LUND UNIVERSITY

CDF/D0 Monte Carlo Tutorial
Fermilab
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The PYTHIA Event Generator

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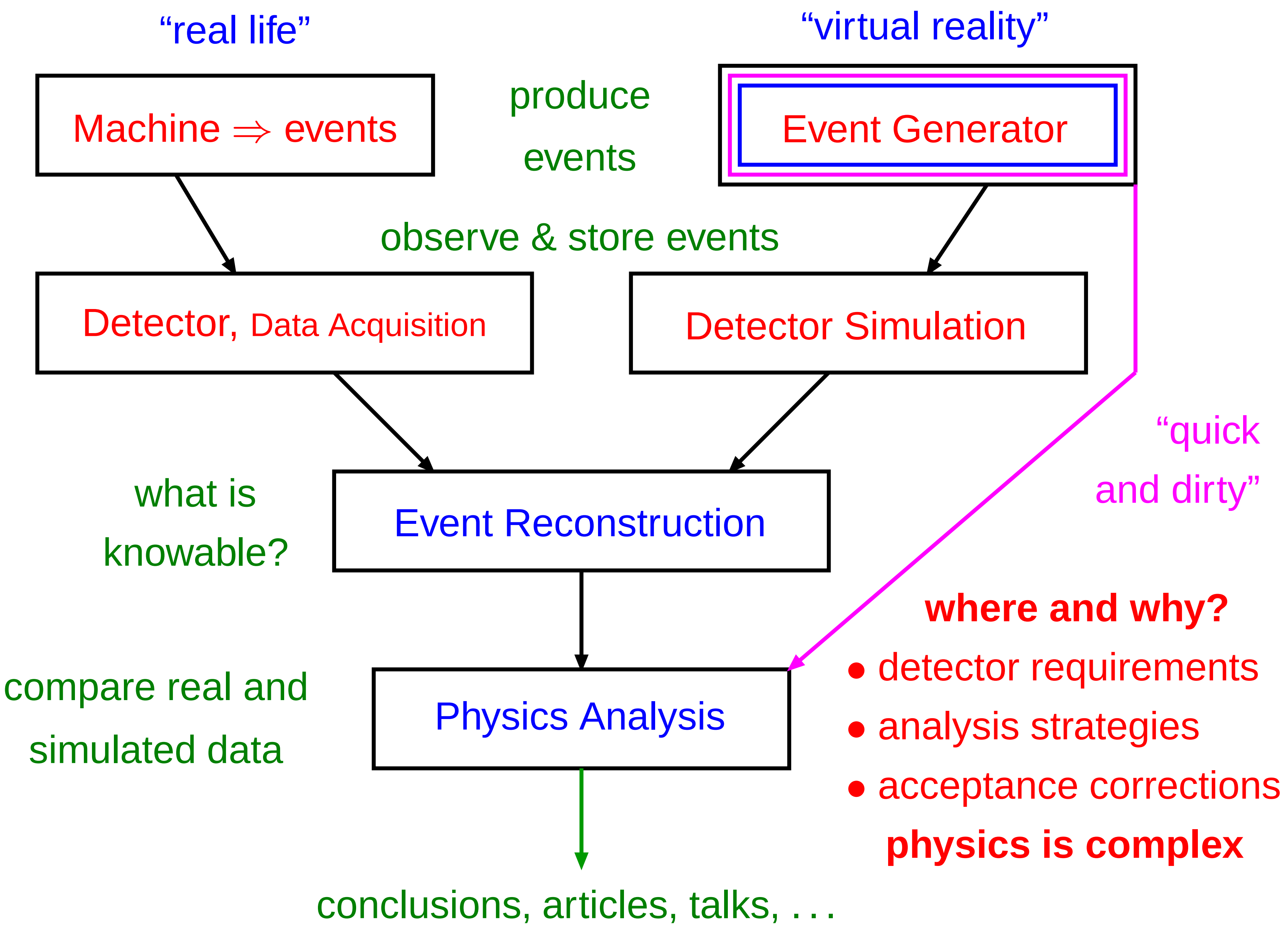
Generator and Physics Overview
Subprocess Survey
Matrix Elements vs. Parton Showers
Underlying Event and Hadronization
Outlook

Event Generator Position



Event Physics Overview

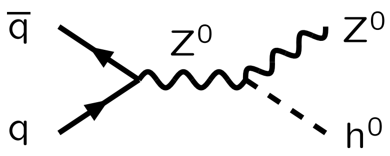
Structure of the basic generation process:

(**Not** in physical time order, but $\sim$ by order of consideration.)

1) Hard subprocess:

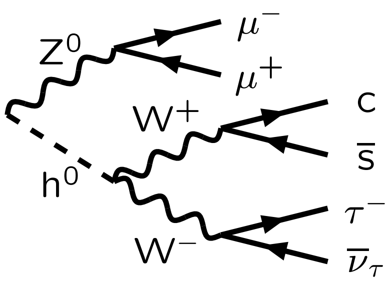
$|\mathcal{M}|^2$, Breit-Wigners,

parton densities.

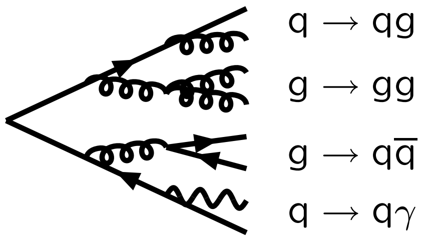


2) Resonance decays:

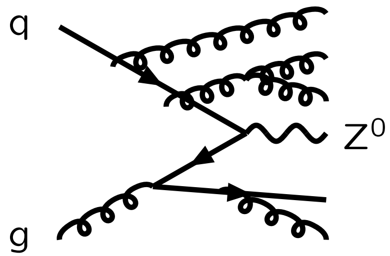
includes correlations.



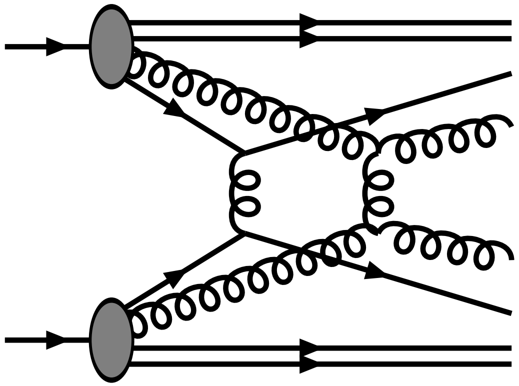
3) Final-state parton showers.



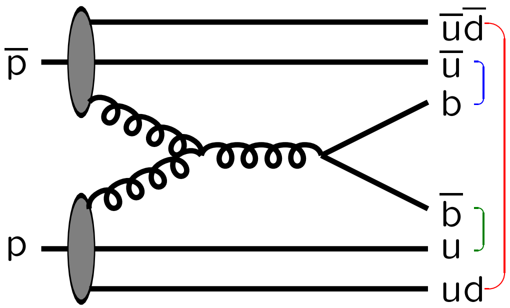
4) Initial-state parton showers.



