LUND UNIVERSITY

H1 Collaboration Meeting
Lund, 3 October 2002

Monte Carlos and NLO

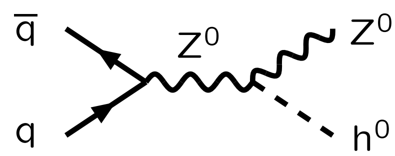
Torbjörn Sjöstrand

Apology: not specifically ep,
but photoproduction $\sim$ pp

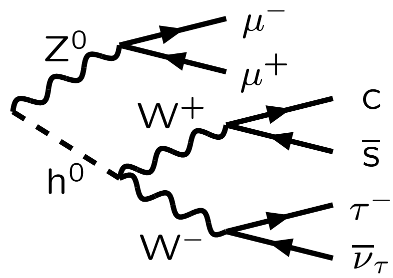
Event physics overview

Structure of the basic generation process:

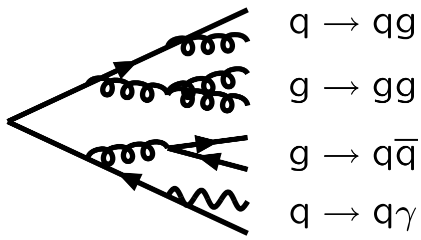
1) Hard subprocess:
$d\hat{\sigma}/d\hat{t}$, Breit-Wigners



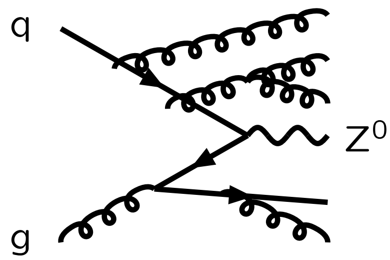
2) Resonance decays:
includes correlations
(where implemented)



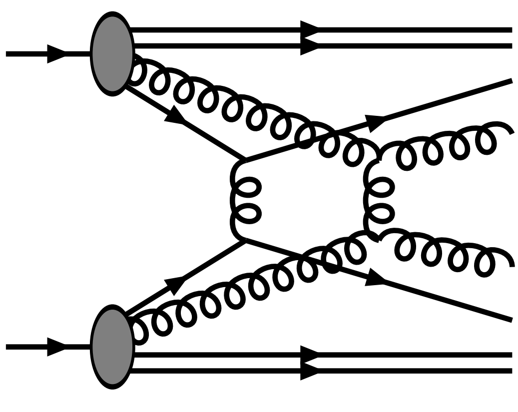
3) Final-state
parton showers:
(or matrix elements)



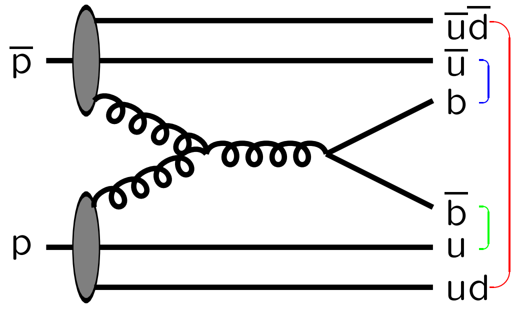
4) Initial-state
parton showers:
(or matrix elements)



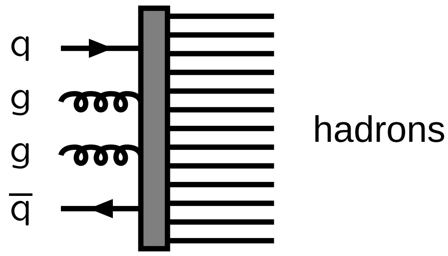
5) Multiple
parton–parton
interactions



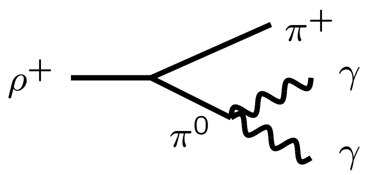
6) Beam remnants: colour-connected to rest of event



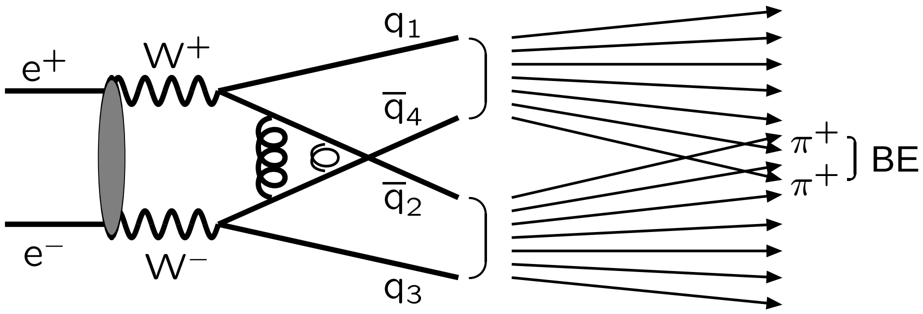
7) Hadronization (or fragmentation)



8) Normal decays: hadronic, τ, charm, . . .



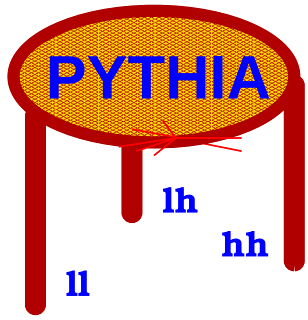
9) QCD interconnection effects:



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

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

PYTHIA Status



JETSET 7.4
PYTHIA 5.7
SPYTHIA

} —— 4 March 1997 : ——→ PYTHIA 6.1

Currently **PYTHIA 6.210**
of 25 September 2002
$\sim$ 58,900 lines Fortran 77

Code, manual, sample main programs, more:

`www.thep.lu.se/~torbjorn/Pythia.html`

short writeup in T. Sjöstrand, P. Edén, C. Friberg,
L. Lönnblad, G. Miu, S. Mrenna and E. Norrbin
Computer Phys. Commun. **135** (2001) 238
[hep-ph/0010017]

hep-ph/0108264
LU TP 01–21
(second edition)
April 2002

Pythia 6.2

Physics and Manual

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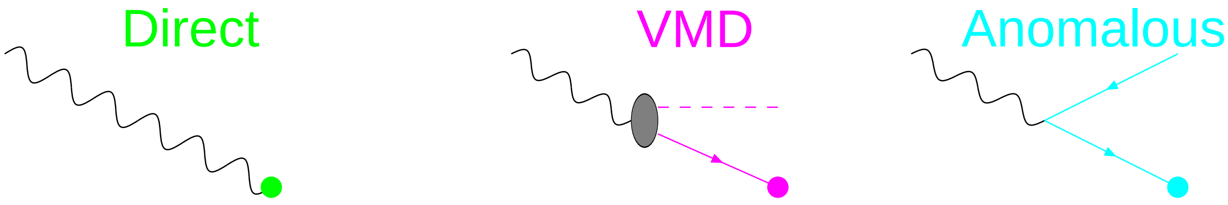
Subprocess summary

