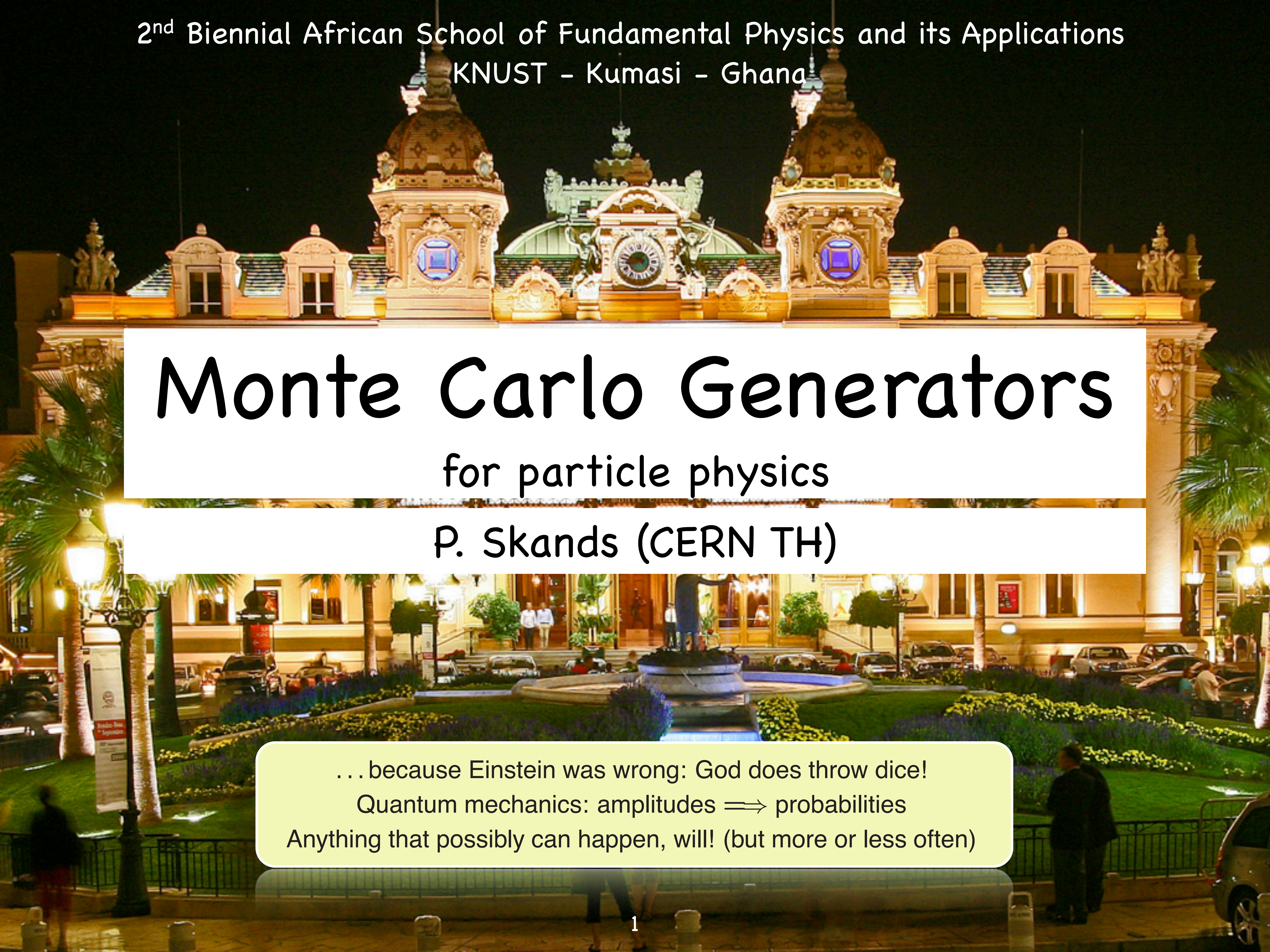


2nd Biennial African School of Fundamental Physics and its Applications
KNUST - Kumasi - Ghana

Monte Carlo Generators

for particle physics

P. Skands (CERN TH)

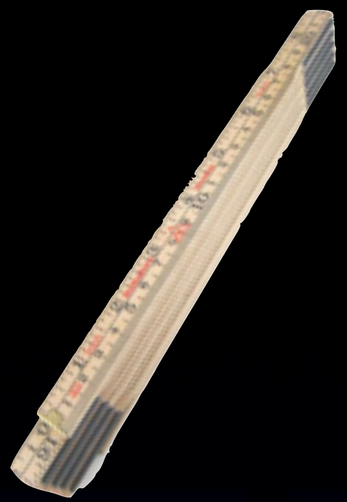
. . . because Einstein was wrong: God does throw dice!
Quantum mechanics: amplitudes $\Longrightarrow$ probabilities
Anything that possibly can happen, will! (but more or less often)

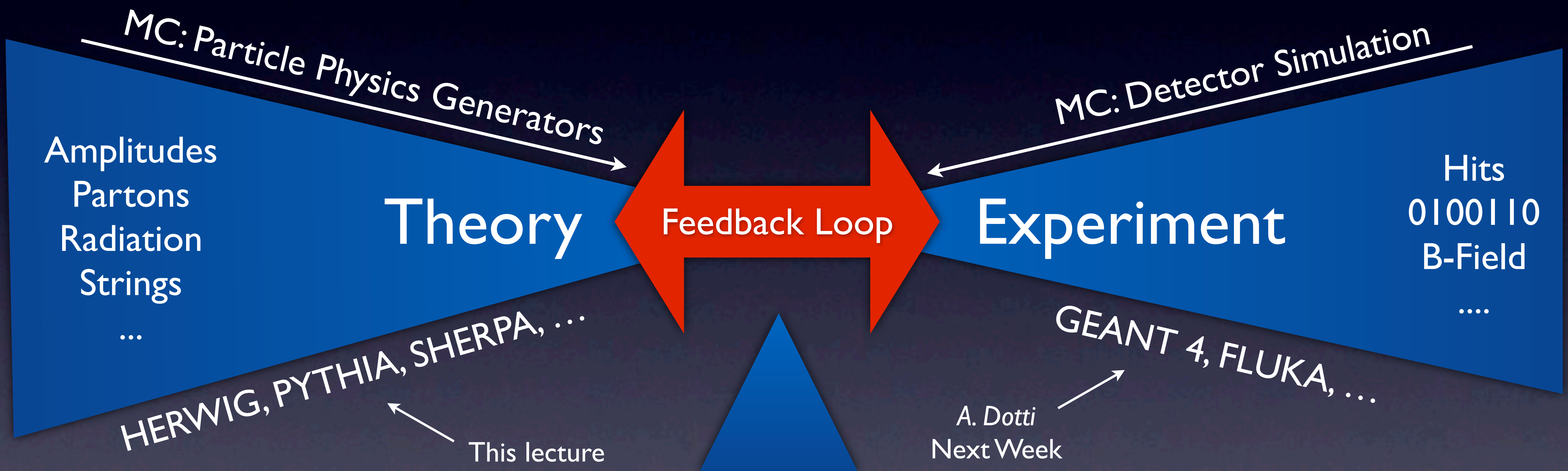
G. Galilei
1564 - 1642

Count what is Countable

Measure what is Measurable

(and keep working on the beam)





Theory: Need predictions for “physical observables”
Experiment: Need simulated events to study detector response

From Theory to Experiment

- **High-Energy Physics: Theory** (see lectures by *J. Govaerts*)
  - Parton-parton scattering cross sections (parton = quark or gluon + sometimes leptons too)
  - Calculated by expansion of quantum field theory around zero coupling → perturbation theory
  - Truncate perturbative series at first non-zero term → lowest order

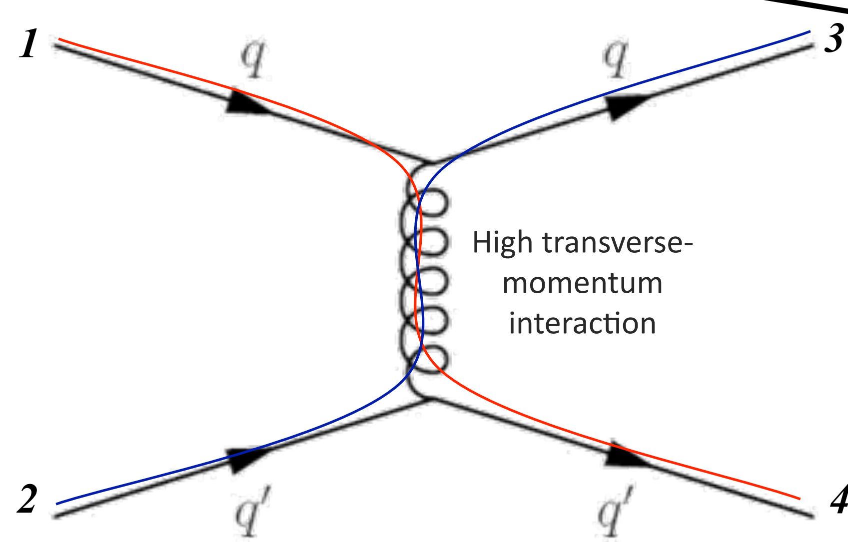
$$\mathrm{qq}' \to \mathrm{qq}' \quad : \quad \frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}\hat{t}} = \frac{\pi}{\hat{s}^2}\frac{4}{9}\alpha_{\mathrm{s}}^2\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}$$

Standard "Mandelstam" variables for kinematics of 2→2 Scattering

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

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

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

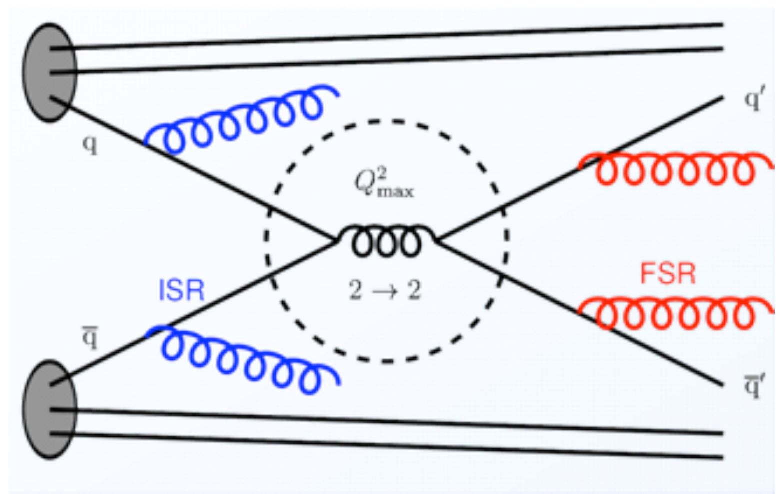


Feynman Diagram
→ *(with time flowing horizontally)* →

Ernest Rutherford,
1st Baron Rutherford of Nelson
(1871-1937)

From Theory to Experiment

Monte Carlo Generators



Calculate Everything → requires compromise!

Include the 'most significant' corrections → simulate complete events

1. *Parton Showers*
2. *Matching*
3. *Hadronisation*
4. *The Underlying Event*

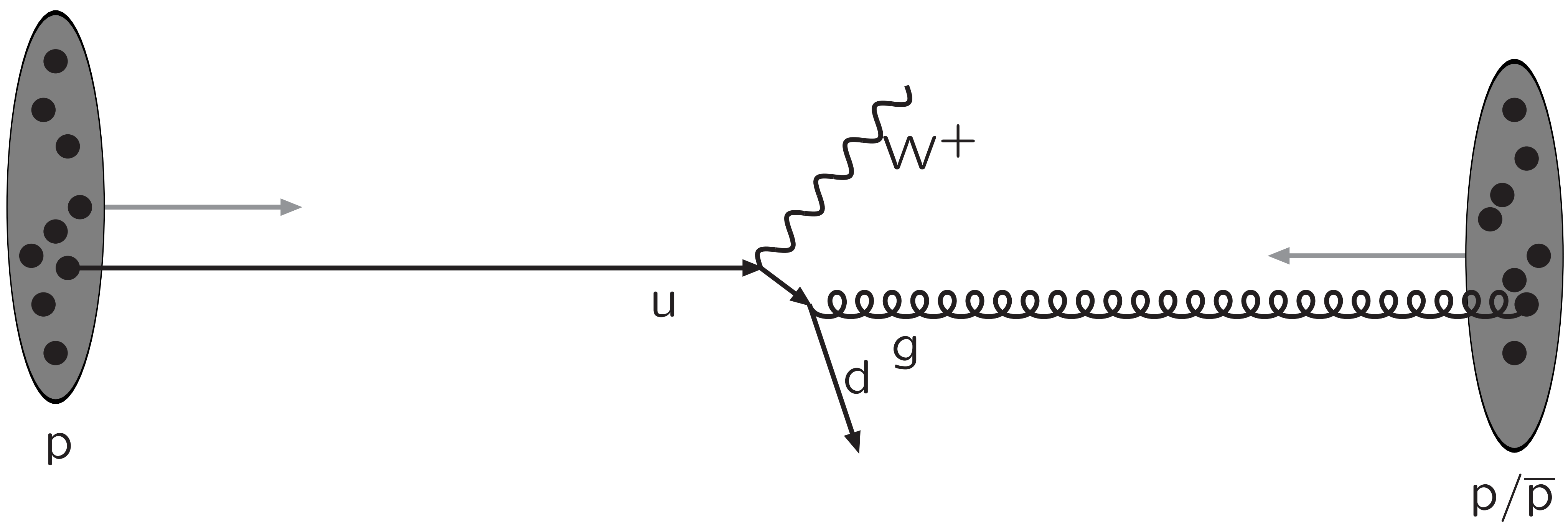
Simulated 'events'

(+ many other ingredients: resonance decays, beam remnants, Bose-Einstein, …)

