LUND UNIVERSITY

CERN–Fermilab Collider School
Fermilab
9 – 18 August 2006

Theory of Hadronic Collisions

Part II: Phenomenology

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1. (today) Introduction and Overview; Parton Showers

2. (tomorrow) Matching Issues; Multiple Interactions I

3. (on Monday) Hadronization; MI II/LHC; Generators & Conclusions

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.

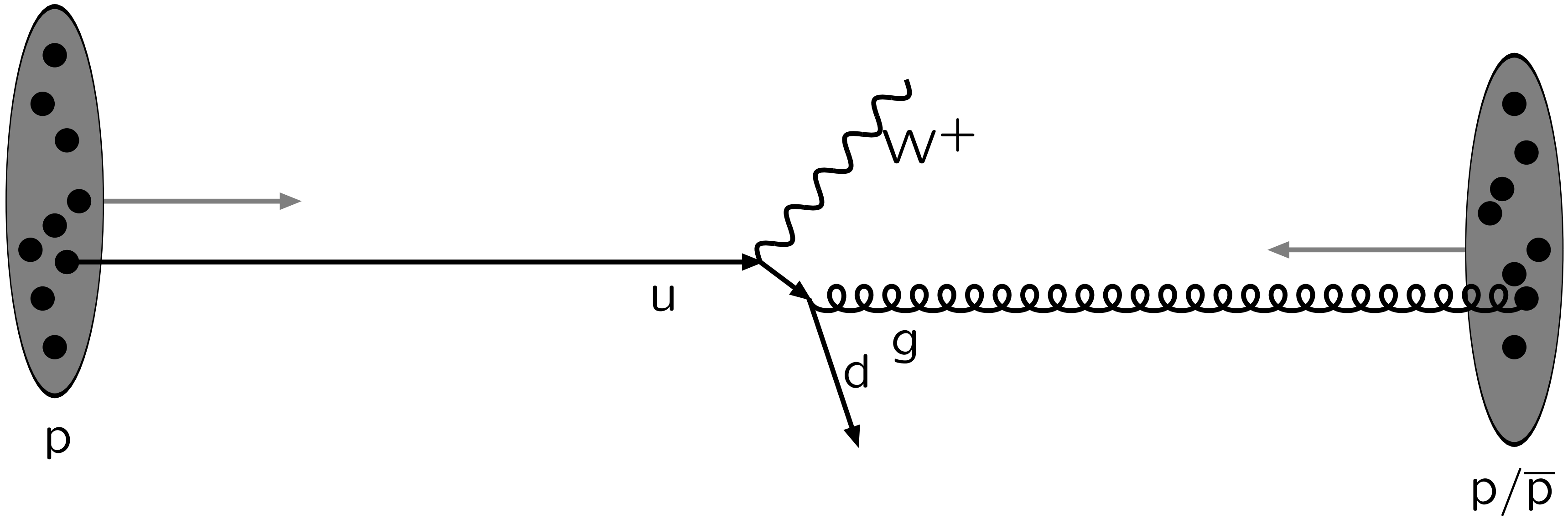
⋆ The modelling of elastic and diffractive topologies.

They *will* cover the “normal” physics that is there at the Tevatron,
and will be there in (essentially) all LHC pp events, from QCD to exotics:
⋆ the “dressing up” of a hard process by parton showers,
⋆ the addition of an underlying event,
⋆ the transition from partons to observable hadrons.
Event generators often only realistic tool, so end with a few words on
⋆ the status and evolution of general-purpose generators.

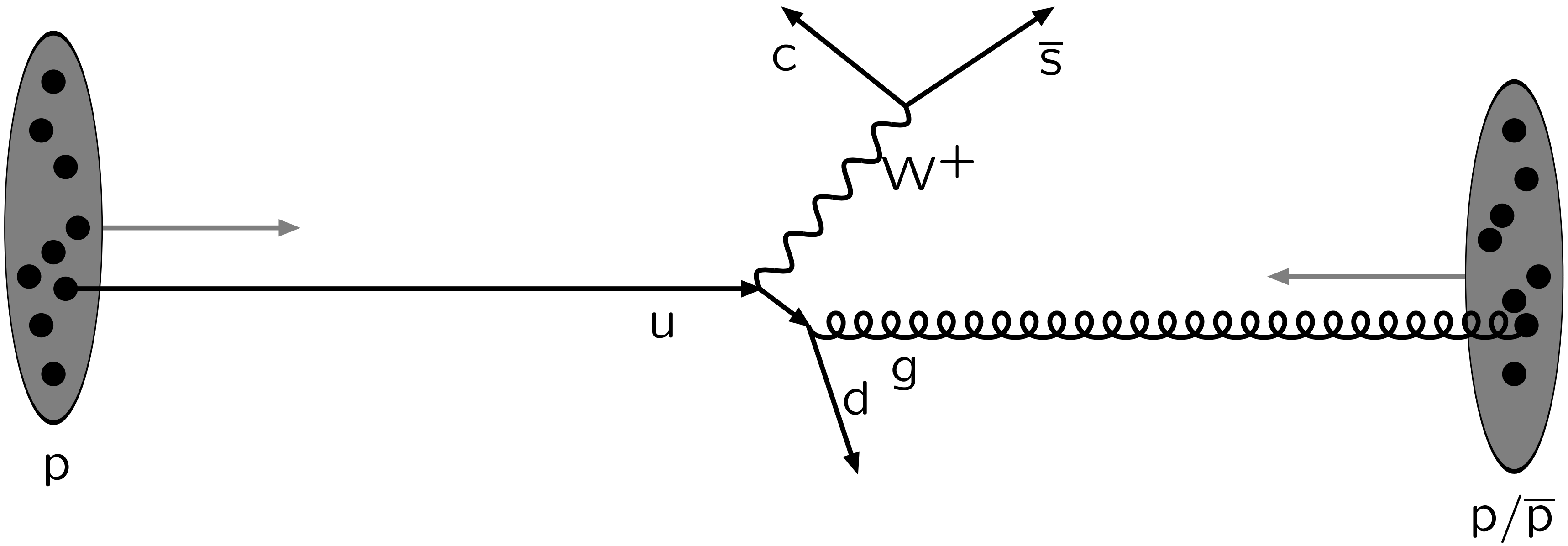
The structure of an event

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

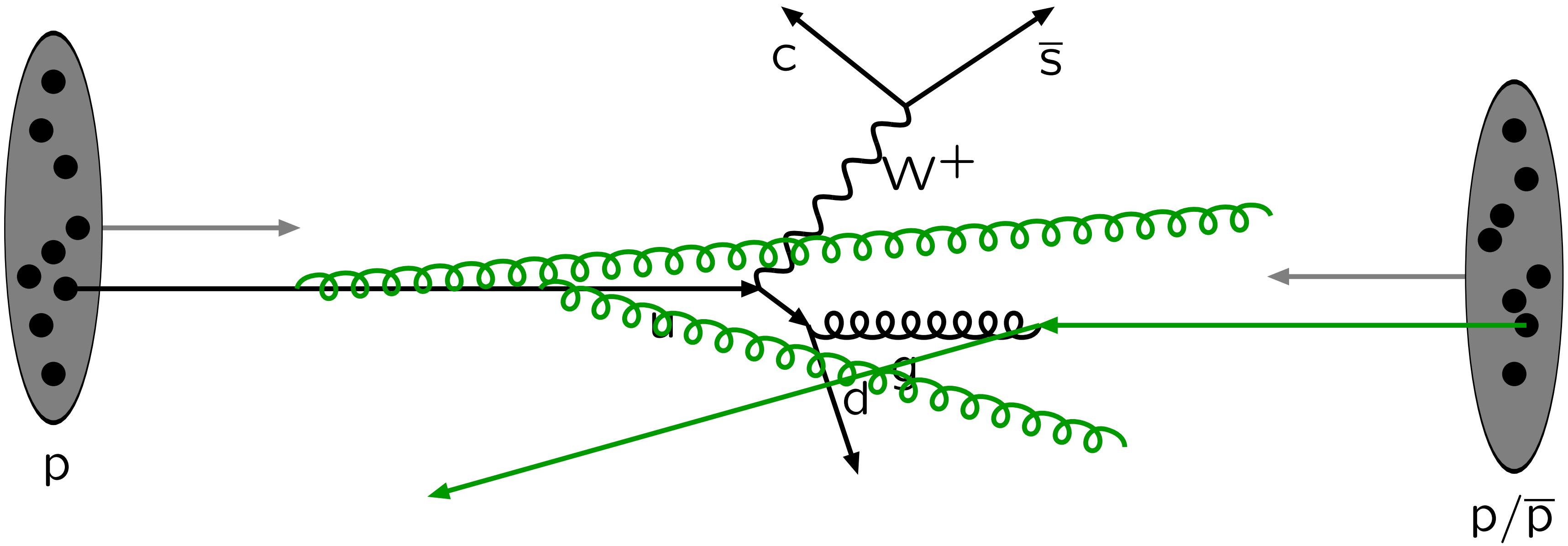
Incoming beams: parton densities



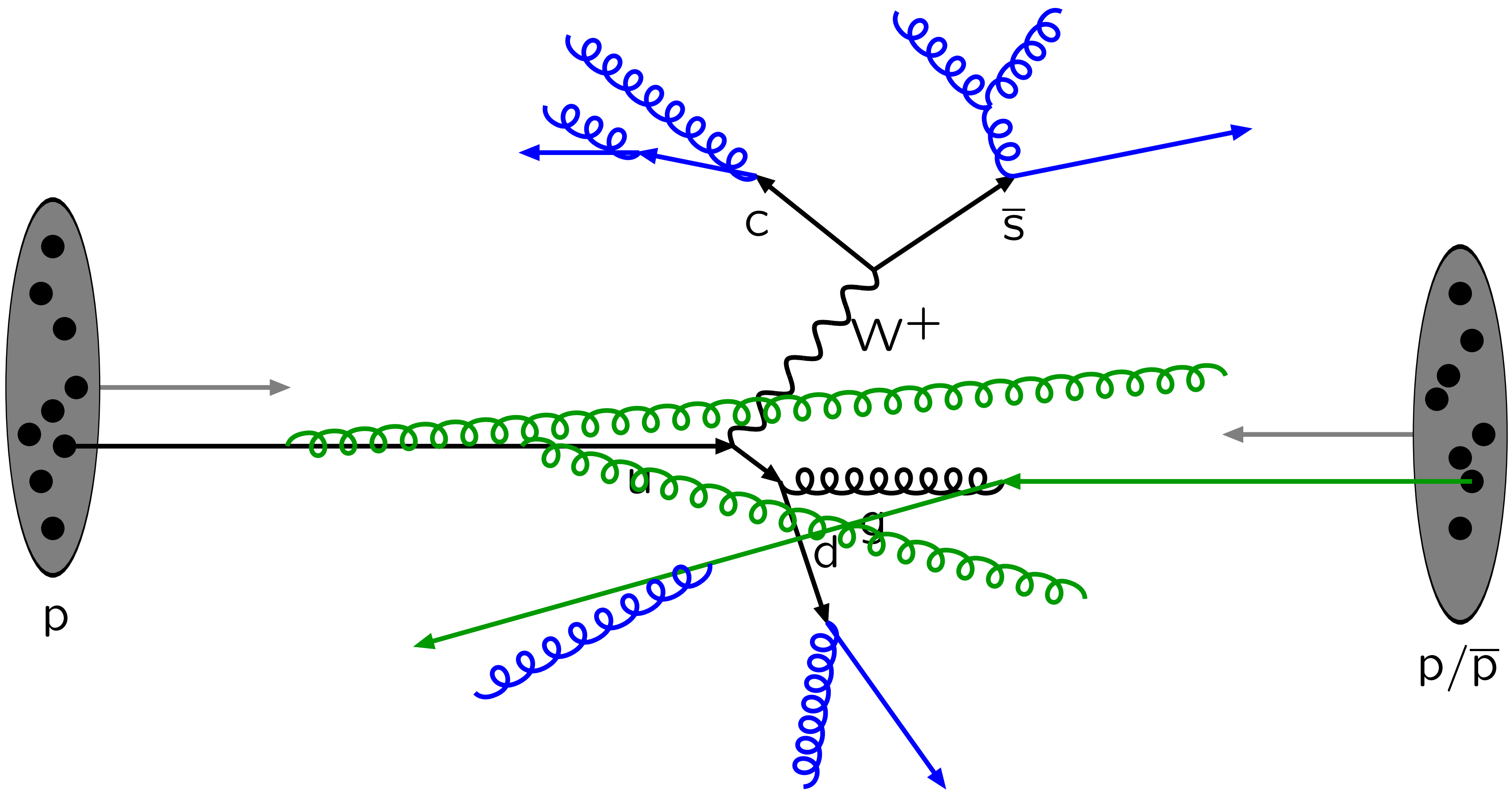
Hard subprocess: described by matrix elements



