LUND UNIVERSITY

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Event Generators: Trends and Needs

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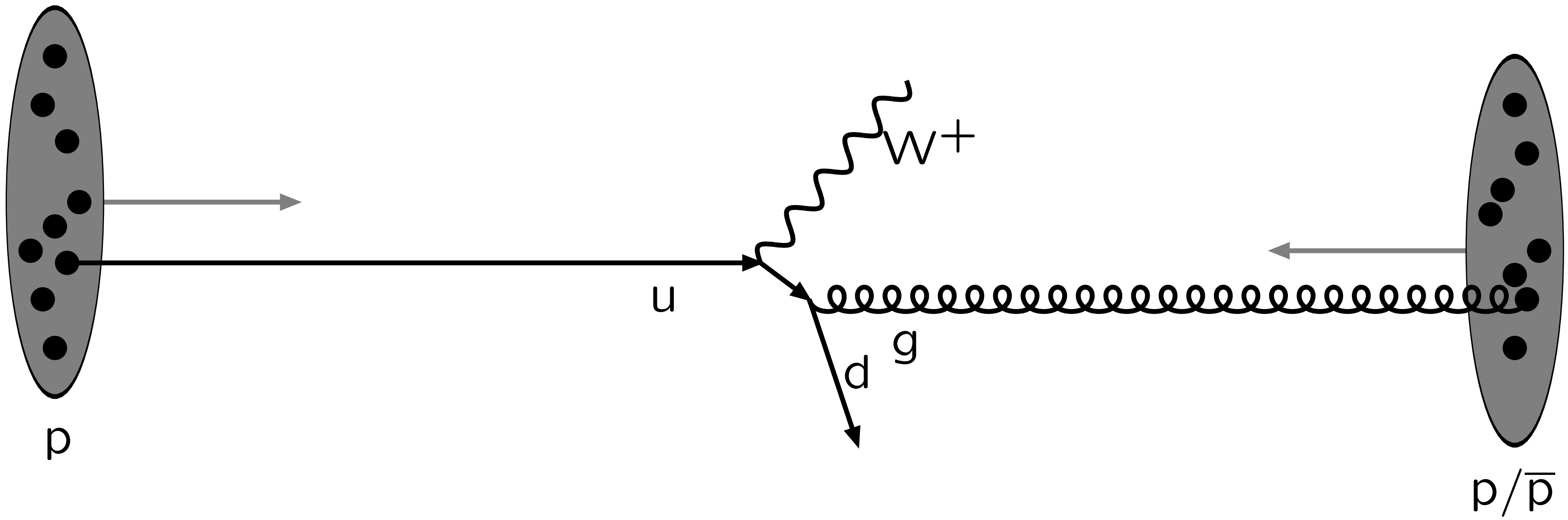
Generator Physics Introduction
Generator Overview, Standards and C++ Transition
Hadronization and Multiple Interactions
Parton Showers and Matrix Elements
Summary