5) Multiple parton–parton interactions.

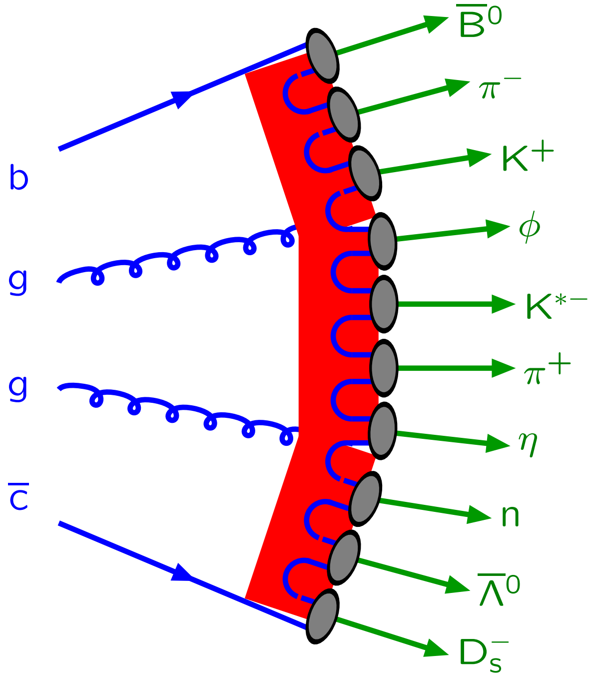


6) Beam remnants, with colour connections.

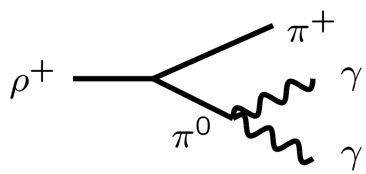


5) + 6) $\approx$ Underlying Event

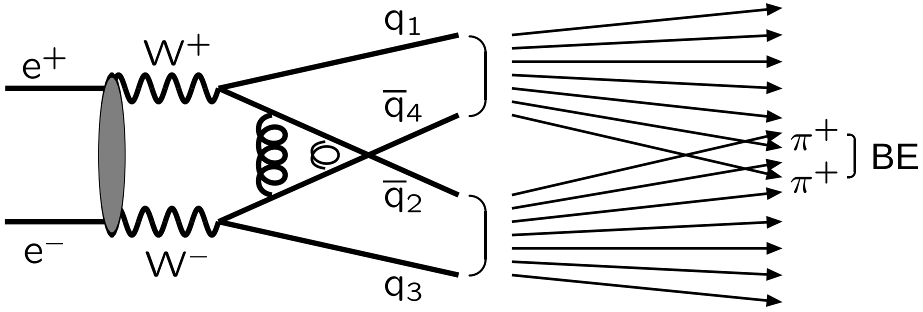
7) Hadronization



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



9) QCD interconnection effects:



a) colour rearrangement

(⇒ rapidity gaps?);

b) Bose-Einstein.

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

Many aspects still poorly understood,

but most good enough to work with

Generator Landscape

	General-Purpose	Specialized
Hard Processes		a lot
Resonance Decays		HDECAY, . . .
Parton Showers		Ariadne/LDC, NLLjet
Underlying Event		DPMJET
Hadronization		none (?)
Ordinary Decays		TAUOLA, EvtGen

General-Purpose (covering all of the above):

HERWIG

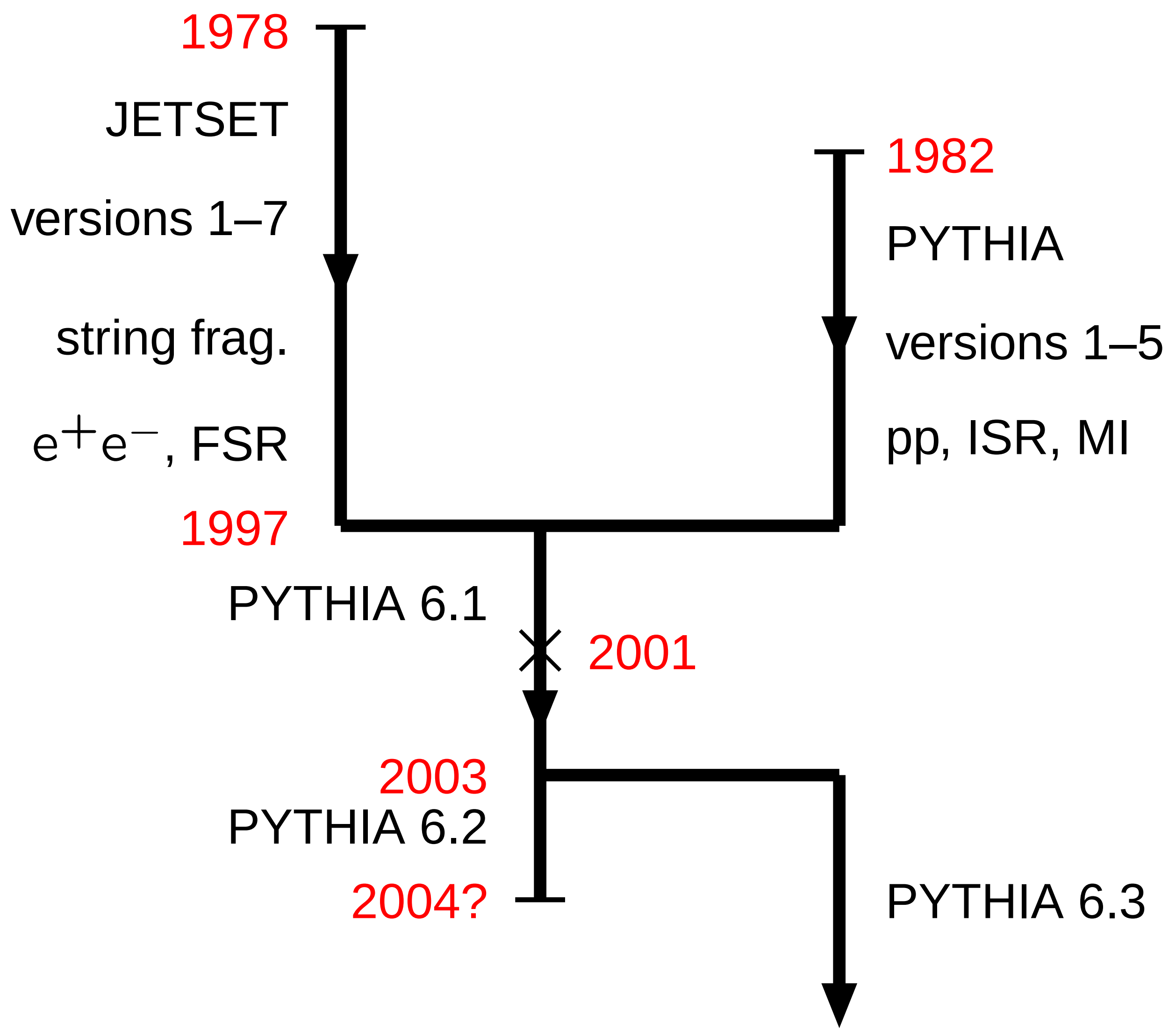
PYTHIA

ISAJET

SHERPA

specialized often best at given task, but need General-Purpose core

PYTHIA history



Time axis
not to scale

PYTHIA standalone,
but other programs
rely on PYTHIA:

LEPTO
ARIADNE/LDC
RAPGAP/CASCADE
POMPYT
HIJING
SHERPA
EVTGEN
...

