LUND UNIVERSITY

CERN Workshop on
Monte Carlo tools for the LHC
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Production and Hadronization of Heavy Quarks

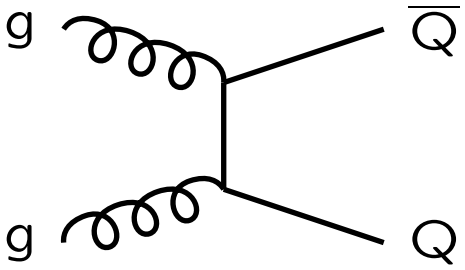
Torbjörn Sjöstrand
Department of Theoretical Physics
Lund University

Production mechanisms
Beam remnant physics
Asymmetries and correlations

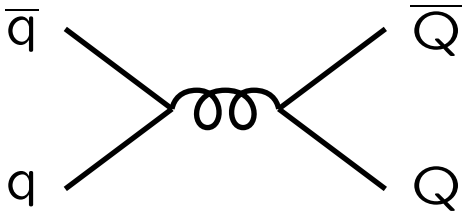
based on E. Norrbin & TS,
Eur. Phys. J. **C17** (2000) 137

Production graphs

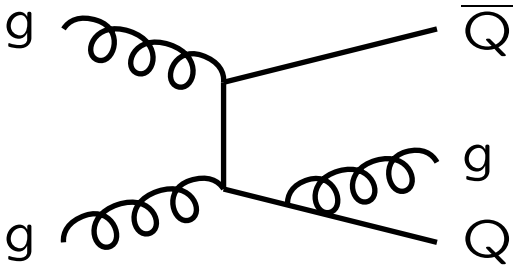
Examples of Q = c/b production diagrams, *not* exhaustive:



Leading order

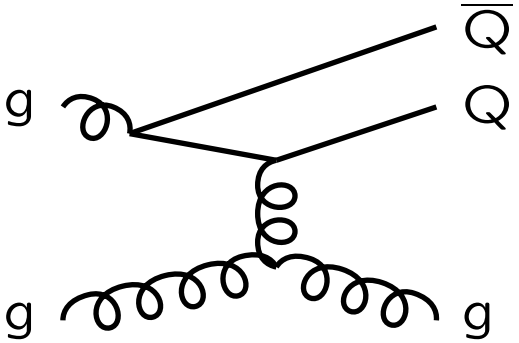


Leading order

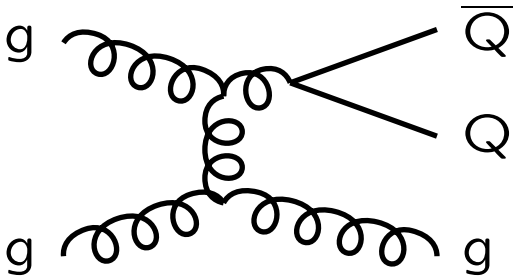


Pair creation

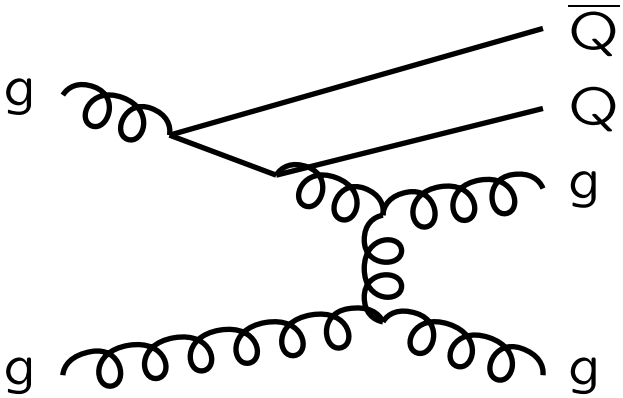
(with gluon emission)



Flavour excitation



Gluon splitting



Gluon splitting

(flavour excitation)

PS approach to heavy quarks

3 main sources (arbitrary names):

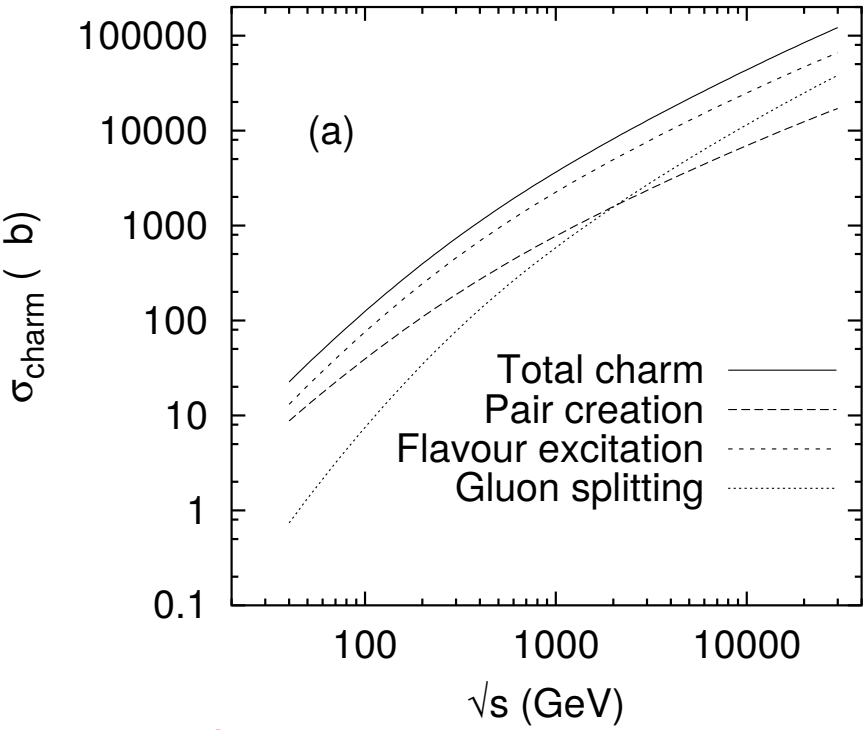
1) pair creation:
based on $\mathrm{gg} \to \mathrm{Q\overline{Q}}$ and $\mathrm{q\overline{q}} \to \mathrm{Q\overline{Q}}$ with masses
+ additional showering

