm{b}\overline{\mathrm{b}}$ by backwards evolution (improved)
$\approx$ t-channel graph of $\mathrm{gg} \to \mathrm{Q}\overline{\mathrm{Q}}$

3) gluon splitting:
ordinary $2 \to 2$ processes, e.g. $\mathrm{gg} \to \mathrm{gg}$
+ $\mathrm{g} \to \mathrm{Q}\overline{\mathrm{Q}}$ branching with threshold
$\sqrt{1 - 4m_{\mathrm{Q}}^2/m_{\mathrm{g}}^2}\,(1 + 2m_{\mathrm{Q}}^2/m_{\mathrm{g}}^2)$
$\approx$ s-channel graphs of $\mathrm{gg}, \mathrm{q}\overline{\mathrm{q}} \to \mathrm{Q}\overline{\mathrm{Q}}$

Avoid doublecounting:
for $2 \to 2$: $Q^2 = \hat{p}_{\perp}^2 + (m_3^2 + m_4^2)/2 \quad (\Rightarrow \hat{s} \gtrsim 4Q^2)$
for FSR: $Q_{\mathrm{max}}^2 = m_{\mathrm{max}}^2 = 4Q^2$
for ISR: $Q_{\mathrm{max}}^2 = Q^2$

Cross sections



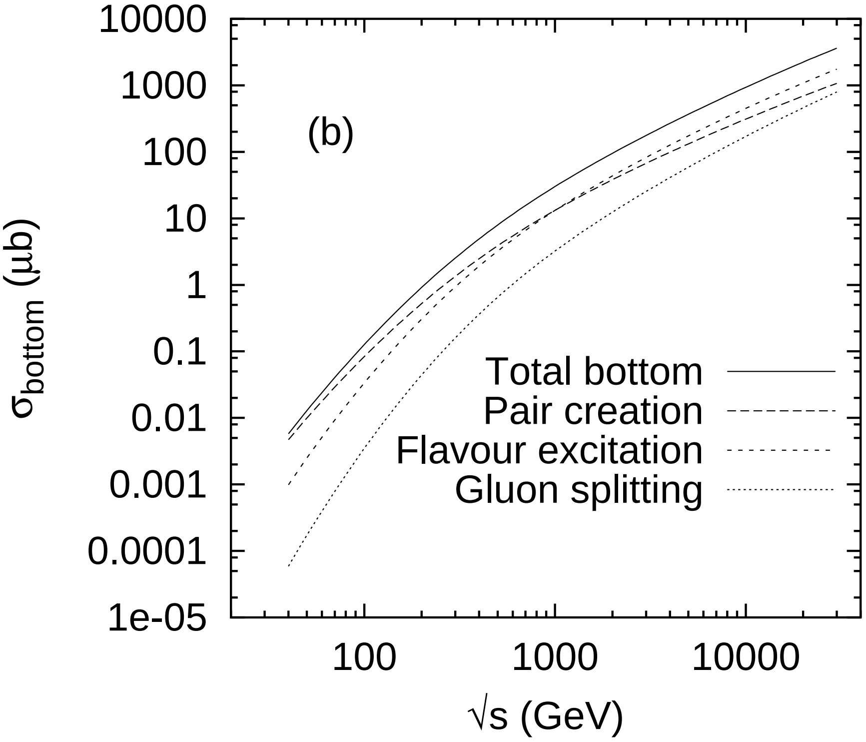
charm

pp

CTEQ 5L

$m_c = 1.5$ GeV

m_c "tuned" to asymmetries



bottom

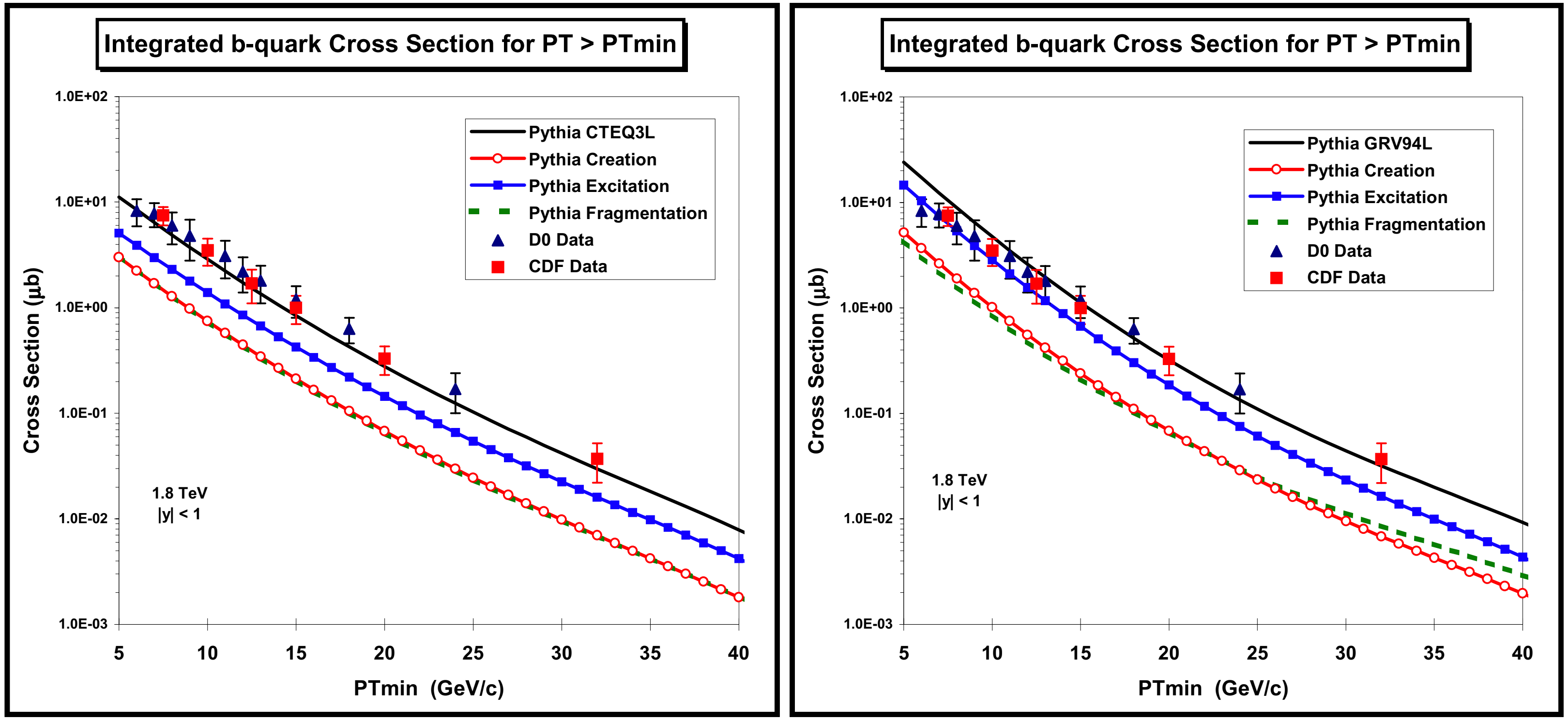
pp

