Monte Carlo generators aim to give fully exclusive descriptions of collider final states - within and beyond the Standard Model

- Including effects of initial- and final-state radiation (ISR & FSR showers)
- + (Sequential) Resonance decays (top quarks, Z/W/H bosons, & BSM)
- + Soft physics: Underlying Event, Hadronisation, Decays, Beam Remnants

Explicit modelling of QCD dynamics \iff comparison to measurements

E.g., MC models were crucial to establish “string effect” in early 80s

Extensively used to design/optimise analyses (& planning future ones)

Study observables, sensitivities, effects of cuts, detector efficiencies, derive correction factors, extract fundamental parameters, cross sections, ...

Lund String Model has probably been the most successful hadronisation model over the last 30 years.

This talk: it is beginning to show some interesting failures at LHC
Impact on hadronisation corrections for high-\( p_T \) analyses?

See, e.g., MCnet review arXiv:1101.2599, or TASI lectures arXiv:1207.2389
QCD is more than a (fixed-order) expansion in $\alpha_s$

Challenges Beyond Fixed Order: “Emergent Phenomena”

**Fractal Structures:** scale Invariance of massless Lagrangian $\rightarrow$ jets-within-jets-within-jets (& loops-within-loops-within-loops)

**Confinement** (win $1,000,000$ if you can prove)

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**Jets** (perturbative QCD, initial- and final-state radiation)

$\leftrightarrow$ QFT amplitude structures, factorisation & unitarity

$\leftrightarrow$ Precision jet (structure) studies, calibrations.


**Hadrons** $\leftrightarrow$ Spectroscopy (incl excited and exotic states), lattice QCD, (rare) decays, mixing, light nuclei. Hadron beams $\rightarrow$ multiparton interactions, diffraction, ...
Ulterior Motives for Studying QCD

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

We strongly suspect there is more to (particle) physics

... but are still looking for deviations from the Standard Model

Accurate modelling of QCD → improve searches & precision

Shakespeare, Hamlet.
The Phenomenology Pipeline

The Pipeline looks something like this:

- **THEORY**
  - Exclusions
  - Hints
  - Evidence
  - Discoveries
  - Surprises

- **PHENOMENOLOGY**
  - Calculations
  - Model
  - Observables

- **EXPERIMENT**
  - Analyses
  - Planning
  - Design
  - R&D
  - Hardware
  - Triggers
  - ... (continued)

- **INTERPRETATION**
  - Validate/Falsify Models
  - Constrain Free Parameters
  - Statistical Tests
  - Measurements
  - Corrections
  - Systematics

Example: "QCD"

\[
g^a \left(-i g_s t_{ij} \gamma^\mu \right)
\]
Monte Carlo Event Generators

Factorization → Split the problem into many (nested) pieces

+ Quantum mechanics → Probabilities → Random Numbers

\[ P_{\text{event}} = P_{\text{hard}} \otimes P_{\text{dec}} \otimes P_{\text{ISR}} \otimes P_{\text{FSR}} \otimes P_{\text{MPI}} \otimes P_{\text{Had}} \otimes \ldots \]

**Hard Process & Decays:**
- Use process-specific (N)LO matrix elements
- → Sets “hard” resolution scale for process: \( Q_{\text{MAX}} \)

**ISR & FSR (Initial & Final-State Radiation):**
- Universal DGLAP equations → differential evolution, \( dP/dQ^2 \), as function of resolution scale; run from \( Q_{\text{MAX}} \) to \( Q_{\text{Confinement}} \approx 1 \text{ GeV} \)

**MPI (Multi-Parton Interactions)**
- Additional (soft) parton-parton interactions: LO matrix elements
- → Additional (soft) “Underlying-Event” activity

**Hadronization**
- Non-perturbative model of color-singlet parton systems → hadrons
Quark-Antiquark Potential

As function of separation distance

\[ \frac{V(r)}{k^2} \]