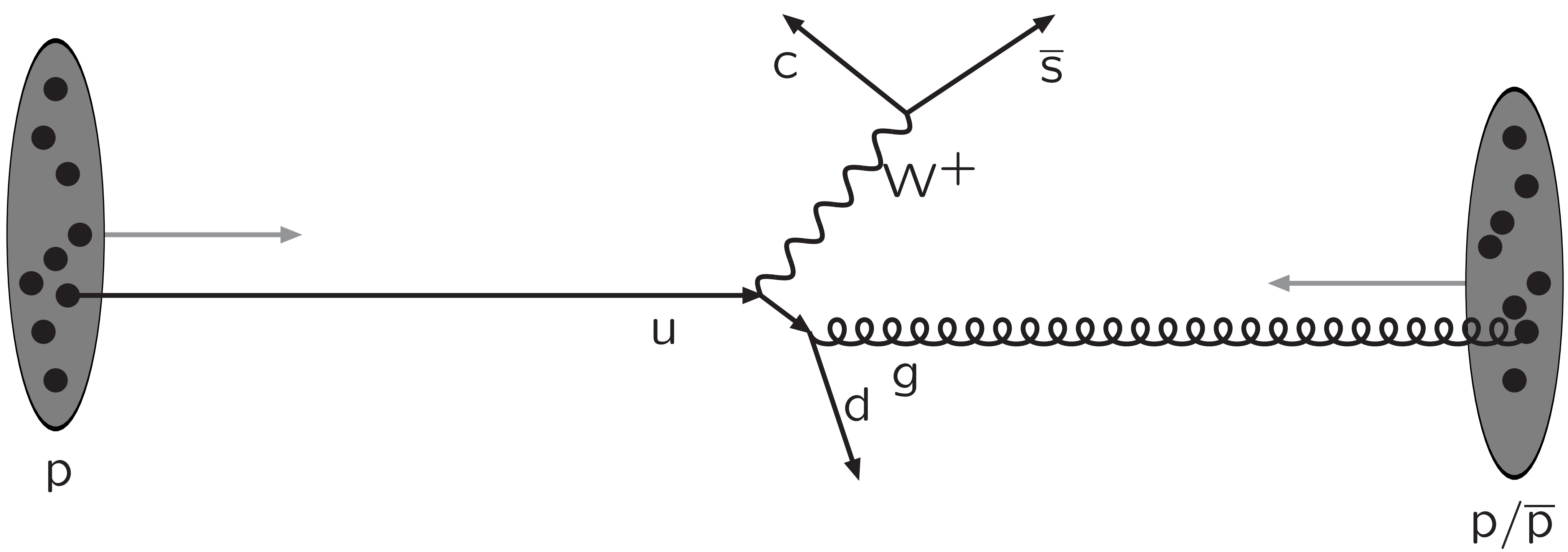
The structure of an event

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

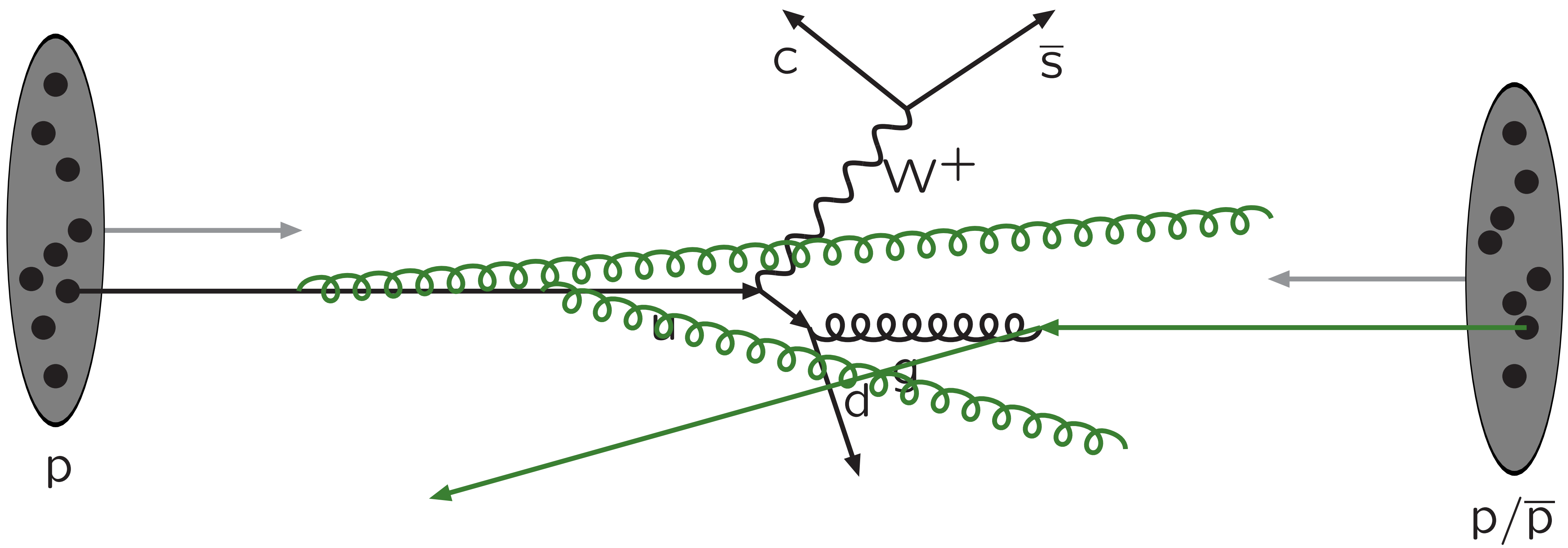
Incoming beams: parton densities



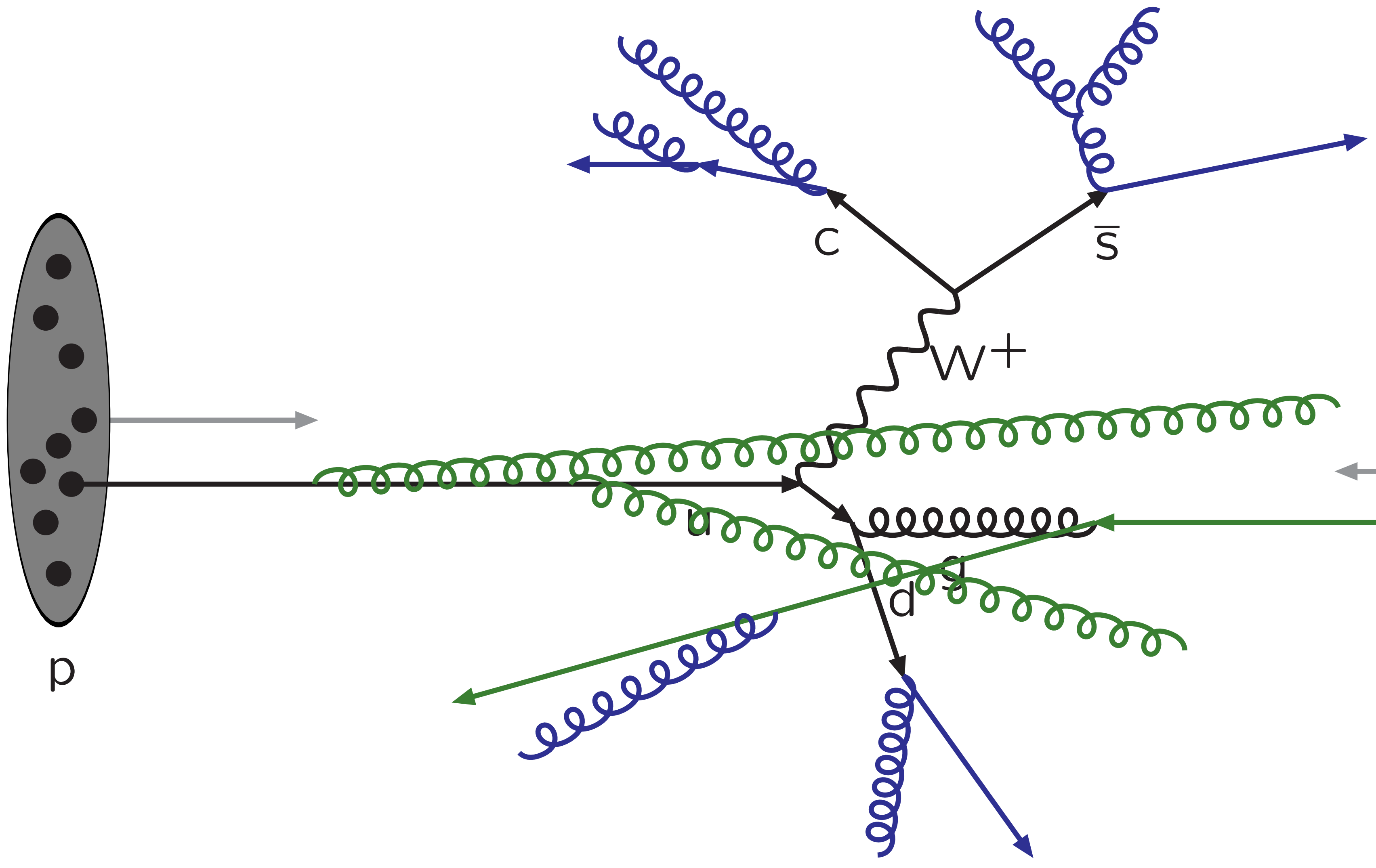
Hard subprocess: described by matrix elements



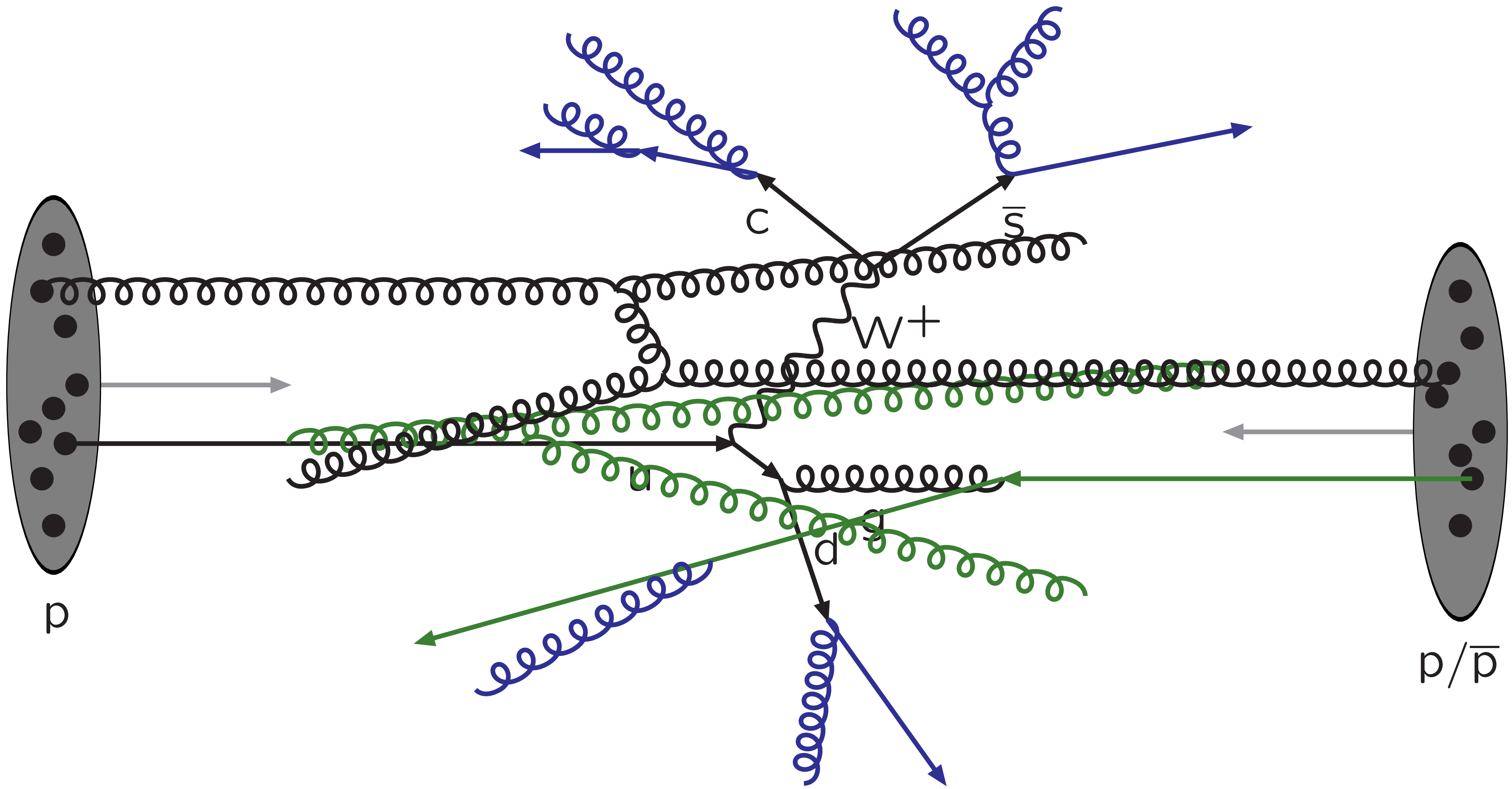
Resonance decays: correlated with hard subprocess



