NORDITA
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LUND UNIVERSITY

# Production and hadronization of heavy quarks

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Introduction: event physics overview
Production: the shower approach
Hadronization: beam drag effects
Uncertainties: multiple interactions

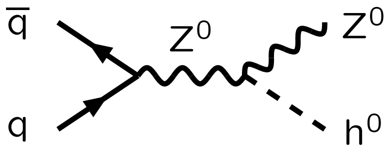
based on E. Norrbin & TS,
Phys. Lett. **B442** (1998) 407,
Eur. Phys. J. **C17** (2000) 137

**Warning: only hh, not hA or AA!**

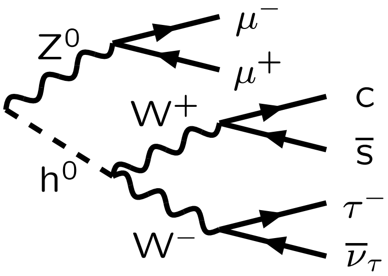
# Event physics overview

## Structure of the basic generation process:

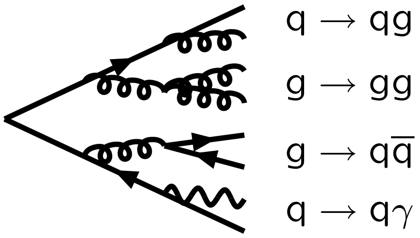
1) Hard subprocess:
$d\hat{\sigma}/d\hat{t}$, Breit-Wigners.



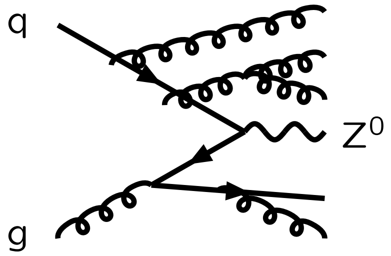
2) Resonance decays:
includes correlations.



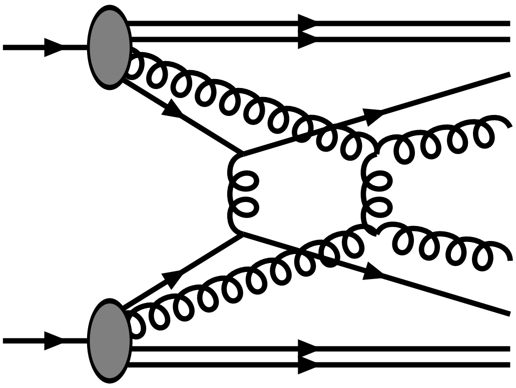
3) Final-state
parton showers:
(or matrix elements).



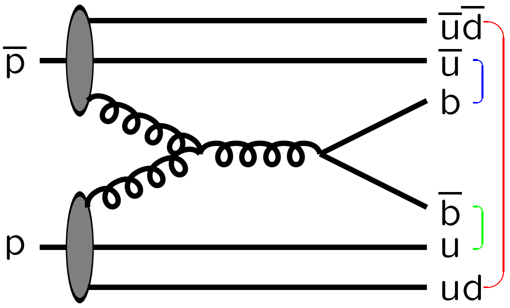
4) Initial-state
parton showers:
(or matrix elements).



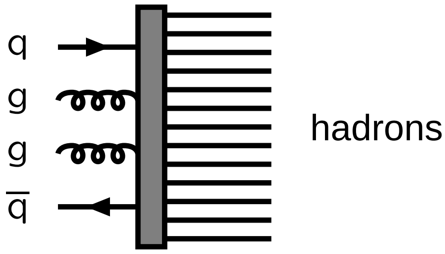
5) Multiple
parton–parton
interactions.



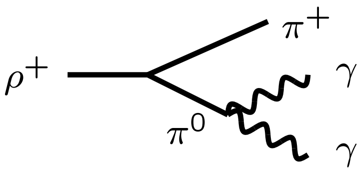
6) Beam remnants:
colour-connected
to rest of event



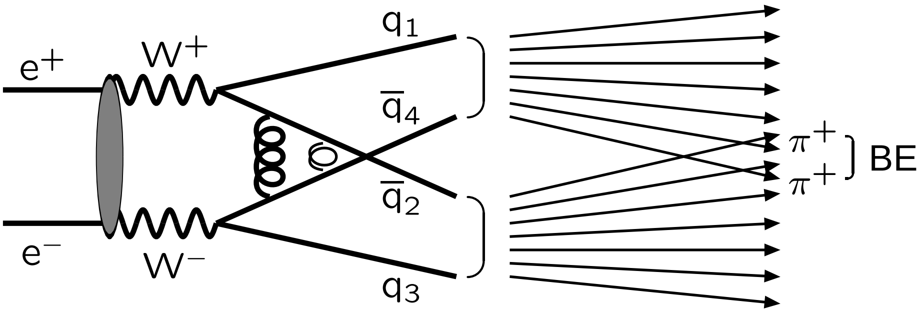
7) Hadronization



8) Normal decays:
hadronic, $\tau$, charm, . . .



9) QCD interconnection effects:

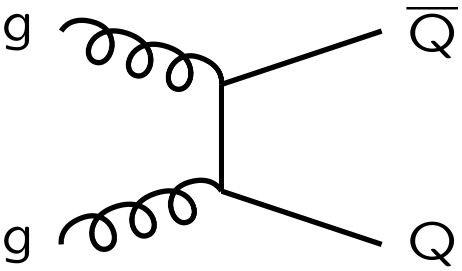


a) colour rearrangement (⇒ rapidity gaps?);
b) Bose-Einstein (within & between strings).

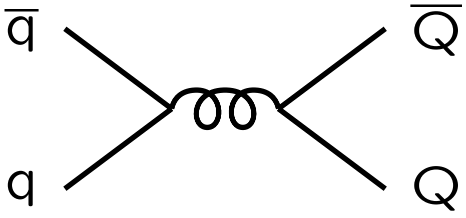
10) The forgotten/unexpected: a chain is never stronger than its weakest link!

# Production graphs

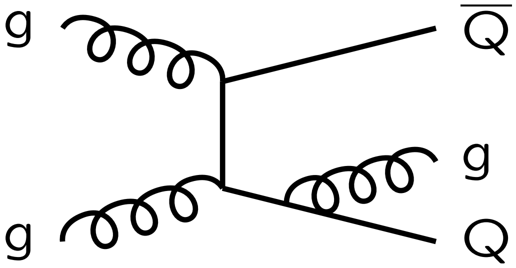
Examples of Q = c/b production diagrams, *not* exhaustive:



Leading order

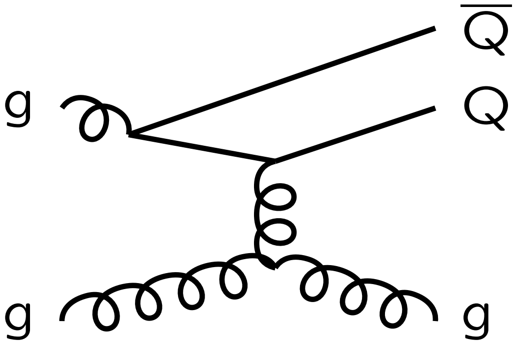


Leading order

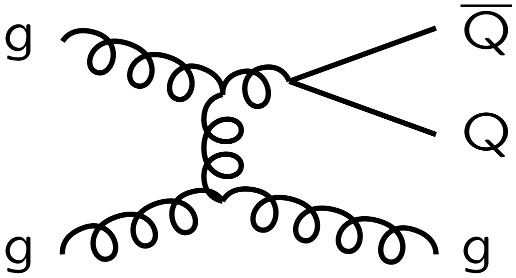


Pair creation

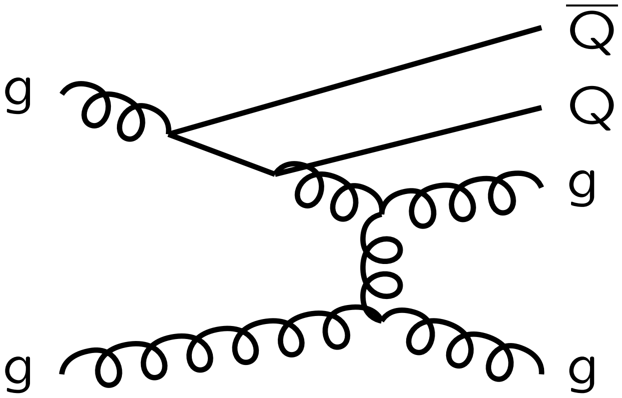
(with gluon emission)