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

~ Force required to lift a 16-ton truck
1.2 Thermodynamics of Superconductors

The differential free energy density of a magnetic material is given by
\[ df = -sdT + \frac{1}{4\pi} H \cdot dB, \]
(1.2)
which says that \( f = f(T, B) \). Here \( s_B \) is the entropy density, and \( B \) the magnetic field. The quantity \( H \) is called the magnetizing field and is thermodynamically conjugate to \( B \):
\[ s_B = -\left( \frac{\partial f}{\partial T} \right)_B, \]
\[ H = 4\pi \left( \frac{\partial f}{\partial B} \right)_T. \]
(1.3)

In the Ampère-Maxwell equation, \( \nabla \times H = 4\pi \left( \frac{1}{c} \right) j_{ext} + \left( \frac{1}{c} \right) \partial_t D \), the sources of \( H \) appear on the RHS.

### 1911: Discover of superconductivity (K. Onnes)

### 1933: Discovery of flux expulsion (Meissner & Ochsenfeld)

- Penetration depth: \( \lambda \) (distance over which field decays by 1/e)

### 1957: Vortex Lines (Abrikosov) (in Type II SC)

- Swirling supercurrents produce a non-SC “core”
- Core size: \( \xi \) (aka “coherence length”; exp decay outside core)
- Flux Quantisation: each core carries a single unit of flux
- Type II if core size small: \( \xi < \sqrt{2}\lambda \) (otherwise Type I)

### 1960’s - 1970’s: “Dual models” for strong force

- Regge Theory: massless endpoints on rotating relativistic strings
- Nielsen-Olesen: Higgs-type Lagrangians \( \rightarrow \) vortex lines \( \leftrightarrow \) Nambu strings
- Advent of SM (QCD) \( \rightarrow \) string models refocus on gravity (\& EW cosmic strings)

After the parton shower finishes, there can be lots of partons, \( \mathcal{O}(10-100) \). The main question is therefore:

**Between which partons do confining potentials arise?**

MC generators use a simple set of rules for colour flow, based on large-\( N_C \) limit (valid to \( \sim 1/N_C^2 \sim 10\% \))

\[
q \rightarrow qg
\]

\[
g \rightarrow q\bar{q}
\]

\[
g \rightarrow gg
\]

Illustrations from: Nason & Skands, PDG Review on *MC Event Generators*, 2014
For an entire Cascade

Example: $Z^0 \rightarrow qq$

For a single fragmenting system:

Coherence of pQCD cascades (angular ordering or boosted dipoles/antennae)
→ not much “overlap” between strings
→ Leading-colour approximation pretty good

(The trouble at LHC: MPI & ISR → many such systems; overlapping)
The (Lund) String Model

Map:

- **Quarks** → String Endpoints
- **Gluons** → Transverse Excitations (kinks)
- Physics then in terms of string worldsheet evolving in spacetime
- Probability of string break (by quantum tunneling) constant per unit area → **AREA LAW**

Simple space-time picture
Details of string breaks more complicated (e.g., baryons, spin multiplets)

Differences Between Quark and Gluon Jets

**Example of Recent Studies**

Gluon connected to two string pieces

Each quark connected to one string piece

→ expect factor $2 \sim C_A/C_F$ larger particle multiplicity in gluon jets vs quark jets

Can be important for discriminating new-physics signals (decays to quarks vs decays to gluons, vs composition of background and bremsstrahlung combinatorics)
The Effects of Hadronisation

Generally, expect few-hundred MeV shifts by hadronisation

Corrections to IR safe observables are “power corrections”

\[ \propto \frac{\Lambda_{QCD}^2}{Q_{OBS}^2} \]

Corrections for jets of radius \( R = \Delta \eta \times \Delta \phi \)

\[ \propto \frac{1}{R} \]

See
Korchemsky, Sterman, NPB 437 (1995) 415
Seymour, NPB 513 (1998) 269
Dasgupta, Magnea, Salam, JHEP 0802 (2008) 055

Simple analytical estimate \[ \rightarrow \sim 0.5 \text{ GeV} / R \text{ correction from hadronisation} \] (scaled by colour factor)

Significant differences between codes/tunes \[ \rightarrow \text{important to pin down with precise QCD hadronisation measurements at LHC} \]

**LES HOUCHE STUDY (arXiv:1605.04692): Q/G can be highly affected by colour reconnections**
Next-to-simplest: 2 string systems

Several studies at LEP2 (ee → WW → 4 jets)

CR implied a non-perturbative uncertainty on the W mass measurement, ΔM_W ~ 40 MeV

CR strength best fit ~ 10% ~ 1/N_c^2

But in WW, overlaps are expected to be suppressed by kinematics, and there are “only” two strings;

In pp, MPI can create (many) more … ?