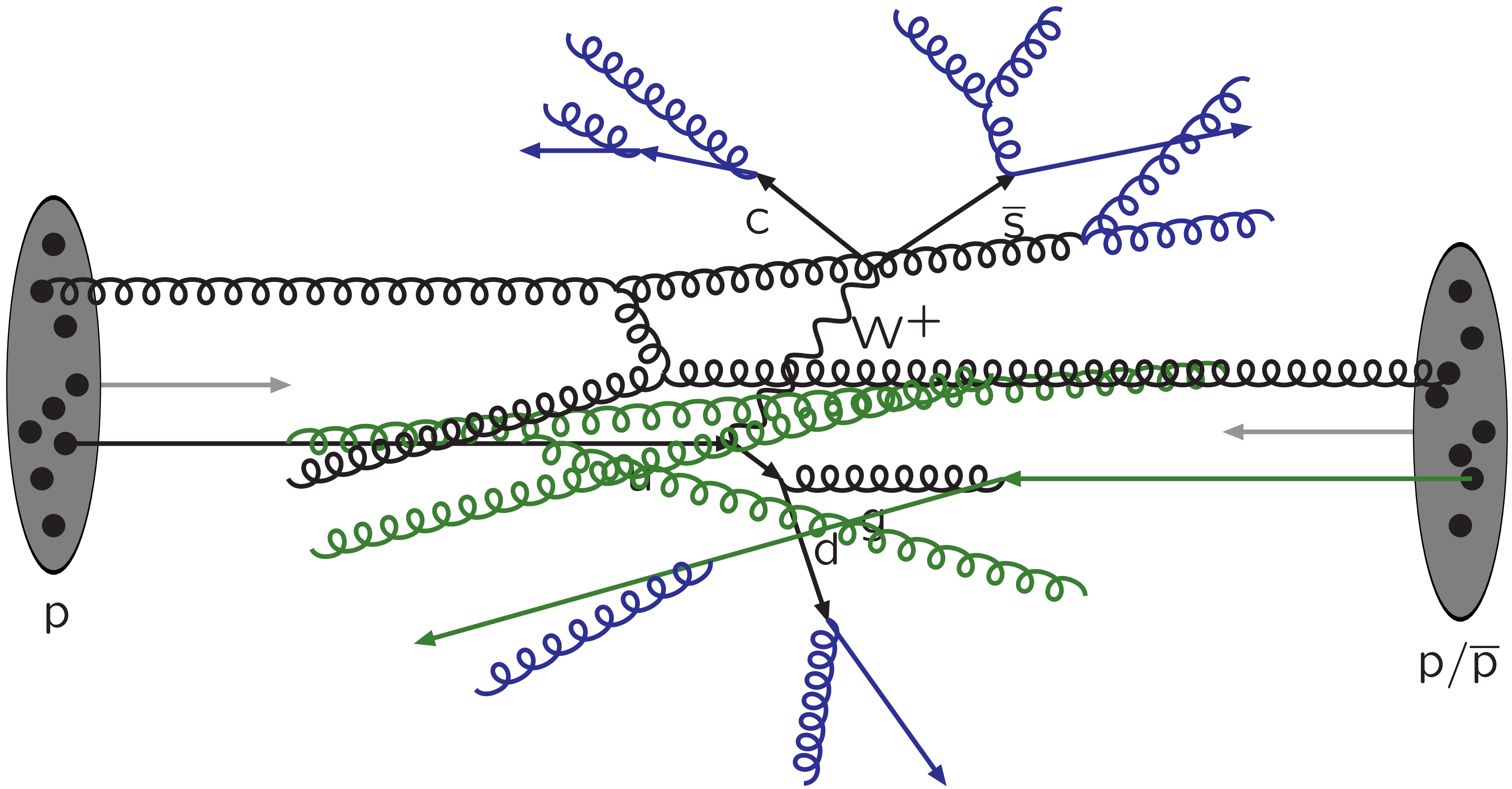
Initial-state radiation: spacelike parton showers



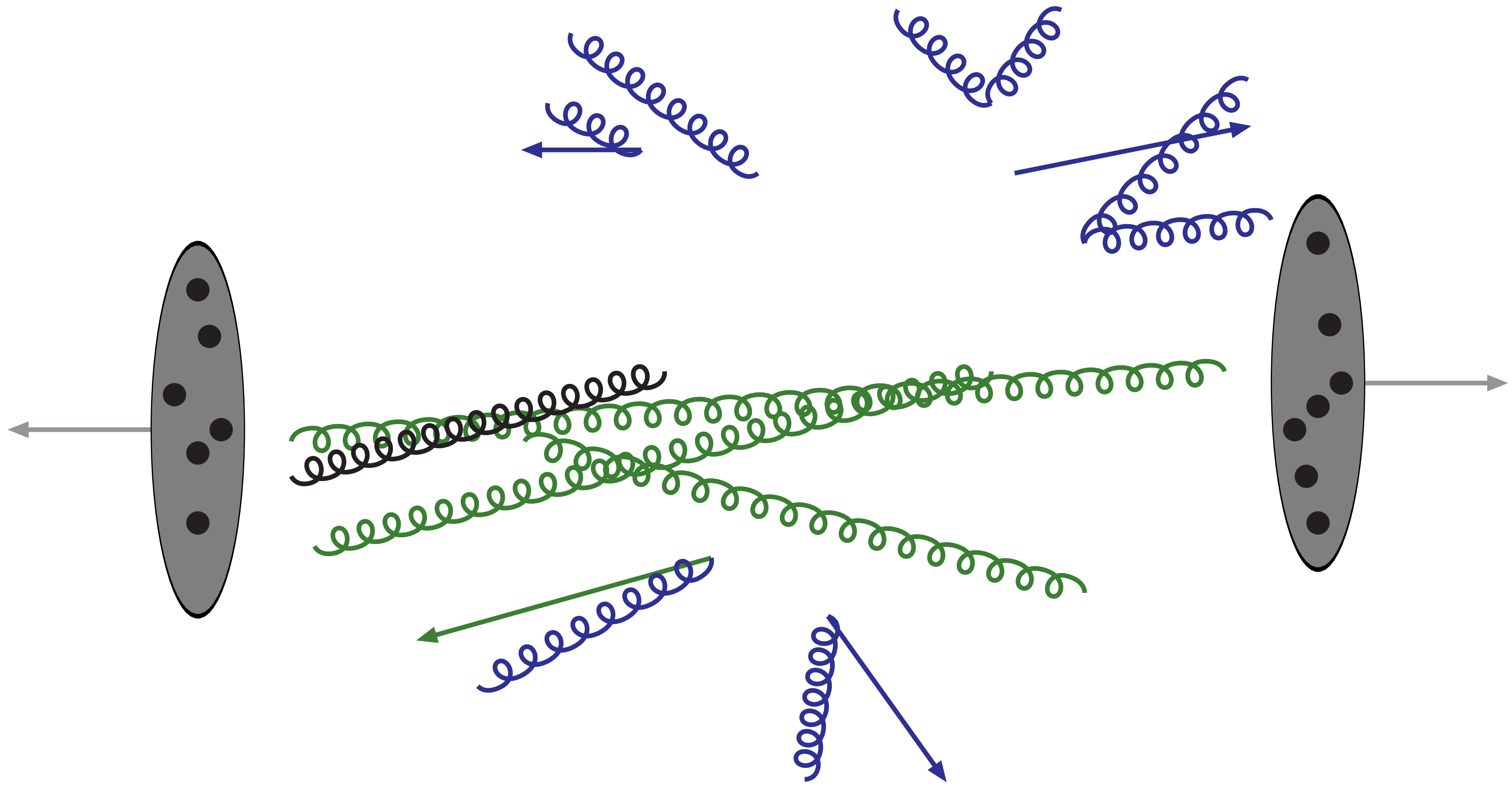
Final-state radiation: timelike parton showers



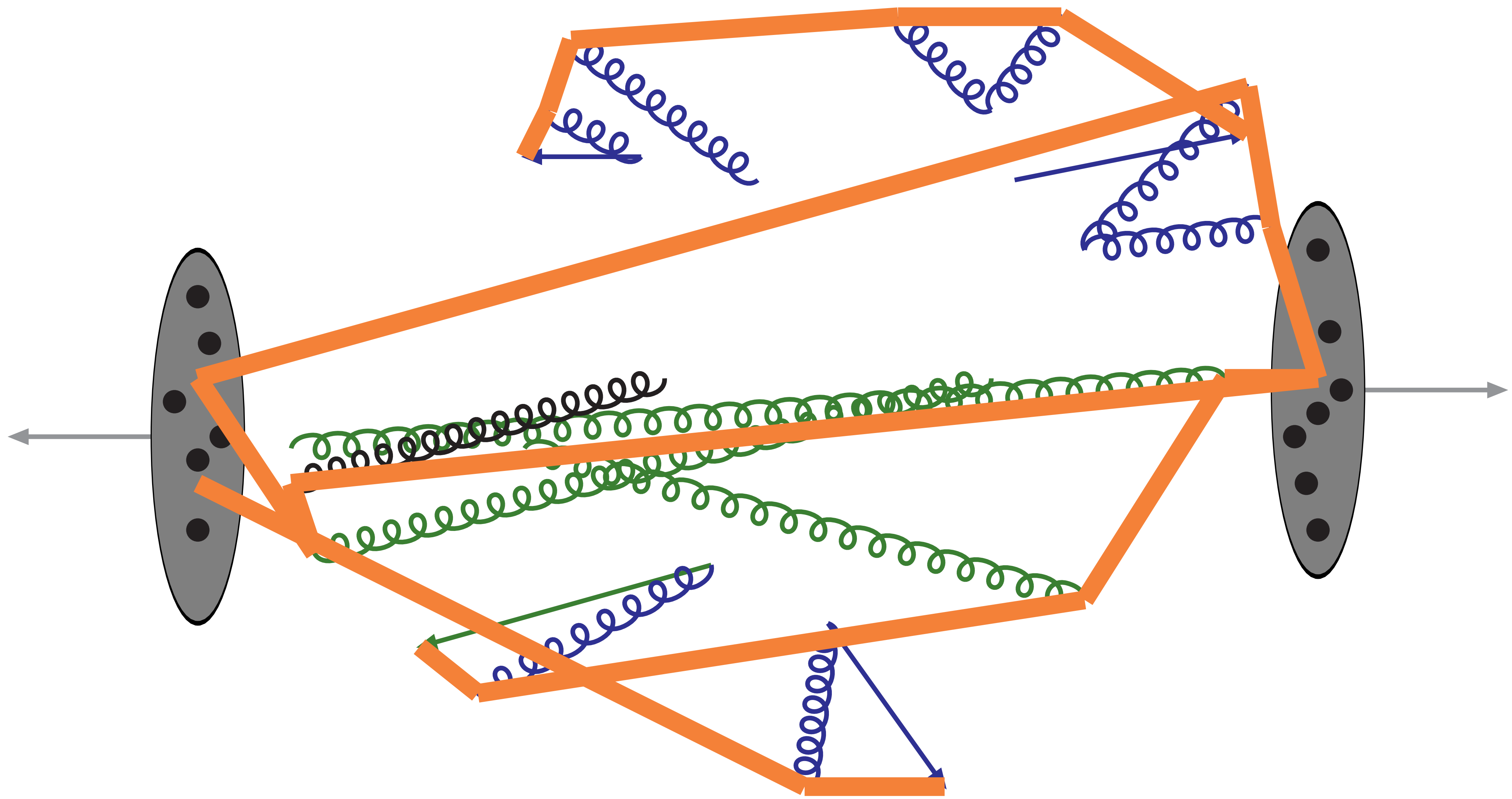
Multiple parton–parton interactions . . .