Flavour excitation



Gluon splitting



Gluon splitting

(flavour excitation)

# ME vs. PS

ME : Matrix Elements

- \+ systematic expansion in $\alpha_{\mathrm{s}}$ (‘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

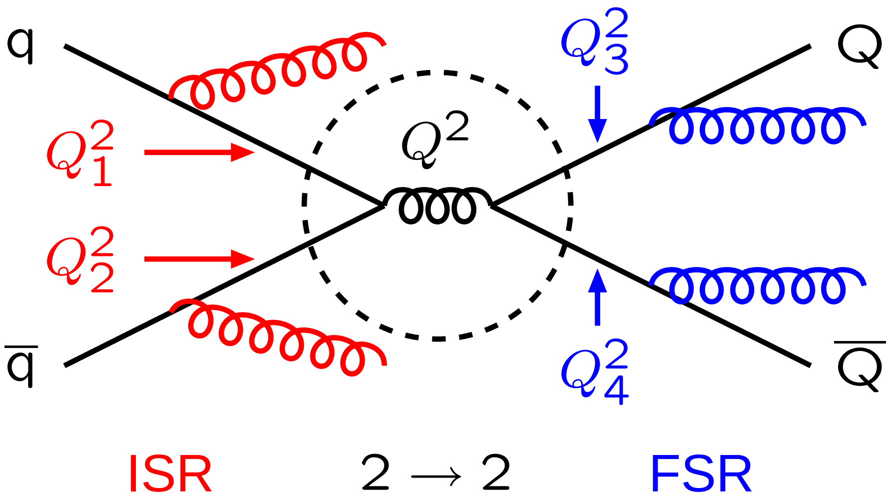
- – approximate
- \+ resums large logarithms
- \+ process-generic $\Rightarrow$ simple multiparton
- \+ Sudakov form factors/resummation $\Rightarrow$ sensible jet/event structure
- \+ *easy to match to hadronization*

Conventional description: ME
Here: PS, as alternative/check/complement

No claim of ultimate truth!

# PS approach

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



$2 \to 2$ = 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 + $\sim$ 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

# PS approach to heavy quarks

3 main sources (arbitrary names):

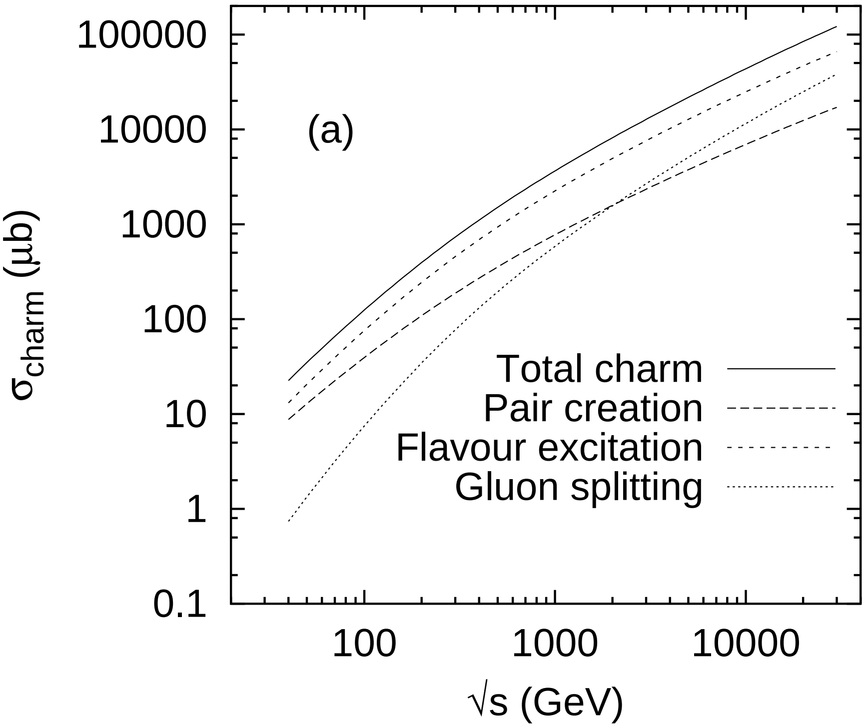
1) pair creation:
based on gg $\to$ $\mathrm{Q\overline{Q}}$ and $\mathrm{q\overline{q}}$ $\to$ $\mathrm{Q\overline{Q}}$ with masses
+ additional showering

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

3) gluon splitting:
ordinary 2 $\to$ 2 processes, e.g. gg $\to$ gg
+ 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 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: $Q_{\mathrm{max}}^2 = m_{\mathrm{max}}^2 = 4Q^2$
for ISR: $Q_{\mathrm{max}}^2 = Q^2$