. . . and then second MC talk by Peter Richardson on Wednesday

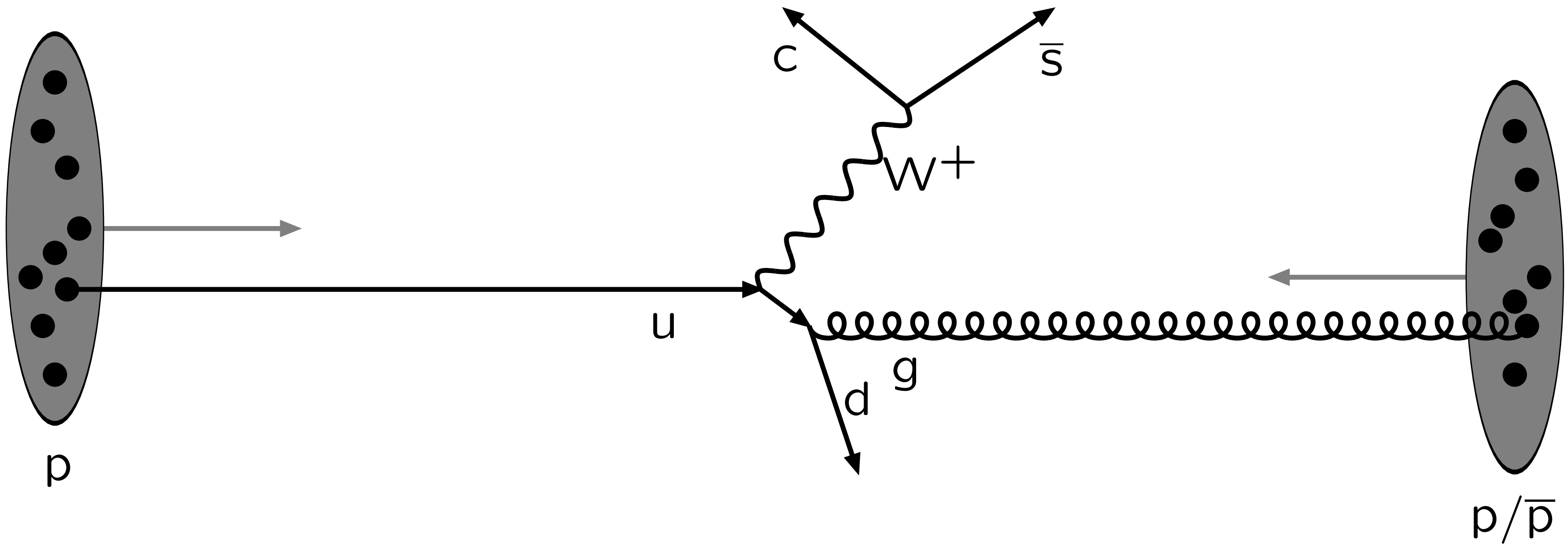
The structure of an event

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

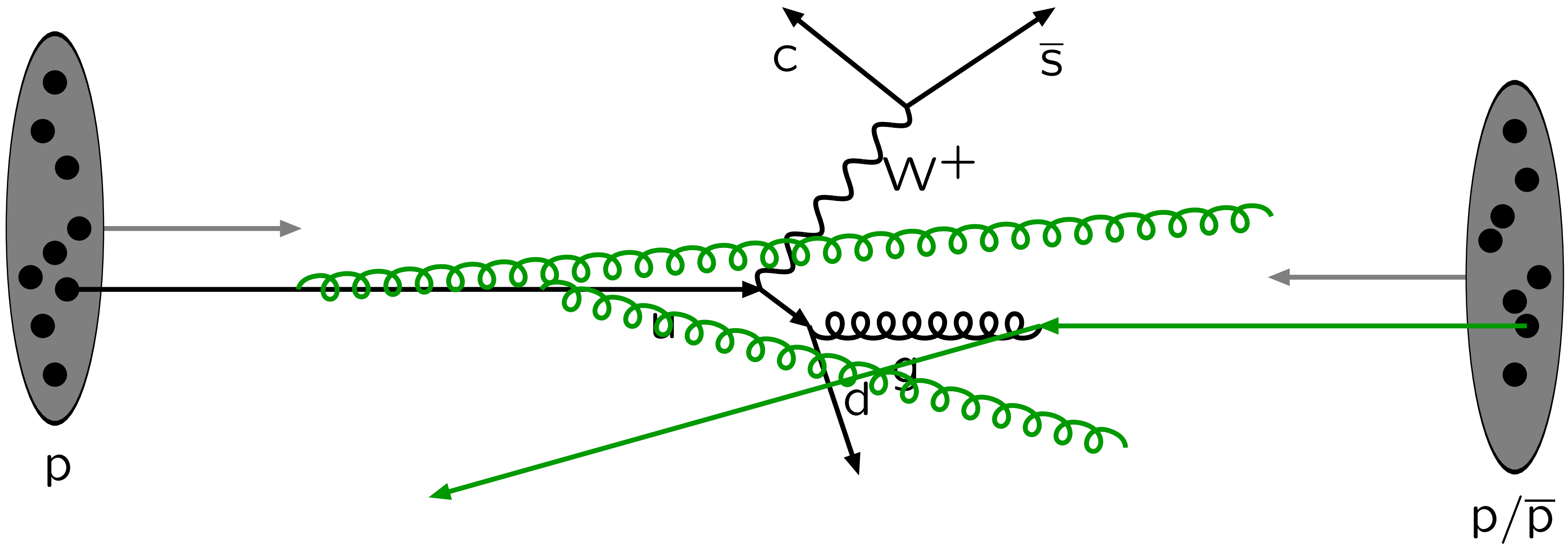
Incoming beams: parton densities



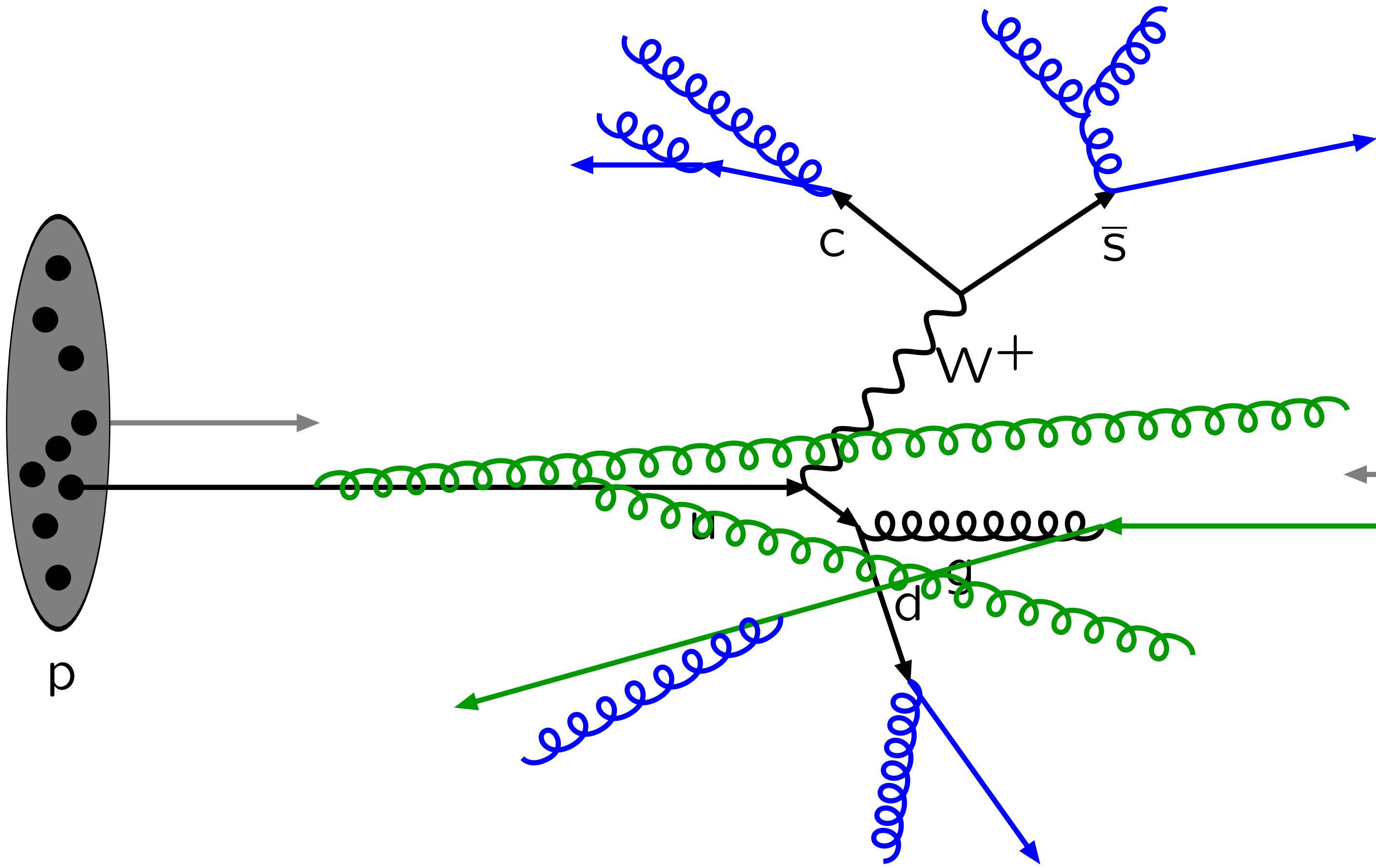
Hard subprocess: described by matrix elements



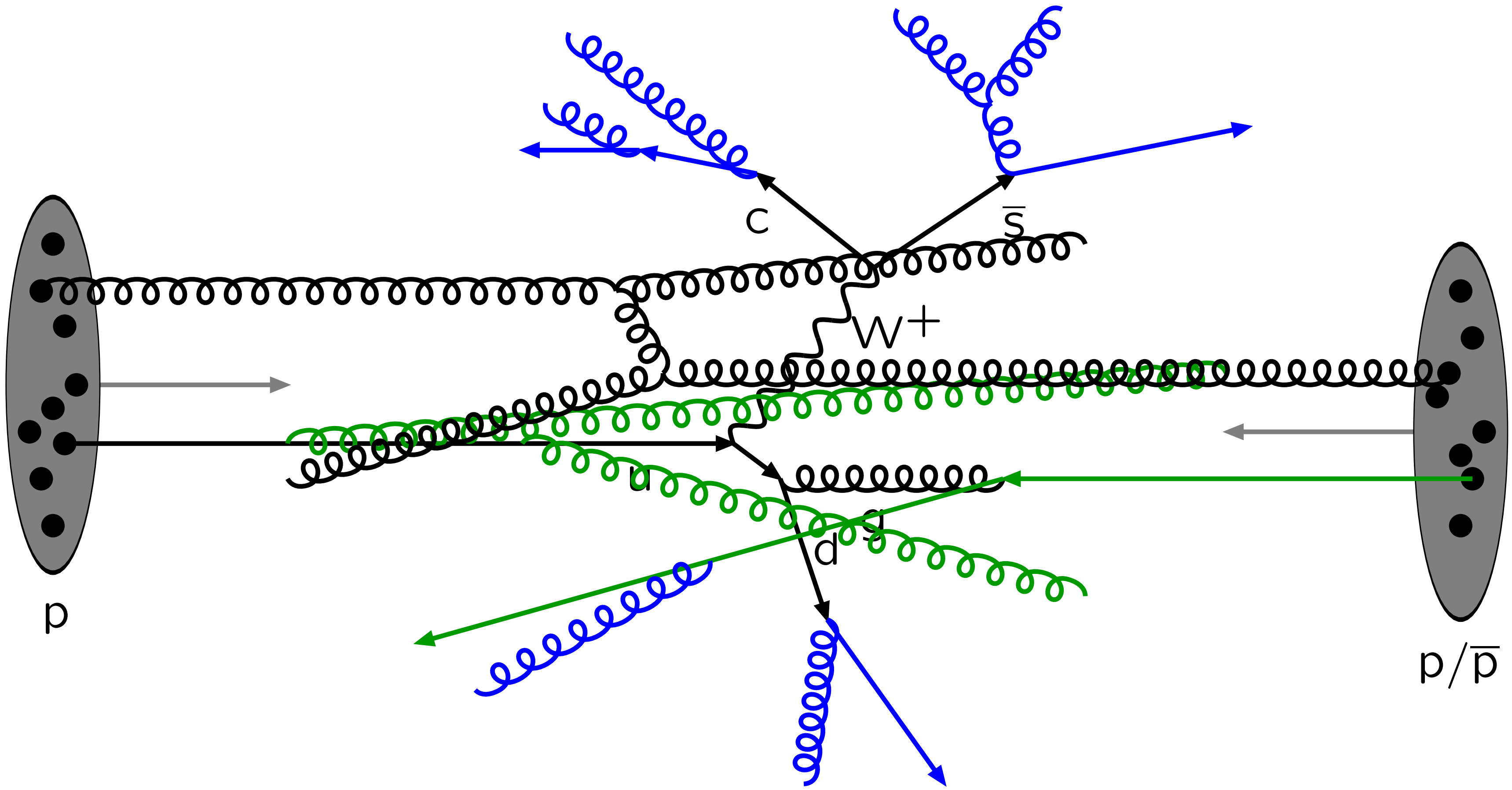
Resonance decays: correlated with hard subprocess



