QCD for LHC

Gavin P. Salam*
Rudolf Peierls Centre for Theoretical Physics
All Souls College

* on leave from CERN and CNRS

International School of Subnuclear physics
57th course, In Search of the Unexpected
Erice, June 2019
what are we trying to learn at the LHC?
what is the underlying Lagrangian of particle physics?

\[ L = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i F \bar{\psi} \gamma^\mu \psi \\
+ \chi_i y_{ij} y_{3\phi} + h.c. \\
+ \left| D_\mu \phi \right|^2 - V(\phi) \]
LHC is first machine to directly access Higgs sector

Is it the minimal version hypothesised in the SM?

origin of mass for W/Z

origin of mass for fermions via Yukawa couplings

a potential $V(\phi)$ that is theorists’ favourite toy ($\phi^4$), but yet to be confirmed in nature
Is there anything else at the $\sim$TeV scale?

If not, then many people worry about fine tuning
what are the values of the parameters of the SM?

couplings
(esp. strong coupling)

masses
(e.g. top & W masses)
what are the values of the parameters of the SM?

couplings
(esp. strong coupling)
masses
(e.g. top & W masses)

\[
\frac{M_h}{\text{GeV}} > 124.2 - \frac{190}{\log_{10} \left( \frac{M_t}{\text{GeV}} \right)} + 2.0 \left( \frac{M_t}{\text{GeV}} - 173.34 \right) - 0.6 \left( \frac{\alpha_s(M_Z) - 0.1184}{0.0007} \right) \pm 1.
\]

\text{arXiv:1505.04825}
A proton–proton collision: INITIAL STATE

proton

proton
A proton–proton collision: FINAL STATE

(Actual final-state multiplicity ~ several hundred hadrons)
how do you make quantitative connection?

through a chain of experimental and theoretical links
Papers commonly cited by ATLAS and CMS (2014-2017) as of 2018-01-14, excluding self-citations; all papers > 0.2

What are the links?
ATLAS and CMS (big LHC expts.) have written ~1000 articles since 2014

links ≡ papers they cite

quantum chromodynamics (QCD) theory papers

experimental & statistics papers

fraction of ATLAS & CMS papers that cite them

Plot by GP Salam based on data from InspireHEP

GEANT4
Anti-k_{t} jet alg.
Pythia 6.4 MC
Pythia 8.1
CT10 PDFs
POWHEG Box
POWHEG (2007)
CTEQ6 PDFs
CTEQ6 PDFs
POWHEG (2004)
MG5aMCatNLO
FastJet Manual
Likelihood tests for new physics
Sherpa 1.1
MadGraph 5
top++
NNLO tbar
Herwig 6 MC
Pileup subtraction
PDF4LHC (2011)
NNPDF23 PDFs
NNPDF30 PDFs
Perugia tunes (2010)
Herwig++ MC
this lecture: 7 small parts

1. structure of QCD Lagrangian
2. a master formula
3. the strong coupling
4. parton distribution functions
5. fixed order calculations
6. Monte Carlo event generators
7. jets
the QCD lagrangian

and lattice QCD
Quantum chromodynamics (QCD)

- Quarks — 3 colours: \( \psi_a = \begin{pmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \end{pmatrix} \)

Quark part of Lagrangian:

\[
L_q = \bar{\psi}_a (i \gamma^\mu \partial_\mu \delta_{ab} - g_s \gamma^\mu t_{ab}^C A^C_\mu - m) \psi_b
\]

- SU(3) local gauge symmetry \( \leftrightarrow 8 (= 3^2 - 1) \) generators \( t_{ab}^1 \ldots t_{ab}^8 \) corresponding to 8 gluons \( A^1_\mu \ldots A^8_\mu \).