# Cross sections



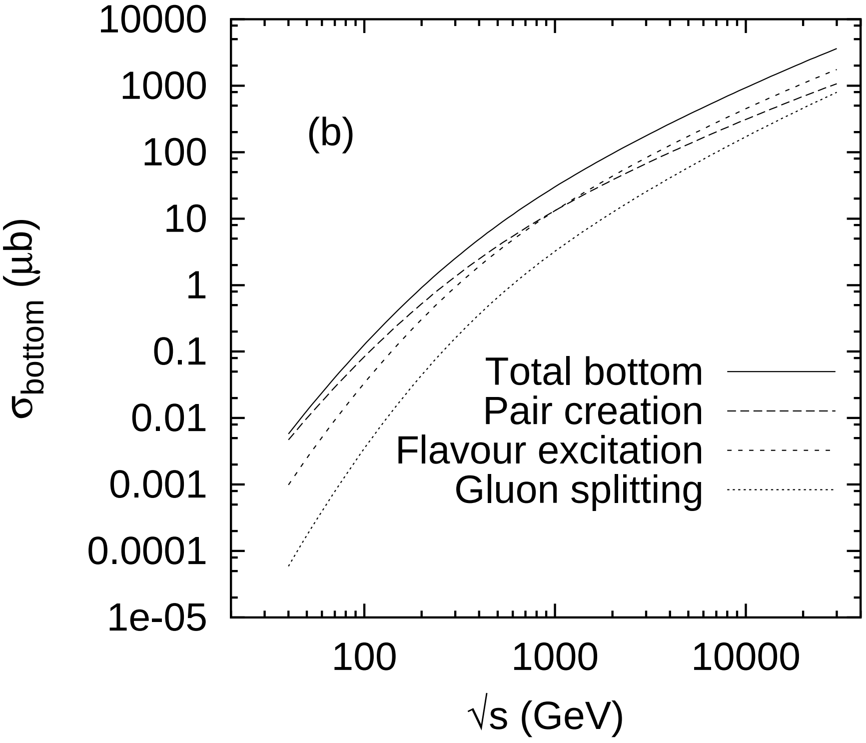
charm

pp

CTEQ 5L

$m_{\text{c}} = 1.5$ GeV

$m_{\text{c}}$ "tuned" to asymmetries



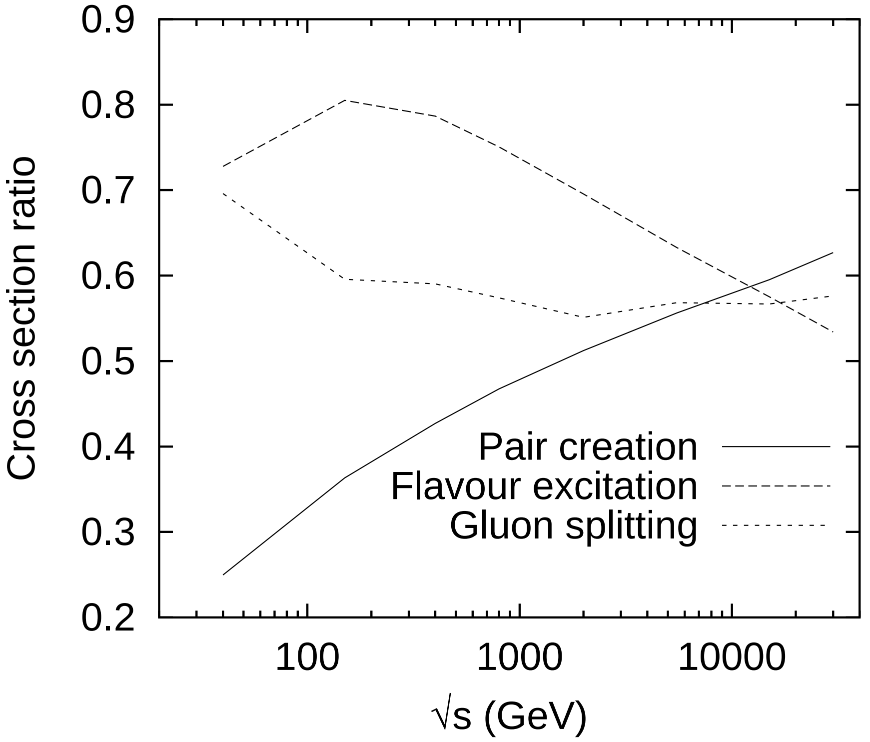
bottom

pp

CTEQ 5L

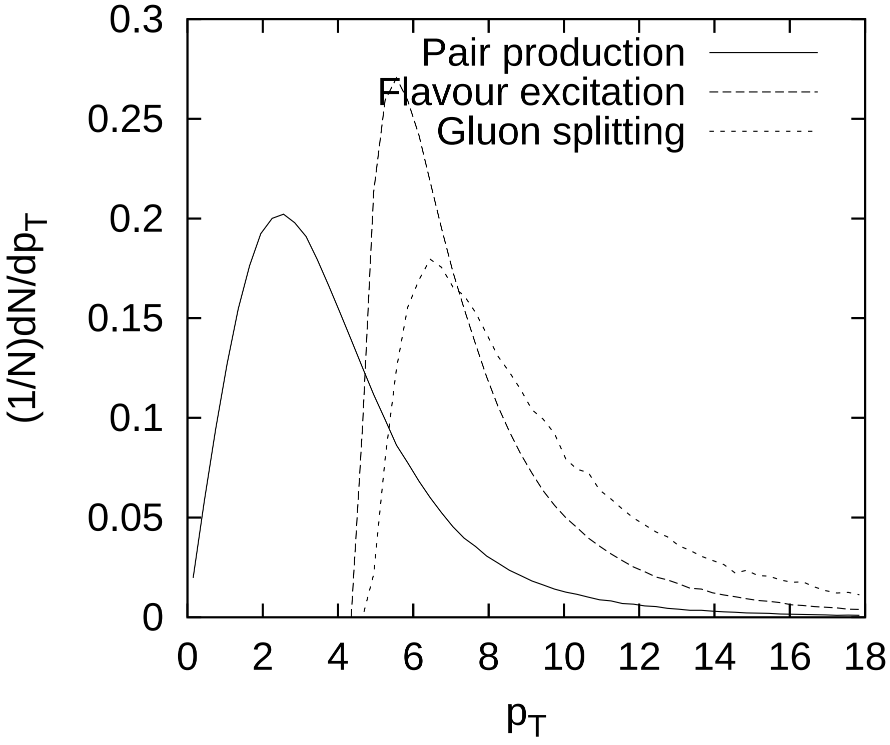
$m_{\text{b}} = 4.8$ GeV

$$\frac{3m_{\text{D}^*} + m_{\text{D}}}{4} - m_{\text{c}} = \frac{3m_{\text{B}^*} + m_{\text{B}}}{4} - m_{\text{b}}$$



charm
pp

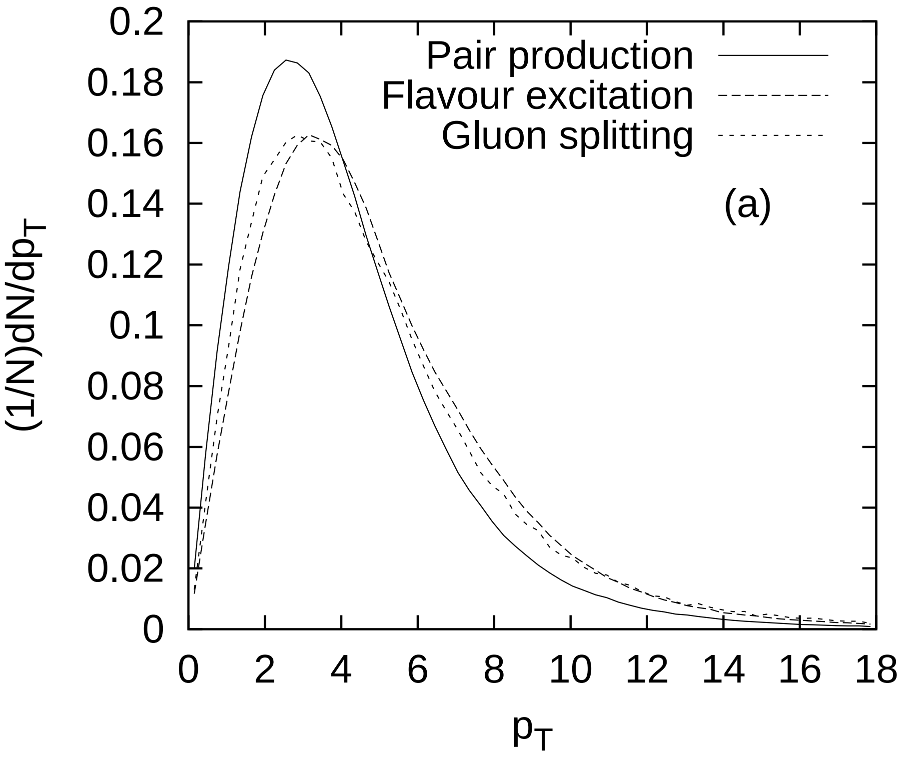
pair creation: $m_{\mathrm{c}} = 1.7$ GeV / $m_{\mathrm{c}} = 1.3$ GeV
flavour excitation: GRV 94L / CTEQ 5L
gluon splitting: $Q^2_{\mathrm{max}} = Q^2$ / $Q^2_{\mathrm{max}} = 4Q^2$



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

normalized to
unit area

$\widehat{p}_{\perp}$ of 2 → 2 hard scattering



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$\mathrm{p}\overline{\mathrm{p}}$ at 2 TeV

