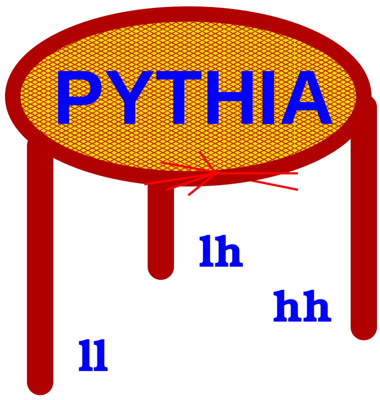
LUND UNIVERSITY

Workshop on
Monte Carlo Generator Physics
for Run II at the Tevatron,
Fermilab, April 18-20, 2001

PYTHIA
Status Report

Torbjörn Sjöstrand



JETSET 7.4
PYTHIA 5.7
SPYTHIA

} 4 March 1997 : → PYTHIA 6.1

Currently PYTHIA 6.158 of 5 April 2001
$\sim 53,100$ lines Fortran 77

Code, manuals, sample main programs:

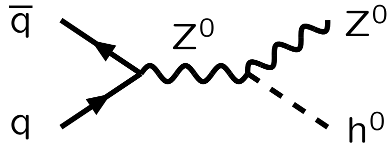
`www.thep.lu.se/~torbjorn/Pythia.html`

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]

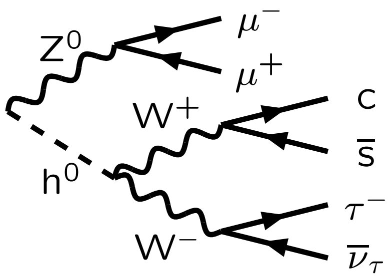
Event physics overview

Structure of the basic generation process:

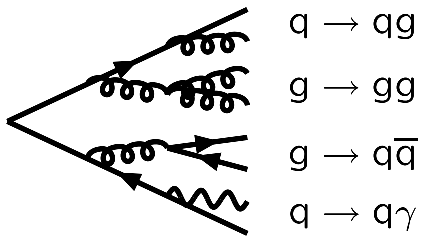
1) Hard subprocess:
$\mathrm{d}\hat{\sigma}/\mathrm{d}\hat{t}$, Breit-Wigners.



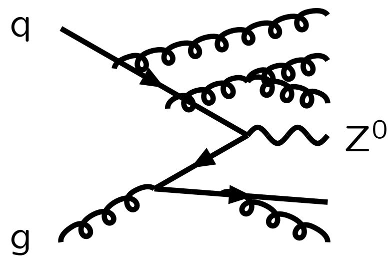
2) Resonance decays:
includes correlations.



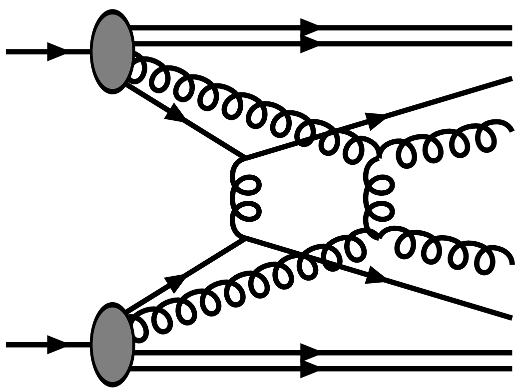
3) Final-state
parton showers:
(or matrix elements).



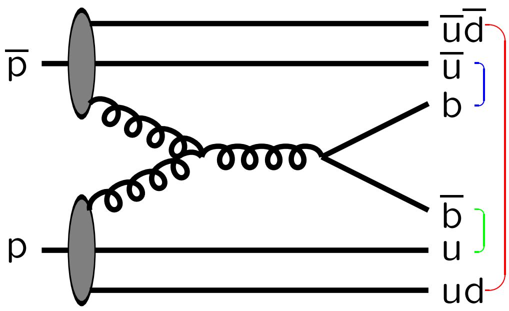
4) Initial-state
parton showers:
(or matrix elements).



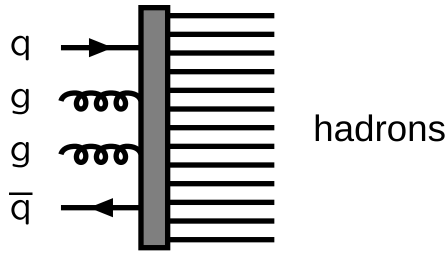
5) Multiple
parton–parton
interactions.



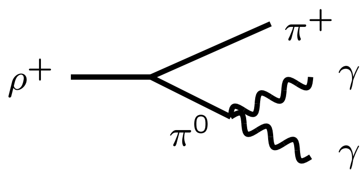
6) Beam remnants:
colour-connected
to rest of event



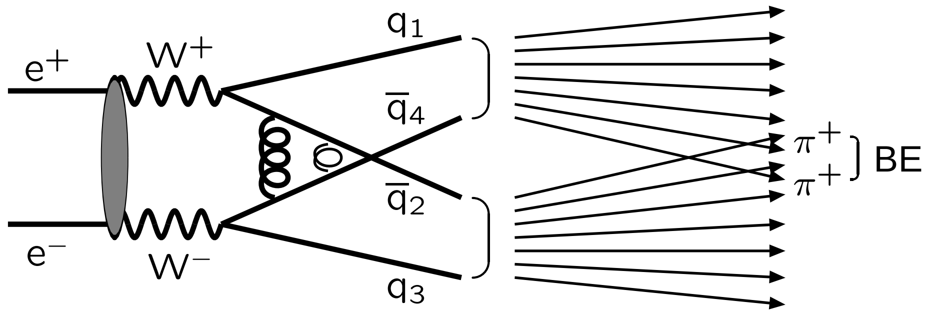
7) Hadronization



8) Normal decays:
hadronic, 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!

