LUND UNIVERSITY

YETI'06–SM

IPPP, Durham, UK

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Monte Carlo Event Generators

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1. (today) Introduction and Overview; Monte Carlo Techniques
2. **(today) Matrix Elements; Parton Showers I**
3. (tomorrow) Parton Showers II; Matching Issues
4. (tomorrow) Multiple Interactions and Beam Remnants
5. (Wednesday) Hadronization and Decays; Summary and Outlook

Matrix Elements and Their Usage

$\mathcal{L}$

$\Rightarrow$ Feynman rules

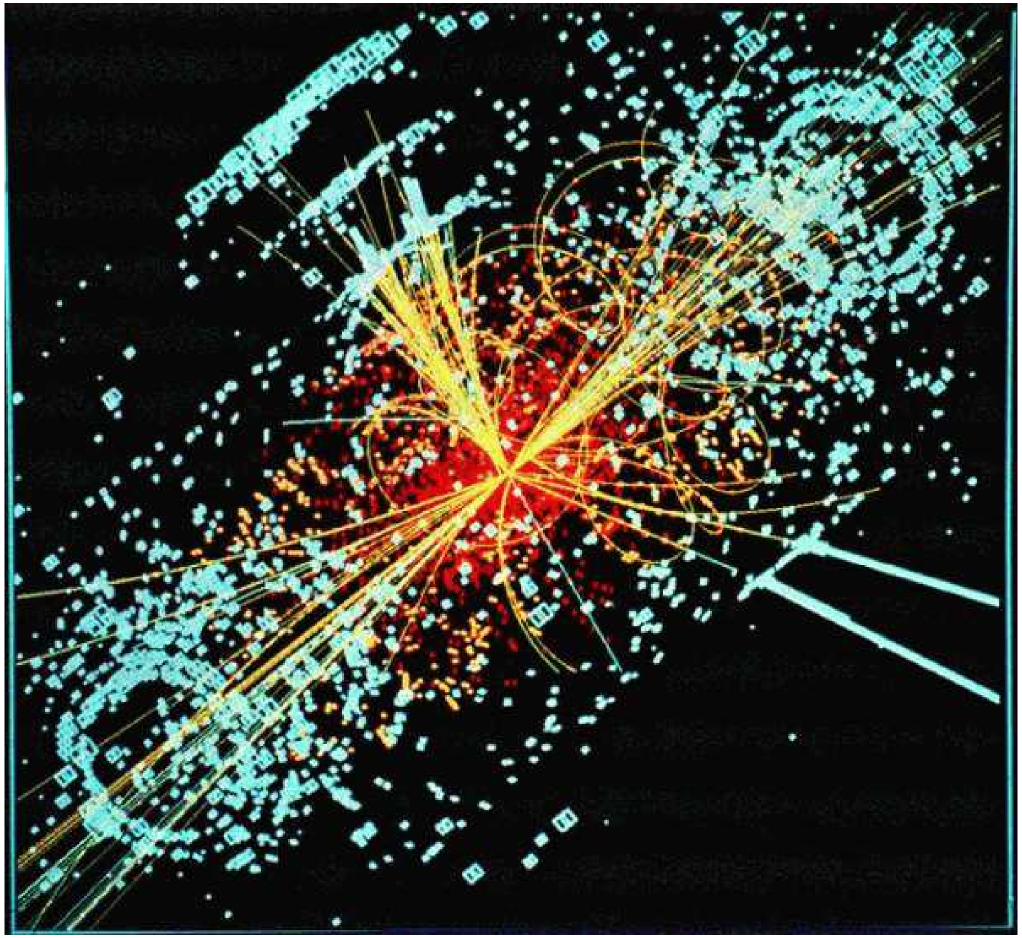
$\Rightarrow$ Matrix Elements

$\Rightarrow$Cross Sections

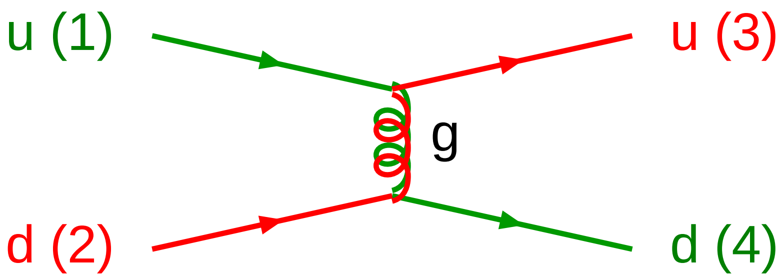
$+$Kinematics

$\Rightarrow$ Processes

$\Rightarrow \ldots \Rightarrow$



Cross sections and kinematics

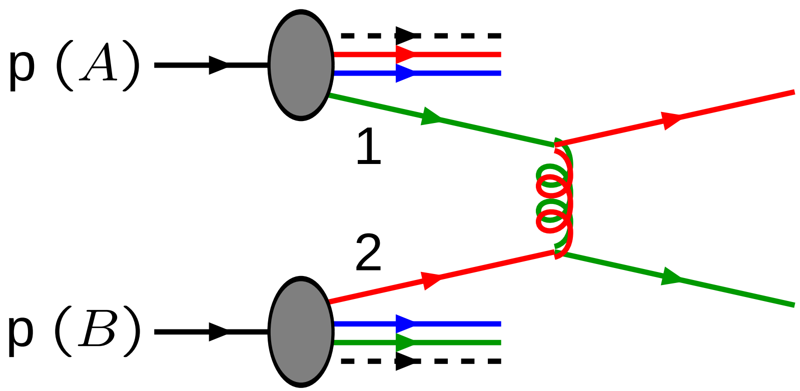


$$\hat{s} = (p_1 + p_2)^2$$

$$\hat{t} = (p_1 - p_3)^2 = -\hat{s}(1 - \cos\hat{\theta})/2$$

$$\hat{u} = (p_1 - p_4)^2 = -\hat{s}(1 + \cos\hat{\theta})/2$$

$$\mathrm{qq}' \to \mathrm{qq}' \quad : \quad \frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}\hat{t}} = \frac{\pi}{\hat{s}^2}\frac{4}{9}\alpha_{\mathrm{s}}^2 \frac{\hat{s}^2 + \hat{u}^2}{\hat{t}^2} \qquad (\sim \text{Rutherford})$$



$$s = (p_A + p_B)^2$$

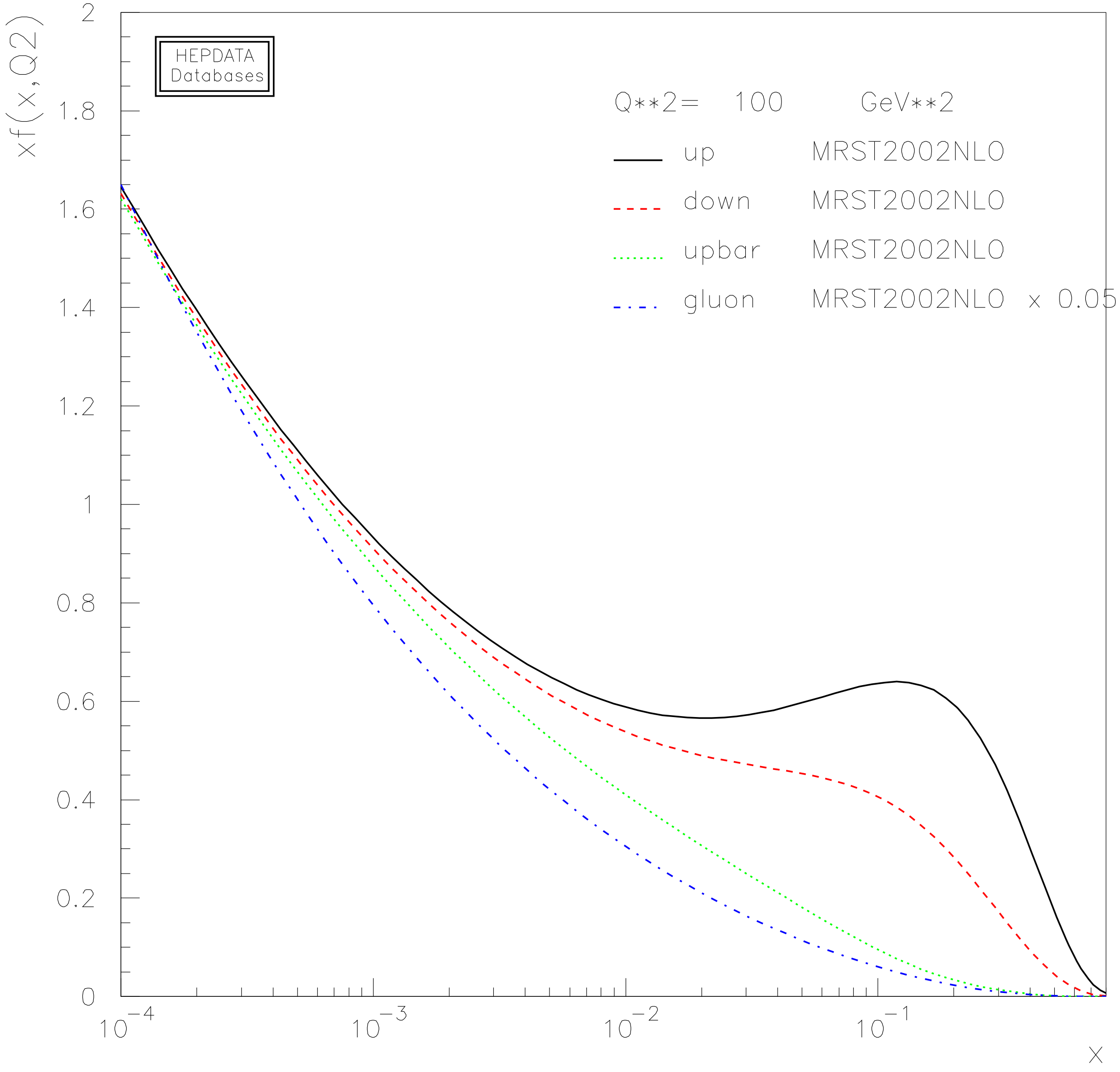
$$x_1 \approx E_1/E_A$$

$$x_2 \approx E_2/E_B$$

$$\hat{s} = x_1 x_2 s$$

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

Parton Distribution/Density Functions (PDF)



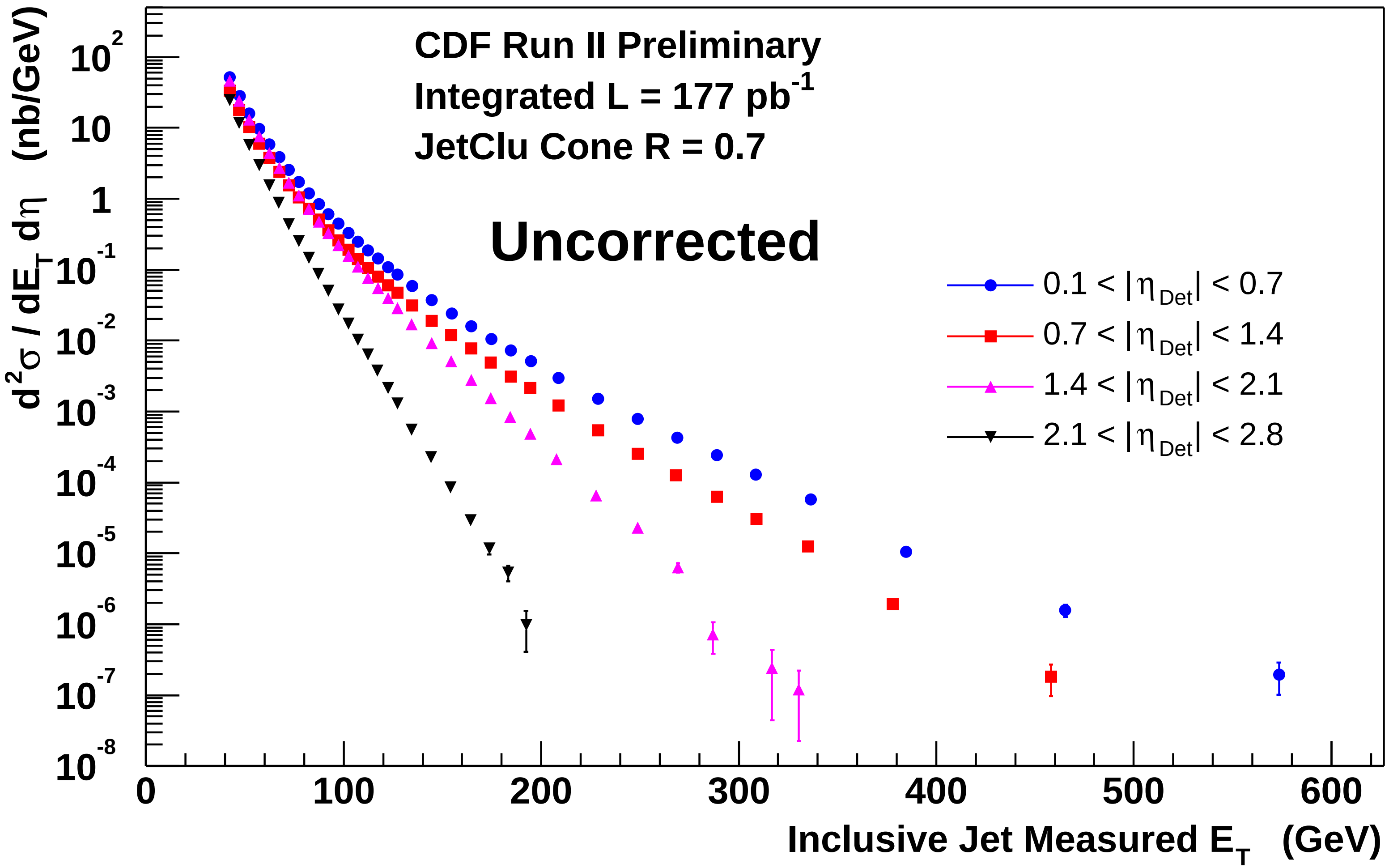
initial
conditions
nonpertubative

evolution
pertubative
(DGLAP)

http://durpdg.dur.ac.uk/hepdata/pdf.html

Peaking of PDF's at small x and of QCD ME's at low $p_\perp$

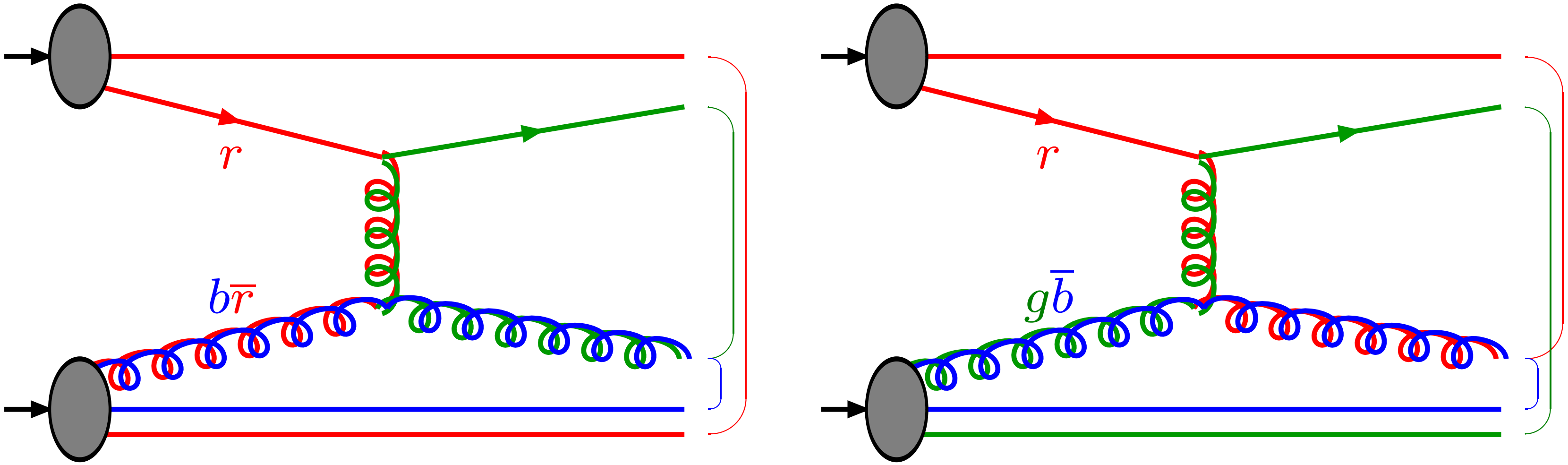
$\Longrightarrow$ most of the physics is at low transverse momenta . . .