Processes	Examples
QCD & related	
Soft QCD	low-$p_\perp$; diffraction
Hard QCD	$\mathrm{qg} \to \mathrm{qg}$
Open heavy flavour	$\mathrm{q\overline{q}} \to \mathrm{t\overline{t}}$
Closed heavy flavour	$\mathrm{gg} \to \mathrm{gJ}/\psi$
$\gamma\gamma$ physics	$\gamma\mathrm{q} \to \mathrm{qg}$
DIS	$\gamma^*\mathrm{q} \to \mathrm{q}$
$\gamma^*\gamma^*$ physics	$\gamma^*_\mathrm{T}\gamma^*_\mathrm{L} \to \mathrm{q\overline{q}}$
Electroweak SM	
Single $\gamma^*/\mathrm{Z}^0/\mathrm{W}^\pm$	$\mathrm{q\overline{q}} \to \gamma^*/\mathrm{Z}^0$
$(\gamma/\gamma^*/\mathrm{Z}^0/\mathrm{W}^\pm/\mathrm{f}/\mathrm{g})^2$	$\mathrm{q\overline{q}} \to \mathrm{W}^+\mathrm{W}^-$
Light SM Higgs	$\mathrm{gg} \to \mathrm{h}^0$
Heavy SM Higgs	$\mathrm{Z}^0_\mathrm{L}\mathrm{Z}^0_\mathrm{L} \to \mathrm{W}^+_\mathrm{L}\mathrm{W}^-_\mathrm{L}$
SUSY BSM	
$\mathrm{h}^0/\mathrm{H}^0/\mathrm{A}^0/\mathrm{H}^\pm$	$\mathrm{q\overline{q}} \to \mathrm{h}^0\mathrm{A}^0$
SUSY	$\mathrm{q\overline{q}'} \to \tilde{\chi}^0_i\tilde{\chi}^\pm_j$
$\not{R}$SUSY	$\tilde{\chi}^0_i \to \mathrm{bcs} \Rightarrow$ **junctions!**
Other BSM	
Technicolor	$\mathrm{q\overline{q}'} \to \pi^0_\mathrm{tc}\pi^\pm_\mathrm{tc}$
New gauge bosons	$\mathrm{q\overline{q}} \to \gamma^*/\mathrm{Z}^0/\mathrm{Z}'^0$
Compositeness	$\mathrm{q\overline{q}} \to \mathrm{e}^\pm\mathrm{e}^{*\mp}$
Leptoquarks	$\mathrm{qg} \to \ell\mathrm{L_Q}$
$\mathrm{H}^{\pm\pm}$ (from LR-sym.)	$\mathrm{q\overline{q}} \to \mathrm{H}^{++}\mathrm{H}^{--}$
Extra dimensions	$\mathrm{gg} \to \mathrm{G}^* \to \mathrm{e}^+\mathrm{e}^-$

+ New User-Defined Process Machinery

Photoproduction

(G.A. Schuler & TS, NPB407 (1993) 539, ZPC73 (1997) 677)



Direct: point-like   Resolved: hadronic state

Spectrum of fluctuations $\gamma \leftrightarrow \mathrm{q\overline{q}} \propto \mathrm{d}k_\perp^2/k_\perp^2$

alt. $m \simeq 2k_\perp$; $\mathrm{d}m^2/m^2$

$\star$ $k_\perp < k_0 \simeq 0.5$ GeV: nonperturbative $\gamma \to \mathrm{q\overline{q}}$

hadronic physics $\Rightarrow$ VMD

(Vector Meson Dominance)

parameterized couplings to ρ^0, ω, ϕ, J/ψ

$\sigma_{\mathrm{tot}}^{\gamma\to\rho} = \mathcal{P}(\gamma \to \rho) \cdot \sigma_{\mathrm{tot}}^{\rho}$

PDF $f_i^{\gamma\to\rho}(x, \mu^2)$, $\sigma_{\mathrm{jet}}^{\gamma\to\rho} = \ldots$

beam remnants, multiple interactions, ...

$\star$ $k_\perp > k_0$: perturbative $\gamma \to \mathrm{q\overline{q}}$

PDF calculable: anomalous part of γ

but $\sigma_{\mathrm{tot}}^{\mathrm{q\overline{q}}}$ not $\Rightarrow$ GVMD   (Generalized VMD)

geometric scaling ansatz $\sigma_{\mathrm{tot}}^{\mathrm{q\overline{q}}} \propto k_V^2/k_\perp^2$,

$k_V \simeq m_\rho/2$ for light quarks

again hadronic character: beam remnants, ...

Deeply Inelastic Scattering

(aim: extend photoproduction to $Q^2 \sim m_\rho^2$)

(Ch. Friberg & TS, EPJC13 (2000) 151, JHEP09 (2000) 10)

Virtual photon: $\gamma^*\mathrm{q} \to \mathrm{q}$

$$\sigma_{\mathrm{tot}}^{\gamma^*\mathrm{p}} \simeq \frac{4\pi^2\alpha_{\mathrm{em}}}{Q^2} F_2(x, Q^2) \simeq \frac{4\pi^2\alpha_{\mathrm{em}}}{Q^2} \sum_{\mathrm{q},\overline{\mathrm{q}}} e_{\mathrm{q}}^2 \, xq(x, Q^2)$$

but $F_2 \to 0$ for $Q^2 \to 0$ by gauge invariance,
+ limit doublecounting with photoproduction

$$\sigma_{\mathrm{DIS}}^{\gamma^*\mathrm{p}} \simeq \left(\frac{Q^2}{Q^2 + m_\rho^2} \right)^2 \frac{4\pi^2\alpha_{\mathrm{em}}}{Q^2} \sum_{\mathrm{q},\overline{\mathrm{q}}} e_{\mathrm{q}}^2 \, xq(x, Q^2)$$

where $q(x, Q^2)$ frozen for $Q^2 < Q_0^2$;
and prefactor ensures $\sigma_{\mathrm{DIS}} \to 0$ for $Q^2 \to 0$

$$\mathcal{O}(\alpha_{\mathrm{s}}) \ \mathrm{DIS} = \left\{ \begin{array}{c} \mathrm{QCDC} \ \gamma^*\mathrm{q} \to \mathrm{qg} \\ \mathrm{BGF} \ \gamma^*\mathrm{g} \to \mathrm{q}\overline{\mathrm{q}} \end{array} \right\} = \mathrm{dir}$$

$$\sigma_{\mathrm{LO\ DIS}}^{\gamma^*\mathrm{p}} = \sigma_{\mathrm{DIS}}^{\gamma^*\mathrm{p}} - \sigma_{\mathrm{dir}}^{\gamma^*\mathrm{p}} \to \sigma_{\mathrm{DIS}}^{\gamma^*\mathrm{p}} \exp\left(- \frac{\sigma_{\mathrm{dir}}^{\gamma^*\mathrm{p}}}{\sigma_{\mathrm{DIS}}^{\gamma^*\mathrm{p}}} \right)$$

corresponds to Sudakov form factor

so 4 components: DIS + dir + VMD + GVMD

From Real to Virtual Photons

$$\sigma_{\mathrm{tot}}^{\gamma^* \mathrm{p}}(W^2, Q^2) = \sigma_{\mathrm{DIS}}^{\gamma^* \mathrm{p}} \exp\left(-\frac{\sigma_{\mathrm{dir}}^{\gamma^* \mathrm{p}}}{\sigma_{\mathrm{DIS}}^{\gamma^* \mathrm{p}}}\right) + \sigma_{\mathrm{dir}}^{\gamma^* \mathrm{p}} + \left(\frac{W^2}{Q^2+W^2}\right)^3 \left(\sigma_{\mathrm{VMD}}^{\gamma^* \mathrm{p}} + \sigma_{\mathrm{GVMD}}^{\gamma^* \mathrm{p}}\right)$$

Direct photon: Q^2 in ME expression

Resolved photon:

total cross section $\sigma_{\mathrm{tot}}^{\gamma \to i}$ dampened by dipole

$\left(\frac{m^2}{m^2 + Q^2}\right)^2$ (fewer fluctuations, smaller size)

VMD: $m = m_\rho, m_\omega, m_\phi, m_{\mathrm{J}/\psi}$

GVMD: $m \simeq 2k_\perp$; in total

$$\int_{k_0^2} \frac{\mathrm{d}k_\perp^2}{k_\perp^2} \frac{k_V^2}{k_\perp^2} \left(\frac{4k_\perp^2}{4k_\perp^2 + Q^2}\right)^2$$

$f_i^{\gamma_{\mathrm{T}}^*}(x, \mu^2, Q^2)$: SaS 1D (also dipole-based)

