LUND UNIVERSITY

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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

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

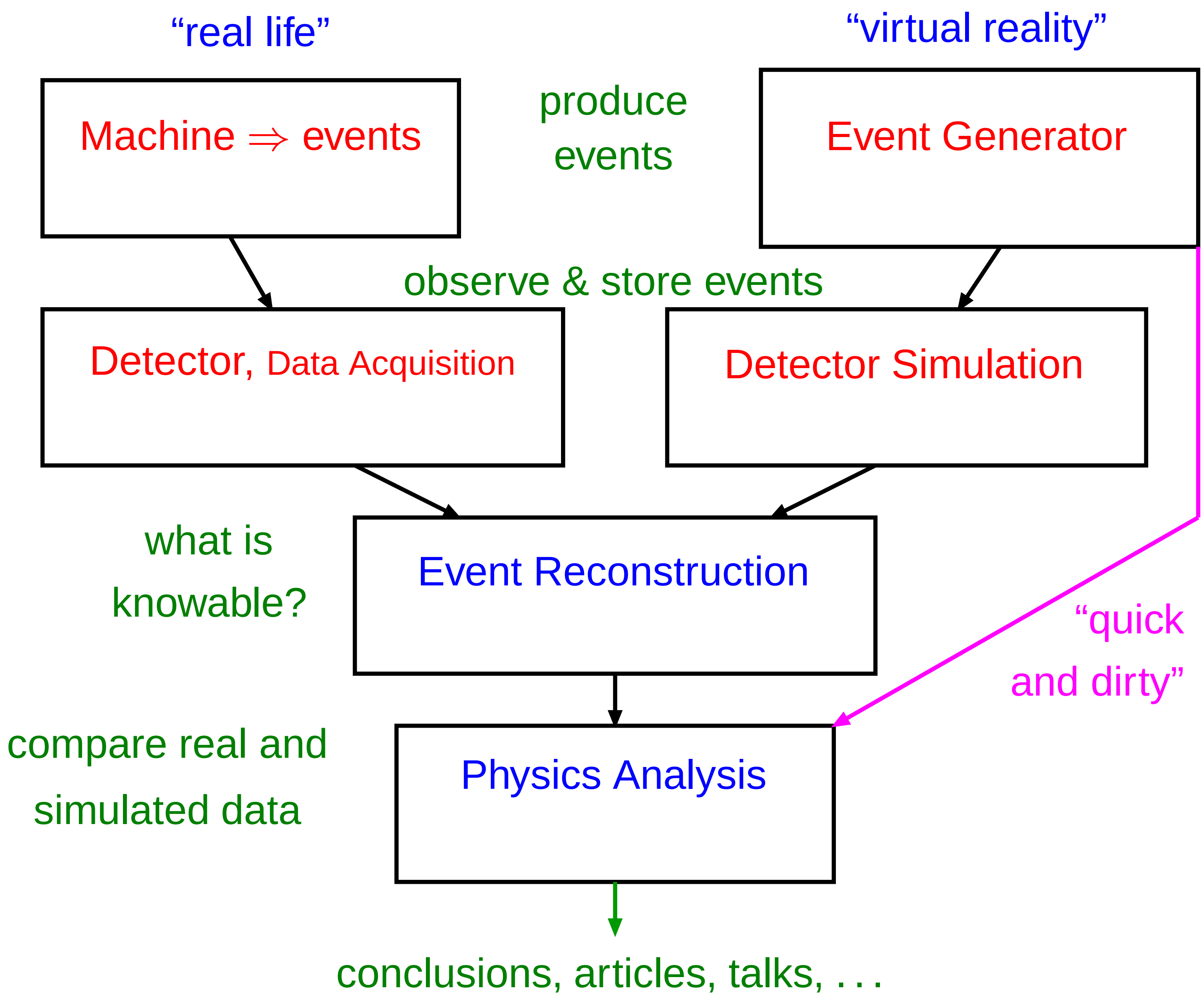
Mike Seymour, Academic Training lectures July 2003:
http://seymour.home.cern.ch/seymour/slides/CERNlectures.html

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

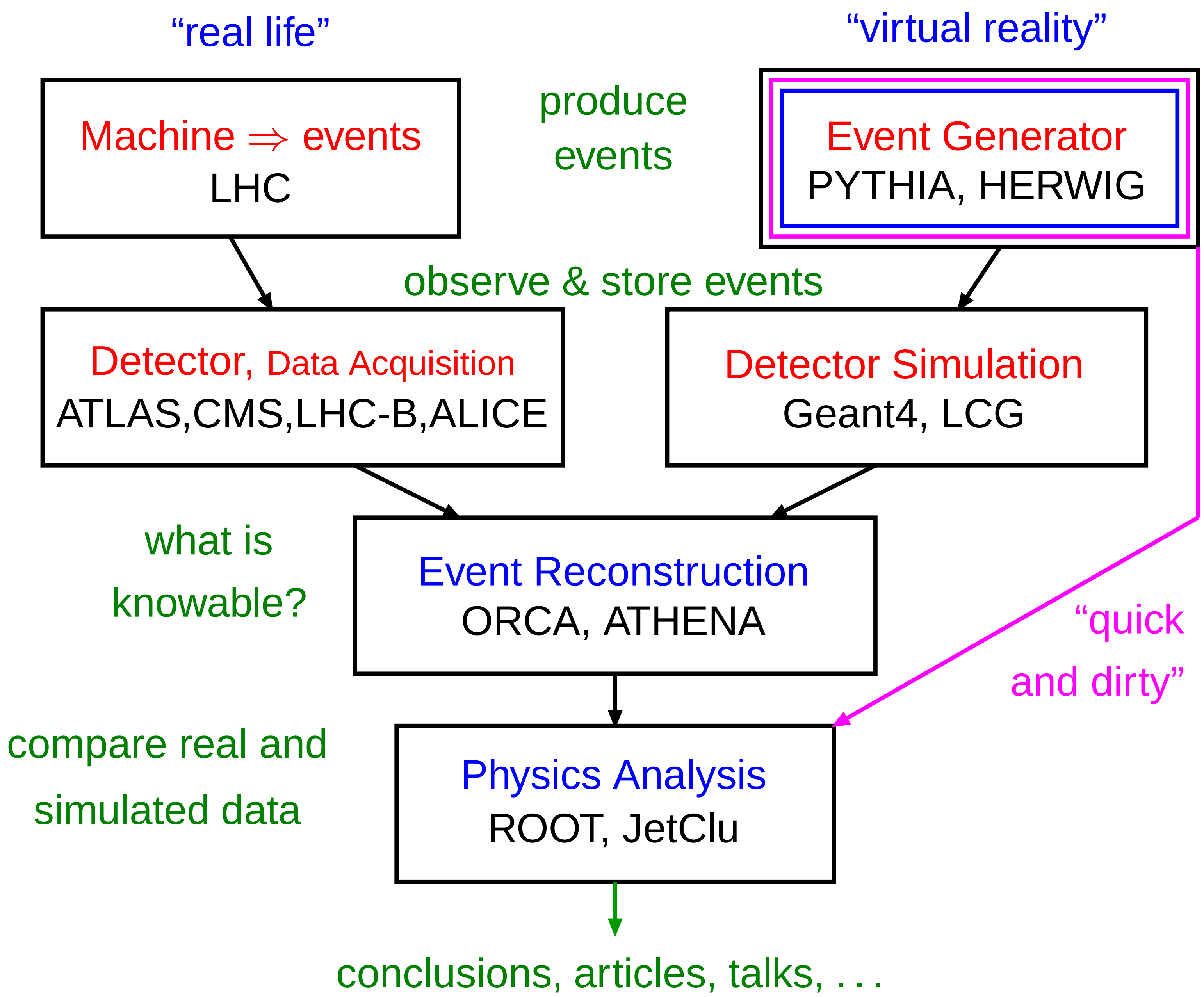
Michelangelo Mangano, KEK LHC simulations workshop, April 2004:
http://mlm.home.cern.ch/mlm/talks/kek04_mlm.pdf

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

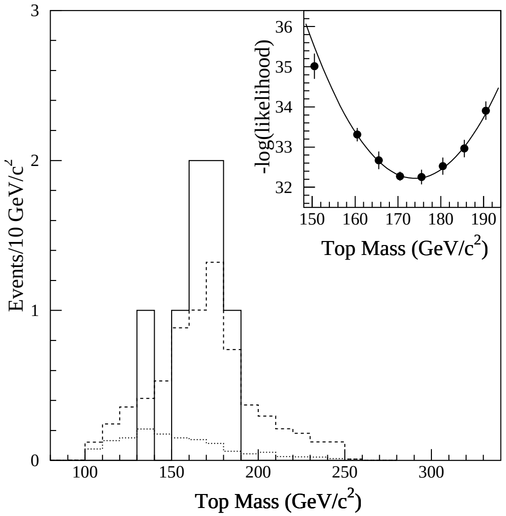
Event Generator Position

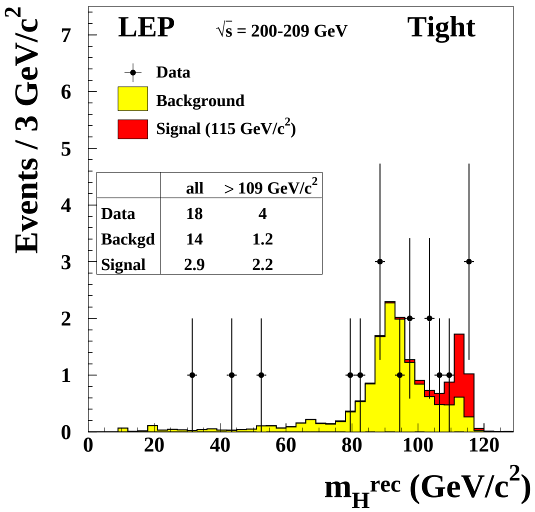


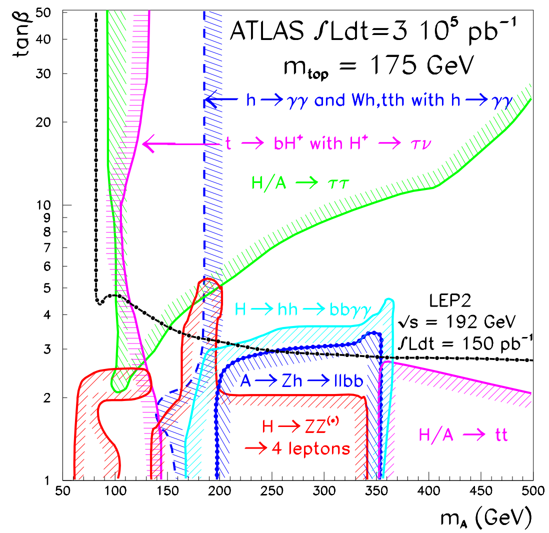
Event Generator Position



Why Generators? (I)