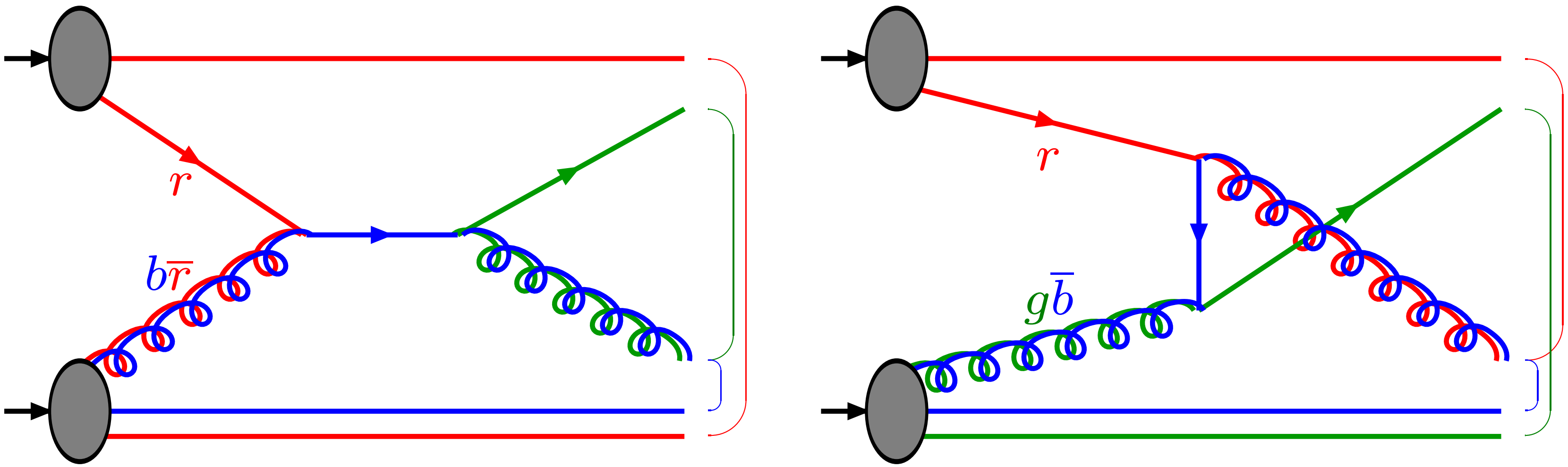
. . . but New Physics likely to show up at large masses/$p_\perp$'s

Colour flow in hard processes

One Feynman graph can correspond to several possible colour flows, e.g. for $qg \to qg$:



while other $qg \to qg$ graphs only admit one colour flow:



so nontrivial mix of kinematics variables $(\hat{s}, \hat{t})$
and colour flow topologies I, II:

$$\begin{aligned} |\mathcal{A}(\hat{s},\hat{t})|^2 &= |\mathcal{A}_{\mathrm{I}}(\hat{s},\hat{t}) + \mathcal{A}_{\mathrm{II}}(\hat{s},\hat{t})|^2 \\ &= |\mathcal{A}_{\mathrm{I}}(\hat{s},\hat{t})|^2 + |\mathcal{A}_{\mathrm{II}}(\hat{s},\hat{t})|^2 + 2\,\mathcal{R}e\left(\mathcal{A}_{\mathrm{I}}(\hat{s},\hat{t})\mathcal{A}_{\mathrm{II}}^*(\hat{s},\hat{t})\right) \end{aligned}$$

with $\mathcal{R}e\left(\mathcal{A}_{\mathrm{I}}(\hat{s},\hat{t})\mathcal{A}_{\mathrm{II}}^*(\hat{s},\hat{t})\right) \neq 0$
$\Rightarrow$ indeterminate colour flow, while

- showers *should* know it (coherence),
- hadronization *must* know it (hadrons singlets).

Normal solution:

$$\frac{\text{interference}}{\text{total}} \propto \frac{1}{N_{\mathrm{C}}^2 - 1}$$

so split $\mathrm{I} : \mathrm{II}$ according to proportions in the $N_{\mathrm{C}} \to \infty$ limit, i.e.

$$\begin{aligned} |\mathcal{A}(\hat{s},\hat{t})|^2 &= |\mathcal{A}_{\mathrm{I}}(\hat{s},\hat{t})|^2_{\mathrm{mod}} + |\mathcal{A}_{\mathrm{II}}(\hat{s},\hat{t})|^2_{\mathrm{mod}} \\ |\mathcal{A}_{\mathrm{I}}(\hat{s},\hat{t})|^2_{\mathrm{mod}} &= |\mathcal{A}_{\mathrm{I}}(\hat{s},\hat{t}) + \mathcal{A}_{\mathrm{II}}(\hat{s},\hat{t})|^2 \left(\frac{|\mathcal{A}_{\mathrm{I}}(\hat{s},\hat{t})|^2}{|\mathcal{A}_{\mathrm{I}}(\hat{s},\hat{t})|^2 + |\mathcal{A}_{\mathrm{II}}(\hat{s},\hat{t})|^2}\right)_{N_{\mathrm{C}}\to\infty} \\ |\mathcal{A}_{\mathrm{II}}(\hat{s},\hat{t})|^2_{\mathrm{mod}} &= \ldots \end{aligned}$$

The Smaller Picture: Subprocess Survey

Kind	Process	PYT	HER	ISA
QCD & related	Soft QCD	$\star$	$\star$	$\star$
	Hard QCD	$\star$	$\star$	$\star$
	Heavy flavour	$\star$	$\star$	$\star$
Electroweak SM	Single $\gamma^*/Z^0/W^\pm$	$\star$	$\star$	$\star$
	$(\gamma/\gamma^*/Z^0/W^\pm/f/g)^2$	$\star$	$\star$	$\star$
	Light SM Higgs	$\star$	$\star$	$\star$
	Heavy SM Higgs	$\star$	$\star$	$\star$
SUSY BSM	$h^0/H^0/A^0/H^\pm$	$\star$	$\star$	$\star$
	SUSY	$\star$	$\star$	$\star$
	$R\!\!\!/$ SUSY	$\star$	$\star$	—
Other BSM	Technicolor	$\star$	—	($\star$)
	New gauge bosons	$\star$	—	—
	Compositeness	$\star$	—	—
	Leptoquarks	$\star$	—	—
	$H^{\pm\pm}$ (from LR-sym.)	$\star$	—	—
	Extra dimensions	($\star$)	($\star$)	($\star$)

PYTHIA Process Library

No.	Subprocess
	Hard QCD processes:
11	$f_i f_j \to f_i f_j$
12	$f_i \overline{f}_i \to f_k \overline{f}_k$
13	$f_i \overline{f}_i \to gg$
28	$f_i g \to f_i g$
53	$gg \to f_k \overline{f}_k$
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	$f_i \overline{f}_i \to Q_k \overline{Q}_k$
82	$gg \to Q_k \overline{Q}_k$
83	$q_i f_j \to Q_k f_l$
84	$g\gamma \to Q_k \overline{Q}_k$
85	$\gamma\gamma \to F_k \overline{F}_k$
	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	$f_i \overline{f}_i \to \gamma^*/Z^0$
2	$f_i \overline{f}_j \to W^\pm$
22	$f_i \overline{f}_i \to Z^0 Z^0$
23	$f_i \overline{f}_j \to Z^0 W^\pm$
25	$f_i \overline{f}_i \to W^+ W^-$
15	$f_i \overline{f}_i \to g Z^0$
16	$f_i \overline{f}_j \to g W^\pm$
30	$f_i g \to f_i Z^0$
31	$f_i g \to f_k W^\pm$
19	$f_i \overline{f}_i \to \gamma Z^0$
20	$f_i \overline{f}_j \to \gamma W^\pm$
35	$f_i \gamma \to f_i Z^0$

No.	Subprocess
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	$f_i \overline{f}_i \to g\gamma$
18	$f_i \overline{f}_i \to \gamma\gamma$
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	$\gamma^* q \to q$
	Photon-induced:
33	$f_i \gamma \to f_i g$
34	$f_i \gamma \to f_i \gamma$
54	$g\gamma \to f_k \overline{f}_k$
58	$\gamma\gamma \to f_k \overline{f}_k$
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	$g \gamma^*_T \to f_i \overline{f}_i$
136	$g \gamma^*_L \to f_i \overline{f}_i$
137	$\gamma^*_T \gamma^*_T \to f_i \overline{f}_i$
138	$\gamma^*_T \gamma^*_L \to f_i \overline{f}_i$
139	$\gamma^*_L \gamma^*_T \to f_i \overline{f}_i$
140	$\gamma^*_L \gamma^*_L \to f_i \overline{f}_i$
80	$q_i \gamma \to q_k \pi^\pm$
	Light SM Higgs:
3	$f_i \overline{f}_i \to h^0$
24	$f_i \overline{f}_i \to Z^0 h^0$
26	$f_i \overline{f}_j \to W^\pm h^0$
32	$f_i g \to f_i h^0$
102	$gg \to h^0$
103	$\gamma\gamma \to h^0$
110	$f_i \overline{f}_i \to \gamma h^0$
111	$f_i \overline{f}_i \to g h^0$
112	$f_i g \to f_i h^0$
113	$gg \to g h^0$
121	$gg \to Q_k \overline{Q}_k h^0$
122	$q_i \overline{q}_i \to Q_k \overline{Q}_k h^0$
123	$f_i f_j \to f_i f_j h^0$
124	$f_i f_j \to f_k f_l h^0$

No.	Subprocess
	New gauge bosons:
141	$f_i \overline{f}_i \to \gamma/Z^0/Z'^0$
142	$f_i \overline{f}_j \to W'^+$
144	$f_i \overline{f}_j \to R$
	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 Higgs:
151	$f_i \overline{f}_i \to H^0$
152	$gg \to H^0$
153	$\gamma\gamma \to H^0$
171	$f_i \overline{f}_i \to Z^0 H^0$
172	$f_i \overline{f}_j \to W^\pm H^0$
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	$gg \to Q_k \overline{Q}_k H^0$
182	$q_i \overline{q}_i \to Q_k \overline{Q}_k H^0$
183	$f_i \overline{f}_i \to g H^0$
184	$f_i g \to f_i H^0$
185	$gg \to g H^0$
156	$f_i \overline{f}_i \to A^0$
157	$gg \to A^0$
158	$\gamma\gamma \to A^0$
176	$f_i \overline{f}_i \to Z^0 A^0$
177	$f_i \overline{f}_j \to W^\pm A^0$
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	$gg \to Q_k \overline{Q}_k A^0$
187	$q_i \overline{q}_i \to Q_k \overline{Q}_k A^0$
188	$f_i \overline{f}_i \to g A^0$
189	$f_i g \to f_i A^0$
190	$gg \to g A^0$
	Charged Higgs:
143	$f_i \overline{f}_j \to H^+$
161	$f_i g \to f_k H^+$
401	$gg \to \overline{t} b H^+$
402	$q\overline{q} \to \overline{t} b H^+$

No.	Subprocess
	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	$f_i \overline{f}_i \to H^+ H^-$
	Leptoquarks:
145	$q_i \ell_j \to L_Q$
162	$qg \to \ell L_Q$
163	$gg \to L_Q \overline{L}_Q$
164	$q_i \overline{q}_i \to L_Q \overline{L}_Q$
	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	$f_i \overline{f}_j \to \gamma \pi^\pm_{tc}$
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	$gg \to Q_k \overline{Q}_k$

No.	Subprocess
	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	$f_i \overline{f}_j (\to W^\pm) \to f_k \overline{f}_l$
	Extra Dimensions:
391	$f\overline{f} \to G^*$
392	$gg \to G^*$
393	$q\overline{q} \to g G^*$
394	$qg \to q G^*$
395	$gg \to g G^*$
	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	$f_i \overline{f}_i \to H^{++}_L H^{--}_L$
350	$f_i \overline{f}_i \to H^{++}_R H^{--}_R$
351	$f_i f_j \to f_k f_l H^{\pm\pm}_L$
352	$f_i f_j \to f_k f_l H^{\pm\pm}_R$
353	$f_i \overline{f}_i \to Z^0_R$
354	$f_i \overline{f}_j \to W^\pm_R$
	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	$f_i \overline{f}_i \to \tilde{\tau}_1 \tilde{\tau}^*_2 +$

No.	Subprocess
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	$f_i \overline{f}_i \to \tilde{\nu}_\ell \tilde{\nu}_\ell^*$
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	$f_i \overline{f}_i \to \tilde{\chi}^\pm_1 \tilde{\chi}^\mp_1$
227	$f_i \overline{f}_i \to \tilde{\chi}^\pm_2 \tilde{\chi}^\mp_2$
228	$f_i \overline{f}_i \to \tilde{\chi}^\pm_1 \tilde{\chi}^\mp_2$
229	$f_i \overline{f}_j \to \tilde{\chi}_1 \tilde{\chi}^\pm_1$
230	$f_i \overline{f}_j \to \tilde{\chi}_2 \tilde{\chi}^\pm_1$
231	$f_i \overline{f}_j \to \tilde{\chi}_3 \tilde{\chi}^\pm_1$
232	$f_i \overline{f}_j \to \tilde{\chi}_4 \tilde{\chi}^\pm_1$
233	$f_i \overline{f}_j \to \tilde{\chi}_1 \tilde{\chi}^\pm_2$
234	$f_i \overline{f}_j \to \tilde{\chi}_2 \tilde{\chi}^\pm_2$
235	$f_i \overline{f}_j \to \tilde{\chi}_3 \tilde{\chi}^\pm_2$
236	$f_i \overline{f}_j \to \tilde{\chi}_4 \tilde{\chi}^\pm_2$
237	$f_i \overline{f}_i \to \tilde{g} \tilde{\chi}_1$
238	$f_i \overline{f}_i \to \tilde{g} \tilde{\chi}_2$
239	$f_i \overline{f}_i \to \tilde{g} \tilde{\chi}_3$
240	$f_i \overline{f}_i \to \tilde{g} \tilde{\chi}_4$
241	$f_i \overline{f}_j \to \tilde{g} \tilde{\chi}^\pm_1$
242	$f_i \overline{f}_j \to \tilde{g} \tilde{\chi}^\pm_2$
243	$f_i \overline{f}_i \to \tilde{g} \tilde{g}$
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	$f_i g \to \tilde{q}_{iR} \tilde{\chi}_2$

No.	Subprocess
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	$f_i \overline{f}_i \to \tilde{t}_1 \tilde{t}^*_1$
262	$f_i \overline{f}_i \to \tilde{t}_2 \tilde{t}^*_2$
263	$f_i \overline{f}_i \to \tilde{t}_1 \tilde{t}^*_2 +$
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	$f_i \overline{f}_j \to \tilde{q}_{iL} \tilde{q}^*_{jL}$
275	$f_i \overline{f}_j \to \tilde{q}_{iR} \tilde{q}^*_{jR}$
276	$f_i \overline{f}_j \to \tilde{q}_{iL} \tilde{q}^*_{jR} +$
277	$f_i \overline{f}_i \to \tilde{q}_{jL} \tilde{q}^*_{jL}$
278	$f_i \overline{f}_i \to \tilde{q}_{jR} \tilde{q}^*_{jR}$
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	$bq_i \to \tilde{b}_1 \tilde{q}_{iR} +$
284	$b\overline{q}_i \to \tilde{b}_1 \tilde{q}^*_{iL}$
285	$b\overline{q}_i \to \tilde{b}_2 \tilde{q}^*_{iR}$
286	$b\overline{q}_i \to \tilde{b}_1 \tilde{q}^*_{iR} +$
287	$f_i \overline{f}_i \to \tilde{b}_1 \tilde{b}^*_1$
288	$f_i \overline{f}_i \to \tilde{b}_2 \tilde{b}^*_2$
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	$b\overline{b} \to \tilde{b}_1 \tilde{b}^*_2 +$