All Fortran; PYTHIA in C++: not for the near future

The Smaller Picture: Subprocess Survey

Kind	Process	PYT	HER	ISA
QCD & related	Soft QCD	⋆	⋆	⋆
	Hard QCD	⋆	⋆	⋆
	Heavy flavour	⋆	⋆	⋆
Electroweak SM	Single $\gamma^*/Z^0/W^\pm$	⋆	⋆	⋆
	$(\gamma/\gamma^*/Z^0/W^\pm/f/g)^2$	⋆	⋆	⋆
	Light SM Higgs	⋆	⋆	⋆
	Heavy SM Higgs	⋆	⋆	⋆
SUSY BSM	$h^0/H^0/A^0/H^\pm$	⋆	⋆	⋆
	SUSY	⋆	⋆	⋆
	$\not{R}$ SUSY	⋆	⋆	—
Other BSM	Technicolor	⋆	—	(⋆)
	New gauge bosons	⋆	—	—
	Compositeness	⋆	—	—
	Leptoquarks	⋆	—	—
	$H^{\pm\pm}$ (from LR-sym.)	⋆	—	—
	Extra dimensions	(⋆)	(⋆)	(⋆)

Subprocess Summary Table

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	$q_i f_j \to Q_k f_l$

No.	Subprocess
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	$f_i \bar{f}_i \to g Z^0$

No.	Subprocess
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	$gg \to g\gamma$
Deeply Inel. Scatt.:	
10	$f_i f_j \to f_k f_l$
99	$\gamma^* q \to q$

. . . part 2

No.	Subprocess
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	$q_i\gamma \to q_k\pi^\pm$
Light SM Higgs:	
3	$f_i\bar{f}_i \to h^0$
24	$f_i\bar{f}_i \to Z^0h^0$
26	$f_i\bar{f}_j \to W^\pm h^0$

No.	Subprocess
32	$f_i g \to f_i h^0$
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	$Z^0Z^0 \to h^0$
8	$W^+W^- \to h^0$
71	$Z^0_LZ^0_L \to Z^0_LZ^0_L$
72	$Z^0_LZ^0_L \to W^+_LW^-_L$
73	$Z^0_LW^\pm_L \to Z^0_LW^\pm_L$
76	$W^+_LW^-_L \to Z^0_LZ^0_L$
77	$W^\pm_LW^\pm_L \to W^\pm_LW^\pm_L$

No.	Subprocess
BSM Neutral Higgs:	
151	$f_i\bar{f}_i \to H^0$
152	$gg \to H^0$
153	$\gamma\gamma \to H^0$
171	$f_i\bar{f}_i \to Z^0H^0$
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	$f_i\bar{f}_i \to Z^0A^0$
177	$f_i\bar{f}_j \to W^\pm A^0$
178	$f_i f_j \to f_i f_j A^0$
179	$f_i f_j \to f_k f_l A^0$

. . . part 3

No.	Subprocess
186	$gg \to Q_k\overline{Q}_k A^0$
187	$q_i\overline{q}_i \to Q_k\overline{Q}_k A^0$
188	$f_i\overline{f}_i \to gA^0$
189	$f_i g \to f_i A^0$
190	$gg \to gA^0$
Charged Higgs:	
143	$f_i\overline{f}_j \to H^+$
161	$f_i g \to f_k H^+$
Higgs pairs:	
297	$f_i\overline{f}_j \to H^\pm h^0$
298	$f_i\overline{f}_j \to H^\pm H^0$
299	$f_i\overline{f}_i \to A^0 h^0$
300	$f_i\overline{f}_i \to A^0 H^0$
301	$f_i\overline{f}_i \to H^+ H^-$
New gauge bosons:	
141	$f_i\overline{f}_i \to \gamma/Z^0/Z'^0$
142	$f_i\overline{f}_j \to W'^+$
144	$f_i\overline{f}_j \to R$

No.	Subprocess
Technicolor:	
149	$gg \to \eta_{tc}$
191	$f_i\overline{f}_i \to \rho^0_{tc}$
192	$f_i\overline{f}_j \to \rho^+_{tc}$
193	$f_i\overline{f}_i \to \omega^0_{tc}$
194	$f_i\overline{f}_i \to f_k\overline{f}_k$
195	$f_i\overline{f}_j \to f_k\overline{f}_l$
361	$f_i\overline{f}_i \to W^+_L W^-_L$
362	$f_i\overline{f}_i \to W^\pm_L \pi^\mp_{tc}$
363	$f_i\overline{f}_i \to \pi^+_{tc}\pi^-_{tc}$
364	$f_i\overline{f}_i \to \gamma\pi^0_{tc}$
365	$f_i\overline{f}_i \to \gamma\pi'^0_{tc}$
366	$f_i\overline{f}_i \to Z^0\pi^0_{tc}$
367	$f_i\overline{f}_i \to Z^0\pi'^0_{tc}$
368	$f_i\overline{f}_i \to W^\pm\pi^\mp_{tc}$
370	$f_i\overline{f}_j \to W^\pm_L Z^0_L$
371	$f_i\overline{f}_j \to W^\pm_L \pi^0_{tc}$
372	$f_i\overline{f}_j \to \pi^\pm_{tc} Z^0_L$
373	$f_i\overline{f}_j \to \pi^\pm_{tc}\pi^0_{tc}$
374	$f_i\overline{f}_j \to \gamma\pi^\pm_{tc}$

No.	Subprocess
375	$f_i\overline{f}_j \to Z^0\pi^\pm_{tc}$
376	$f_i\overline{f}_j \to W^\pm\pi^0_{tc}$
377	$f_i\overline{f}_j \to W^\pm\pi'^0_{tc}$
381	$q_i q_j \to q_i q_j$
382	$q_i\overline{q}_i \to q_k\overline{q}_k$
383	$q_i\overline{q}_i \to gg$
384	$f_i g \to f_i g$
385	$gg \to q_k\overline{q}_k$
386	$gg \to gg$
387	$f_i\overline{f}_i \to Q_k\overline{Q}_k$
388	$gg \to Q_k\overline{Q}_k$
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	$q_i\overline{q}_i \to e^\pm e^{*\mp}$
165	$f_i\overline{f}_i(\to \gamma^*/Z^0) \to f_k\overline{f}_k$
166	$f_i\overline{f}_j(\to W^\pm) \to f_k\overline{f}_l$

