Happy 40th birthday, Jets!

ASYMPTOTIC FREEDOM IN PARTON LANGUAGE

G. ALTARELLI *

*Laboratoire de Physique Théorique de l'Ecole Normale Supérieure **, Paris, France*

G. PARISI ***

Institut des Hautes Etudes Scientifiques, Bures-sur-Yvette, France

Received 12 April 1977

A novel derivation of the Q^2 dependence of quark and gluon densities (of given helicity) as predicted by quantum chromodynamics is presented. The main body of predictions of the theory for deep-inleastic scattering on either unpolarized or polarized targets is re-obtained by a method which only makes use of the simplest tree diagrams and is entirely phrased in parton language with no reference to the conventional operator formalism.

+ Dokshitzer

Jets from Quantum Chromodynamics

George Sterman

itute for Theoretical Physics, State University of New York at Stony Brook, Stony Brook, New Yo

and

Steven Weinberg

Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138

(Received 26 July 1977)

The properties of hadronic jets in e^+e^- annihilation are examined in quantum chromodynamics, without using the assumptions of the parton model. We find that two-jet events dominate the cross section at high energy, and have the experimentally observed angular distribution. Estimates are given for the jet angular radius and its energy dependence. We argue that the detailed results of perturbation theory for production of arbitrary numbers of quarks and gluons can be reinterpreted in quantum chromodynamics as predictions for the production of jets.

Simple Quantum-Chromodynamics Prediction of Jet Structure in e^+e^- Annihilation

Howard Georgi and Marie Machacek

Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138

(Received 26 September 1977)

We propose a simple alternative to the sphericity as a measure of jet structure in e^+e^- annihilation. Our variable has the property that it can be reliably calculated in perturbation theory in quantum chromodynamics (QCD) for large Q^2. It is not sensitive to the details of quark and gluon decay into color-singlet hadrons. We discuss the nonperturbative effects which are important at moderate Q^2.

Quantum Chromodynamics Test for Jets

Edward Farhi

Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138

(Received 26 September 1977)

A new quantity, the maximum of the directed momentum, is proposed which measures jetlikeness in e^+e^- annihilation. This quantity is computed in the quark-gluon model by using renormalization-group improved perturbation theory.

Quark elastic scattering as a source of high-transverse-momentum mesons*

R. D. Field and R. P. Feynman

California Institute of Technology, Pasadena, California 91125

(Received 20 October 1976)

We investigate the consequences of the assumption that the high-transverse-momentum particles seen in hadron-hadron collisions are produced by a single, hard, large-angle elastic scattering of quarks, one from the target and one from the beam. The fast outgoing quarks are assumed to fragment into a cascade jet of hadrons. The distributions of quarks in the incoming hadrons are determined from lepton-hadron inelastic scattering data, together with certain theoretical constraints such as sum rules, etc. The manner in which quarks cascade into hadrons is determined from particle distributions seen in lepton-hadron and lepton-lepton collisions supplemented by theoretical arguments. The quark elastic scattering cross section is parametrized in a purely phenomenological way and the choice $d\hat{\sigma}/d\hat{t} = 2.3\times10^6/(-\hat{s}\,\hat{t}^3)$ μb GeV^6 gives a reasonable fit to all the data for hadron + hadron → meson + anything for $p_\perp \gtrsim 2$ GeV/c. Many predictions do not depend sensitively on the exact form for $d\hat{\sigma}/d\hat{t}$ and therefore test our basic assumption. The data examined include single-particle production in pp collisions at various energies and angles. Particle ratios (π^+, π^-, K^+, K^-, and η) are predicted and discussed. In addition, the ratio of production of π^0's by beams of π^+ and protons on a proton target is explained. With this model we have found no serious inconsistency with data, but several predictions for charge ratios and beam ratios at other angles are presented that have yet to be tested experimentally.

Back-to-Back-to Basics

Andrew Larkoski
Reed College

BOOST 2017, Jane Austen’s death + 200 years - 1 day

In a talk like this, it’s good to re-visit the past,
to see how far we have come.

Let’s review what our goals as a community were.

I will focus on the clearly stated theory goals.