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 $Q^2 > m^2_{\mathrm{Q}}$ (so PDF>0) and $Q^2_i < Q^2$;
$\mathrm{g} \to \mathrm{b\overline{b}}$ 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
$\sqrt{1 - 4m^2_{\mathrm{Q}}/m^2_{\mathrm{g}}}\,(1 + 2m^2_{\mathrm{Q}}/m^2_{\mathrm{g}})$
$\approx s$-channel graphs of $\mathrm{gg}, \mathrm{q\overline{q}} \to \mathrm{Q\overline{Q}}$

Avoid doublecounting:
for $2 \to 2$: $Q^2 = \hat{p}^2_\perp + (m^2_3 + m^2_4)/2 \quad (\Rightarrow \hat{s} \gtrsim 4Q^2)$
for FSR: $Q^2_{\mathrm{max}} = m^2_{\mathrm{max}} = 4Q^2$
for ISR: $Q^2_{\mathrm{max}} = Q^2$

Cross sections



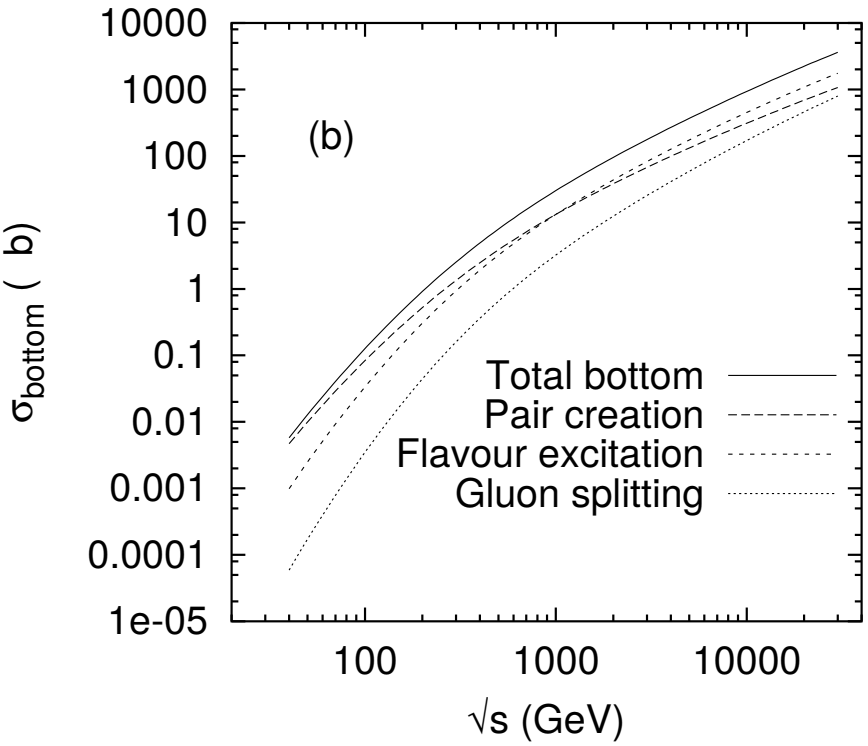
charm

pp

CTEQ 5L

$m_c = 1.5$ GeV

m_c "tuned" to asymmetries



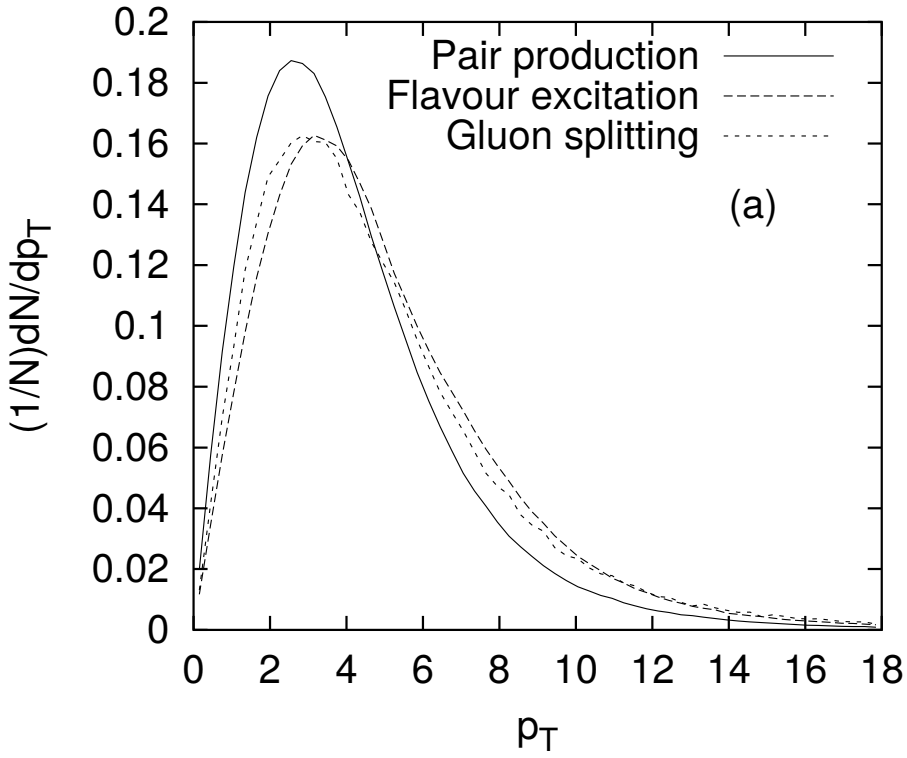
bottom

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

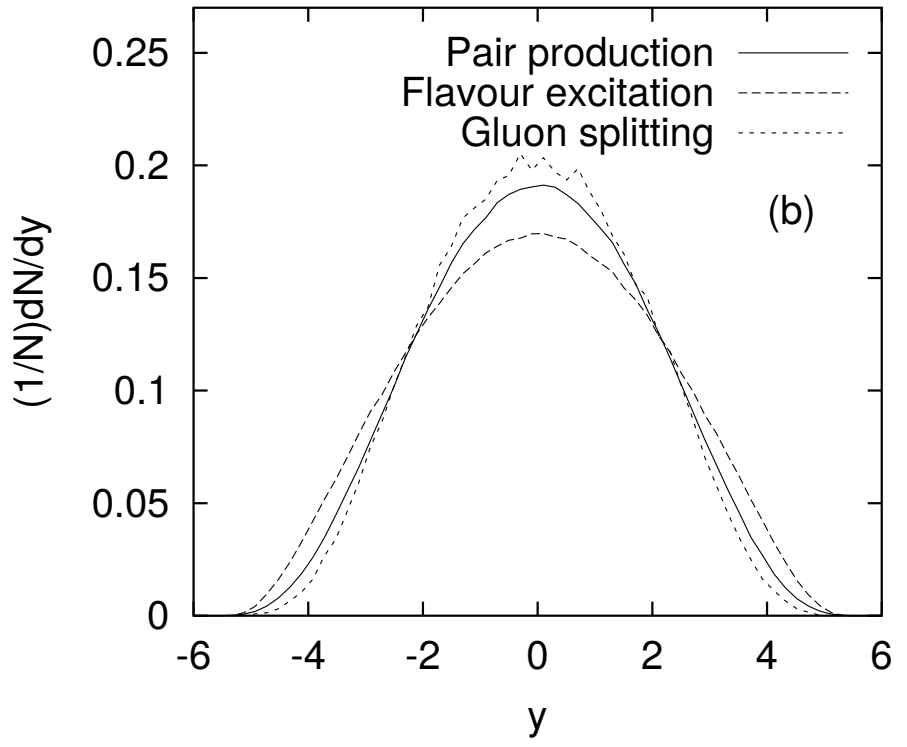