Proton-Proton (LHC)

A lot more colour kicked around (& also colour in initial state)

Include “Beam Remnants”

Still might look relatively simple, to begin with

(+baryon beam remnants → “string junctions”)
**Colour: What’s the Problem?**

(including **MPI**: Multiple Parton-Parton Interactions ~ the “underlying event”)

**Without Colour Reconnections**
Each MPI hadronizes **independently** of all others
(including **MPI**: Multiple Parton-Parton Interactions ~ the “underlying event”)

**Without Colour Reconnections**
Each MPI hadronizes **independently** of all others

So many strings in so little space
If true $\rightarrow$ Very high energy densities
QGP-like “core” with hydro?

→ Thermal? **E.g., EPOS**
Colour Reconnections

(including **MPI**: Multiple Parton-Parton Interactions ~ the “underlying event”)

**With Colour Reconnections**

MPI hadronize **collectively**

Highly interesting theory questions now.

**Is there collective flow in pp?**
**If yes, what is its origin?**
Is it stringy, or hydrodynamic? (or …?)

E.g., do most patches of event look the same (thermalised?) or do they look more independent?

See e.g., Ortiz et al., Phys.Rev.Lett. 111 (2013) 4, 042001

See e.g., Skands & Wraight: arXiv:1101.5215

**Beam Direction**

**String-Length Minimisation**  
E.g., PYTHIA, HERWIG  
Or Thermal? E.g., EPOS  
Or Higher String Tension? E.g., DIPSY rope

**Outgoing parton**
**String Piece**

**comoving hadrons**
What do we see?

submicron particles dispersed in superfluid 4He

“Direct observation of Kelvin waves excited by quantized vortex reconnection”

Visualisation by: Fonda, Meichle, Ouellette, Hormoz, Lathrop, PNAS 111(2014)4707

http://www.pnas.org/content/suppl/2014/03/20/1312536110.DCSupplemental
What do we see in pp collisions?

Average pT increases with particle multiplicity and (faster than predicted) with particle mass

Note: from RHIC (200 GeV)
The “CMS Ridge”

High-Multiplicity pp collisions

CMS pp $|\sqrt{s}| = 13$ TeV, $N_{\text{trk}}^{\text{offline}} \geq 105$

$1 < p_T < 3$ GeV/c

Reminiscent of the (much stronger) ridge seen in HI collisions.

Surprisingly strong also in proton-Lead
Strangeness

Plots from the Monash tune paper

This is the data used to tune the models
Note: rates normalised to unity now

Kaon spectrum at LEP


Strangeness Spectra

(+ Several measurements by ALICE, LHCb)
Strangeness Spectra

Note: rates normalised to unity now

Lambda spectrum at LEP

Data from EPJ C16 (2000) 613
Pythia 8.183

Lambda spectrum at LHC

Data from JHEP 1105 (2011) 064
Pythia 8.181

(+ Several measurements by ALICE, LHCb)
**CMS: Strangeness in the Underlying Event**

**Effect also present in UE** *(note: effect enhanced by $p_T$ cuts, cf spectra)*

Do MC jets have the right particle content and spectra?  
Implications for particle-flow modeling, JES calibrations, Q/G discrimination?  
Further measurements? (in jets, along jet rapidity axis, …)

Plots from mcplots.cern.ch

Protons more numerous than Lambda; but probably have to ask ALICE?
Extensions of CMS UE Study?