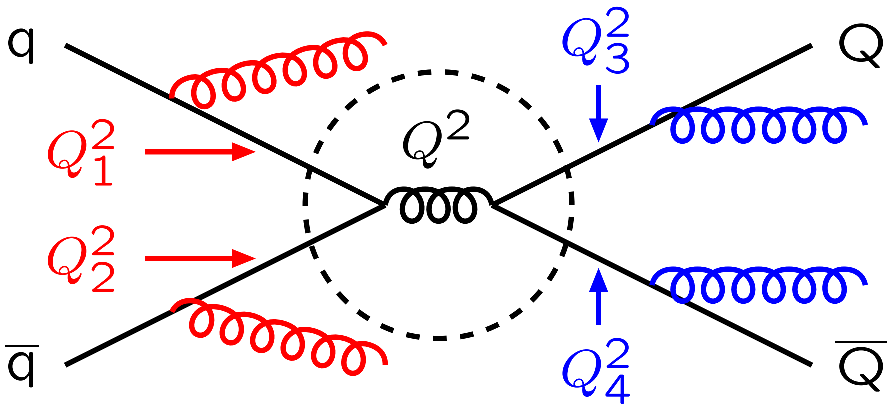
$f_i^{\gamma_{\mathrm{L}}^*}(x, \mu^2, Q^2)$: simple multiplicative factor
or Chýla (hep-ph/0006232)

$(1 - x)^3$ reduces doublecounting at large x

$\oplus$ virtual photon flux (T & L)

Parton Shower approach

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



$2 \to 2$ = hard scattering (on-shell)

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

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

ME vs. PS

ME : Matrix Elements

- \+ systematic expansion in α_s ('*exact*')
- \+ powerful for multiparton Born level
- \+ flexible phase space cuts
- – loop calculations very tough
- – negative cross section in collinear regions
  $\Rightarrow$ unpredictive jet/event structure
- – *no easy match to hadronization*

PS : Parton Showers

- – approximate, to LL (or NLL)
- – main topology not predetermined
  $\Rightarrow$ inefficient for exclusive states
- \+ process-generic $\Rightarrow$ simple multiparton
- \+ Sudakov form factors/resummation
  $\Rightarrow$ sensible jet/event structure
- \+ *easy to match to hadronization*

Marriage desirable! But how?

Problems:

- gaps in coverage?
- doublecounting of radiation?
- Sudakov?
- NLO consistency?

Merging

= smooth transition ME/PS, no sharp edge.
$+$ emissions can cover full phase space
$-$ coherence not straightforward

Want to reproduce

$$W^{\text{ME}} = \frac{1}{\sigma(\text{LO})} \frac{\text{d}\sigma(\text{LO}+\text{g})}{\text{d(phasespace)}}$$

by shower generation + correction procedure

$$\overbrace{W^{\text{ME}}}^{\text{wanted}} = \overbrace{W^{\text{PS}}}^{\text{generated}} \quad \frac{\overbrace{W^{\text{ME}}}^{\text{correction}}}{W^{\text{PS}}}$$

Comments:

• Do not normalize W^{ME} to $\sigma(\text{NLO})$, since extra work without clear gain (expect radiation also in events added by K-factor ≥ 1)

• Exponentiate ME correction by shower Sudakov form factor:

$$W^{\text{PS}}_{\text{actual}}(Q^2) =$$

$$W^{\text{ME}}(Q^2) \exp\left(- \int_{Q^2}^{Q^2_{\text{max}}} W^{\text{ME}}(Q'^2) \, \text{d}Q'^2 \right)$$

• Normally several shower histories
$\Rightarrow$ alternative approaches, largely equivalent

Final-state showers

Merging with $\gamma^*/\mathrm{Z}^0 \to \mathrm{q\overline{q}g}$ since long

(M. Bengtsson & TS, PLB185 (1987) 435, NPB289 (1987) 810)

. . . but problems with $\gamma^*/\mathrm{Z}^0 \to \mathrm{b\overline{b}g}$ noted:

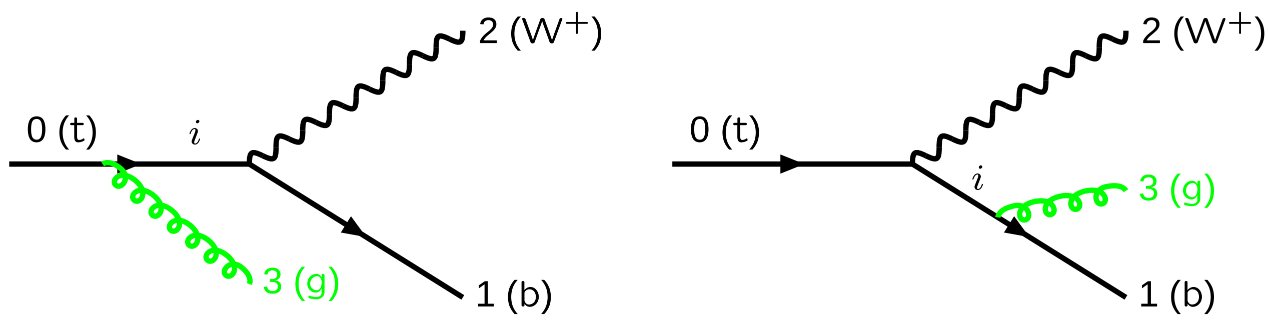
$Q_i^2 = m_i^2$ gives wrong singularity structure,

$Q_i^2 = m_i^2 - m_{i,\mathrm{onshell}}^2$ is relevant propagator!

$$W^{\mathrm{ME}} = \frac{(\ldots)}{Q_1^2 Q_2^2} - \frac{(\ldots)}{Q_1^4} - \frac{(\ldots)}{Q_2^4}$$

(also weight from splitting kernels in PS)

Coloured decaying particle also radiates:



ME $\frac{1}{Q_0^2 Q_1^2}$ matches PS $\mathrm{b} \to \mathrm{bg}$

$\Rightarrow$ can merge PS with generic $a \to bc\mathrm{g}$ ME

(E. Norrbin & TS, NPB603 (2001) 297)

Subsequent branchings $\mathrm{q} \to \mathrm{qg}$: also matched to ME, with reduced energy of system

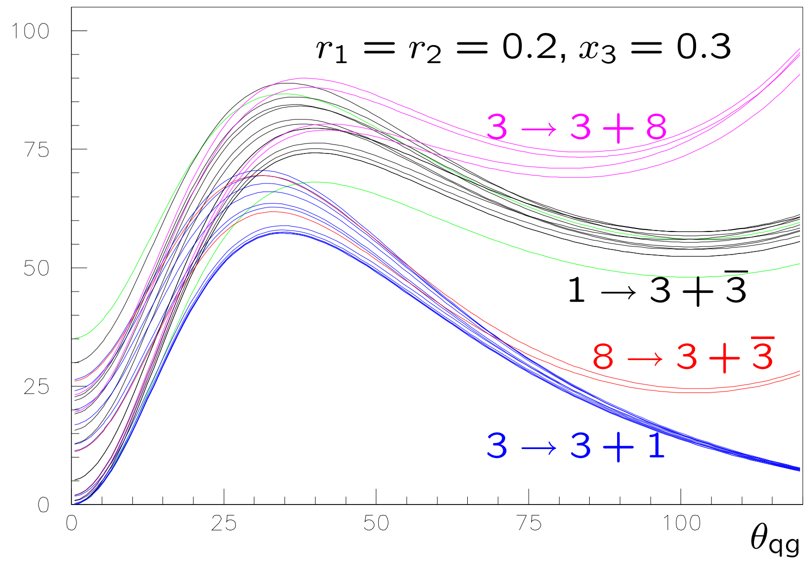
Calculate for $1 \rightarrow 2$ processes in SM + MSSM:

$$W^{\mathrm{ME}}(x_1, x_2) = \frac{1}{\sigma(a \rightarrow bc)} \frac{\mathrm{d}\sigma(a \rightarrow bcg)}{\mathrm{d}x_1\,\mathrm{d}x_2}$$