$p\overline{p}$ at 2 TeV

CTEQ 5L

$m_b = 4.8$ GeV

normalized to unit area

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



bottom

$p\overline{p}$ at 2 TeV

CTEQ 5L

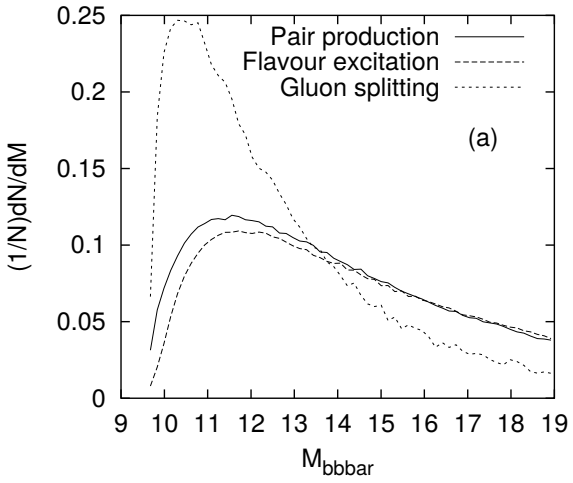
$m_b = 4.8$ GeV

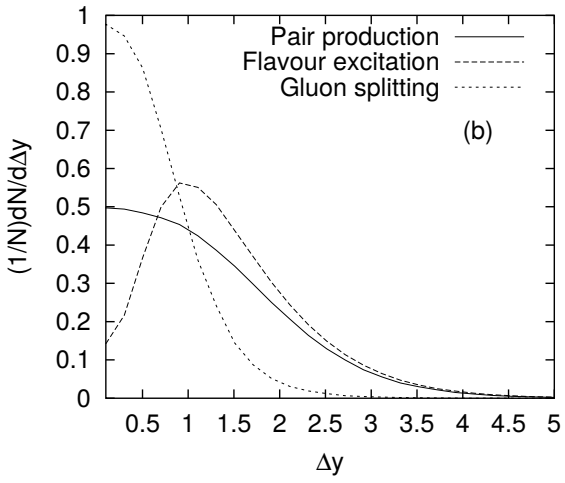
normalized to unit area

y of b quarks after shower etc.

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

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

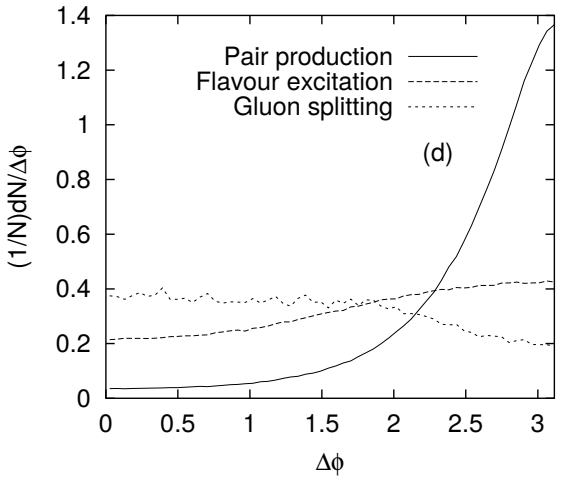


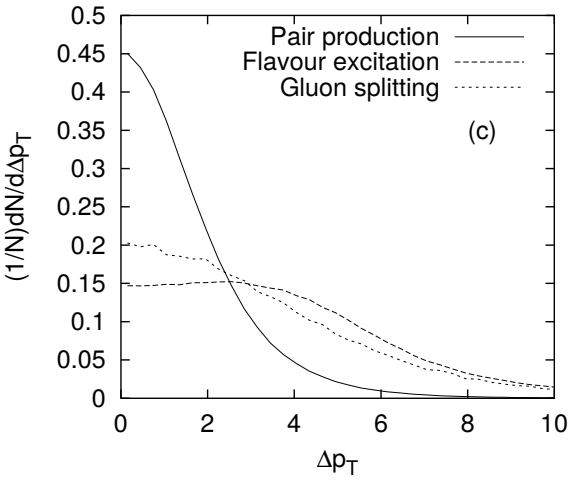


pair production: s- and t-channel

flavour excitation: t-channel

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





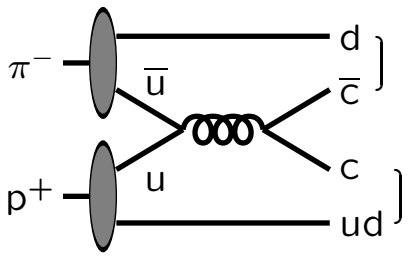
pair production: back-to-back in ϕ and $p_\perp$

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 $g \to q\bar{q}$ 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.