Subprocesses

No.	Subprocess
Hard QCD processes:	
11	$f_i f_j \to f_i f_j$
12	$f_i \bar{f}_i \to f_k \bar{f}_k$
13	$f_i \bar{f}_i \to gg$
28	$f_i g \to f_i g$
53	$gg \to f_k \bar{f}_k$
68	$gg \to gg$
Soft QCD processes:	
91	elastic scattering
92	single diffraction (XB)
93	single diffraction (AX)
94	double diffraction
95	low-$p_\perp$ production
Open heavy flavour: (also fourth generation)	
81	$f_i \bar{f}_i \to Q_k \bar{Q}_k$
82	$gg \to Q_k \bar{Q}_k$
83	$q_i f_j \to Q_k f_l$
84	$g\gamma \to Q_k \bar{Q}_k$
85	$\gamma\gamma \to F_k \bar{F}_k$
Closed heavy flavour:	
86	$gg \to J/\psi g$
87	$gg \to \chi_{0c} g$
88	$gg \to \chi_{1c} g$
89	$gg \to \chi_{2c} g$
104	$gg \to \chi_{0c}$
105	$gg \to \chi_{2c}$
106	$gg \to J/\psi \gamma$
107	$g\gamma \to J/\psi g$
108	$\gamma\gamma \to J/\psi \gamma$
W/Z production:	
1	$f_i \bar{f}_i \to \gamma^*/Z^0$
2	$f_i \bar{f}_j \to W^\pm$
22	$f_i \bar{f}_i \to Z^0 Z^0$
23	$f_i \bar{f}_j \to Z^0 W^\pm$
25	$f_i \bar{f}_i \to W^+ W^-$
15	$f_i \bar{f}_i \to g Z^0$
16	$f_i \bar{f}_j \to g W^\pm$
30	$f_i g \to f_i Z^0$
31	$f_i g \to f_k W^\pm$
19	$f_i \bar{f}_i \to \gamma Z^0$
20	$f_i \bar{f}_j \to \gamma W^\pm$
35	$f_i \gamma \to f_i Z^0$
36	$f_i \gamma \to f_k W^\pm$
69	$\gamma\gamma \to W^+ W^-$
70	$\gamma W^\pm \to Z^0 W^\pm$
Prompt photons:	
14	$f_i \bar{f}_i \to g\gamma$
18	$f_i \bar{f}_i \to \gamma\gamma$
29	$f_i g \to f_i \gamma$
114	$gg \to \gamma\gamma$
115	$gg \to g\gamma$
Deep inelastic scatt.:	
10	$f_i f_j \to f_i f_j$
99	$\gamma^* f_i \to f_i$
Photon-induced:	
33	$f_i \gamma \to f_i g$
34	$f_i \gamma \to f_i \gamma$
54	$g\gamma \to f_k \bar{f}_k$
58	$\gamma\gamma \to f_k \bar{f}_k$
131	$f_i \gamma^*_T \to f_i g$
132	$f_i \gamma^*_L \to f_i g$
133	$f_i \gamma^*_T \to f_i \gamma$
134	$f_i \gamma^*_L \to f_i \gamma$
135	$g\gamma^*_T \to f_i \bar{f}_i$
136	$g\gamma^*_L \to f_i \bar{f}_i$
137	$\gamma^*_T \gamma^*_T \to f_i \bar{f}_i$
138	$\gamma^*_T \gamma^*_L \to f_i \bar{f}_i$

No.	Subprocess
139	$\gamma^*_L \gamma^*_T \to f_i \bar{f}_i$
140	$\gamma^*_L \gamma^*_L \to f_i \bar{f}_i$
80	$q_i \gamma \to q_k \pi^\pm$
Light SM Higgs:	
3	$f_i \bar{f}_i \to h^0$
24	$f_i \bar{f}_i \to Z^0 h^0$
26	$f_i \bar{f}_j \to W^\pm h^0$
102	$gg \to h^0$
103	$\gamma\gamma \to h^0$
110	$f_i \bar{f}_i \to \gamma h^0$
121	$gg \to Q_k \bar{Q}_k h^0$
122	$q_i \bar{q}_i \to Q_k \bar{Q}_k h^0$
123	$f_i f_j \to f_i f_j h^0$
124	$f_i f_j \to f_k f_l h^0$
Heavy SM Higgs:	
5	$Z^0 Z^0 \to h^0$
8	$W^+ W^- \to h^0$
71	$Z^0_L Z^0_L \to Z^0_L Z^0_L$
72	$Z^0_L Z^0_L \to W^+_L W^-_L$
73	$Z^0_L W^\pm_L \to Z^0_L W^\pm_L$
76	$W^+_L W^-_L \to Z^0_L Z^0_L$
77	$W^\pm_L W^\pm_L \to W^\pm_L W^\pm_L$
BSM Neutral Higgses:	
151	$f_i \bar{f}_i \to H^0$
152	$gg \to H^0$
153	$\gamma\gamma \to H^0$
171	$f_i \bar{f}_i \to Z^0 H^0$
172	$f_i \bar{f}_j \to W^\pm H^0$
173	$f_i f_j \to f_i f_j H^0$
174	$f_i f_j \to f_k f_l H^0$
181	$gg \to Q_k \bar{Q}_k H^0$
182	$q_i \bar{q}_i \to Q_k \bar{Q}_k H^0$
156	$f_i \bar{f}_i \to A^0$
157	$gg \to A^0$
158	$\gamma\gamma \to A^0$
176	$f_i \bar{f}_i \to Z^0 A^0$
177	$f_i \bar{f}_j \to W^\pm A^0$
178	$f_i f_j \to f_i f_j A^0$
179	$f_i f_j \to f_k f_l A^0$
186	$gg \to Q_k \bar{Q}_k A^0$
187	$q_i \bar{q}_i \to Q_k \bar{Q}_k A^0$
Charged Higgs:	
143	$f_i \bar{f}_j \to H^+$
161	$f_i g \to f_k H^+$
Higgs pairs:	
297	$f_i \bar{f}_j \to H^\pm h^0$
298	$f_i \bar{f}_j \to H^\pm H^0$
299	$f_i \bar{f}_i \to A^0 h^0$
300	$f_i \bar{f}_i \to A^0 H^0$
301	$f_i \bar{f}_i \to H^+ H^-$
Doubly-charged Higgs:	
341	$\ell_i \ell_j \to H^{\pm\pm}_L$
342	$\ell_i \ell_j \to H^{\pm\pm}_R$
343	$\ell^\pm_i \gamma \to H^{\pm\pm}_L e^\mp$
344	$\ell^\pm_i \gamma \to H^{\pm\pm}_R e^\mp$
345	$\ell^\pm_i \gamma \to H^{\pm\pm}_L \mu^\mp$
346	$\ell^\pm_i \gamma \to H^{\pm\pm}_R \mu^\mp$
347	$\ell^\pm_i \gamma \to H^{\pm\pm}_L \tau^\mp$
348	$\ell^\pm_i \gamma \to H^{\pm\pm}_R \tau^\mp$
349	$f_i \bar{f}_i \to H^{++}_L H^{--}_L$
350	$f_i \bar{f}_i \to H^{++}_R H^{--}_R$
351	$f_i f_j \to f_k f_l H^{\pm\pm}_L$
352	$f_i f_j \to f_k f_l H^{\pm\pm}_R$
New gauge bosons:	
141	$f_i \bar{f}_i \to \gamma/Z^0/Z'^0$
142	$f_i \bar{f}_j \to W'^+$
144	$f_i \bar{f}_j \to R$