Depends on

- mass ratios $r_1 = m_b/m_a$ and $r_2 = m_c/m_a$
- colour and spin structure
- vector vs. axial vector etc. (γ_5)

colour	spin	γ_5	example
$1 \rightarrow 3 + \overline{3}$	—	—	(eikonal)
$1 \rightarrow 3 + \overline{3}$	$1 \rightarrow \frac{1}{2} + \frac{1}{2}$	$1, \gamma_5, 1 \pm \gamma_5$	$Z^0 \rightarrow q\overline{q}$
$3 \rightarrow 3 + 1$	$\frac{1}{2} \rightarrow \frac{1}{2} + 1$	$1, \gamma_5, 1 \pm \gamma_5$	$t \rightarrow bW^+$
$1 \rightarrow 3 + \overline{3}$	$0 \rightarrow \frac{1}{2} + \frac{1}{2}$	$1, \gamma_5, 1 \pm \gamma_5$	$H^0 \rightarrow q\overline{q}$
$3 \rightarrow 3 + 1$	$\frac{1}{2} \rightarrow \frac{1}{2} + 0$	$1, \gamma_5, 1 \pm \gamma_5$	$t \rightarrow bH^+$
$1 \rightarrow 3 + \overline{3}$	$1 \rightarrow 0 + 0$	1	$Z^0 \rightarrow \tilde{q}\overline{\tilde{q}}$
$3 \rightarrow 3 + 1$	$0 \rightarrow 0 + 1$	1	$\tilde{q} \rightarrow \tilde{q}'W^+$
$1 \rightarrow 3 + \overline{3}$	$0 \rightarrow 0 + 0$	1	$H^0 \rightarrow \tilde{q}\overline{\tilde{q}}$
$3 \rightarrow 3 + 1$	$0 \rightarrow 0 + 0$	1	$\tilde{q} \rightarrow \tilde{q}'H^+$
$1 \rightarrow 3 + \overline{3}$	$\frac{1}{2} \rightarrow \frac{1}{2} + 0$	$1, \gamma_5, 1 \pm \gamma_5$	$\chi \rightarrow q\overline{\tilde{q}}$
$3 \rightarrow 3 + 1$	$0 \rightarrow \frac{1}{2} + \frac{1}{2}$	$1, \gamma_5, 1 \pm \gamma_5$	$\tilde{q} \rightarrow q\chi$
$3 \rightarrow 3 + 1$	$\frac{1}{2} \rightarrow 0 + \frac{1}{2}$	$1, \gamma_5, 1 \pm \gamma_5$	$t \rightarrow \tilde{t}\chi$
$8 \rightarrow 3 + \overline{3}$	$\frac{1}{2} \rightarrow \frac{1}{2} + 0$	$1, \gamma_5, 1 \pm \gamma_5$	$\tilde{g} \rightarrow q\overline{\tilde{q}}$
$3 \rightarrow 3 + 8$	$0 \rightarrow \frac{1}{2} + \frac{1}{2}$	$1, \gamma_5, 1 \pm \gamma_5$	$\tilde{q} \rightarrow q\tilde{g}$
$3 \rightarrow 3 + 8$	$\frac{1}{2} \rightarrow 0 + \frac{1}{2}$	$1, \gamma_5, 1 \pm \gamma_5$	$t \rightarrow \tilde{t}\tilde{g}$



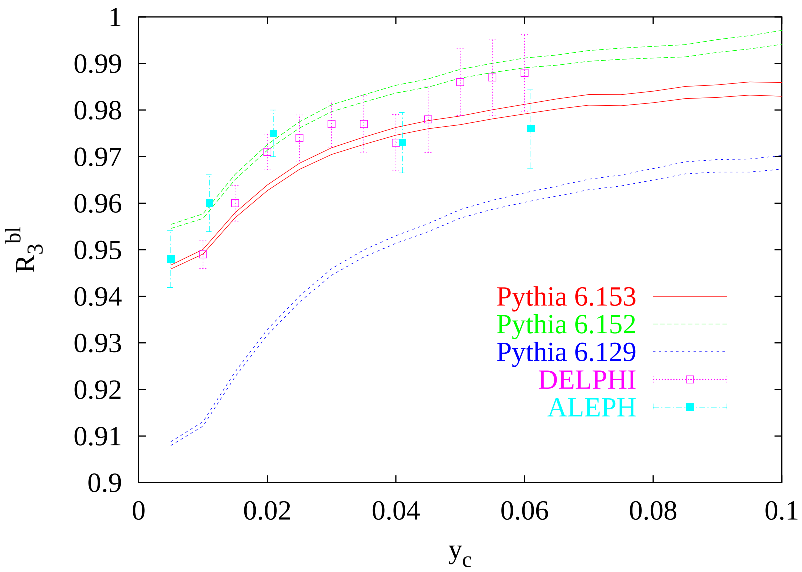
$W^{\mathrm{ME}}(x_1, x_2)$

g emission rate

for different

colour, spin and

parity structures



$R_3^{\mathrm{bl}}(y_c)$

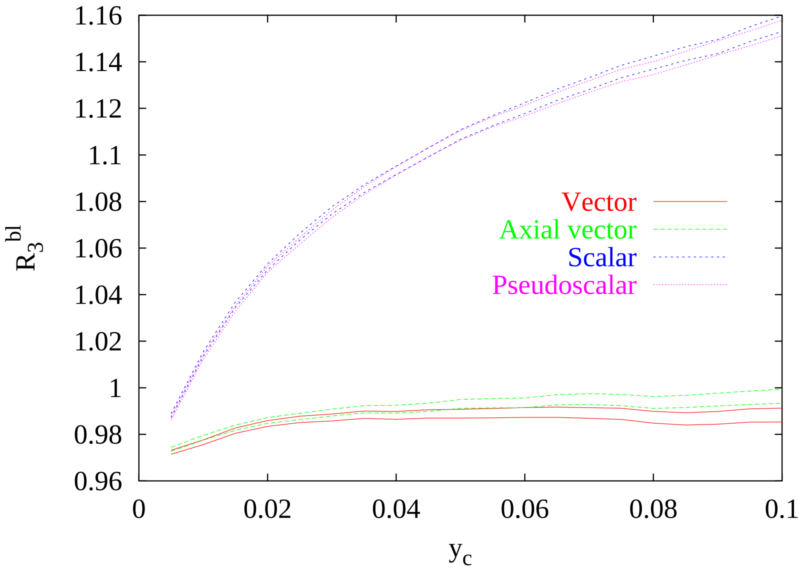
$E_{\mathrm{CM}} = 91$ GeV

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

ratio of 3-jets

in b and uds (=l)

