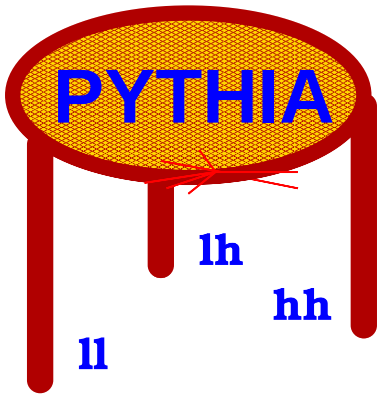
ATLAS Physics Workshop
Lund, 12 – 16 September 2001

LUND UNIVERSITY

PYTHIA
Status Report

Torbjörn Sjöstrand



JETSET 7.4
PYTHIA 5.7
SPYTHIA

} 4 March 1997 : → PYTHIA 6.1

Currently **PYTHIA 6.200** of 31 August 2001
$\sim$ 56, 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]

Lund Productions

Proudly Presents

hep-ph/0108264
LU TP 01–21
August 2001

Pythia 6.2

Physics and Manual

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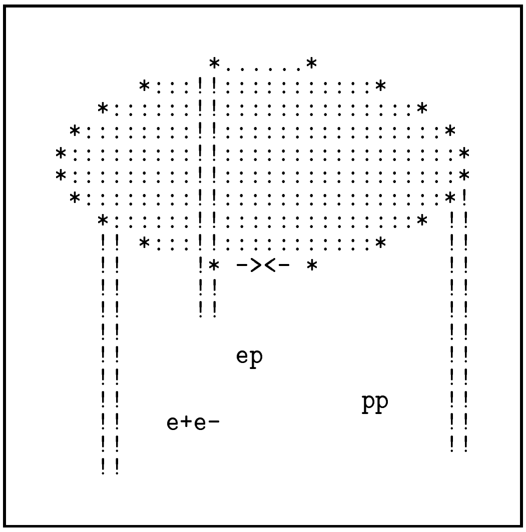
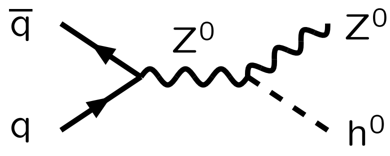


with 420 new or revised pages!

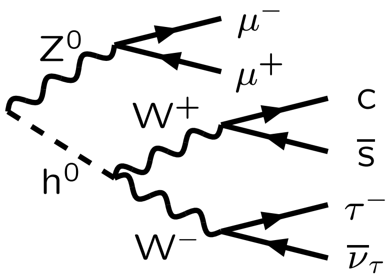
Event physics overview

Structure of the basic generation process:

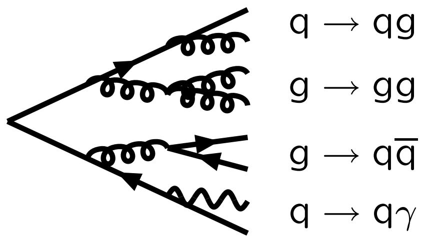
1) Hard subprocess:
$\mathrm{d}\hat{\sigma}/\mathrm{d}\hat{t}$, Breit-Wigners



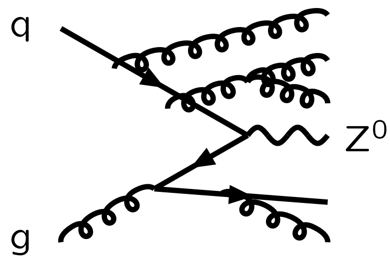
2) Resonance decays:
includes correlations
(where implemented)



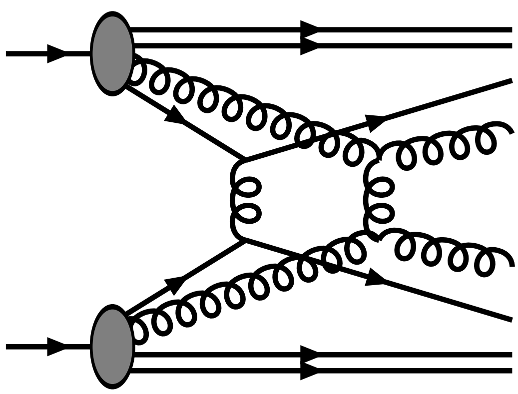
3) Final-state
parton showers:
(or matrix elements)



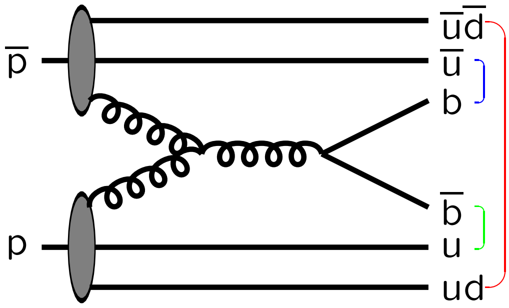
4) Initial-state
parton showers:
(or matrix elements)