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

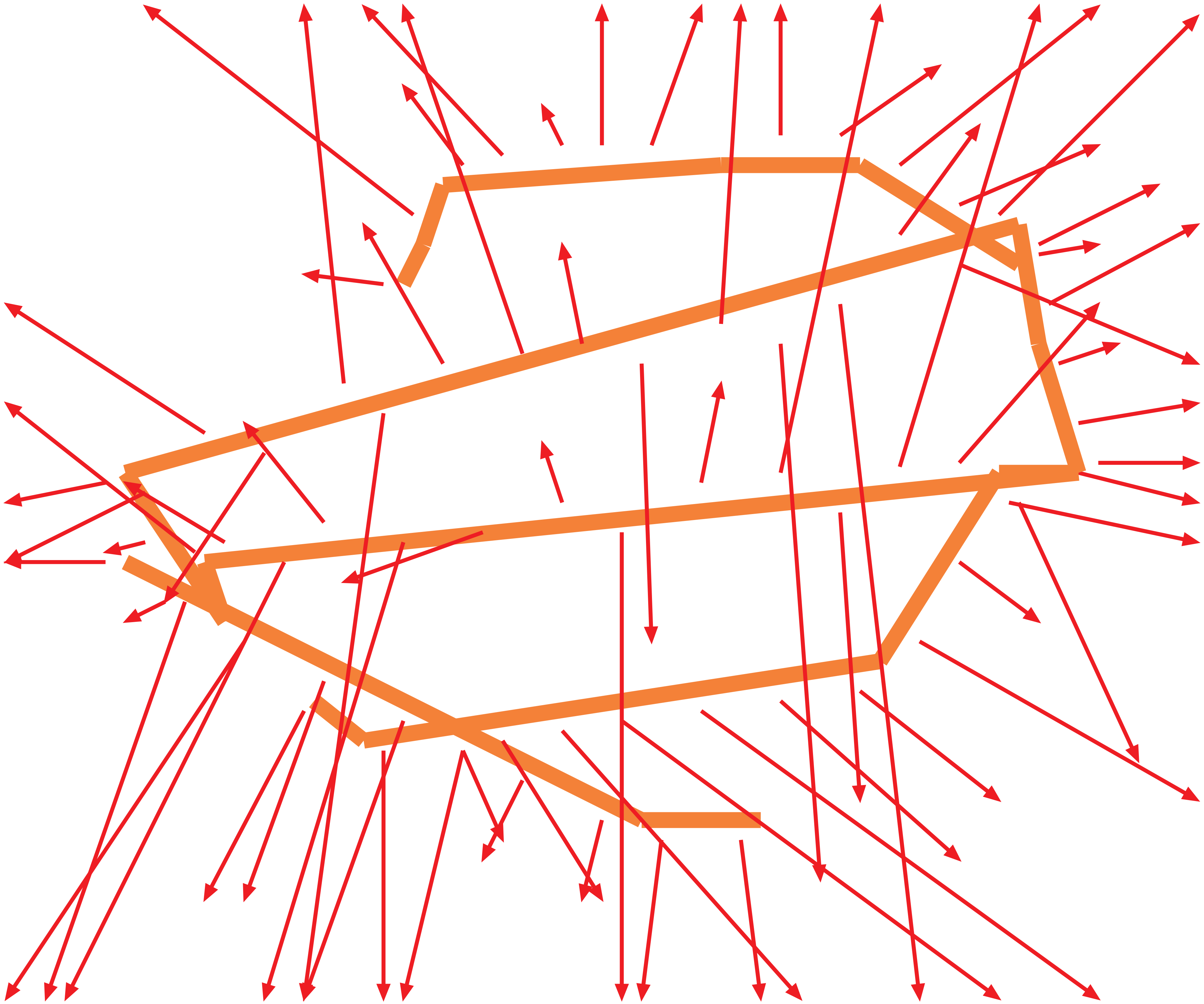


Beam remnants and other outgoing partons



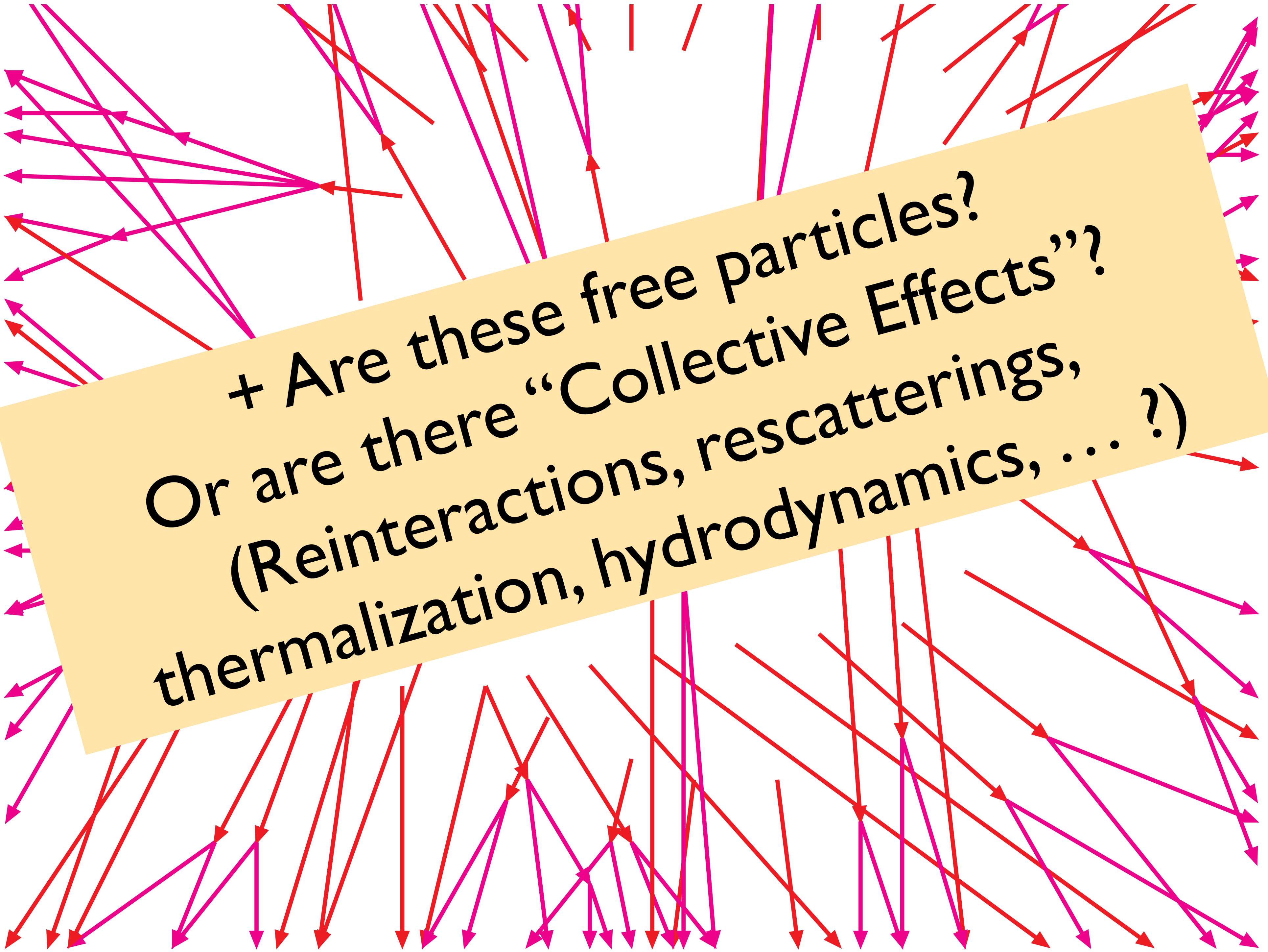
Everything is connected by colour confinement strings

Recall! Not to scale: strings are of hadronic widths



The strings fragment to produce primary hadrons

These are the particles that hit the detector



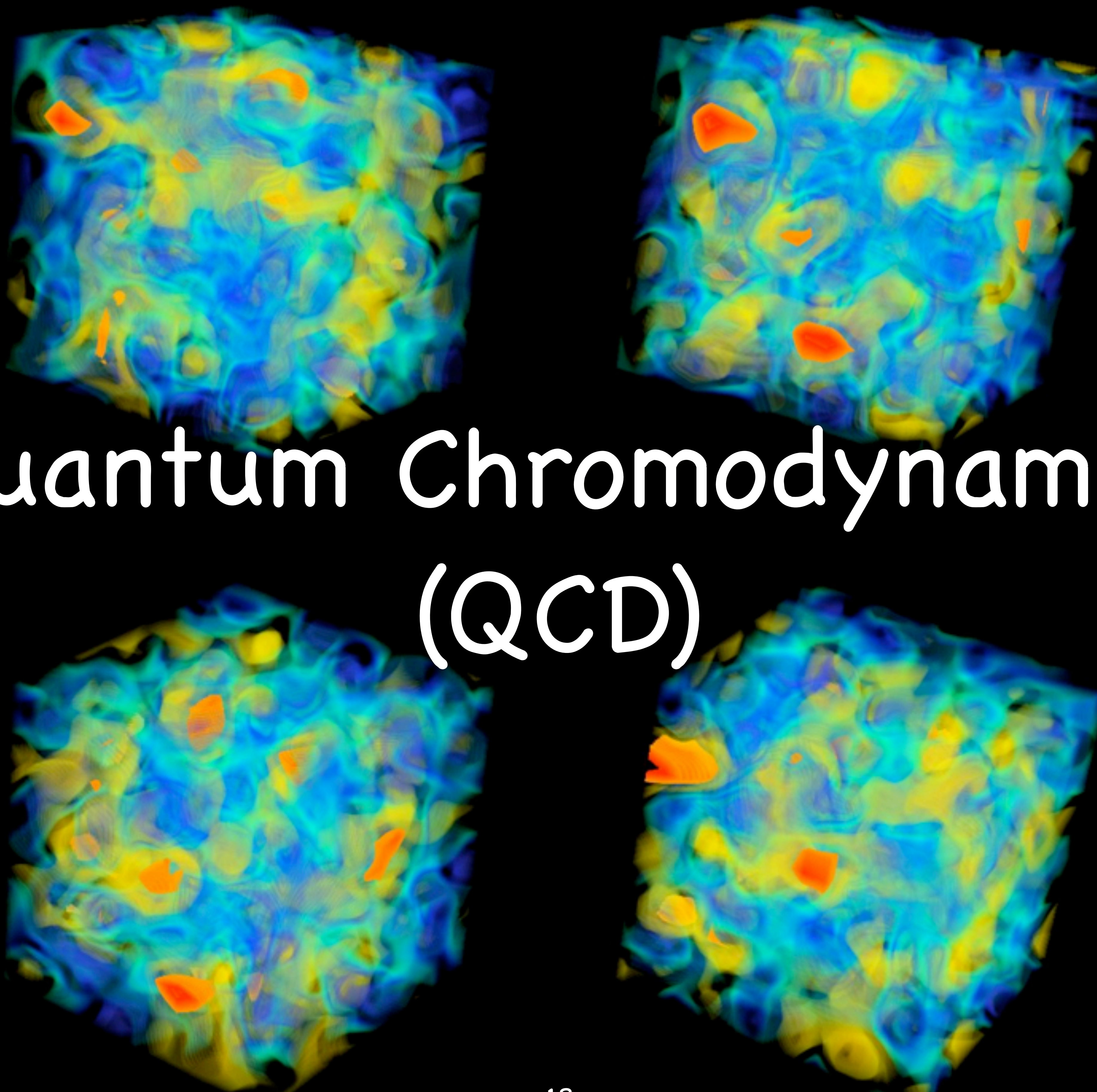
+ Are these free particles?
Or are there "Collective Effects"?
(Reinteractions, rescatterings,
thermalization, hydrodynamics, … ?)

Many hadrons are unstable and decay further

These are the particles that hit the detector

LHC Collision at 7 TeV
ATLAS, March 2010

Vacuum Topological Charge, Data courtesy of M. McGuigan BNL-CSC, T. Izubuchi RIKEN-BNL, and S. Tomov University of Tennessee



Quantum Chromodynamics (QCD)

Colour

E. Noether (1882-1935)

Gauge Group (= local internal symmetry)

See lectures by J. Govaerts

- Special Unitary group in 3 (complex) dimensions, **SU(3)**
  - Group of 3x3 unitary complex matrices with det=1

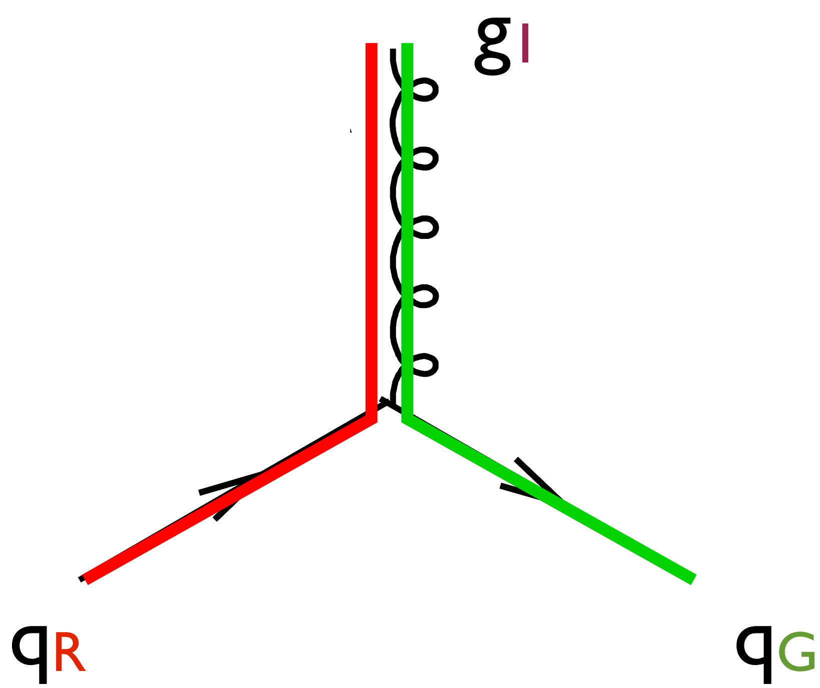
Gluons

- One "gauge boson" for each linearly independent such matrix
  - 3^2-1 = 8 : gluons are **octets** *(each being a 3×3 matrix)*

Quarks

- One quark "color" for each degree of SU(3)
  - 3 : quarks are **triplets** *(each being a 3-vector, on which matrices operate)*

Quark-Gluon interactions

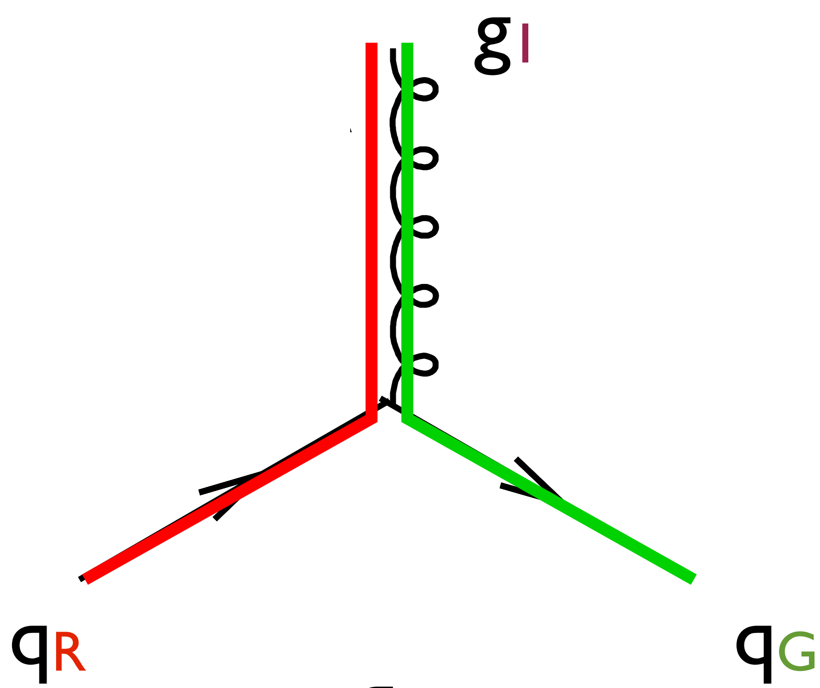


$$\underset{g_I}{\begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}} \underset{q_R}{\begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}} = \underset{q_G}{\begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}}$$

SU(3) : 8 "Gell-Mann" Matrices

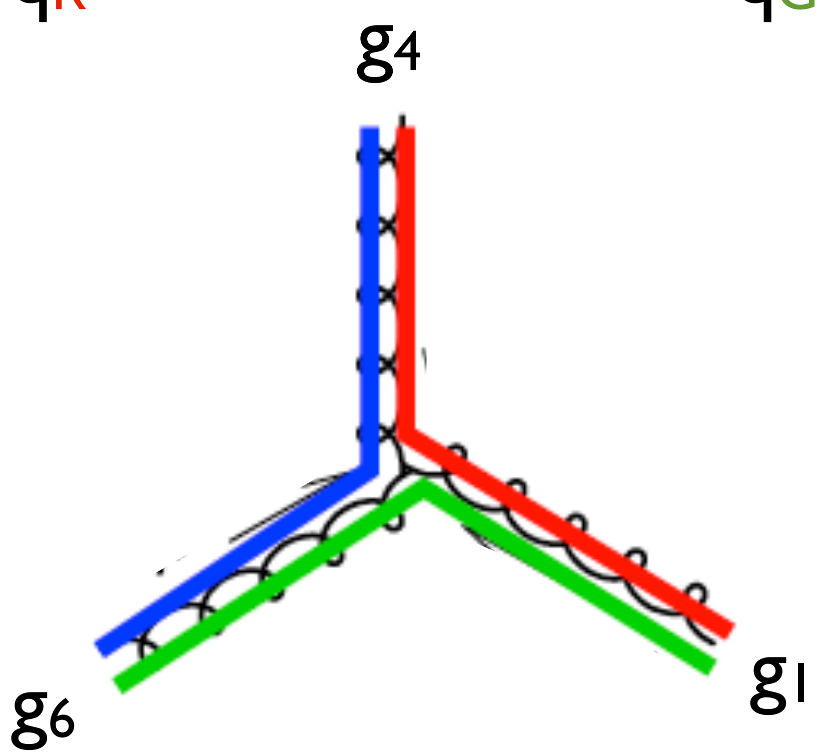
(equivalent to Pauli σ matrices in SU(2))