events



$R_3^{\mathrm{bl}}(y_c)$

$E_{\mathrm{CM}} = m_{\mathrm{h/H/A}}$

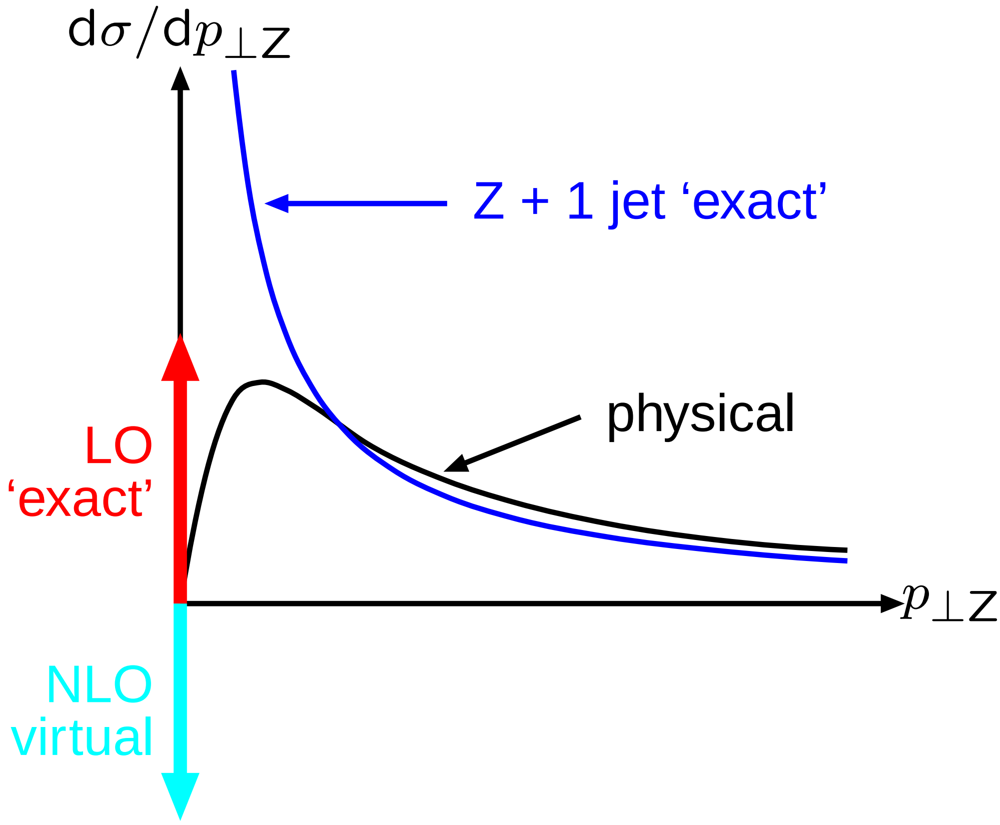
$= 120$ GeV

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

reference light q

from γ^*/Z^*

Initial-state showers



resummation: physical $p_{\perp Z}$ spectrum

shower: ditto + accompanying jets (exclusive)

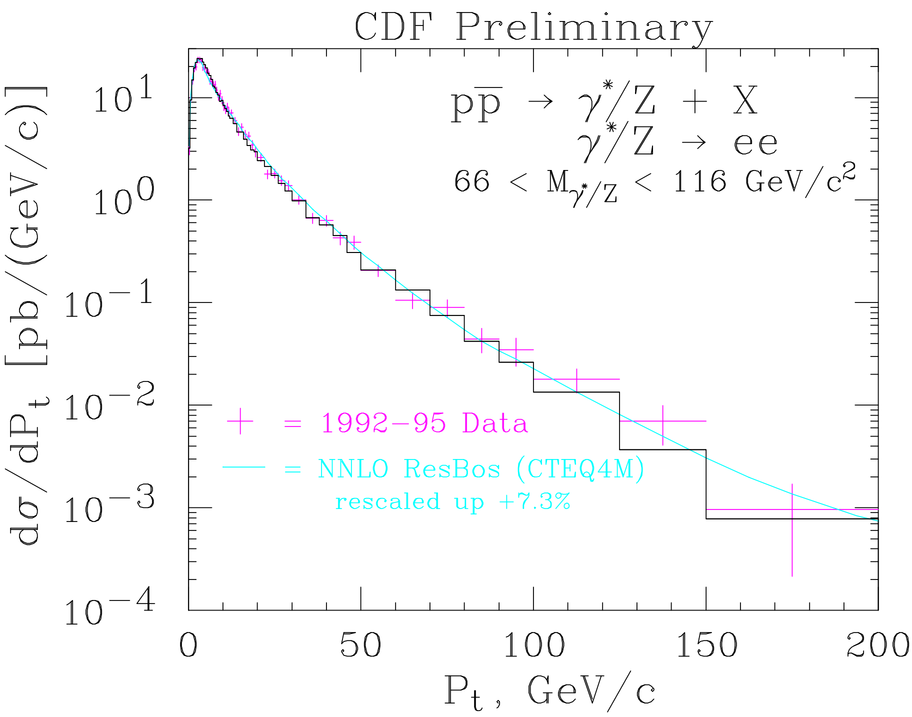
Merged with matrix elements for

$q\overline{q} \to (\gamma^*/Z^0/W^\pm)g$ and $qg \to (\gamma^*/Z^0/W^\pm)q'$:

(G. Miu & TS, PLB449 (1999) 313)

$$\left(\frac{W^{ME}}{W^{PS}}\right)_{q\overline{q}'\to gW} = \frac{\hat{t}^2 + \hat{u}^2 + 2m_W^2\hat{s}}{\hat{s}^2 + m_W^4} \leq 1$$

$$\left(\frac{W^{ME}}{W^{PS}}\right)_{qg\to q'W} = \frac{\hat{s}^2 + \hat{u}^2 + 2m_W^2\hat{t}}{(\hat{s} - m_W^2)^2 + m_W^4} < 3$$



curve=ResBos

black=PYTHIA

$K_{\text{PYTHIA}} = 1.4$

$Q^2_{\text{max}} = s$

C. Balázs, J. Huston and I. Puljak, PRD63 (2001) 014021

Problem: requires large primordial $k_\perp \approx 2$ GeV
$\Rightarrow$ need BFKL/CCFM non-ordered evolution ?

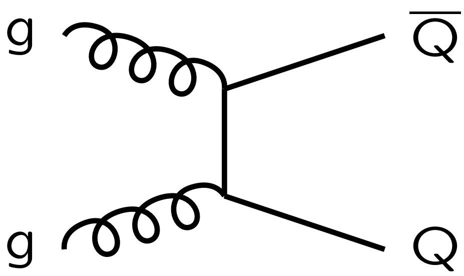
Modified algorithm also affects other processes
- prefer $Q^2_{\text{max}} = s$ where no doublecounting
  $\Rightarrow$ more radiation at large $p_\perp$
- require $\hat{u} = Q^2 - \hat{s}(1-z) < 0$ in branchings
  $\Rightarrow$ fewer but harder emissions

Similarly for Higgs production in $m_t \rightarrow \infty$ limit:
- gg $\rightarrow$ gh^0 and qg $\rightarrow$ qh^0 simple
- q$\bar{\text{q}}$ $\rightarrow$ gh^0 nonsingular & small $\Rightarrow$ add

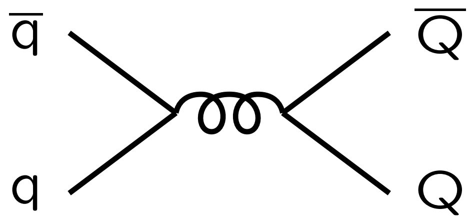
Challenges:
- gauge boson pairs (S. Burby)
- QCD 2 $\rightarrow$ 2 with ISR+FSR+interference

Production graphs

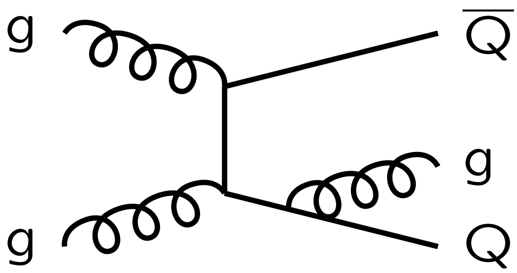
Examples of Q = c/b production diagrams, *not* exhaustive:



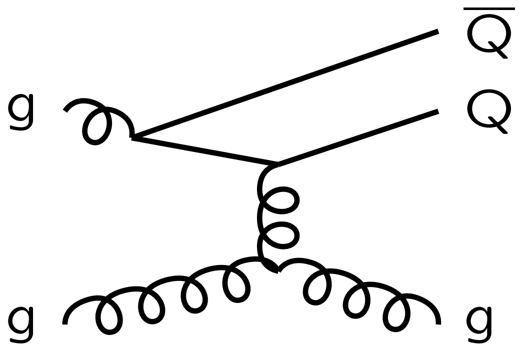
Leading order



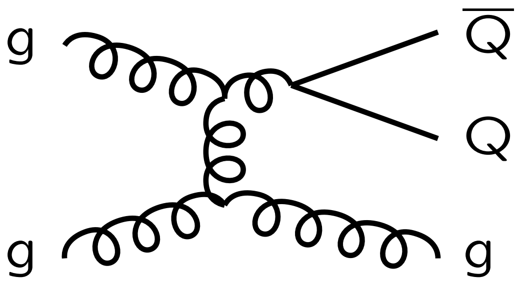
Leading order



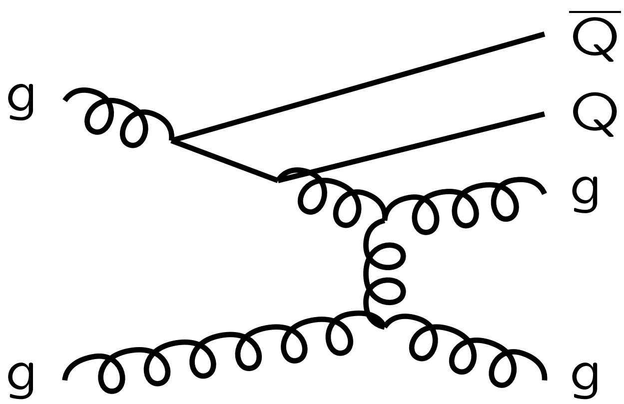
Pair creation
(with gluon emission)



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 $\mathrm{gg} \to \mathrm{Q}\overline{\mathrm{Q}}$

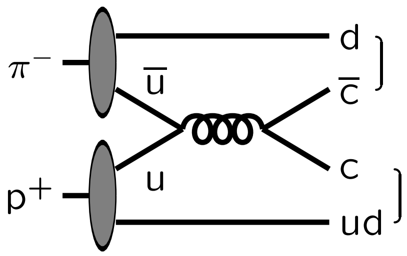
3) gluon splitting:
ordinary $2 \to 2$ processes, e.g. $\mathrm{gg} \to \mathrm{gg}$
+ $\mathrm{g} \to \mathrm{Q}\overline{\mathrm{Q}}$ branching with threshold
$\sqrt{1 - 4m_{\mathrm{Q}}^2/m_{\mathrm{g}}^2}\,(1 + 2m_{\mathrm{Q}}^2/m_{\mathrm{g}}^2)$
$\approx s$-channel graphs of $\mathrm{gg}, \mathrm{q}\overline{\mathrm{q}}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

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

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.



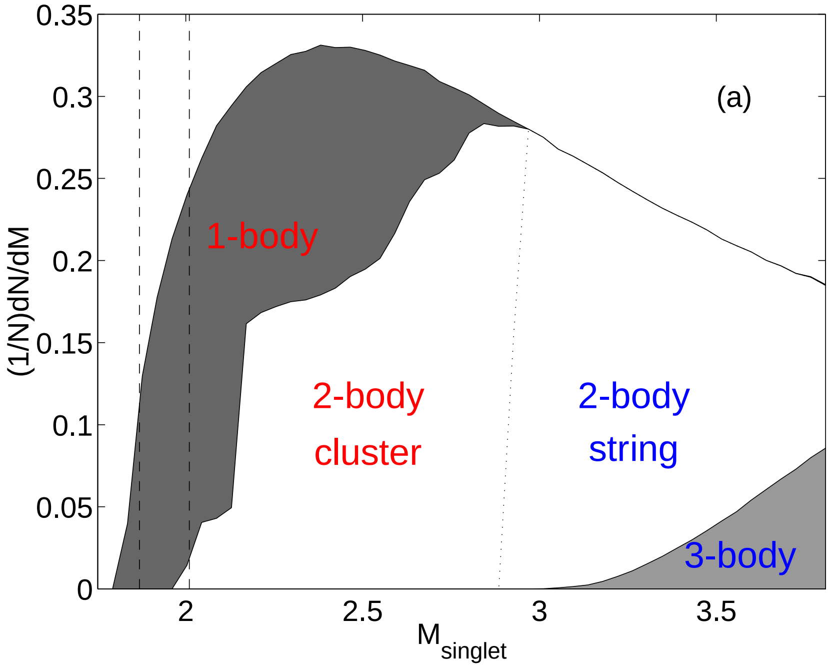
If collapse:
$\bar{c}d$: D^-, D^{*-}, ...
cud: Λ_c^+, Σ_c^+, Σ_c^{*+}, ...
$\Rightarrow$ flavour asymmetries

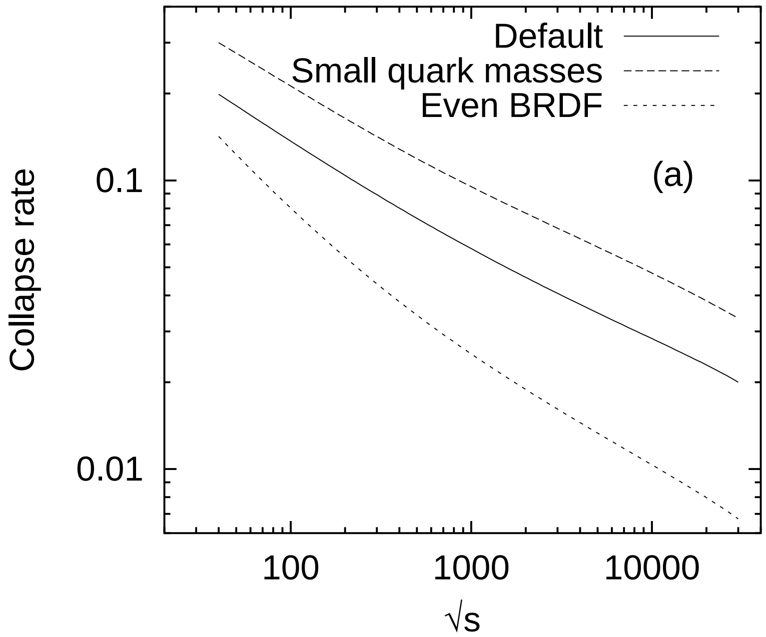
Can give D "drag" to larger x_F than c quark.

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:
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:

$\bar{\mathrm{c}} \longleftarrow\!\!\longrightarrow \mathrm{d} \qquad \longrightarrow z$

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

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

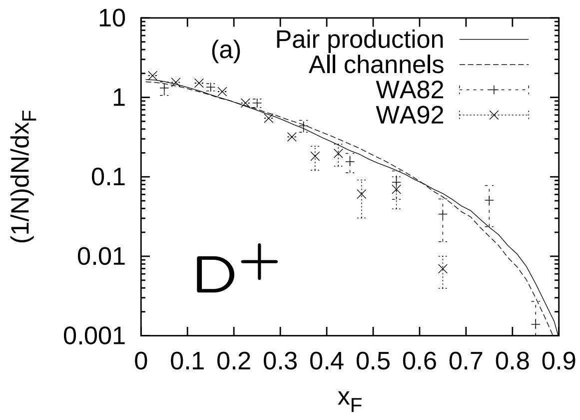
$$\Rightarrow p_{+\mathrm{D}} = \frac{m_{\perp\mathrm{D}}^2}{p_{-\mathrm{D}}} = \frac{m_{\perp\mathrm{D}}^2}{z p_{-\mathrm{c}}} \overset{\text{normally}}{>} \frac{m_{\perp\mathrm{c}}^2}{z p_{-\mathrm{c}}} = \frac{p_{+\mathrm{c}}}{z}$$

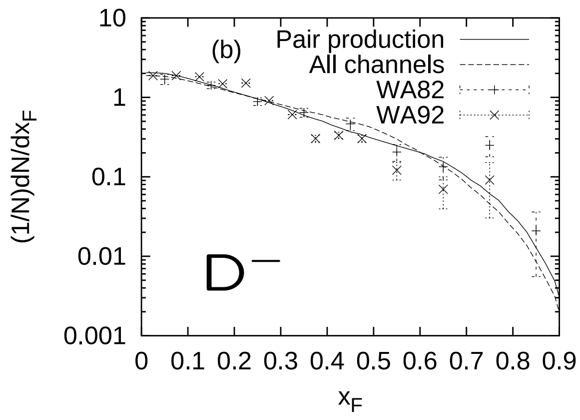
i.e. again drag.