Caveat:
In 2013 and earlier, many links from BOOST conference websites to the Indico agenda are broken.

Other selected goals/wishlists from previous BOOST conferences can be found in backup slides.

Hadronic Final States Working Group
BOOST 2009

Charge 1: Theory Advances

- “List two advances that could improve the theory predictions for new signals and explain what steps need to be taken to achieve those advances.”
  - Do we have the tools needed to compare with data in order to calibrate our simulations?
    - Can we improve things by incorporating higher orders, resummation, etc to produce more sophisticated tools?
    - Can we guess where effort of this kind will pay off?
      - Quarks versus gluon jets?
      - It was suggested jet + γ/Z/W/etc could help dig out different mixes of subprocesses.
    - Part of the challenge: It’s easy to tell if everything is working correctly, but hard to isolate a problem if we have one...

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Hadronic Final States Working Group
BOOST 2009

Theory Advances, Continued...

- "List two advances that could improve the theory predictions for new signals and explain what steps need to be taken to achieve those advances."
  - Can we better understand and calibrate our theoretical tools and understand which variables are better simulated or more robust?
    - Systematic study of spectrum of variables and various MC generators.
      - Gilad Perez showed some results yesterday that represent at least a first step toward doing this.
      - Can we understand which variables and MCs work best together and why from first principles?
      - Can we make progress on theoretical uncertainties?!
    - Do we understand the transition regions where showering needs to be supplemented with exact matrix elements?

Hadronic Final States Working Group
BOOST 2009

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Hadronic Final States Working Group
BOOST 2009

We now know the answers to these questions.

Concrete theoretical calculations have been vital for construction of robust methods.

New observables are regularly introduced that are motivated from first-principle understanding of QCD.

Measurability and Calculability Working Group Minutes BOOST 2011

3 Grooming

3.1 Input from theorists needed:

The grooming jet algorithms are going to be fixed soon for the near future by the experimentalists. They need input from the theorists on which grooming algorithms would be useful to measure, and for what signals/channels. Are any grooming algorithms useful to measure on jets outside of jet substructure (for general use)? Are there any important theoretical considerations for the calculability/feasibility of the grooming algorithms? What grooming methods can reasonably be measured in the coming year by each collaboration?

- which removes contamination best?
- which is calculable?

Measurability and Calculability Working Group Minutes BOOST 2011

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In the “early” days, it was unclear if any grooming methods could be understood theoretically at all.

Measurability and Calculability Working Group Minutes BOOST 2011

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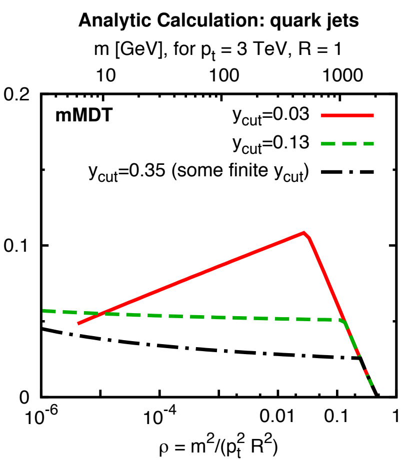
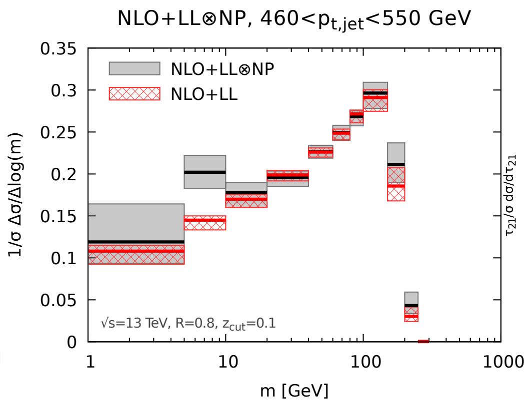
Now, we know that grooming can in some cases dramatically simplify theory calculations.