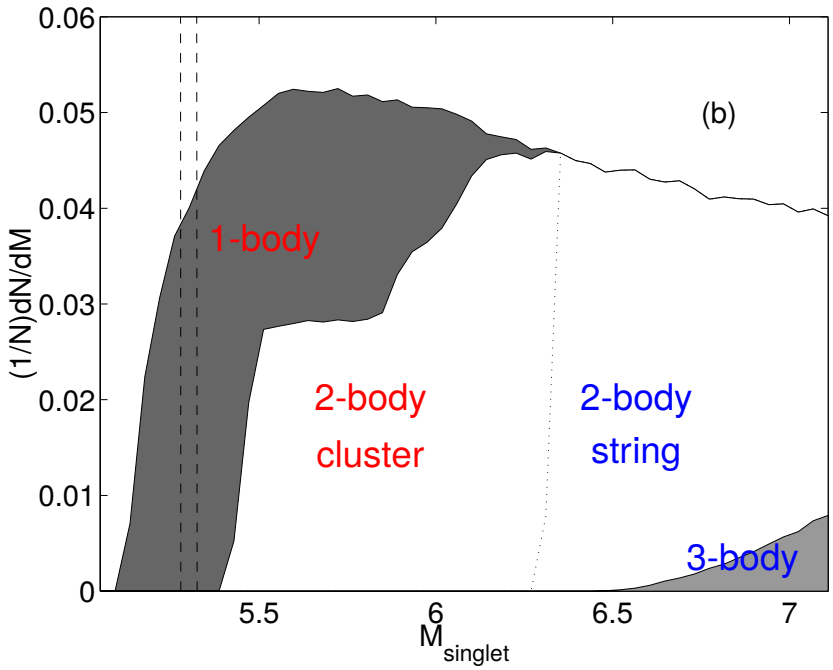
If collapse:
$\bar{c}d$: D^-, D^{*-}, ...
cud: Λ_c^+, Σ_c^+, Σ_c^{*+}, ...
$\Rightarrow$ flavour asymmetries

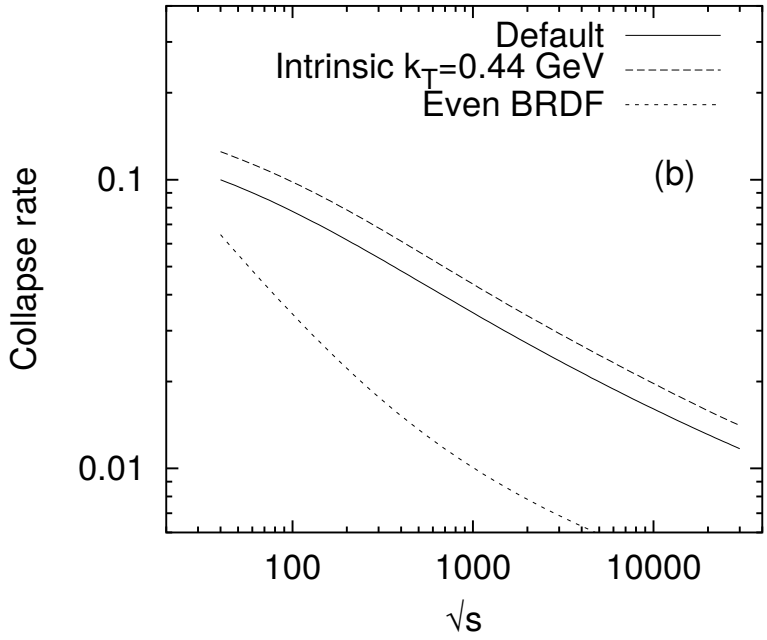
Can give D "drag" to larger x_F than c quark.

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:

$p_\pm = E \pm p_z$

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

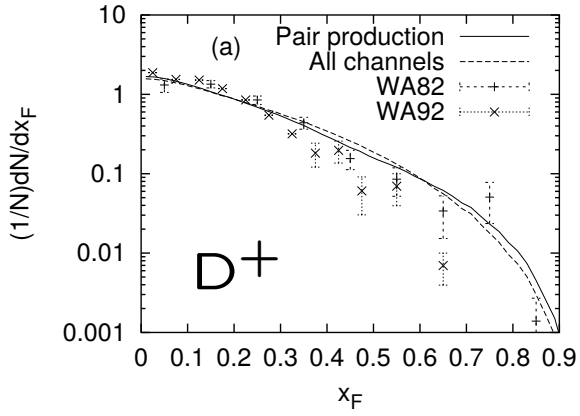
$$\Rightarrow p_{+\mathrm{D}} = \frac{m^2_{\perp \mathrm{D}}}{p_{-\mathrm{D}}} = \frac{m^2_{\perp \mathrm{D}}}{z p_{-\mathrm{c}}} \overset{\text{normally}}{>} \frac{m^2_{\perp \mathrm{c}}}{z p_{-\mathrm{c}}} = \frac{p_{+\mathrm{c}}}{z}$$

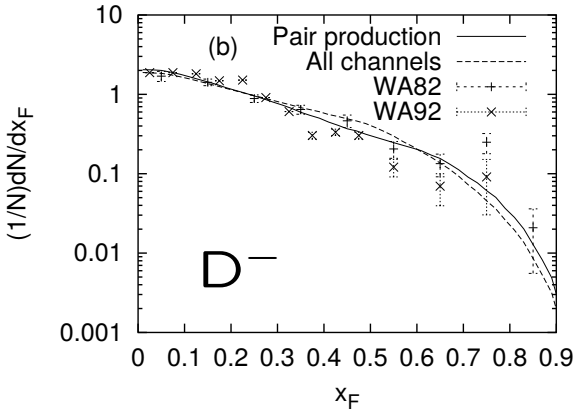
i.e. again drag.