HERWIG Process Library

IPROC	Process
100	$\ell^+\ell^- \to q\bar{q}(g)$ (all q flavours)
100+IQ	$\ell^+\ell^- \to q\bar{q}(g)$ ($\texttt{IQ} = 1,2,3,4,5,6$ for $q = d,u,s,c,b,t$)
107	$\ell^+\ell^- \to gg(g)$ (fictitious process)
110	$\ell^+\ell^- \to q\bar{q}g$ (all flavours)
110+IQ	$\ell^+\ell^- \to q\bar{q}g$ (IQ as above)
120	$\ell^+\ell^- \to q\bar{q}$ (all flavours, no hard gluon correction)
120+IQ	$\ell^+\ell^- \to q\bar{q}$ (IQ as above, no hard gluon correction)
127	$\ell^+\ell^- \to gg$ (fictitious process, no hard gluon correction)
150+IL	$\ell^+\ell^- \to \ell'\bar{\ell}'$ ($\texttt{IL} = 1,2,3$ for $\ell' = e,\mu,\tau$, N.B. $\ell \neq \ell'$)
200	$\ell^+\ell^- \to W^+W^-$ (see sect. ?? on control of W/Z decays)
250	$\ell^+\ell^- \to Z^0Z^0$ (see sect. ?? on control of W/Z decays)
300	$\ell^+\ell^- \to Z^0H^0_{\rm SM} \to Z^0q\bar{q}$ (all flavours)
300+IQ	$\ell^+\ell^- \to Z^0H^0_{\rm SM} \to Z^0q\bar{q}$ (IQ as above)
306+IL	$\ell^+\ell^- \to Z^0H^0_{\rm SM} \to Z^0\ell\bar{\ell}$ (IL as above)
310, 311	$\ell^+\ell^- \to Z^0H^0_{\rm SM} \to Z^0W^+W^-$, $Z^0Z^0Z^0$
312	$\ell^+\ell^- \to Z^0H^0_{\rm SM} \to Z^0\gamma\gamma$
399	$\ell^+\ell^- \to Z^0H^0_{\rm SM} \to Z^0$ anything
400+ID	$\ell^+\ell^- \to \nu\bar{\nu}H^0_{\rm SM} + \ell^+\ell^-H^0_{\rm SM}$ (ID as in $\texttt{IPROC} = 300 + \texttt{ID}$)
500+ID	$\ell^+\ell^- \to \ell^+\ell^-\gamma\gamma \to \ell^+\ell^-q\bar{q}/\ell\ell/W^+W^-$
	(ID=0–10 as in $\texttt{IPROC} = 300 + \texttt{ID}$)
550+ID	$\ell^+\ell^- \to \ell\nu_\ell\gamma W \to \ell\nu_\ell q\bar{q}'/\ell\bar{\ell}'$ (ID=0–9 as in $\texttt{IPROC} = 300 + \texttt{ID}$)
600	$\ell^+\ell^- \to q\bar{q}gg, q\bar{q}q'\bar{q}'$ (all q flavours)
600+IQ	$\ell^+\ell^- \to q\bar{q}gg, q\bar{q}q'\bar{q}'$ (IQ as above)
	After generation, IHPRO is subprocess (see sect. ??)
700-99	Minimal Supersymmetric Standard Model (MSSM) processes
700	$\ell^+\ell^- \to$ 2-sparticle processes (sum of 710, 730, 740 and 760)
710	$\ell^+\ell^- \to$ neutralino pairs (all neutralinos)
706+4IN1+IN2	$\ell^+\ell^- \to \widetilde{\chi}^0_{\rm IN1}\widetilde{\chi}^0_{\rm IN2}$ (IN1,2=neutralino mass eigenstate)
730	$\ell^+\ell^- \to$ chargino pairs (all charginos)
728+2IC1+IC2	$\ell^+\ell^- \to \widetilde{\chi}^+_{\rm IC1}\widetilde{\chi}^-_{\rm IC2}$ (IC1,2=chargino mass eigenstate)
740	$\ell^+\ell^- \to$ slepton pairs (all flavours)
736+5IL	$\ell^+\ell^- \to \widetilde{\ell}_{L,R}\widetilde{\ell}^*_{L,R}$ ($\texttt{IL} = 1,2,3$ for $\widetilde{\ell} = \tilde{e},\tilde{\mu},\tilde{\tau}$)
737+5IL	$\ell^+\ell^- \to \widetilde{\ell}_L\widetilde{\ell}^*_L$ (IL as above)
738+5IL	$\ell^+\ell^- \to \widetilde{\ell}_L\widetilde{\ell}^*_R$ (IL as above)
739+5IL	$\ell^+\ell^- \to \widetilde{\ell}_R\widetilde{\ell}^*_R$ (IL as above)
740+5IL	$\ell^+\ell^- \to \widetilde{\nu}_L\widetilde{\nu}^*_L$ ($\texttt{IL} = 1,2,3$ for $\widetilde{\nu}_e,\widetilde{\nu}_\mu,\widetilde{\nu}_\tau$)
760	$\ell^+\ell^- \to$ squark pairs (all flavours)
757+4IQ	$\ell^+\ell^- \to \widetilde{q}_{L,R}\widetilde{q}^*_{L,R}$ ($\texttt{IQ} = 1,2,3,4,5,6$ for $\widetilde{q} = \tilde{d},\tilde{u},\tilde{s},\tilde{c},\tilde{b},\tilde{t}$)
758+4IQ	$\ell^+\ell^- \to \widetilde{q}_L\widetilde{q}^*_L$ (IQ as above)
759+4IQ	$\ell^+\ell^- \to \widetilde{q}_L\widetilde{q}^*_R$ (IQ as above)
760+4IQ	$\ell^+\ell^- \to \widetilde{q}_R\widetilde{q}^*_R$ (IQ as above)
800-99	R-parity violating supersymmetric processes
800	Single sparticle production, sum of 810–840
810	$\ell^+\ell^- \to \widetilde{\chi}^0\nu_i$, (all neutralinos)
810+IN	$\ell^+\ell^- \to \widetilde{\chi}^0_{\rm IN}\nu_i$, (IN=neutralino mass state)
820	$\ell^+\ell^- \to \widetilde{\chi}^-e^+_i$ (all charginos)
820+IC	$\ell^+\ell^- \to \widetilde{\chi}^-_{\rm IC}e^+_i$, (IC=chargino mass state)
830	$\ell^+\ell^- \to \widetilde{\nu}_iZ^0$ and $\ell^+\ell^- \to \widetilde{\ell}^+_iW^-$
840	$\ell^+\ell^- \to \widetilde{\nu}_ih^0/H^0/A^0$ and $\ell^+\ell^- \to \widetilde{\ell}^+_iH^-$
850	$\ell^+\ell^- \to \widetilde{\nu}_i\gamma$
860	Sum of 870 and 880
870	$\ell^+\ell^- \to \ell^+\ell^-$, via LLE only
867+3IL1+IL2	$\ell^+\ell^- \to \ell^+_{\rm IL1}\ell^-_{\rm IL2}$ (IL1,2=1,2,3 for e,μ,τ)
880	$\ell^+\ell^- \to dd$, via LLE and LQD
877+3IQ1+IQ2	$\ell^+\ell^- \to d_{\rm IL1}\bar{d}_{\rm IL2}$ (IQ1,2=1,2,3 for d,s,b)
910	$\ell^+\ell^- \to \nu_e\bar{\nu}_eh^0 + e^+e^-h^0$
920	$\ell^+\ell^- \to \nu_e\bar{\nu}_eH^0 + e^+e^-H^0$
960	$\ell^+\ell^- \to Z^0h^0$
970	$\ell^+\ell^- \to Z^0H^0$
955	$\ell^+\ell^- \to H^+H^-$
965	$\ell^+\ell^- \to A^0h^0$
965	$\ell^+\ell^- \to A^0H^0$
1000+ID	$\ell^+\ell^- \to t\,\bar{t}\,H^0_{\rm SM}$ (ID as in IPROC=300+ID)
1110+IQ	$\ell^+\ell^- \to q\,\bar{q}\,h^0$ (IQ as in IPROC=100+IQ)
1116+IL	$\ell^+\ell^- \to \ell^+\ell^-h^0$ (IL=1,2,3 for e,μ,τ)
1120+IQ	$\ell^+\ell^- \to q\,\bar{q}\,H^0$ (IQ as in IPROC=100+IQ)
1126+IL	$\ell^+\ell^- \to \ell^+\ell^-H^0$ (IL=1,2,3 for e,μ,τ)
1130+IQ	$\ell^+\ell^- \to q\,\bar{q}\,A^0$ (IQ as in IPROC=100+IQ)
1136+IL	$\ell^+\ell^- \to \ell^+\ell^-A^0$ (IL=1,2,3 for e,μ,τ)
1140	$\ell^+\ell^- \to d\,\bar{u}\,H^+ +$ ch. conj.
1141	$\ell^+\ell^- \to s\,\bar{c}\,H^+ +$ ch. conj.
1142	$\ell^+\ell^- \to b\,\bar{t}\,H^+ +$ ch. conj.
1143	$\ell^+\ell^- \to e\,\bar{\nu}_eH^+ +$ ch. conj.
1144	$\ell^+\ell^- \to \mu\,\bar{\nu}_\mu H^+ +$ ch. conj.

IPROC	Process
1145	$\ell^+\ell^- \to \tau\,\bar{\nu}_\tau H^+ +$ ch. conj.
1200–99	Reserved for other $\ell^+\ell^-$ processes
1300	$q\bar{q} \to Z^0/\gamma \to q'\bar{q}'$ (all flavours)
1300+IQ	$q\bar{q} \to Z^0/\gamma \to q'\bar{q}'$ ($\texttt{IQ} = 1,2,3,4,5,6$ for $q = d,u,s,c,b,t$)
1350	$q\bar{q} \to Z^0/\gamma \to \ell\bar{\ell}$ (all lepton species)
1350+IL	$q\bar{q} \to Z^0/\gamma \to \ell\bar{\ell}$ ($\texttt{IL} = 1-6$ for $\ell = e,\nu_e,\mu,\nu_\mu$, etc.)
1399	$q\bar{q} \to Z^0/\gamma \to$ anything
1400	$q\bar{q} \to W^\pm \to q'\bar{q}''$ (all flavours)
1400+IQ	$q\bar{q} \to W^\pm \to q'\bar{q}''$ (q' or q'' as above)
1450	$q\bar{q} \to W^\pm \to \ell\nu_\ell$ (all lepton species)
1450+IL	$q\bar{q} \to W^\pm \to \ell\nu_\ell$ ($\texttt{IL} = 1,2,3$ for $\ell = e,\mu,\tau$)
1499	$q\bar{q} \to W^\pm \to$ anything
1500	QCD $2\to2$ hard parton scattering
	After generation, IHPRO is subprocess (see sect. ??)
1600+ID	$gg/q\bar{q} \to H^0_{\rm SM}$ (ID as in $\texttt{IPROC} = 300 + \texttt{ID}$)
1700+IQ	QCD heavy quark production (IQ as above)
	After generation, IHPRO is subprocess (see sect. ??)
1800	QCD direct photon + jet production
	After generation, IHPRO is subprocess (see sect. ??)
1900+ID	$q\bar{q} \to q'\bar{q}'W^+W^-/Z^0Z^0 \to q'\bar{q}'H^0_{\rm SM}$ (ID as in $\texttt{IPROC} = 300 + \texttt{ID}$)
2000	t production via $W^\pm$ exchange (sum of 2001–2008)
2001–4	$\bar{u}b \to \bar{d}t$, $\bar{d}b \to u\bar{t}$, $\bar{d}b \to \bar{u}t$, $ub \to dt$
2005–8	$\bar{c}b \to \bar{s}t$, $s\bar{b} \to c\bar{t}$, $\bar{s}b \to \bar{c}t$, $cb \to st$
2100	$W^\pm$ + jet production
2110	$W^\pm$ + jet production (Compton only: $gq \to Wq$)
2120	$W^\pm$ + jet production (annihilation only: $q\bar{q} \to Wg$)
2150	Z^0 + jet production
2160	Z^0 + jet production (Compton only: $gq \to Zq$)
2170	Z^0 + jet production (annihilation only: $q\bar{q} \to Zg$)
2200	QCD direct photon pair production
	After generation, IHPRO is subprocess (see sect. ??)
2300+ID	QCD SM Higgs + jet production (ID as in IPROC=300+ID)
	After generation, IHPRO is subprocess (see sect. ??)
2400	Mueller-Tang colour singlet exchange
2450	Quark scattering via photon exchange
2500+ID	$gg/q\bar{q} \to t\bar{t}H^0_{\rm SM}$ (ID as in IPROC=300+ID)
2600+ID	$q\bar{q}' \to W^\pm H^0_{\rm SM}$ (ID as in IPROC=300+ID)
2700+ID	$q\bar{q} \to Z^0H^0_{\rm SM}$ (ID as in IPROC=300+ID)
2800	W^+W^- production in hadron-hadron collisions
2810	Z^0Z^0 production in hadron-hadron collisions (including photon terms)
2815	Z^0Z^0 production in hadron-hadron collisions (Z^0 only)
2820	$W^\pm Z^0$ production in hadron-hadron collisions (including photon terms)
2825	$W^\pm Z^0$ production in hadron-hadron collisions (Z^0 only)
2850	hadron-hadron $\to W^+W^-X$ using MC@NLO
2860	hadron-hadron $\to Z^0Z^0X$ using MC@NLO
2870	hadron-hadron $\to W^+Z^0X$ using MC@NLO
2880	hadron-hadron $\to W^-Z^0X$ using MC@NLO
2900+IQ	$gg + q\bar{q} \to QQZ^0$ for massless Q and $\bar{Q}$ (IQ=1…6 for $Q = d\ldots t$)
2910+IQ	$gg + q\bar{q} \to Q\bar{Q}Z^0$, for massive Q and $\bar{Q}$ (IQ=1…6 for $Q = d\ldots t$)
3000-3999	Minimal Supersymmetric Standard Model (MSSM) processes
3000	2-parton $\to$ 2-sparticle processes (sum of those below)
3010	2-parton $\to$ 2-sparton processes
3020	2-parton $\to$ 2-gaugino processes
3030	2-parton $\to$ 2-slepton processes
3100+ISQ	$gg/q\bar{q} \to \tilde{q}\tilde{q}^*H^\pm$ (ISQ=IPROC−3100 as from table ??)
3200+ISQ	$gg/q\bar{q} \to \tilde{q}\tilde{q}^*h, H, A$ (ISQ=IPROC−3200 as from table ??)
3310,3315	$q\bar{q}' \to W^\pm h^0, H^\pm h^0$(all q,q' flavours – gauge bosons mediated only)
3320,3325	$q\bar{q}' \to W^\pm H^0, H^\pm H^0$ (")
3335	$q\bar{q}' \to H^\pm A^0$ (")
3350	$q\bar{q} \to W^\pm H^\mp$ (Higgstrahlung and Higgs mediated)
3355	$q\bar{q} \to H^\pm H^\mp$ (all q flavours — gauge boson mediated only)
3360,3365	$q\bar{q} \to Z^0h^0, A^0h^0$ (")
3370,3375	$q\bar{q} \to Z^0H^0, A^0H^0$ (")
3410	$bg \to b\;h^0$ + ch. conj.
3420	$bg \to b\;H^0$ + ch. conj.
3430	$bg \to b\;A^0$ + ch. conj.
3450	$bg \to t\;H^-$ + ch. conj.
3500	$bq \to bq'H^+$ + ch. conj.
3610	$q\bar{q}/gg \to h^0$ (light scalar Higgs)
3620	$q\bar{q}/gg \to H^0$ (heavy scalar Higgs)
3630	$q\bar{q}/gg \to A^0$ (pseudoscalar Higgs)
3710	$q\bar{q} \to q'\bar{q}'W^+W^-/Z^0Z^0 \to q'\bar{q}'h^0$
3720	$q\bar{q} \to q'\bar{q}'W^+W^-/Z^0Z^0 \to q'\bar{q}'H^0$
3810+IQ	$gg + q\bar{q} \to Q\bar{Q}h^0$ (all q flavours in s-channel, IQ as usual for Q flavour)
3820+IQ	$gg + q\bar{q} \to Q\bar{Q}H^0$ (")