A representation is: \( t^A = \frac{1}{2} \lambda^A \),

- \( \lambda^1 = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \), \( \lambda^2 = \begin{pmatrix} 0 & -i & 0 \\ i & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \), \( \lambda^3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix} \), \( \lambda^4 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix} \),

- \( \lambda^5 = \begin{pmatrix} 0 & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & 0 \end{pmatrix} \), \( \lambda^6 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} \), \( \lambda^7 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -i \\ 0 & i & 0 \end{pmatrix} \), \( \lambda^8 = \begin{pmatrix} \frac{1}{\sqrt{3}} & 0 & 0 \\ 0 & \frac{1}{\sqrt{3}} & 0 \\ 0 & 0 & -\frac{2}{\sqrt{3}} \end{pmatrix} \),

- A gluon itself carries colour and anti-colour.

quantum chromodynamics (QCD)

Field tensor: \( F_{\mu\nu}^A = \partial_\mu A_\nu^A - \partial_\nu A_\mu^A - g_s f_{ABC} A_\mu^B A_\nu^C \) \[ [t^A, t^B] = if_{ABC} t^C \]

\( f_{ABC} \) are structure constants of \( SU(3) \) (antisymmetric in all indices — \( SU(2) \) equivalent was \( \epsilon^{ABC} \)). Needed for gauge invariance of gluon part of Lagrangian:

\[ \mathcal{L}_G = -\frac{1}{4} F_{\mu\nu}^A F^{A\mu\nu} \]
quantum chromodynamics (QCD)

The only complete solution uses **lattice QCD**

➤ put all quark & gluon fields on a 4d lattice (NB: imaginary time)

➤ Figure out most likely configurations (Monte Carlo sampling)

[Image credit: fdecomite [flickr]]
quantum chromodynamics (QCD)

The only complete solution uses **lattice QCD**

- put all quark & gluon fields on a 4d lattice (NB: imaginary time)
- Figure out most likely configurations (Monte Carlo sampling)

For LHC reactions, lattice would have to

- Resolve smallest length scales (2 TeV ~ $10^{-4}$ fm)
- Contain whole reaction (pion formed on timescale ~ 1 fm, with boost of $10^4$ — i.e. $10^4$ fm)

That implies $10^8$ nodes in each dimension, i.e. $10^{32}$ nodes — **inconceivable**

Durr et al, arXiv:0906.3599
the strong coupling, $\alpha_s$

it feeds into everything else in collider QCD

for more info see arXiv:1712.05165, arXiv:1902.08191
All couplings run: the QCD coupling runs fastest

$$\frac{Q^2}{dQ^2} \frac{d\alpha_s}{dQ^2} \simeq -b_0 \alpha_s^2 \Rightarrow \alpha_s(Q^2) \simeq \frac{\alpha_s(Q_0^2)}{1 + b_0 \alpha_s(Q_0^2) \ln \frac{Q^2}{Q_0^2}} = \frac{1}{b_0 \ln \frac{Q^2}{\Lambda^2}}$$

$\Lambda \approx 0.2$ GeV (aka $\Lambda_{QCD}$) is the fundamental scale of QCD, at which perturbative coupling blows up.

➤ it sets the mass scale for most hadrons

➤ perturbation theory only valid for $Q \gg \Lambda$, where $\alpha_s$ is small

**PDG World Average:**

$\alpha_s(M_Z) = 0.1181 \pm 0.0011$ (0.9%)
strong-coupling determinations

➢ Most consistent set of independent determinations is from lattice

➢ Two determinations with smallest errors are from same group (HPQCD, 1004.4285, 1408.4169)

\[ \alpha_s(M_Z) = 0.1183 \pm 0.0007 \text{ (0.6%)} \] [heavy-quark correlators]

\[ \alpha_s(M_Z) = 0.1183 \pm 0.0007 \text{ (0.6%)} \] [Wilson loops]

➢ Many determinations quote small uncertainties (\(\lesssim 1\%\)). Most are disputed!