No.	Subprocess
Technicolor:	
149	$gg \to \eta_{tc}$
191	$f_i \bar{f}_i \to \rho^0_{tc}$
192	$f_i \bar{f}_j \to \rho^+_{tc}$
193	$f_i \bar{f}_i \to \omega^0_{tc}$
194	$f_i \bar{f}_i \to f_k \bar{f}_k$
195	$f_i \bar{f}_j \to f_k \bar{f}_l$
361	$f_i \bar{f}_i \to W^+_L W^-_L$
362	$f_i \bar{f}_i \to W^\pm_L \pi^\mp_{tc}$
363	$f_i \bar{f}_i \to \pi^+_{tc} \pi^-_{tc}$
364	$f_i \bar{f}_i \to \gamma \pi^0_{tc}$
365	$f_i \bar{f}_i \to \gamma \pi'^0_{tc}$
366	$f_i \bar{f}_i \to Z^0 \pi^0_{tc}$
367	$f_i \bar{f}_i \to Z^0 \pi'^0_{tc}$
368	$f_i \bar{f}_i \to W^\pm \pi^\mp_{tc}$
370	$f_i \bar{f}_j \to W^\pm_L Z^0_L$
371	$f_i \bar{f}_j \to W^\pm_L \pi^0_{tc}$
372	$f_i \bar{f}_j \to \pi^\pm_{tc} Z^0_L$
373	$f_i \bar{f}_j \to \pi^\pm_{tc} \pi^0_{tc}$
374	$f_i \bar{f}_j \to \gamma \pi^\pm_{tc}$
375	$f_i \bar{f}_j \to Z^0 \pi^\pm_{tc}$
376	$f_i \bar{f}_j \to W^\pm \pi^0_{tc}$
377	$f_i \bar{f}_j \to W^\pm \pi'^0_{tc}$
Compositeness:	
146	$e\gamma \to e^*$
147	$dg \to d^*$
148	$ug \to u^*$
167	$q_i q_j \to d^* q_k$
168	$q_i q_j \to u^* q_k$
169	$q_i \bar{q}_i \to e^\pm e^{*\mp}$
165	$f_i \bar{f}_i (\to \gamma^*/Z^0) \to f_k \bar{f}_k$
166	$f_i \bar{f}_j (\to W^\pm) \to f_k \bar{f}_l$
Leptoquarks:	
145	$q_i \ell_j \to L_Q$
162	$qg \to \ell L_Q$
163	$gg \to L_Q \bar{L}_Q$
164	$q_i \bar{q}_i \to L_Q \bar{L}_Q$
SUSY:	
201	$f_i \bar{f}_i \to \tilde{e}_L \tilde{e}^*_L$
202	$f_i \bar{f}_i \to \tilde{e}_R \tilde{e}^*_R$
203	$f_i \bar{f}_i \to \tilde{e}_L \tilde{e}^*_R +$
204	$f_i \bar{f}_i \to \tilde{\mu}_L \tilde{\mu}^*_L$
205	$f_i \bar{f}_i \to \tilde{\mu}_R \tilde{\mu}^*_R$
206	$f_i \bar{f}_i \to \tilde{\mu}_L \tilde{\mu}^*_R +$
207	$f_i \bar{f}_i \to \tilde{\tau}_1 \tilde{\tau}^*_1$
208	$f_i \bar{f}_i \to \tilde{\tau}_2 \tilde{\tau}^*_2$
209	$f_i \bar{f}_i \to \tilde{\tau}_1 \tilde{\tau}^*_2 +$
210	$f_i \bar{f}_j \to \tilde{\ell}_L \tilde{\nu}^*_\ell +$
211	$f_i \bar{f}_j \to \tilde{\tau}_1 \tilde{\nu}^*_\tau +$
212	$f_i \bar{f}_j \to \tilde{\tau}_2 \tilde{\nu}_\tau{}^* +$
213	$f_i \bar{f}_i \to \tilde{\nu}_\ell \tilde{\nu}^*_\ell$
214	$f_i \bar{f}_i \to \tilde{\nu}_\tau \tilde{\nu}^*_\tau$
216	$f_i \bar{f}_i \to \tilde{\chi}_1 \tilde{\chi}_1$
217	$f_i \bar{f}_i \to \tilde{\chi}_2 \tilde{\chi}_2$
218	$f_i \bar{f}_i \to \tilde{\chi}_3 \tilde{\chi}_3$
219	$f_i \bar{f}_i \to \tilde{\chi}_4 \tilde{\chi}_4$
220	$f_i \bar{f}_i \to \tilde{\chi}_1 \tilde{\chi}_2$
221	$f_i \bar{f}_i \to \tilde{\chi}_1 \tilde{\chi}_3$
222	$f_i \bar{f}_i \to \tilde{\chi}_1 \tilde{\chi}_4$
223	$f_i \bar{f}_i \to \tilde{\chi}_2 \tilde{\chi}_3$
224	$f_i \bar{f}_i \to \tilde{\chi}_2 \tilde{\chi}_4$
225	$f_i \bar{f}_i \to \tilde{\chi}_3 \tilde{\chi}_4$
226	$f_i \bar{f}_i \to \tilde{\chi}^\pm_1 \tilde{\chi}^\mp_1$
227	$f_i \bar{f}_i \to \tilde{\chi}^\pm_2 \tilde{\chi}^\mp_2$
228	$f_i \bar{f}_i \to \tilde{\chi}^\pm_1 \tilde{\chi}^\mp_2$