Probing Collective Effects in Hadronisation with the Extremes of the Underlying Event

“Extreme UE”

From T. Martin, ICHEP 2016

<table>
<thead>
<tr>
<th>$R_T &gt; 3$</th>
<th>$R_T &gt; 2$</th>
<th>$R_T &gt; 1$</th>
<th>$R_T &lt; 1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{p}N/\bar{p}\bar{N}$</td>
<td>$\Lambda/\bar{p}$</td>
<td>$\Lambda/\bar{N}$</td>
<td>$\Xi/\bar{N}$</td>
</tr>
</tbody>
</table>

$\sqrt{s} = 13$ TeV

Lead $p_T$

$<N_{nc}\rangle = \langle N_{all}/N(\bar{N})\rangle$

$\text{MC Monash}$

Pythia 8.210 Monash
Pythia 8.210 Monash + New CR
EPOS 1.3 LHC
DIPSY NoSwing
DIPSY Rope

$\text{EPOS 1.3 LHC}$

$\text{Pythia 8.210 Monash}$

$\text{DIPSY NoSwing}$

$\text{DIPSY Rope}$

$\bar{p}N/\bar{p}\bar{N} > \text{[Trans.]}$

$\Lambda/\bar{p}$

$\Lambda/\bar{N}$

$\Xi/\bar{N}$

$2 \times 10^{-1}$ $1$ $2$ $3$ $4$

$\text{MC Monash}$

$\text{Pythia 8.210 Monash}$

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Pythia 8.210 Monash + New CR
EPOS 1.3 LHC
DIPSY NoSwing
DIPSY Rope

$\bar{p}N/\bar{p}\bar{N} > \text{[Trans.]}$
A clear enhancement of strangeness with (pp) event multiplicity is observed

Especially for multi-strange baryons

No corresponding enhancement for protons → this really must be a strangeness effect

Cross-check measurements of the phi meson are now underway

Jet universality: jets at LHC modelled the same as jets at LEP

Flat line ! (cf PYTHIA)

DIPSY includes “colour ropes”

EPOS includes hydrodynamic “core”
The Plot Thickens

Looks like the effect, whatever it is, continues smoothly into p-Pb
The Plot Thickens

Looks like the effect, whatever it is, continues smoothly into p-Pb … and into Pb-Pb!

Unexpected.

Looks like jet universality and hadronisation in pp is up for revision.

Is it thermal? Stringy? Both?

Collective? Flowy? …

Physics must explain smooth transition to heavy ions. No abrupt “phase transition” seen in these observables
Higgs-type Lagrangians $\rightarrow$ Vortex Lines $\rightarrow$ String Models

Remain our best bet at modelling hadronisation in QCD

**High-multiplicity & high-$p_T$ triggered events:** large amounts of colour kicked around: soft event structure appears to require (at least) going beyond Leading Colour $\rightarrow$ *Colour Reconnections (CR)*

Beyond CR, it now appears that the effective QCD scale is *increasing*

What are the *dynamics* of pp / multi-string environments?

**Phenomenology:** Modern revisions of the Lund string model

**What measurements** can be performed to shed more light?

Possible to get more information from *lattice*? Multi-string systems?

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By the way (advertisement):

Did you know you can get automated shower-uncertainty weights?

*Automated Parton-Shower Uncertainties in PYTHIA 8*  
Mrenna & Skands, *arXiv:1605.08352*

*Similar capabilities in HERWIG++, SHERPA, VINCIA*  
Bellm, Plätzer, Richardson, Siodmok, Webster *1605.08256*  
Bothmann, Schönherr, Schumann *1606.08753*  
Giele, Kosower, Skands *PRD84 (2011) 054003*
New research at Monash

**Precision LHC Phenomenology**
- **PYTHIA & VINCIA**
- **NLO Event Generators**
- **QCD Strings, Hadronisation**

**Support LHC Experiments, Astro-Particle Community, and Future Accelerators**
+ Outreach and Citizen Science

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**Partnerships:** Warwick Alliance, MCnet, CoEPP

New joint research program with Warwick ATLAS, on developing and testing advanced collider-QCD models. **Opportunities for PhD students** based at Monash + exchange to UK/CERN.