CTEQ 5L

$m_b = 4.8$ GeV

$$\frac{3m_{D^*} + m_D}{4} - m_c = \frac{3m_{B^*} + m_B}{4} - m_b$$

Inclusive b-quark Cross Section

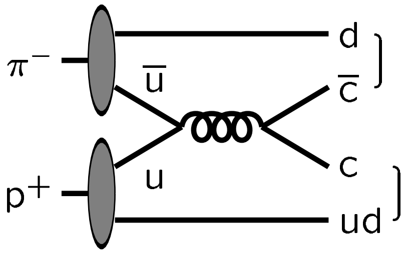


- **Data on the integrated b-quark total cross section (P_T > PTmin, |y| < 1) for proton-antiproton collisions at 1.8 TeV compared with the QCD Monte-Carlo model predictions of PYTHIA (CTEQ3L) and PYTHIA (GRV94L). The four curves correspond to the contribution from flavor creation, flavor excitation, shower/fragmentation, and the resulting total.**

Beam Remnant Physics

Strings normally ‘large’ mass, but at times small because of beam remnant structure or by $g \to q\overline{q}$ in shower. Thus three hadronization mechanisms (regions):

1. Normal string fragmentation:
   continuum of phase-space states.
2. Cluster decay:
   low mass ⇒ exclusive two-body state.
3. Cluster collapse:
   very low mass ⇒ only one hadron.