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

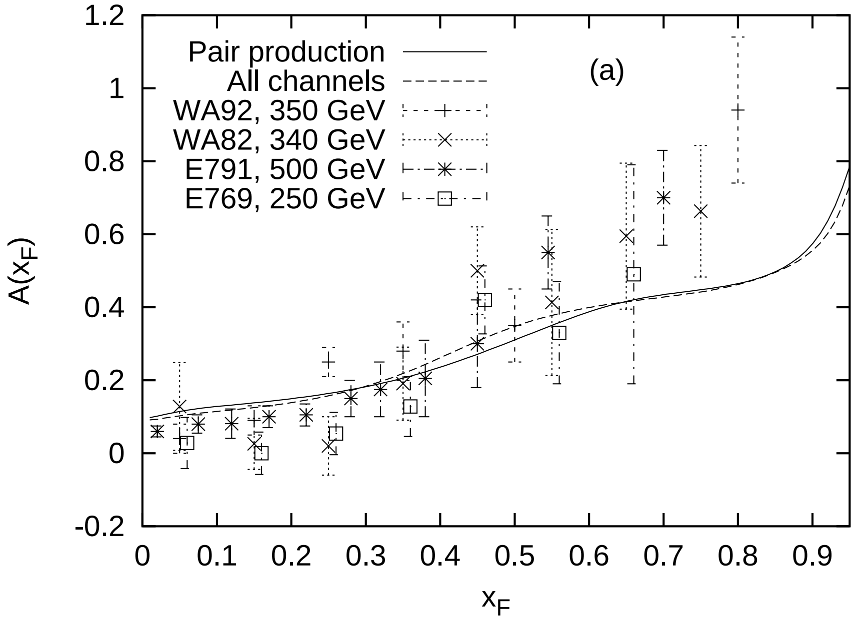


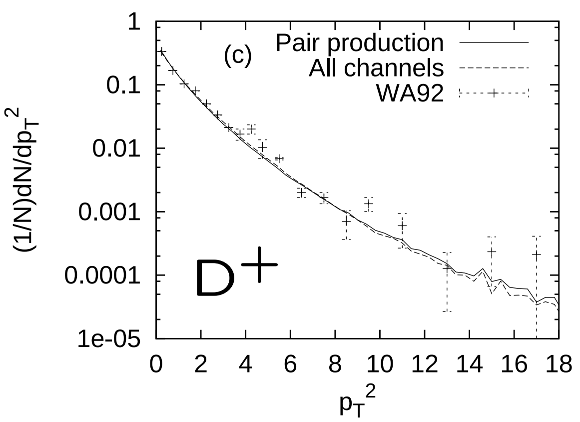


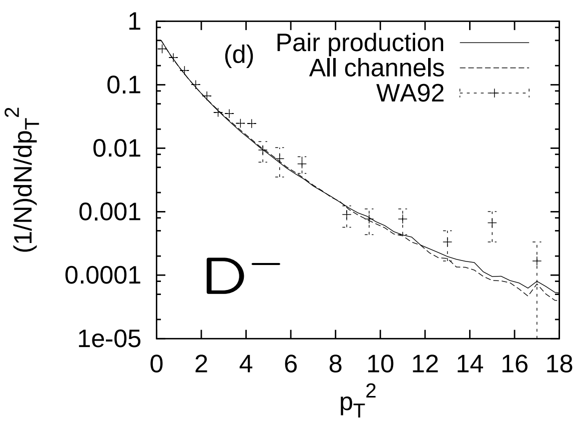
$A(x_F) =$

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

in $\pi^- p$



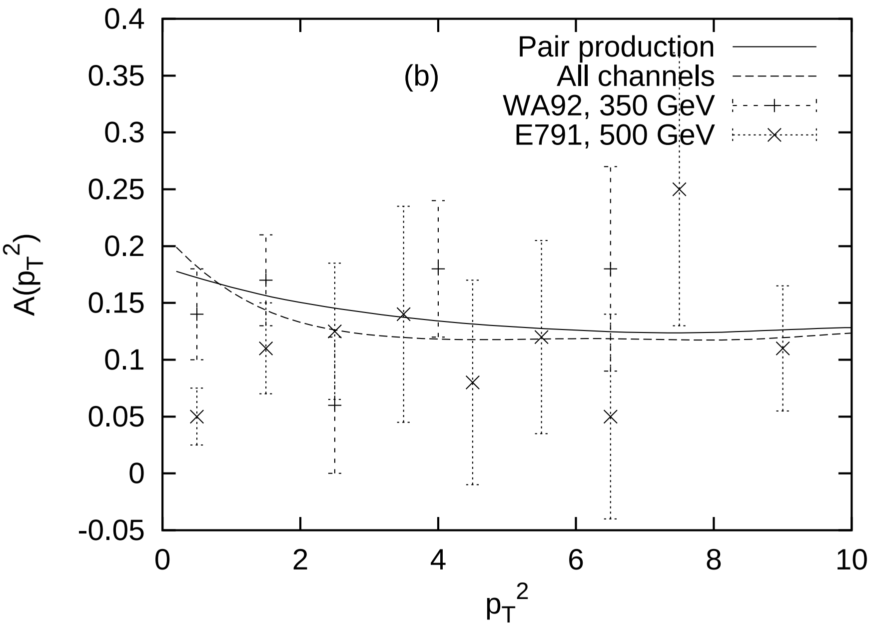


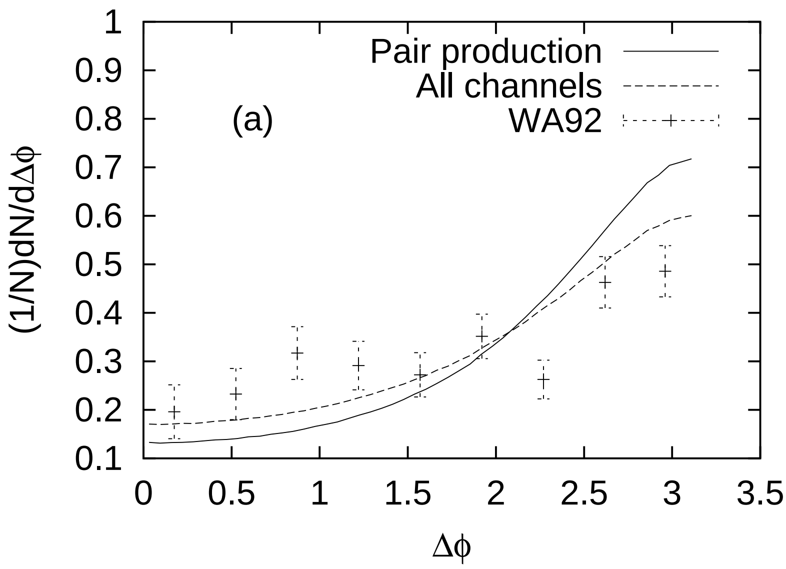


$A(p_\perp) =$

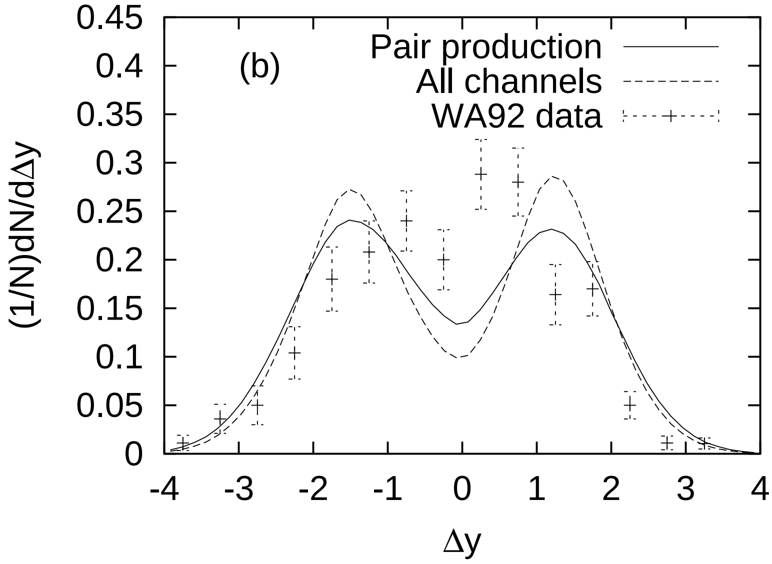
$$\frac{\#D^- - \#D^+}{\#D^- + \#D^+}$$

in $\pi^- p$





ϕ correlations improved . . .