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)

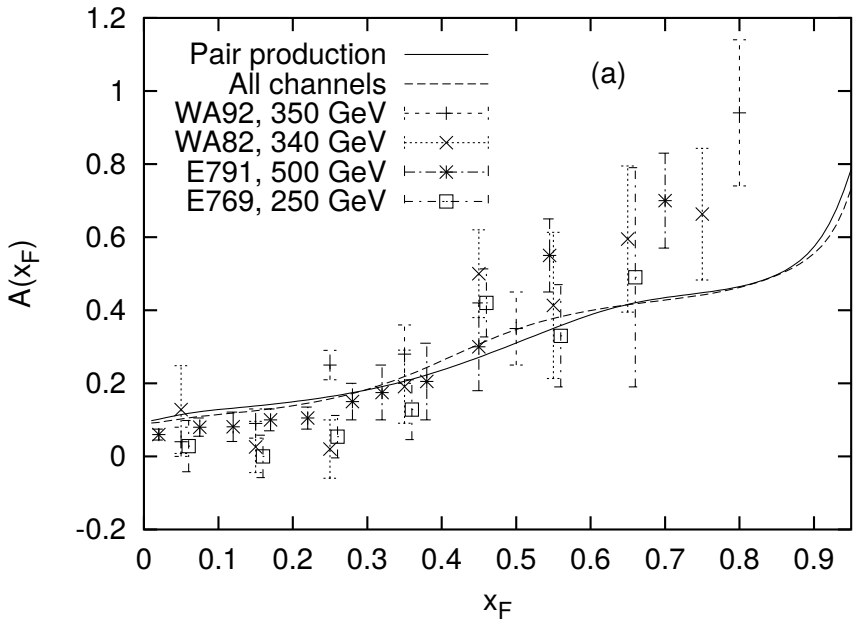
Asymmetries and correlations

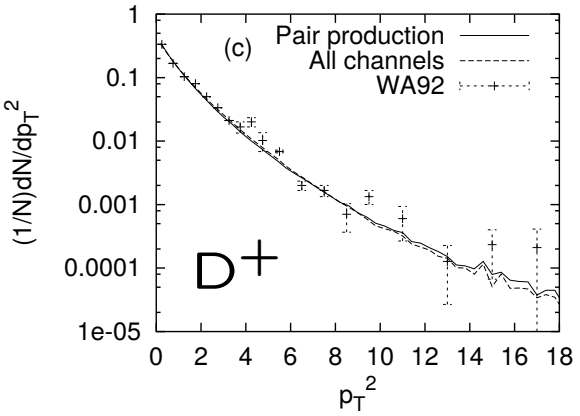


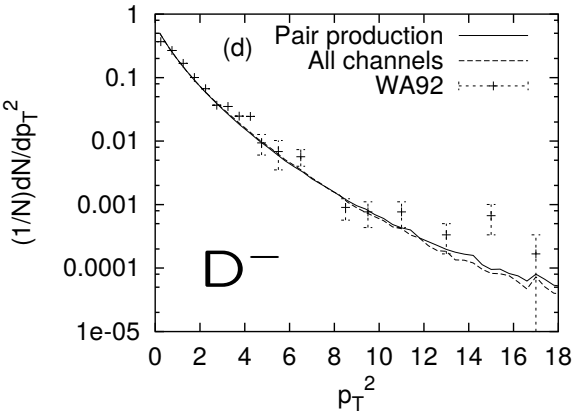


$$A(x_F) = \frac{\#D^- - \#D^+}{\#D^- + \#D^+}$$

in $\pi^- p$