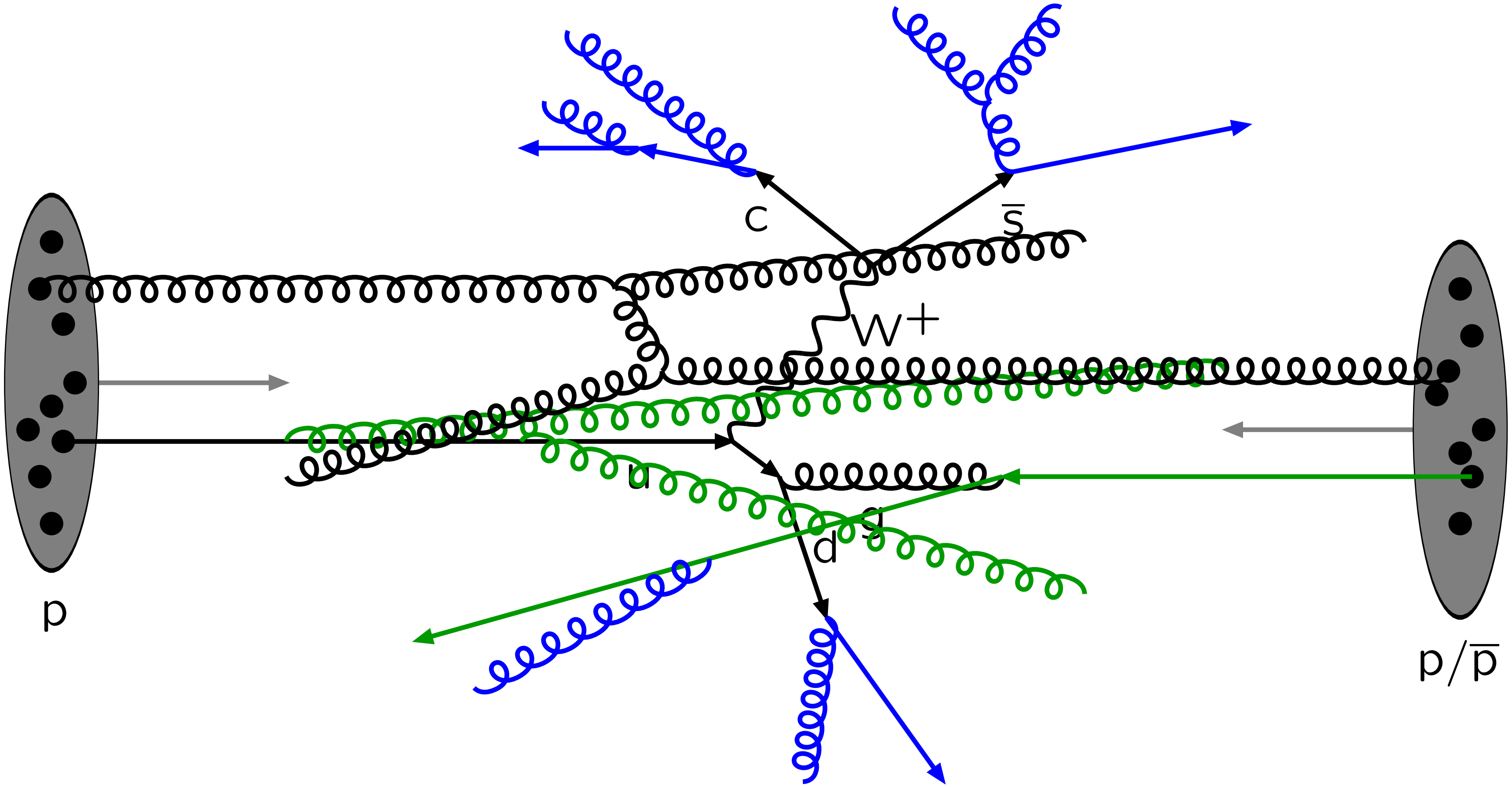
Resonance decays: correlated with hard subprocess



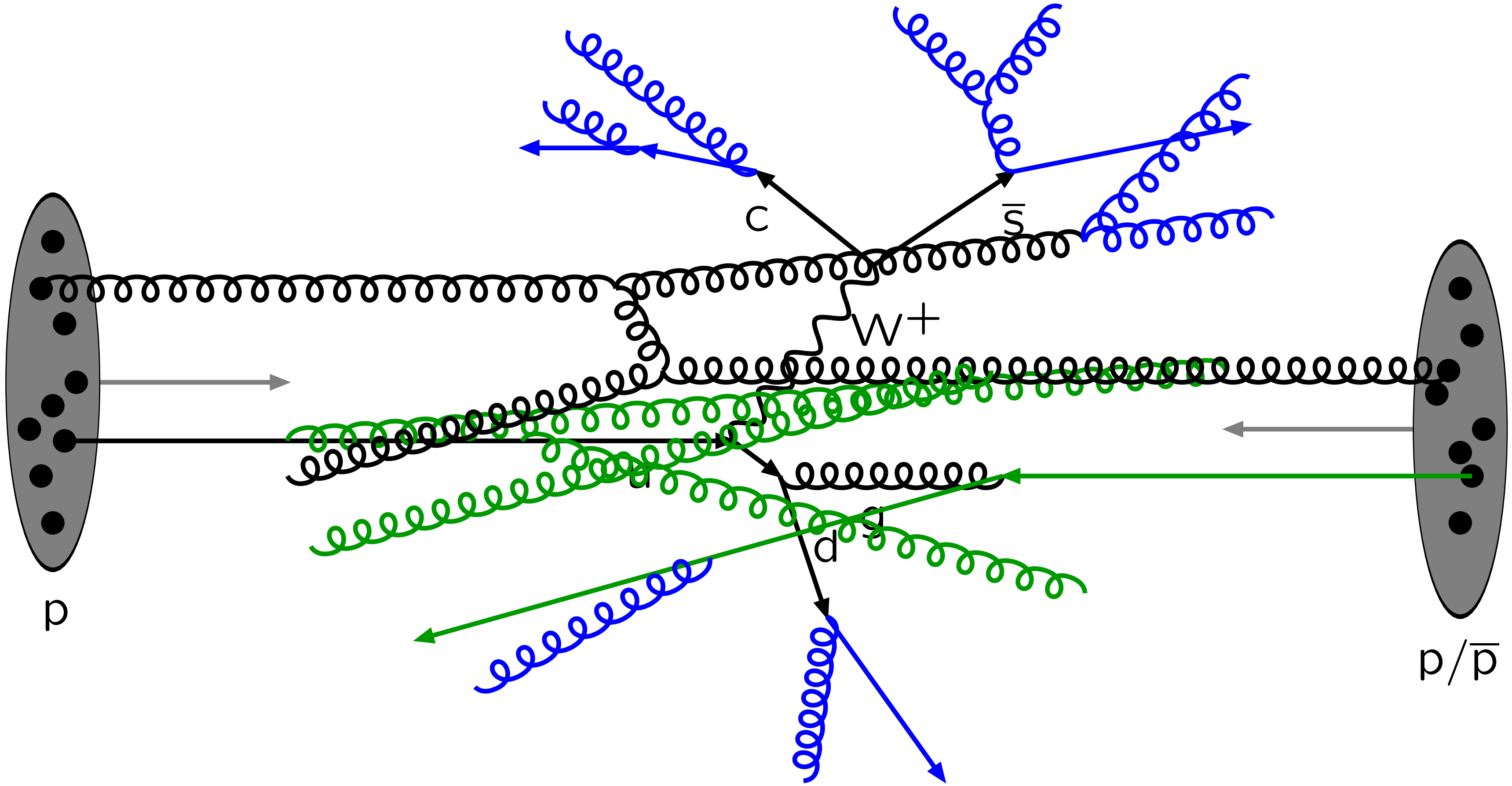
Initial-state radiation: spacelike parton showers



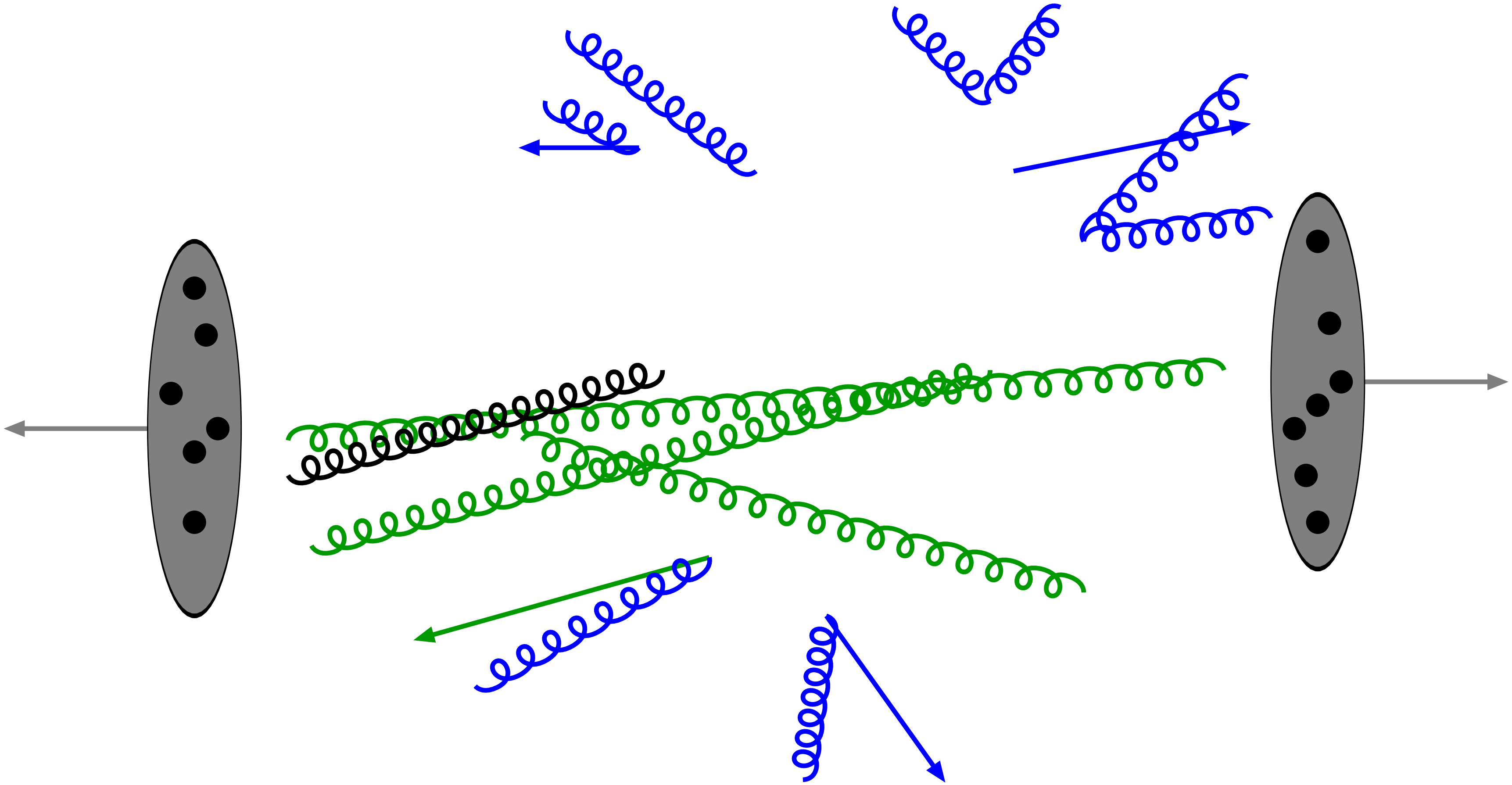
Final-state radiation: timelike parton showers



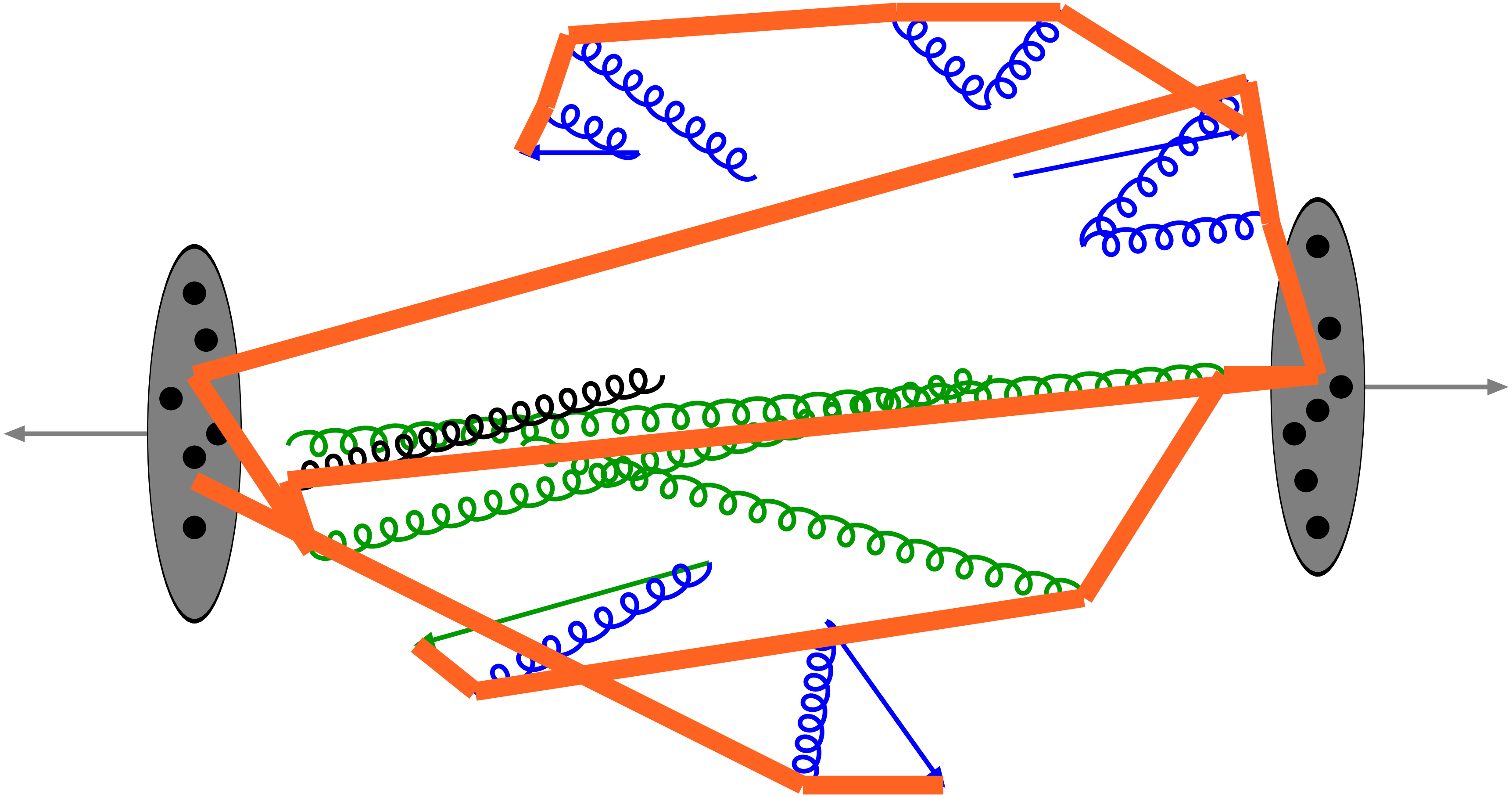
Multiple parton–parton interactions . . .