No.	Subprocess
229	$f_i \bar{f}_j \to \tilde{\chi}_1 \tilde{\chi}^\pm_1$
230	$f_i \bar{f}_j \to \tilde{\chi}_2 \tilde{\chi}^\pm_1$
231	$f_i \bar{f}_j \to \tilde{\chi}_3 \tilde{\chi}^\pm_1$
232	$f_i \bar{f}_j \to \tilde{\chi}_4 \tilde{\chi}^\pm_1$
233	$f_i \bar{f}_j \to \tilde{\chi}_1 \tilde{\chi}^\pm_2$
234	$f_i \bar{f}_j \to \tilde{\chi}_2 \tilde{\chi}^\pm_2$
235	$f_i \bar{f}_j \to \tilde{\chi}_3 \tilde{\chi}^\pm_2$
236	$f_i \bar{f}_j \to \tilde{\chi}_4 \tilde{\chi}^\pm_2$
237	$f_i \bar{f}_i \to \tilde{g} \tilde{\chi}_1$
238	$f_i \bar{f}_i \to \tilde{g} \tilde{\chi}_2$
239	$f_i \bar{f}_i \to \tilde{g} \tilde{\chi}_3$
240	$f_i \bar{f}_i \to \tilde{g} \tilde{\chi}_4$
241	$f_i \bar{f}_j \to \tilde{g} \tilde{\chi}^\pm_1$
242	$f_i \bar{f}_j \to \tilde{g} \tilde{\chi}^\pm_2$
243	$f_i \bar{f}_i \to \tilde{g} \tilde{g}$
244	$gg \to \tilde{g} \tilde{g}$
246	$f_i g \to \tilde{q}_{iL} \tilde{\chi}_1$
247	$f_i g \to \tilde{q}_{iR} \tilde{\chi}_1$
248	$f_i g \to \tilde{q}_{iL} \tilde{\chi}_2$
249	$f_i g \to \tilde{q}_{iR} \tilde{\chi}_2$
250	$f_i g \to \tilde{q}_{iL} \tilde{\chi}_3$
251	$f_i g \to \tilde{q}_{iR} \tilde{\chi}_3$
252	$f_i g \to \tilde{q}_{iL} \tilde{\chi}_4$
253	$f_i g \to \tilde{q}_{iR} \tilde{\chi}_4$
254	$f_i g \to \tilde{q}_{jL} \tilde{\chi}^\pm_1$
256	$f_i g \to \tilde{q}_{jL} \tilde{\chi}^\pm_2$
258	$f_i g \to \tilde{q}_{iL} \tilde{g}$
259	$f_i g \to \tilde{q}_{iR} \tilde{g}$
261	$f_i \bar{f}_i \to \tilde{t}_1 \tilde{t}^*_1$
262	$f_i \bar{f}_i \to \tilde{t}_2 \tilde{t}^*_2$
263	$f_i \bar{f}_i \to \tilde{t}_1 \tilde{t}^*_2 +$
264	$gg \to \tilde{t}_1 \tilde{t}^*_1$
265	$gg \to \tilde{t}_2 \tilde{t}^*_2$
271	$f_i f_j \to \tilde{q}_{iL} \tilde{q}_{jL}$
272	$f_i f_j \to \tilde{q}_{iR} \tilde{q}_{jR}$
273	$f_i f_j \to \tilde{q}_{iL} \tilde{q}_{jR} +$
274	$f_i \bar{f}_j \to \tilde{q}_{iL} \tilde{q}^*_{jL}$
275	$f_i \bar{f}_j \to \tilde{q}_{iR} \tilde{q}^*_{jR}$
276	$f_i \bar{f}_j \to \tilde{q}_{iL} \tilde{q}^*_{jR} +$
277	$f_i \bar{f}_i \to \tilde{q}_{jL} \tilde{q}^*_{jL}$
278	$f_i \bar{f}_i \to \tilde{q}_{jR} \tilde{q}^*_{jR}$
279	$gg \to \tilde{q}_{iL} \tilde{q}^*_{iL}$
280	$gg \to \tilde{q}_{iR} \tilde{q}^*_{iR}$
281	$bq_i \to \tilde{b}_1 \tilde{q}_{iL}$
282	$bq_i \to \tilde{b}_2 \tilde{q}_{iR}$
283	$bq_i \to \tilde{b}_1 \tilde{q}_{iR} + \tilde{b}_2 \tilde{q}_{iL}$
284	$b\bar{q}_i \to \tilde{b}_1 \tilde{q}^*_{iL}$
285	$b\bar{q}_i \to \tilde{b}_2 \tilde{q}^*_{iR}$
286	$b\bar{q}_i \to \tilde{b}_1 \tilde{q}^*_{iR} + \tilde{b}_2 \tilde{q}^*_{iL}$
287	$q_i \bar{q}_i \to \tilde{b}_1 \tilde{b}^*_1$
288	$q_i \bar{q}_i \to \tilde{b}_2 \tilde{b}^*_2$
289	$gg \to \tilde{b}_1 \tilde{b}^*_1$
290	$gg \to \tilde{b}_2 \tilde{b}^*_2$
291	$bb \to \tilde{b}_1 \tilde{b}_1$
292	$bb \to \tilde{b}_2 \tilde{b}_2$
293	$bb \to \tilde{b}_1 \tilde{b}_2$
294	$bg \to \tilde{b}_1 \tilde{g}$
295	$bg \to \tilde{b}_2 \tilde{g}$
296	$b\bar{b} \to \tilde{b}_1 \tilde{b}^*_2 +$
Extra dimensions:	
391	$f_i \bar{f}_i \to G^*$
392	$gg \to G^*$
393	$q_i \bar{q}_i \to gG^*$
394	$q_i g \to q_i G^*$
395	$gg \to gG^*$

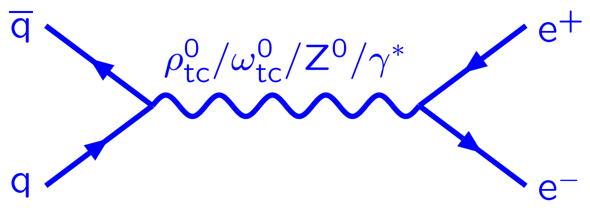
Subprocess summary

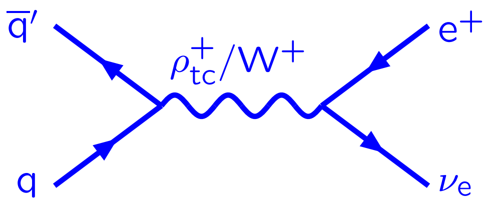
Processes	Examples
QCD & related	
Soft QCD	low-$p_\perp$; diffraction
Hard QCD	$\mathrm{qg} \to \mathrm{qg}$
Open heavy flavour	$\mathrm{q\overline{q}} \to \mathrm{t\overline{t}}$
Closed heavy flavour	$\mathrm{gg} \to \mathrm{gJ}/\psi$
$\gamma\gamma$ physics	$\gamma\mathrm{q} \to \mathrm{qg}$
DIS	$\gamma^*\mathrm{q} \to \mathrm{q}$
$\gamma^*\gamma^*$ 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	(/Lin progress)
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	$\mathrm{gg} \to \mathrm{G}^* \to \mathrm{e}^+\mathrm{e}^-$

Beyond the Standard Model

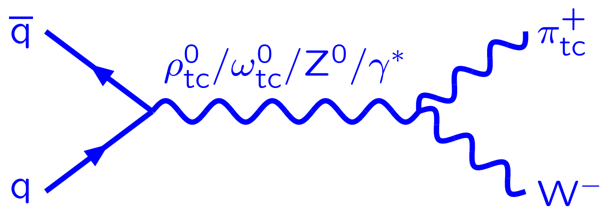
SUSY: see talk by Stephen Mrenna

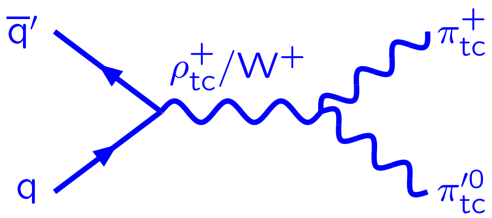
Technicolor: interferences included, e.g



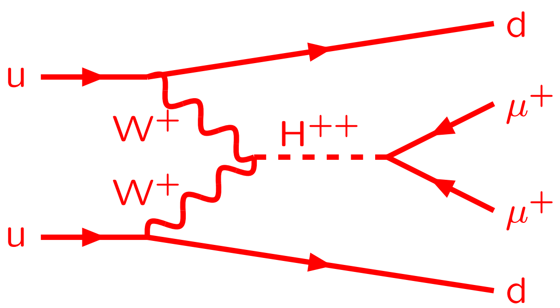


gives new set of pair production of
$\pi^{\pm}_{\mathrm{tc}}/\pi^0_{\mathrm{tc}}/\pi'^0_{\mathrm{tc}}/\mathrm{W}^{\pm}_{\mathrm{L}}/\mathrm{Z}^0_{\mathrm{L}}/\mathrm{W}^{\pm}/\mathrm{Z}^0/\gamma$, e.g.