➢ Most robust is perhaps ALPHA lattice result

\[ \alpha_s(M_Z) = 0.1185 \pm 0.00084 \text{ (0.7%)} \]

➢ Some determinations quote anomalously small central values (\(\sim 0.113\) v. world avg. of \(0.1181 \pm 0.0011\)). Also disputed
strong-coupling determinations

Most consistent set of independent determinations is from lattice

Two determinations with smallest errors are from same group (HPQCD, 1004.4285, 1408.4169)

\[ \alpha_s(M_Z) = 0.1183 \pm 0.0007 \ (0.6\%) \]  
[heavy-quark correlators]

\[ \alpha_s(M_Z) = 0.1183 \pm 0.0007 \ (0.6\%) \]  
[Wilson loops]

Many determinations quote small uncertainties (\(\lesssim\)1%). Most are disputed!

Most robust is perhaps ALPHA lattice result

\[ \alpha_s(M_Z) = 0.1185 \pm 0.00084 \ (0.7\%) \]

Some determinations quote anomalously small central values (\(~0.113\ v.\ world\ avg.\ of\ 0.1181\pm0.0011\)). Also disputed
strong-coupling determinations

- Most consistent set of independent determinations is from lattice
- Two determinations with smallest errors are from same group (HPQCD, 1004.4285, 1408.4169)
  \[ \alpha_s(M_Z) = 0.1183 \pm 0.0007 \ (0.6\%) \] [heavy-quark correlators]
  \[ \alpha_s(M_Z) = 0.1183 \pm 0.0007 \ (0.6\%) \] [Wilson loops]
- Many determinations quote small uncertainties (~1%). Most are disputed!
- Most robust is perhaps ALPHA lattice result
  \[ \alpha_s(M_Z) = 0.1185 \pm 0.00084 \ (0.7\%) \]
- Some determinations quote anomalously small central values (~0.113 v. world avg. of 0.1181±0.0011). Also disputed

Most consistent set of independent determinations is from lattice

Two determinations with smallest errors are from same group (HPQCD, 1004.4285, 1408.4169)

\[ \alpha_s(M_Z) = 0.1183 \pm 0.0007 \ (0.6\%) \] [heavy-quark correlators]

\[ \alpha_s(M_Z) = 0.1183 \pm 0.0007 \ (0.6\%) \] [Wilson loops]

Many determinations quote small uncertainties (~1%). Most are disputed!

Most robust is perhaps ALPHA lattice result

\[ \alpha_s(M_Z) = 0.1185 \pm 0.00084 \ (0.7\%) \]

Some determinations quote anomalously small central values (~0.113 v. world avg. of 0.1181±0.0011). Also disputed
strong-coupling determinations

Most consistent set of independent determinations is from lattice

Two determinations with smallest errors are from same group (HPQCD, 1004.4285, 1408.4169)

\[ \alpha_s(M_Z) = 0.1183 \pm 0.0007 \ (0.6\%) \] [heavy-quark correlators]

\[ \alpha_s(M_Z) = 0.1183 \pm 0.0007 \ (0.6\%) \] [Wilson loops]

Many determinations quote small uncertainties (~1%). Most are disputed!

Most robust is perhaps ALPHA lattice result

\[ \alpha_s(M_Z) = 0.1185 \pm 0.00084 \ (0.7\%) \]

Some determinations quote anomalously small central values (~0.113 v. world avg. of 0.1181±0.0011). Also disputed
Most consistent set of independent determinations is from lattice

Two determinations with smallest errors are from same group (HPQCD, 1004.4285, 1408.4169)
\[ \alpha_s(M_Z) = 0.1183 \pm 0.0007 \text{ (0.6\%)} \] [heavy-quark correlators]
\[ \alpha_s(M_Z) = 0.1183 \pm 0.0007 \text{ (0.6\%)} \] [Wilson loops]

Many determinations quote small uncertainties (\( \leq 1\% \)). Most are disputed!