IPROC	Process
3830+IQ	$gg + q\bar{q} \to Q\bar{Q}A^0$ (")
3839	$gg + q\bar{q} \to b\bar{t}H^+$ + ch. conjg. (all q flavours in s-channel)
3840+IQ	$gg \to Q\bar{Q}h^0$ (IQ as above)
3850+IQ	$gg \to Q\bar{Q}H^0$ (")
3860+IQ	$gg \to Q\bar{Q}A^0$ (")
3869	$gg \to b\bar{t}H^+$ + ch. conjg.
3870+IQ	$q\bar{q} \to Q\bar{Q}h^0$ (all q flavours in s-channel, IQ as above)
3880+IQ	$q\bar{q} \to Q\bar{Q}H^0$ (")
3890+IQ	$q\bar{q} \to Q\bar{Q}A^0$ (")
3899	$q\bar{q} \to b\bar{t}H^+$ + ch. conjg. (all q flavours in s-channel)
3900–99	Reserved for other hadron-hadron MSSM processes
4000–99	R-parity violating supersymmetric processes via LQD
4000	single sparticle production, sum of 4010–4050
4010	$\bar{u}_jd_k \to \widetilde{\chi}^0l^-_i$, $\bar{d}_jd_k \to \widetilde{\chi}^0\nu_i$ (all neutralinos)
4010+IN	$\bar{u}_jd_k \to \widetilde{\chi}^0_{\rm IN}l^-_i$, $\bar{d}_jd_k \to \widetilde{\chi}^0_{\rm IN}\nu_i$ (IN=neutralino mass state)
4020	$\bar{u}_jd_k \to \widetilde{\chi}^-\nu_i$, $\bar{d}_jd_k \to \widetilde{\chi}^-e^+_i$ (all charginos)
4020+IC	$\bar{u}_jd_k \to \widetilde{\chi}^-_{\rm IC}\nu_i$, $\bar{d}_jd_k \to \widetilde{\chi}^-_{\rm IC}e^+_i$ (IC=chargino mass state)
4040	$u_j\bar{d}_k \to \widetilde{\tau}^+_iZ^0$, $u_j\bar{d}_k \to \widetilde{\nu}_iW^+$ and $d_j\bar{d}_k \to \widetilde{\ell}^+_iW^-$
4050	$u_j\bar{d}_k \to \widetilde{\ell}^+_ih^0/H^0/A^0$, $u_j\bar{d}_k \to \widetilde{\nu}_iH^+$ and $d_j\bar{d}_k \to \widetilde{\ell}^+_iH^-$
4060	Sum of 4070 and 4080
4070	$\bar{u}_jd_k \to \bar{u}_ld_m$ and $\bar{d}_jd_k \to \bar{d}_ld_m$, via LQD only
4080	$\bar{u}_jd_k \to \nu_jl^-_k$ and $\bar{d}_jd_k \to l^+_jl^-_k$, via LQD and LLE
4100-99	R-parity violating supersymmetric processes via UDD
4100	single sparticle production, sum of 4110–4150
4110	$u_id_j \to \widetilde{\chi}^0\bar{d}_k$, $d_jd_k \to \widetilde{\chi}^0\bar{u}_i$ (all neutralinos)
4110 +IN	$u_id_j \to \widetilde{\chi}^0_{\rm IN}\bar{d}_k$, $d_jd_k \to \widetilde{\chi}^0_{\rm IN}\bar{u}_i$(IN as above)
4120	$u_id_j \to \widetilde{\chi}^+\bar{u}_k$, $d_jd_k \to \widetilde{\chi}^-\bar{d}_i$ (all charginos)
4120 +IC	$u_id_j \to \widetilde{\chi}^+_{\rm IC}\bar{u}_k$, $d_jd_k \to \widetilde{\chi}^-_{\rm IC}\bar{d}_i$ (IC as above)
4130	$u_id_j \to \widetilde{g}\bar{d}_k$, $d_jd_k \to \widetilde{g}\bar{u}_i$
4140	$u_id_j \to \widetilde{b}^*_iZ^0$, $d_jd_k \to \widetilde{t}^*_iZ^0$, $u_id_j \to \widetilde{t}^*_iW^+$ and $d_jd_k \to \widetilde{b}^*_iW^-$
4150	$u_id_j \to \widetilde{d}^*_{k1}h^0/H^0/A^0, d_jd_k \to \widetilde{u}^*_{i1}h^0/H^0/A^0, u_id_j \to \widetilde{u}^*_{k\alpha}H^+,$
	$d_jd_k \to \widetilde{d}^*_{i\alpha}H^-$
4160	$u_id_j \to u_ld_m$, $d_jd_k \to d_ld_m$ via UDD.
4200-99	Graviton resonance production
4200	Sum of 4210, 4250 and 4270
4210	$gg/q\bar{q} \to G \to gg/q\bar{q}$ (all partons)
4210+IQ	$gg/q\bar{q} \to G \to q\bar{q}$ (IQ as above)
4220	$gg/q\bar{q} \to G \to gg$
4250	$gg/q\bar{q} \to G \to \ell\bar{\ell}$ (all leptons)
4250+IL	$gg/q\bar{q} \to G \to \ell\bar{\ell}$ ($\texttt{IL} = 1-6$ for $\ell = e,\nu_e,\mu,\nu_\mu$, etc.)
4260	$gg/q\bar{q} \to G \to \gamma\gamma$
4270	$gg/q\bar{q} \to G \to W^+W^-/Z^0Z^0/H^0_{\rm SM}H^0_{\rm SM}$
4271	$gg/q\bar{q} \to G \to W^+W^-$
4272	$gg/q\bar{q} \to G \to Z^0Z^0$
4273	$gg/q\bar{q} \to G \to H^0_{\rm SM}H^0_{\rm SM}$
5000	Pointlike photon-hadron jet production (all flavours)
5100+IQ	Pointlike photon heavy flavour pair production (IQ as above)
5200+IQ	Pointlike photon heavy flavour single excitation (IQ as above)
	After generation, IHPRO is subprocess (see sect. ??)
5300	Quark-photon Compton scattering
5500	Pointlike photon production of light (u,d,s) L=0 mesons
5510,20	S=0 mesons only, S=1 mesons only
	After generation, IHPRO is subprocess (see sect. ??)
6000	$\gamma\gamma \to q\bar{q}$ (all flavours)
6000+IQ	$\gamma\gamma \to q\bar{q}$ (IQ as above)
6006+IL	$\gamma\gamma \to \ell\bar{\ell}$ ($\texttt{IL} = 1,2,3$ for $\ell = e,\mu,\tau$)
6010	$\gamma\gamma \to W^+W^-$
7000 –	Baryon-number violating and other multi-$W^\pm$ processes
7999	generated by HERBVI package
8000	Minimum bias soft hadron-hadron event
9000	Deep inelastic lepton scattering (all neutral current)
9000+IQ	Deep inelastic lepton scattering (NC on flavour IQ)
9010	Deep inelastic lepton scattering (all charged current)
9010+IQ	Deep inelastic lepton scattering (CC on flavour IQ)
9100	Boson-gluon fusion in neutral current DIS (all flavours)
9100+IQ	Boson-gluon fusion in neutral current DIS (IQ as above)
9107	J/ψ + gluon production by boson-gluon fusion
9110	QCD Compton process in neutral current DIS (all flavours)
9110+IP	QCD Compton process in NC DIS (IP=1–12 for $d-t, \bar{d}-\bar{t}$)
9130	All $\mathcal{O}(\alpha_S)$ NC processes (i.e. 9100+9110)
9140+IP	Heavy quark production by charged-current boson-gluon fusion
	IP: $1 = s\bar{c}, 2 = b\bar{c}, 3 = s\bar{t}, 4 = b\bar{t}$ (+ ch. conj.)
9500+ID	$W^+W^-/Z^0Z^0 \to H^0_{\rm SM}$ in DIS (ID as in $\texttt{IPROC} = 300 + \texttt{ID}$)
10000+IP	as IPROC = IP but with soft underlying event
	(soft remnant fragmentation in lepton-hadron) suppressed

A Giant on Clay Feet

Subprocess lists *look* impressive, and have 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

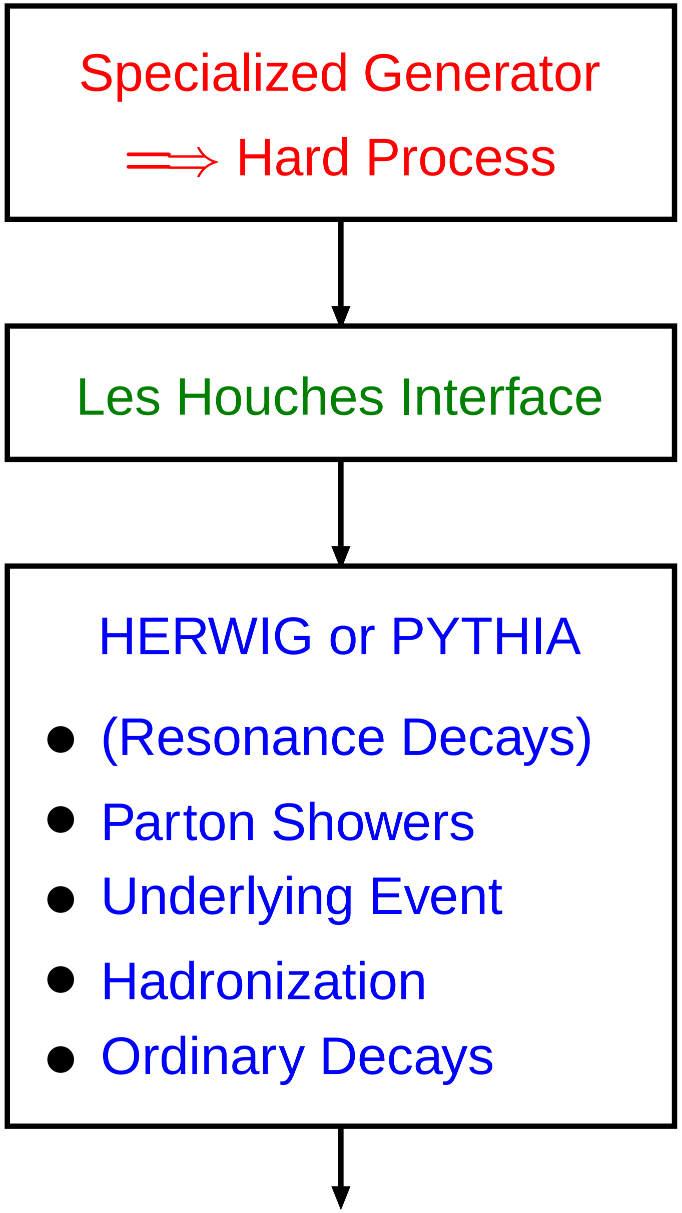
$\star$ Spin correlations often absent or incomplete
e.g. top produced unpolarized, while $\mathrm{t} \to \mathrm{bW}^+ \to \mathrm{b}\ell^+\nu_\ell$ decay correct
$\Rightarrow$ have to use external programs when important

$\star$ 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 were the process libraries ever built?
A: Automatic code generation only maturing in recent years!)

The Les Houches Accord



Some Specialized Generators:

- AcerMC: $\mathrm{t\bar{t}b\bar{b}}, \ldots$
- ALPGEN: $\mathrm{W/Z}+ \leq 6\mathrm{j}$, $n\mathrm{W} + m\mathrm{Z} + k\mathrm{H} + \leq 3\mathrm{j}, \ldots$
- AMEGIC++: generic LO
- CompHEP: generic LO
- GRACE+Bases/Spring: generic LO+ some NLO loops
- GR@PPA: $\mathrm{b\bar{b}b\bar{b}}$
- MadCUP: $\mathrm{W/Z}+ \leq 3\mathrm{j}, \mathrm{t\bar{t}b\bar{b}}$
- MadGraph+HELAS: generic LO
- MCFM: NLO $\mathrm{W/Z}+ \leq 2\mathrm{j}$, WZ, WH, $\mathrm{H}+ \leq 1\mathrm{j}$
- O'Mega+WHIZARD: generic LO
- VECBOS: $\mathrm{W/Z}+ \leq 4\mathrm{j}$

Apologies for all unlisted programs

Initialization

```
 INTEGER MAXPUP
 PARAMETER (MAXPUP=100)
 INTEGER IDBMUP,PDFGUP,PDFSUP,IDWTUP,NPRUP,LPRUP
 DOUBLE PRECISION EBMUP,XSECUP,XERRUP,XMAXUP
 COMMON/HEPRUP/IDBMUP(2),EBMUP(2),PDFGUP(2),PDFSUP(2),IDWTUP,
&NPRUP,XSECUP(MAXPUP),XERRUP(MAXPUP),XMAXUP(MAXPUP),LPRUP(MAXPUP)
```

`IDBMUP`: incoming beam particles (PDG codes, $\mathrm{p} = 2212$, $\overline{\mathrm{p}} = -2212$)

`EBMUP`: incoming beam energies (GeV)

`PDFGUP`, `PDFSUP`: PDFLIB parton distributions (not used by PYTHIA)

`IDWTUP`: weighting strategy

- = `1`: PYTHIA mixes and unweights events, according to known $\mathrm{d}\sigma_{\mathrm{max}}$
- = `2`: PYTHIA mixes and unweights events, according to known σ_{tot}
- = **3**: unit-weight events, given by user, always to be kept
- = `4`: weighted events, given by user, always to be kept
- = `-1, -2, -3, -4`: also allow negative $\mathrm{d}\sigma$

`NPRUP`: number of separate user processes

`XSECUP(i)`: σ_{tot} for each user process

`XERRUP(i)`: error on σ_{tot} for each user process

`XMAXUP(i)`: $\mathrm{d}\sigma_{\mathrm{max}}$ for each user process

`LPRUP(i)`: integer identifier for each user process

The event

```
 INTEGER MAXNUP
 PARAMETER (MAXNUP=500)
 INTEGER NUP,IDPRUP,IDUP,ISTUP,MOTHUP,ICOLUP
 DOUBLE PRECISION XWGTUP,SCALUP,AQEDUP,AQCDUP,PUP,VTIMUP,SPINUP
 COMMON/HEPEUP/NUP,IDPRUP,XWGTUP,SCALUP,AQEDUP,AQCDUP,
&IDUP(MAXNUP),ISTUP(MAXNUP),MOTHUP(2,MAXNUP),ICOLUP(2,MAXNUP),
&PUP(5,MAXNUP),VTIMUP(MAXNUP),SPINUP(MAXNUP)
```

`IDPRUP`: identity of current process

`XWGTUP`: event weight (meaning depends on `IDWTUP` weighting strategy)

`SCALUP`: scale Q of parton distributions etc.

`AQEDUP`: α_{em} used in event

`AQCDUP`: α_{s} used in event

`NUP`: number of particles in event

`IDUP(i)`: PDG identity code for particle `i`

`ISTUP(i)`: status code

`MOTHUP(j,i)`: position of one or two mothers

`ICOLUP(j,i)`: colour and anticolour indices

`PUP(j,i)`: (p_x, p_y, p_z, E, m)

`VTIMUP(i)`: invariant lifetime $c\tau$

`SPINUP(i)`: spin (helicity) information

Do it yourself

CompHEP and MadGraph can easily be run interactively:

- user specifies process, e.g. $gg \to W^+\bar{u}d$,
- program finds all contributing lowest-order Feynman graphs,
- the required amplitudes/cross sections are calculated,
- phase-space is sampled (with tricks) and unweighted
  to give a set of parton-level events,
- parton-level properties can be histogrammed,
- Les Houches Accord $\Longrightarrow$ complete events.

CompHEP (matrix-elements-based, good for $\sim\leq$ 4 outgoing partons):
`http://theory.sinp.msu.ru/comphep/`

MadGraph (amplitude-based, can handle $\sim\leq$ 7 outgoing partons):
`http://madgraph.physics.uiuc.edu/`

. . . but

- stiff price to pay for each additional parton $\Longrightarrow$ LO libraries,
- confined to lowest-order processes $\Longrightarrow$ NLO libraries.

Ready-made libraries

Many leading-order (LO) ones, e.g.:

•ALPGEN: $\mathrm{W}/\mathrm{Z}+\leq 6\mathrm{j}$, $n\mathrm{W}+m\mathrm{Z}+k\mathrm{H}+\leq 3\mathrm{j}$, $\mathrm{Q}\overline{\mathrm{Q}}+\leq 6\mathrm{j}$, ...

`http://mlm.home.cern.ch/mlm/alpgen/`

•AcerMC: $\mathrm{t}\bar{\mathrm{t}}\mathrm{b}\bar{\mathrm{b}}$, $\mathrm{WWb}\bar{\mathrm{b}}$, ...

`http://borut.home.cern.ch/borut/`

• VECBOS: $\mathrm{W}/\mathrm{Z}+\leq 4\mathrm{j}$

• GR@PPA: $\mathrm{b}\bar{\mathrm{b}}\mathrm{b}\bar{\mathrm{b}}$, ...

• TopReX: $\mathrm{t}\bar{\mathrm{t}}$, ...