top discovery and mass determination

Higgs (non) discovery

Higgs and supersymmetry exploration

not feasible without generators

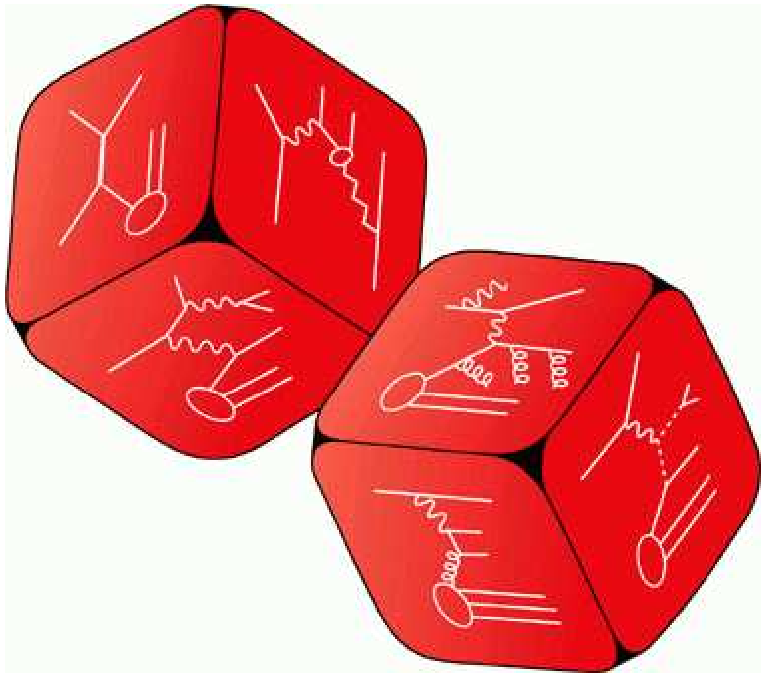
Why Generators? (II)

- 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!

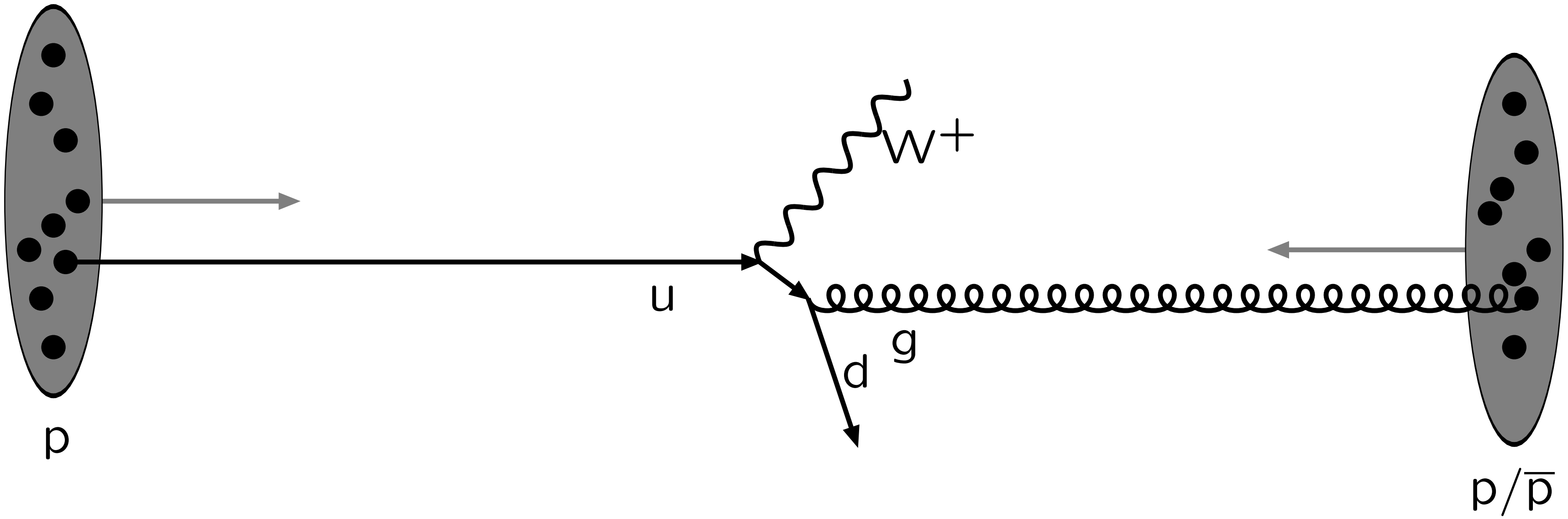
Quantum mechanics: amplitudes $\Longrightarrow$ probabilities