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

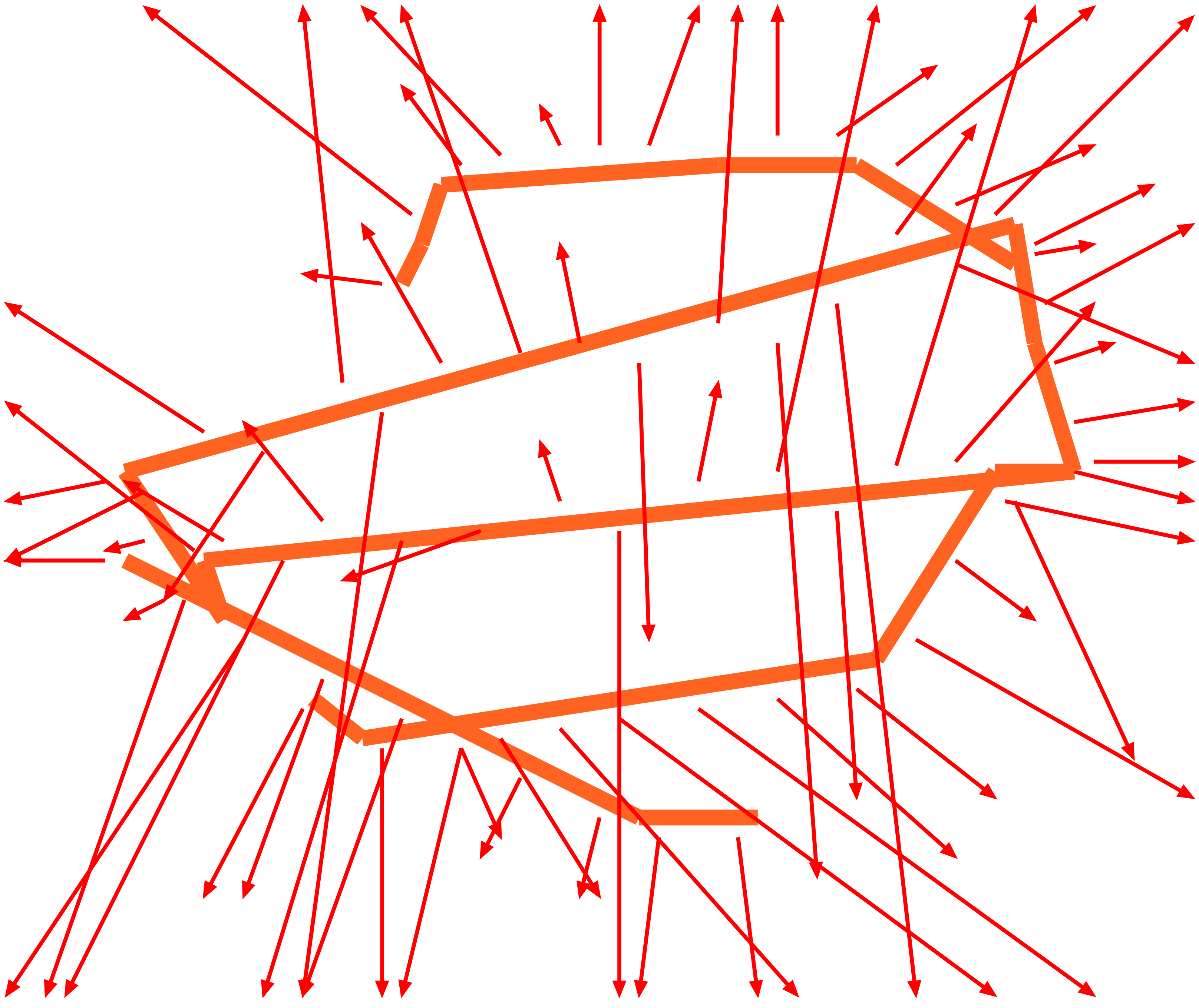


Beam remnants and other outgoing partons

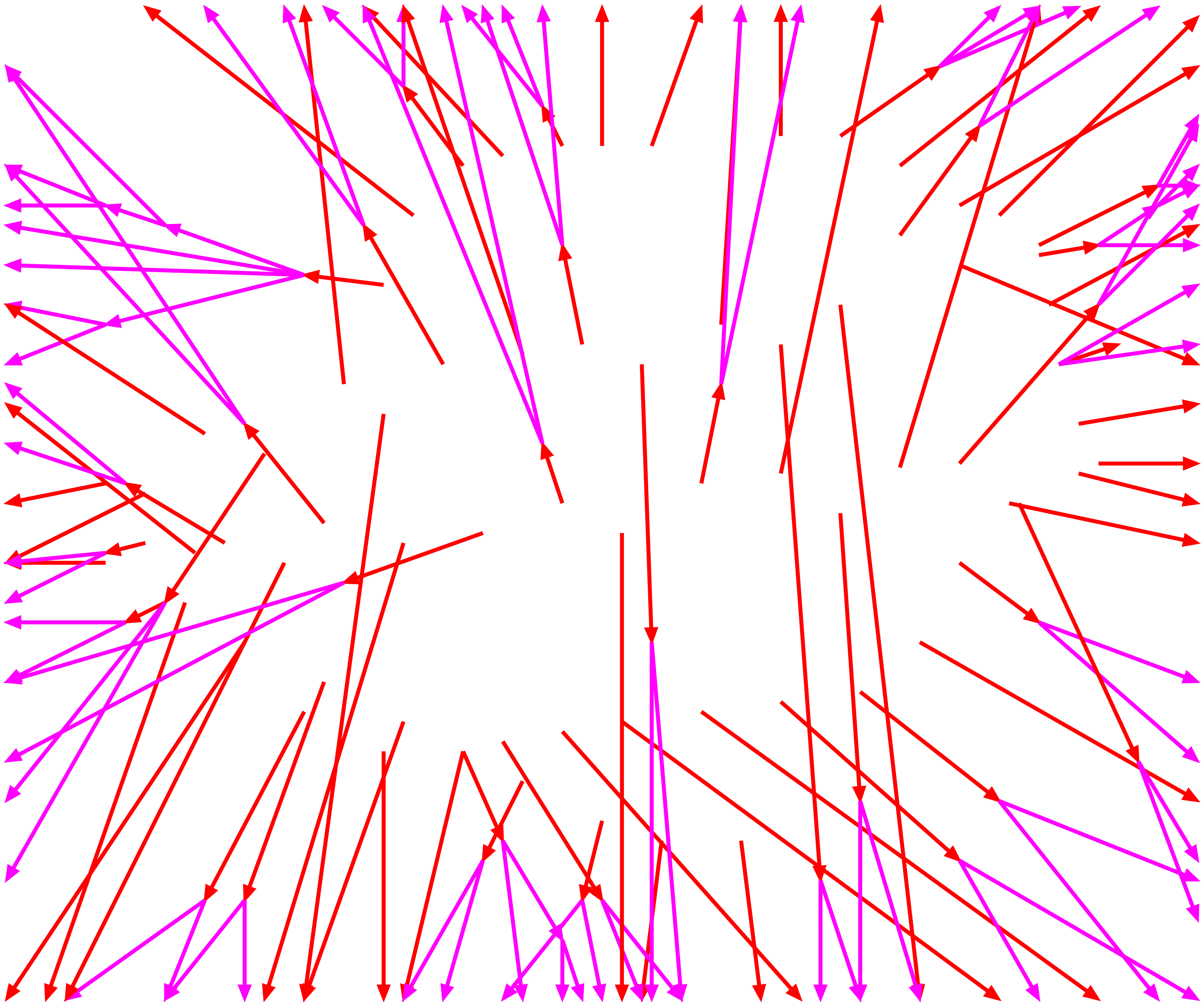


Everything is connected by colour confinement strings

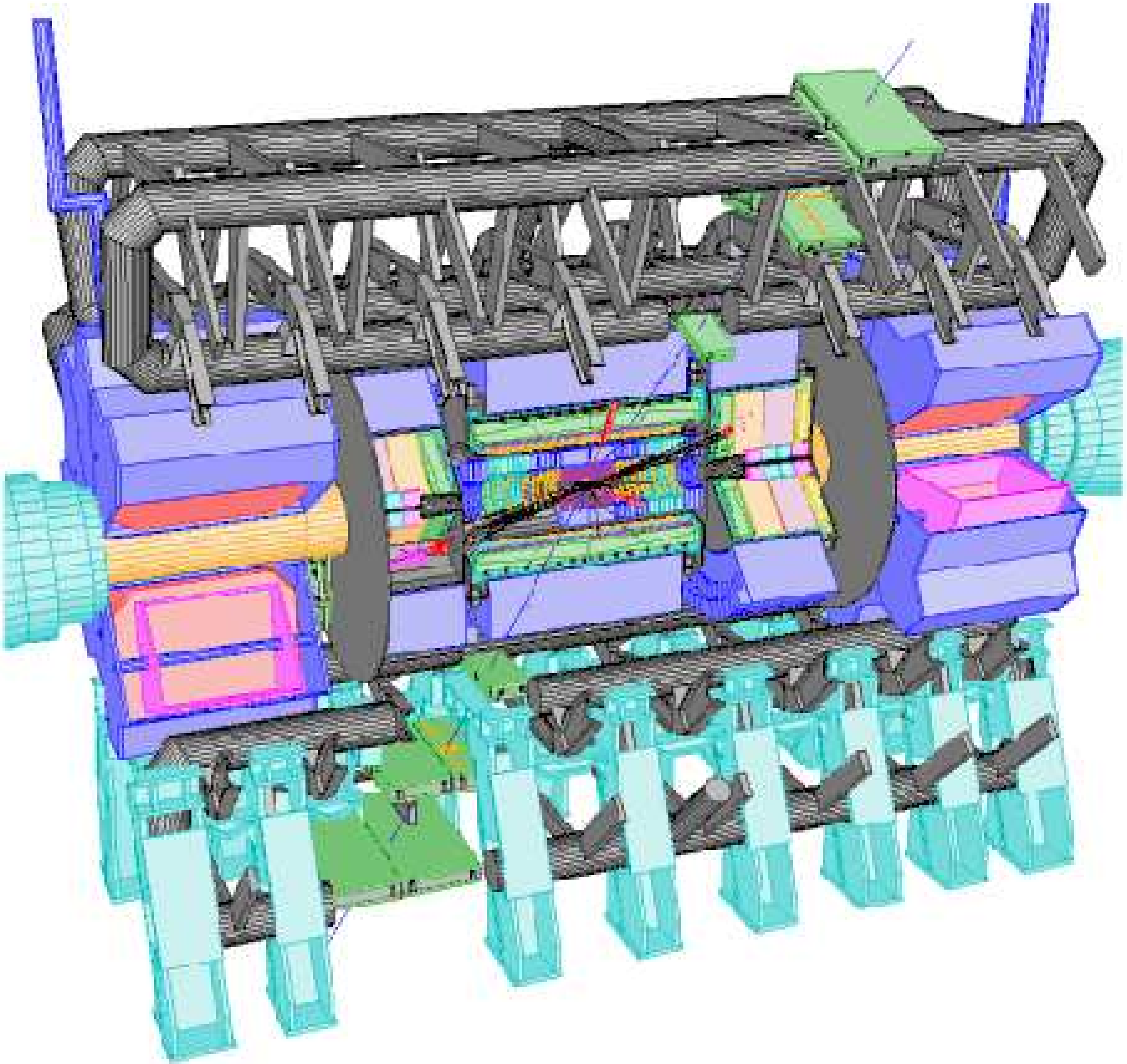
Recall! Not to scale: strings are of hadronic widths