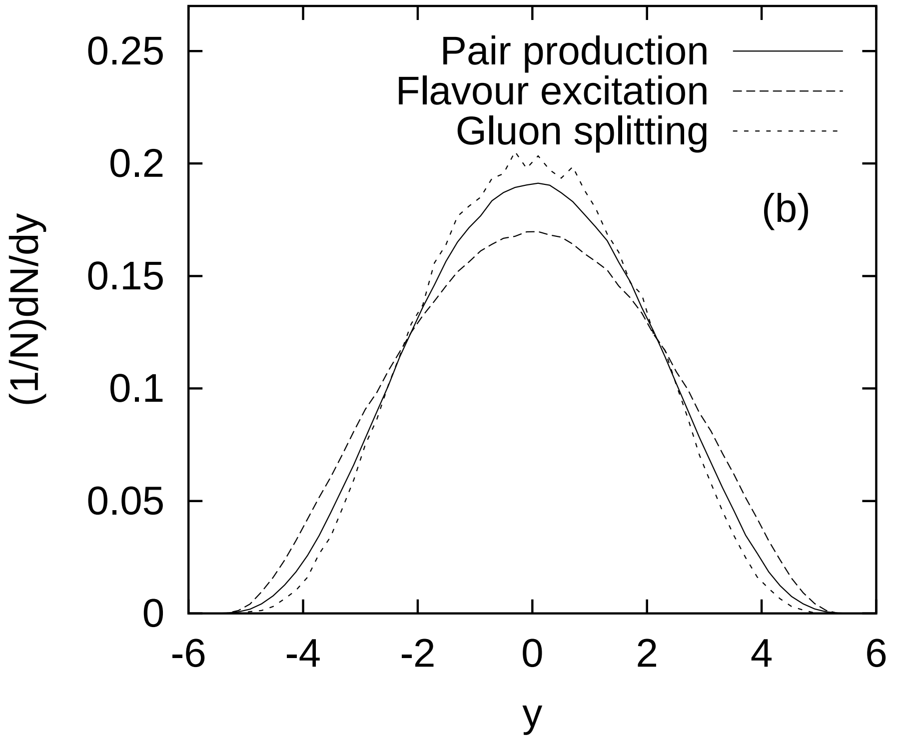
CTEQ 5L

$m_{\mathrm{b}} = 4.8$ GeV

normalized to

unit area

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



bottom

$\mathrm{p}\overline{\mathrm{p}}$ at 2 TeV

CTEQ 5L

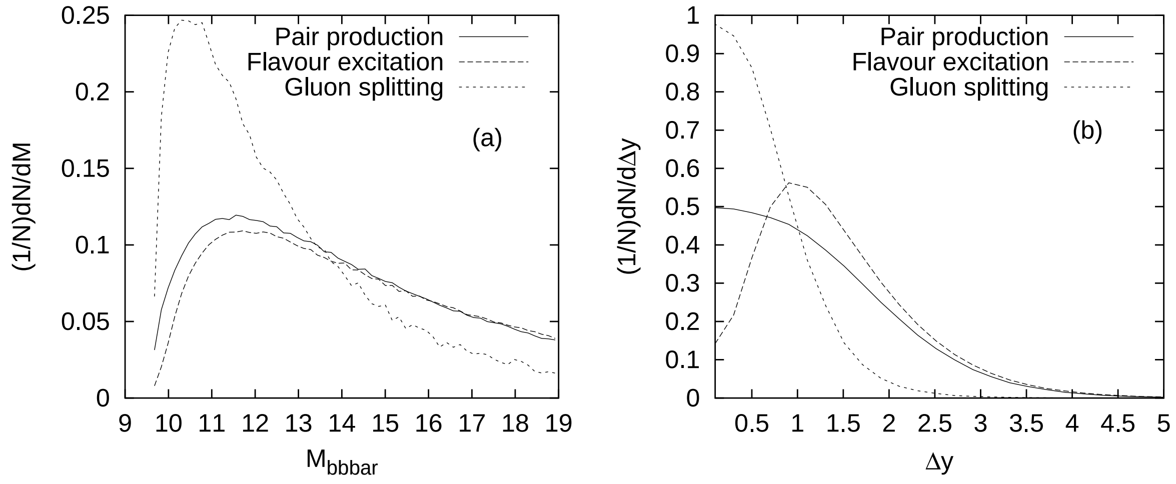
$m_{\mathrm{b}} = 4.8$ GeV

normalized to

unit area

$y$ of b quarks after shower etc.

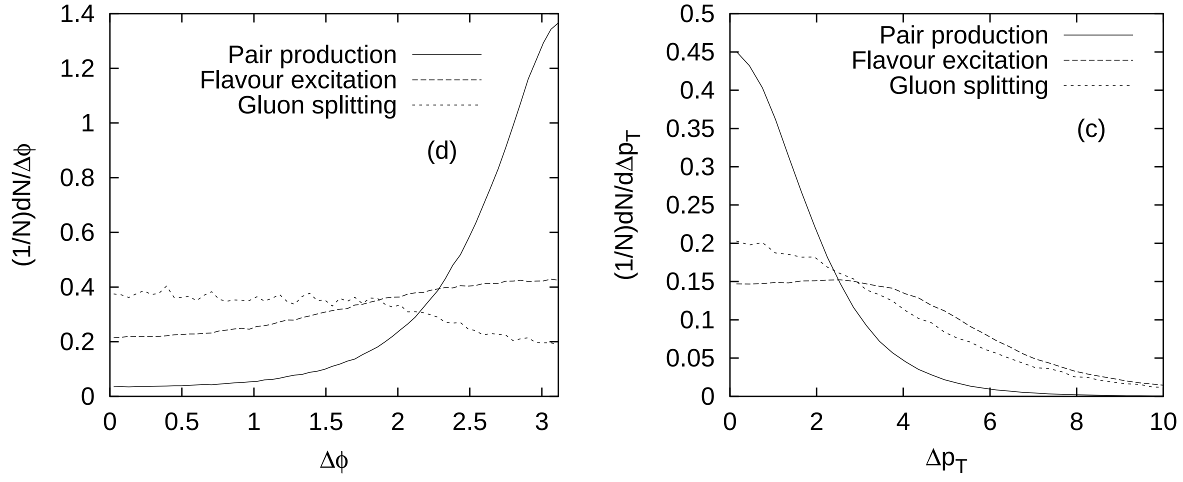
# Correlations between b and $\overline{\text{b}}$
## p$\overline{\text{p}}$ at 2 TeV, CTEQ 5L, $m_{\text{b}} = 4.8$ GeV



pair production: $s$- and $t$-channel

flavour excitation: $t$-channel

gluon splitting: $s$-channel ⇒ smaller masses



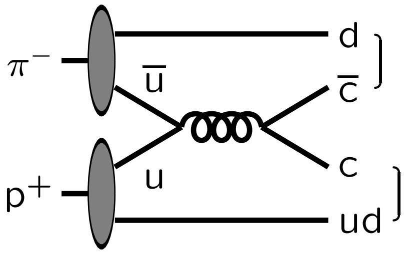
pair production: back-to-back in $\phi$ and $p_\perp$

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



If collapse:
$\overline{c}d$: $D^-$, $D^{*-}$, …
$cud$: $\Lambda_c^+$, $\Sigma_c^+$, $\Sigma_c^{*+}$, …
⇒ flavour asymmetries

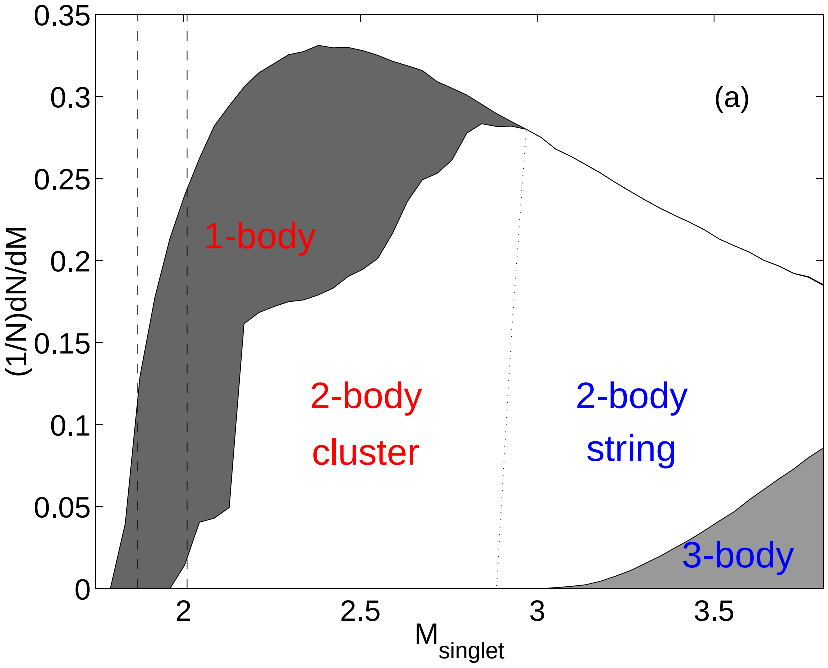
Can give D “drag” to larger $x_F$ than c quark.

