LUND UNIVERSITY

CERN Workshop on
Monte Carlo tools for the LHC
25 July 2003

Production and Hadronization of Heavy Quarks

Torbjörn Sjöstrand

Department of Theoretical Physics

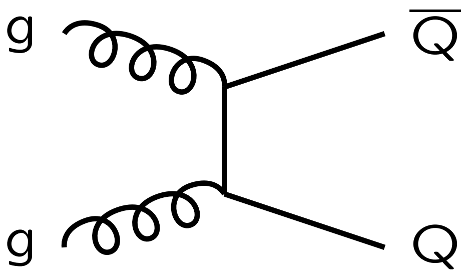
Lund University

Production mechanisms
Beam remnant physics
Asymmetries and correlations

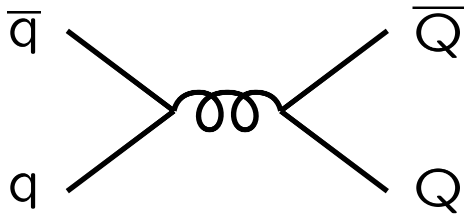
based on E. Norrbin & TS,
Eur. Phys. J. **C17** (2000) 137

Production graphs

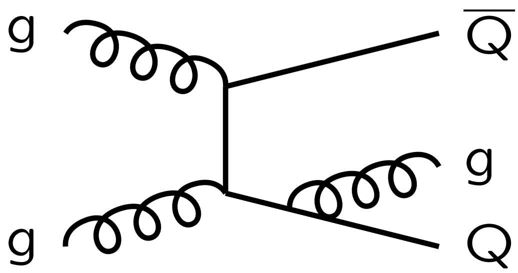
Examples of Q = c/b production diagrams, *not* exhaustive:



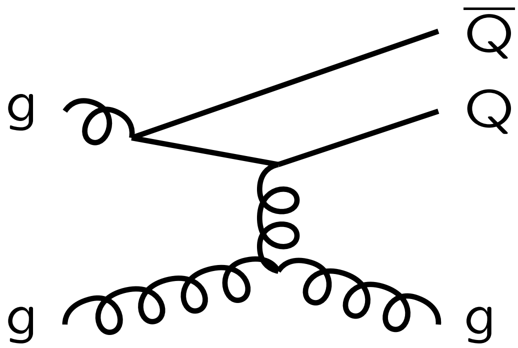
Leading order



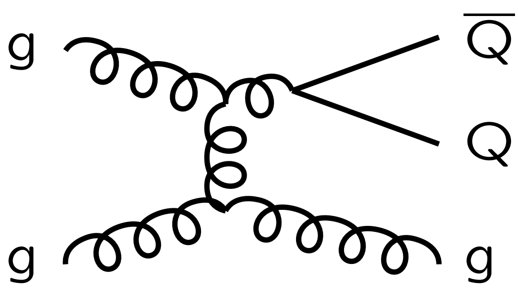
Leading order



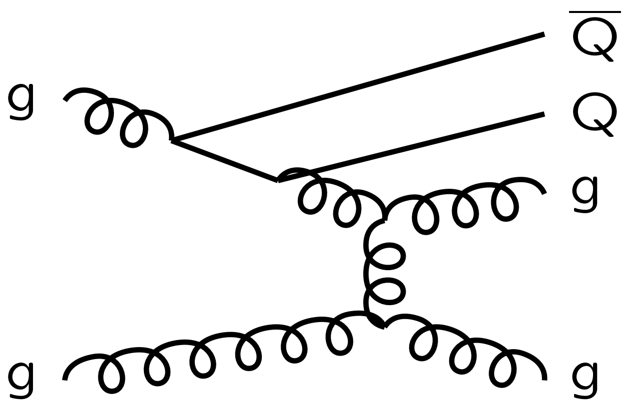
Pair creation
(with gluon emission)



Flavour excitation



Gluon splitting



Gluon splitting
(flavour excitation)

PS approach to heavy quarks

3 main sources (arbitrary names):

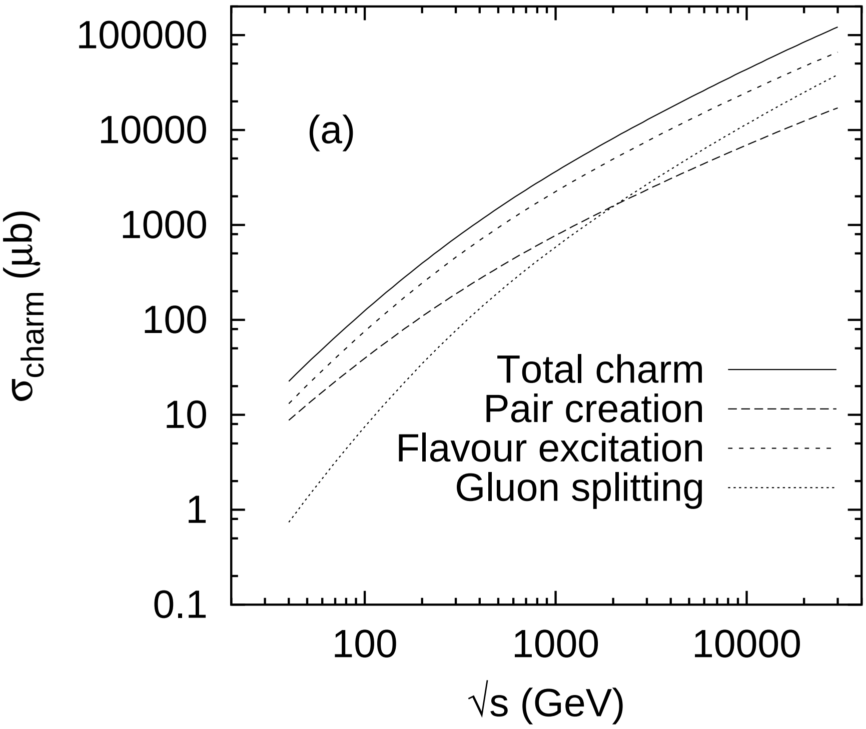
1) pair creation:
based on $\mathrm{gg} \to \mathrm{Q\overline{Q}}$ and $\mathrm{q\overline{q}} \to \mathrm{Q\overline{Q}}$ with masses
+ additional showering