Left-right symmetry: Higgs triplets



$\mathrm{H}^{\pm\pm}_{L,R}$ production

$\mathrm{H}^{\pm\pm}_{L,R} \to \ell^{\pm}\ell^{\pm}/\mathrm{W}^{\pm}_{L,R}\mathrm{W}^{\pm}_{L,R}$

$\mathrm{W}^{+}_{R} \to \mathrm{q}_i\overline{\mathrm{q}}_j/\ell^{+}\nu_R$

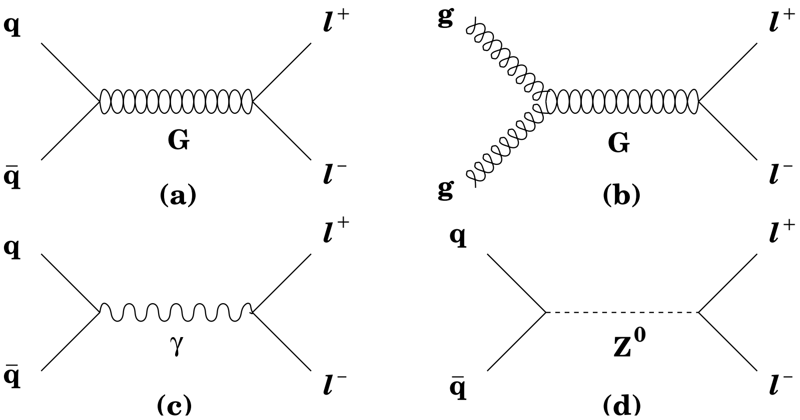
Higgs: pair production, e.g. $\mathrm{h}^0\mathrm{A}^0$ or $\mathrm{h}^0\mathrm{H}^{\pm}$
(earlier partly as $\gamma^*/\mathrm{Z}^0/\mathrm{Z}'^0$ decays)

Z'^0: flavour-dependent couplings

Compositeness: a few further $\mathrm{e}^*/\mathrm{q}^*$ processes

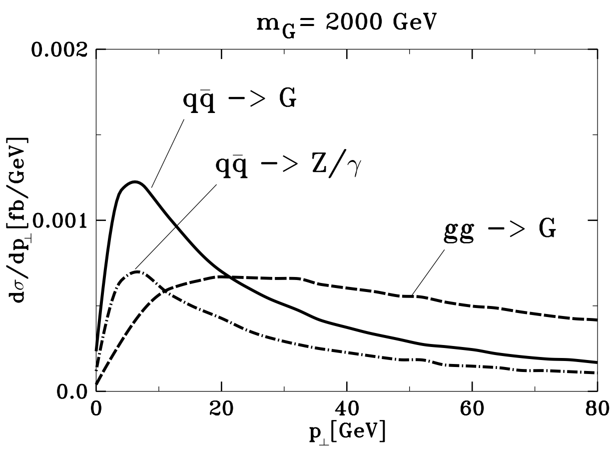
Extra dimensions: only begun;
now: Randall-Sundrum graviton excitation G^*

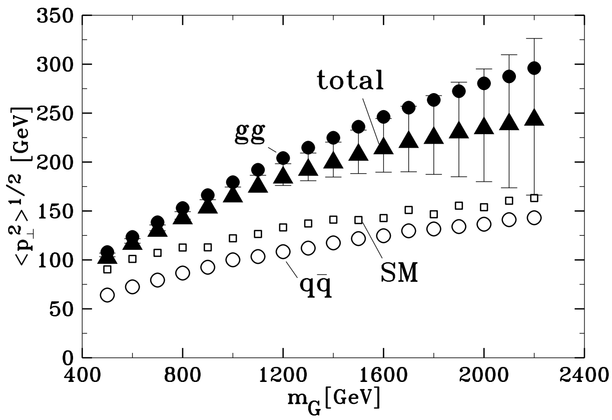
(J. Bijnens, P. Eerola, M. Maul, A. Månsson, TS ⇒ PLB)



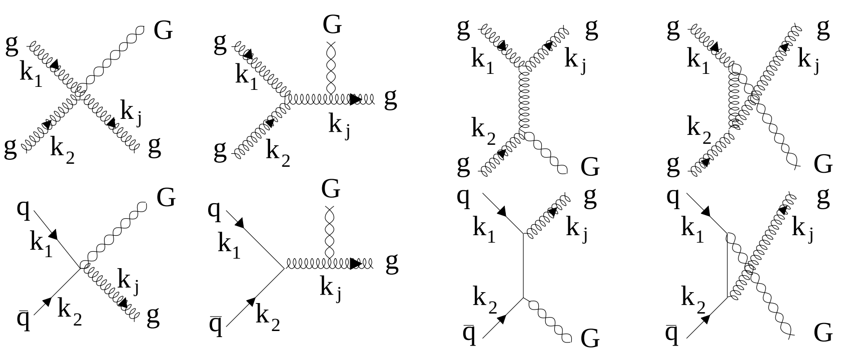
lowest order:
$q\bar{q} \to G^*$
$gg \to G^*$

γ^*/Z^0 backgr.





Higher $p_\perp$ for gg fusion ⇒ extra signal/check
(in addition to angular decay distribution)



also NLO:
$q\bar{q} \to gG^*$
$qg \to qG^*$
$gg \to gG^*$
confirms PS

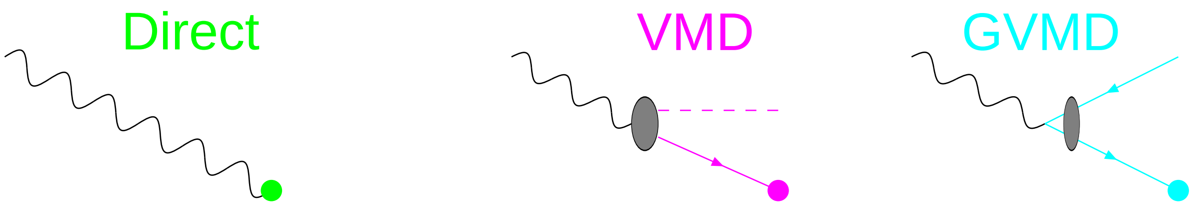
$\gamma^{(*)}\gamma^{(*)}$ physics

(C. Friberg & TS, EPJC13 (2000) 151,JHEP 09 (2000) 10)

Objective: “complete” framework for
$\gamma\gamma/\gamma^*\gamma/\gamma^*\gamma^*$ interactions at all Q_i^2,
especially transition region $Q_i^2 \sim m_\rho^2$

New machinery for flux of bremsstrahlung γ's
(transverse and longitudinal)

Real photons can be of three kinds
(with further subdivisions):



Direct: point-like
All: ‘high’-$p_\perp$ jets;

Resolved: hadronic state
resolved: also soft physics

Virtual photon: add the DIS process γ^*q $\to$ q,
e.g. q in (VMD) ρ^0

$\gamma\gamma$:	9	combinations = (dir+VMD+GVMD)^2
$\gamma^*\gamma^*$:	+ 4	combinations = 2 sides$\times$(VMD+GVMD)
	13 !!	