The strings fragment to produce primary hadrons

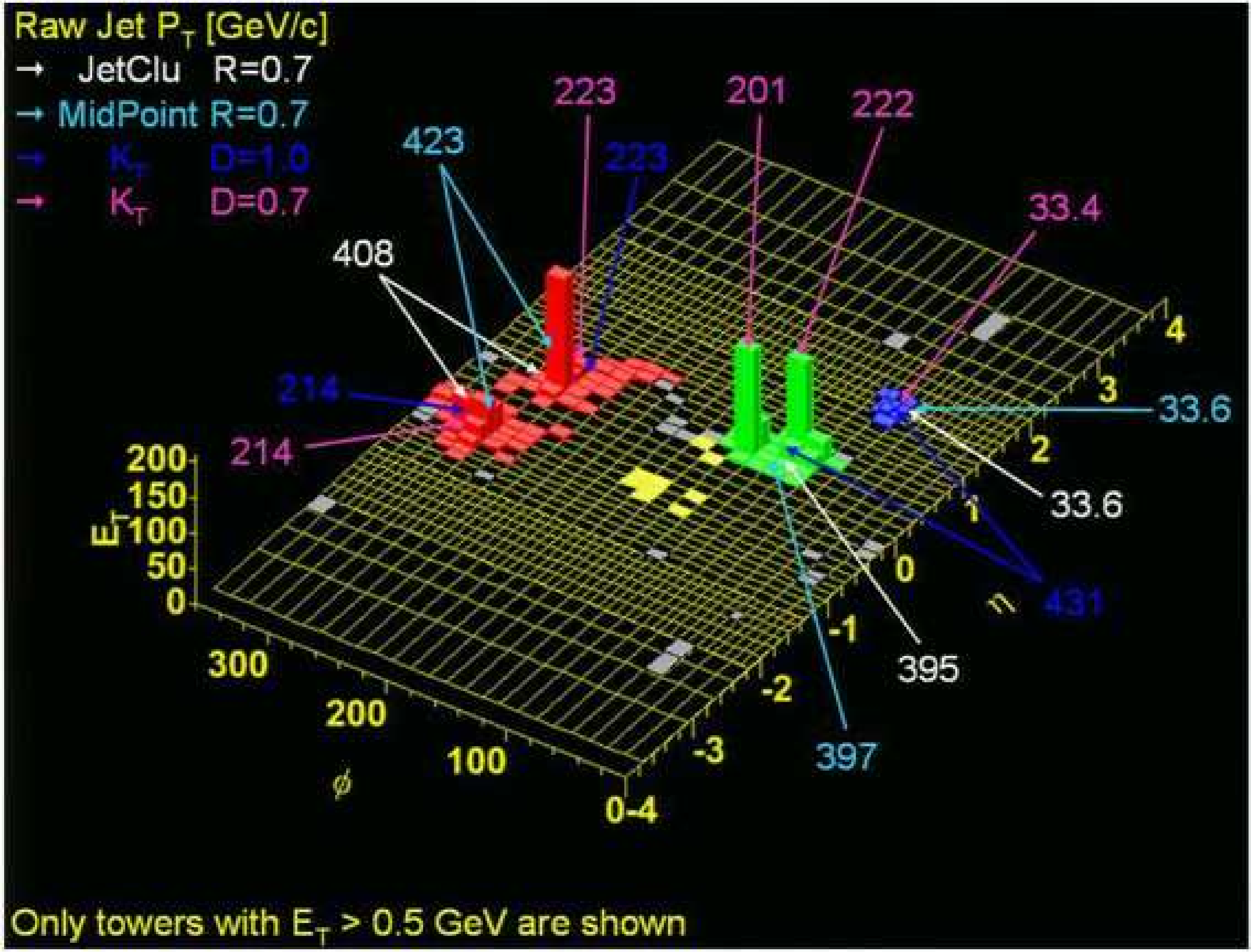


Many hadrons are unstable and decay further



These are the particles that hit the detector

Parton Showers



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

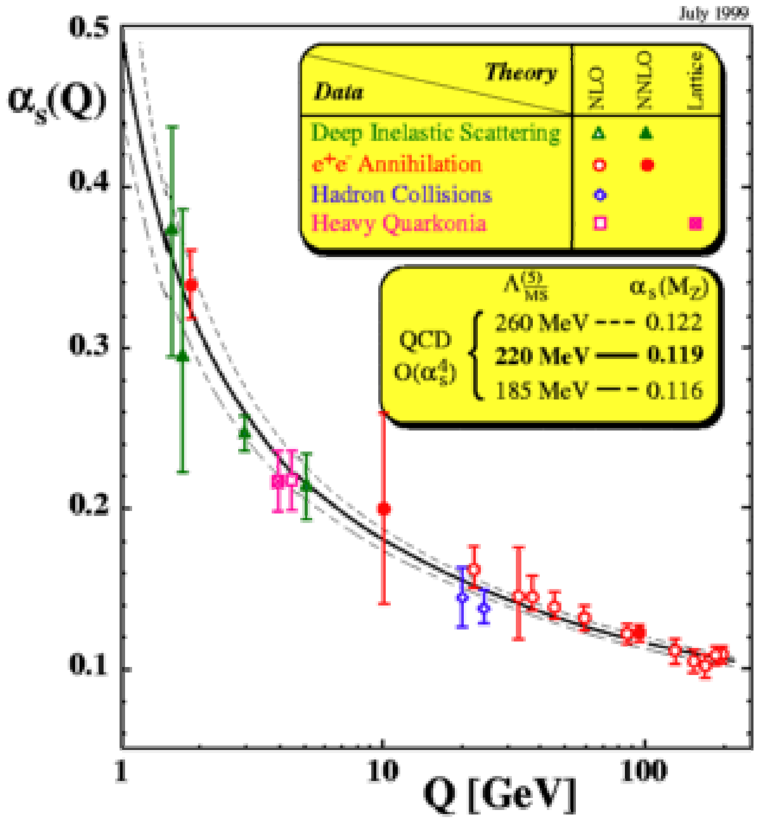
Divergences

Emission rate q $\to$ qg diverges when

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

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

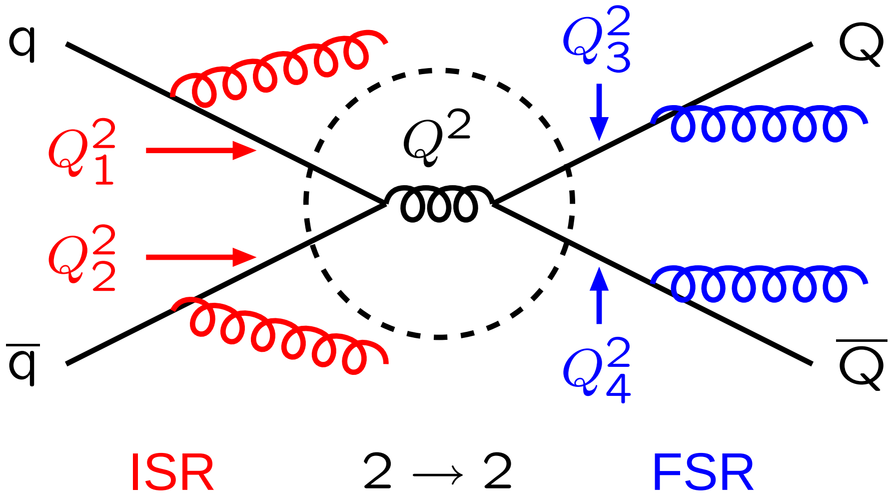
- g $\to$ gg similarly divergent
- $\alpha_{\mathrm{s}}(Q^2)$ diverges for $Q^2 \to 0$
  (actually for $Q^2 \to \Lambda^2_{\mathrm{QCD}}$)



Big probability for one emission $\Longrightarrow$ also big for several
$\Longrightarrow$ with ME's need to calculate to high order **and** with many loops
$\Longrightarrow$ extremely demanding technically (not solved!), and
involving big cancellations between positive and negative contributions.
Alternative approach: **parton showers**

The Parton-Shower Approach

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



FSR = Final-State Rad.;

timelike shower

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

ISR = Initial-State Rad.;

spacelike shower

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

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

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

Shower evolution is viewed as a probabilistic process,

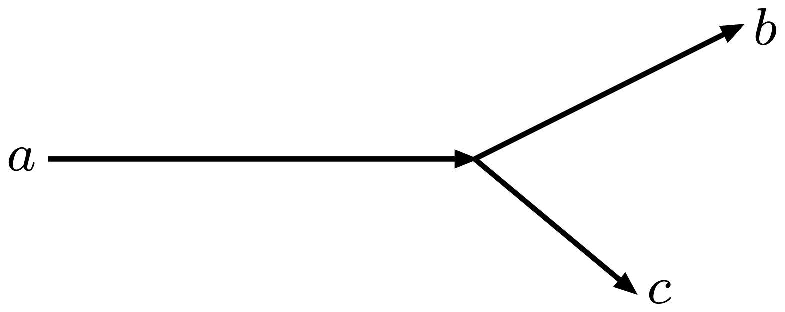
which occurs with unit total probability:

the cross section is not directly affected,

but indirectly it is, via the changed event shape

Technical aside: why timelike/spacelike?

Consider four-momentum conservation in a branching $a \to b\, c$



$$\mathbf{p}_{\perp a} = 0 \;\Rightarrow\; \mathbf{p}_{\perp c} = -\mathbf{p}_{\perp b}$$
$$p_+ = E + p_{\mathrm{L}} \;\Rightarrow\; p_{+a} = p_{+b} + p_{+c}$$
$$p_- = E - p_{\mathrm{L}} \;\Rightarrow\; p_{-a} = p_{-b} + p_{-c}$$

Define $p_{+b} = z\, p_{+a}, \quad p_{+c} = (1-z)\, p_{+a}$

Use $p_+ p_- = E^2 - p_{\mathrm{L}}^2 = m^2 + p_\perp^2$

$$\frac{m_a^2 + p_{\perp a}^2}{p_{+a}} = \frac{m_b^2 + p_{\perp b}^2}{z\, p_{+a}} + \frac{m_c^2 + p_{\perp c}^2}{(1-z)\, p_{+a}}$$

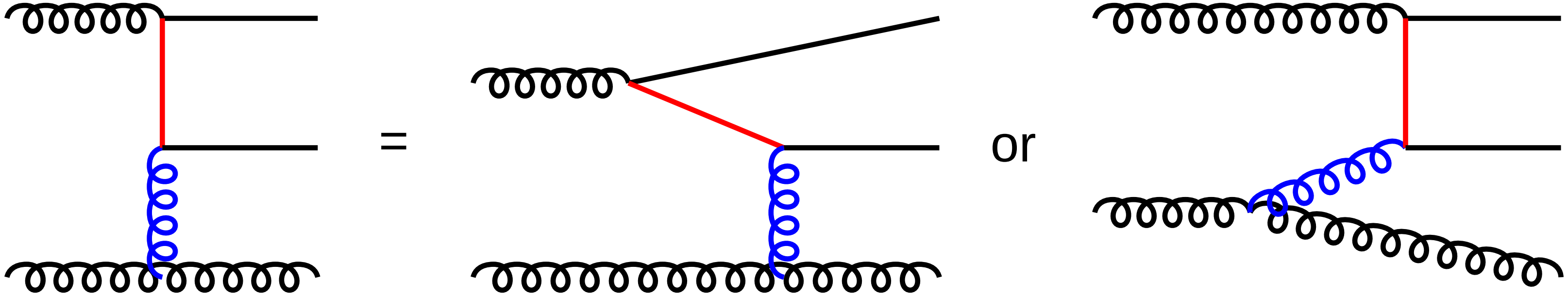
$$\Rightarrow \quad m_a^2 = \frac{m_b^2 + p_\perp^2}{z} + \frac{m_c^2 + p_\perp^2}{1-z} = \frac{m_b^2}{z} + \frac{m_c^2}{1-z} + \frac{p_\perp^2}{z(1-z)}$$

Final-state shower: $m_b = m_c = 0 \Rightarrow m_a^2 = \frac{p_\perp^2}{z(1-z)} > 0 \Rightarrow$ timelike

Initial-state shower: $m_a = m_c = 0 \Rightarrow m_b^2 = -\frac{p_\perp^2}{1-z} < 0 \Rightarrow$ spacelike

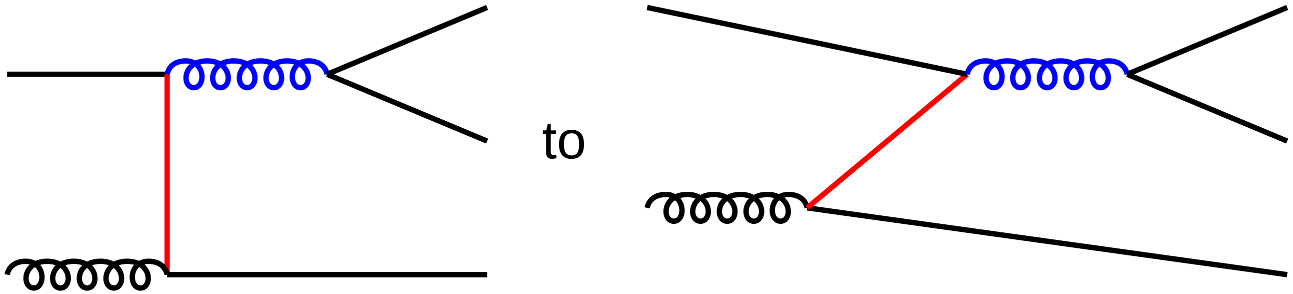
Doublecounting

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



$\mathrm{g} \to \mathrm{q}\overline{\mathrm{q}} \oplus \mathrm{qg} \to \mathrm{qg}$ $\qquad$ $\mathrm{g} \to \mathrm{gg} \oplus \mathrm{gg} \to \mathrm{q}\overline{\mathrm{q}}$

or deform

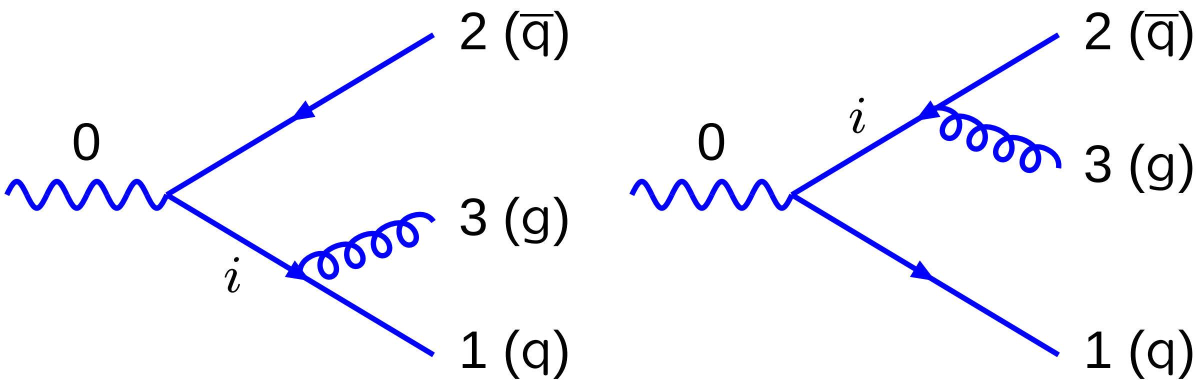


FSR $\qquad$ ISR

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

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

From Matrix Elements to Parton Showers



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

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

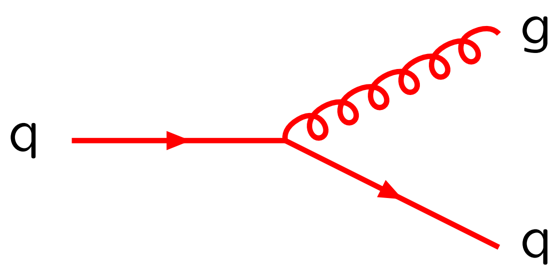
$$m_{\mathrm{q}} = 0: \quad \frac{\mathrm{d}\sigma_{\mathrm{ME}}}{\sigma_0} = \frac{\alpha_{\mathrm{s}}}{2\pi}\,\frac{4}{3}\,\frac{x_1^2 + x_2^2}{(1-x_1)(1-x_2)}\,\mathrm{d}x_1\,\mathrm{d}x_2$$

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

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

$$x_1 \approx z \;\Rightarrow\; \mathrm{d}x_1 \approx \mathrm{d}z$$

$$x_3 \approx 1 - z$$

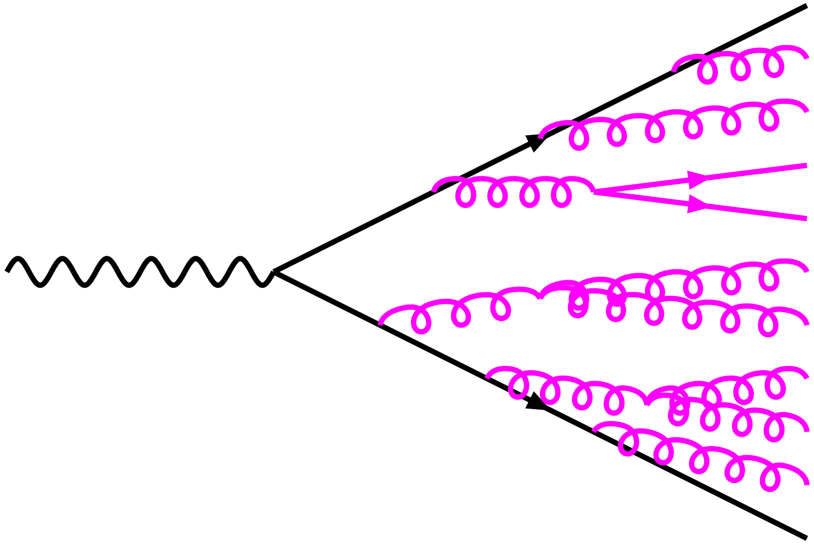


$$\Rightarrow\; \mathrm{d}\mathcal{P} = \frac{\mathrm{d}\sigma}{\sigma_0} = \frac{\alpha_{\mathrm{s}}}{2\pi}\,\frac{\mathrm{d}x_2}{(1-x_2)}\,\frac{4}{3}\,\frac{x_2^2 + x_1^2}{(1-x_1)}\,\mathrm{d}x_1 \approx \frac{\alpha_{\mathrm{s}}}{2\pi}\,\frac{\mathrm{d}Q^2}{Q^2}\,\frac{4}{3}\,\frac{1+z^2}{1-z}\,\mathrm{d}z$$

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

$$
\begin{aligned}
\mathrm{d}\mathcal{P}_{a\to bc} &= \frac{\alpha_{\mathrm{s}}}{2\pi}\,\frac{\mathrm{d}Q^2}{Q^2}\,P_{a\to bc}(z)\,\mathrm{d}z \\
P_{\mathrm{q}\to\mathrm{qg}} &= \frac{4}{3}\,\frac{1+z^2}{1-z} \\
P_{\mathrm{g}\to\mathrm{gg}} &= 3\,\frac{(1-z(1-z))^2}{z(1-z)} \\
P_{\mathrm{g}\to\mathrm{q\overline{q}}} &= \frac{n_f}{2}\,(z^2+(1-z)^2) \quad (n_f = \text{no. of quark flavours})
\end{aligned}
$$

Iteration gives final-state parton showers



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

Details model-dependent, e.g.