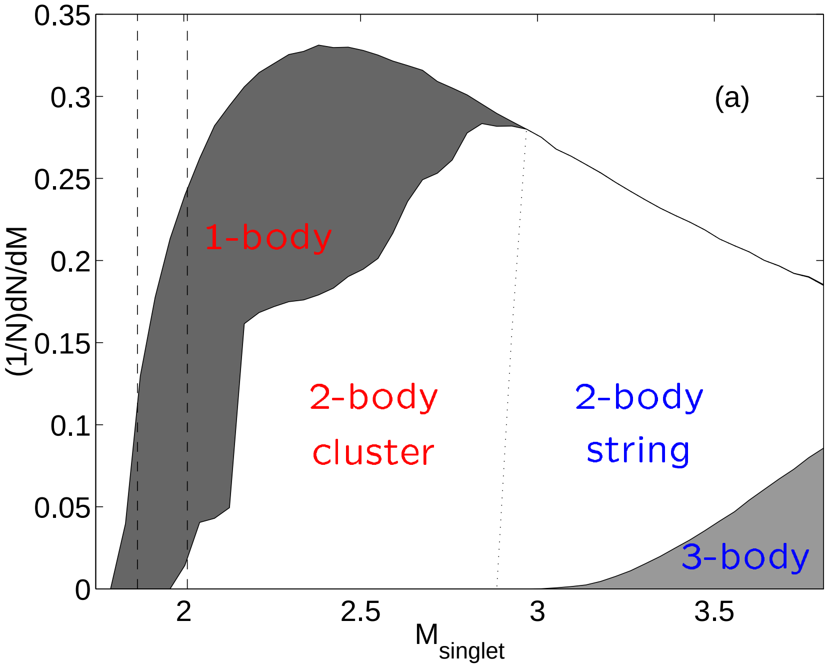
If collapse:
$\overline{c}$d: D^-, D^{*-}, . . .
cud: Λ_c^+, Σ_c^+, Σ_c^{*+}, . . .
⇒ flavour asymmetries

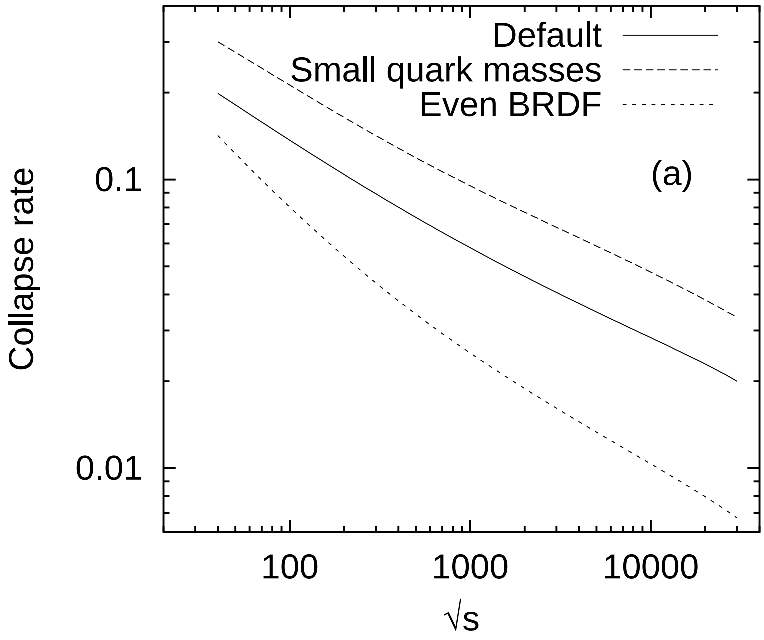
Can give D “drag” to larger x_F than c quark.

PYTHIA *pre*dicted qualitative behaviour.
Quantitative one sensitive to details
⇒ develop model & tune

Improved description of when collapse occurs (mass spectrum $\Leftarrow$ constituent quark masses)

example:
charm
string
in πp
collision





charm string
collapse rate
in pp collisions

(variations)

and
1-body collapse: energy-momentum shuffling
2-body decay: smoother joining to string picture (matched anisotropic decay)

