LUND UNIVERSITY

Academic Training Lectures
CERN
4, 5, 6, 7 April 2005

Monte Carlo Generators for the LHC

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1. (today) Introduction and Overview; Matrix Elements

2. (Tuesday) Parton Showers; Matching Issues

3. (Wednesday) Multiple Interactions and Beam Remnants

4. (Thursday) Hadronization and Decays; Summary and Outlook

Apologies

These lectures will *not* cover:

⋆ Heavy-ion physics:
- without quark-gluon plasma formation, or
- with quark-gluon plasma formation.

⋆ Specific physics studies for topics such as
- B production,
- Higgs discovery,
- SUSY phenomenology,
- other new physics discovery potential.

⋆ The modelling of elastic and diffractive topologies.

They *will* cover the “normal” physics that will be there in (essentially) all LHC pp events, from QCD to exotics:

⋆ the generation and availability of different processes,
⋆ the addition of parton showers,
⋆ the addition of an underlying event,
⋆ the transition from partons to observable hadrons, plus
⋆ the status and evolution of general-purpose generators.

Read More

These lectures (and more):
http://www.thep.lu.se/∼torbjorn/ and click on "Talks"

Steve Mrenna, CTEQ Summer School lectures, June 2004:
http://www.phys.psu.edu/∼cteq/schools/summer04/mrenna/mrenna.pdf

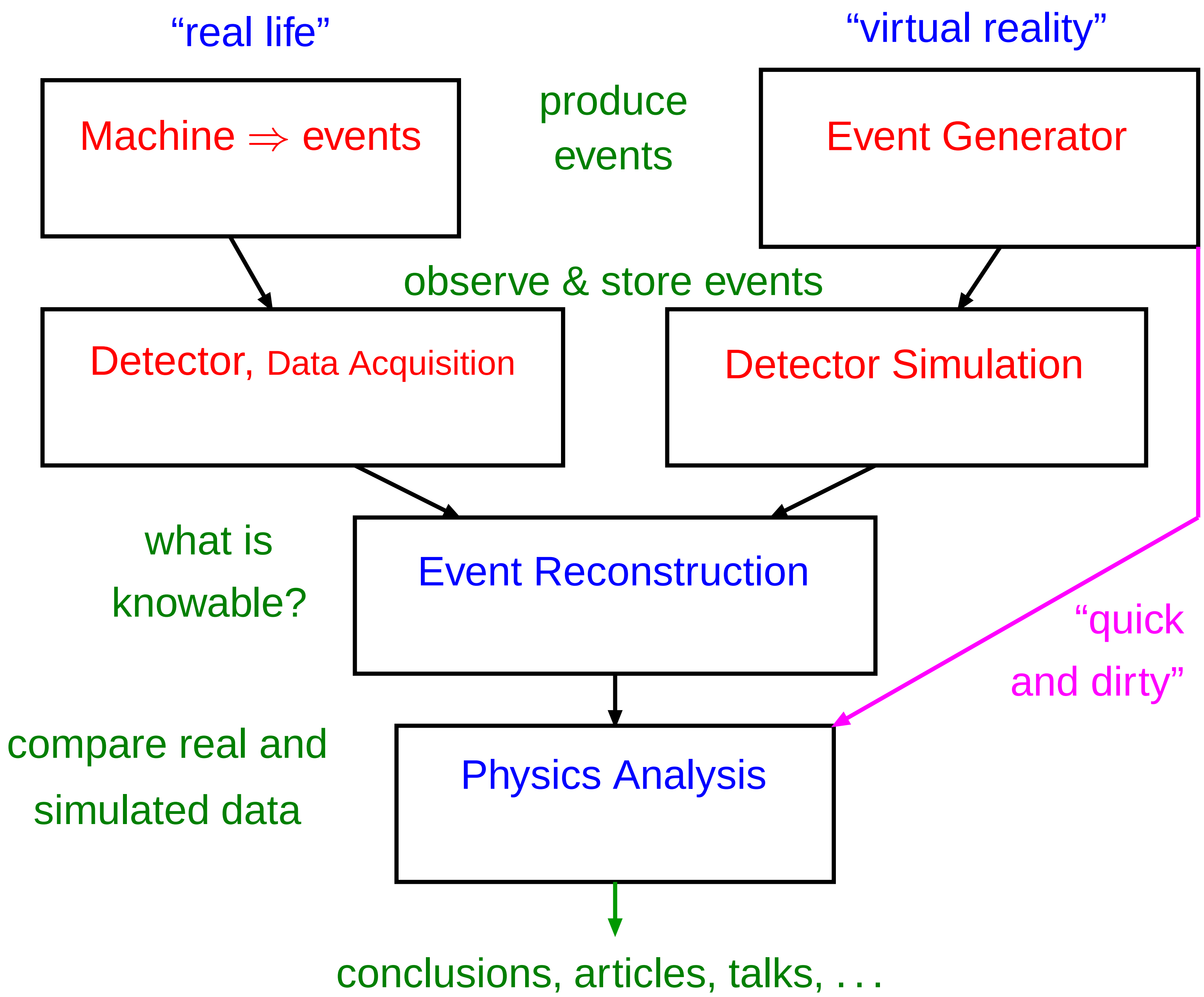
Mike Seymour, Academic Training lectures July 2003:
http://seymour.home.cern.ch/seymour/slides/CERNlectures.html

Bryan Webber, HERWIG lectures for CDF, October 2004:
http://www-cdf.fnal.gov/physics/lectures/herwig_Oct2004.html

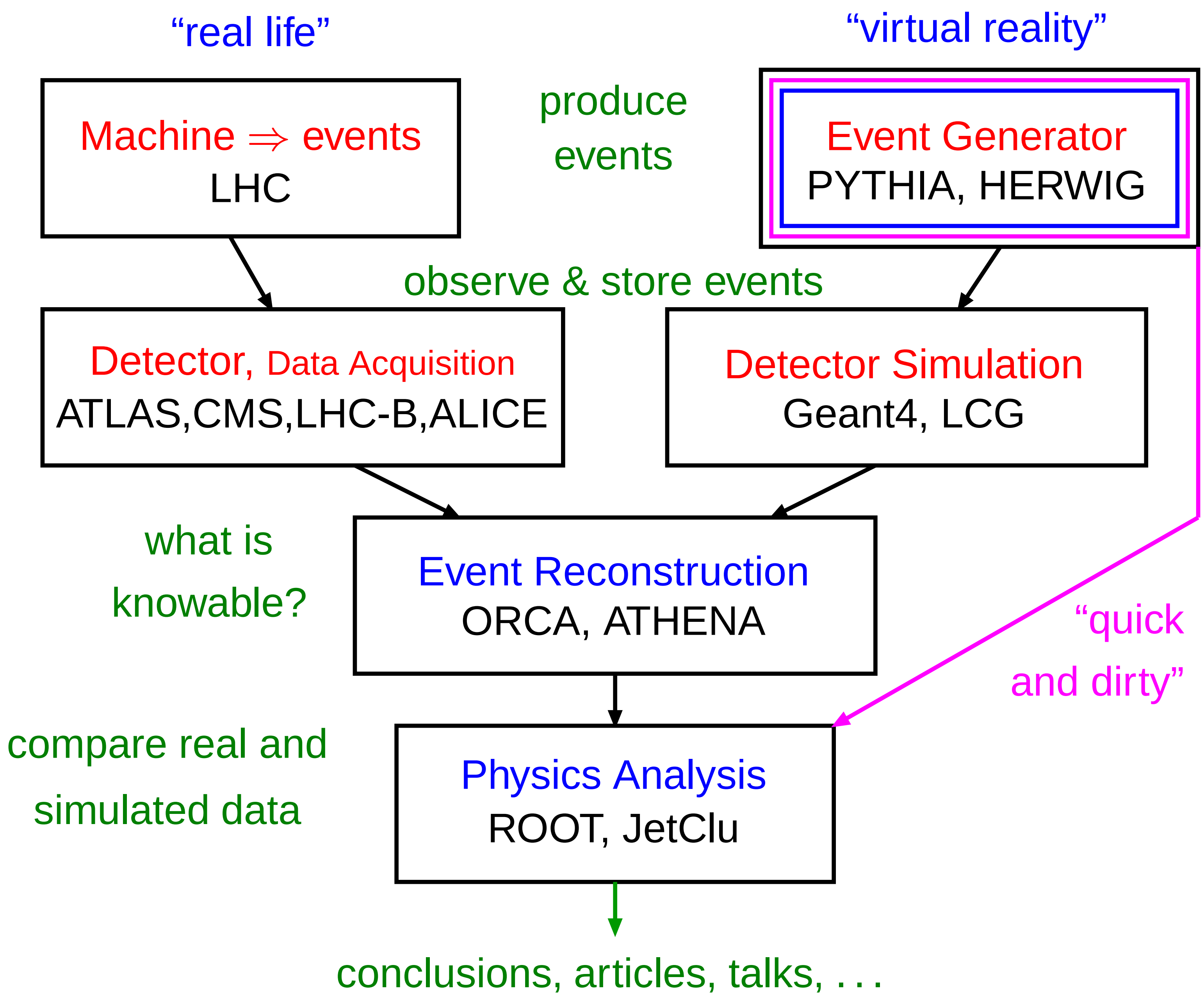
Michelangelo Mangano, KEK LHC simulations workshop, April 2004:
http://mlm.home.cern.ch/mlm/talks/kek04_mlm.pdf

The "Les Houches Guidebook to Monte Carlo Generators
for Hadron Collider Physics", hep-ph/0403045
http://arxiv.org/pdf/hep-ph/0403045

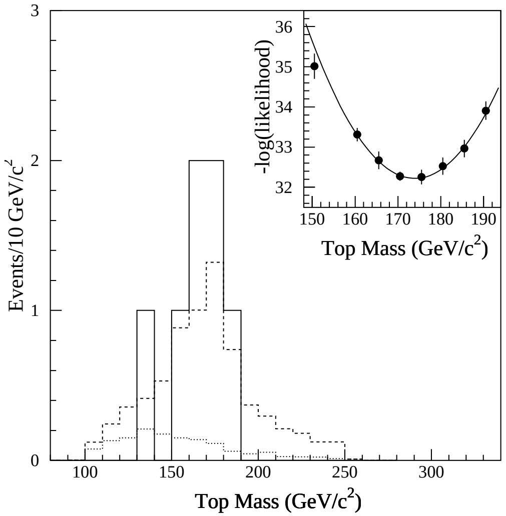
Event Generator Position



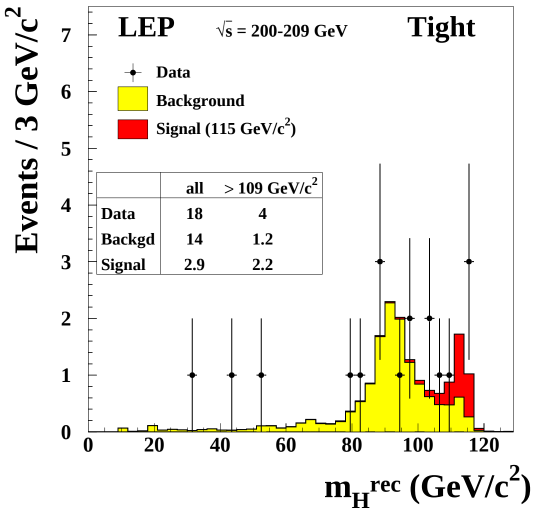
Event Generator Position



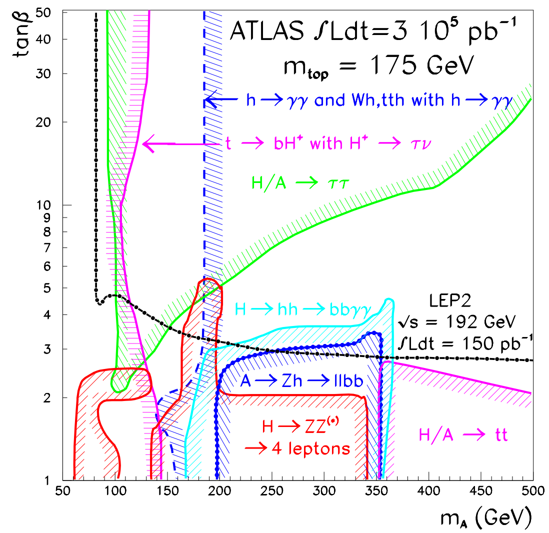
Why Generators? (I)



top discovery
and mass
determination



Higgs (non)
discovery



Higgs and
supersymmetry
exploration

not feasible without generators

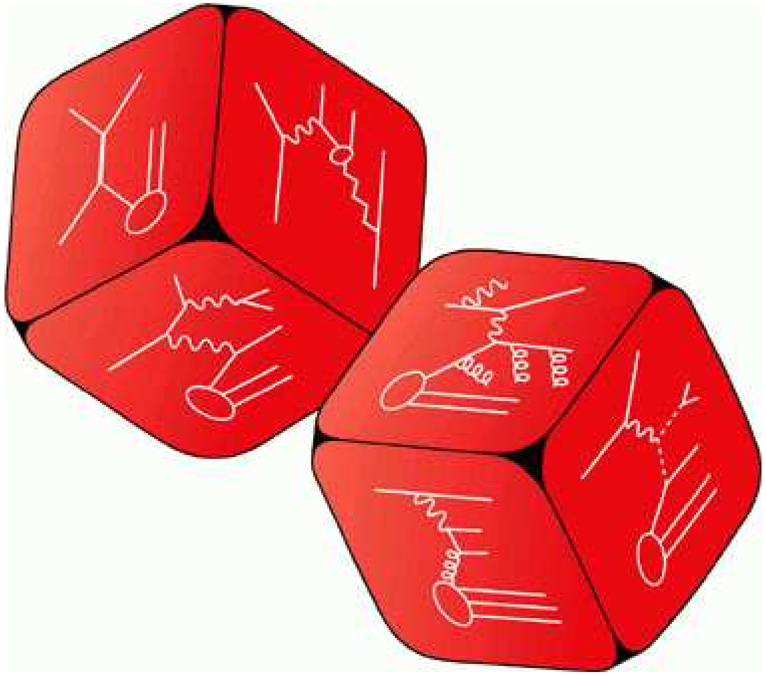
Why Generators? (II)

- 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

A tour to Monte Carlo



. . . because Einstein was wrong: God does throw dice!