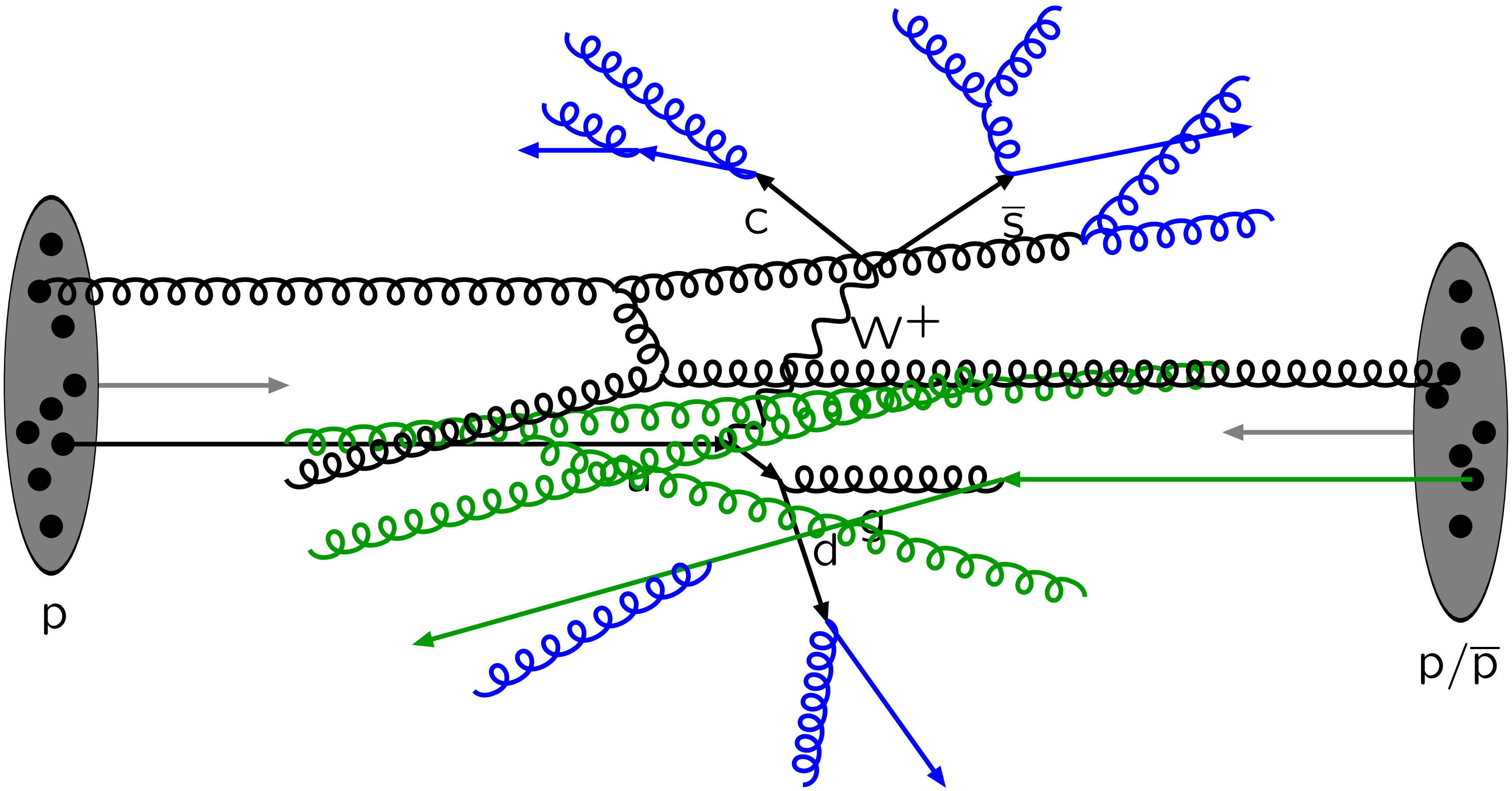
Initial-state radiation: spacelike parton showers



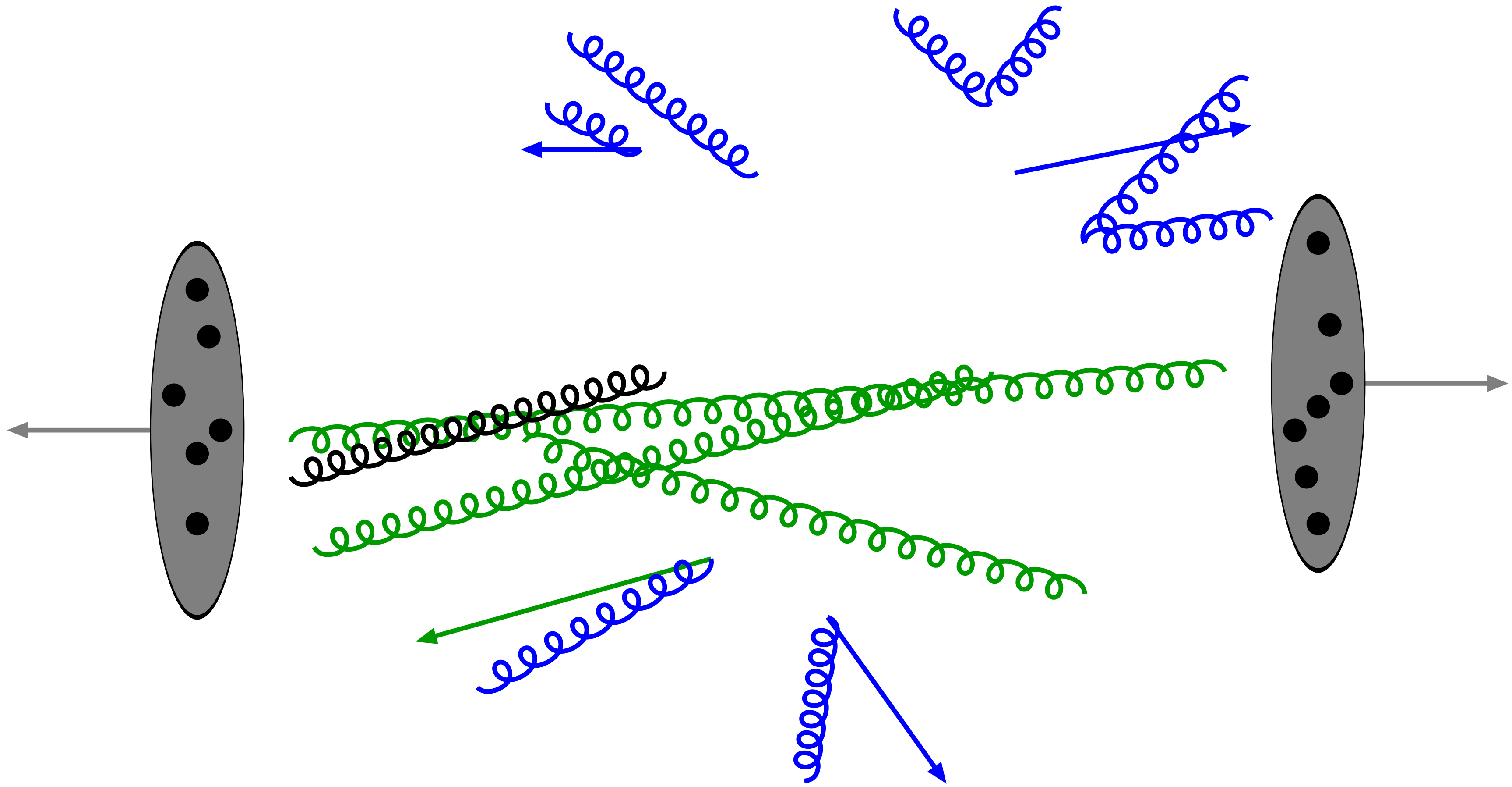
Final-state radiation: timelike parton showers



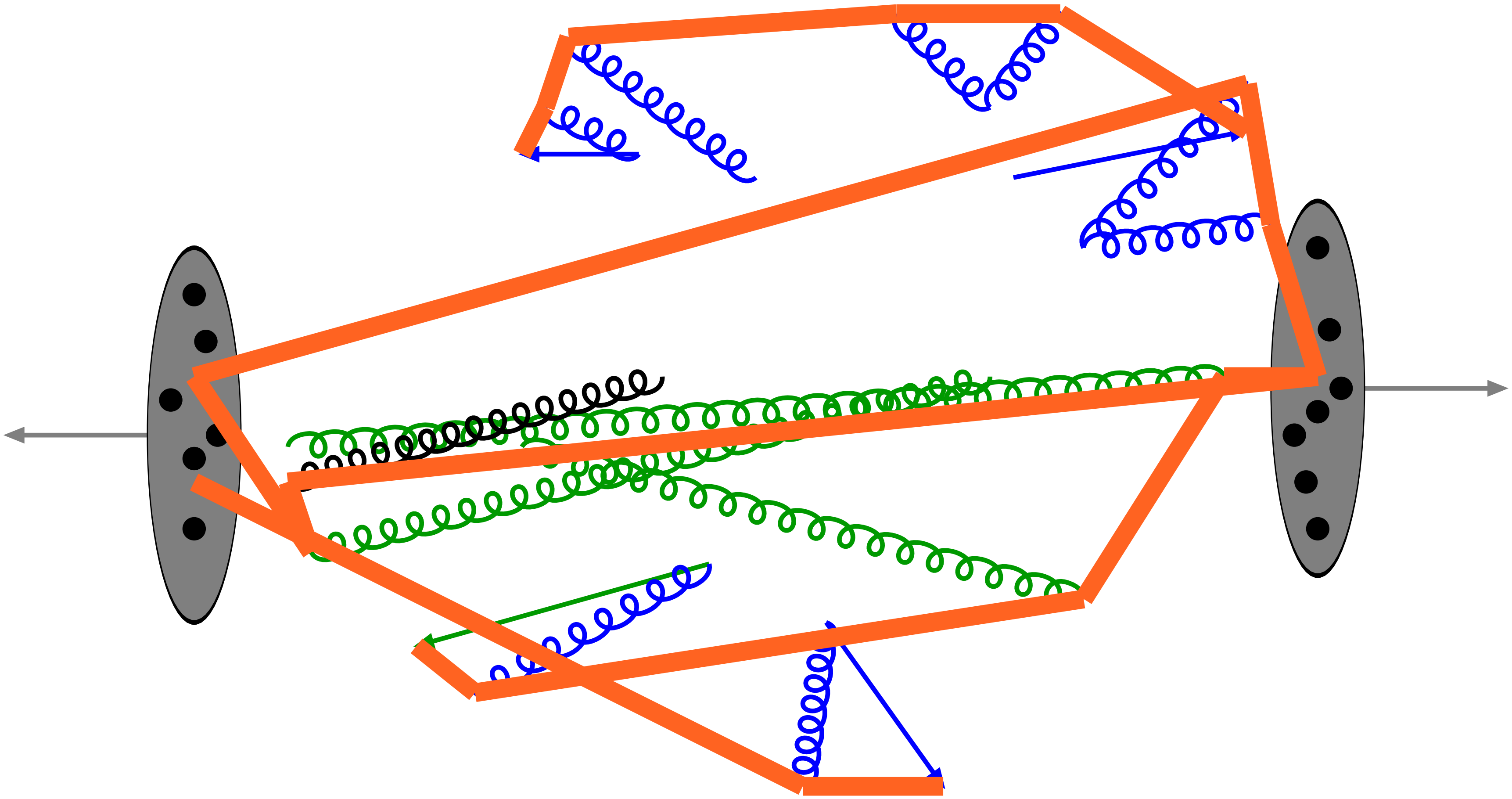
Multiple parton–parton interactions . . .



