Emergent Phenomena in High-Energy Particle Collisions

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Emergence

G. H. Lewes (1875): "the emergent is unlike its components insofar as … it cannot be reduced to their sum or their difference."

In Quantum Field Theory:
Components = Elementary interactions encoded in the Lagrangian
Perturbative expansions ~ elementary interactions to n\textsuperscript{th} power

What else is there? Structure beyond (fixed-order) perturbative expansions (in Quantum Chromodynamics):
\textit{Fractal scaling, of jets within jets within jets} … (can actually be guessed)
\textit{Confinement, of coloured partons within hadrons} ($1M for proof)
THE THEORY OF QUARKS AND GLUONS; THE STRONG NUCLEAR FORCE

Elementary interactions encoded in the Lagrangian

$$L = \bar{\psi}_q(i\gamma^\mu)(D_\mu)_{ij}\psi_q - m_q\bar{\psi}_q\psi_q - \frac{1}{4}F_{\mu\nu}^a F^{a\mu\nu}$$

$$D_\mu_{ij} = \delta_{ij}\partial_\mu - ig_sT^a_{ij}A^a_\mu$$

Gauge Covariant Derivative: makes $L$ invariant under SU(3)$_C$ rotations of $\psi_q$

$F_{\mu\nu}^a = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g_s f^{abc} A^b_\mu A^c_\nu$

Perturbative expansions $\rightarrow$ Feynman diagrams

$$\psi_q^j = \begin{pmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \end{pmatrix}$$

Would anything interesting happen if we put lots of these together?
Proton-Proton Collision at $E_{CM} = 7$ TeV
More than just a \( \text{(fixed-order perturbative)} \) expansion in \( \alpha_s \)

Multi-parton structures beyond fixed-order perturbation theory

Jets \( \text{(the fractal of perturbative QCD)} \) \( \leftrightarrow \) Infinite-order perturbative structures of indefinite particle number \( \leftrightarrow \) universal amplitude structures in QFT

Strings \( \text{(strong gluon fields)} \) \( \leftrightarrow \) Dynamics of confinement \( \leftrightarrow \) Hadronization phase transition \( \leftrightarrow \) quantum-classical correspondence. Non-perturbative dynamics. String physics. String breaks.

Hadrons \( \leftrightarrow \) Spectroscopy (incl excited and exotic states), lattice QCD, \( \text{(rare)} \) decays, mixing, light nuclei. Hadron beams \( \rightarrow \) multiparton interactions, diffraction, ...
LHC Run 1+2: no “low-hanging” new physics

90% of data still to come $\Rightarrow$ higher sensitivity to smaller signals.

High-statistics data $\leftrightarrow$ high-accuracy theory

There are more things in heaven and earth, Horatio, than are dreamt of in your philosophy

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The Standard Model

$$\mathcal{L} = -\frac{i}{4} F_{\mu\nu} F^{\mu\nu}$$

$$+ \bar{\psi} \gamma^\mu \psi + h.c.$$

$$+ \bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$

$$+ \partial_\mu \phi \partial^\mu \phi - V(\phi)$$

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$+$ … … … … $?$

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Hamlet

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Peter Skands
1) Perturbative QCD

The “running” of $\alpha_s$:

$$Q^2 \frac{\partial \alpha_s}{\partial Q^2} = -\alpha_s^2 (b_0 + b_1 \alpha_s + b_2 \alpha_s^2 + \ldots),$$

$$b_0 = \frac{11 C_A - 2n_f}{12\pi} \quad C_A=3 \text{ for } SU(3)$$

$$b_1 = \frac{17 C_A^2 - 5 C_A n_f - 3 C_F n_f}{24\pi^2} \quad b_2 = \frac{153 - 19n_f}{24\pi^2} - \frac{5033n_f + 325n_f^2}{128\pi^3}$$

At high scales $Q \gg 1$ GeV

Coupling $\alpha_s(Q) \ll 1$

Perturbation theory in $\alpha_s$ should be reliable: LO, NLO, NNLO, ...