Gluon self-interaction



$$\begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}$$

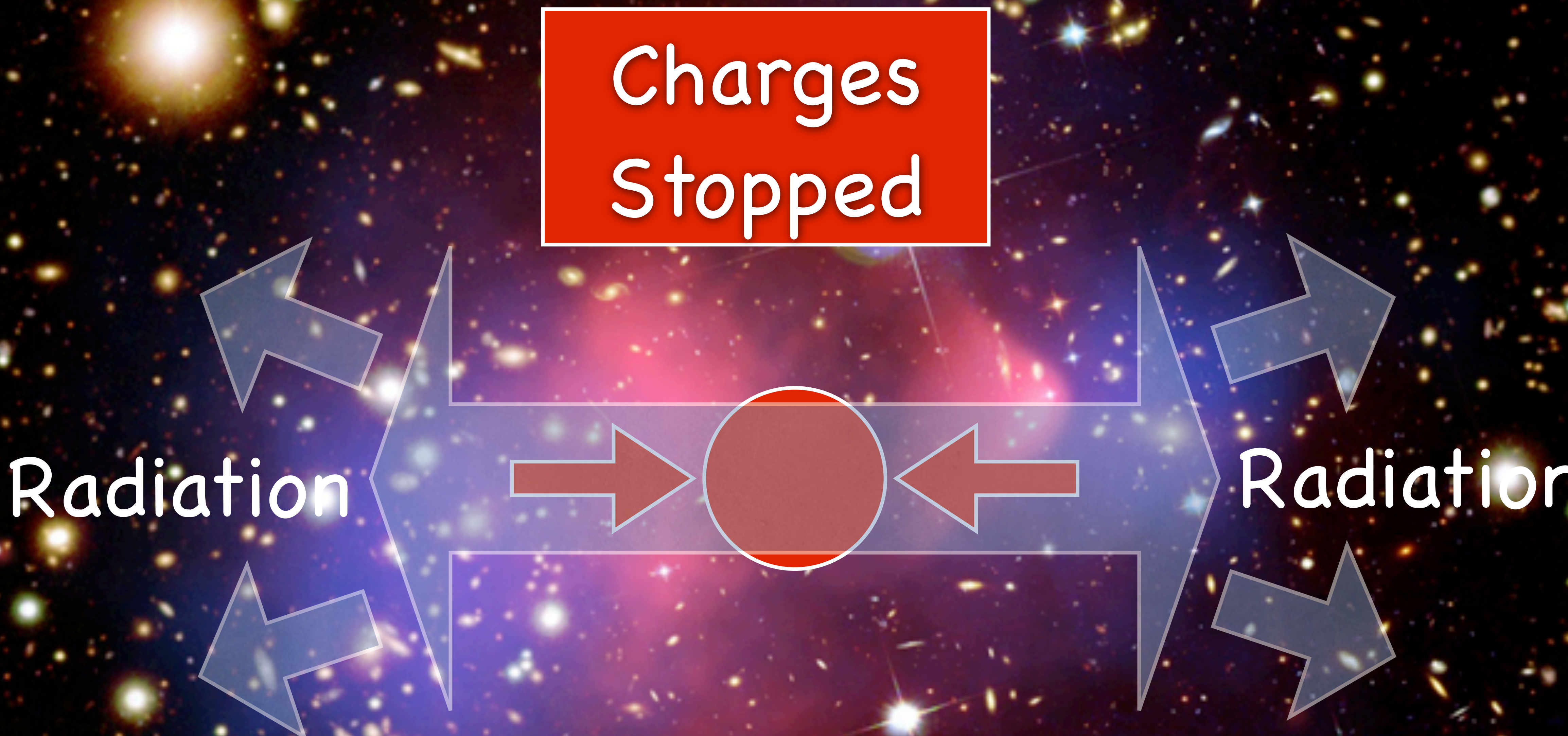
g_1 $\quad$ q_R $\quad$ q_G



Absent in QED

Twice as strong as quark-gluon interaction

Brems Strahlung

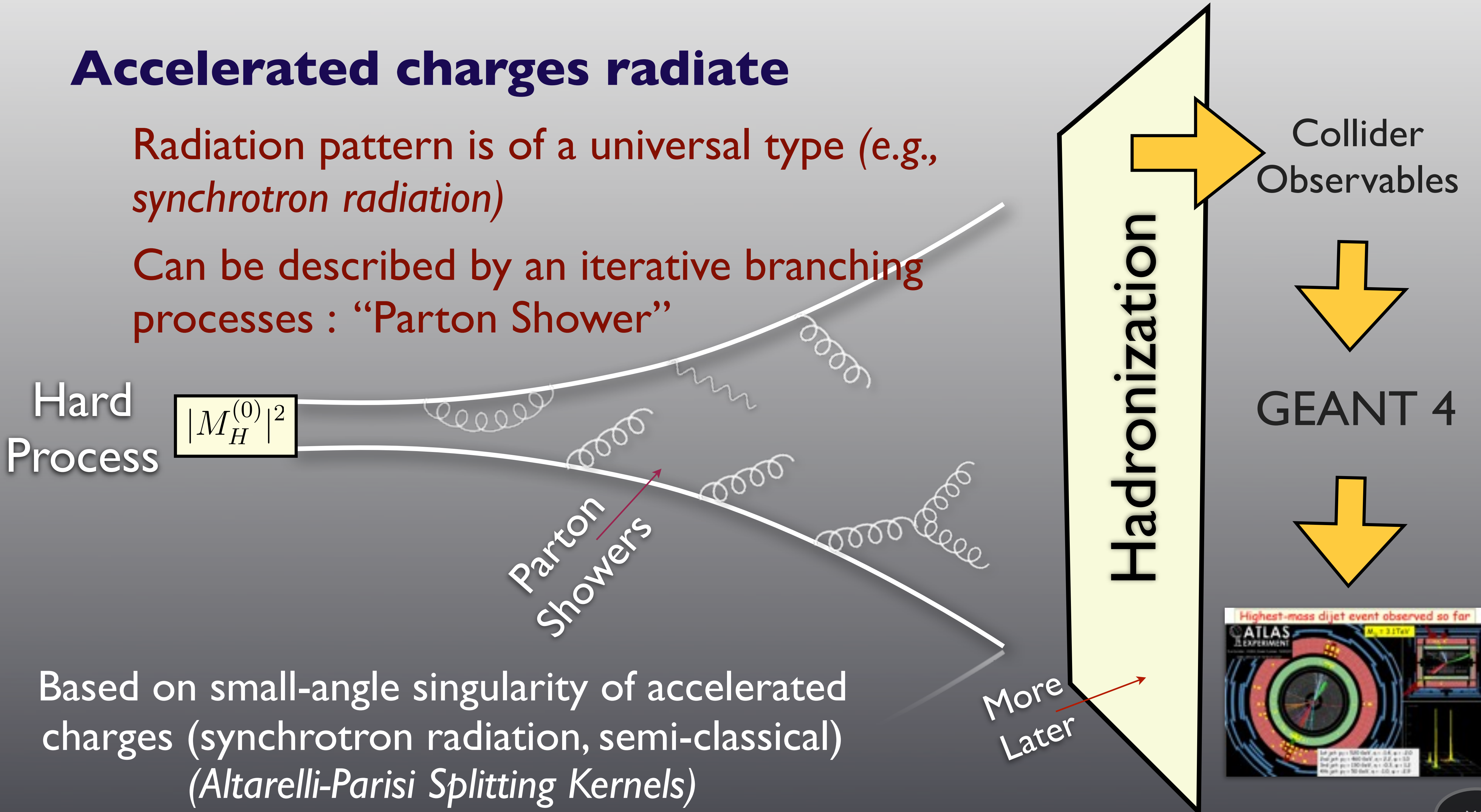


The harder they stop, the harder the fluctations that continue to become strahlung

Accelerated charges radiate

Radiation pattern is of a universal type (e.g., *synchrotron radiation)*

Can be described by an iterative branching processes : "Parton Shower"



Based on small-angle singularity of accelerated charges (synchrotron radiation, semi-classical)
(Altarelli-Parisi Splitting Kernels)

Formation Time *(a.k.a. Factorization Scale)*

The Strong Coupling

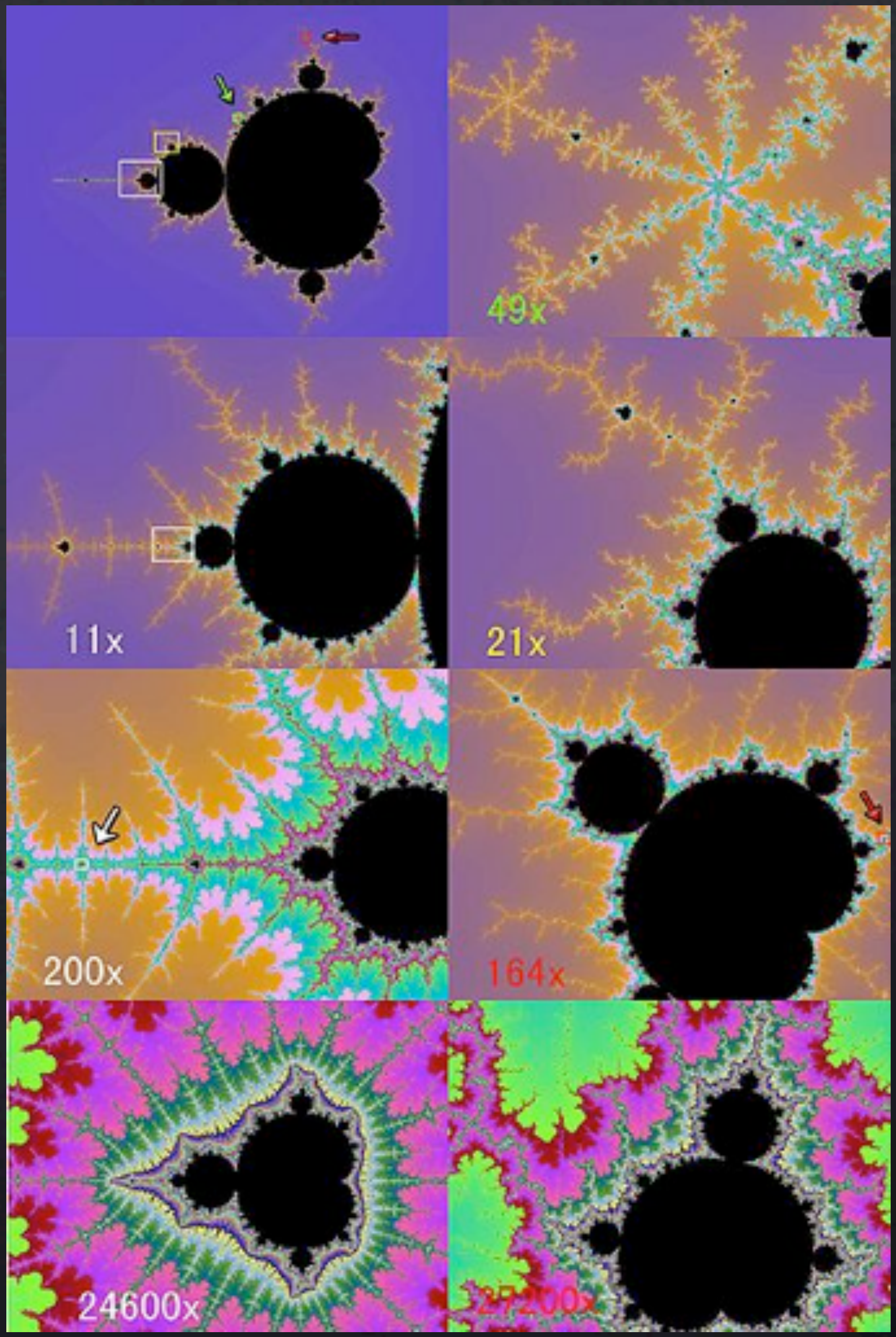
Bjorken scaling

To first approximation, gauge theories are SCALE INVARIANT

A quantum fluctuation inside a fluctuation inside a fluctuation ...

A gluon emits a gluon emits a gluon emits a gluon ...

If the coupling "constant" of the strong force was a constant, this would be absolutely true



Asymptotic Freedom

"What this year's Laureates discovered was something that, at first sight, seemed completely contradictory. The interpretation of their mathematical result was that the closer the quarks are to each other, the *weaker* is the 'colour charge'. When the quarks are really close to
*1 each other, the ~~force~~ charge is so weak that they behave almost as free particles. This phenomenon is called 'asymptotic freedom'. The converse is true when the quarks move apart:
*2 the ~~force~~ potential becomes stronger when the distance increases."

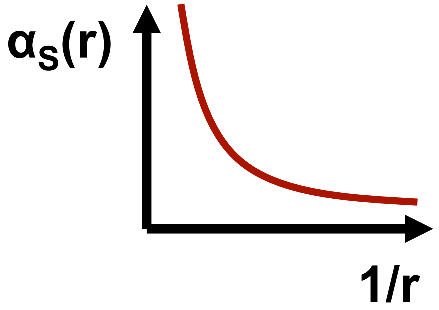
Nobelprize.org
The Official Web Site of the Nobel Prize

2004

The Nobel Prize in Physics 2004
David J. Gross, H. David Politzer, Frank Wilczek

David J. Gross | H. David Politzer | Frank Wilczek

The Nobel Prize in Physics 2004 was awarded jointly to David J. Gross, H. David Politzer and Frank Wilczek *"for the discovery of asymptotic freedom in the theory of the strong interaction"*.