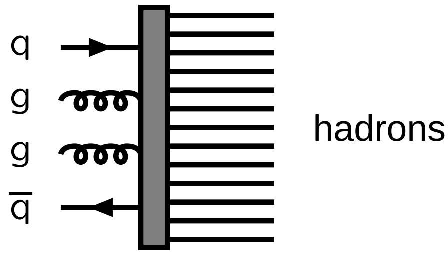
5) Multiple
parton–parton
interactions



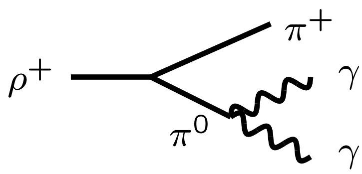
6) Beam remnants: colour-connected to rest of event



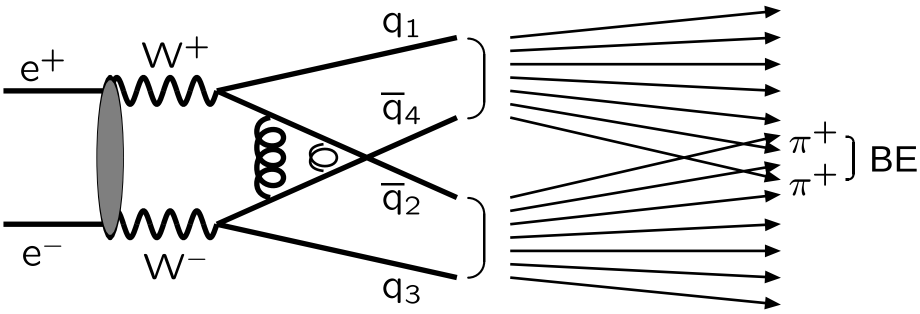
7) Hadronization (or fragmentation)



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!

Subprocess summary

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

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	$\gamma^*_T \gamma^*_L \to f_i \bar{f}_i$
139	$\gamma^*_L \gamma^*_T \to f_i \bar{f}_i$
140	$\gamma^*_L \gamma^*_L \to f_i \bar{f}_i$
80	$q_i \gamma \to q_k \pi^\pm$

No.	Subprocess
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	$f_i \bar{f}_i \to \gamma h^0$
111	$f_i \bar{f}_i \to g h^0$
112	$f_i g \to f_i h^0$
113	$gg \to g h^0$
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	$q_i \bar{q}_i \to Q_k \bar{Q}_k H^0$
183	$f_i \bar{f}_i \to g H^0$
184	$f_i g \to f_i H^0$
185	$gg \to g H^0$
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	$q_i \bar{q}_i \to Q_k \bar{Q}_k A^0$
188	$f_i \bar{f}_i \to g A^0$
189	$f_i g \to f_i A^0$
190	$gg \to g A^0$
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	$f_i \bar{f}_i \to H^+ H^-$
Left–right symmetry:	
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	$f_i f_j \to f_k f_l H^{\pm\pm}_R$
353	$f_i \bar{f}_i \to Z^0_R$
354	$f_i \bar{f}_j \to W^\pm_R$

No.	Subprocess
New gauge bosons:	
141	$f_i \bar{f}_i \to \gamma/Z^0/Z'^0$
142	$f_i \bar{f}_j \to W'^+$
144	$f_i \bar{f}_j \to R$
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	$f_i \bar{f}_i \to \tilde{\chi}^\pm_1 \tilde{\chi}^\mp_1$

No.	Subprocess
227	$f_i \bar{f}_i \to \tilde{\chi}^\pm_2 \tilde{\chi}^\mp_2$
228	$f_i \bar{f}_i \to \tilde{\chi}^\pm_1 \tilde{\chi}^\mp_2$
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	$q_i \bar{q}_i \to g G^*$
394	$q_i g \to q_i G^*$
395	$gg \to g G^*$

$\sum \approx 250$ processes

Process news

SUSY:

- $\not{L} \Rightarrow\ >$1200 new decay channels (not $\tilde{\mathrm{g}}$)

  (P. Skands, Master's thesis, hep-ph/0108207)
- Complex phases in $\tilde{\chi}^0$, $\tilde{\chi}^{\pm}$, $\tilde{\mathrm{g}}$ sectors
- ME weighting in 3-body decays
- H mass calculation corrected for large tanβ