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

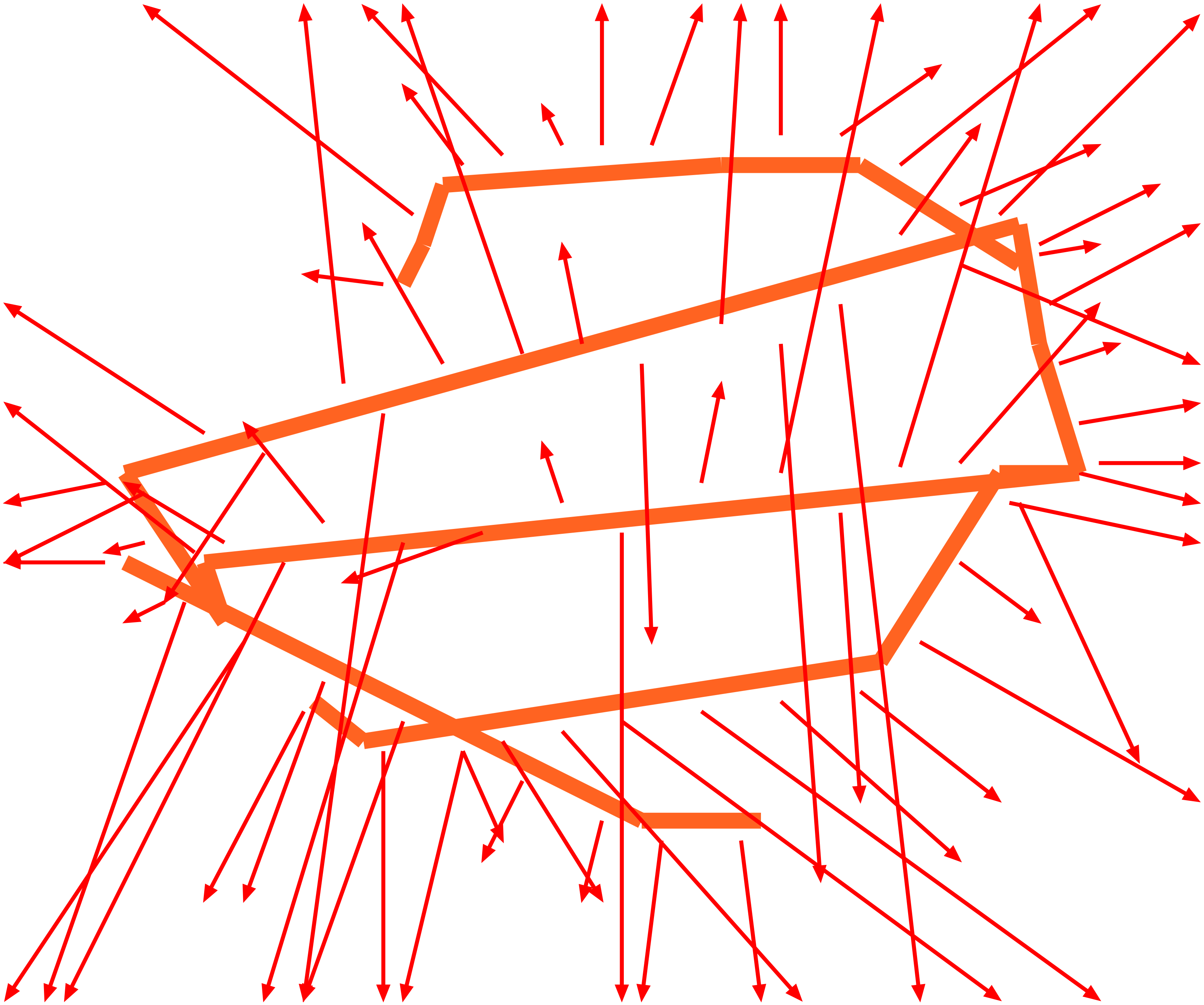


Beam remnants and other outgoing partons

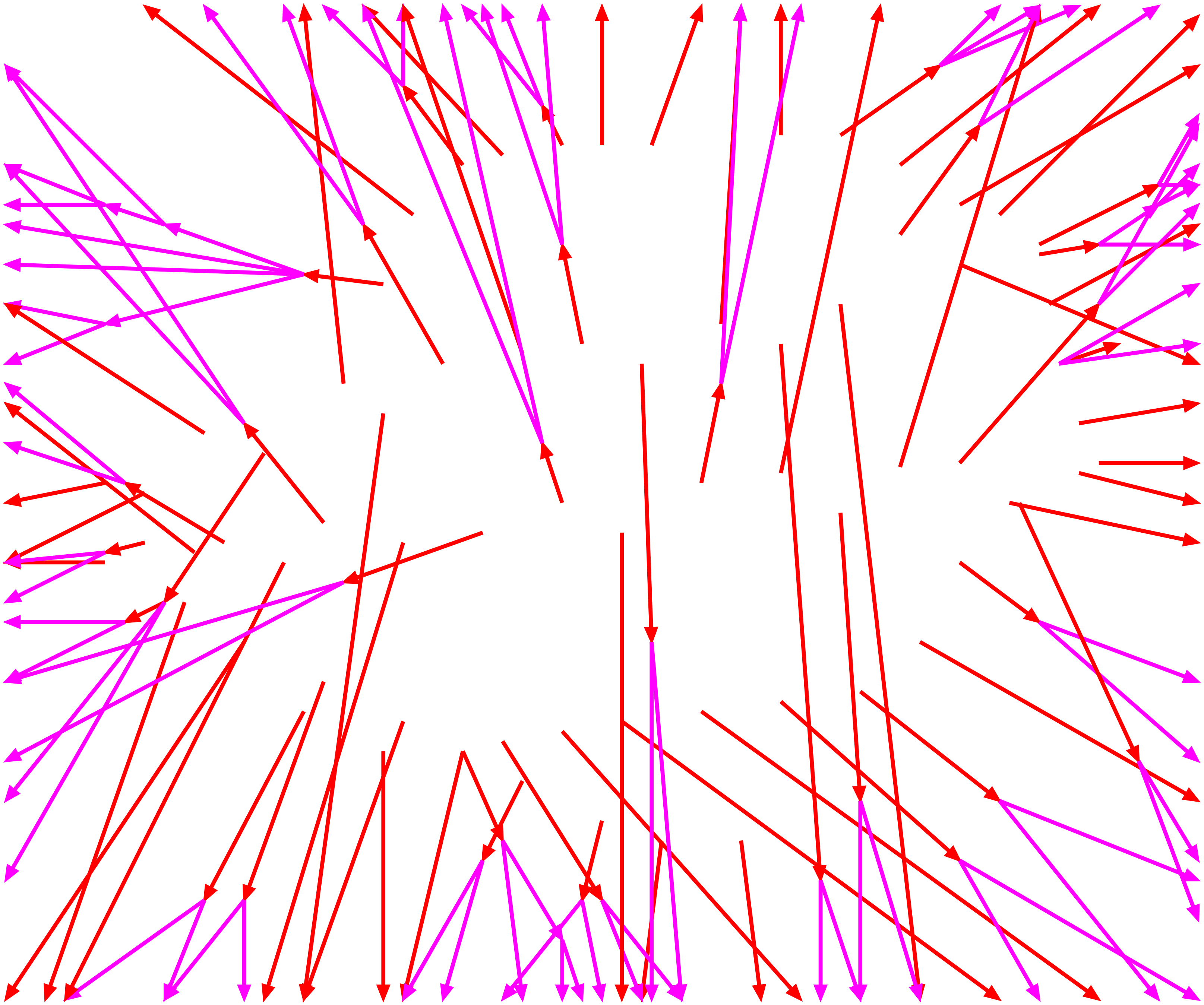


Everything is connected by colour confinement strings

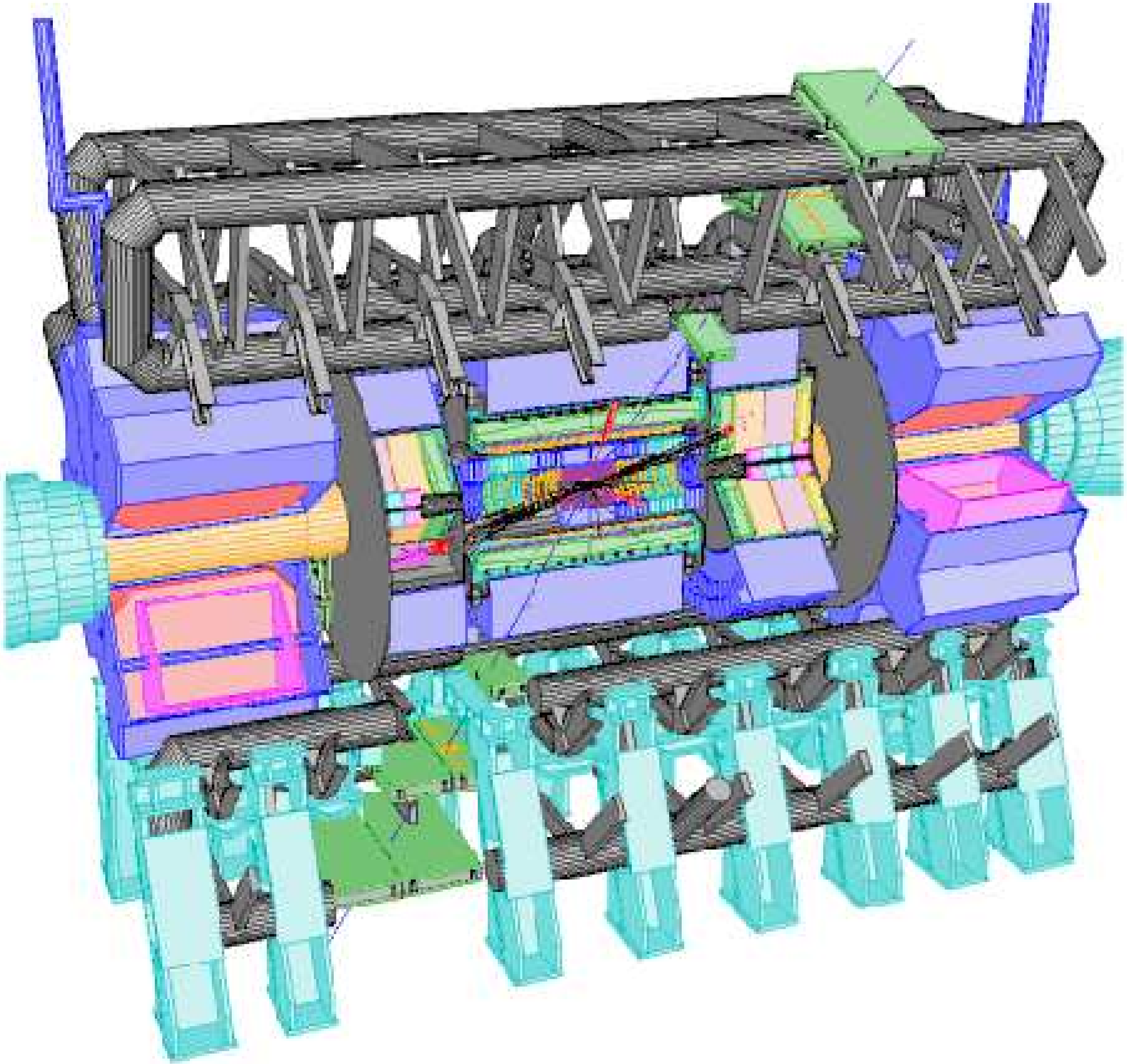
Recall! Not to scale: strings are of hadronic widths



The strings fragment to produce primary hadrons



Many hadrons are unstable and decay further



These are the particles that hit the detector

Event Generators: Program Mission

- 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

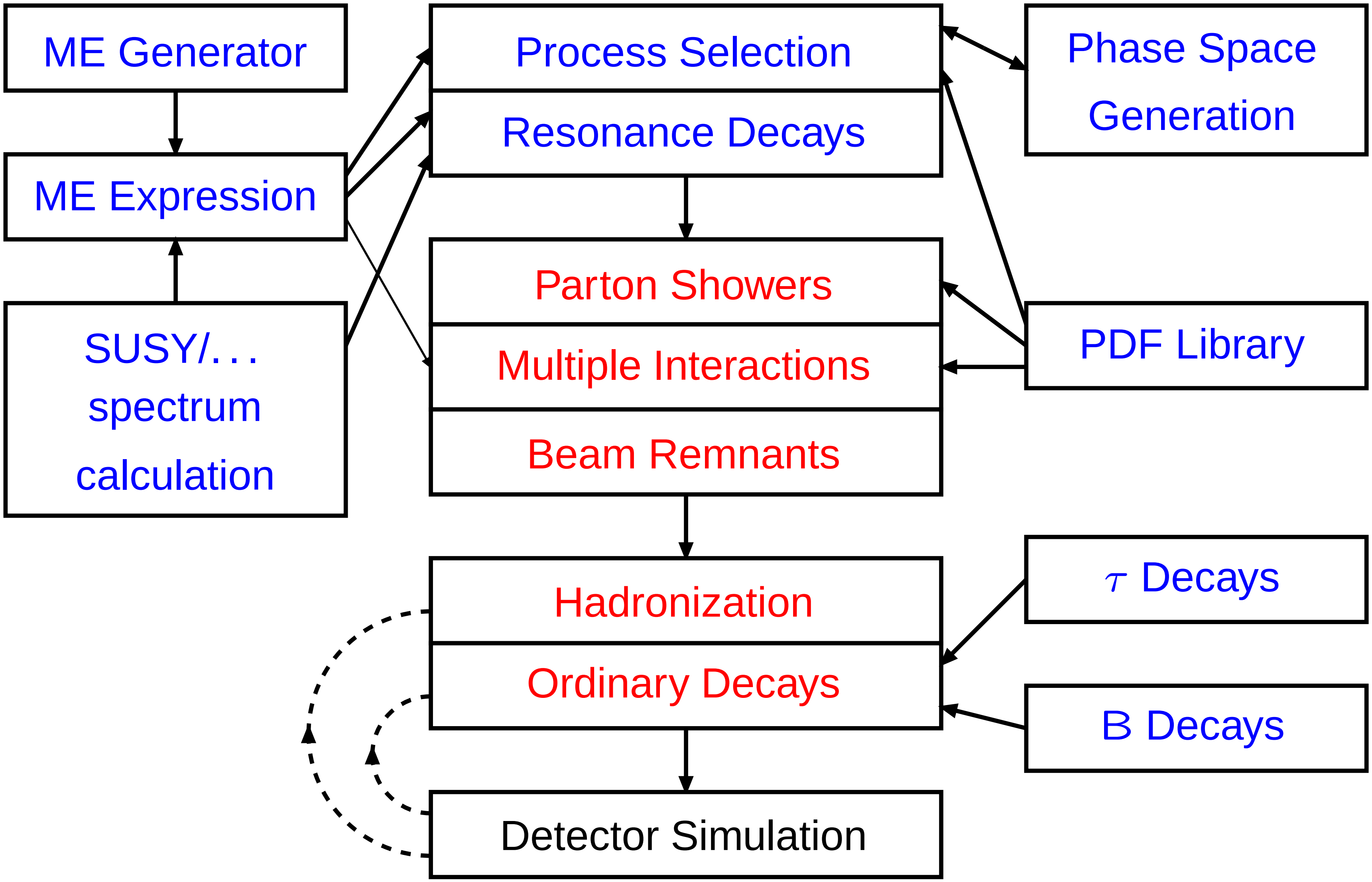