Not as many NLO, but still quite a few, e.g.

• MCFM: NLO $\mathrm{W}/\mathrm{Z}+\leq 2\mathrm{j}$, WZ, WH, $\mathrm{H}+\leq 1\mathrm{j}$

`http://mcfm.fnal.gov/`

• PHOX family: photons + jets

`http://wwwlapp.in2p3.fr/lapth/PHOX_FAMILY/main.html`

• MNR: $\mathrm{c}\bar{\mathrm{c}}$, $\mathrm{b}\bar{\mathrm{b}}$

• AYLEN/EMILIA: WW, WZ, ZZ, $\mathrm{W}\gamma$, $\mathrm{Z}\gamma$

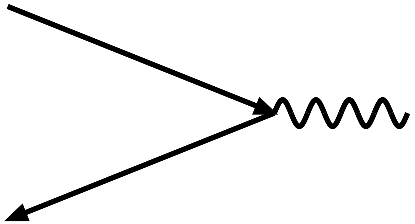
• EKS: 2j

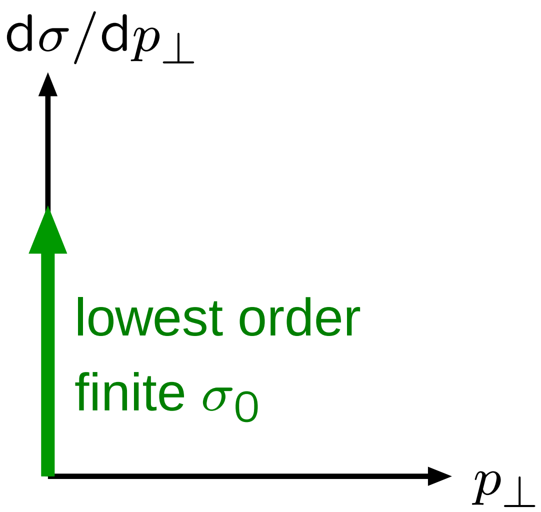
• PROSPINO: $\tilde{\mathrm{q}}\tilde{\mathrm{q}}$, $\tilde{\mathrm{q}}\tilde{\mathrm{g}}$, $\tilde{\mathrm{g}}\tilde{\mathrm{g}}$

• HIGLU: $\mathrm{gg}\to\mathrm{H}$

Next-to-leading order (NLO) calculations

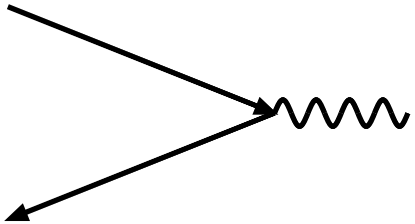
I. Lowest order,
$\mathcal{O}(\alpha_{\mathrm{em}})$:
$\mathrm{q}\overline{\mathrm{q}} \to \mathrm{Z}^0$

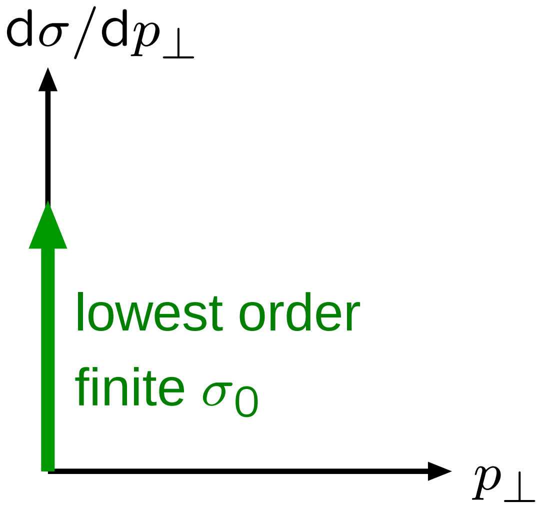




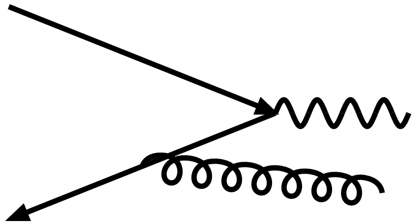
Next-to-leading order (NLO) calculations

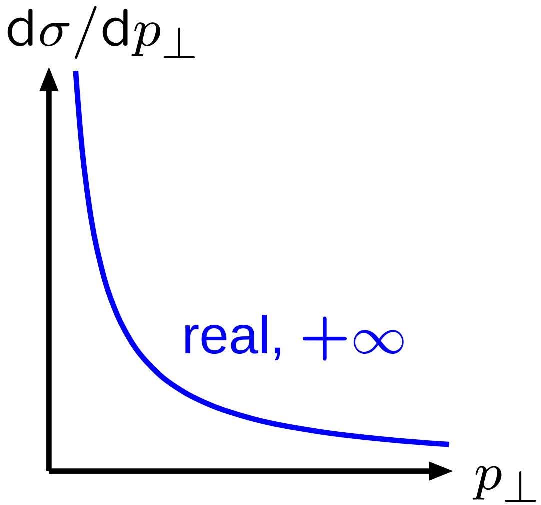
I. Lowest order,
$\mathcal{O}(\alpha_{\rm em})$:
$q\bar{q} \to Z^0$





II. First-order real,
$\mathcal{O}(\alpha_{\rm em}\alpha_{\rm s})$:
$q\bar{q} \to Z^0 g$ etc.



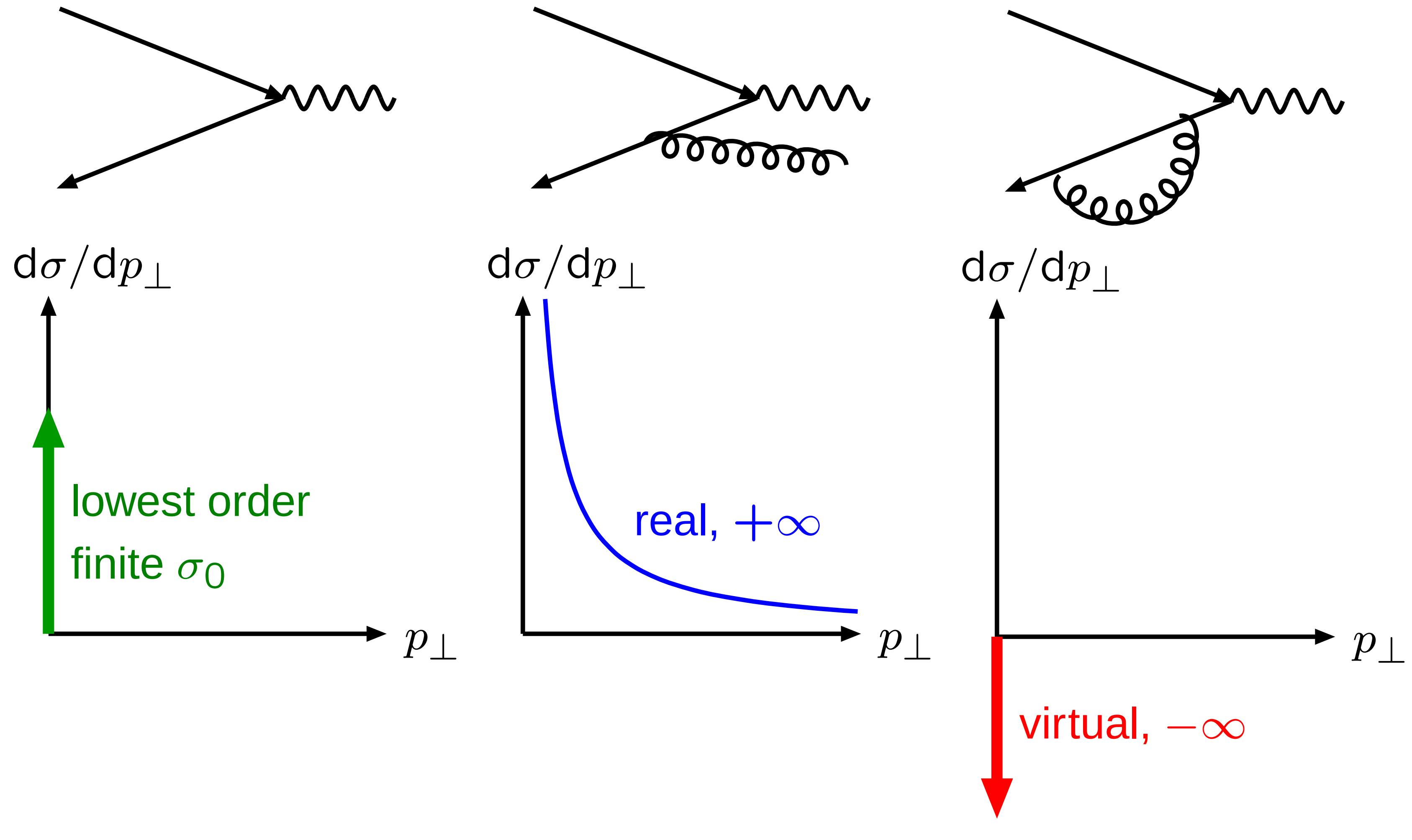


Next-to-leading order (NLO) calculations

I. Lowest order, $\mathcal{O}(\alpha_{\mathrm{em}})$: $\mathrm{q\overline{q}} \rightarrow \mathrm{Z}^0$

II. First-order real, $\mathcal{O}(\alpha_{\mathrm{em}}\alpha_{\mathrm{s}})$: $\mathrm{q\overline{q}} \rightarrow \mathrm{Z}^0\mathrm{g}$ etc.

III. First-order virtual, $\mathcal{O}(\alpha_{\mathrm{em}}\alpha_{\mathrm{s}})$: $\mathrm{q\overline{q}} \rightarrow \mathrm{Z}^0$ with loops



$$\sigma_{\mathrm{NLO}} = \int_n \mathrm{d}\sigma_{\mathrm{LO}} + \int_{n+1} \mathrm{d}\sigma_{\mathrm{Real}} + \int_n \mathrm{d}\sigma_{\mathrm{Virt}}$$

Simple one-dimensional example: $x \sim p_\perp / p_{\perp\mathrm{max}}$, $0 \le x \le 1$

Divergences regularized by $d = 4 - 2\epsilon$ dimensions, $\epsilon < 0$

$$\sigma_{\mathrm{R+V}} = \int_0^1 \frac{\mathrm{d}x}{x^{1+\epsilon}} M(x) + \frac{1}{\epsilon} M_0$$

KLN cancellation theorem: $M(0) = M_0$

Phase Space Slicing:

Introduce arbitrary *finite* cutoff $\delta << 1$ (so $\delta \gg |\epsilon|$)

$$\begin{aligned}
\sigma_{\mathrm{R+V}} &= \int_\delta^1 \frac{\mathrm{d}x}{x^{1+\epsilon}} M(x) + \int_0^\delta \frac{\mathrm{d}x}{x^{1+\epsilon}} M(x) + \frac{1}{\epsilon} M_0 \\
&\approx \int_\delta^1 \frac{\mathrm{d}x}{x} M(x) + \int_0^\delta \frac{\mathrm{d}x}{x^{1+\epsilon}} M_0 + \frac{1}{\epsilon} M_0 \\
&= \int_\delta^1 \frac{\mathrm{d}x}{x} M(x) + \frac{1}{\epsilon}\left(1 - \delta^{-\epsilon}\right) M_0 \\
&\approx \int_\delta^1 \frac{\mathrm{d}x}{x} M(x) + \ln\delta \, M_0
\end{aligned}$$

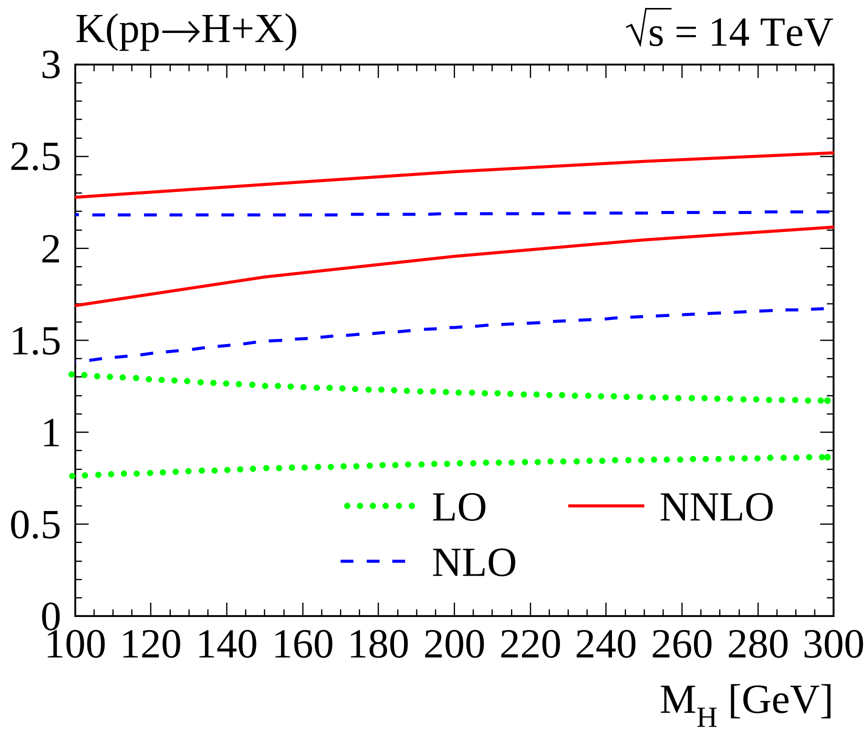
Alternatively **Subtraction**:

$$\sigma_{\mathrm{R+V}} = \int_0^1 \frac{\mathrm{d}x}{x^{1+\epsilon}} M(x) - \int_0^1 \frac{\mathrm{d}x}{x^{1+\epsilon}} M_0 + \int_0^1 \frac{\mathrm{d}x}{x^{1+\epsilon}} M_0 + \frac{1}{\epsilon} M_0$$

$$= \int_0^1 \frac{M(x) - M_0}{x^{1+\epsilon}} \mathrm{d}x + \left(-\frac{1}{\epsilon} + \frac{1}{\epsilon}\right) M_0$$

$$\approx \int_0^1 \frac{M(x) - M_0}{x} \mathrm{d}x + \mathcal{O}(1) M_0$$

NLO provides a more accurate answer for an integrated cross section:



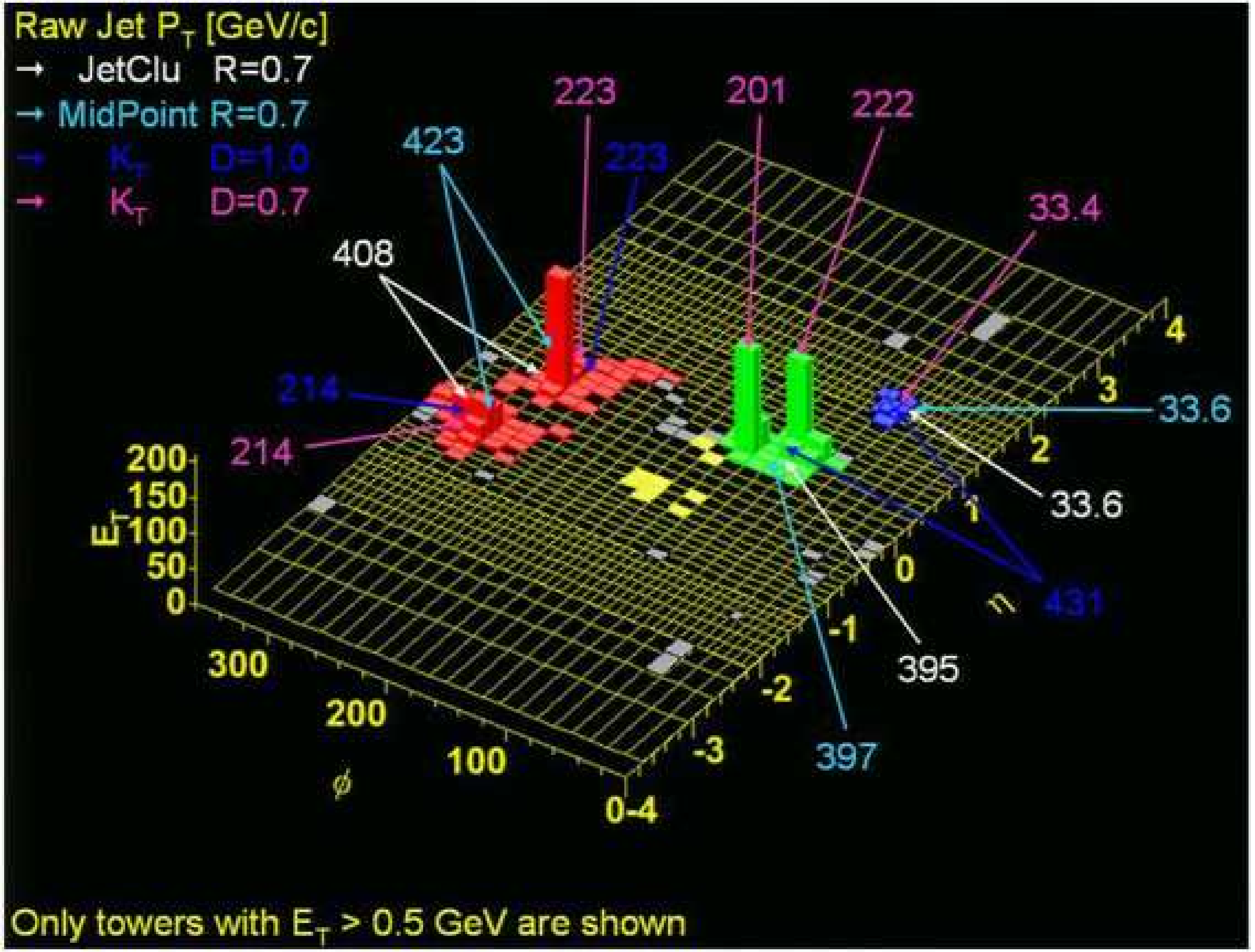
Warning!

