LUND UNIVERSITY

Teilchenkolloquium
Heidelberg, 30 January 2001

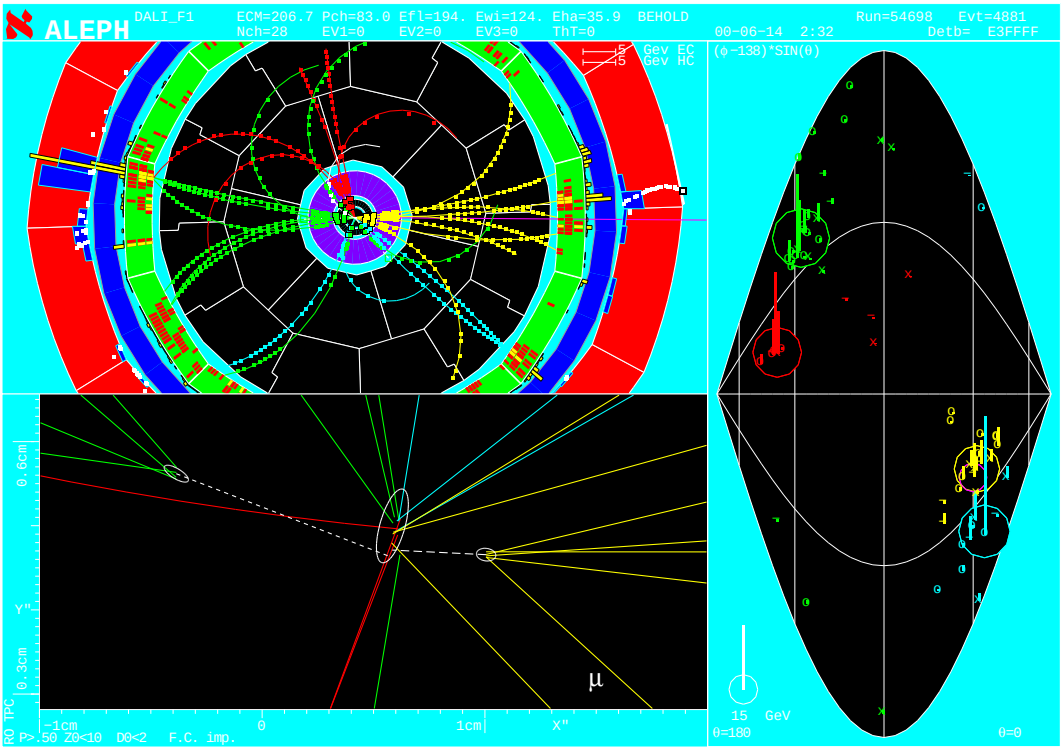
Event Generator Physics

Torbjörn Sjöstrand
Department of Theoretical Physics
Lund University

Introduction
Generator Overview
Subprocess Survey
Parton Showers
Hadronization
Beam Remnant Physics
Multiple Interactions
QCD Interconnection
Outlook

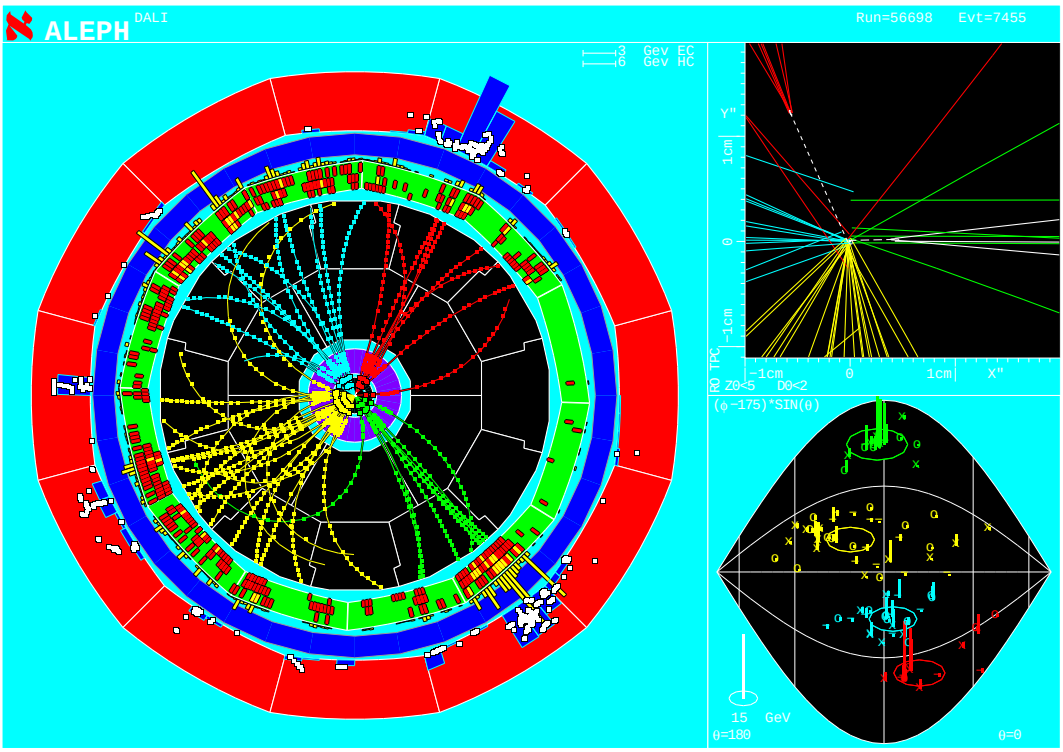
Higgs candidates from ALEPH

$m_h = 112.4$ GeV, $m_Z = 93.3$ GeV

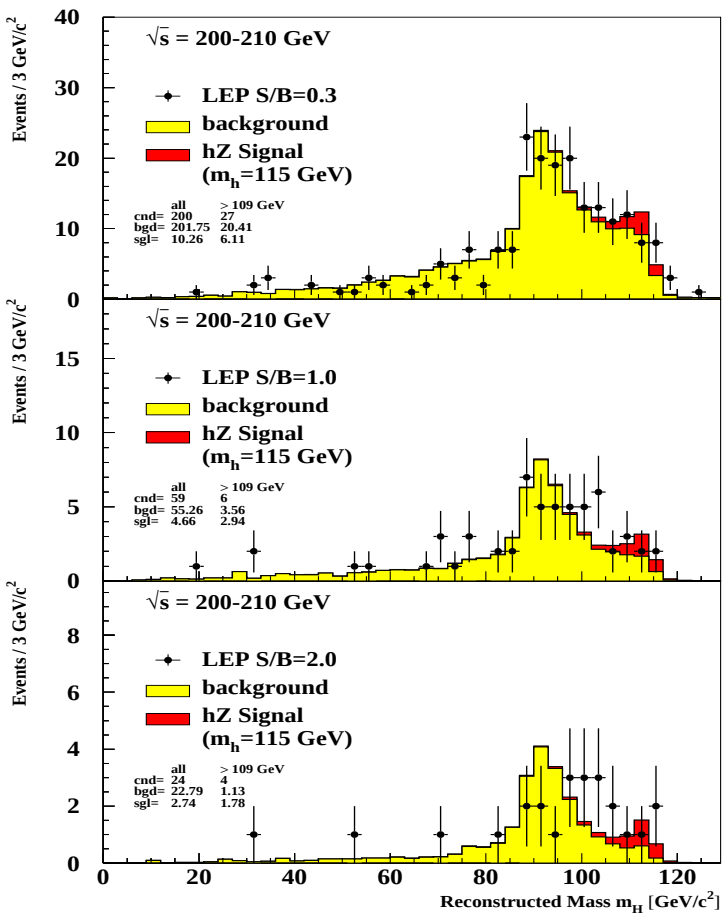


Made on 29-Aug-2000 17:06:54 by DREVERMANN with DALI_F1.
Filename: DC054698_004881_000829_1706.PS_H_CAND

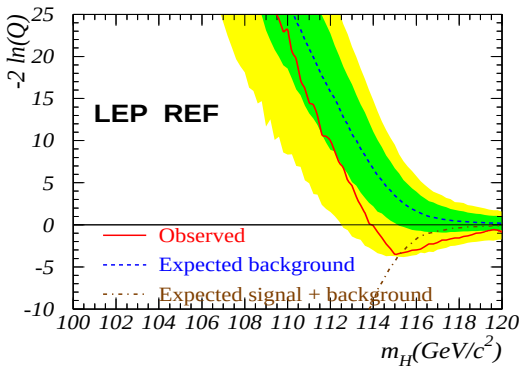
$m_h = 109.8$ GeV, $m_Z = 93.2$ GeV

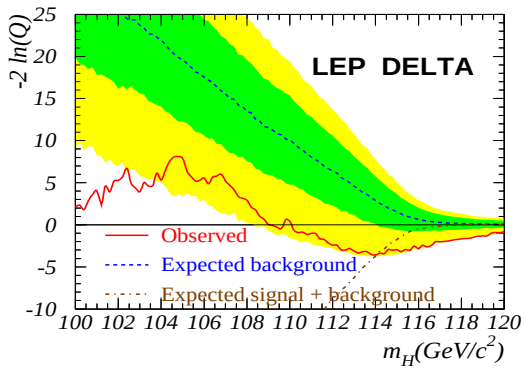


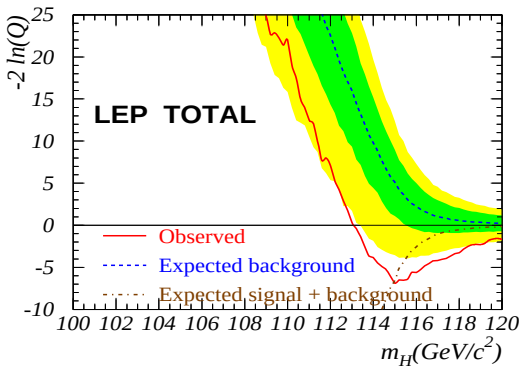
Made on 30-Aug-2000 17:24:02 by konstant with DALI_F1.
Filename: DC056698_007455_000830_1723.PS



$-2\ln(Q)$ ... REF, DELTA, TOTAL







$\Leftarrow$

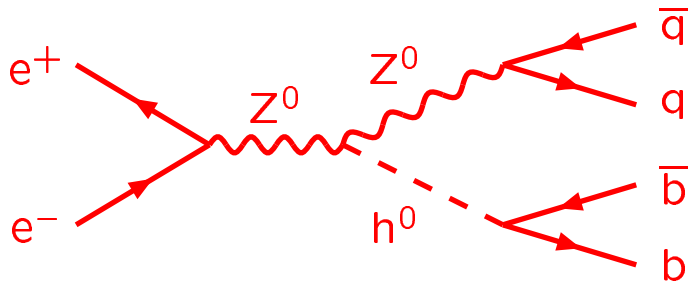
Minimum @$m_H \approx 115$ GeV

Agreement with SM Higgs cross-sect. for

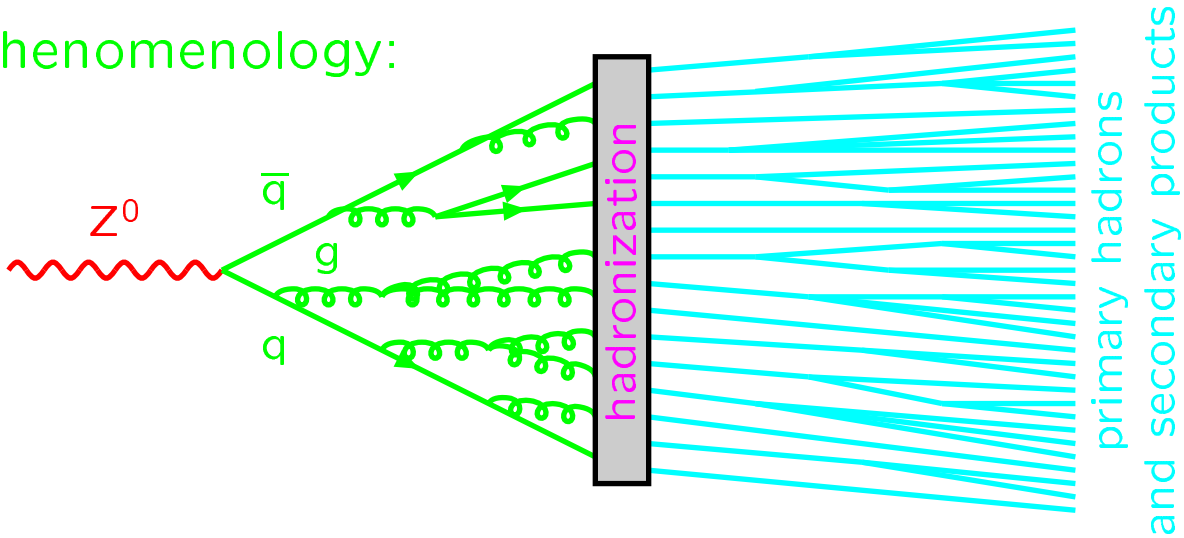
$$m_H = 115.0^{+1.3}_{-0.9} \text{ GeV}$$

True Theory: $\mathcal{L} = i\overline{\psi}\gamma^{\mu}\mathcal{D}_{\mu}\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \ldots$

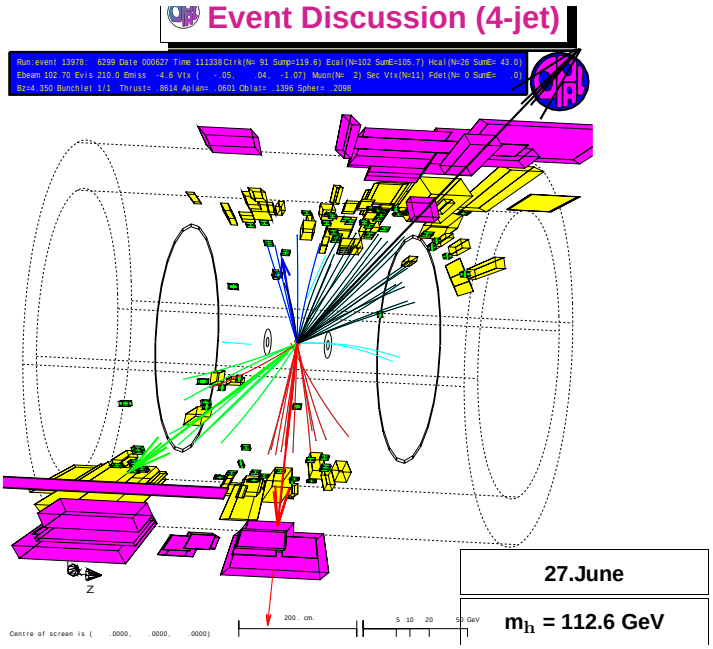
Applied Theory:



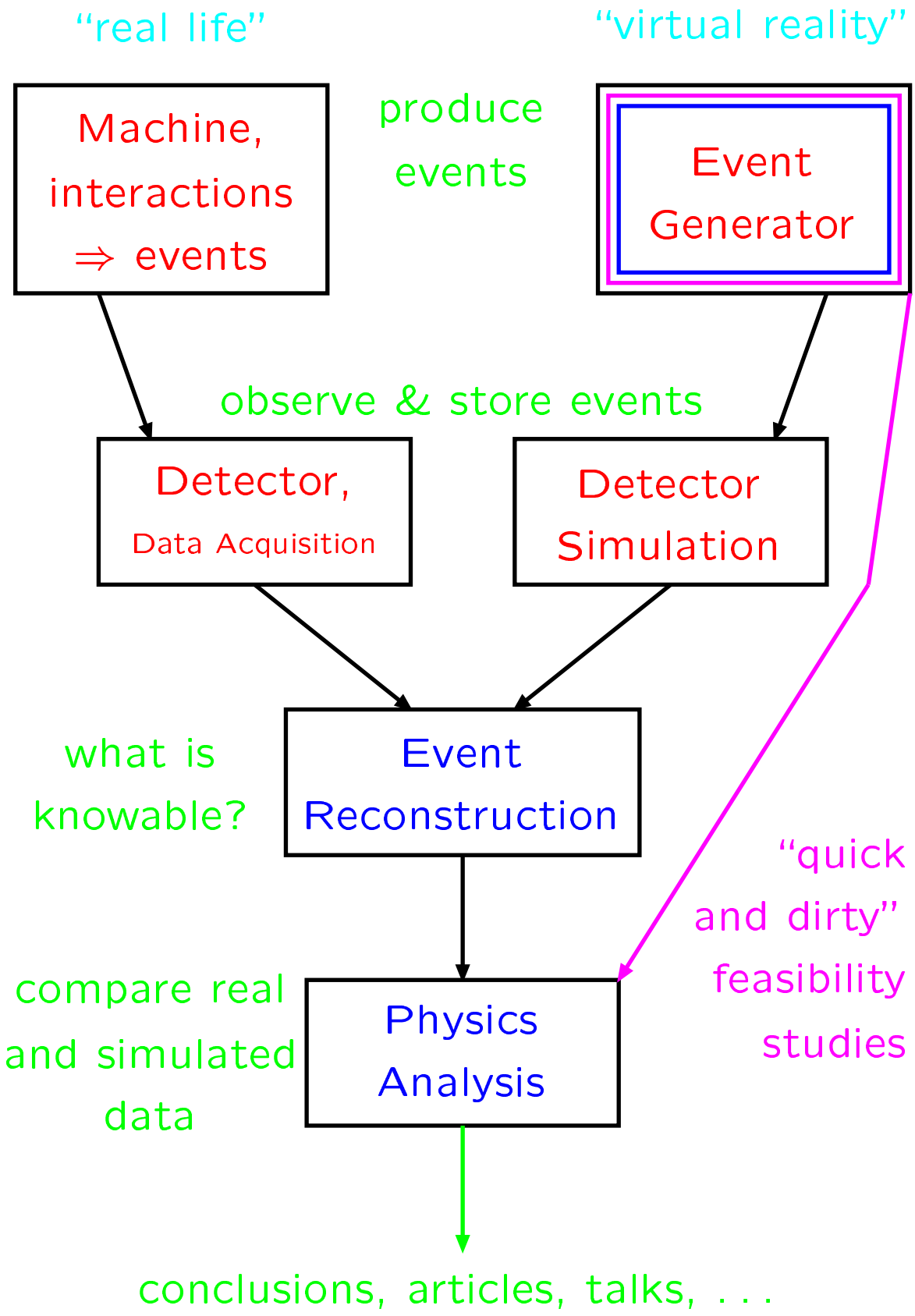
Phenomenology:



Reality:



Event Generator Position



Why Generators?

- Allow theoretical and experimental studies of *complex* multiparticle physics
- Large flexibility in physical quantities that can be addressed
- Vehicle of ideology to disseminate ideas from theorists to experimentalists

Can be used to

- predict event rates and topologies
$\Rightarrow$ can estimate feasibility
- simulate possible backgrounds
$\Rightarrow$ can devise analysis strategies
- study detector requirements
$\Rightarrow$ can optimize detector/trigger design
- study detector imperfections
$\Rightarrow$ can evaluate acceptance corrections

God does not throw dice . . .
. . . but Mother Nature does!

Which Generators?

Large spectrum, from big to small

"Lund family" and Lund-based
PYTHIA ($\Leftarrow$ JETSET): general-purpose
ARIADNE: dipole showers (Lönnblad)
LEPTO: leptoproduction (Ingelman et al.)
and many more: RAPGAP, SPHINX, . . .

HERWIG: general-purpose (Webber et al.)

ISAJET: pp & general-purpose (Paige et al.)

Specialized QCD: NLLjet, heavy ions, . . .

Single- or multiprocess parton-level only:
KORALZ, EXCALIBUR, PANDORA,
SUSYGEN, HERACLES, JETVIP,
VECBOS, NJETS, . . .

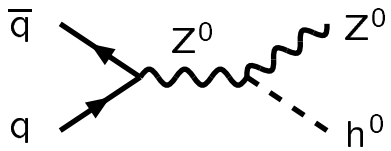
Generators of generators:
CompHEP, GRACE, HELAS, MADGRAPH,
O'Mega/WHIZARD, . . .

Many more documented in workshops: LEP 1,
LEP 2, HERA, LHC, linear colliders, . . .

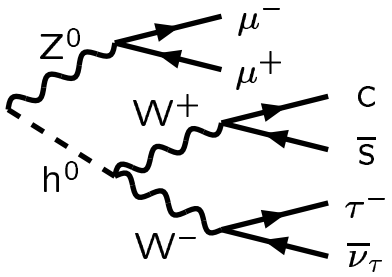
Event Physics Overview

Structure of the basic generation process:

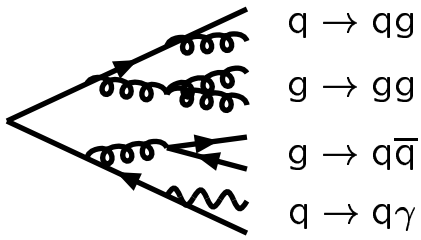
1) Hard subprocess:
$d\hat{\sigma}/d\hat{t}$, Breit-Wigners.



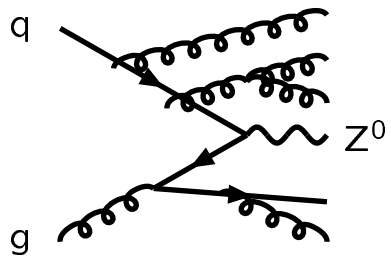
2) Resonance decays:
includes correlations.



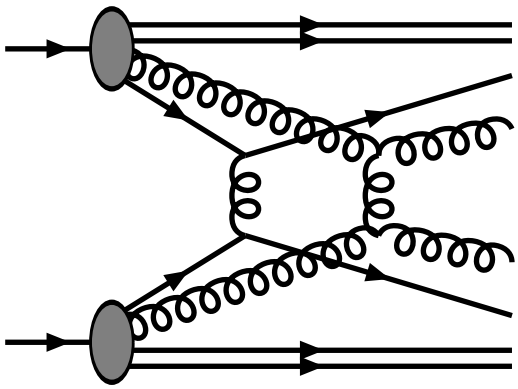
3) Final-state
parton showers:
(or matrix elements).



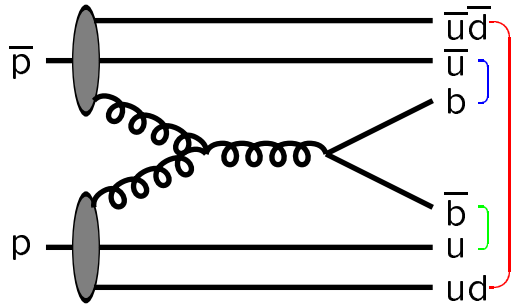
4) Initial-state
parton showers:
(or matrix elements).



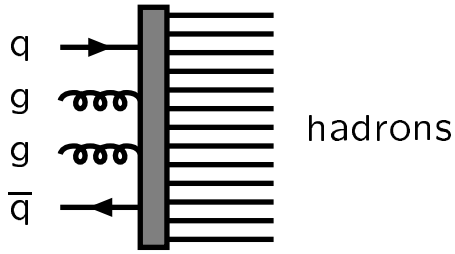
5) Multiple
parton–parton
interactions.



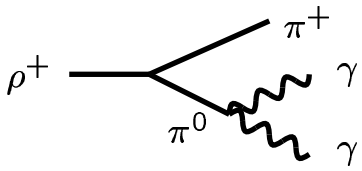
6) Beam remnants: colour-connected to rest of event



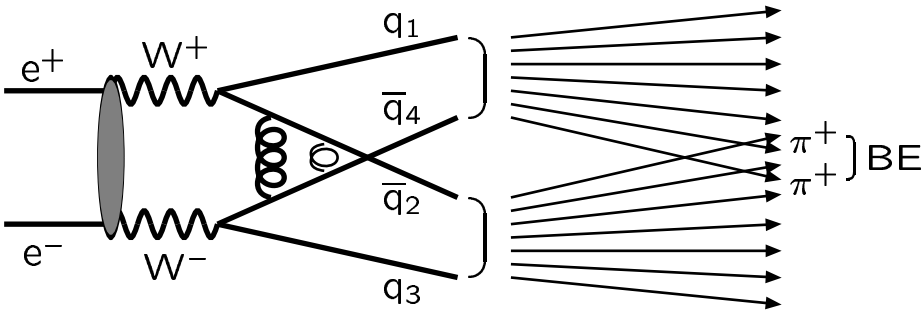
7) Hadronization (PYTHIA: string; HERWIG: cluster; ISAJET: independent).



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



9) QCD interconnection effects:



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

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

Subprocess Survey

Process	PYT	HER	ISA
QCD & related			
Soft QCD	⋆	⋆	⋆
Hard QCD	⋆	⋆	⋆
Heavy flavour	⋆	⋆	⋆
Top threshold	—	—	—
$\gamma\gamma$ physics	⋆	⋆	—
DIS	⋆	⋆	—
$\gamma^*\gamma^*$ physics	⋆	(⋆)	—
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	(⋆)	(⋆)	(⋆)

⋆ = yes, (⋆) = partial/in progress, — = no

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	$\gamma_T^* \gamma_L^* \to f_i \bar{f}_i$

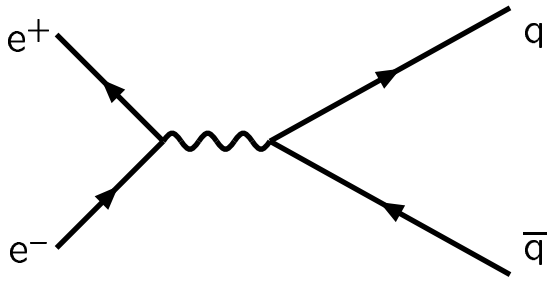
No.	Subprocess
139	$\gamma_L^* \gamma_T^* \to f_i \bar{f}_i$
140	$\gamma_L^* \gamma_L^* \to f_i \bar{f}_i$
80	$q_i \gamma \to q_k \pi^\pm$
Light SM Higgs:	
3	$f_i \bar{f}_i \to h^0$
24	$f_i \bar{f}_i \to Z^0 h^0$
26	$f_i \bar{f}_j \to W^\pm h^0$
102	$gg \to h^0$
103	$\gamma\gamma \to h^0$
110	$f_i \bar{f}_i \to \gamma h^0$
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	$Z_L^0 Z_L^0 \to Z_L^0 Z_L^0$
72	$Z_L^0 Z_L^0 \to W_L^+ W_L^-$
73	$Z_L^0 W_L^\pm \to Z_L^0 W_L^\pm$
76	$W_L^+ W_L^- \to Z_L^0 Z_L^0$
77	$W_L^\pm W_L^\pm \to W_L^\pm W_L^\pm$
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	$\ell_i \ell_j \to H_L^{\pm\pm}$
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	$f_i \bar{f}_i \to H_L^{++} H_L^{--}$
350	$f_i \bar{f}_i \to H_R^{++} H_R^{--}$
351	$f_i f_j \to f_k f_l H_L^{\pm\pm}$
352	$f_i f_j \to f_k f_l H_R^{\pm\pm}$
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	$f_i \bar{f}_i \to \rho_{tc}^0$
192	$f_i \bar{f}_j \to \rho_{tc}^+$
193	$f_i \bar{f}_i \to \omega_{tc}^0$
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	$f_i \bar{f}_i \to W_L^\pm \pi_{tc}^\mp$
363	$f_i \bar{f}_i \to \pi_{tc}^+ \pi_{tc}^-$
364	$f_i \bar{f}_i \to \gamma \pi_{tc}^0$
365	$f_i \bar{f}_i \to \gamma \pi'^0_{tc}$
366	$f_i \bar{f}_i \to Z^0 \pi_{tc}^0$
367	$f_i \bar{f}_i \to Z^0 \pi'^0_{tc}$
368	$f_i \bar{f}_i \to W^\pm \pi_{tc}^\mp$
370	$f_i \bar{f}_j \to W_L^\pm Z_L^0$
371	$f_i \bar{f}_j \to W_L^\pm \pi_{tc}^0$
372	$f_i \bar{f}_j \to \pi_{tc}^\pm Z_L^0$
373	$f_i \bar{f}_j \to \pi_{tc}^\pm \pi_{tc}^0$
374	$f_i \bar{f}_j \to \gamma \pi_{tc}^\pm$
375	$f_i \bar{f}_j \to Z^0 \pi_{tc}^\pm$
376	$f_i \bar{f}_j \to W^\pm \pi_{tc}^0$
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	$f_i \bar{f}_i \to \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$
227	$f_i \bar{f}_i \to \tilde{\chi}_2^\pm \tilde{\chi}_2^\mp$
228	$f_i \bar{f}_i \to \tilde{\chi}_1^\pm \tilde{\chi}_2^\mp$