Technicolor: interferences included
e.g. for $\rho^0_{\mathrm{tc}}/\omega^0_{\mathrm{tc}}/\mathrm{Z}^0/\gamma^*$ and $\rho^+_{\mathrm{tc}}/\mathrm{W}^+$,
gives new set of pair production of
$\pi^{\pm}_{\mathrm{tc}}/\pi^0_{\mathrm{tc}}/\pi'^0_{\mathrm{tc}}/\mathrm{W}^{\pm}_{\mathrm{L}}/\mathrm{Z}^0_{\mathrm{L}}/\mathrm{W}^{\pm}/\mathrm{Z}^0/\gamma$

Left-right symmetry: Z^0_R, $\mathrm{W}^{\pm}_R$, ν_R, $\mathrm{H}^{\pm\pm}_{L,R}$
production $\mathrm{H}^{\pm\pm}_{L,R}$ singly or pairs, $\mathrm{Z}^0_R/\mathrm{W}^{\pm}_R$ singly
decays $\mathrm{H}^{\pm\pm}_{L,R} \to \ell^{\pm}\ell^{\pm}/\mathrm{W}^{\pm}_{L,R}\mathrm{W}^{\pm}_{L,R}$ etc.

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

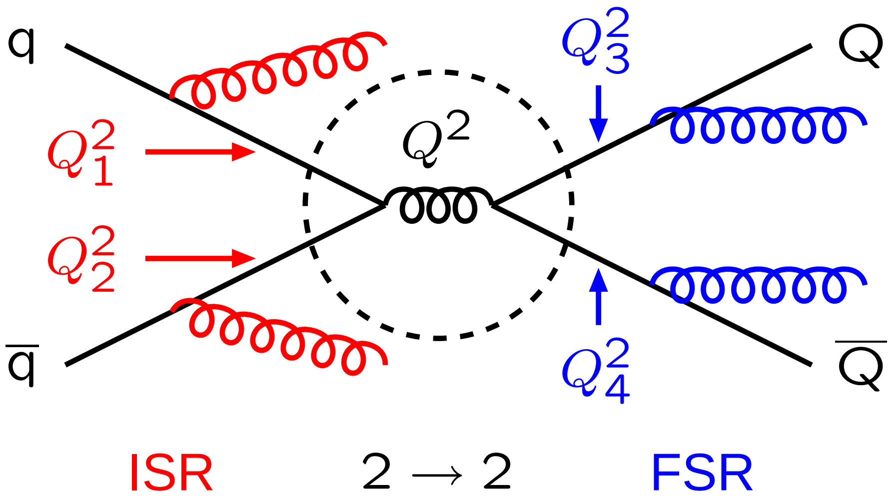
(J. Bijnens, P. Eerola, M. Maul, A. Månsson, TS, PLB503, 341)

+ Higgs pair production, Higgs decay,
  Z'^0, compositeness, . . .

+ New User-Defined Process Machinery
(see talk by M. Dobbs)

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

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

by shower generation + correction procedure

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

Comments:

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

• Exponentiate ME correction by shower Sudakov form factor:

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

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

Final-state showers

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

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

…but problems with $\gamma^*/Z^0 \to b\bar{b}g$ noted:

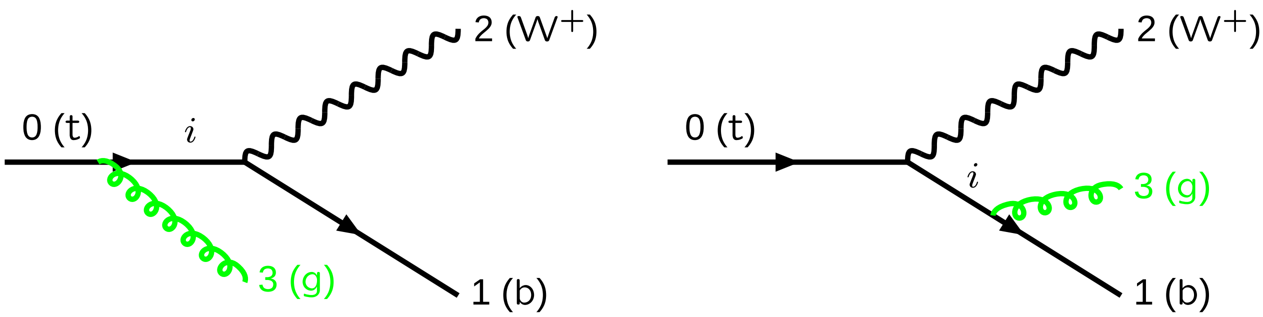
$Q_i^2 = m_i^2$ gives wrong singularity structure,

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

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

(also weight from splitting kernels in PS)

Coloured decaying particle also radiates:



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

$\Rightarrow$ can merge PS with generic $a \to bcg$ ME

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

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

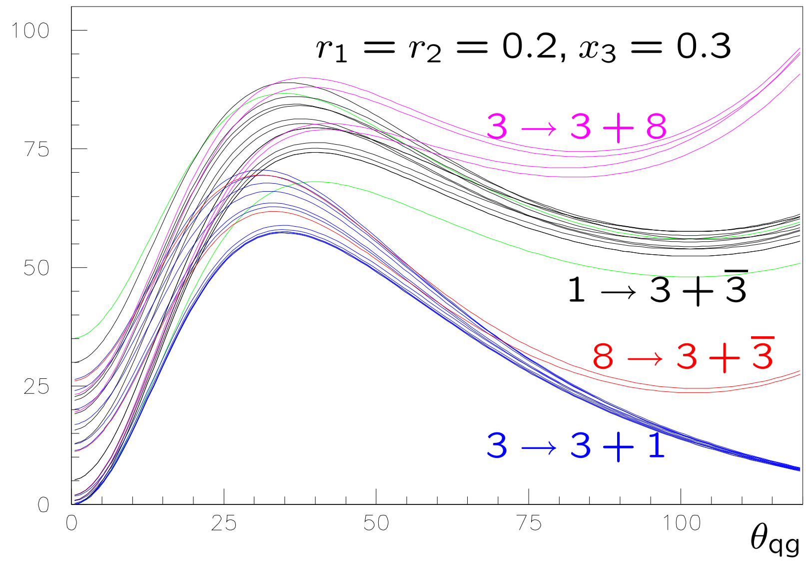
Calculate for $1 \to 2$ processes in SM + MSSM:

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

Depends on

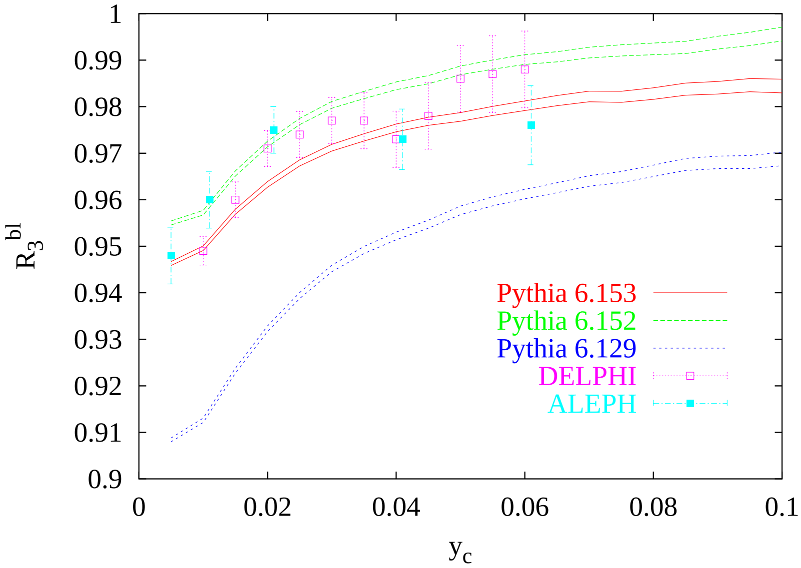
- mass ratios $r_1 = m_b/m_a$ and $r_2 = m_c/m_a$
- colour and spin structure
- vector vs. axial vector etc. (γ_5)