E.g., in the event shown a few slides ago, each of the six “jets” had $Q \sim E_T = 84 - 203$ GeV
The Infrared Strikes Back

Naively, QCD radiation suppressed by $\alpha_s \approx 0.1$

Truncate at fixed order = LO, NLO, …

E.g., $\sigma(X+\text{jet})/\sigma(X) \propto \alpha_s$

Example: Pair production of SUSY particles at LHC$_{14}$, with $M_{\text{SUSY}} \approx 600$ GeV

<table>
<thead>
<tr>
<th>LHC - sps1a - m~600 GeV</th>
<th>Plehn, Rainwater, PS PLB645(2007)217</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FIXED ORDER pQCD</strong></td>
<td><strong>$\sigma_{\text{tot}}[pb]$</strong></td>
</tr>
<tr>
<td>$p_T,j &gt; 100$ GeV</td>
<td>$\sigma_{0,j}$</td>
</tr>
<tr>
<td>inclusive X + 1 “jet”</td>
<td>$\sigma_{1,j}$</td>
</tr>
<tr>
<td>inclusive X + 2 “jets”</td>
<td>$\sigma_{2,j}$</td>
</tr>
<tr>
<td>$p_T,j &gt; 50$ GeV</td>
<td>$\sigma_{0,j}$</td>
</tr>
<tr>
<td></td>
<td>$\sigma_{1,j}$</td>
</tr>
<tr>
<td></td>
<td>$\sigma_{2,j}$</td>
</tr>
</tbody>
</table>

(Computed with SUSY-MadGraph)

$\sigma$ for $X + \text{jets}$ much larger than naive estimate

$\sigma_{50} \sim \sigma_{\text{tot}}$ tells us that there will “always” be a $\sim 50$-GeV jet “inside” a 600-GeV process

All the scales are high, $Q >> 1$ GeV, so perturbation theory **should** be OK …
This is just the physics of Bremsstrahlung

The harder they get kicked, the harder the fluctuations that continue to become strahlung.
Can we build a simple theoretical model of this?

The Lagrangian of QCD is **scale invariant** (neglecting small quark masses)

Characteristic of point-like constituents ➤ Observables depend on **dimensionless quantities**, like **angles** and energy **ratios**
The rules of bremsstrahlung

Most bremsstrahlung is driven by divergent propagators → simple structure

Gauge amplitudes factorize in singular limits (→ universal "conformal" or "fractal" structure)

Partons $ab$ → collinear:

$$|M_{F+1}(...,a,b,...)|^2 \xrightarrow{a \parallel b} g_s^2 C \frac{P(z)}{2(p_a \cdot p_b)} |M_F(..., a + b, ...)|^2$$

Gluon $j$ → soft:

$$|M_{F+1}(...,i,j,k...)|^2 \xrightarrow{j_g \rightarrow 0} g_s^2 C \frac{(p_i \cdot p_k)}{(p_i \cdot p_j)(p_j \cdot p_k)} |M_F(..., i, k, ...)|^2$$

+ scaling violation: $g_s^2 \rightarrow 4\pi\alpha_s(Q^2)$

see e.g PS, Introduction to QCD, TASI 2012, arXiv:1207.2389
Iterating the structure

Repeated application of bremsstrahlung rules → nested factorizations

More and more partons resolved at increasingly smaller scales

Can be cast as a **differential evolution**:

\( d\mathcal{P}/dQ^2 \): differential probability to resolve more structure as function of a “resolution scale”, \( Q^2 \sim \text{virtuality} \)

It’s a **quantum fractal**: \( \mathcal{P} \) is probability to resolve another parton as we decrease \( Q^2 \): gluon → two gluons, quark → quark + gluon, gluon → quark-antiquark pair.

As we continue to “zoom”, the integrated probability for resolving another “jet” can naively exceed 100%

That’s what the \( X + \text{jet} \) cross sections were trying to tell us earlier: \( \sigma(X + \text{jet}) > \sigma(X) \)
Parton Showers: reformulation of pQCD corrections as gain-loss diff eq.