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 $Q_i^2 < Q^2$;
$\mathrm{g} \to \mathrm{b\overline{b}}$ by backwards evolution (improved)
$\approx t$-channel graph of $\mathrm{gg} \to \mathrm{Q\overline{Q}}$

3) gluon splitting:
ordinary $2 \to 2$ processes, e.g. $\mathrm{gg} \to \mathrm{gg}$
+ $\mathrm{g} \to \mathrm{Q\overline{Q}}$ 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 $\mathrm{gg}, \mathrm{q\overline{q}} \to \mathrm{Q\overline{Q}}$

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: $Q^2_{\mathrm{max}} = m^2_{\mathrm{max}} = 4Q^2$
for ISR: $Q^2_{\mathrm{max}} = Q^2$

Cross sections



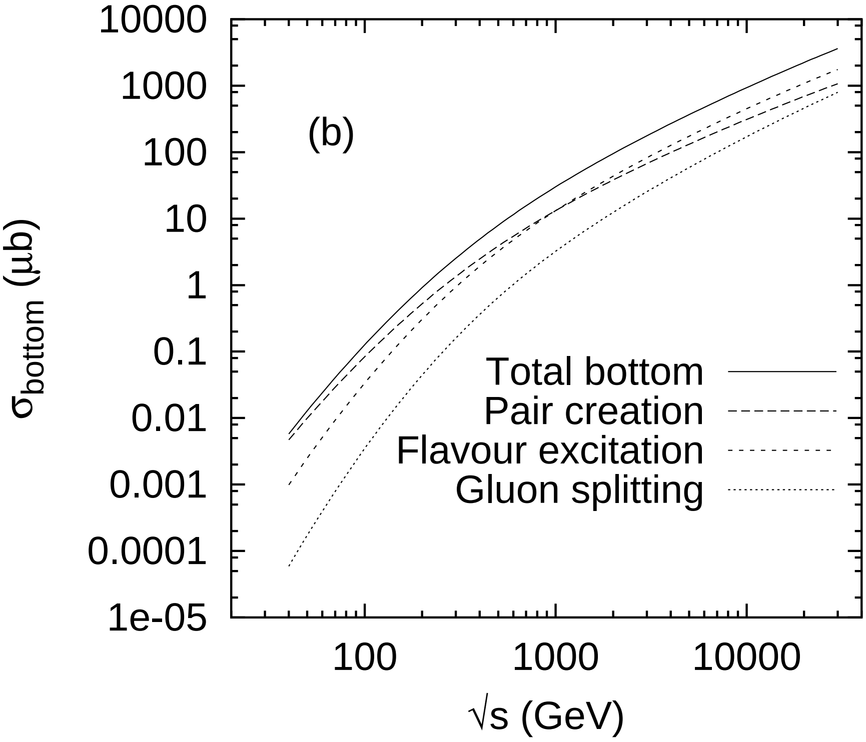
charm

pp

CTEQ 5L

$m_c = 1.5$ GeV

m_c “tuned” to asymmetries



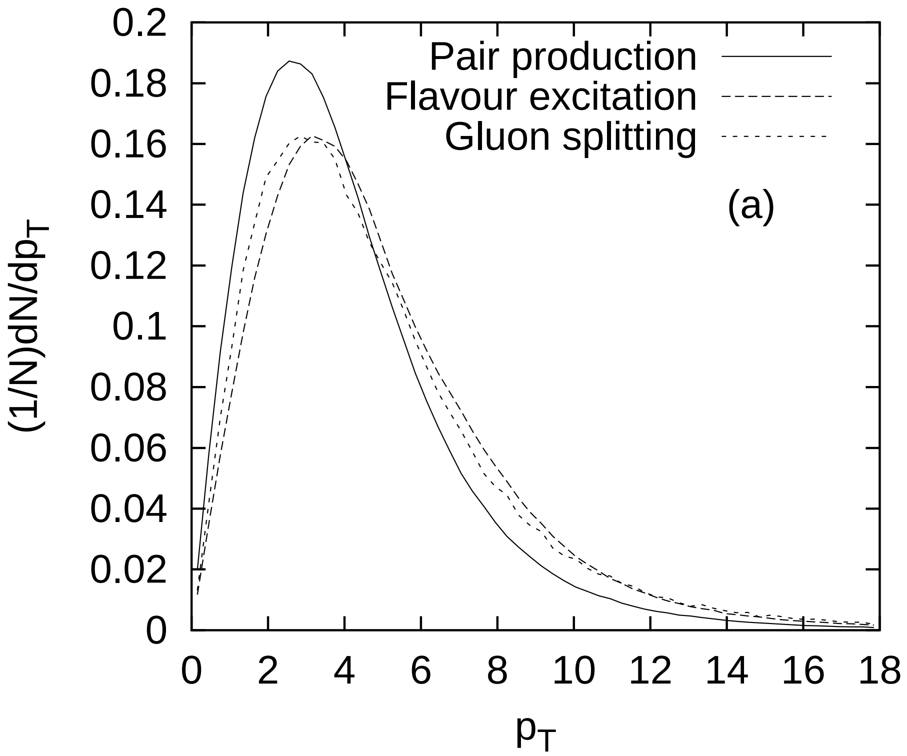
bottom

pp

CTEQ 5L

$m_b = 4.8$ GeV

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



bottom