- predict event rates and topologies
  $\Rightarrow$ can estimate feasibility
- simulate possible backgrounds
  $\Rightarrow$ can devise analysis strategies
- study detector requirements
  $\Rightarrow$ can optimize detector/trigger design
- study detector imperfections
  $\Rightarrow$ can evaluate acceptance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

Generator Landscape

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

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

The Bigger Picture



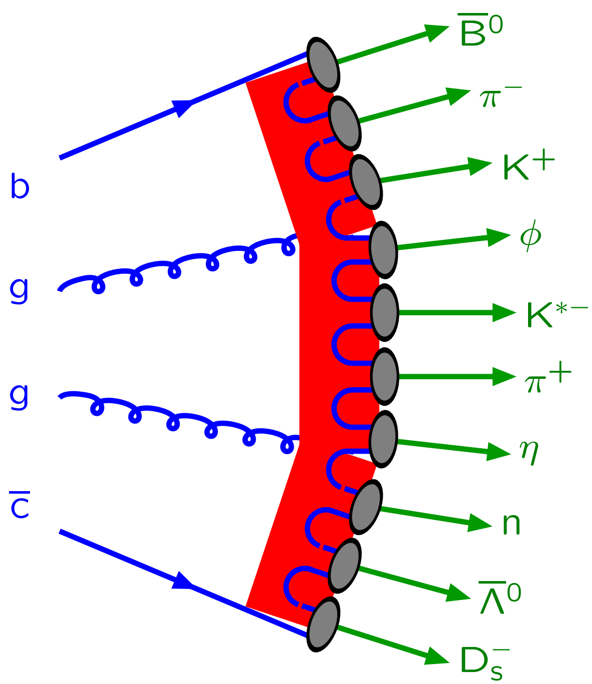
$\Longrightarrow$ **need standardized interfaces** (and need to make people use them):