Neither approach operates with positive definite quantities

No obvious event-generator implementation

No trivial connection to physical events

Parton Showers

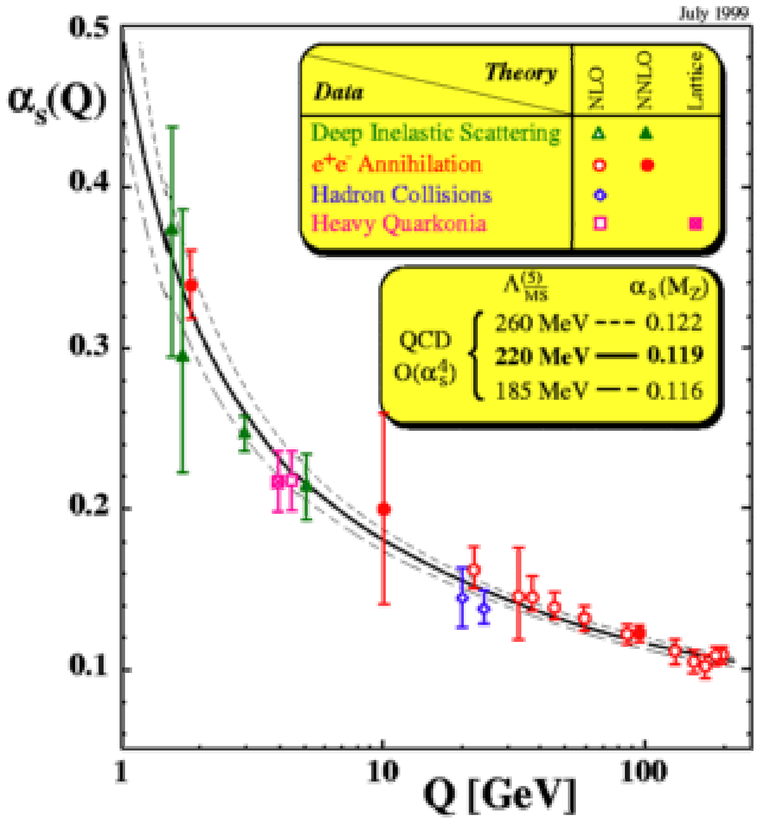


- Final-State (Timelike) Showers
- Initial-State (Spacelike) Showers
- Matching to Matrix Elements

Divergences

Emission rate q $\to$ qg diverges when

- collinear: opening angle $\theta_{\mathrm{qg}} \to 0$
- soft: gluon energy $E_{\mathrm{g}} \to 0$



Almost identical to e $\to$ eγ ("bremsstrahlung"), but QCD is non-Abelian so additionally

- g $\to$ gg similarly divergent
- $\alpha_{\mathrm{s}}(Q^2)$ diverges for $Q^2 \to 0$ (actually for $Q^2 \to \Lambda^2_{\mathrm{QCD}}$)

Big probability for one emission $\Longrightarrow$ also big for several

$\Longrightarrow$ with ME's need to calculate to high order **and** with many loops

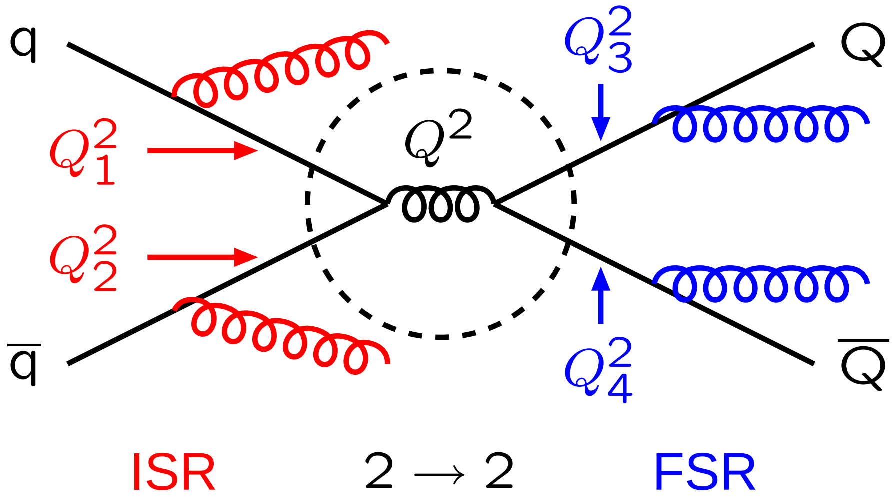
$\Longrightarrow$ extremely demanding technically (not solved!), and

involving big cancellations between positive and negative contributions.

Alternative approach: **parton showers**

The Parton-Shower Approach

$$2 \rightarrow n \;=\; (2 \rightarrow 2) \oplus \text{ISR} \oplus \text{FSR}$$



FSR = Final-State Rad.;

timelike shower

$Q_i^2 \sim m^2 > 0$ decreasing

ISR = Initial-State Rad.;

spacelike shower

$Q_i^2 \sim -m^2 > 0$ increasing

$2 \rightarrow 2$ = hard scattering (on-shell):

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

Shower evolution is viewed as a probabilistic process,

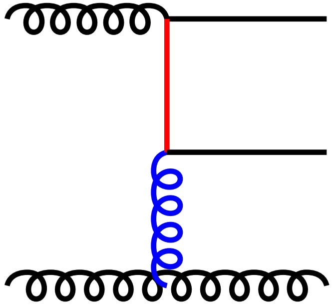
which occurs with unit total probability:

the cross section is not directly affected,

but indirectly it is, via the changed event shape

Doublecounting

A $2 \to n$ graph can be “simplified” to $2 \to 2$ in different ways:



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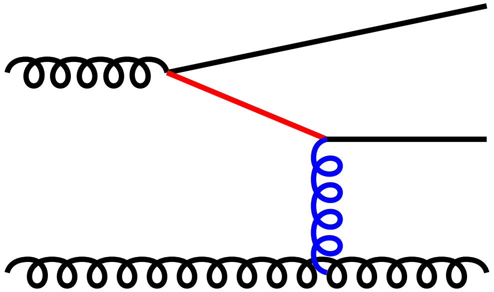
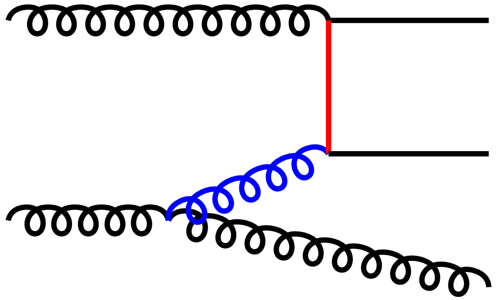


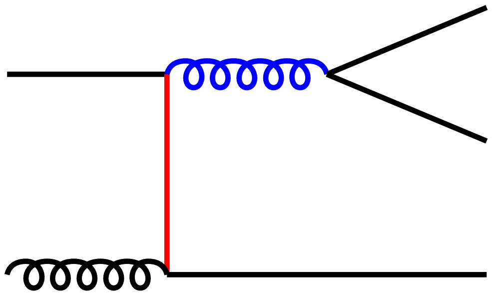
$g \to q\bar{q} \oplus qg \to qg$

or



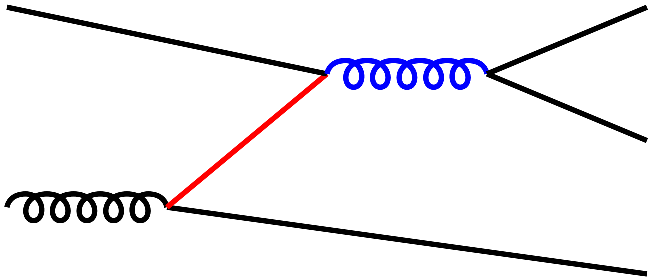
$g \to gg \oplus gg \to q\bar{q}$

or deform



FSR

to

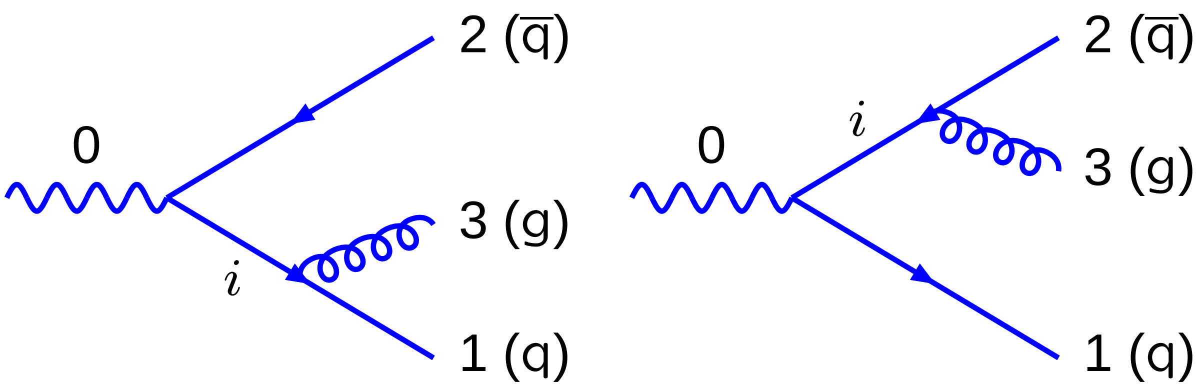


ISR

Do not doublecount: $2 \to 2$ *= most virtual = shortest distance*

Conflict: theory derivations often assume virtualities strongly ordered; interesting physics often in regions where this is not true!

From Matrix Elements to Parton Showers



$\text{e}^+\text{e}^- \to \text{q}\overline{\text{q}}\text{g}$

$x_j = 2E_j/E_{\text{cm}} \Rightarrow$

$x_1 + x_2 + x_3 = 2$

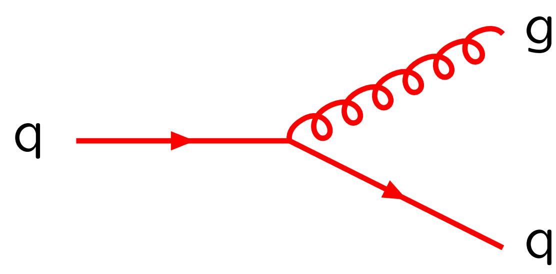
$$m_{\text{q}} = 0: \quad \frac{\text{d}\sigma_{\text{ME}}}{\sigma_0} = \frac{\alpha_{\text{s}}}{2\pi}\,\frac{4}{3}\,\frac{x_1^2 + x_2^2}{(1-x_1)(1-x_2)}\,\text{d}x_1\,\text{d}x_2$$

Rewrite for $x_2 \to 1$, i.e. q–g collinear limit:

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

$$x_1 \approx z \quad \Rightarrow \quad \text{d}x_1 \approx \text{d}z$$

$$x_3 \approx 1 - z$$



$$\Rightarrow \text{d}\mathcal{P} = \frac{\text{d}\sigma}{\sigma_0} = \frac{\alpha_{\text{s}}}{2\pi}\,\frac{\text{d}x_2}{(1-x_2)}\,\frac{4}{3}\,\frac{x_2^2 + x_1^2}{(1-x_1)}\,\text{d}x_1 \approx \frac{\alpha_{\text{s}}}{2\pi}\,\frac{\text{d}Q^2}{Q^2}\,\frac{4}{3}\,\frac{1+z^2}{1-z}\,\text{d}z$$

Generalizes to DGLAP (Dokshitzer–Gribov–Lipatov–Altarelli–Parisi)

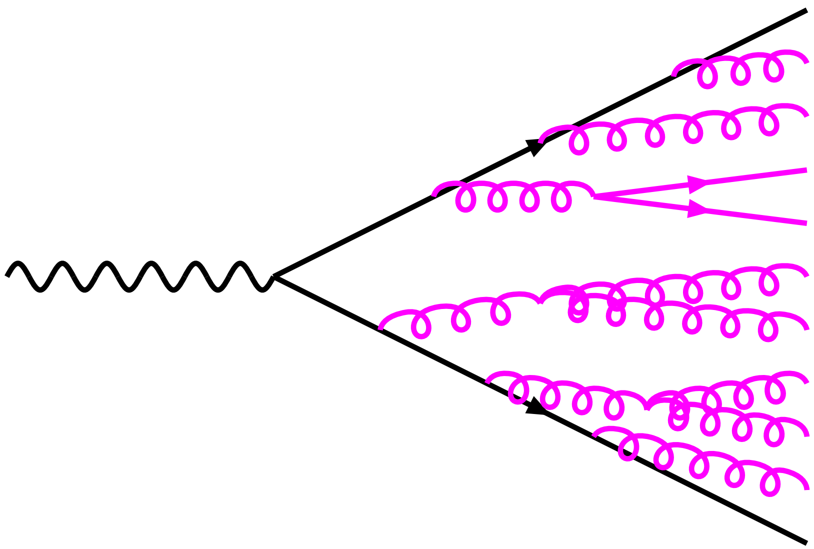
$$\mathrm{d}\mathcal{P}_{a\to bc} = \frac{\alpha_s}{2\pi}\frac{\mathrm{d}Q^2}{Q^2}P_{a\to bc}(z)\,\mathrm{d}z$$

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

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

$$P_{g\to q\bar{q}} = \frac{n_f}{2}(z^2+(1-z)^2) \quad (n_f = \text{no. of quark flavours})$$

Iteration gives final-state parton showers



Need soft/collinear cut-offs to stay away from nonperturbative physics.

Details model-dependent, e.g.