Iterative (Markov-Chain) evolution algorithm, based on universality and unitarity
With evolution kernel $\sim \frac{|M_{n+1}|^2}{|M_n|^2}$ (or soft/collinear approx thereof)
Generate explicit fractal structure across all scales (via Monte Carlo Simulation)
Evolve in some measure of resolution $\sim$ hardness, virtuality, 1/time ... $\sim$ fractal scale
+ account for scaling violation via quark masses and $g_s^2 \rightarrow 4\pi\alpha_s(Q^2)$

Acceptable non-singular piece, $F \rightarrow$ "Leading-Logarithmic" (LL) Approximation

→ Can also include loops-within-loops-within-loops ... → Bootstrap for All-Orders Quantum Corrections!

Unitarity: $\text{sum(probability)} = 1$

Kinoshita-Lee-Nauenberg: (sum over degenerate quantum states = finite: infinities must cancel!)

$\text{Loop} = - \int \text{Tree} + F \left| M_{n+1}^0 \right|^2$

Neglect non-singular piece, $F \rightarrow$ "Leading-Logarithmic" (LL) Approximation

see e.g PS, Introduction to QCD, TASI 2012, arXiv:1207.2389

(From Legs to Loops)
Divide and Conquer

Iterated/Nested Factorizations $\rightarrow$ Split the problem into many $\sim$ simple pieces

$$\mathcal{P}_{\text{event}} = \mathcal{P}_{\text{hard}} \otimes \mathcal{P}_{\text{dec}} \otimes \mathcal{P}_{\text{ISR}} \otimes \mathcal{P}_{\text{FSR}} \otimes \mathcal{P}_{\text{MPI}} \otimes \mathcal{P}_{\text{Had}} \otimes \ldots$$

Quantum mechanics $\rightarrow$ Probabilities $\rightarrow$ Make Random Choices (as in nature) $\rightarrow$ Method of Choice: **Markov-Chain Monte Carlo** $\rightarrow$ "Event Generators"

Hard Process & Decays:

Use process-specific (N)LO matrix elements

$\rightarrow$ Sets "hard" resolution scale for process: $Q_{\text{MAX}}$

ISR & FSR (Initial & Final-State Radiation):

Universal DGLAP equations $\rightarrow$ differential evolution, $dP/dQ^2$, as function of resolution scale; run from $Q_{\text{MAX}}$ to $Q_{\text{Confinement}} \sim 1$ GeV

MPI (Multi-Parton Interactions)

Additional (soft) parton-parton interactions: LO matrix elements

$\rightarrow$ Additional (soft) "Underlying-Event" activity (Not the topic for today)

Hadronization

Non-perturbative model of color-singlet parton systems $\rightarrow$ hadrons
Parton Showers are based on $1\rightarrow 2$ splittings

Each parton undergoes a sequence of splittings

Some interference effects included via “angular ordering” or via “dipole functions” (~dipole pattern partitioned into 2 terms) (E,p) conservation achieved via (ambiguous) recoil effects

At Monash, we develop an Antenna Shower, in which splittings are fundamentally $2\rightarrow 3$ (+ working on $2\rightarrow 4$…)

Evolution in terms of colour dipoles/antennae

+ Intrinsically coherent (to leading power of $1/N_C^2 \sim 10\%$)
+ Manifestly Lorentz invariant kinematics with local (E,p) cons.

What’s new in our approach?

Antenna evolution also for initial state and coloured resonances

Higher-order perturbative corrections can be introduced via calculable corrections in an elegant and very efficient way

Includes dipole interference
Example: Coherence in Quark-Quark Scattering

Quark-quark scattering in hadron collisions (eg at LHC)

Consider one specific phase-space point (eg scattering at 45°)
2 possible colour flows: a and b

![Diagram showing forward and backward color flows]

Figure 4: Angular distribution of the first gluon emission in $qq \rightarrow qq$ scattering at 45°, for the two different color flows. The light (red) histogram shows the emission density for the forward flow, and the dark (blue) histogram shows the emission density for the backward flow.