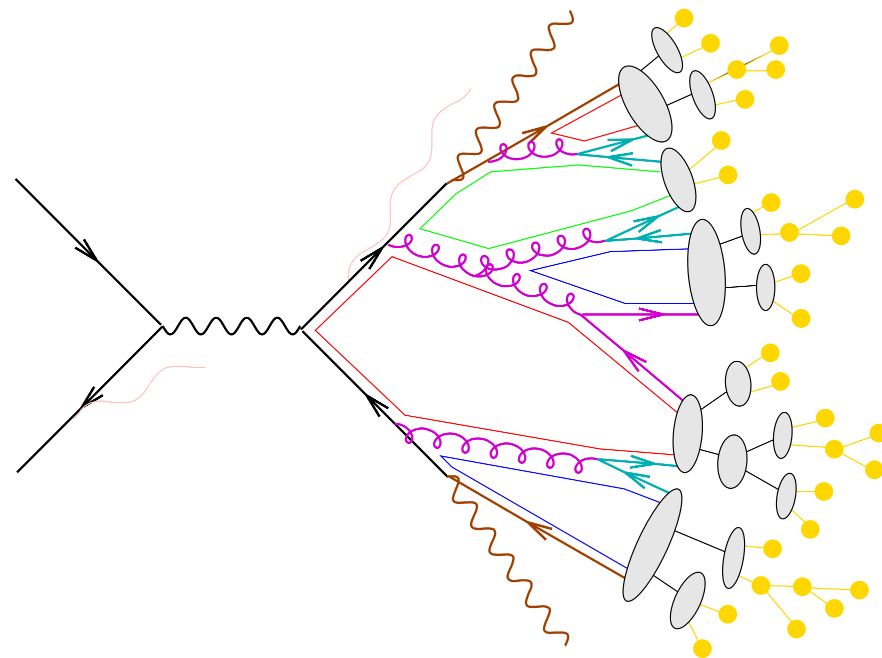
PDG ID codes, LHA/LHEF, SUSY LHA, LHAPDF, HEPMC, . . .

The C++ Transition

- CERN/LHC policy decision: Fortran not supported, move to C++
- 3 general-purpose generators rose to challenge:
  - SHERPA: new, in C++ from onset, first version 2003, now at 1.0.11
    hallmark: automatic ME generation and matching to showers
  - HERWIG++: first version 2003, first production release 2.1 in Nov
    hallmark: angular-ordered showers with coherence, spin tracing
  - PYTHIA 8: first draft 2005, first production release 8.1 in Oct
    hallmark: multiple interactions, string fragmentation
- Message to experimentalists: **You asked for it, now you use it!**
  - **implement** in your generation frameworks
  - **try out** complete generation chain, **report** problems
  - appoint **contact persons** to funnel interaction with authors
  - plan for a **transition period** over the next 1 - 2 years
    (be forgiving about teething problems)
  - plan for long-time **support & tuning** to experimental data

Hadronization Models





program	PYTHIA	HERWIG
model	string	cluster
energy–momentum picture	powerful	simple
	predictive	unpredictive
parameters	few	many
flavour composition	messy	simple
	unpredictive	in-between
parameters	many	few

Hadronization Issues

- No (promising) new fragmentation frameworks in last 25 years
- String model best bet (?), but too many "materials constants"
  $\star$ will lattice QCD one day be able to help?
  $\star$ mass dependence goes part of the way (UCLA model)
- Cluster model also has evolved towards many parameters
  $\Rightarrow$ there is no few-parameter *good* description

Many unsolved issues, especially:
multiple interactions $\Rightarrow$ *dense-packing of strings* $\Rightarrow$ collective effects?

- Higher colour representations (colour ropes)
- Colour reconnections (= colour exchange between q's and g's)?
- Bose–Einstein correlations?
- Partial formation of Quark-Gluon Plasma (QGP)?
- Rescattering of hadrons $\Rightarrow$ strangeness content, collective flow?

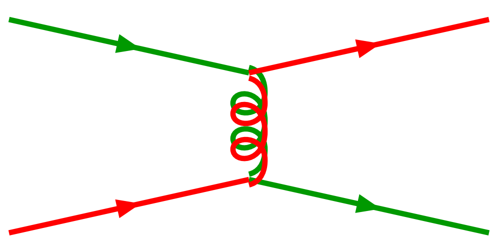
Action items:

- **Full-fledged experimental program**, whatever detectors can do
  e.g. $\Lambda^0 - \overline{\Lambda}^0 \Rightarrow$ baryon flow to central region
- **Models for hadronization in context of (partial) QGP**

What is multiple interactions?

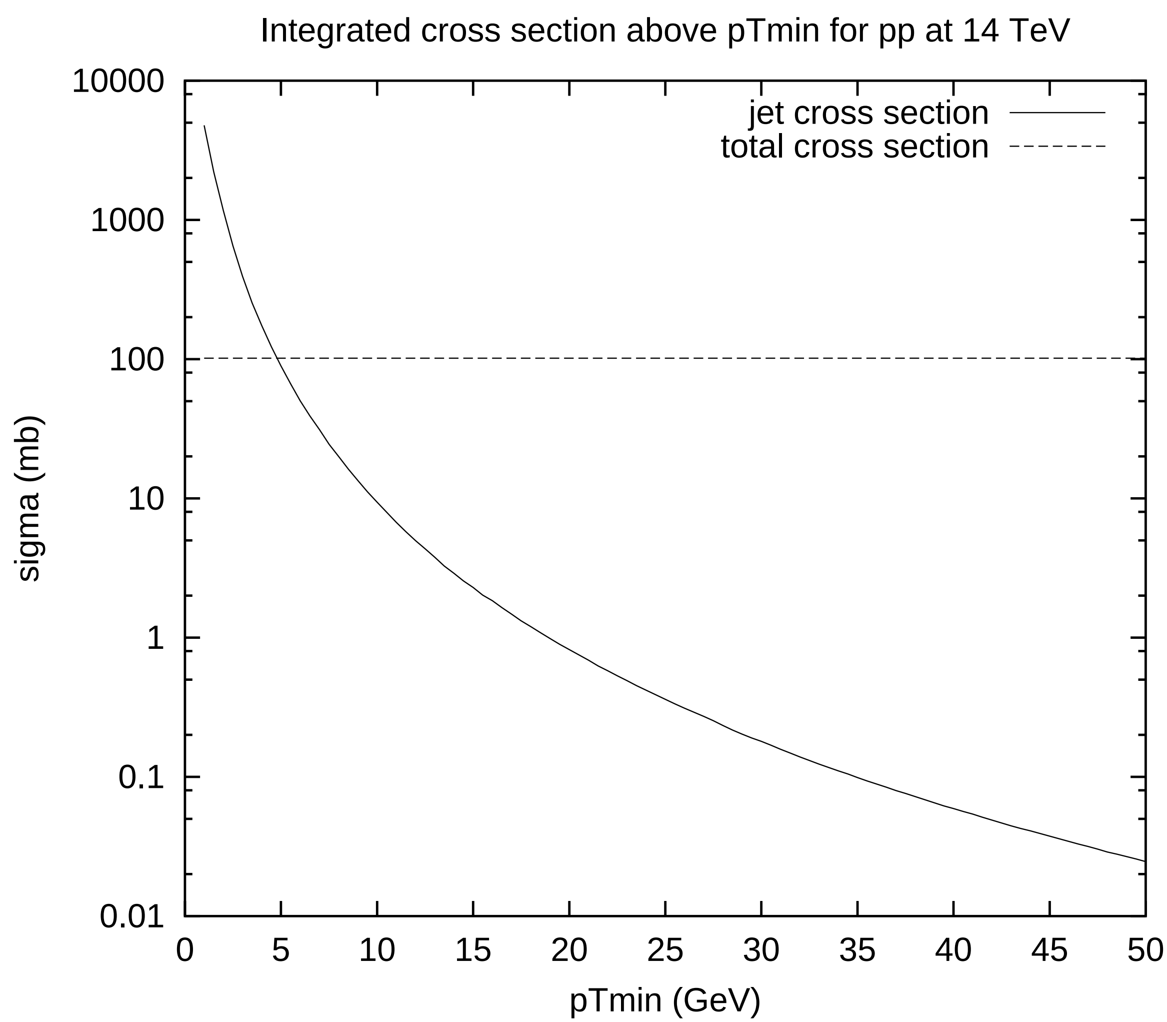
Cross section for $2 \to 2$ interactions is dominated by t-channel gluon exchange, so diverges like $\mathrm{d}\sigma/\mathrm{d}p_\perp^2 \approx 1/p_\perp^4$ for $p_\perp \to 0$.