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

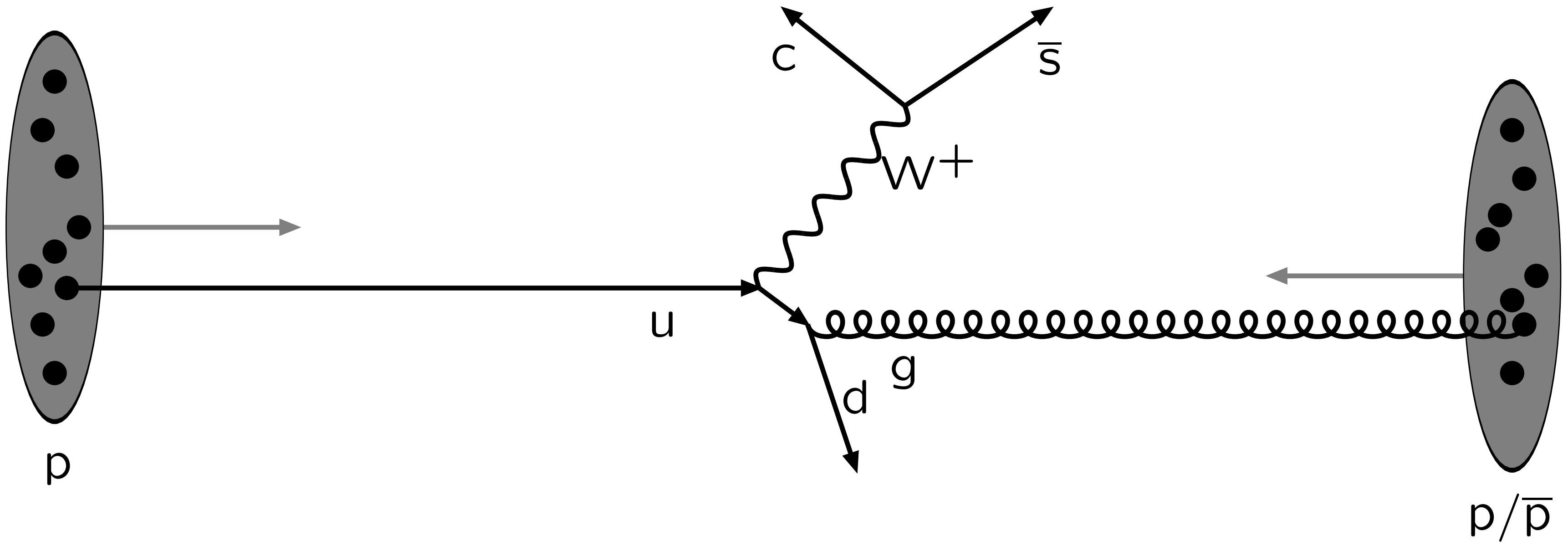
The structure of an event

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

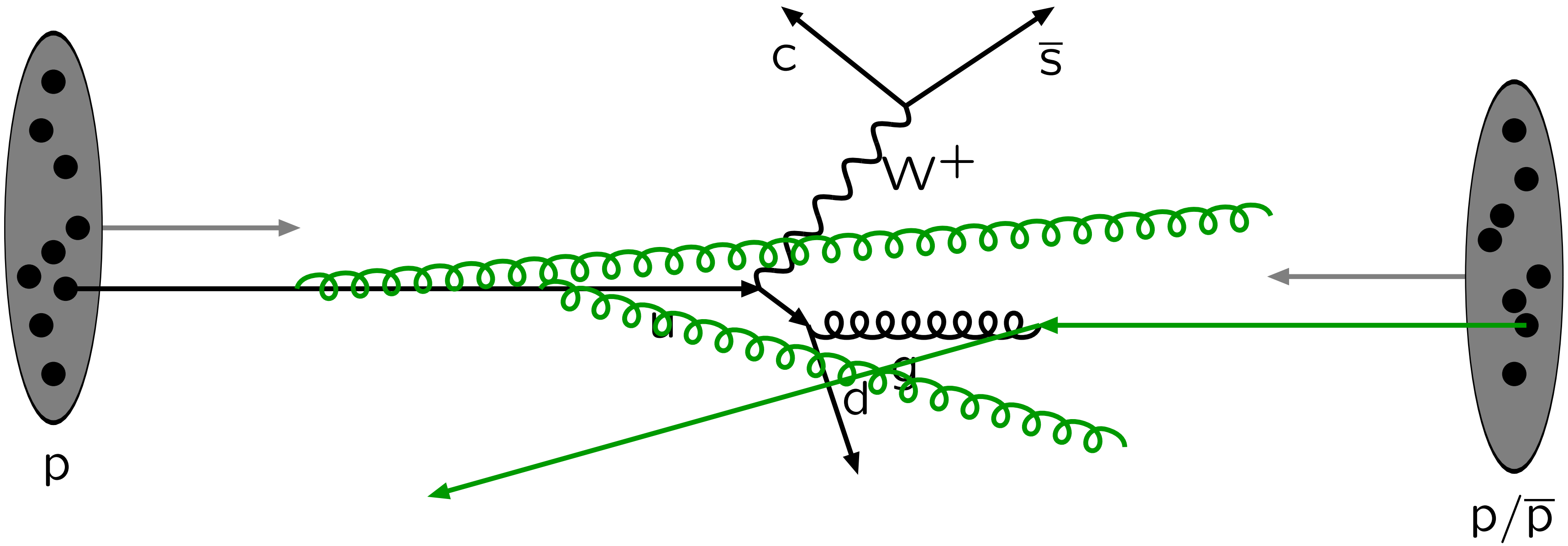
Incoming beams: parton densities



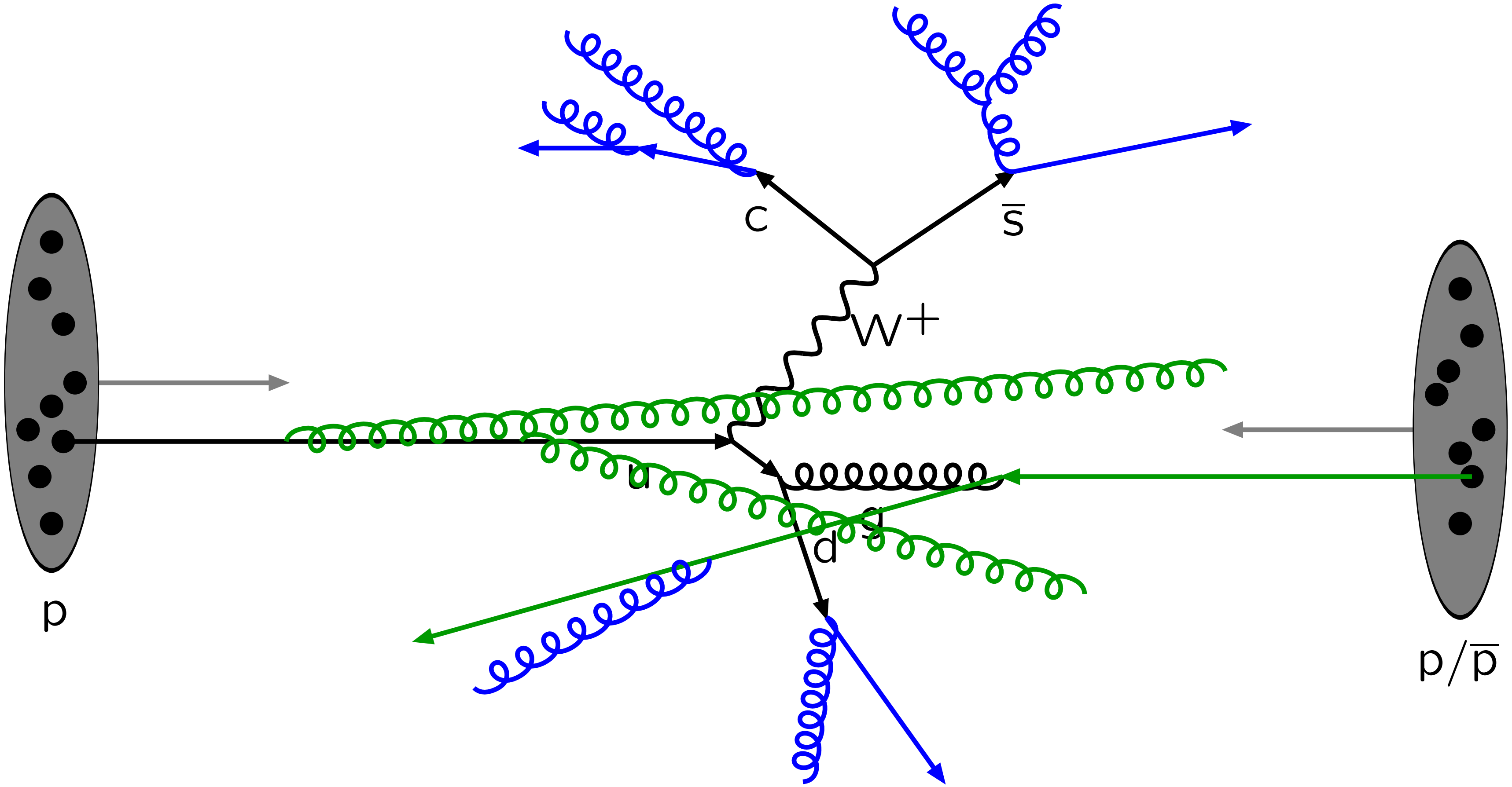
Hard subprocess: described by matrix elements



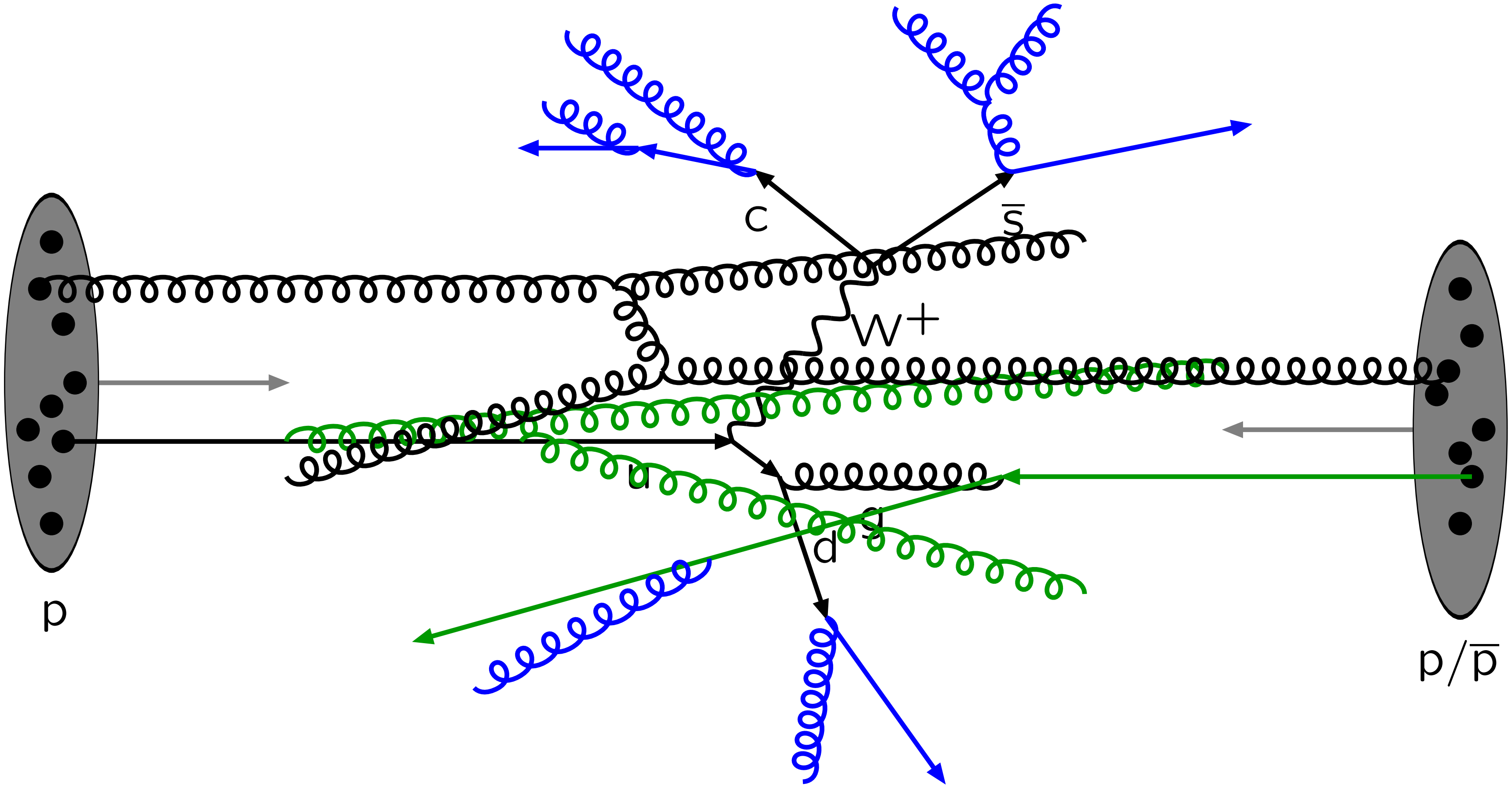
Resonance decays: correlated with hard subprocess



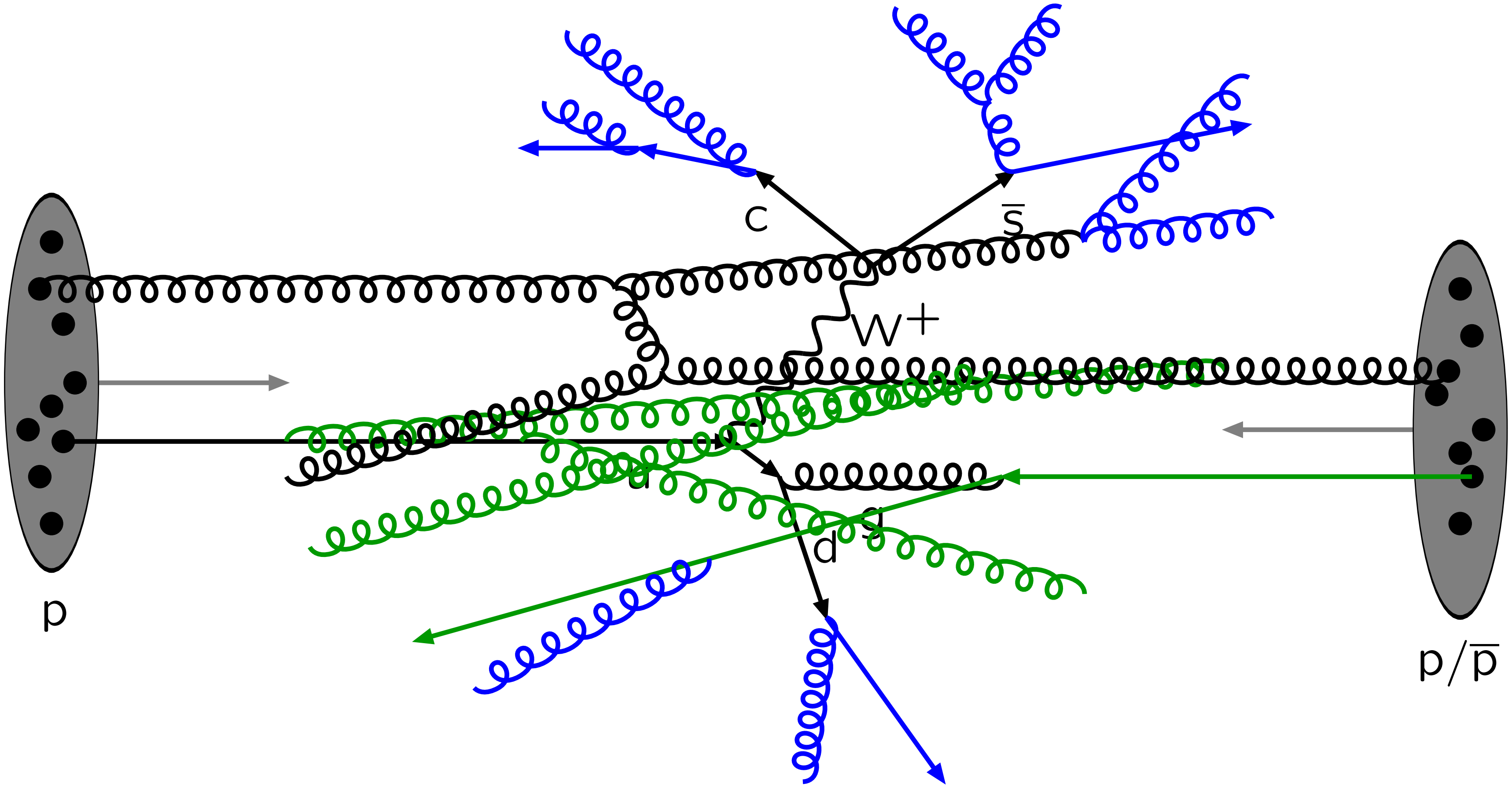
Initial-state radiation: spacelike parton showers