Most robust is perhaps ALPHA lattice result
\[ \alpha_s(M_Z) = 0.1185 \pm 0.00084 \text{ (0.7\%)} \]

Some determinations quote anomalously small central values (~0.113 v. world avg. of 0.1181±0.0011). Also disputed
factorisation

and perturbative expansions
a proton–proton collision: FILLING IN THE PICTURE
Why is simplification “allowed”?  

key idea #1  

FACTORISATION

- Proton’s dynamics occurs on timescale $\mathcal{O}(1-10^4 \text{ fm/c})$
  Final-state hadron dynamics occurs on timescale $\mathcal{O}(1-10^4 \text{ fm/c})$

- Production of Higgs, Z (and other “hard processes”) occurs on timescale $1/M_H \sim 1/125 \text{ GeV} \sim 0.002 \text{ fm/c}$

That means we can separate — “factorise” — the hard process, i.e. treat it as independent from all the hadronic dynamics.
Why is simplification “allowed”?

key idea #2  USE PERTURBATION THEORY

➤ On timescales \(1/M_H \sim 1/125 \text{ GeV} \sim 0.002 \text{ fm}\) you can take advantage of asymptotic freedom

➤ i.e. you can write results in terms of an expansion in the (not so) strong coupling constant \(\alpha_s(125 \text{ GeV}) \sim 0.11\)

\[
\hat{\sigma} = \hat{\sigma}_0 \left(1 + c_1 \alpha_s + c_2 \alpha_s^2 + \cdots \right)
\]

LO
(Leading Order)
Why is simplification “allowed”?  key idea #2 short-distance QCD corrections are perturbative

➤ On timescales $1/M_H \sim 1/125 \text{ GeV} \sim 0.002 \text{ fm}$ you can take advantage of asymptotic freedom

➤ i.e. you can write results in terms of an expansion in the (not so) strong coupling constant $\alpha_s(125 \text{ GeV}) \sim 0.11$

$$\hat{\sigma} = \hat{\sigma}_0 \left(1 + c_1 \alpha_s + c_2 \alpha_s^2 + \cdots\right)$$

NNLO
(Next-to-next-to-Leading Order)
the master equation

\[
\sigma(h_1 h_2 \to Z H + X) = \sum_{n=0}^{\infty} \alpha_s^n \left( \mu_R^2 \right) \sum_{i,j} \int dx_1 dx_2 \, f_{i/h_1} \left( x_1, \mu_F^2 \right) f_{j/h_2} \left( x_2, \mu_F^2 \right) \\
\times \hat{\sigma}_{ij \to ZH+X}^{(n)} \left( x_1 x_2 s, \mu_R^2, \mu_F^2 \right) + \mathcal{O} \left( \frac{A^2}{M_W^4} \right),
\]
the master equation

\[
\sigma(h_1 h_2 \rightarrow ZH + X) = \sum_{n=0}^{\infty} \alpha_s^n \left( \mu_R^2 \right) \sum_{i,j} \int dx_1 dx_2 f_{i/h_1}(x_1, \mu_F^2) f_{j/h_2}(x_2, \mu_F^2) \times \hat{\sigma}_{ij \rightarrow ZH+X}^{(n)}(x_1 x_2 s, \mu_R^2, \mu_F^2) + \mathcal{O} \left( \frac{A^2}{M_W^4} \right),
\]

Parton distribution function (PDF): e.g. number of up anti-quarks carrying fraction \( x_2 \) of proton’s momentum
the master equation

\[ \sigma(h_1 h_2 \rightarrow ZH + X) = \sum_{n=0}^{\infty} \alpha_s^n \left( \mu_R^2 \right) \sum_{i,j} \int dx_1 dx_2 f_{i/h_1} \left( x_1, \mu_F^2 \right) f_{j/h_2} \left( x_2, \mu_F^2 \right) \times \hat{\sigma}_{ij \rightarrow ZH+X} \left( x_1 x_2 s, \mu_R^2, \mu_F^2 \right) + \mathcal{O} \left( \frac{A^2}{M_W^4} \right), \]