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



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

g emission rate for different colour, spin and parity structures

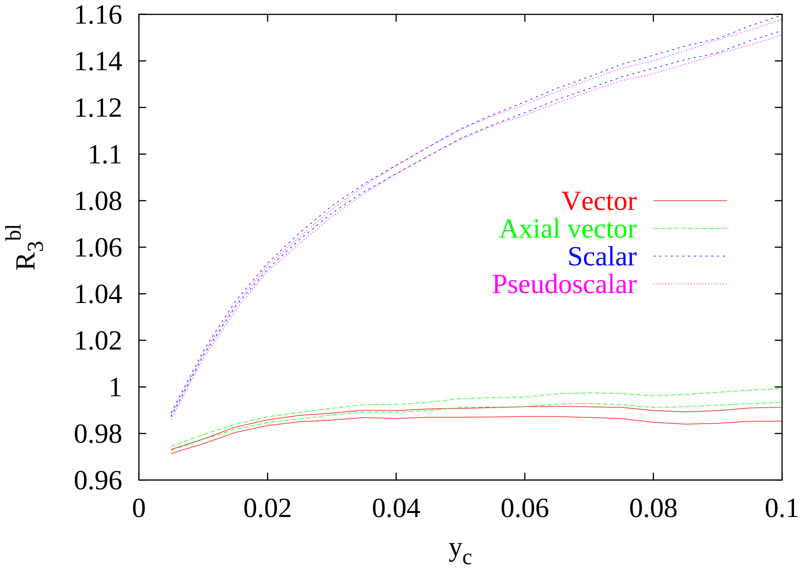


$R_3^{\mathrm{bl}}(y_c)$

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

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

ratio of 3-jets in b and uds (=l) events



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

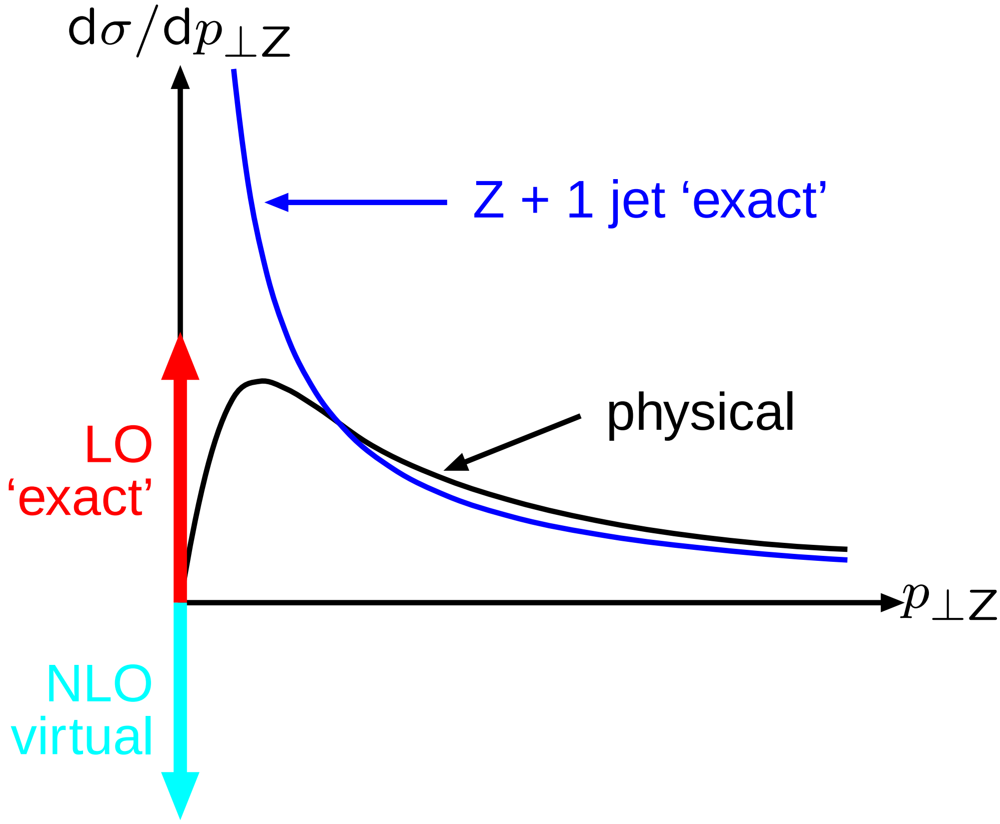
$E_{\mathrm{CM}} = m_{\mathrm{h/H/A}}$

$= 120$ GeV

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

reference light q from γ^*/Z^*

Initial-state showers

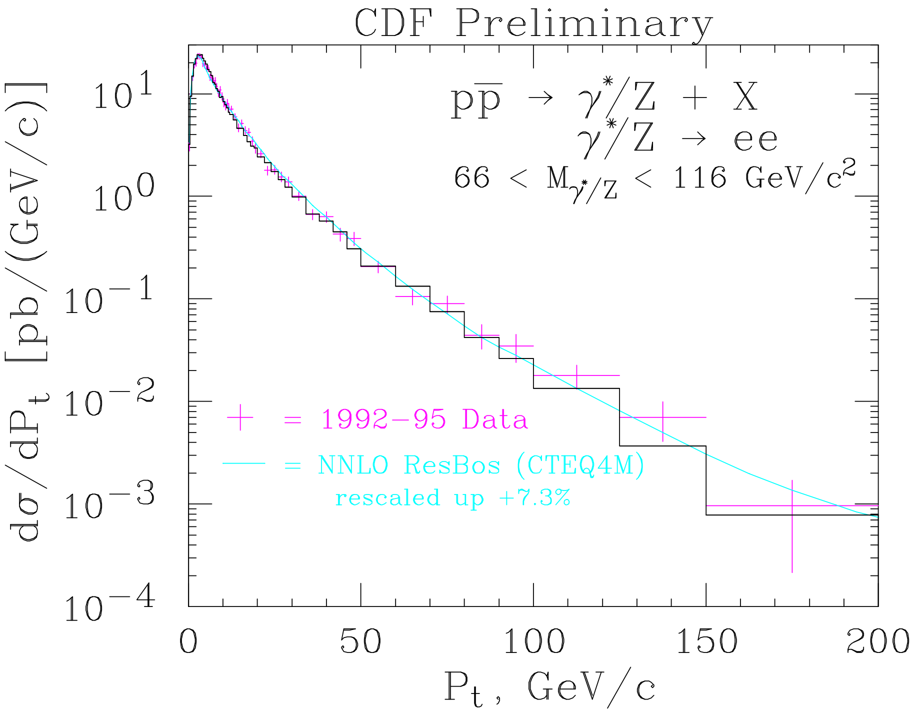


resummation: physical $p_{\perp Z}$ spectrum
shower: ditto + accompanying jets (exclusive)