But also normal string fragmentation:

$$\bar{\mathrm{c}} \longleftrightarrow \mathrm{d} \qquad \longrightarrow z$$

$$p_{\pm} = E \pm p_z$$

$$p_{-\mathrm{D}} = z p_{-\mathrm{c}} \qquad 0 < z < 1$$

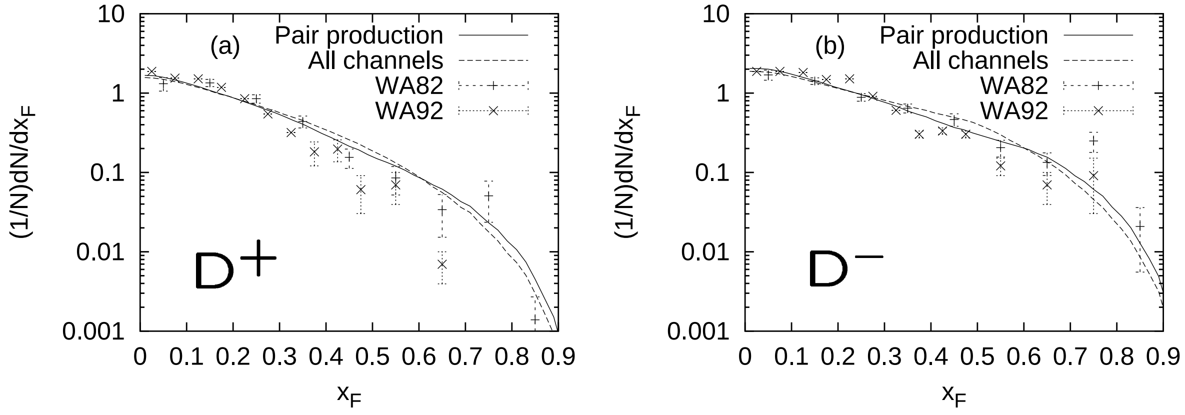
$$\Rightarrow p_{+\mathrm{D}} = \frac{m_{\perp \mathrm{D}}^2}{p_{-\mathrm{D}}} = \frac{m_{\perp \mathrm{D}}^2}{z p_{-\mathrm{c}}} \overset{\text{normally}}{>} \frac{m_{\perp \mathrm{c}}^2}{z p_{-\mathrm{c}}} = \frac{p_{+\mathrm{c}}}{z}$$

i.e. again drag.

Technical components of modelling:

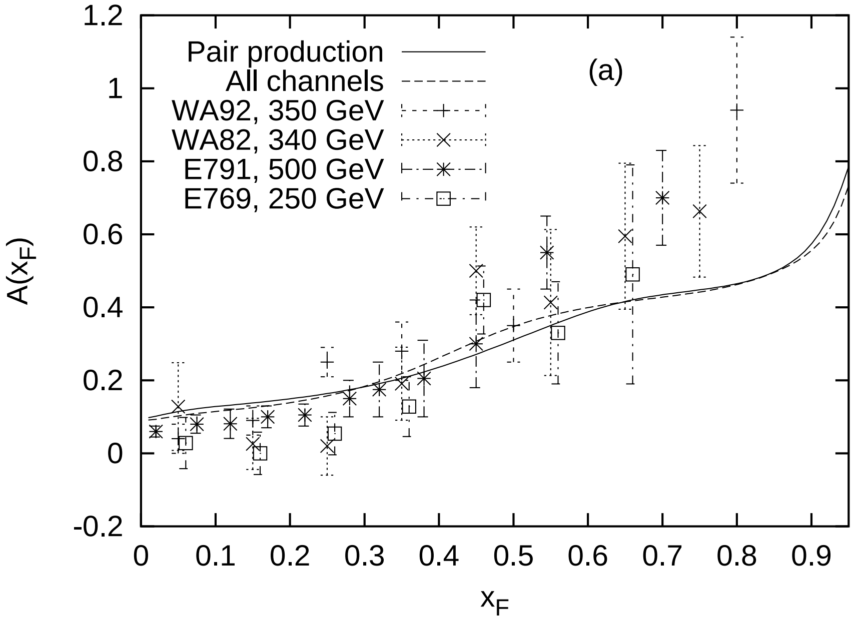
- Charm and bottom masses: c and b cross sections ($m_{\mathrm{c}} = 1.5$, $m_{\mathrm{b}} = 4.8$)
- Light-quark masses: threshold for cluster mass spectrum, together with m_{c} ($m_{\mathrm{u}} = m_{\mathrm{d}} = 0.33$, $m_{\mathrm{s}} = 0.50$)
- Beam remnant distribution function: (p − g = ud$_0$ + u in colour octet state) hadron asymmetries also without collapse (uneven sharing, but not extremely so)
- Primordial $k_{\perp}$: collapse rate at large $p_{\perp}$ (Gaussian width 1 GeV)
- Threshold behaviour for non-collapse: all at Dπ or gradually at Dπ, D$^*\pi$, Dρ, . . .
- Collapse energy–momentum conservation: practical solution to mass δ function (several models tried; not very sensitive)