No.	Subprocess
229	$f_i \bar{f}_j \to \tilde{\chi}_1 \tilde{\chi}_1^\pm$
230	$f_i \bar{f}_j \to \tilde{\chi}_2 \tilde{\chi}_1^\pm$
231	$f_i \bar{f}_j \to \tilde{\chi}_3 \tilde{\chi}_1^\pm$
232	$f_i \bar{f}_j \to \tilde{\chi}_4 \tilde{\chi}_1^\pm$
233	$f_i \bar{f}_j \to \tilde{\chi}_1 \tilde{\chi}_2^\pm$
234	$f_i \bar{f}_j \to \tilde{\chi}_2 \tilde{\chi}_2^\pm$
235	$f_i \bar{f}_j \to \tilde{\chi}_3 \tilde{\chi}_2^\pm$
236	$f_i \bar{f}_j \to \tilde{\chi}_4 \tilde{\chi}_2^\pm$
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	$f_i \bar{f}_j \to \tilde{g} \tilde{\chi}_1^\pm$
242	$f_i \bar{f}_j \to \tilde{g} \tilde{\chi}_2^\pm$
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	$f_i g \to \tilde{q}_{jL} \tilde{\chi}_1^\pm$
256	$f_i g \to \tilde{q}_{jL} \tilde{\chi}_2^\pm$
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	$b q_i \to \tilde{b}_1 \tilde{q}_{iL}$
282	$b q_i \to \tilde{b}_2 \tilde{q}_{iR}$
283	$b q_i \to \tilde{b}_1 \tilde{q}_{iR} + \tilde{b}_2 \tilde{q}_{iL}$
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	$gg \to g G^*$

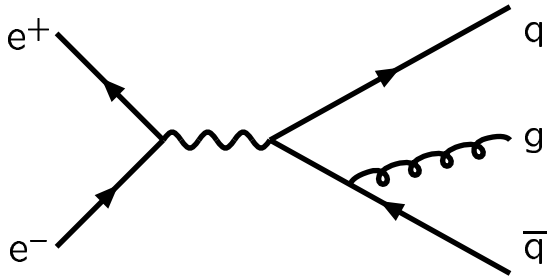
Parton Showers

$\mathcal{O}(1)$



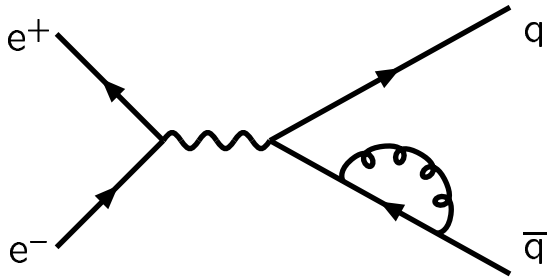
Matrix Elements exact to given order. . . but blind to higher orders

$\mathcal{O}(\alpha_s)$



$\mathcal{O}(\alpha_s L^2)$

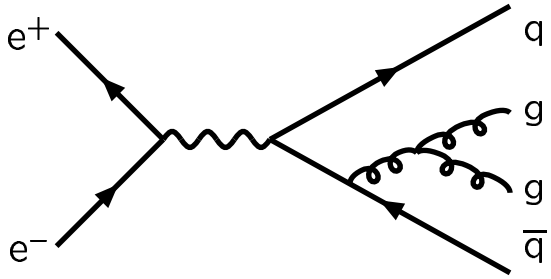
$\mathcal{O}(\alpha_s)$



$L \simeq -\ln y$

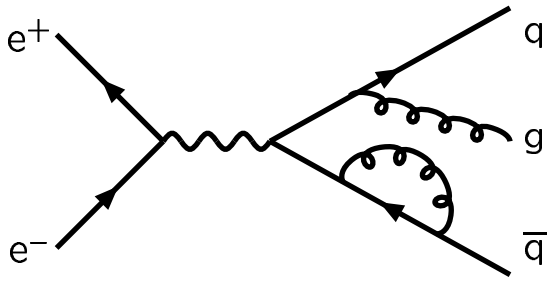
$y \simeq \min \frac{m_{ij}^2}{E_{\mathrm{cm}}^2}$

$\mathcal{O}(\alpha_s^2)$



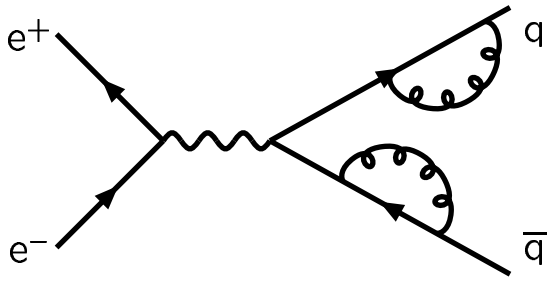
$\mathcal{O}(\alpha_s^2 L^4)$

$\mathcal{O}(\alpha_s^2)$

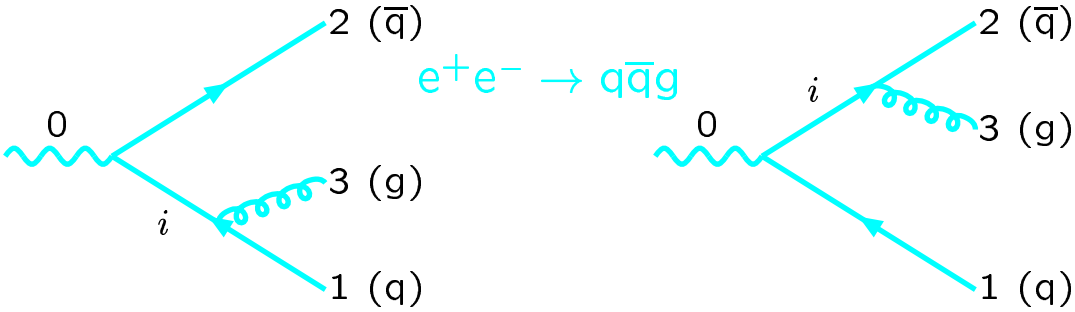


collinear and soft emission divergences $\Rightarrow$ large higher orders

$\mathcal{O}(\alpha_s^2)$



From Matrix Elements to Parton Showers:



$$x_j = 2E_j/E_{\text{cm}} \quad \Rightarrow \quad x_1 + x_2 + x_3 = 2$$

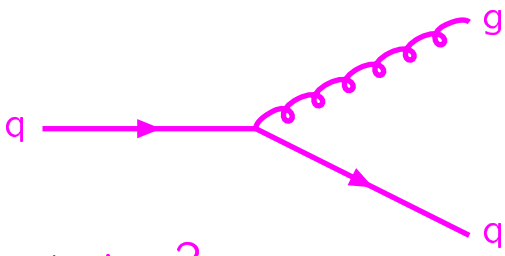
$$m_q = 0: \quad \frac{1}{\sigma_0}\frac{d\sigma_{\text{ME}}}{dx_1\,dx_2} = \frac{\alpha_s}{2\pi}\frac{4}{3}\frac{x_1^2 + x_2^2}{(1-x_1)(1-x_2)}$$

rewrite for $x_2 \to 1$:

$$1 - x_2 = \frac{m_{13}^2}{E_{\text{cm}}^2} = \frac{Q^2}{E_{\text{cm}}^2}$$

$$x_1 \approx z$$

$$x_3 \approx 1 - z$$



$$\Rightarrow \quad d\mathcal{P} = \frac{d\sigma}{\sigma_0} \approx \frac{\alpha_s}{2\pi}\frac{dQ^2}{Q^2}\frac{4}{3}\frac{1+z^2}{1-z}\,dz$$

generalizes to

$$d\mathcal{P}_{a\to bc} = \frac{\alpha_s}{2\pi}\frac{dQ^2}{Q^2}P_{a\to bc}(z)\,dz$$

$$P_{q\to qg} = \frac{4}{3}\frac{1+z^2}{1-z}$$

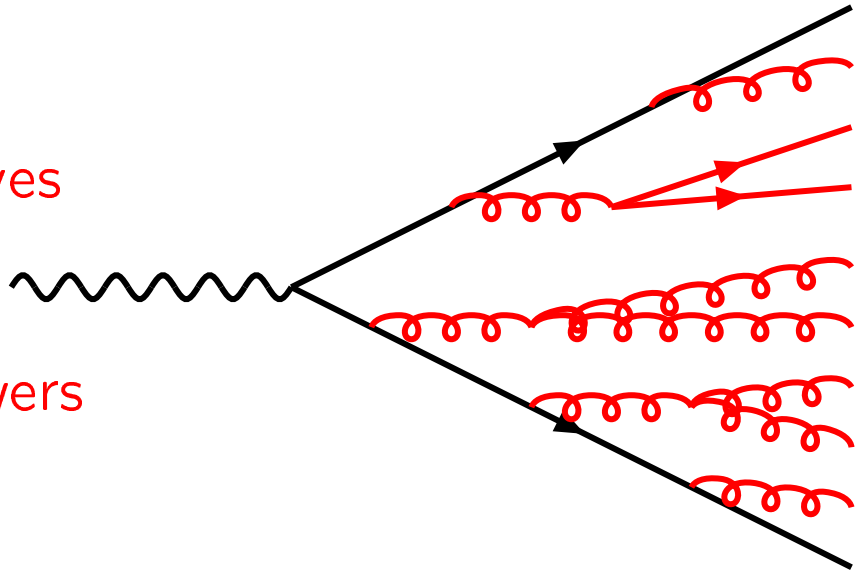
$$P_{g\to gg} = 3\frac{(1-z(1-z))^2}{z(1-z)}$$

$$P_{g\to q\overline{q}} = \frac{n_f}{2}(z^2 + (1-z)^2)$$

Iteration gives

final-state

parton showers

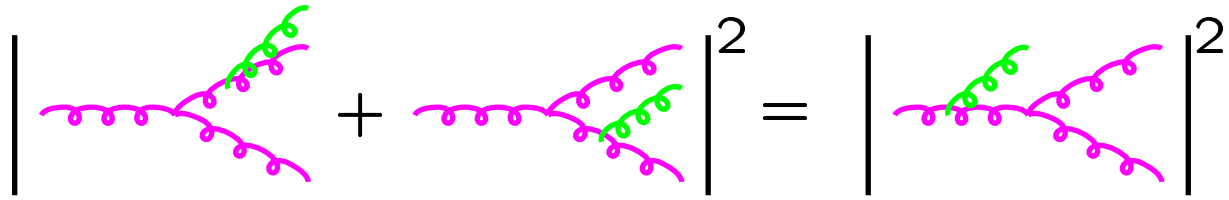


Sudakov form factor

$$\mathcal{P}^{\text{corr}}(Q^2) = \frac{\mathrm{d}\mathcal{P}}{\mathrm{d}Q^2} \exp\left(-\int_{Q^2}^{Q^2_{\text{max}}} \frac{\mathrm{d}\mathcal{P}}{\mathrm{d}Q^2}\,\mathrm{d}Q^2\right)$$

(cf. radioactive decay; 'time' ordering)

Coherence $\Rightarrow$ angular ordering



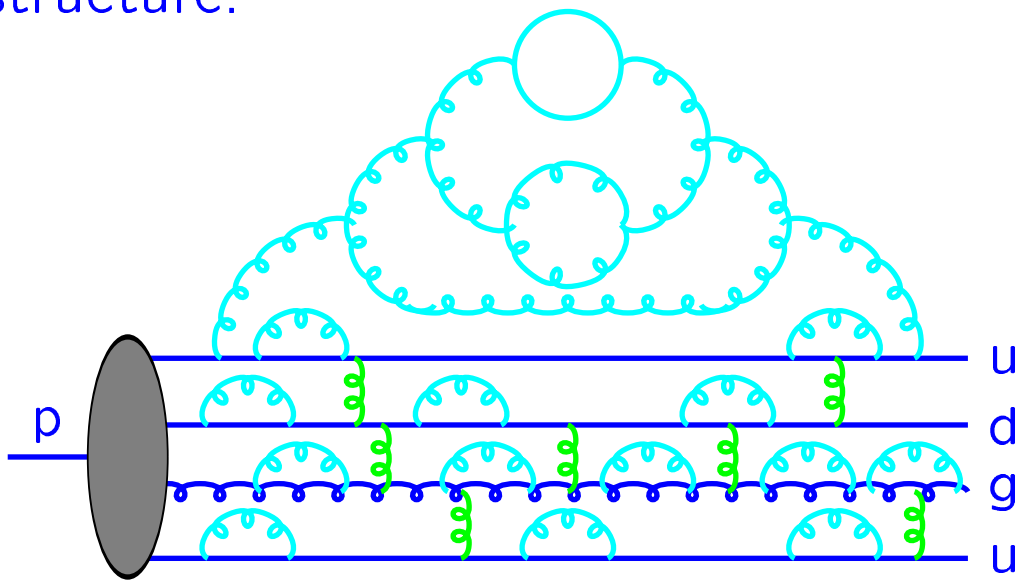
Loop corrections $\Rightarrow \alpha_s(p_\perp^2)$

Soft/collinear cut-off $m_0 = \min(m_{ij}) \approx 1$ GeV

Matching of PS to ME (first emissions): if $\mathrm{d}\sigma_{\text{ME}} \leq \mathrm{d}\sigma_{\text{PS}}$ then generate events by PS and retain branchings with probability $\mathrm{d}\sigma_{\text{ME}}/\mathrm{d}\sigma_{\text{PS}}$

Initial-state showers:

Hadrons are composite, with time-dependent structure:



$f_i(x, Q^2)$ = number density of partons i at momentum fraction x and probing scale Q^2

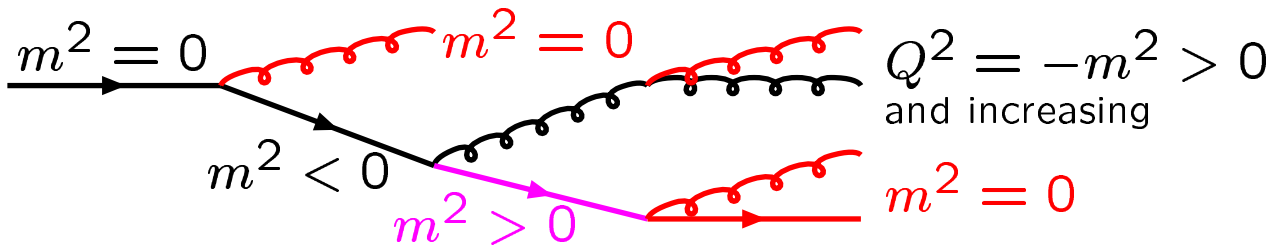
$$F_2(x, Q^2) \;=\; \sum_i e_i^2 \, x f_i(x, Q^2)$$

structure function parton distributions

Resolution dependence by DGLAP

$$\frac{\partial f_i(x, Q^2)}{\partial \ln Q^2} = \sum_j \int_x^1 \frac{\mathrm{d}y}{y} f_j(y, Q^2) \frac{\alpha_s}{2\pi} P_{j\to i}\left(\frac{x}{y}\right)$$