*1 The force still goes to ∞ as $r \to 0$ (Coulomb potential), just less slowly

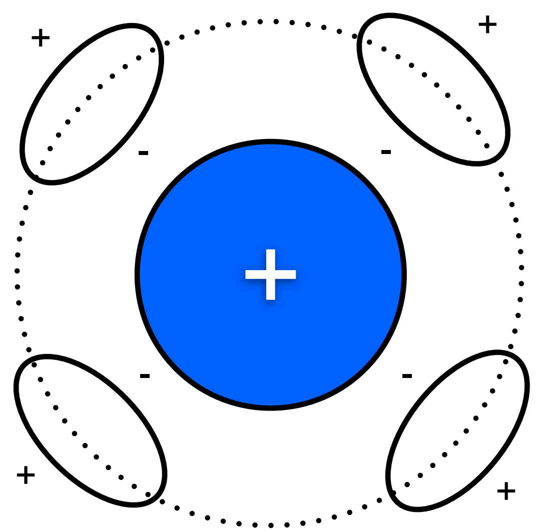
*2 The potential grows linearly as $r \to \infty$, so the force actually becomes constant (even this is only true in "quenched" QCD. In real QCD, the force eventually vanishes for r>>1fm)

Running Couplings

QED:

Vacuum polarization

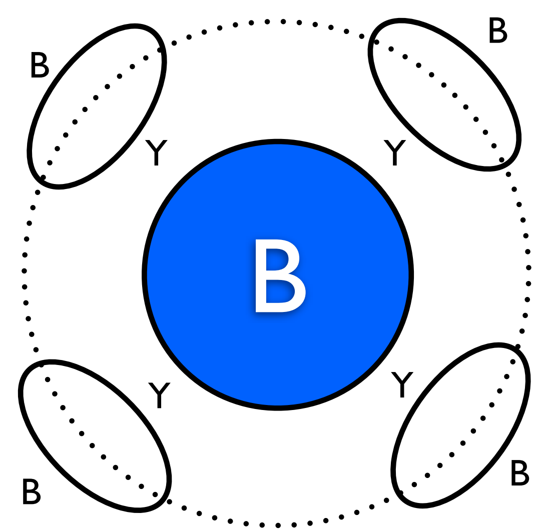
→ Charge screening



QCD:

Quark Loops

→ Also charge screening



But only dominant if > 16 flavors!

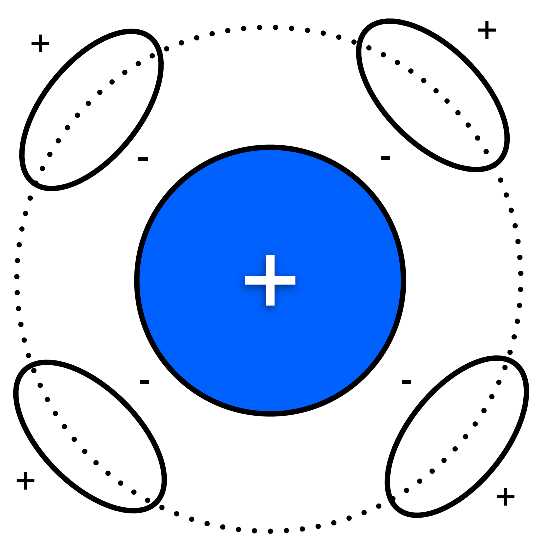
QED: Quantum Electrodynamics = Electromagnetism
QCD: Quantum Chromodynamics = The Strong Nuclear Force

Running Couplings

QED:

Vacuum polarization

→ Charge screening

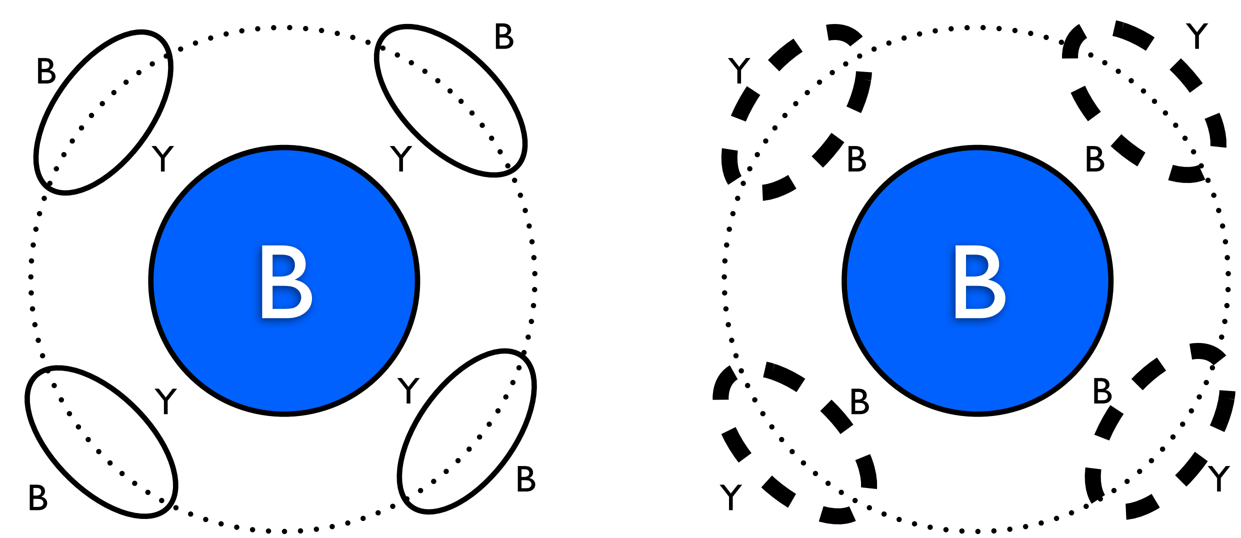


QCD:

$$b_0 = \frac{11C_A - 2n_f}{12\pi}$$

Gluon Loops

Dominate if ≤ 16 flavors

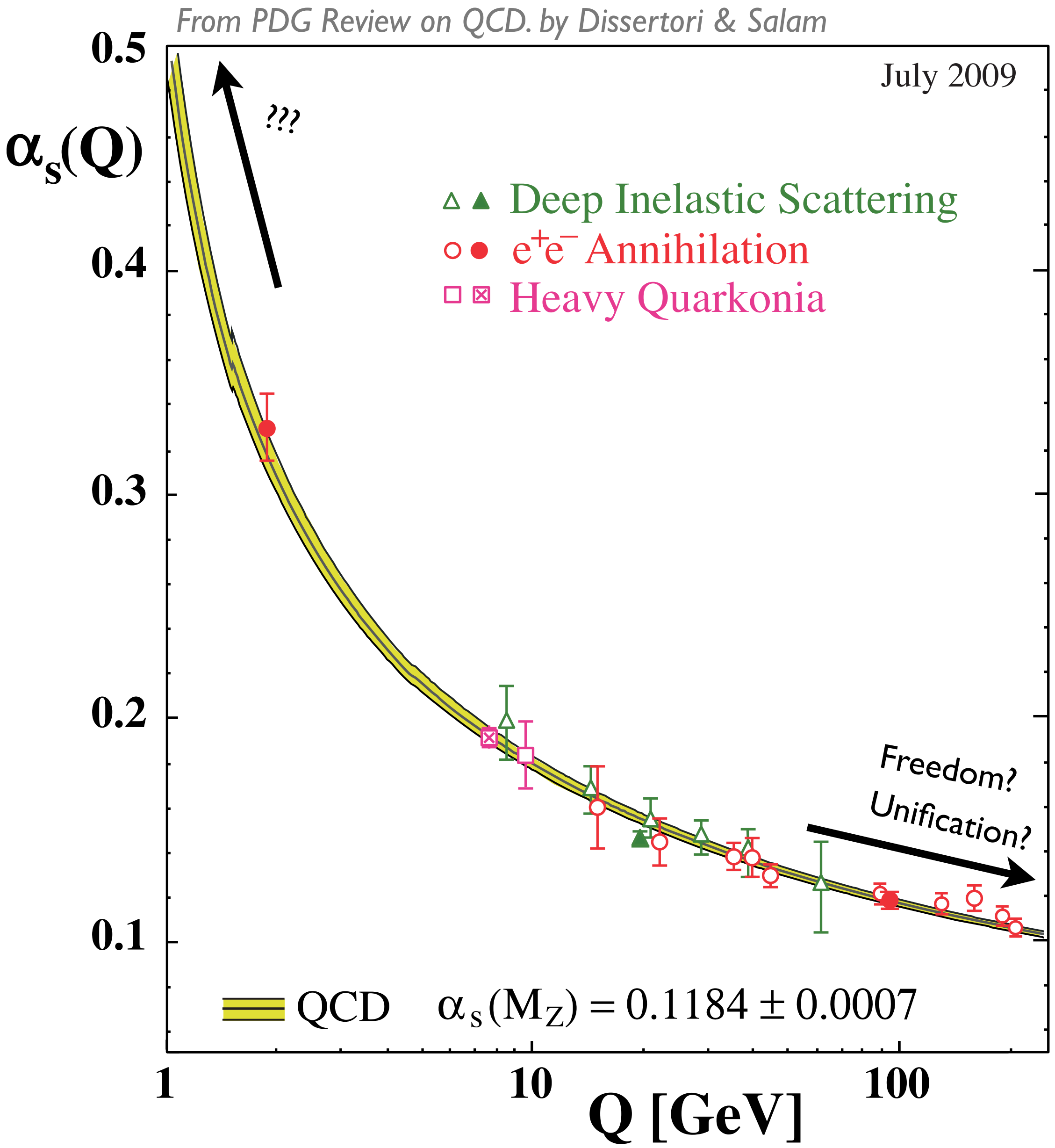


Spin-1 → Opposite Sign

QED: Quantum Electrodynamics = Electromagnetism
QCD: Quantum Chromodynamics = The Strong Nuclear Force

The Strong Coupling "Constant"

The Strong Coupling "Constant"
as function of energy scale, Q



At low scales

Coupling $\alpha_s(Q)$ actually runs rather fast with Q

Perturbative solution diverges at a scale Λ_{QCD} somewhere below

$\approx$ 1 GeV

So, to specify the strength of the strong force, we usually give the value of α_s at a unique reference scale that everyone agrees on: M_Z = 91.2 GeV/c