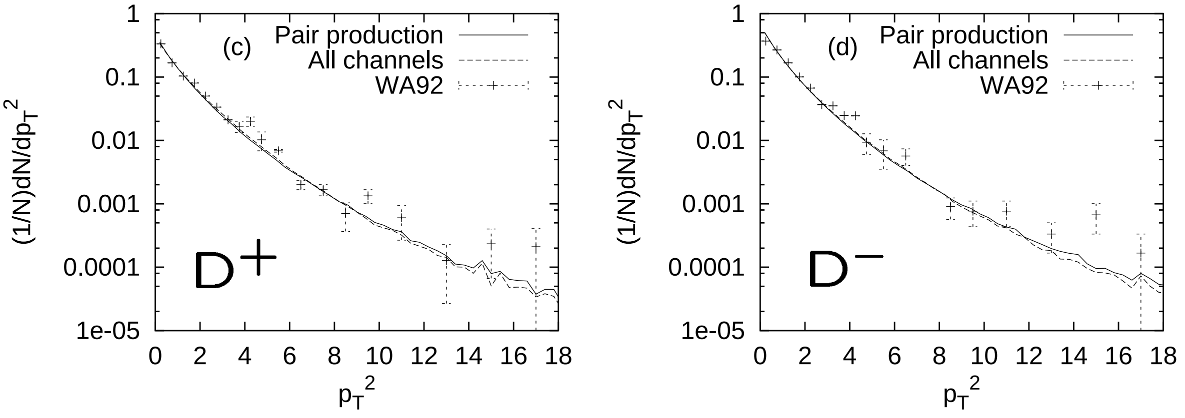
Asymmetries and correlations



$$A(x_F) = \frac{\#D^- - \#D^+}{\#D^- + \#D^+}$$

in $\pi^- p$

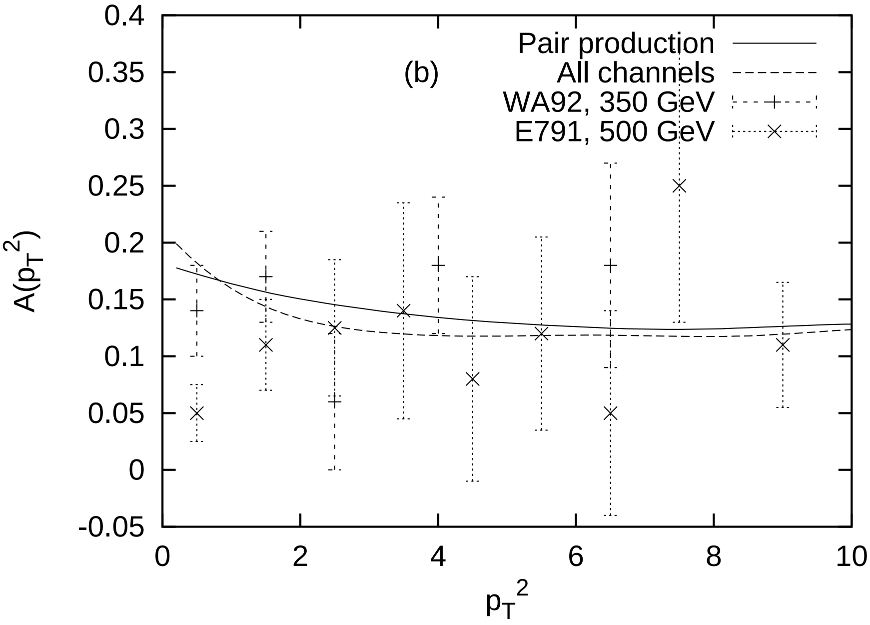