Parton distribution function (PDF): e.g. number of up quarks carrying fraction \( x_1 \) of proton’s momentum
The master equation

**Perturbative sum over powers of the strong coupling: typically we use first 2-4 orders**

\[
\sigma(h_1 h_2 \rightarrow ZH + X) = \sum_{n=0}^{\infty} \alpha_s^n \left( \frac{\mu_R^2}{\mu_F^2} \right) \sum_{i,j} \int dx_1 dx_2 f_{i/h_1} \left( x_1, \mu_F^2 \right) f_{j/h_2} \left( x_2, \mu_F^2 \right) \\
\times \hat{\sigma}_{ij \rightarrow ZH+X} \left( x_1 x_2 s, \mu_R^2, \mu_F^2 \right) + \mathcal{O} \left( \frac{A^2}{M_W^4} \right),
\]

![Diagram of the reaction process](image)
the master equation

\[ \sigma(h_1 h_2 \rightarrow ZH + X) = \sum_{n=0}^{\infty} \alpha_s^n(\mu_R^2) \sum_{i,j} \int dx_1 dx_2 f_{i/h_1}(x_1, \mu_F^2) f_{j/h_2}(x_2, \mu_F^2) \]

\[ \times \hat{\sigma}^{(n)}_{ij \rightarrow ZH+X}(x_1 x_2 s, \mu_R^2, \mu_F^2) + \mathcal{O}\left(\frac{A^2}{M_W^4}\right), \]

At each perturbative order \( n \) we have a specific “hard matrix element” (sometimes several for different subprocesses)
the master equation

\[ \sigma (h_1 h_2 \rightarrow ZH + X) = \sum_{n=0}^{\infty} \alpha_s^n \left( \mu_R^2 \right) \sum_{i,j} \int dx_1 dx_2 \, f_{i/h_1} (x_1, \mu_F^2) \, f_{j/h_2} (x_2, \mu_F^2) \]

\[ \times \hat{\sigma}_{ij \rightarrow ZH+X}^{(n)} \left( x_1 x_2 s, \mu_R^2, \mu_F^2 \right) + O \left( \frac{\Lambda^2}{M_W^4} \frac{1}{\mu} \right) \]

Additional corrections from non-perturbative effects: higher “twist”, suppressed by powers of QCD scale \((\Lambda) / \text{hard scale}\)
For visualisations of PDFs and related quantities, a good place to start is
http://apfel.mi.infn.it/ (ApfelWeb)
Papers commonly cited by ATLAS and CMS (2014-2017) as of 2018-01-14, excluding self-citations; all papers > 0.2 fraction of ATLAS & CMS papers that cite them.

Plot by GP Salam based on data from InspireHEP.
Deep Inelastic Scattering — the simpler context to determine PDFs

\[ Q^2 = 25030 \text{ GeV}^2, \ y = 0.56, \ x = 0.50 \]

two major kinematic variables:

- \( x \) = longitudinal momentum fraction of structure quark
- \( Q^2 \) = photon virtuality → transverse resolution at which is probes proton structure

\[ \text{H1 Run 122145 Event 69506} \]
\[ \text{Date 19/09/1995} \]
Parton distribution and DGLAP

- Write up-quark distribution in proton as

\[ f_{u/p}(x, \mu_F^2) \]

- \( \mu_F \) is the **factorisation scale** — a bit like the renormalisation scale \( (\mu_R) \) for the running coupling.