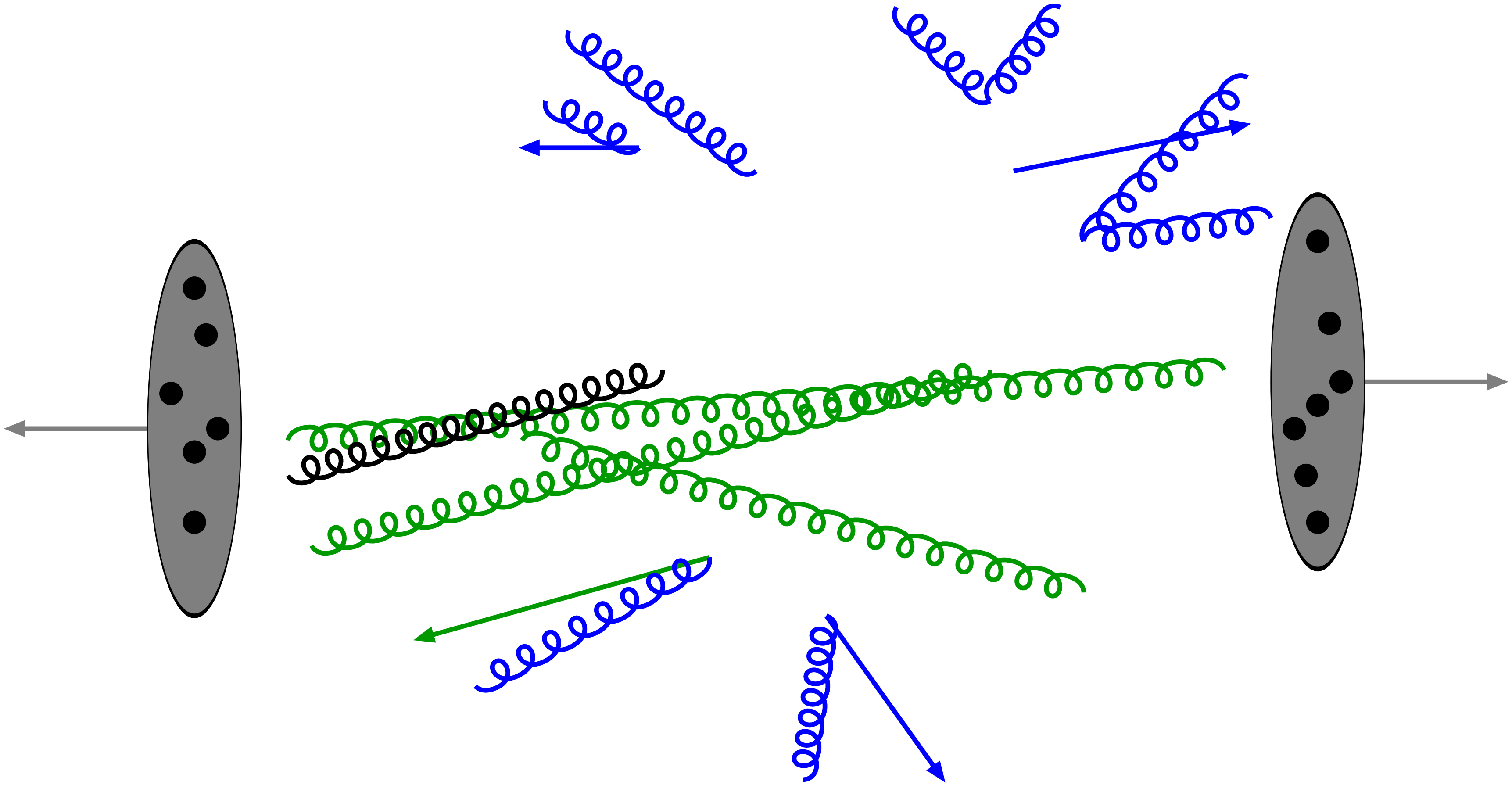
Final-state radiation: timelike parton showers



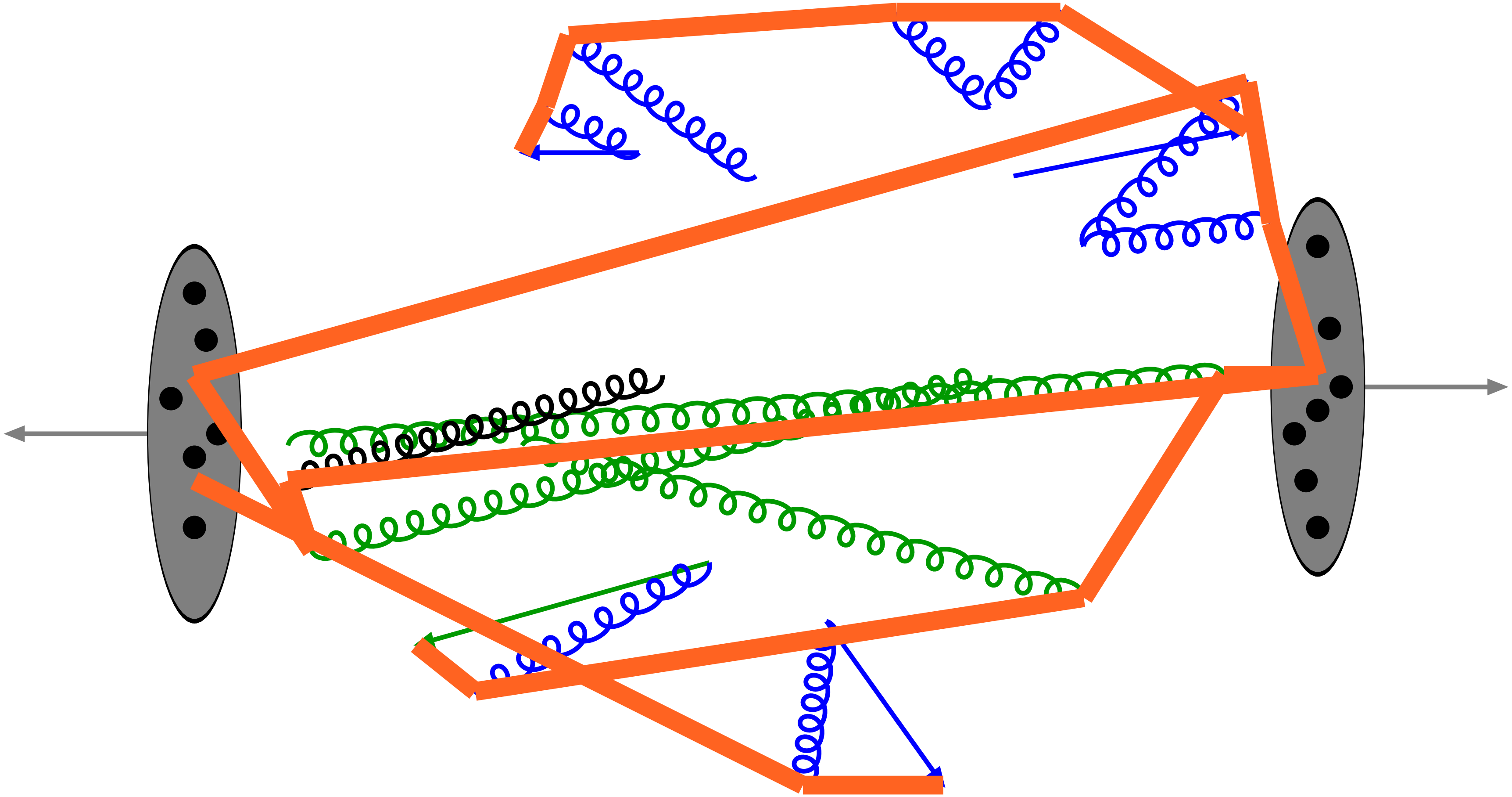
Multiple parton–parton interactions . . .