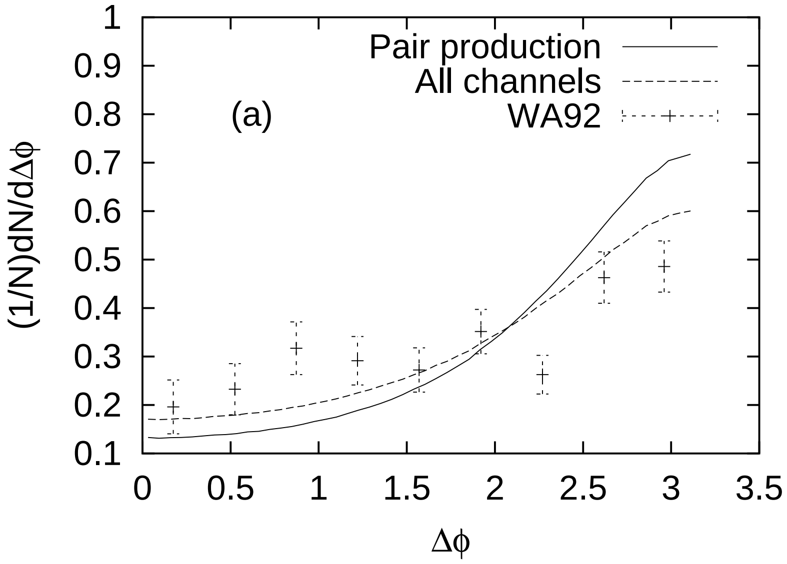


$A(p_\perp) =$

$\frac{\#D^- - \#D^+}{\#D^- + \#D^+}$

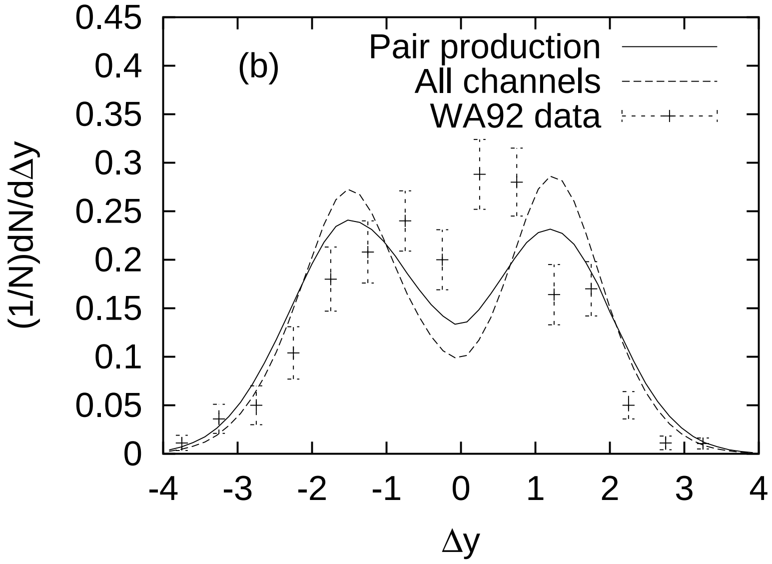
in $\pi^- p$





ϕ correlations

improved . . .