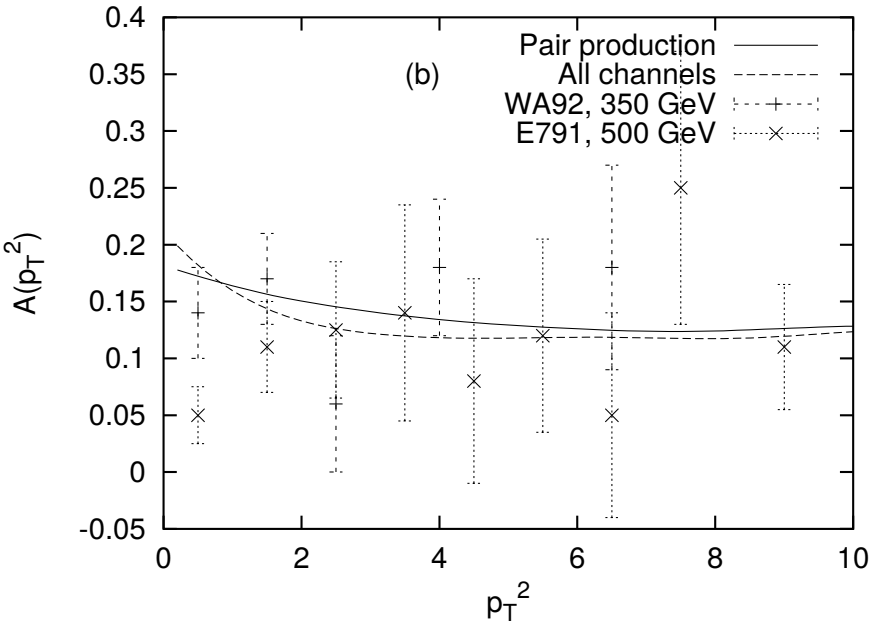


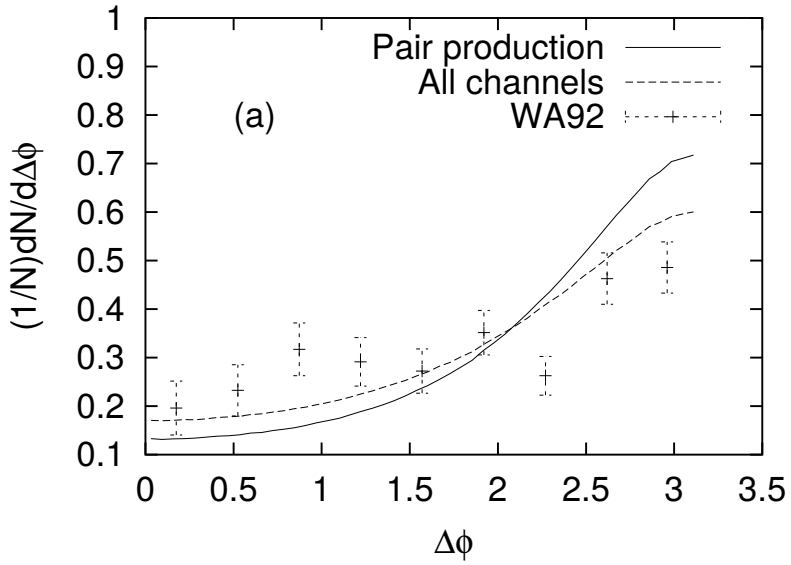


$A(p_\perp) =$

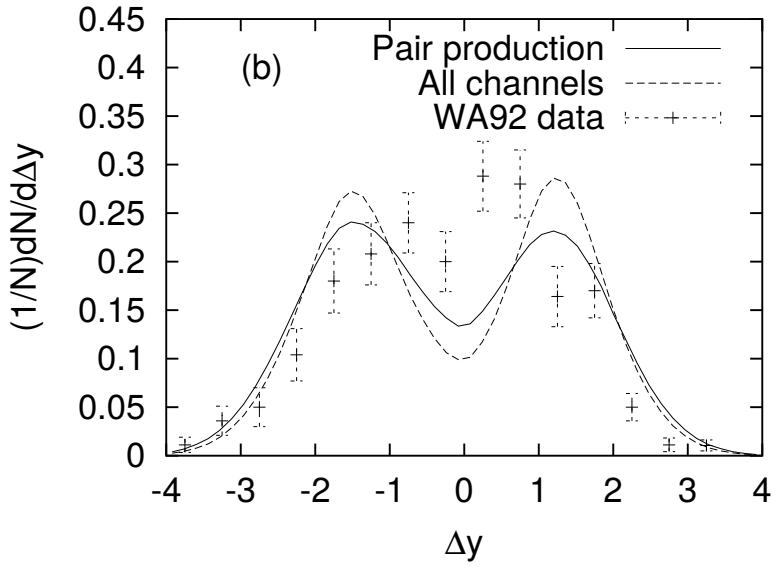
$\frac{\#D^- - \#D^+}{\#D^- + \#D^+}$

in $\pi^- p$

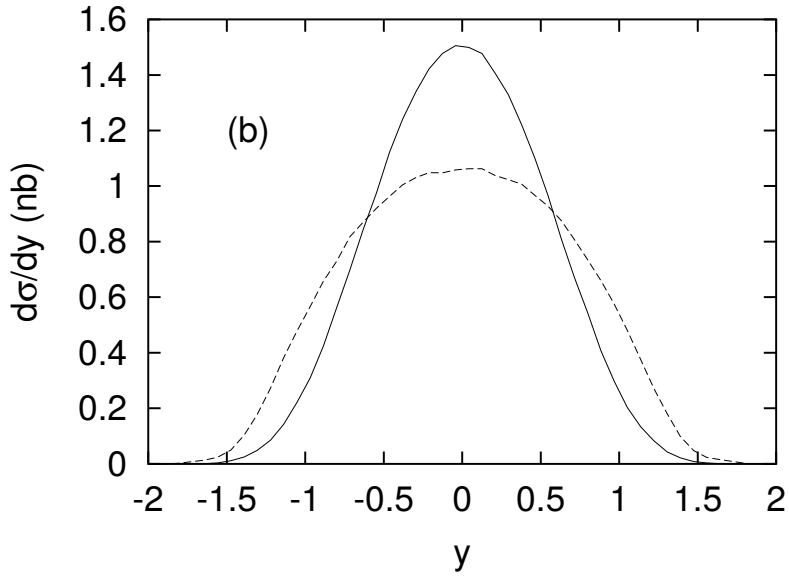




ϕ correlations improved . . .