- As you vary the factorisation scale, the parton distributions evolve with a renormalisation-group type equation

Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) equations

\[ Q^2 \text{ increase} \rightarrow \text{proton non-perturbative dynamics from perturbative hard cross section.} \]

\[ \text{Choice of factorization scale, } \mu_F^2 \text{ is arbitrary between } 1 \text{ GeV}^2 \text{ and } Q^2. \]
Today’s PDF fits

H1 and ZEUS

NNPDF 3.1

Kinematic coverage

- Fixed target DIS
- Fixed target Drell-Yan
- Collider DIS
- Collider Inclusive Jet Production
- Collider Drell-Yan
- Z transverse momentum
- Top-quark pair production
- 8TeV: New in NNPDF3.1

Figure 2.1: The kinematic coverage of the NNPDF3.1 dataset in the $x$, $Q^2$ plane.
Today’s PDF fits

- LHC EW physics probes $x$ 
  $\sim \frac{m_H}{\sqrt{s}} \sim 0.01$

- gluon distribution is $\sim 10 \times$ larger than (up) quark distribution
Today’s PDF fits

- LHC EW physics probes $x \sim m_H/\sqrt{s} \sim 0.01$
- Gluon distribution is $\sim 10\times$ larger than (up) quark distribution
- Viewing proton at scales from 2 GeV to 100 GeV, DGLAP evolution modifies PDFs by $\sim \times 2$–10

$\mu = 100$ GeV

$x = \text{fraction of proton momentum carried by quark/gluon}$
fixed-order calculations

\[ \sigma \sim \sigma_2 \alpha_s^2 + \sigma_3 \alpha_s^3 + \sigma_4 \alpha_s^4 + \sigma_5 \alpha_s^5 + \cdots \]

LO NLO NNLO N3LO
Papers commonly cited by ATLAS and CMS (2014-2017) as of 2018-01-14, excluding self-citations; all papers > 0.2

**Plot by GP Salam based on data from InspireHEP**

**fixed order calculations**
(only modestly represented in plot, but arguably the core of the field)
Ingredients for a calculation (generic 2→2 process)

Tree
2→2

Tree
2→3

1-loop
2→2

\[ \times \]

+ complex conj.

to illustrate the concepts, we don’t care what the particles are — just draw lines
Ingredients for a calculation (generic $2\to 2$ process)

Tree

$2\to 4$

1-loop

$2\to 3$

2-loop

$2\to 2$

1-loop

$2\to 2$
Tree-level example: Five gluons

Consider the five-gluon process:

If you evaluate this following textbook Feynman rules you find…

Force carriers in QCD are gluons. Similar to photons of QED except they self interact.

Used in calculation of scattering processes at the LHC

+ 22 similar terms

Massive simplification!

\[
A_5^{\text{tree}}(1^\pm, 2^+, 3^+, 4^+, 5^+) = 0
\]

\[
A_5^{\text{tree}}(1^-, 2^-, 3^+, 4^+, 5^+) = i \frac{\langle 12 \rangle^4}{\langle 12 \rangle \langle 23 \rangle \langle 34 \rangle \langle 45 \rangle \langle 51 \rangle}
\]

\[
A_5^{\text{tree}}(1^-, 2^+, 3^-, 4^+, 5^+) = i \frac{\langle 13 \rangle^4}{\langle 12 \rangle \langle 23 \rangle \langle 34 \rangle \langle 45 \rangle \langle 51 \rangle}
\]

Mathematically equivalent
major advances in NNLO calculations v. time

as of 2019-05, with input from Fabrizio Caola
Higher precision needs more legs & more loops

Analytic Form of the Planar Two-Loop Five-Parton Scattering Amplitudes in QCD

S. Abreu, J. Dormans, F. Febres Cordero, H. Ita, B. Page, and V. Sotnikov

Abstract: We present the analytic form of all leading-color two-loop five-parton helicity amplitudes in QCD. The results are analytically reconstructed from exact numerical evaluations over finite fields. Combining a judicious choice of variables with a new approach to the treatment of particle states in $D$ dimensions for the numerical evaluation of amplitudes, we obtain the analytic expressions with a modest computational effort. Their systematic simplification using multivariate partial-fraction decomposition leads to a particularly compact form. Our results provide all two-loop amplitudes required for the calculation of next-to-next-to-leading order QCD corrections to the production of three jets at hadron colliders in the leading-color approximation.