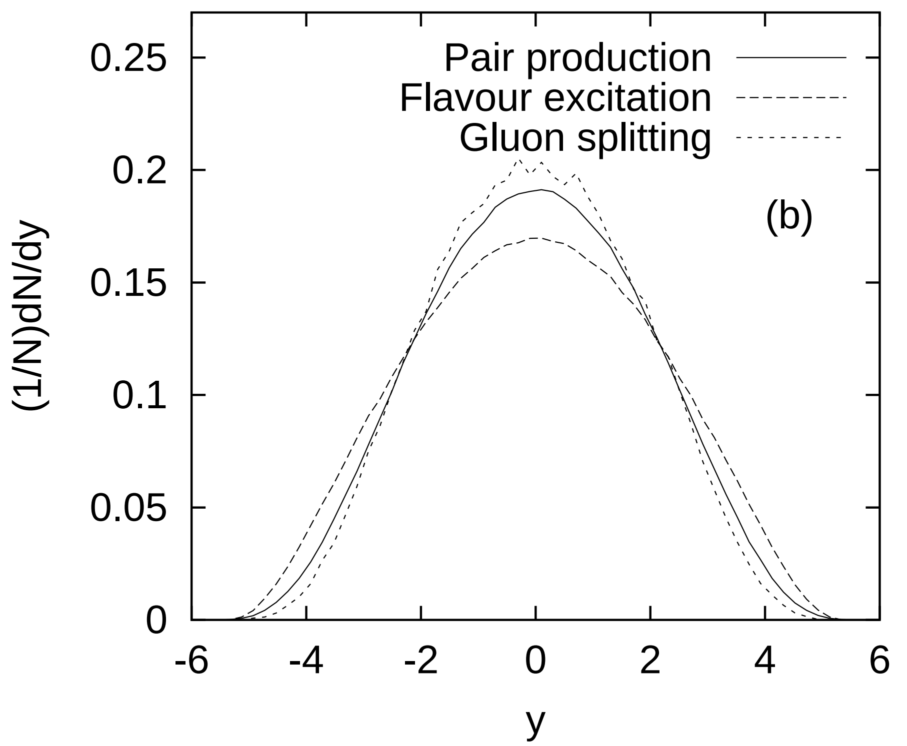
$p\bar{p}$ at 2 TeV

CTEQ 5L

$m_b = 4.8$ GeV

normalized to unit area

$p_\perp$ of b quarks after shower etc.



bottom

$p\bar{p}$ at 2 TeV

CTEQ 5L

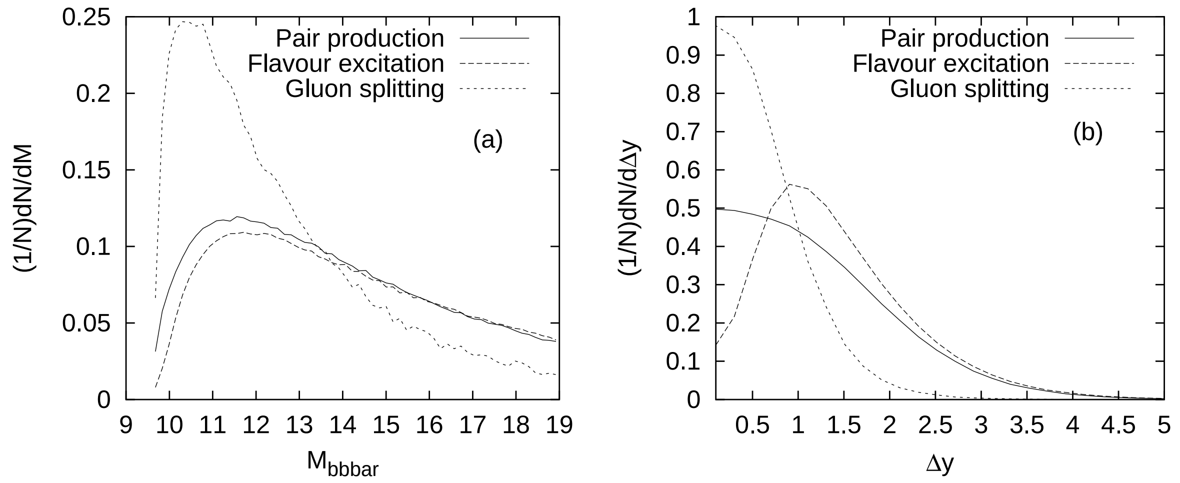
$m_b = 4.8$ GeV

normalized to unit area

y of b quarks after shower etc.

Correlations between b and $\overline{\text{b}}$

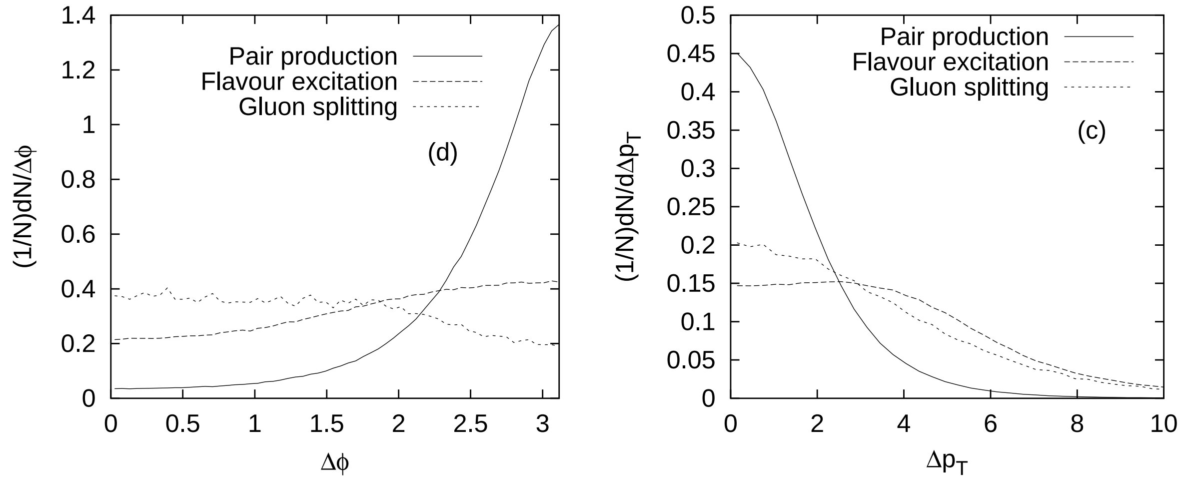
p$\overline{\text{p}}$ at 2 TeV, CTEQ 5L, $m_{\text{b}} = 4.8$ GeV



pair production: s- and t-channel

flavour excitation: t-channel

gluon splitting: s-channel $\Rightarrow$ smaller masses



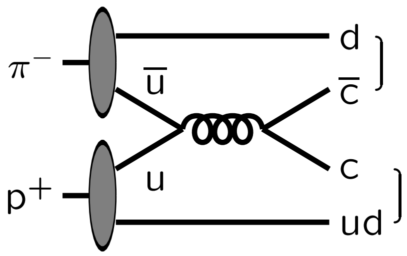
pair production: back-to-back in ϕ and $p_\perp$

except for showers and primordial $k_\perp$

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 $\Rightarrow$ exclusive two-body state.
3. Cluster collapse:
   very low mass $\Rightarrow$ only one hadron.