…part 4

No.	Subprocess
Leptoquarks:	
145	$q_i \ell_j \to L_Q$
162	$qg \to \ell L_Q$
163	$gg \to L_Q \overline{L}_Q$
164	$q_i \overline{q}_i \to L_Q \overline{L}_Q$
Left–right symmetry:	
341	$\ell_i \ell_j \to H_L^{\pm\pm}$
342	$\ell_i \ell_j \to H_R^{\pm\pm}$
343	$\ell_i^{\pm} \gamma \to H_L^{\pm\pm} e^{\mp}$
344	$\ell_i^{\pm} \gamma \to H_R^{\pm\pm} e^{\mp}$
345	$\ell_i^{\pm} \gamma \to H_L^{\pm\pm} \mu^{\mp}$
346	$\ell_i^{\pm} \gamma \to H_R^{\pm\pm} \mu^{\mp}$
347	$\ell_i^{\pm} \gamma \to H_L^{\pm\pm} \tau^{\mp}$
348	$\ell_i^{\pm} \gamma \to H_R^{\pm\pm} \tau^{\mp}$
349	$f_i \overline{f}_i \to H_L^{++} H_L^{--}$
350	$f_i \overline{f}_i \to H_R^{++} H_R^{--}$
351	$f_i f_j \to f_k f_l H_L^{\pm\pm}$
352	$f_i f_j \to f_k f_l H_R^{\pm\pm}$
353	$f_i \overline{f}_i \to Z_R^0$
354	$f_i \overline{f}_j \to W_R^{\pm}$

No.	Subprocess
Extra Dimensions:	
391	$f\overline{f} \to G^*$
392	$gg \to G^*$
393	$q\overline{q} \to gG^*$
394	$qg \to qG^*$
395	$gg \to gG^*$
SUSY:	
201	$f_i \overline{f}_i \to \tilde{e}_L \tilde{e}_L^*$
202	$f_i \overline{f}_i \to \tilde{e}_R \tilde{e}_R^*$
203	$f_i \overline{f}_i \to \tilde{e}_L \tilde{e}_R^* +$
204	$f_i \overline{f}_i \to \tilde{\mu}_L \tilde{\mu}_L^*$
205	$f_i \overline{f}_i \to \tilde{\mu}_R \tilde{\mu}_R^*$
206	$f_i \overline{f}_i \to \tilde{\mu}_L \tilde{\mu}_R^* +$
207	$f_i \overline{f}_i \to \tilde{\tau}_1 \tilde{\tau}_1^*$
208	$f_i \overline{f}_i \to \tilde{\tau}_2 \tilde{\tau}_2^*$
209	$f_i \overline{f}_i \to \tilde{\tau}_1 \tilde{\tau}_2^* +$
210	$f_i \overline{f}_j \to \tilde{\ell}_L \tilde{\nu}_\ell^* +$
211	$f_i \overline{f}_j \to \tilde{\tau}_1 \tilde{\nu}_\tau^* +$
212	$f_i \overline{f}_j \to \tilde{\tau}_2 \tilde{\nu}_\tau^* +$
213	$f_i \overline{f}_i \to \tilde{\nu}_\ell \tilde{\nu}_\ell^*$

No.	Subprocess
214	$f_i \overline{f}_i \to \tilde{\nu}_\tau \tilde{\nu}_\tau^*$
216	$f_i \overline{f}_i \to \tilde{\chi}_1 \tilde{\chi}_1$
217	$f_i \overline{f}_i \to \tilde{\chi}_2 \tilde{\chi}_2$
218	$f_i \overline{f}_i \to \tilde{\chi}_3 \tilde{\chi}_3$
219	$f_i \overline{f}_i \to \tilde{\chi}_4 \tilde{\chi}_4$
220	$f_i \overline{f}_i \to \tilde{\chi}_1 \tilde{\chi}_2$
221	$f_i \overline{f}_i \to \tilde{\chi}_1 \tilde{\chi}_3$
222	$f_i \overline{f}_i \to \tilde{\chi}_1 \tilde{\chi}_4$
223	$f_i \overline{f}_i \to \tilde{\chi}_2 \tilde{\chi}_3$
224	$f_i \overline{f}_i \to \tilde{\chi}_2 \tilde{\chi}_4$
225	$f_i \overline{f}_i \to \tilde{\chi}_3 \tilde{\chi}_4$
226	$f_i \overline{f}_i \to \tilde{\chi}_1^{\pm} \tilde{\chi}_1^{\mp}$
227	$f_i \overline{f}_i \to \tilde{\chi}_2^{\pm} \tilde{\chi}_2^{\mp}$
228	$f_i \overline{f}_i \to \tilde{\chi}_1^{\pm} \tilde{\chi}_2^{\mp}$
229	$f_i \overline{f}_j \to \tilde{\chi}_1 \tilde{\chi}_1^{\pm}$
230	$f_i \overline{f}_j \to \tilde{\chi}_2 \tilde{\chi}_1^{\pm}$
231	$f_i \overline{f}_j \to \tilde{\chi}_3 \tilde{\chi}_1^{\pm}$
232	$f_i \overline{f}_j \to \tilde{\chi}_4 \tilde{\chi}_1^{\pm}$
233	$f_i \overline{f}_j \to \tilde{\chi}_1 \tilde{\chi}_2^{\pm}$
234	$f_i \overline{f}_j \to \tilde{\chi}_2 \tilde{\chi}_2^{\pm}$

... part 5

No.	Subprocess
235	$f_i\bar{f}_j \rightarrow \tilde{\chi}_3\tilde{\chi}_2^\pm$
236	$f_i\bar{f}_j \rightarrow \tilde{\chi}_4\tilde{\chi}_2^\pm$
237	$f_i\bar{f}_i \rightarrow \tilde{g}\tilde{\chi}_1$
238	$f_i\bar{f}_i \rightarrow \tilde{g}\tilde{\chi}_2$
239	$f_i\bar{f}_i \rightarrow \tilde{g}\tilde{\chi}_3$
240	$f_i\bar{f}_i \rightarrow \tilde{g}\tilde{\chi}_4$
241	$f_i\bar{f}_j \rightarrow \tilde{g}\tilde{\chi}_1^\pm$
242	$f_i\bar{f}_j \rightarrow \tilde{g}\tilde{\chi}_2^\pm$
243	$f_i\bar{f}_i \rightarrow \tilde{g}\tilde{g}$
244	$gg \rightarrow \tilde{g}\tilde{g}$
246	$f_ig \rightarrow \tilde{q}_{iL}\tilde{\chi}_1$
247	$f_ig \rightarrow \tilde{q}_{iR}\tilde{\chi}_1$
248	$f_ig \rightarrow \tilde{q}_{iL}\tilde{\chi}_2$
249	$f_ig \rightarrow \tilde{q}_{iR}\tilde{\chi}_2$
250	$f_ig \rightarrow \tilde{q}_{iL}\tilde{\chi}_3$
251	$f_ig \rightarrow \tilde{q}_{iR}\tilde{\chi}_3$
252	$f_ig \rightarrow \tilde{q}_{iL}\tilde{\chi}_4$
253	$f_ig \rightarrow \tilde{q}_{iR}\tilde{\chi}_4$