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)

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

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



curve=ResBos

black=PYTHIA

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

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

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 $Q^2_{\mathrm{max}} = s$ 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 $m_{\mathrm{t}} \to \infty$ limit:

- gg $\to$ gh^0 and qg $\to$ qh^0 simple
- q$\bar{\mathrm{q}}$ $\to$ gh^0 nonsingular & small $\Rightarrow$ add

Challenges:

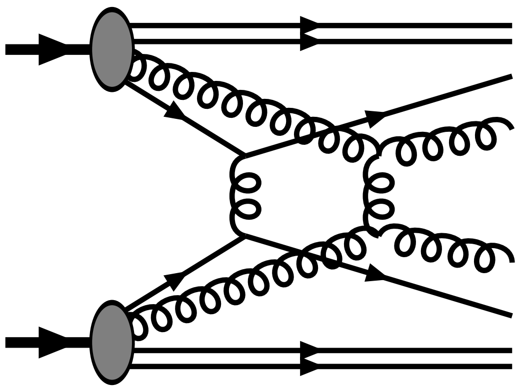
- gauge boson pairs (S. Burby)
- QCD 2 $\to$ 2 with ISR+FSR+interference

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

(At least) one new free parameter: $p_{\perp\mathrm{min}}$

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

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

Measure of colour screening length d in hadron

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

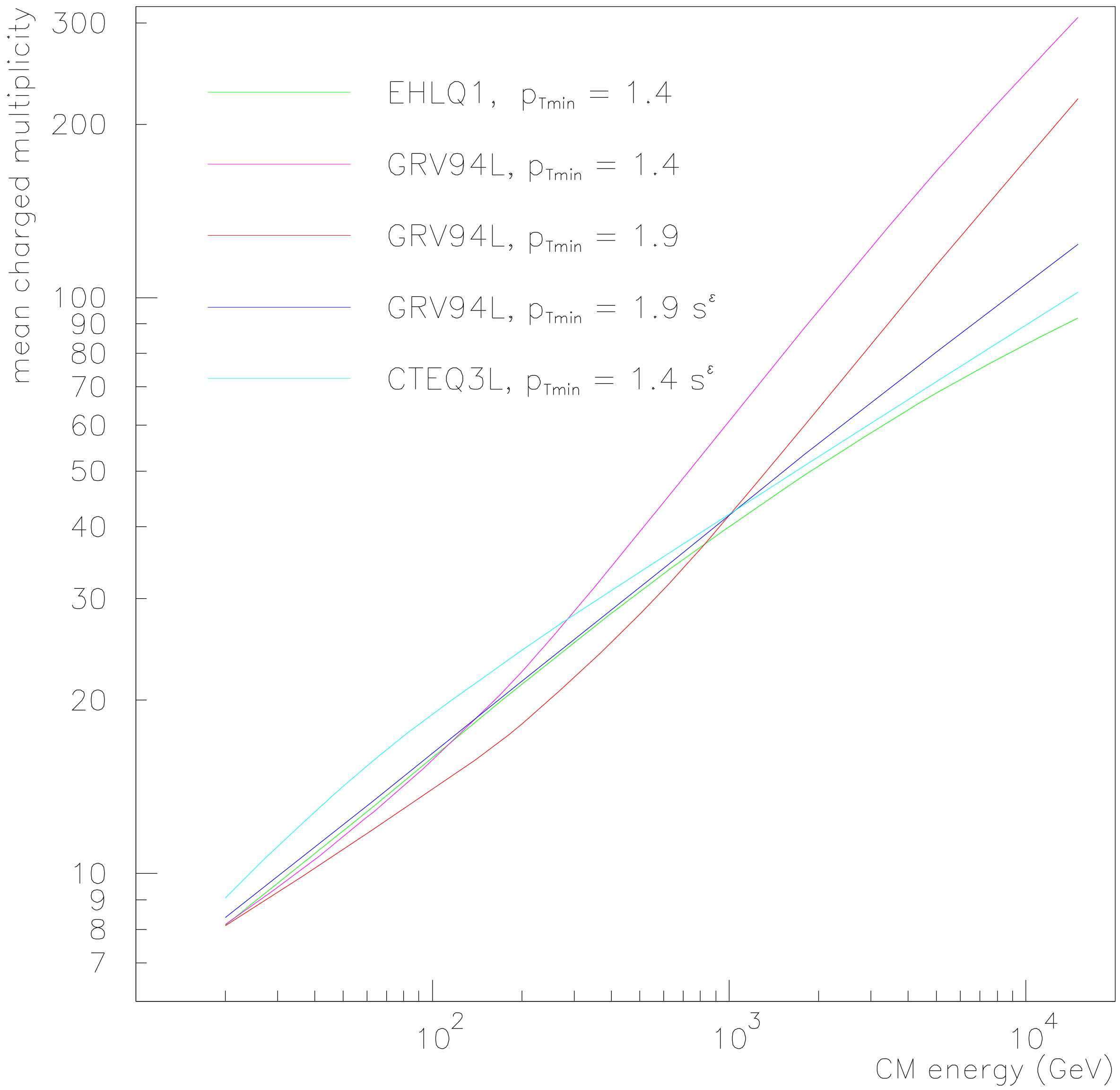
HERA $\Rightarrow$ more partons at small x and Q^2