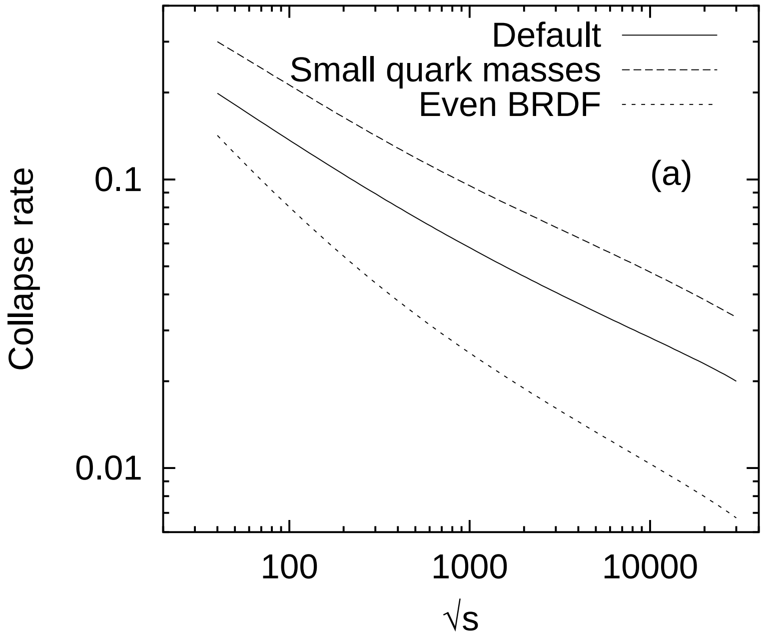
PYTHIA *pre*dicted qualitative behaviour.
Quantitative one sensitive to details
⇒ develop model & tune

# Improved description of when collapse occurs

(mass spectrum $\Leftarrow$ constituent quark masses)

example:
charm
string
in $\pi$p
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:

$$p_\pm = E \pm p_z$$

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

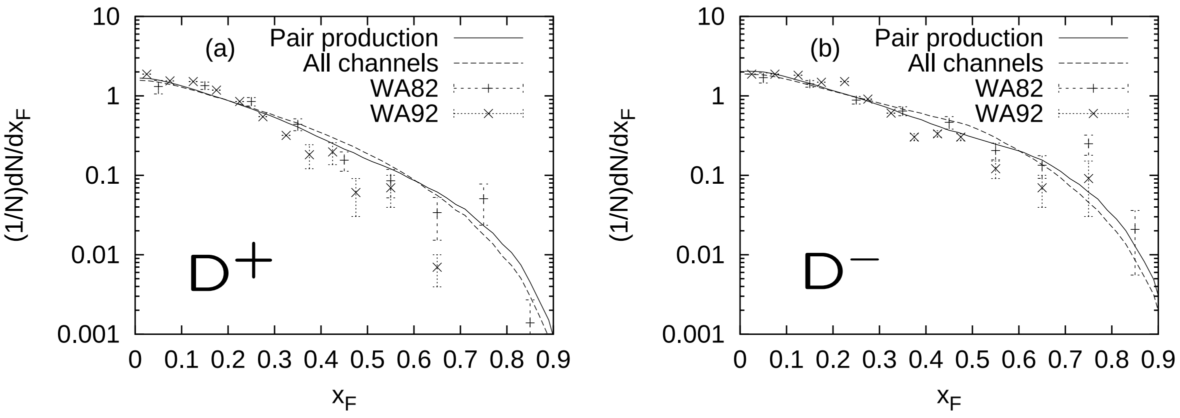
$$\Rightarrow p_{+\mathrm{D}} = \frac{m_{\perp\mathrm{D}}^2}{p_{-\mathrm{D}}} = \frac{m_{\perp\mathrm{D}}^2}{z p_{-\mathrm{c}}} \overset{\text{normally}}{>} \frac{m_{\perp\mathrm{c}}^2}{z p_{-\mathrm{c}}} = \frac{p_{+\mathrm{c}}}{z}$$

i.e. again drag.

Technical components of modelling:

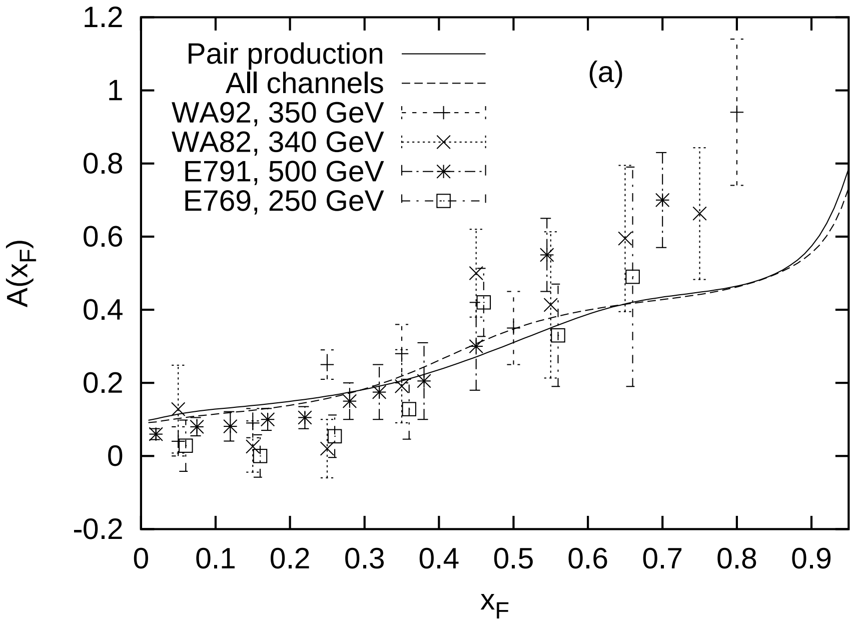
- Charm and bottom masses: c and b cross sections ($m_\mathrm{c} = 1.5$, $m_\mathrm{b} = 4.8$)
- Light-quark masses: threshold for cluster mass spectrum, together with $m_\mathrm{c}$ ($m_\mathrm{u} = m_\mathrm{d} = 0.33$, $m_\mathrm{s} = 0.50$)
- Beam remnant distribution function: ($\mathrm{p} - \mathrm{g} = \mathrm{ud}_0 + \mathrm{u}$ 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 D$\pi$ or gradually at D$\pi$, D$^*\pi$, D$\rho$, …
- Collapse energy–momentum conservation: practical solution to mass $\delta$ function (several models tried; not very sensitive)