Hard scattering on one branch inhibits cascade recombination. Convenient reinterpretation:



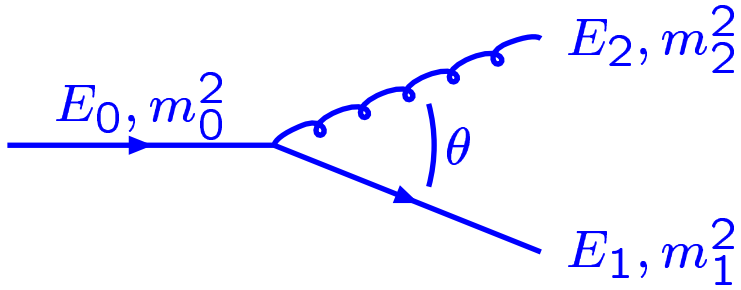
Initial- vs. final-state showers:

Both controlled by same evolution equations

$$\mathrm{d}\mathcal{P}_{a\to bc} = \frac{\alpha_s}{2\pi}\frac{\mathrm{d}Q^2}{Q^2} P_{a\to bc}(z)\,\mathrm{d}z \cdot \text{(Sudakov)}$$

but

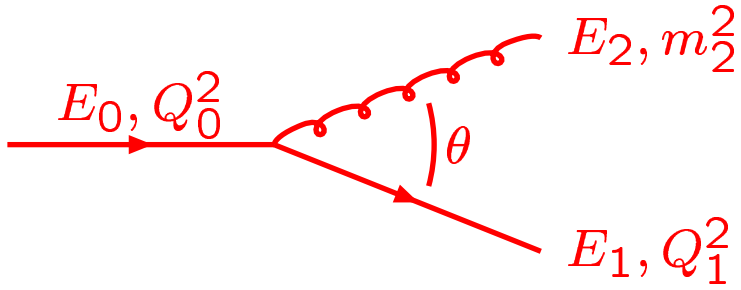
Final-state showers: Q^2 timelike ($\approx m^2$)



decreasing E
decreasing m^2
decreasing θ

daughters on equal footing, both $m^2 \geq 0$
$Q^2, z, \ldots$ choice gives several algorithms

Initial-state showers: Q^2 spacelike ($\approx -m^2$)



decreasing E
increasing Q^2
increasing θ

daughters unequal, one $m^2 \geq 0$, one $m^2 < 0$

$\Rightarrow$ kinematics & coherence more complicated
$+$ more messy hadronic environment
gives many attempts: BFKL, CCFM, GLR, ...

Gluon emission off heavy particles:

(E. Norrbin & TS, LUTP 00-42 [hep-ph/0010012])

Objective:

- improved parton shower description,
- including mass effects ("dead cone"), and
- matched to process-specific $\mathcal{O}(\alpha_s)$ ME's

Q^2: evolution variable, $= m^2$ in PYTHIA

z: energy/momentum sharing in branching

3-jet events in $e^+e^- \to \gamma^*/Z^* \to q\bar{q} \to q\bar{q}g$:
map PS variables on to ME ones:

$$\Rightarrow \quad \frac{1}{\sigma_0}\frac{d\sigma_{ME}}{dx_1\,dx_2} \leq \frac{1}{\sigma_0}\frac{d\sigma_{PS}}{dQ^2\,dz} \qquad \text{for } m_q = 0$$

so can generate events with PS
and correct first branching by ME/PS

Fails for $m_q > 0$ in part of phase space
$\Rightarrow$ have had exaggerated dead cone effect

Restore by $Q_j^2 = m_{j,\text{offshell}}^2 - m_{j,\text{onshell}}^2$

Also works for decaying coloured state,
e.g. ME for $t \to bWg$ matches PS for $b \to bg$

$\boxed{\Rightarrow \text{ can match PS to generic } a \to bcg \text{ ME}}$

. . . but often ME $\ll$ PS
$\Rightarrow$ need ME input for good description

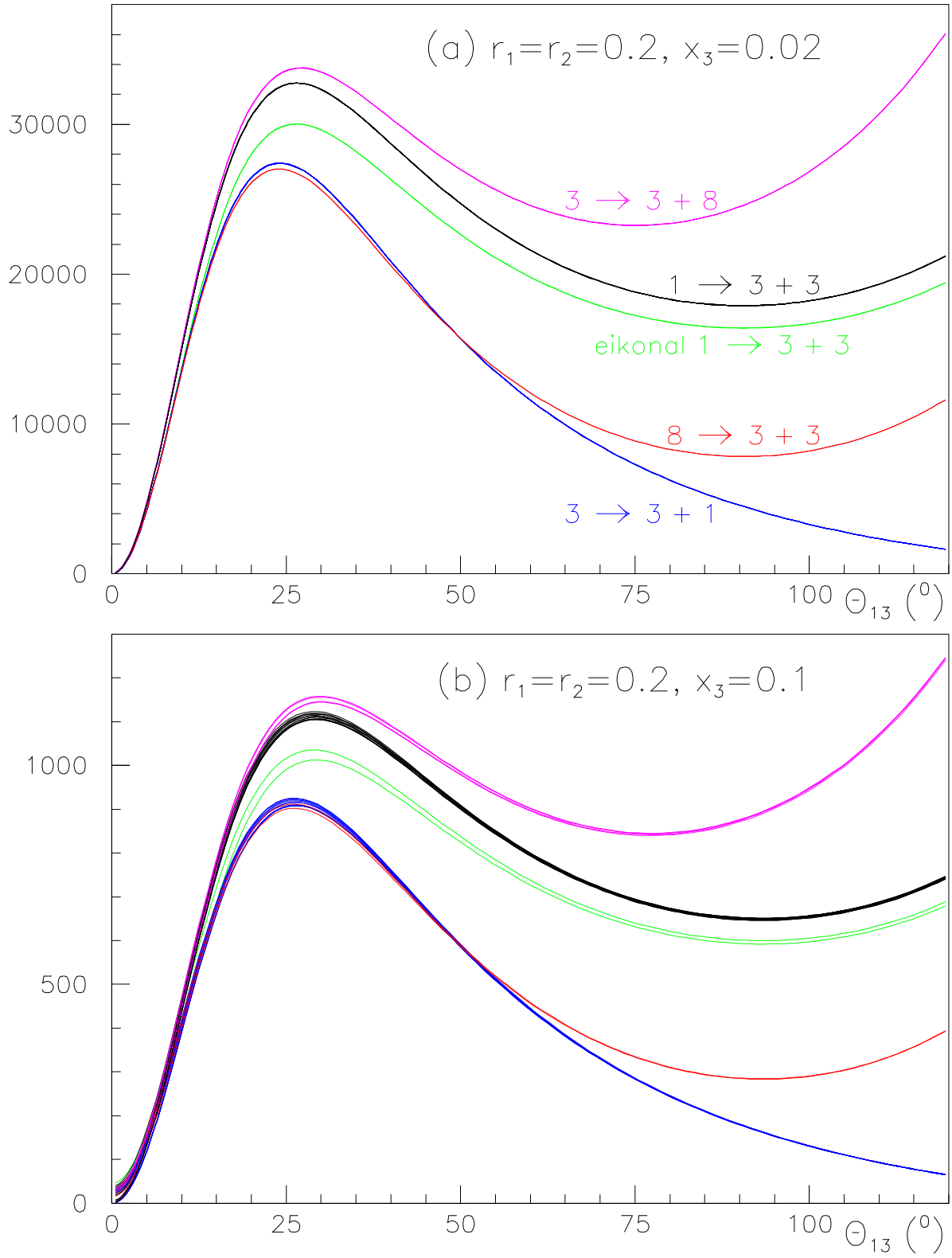
Calculate for $1 \to 2$ processes in SM + MSSM:

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

Depends on mass ratios, colour and spin structure, and parity (γ_5)

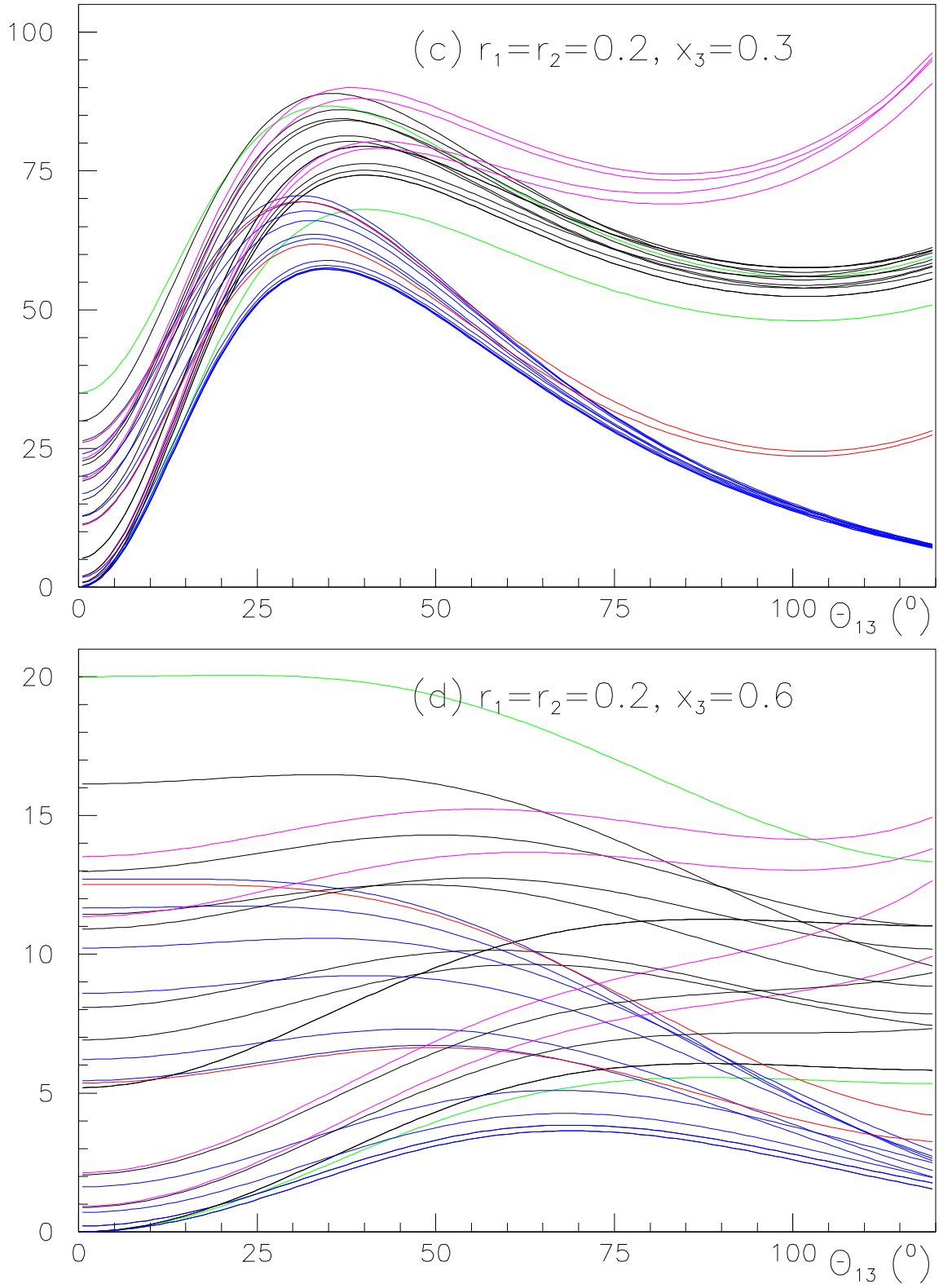
colour	spin	γ_5	example
$1 \to 3 + \overline{3}$	—	—	(eikonal)
$1 \to 3 + \overline{3}$	$1 \to \frac{1}{2} + \frac{1}{2}$	$1, \gamma_5, 1 \pm \gamma_5$	$\mathrm{Z}^0 \to \mathrm{q}\overline{\mathrm{q}}$
$3 \to 3 + 1$	$\frac{1}{2} \to \frac{1}{2} + 1$	$1, \gamma_5, 1 \pm \gamma_5$	$\mathrm{t} \to \mathrm{bW}^+$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

Universal gluon radiation patterns (= no spin dependence) for small gluon energies . . .



(with textbook dead cone)

. . . but very process-dependent for large gluon energies . . .

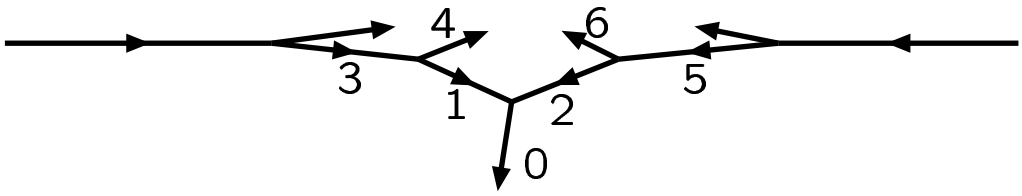


(and no dead cone except for spin $0 \to 0 + 0$)

ME matching of initial-state showers:

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

$2 \to 1$ process $\mathrm{q}(1) + \overline{\mathrm{q}}'(2) \to \mathrm{W}(0)$ starting point for backwards shower evolution:



Alternatively $2 \to 2$ matrix element processes $\mathrm{q}(3) + \overline{\mathrm{q}}'(2) \to \mathrm{g}(4) + \mathrm{W}(0)$ and mirror $\mathrm{q}(1) + \overline{\mathrm{q}}'(5) \to \mathrm{g}(6) + \mathrm{W}(0)$:

$$R_{\mathrm{q}\overline{\mathrm{q}}'\to\mathrm{gW}}(\hat{s},\hat{t}) = \frac{(\mathrm{d}\hat{\sigma}/\mathrm{d}\hat{t})_{\mathrm{ME}}}{(\mathrm{d}\hat{\sigma}/\mathrm{d}\hat{t})_{\mathrm{PS}}} = \frac{\hat{t}^2 + \hat{u}^2 + 2m_{\mathrm{W}}^2\hat{s}}{\hat{s}^2 + m_{\mathrm{W}}^4}$$

$$\frac{1}{2} < R_{\mathrm{q}\overline{\mathrm{q}}'\to\mathrm{gW}}(\hat{s},\hat{t}) \leq 1$$