$\Rightarrow$ energy-dependent $p_{\perp\mathrm{min}}$?

$\Rightarrow$ 'new' PYTHIA default:

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

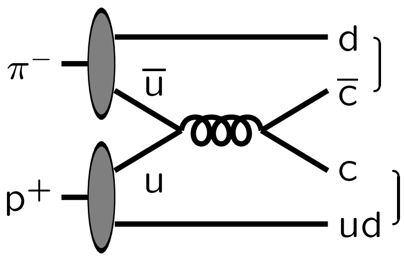
Mean charged multiplicity in inelastic non-diffractive 'minimum bias':



Beam remnant physics

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

Colour flow connects hard scattering to beam remnants. Can have consequences, e.g.

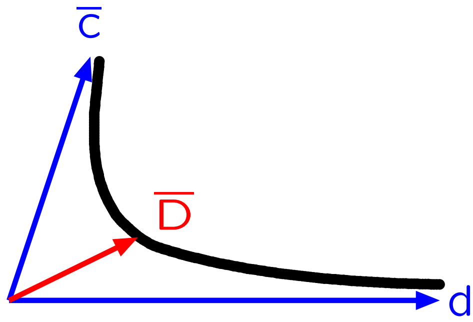


If low-mass string:

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

cud: Λ_c^+, Σ_c^+, Σ_c^{*+}, ...