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

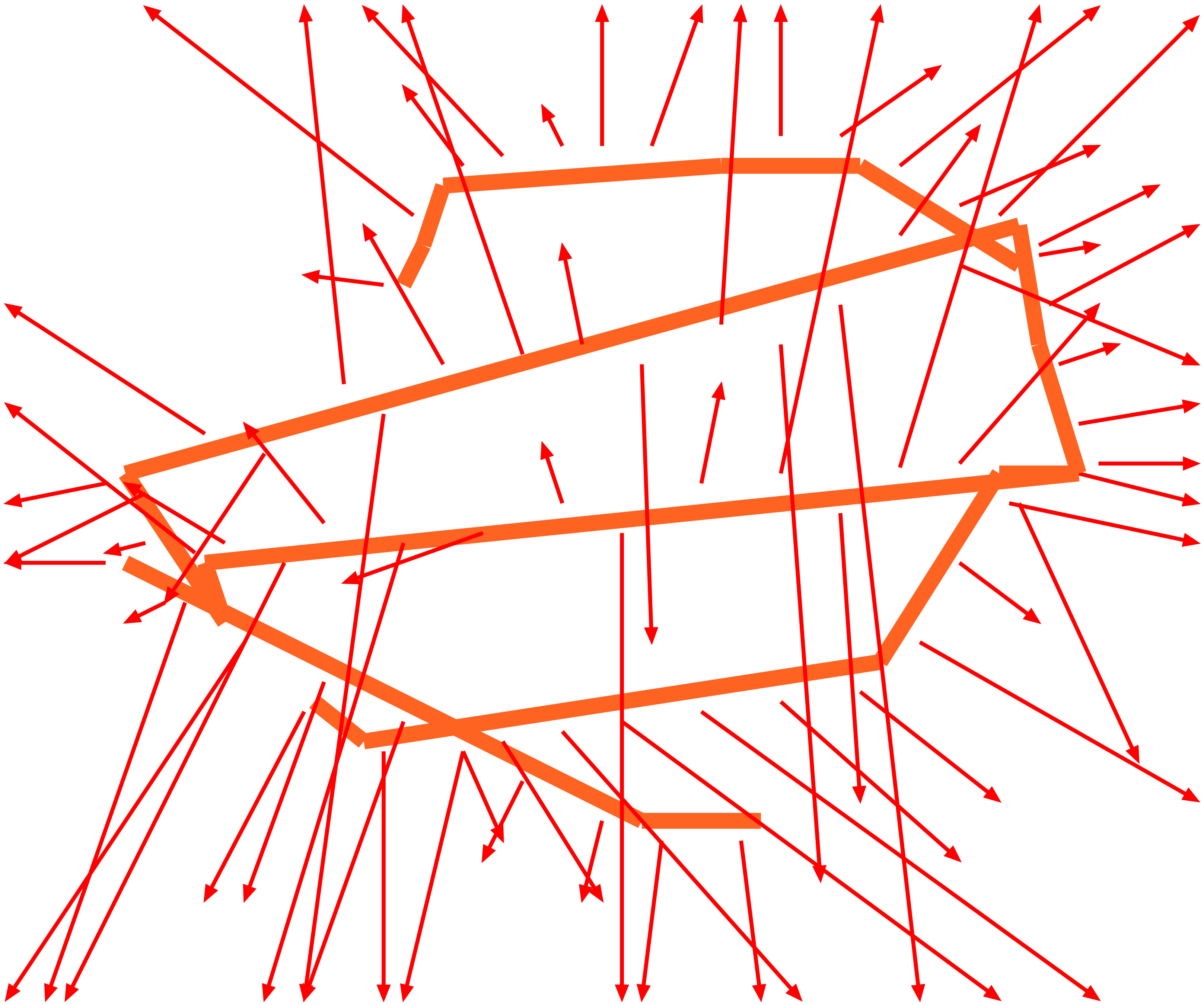


Beam remnants and other outgoing partons

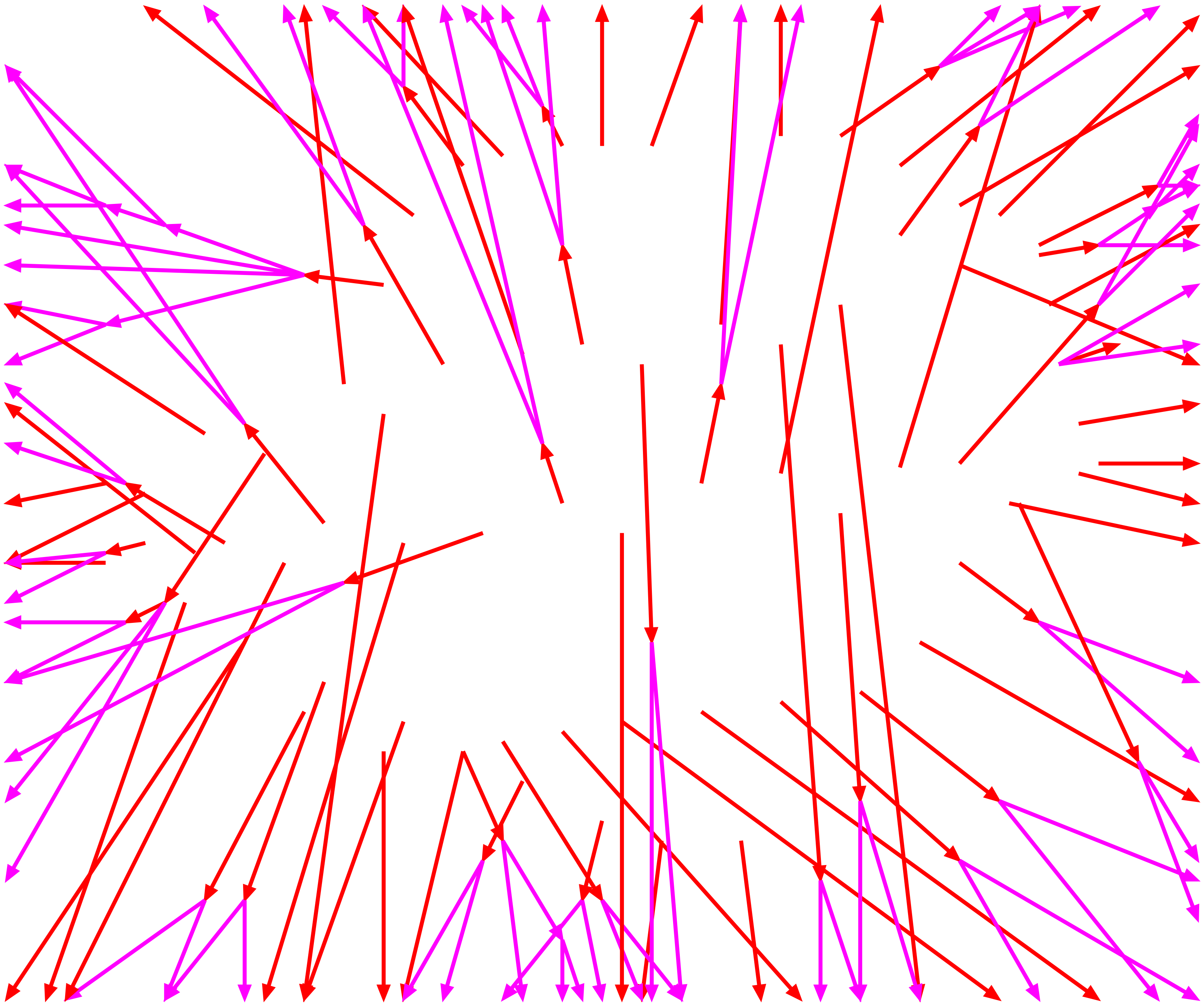


Everything is connected by colour confinement strings

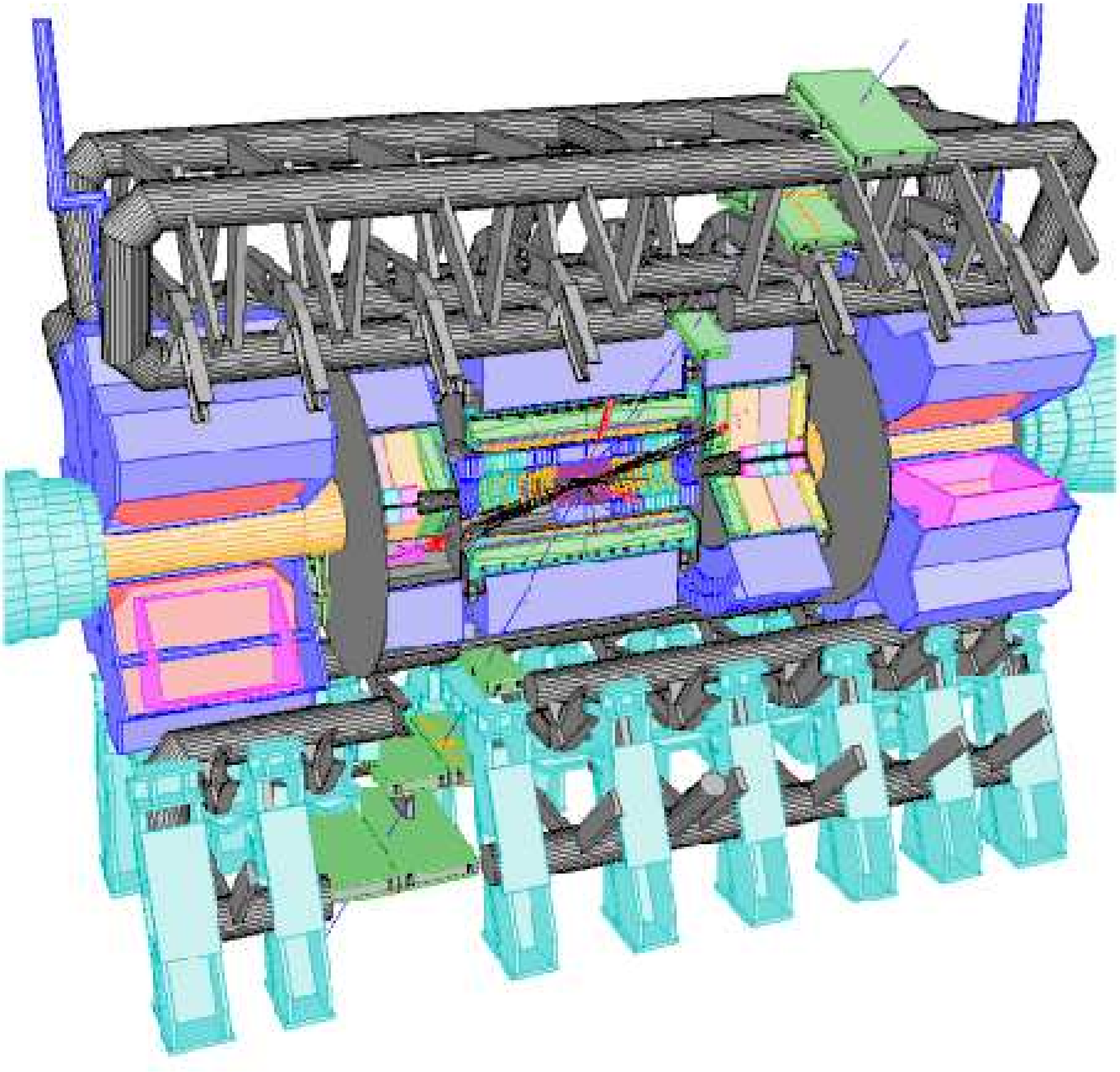
Recall! Not to scale: strings are of hadronic widths