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

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

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

The Sudakov Form Factor

Conservation of total probability:

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

"multiplicativeness" in "time" evolution:

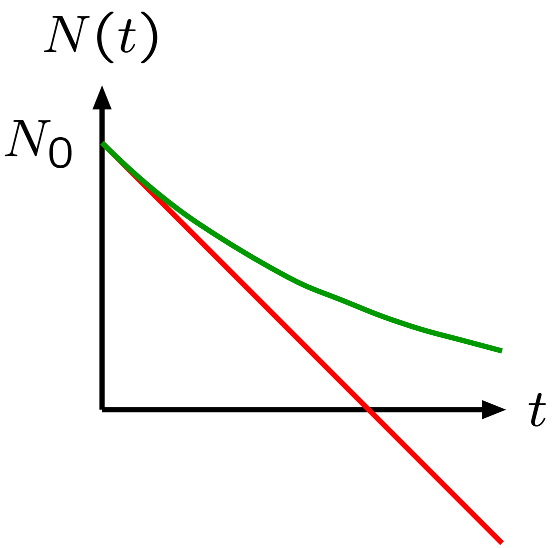
$\mathcal{P}_{\text{nothing}}(0 < t \leq T) = \mathcal{P}_{\text{nothing}}(0 < t \leq T_1)\, \mathcal{P}_{\text{nothing}}(T_1 < t \leq T)$

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

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

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

Example: radioactive decay of nucleus



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

depletion: a given nucleus can only decay once

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

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

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

sequence allowed: nucleus$_1 \to$ nucleus$_2 \to$ nucleus$_3 \to \ldots$

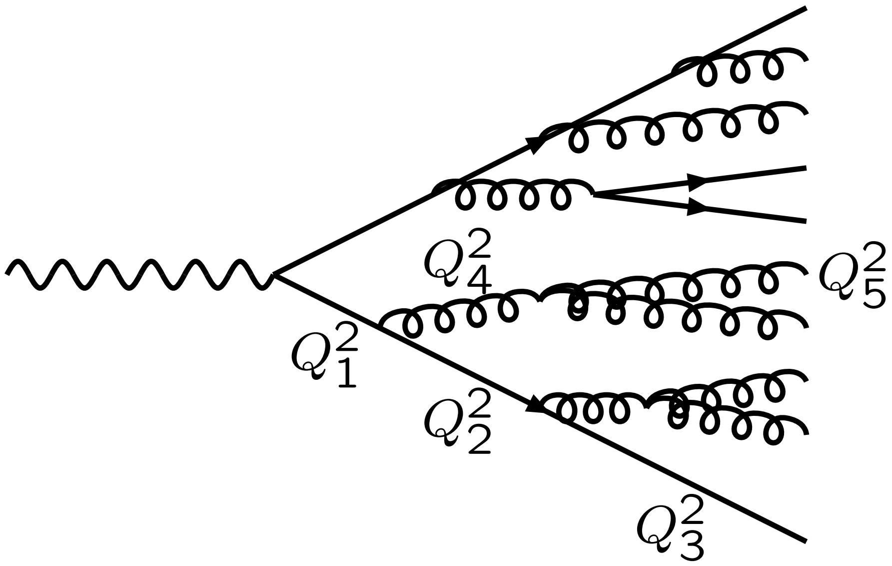
Correspondingly, with $Q \sim 1/t$ (Heisenberg)

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

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

$\boxed{\text{A given parton can only branch once, i.e. if it did not already do so}}$

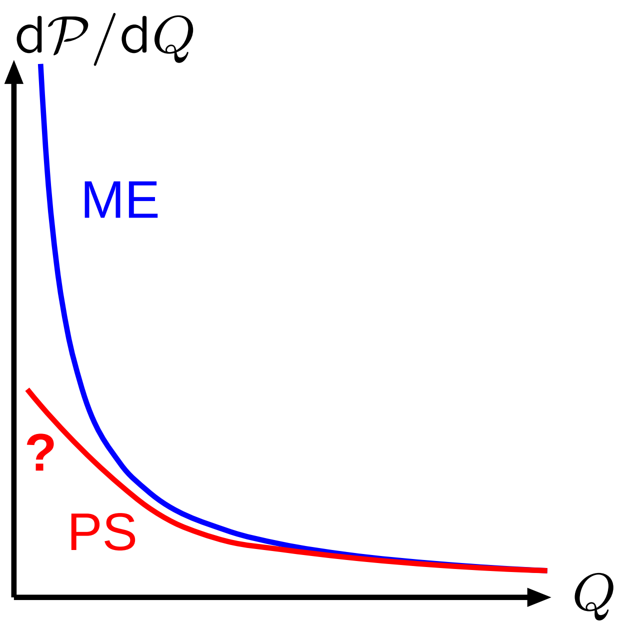
Note that $\sum_{b,c}\int\int\ \mathrm{d}\mathcal{P}_{a\to bc} \equiv 1 \Rightarrow$ *convenient for Monte Carlo*
($\equiv 1$ if extended over whole phase space, else possibly nothing happens)



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

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

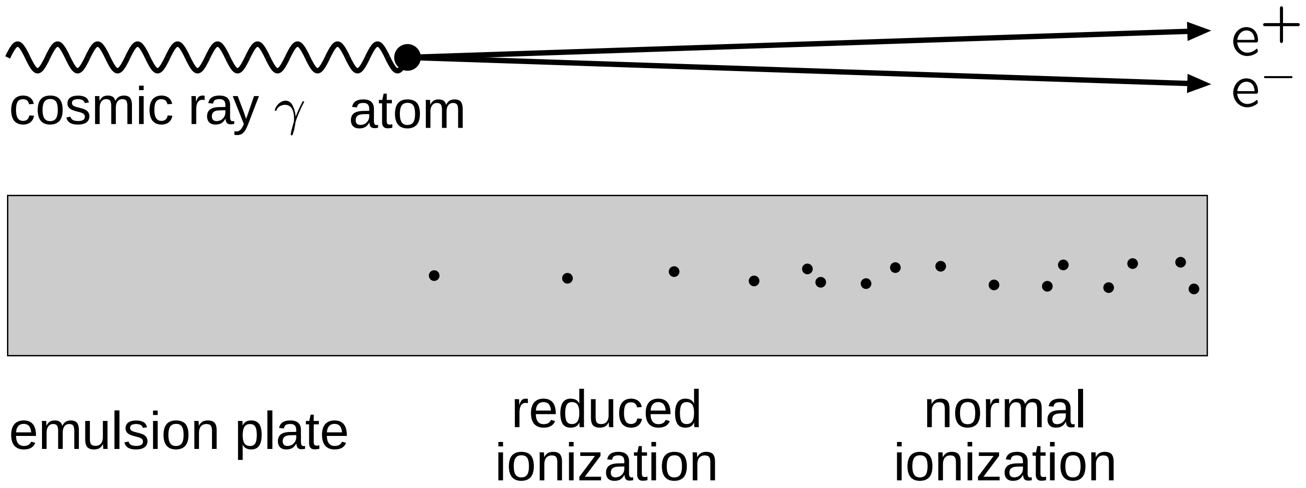
Sudakov regulates singularity for *first* emission . . .



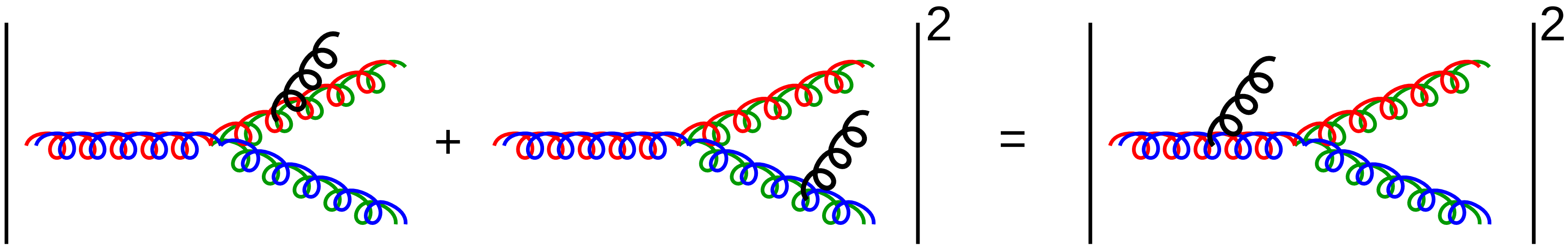
. . . but in limit of *repeated soft* emissions q $\rightarrow$ qg (g $\rightarrow$ gg, g $\rightarrow$ q$\overline{\text{q}}$ not considered) one obtains the same inclusive Q emission spectrum as for ME, i.e. divergent ME spectrum $\Longleftrightarrow$ infinite number of PS emissions

Coherence

QED: Chudakov effect (mid-fifties)



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



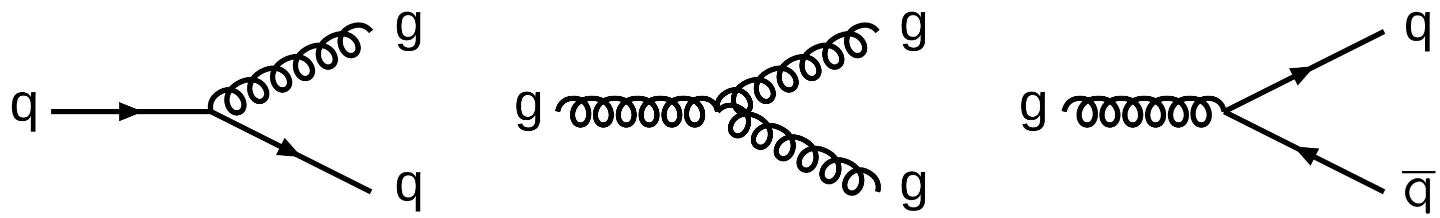
solved by • requiring emission angles to be decreasing

or • requiring transverse momenta to be decreasing

The Common Showering Algorithms

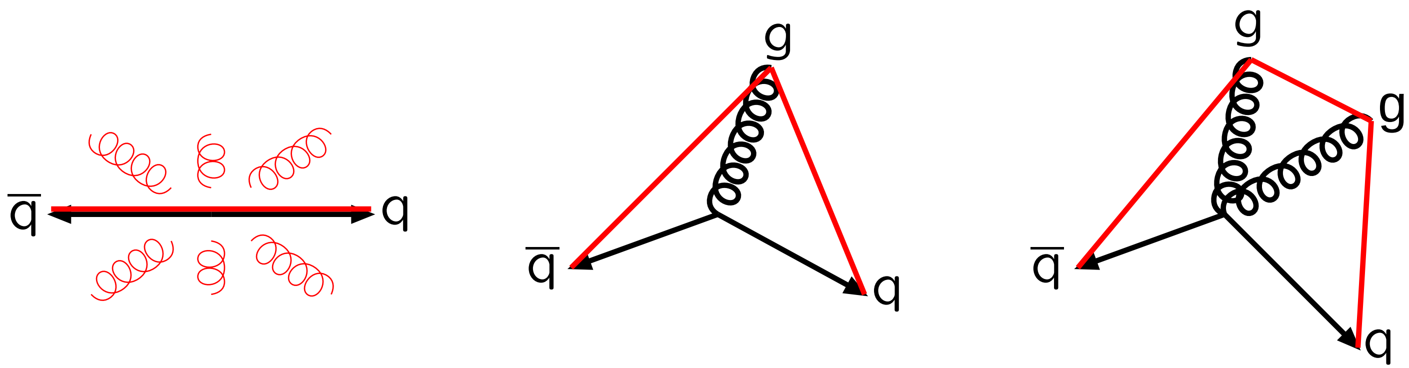
Three main approaches to showering in common use:

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



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

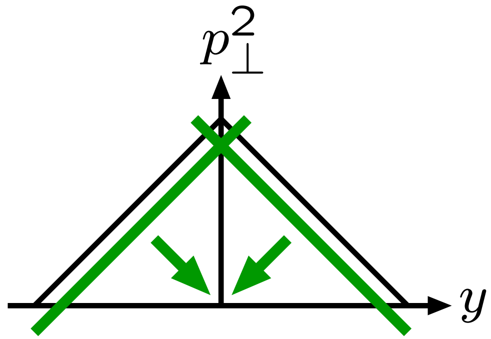
One is based on a picture of dipole emission $ab \to cde$:



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

Ordering variables in final-state radiation

PYTHIA: $Q^2 = m^2$



large mass first

$\Rightarrow$ "hardness" ordered

coherence brute force

covers phase space

ME merging simple

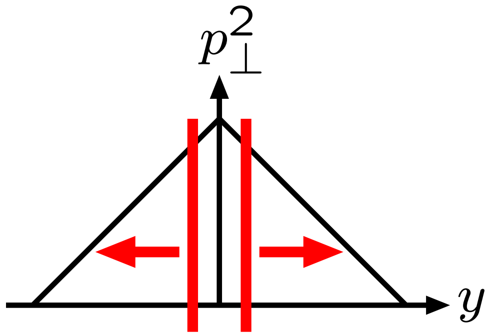
g $\rightarrow$ q$\overline{\text{q}}$ simple

not Lorentz invariant

no stop/restart

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

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



large angle first

$\Rightarrow$ **hardness not ordered**

coherence inherent

gaps in coverage

ME merging messy

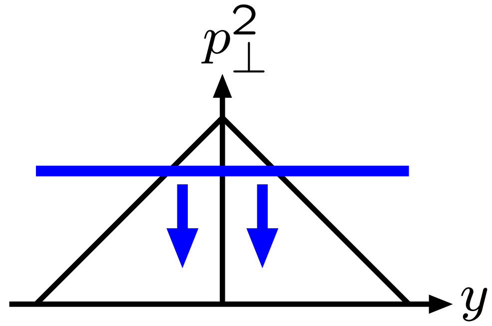
g $\rightarrow$ q$\overline{\text{q}}$ simple

not Lorentz invariant

no stop/restart

ISR: $\theta \rightarrow \theta$

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



large $p_\perp$ first

$\Rightarrow$ "hardness" ordered

coherence inherent

covers phase space

ME merging simple

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

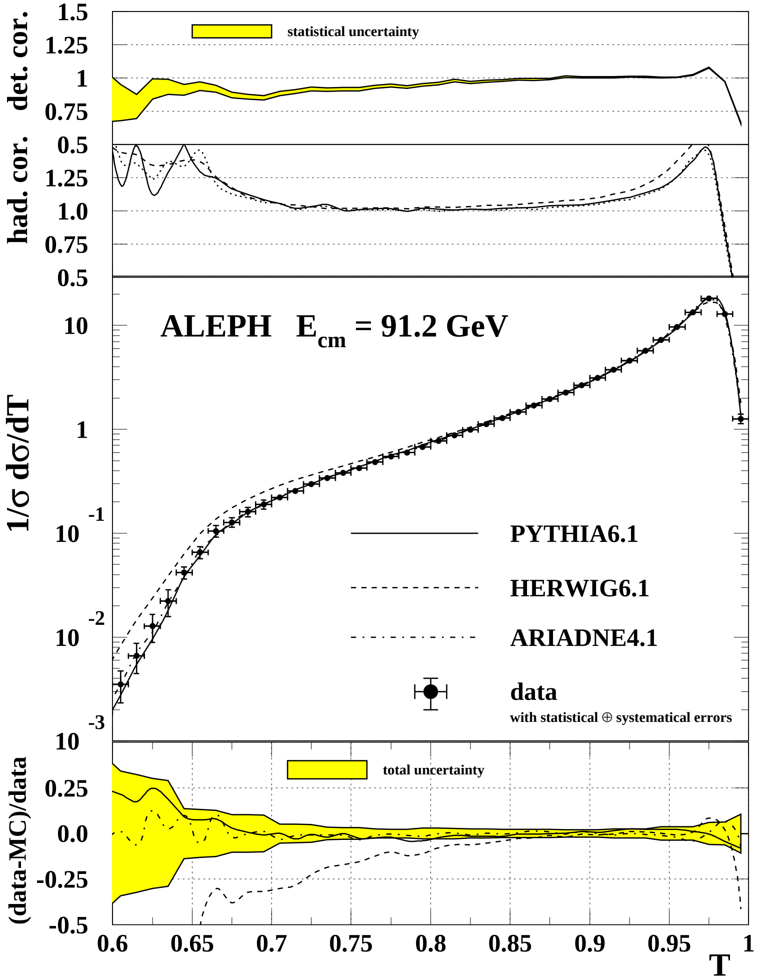
Lorentz invariant

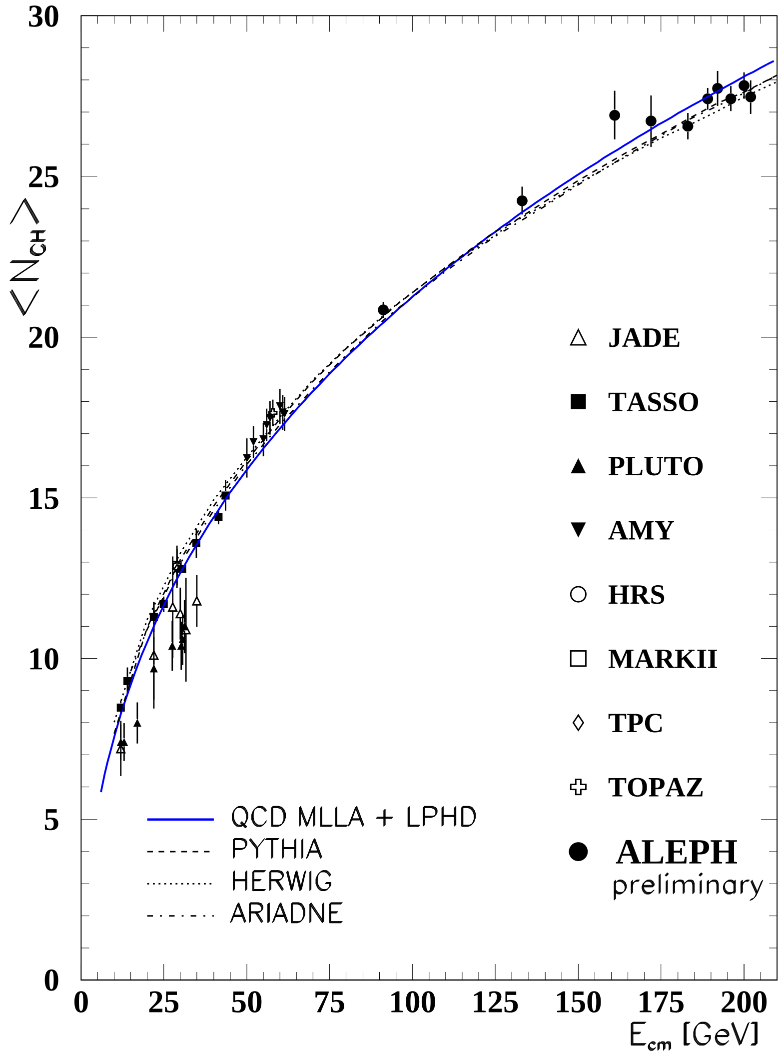
can stop/restart

ISR: more messy

Data comparisons

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





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

Leading Log and Beyond

Neglecting Sudakovs, rate of one emission is:

$$\mathcal{P}_{\mathrm{q}\to\mathrm{qg}} \approx \int \frac{\mathrm{d}Q^2}{Q^2} \int \mathrm{d}z \, \frac{\alpha_{\mathrm{s}}}{2\pi} \frac{4}{3} \frac{1+z^2}{1-z}$$
$$\approx \alpha_{\mathrm{s}} \ln\left(\frac{Q^2_{\mathrm{max}}}{Q^2_{\mathrm{min}}}\right) \frac{8}{3} \ln\left(\frac{1-z_{\mathrm{min}}}{1-z_{\mathrm{max}}}\right) \sim \alpha_{\mathrm{s}} \ln^2$$

Rate for n emissions is of form:

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

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

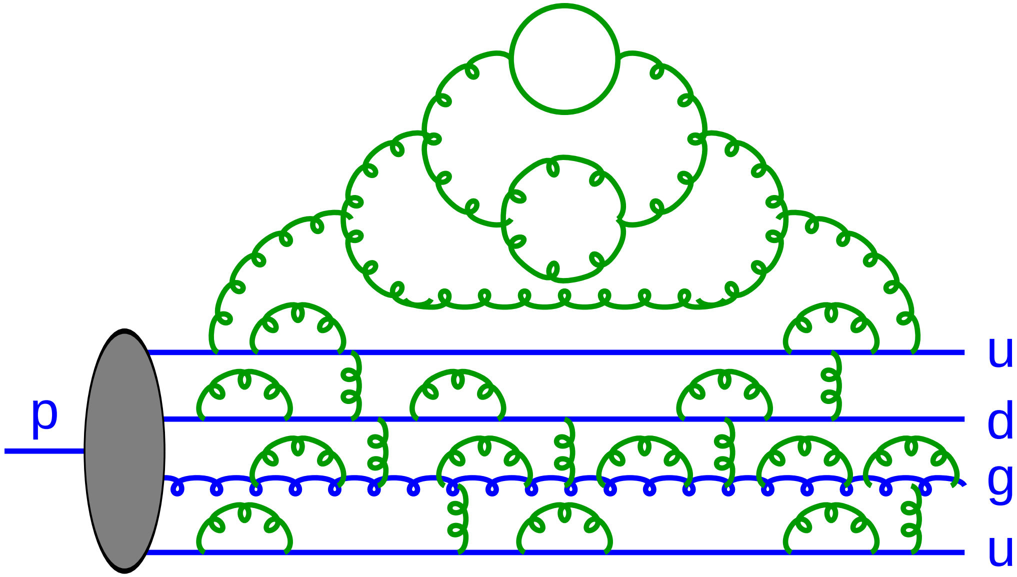
No existing $\mathrm{pp}/\mathrm{p}\overline{\mathrm{p}}$ generator completely NLL, but

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

$\Rightarrow$ far better than naive, analytical LL

Parton Distribution Functions

Hadrons are composite, with time-dependent structure:



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

Linguistics (example):

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

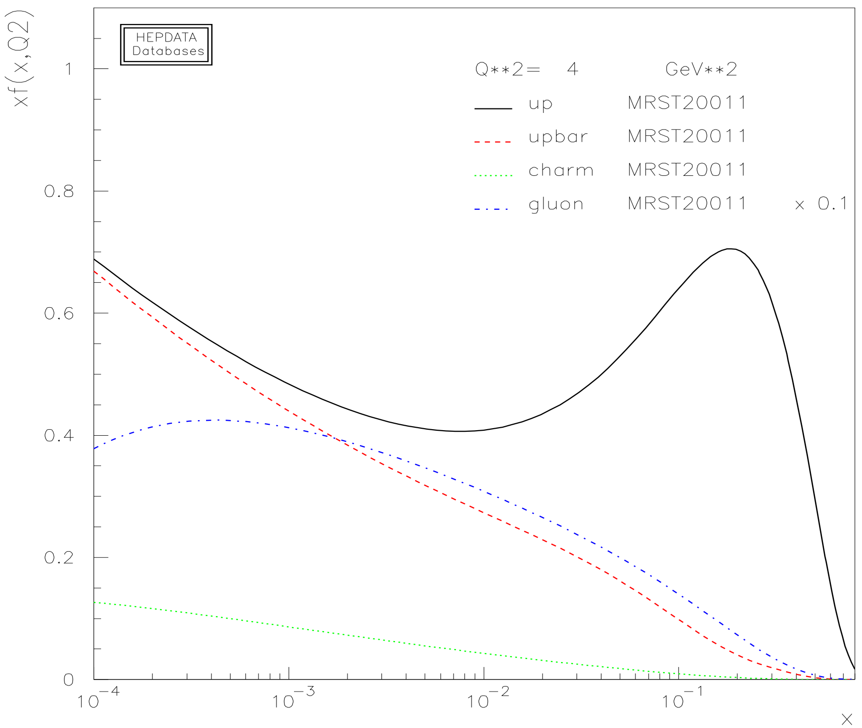
structure function parton distributions

Absolute normalization at small Q_0^2 unknown.

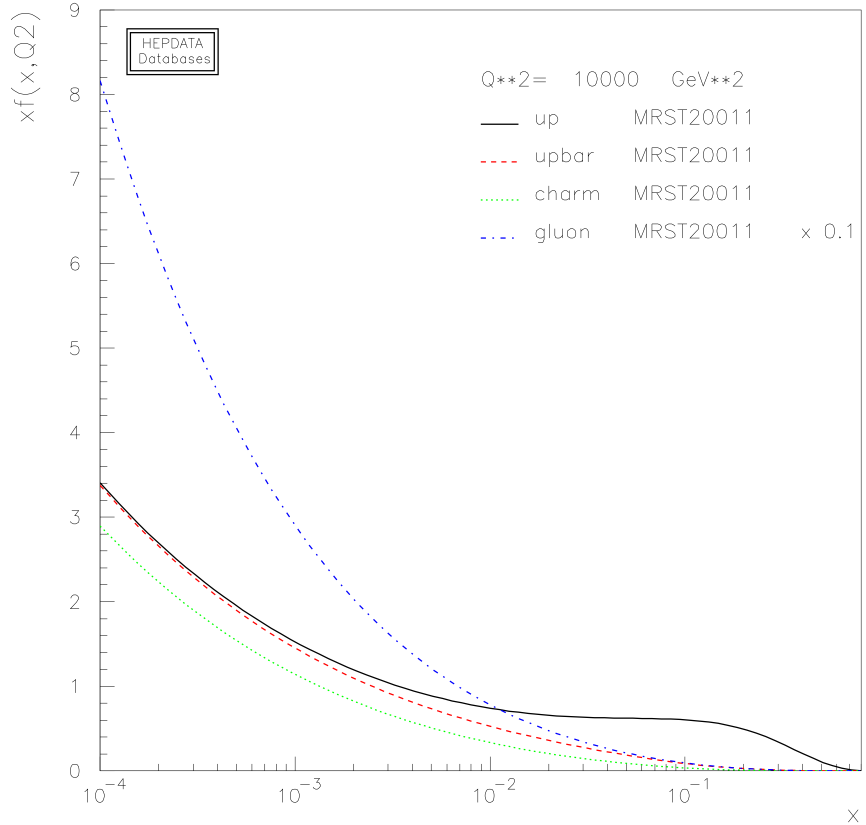
Resolution dependence by DGLAP:

$$\frac{\mathrm{d} f_b(x,Q^2)}{\mathrm{d}(\ln Q^2)} = \sum_a \int_x^1 \frac{\mathrm{d}z}{z}\, f_a(x',Q^2)\, \frac{\alpha_s}{2\pi}\, P_{a\to bc}\left(z=\frac{x}{x'}\right)$$