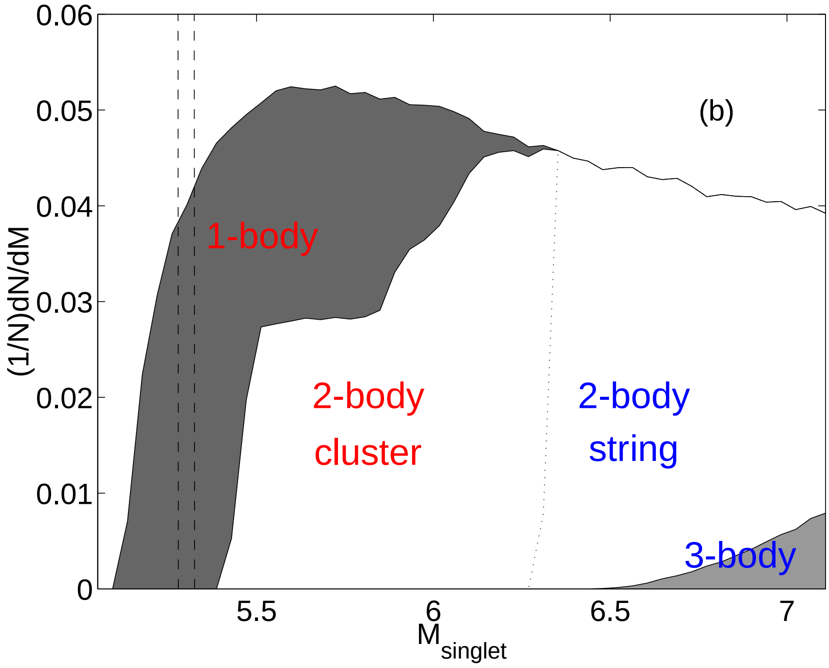
If collapse:
$\overline{c}d$: D^-, D^{*-}, ...
cud: Λ_c^+, Σ_c^+, Σ_c^{*+}, ...
$\Rightarrow$ flavour asymmetries

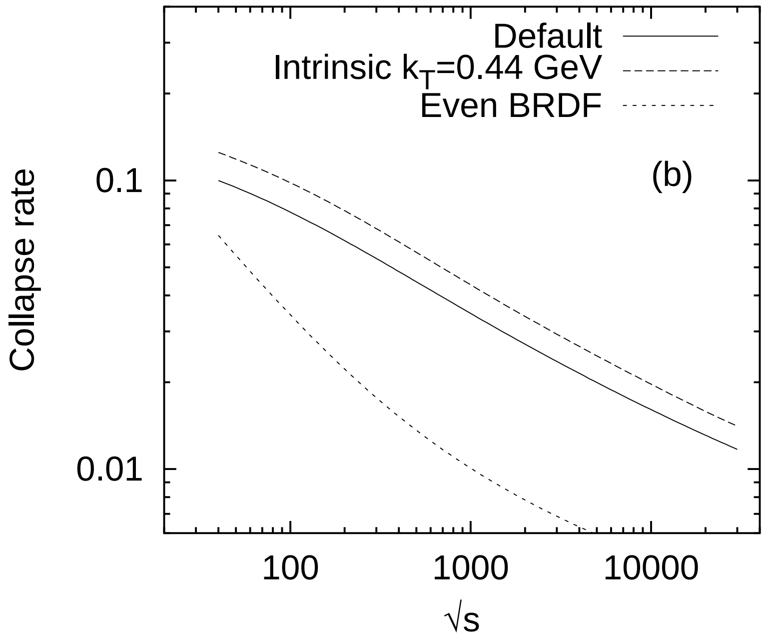
Can give D “drag” to larger x_F than c quark.

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

Improved description of when collapse occurs
(mass spectrum ⇐ constituent quark masses)

example:
bottom
string
in $p\bar{p}$
collision





beauty 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:

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

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

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

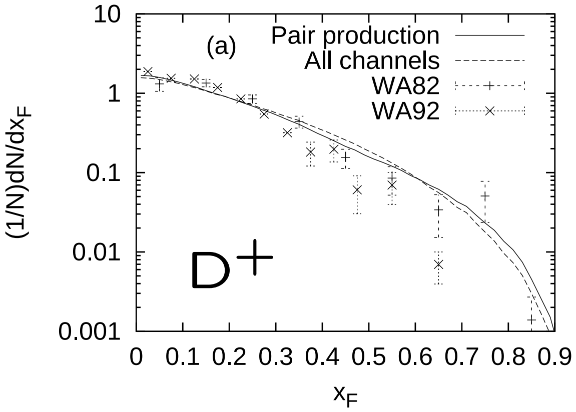
$$\Rightarrow p_{+\mathrm{D}} = \frac{m_{\perp \mathrm{D}}^2}{p_{-\mathrm{D}}} = \frac{m_{\perp \mathrm{D}}^2}{z p_{-\mathrm{c}}} \overset{\text{normally}}{>} \frac{m_{\perp \mathrm{c}}^2}{z p_{-\mathrm{c}}} = \frac{p_{+\mathrm{c}}}{z}$$

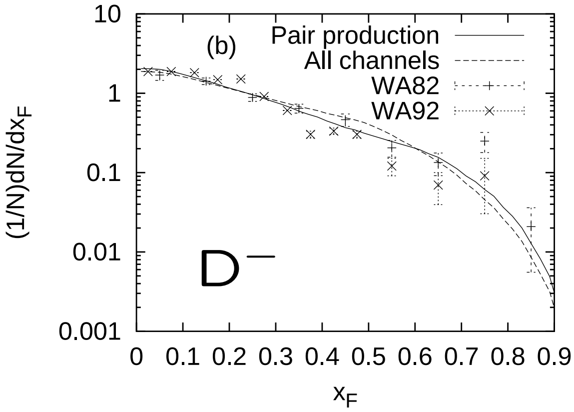
i.e. again drag.