Have to include dampening factors to remove double-counting (reasonably) consistently

Small-x evolution

(summary by L. Lönnblad)

There are no reliable generators for small-x evolution. In fact there is no reliable description at all of small-x evolution.

In the limit of asymptotically large energies ($\ggg$ 2 TeV) the right description is given by BFKL evolution.

After ten years of hard work by Fadin–Lipatov, the next-to-leading log corrections to the BFKL evolution turned out to be HUGE.

CCFM: interpolation between DGLAP and BFKL, more likely to be relevant at finite energies. Includes gluon coherence.

There are three generators which implement CCFM evolution.

SMALLX (Hannes Jung, previously Marchesini and Webber) implements forward evolution, initial-state emissions only and interfaced to PYTHIA for hadronization.

CASCADE (Hannes Jung) implements backward evolution, initial-state emissions only and interfaced to PYTHIA for hadronization.

LDCMC (Leif Lönnblad, Hamid Kharraziha) implements forward–backward symmetric initial-state evolution (according to the Linked Dipole Chain model), final-state dipole cascade and interfaced to PYTHIA for hadronization.

All three give compatible results for small-x final states at HERA DIS. Estimates of NLL corrections are more favorable than for straight BFKL (much thanks to energy–momentum conservation). But still, all three are very sensitive to the treatment of non-leading terms.

Using only the pole terms in the gluon splitting function, a good description of e.g. forward jet rates is obtained. Also with the un-integrated gluon densities from SMALLX and off-shell ME's, one obtains a good description of F_2 and F_2^c at HERA, heavy quark cross-sections at the Tevatron, etc.

But using the full gluon splitting destroys at least some of the nice results.

Should we worry about small-x effects at the Tevatron?

Yes, for low $E_\perp$ jets. But there we also have problem with multiple scatterings etc.

Yes, for heavy quark production.

Yes, for $\delta\eta \gtrsim 4$

Yes

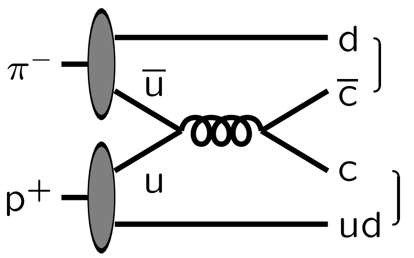
None of the generators are available for $\mathrm{p\overline{p}}$ (There are plans but don't hold your breath)

Beam Remnant Physics

(E. Norrbin & TS, PL B442 (1998) 407, EPJ C17 (2000) 137)

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.



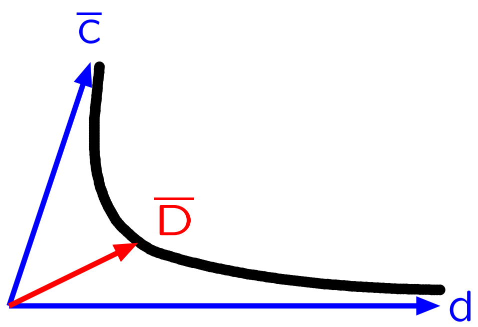
If collapse:

$\overline{c}d$: D^-, D^{*-}, ...

cud: Λ_c^+, Σ_c^+, Σ_c^{*+}, ...