$Q^2 = 4\ \mathrm{GeV}^2$

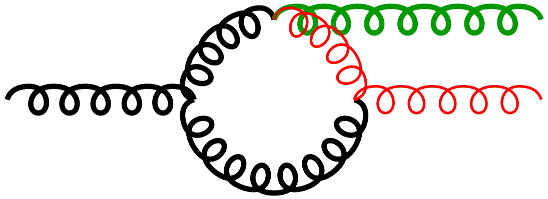


$Q^2 = 10000\ \mathrm{GeV}^2$

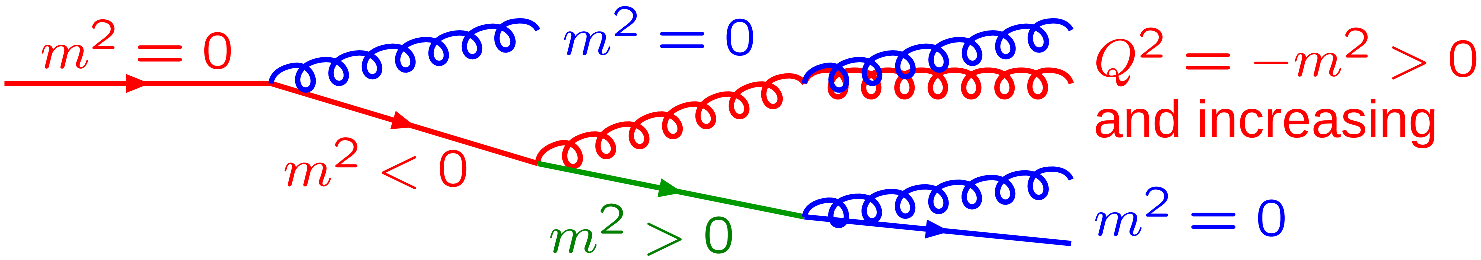


Initial-State Shower Basics

- Parton cascades in p are continuously born and recombined.
- Structure at Q is resolved at a time $t \sim 1/Q$ *before* collision.
- A hard scattering at Q^2 probes fluctuations up to that scale.
- A hard scattering inhibits full recombination of the cascade.



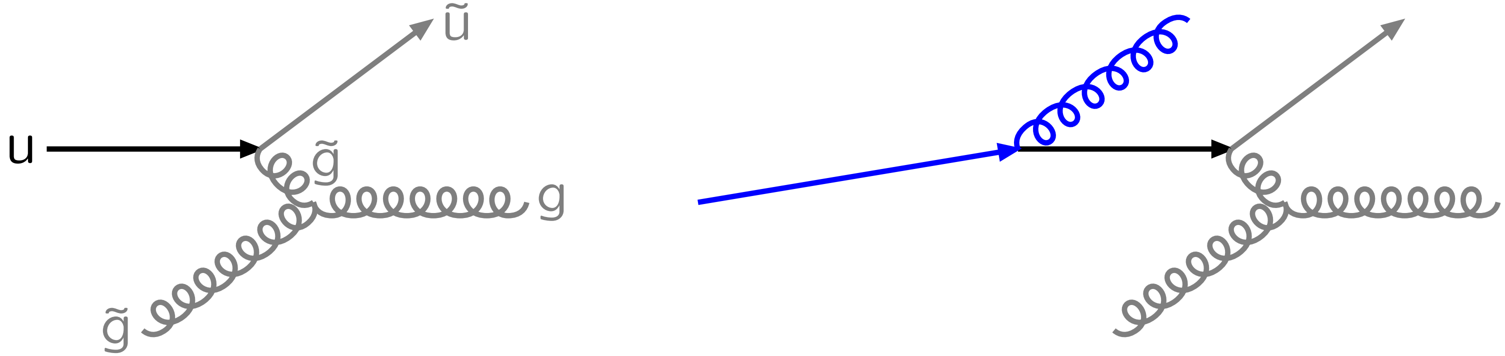
- Convenient reinterpretation:



Event generation could be addressed by **forwards evolution**:
pick a complete partonic set at low Q_0 and evolve, see what happens.
Inefficient:
1) have to evolve and check for *all* potential collisions, but 99.9. . . % inert
2) impossible to steer the production e.g. of a narrow resonance (Higgs)

Backwards evolution

Backwards evolution is viable and $\sim$equivalent alternative:
start at hard interaction and trace what happened "before"



Monte Carlo approach, based on *conditional probability*: recast

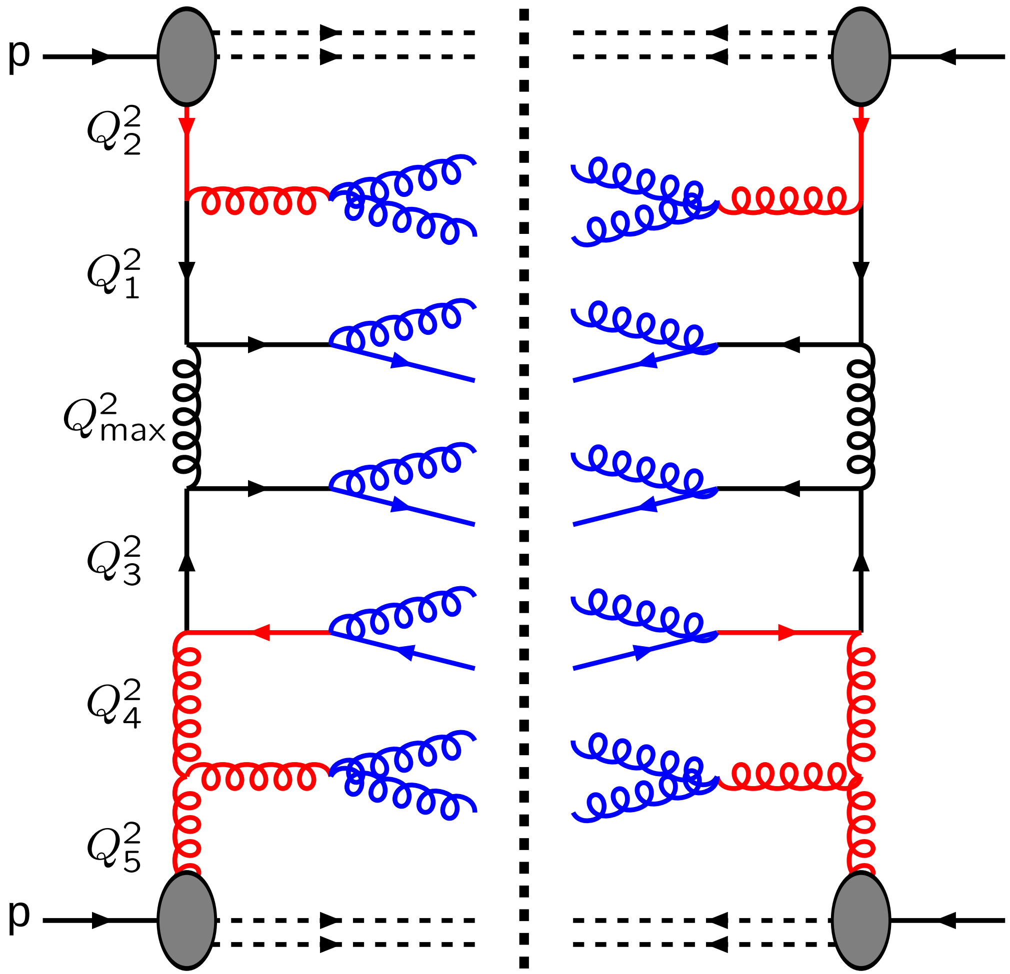
$$\frac{\mathrm{d}f_b(x,Q^2)}{\mathrm{d}t} = \sum_a \int_x^1 \frac{\mathrm{d}z}{z} f_a(x',Q^2) \frac{\alpha_s}{2\pi} P_{a\to bc}(z)$$

with $t = \ln(Q^2/\Lambda^2)$ and $z = x/x'$ to

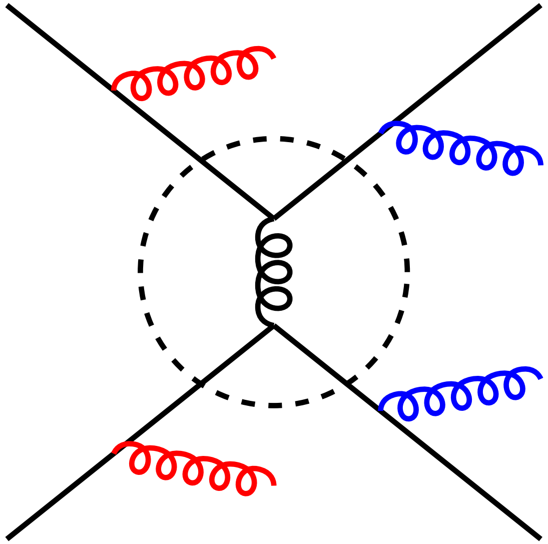
$$\mathrm{d}\mathcal{P}_b = \frac{\mathrm{d}f_b}{f_b} = |\mathrm{d}t| \sum_a \int \mathrm{d}z \frac{x' f_a(x',t)}{x f_b(x,t)} \frac{\alpha_s}{2\pi} P_{a\to bc}(z)$$

then solve for *de*creasing t, i.e. backwards in time,
starting at high Q^2 and moving towards lower,
with Sudakov form factor $\exp(-\int \mathrm{d}\mathcal{P}_b)$

Ladder representation combines whole event:



cf. previously:



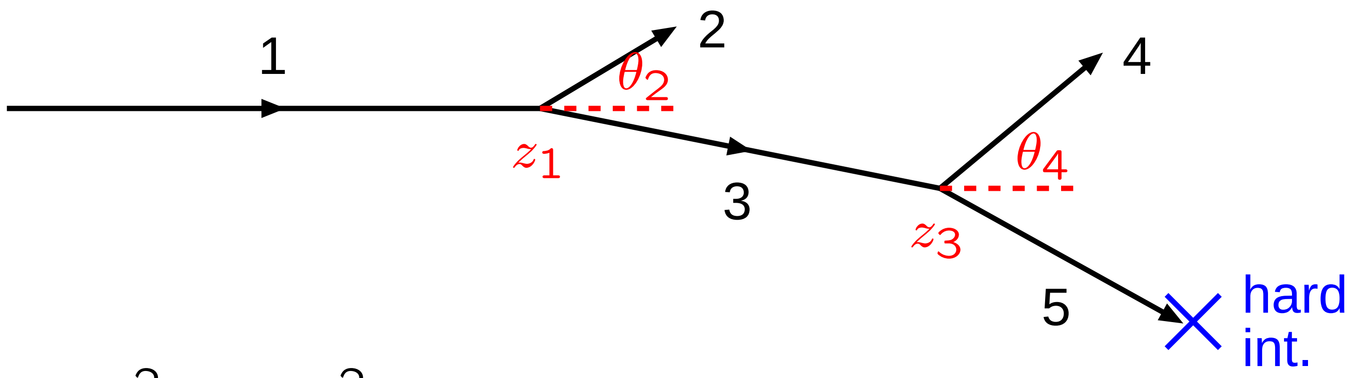
DGLAP: $Q^2_{\mathrm{max}} > Q_1^2 > Q_2^2 \sim Q_0^2$

$Q^2_{\mathrm{max}} > Q_3^2 > Q_4^2 > Q_5^2 \sim Q_0^2$

One possible
Monte Carlo order:

1) Hard scattering
2) Initial-state shower
   from center outwards
3) Final-state showers

Coherence in spacelike showers



$z_1 = E_3/E_1$
$z_3 = E_5/E_3$
$\theta_2 = \theta_{12}$
$\theta_4 = \theta_{14}$!!

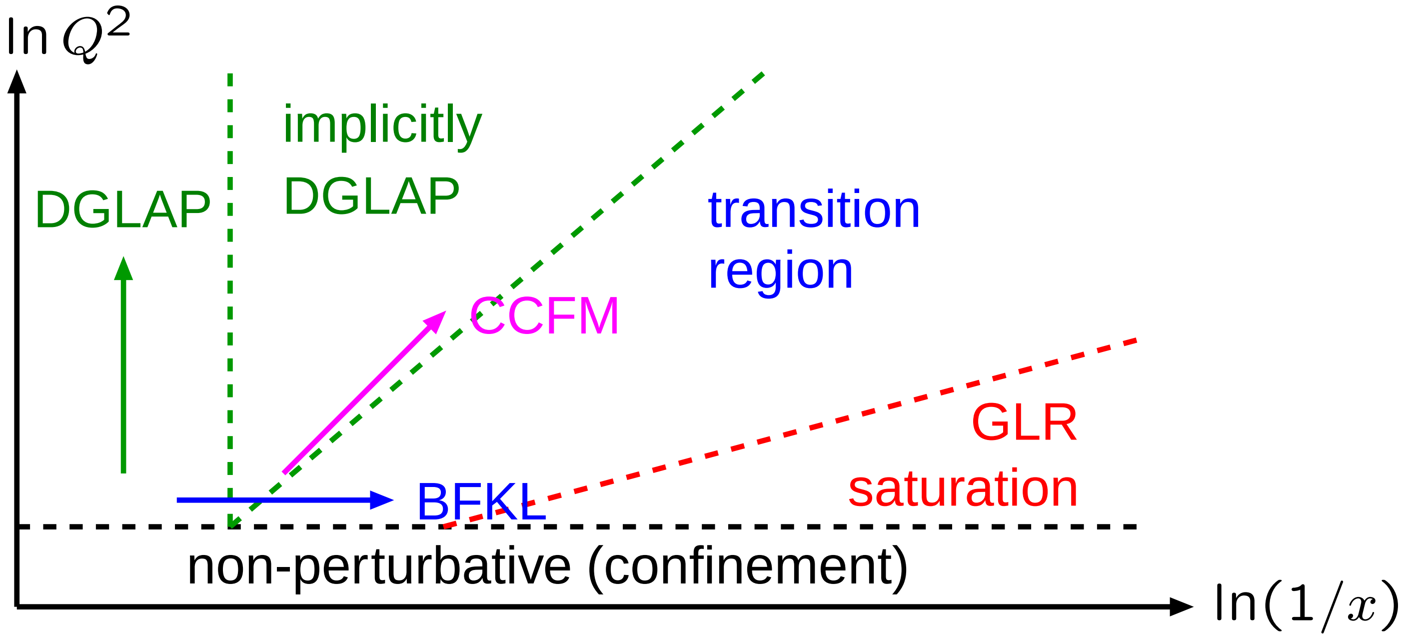
with $Q^2 = -m^2 =$ spacelike virtuality