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:
  ($\mathrm{p} - \mathrm{g} = \mathrm{ud}_0 + \mathrm{u}$ 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)

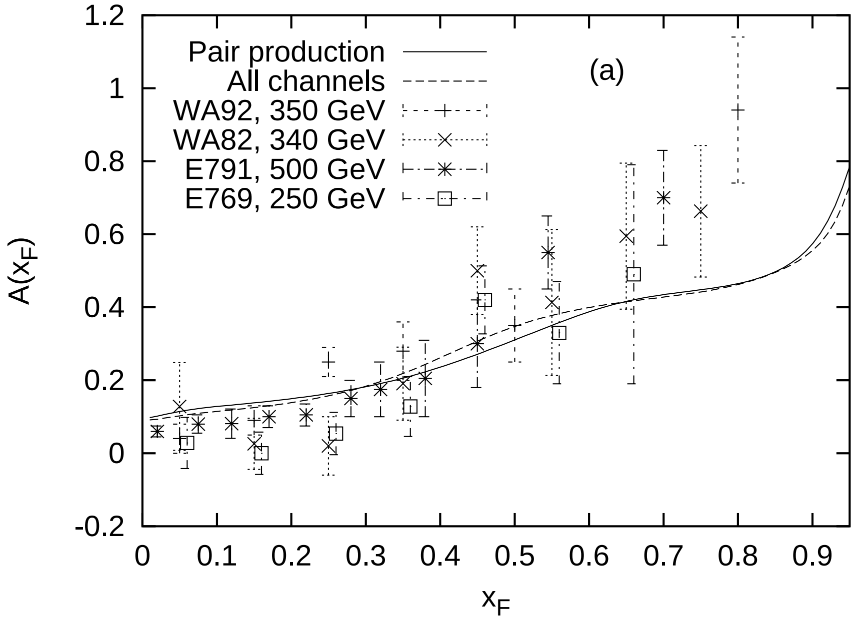
Asymmetries and correlations

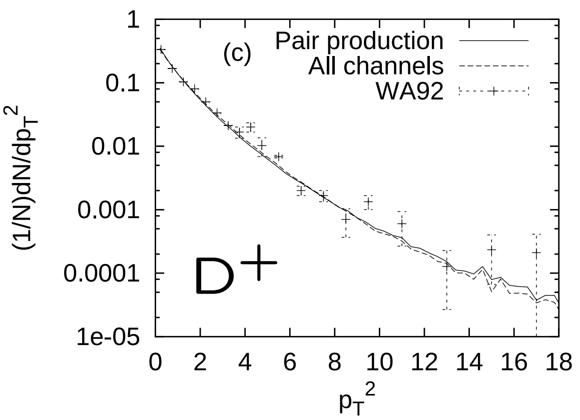


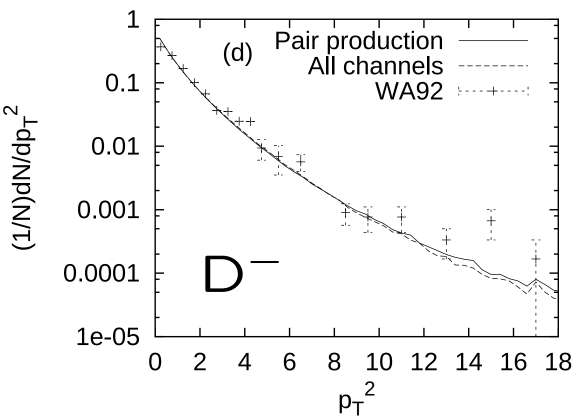