$\Rightarrow$ flavour asymmetries

$p\overline{p}$; p side: Λ_b^0, B^+, B^0

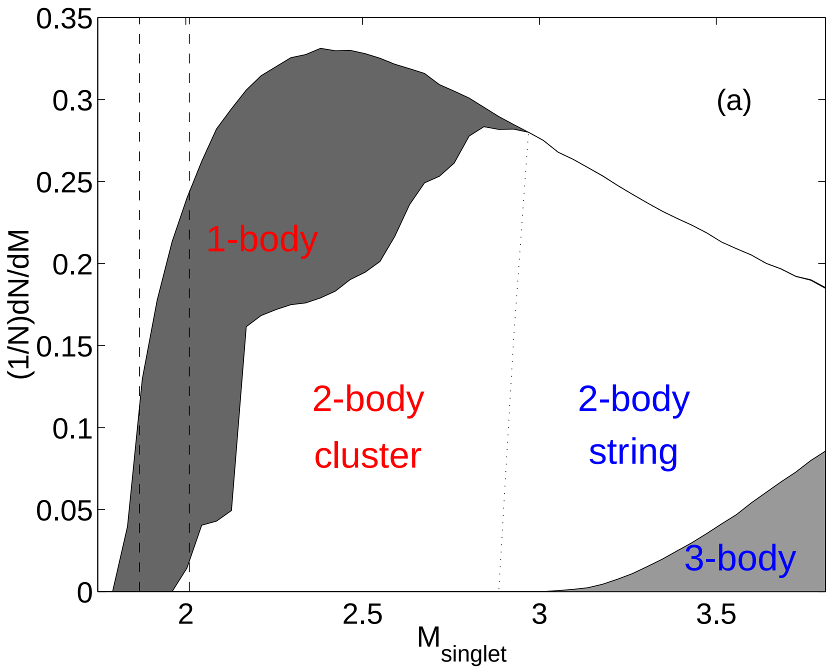


Can give D ‘drag’ to larger x_F than c quark in all three cases

But many parameters: $\Rightarrow$ tune

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

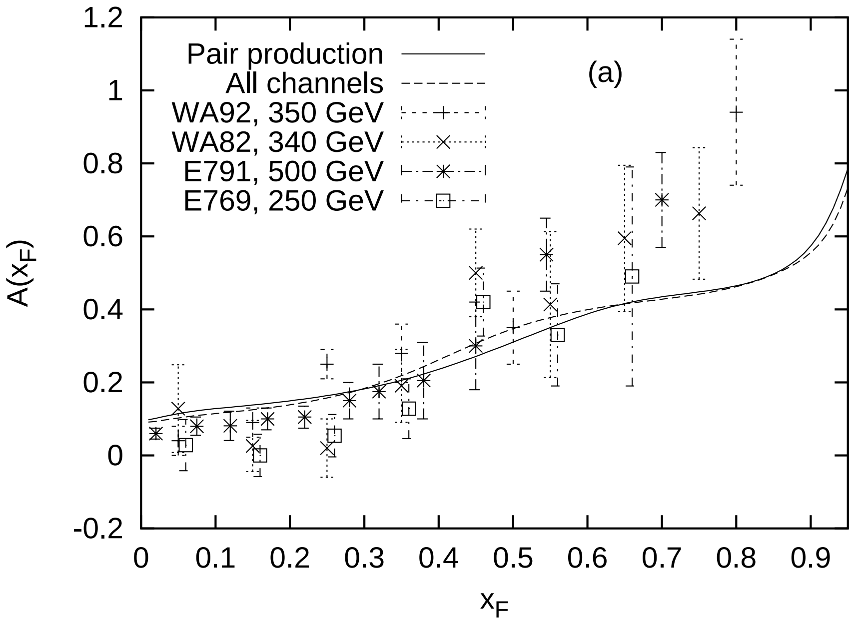
example:
charm
string
in πp
collision

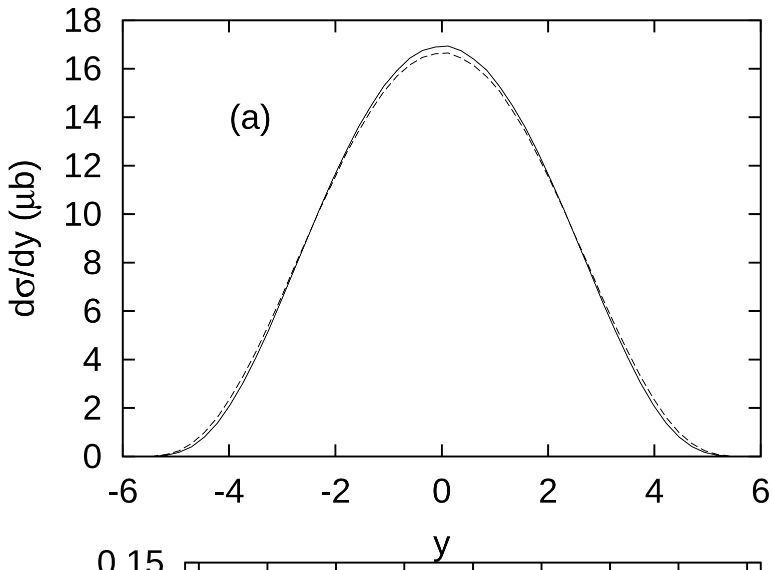


and
1-body collapse: energy-momentum shuffling
2-body decay: smoother joining to string
picture (matched anisotropic decay)

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

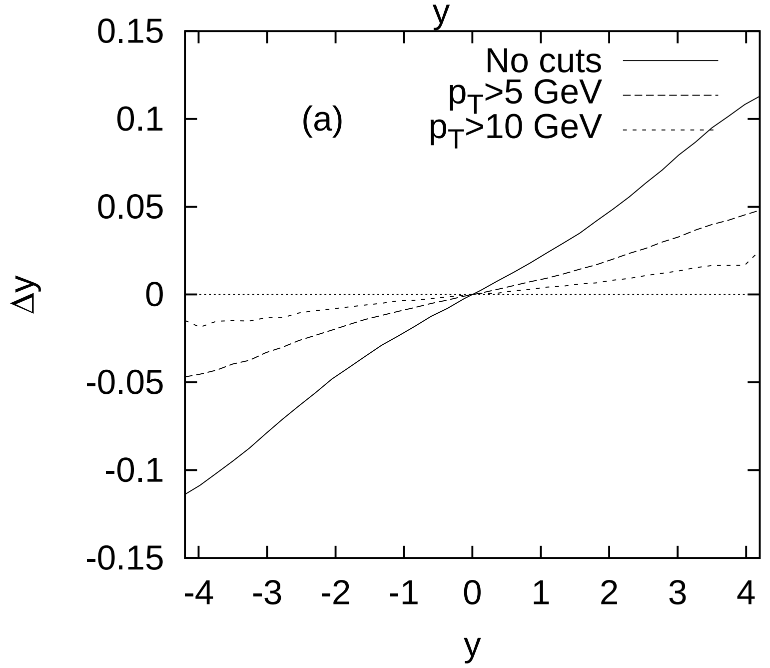
in π^-p



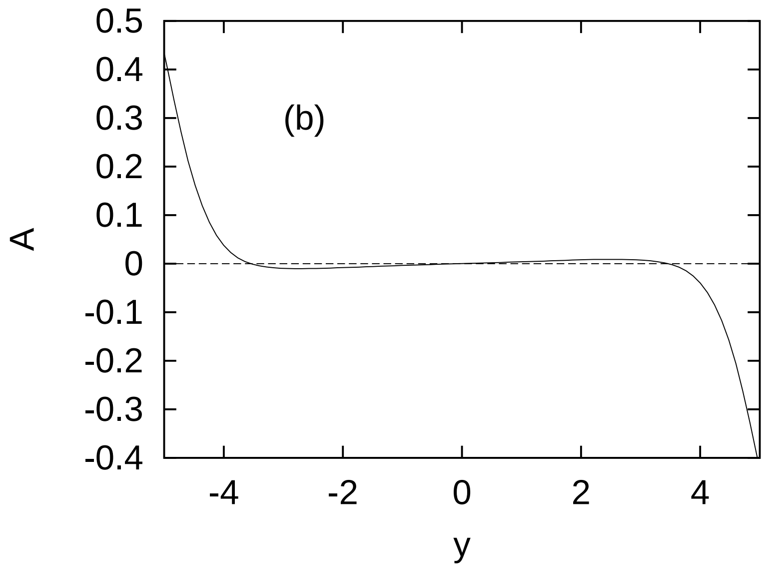


Bottom production
at the Tevatron

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}

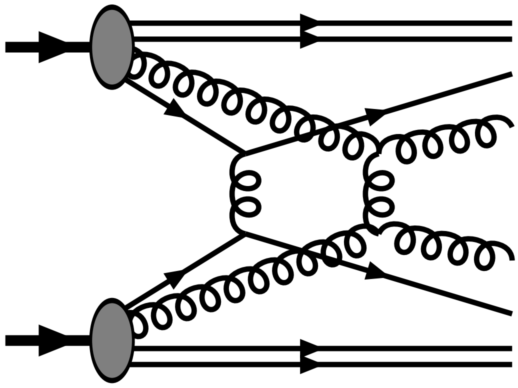
Only pair production
for simplicity

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

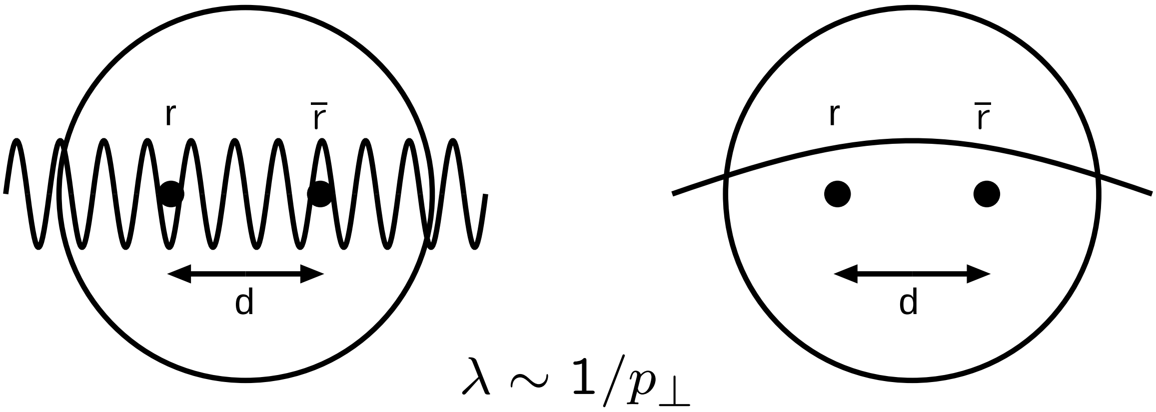
One new free parameter: $p_{\perp\mathrm{min}}$