Order in perturbation theory:

$$\frac{n_{\text{legs}} + n_{\text{loops}} - 2}{\alpha_s}$$

Image: adapted from Kaori Kurokawa
Even though $\alpha_s(m_H) \approx 0.11$, perturbative series requires a number of orders in order to start converging. A similar phenomenon holds for almost all hadron collider cross sections (though not usually quite this bad).

NB: here, only the renorm. scale $\mu(=\mu_R)$ has been varied to estimate uncertainty. In real life you need to change renorm. and factorisation ($\mu_F$) scales.

Results from arXiv:1503.06056
Monte Carlo event generators

see e.g. arXiv:1202.1251, PDG review
predicting what
collider events look like
IN DETAIL
QCD Parton Shower \[ \text{[parton = quark or gluon]} \]
QCD Parton Shower  

[parton = quark or gluon]
Pattern of branching usually simulated with a **Monte Carlo Parton Shower algorithm**

Experiments **always compare data to Monte Carlo simulations** to establish fundamental hypotheses.

Robustness & accuracy of multi-scale properties of these simulations is one of the open questions of the field.
At its simplest: the perturbative part of event generators

\[ \sum_{n=0}^{\infty} \prod_{i=1}^{n} (\text{}\rightarrow\left\langle\text{ }\right\rangle) = \text{---} \]

Iteration of 2→3 (or 1→2) splitting kernel

In what sense does it give the right answer when you ask arbitrary questions about the final state?

cf. arXiv:1805.09327
parton–hadron transition ("hadronisation") can, today, only be modelled

reorganise coloured partons into colour-singlet hadrons

String Fragmentation (Pythia and friends)

Cluster Fragmentation (Herwig) (& Sherpa)

Pictures from ESW book
i.e. how we make sense of the hadronic part of events

see e.g. arXiv:0906.1833
arXiv:1901.10342
jets

i.e. how we make sense of the hadronic part of events
Papers commonly cited by ATLAS and CMS (2014-2017) as of 2018-01-14, excluding self-citations; all papers > 0.2

Plot by GP Salam based on data from InspireHEP

- GEANT4
- Anti-k jet alg.
- Pythia 6.4 MC
- Pythia 8.1
- CT10 PDFs
- POWHEG Box
- POWHEG (2007)
- CTEQ6 PDFs
- POWHEG (2004)
- MG5aMCatNLO
- MSTW2008 PDFs
- FastJet Manual
- Likelihood tests for new physics
- Sherpa 1.1
- MadGraph 5
- top++
- NNLO tbar
- Herwig 6 MC
- Pileup subtraction
- PDF4LHC (2011)
- NNPDF23 PDFs
- NNPDF30 PDFs
- Perugia tunes (2010)
- Herwig++ MC

jets: organising event information
what should a jet definition achieve? A projection to a simple picture of energy flow

projection to jets should be resilient to QCD effects
anti-$k_t$ jet algorithm

- successive recombination of closest pair of particles (with some distance measure)
- parameter for reach in angle ($R$)
- parameter for minimum energy of jet ($p_{t,\text{min}}$)
anti-$k_t$ jet algorithm

- successive recombination of closest pair of particles (with some distance measure)
- parameter for reach in angle (R)
- parameter for minimum energy of jet ($p_{T,\text{min}}$)

Too soft for a jet ($p_T < p_{T,\text{min}}$)

Good Jet ($p_T > p_{T,\text{min}}$)
using full event information: jet substructure for W tagging

QCD rejection with just jet mass

QCD rejection with use of full jet substructure 5–10x better

taken from Dreyer, GPS & Soyez ‘18
For identifying spatial clusters, we have implemented both centroid-linkage hierarchical clustering using **FastJet** [...]