Similarly for $\mathrm{q}(1) + \mathrm{g}(5) \to \mathrm{q}'(6) + \mathrm{W}(0)$:

$$R_{\mathrm{qg}\to\mathrm{q}'\mathrm{W}}(\hat{s},\hat{t}) = \frac{(\mathrm{d}\hat{\sigma}/\mathrm{d}\hat{t})_{\mathrm{ME}}}{(\mathrm{d}\hat{\sigma}/\mathrm{d}\hat{t})_{\mathrm{PS}}} = \frac{\hat{s}^2 + \hat{u}^2 + 2m_{\mathrm{W}}^2\hat{t}}{(\hat{s} - m_{\mathrm{W}}^2)^2 + m_{\mathrm{W}}^4}$$

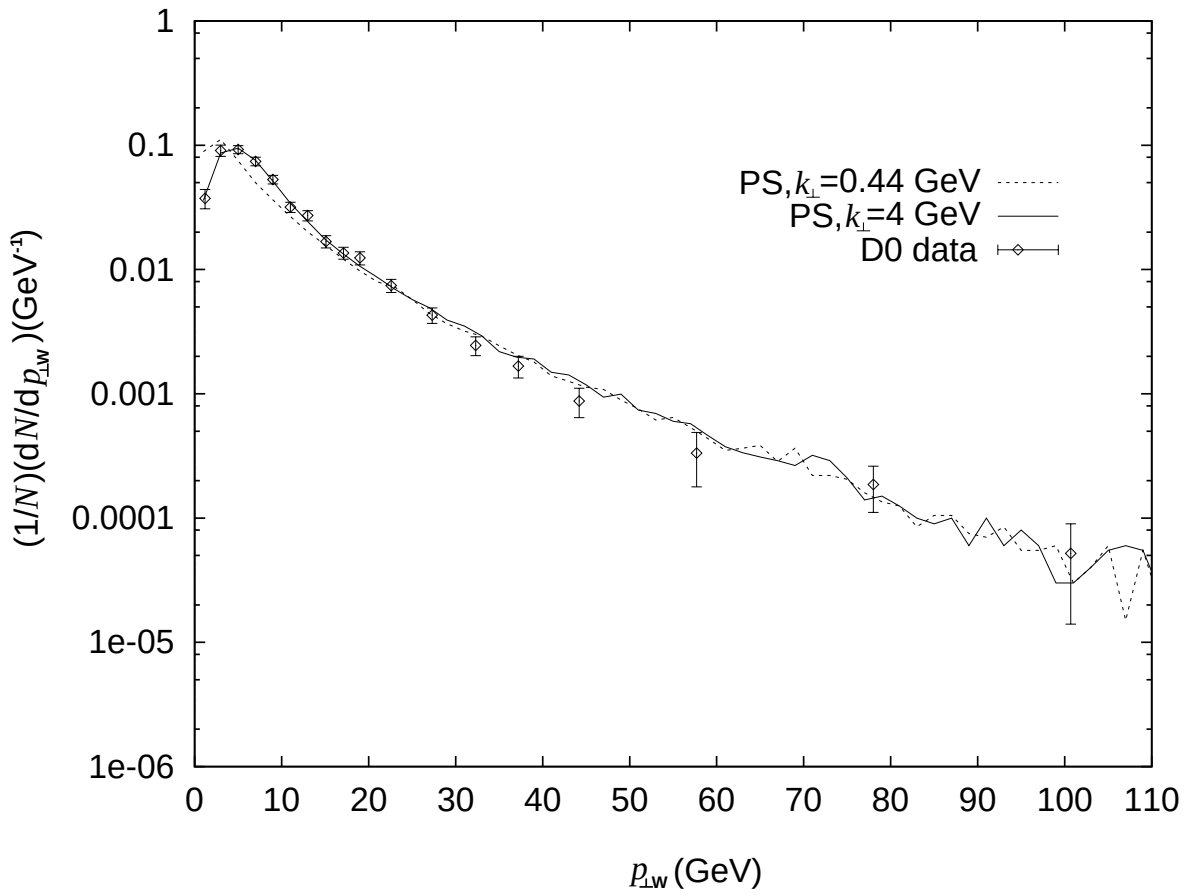
$$1 \leq R_{\mathrm{qg}\to\mathrm{q}'\mathrm{W}}(\hat{s},\hat{t}) \leq \frac{\sqrt{5}-1}{2(\sqrt{5}-2)} < 3$$

Improve PS:

- $Q^2_{\text{max}} = s$, not $Q^2_{\text{max}} \approx m^2_{\text{W}}$ (intermediate)
- MC correction by $R(\hat{s}, \hat{t})$ for first ($\approx$ hardest) emission on each side (new)

Same for all colourless vector gauge bosons: γ^*, Z^0, Z'^0, $\text{W}'^{\pm}$, ...

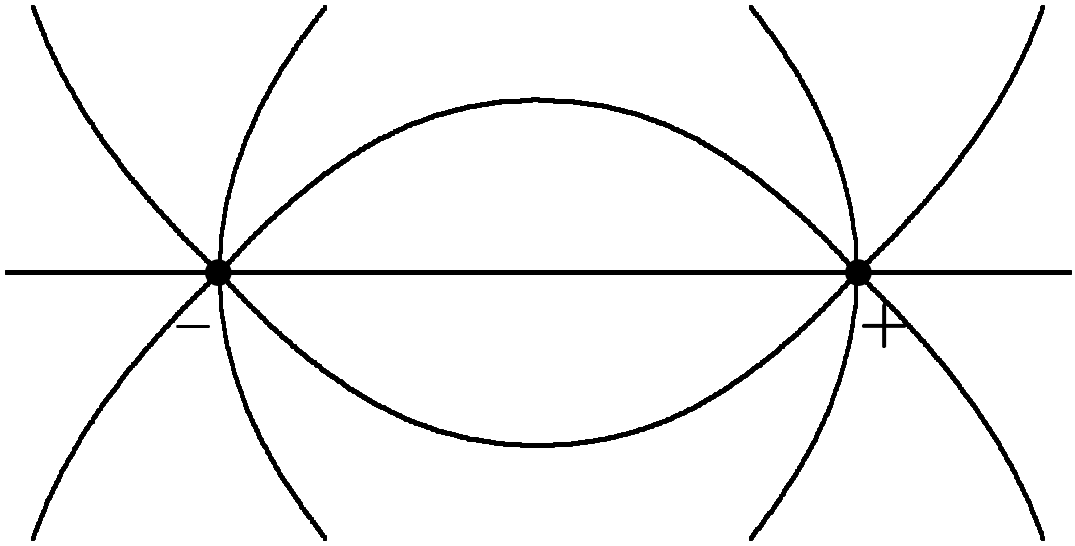
Complete simulation at 1.8 TeV:



Requires large primordial $k_\perp$, around 2 GeV. (4 GeV in plot; miscorrection in data.)
In line with resummation descriptions, etc.
Solved by better understanding of soft part of showers: BFKL, CCFM, ...?

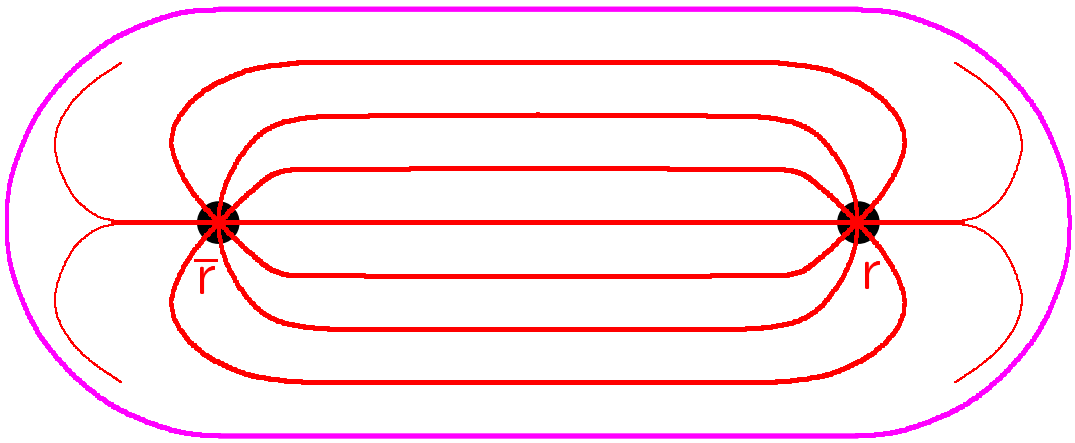
Hadronization

In QED field lines go all the way to infinity



since photons cannot interact with each other

In QCD, for large charge separation, field lines seem to be compressed to tubelike region



by nonperturbative self-interaction among infinitely many soft gluons forming the field.

Analogy: vortex lines in type II superconductor

Lattice QCD — in quenched approximation — confirms large-distance behaviour

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

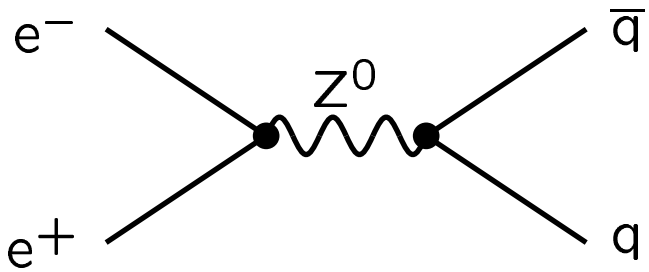
Input from hadronic spectroscopy gives string tension

$\kappa \approx 1$ GeV/fm (= 160 kJ/m = 16 ton/m)

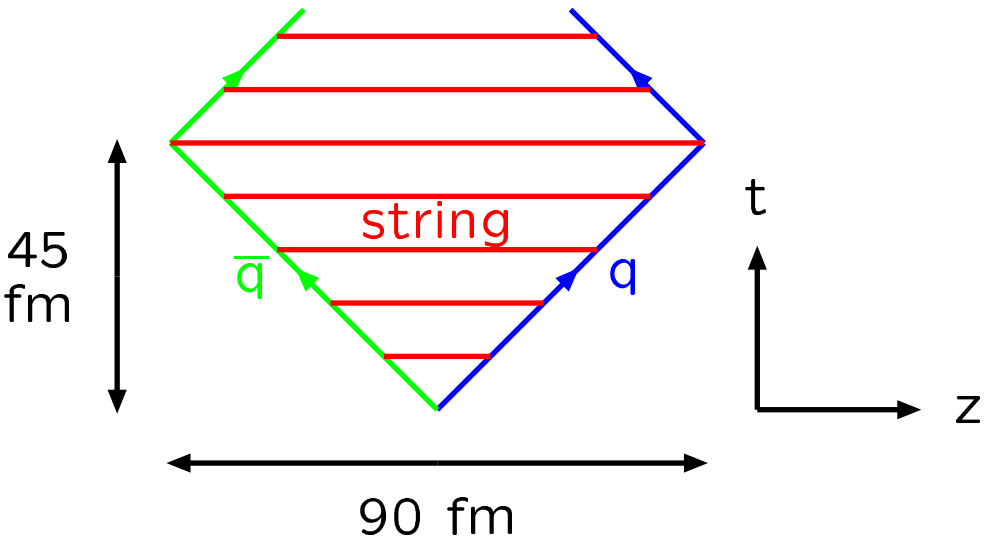
Consider LEP1 events:

$E_{cm} = m_Z$

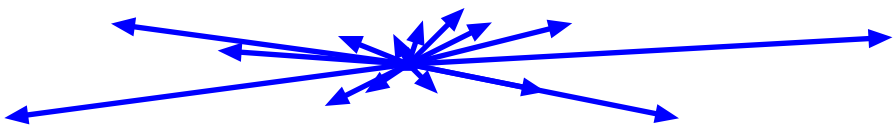
≈ 90 GeV



Should give stable oscillating system

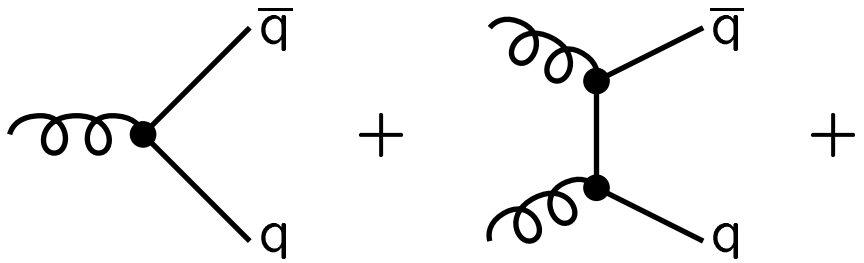


but experimental reality is jet production

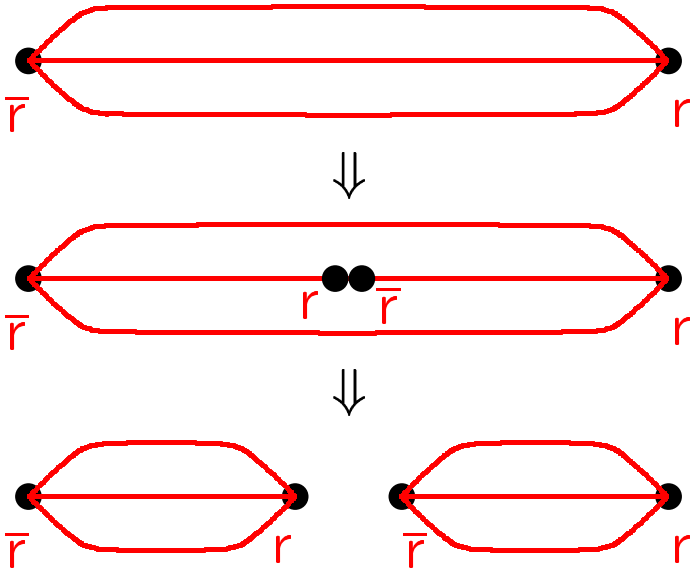


with transverse width ≈ 0.4 GeV

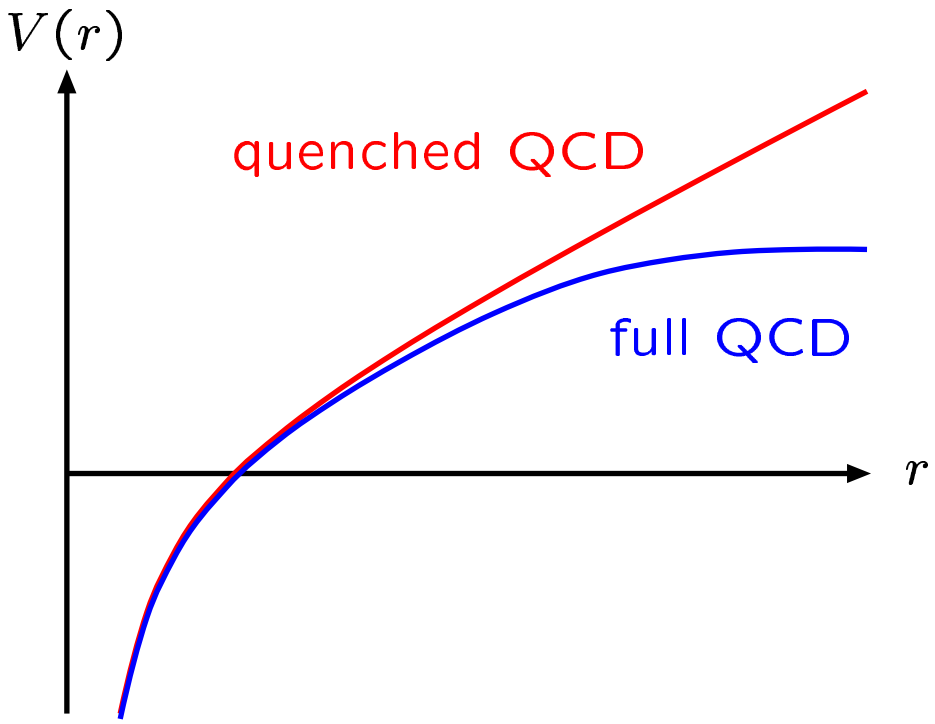
Extra: nonperturbative splittings $g \to q\bar{q}$