$\Rightarrow$ flavour asymmetries

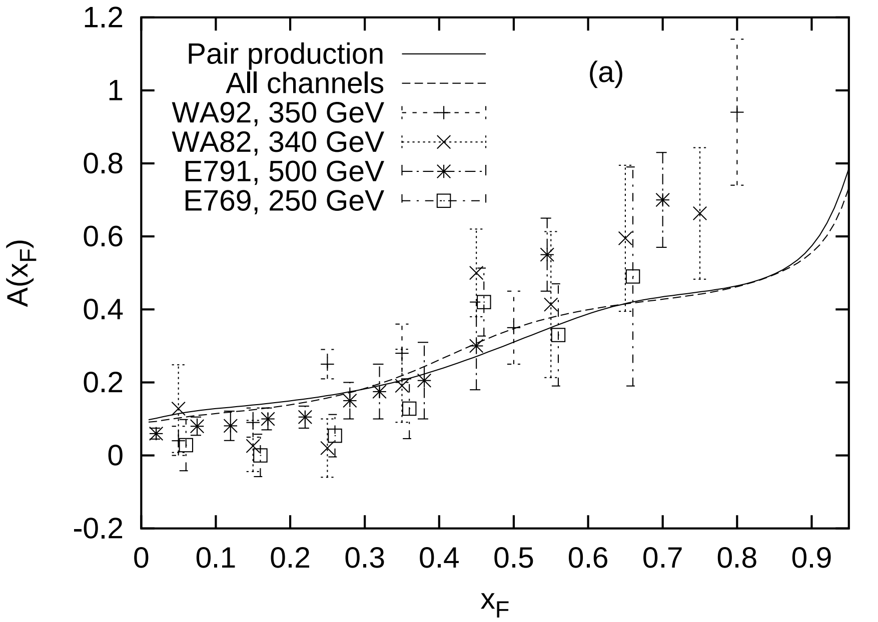


Can give D 'drag' to larger x_F than c quark for any string mass

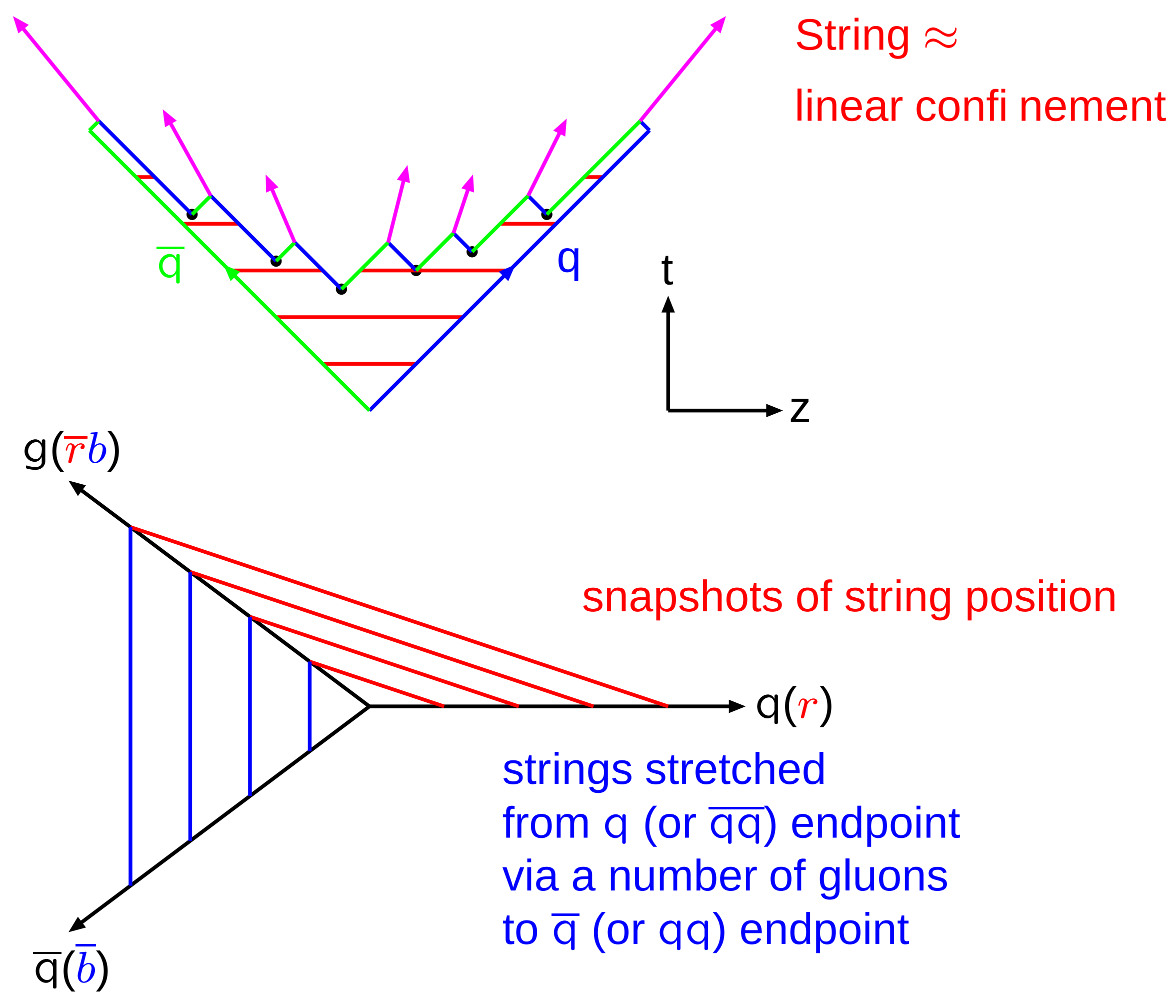
But many parameters: $\Rightarrow$ 'tune' to data

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

in π^-p



Hadronization



Lund string most sophisticated and successful description of hadronization!
. . . but also many parameters and problems.

Code expanded/upgraded for
- small-mass strings and beam remnants
- baryon production (optional)
- Bose–Einstein correlations (optional)
- colour rearrangement (optional)

Future plans

PYTHIA 6.?

- Steady trickle of new processes
- $\not{B}$SUSY decays (P. Skands)
- ME/PS matching for gauge boson pairs (e.g. $q\overline{q} \to W^+W^-$) (S. Burby)
- ME/PS matching for QCD processes
- Improved FSR/ISR shower algorithms
- ISR shower with BFKL/CCFM features
- Multiple parton–parton interactions with more complicated colour topologies

PYTHIA 7 —the C++ future (L. L önnblad)

- Mainly driven by external factors
- Generic model of event generation process
- Completely new code $\Rightarrow$ slow process
- 2000: basic generation machinery, string fragmentation
- 2001: first processes and HERWIG code
- 2002: parton showers $\Rightarrow$ usable (?)
- 2005: competitive with PYTHIA 6 (??)
- Death of Fortran code over $\sim 5 - 10$ years