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**

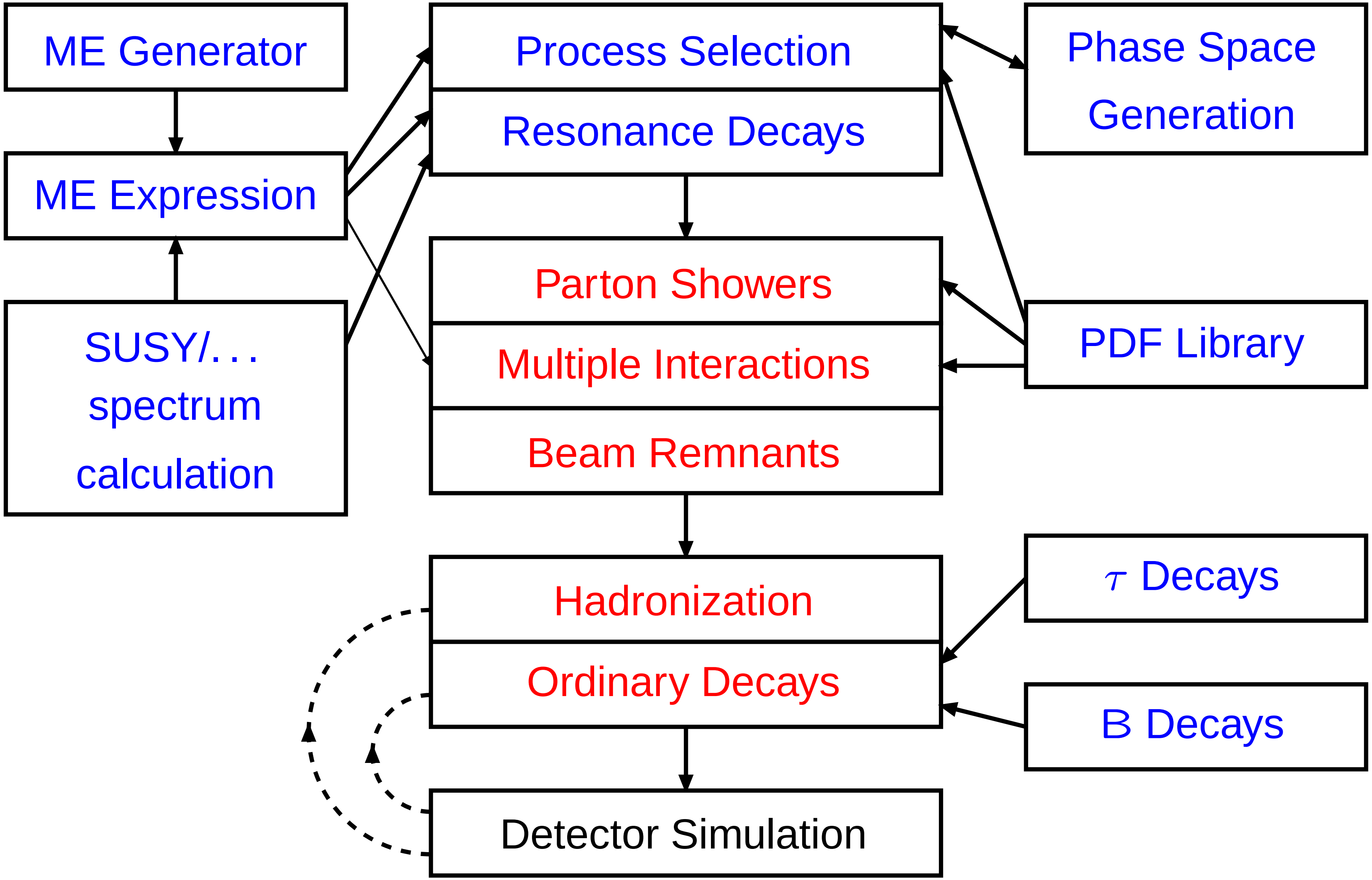
an event with n particles involves $\mathcal{O}(10n)$ random choices,
(flavour, mass, momentum, spin, production vertex, lifetime, ...)
LHC: ~ 100 charged and ~ 200 neutral ($+$ intermediate stages)
$\Longrightarrow$ several thousand choices
(of $\mathcal{O}(100)$ different kinds)

Generator Landscape

<table>
<tr><th></th><th>General-Purpose</th><th>Specialized</th></tr>
<tr><td>Hard Processes</td><td rowspan="6">HERWIG
PYTHIA
ISAJET
SHERPA</td><td>a lot</td></tr>
<tr><td>Resonance Decays</td><td>HDECAY, . . .</td></tr>
<tr><td>Parton Showers</td><td>Ariadne/LDC, NLLjet</td></tr>
<tr><td>Underlying Event</td><td>DPMJET</td></tr>
<tr><td>Hadronization</td><td>none (?)</td></tr>
<tr><td>Ordinary Decays</td><td>TAUOLA, EvtGen</td></tr>
</table>

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

The Bigger Picture



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

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^0_L	221	η^0	411	D^+	431	D_s^+
211	π^+	321	K^+	310	K^0_S	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^-

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

Generator Homepages

HERWIG

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

http://hepforge.cedar.ac.uk/herwig/

PYTHIA

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

ISAJET

http://www.phy.bnl.gov/∼isajet/

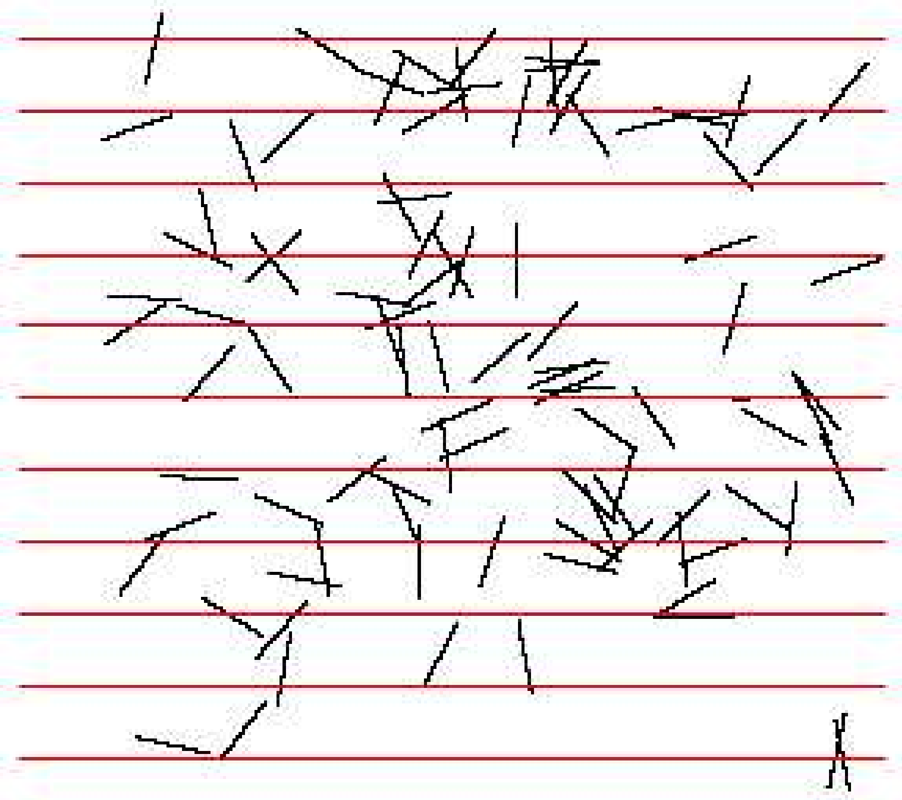
SHERPA

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

HEPCODE Program Listing

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

Monte Carlo Techniques



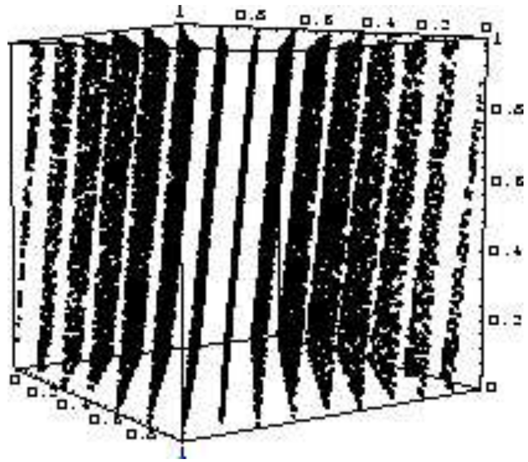
- Random Numbers
- Monte Carlo Methods
- The Veto Algorithm

Buffon's needles

Random Numbers

Monte Carlos assume access to a good random number generator R:
(*i*) inclusively R is uniformly distributed in $0 < R < 1$
(*ii*) there are no correlations between R values along sequence

Radioactive decay $\Rightarrow$ true random numbers
Computer algorithms $\Rightarrow$ pseudorandom numbers



Many (in)famous pitfalls:
- short periods
- Marsaglia effect: multiplets along hyperplanes

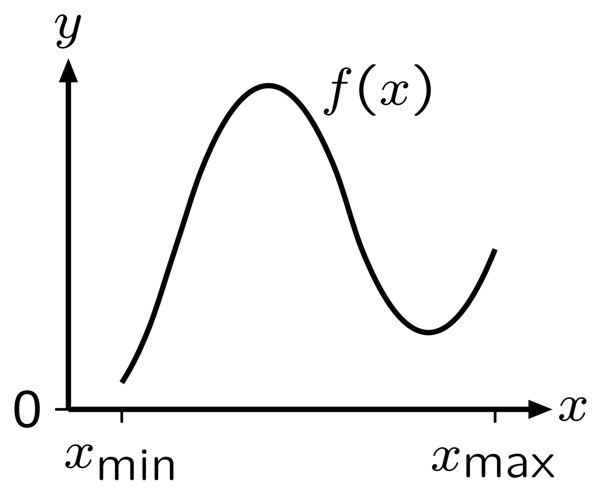
$\Rightarrow$ do not trust "standard libraries" with compiler

Recommended:

- Marsaglia–Zaman–Tsang (`RANMAR`), improved by Lüscher (`RANLUX`):
can pick $\sim 900,000,000$ different sequences, each with period $> 10^{43}$
but state is specified by 100 words (97 double precision reals, 3 integers)
- l'Ecuyer (`RANECU`):
can pick 100 different sequences, each with period $> 10^{18}$, by two seeds

Monte Carlo Methods

Assume function $f(x)$,
studied range $x_{\text{min}} < x < x_{\text{max}}$,
where $f(x) \geq 0$ everywhere
(in practice x is multidimensional)



Two standard tasks:

1) Calculate (approximatively)

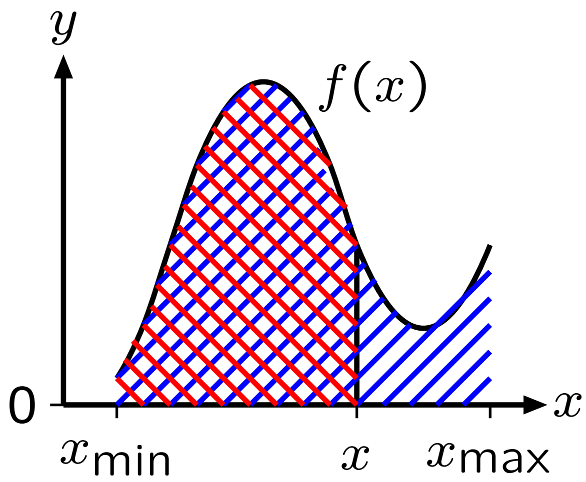
$$\int_{x_{\text{min}}}^{x_{\text{max}}} f(x')\,\mathrm{d}x'$$

usually: integrated cross section from differential one

2) Select x at random according to $f(x)$
usually: probability distribution from quantum mechanics,
normalization to unit area implicit