Note: coherence also influences the Tevatron top-quark forward-backward asymmetry: see PS, Webber, Winter, JHEP 1207 (2012) 151
We have an explicit representation of the fractal structure - great
Required approximations: “Leading Logarithm”, “Leading Colour”, …
➤ Only good to about 10%

I thought LHC physics was supposed to be high-precision stuff?
What good is Peta-Bytes of data if we can only calculate to 10%?

Go back to fixed order? Sum inclusively over the fractal structure
In fixed order, I can predict ~ the number of jets (at some fixed scale)
   Good enough if I don’t ask questions about their internal structure, or the number of jets at disparate scales
State of the art is NNLO (few-% accuracy), some calculations even N^3LO
But somewhat unsatisfactory … even at N^3LO the events look far from real
Why not combine the two types of calculations?
Problem: double counting of terms present in both expansions
VINCI A: Markovian pQCD*

**Start at Born level**

\[ |M_F|^2 \]

**Generate “shower” emission**

\[ |M_{F+1}|^2 \sum_{i_{\text{ant}}} a_i |M_F|^2 \]

**Correct to Matrix Element**

\[ a_i \rightarrow \frac{|M_{F+1}|^2}{\sum a_i |M_F|^2} a_i \]

**Unitarity of Shower**

Virtual = \(- \int \text{Real}\)

**Correct to Matrix Element**

\[ |M_F|^2 \rightarrow |M_F|^2 + 2\text{Re}[M_F^1 M_F^0] + \int \text{Real} \]

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Cutting Edge:
Embedding virtual amplitudes
= Next Perturbative Order
→ Precision Monte Carlos

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*)pQCD : perturbative QCD

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PYTHIA 8

“Higher-Order Corrections To Timelike Jets”
GeeKS: Giele, Kosower, Skands, PRD 84 (2011) 054003

“An Introduction to PYTHIA 8.2”
Future Applications (why other people care)

Example: The Top Quark

Heaviest known elementary particle:

\[ m_t \sim 187 \text{ u} \left( \sim m_{\text{Au}} \right) \]

Lifetime: \( 10^{-24} \text{ s} \)

Complicated decay chains:

\[ t \rightarrow bW^+ \quad \bar{t} \rightarrow \bar{b}W^- \]

\[ W \rightarrow \{ q\bar{q}', \ell\nu \} \]

quarks \( \rightarrow \) jets  

b-quarks \( \rightarrow \) b-jets

\[ m_t^2 \approx (p_b + p_{W^+})^2 \]

\[ \approx (p_{b-\text{jet}} + p_{q-\text{jet}} + p_{\bar{q}-\text{jet}})^2 \]

**Accurate** jet energy calibrations \( \rightarrow m_t \)

**Analogously** for any process / measurement involving coloured partons


Brooks, Skands, “Coherent Showers in Decays of Coloured Particles”, *PRD100* (2019) 076006
Here's a fast parton

**Fast:** It starts at a high factorization scale
\[ Q = Q_F = Q_{\text{hard}} \]

It showers (bremsstrahlung)

It ends up at a low effective factorization scale
\[ Q \sim m_p \sim 1 \text{ GeV} \]
2) Non-Perturbative QCD

Here’s a fast parton

**Fast:** It starts at a high factorization scale
\[ Q = Q_F = Q_{\text{hard}} \]

It showers (bremsstrahlung)

It ends up at a low effective factorization scale
\[ Q \sim m_\rho \sim 1 \text{ GeV} \]

How about I just call it a hadron?