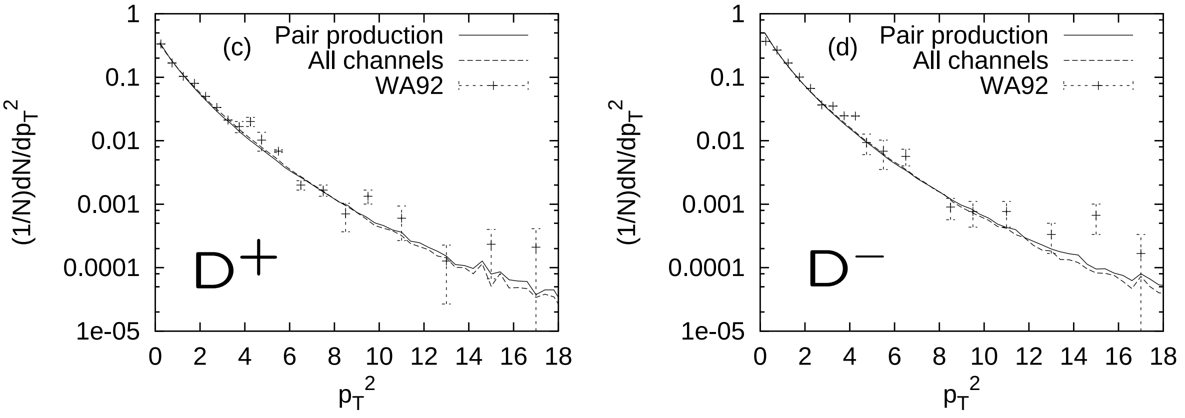
# Asymmetries and correlations



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

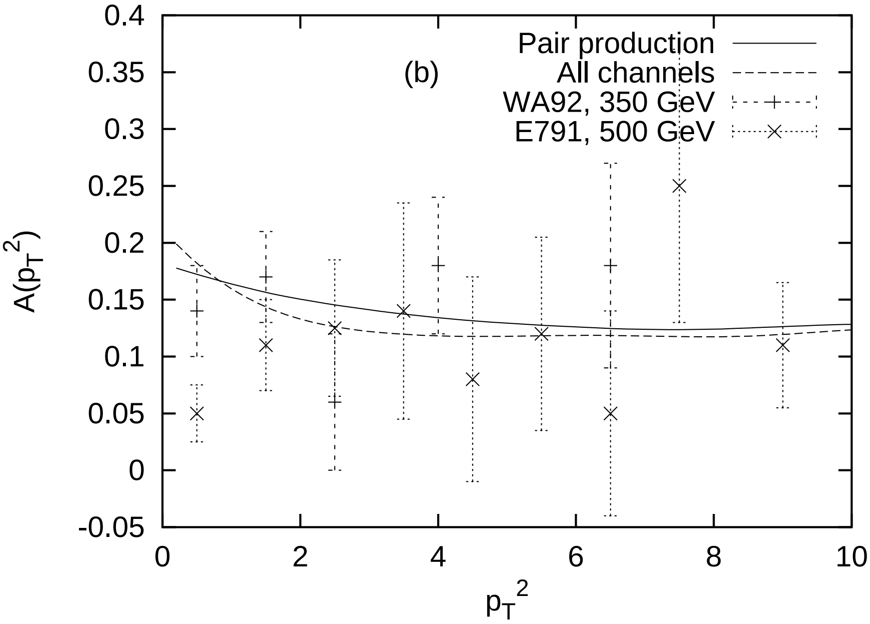
in $\pi^- p$

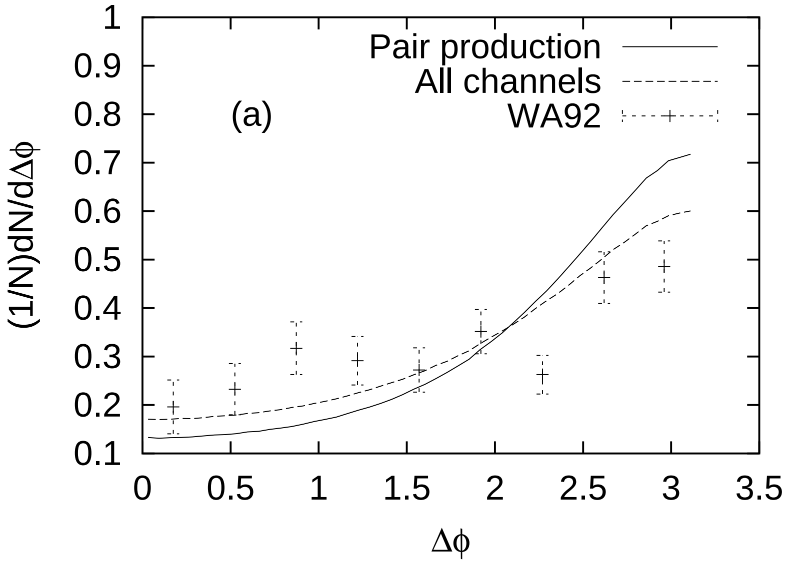




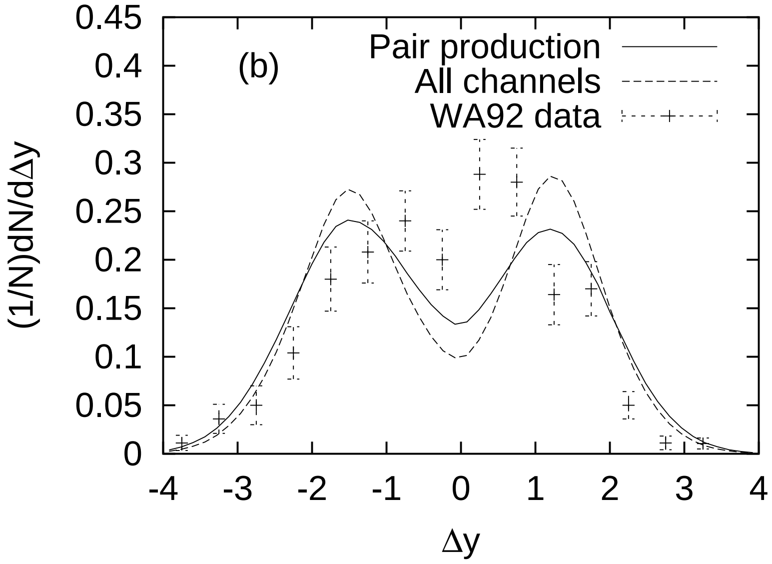
$$A(p_\perp) = \frac{\#\mathrm{D}^- - \#\mathrm{D}^+}{\#\mathrm{D}^- + \#\mathrm{D}^+}$$

in $\pi^-$p



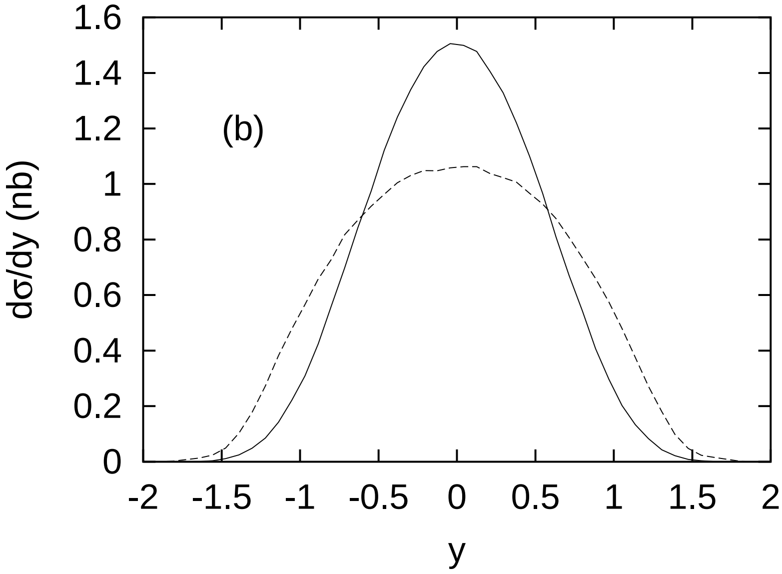


$\phi$ correlations improved . . .