can break string



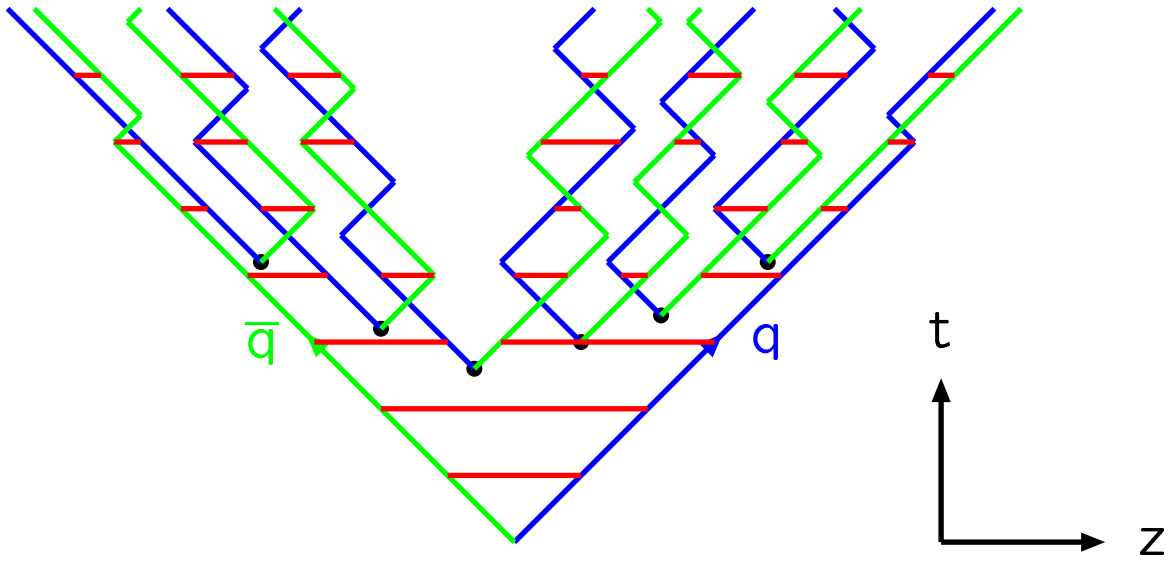
simplified colour representation



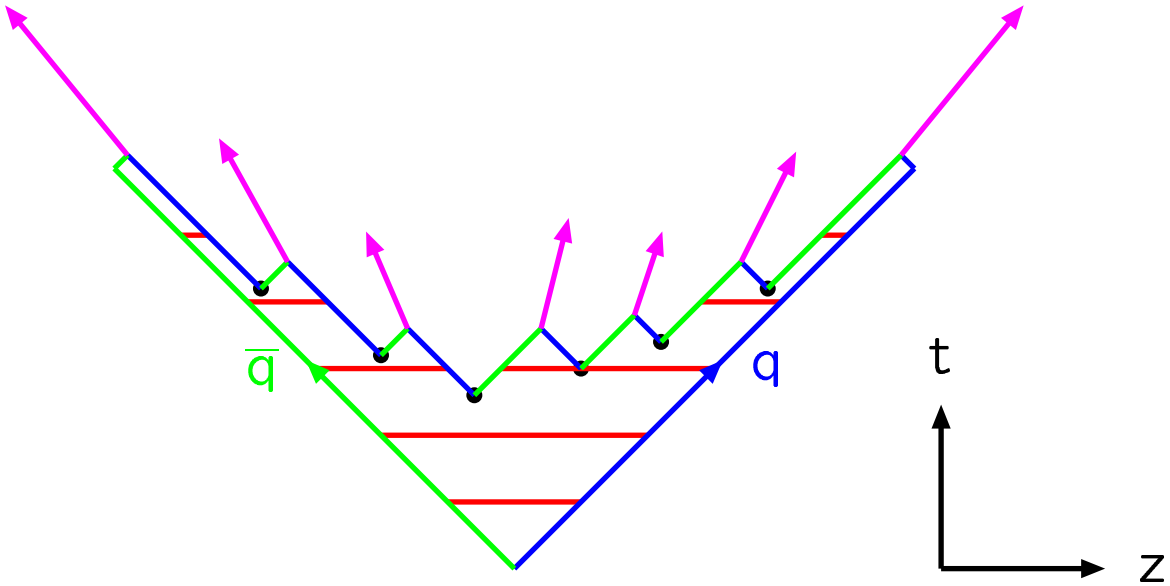
Repeat for large system ⇒ *Lund model* which neglects Coulomb part:

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

Motion of quarks and antiquarks:



gives simplified picture of hadron production:



with Lorentz contraction for fast hadrons

Fragmentation properties and parameters:

String breaking modelled by tunneling:

$$\mathcal{P} \propto \exp\left(-\frac{\pi m_\perp^2}{\kappa}\right) = \exp\left(-\frac{\pi p_\perp^2}{\kappa}\right) \exp\left(-\frac{\pi m^2}{\kappa}\right)$$

1) common Gaussian $p_\perp$ spectrum
2) suppression of heavy quarks
   $u\bar{u} : d\bar{d} : s\bar{s} : c\bar{c} \approx 1 : 1 : 0.3 : 10^{-11}$

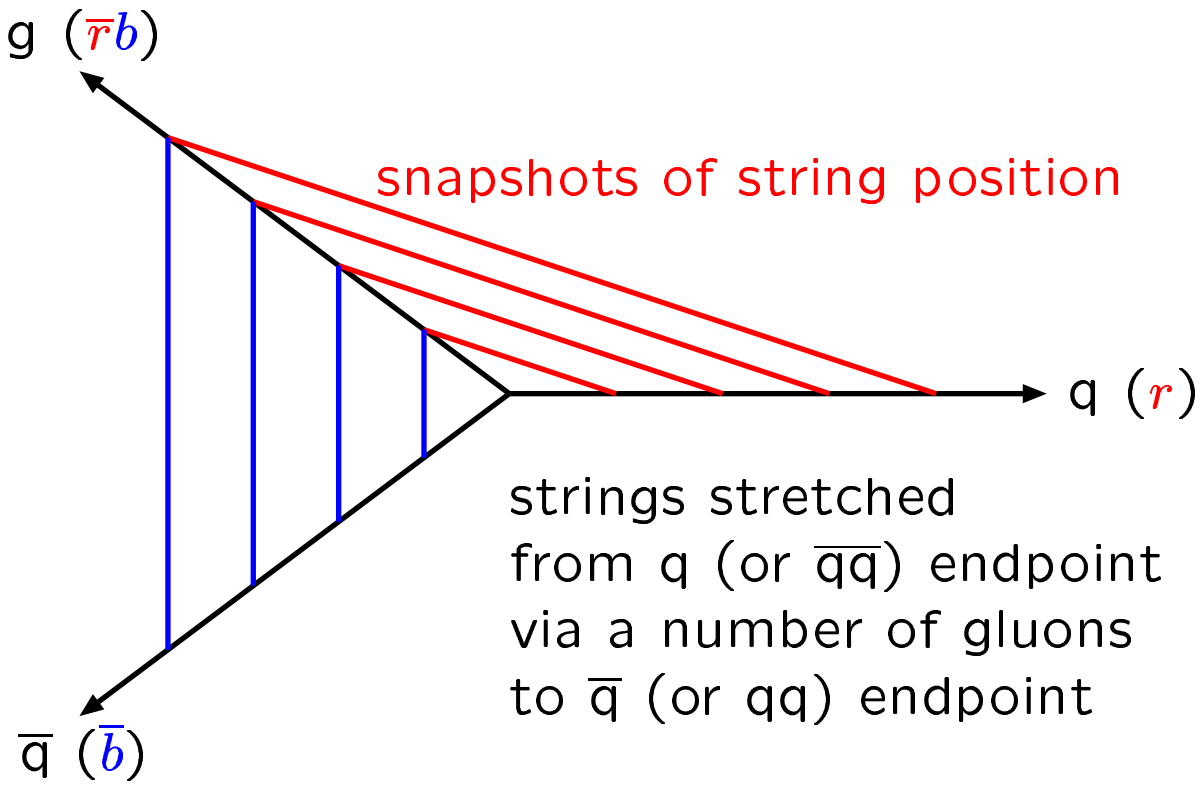
Hadron composition also depends on spin probabilities, hadronic wave functions, phase space, ... $\Rightarrow$ moderate predictivity

Spacelike separation of breakups $\Rightarrow$ arbitrary order, iterative ansatz from endpoints.
Left–right symmetry $\Rightarrow$
Lund symmetric fragmentation function

$$\mathcal{P}(z) \propto \frac{1}{z}(1-z)^a \exp\left(-\frac{b m_\perp^2}{z}\right)$$

where $z = \frac{(E+p_z)_{\text{hadron}}}{(E+p_z)_{\text{remaining}}}$ or $z = \frac{(E-p_z)_{\text{hadron}}}{(E-p_z)_{\text{remaining}}}$
and $a \approx 0.3$, $b \approx 0.6$ GeV^{-2}.
Scale by $(E \pm p_z)_{\text{remaining}} \Rightarrow$ flat rapidity plateau

The Lund gluon picture:



Gluon = kink on string, carrying $(E, \mathbf{p})$

Force ratio gluon/ quark = 2,

cf. QCD $N_C/C_F = 9/4$

String effect (JADE) $\approx$ coherence:

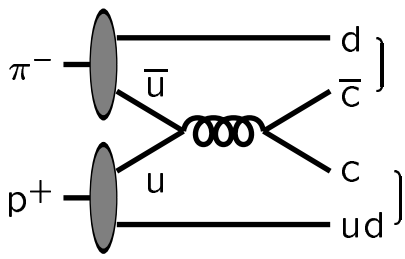
(JADE figure omitted for technical reasons)

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 $g \to q\bar{q}$ 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.



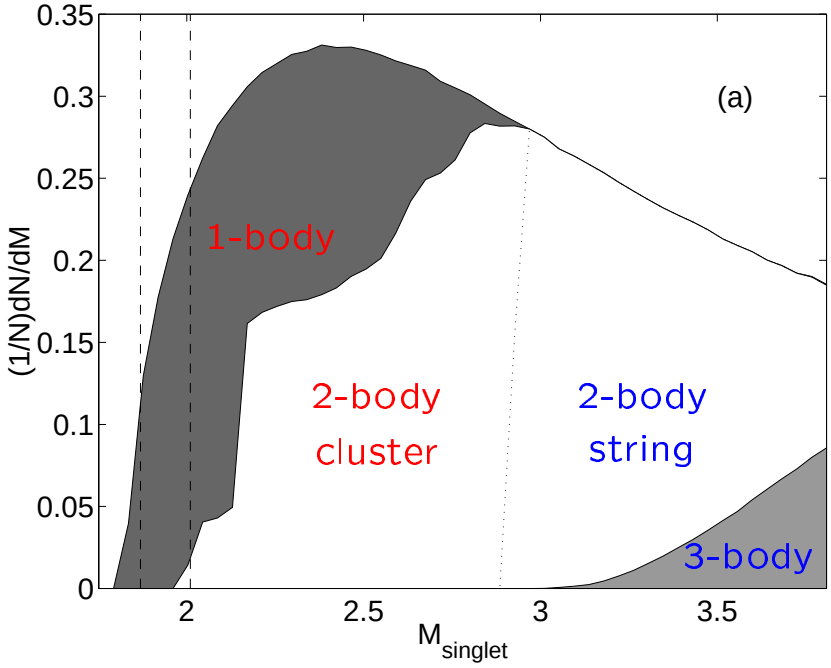
If collapse:
$\bar{c}d$: D^-, D^{*-}, ...
cud: Λ_c^+, Σ_c^+, Σ_c^{*+}, ...
$\Rightarrow$ flavour asymmetries

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

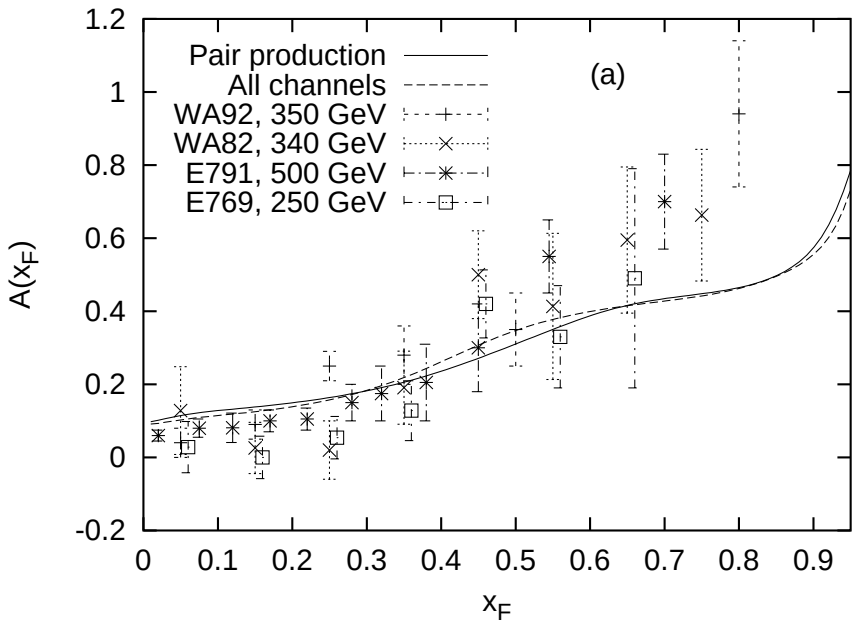


and

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



But also normal string fragmentation:

$p_\pm = E \pm p_z$

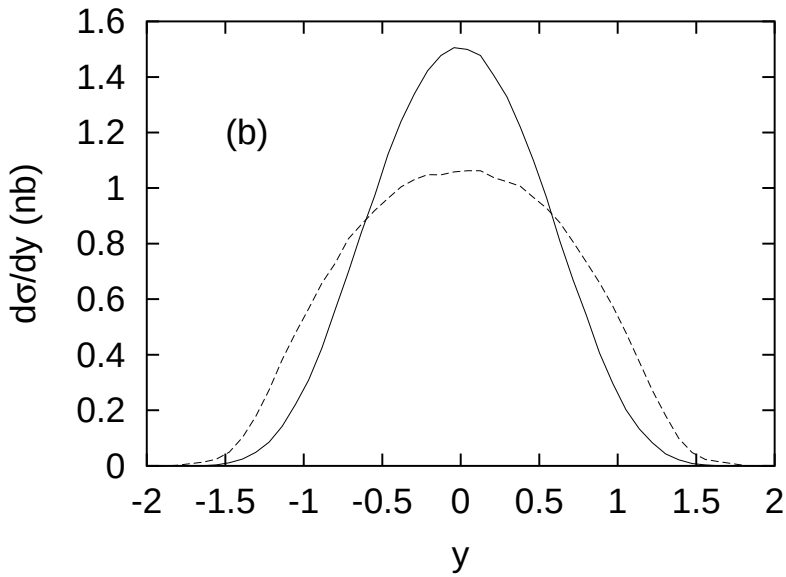
$p_{-\mathrm{D}} = z p_{-\mathrm{c}} \qquad 0 < z < 1$

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

i.e. again drag.