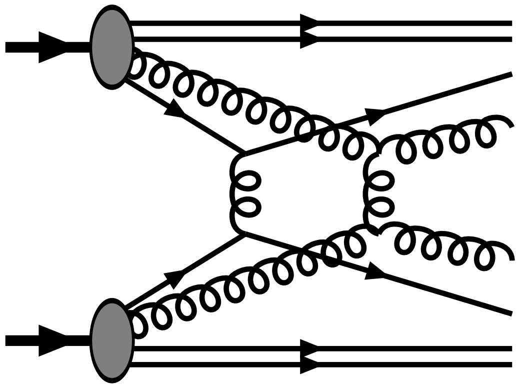
. . . but y correlations worsened

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

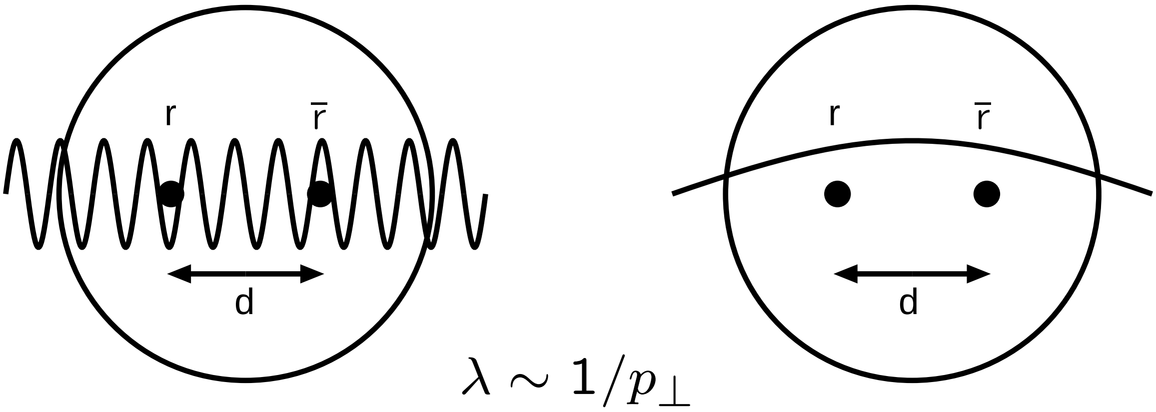
One new free parameter: $p_{\perp\mathrm{min}}$

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

$$\Leftarrow \int_0^{s/4} \frac{\mathrm{d}\sigma}{\mathrm{d}p^2_\perp}\,\frac{p^4_\perp}{(p^2_{\perp 0}+p^2_\perp)^2}\,\mathrm{d}p^2_\perp$$

Measure of colour screening length d in hadron

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



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

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

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

Olden days:

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

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

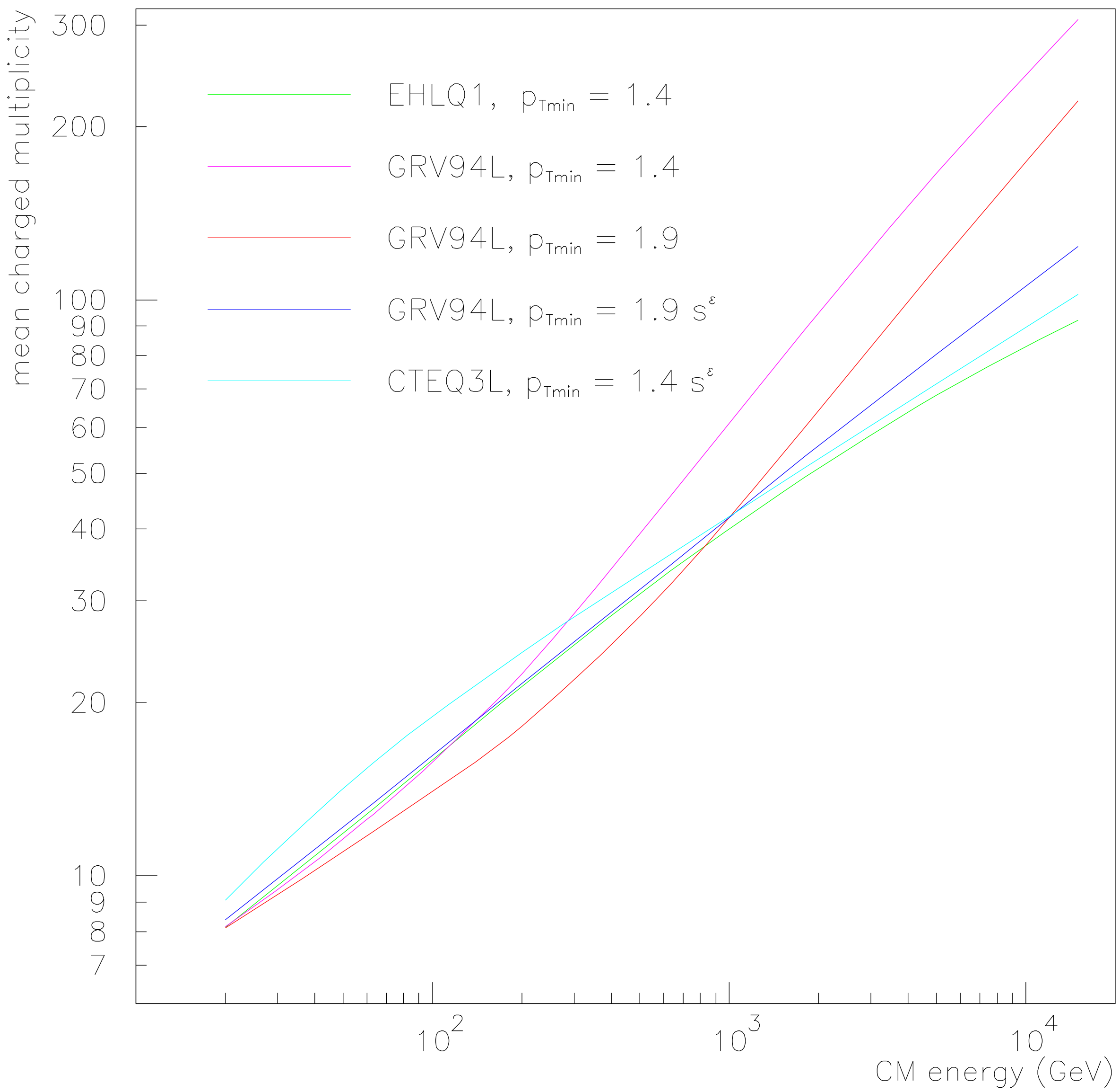
Post-HERA:

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

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

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

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:

- comparison of data at 630 GeV & 1.8 TeV
- extrapolations to LHC

Summary

- PYTHIA evolving – do not use old versions!
- Test photoproduction/DIS transition region.

- Many ongoing efforts to improve showers.
  Objective not NLO but good description.
  Merging: "NLO ME" $\Rightarrow$ shower smoothly;
  applicable to ISR and FSR alike.

- Heavy flavour production/hadronization
  understood in pp?
  Perturbative by non-overlapping
  LO + flavour excitation + gluon splitting.
  Combined with string hadronization;
  small string = cluster, with special treatment

- Multiple interactions getting to be orthodoxy!
  CDF: min bias & underlying event agree.
  Varying impact parameter $\Rightarrow$ "hot spots".