$Q > m_0 = \min(m_{ij}) \approx 1$ GeV,

$z_{\min}(E,Q) < z < z_{\max}(E,Q)$

or $p_\perp > p_{\perp\min} \approx 0.5$ GeV

The Sudakov Form Factor

Conservation of total probability:

$\mathcal{P}(\text{nothing happens}) = 1 - \mathcal{P}(\text{something happens})$

"multiplicativeness" in "time" evolution:

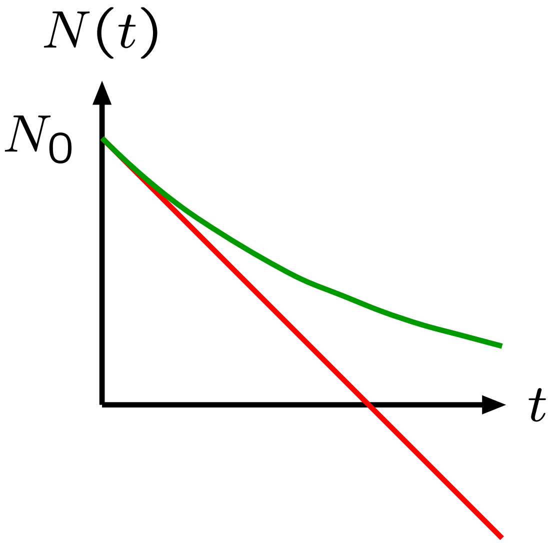
$\mathcal{P}_{\text{nothing}}(0 < t \le T) = \mathcal{P}_{\text{nothing}}(0 < t \le T_1)\, \mathcal{P}_{\text{nothing}}(T_1 < t \le T)$

Subdivide further, with $T_i = (i/n)T$, $0 \le i \le n$:

$$\begin{aligned}
\mathcal{P}_{\text{nothing}}(0 < t \le T) &= \lim_{n\to\infty} \prod_{i=0}^{n-1} \mathcal{P}_{\text{nothing}}(T_i < t \le T_{i+1}) \\
&= \lim_{n\to\infty} \prod_{i=0}^{n-1} \left(1 - \mathcal{P}_{\text{something}}(T_i < t \le T_{i+1})\right) \\
&= \exp\left(-\lim_{n\to\infty} \sum_{i=0}^{n-1} \mathcal{P}_{\text{something}}(T_i < t \le T_{i+1})\right) \\
&= \exp\left(-\int_0^T \frac{\mathrm{d}\mathcal{P}_{\text{something}}(t)}{\mathrm{d}t}\mathrm{d}t\right)
\end{aligned}$$

$$\Longrightarrow \quad \mathrm{d}\mathcal{P}_{\text{first}}(T) = \mathrm{d}\mathcal{P}_{\text{something}}(T)\, \exp\left(-\int_0^T \frac{\mathrm{d}\mathcal{P}_{\text{something}}(t)}{\mathrm{d}t}\mathrm{d}t\right)$$

Example: radioactive decay of nucleus



naively: $\frac{\mathrm{d}N}{\mathrm{d}t} = -cN_0 \Rightarrow N(t) = N_0\,(1 - ct)$

depletion: a given nucleus can only decay once

correctly: $\frac{\mathrm{d}N}{\mathrm{d}t} = -cN(t) \Rightarrow N(t) = N_0\,\exp(-ct)$

generalizes to: $N(t) = N_0\,\exp\left(-\int_0^t c(t')\mathrm{d}t'\right)$

or: $\frac{\mathrm{d}N(t)}{\mathrm{d}t} = -c(t)\,N_0\,\exp\left(-\int_0^t c(t')\mathrm{d}t'\right)$

sequence allowed: $\text{nucleus}_1 \to \text{nucleus}_2 \to \text{nucleus}_3 \to \ldots$

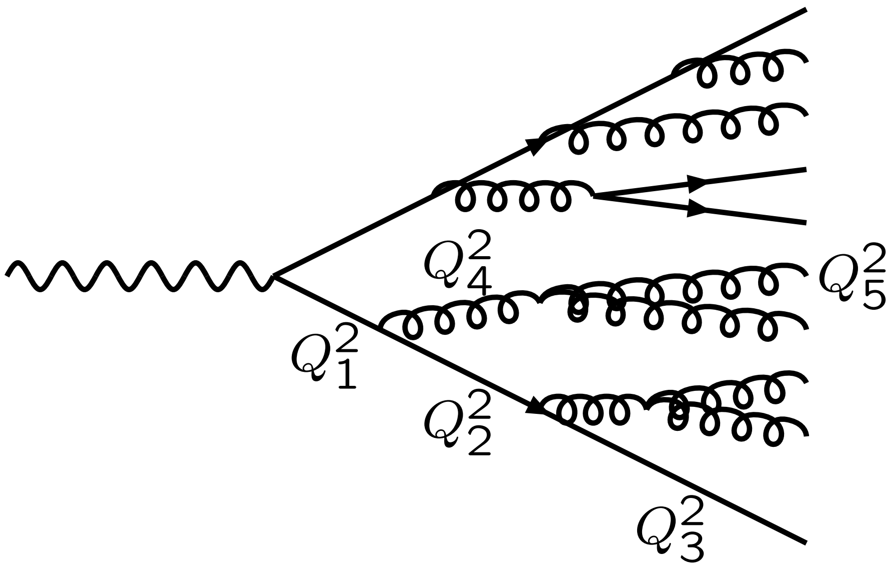
Correspondingly, with $Q \sim 1/t$ (Heisenberg)

$$\mathrm{d}\mathcal{P}_{a\to bc} = \frac{\alpha_s}{2\pi}\frac{\mathrm{d}Q^2}{Q^2}P_{a\to bc}(z)\,\mathrm{d}z\;\exp\left(-\sum_{b,c}\int_{Q^2}^{Q^2_{\mathrm{max}}}\frac{\mathrm{d}Q'^2}{Q'^2}\int\frac{\alpha_s}{2\pi}P_{a\to bc}(z')\,\mathrm{d}z'\right)$$

where the exponent is (one definition of) the Sudakov form factor

A given parton can only branch once, i.e. if it did not already do so

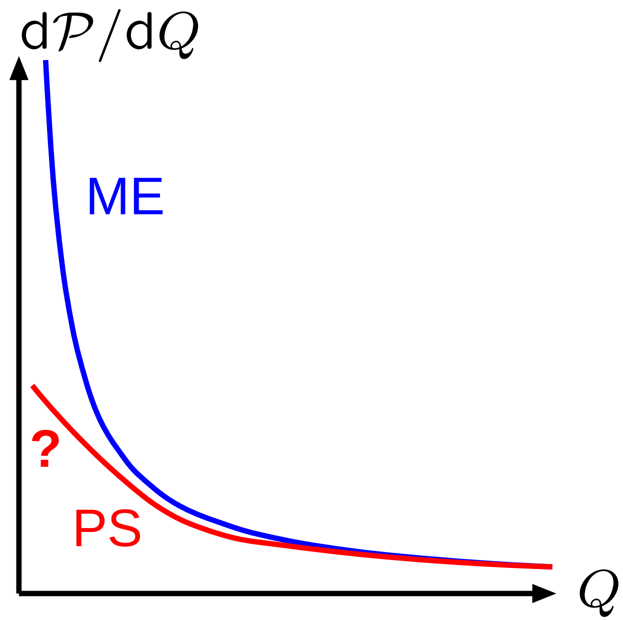
Note that $\sum_{b,c}\int\int\;\mathrm{d}\mathcal{P}_{a\to bc} \equiv 1 \Rightarrow$ *convenient for Monte Carlo*
($\equiv 1$ if extended over whole phase space, else possibly nothing happens)



Sudakov form factor provides "time" ordering of shower: lower Q^2 $\Longleftrightarrow$ longer times

$Q_1^2 > Q_2^2 > Q_3^2$
$Q_1^2 > Q_4^2 > Q_5^2$
etc.

Sudakov regulates singularity for *first* emission . . .

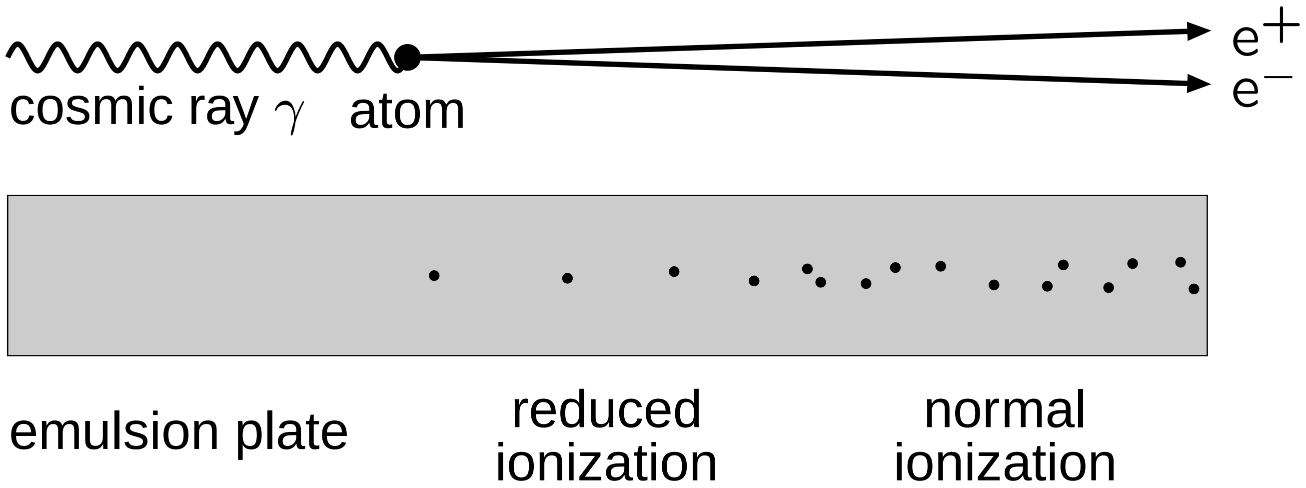


. . . but in limit of *repeated soft* emissions q $\to$ qg (but no g $\to$ gg) one obtains the same inclusive Q emission spectrum as for ME, i.e. divergent ME spectrum $\Longleftrightarrow$ infinite number of PS emissions

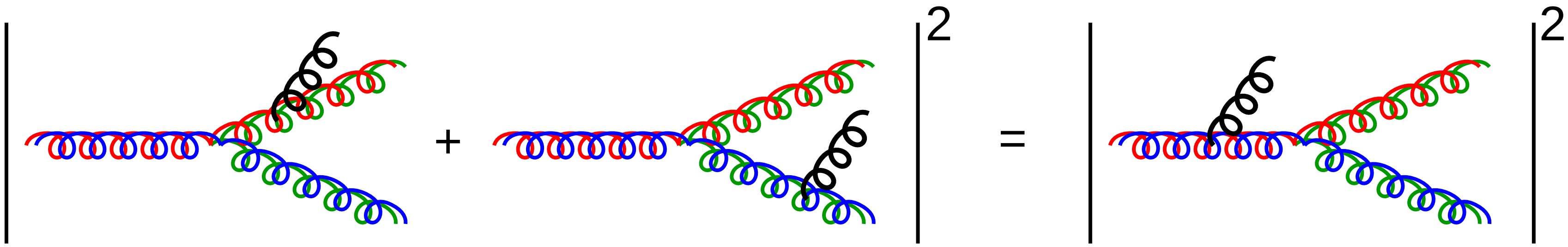
Proof: as for veto algorithm (what is probability to have an emission at Q after 0, 1, 2, 3, . . . previous ones?)

Coherence

QED: Chudakov effect (mid-fifties)



QCD: colour coherence for **soft** gluon emission



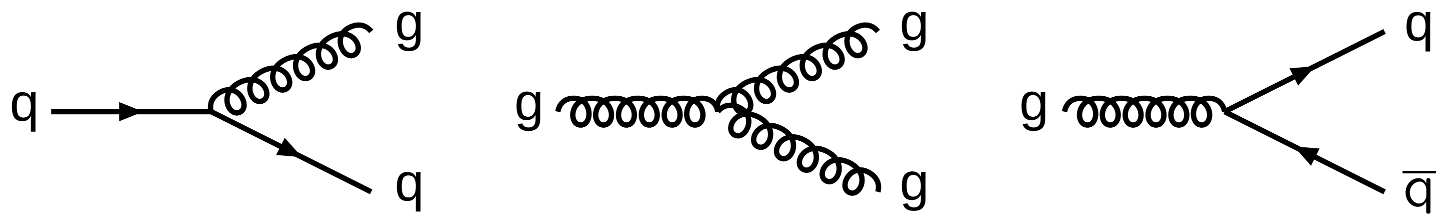
solved by • requiring emission angles to be decreasing

or • requiring transverse momenta to be decreasing

The Common Showering Algorithms

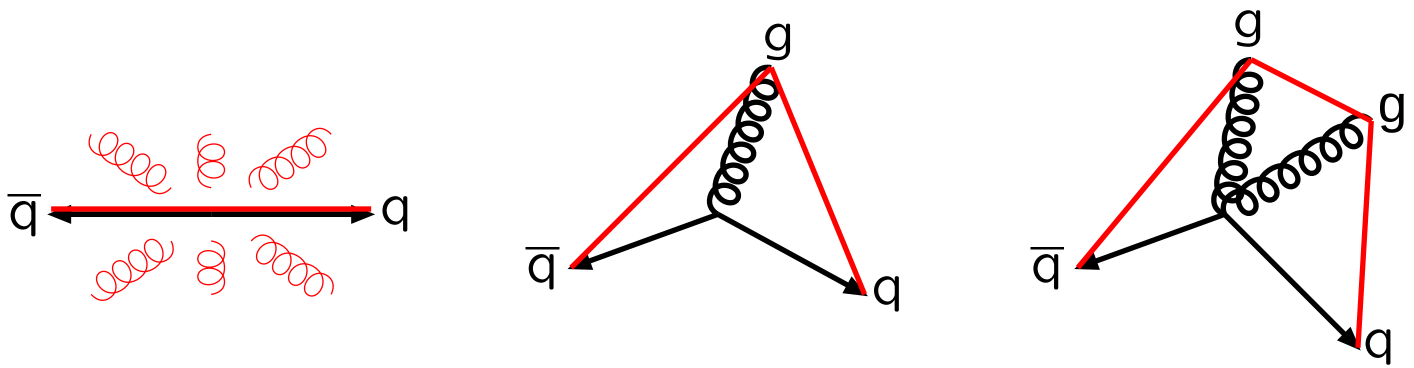
Three main approaches to showering in common use:

Two are based on the standard shower language of $a \to bc$ successive branchings:



HERWIG: $Q^2 \approx E^2(1 - \cos\theta) \approx E^2\theta^2/2$
PYTHIA: $Q^2 = m^2$ (timelike) or $= -m^2$ (spacelike)

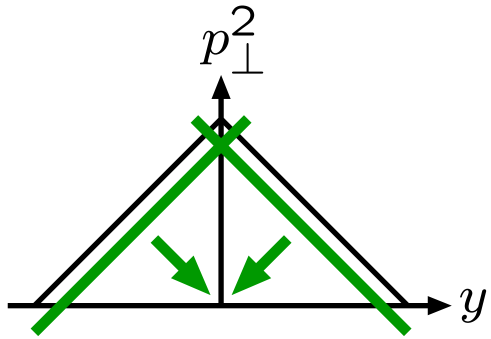
One is based on a picture of dipole emission $ab \to cde$:



ARIADNE: $Q^2 = p_\perp^2$; FSR mainly, ISR is primitive;
there instead LDCMC: sophisticated but complicated