No.	Subprocess
254	$f_ig \rightarrow \tilde{q}_{jL}\tilde{\chi}_1^\pm$
256	$f_ig \rightarrow \tilde{q}_{jL}\tilde{\chi}_2^\pm$
258	$f_ig \rightarrow \tilde{q}_{iL}\tilde{g}$
259	$f_ig \rightarrow \tilde{q}_{iR}\tilde{g}$
261	$f_i\bar{f}_i \rightarrow \tilde{t}_1\tilde{t}_1^*$
262	$f_i\bar{f}_i \rightarrow \tilde{t}_2\tilde{t}_2^*$
263	$f_i\bar{f}_i \rightarrow \tilde{t}_1\tilde{t}_2^* +$
264	$gg \rightarrow \tilde{t}_1\tilde{t}_1^*$
265	$gg \rightarrow \tilde{t}_2\tilde{t}_2^*$
271	$f_if_j \rightarrow \tilde{q}_{iL}\tilde{q}_{jL}$
272	$f_if_j \rightarrow \tilde{q}_{iR}\tilde{q}_{jR}$
273	$f_if_j \rightarrow \tilde{q}_{iL}\tilde{q}_{jR} +$
274	$f_i\bar{f}_j \rightarrow \tilde{q}_{iL}\tilde{q}^*_{jL}$
275	$f_i\bar{f}_j \rightarrow \tilde{q}_{iR}\tilde{q}^*_{jR}$
276	$f_i\bar{f}_j \rightarrow \tilde{q}_{iL}\tilde{q}^*_{jR} +$
277	$f_i\bar{f}_i \rightarrow \tilde{q}_{jL}\tilde{q}^*_{jL}$
278	$f_i\bar{f}_i \rightarrow \tilde{q}_{jR}\tilde{q}^*_{jR}$
279	$gg \rightarrow \tilde{q}_{iL}\tilde{q}^*_{iL}$

No.	Subprocess
280	$gg \rightarrow \tilde{q}_{iR}\tilde{q}^*_{iR}$
281	$bq_i \rightarrow \tilde{b}_1\tilde{q}_{iL}$
282	$bq_i \rightarrow \tilde{b}_2\tilde{q}_{iR}$
283	$bq_i \rightarrow \tilde{b}_1\tilde{q}_{iR} + \tilde{b}_2\tilde{q}_{iL}$
284	$b\bar{q}_i \rightarrow \tilde{b}_1\tilde{q}^*_{iL}$
285	$b\bar{q}_i \rightarrow \tilde{b}_2\tilde{q}^*_{iR}$
286	$b\bar{q}_i \rightarrow \tilde{b}_1\tilde{q}^*_{iR} + \tilde{b}_2\tilde{q}^*_{iL}$
287	$f_i\bar{f}_i \rightarrow \tilde{b}_1\tilde{b}_1^*$
288	$f_i\bar{f}_i \rightarrow \tilde{b}_2\tilde{b}_2^*$
289	$gg \rightarrow \tilde{b}_1\tilde{b}_1^*$
290	$gg \rightarrow \tilde{b}_2\tilde{b}_2^*$
291	$bb \rightarrow \tilde{b}_1\tilde{b}_1$
292	$bb \rightarrow \tilde{b}_2\tilde{b}_2$
293	$bb \rightarrow \tilde{b}_1\tilde{b}_2$
294	$bg \rightarrow \tilde{b}_1\tilde{g}$
295	$bg \rightarrow \tilde{b}_2\tilde{g}$
296	$b\bar{b} \rightarrow \tilde{b}_1\tilde{b}_2^* +$

A Giant on Clay Feet

Subprocess list *looks* impressive, and has involved a lot of hard work, but:

$\star$ Processes usually only in lowest nontrivial order
$\Rightarrow$ need programs that include HO loop corrections to cross sections, alternatively do $(p_\perp, y)$-dependent rescaling by hand?

$\star$ No multijet topologies
$\Rightarrow$ have to trust shower to get it right,
alternatively match to HO (non-loop) ME generators

$\star$ Spin correlations often absent or incomplete
e.g. top produced unpolarized, while $\mathrm{t} \to \mathrm{bW}^+ \to \mathrm{b}\ell^+\nu_\ell$ decay correct
$\Rightarrow$ have to use external programs when important

$\star$ New physics scenarios appear at rapid pace
$\Rightarrow$ need to have a bigger class of “one-issue experts” contributing code

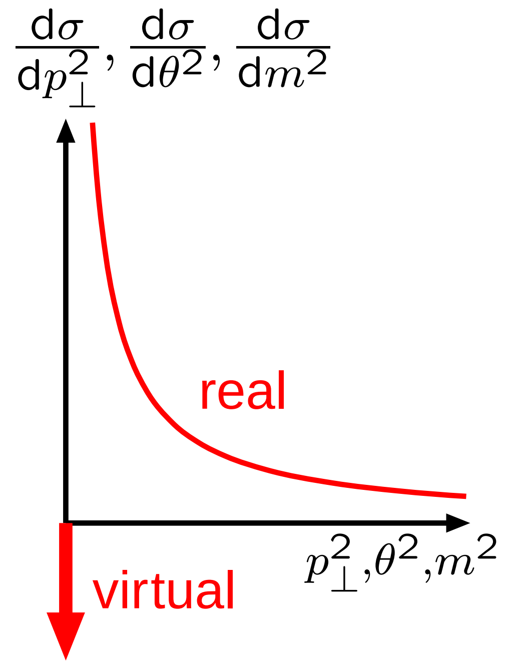
$\Longrightarrow$The Les Houches Accord

(Q: So why was the PYTHIA process library ever built? A: Automatic code generation has only reached maturity in the last few years!)

Matrix Elements vs. Parton Showers

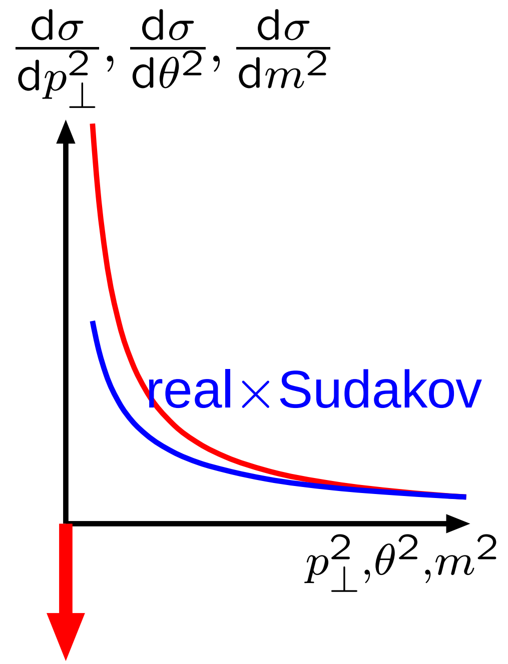
ME : Matrix Elements

- $+$ 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*



Parton Shower Approach

(already well covered by B.R. Webber, so brief here)

3 common algorithms, each with its advantages and disadvantages:

HERWIG: θ-ordered emissions (ISR & FSR)

ARIADNE: $p_\perp$-ordered emissions (FSR primarily)

PYTHIA: M^2, Q^2-ordered emissions (ISR & FSR)

New in PYTHIA 6.3: $p_\perp$-ordered emissions (ISR & FSR)

Matrix Elements and Parton Showers

Marriage desirable! But how?