Technical components of modelling:

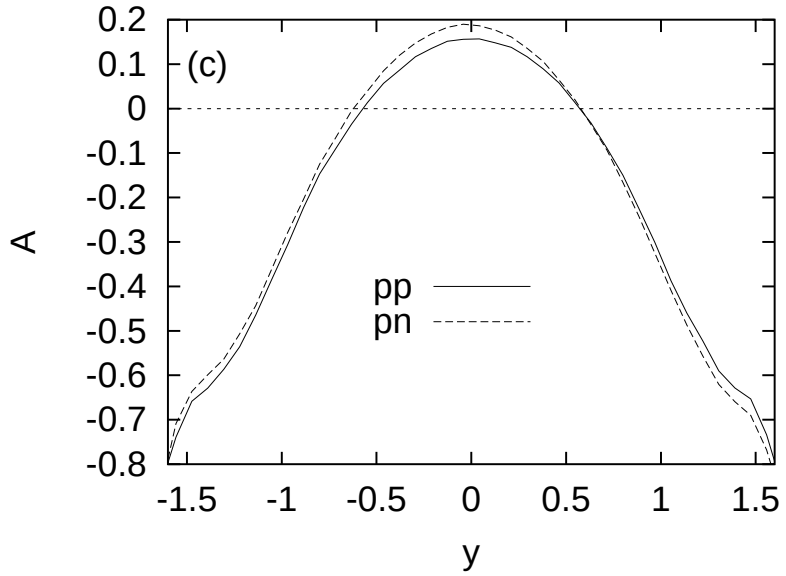
- Charm and bottom masses: c and b cross sections ($m_\mathrm{c} = 1.5$, $m_\mathrm{b} = 4.8$)
- Light-quark masses: threshold for cluster mass spectrum, together with m_c ($m_\mathrm{u} = m_\mathrm{d} = 0.33$, $m_\mathrm{s} = 0.50$)
- Beam remnant distribution function: (p − g = ud$_0$ + u in colour 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)



HERA-B
predictions

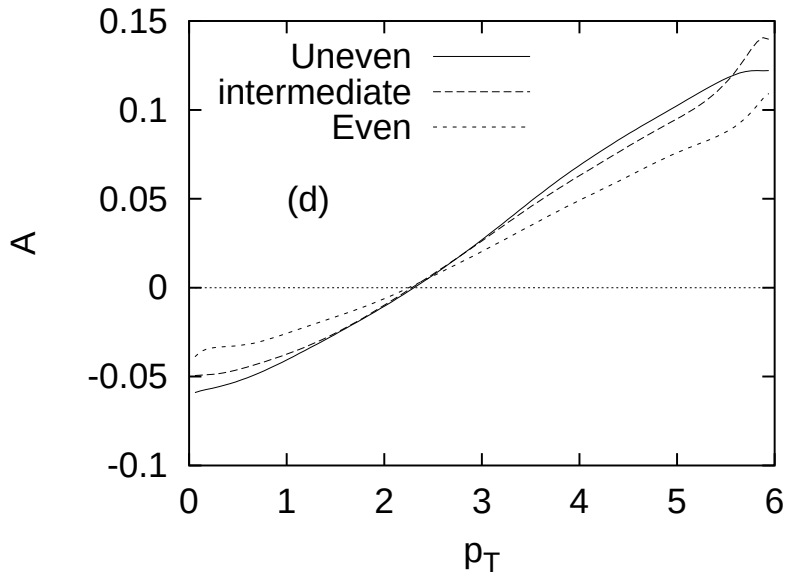
B^0 full

$\overline{B}^0$ dashed



y dependence

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



$p_\perp$ dependence

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

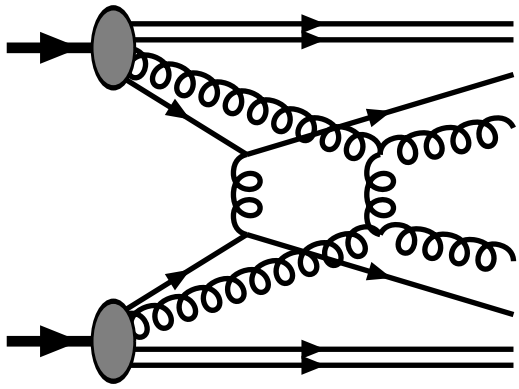
(vary beam remn dist)

Multiple Interactions

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

J. Dischler & TS, LU TP 00-47 [hep-ph/0011282])

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

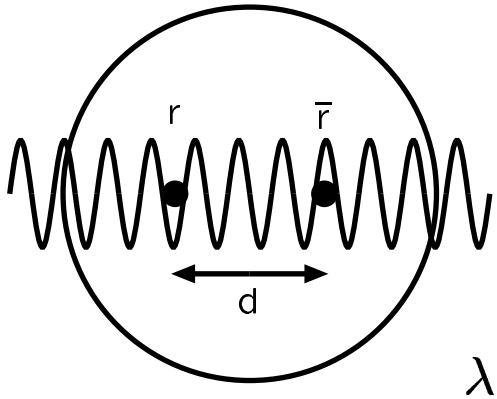
One new free parameter: $p_{\perp\mathrm{min}}$

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

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

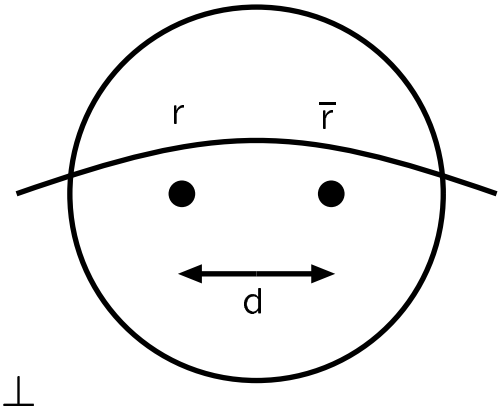
Measure of colour screening length d in hadron

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



resolved

$\lambda \sim 1/p_\perp$



screened

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

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

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

Olden days:

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

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

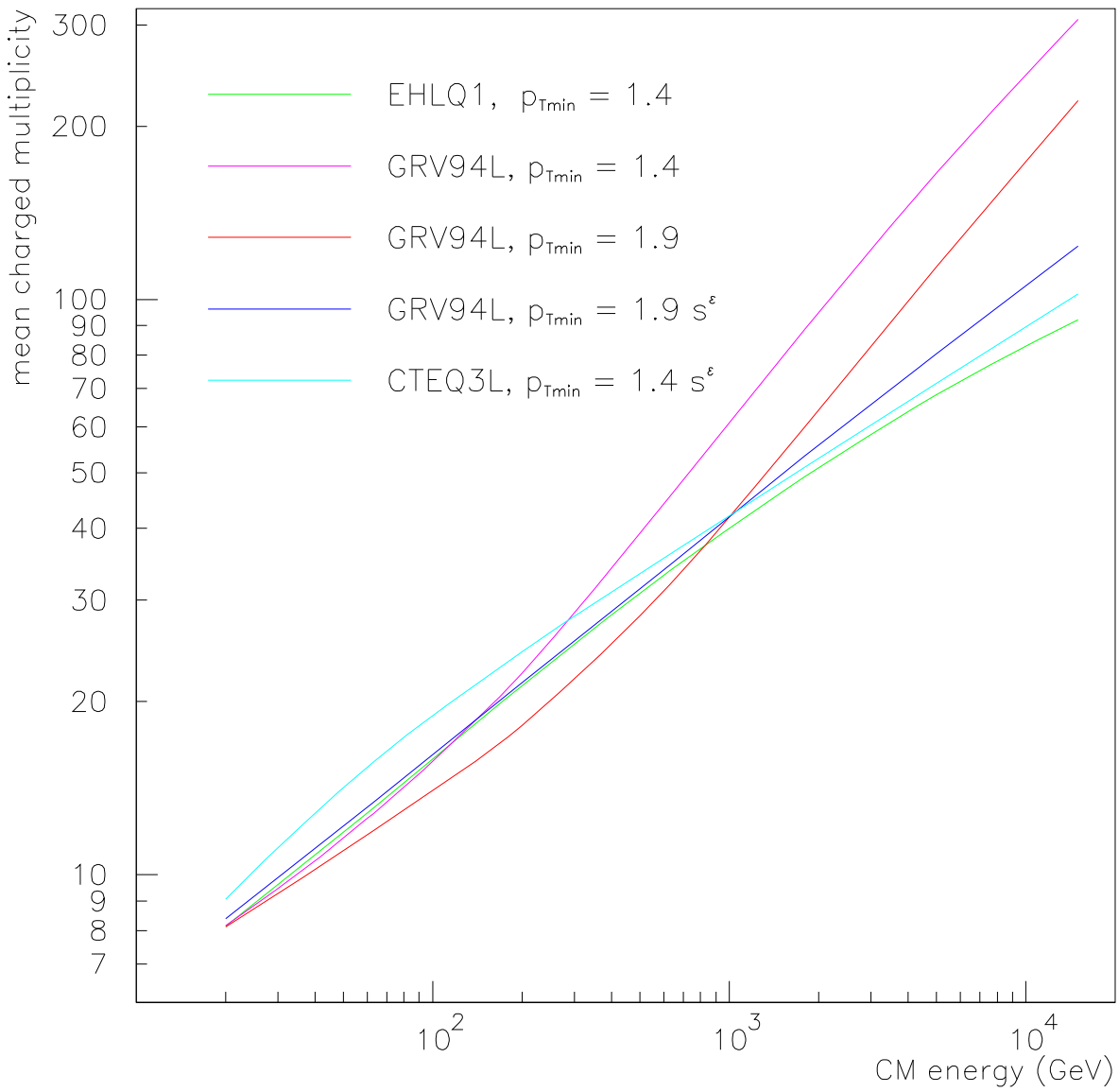
Post-HERA:

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

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

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

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

QCD Interconnection

(V.A. Khoze & TS, PRL72 (1994) 28, ZPC62 (1994) 281, PLB328 (1994) 466, EPJC6 (1999) 271;
L. Lönnblad & TS, PLB351 (1995) 293, EPJC2 (1998) 165)

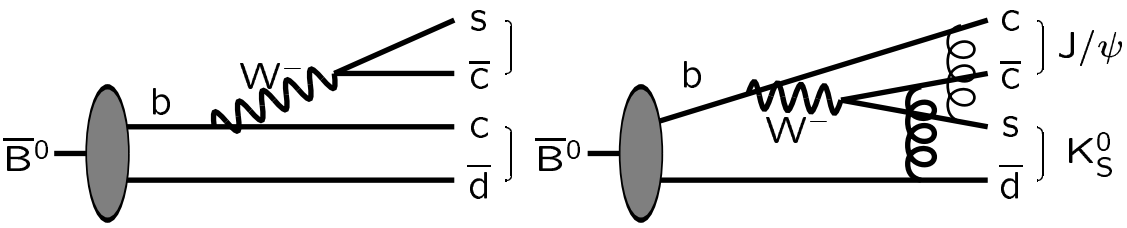
$\Gamma_W, \Gamma_Z, \Gamma_t \approx 2$ GeV
$\Gamma_h > 1.5$ GeV for $m_h > 200$ GeV
$\Gamma_{SUSY} \sim$ GeV (often)
Not too far from threshold:

$$\tau = \frac{1}{\Gamma} \approx \frac{0.2\,\text{GeV fm}}{2\,\text{GeV}} = 0.1\,\text{fm} \ll r_{had} \approx 1\,\text{fm}$$

$\Rightarrow$ hadronic decay systems overlap,
between pairs of resonances (WW, ZZ, $t\bar{t}$, ...)
$\Rightarrow$ cannot be considered separate systems!

Three main eras for interconnection:

1. Perturbative: suppressed for $\omega > \Gamma$ by propagators/timescales $\Rightarrow$ only soft gluons.
2. Nonperturbative, hadronization process: colour rearrangement.



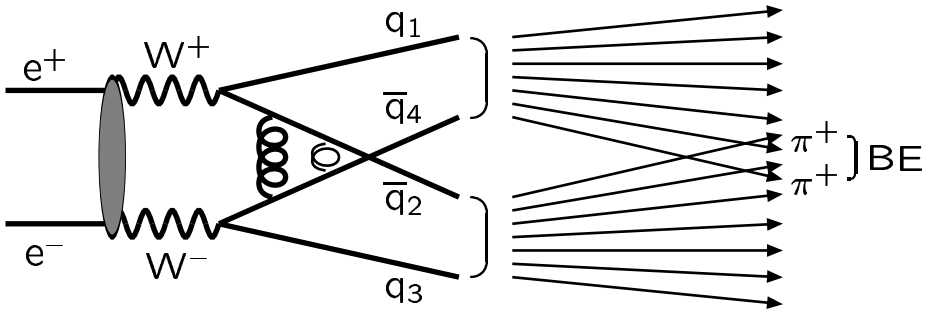
3. Nonperturbative, hadronic phase: e.g. Bose–Einstein.