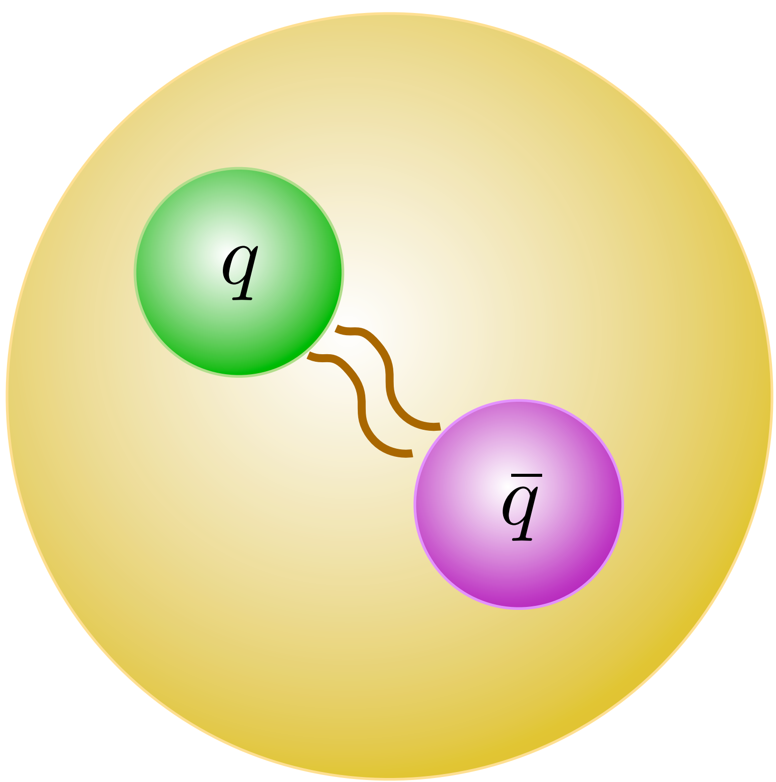
Confinement

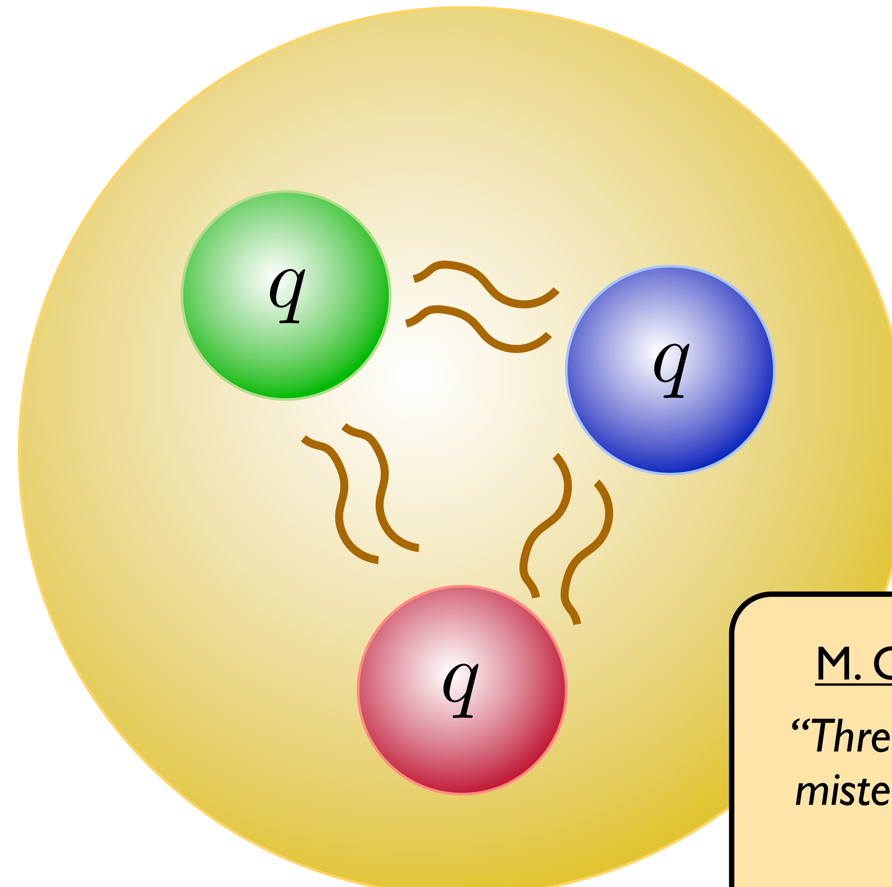
We don't see quarks and gluons …

Mesons

Quark-Antiquark Bound States

$\pi^0, \pi^\pm, K^0, K^\pm, \eta, \ldots$





M. Gell-Mann:
"Three quarks for mister Mark, …"
James Joyce, Finnegans Wake

Baryons

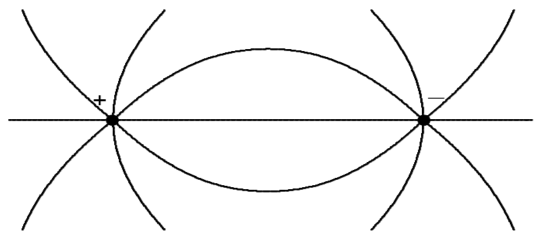
Quark-Quark-Quark Bound States

$p^\pm, n^0, \Lambda^0, \ldots$

Linear Confinement

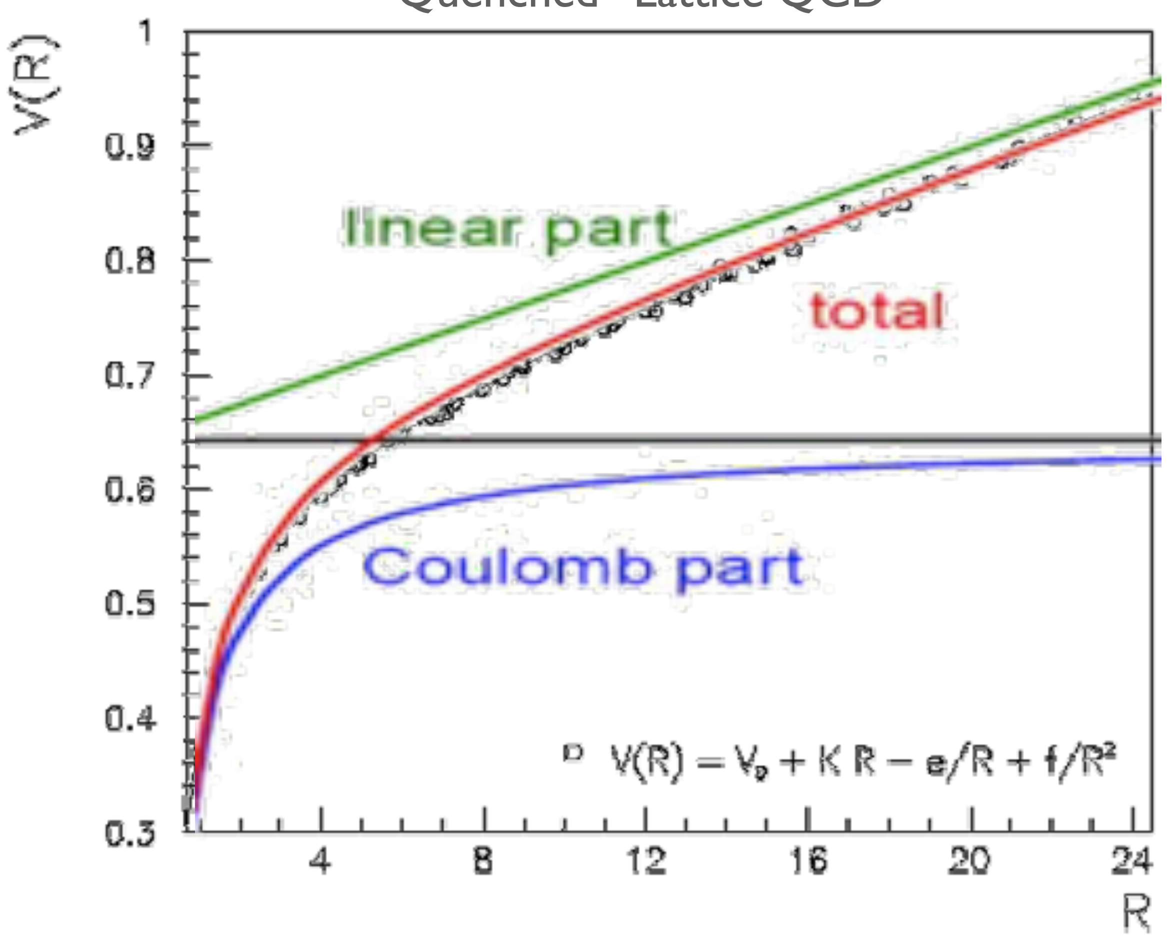
Lattice QCD: Potential between a quark and an antiquark as function of distance, R

Short Distances ~ pQCD

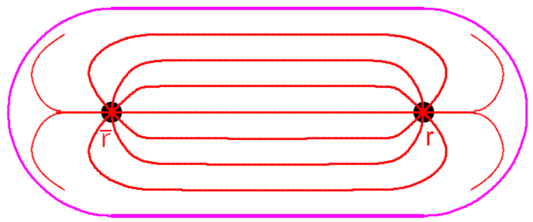


Partons

“Quenched” Lattice QCD



Long Distances ~ Linear Confinement

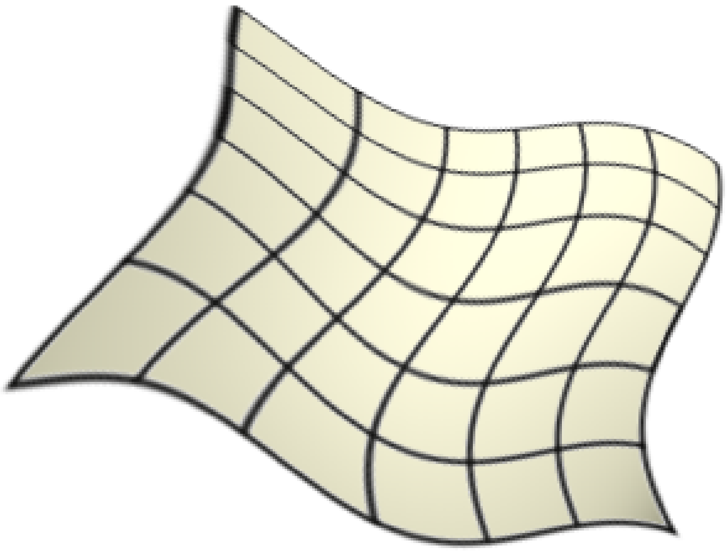


Hadrons

Question:
What physical system has a linear potential?

$$F(r) \approx \text{const} = \kappa \approx 1\ \text{GeV/fm} \iff V(r) \approx \kappa r$$

From Partons to Strings



$$F(r) \approx \text{const} = \kappa \approx 1\ \text{GeV/fm} \quad \Longleftrightarrow \quad V(r) \approx \kappa r$$

Motivates a model:

Model: assume the color field collapses into a (infinitely) narrow flux tube of uniform energy density κ ~ 1 GeV / fm

→ Relativistic 1+1 dimensional worldsheet – string

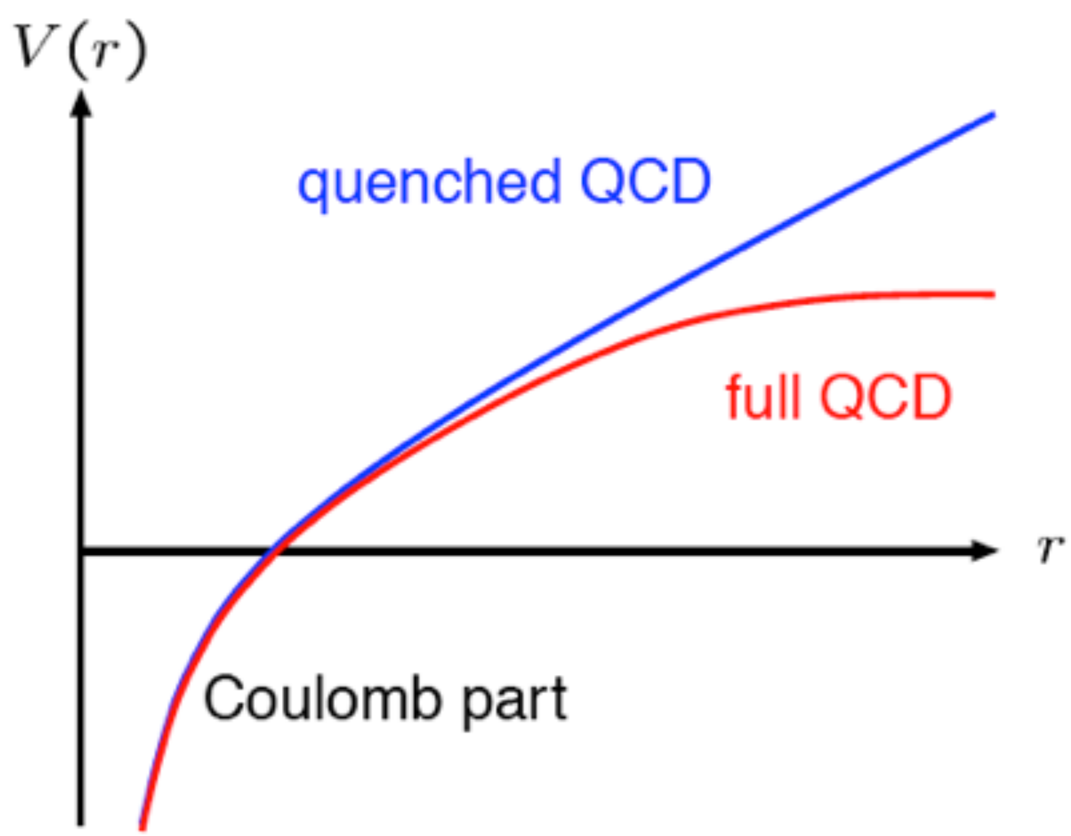
⇒ ***Lund String Model of Hadronization***

Pedagogical Review: B. Andersson, *The Lund model.* Camb. Monogr. Part. Phys. Nucl. Phys. Cosmol., 1997.

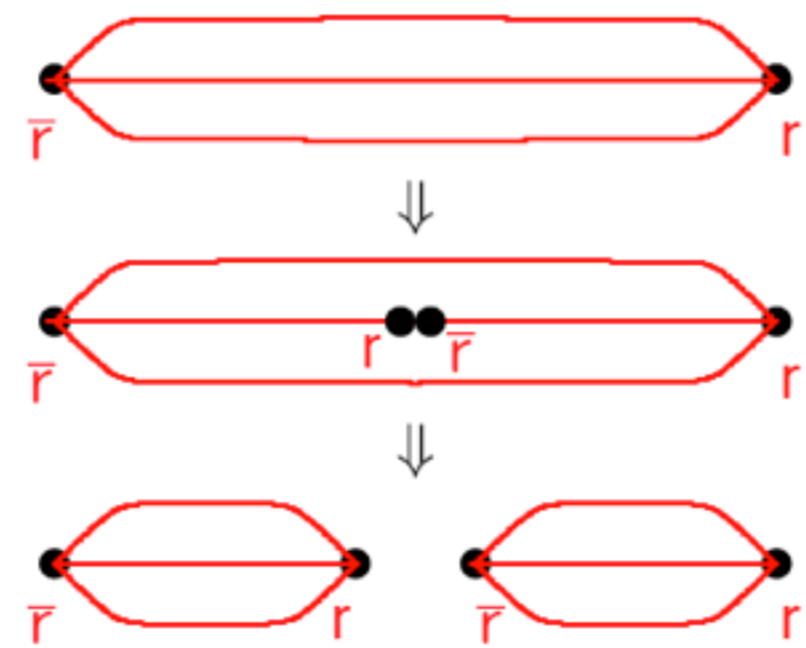
String Breaks

In “unquenched” QCD

g→qq → The strings would break



simplified colour representation:



Illustrations by T. Sjöstrand

Hadronization Models

The problem:

- Given a set of *partons* resolved at a scale of ~ 1 GeV (~ 10^{-15} m), need a **"mapping"** from this set onto a set of on-shell (confined) *hadrons*.

MC models do this in three steps

1. Map partons onto **continuum of excited hadronic states** *(called 'strings' or 'clusters')*
2. Iteratively break strings/clusters into **discrete set of primary hadrons** *(string breaks / cluster splittings / cluster decays)*
3. Sequential decays into **secondary hadrons** (e.g., $\rho > \pi\ \pi$, $\Lambda^0 > n\ \pi^0$, $\pi^0 > \gamma\gamma$, ...)

Distance Scales ~ 10^{-15} m = 1 fermi

PYTHIA anno 1978

(then called JETSET)

LU TP 78-18
November, 1978

A Monte Carlo Program for Quark Jet Generation

T. Sjöstrand, B. Söderberg

A Monte Carlo computer program is presented, that simulates the fragmentation of a fast parton into a jet of mesons. It uses an iterative scaling scheme and is compatible with the jet model of Field and Feynman.

```
      SUBROUTINE JETGEN(N)
      COMMON /JET/ K(100,2), P(100,5)
      COMMON /PAR/ PUD, PS1, SIGMA, CX2, EBEG, WFIN, IFLBEG
      COMMON /DATA1/ MESO(9,2), CMIX(6,2), PMAS(19)
      IFLSGN=(10-IFLBEG)/5
      W=2.*EBEG
      I=0
      IPD=0
C 1 FLAVOUR AND PT FOR FIRST QUARK
      IFL1=IABS(IFLBEG)
      PT1=SIGMA*SQRT(-ALOG(RANF(0)))
      PHI1=6.2832*RANF(0)
      PX1=PT1*COS(PHI1)
      PY1=PT1*SIN(PHI1)
  100 I=I+1
C 2 FLAVOUR AND PT FOR NEXT ANTIQUARK
      IFL2=1+INT(RANF(0)/PUD)
      PT2=SIGMA*SQRT(-ALOG(RANF(0)))
      PHI2=6.2832*RANF(0)
      PX2=PT2*COS(PHI2)
      PY2=PT2*SIN(PHI2)
C 3 MESON FORMED, SPIN ADDED AND FLAVOUR MIXED
      K(I,1)=MESO(3*(IFL1-1)+IFL2,IFLSGN)
      ISPIN=INT(PS1+RANF(0))
      K(I,2)=1+9*ISPIN+K(I,1)
      IF(K(I,1).LE.6) GOTO 110
      TMIX=RANF(0)
      KM=K(I,1)-6+3*ISPIN
      K(I,2)=8+9*ISPIN+INT(TMIX+CMIX(KM,1))+INT(TMIX+CMIX(KM,2))
C 4 MESON MASS FROM TABLE, PT FROM CONSTITUENTS
  110 P(I,5)=PMAS(K(I,2))
      P(I,1)=PX1+PX2
      P(I,2)=PY1+PY2
      PMTS=P(I,1)**2+P(I,2)**2+P(I,5)**2
C 5 RANDOM CHOICE OF X=(E+PZ)MESON/(E+PZ)AVAILABLE GIVES E AND PZ
      X=RANF(0)
      IF(RANF(0).LT.CX2) X=1.-X**(1./3.)
      P(I,3)=(X*W-PMTS/(X*W))/2.
      P(I,4)=(X*W+PMTS/(X*W))/2.
C 6 IF UNSTABLE, DECAY CHAIN INTO STABLE PARTICLES
  120 IPD=IPD+1
      IF(K(IPD,2).GE.8) CALL DECAY(IPD,I)
      IF(IPD.LT.I.AND.I.LE.96) GOTO 120
C 7 FLAVOUR AND PT OF QUARK FORMED IN PAIR WITH ANTIQUARK ABOVE
      IFL1=IFL2
      PX1=-PX2
      PY1=-PY2
C 8 IF ENOUGH E+PZ LEFT, GO TO 2
      W=(1.-X)*W
      IF(W.GT.WFIN.AND.I.LE.95) GOTO 100
      N=I
      RETURN
      END
```

Note: Field-Feynman was an early fragmentation model
Now superseded by the String (in PYTHIA) and Cluster (in HERWIG & SHERPA) models.