$$A(x_F) = \frac{\#D^- - \#D^+}{\#D^- + \#D^+}$$

in $\pi^- p$



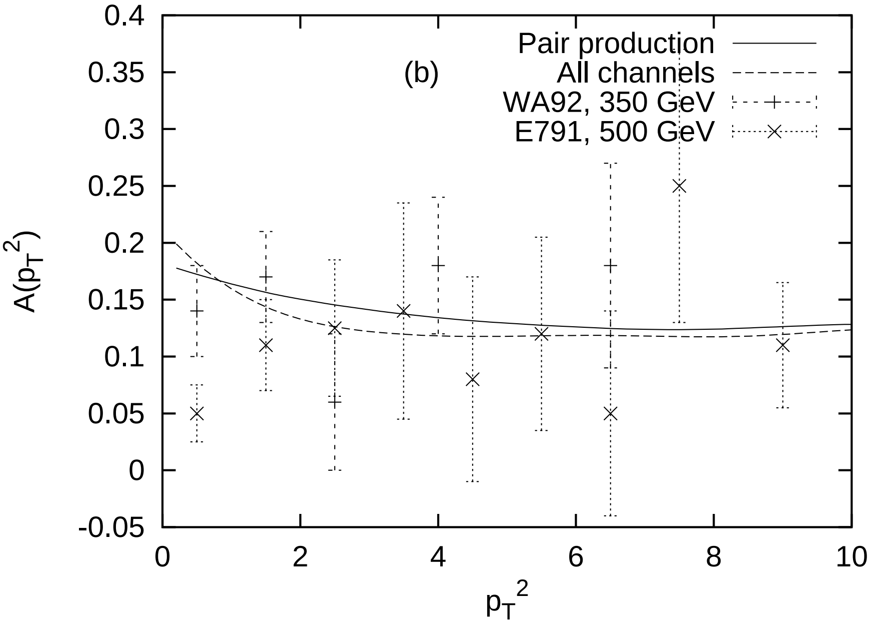


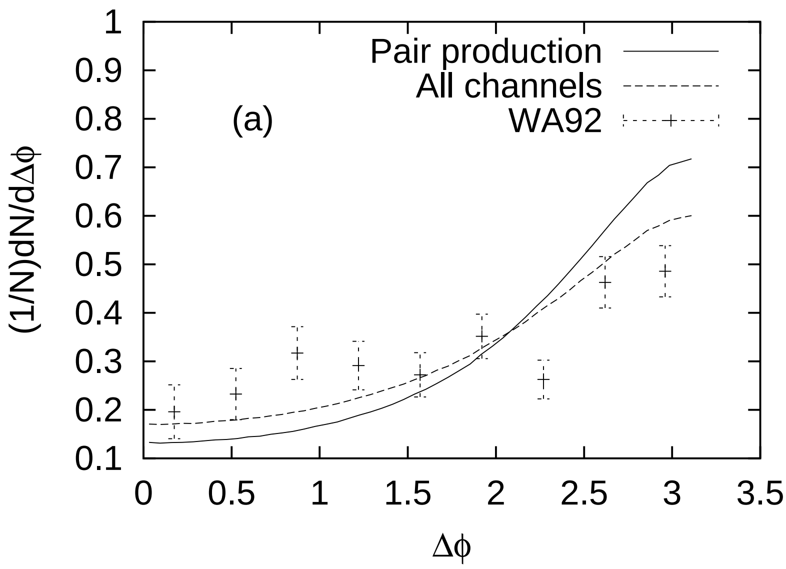


$A(p_\perp) =$

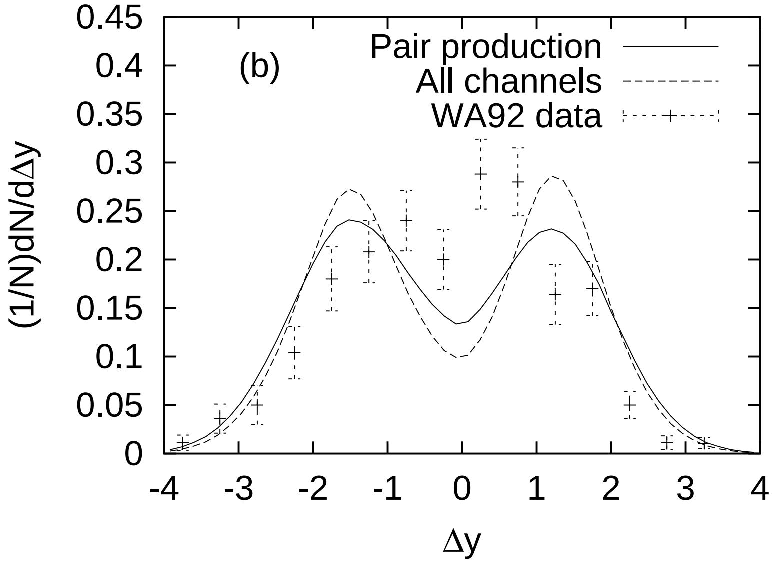
$\frac{\#D^- - \#D^+}{\#D^- + \#D^+}$

in π^-p



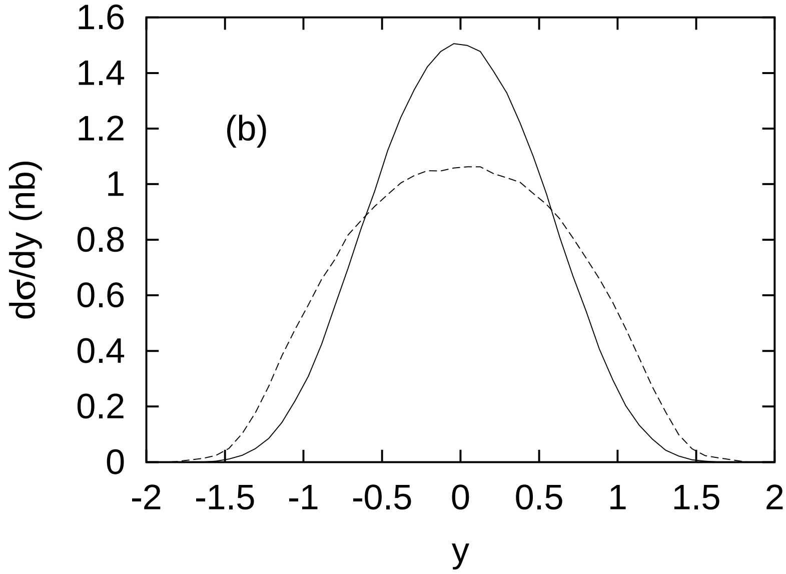


ϕ correlations improved . . .