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

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

Measure of colour screening length d in hadron

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



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

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

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

Olden days:

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

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

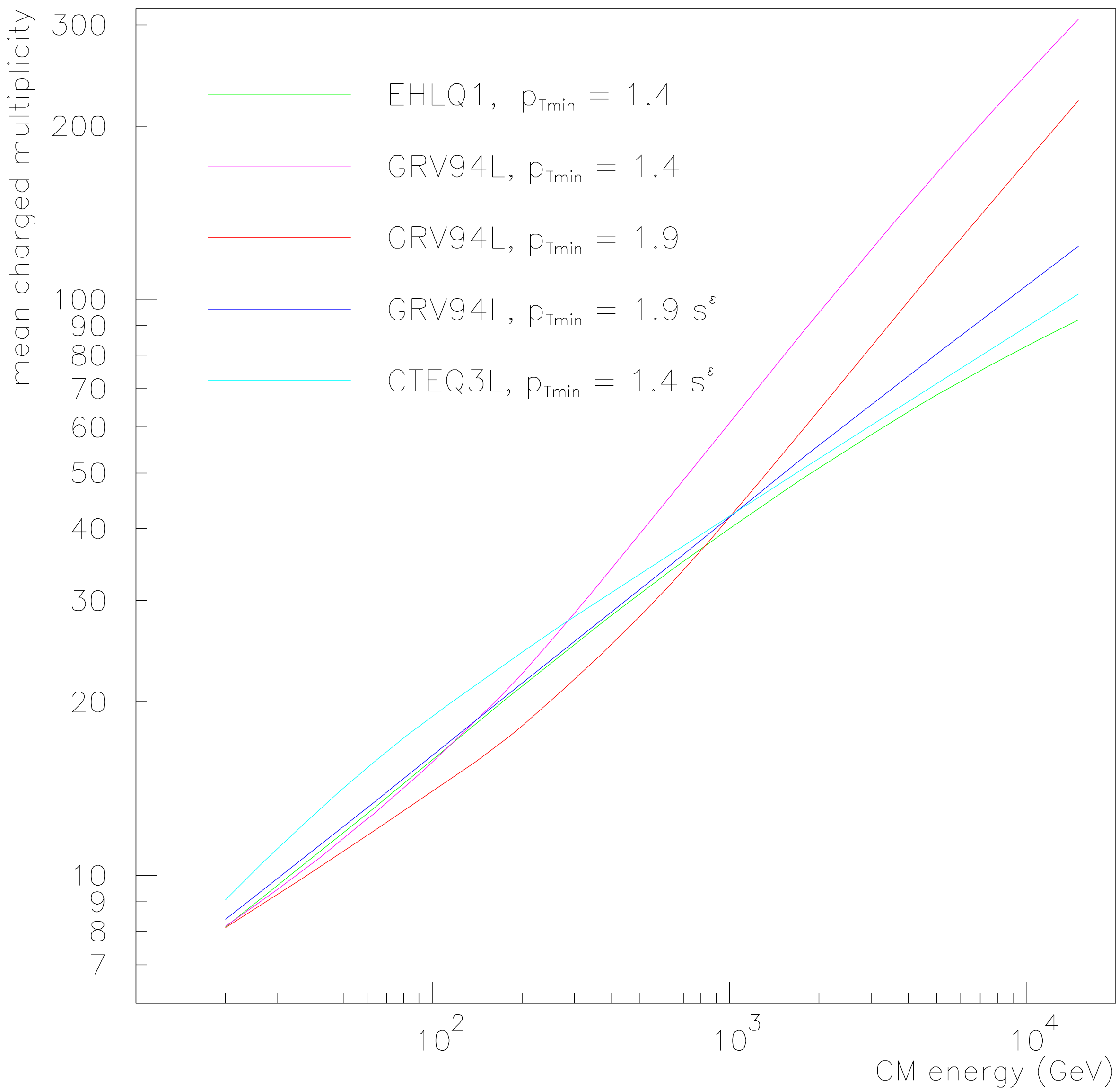
Post-HERA:

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

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

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

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

Other PYTHIA 6.1 news

- JETSET routines renamed: `LUxxxx` $\longrightarrow$ `PYxxxx` + some more
- All real variables in `DOUBLE PRECISION`
- Improved resonance decay machinery
- ME/PS matching: see separate talk
- Newer parton distributions (CTEQ5, ...)
- QED radiation off an incoming muon
- Colour rearrangement options
- Expanded Bose-Einstein algorithm
- New baryon production scheme (optional)
- One-dimensional histograms (GBOOK)
- Gone: top hadrons, $gg \to Z^0 b\bar{b}$

2–, 4– and 6–fermion standard interfaces for showers and hadronization:

```
  CALL PY2FRM(IRAD,ITAU,ICOM)
  CALL PY4FRM(ATOTSQ,A1SQ,A2SQ,ISTRAT,
&IRAD,ITAU,ICOM)
  CALL PY6FRM(P12,P13,P21,P23,P31,P32,PTOP,
&IRAD,ITAU,ICOM)
```

$q\bar{q}gg$ and $q\bar{q}q'\bar{q}'$ QCD 4–jet standard interface for showers and hadronization:

```
  CALL PY4JET(PMAX,IRAD,ICOM)
```

Future Plans

PYTHIA 6.2: before end of summer?

- Completely updated long manual ($>$ 370 pp!)
- Lepton-number-violating SUSY decays (P. Skands)
- Reversed order resonance decays and showers, e.g. $\mathrm{t} \to \mathrm{bW} \to \mathrm{bq\overline{q}'}$

now:	future:
1. $\mathrm{t} \to \mathrm{bW}$	1. $\mathrm{t} \to \mathrm{bW}$
2. bW cascade $\Rightarrow$ boost W	2. $\mathrm{W} \to \mathrm{q\overline{q}'}$
3. $\mathrm{W} \to \mathrm{q\overline{q}'}$	3. bW cascade $\Rightarrow$ boost $\mathrm{q\overline{q}'}$
4. $\mathrm{q\overline{q}'}$ cascade	4. $\mathrm{q\overline{q}'}$ cascade

- Improved interfacing of external processes, e.g. with **COMPHEP** see talk?

now:	future:
can predefine 1) externally	can predefine 1) and 2) externally

PYTHIA 6.?

- Steady trickle of new processes?
- Triple gauge boson production?
- Baryon-number-violating SUSY decays?
- ME/PS matching for gauge boson pairs (e.g. $\mathrm{q\overline{q}} \to \mathrm{W^+W^-}$) (S. Burby)?
- ME/PS matching for QCD processes?
- Improved FSR shower algorithm?
- Improved ISR shower algorithm?
- Modified ISR shower to bring in some BFKL/CCFM features?
- Understand primordial $k_{\perp}$ better?
- Multiple parton–parton interactions with more complicated colour topologies?

PYTHIA 7: see talk by Leif Lönnblad

Onwards C++ Soldiers!