PYTHIA anno 2012

(now called PYTHIA 8)

~ 80,000 lines of C++

LU TP 07-28 (CPC 178 (2008) 852)
October, 2007

A Brief Introduction to PYTHIA 8.1

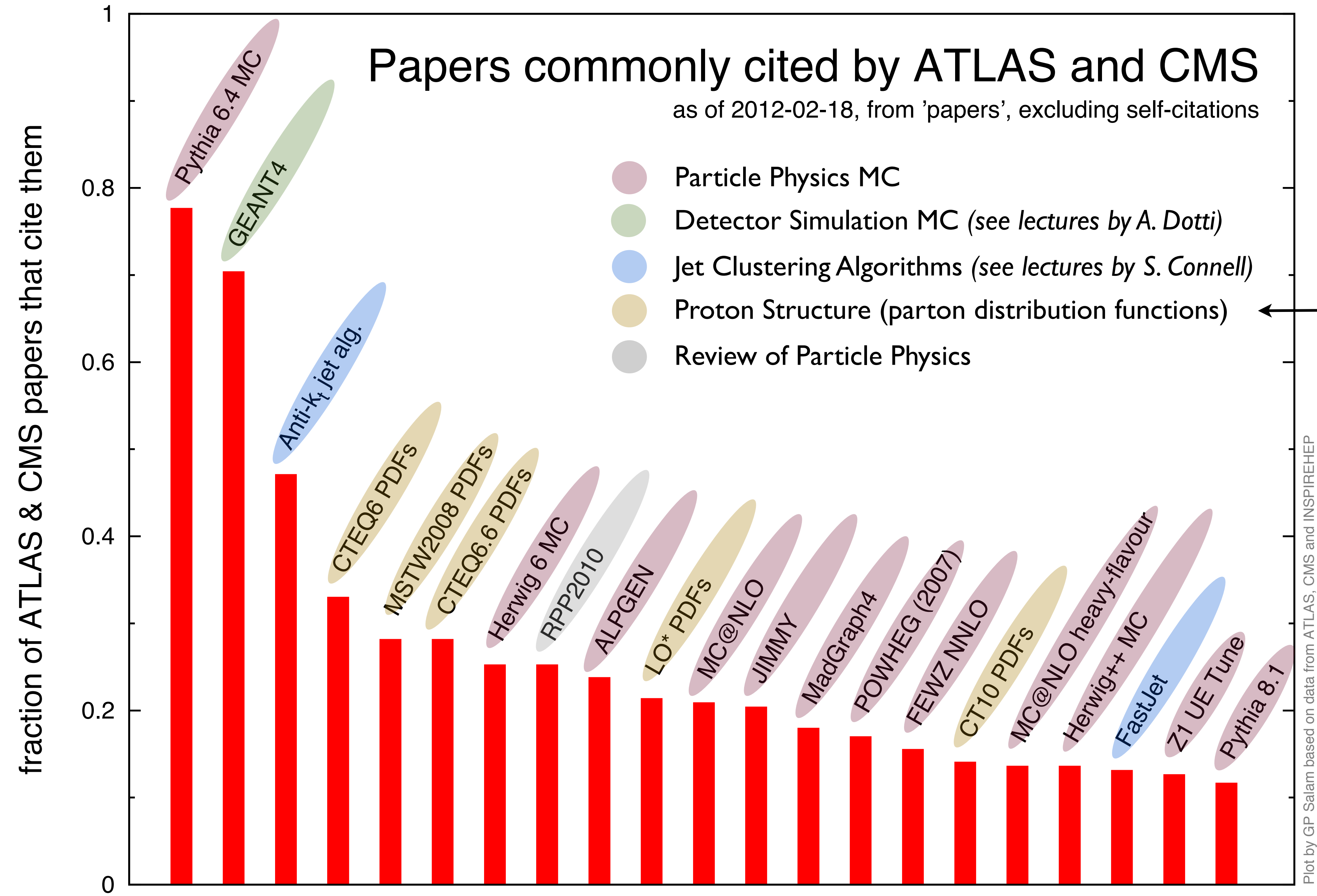
T. Sjöstrand, S. Mrenna, P. Skands

The Pythia program is a standard tool for the generation of high-energy collisions, comprising a coherent set of physics models for the evolution from a few-body hard process to a complex multihadronic final state. It contains a library of hard processes and models for initial- and final-state parton showers, multiple parton-parton interactions, beam remnants, string fragmentation and particle decays. It also has a set of utilities and interfaces to external programs. [...]

What a modern MC generator has inside:

- Hard Processes (internal, semi-internal, or via Les Houches events)
- BSM (internal or via interfaces)
- PDFs (internal or via interfaces)
- Showers (internal or inherited)
- Multiple parton interactions
- Beam Remnants
- String Fragmentation
- Decays (internal or via interfaces)
- Examples and Tutorial
- Online HTML / PHP Manual
- Utilities and interfaces to external programs

ATLAS and CMS: the two largest experiments at the Large Hadron Collider *(see lectures next week)*

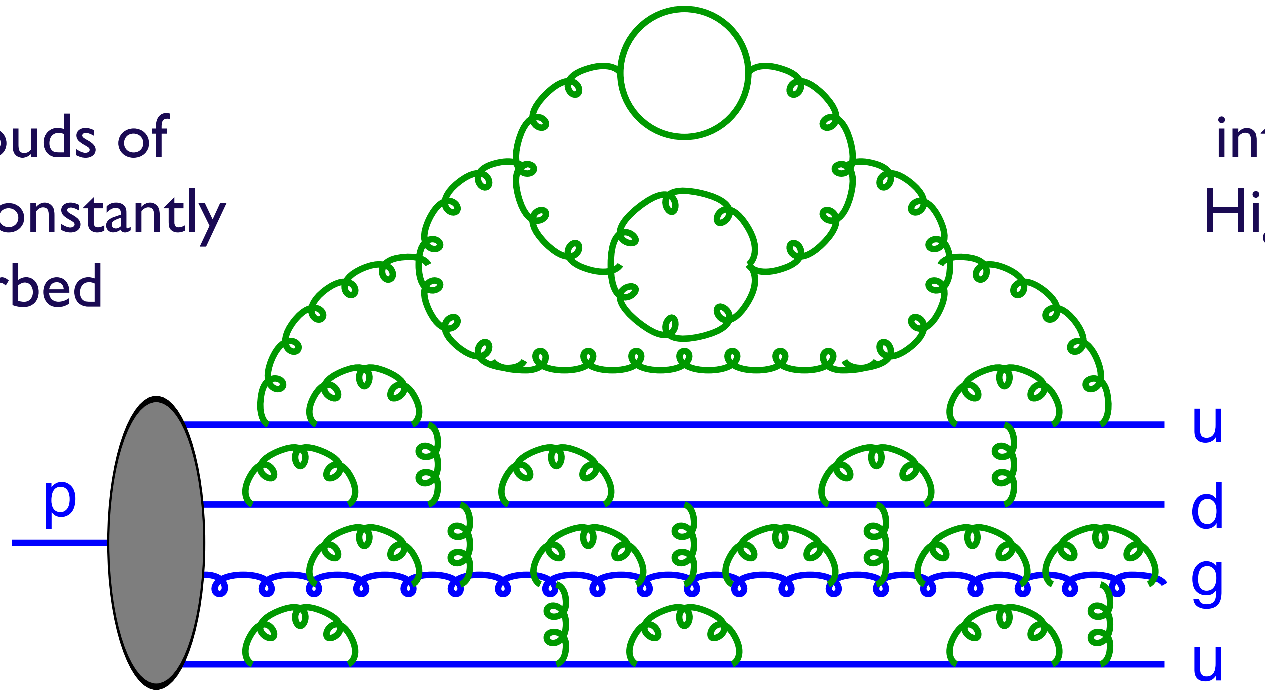


Sorry, skipped in these lectures

(Parton Distributions)

Hadrons are composite, with time-dependent structure:

Partons within clouds of further partons, constantly emitted and absorbed



For hadron to remain intact, virtualities $k^2 < M_h^2$ High-virtuality fluctuations suppresed by powers of

$$\frac{\alpha_s M_h^2}{k^2}$$

M_h : mass of hadron

k^2 : virtuality of fluctuation

→ Lifetime of fluctuations ~ $1/M_h$

Hard incoming probe interacts over much shorter time scale ~ 1/Q

On that timescale, partons ~ frozen

Hard scattering knows nothing of the target hadron apart from the fact that it contained the struck parton

Illustration from T. Sjöstrand

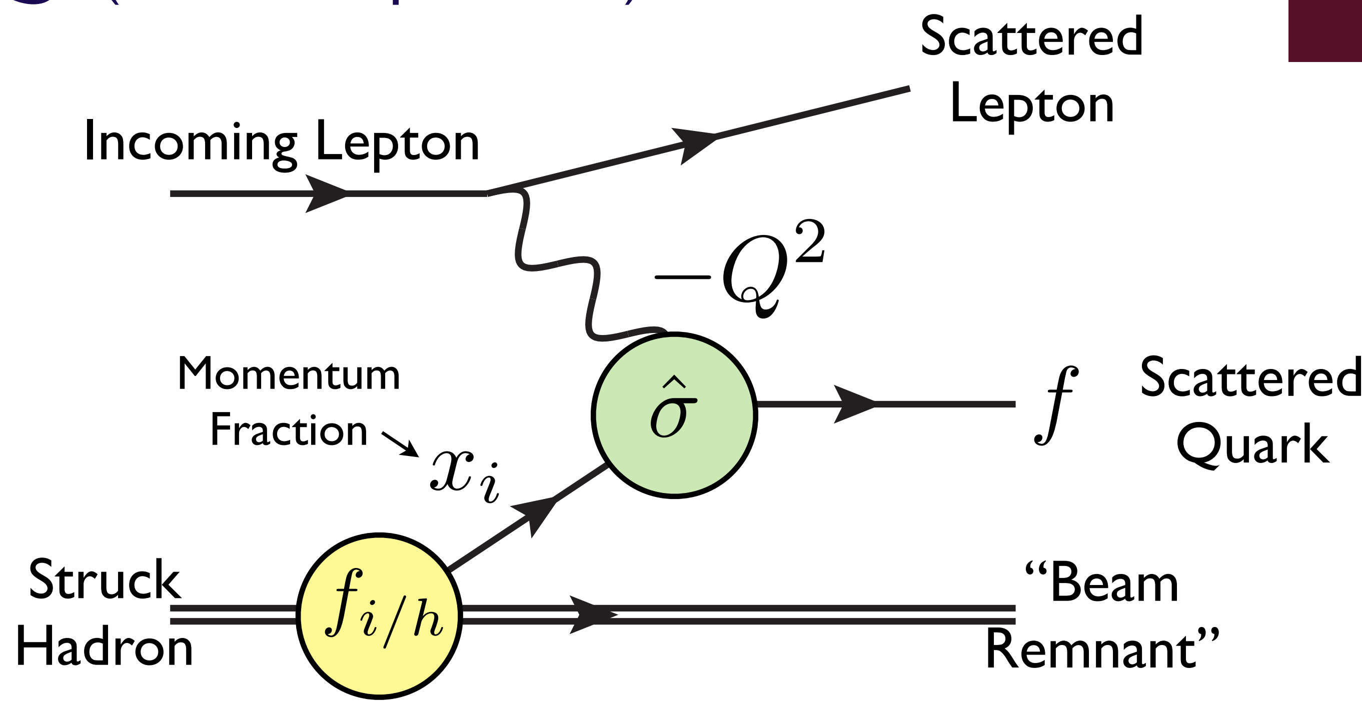
(Factorization Theorem)

See also electron-nucleon scattering in lectures by K. Assamagan

Example: DIS (Collins, Soper, 1987)

Deep Inelastic Scattering (DIS)

(By "deep", we mean $Q^2 >> M_h^2$)



→ We really can write the cross section in factorized form :

$$\sigma^{\ell h} = \sum_i \sum_f \int dx_i \int d\Phi_f \, f_{i/h}(x_i, Q_F^2) \, \frac{d\hat{\sigma}^{\ell i \to f}(x_i, \Phi_f, Q_F^2)}{dx_i \, d\Phi_f}$$

Sum over Initial (i) and final (f) parton flavors

Φ_f = Final-state phase space

$f_{i/h}$ = PDFs Universal Constrained by fits to data

Differential partonic Hard-scattering Matrix Element(s)

Summary - Lecture 2

Monte Carlo Generators are used in particle physics to simulate realistic "events" in as much detail as mother nature (but with approximations)

Hard Processes → Perturbative Quantum Field Theory (based on Lagrangian of Standard Model - or BSM extensions)

Hard partons emit bremsstrahlung → simulated by iterating universal radiation patterns (e.g., *dipoles*) in a *parton shower,* ordered in a measure of formation time

Linear Confinement → Quarks and Gluons turn into hadrons. Hadronization modeled by *color strings* + *string breaking via quantum mechanical tunelling (in PYTHIA)*

Recommended Reading

G. Dissertori, I. Knowles, S. Schmelling
Quantum Chromodynamics
Oxford Science Publications, 2003

P. Skands
Lecture notes from TASI, June 2012, Boulder, Colorado
Introduction to QCD
e-Print: arXiv:1207.2389

MC*net* Review : A. Buckley et al.
General-purpose Event Generators for LHC Physics
Phys.Rept. 504 (2011) 145