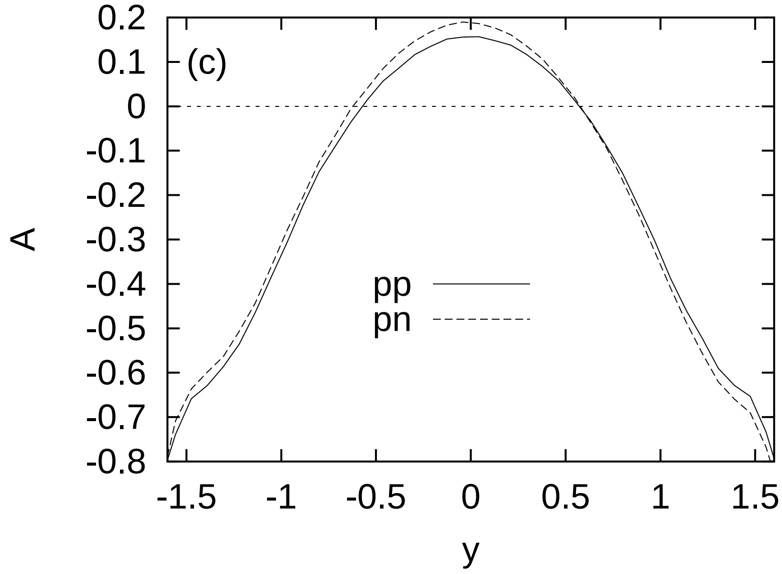
. . . but y correlations worsened

HERA-B predictions



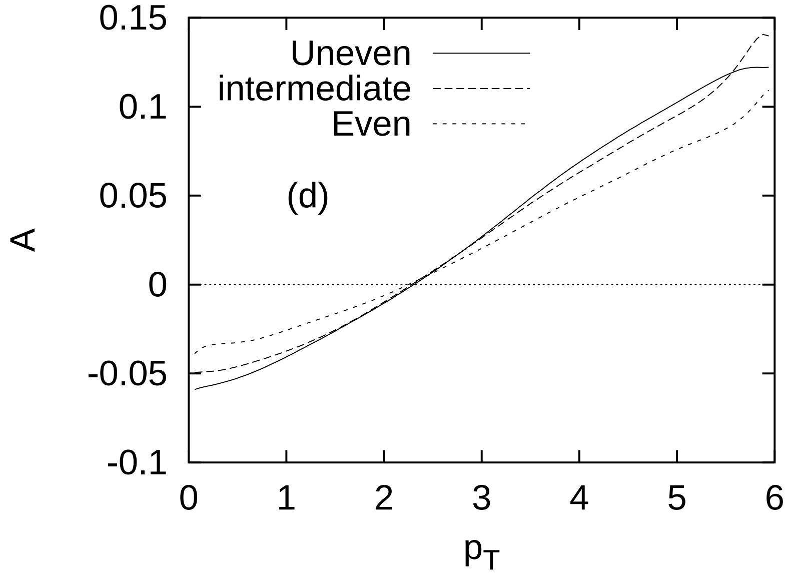
B^0 full

$\overline{B}^0$ dashed



y dependence

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

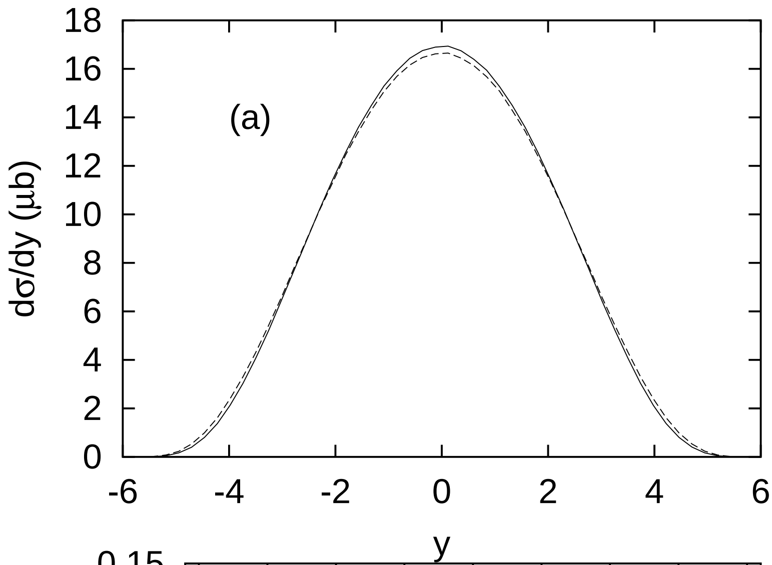


$p_\perp$ dependence

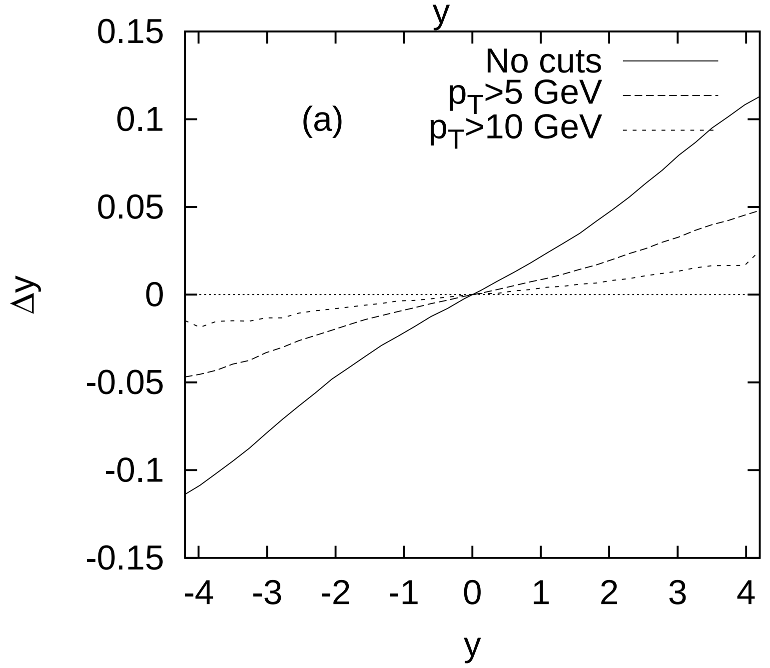
$$A = \frac{B^0 - \overline{B}^0}{B^0 + \overline{B}^0}$$

(vary beam remn dist)