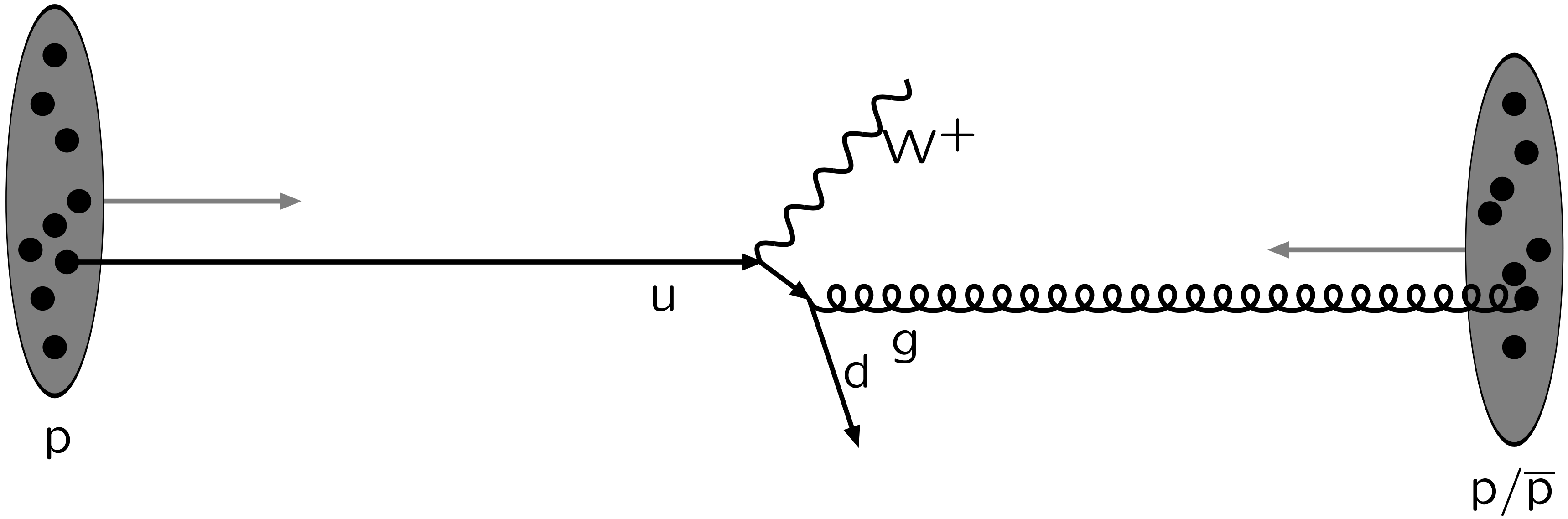
Quantum mechanics: amplitudes $\Longrightarrow$ probabilities

Anything that possibly can happen, will! (but more or less often)

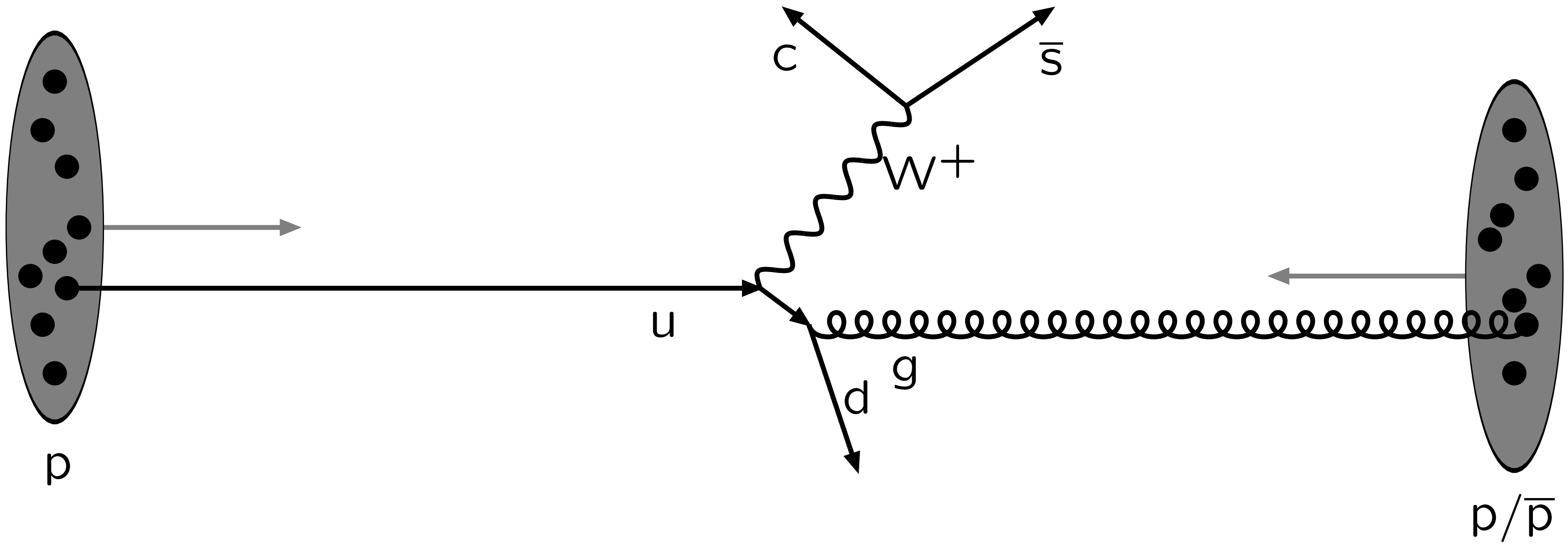
The structure of an event

Warning: schematic only, everything simplified, nothing to scale, . . .

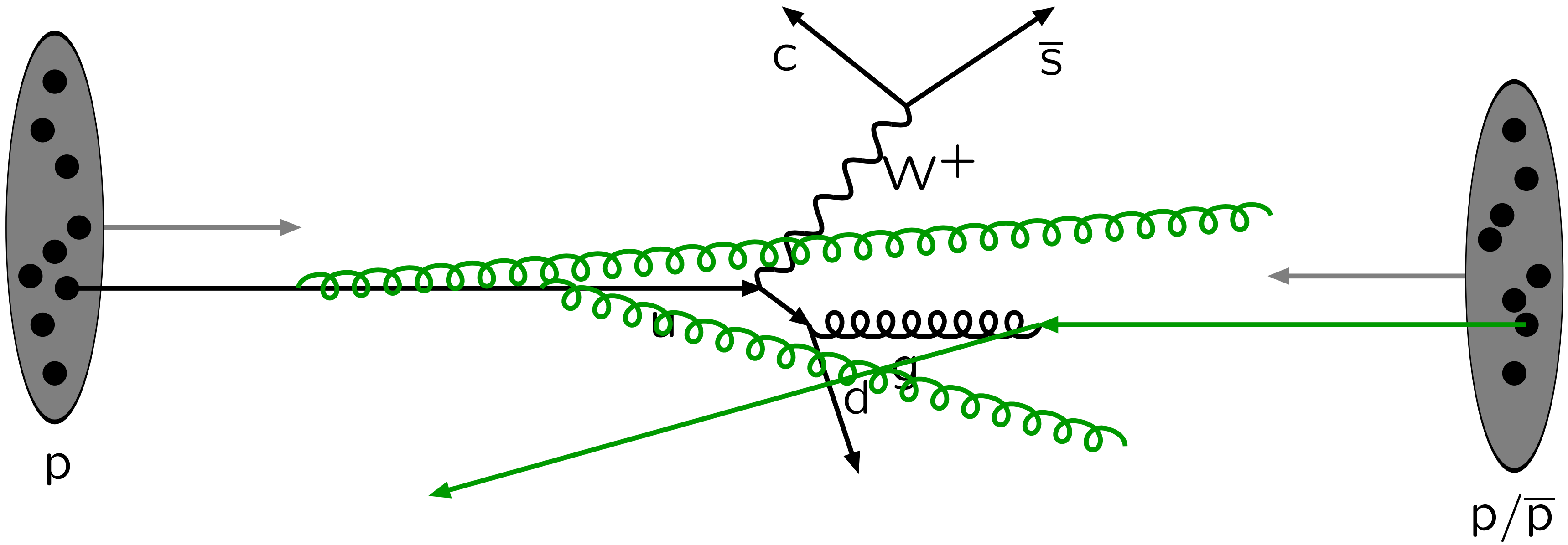
Incoming beams: parton densities



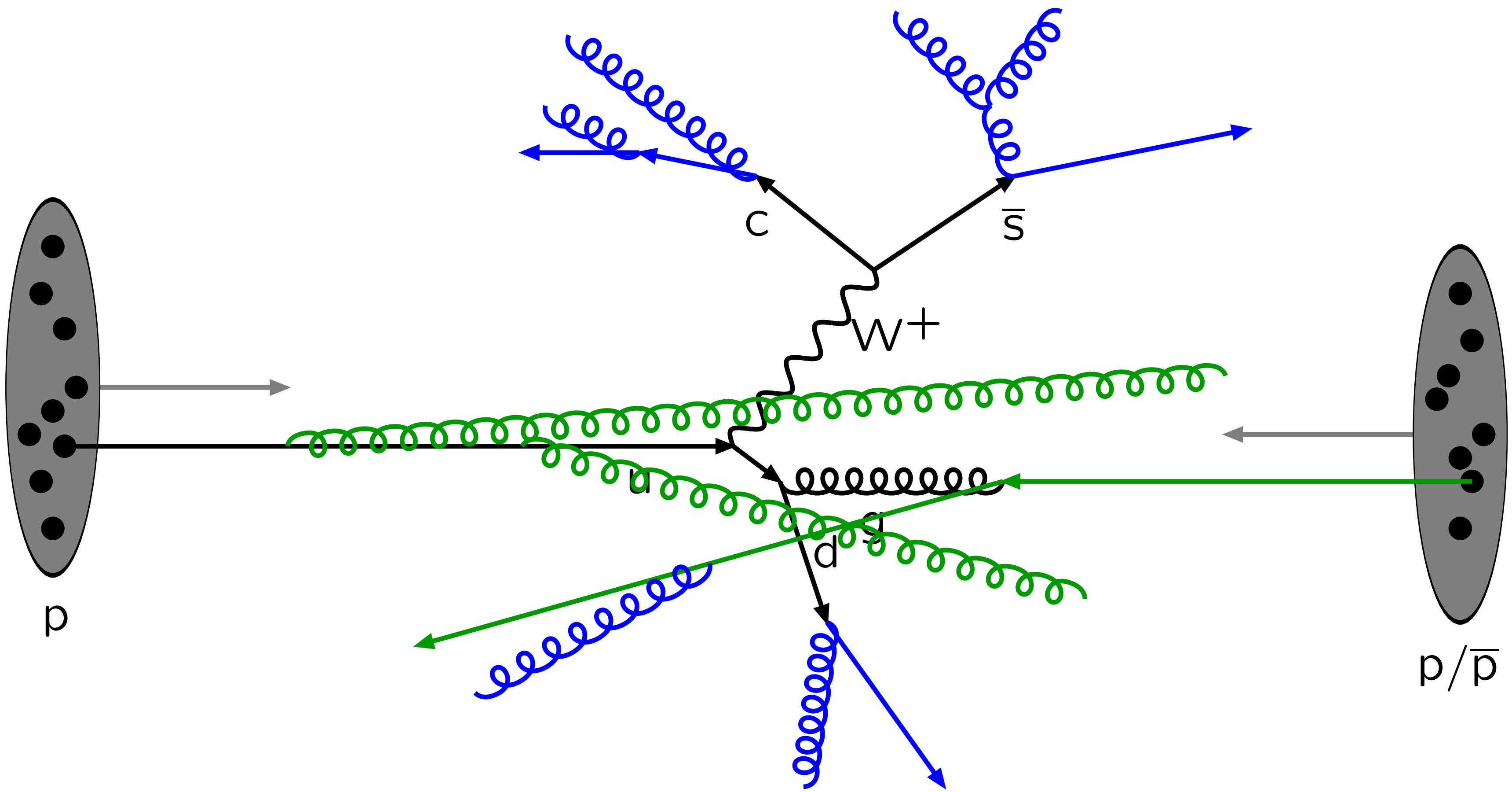
Hard subprocess: described by matrix elements