. . . but y correlations worsened

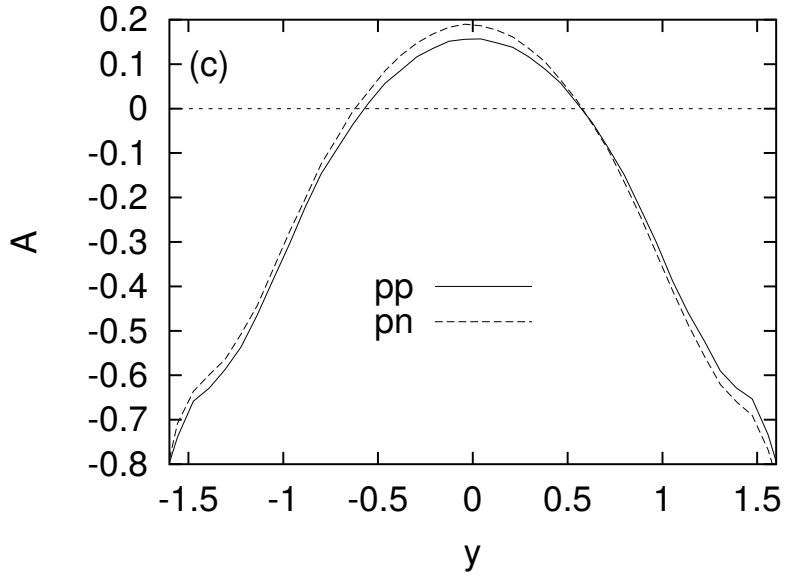


HERA-B

predictions

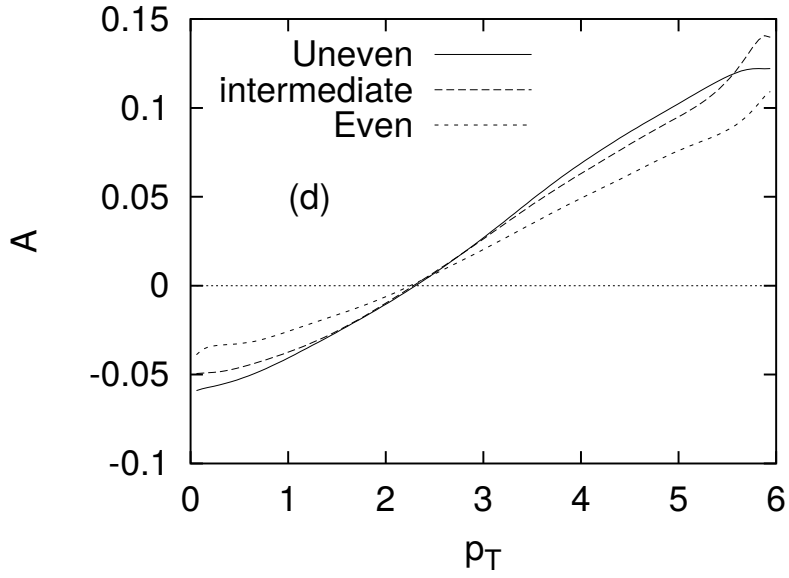
B^0 full

$\overline{B}^0$ dashed



y dependence

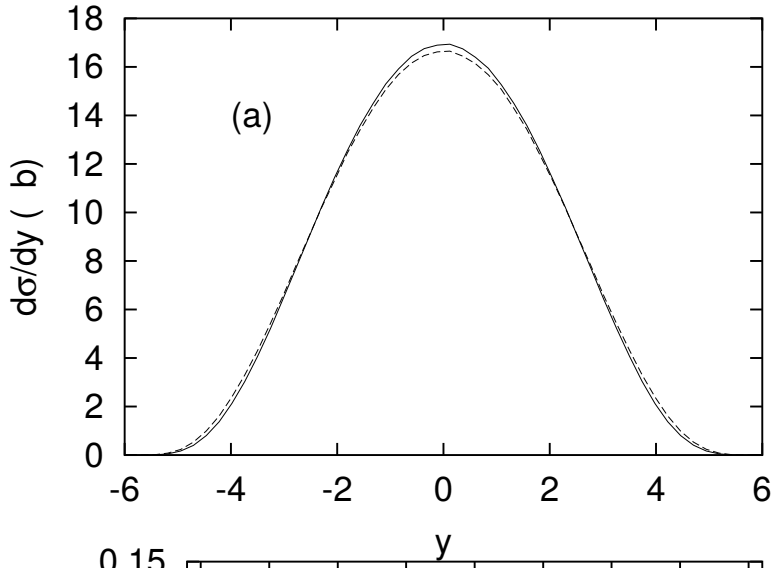
$$A = \frac{B^0 - \overline{B}^0}{B^0 + \overline{B}^0}$$