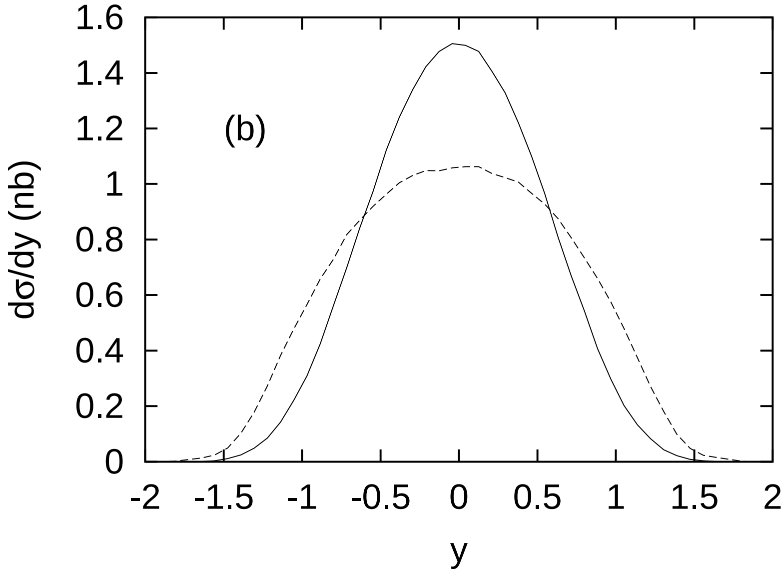


. . . but

y correlations

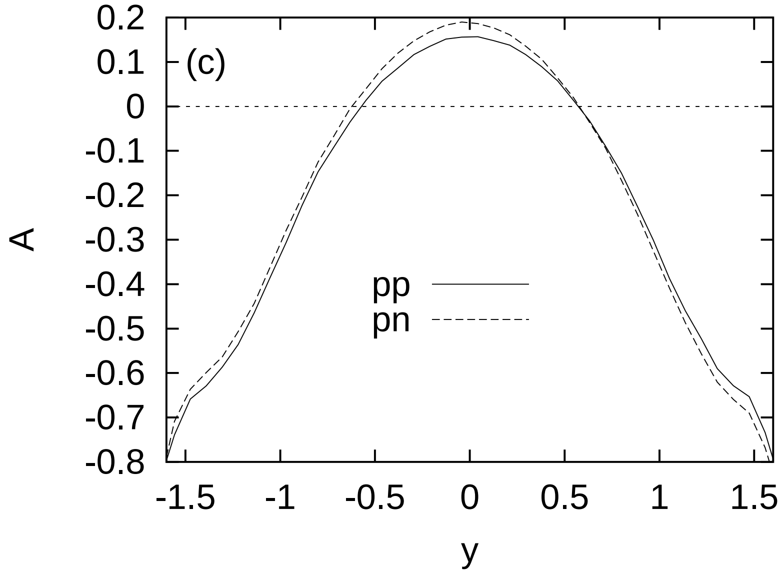
worsened

HERA-B
predictions



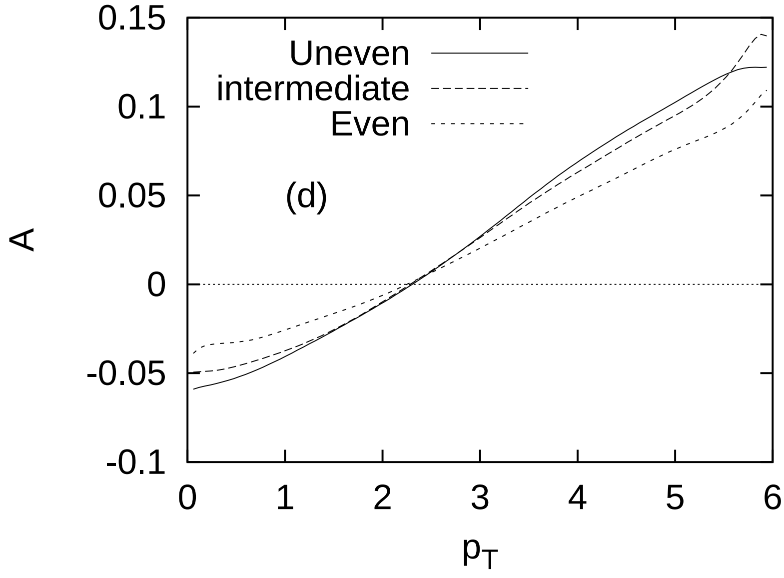
B^0 full

$\overline{B}^0$ dashed



y dependence

$$A = \frac{B^0 - \overline{B}^0}{B^0 + \overline{B}^0}$$

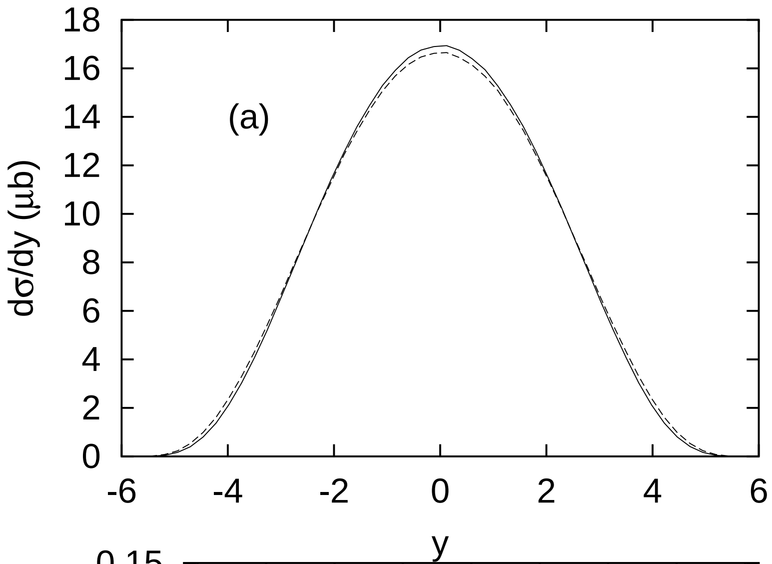


$p_\perp$ dependence

$$A = \frac{B^0 - \overline{B}^0}{B^0 + \overline{B}^0}$$

(vary beam remn dist)