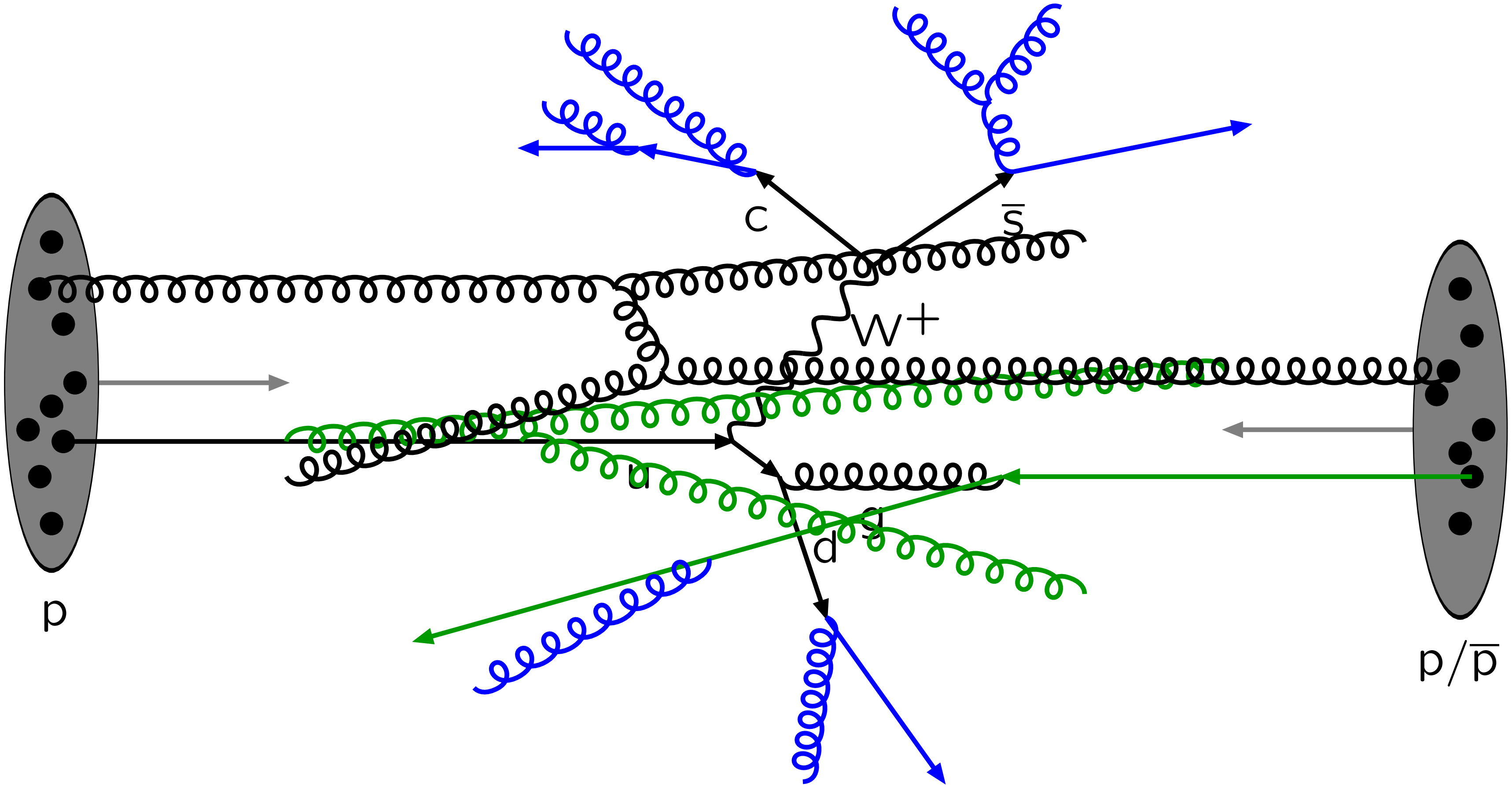
Resonance decays: correlated with hard subprocess



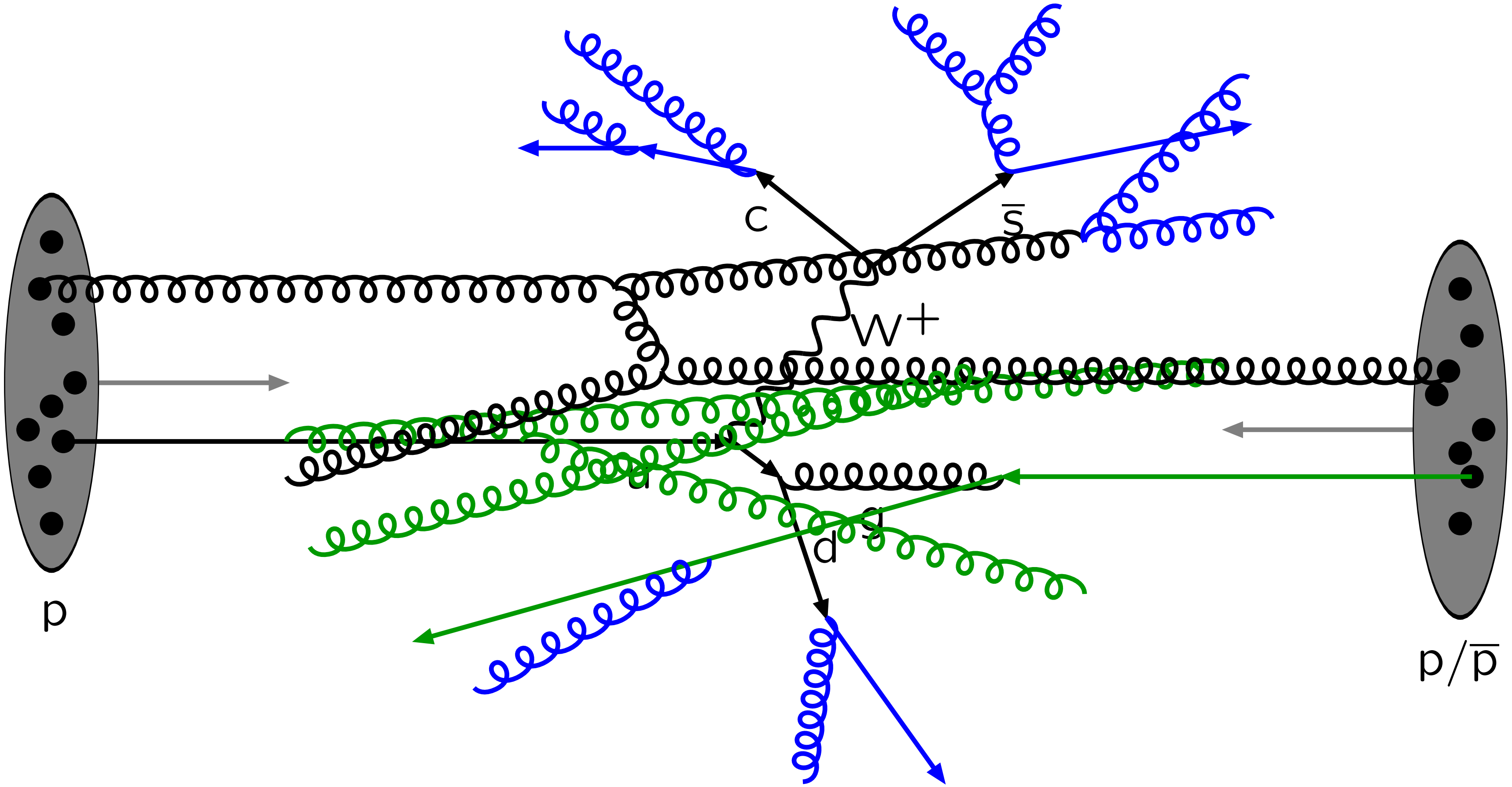
Initial-state radiation: spacelike parton showers



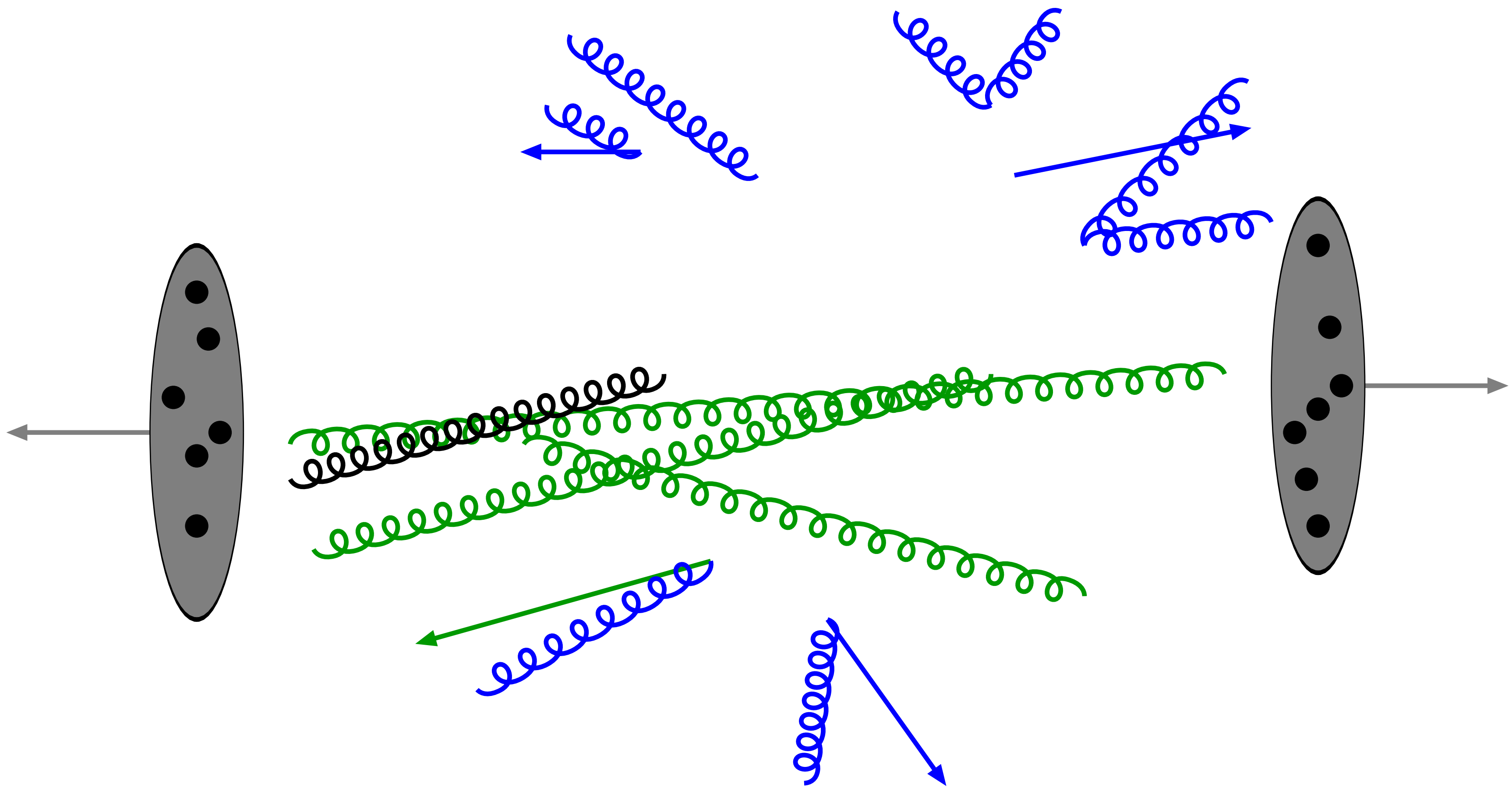
Final-state radiation: timelike parton showers



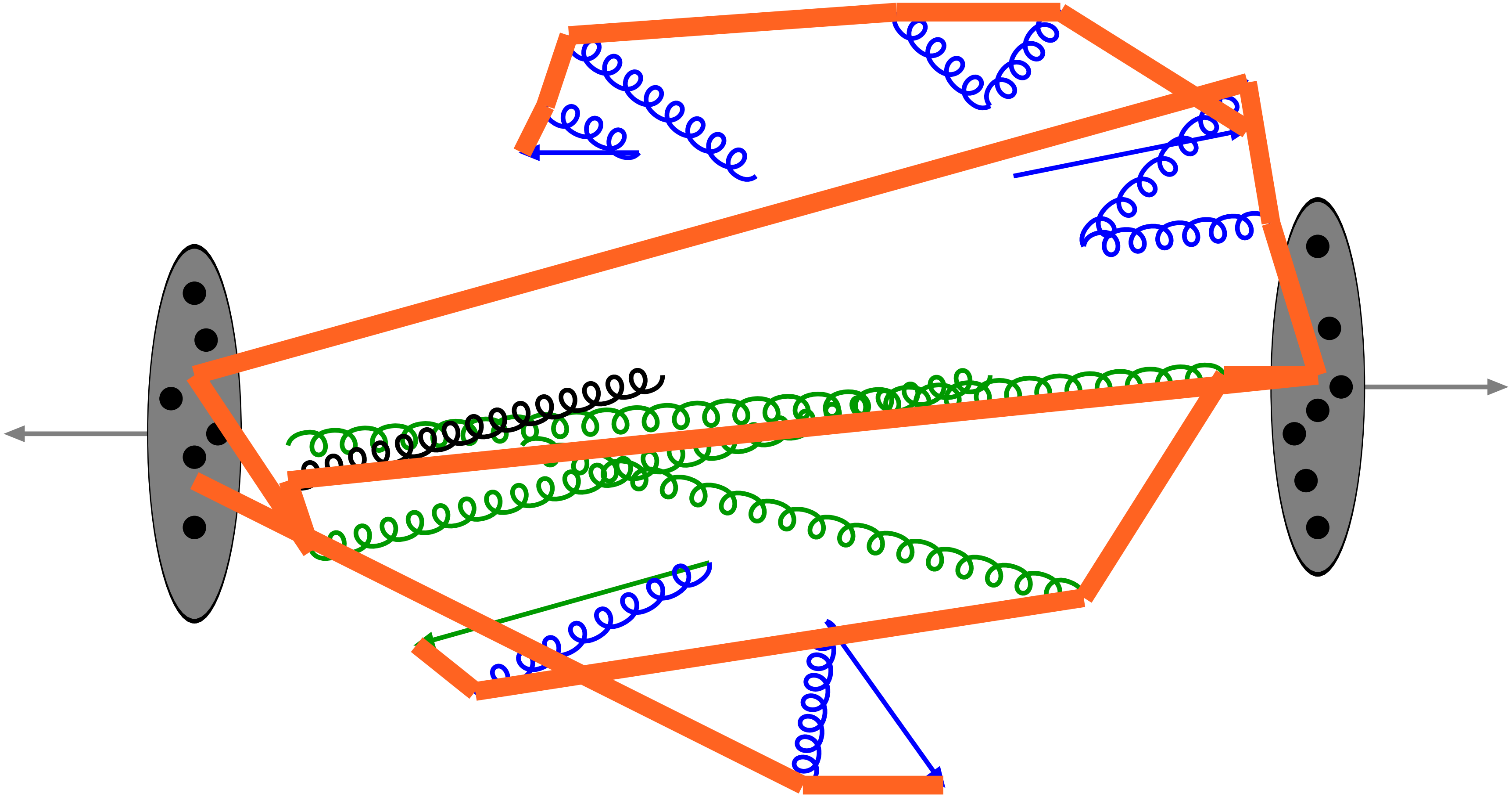
Multiple parton–parton interactions . . .



