QCD Phenomenology and Event Generators

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QCD at the LHC

Chart adapted from Gavin Salam

Papers commonly cited by ATLAS and CMS (2014-2016)

as of 2016-06-10, excluding self-citations; all papers > 0.2
Experiments to learn from:
High & low-energy DIS, $\ell\ell + hh$
collider measurements, cosmic
rays, heavy-ion collisions...

(QCD) theory toolbox:
Factorization, fixed-order QCD, resummation, double parton
scattering, diffraction, (3D) nucleon structure

Hard interaction $\rightarrow$ Radiative cascade
$\rightarrow$ Secondary interactions $\rightarrow$ Hadron formation
$\rightarrow$ Hadron decay, rescattering, Bose-Einstein effects...
Why Monte Carlo Event Generators?

General Purpose Monte Carlo Event Generators (MCEGs)
– Combine all aspects of scattering events.
– Are repositories for our knowledge of scattering processes.

Common high-energy MCEGs are **HERWIG**, **PYTHIA** and **SHERPA**.

They include knowledge of $\mathcal{O}(40$ research years) – per person, in some cases …and still, there are many things yet to learn!
## Generator cheat-sheet and news

<table>
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<tr>
<th>Handles</th>
<th>“Best” PQCD</th>
<th>pp Multiple Int\textsuperscript{n,s}</th>
<th>Fragmentation</th>
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<tr>
<td>HERWIG</td>
<td>(ee, ep, pp)</td>
<td>NLO+PS matched</td>
<td>Eikonal</td>
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<tr>
<td>PYTHIA</td>
<td>(ee, ep, pp)</td>
<td>NLO+PS merged</td>
<td>Interleaved</td>
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<tr>
<td>SHERPA</td>
<td>(ee, ep, pp)</td>
<td>NNLO+PS matched</td>
<td>Traditional</td>
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<tr>
<th>HERWIG7 news</th>
<th>PYTHIA8 news</th>
<th>SHERPA news</th>
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<tr>
<td>on-the-fly PQCD uncertainties, two (three) new NLO matching schemes, NLO merging, improved online documentation</td>
<td>on-the-fly PQCD uncertainties, two new showers, improved diffraction, thermodynamic string hadronization</td>
<td>on-the-fly PQCD uncertainties, one new shower, NLO electroweak effects, news on (V+b) processes.</td>
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Fundamental assumption: Factorisation

Long-distance effects factorize from short-distance physics

\[ \sigma = \int d\sigma_{(ab \to X+N \text{ partons})} \text{(high energy)} \]
\[ \otimes f_{a \in A}(\{x\}_a, \text{high energy}) \otimes f_{b \in B}(\{x\}_b, \text{high energy}) \]
\[ \otimes D(p_A, p_B, p_1, \ldots, p_N) + \text{power corrections} \]

\( f \) & \( D \) are non-perturbative functions

\( \Diamond \) Extract/fit \( f \) and \( D \) where corrections are small (low energy).
\( \Diamond \) Use perturbation theory to calculate \( d\sigma \) at high energy.
Use perturbative (NLO, NNLO) QCD for largest possible part of the dynamics before using non-perturbative physics.

⇒ Well-defined uncertainty, non-perturbative model can still be universal.
The NNLO explosion

17 calc<sup>nS</sup> in [2000, 2014]
20+ calc<sup>nS</sup> in [2014, present]

due to breakthrough in reg<sup>n</sup> schemes:

“Slicing<sup>†</sup>”

\[ \sigma = [c + \ln(\text{cut})] f(0) + \int_{\text{cut}} dz \frac{f(z)}{z} \]

“Subtraction<sup>‡</sup>”

\[ \sigma = [c + ct] f(0) + \int dz \frac{f(z) - f(0)}{z} \]

Bottleneck: 2-loop master integrals

<sup>†</sup> qT subt<sup>n</sup> (e.g. MATRIX), N-jettiness subt<sup>n</sup> (e.g. MCFM)
<sup>‡</sup> sector dec<sup>n</sup>, antenna subt<sup>n</sup> (e.g. NNLOJET), sector-improved residue subt<sup>n</sup>, Colorful subt<sup>n</sup>, Projection-to-Born
Fixed-order corrections are calculated at a **high energy**. Distribution functions extracted at **low energy**.

**Parton shower** (PS) evolves **high energy** fixed-order cross section to **low energy**, summing large perturbative corrections. 
⇒ All perturbatively calculable differential information generated.
Reliable predictions need
- accurate fixed-order
- accurate parton shower
- reliable combination scheme
- smooth match to NP physics.