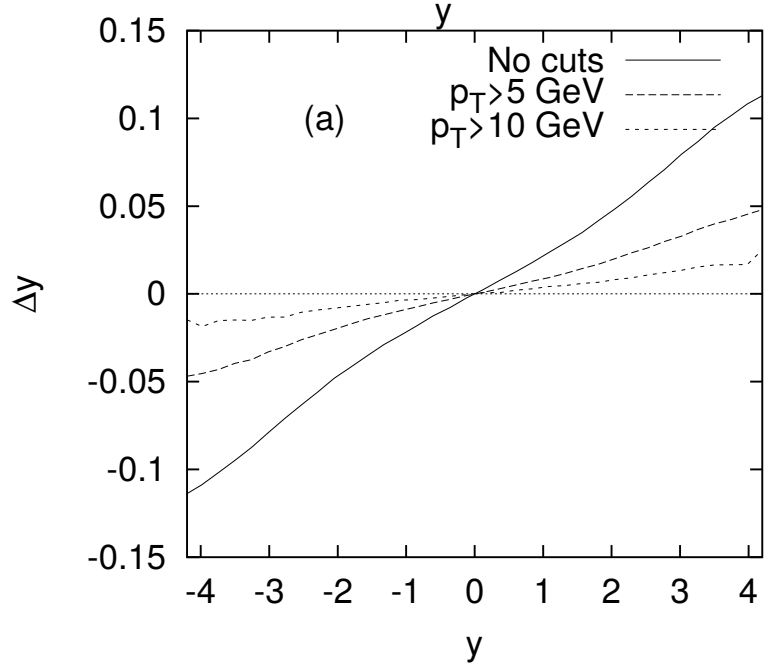


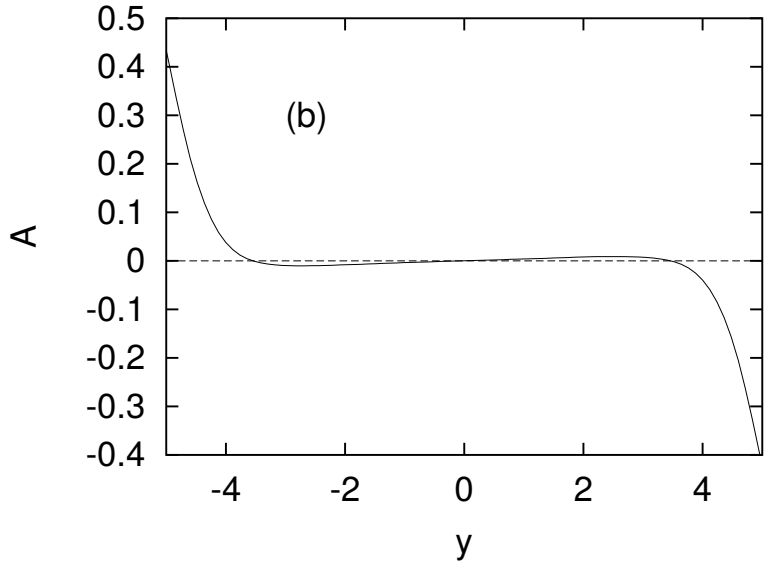
$p_\perp$ dependence

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

(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

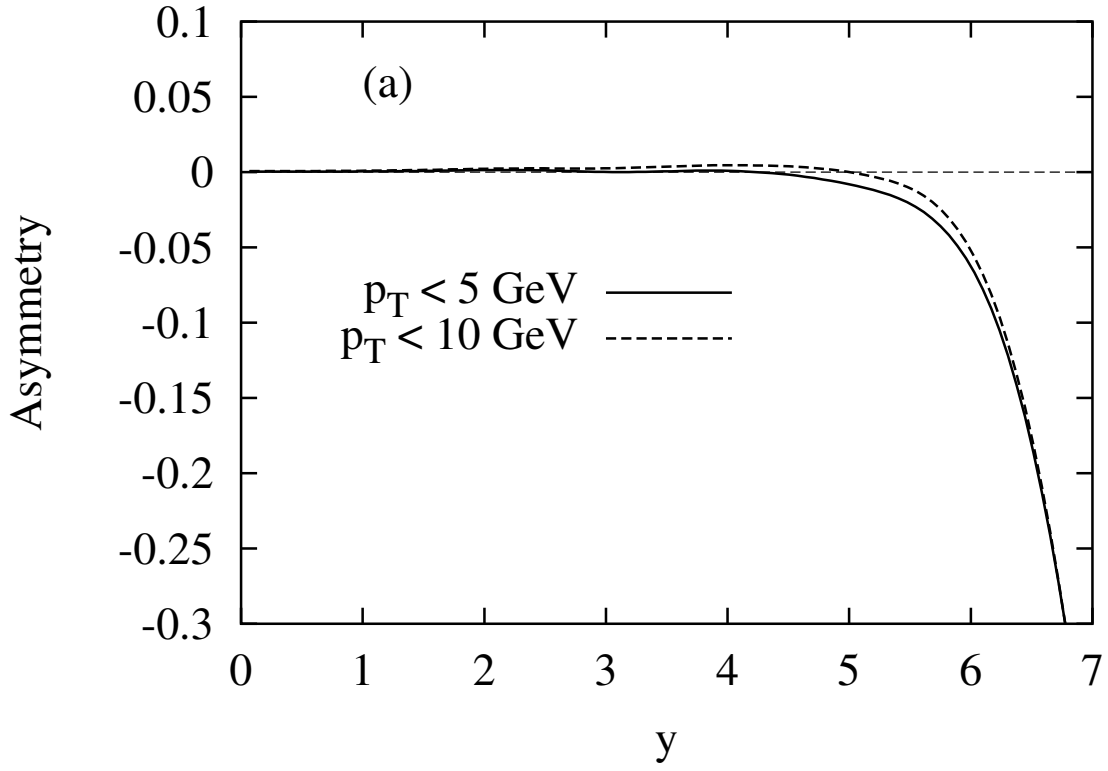
B asymmetry

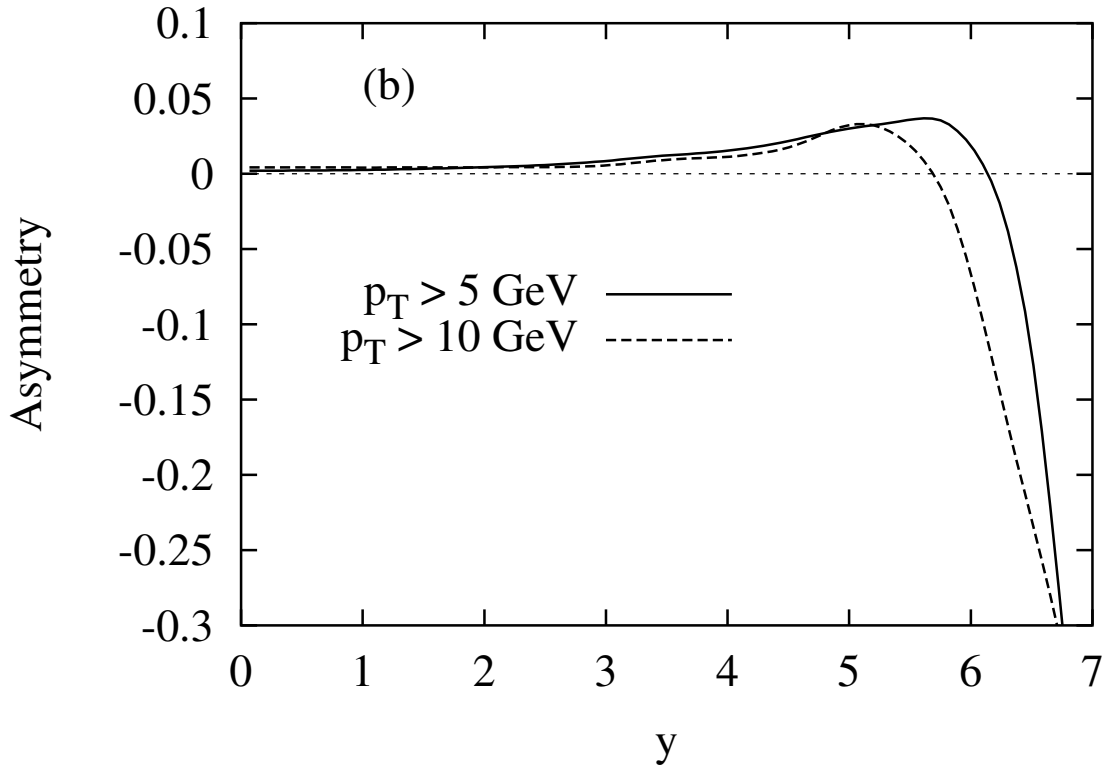
$$A = \frac{\sigma(\mathrm{B}^0) - \sigma(\overline{\mathrm{B}}^0)}{\sigma(\mathrm{B}^0) + \sigma(\overline{\mathrm{B}}^0)}$$

as function of y_{B}

Only pair production for simplicity

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





Notes

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

• Beam drag favours $\bar{B}^0$ from $b - ud_0 \Rightarrow A < 0$; dominates at large $|y|$ and small $p_\perp$

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

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

	$\lvert y\rvert < 2.5$, $p_\perp > 5$	$3 < \lvert y\rvert < 5$, $p_\perp > 5$	$\lvert y\rvert > 3$, $p_\perp < 5$
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 $B^0 - \bar{B}^0$ for CP reasons, but $B^+ - B^-$, $B_s^0 - \bar{B}_s^0$ 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