Ordering variables in final-state radiation

PYTHIA: $Q^2 = m^2$



large mass first

$\Rightarrow$ "hardness" ordered

coherence brute force

covers phase space

ME merging simple

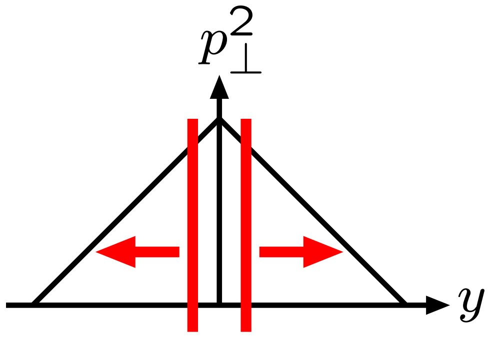
g $\rightarrow$ q$\overline{\text{q}}$ simple

not Lorentz invariant

no stop/restart

ISR: $m^2 \rightarrow -m^2$

HERWIG: $Q^2 \sim E^2\theta^2$



large angle first

$\Rightarrow$ **hardness not ordered**

coherence inherent

gaps in coverage

ME merging messy

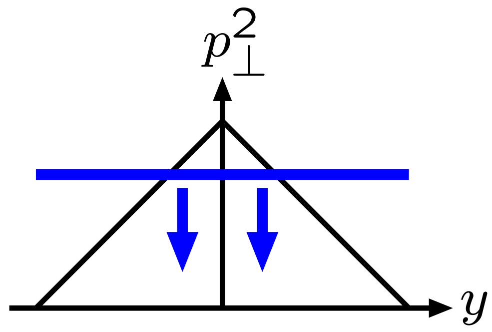
g $\rightarrow$ q$\overline{\text{q}}$ simple

not Lorentz invariant

no stop/restart

ISR: $\theta \rightarrow \theta$

ARIADNE: $Q^2 = p_\perp^2$



large $p_\perp$ first

$\Rightarrow$ "hardness" ordered

coherence inherent

covers phase space

ME merging simple

g $\rightarrow$ q$\overline{\text{q}}$ messy

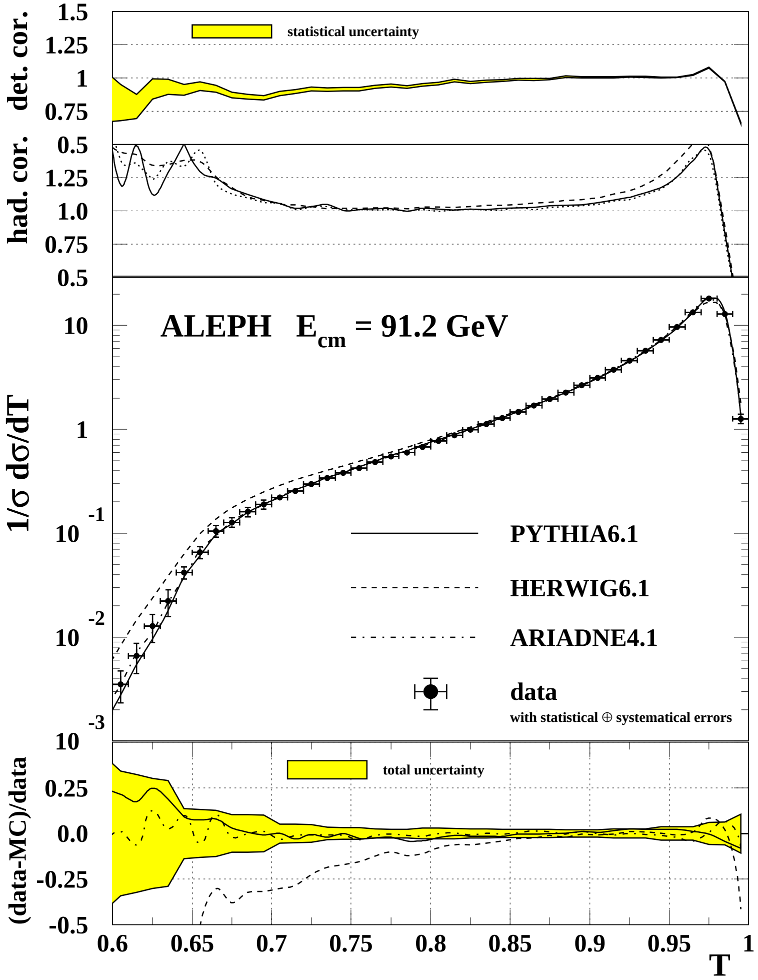
Lorentz invariant

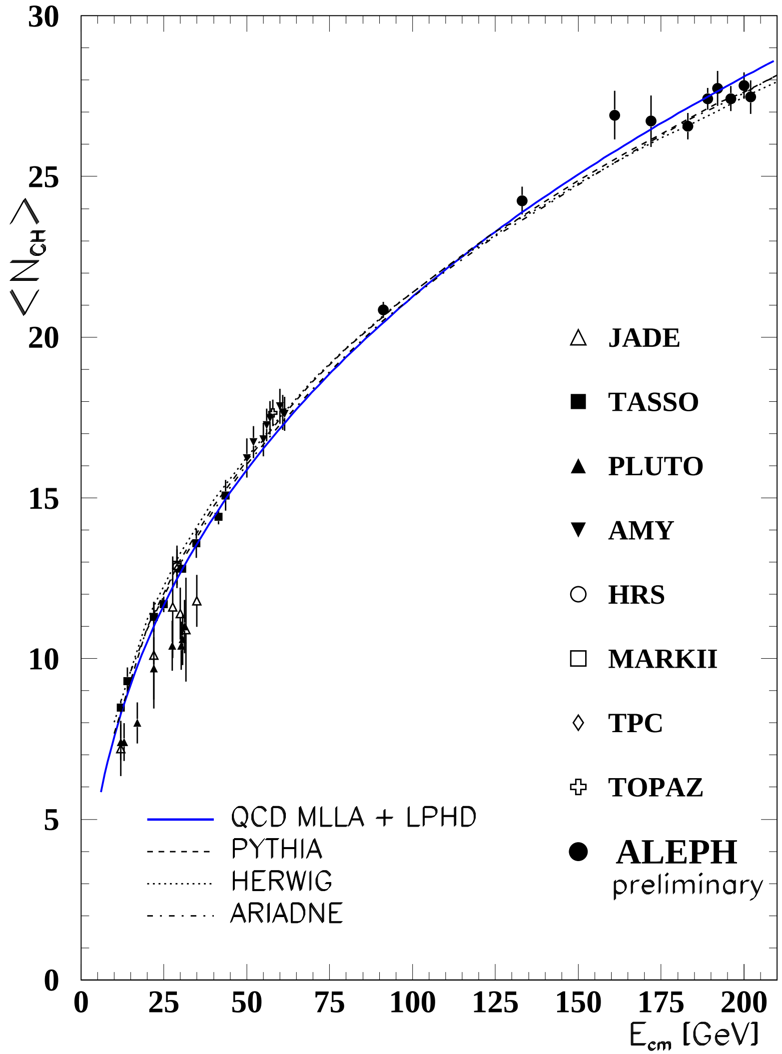
can stop/restart

ISR: more messy

Data comparisons

All three algorithms do a reasonable job of describing LEP data, but typically ARIADNE ($p_\perp^2$) $>$ PYTHIA (m^2) $>$ HERWIG (θ)



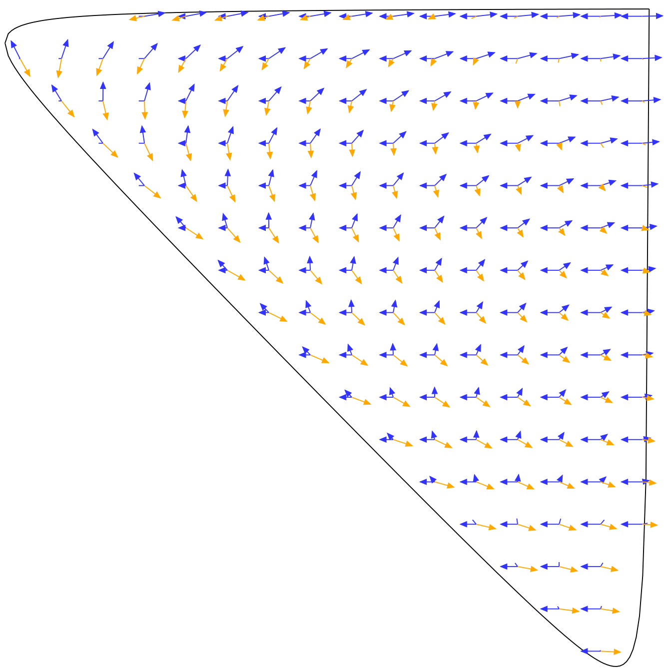


. . . and programs evolve to do even better . . .

HERWIG shower improvements

Quasi–Collinear Limit (Heavy Quarks)

$q\bar{q}g$–Phase space $(x, \bar{x})$



Sudakov-basis p, n with $p^2 = M^2$ ('forward'), $n^2 = 0$ ('backward'),

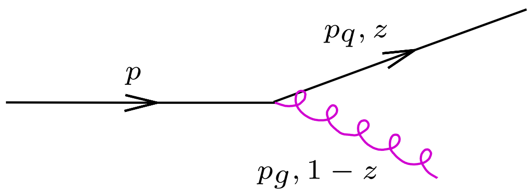
$$p_q = zp + \beta_q n - q_\perp$$
$$p_g = (1-z)p + \beta_g n + q_\perp$$

Collinear limit for radiation off heavy quark,

$$P_{gq}(z, \boldsymbol{q}^2, m^2) = C_F \left[\frac{1+z^2}{1-z} - \frac{2z(1-z)m^2}{\boldsymbol{q}^2 + (1-z)^2 m^2} \right]$$
$$= \frac{C_F}{1-z} \left[1 + z^2 - \frac{2m^2}{z\tilde{q}^2} \right]$$

$\longrightarrow$ $\tilde{q}^2 \sim \boldsymbol{q}^2$ may be used as evolution variable.

Single emission:



New evolution variables

Kinematics to allow better treatment of heavy particles, avoiding overlapping regions in phase space, in particular for soft emissions

We choose $\tilde{q}^2$ as new evolution variable,

$$\tilde{q}^2 = \frac{\boldsymbol{q}^2}{z^2(1-z)^2} + \frac{m^2}{z^2} \quad \text{for} \quad q \to qg$$

and with the argument of running α_S chosen according to

$$\alpha_S(z^2(1-z)^2\tilde{q}^2)$$

angular ordering

$$\tilde{q}_{i+1} < z_i\tilde{q}_i \qquad \tilde{k}_{i+1} < (1-z_i)\tilde{q}_i$$

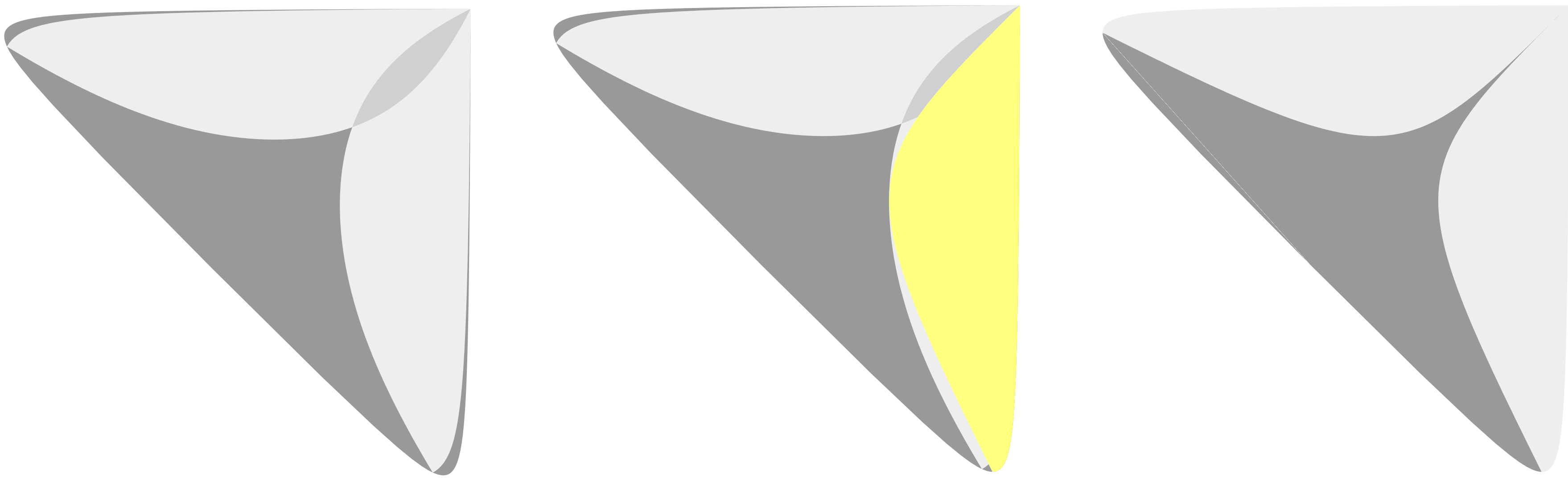
Technically: *reinterpretation* of known evolution variables, i.e. the branching probability for $a \to bc$ still is

$$dP(a \to bc) = \frac{d\tilde{q}^2}{\tilde{q}^2}\frac{C_i\alpha_S}{2\pi}P_{bc}(z,\tilde{q})\,dz$$

$\longrightarrow$ Sudakov's etc. technically remain the same!

$q\bar{q}g$ Phase Space old vs new variables

Consider $(x, \bar{x})$ phase space for $e^+e^- \to q\bar{q}g$



HERWIG Comparison Herwig++

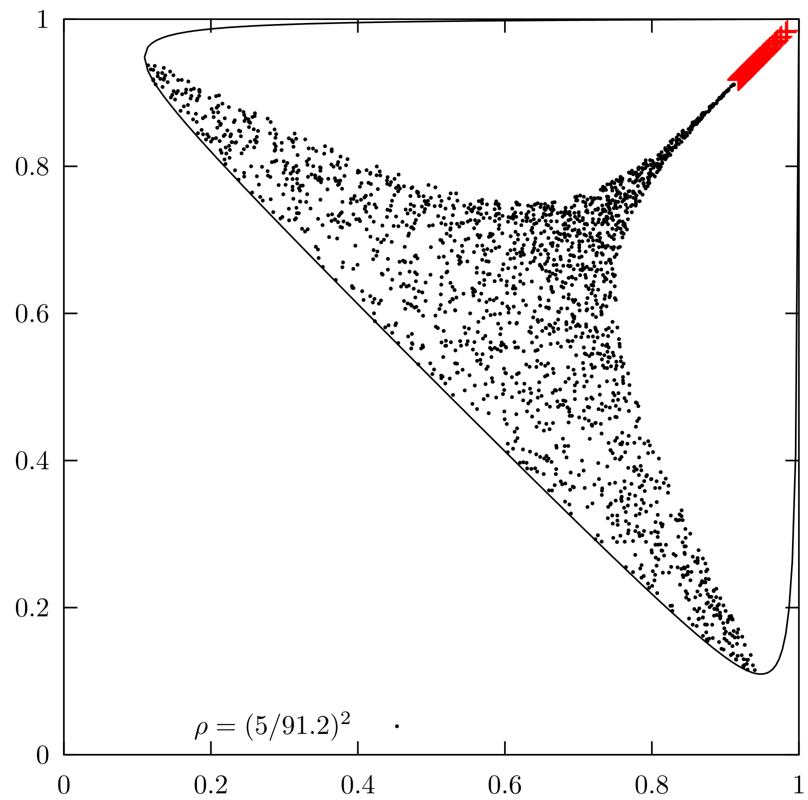
✗ Larger dead region with new variables.

✓ Smooth coverage of soft gluon region.

✓ No overlapping regions in phase space.

Hard Matrix Element Corrections

- Points $(x, \bar{x})$ in dead region chosen acc to LO $e^+e^- \to q\bar{q}g$ matrix element and accepted acc to ME weight.
- About 3% of all events are actually hard $q\bar{q}g$ events.
- Red points have weight > 1, practically no error by setting weight to one.
- Event oriented according to given $q\bar{q}$ geometry. Quark direction is kept with weight $x^2/(x^2 + \bar{x}^2)$.



Leading Log and Beyond

Neglecting Sudakovs, rate of one emission is:

$$\mathcal{P}_{\mathrm{q}\to\mathrm{qg}} \approx \int \frac{\mathrm{d}Q^2}{Q^2} \int \mathrm{d}z \, \frac{\alpha_\mathrm{s}}{2\pi} \frac{4}{3} \frac{1+z^2}{1-z}$$

$$\approx \alpha_\mathrm{s} \ln\left(\frac{Q^2_{\mathrm{max}}}{Q^2_{\mathrm{min}}}\right) \frac{8}{3} \ln\left(\frac{1-z_{\mathrm{min}}}{1-z_{\mathrm{max}}}\right) \sim \alpha_\mathrm{s} \ln^2$$

Rate for n emissions is of form:

$$\mathcal{P}_{\mathrm{q}\to\mathrm{q}n\mathrm{g}} \sim (\mathcal{P}_{\mathrm{q}\to\mathrm{qg}})^n \sim \alpha_\mathrm{s}^n \ln^{2n}$$

Next-to-leading log (NLL): inclusion of *all* corrections of type $\alpha_\mathrm{s}^n \ln^{2n-1}$

No existing generator completely NLL (NLLJET?), but

- energy-momentum conservation (and “recoil” effects)
- coherence
- $2/(1-z) \to (1+z^2)/(1-z)$
- scale choice $\alpha_\mathrm{s}(p_\perp^2)$ absorbs singular terms $\propto \ln z, \ln(1-z)$ in $\mathcal{O}(\alpha_\mathrm{s}^2)$ splitting kernels $P_{\mathrm{q}\to\mathrm{qg}}$ and $P_{\mathrm{g}\to\mathrm{gg}}$
- ...

$\Rightarrow$ far better than naive, analytical LL

Summary Lecture 2

• Hard processes: •

⋆ Simple ones: probably built-in in PYTHIA/HERWIG ⋆

⋆ Multiparton LO: external generator + Les Houches Accord ⋆

⋆ NLO: not easily related to physical events ⋆

• Parton Showers: •

⋆ 2 kinds: initial-state and final-state ⋆

⋆ related to and derived from matrix elements ⋆

⋆ Sudakov form factor ensures sensible physics ⋆

⋆ Ordering variable ambiguous: θ, $p_\perp^2$, m^2 ⋆

⋆ Constraints from coherence arguments, and from data ⋆

⋆ In state of continuous development ⋆

⋆ *More to come tomorrow!* ⋆