Often combined: for $2 \to 2$ process
- select phase-space points $x = (x_1, x_2, \hat{t})$
- *and* integrate differential cross section (parton densities, $\mathrm{d}\hat{\sigma}/\mathrm{d}\hat{t}$)

Selection of x according to $f(x)$
is equivalent to uniform selection of (x, y) in the area
$x_{\mathrm{min}} < x < x_{\mathrm{max}}$, $0 < y < f(x)$
since $\mathcal{P}(x) \propto \int_0^{f(x)} 1\,\mathrm{d}y = f(x)$



Therefore

$$\int_{x_{\mathrm{min}}}^{x} f(x')\,\mathrm{d}x' = R \int_{x_{\mathrm{min}}}^{x_{\mathrm{max}}} f(x')\,\mathrm{d}x'$$

Method 1: Analytical solution

If know primitive function $F(x)$ and know inverse $F^{-1}(y)$ then

$$F(x) - F(x_{\mathrm{min}}) = R\,(F(x_{\mathrm{max}}) - F(x_{\mathrm{min}})) = R\,A_{\mathrm{tot}}$$
$$\Longrightarrow x = F^{-1}(F(x_{\mathrm{min}}) + R\,A_{\mathrm{tot}})$$

Proof:

introduce $z = F(x_{\mathrm{min}}) + R\,A_{\mathrm{tot}}$. Then

$$\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}x} = \frac{\mathrm{d}\mathcal{P}}{\mathrm{d}R}\,\frac{\mathrm{d}R}{\mathrm{d}x} = 1\,\frac{1}{\frac{\mathrm{d}x}{\mathrm{d}R}} = \frac{1}{\frac{\mathrm{d}x}{\mathrm{d}z}\,\frac{\mathrm{d}z}{\mathrm{d}R}} = \frac{1}{\frac{\mathrm{d}F^{-1}(z)}{\mathrm{d}z}\,\frac{\mathrm{d}z}{\mathrm{d}R}} = \frac{\frac{\mathrm{d}F(x)}{\mathrm{d}x}}{\frac{\mathrm{d}z}{\mathrm{d}R}} = \frac{f(x)}{A_{\mathrm{tot}}}$$

Example 1:

$f(x) = 2x$, $0 < x < 1$, $\Longrightarrow F(x) = x^2$

$F(x) - F(0) = R\,(F(1) - F(0)) \Longrightarrow x^2 = R \Longrightarrow x = \sqrt{R}$

Example 2:

$f(x) = e^{-x}$, $x > 0$, $F(x) = 1 - e^{-x}$

$1 - e^{-x} = R \Longrightarrow e^{-x} = 1 - R = R \Longrightarrow x = -\ln R$

Method 2: Hit-and-miss

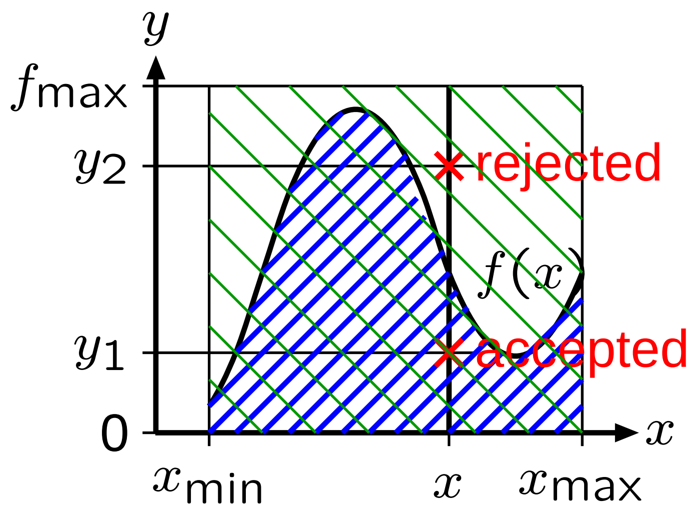
If $f(x) \leq f_{\max}$ in $x_{\min} < x < x_{\max}$

use interpretation as an area

1) select $x = x_{\min} + R\,(x_{\max} - x_{\min})$

2) select $y = R\, f_{\max}$ (new R!)

3) while $y > f(x)$ cycle to 1)



Integral as by-product:

$$I = \int_{x_{\min}}^{x_{\max}} f(x)\, \mathrm{d}x = f_{\max}\,(x_{\max} - x_{\min})\,\frac{N_{\mathrm{acc}}}{N_{\mathrm{try}}} = A_{\mathrm{tot}}\,\frac{N_{\mathrm{acc}}}{N_{\mathrm{try}}}$$

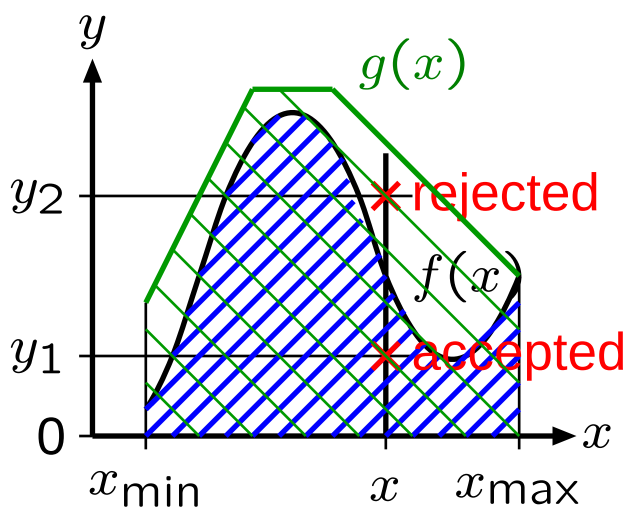
Binomial distribution with $p = N_{\mathrm{acc}}/N_{\mathrm{try}}$ and $q = N_{\mathrm{fail}}/N_{\mathrm{try}}$, so error

$$\frac{\delta I}{I} = \frac{A_{\mathrm{tot}}\sqrt{p\,q/N_{\mathrm{try}}}}{A_{\mathrm{tot}}\,p} = \sqrt{\frac{q}{p\,N_{\mathrm{try}}}} = \sqrt{\frac{q}{N_{\mathrm{acc}}}} \longrightarrow \frac{1}{\sqrt{N_{\mathrm{acc}}}} \quad \text{for } p \ll 1$$

Method 3: Improved hit-and-miss (importance sampling)

If $f(x) \leq g(x)$ in $x_{\text{min}} < x < x_{\text{max}}$
and $G(x) = \int g(x')\,\mathrm{d}x'$ is simple
and $G^{-1}(y)$ is simple

1) select x according to $g(x)$ distribution
2) select $y = R\,g(x)$ (new R!)
3) while $y > f(x)$ cycle to 1)



Example 3:

$f(x) = x\,e^{-x}$, $x > 0$

Attempt 1: $F(x) = 1 - (1 + x)\,e^{-x}$ not invertible

Attempt 2: $f(x) \leq f(1) = e^{-1}$ but $0 < x < \infty$

Attempt 3: $g(x) = N\,e^{-x/2}$

$$\frac{f(x)}{g(x)} = \frac{x\,e^{-x}}{N\,e^{-x/2}} = \frac{x\,e^{-x/2}}{N} \leq 1$$

for rejection to work, so find maximum:

$$\frac{\mathrm{d}}{\mathrm{d}x}\left(\frac{f(x)}{g(x)}\right) = \frac{1}{N}\left(1 - \frac{x}{2}\right)e^{-x/2} = 0 \Longrightarrow x = 2$$

Normalize so $g(2) = f(2) \Longrightarrow N = 2/e$

$G(x) \propto 1 - e^{-x/2} = R$

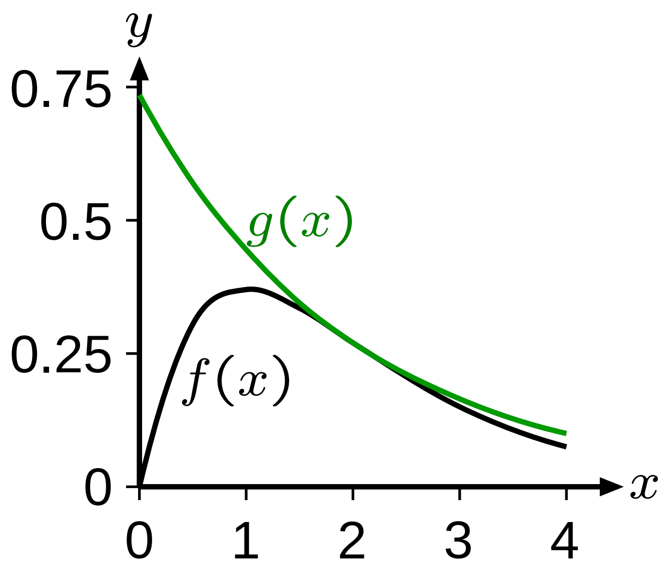
$\Longrightarrow x = -2 \ln R$ so

1) select $x = -2 \ln R$

2) select $y = R\, g(x) = R\, 2e^{-(1+x/2)}$

3) while $y > f(x) = x\, e^{-x}$ cycle to 1)

$$\text{efficiency} = \frac{\int_0^\infty f(x)\,\mathrm{d}x}{\int_0^\infty g(x)\,\mathrm{d}x} = \frac{e}{4}$$

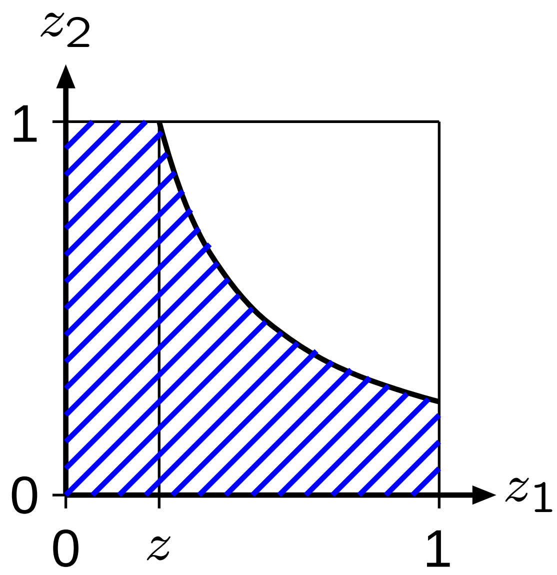


Attempt 4: pull the rabbit . . .