- kinematics only:
  $Q_3^2 > z_1 Q_1^2$, $Q_5^2 > z_3 Q_3^2$, $\ldots$
  i.e. Q_i^2 need not even be ordered

- coherence of leading collinear singularities:
  $Q_5^2 > Q_3^2 > Q_1^2$, i.e. Q^2 ordered

- coherence of leading soft singularities (more messy):
  $E_3\theta_4 > E_1\theta_2$, i.e. $z_1\theta_4 > \theta_2$
  $z \ll 1$: $E_1\theta_2 \approx p_{\perp 2}^2 \approx Q_3^2$, $E_3\theta_4 \approx p_{\perp 4}^2 \approx Q_5^2$
  i.e. reduces to Q^2 ordering as above
  $z \approx 1$: $\theta_4 > \theta_2$, i.e. angular ordering of soft gluons
  $\Longrightarrow$ reduced phase space

Evolution procedures



DGLAP: Dokshitzer–Gribov–Lipatov–Altarelli–Parisi
evolution towards larger Q^2 and (implicitly) towards smaller x

BFKL: Balitsky–Fadin–Kuraev–Lipatov
evolution towards smaller x (with small, unordered Q^2)

CCFM: Ciafaloni–Catani–Fiorani–Marchesini
interpolation of DGLAP and BFKL

GLR: Gribov–Levin–Ryskin
nonlinear equation in dense-packing (saturation) region,
where partons recombine, not only branch

Initial-State Shower Comparison

Two(?) CCFM Generators:

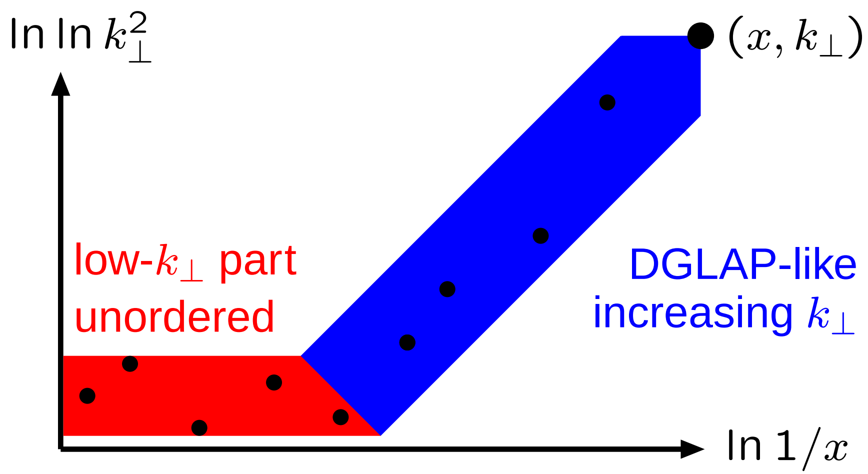
(SMALLX (Marchesini, Webber))

CASCADE (Jung, Salam)

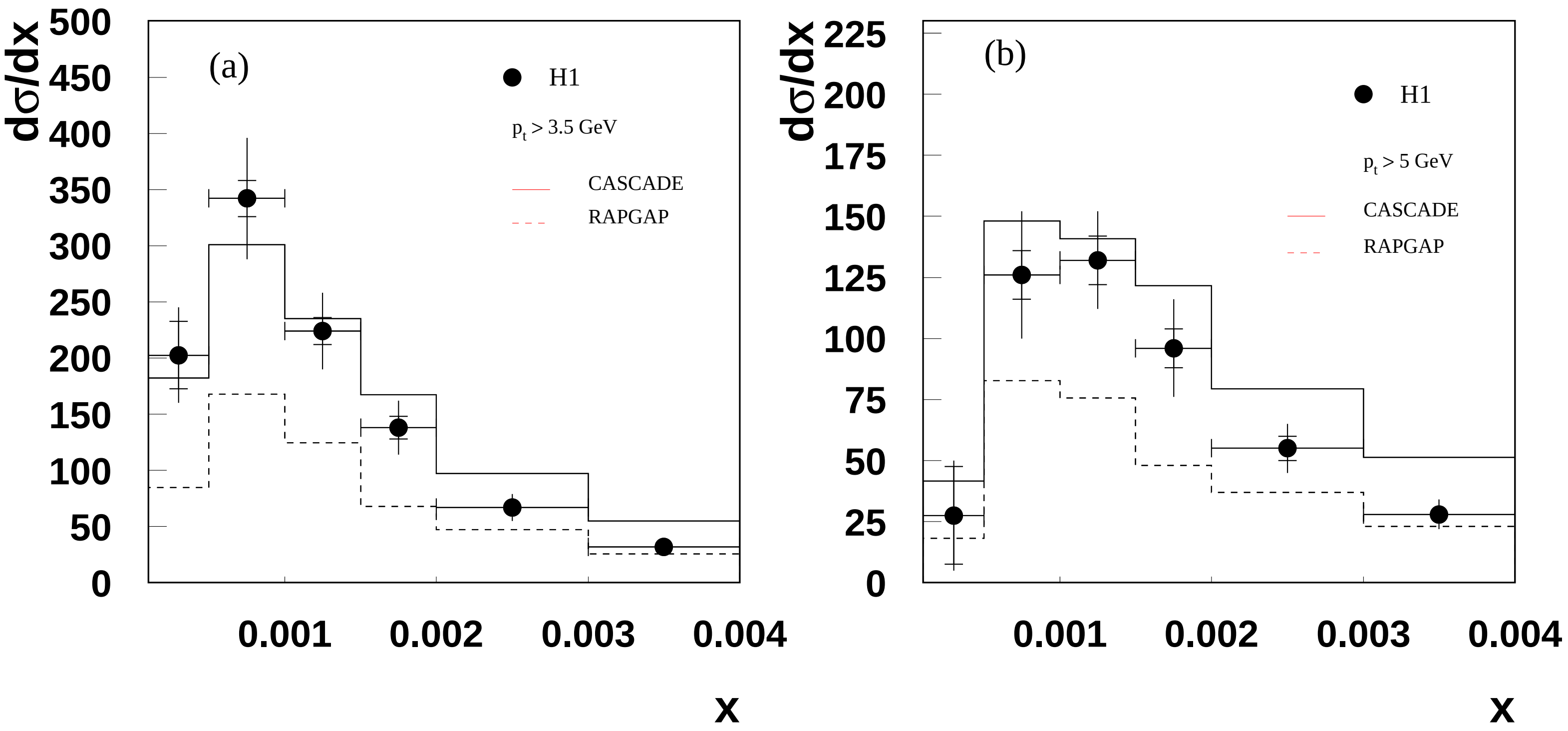
LDC (Gustafson, Lönnblad):

reformulated initial/final rad.

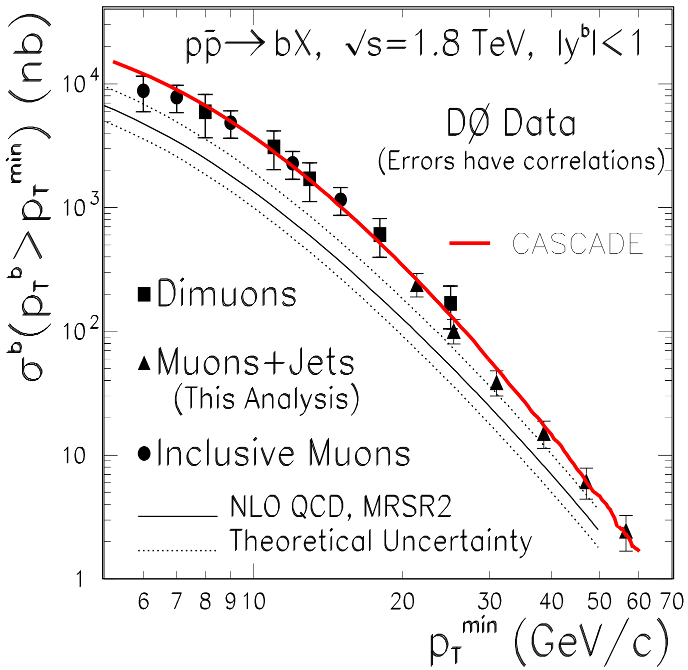
$\Longrightarrow$ eliminate non-Sudakov

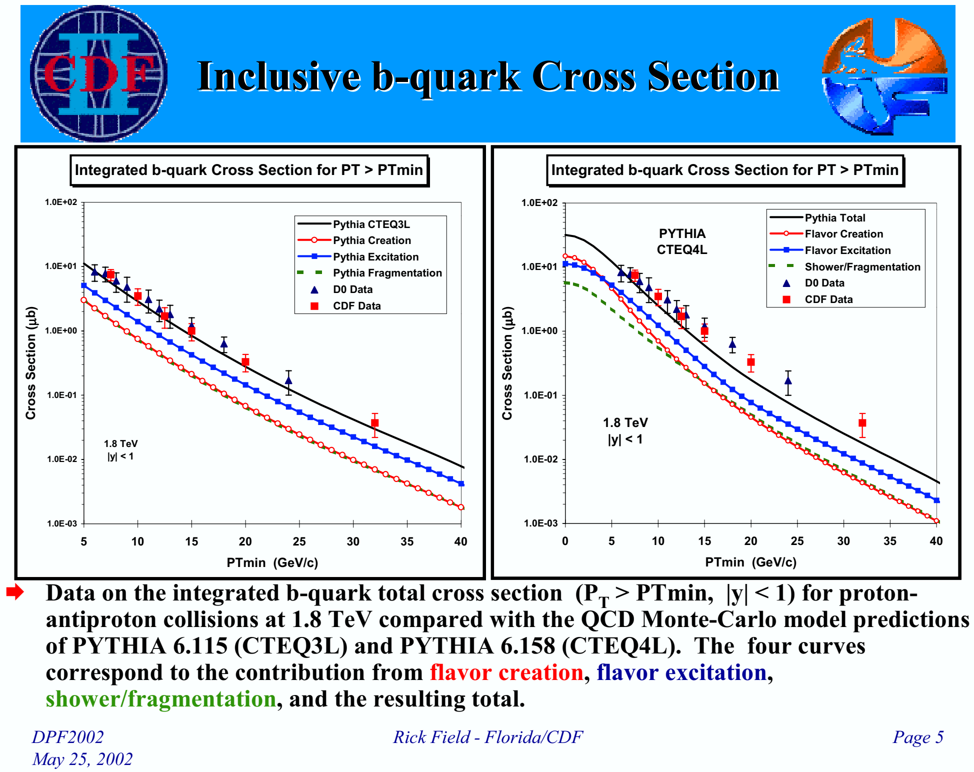


Test 1) forward (= p direction) jet activity at HERA



2) Heavy flavour production





but also explained by DGLAP with leading order pair creation
+ flavour excitation ($\approx$ unordered chains)
+ gluon splitting (final-state radiation)

CCFM requires off-shell ME's + unintegrated parton densities

$$F(x,Q^2) = \int^{Q^2} \frac{\mathrm{d}k_\perp^2}{k_\perp^2} \mathcal{F}(x,k_\perp^2) + (\text{suppressed with } k_\perp^2 > Q^2)$$

so not ready for prime time in pp

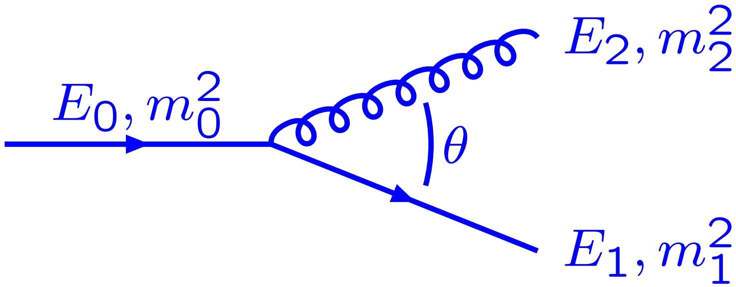
Initial- vs. final-state showers

Both controlled by same evolution equations

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

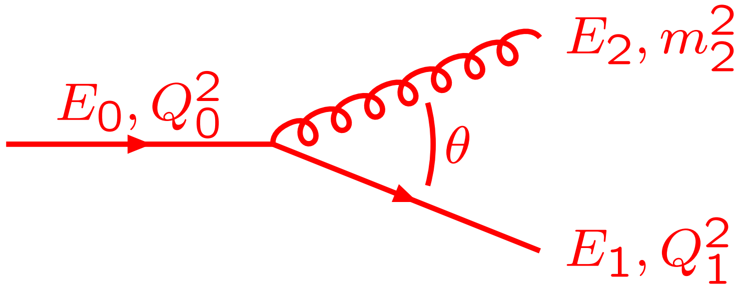
but

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



decreasing E, m^2, θ
both daughters $m^2 \geq 0$
physics relatively simple
$\Rightarrow$ "minor" variations:
Q^2, shower vs. dipole, . . .

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



decreasing E, increasing Q^2, θ
one daughter $m^2 \geq 0$, one $m^2 < 0$
physics more complicated
$\Rightarrow$ more formalisms:
DGLAP, BFKL, CCFM, GLR, . . .

Future of showers

Showers still evolving:

HERWIG has new evolution variable better suited for heavy particles

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

Gives smooth coverage of soft-gluon region, no overlapping regions in FSR phase space, but larger dead region.

PYTHIA is moving to transverse-momentum ordered showers (borrowing some of ARIADNE dipole approach, but still showers)

$p^2_{\perp\mathrm{evol}} = z(1-z)Q^2 = z(1-z)M^2$ for FSR

$p^2_{\perp\mathrm{evol}} = (1-z)Q^2 = (1-z)(-M^2)$ for ISR

Guarantees better coherence for FSR, hopefully also better for ISR.

However, main evolution is *matching to matrix elements* $\Rightarrow$ tomorrow