integrate QCD $2 \to 2$



$\mathrm{qq}' \to \mathrm{qq}'$
$\mathrm{q\overline{q}} \to \mathrm{q}'\overline{\mathrm{q}}'$
$\mathrm{q\overline{q}} \to \mathrm{gg}$
$\mathrm{qg} \to \mathrm{qg}$
$\mathrm{gg} \to \mathrm{gg}$
$\mathrm{gg} \to \mathrm{q\overline{q}}$

with CTEQ 5L PDF's



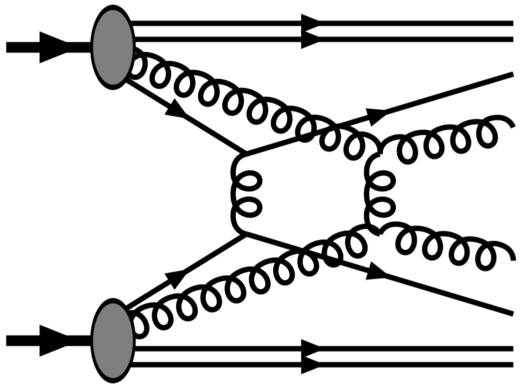
So $\sigma_{\text{int}}(p_{\perp\text{min}}) > \sigma_{\text{tot}}$ for $p_{\perp\text{min}} \lesssim 5$ GeV

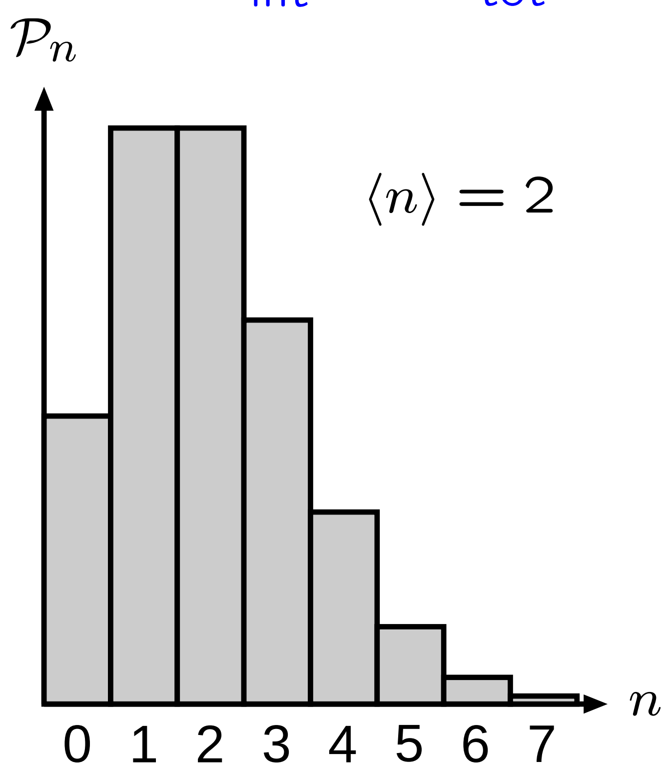
Half a solution: many interactions per event

$$\sigma_{\text{tot}} = \sum_{n=0}^{\infty} \sigma_n$$

$$\sigma_{\text{int}} = \sum_{n=0}^{\infty} n\,\sigma_n$$

$$\sigma_{\text{int}} > \sigma_{\text{tot}} \Longleftrightarrow \langle n \rangle > 1$$





If interactions occur independently

then Poissonian statistics

$$\mathcal{P}_n = \frac{\langle n \rangle^n}{n!}\, e^{-\langle n \rangle}$$

but energy–momentum conservation

$\Rightarrow$ large n suppressed

Note: $e^{-\langle n \rangle}$ = “virtual corrections”

= “eikonalization” = “unitarity”

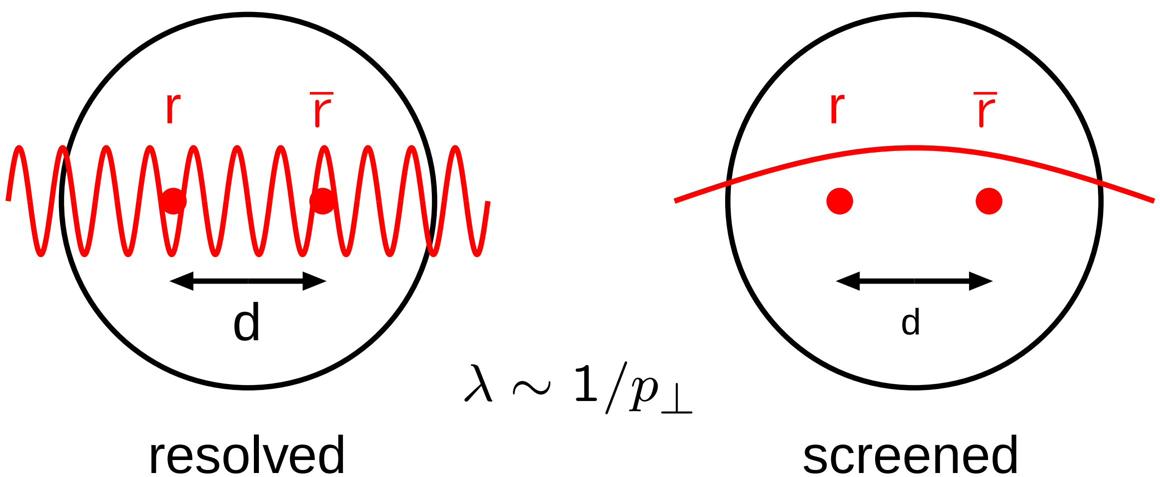
= “Sudakov form factor”

Other half of solution:
perturbative QCD not valid at small $p_\perp$ since q, g not asymptotic states (confinement!).

Naively breakdown at

$$p_{\perp\text{min}} \simeq \frac{\hbar}{r_\text{p}} \approx \frac{0.2\ \text{GeV} \cdot \text{fm}}{0.7\ \text{fm}} \approx 0.3\ \text{GeV} \simeq \Lambda_\text{QCD}$$

. . . but better replace r_p by (unknown) colour screening length d in hadron



Multiple Interactions Models

nonperturbative picture
multiple cut Pomerons
many, $p_\perp = 0$
ISAJET, DTUJET

perturbative picture
multiple hard interactions
few, large $p_\perp$
no generators

PYTHIA (TS, van Zijl, 1987)
purely perturbative picture, all the way to $p_\perp = 0$
but colour screening factor $\approx \left(\frac{p_\perp^2}{p_\perp^2 + p_{\perp 0}^2}\right)^2$
with $p_{\perp 0} = 2$ GeV (Tevatron) – 3 GeV (LHC?)
model for minimum-bias *and* underlying event
impact parameter profile $\Rightarrow$ pedestal effect

PHOJET/DPMJET (Ranft, Engel, . . .)
soft + hard cut Pomerons
eikonalized diffraction

JIMMY (Butterworth, Forshaw, Seymour)
model only for underlying event

IVAN (unpublished) (Borozan, Seymour)

Multiple Interactions: A New Evolution Equation

	time	evolution	probability
FSR	forwards	$p_\perp \searrow 0$	normal & local
ISR	backwards	$p_\perp \searrow 0$	conditional
MI	simultaneous	$p_\perp \searrow 0$	conditional

ISR + MI: PDF competition $\Rightarrow$ interleaving (PYTHIA 6.3)

FSR: previously at end, now also interleaved (PYTHIA 8.1):

$$\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}p_\perp} = \left(\frac{\mathrm{d}\mathcal{P}_{\mathrm{MI}}}{\mathrm{d}p_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{ISR}}}{\mathrm{d}p_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{FSR}}}{\mathrm{d}p_\perp} \right) \times \exp\left(- \int_{p_\perp}^{p_{\perp i-1}} \left(\frac{\mathrm{d}\mathcal{P}_{\mathrm{MI}}}{\mathrm{d}p'_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{ISR}}}{\mathrm{d}p'_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{FSR}}}{\mathrm{d}p'_\perp} \right) \mathrm{d}p'_\perp \right)$$

“resolution evolution”

Monte Carlo: winner takes all

\+ many other assumptions/models

Multiple Interactions Outlook

Issues requiring further thought and study:

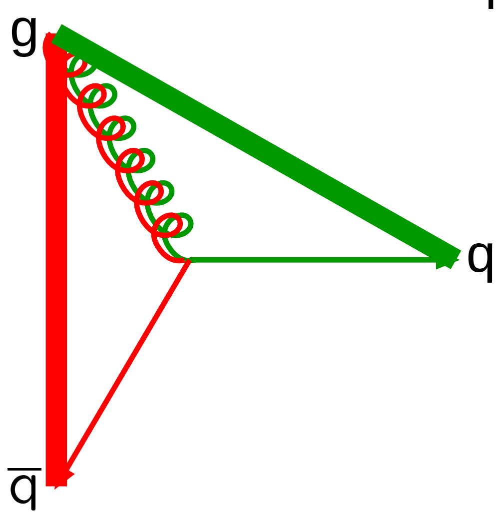
- Multi-parton PDF's $f_{a_1 a_2 a_3 \cdots}(x_1, Q_1^2, x_2, Q_2^2, x_3, Q_3^2, \ldots)$
- Close-packing in initial state, especially small x
- Impact-parameter picture and (x, b) correlations
  e.g. large-x partons more central!, valence quarks more central?
- Details of colour-screening mechanism
- Rescattering: one parton scattering several times
- Intertwining: one parton splits in two that scatter separately
- Colour sharing: two FS–IS dipoles become one FS–FS one
- Colour reconnection: required for $\langle p_\perp \rangle (n_{\mathrm{charged}})$
- Collective effects (e.g. QGP, cf. Hadronization above)
- Relation to diffraction: eikonalization, multi-gap topologies, . . .