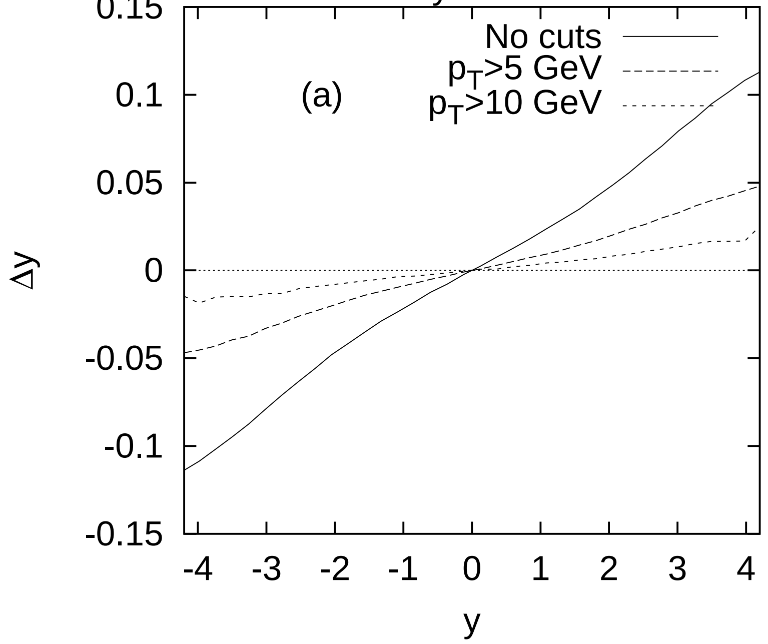
Tevatron predictions



Rapidity distribution

full: b quarks

dashed: B hadrons



Average

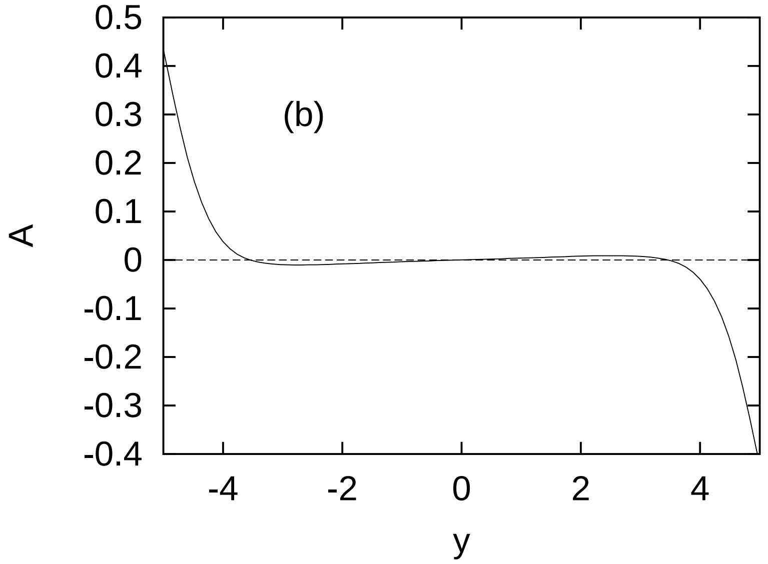
rapidity shift

$\Delta y = y_{\mathrm{B}} - y_{\mathrm{b}}$

as function of y_{b}

above different

$p_{\perp\mathrm{b}}$ thresholds



B asymmetry

$$A = \frac{\sigma(\mathrm{B}^0) - \sigma(\overline{\mathrm{B}}^0)}{\sigma(\mathrm{B}^0) + \sigma(\overline{\mathrm{B}}^0)}$$

as function of y_{B}

Only pair production

for simplicity

Summary

- Shower approach implies 3 sources
  1) pair creation
  2) flavour excitation
  3) gluon splitting

  of $\sim$ equal size
- To be combined with string hadronization; small string = cluster, with special treatment
- Have not used – but also not excluded – intrinsic heavy flavours, nonperturbative production, . . .
- Sensible agreement with data – both cross sections and event characteristics – but not perfect
- Several phenomenological parameters $\Rightarrow$ large slop within framework
- . . . and also poorly understood aspects (multiple interactions, . . .)
- List of uncertainties in other approaches (e.g. ME-based) about as long