. . . with its initial- and final-state radiation

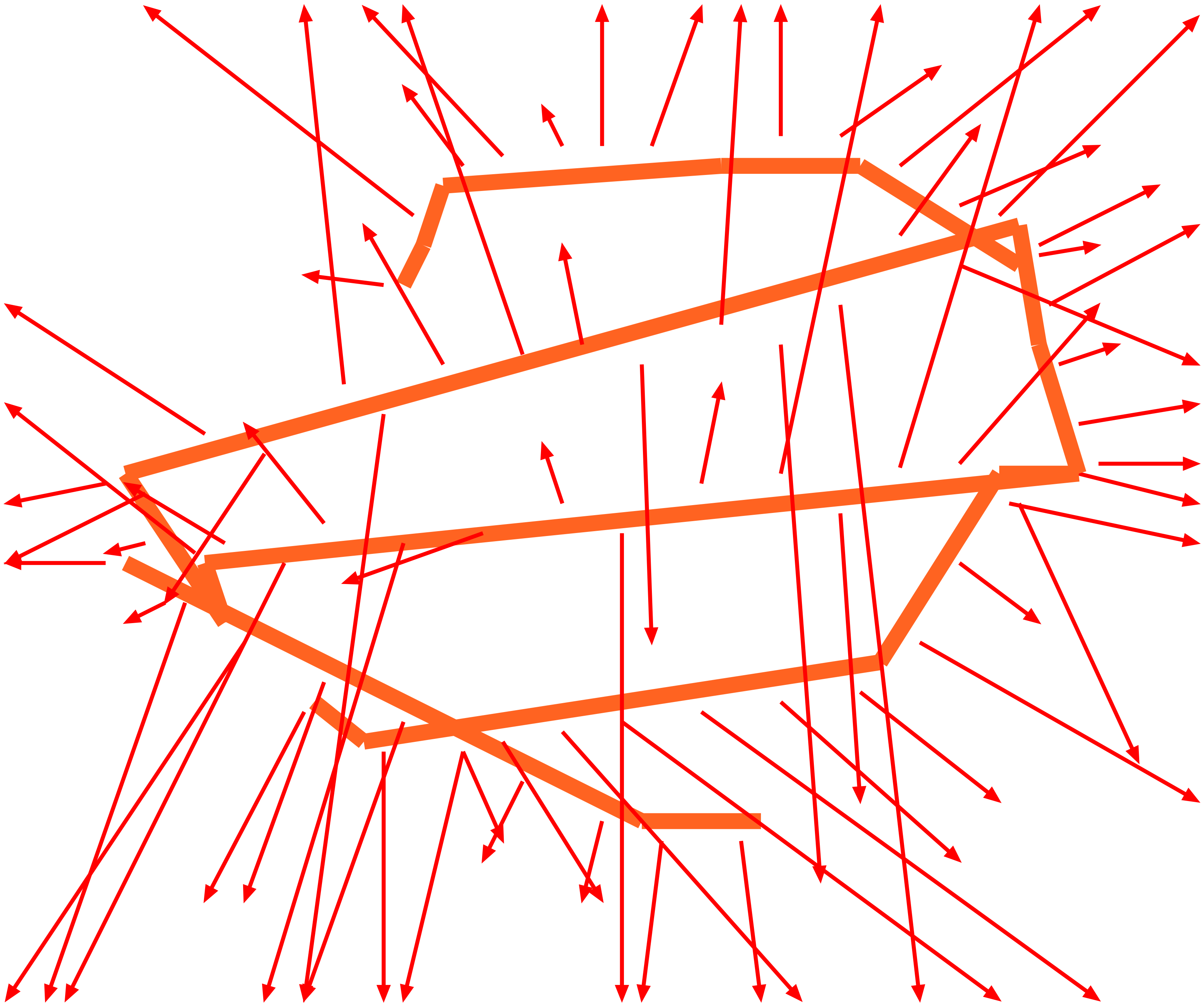


Beam remnants and other outgoing partons

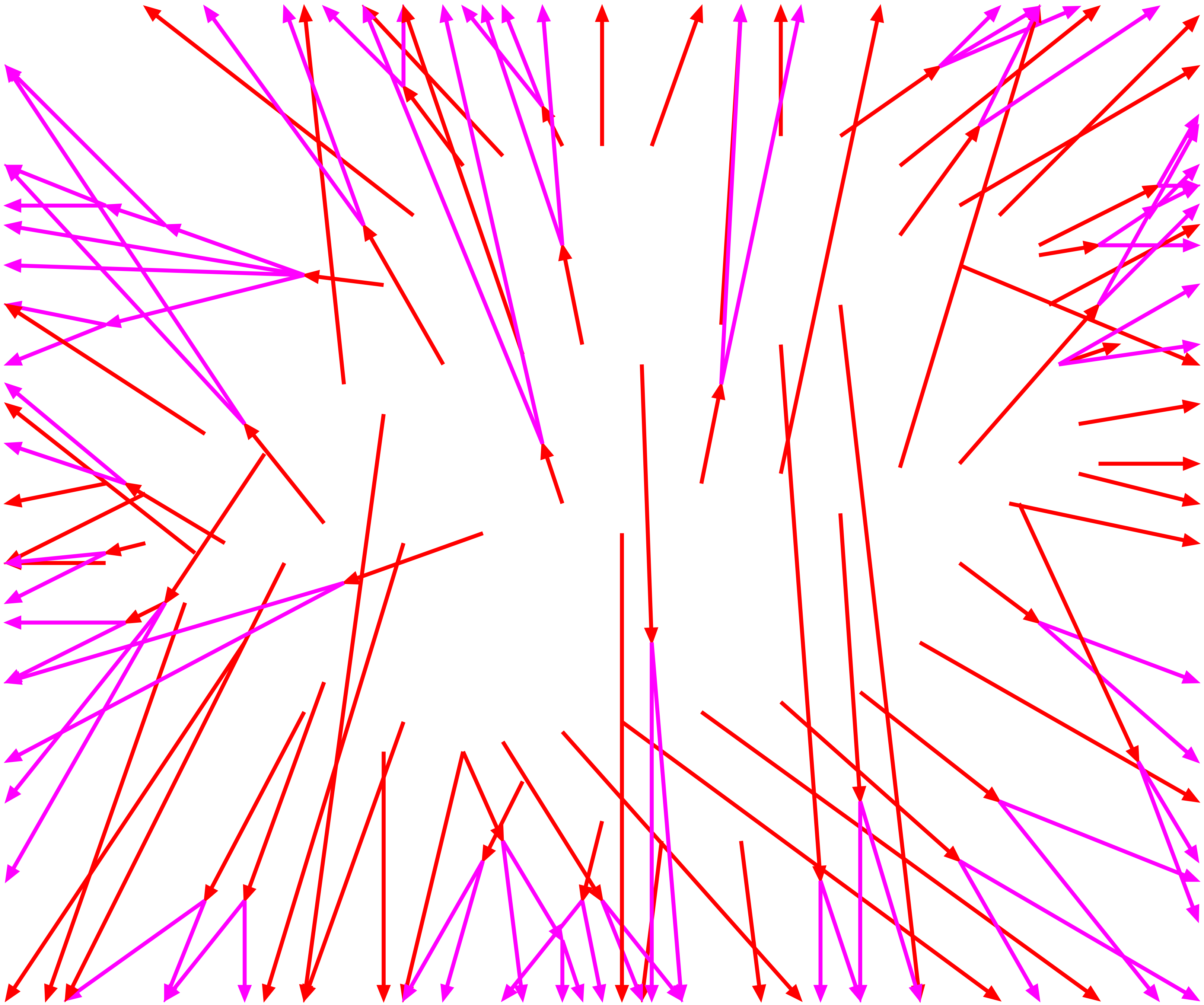


Everything is connected by colour confinement strings

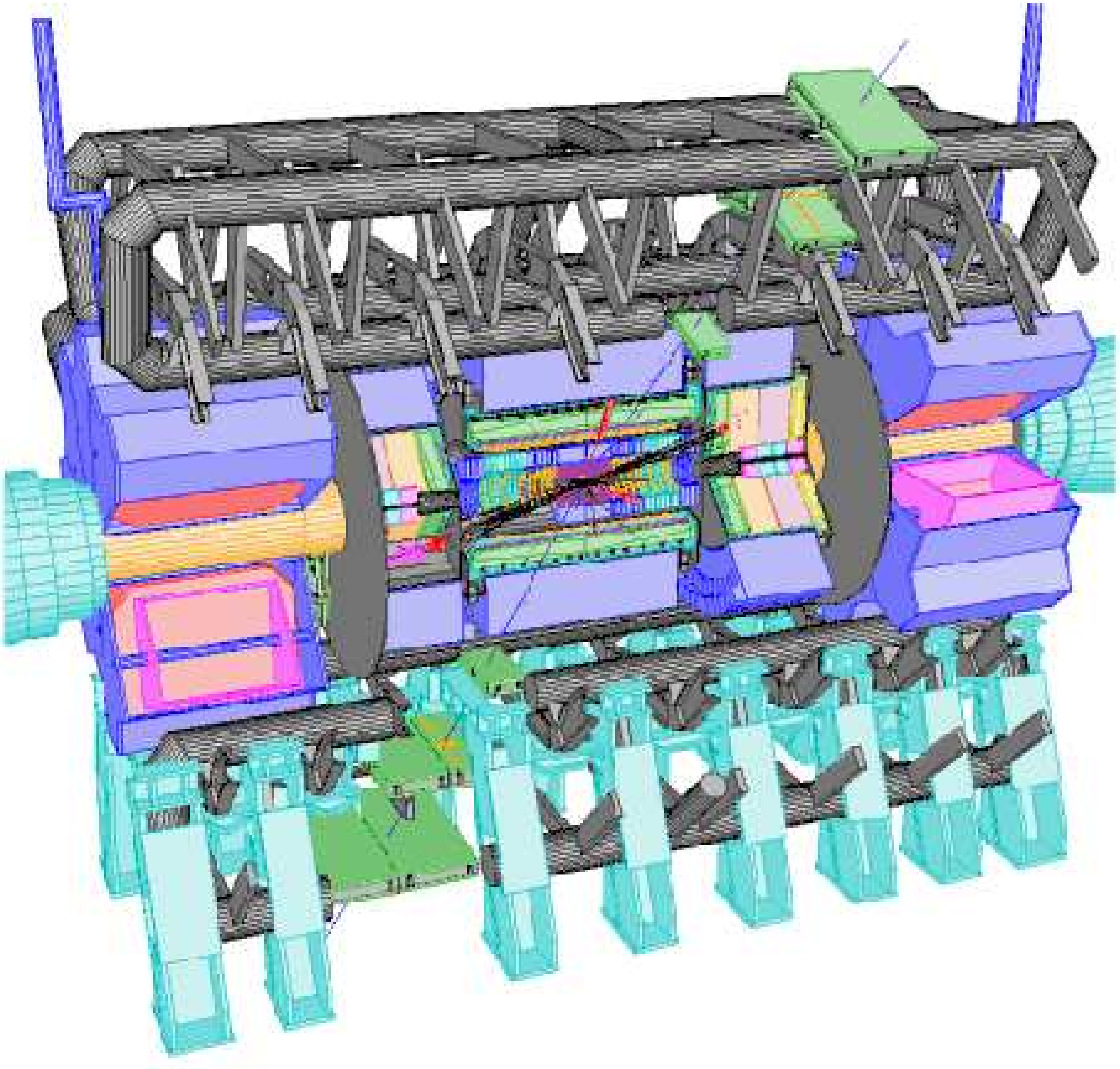
Recall! Not to scale: strings are of hadronic widths



The strings fragment to produce primary hadrons



Many hadrons are unstable and decay further



These are the particles that hit the detector

The Monte Carlo method

Want to generate events in as much detail as Mother Nature

$\Longrightarrow$ get average *and* fluctutations right

$\Longrightarrow$ make random choices, $\sim$ as in nature

$$\sigma_{\text{final state}} = \sigma_{\text{hard process}} \mathcal{P}_{\text{tot,hard process}\to\text{final state}}$$

(appropriately summed & integrated over non-distinguished final states)

where $\mathcal{P}_{\text{tot}} = \mathcal{P}_{\text{res}} \mathcal{P}_{\text{ISR}} \mathcal{P}_{\text{FSR}} \mathcal{P}_{\text{MI}} \mathcal{P}_{\text{remnants}} \mathcal{P}_{\text{hadronization}} \mathcal{P}_{\text{decays}}$

with $\mathcal{P}_i = \prod_j \mathcal{P}_{ij} = \prod_j \prod_k \mathcal{P}_{ijk} = \ldots$ in its turn

$\Longrightarrow$ **divide and conquer**

an event with n particles involves $\mathcal{O}(10n)$ random choices,

(flavour, mass, momentum, spin, production vertex, lifetime, . . .)