Matching & Merging
- NLO (NNLO) hard scattering (can combine many calc_{ns}
- PS higher-order corrections

Well-developed for “simple” processes.
Landmark: NNLO+PS matching

- NNLO for incl. cross-section
- NLO+PS for 1-parton observables
- LO+PS for 2-parton observables

Two schemes: NNLOPS/MINLO and UN$^2$LOPS
Remember the skeletons…

Assigning correct “higher-order correction” very important
… for precision measurements
… when many different final-state objects are combined
Both apply to calculations for top mass extraction.
Matching $WbWb$ with POWHEG-BOX-RES

$\ell\ell\nu\nu b\bar{b}$ @ NLO with massive b-quarks $\implies$ Most realistic calc of $m_{t,rec}$

Much more sophisticated/subtle matching compared to e.g. Drell-Yan

$b$ fragmentation very sensitive to details of matching/shower.
How large are shower uncertainties?

MCEGs offer efficient automatic PQCD scale variations.

Large uncertainties at low $p_{\perp}$. Reduced if sub-leading logs were fixed?
Motivations for new parton showers

- PQCD evol$^n$ dominant uncertainty in resummation/TMD region
DIRE showers: PYTHIA & SHERPA joining forces

Disentangle soft limit and collinear limits
Reproduce dominant two-particle correlation in soft limit
Use simple phase space boundaries
⇒ Manageable analytic structure allows systematic improvements

- Combines “traditional” parton showers and dipole showers.
- Two independent implementations, carefully cross-validated
- PQCD model of one MCEG fully reproducible in another.
DIRE predictions

$p_T$ spectrum, $Z \rightarrow ee$ (dressed)

- $0 \leq |y_Z| \leq 1$
- $1 \leq |y_Z| \leq 2$ ($\times 0.1$)
- $2 \leq |y_Z| \leq 2.4$ ($\times 0.01$)

- ATLAS data
- JHEP 09 (2014) 145
- ME+PS (1-jet)
- $5 \leq Q_{cut} \leq 20$ GeV


\[ \frac{1}{\sigma} \frac{d\sigma}{d(1-T)} \]

\[ \frac{1}{e_d} \frac{d\varepsilon}{dB} \]
DEDUCTOR framework:
- PS based on Nagy-Soper dipoles, set up for amplitude-level evolution
- Recovers CSS equation @ NLL Drell-Yan $q_{\perp}$ spectrum

**First fully exclusive resummation of threshold logarithms**

*Achieved by relaxing PS unitarity condition in controlled fashion*
Simultaneously integrates $+$ resums fixed-order multi-jet MEs.

Take-home message: PS resummation should systematically move beyond LL. Old and new improvement ideas are becoming feasible.
Multiparticle states have many sources!

Inclusion of all (soft) particle production mechanisms important.

Crucial for forward physics, e.g.

*cosmic ray measurements $\leftrightarrow$ fixed-target on steroids*
New PYTHIA8 diffraction, including dynamical gap survival probability.

Physical mechanism separating diffractive & non-diffractive proc's.

Double diffraction currently missing.


No additional parameters w.r.t. old model.

Describes MinBias very well.
Hadronization news: How does a string break?

String model very predictive for dynamics, but not for flavour: Motivated by tunneling, $p_{\perp h}$ inherited from $m_{\perp q} \Rightarrow \mathcal{O}(20)$ parameters.

New: Motivated by Hagedorn phase transition ($QGP \rightarrow$ hadrons), use mechanism directly based on $m_{\perp h} \Rightarrow \mathcal{O}(5)$ parameters.
Ideas about dense color fields

Color ropes in DIPSY:

High string density converts strings to “ropes”. Ropes have higher tension → changed hadron spectrum.

New color-recon\(^n\) in PYTHIA:

Non-perturbative color swaps (determined from weight in SU(3) multiplets) before strings form.
QCD phenomena are omnipresent in measurements.

Availability of NNLO QCD calculations rapidly increasing.

Event generators crucial for many experiments. Development continues on many topics:
- Matching & merging community very active.
- Renewed interest in improved parton showers.
- More physical/microscopic diffractive models being developed.
- Hadrochemistry at LHC tackled from many angles.

Still a lot to do, and a lot to learn!
Thank you for your time!
Back-up
Remember: Jets are only an approximation!

Data shows that jets at LEP “talk to each other”. The phenomenon is called string effect. It’s perturbative incarnation is called color coherence.