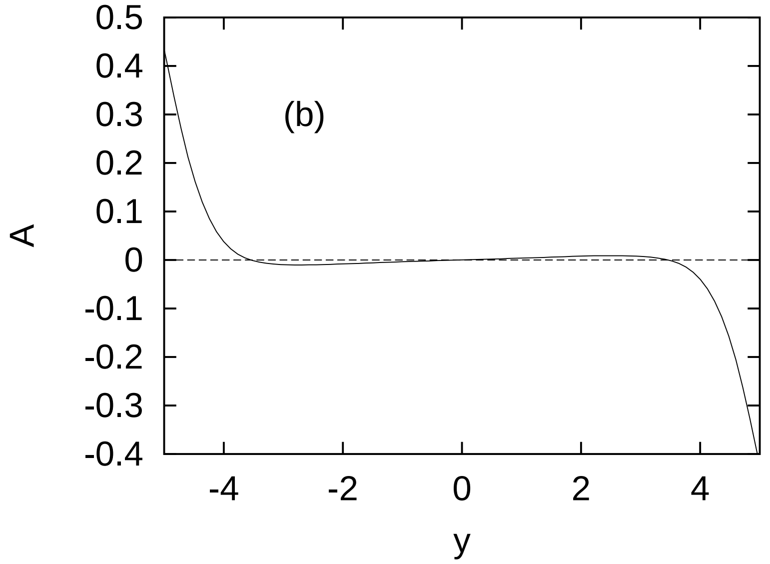
Tevatron predictions



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



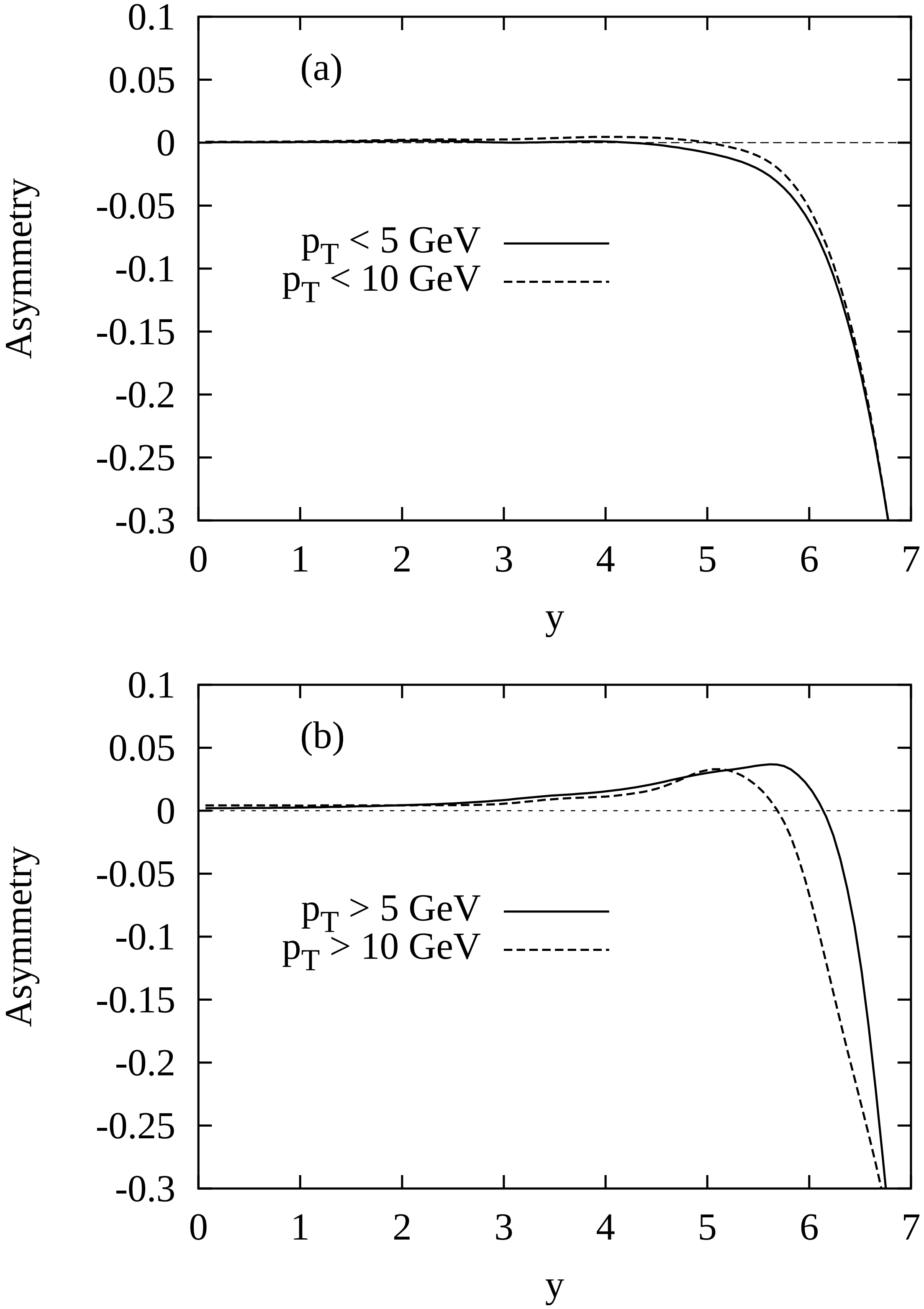
B asymmetry

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

as function of y_{B}

Only pair production for simplicity

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



Notes

• Cluster collapse favours $\mathrm{B}^0 = \overline{\mathrm{b}}\mathrm{d} \;\Rightarrow\; A > 0$; dominates at small $|y|$

• Beam drag favours $\overline{\mathrm{B}}^0$ from $b - \mathrm{ud}_0 \;\Rightarrow\; A < 0$; dominates at large $|y|$ and small $p_\perp$

• LHC asymmetries sensitive to technical details like beam remnant energy sharing and quark masses:

$$A = \frac{\mathrm{B}^0 - \overline{\mathrm{B}}^0}{\mathrm{B}^0 + \overline{\mathrm{B}}^0} \text{ (pair creation only)}$$

	$\lvert y\rvert < 2.5$, $p_\perp > 5$	$3 < \lvert y\rvert < 5$, $p_\perp > 5$	$\lvert y\rvert > 3$, $p_\perp < 5$
New	0.003(1)	0.015(2)	−0.008(1)
Even	−0.000(2)	0.009(3)	−0.005(2)
Old	0.013(2)	0.020(3)	−0.018(2)

• High-$p_\perp$ asymmetry as well, $\lesssim 10^{-3}$, from collapse with scattered valence quark and beam drag effects

• Have studied $\mathrm{B}^0 - \overline{\mathrm{B}}^0$ for CP reasons, but $\mathrm{B}^+ - \mathrm{B}^-$, $\mathrm{B}_s^0 - \overline{\mathrm{B}}_s^0$ also

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 approach
  (e.g. ME-based) about as long