See: arXiv:1603.05298

**MCnet** is an EU Marie Curie Training Network (ITN) on MC generators for LHC (Herwig, Pythia, Sherpa). **Funded for Horizon 2020!** Starting in 2017 with Monash an associate partner.
No Enhancement for Protons

D.D. Chinellato – 38th International Conference on High Energy Physics
All on the same plot

Including $K^*$ and protons

![Graph with particle ratios across colliding systems]
**p_T Dependence**

Spectra become harder at high multiplicities
More pronounced for baryons than mesons

\[
\left( \frac{p + \bar{p}}{\pi^+ + \pi^-} \right) / (\pi^+ + \pi^-)
\]

**ALICE Preliminary pp \( \sqrt{s} = 7 \text{ TeV} \)**

- **V0M Class I**, \( \langle dN_{ch}/d\eta \rangle = 21.3 \)
- **V0M Class X**, \( \langle dN_{ch}/d\eta \rangle = 2.3 \)

(V0M Multiplicity Classes)

\[
\langle dN_{ch}/d\eta \rangle^{\text{INEL>0}} \approx 6.0
\]

**Modification of Transverse Momentum Spectra**

Spectra become harder at high multiplicities
More pronounced for baryons than mesons

\[
\langle dN/d\eta \rangle = 21.3
\]

\[
\langle dN/d\eta \rangle \approx 3?
\]
1980: string (colour coherence) effect

Predicted unique event structure; inside & between jets. Confirmed first by JADE 1980. Generator crucial to sell physics! (today: PS, M&M, MPI, ...)
1980: string (colour coherence) effect

Predicted unique event structure; inside & between jets.
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Generator crucial to sell physics!
(today: PS, M&M, MPI, ...)

string motion in the event plane (without breakups)
In “unquenched” QCD

g\rightarrow qq \rightarrow The strings will break

Schwinger Effect

Non-perturbative creation of e^+e^- pairs in a strong external Electric field

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

(\kappa is the string tension equivalent)

→ Gaussian p_T spectrum

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

• Breakup vertices causally disconnected → order is irrelevant → iterative algorithm
In QCD, strings can (and do) break!

In superconductors, would require magnetic monopoles
In QCD, the roles of electric and magnetic are reversed
Quarks (and antiquarks) are “chromoelectric monopoles”
There are at least two possible analogies ~ tunneling:

1) Schwinger Effect

Non-perturbative creation of $e^+e^-$ pairs in a strong external Electric field

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

($\kappa$ is the string tension equivalent)

2) Hawking Radiation

Non-perturbative creation of radiation quanta in a strong gravitational field

\[ \mathcal{P} \propto \exp \left( \frac{-E}{k_B T_H} \right) \]

Linear Energy Exponent
What are “Colour Reconnections”?  

Simple example: \( e^+e^- \rightarrow W^+W^- \rightarrow \text{hadrons} \)
- Intensely studied at LEP2.  
  - CR implied a non-perturbative uncertainty on the W mass measurement, \( \Delta MW \sim 40 \text{ MeV} \)
- CR constrained to \( \sim 10\% \sim 1/NC^2 \)
- Simple two-string system. What about pp?

Several modelling attempts
- Based on “just” minimising the string action
  - String interactions (Khoze, Sjostrand)
  - Generalized Area Law (Rathsman et al.)
  - Colour Annealing (Skands et al.)
  - Gluon Move Model (Sjostrand et al.)
- More recently: SU(3)\(_C\) group multiplet weights
  - Dipole Swing (Lonnblad et al.); Colour Ropes (Bierlich et al.)
  - String Formation Beyond Leading Colour (Skands et al.)

\[ \begin{align*}
3 \otimes 3 &= 8 \oplus 1 \\
3 \otimes 3 &= 6 \oplus 3 \\
3 \otimes 8 &= 15 \oplus 6 \oplus 3 \\
8 \otimes 8 &= 27 \oplus 10 \oplus 10 \oplus 8 \oplus 8 \oplus 1
\end{align*} \]