→ “Local Parton-Hadron Duality”
Early models: “Independent Fragmentation”

Local Parton Hadron Duality (LPHD) can give useful results for inclusive quantities in collinear fragmentation

Motivates a simple model:

“Independent Fragmentation”

But …

The point of confinement is that partons are coloured

Hadronisation = the process of **colour neutralisation**

→ Unphysical to think about independent fragmentation of a single parton into hadrons

→ Too naive to see LPHD (inclusive) as a justification for Independent Fragmentation (exclusive)

→ More physics needed
A physical hadronization model

Should involve at least TWO partons, with opposite color charges (e.g., $R$ and anti-$R$)

Strong “confining” field emerges between the two charges when their separation $> \sim 1\text{fm}$
Quark-Antiquark Potential

As function of separation distance

LATTICE QCD SIMULATION.
(in “quenched” approximation)

Scaling plot

\[ F(r) \approx \text{const} = \kappa \approx 1 \text{ GeV/fm} \quad \text{↔} \quad V(r) \approx \kappa r \]

~ Force required to lift a 16-ton truck

What physical system has a linear potential?

“Confined” Partons (a.k.a. Hadrons)

Long Distances ~ Linear Potential

“Free” Partons

Short Distances ~ “Coulomb”
From Partons to Strings

Motivates a model:

Let colour field collapse into a (infinitely) narrow flux tube of uniform energy density

\[ \kappa \sim 1 \text{ GeV} / \text{fm} \]

\[ \rightarrow \text{Relativistic 1+1 dimensional worldsheet} \]

String

In “unquenched” QCD

\[ g \rightarrow qq \rightarrow \text{The strings will break} \]

Schwinger Effect

- Non-perturbative creation of \( e^+e^- \) pairs in a strong external Electric field
- Probability from Tunneling Factor

\[ P \propto \exp \left( \frac{-m^2 - p_T^2}{\kappa / \pi} \right) \]

(\( \kappa \) is the string tension equivalent)

\[ \rightarrow \text{Gaussian } p_T \text{ spectrum} \]

Heavier quarks suppressed. \( \text{Prob}(q=d,u,s,c) \approx 1 : 1 : 0.2 : 10^{-11} \)

Hadronisation and Jets

Consider a quark and anti-quark produced in $e^+e^-$ annihilation

i) Initially Quarks separate at high velocity

ii) Colour flux tube forms between quarks

iii) Energy stored in the flux tube sufficient to produce $q\bar{q}$ pairs

iv) Process continues until quarks pair up into jets of colourless hadrons

This process is called hadronisation. It is not (yet) calculable from first principles.

The main consequence is that at collider experiments quarks and gluons observed as multi-particle states: jets of particles
Models vs Data — A Recent Example

Around 2015, a few teams of theorists proposed a new set of measurements to test a fundamental property of the strong force:

Is the fraction of “**strange**” particles produced in the LHC experiments a constant, or does it depend on how violent the collisions are?

**How are 2 colliding protons turned into hundreds of outgoing particles?**

Fact: quarks (and gluons) are “confined” inside the proton

What happens if we give one of them a really hard kick?

**Fragmentation**: Field energy converted to mass of new quark-antiquark pairs

Strange quarks are heavier (need more energy) $\rightarrow$ produced less often
What a strange world we live in, said Alice [to the queen of hearts]

We wanted to know if “violent” collision events produced higher-strength fields.

Smoking gun would be a higher fraction of strange particles being produced

(higher-strength fields → more energy per “space-time volume” → easier to produce higher-mass quark-antiquark pairs)

Jackpot!
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Jackpot!

Now working on models in which nearby fragmenting fields interact with each other.

**Interactions between QCD strings!**

Higher tensions + repulsion effects $\blacktriangleright$ modifications in high-density environments

(Competing idea: the whole thing turns into a near-perfect liquid which gets heated up.)
New research at Monash

- **Precision LHC phenomenology** & future collider studies (FCC, CEPC)
- **Monte Carlo Event Generators**: PYTHIA & VINCIA
- **QCD jets and (sub)structure**: Next order of precision
- **Dynamics of confinement**: hadronisation, QCD strings, interactions

**Partnerships:** MCnet, Warwick Alliance, Bologna, CERN/LHC@Home, LHCB

MCnet is an EU Marie Curie “Innovative Training Network” (ITN) on MC generators for LHC (Herwig, Pythia, Sherpa). **Funded 2017-2020** with Monash as associate partner.

**Studentship programme** open for applications: 3-6 month placements at European university nodes, or with industrial partners.

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