LHC: $\sim$ 100 charged and $\sim$ 200 neutral (+ intermediate stages)

$\Longrightarrow$ several thousand choices

(of $\mathcal{O}(100)$ different kinds)

Generator Landscape

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

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

Generator Homepages

HERWIG

`http://hepwww.rl.ac.uk/theory/seymour/herwig/`

PYTHIA

`http://www.thep.lu.se/∼torbjorn/Pythia.html`

ISAJET

`http://www.phy.bnl.gov/∼isajet/`

SHERPA

`http://www.physik.tu-dresden.de/∼krauss/hep/`

HEPCODE Program Listing

`http://www.ippp.dur.ac.uk/%7Ewjs/HEPCODE/index.html`

Matrix Elements and Their Usage

$\mathcal{L}$

$\Rightarrow$ Feynman rules

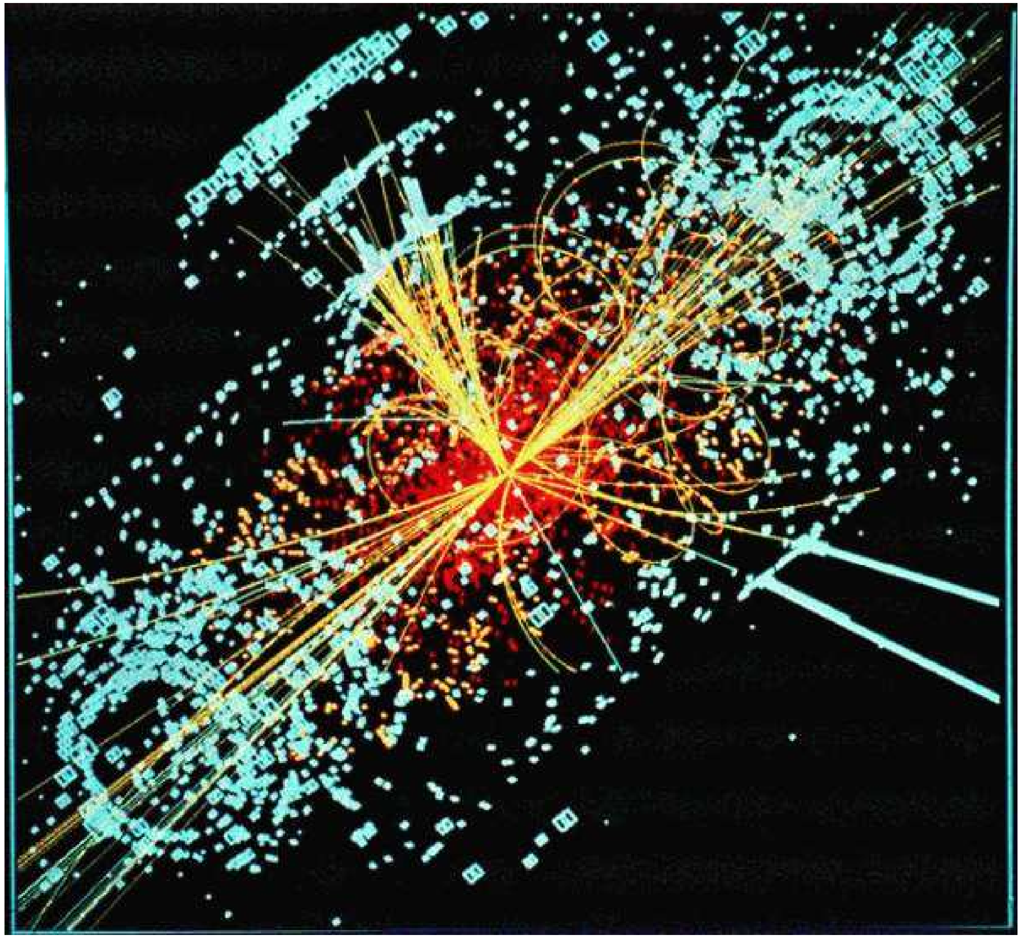
$\Rightarrow$ Matrix Elements

$\Rightarrow$Cross Sections

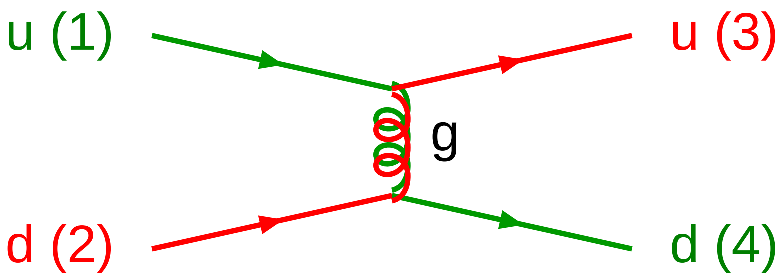
$+$Kinematics

$\Rightarrow$ Processes

$\Rightarrow \ldots \Rightarrow$



Cross sections and kinematics

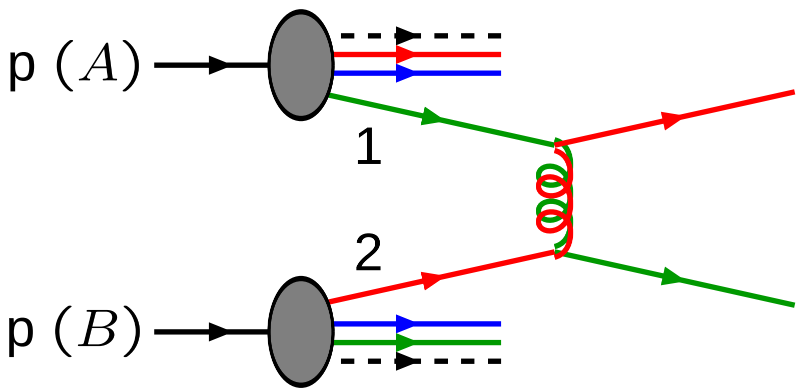


$$\hat{s} = (p_1 + p_2)^2$$

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

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

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



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

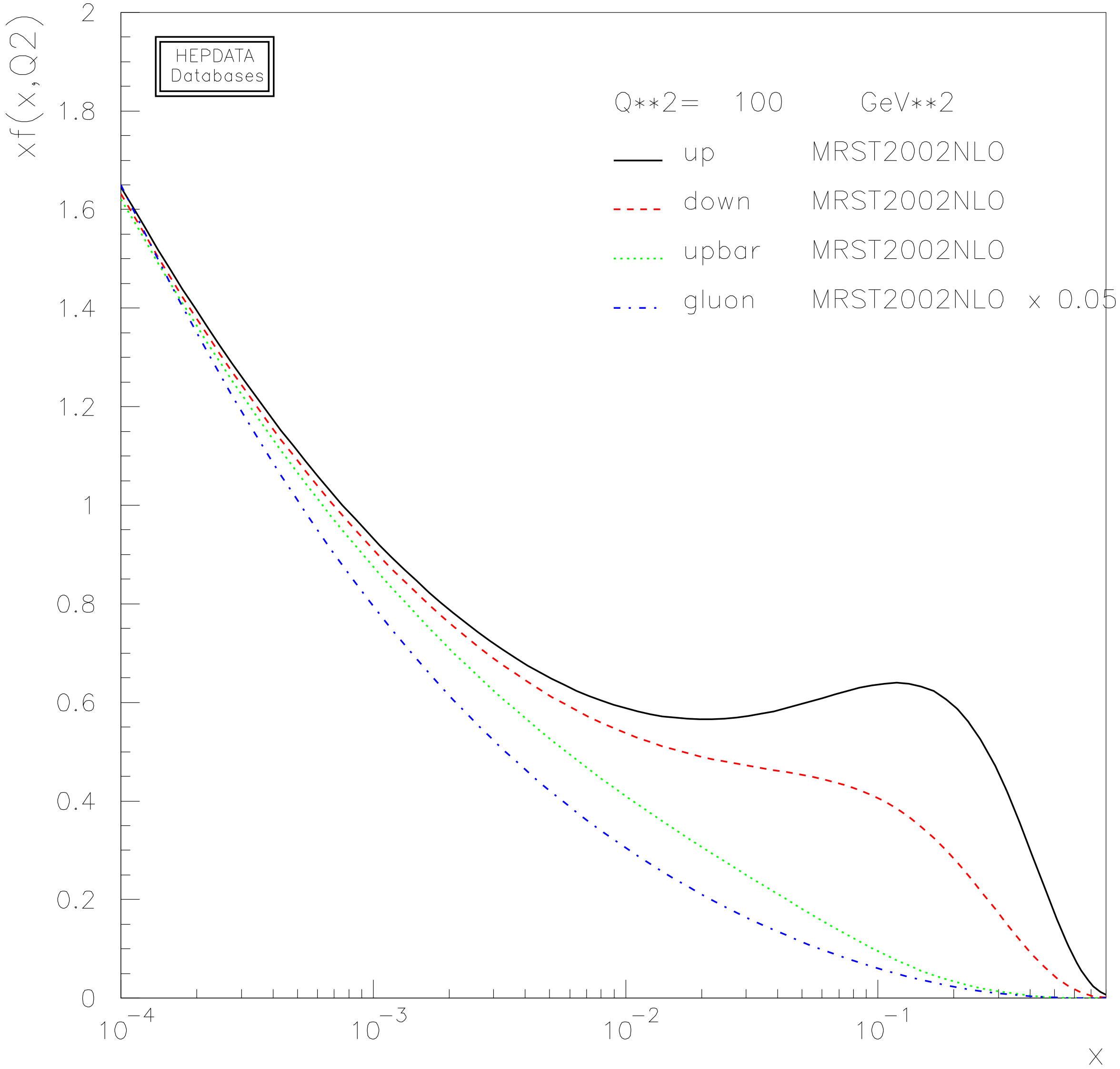
$$x_1 \approx E_1/E_A$$

$$x_2 \approx E_2/E_B$$

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

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

Parton Distribution/Density Functions (PDF)



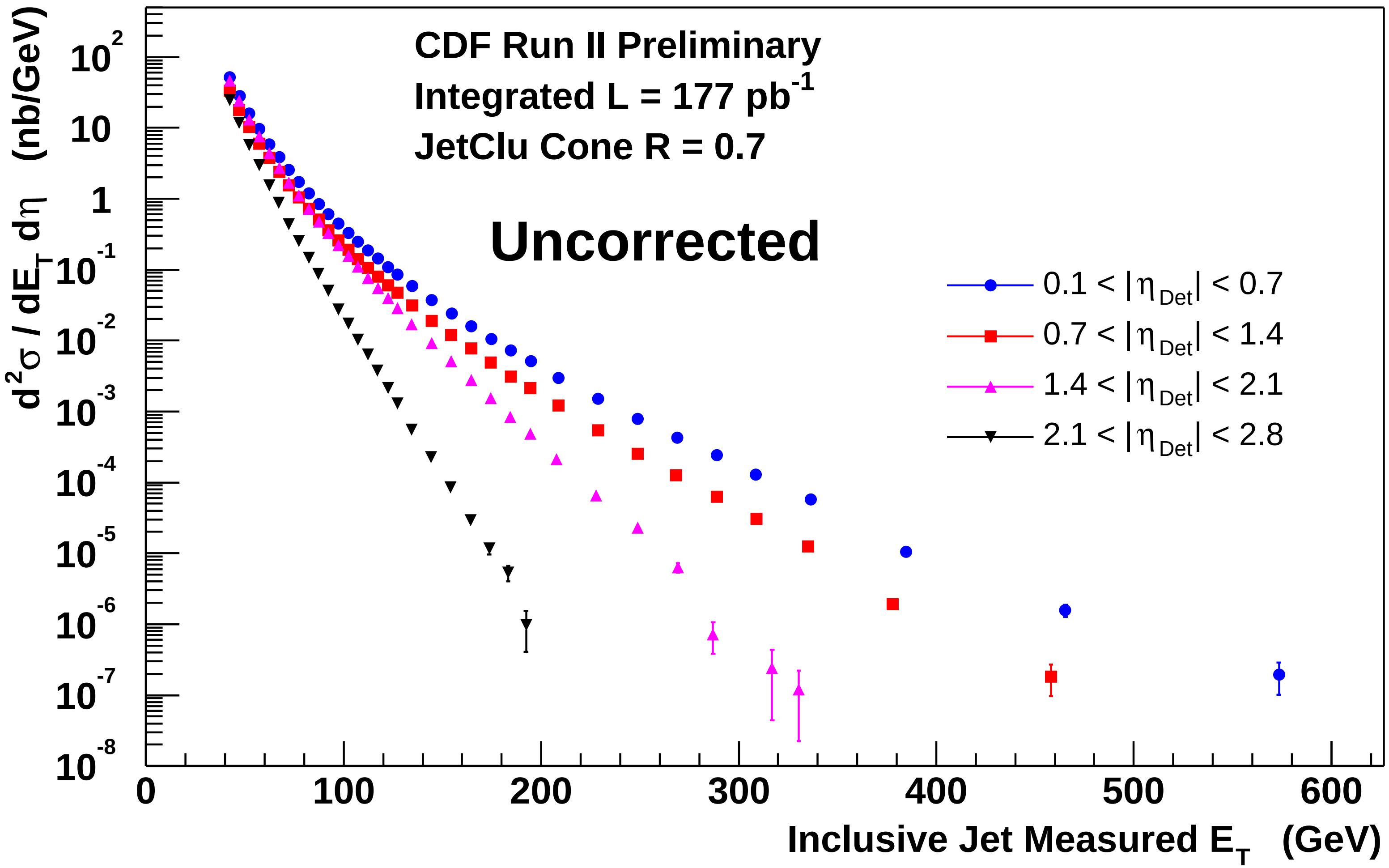
initial
conditions
nonpertubative

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

The Smaller Picture: Subprocess Survey

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

PYTHIA Process Library

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	$f_i \gamma \to f_i Z^0$

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	$f_i \bar{f}_i \to g\gamma$
18	$f_i \bar{f}_i \to \gamma\gamma$
29	$f_i g \to f_i \gamma$
114	$gg \to \gamma\gamma$
115	$gg \to g\gamma$
Deeply Inel. Scatt.:	
10	$f_i f_j \to f_k f_l$
99	$\gamma^* q \to q$
Photon-induced:	
33	$f_i \gamma \to f_i g$
34	$f_i \gamma \to f_i \gamma$
54	$g\gamma \to f_k \bar{f}_k$
58	$\gamma\gamma \to f_k \bar{f}_k$
131	$f_i \gamma^*_T \to f_i g$
132	$f_i \gamma^*_L \to f_i g$
133	$f_i \gamma^*_T \to f_i \gamma$
134	$f_i \gamma^*_L \to f_i \gamma$
135	$g\gamma^*_T \to f_i \bar{f}_i$
136	$g\gamma^*_L \to f_i \bar{f}_i$
137	$\gamma^*_T \gamma^*_T \to f_i \bar{f}_i$
138	$\gamma^*_T \gamma^*_L \to f_i \bar{f}_i$
139	$\gamma^*_L \gamma^*_T \to f_i \bar{f}_i$
140	$\gamma^*_L \gamma^*_L \to f_i \bar{f}_i$
80	$q_i \gamma \to q_k \pi^\pm$
Light SM Higgs:	
3	$f_i \bar{f}_i \to h^0$
24	$f_i \bar{f}_i \to Z^0 h^0$
26	$f_i \bar{f}_j \to W^\pm h^0$
32	$f_i g \to f_i h^0$
102	$gg \to h^0$
103	$\gamma\gamma \to h^0$
110	$f_i \bar{f}_i \to \gamma h^0$
111	$f_i \bar{f}_i \to g h^0$
112	$f_i g \to f_i h^0$
113	$gg \to g h^0$
121	$gg \to Q_k \bar{Q}_k h^0$
122	$q_i \bar{q}_i \to Q_k \bar{Q}_k h^0$
123	$f_i f_j \to f_i f_j h^0$
124	$f_i f_j \to f_k f_l h^0$