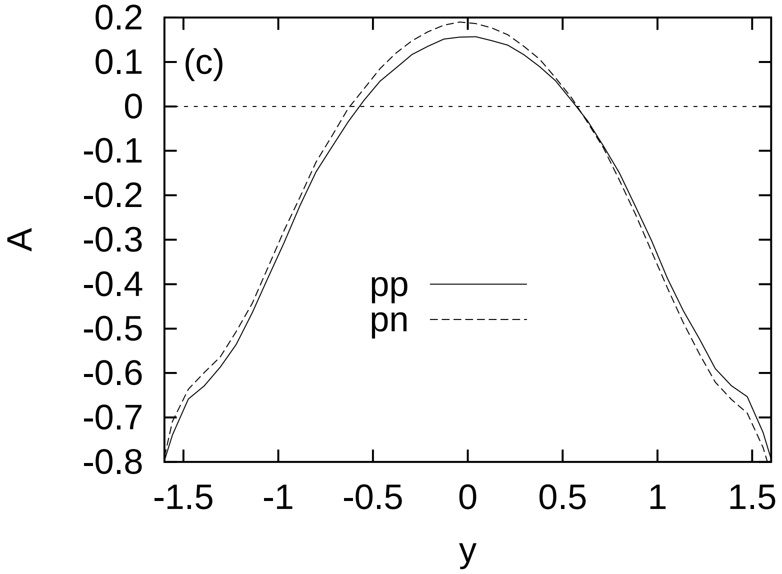
. . . but $y$ correlations worsened

## HERA-B
predictions



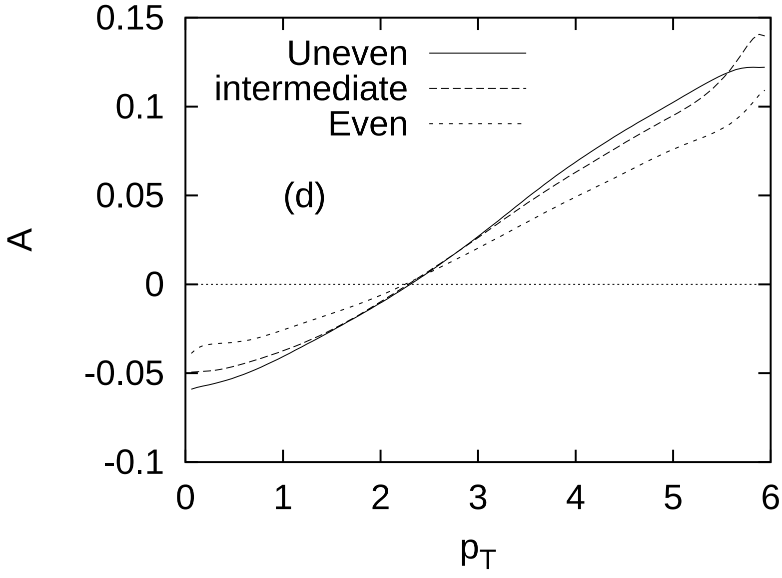
$B^0$ full

$\overline{B}^0$ dashed



$y$ dependence

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

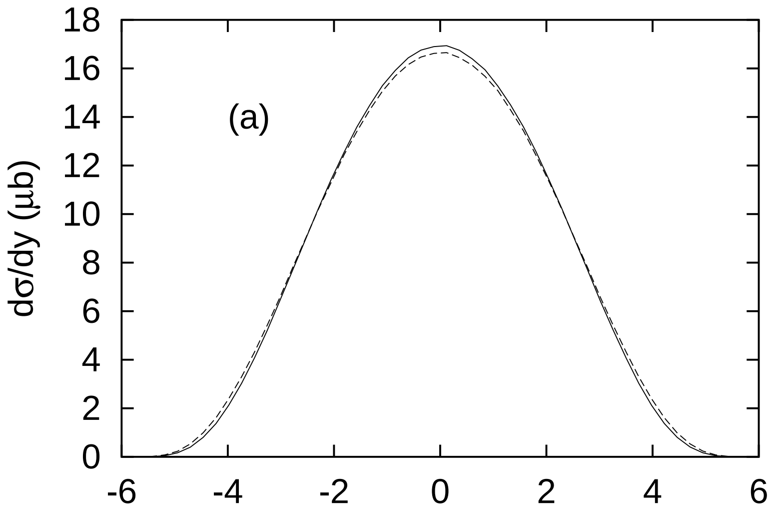


$p_\perp$ dependence

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

(vary beam
remn dist)

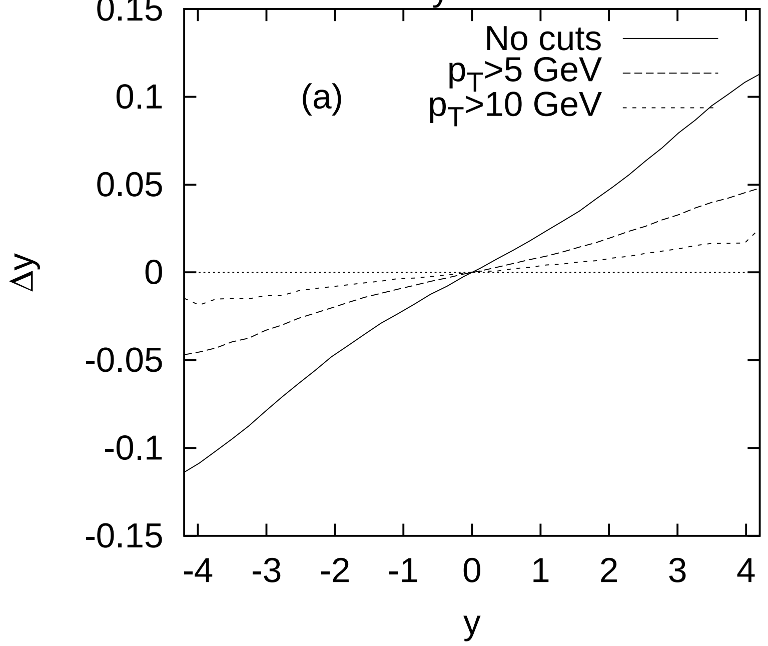
# Tevatron
## predictions



Rapidity distribution

full: b quarks

dashed: B hadrons



Average

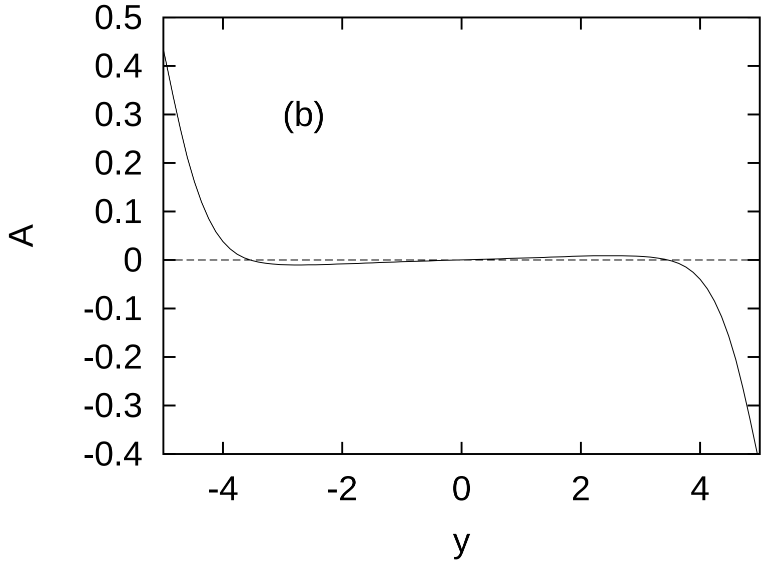
rapidity shift

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

as function of $y_{\mathrm{b}}$

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 $y_{\mathrm{B}}$

Only pair production

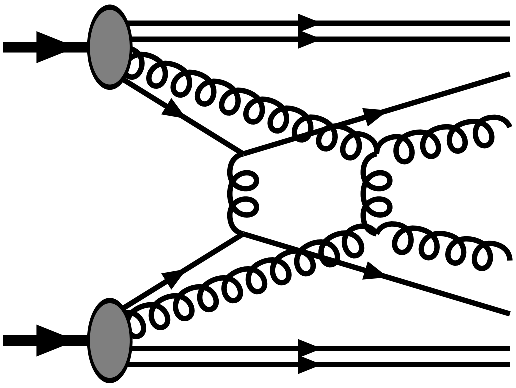
for simplicity

# Multiple Interactions

(TS & M. van Zijl, PRD36 (1987) 2019,

J. Dischler & TS, EPJdir C2 (2001) 1)

Consequence of composite nature of hadrons:



Evidence:

- direct observation: AFS, UA1, CDF
- implied by width of multiplicity distribution + jet universality: UA5
- forward–backward correlations: UA5
- pedestal effect: UA1, H1