Much work ongoing $\Longrightarrow$ no established orthodoxy

Three main areas, in ascending order of complication:

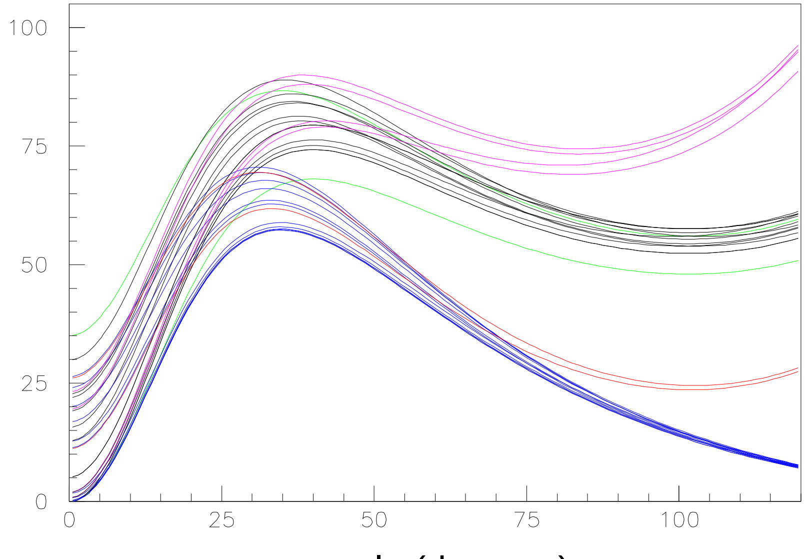
1) Match to lowest-order nontrivial process — merging

2) Combine leading-order multiparton process — vetoed parton showers

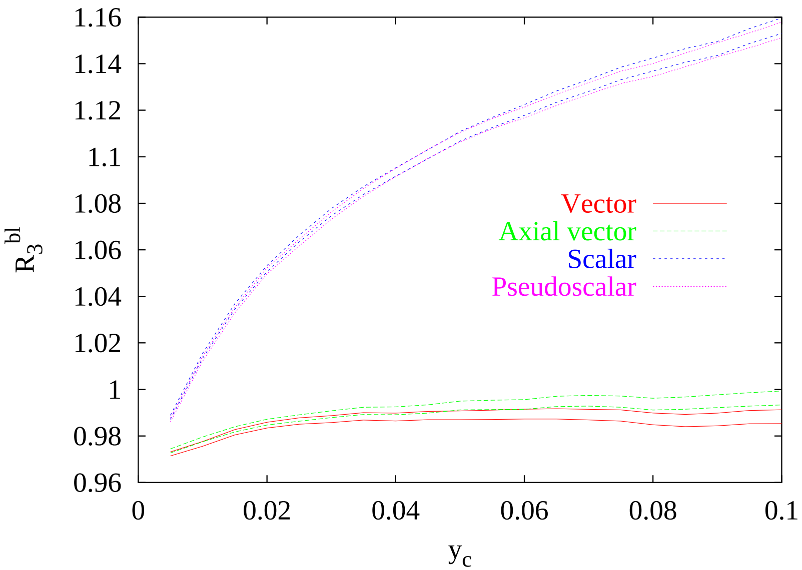
3) Match to next-to-leading order process — MC@NLO

PYTHIA performs merging with generic FSR $a \to bc\mathrm{g}$ ME,
in SM: $\gamma^*/\mathrm{Z}^0/\mathrm{W}^\pm \to \mathrm{q}\overline{\mathrm{q}}$, $\mathrm{t} \to \mathrm{bW}^+$, $\mathrm{H}^0 \to \mathrm{q}\overline{\mathrm{q}}$,
and MSSM: $\mathrm{t} \to \mathrm{bH}^+$, $\mathrm{Z}^0 \to \tilde{\mathrm{q}}\overline{\tilde{\mathrm{q}}}$, $\tilde{\mathrm{q}} \to \tilde{\mathrm{q}}'\mathrm{W}^+$, $\mathrm{H}^0 \to \tilde{\mathrm{q}}\overline{\tilde{\mathrm{q}}}$, $\tilde{\mathrm{q}} \to \tilde{\mathrm{q}}'\mathrm{H}^+$,
$\chi \to \mathrm{q}\overline{\tilde{\mathrm{q}}}$, $\chi \to \mathrm{q}\overline{\tilde{\mathrm{q}}}$, $\tilde{\mathrm{q}} \to \mathrm{q}\chi$, $\mathrm{t} \to \tilde{\mathrm{t}}\chi$, $\tilde{\mathrm{g}} \to \mathrm{q}\overline{\tilde{\mathrm{q}}}$, $\tilde{\mathrm{q}} \to \mathrm{q}\tilde{\mathrm{g}}$, $\mathrm{t} \to \tilde{\mathrm{t}}\tilde{\mathrm{g}}$

g emission for different colour, spin and parity:



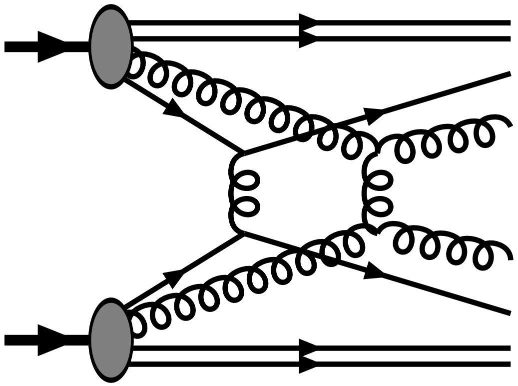
$R_3^{\mathrm{bl}}(y_c)$: mass effects in Higgs decay:



PYTHIA ISR: only $\mathrm{q}\overline{\mathrm{q}} \to \gamma^*/\mathrm{Z}^0/\mathrm{W}^\pm$ and $\mathrm{gg} \to \mathrm{H}^0$ (for $m_\mathrm{t} \to \infty$)
(but K factor not implemented here)

Multiple Interactions

Consequence of composite nature of hadrons!