No.	Subprocess
New gauge bosons:	
141	$f_i \bar{f}_i \to \gamma/Z^0/Z'^0$
142	$f_i \bar{f}_j \to W'^+$
144	$f_i \bar{f}_j \to R$
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	$f_i \bar{f}_i \to H^0$
152	$gg \to H^0$
153	$\gamma\gamma \to H^0$
171	$f_i \bar{f}_i \to Z^0 H^0$
172	$f_i \bar{f}_j \to W^\pm H^0$
173	$f_i f_j \to f_i f_j H^0$
174	$f_i f_j \to f_k f_l H^0$
181	$gg \to Q_k \bar{Q}_k H^0$
182	$q_i \bar{q}_i \to Q_k \bar{Q}_k H^0$
183	$f_i \bar{f}_i \to g H^0$
184	$f_i g \to f_i H^0$
185	$gg \to g H^0$
156	$f_i \bar{f}_i \to A^0$
157	$gg \to A^0$
158	$\gamma\gamma \to A^0$
176	$f_i \bar{f}_i \to Z^0 A^0$
177	$f_i \bar{f}_j \to W^\pm A^0$
178	$f_i f_j \to f_i f_j A^0$
179	$f_i f_j \to f_k f_l A^0$
186	$gg \to Q_k \bar{Q}_k A^0$
187	$q_i \bar{q}_i \to Q_k \bar{Q}_k A^0$
188	$f_i \bar{f}_i \to g A^0$
189	$f_i g \to f_i A^0$
190	$gg \to g A^0$
Charged Higgs:	
143	$f_i \bar{f}_j \to H^+$
161	$f_i g \to f_k H^+$
401	$gg \to \bar{t} b H^+$
402	$q\bar{q} \to \bar{t} b H^+$

No.	Subprocess
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	$f_i \bar{f}_i \to H^+ H^-$
Leptoquarks:	
145	$q_i \ell_j \to L_Q$
162	$qg \to \ell L_Q$
163	$gg \to L_Q \bar{L}_Q$
164	$q_i \bar{q}_i \to L_Q \bar{L}_Q$
Technicolor:	
149	$gg \to \eta_{tc}$
191	$f_i \bar{f}_i \to \rho^0_{tc}$
192	$f_i \bar{f}_j \to \rho^+_{tc}$
193	$f_i \bar{f}_i \to \omega^0_{tc}$
194	$f_i \bar{f}_i \to f_k \bar{f}_k$
195	$f_i \bar{f}_j \to f_k \bar{f}_l$
361	$f_i \bar{f}_i \to W^+_L W^-_L$
362	$f_i \bar{f}_i \to W^\pm_L \pi^\mp_{tc}$
363	$f_i \bar{f}_i \to \pi^+_{tc} \pi^-_{tc}$
364	$f_i \bar{f}_i \to \gamma \pi^0_{tc}$
365	$f_i \bar{f}_i \to \gamma \pi'^0_{tc}$
366	$f_i \bar{f}_i \to Z^0 \pi^0_{tc}$
367	$f_i \bar{f}_i \to Z^0 \pi'^0_{tc}$
368	$f_i \bar{f}_i \to W^\pm \pi^\mp_{tc}$
370	$f_i \bar{f}_j \to W^\pm_L Z^0_L$
371	$f_i \bar{f}_j \to W^\pm_L \pi^0_{tc}$
372	$f_i \bar{f}_j \to \pi^\pm_{tc} Z^0_L$
373	$f_i \bar{f}_j \to \pi^\pm_{tc} \pi^0_{tc}$
374	$f_i \bar{f}_j \to \gamma \pi^\pm_{tc}$
375	$f_i \bar{f}_j \to Z^0 \pi^\pm_{tc}$
376	$f_i \bar{f}_j \to W^\pm \pi^0_{tc}$
377	$f_i \bar{f}_j \to W^\pm \pi'^0_{tc}$
381	$q_i q_j \to q_i q_j$
382	$q_i \bar{q}_i \to q_k \bar{q}_k$
383	$q_i \bar{q}_i \to gg$
384	$f_i g \to f_i g$
385	$gg \to q_k \bar{q}_k$
386	$gg \to gg$
387	$f_i \bar{f}_i \to Q_k \bar{Q}_k$
388	$gg \to Q_k \bar{Q}_k$

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	$q_i \bar{q}_i \to e^\pm e^{*\mp}$
165	$f_i \bar{f}_i (\to \gamma^*/Z^0) \to f_k \bar{f}_k$
166	$f_i \bar{f}_j (\to W^\pm) \to f_k \bar{f}_l$
Extra Dimensions:	
391	$f\bar{f} \to G^*$
392	$gg \to G^*$
393	$q\bar{q} \to gG^*$
394	$qg \to qG^*$
395	$gg \to gG^*$
Left–right symmetry:	
341	$\ell_i \ell_j \to H^{\pm\pm}_L$
342	$\ell_i \ell_j \to H^{\pm\pm}_R$
343	$\ell^\pm_i \gamma \to H^{\pm\pm}_L e^\mp$
344	$\ell^\pm_i \gamma \to H^{\pm\pm}_R e^\mp$
345	$\ell^\pm_i \gamma \to H^{\pm\pm}_L \mu^\mp$
346	$\ell^\pm_i \gamma \to H^{\pm\pm}_R \mu^\mp$
347	$\ell^\pm_i \gamma \to H^{\pm\pm}_L \tau^\mp$
348	$\ell^\pm_i \gamma \to H^{\pm\pm}_R \tau^\mp$
349	$f_i \bar{f}_i \to H^{++}_L H^{--}_L$
350	$f_i \bar{f}_i \to H^{++}_R H^{--}_R$
351	$f_i f_j \to f_k f_l H^{\pm\pm}_L$
352	$f_i f_j \to f_k f_l H^{\pm\pm}_R$
353	$f_i \bar{f}_i \to Z^0_R$
354	$f_i \bar{f}_j \to W^\pm_R$
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	$f_i \bar{f}_i \to \tilde{\tau}_1 \tilde{\tau}^*_2 +$

No.	Subprocess
210	$f_i \bar{f}_j \to \tilde{\ell}_L \tilde{\nu}^*_\ell +$
211	$f_i \bar{f}_j \to \tilde{\tau}_1 \tilde{\nu}^*_\tau +$
212	$f_i \bar{f}_j \to \tilde{\tau}_2 \tilde{\nu}^*_\tau +$
213	$f_i \bar{f}_i \to \tilde{\nu}_\ell \tilde{\nu}_\ell{}^*$
214	$f_i \bar{f}_i \to \tilde{\nu}_\tau \tilde{\nu}^*_\tau$
216	$f_i \bar{f}_i \to \tilde{\chi}_1 \tilde{\chi}_1$
217	$f_i \bar{f}_i \to \tilde{\chi}_2 \tilde{\chi}_2$
218	$f_i \bar{f}_i \to \tilde{\chi}_3 \tilde{\chi}_3$
219	$f_i \bar{f}_i \to \tilde{\chi}_4 \tilde{\chi}_4$
220	$f_i \bar{f}_i \to \tilde{\chi}_1 \tilde{\chi}_2$
221	$f_i \bar{f}_i \to \tilde{\chi}_1 \tilde{\chi}_3$
222	$f_i \bar{f}_i \to \tilde{\chi}_1 \tilde{\chi}_4$
223	$f_i \bar{f}_i \to \tilde{\chi}_2 \tilde{\chi}_3$
224	$f_i \bar{f}_i \to \tilde{\chi}_2 \tilde{\chi}_4$
225	$f_i \bar{f}_i \to \tilde{\chi}_3 \tilde{\chi}_4$
226	$f_i \bar{f}_i \to \tilde{\chi}^\pm_1 \tilde{\chi}^\mp_1$
227	$f_i \bar{f}_i \to \tilde{\chi}^\pm_2 \tilde{\chi}^\mp_2$
228	$f_i \bar{f}_i \to \tilde{\chi}^\pm_1 \tilde{\chi}^\mp_2$
229	$f_i \bar{f}_j \to \tilde{\chi}_1 \tilde{\chi}^\pm_1$
230	$f_i \bar{f}_j \to \tilde{\chi}_2 \tilde{\chi}^\pm_1$
231	$f_i \bar{f}_j \to \tilde{\chi}_3 \tilde{\chi}^\pm_1$
232	$f_i \bar{f}_j \to \tilde{\chi}_4 \tilde{\chi}^\pm_1$
233	$f_i \bar{f}_j \to \tilde{\chi}_1 \tilde{\chi}^\pm_2$
234	$f_i \bar{f}_j \to \tilde{\chi}_2 \tilde{\chi}^\pm_2$
235	$f_i \bar{f}_j \to \tilde{\chi}_3 \tilde{\chi}^\pm_2$
236	$f_i \bar{f}_j \to \tilde{\chi}_4 \tilde{\chi}^\pm_2$
237	$f_i \bar{f}_i \to \tilde{g} \tilde{\chi}_1$
238	$f_i \bar{f}_i \to \tilde{g} \tilde{\chi}_2$
239	$f_i \bar{f}_i \to \tilde{g} \tilde{\chi}_3$
240	$f_i \bar{f}_i \to \tilde{g} \tilde{\chi}_4$
241	$f_i \bar{f}_j \to \tilde{g} \tilde{\chi}^\pm_1$
242	$f_i \bar{f}_j \to \tilde{g} \tilde{\chi}^\pm_2$
243	$f_i \bar{f}_i \to \tilde{g} \tilde{g}$
244	$gg \to \tilde{g} \tilde{g}$
246	$f_i g \to \tilde{q}_{iL} \tilde{\chi}_1$
247	$f_i g \to \tilde{q}_{iR} \tilde{\chi}_1$
248	$f_i g \to \tilde{q}_{iL} \tilde{\chi}_2$
249	$f_i g \to \tilde{q}_{iR} \tilde{\chi}_2$

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	$f_i \bar{f}_i \to \tilde{t}_1 \tilde{t}^*_1$
262	$f_i \bar{f}_i \to \tilde{t}_2 \tilde{t}^*_2$
263	$f_i \bar{f}_i \to \tilde{t}_1 \tilde{t}^*_2 +$
264	$gg \to \tilde{t}_1 \tilde{t}^*_1$
265	$gg \to \tilde{t}_2 \tilde{t}^*_2$
271	$f_i f_j \to \tilde{q}_{iL} \tilde{q}_{jL}$
272	$f_i f_j \to \tilde{q}_{iR} \tilde{q}_{jR}$
273	$f_i f_j \to \tilde{q}_{iL} \tilde{q}_{jR} +$
274	$f_i \bar{f}_j \to \tilde{q}_{iL} \tilde{q}^*_{jL}$
275	$f_i \bar{f}_j \to \tilde{q}_{iR} \tilde{q}^*_{jR}$
276	$f_i \bar{f}_j \to \tilde{q}_{iL} \tilde{q}^*_{jR} +$
277	$f_i \bar{f}_i \to \tilde{q}_{jL} \tilde{q}^*_{jL}$
278	$f_i \bar{f}_i \to \tilde{q}_{jR} \tilde{q}^*_{jR}$
279	$gg \to \tilde{q}_{iL} \tilde{q}^*_{iL}$
280	$gg \to \tilde{q}_{iR} \tilde{q}^*_{iR}$
281	$bq_i \to \tilde{b}_1 \tilde{q}_{iL}$
282	$bq_i \to \tilde{b}_2 \tilde{q}_{iR}$
283	$bq_i \to \tilde{b}_1 \tilde{q}_{iR} +$
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	$b\bar{q}_i \to \tilde{b}_1 \tilde{q}^*_{iR} +$
287	$f_i \bar{f}_i \to \tilde{b}_1 \tilde{b}^*_1$
288	$f_i \bar{f}_i \to \tilde{b}_2 \tilde{b}^*_2$
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	$b\bar{b} \to \tilde{b}_1 \tilde{b}^*_2 +$

HERWIG Process Library

IPROC	Process
100	$\ell^+\ell^- \to q\bar{q}(g)$ (all q flavours)
100+IQ	$\ell^+\ell^- \to q\bar{q}(g)$ (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	$\ell^+\ell^- \to \ell'\bar{\ell}'$ (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 IPROC $= 300 +$ 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 IPROC $= 300 +$ 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 IPROC $= 300 +$ 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	$\ell^+\ell^- \to \widetilde{\ell}_{L,R}\widetilde{\ell}^*_{L,R}$ (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	$\ell^+\ell^- \to \widetilde{\nu}_L\widetilde{\nu}^*_L$ (IL $= 1,2,3$ for $\widetilde{\nu}_e,\widetilde{\nu}_\mu,\widetilde{\nu}_\tau$)
760	$\ell^+\ell^- \to$ squark pairs (all flavours)
757+4IQ	$\ell^+\ell^- \to \widetilde{q}_{L,R}\widetilde{q}^*_{L,R}$ (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	$q\bar{q} \to Z^0/\gamma \to q'\bar{q}'$ (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	$q\bar{q} \to Z^0/\gamma \to \ell\bar{\ell}$ (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	$q\bar{q} \to W^\pm \to \ell\nu_\ell$ (IL $= 1,2,3$ for $\ell = e,\mu,\tau$)
1499	$q\bar{q} \to W^\pm \to$ anything
1500	QCD $2 \to 2$ hard parton scattering
	After generation, IHPRO is subprocess (see sect. ??)
1600+ID	$gg/q\bar{q} \to H^0_{\rm SM}$ (ID as in IPROC $= 300 +$ 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 IPROC $= 300 +$ ID)
2000	t production via $W^\pm$ exchange (sum of 2001–2008)
2001–4	$\bar{u}\bar{b} \to \bar{d}\bar{t}$, $d\bar{b} \to u\bar{t}$, $\bar{d}\bar{b} \to \bar{u}\bar{t}$, $ub \to dt$
2005–8	$\bar{c}\bar{b} \to \bar{s}\bar{t}$, $s\bar{b} \to c\bar{t}$, $\bar{s}b \to \bar{c}t$, $cb \to st$
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	$gg + q\bar{q} \to Q\bar{Q}Z^0$ 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	$bq \to bq'H^\pm$ + 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	$u_id_j \to \bar{u}_ld_m$, $d_jd_k \to \bar{d}_ld_m$ 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	$gg/q\bar{q} \to G \to \ell\bar{\ell}$ (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	$\gamma\gamma \to \ell\bar{\ell}$ (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 IPROC $= 300 +$ 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