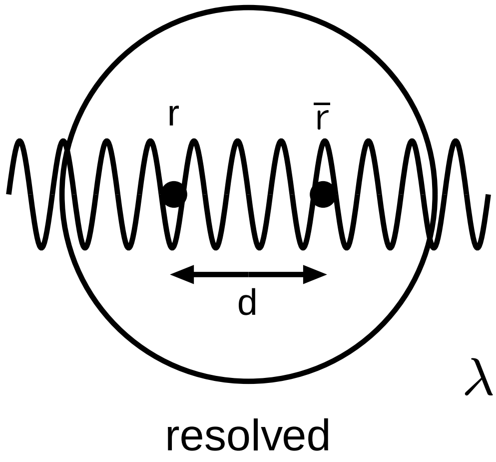
One new free parameter: $p_{\perp\mathrm{min}}$

$$\frac{1}{2}\sigma_{\mathrm{jet}} = \int_{p^2_{\perp\mathrm{min}}}^{s/4} \frac{\mathrm{d}\sigma}{\mathrm{d}p^2_{\perp}}\,\mathrm{d}p^2_{\perp}$$

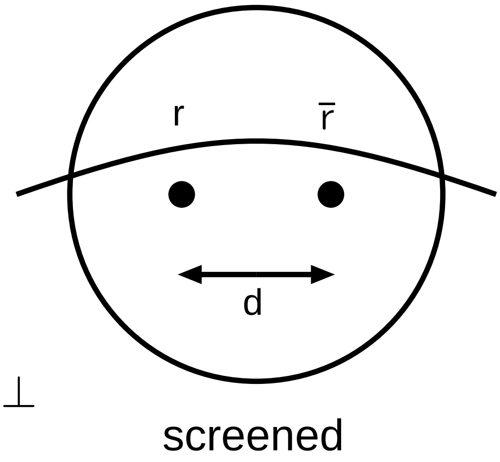
$$\Leftarrow \int_{0}^{s/4} \frac{\mathrm{d}\sigma}{\mathrm{d}p^2_{\perp}}\,\frac{p^4_{\perp}}{(p^2_{\perp 0}+p^2_{\perp})^2}\,\mathrm{d}p^2_{\perp}$$

Measure of colour screening length $d$ in hadron

$p_{\perp\mathrm{min}}\,\langle d\rangle \approx 1 (= \hbar)$



$\lambda \sim 1/p_\perp$



$$\langle d \rangle \sim \frac{r_\mathrm{p}}{\sqrt{N_\mathrm{partons}}} \qquad \text{no correlations}$$

$$\sim \frac{r_\mathrm{p}}{N_\mathrm{partons}} \qquad \text{with correlations?}$$

$$N_\mathrm{partons} \sim N_\mathrm{g} = \int_{\sim 4p_{\perp\mathrm{min}}^2/s}^{1} g(x, \sim p_{\perp\mathrm{min}}^2)\,\mathrm{d}x$$

Olden days:

$xg(x, Q_0^2) \to$ const. for $x \to 0$

$$\Rightarrow N_\mathrm{partons} \sim \ln \frac{s}{4p_{\perp\mathrm{min}}^2} \sim \text{const.}$$

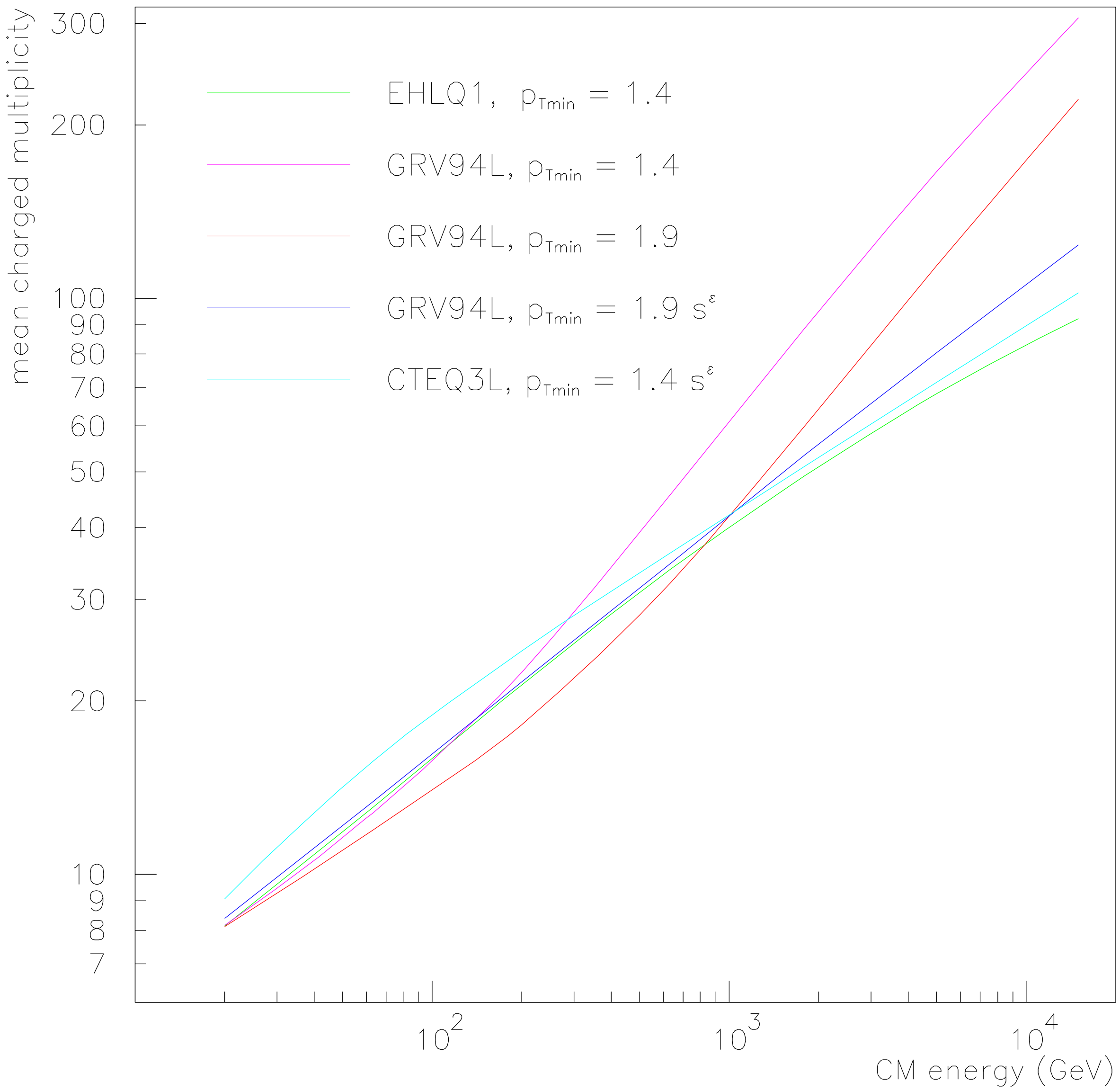
Post-HERA:

$xg(x, Q_0^2) \sim x^{-\epsilon}$ for $x \to 0$, $\epsilon \gtrsim 0.08$

$$\Rightarrow N_\mathrm{partons} \sim \left( \frac{s}{4p_{\perp\mathrm{min}}^2} \right)^{\epsilon}$$

$$\Rightarrow p_{\perp\mathrm{min}} \sim \frac{1}{\langle d \rangle} \sim N_\mathrm{partons} \sim s^{\epsilon}$$

Mean charged multiplicity in inelastic non-diffractive ‘minimum bias’:



‘New’ PYTHIA default:

$$p_{\perp\mathrm{min}} = (1.9\ \mathrm{GeV}) \left( \frac{s}{1\ \mathrm{TeV}^2} \right)^{0.08}$$

Importance:

charm (bottom) production at small $p_{\perp}$ should be dampened at large energies

# Summary

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

  of ∼ 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,
  but not perfect

- Several phenomenological parameters
  ⇒ large slop within framework
- . . . and also poorly understood aspects
  (multiple interactions, . . . )

- List of uncertainties in perturbative approach
  about as long