$x = -\ln(R_1\, R_2)$

since with $z = z_1\, z_2 = R_1\, R_2$

$$F(z) = \int_0^z f(z')\,\mathrm{d}z'$$
$$= \int_0^z 1\,\mathrm{d}z_1 + \int_z^1 \frac{z}{z_1}\,\mathrm{d}z_1$$
$$= z - z \ln z$$



and using that $x = -\ln z \Longleftrightarrow z = e^{-x}$

$$F(x) = 1 - F(z = e^{-x}) = 1 - e^{-x} + e^{-x}\,(-x) \Longrightarrow f(x) = x\, e^{-x}$$

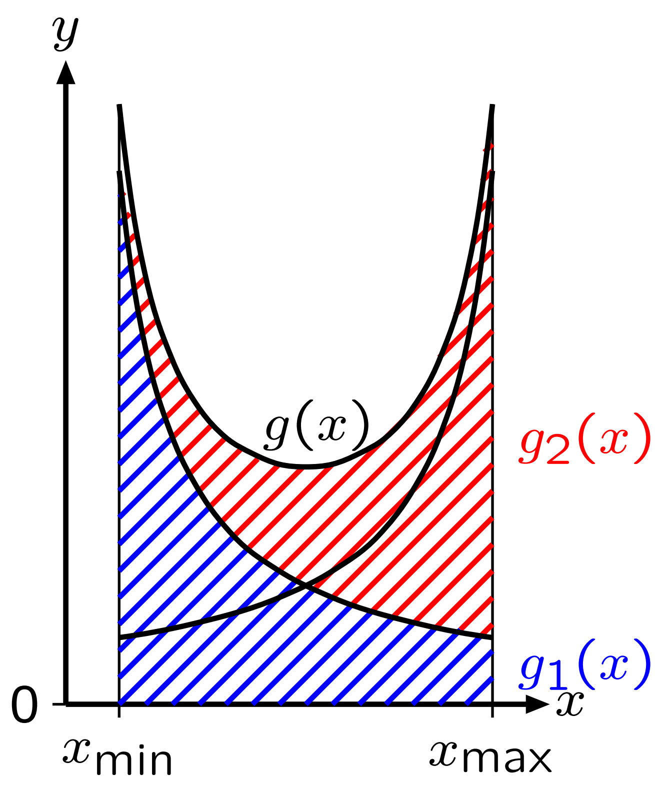
Method 4: Multichannel

If $f(x) \leq g(x) = \sum_i g_i(x)$,
where all g_i "nice" (but $g(x)$ not)

1) select i with relative probability

$$A_i = \int_{x_{\mathrm{min}}}^{x_{\mathrm{max}}} g_i(x')\,\mathrm{d}x'$$

2) select x according to $g_i(x)$
3) select $y = R\,g(x) = R\,\sum_i g_i(x)$
4) while $y > f(x)$ cycle to 1)



Example 4:

$$f(x) = \frac{1}{\sqrt{x(1-x)}}\,, \quad 0 < x < 1$$

$$g(x) = \frac{1}{\sqrt{x}} + \frac{1}{\sqrt{1-x}} = \frac{\sqrt{x}+\sqrt{1-x}}{\sqrt{x(1-x)}}\,, \quad \frac{1}{\sqrt{2}} \leq \frac{f(x)}{g(x)} \leq 1$$

1) if $R < 1/2$ then $g_1(x)$ else $g_2(x)$
2) g_1: $G_1(x) = 2\sqrt{x} = 2R \Longrightarrow x = R^2$
g_2: $G_2(x) = 2(1-\sqrt{1-x}) = 2R \Longrightarrow x = 1 - R^2$

Method 5: Variable transformations

- map to finite x range
- map away singular/peaked regions

Method 6: Special tricks

e.g. $f(x) \propto e^{-x^2}$ is not integrable, but

$$\begin{aligned} f(x)\,\mathrm{d}x\,f(y)\,\mathrm{d}y &\propto e^{-(x^2+y^2)}\,\mathrm{d}x\,\mathrm{d}y \\ &= e^{-r^2}\,r\mathrm{d}r\,\mathrm{d}\phi \propto e^{-r^2}\,\mathrm{d}r^2\,\mathrm{d}\phi \\ F(r^2) = 1 - e^{-r^2} &\Longrightarrow r^2 = -\ln R_1 \\ x &= \sqrt{-\ln R_1}\,\cos(2\pi\,R_2) \\ y &= \sqrt{-\ln R_1}\,\sin(2\pi\,R_2) \end{aligned}$$

Comment:

In practice almost always multidimensional integrals

$$\int_V f(\mathbf{x})\,\mathrm{d}\mathbf{x} = V\,\frac{1}{N_{\mathrm{try}}}\sum_i f(\mathbf{x}_i) \quad \text{or} \quad = \int_V g(\mathbf{x})\,\mathrm{d}\mathbf{x}\,\frac{N_{\mathrm{acc}}}{N_{\mathrm{try}}}$$

gives error $\propto 1/\sqrt{N}$ irrespective of dimension
whereas trapezium rule error $\propto 1/N^2 \to 1/N^{2/d}$ in d dimensions,
and Simpson's rule error $\propto 1/N^4 \to 1/N^{4/d}$ in d dimensions

The Veto Algorithm

Consider "radioactive decay":
$N(t)$ = number of remaining nuclei at time t
but normalized to $N(0) = 1$ instead, so equivalently
$N(t)$ = probability that nuclei has not decayed by time t
$P(t) = -\mathrm{d}N(t)/\mathrm{d}t$ = probability for decay at time t

Normally $P(t) = cN(t)$, with c constant, but assume time-dependence:

$$P(t) = -\frac{\mathrm{d}N(t)}{\mathrm{d}t} = f(t)N(t) \; ; \quad f(t) \geq 0$$

Standard solution:

$$\frac{\mathrm{d}N(t)}{\mathrm{d}t} = -f(t)N(t) \iff \frac{\mathrm{d}N}{N} = \mathrm{d}(\ln N) = -f(t)\,\mathrm{d}t$$

$$\ln N(t) - \ln N(0) = -\int_0^t f(t')\,\mathrm{d}t' \implies N(t) = \exp\left(-\int_0^t f(t')\,\mathrm{d}t'\right)$$

$$F(t) = \int^t f(t')\,\mathrm{d}t' \implies N(t) = \exp\left(-(F(t) - F(0))\right)$$

$$N(t) = R \implies t = F^{-1}(F(0) - \ln R)$$

What now if $f(t)$ has no simple $F(t)$ or F^{-1}?

Hit-and-miss not good enough, since for $f(t) \leq g(t)$, g “nice”,

$$t = G^{-1}(G(0) - \ln R) \implies N(t) = \exp\left(-\int_0^t g(t')\,\mathrm{d}t'\right)$$

$$P(t) = -\frac{\mathrm{d}N(t)}{\mathrm{d}t} = g(t)\,\exp\left(-\int_0^t g(t')\,\mathrm{d}t'\right)$$

and hit-or-miss provides rejection factor $f(t)/g(t)$, so that

$$P(t) = f(t)\,\exp\left(-\int_0^t g(t')\,\mathrm{d}t'\right)$$

where it ought to have been

$$P(t) = f(t)\,\exp\left(-\int_0^t f(t')\,\mathrm{d}t'\right)$$

Correct answer is:

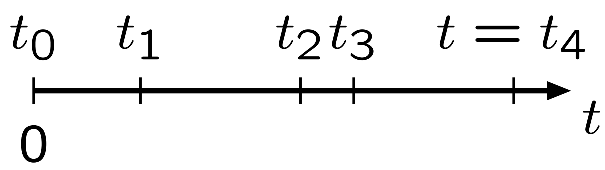
0) start with $i = 0$ and $t_0 = 0$

1) $++i$ (i.e. increase i by one)

2) $t_i = G^{-1}(G(t_{i-1}) - \ln R)$, i.e $t_i > t_{i-1}$

3) $y = R\,g(t)$

4) while $y > f(t)$ cycle to 1)



Proof:

define $S_g(t_a, t_b) = \exp\left(-\int_{t_a}^{t_b} g(t')\,\mathrm{d}t'\right)$

$$
\begin{aligned}
P_0(t) &= P(t = t_1) = g(t)\, S_g(0,t)\, \frac{f(t)}{g(t)} = f(t)\, S_g(0,t) \\
P_1(t) &= P(t = t_2) = \int_0^t \mathrm{d}t_1\, g(t_1) S_g(0,t_1) \left(1 - \frac{f(t_1)}{g(t_1)}\right) g(t)\, S_g(t_1,t)\, \frac{f(t)}{g(t)} \\
&= f(t)\, S_g(0,t) \int_0^t \mathrm{d}t_1\, (g(t_1) - f(t_1)) = P_0(t)\, I_{g-f} \\
P_2(t) &= \cdots = P_0(t) \int_0^t \mathrm{d}t_1\, (g(t_1) - f(t_1)) \int_{t_2}^t \mathrm{d}t_2\, (g(t_2) - f(t_2)) \\
&= P_0(t) \int_0^t \mathrm{d}t_1\, (g(t_1) - f(t_1)) \int_0^t \mathrm{d}t_2\, (g(t_2) - f(t_2))\, \theta(t_2 - t_1) \\
&= P_0(t)\, \frac{1}{2} \left(\int_0^t \mathrm{d}t_1\, (g(t_1) - f(t_1))\right)^2 = P_0(t)\, \frac{1}{2}\, I_{g-f}^2 \\
P(t) &= \sum_{i=0}^{\infty} P_i(t) = P_0(t) \sum_{i=0}^{\infty} \frac{I_{g-f}^i}{i!} = P_0(t) \exp(I_{g-f}) \\
&= f(t)\, \exp\left(-\int_0^t g(t')\,\mathrm{d}t'\right) \exp\left(\int_0^t \mathrm{d}t_1\, (g(t_1) - f(t_1))\right) \\
&= f(t)\, \exp\left(-\int_0^t f(t')\,\mathrm{d}t'\right)
\end{aligned}
$$

Summary Lecture 1

• Event generators indispensable •

• Quantum Mechanics $\Longrightarrow$ probabilities •

$\star$ Divide and conquer $\star$

• Main physics components: •

$\star$ Hard processes and resonance decays $\star$

$\star$ Initial- and final-state radiation $\star$

$\star$ Multiple parton–parton interactions and beam remnants $\star$

$\star$ Hadronization and decays $\star$

• Monte Carlo Techniques: •

$\star$ Use good random number generator $\star$

$\star$ Monte Carlo = selection *and* integration $\star$

$\star$ Adapt Monte Carlo approach to problem at hand $\star$

$\star$ Multichannel and Veto algorithms common $\star$