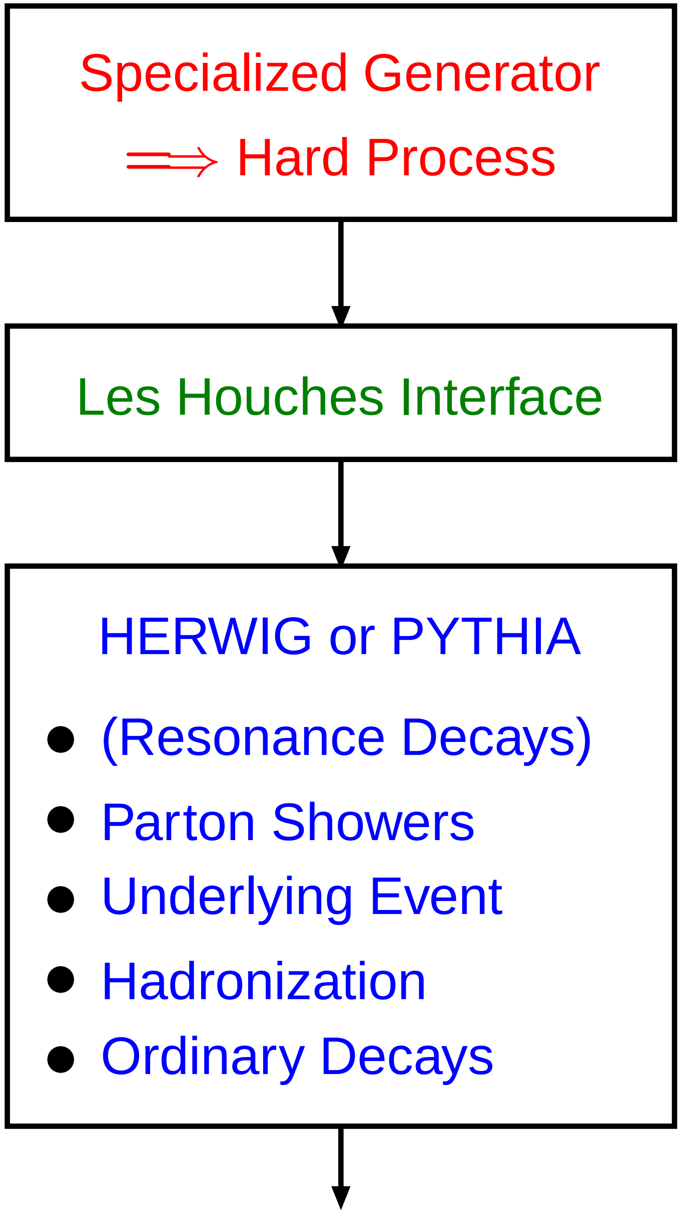
$\star$ Spin correlations often absent or incomplete
e.g. top produced unpolarized, while $\mathrm{t} \to \mathrm{bW}^+ \to \mathrm{b}\ell^+\nu_\ell$ decay correct
$\Rightarrow$ have to use external programs when important

$\star$ 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 $\mathrm{W/Z} + \leq 2\mathrm{j}$, $\mathrm{WZ}, \mathrm{WH}, \mathrm{H} + \leq 1\mathrm{j}$
- 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

PDG Particle Codes

A. Fundamental objects

1	d	11	e^-	21	g				
2	u	12	ν_e	22	γ	32	Z'^0		
3	s	13	μ^-	23	Z^0	33	Z''^0		
4	c	14	ν_μ	24	W^+	34	W'^+		
5	b	15	τ^-	25	h^0	35	H^0	37	H^+
6	t	16	ν_τ			36	A^0	39	Graviton

add $-$ sign for antiparticle, where appropriate

+ diquarks, SUSY, technicolor, . . .

B. Mesons

$100\,|q_1| + 10\,|q_2| + (2s+1)$ with $|q_1| \geq |q_2|$

particle if heaviest quark u, $\bar{\text{s}}$, c, $\bar{\text{b}}$; else antiparticle

111	π^0	311	K^0	130	K_L^0	221	η^0	411	D^+	431	D_s^+
211	π^+	321	K^+	310	K_S^0	331	η'^0	421	D^0	443	J/ψ

C. Baryons

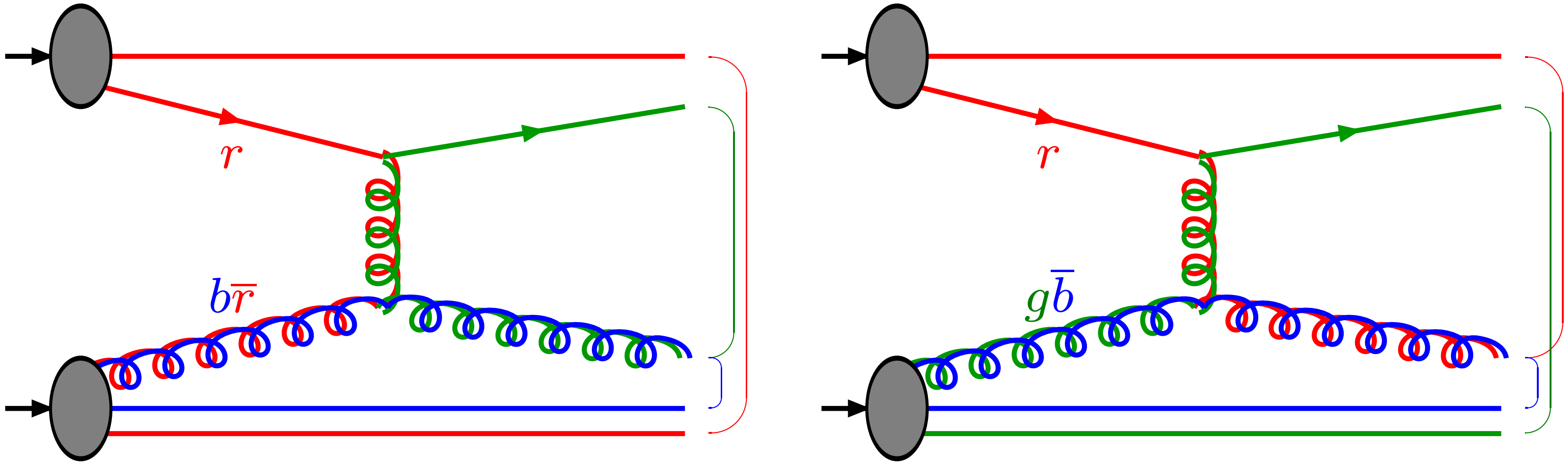
$1000\,q_1 + 100\,q_2 + 10\,q_3 + (2s+1)$

with $q_1 \geq q_2 \geq q_3$, or Λ-like $q_1 \geq q_3 \geq q_2$

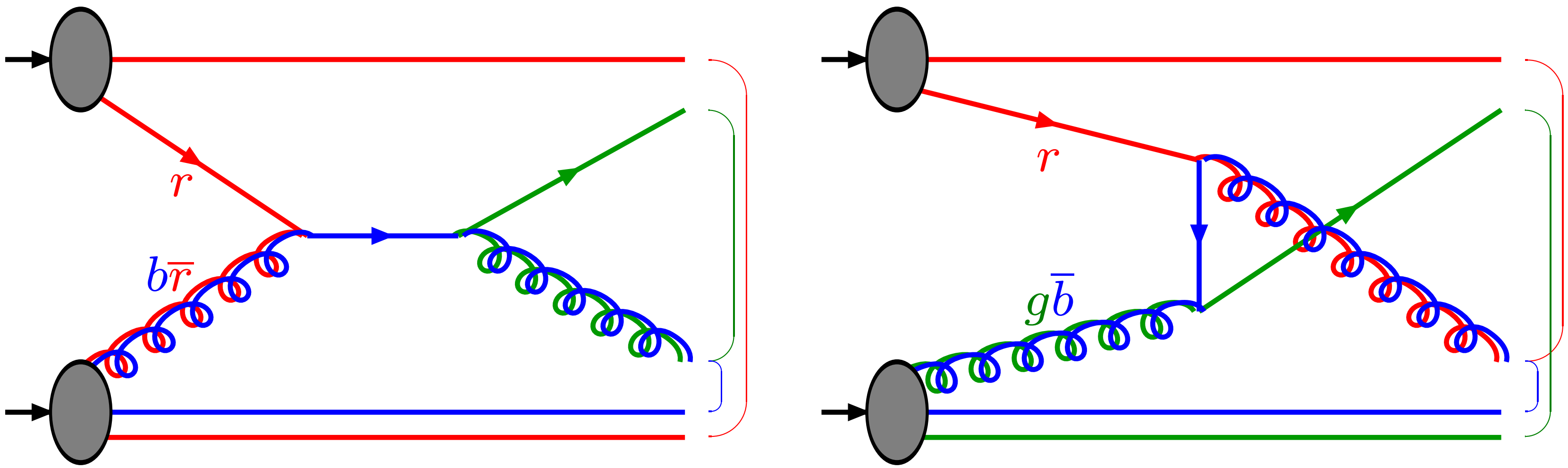
2112	n	3122	Λ^0	2224	Δ^{++}	3214	Σ^{*0}
2212	p	3212	Σ^0	1114	Δ^-	3334	Ω^-

Colour flow in hard processes

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



while other $\mathrm{qg} \rightarrow \mathrm{qg}$ graphs only admit one colour flow:



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

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

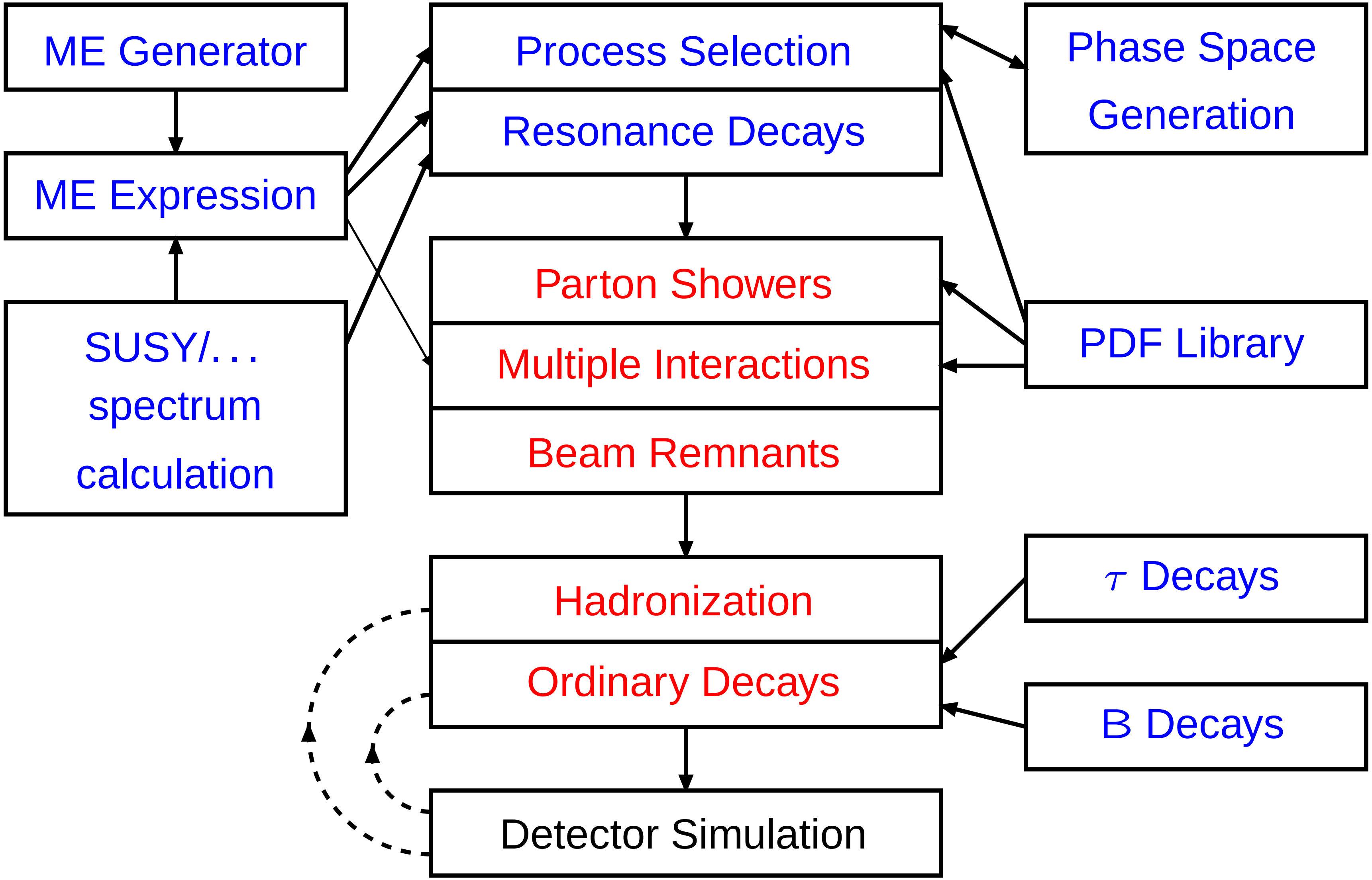
with $\mathcal{R}e\left(\mathcal{A}_{\mathrm{I}}(\hat{s},\hat{t})\mathcal{A}^*_{\mathrm{II}}(\hat{s},\hat{t})\right) \neq 0$
$\Rightarrow$ indeterminate colour flow, while
• showers *should* know it (coherence),
• hadronization *must* know it (hadrons singlets).
Normal solution:

$$\frac{\text{interference}}{\text{total}} \propto \frac{1}{N_C^2 - 1}$$

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

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

The Bigger Picture



$\Longrightarrow$ need standardized interfaces (LHAPDF, SUSY LHA, . . .)