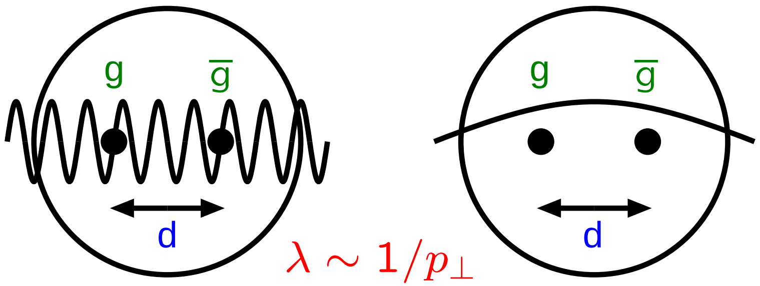


Evidence:

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

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

$$\frac{1}{2}\sigma_{\mathrm{jet}} = \int_{p^2_{\perp\mathrm{min}}}^{s/4} \frac{\mathrm{d}\sigma}{\mathrm{d}p^2_\perp}\,\mathrm{d}p^2_\perp \quad \Longleftarrow \quad \int_0^{s/4} \frac{\mathrm{d}\sigma}{\mathrm{d}p^2_\perp}\,\frac{p^4_\perp}{(p^2_{\perp0}+p^2_\perp)^2}\,\mathrm{d}p^2_\perp$$



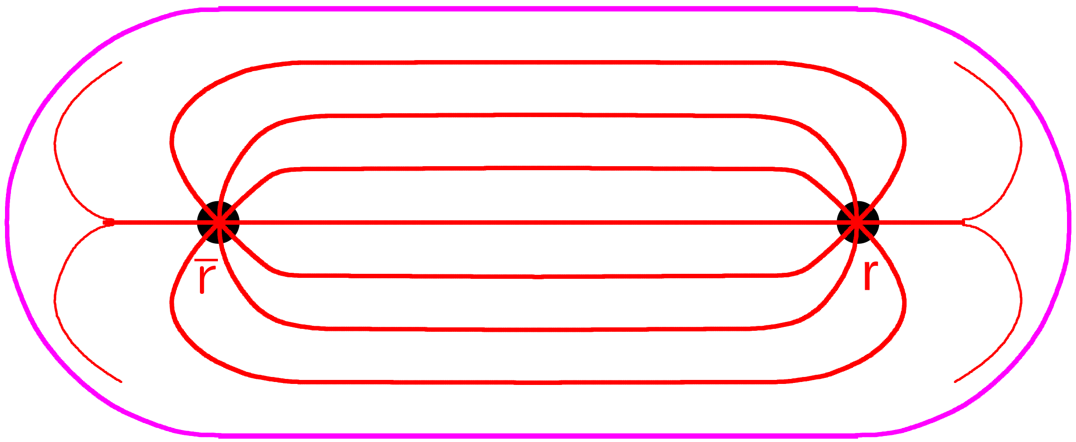
resolved screened

Measure of colour screening length d in hadron:

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

Hadronization: Lund String Model

In QCD, for large charge separation, field lines seem to be compressed to tubelike region(s) $\Rightarrow$ **string(s)**



by self-interactions among soft gluons in the "vacuum".

(Analogy: vortex lines in type II superconductor)

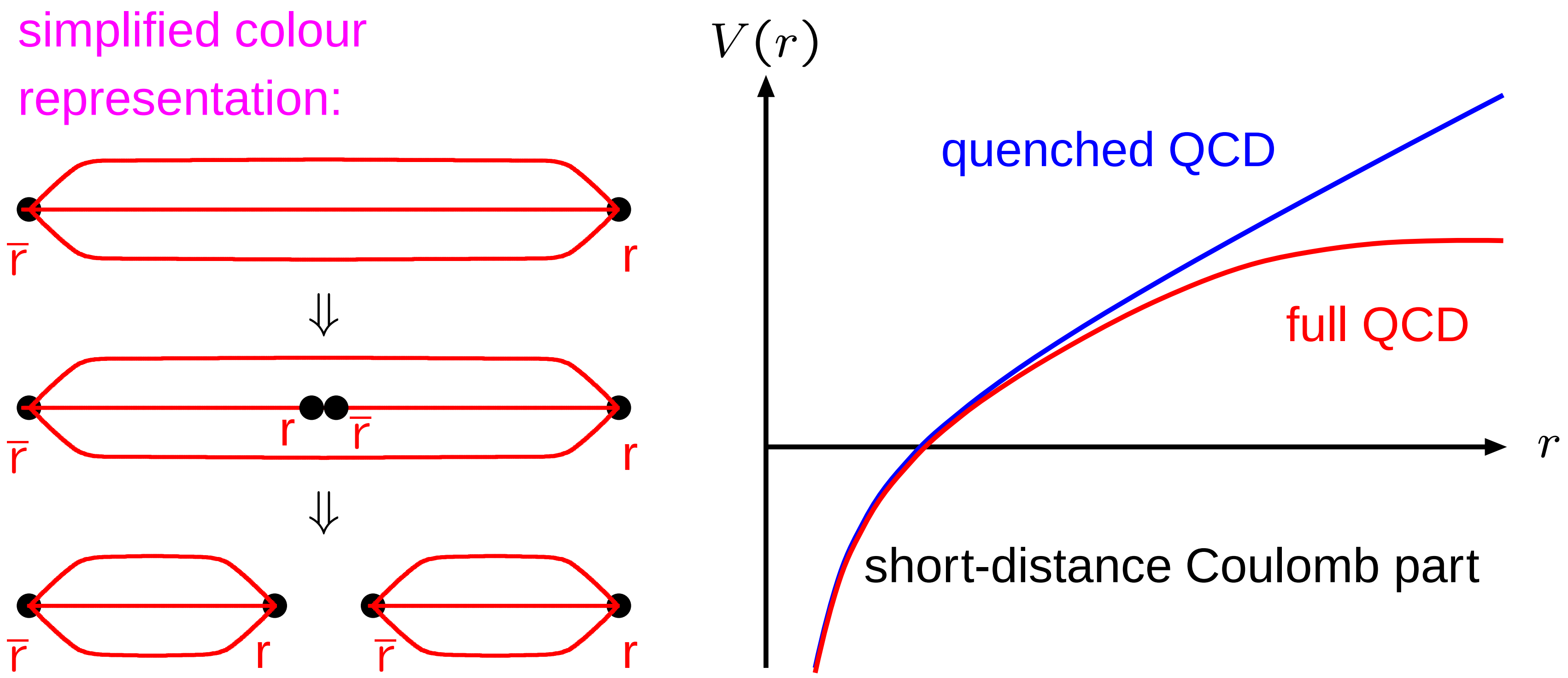
Gives linear confinement with string tension:

$$F(r) \approx \text{const} = \kappa \approx 1\ \text{GeV/fm} \quad \Longleftrightarrow \quad V(r) \approx \kappa r$$

Confirmed e.g. by quenched lattice QCD

Real world (??, or at least unquenched lattice QCD)

$\Longrightarrow$ nonperturbative string breakings $\mathrm{gg}\ldots \to \mathrm{q\overline{q}}$