Action items:

- **Vigorous experimental program at LHC**
- Study energy dependence: **RHIC (pp)** $\longrightarrow$ **Tevatron** $\longrightarrow$ **LHC**
- MI studies have become PYTHIA-centric
  $\Rightarrow$ **develop & support alternatives, such as PHOJET**
- increase contact/exchange with cosmic-ray community (e.g. Engel)

Shower Algorithms (1)

Two main trends:
- use $p_\perp$ as evolution variable
- dipole kinematics = radiator + recoiler



Lund string

↓

Leningrad antenna

(Azimov, Dokshitzer, Khoze, Troyan)

↓

Lund dipole (Gustafson) → ARIADNE (Lönnblad), Catani–Seymour dipole

NLO ME's → Catani–Seymour dipole

ARIADNE (Lönnblad)

LDCMC

traditional showers

PYTHIA 6.3, *8.1*

VINCIA (Giele, Kosower, Skands)

Catani–Seymour dipole

↓

Nagy, Soper

↓

Krauss, Schumann ($\longrightarrow$ SHERPA)

Dinsdale, Ternick, Weinzierl ($\longrightarrow$?)

Winter (in preparation)

Shower Algorithms (2)

- Improved angular-ordering in HERWIG++, especially massive quarks
- Quantum showers (Nagy, Soper)
- Soft Collinear Effective Showers (Bauer, Schwartz)
- PHOTOS strategy extended to QCD (Was)
- Constrained showers (Jadach et al.)
- NLO showers (Kato, Munehisa)
- CCFM-based showers for small-x physics:
  LDCMC (Andersson, Gustafson, Lönnblad)
  CASCADE (Jung)
- multi-scale showers showers for resonance decays (to be done)
- . . .

Recent explosion in number of shower algorithms and authors!
This is healthy; there must not be one unique answer for all.
(If only other key topics, like say multiple interactions, were as well provided for . . . .)
Further evolution should be supported!
One possible long-term project: a robust and trustworthy NLO shower.
Another: a small-x shower encompassing all relevant physics.

Shower Matching: Loops

More loops (NLO, NNLO, . . .):

$+$ improved cross section for rate predictions and precision tests

$-$ negligible improvement for event shapes

- MC@NLO (Frixione, Webber; Nason, Latunde-Dada)
  subtraction of generator-specific counterterm (HERWIG, HERWIG++)
- POWHEG (Nason; Frixione, Oleari, Ridolfi , Latunde-Dada, Gieseke, Webber)
  construct hardest (= highest-$p_\perp$) branching with Sudakov:

$$\mathrm{d}\sigma = \left(B(v) + V(v) + \int (R(v,r) - C(v,r))\mathrm{d}\Phi_r \right) \exp\left(- \int_{p_\perp} \frac{R(v,r)}{B(v)} \mathrm{d}\Phi_r \right)$$

marries well with ($p_\perp$-ordered) showers*, is more robust than MC@NLO

$\Rightarrow$ **NLO programs should be able to produce POWHEG-style output**

difference MC@NLO–POWHEG a measure of higher-order uncertainty

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*"POWHEG" first done 1987 for $\mathrm{e}^+\mathrm{e}^-$ (Bengtsson, TS):

1) evolve shower in Q^2 with $\mathrm{d}\sigma^{\mathrm{PS}}_{\mathrm{q\overline{q}g}} > \mathrm{d}\sigma^{\mathrm{ME}}_{\mathrm{q\overline{q}g}}$

2) weight by $\mathrm{d}\sigma^{\mathrm{ME}}_{\mathrm{q\overline{q}g}}/\mathrm{d}\sigma^{\mathrm{PS}}_{\mathrm{q\overline{q}g}}$ in with veto algorithm $\Rightarrow$ exp $\left(- \int \mathrm{d}\sigma^{\mathrm{ME}}_{\mathrm{q\overline{q}g}}/\sigma_{\mathrm{q\overline{q}}} \right)$

3) rescale to $\sigma_{\mathrm{NLO}} = (1 + \alpha_{\mathrm{s}}/\pi)\ \sigma_{\mathrm{LO}}$

Shower Matching: Legs

More legs:

$+$ address complicated multiparton topologies $\Rightarrow$ what you need for searches

$-$ no (systematic) improvement of absolute cross sections

LO ME's are inclusive: $2 \to 2, \quad 2 \to 3, \quad 2 \to 4, \ldots,$ doublecount

Use Sudakovs to express that $2 \to 2$ should *not* radiate into $2 \to 3$, etc.,

$\Rightarrow$ exclusive picture, no doublecounting

Sudakov = all-orders *estimate* of virtual corrections $\Rightarrow$ some freedom

- CKKW (Catani, Krauss, Kuhn, Webber): analytical Sudakovs
- L-CKKW (Lönnblad; Lavesson): use trial showers (= as for real emissions), so "optimal" match of Sudakovs $\Rightarrow$ my favourite
- MLM (Mangano): try to match final jets to initial partons and reject if fails

with room for refinements

Another possible long-term project (VINCIA vision):

develop a shower that does matching both to loop(s) and legs

Likely more useful than a NLO shower without multi-leg capability

Showers and Parton Distributions

Trends in recent years:

- NLO fits only
- error PDF's (for NLO)

Folklore: shower is LO, then $\otimes$ LO or $\otimes$ NLO PDF's $\Rightarrow$ LO either way
so *no need for LO fits*

However:

- NLO PDF's don't have to be positive definite, only $\sigma \otimes$ PDF
- σ_{NLO} contain $+$ive $\ln(1/x)$ terms $\Rightarrow$ $\mathrm{PDF}_{\mathrm{NLO}}$ reduced at small x
  $\Rightarrow$ $\sigma_{\mathrm{LO}} \otimes \mathrm{PDF}_{\mathrm{NLO}}$ skewed, often worse than $\sigma_{\mathrm{LO}} \otimes \mathrm{PDF}_{\mathrm{LO}}$

Solutions, "turning the tide":

- **Improved "effective" LO PDF's** (Thorne, Sherstnev)
  e.g. do not conserve momentum exactly ($\sim$ K factor in gluon sector)
- **PDF4MC** (Jung et al.)
  tune PDF's for agreement with data ($\mathrm{d}\sigma_{\mathrm{jet}}$, $\mathrm{d}\sigma_{\mathrm{W/Z}}, \ldots$)
  as simulated by a specific generator

Matrix-Element Generators

Two main classes for LO generators:

- Generic: MadGraph, CompHep/CalcHep, . . .
- Preconfigured: AlpGen, Phase, . . .

see e.g. `http://www.cedar.ac.uk/hepcode/` for longer list
and `http://www.ippp.dur.ac.uk/montecarlo/BSM/` for BSM
MadGraph very useful, but should be extended to cover more BSM

Rather splintered picture for NLO:

- MCFM (& many others): more integrator than generator
- MC@NLO: tied to HERWIG, limited number of processes

Fast way forward: NLO programs $\Rightarrow$ POWHEG-style output (see above)

Ultimate goal, in MadGraph spirit:
user-friendly machinery for automatized NLO calculations

Summary

Obviously no claim for complete coverage or objectivity,
so apologies if your favourite project was not mentioned.

- Support new generation of C++-based generators
- Embrace standards for interoperability
- Start full-fledged program of hadronization studies
- Vigorous multiple-interactions program absolutely crucial
  — experimental and theoretical
- Continue current development of shower algorithms
  - ⋆ towards matching to more loops and legs (simultaneously?)
  - ⋆ ultimately towards a complete NLO shower
- Develop a user-friendly machinery for automatized NLO calculations
  ... in spirit of POWHEG approach
- Provide generator-friendly PDF sets

Final warning: one-shot efforts often lead to nothing!
Good documentation and long-term support of code is the key.
This must be allowed to cost.