The HEPEVT Event Record

Old standard output of the *final* event; being replaced by HepMC (in C++).

```
 PARAMETER (NMXHEP=4000)
 COMMON/HEPEVT/NEVHEP,NHEP,ISTHEP(NMXHEP),IDHEP(NMXHEP),
&JMOHEP(2,NMXHEP),JDAHEP(2,NMXHEP),PHEP(5,NMXHEP),
&VHEP(4,NMXHEP)
 DOUBLE PRECISION PHEP, VHEP
```

`NMXHEP` = maximum number of entries
`NEVHEP` = event number

`NHEP` = number of entries in current event

`ISTHEP` = status code of entry (0 = null entry, 1 = existing entry,
2 = fragmented/decayed entry, 3 = documentation entry)
`IDHEP` = PDG particle identity (+ some internal, e.g. 92 = string)

`JMOHEP` = mother position(s)
`JDAHEP` = first and last daughter position

`PHEP` = momentum (p_x, p_y, p_z, E, m) in GeV
`VHEP` = production vertex (x, y, z, t) in mm

Do it yourself

CompHEP and MadGraph can easily be run interactively:

- user specifies process, e.g. $gg \to W^+\overline{u}d$,
- 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: $\mathrm{W}/\mathrm{Z}+\leq 6\mathrm{j}$, $n\mathrm{W}+m\mathrm{Z}+k\mathrm{H}+\leq 3\mathrm{j}$, $\mathrm{Q}\overline{\mathrm{Q}}+\leq 6\mathrm{j}, \ldots$

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

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

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

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

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

• TopReX: $\mathrm{t\bar{t}}, \ldots$

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

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

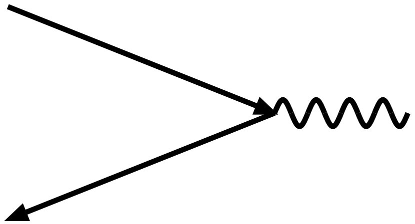
• EKS: 2j

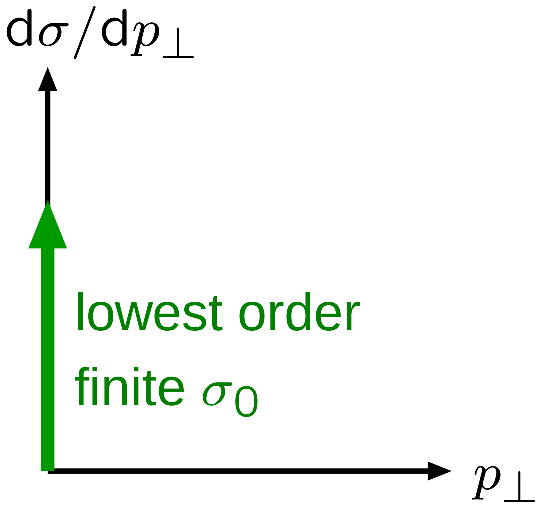
• PROSPINO: $\tilde{\mathrm{q}}\tilde{\mathrm{q}}$, $\tilde{\mathrm{q}}\tilde{\mathrm{g}}$, $\tilde{\mathrm{g}}\tilde{\mathrm{g}}$

• HIGLU: $\mathrm{gg}\rightarrow\mathrm{H}$

Next-to-leading order (NLO) calculations

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





Next-to-leading order (NLO) calculations

I. Lowest order,
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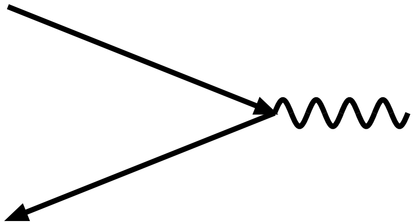
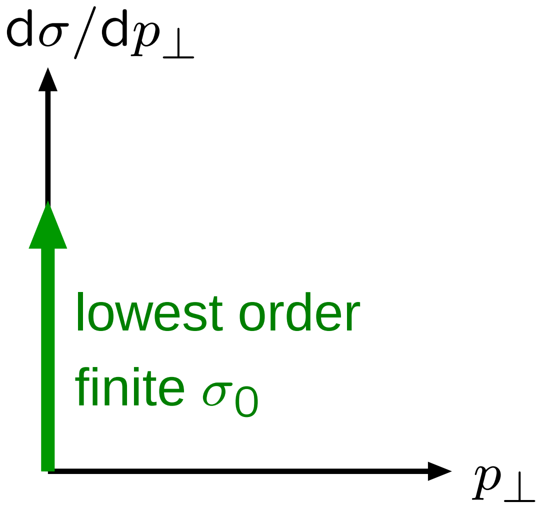
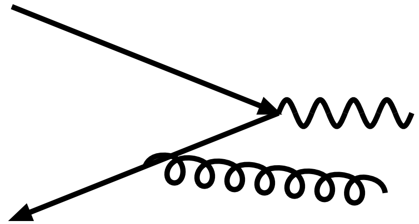
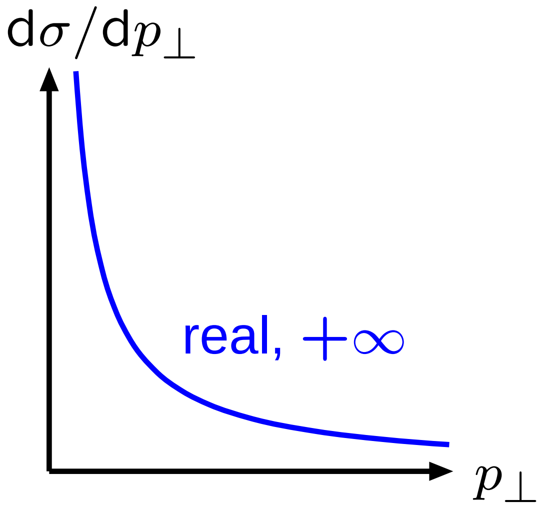




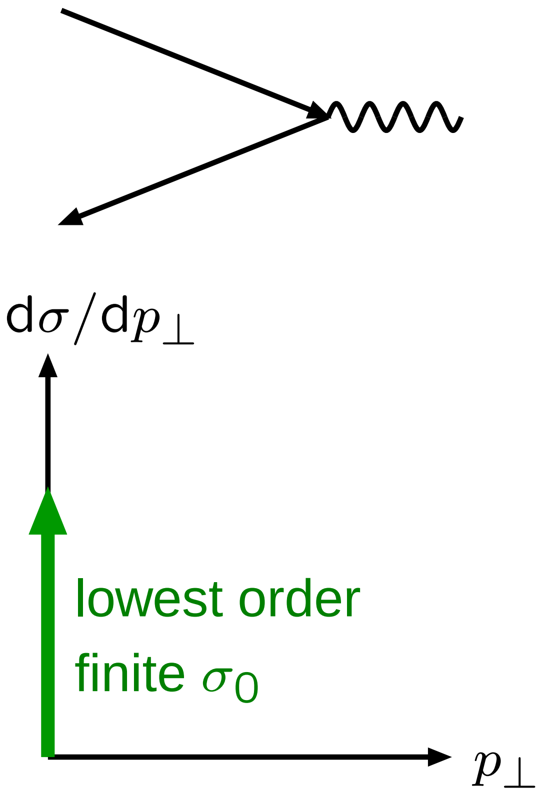
II. First-order real,
$\mathcal{O}(\alpha_{\mathrm{em}}\alpha_{\mathrm{s}})$:
$\mathrm{q\overline{q}} \to \mathrm{Z}^0\mathrm{g}$ etc.



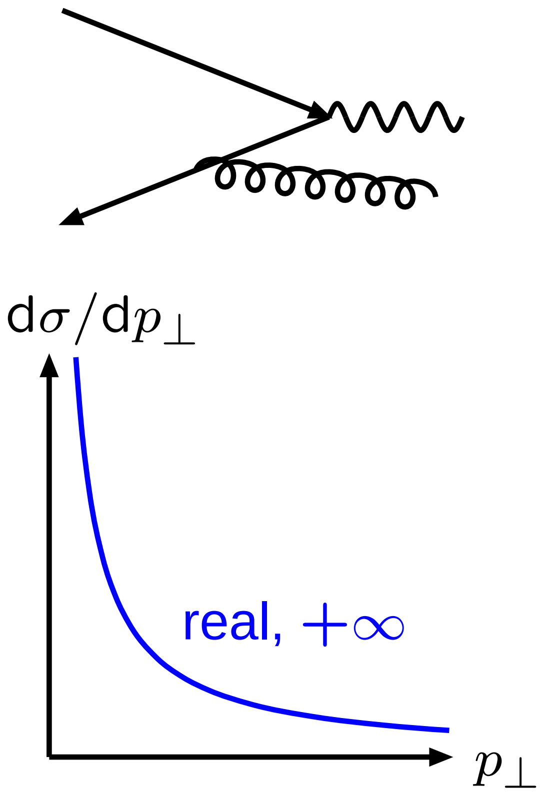


Next-to-leading order (NLO) calculations

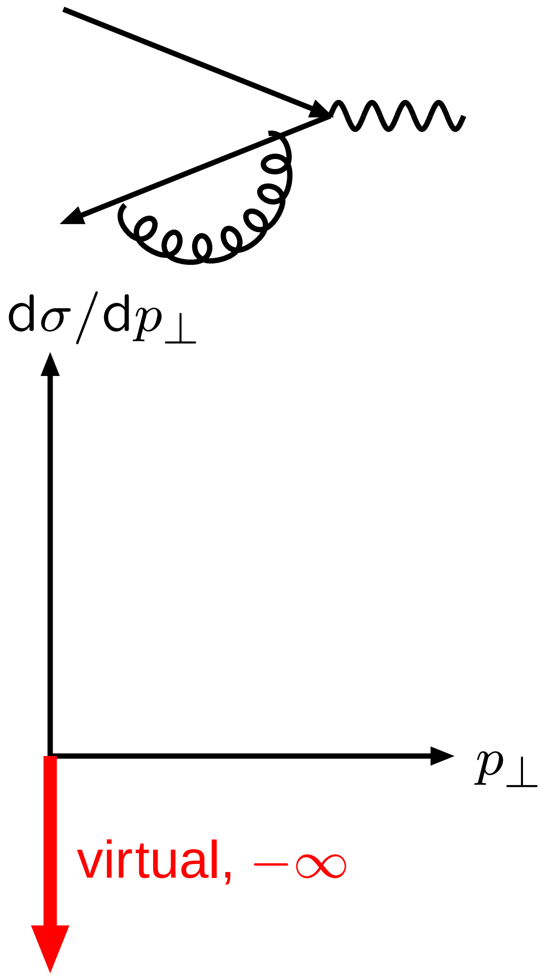
I. Lowest order,
$\mathcal{O}(\alpha_{\text{em}})$:
$q\overline{q} \to Z^0$



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



III. First-order virtual,
$\mathcal{O}(\alpha_{\text{em}}\alpha_{\text{s}})$:
$q\overline{q} \to Z^0$ 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: $x \sim p_\perp / p_{\perp\mathrm{max}}$, $0 \leq x \leq 1$

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:

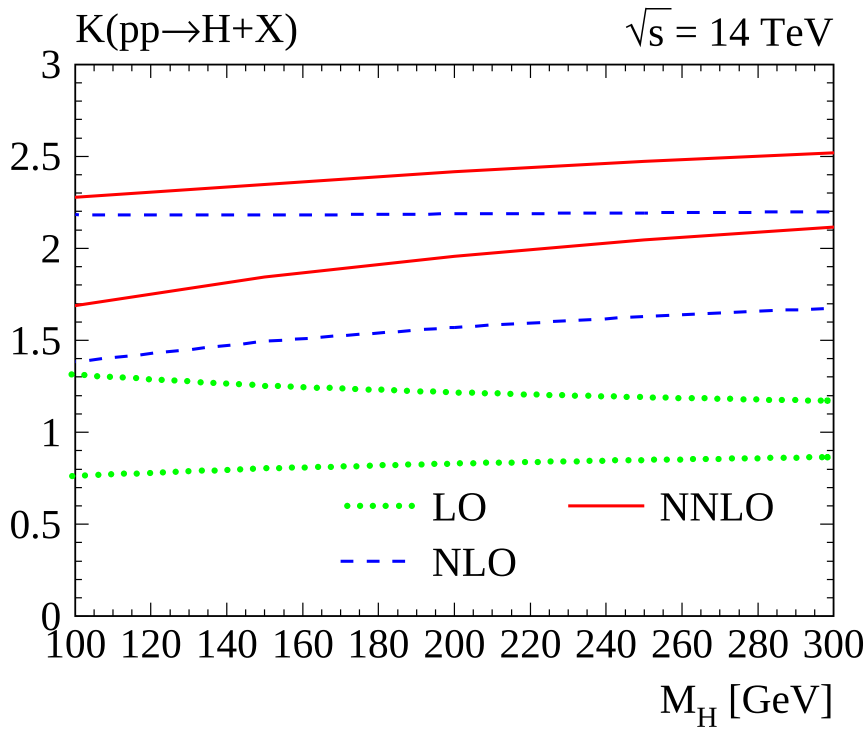
Introduce arbitrary *finite* cutoff $\delta << 1$ (so $\delta \gg |\epsilon|$)

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

Alternatively **Subtraction**:

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

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

Summary so far

• Event generators indispensable •

• Quantum Mechanics $\Longrightarrow$ probabilities •

⋆ Divide and conquer ⋆

• Main physics components: •

⋆ Hard processes and resonance decays ⋆

⋆ Initial- and final-state radiation ⋆

⋆ Multiple parton–parton interactions and beam remnants ⋆

⋆ Hadronization and decays ⋆

• Hard processes: •

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

⋆ Multiparton LO: external generator + Les Houches Accord ⋆

⋆ NLO: not easily related to physical events ⋆

• Tomorrow: initial- and final-state radiation •