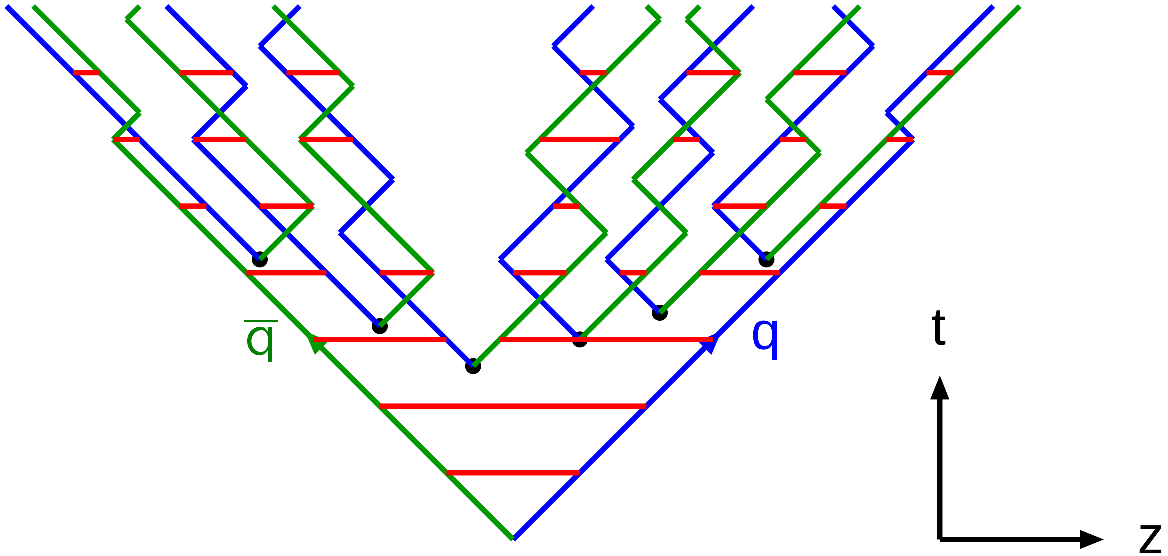


Repeat for large system ⇒ *Lund model*

which neglects Coulomb part:

$$\left|\frac{\mathrm{d}E}{\mathrm{d}x}\right| = \left|\frac{\mathrm{d}p}{\mathrm{d}x}\right| = \left|\frac{\mathrm{d}E}{\mathrm{d}t}\right| = \left|\frac{\mathrm{d}p}{\mathrm{d}t}\right| = \kappa$$

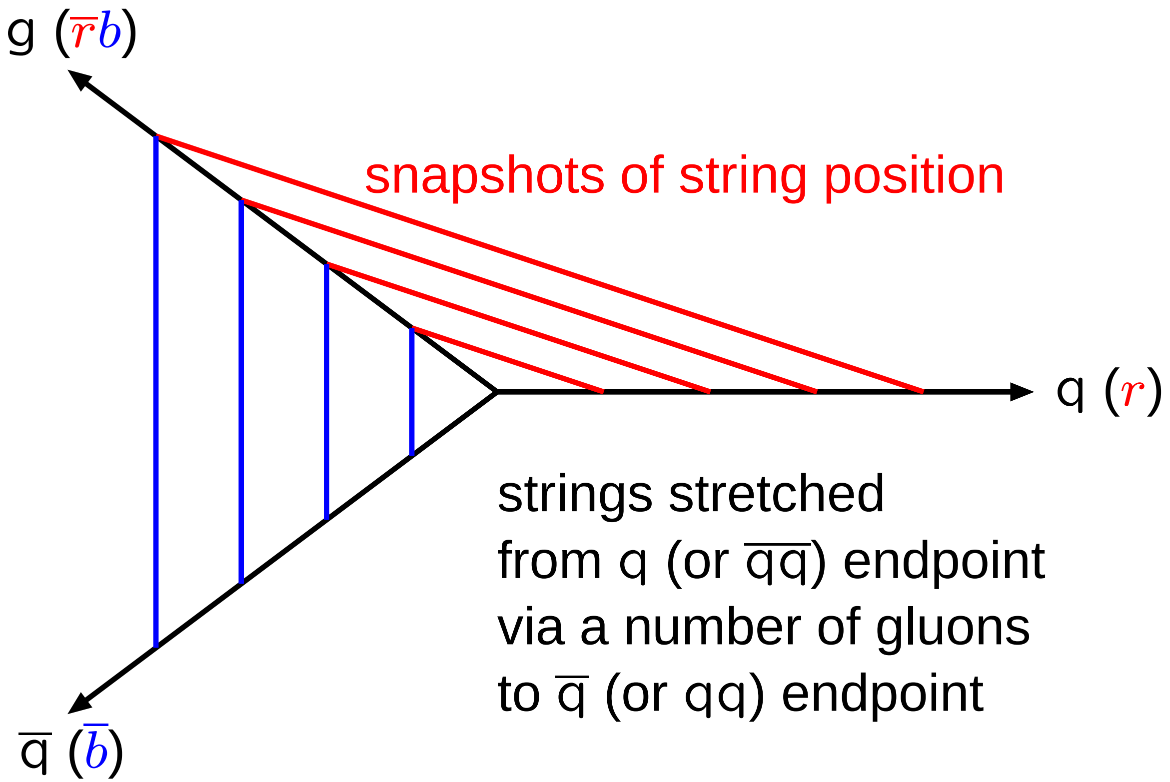
Motion of quarks and antiquarks in a $\mathrm{q}\overline{\mathrm{q}}$ system:



gives simple but powerful picture of hadron production

(with extensions to massive quarks, baryons, . . .)

The Lund gluon picture — the most characteristic feature:



Gluon = kink on string,
carrying energy
and momentum.
Force ratio
gluon/ quark = 2,
cf. QCD
$N_C/C_F = 9/4$

- Few parameters to describe energy–momentum structure!
- Many parameters to describe flavour composition!

HERWIG cluster fragmentation: the opposite

Numerous and detailed tests at LEP favour string picture
. . . but much uncertain when moving to hadron colliders.

Summary (so far)

$\star$ Big selection of subprocesses $\star$

but often not enough, so

$\star$ Standard interface for including external processes $\star$

$\star$ State-of-the-art parton showers $\star$

. . . but much to be done on ME + PS matching

$\star$ *The* trend-setting model for underlying events $\star$

$\star$ *The* most realistic and successful model for hadronization $\star$

$\star$ Extensive documentation: 450 pp manual + update notes $\star$

$\star$ Webpage `http://www.thep.lu.se/∼torbjorn/Pythia.html` $\star$

Nobody ever got fired for using PYTHIA! (?)

but also

Nobody is perfect!

So, whichever is your favourite generator,

you always need cross-checks!

Final Words of Warning

[. . .] The Monte Carlo simulation has become the major means of visualization of not only detector performance but also of physics phenomena. So far so good. But it often happens that the physics simulations provided by the Monte Carlo generators carry the authority of data itself. They look like data and feel like data, and if one is not careful they are accepted as if they were data.

[. . .] I am prepared to believe that the computer-literate generation (of which I am a little too old to be a member) is in principle no less competent and in fact benefits relative to us in the older generation by having these marvelous tools. They do allow one to look at, indeed visualize, the problems in new ways. But I also fear a kind of "terminal illness", perhaps traceable to the influence of television at an early age. There the way one learns is simply to passively stare into a screen and wait for the truth to be delivered. A number of physicists nowadays seem to do just this.

J.D. Bjorken

from a talk given at the 75th anniversary celebration of the Max-Planck Institute of Physics, Munich, Germany, December 10th, 1992. As quoted in: Beam Line, Winter 1992, Vol. 22, No. 4