Via the qSR software, FastJet can analyze a typical super-resolution dataset within a few seconds. By storing the full tree structure, the user can quickly re-cluster data and compare the resulting clusters at varying characteristic sizes.

**Figure S6**: FastJet hierarchical clustering. (A) FastJet clusters found with a length scale of 140nm. (B-D) Zoomed in view of the region in the blue box from A. The clusters were generated by cutting the tree with a length scale of 93 nm, 140 nm, and 210 nm respectively. The black + signs mark the centroids of each cluster. Scale Bars – A: 5 μm B - D: 500 nm
closing

does it work?
does it work sufficiently well?
A vast array of LHC data agrees with QCD predictions.
March 2019

CMS Preliminary

Production Cross Section, $\sigma$ [pb]

$\geq n$ jet(s)

$\geq n$ jet(s)

7 TeV CMS measurement ($L \leq 5.0 \text{ fb}^{-1}$)

8 TeV CMS measurement ($L \leq 19.6 \text{ fb}^{-1}$)

13 TeV CMS measurement ($L \leq 137 \text{ fb}^{-1}$)

Theory prediction

CMS 95%CL limits at 7, 8 and 13 TeV

All results at: http://cern.ch/go/pNj7
Higgs cross-sections v. QCD theory

\( \sqrt{s} = 13 \text{ TeV}, 36.1 - 79.8 \text{ fb}^{-1} \)
\( m_H = 125.09 \text{ GeV}, |y_H| < 2.5 \)

**ATLAS Preliminary**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>ggF</td>
<td>1.07 ± 0.09</td>
<td>0.09</td>
<td>(± 0.07, ± 0.07)</td>
</tr>
<tr>
<td>VBF</td>
<td>1.21 ± 0.22</td>
<td>0.21</td>
<td>(± 0.18, ± 0.13)</td>
</tr>
<tr>
<td>WH</td>
<td>1.57 ± 0.52</td>
<td>0.48</td>
<td>(± 0.37, ± 0.32)</td>
</tr>
<tr>
<td>ZH</td>
<td>0.74 ± 0.42</td>
<td>0.40</td>
<td>(± 0.34, ± 0.25)</td>
</tr>
<tr>
<td>ttH + tH</td>
<td>1.22 ± 0.26</td>
<td>0.25</td>
<td>(± 0.17, ± 0.20)</td>
</tr>
</tbody>
</table>

Cross-section normalized to SM value
Higgs precision ($H \rightarrow \gamma\gamma$) : optimistic estimate v. luminosity & time

extrapolation of $\mu_{\gamma\gamma}$ precision from 7+8 TeV results

Today, Higgs coupling precisions are in the 10-20% range.

The LHC has the statistical potential to take Higgs physics from “observation” to 1–2% precision

1 fb$^{-1} = 10^{14}$ collisions
We wouldn’t consider electromagnetism established (textbook level) if we only knew it to 10%.

HL-LHC can deliver 1–2% for a range of couplings.
ATLAS, CMS and LHCb results would further improve this constraint to (the examples given in the Fig. channels, some of which were not considered in previous projections: constraints on the total cross sections of total width from off-shell couplings measurements of 20%); (iv) a generation quarks from a variety of observables is given in Fig. cross sections of the Higgs into quarkonia; (ii) constraints from fits to differential physics entering the uncertainty of 1.4%, and operation quarks from a variety of observables is given in Fig. HL-LHC in all production channels, VBF being the most sensitive.

A summary of the limits obtained on first and second generation quarks from a variety of observables is given in Fig.

We wouldn’t consider electromagnetism established (textbook level) if we only knew it to 10%

HL-LHC can deliver 1–2% for a range of couplings if theoretical interpretations can be made sufficiently accurate theory (QCD) uncertainty dominates, even with an assumption of $\times2$ improvement by 2030s

can we ensure that QCD is up to the task?