Above topics among unsolved problems of strong interactions: confinement dynamics, $1/N_C^2$ effects, QM interferences, . . . :

- opportunity to study dynamics of unstable particles,
- new ways to probe confinement dynamics in space and time, *but*
- risk to limit/spoil precision mass measurements.

So far mainly studied for m_W at LEP2:

1. Perturbative: $\langle \delta m_W \rangle \lesssim 5$ MeV.
2. Colour rearrangement: many models, conservatively $\langle \delta m_W \rangle \lesssim 40$ MeV.

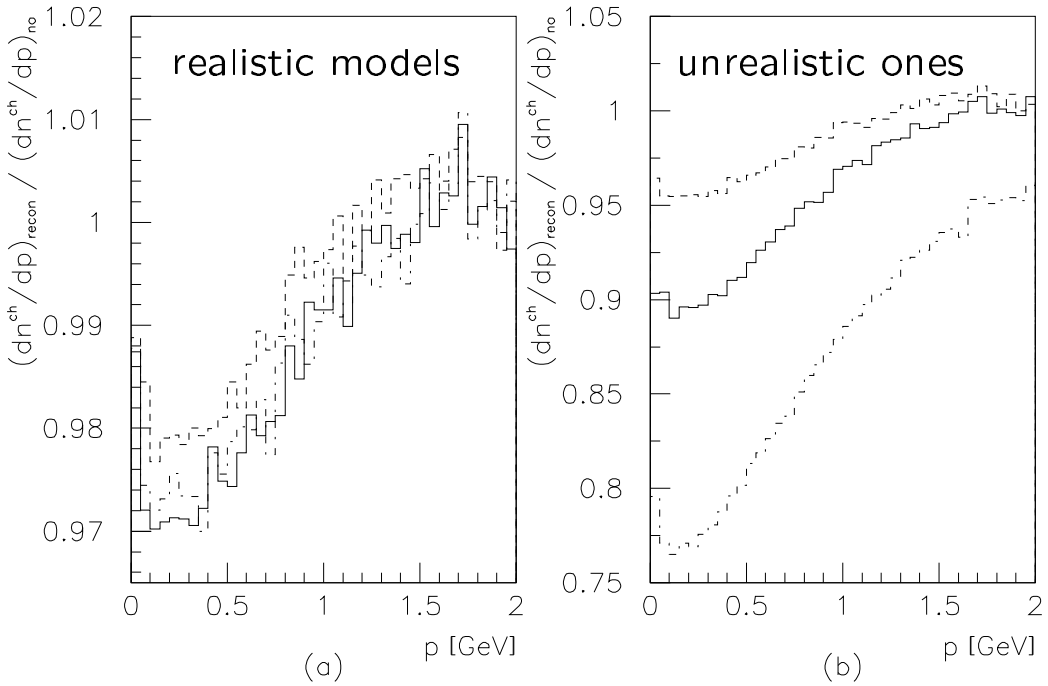


3. Bose-Einstein: symmetrization of unknown amplitude, wider spread among models, but again conservatively $\langle \delta m_W \rangle \lesssim 40$ MeV.

In sum: $\langle \delta m_W \rangle_{\rm tot} < m_\pi$, $\langle \delta m_W \rangle_{\rm tot}/m_W \lesssim 0.1\%$; a small number that becomes of interest only because we aim for high accuracy.

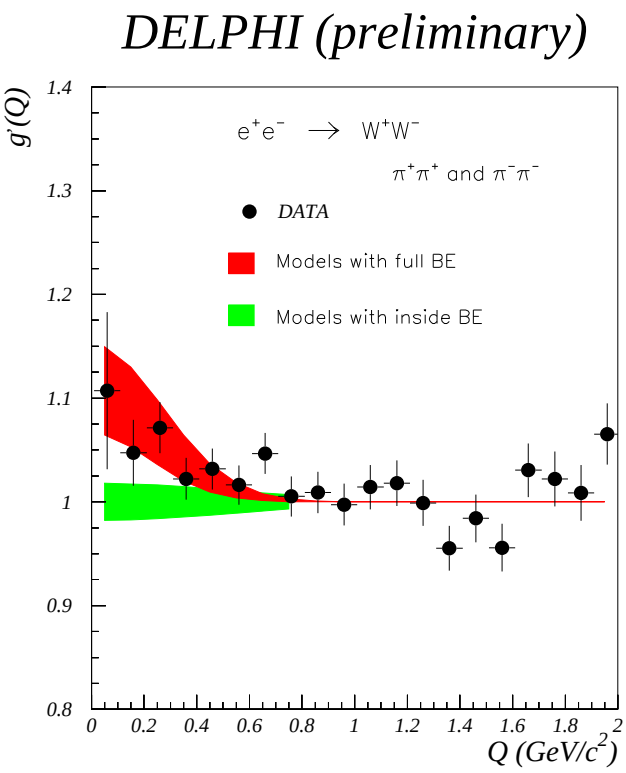
Connectometry – diagnosing interconnections:

Threshold: low-momentum particles depleted



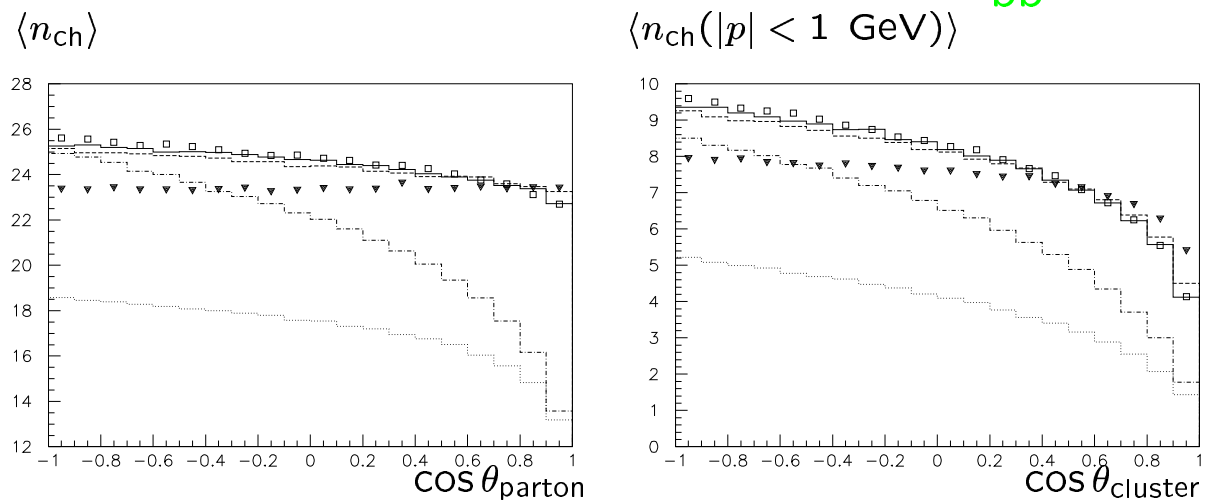
$\sim 4\sigma$ ($\sim 2\sigma$) signal/experiment if 500 pb^{-1} at 172 (195) GeV. (Hint in DELPHI data?)

BE:
first promising indication from DELPHI (Moriond 99)
but not agreement between LEP groups



Top near threshold:
$e^+e^- \to t\bar{t} \to bW^+\bar{b}W^- \to b\bar{b}\ell^+\nu_\ell\ell'^-\bar{\nu}'_\ell$.

Hadronic multiplicity as function of $\theta_{b\bar{b}}$:



Curves: various scenarios for QCD radiation from $\widehat{tb}$, $\widehat{\bar{t}\bar{b}}$ and $\widehat{b\bar{b}}$ colour dipoles, realistically

$$\mathcal{I} \propto \frac{\omega^2}{\Gamma_t^2 + \omega^2}\left(\widehat{tb} + \widehat{\bar{t}\bar{b}}\right) + \frac{\Gamma_t^2}{\Gamma_t^2 + \omega^2}\widehat{b\bar{b}}$$

Unrealistic: $\langle \delta m_t \rangle = 100 - 500$ MeV.
Realistic: $\langle \delta m_t \rangle \approx 30$ MeV.
(W. Beenakker et al., hep-ph/9902304:) $\langle \delta m_t \rangle \lesssim 100$ MeV.

Interconnection outlook for hadron colliders:

- 'trivial' to exend from W^+W^- to any pair of resonances;
- more bookkeeping for 'triplets' like $t\bar{t} \to b\bar{b}q_1\bar{q}_2q_3\bar{q}_4$;
- extension to $p\bar{p}$ underlying event requires further thought.

Wild guess: $\langle \delta m_t \rangle \sim 200$ MeV.

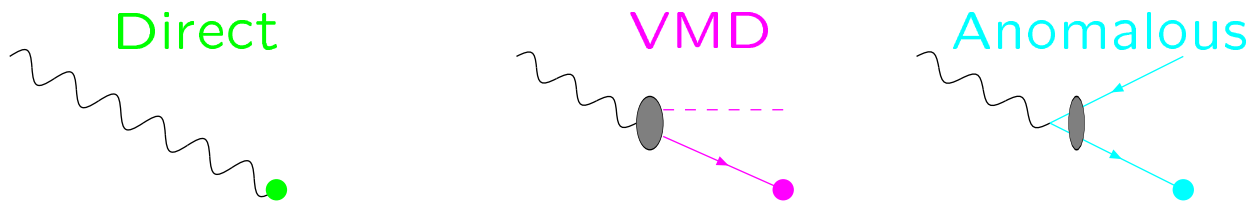
γ^*p and $\gamma^*\gamma^*$ Interactions

(C. Friberg & TS, EPJ C13 (2000) 151,
JHEP 09 (2000) 10, PLB492 (2000) 123)

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

First step: machinery for flux of virtual γ's (transverse and longitudinal)

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



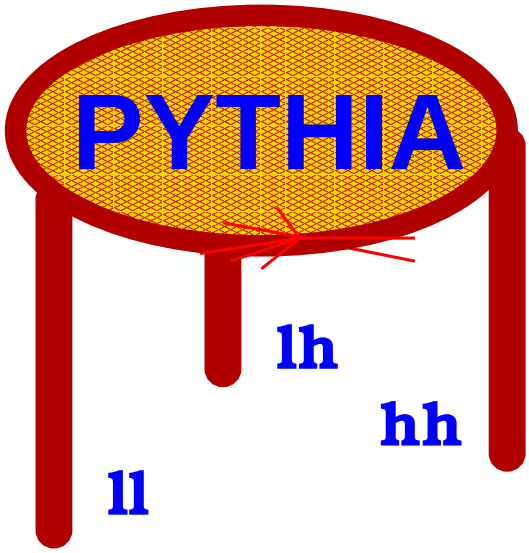
Direct: point-like Resolved: hadronic state
All: 'high'-$p_\perp$ jets; resolved: also soft physics

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 doublecounting (reasonably) consistently

PYTHIA Status



JETSET 7.4
PYTHIA 5.7
SPYTHIA

$\xrightarrow{\text{4 March 1997 :}}$ PYTHIA 6.1

Currently PYTHIA 6.156 of 16 Nov. 2000
$\sim 53,000$ lines Fortran 77

Code, manuals, sample main programs:

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

Short writeup (summary of news):
TS, P. Edén, C. Friberg, L. Lönnblad, G. Miu, S. Mrenna and E. Norrbin, LU TP 00-30 [hep-ph/0010017] $\Rightarrow$ Computer Phys. Comm.

Long writeup in preparation ($\sim$ month)

On to C++

(L. Lönnblad, CPC 118 (1999) 213;
M. Bertini, L. Lönnblad & TS, LUTP 00-23 [hep-ph/0006152];
input to `leif@thep.lu.se`)

Why Fortran → C++?

- SLAC →, FNAL →, CERN → LHC era.
- Industrial standard.
- Educational and professional continuity for students.
- Better to program – for experts.
- User-friendy interfaces – for the rest of us.

PYTHIA 7 milestones:

- January 1998: project formally started.
- June 2000: "proof of concept" version, with generic event generation machinery, some processes and string fragmentation.
- 2001–2002: useful version (?), but limited in scope.
- ??: more and better than current PYTHIA.

HERWIG++ progress:
PPARC funds 2 dedicated "postdocs",
3-year work started a year ago.

Outlook

Generators in state of continuous development

- new physics processes
- more precise parton showers
- improved models soft physics
- and much more

$\Rightarrow$ always better, but never enough

Physics & bug warning:

Due to the large uncertainties present in any realistic QCD Monte Carlo, physics studies must be based on the use of at least two complete and independent programs.

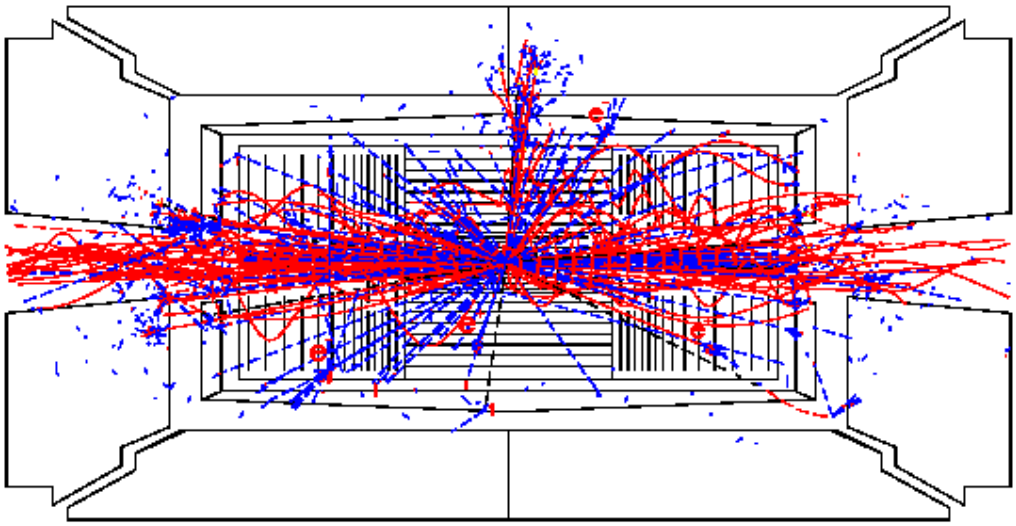
LEP1 workshop

But what are the alternatives?:

H -> ZZ* -> 4 electrons

CMS full GEANT simulation of

H(150 GeV) --> ZZ*--> 4e



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