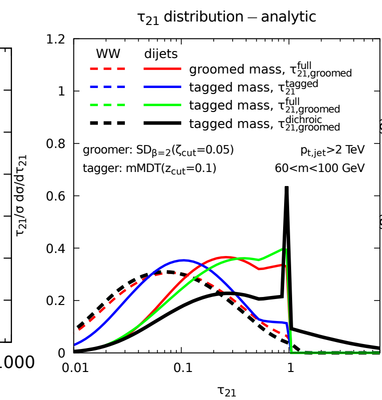
In particular, non-global logarithms can be removed by grooming with mMDT/soft drop.

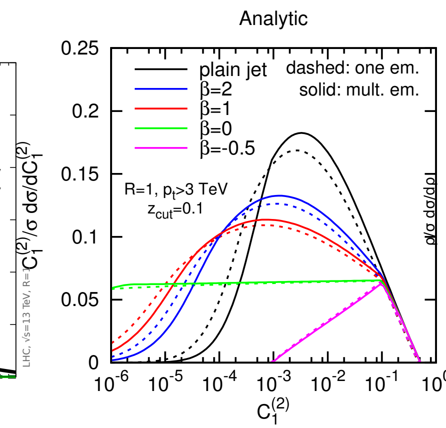
Measurability and Calculability Working Group Minutes BOOST 2011

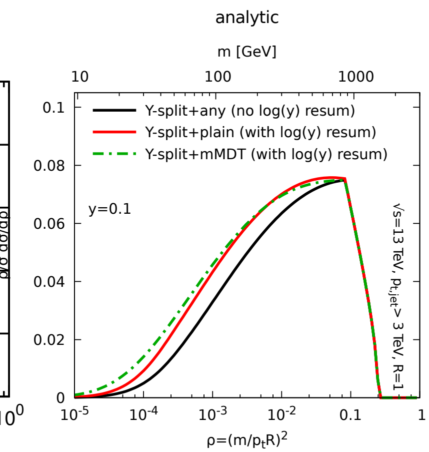
Explosion of theory predictions!

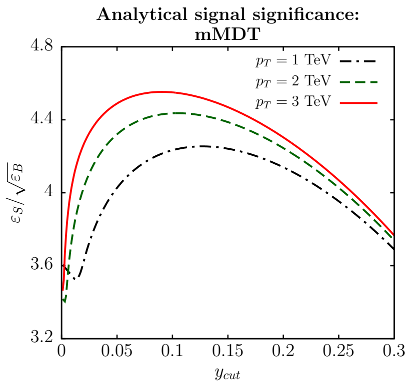


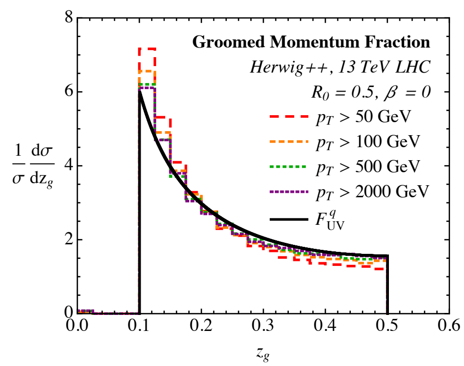


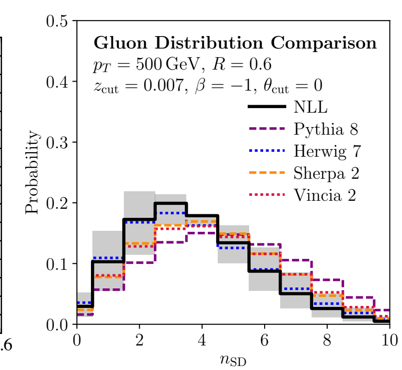


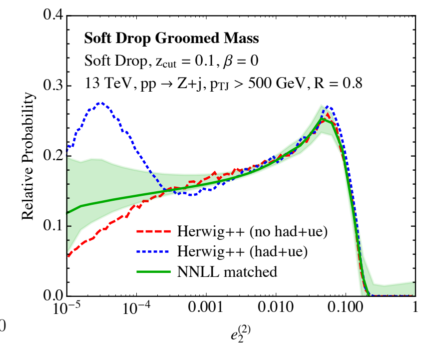












1307.0007, 1402.2657, 1502.01719, 1503.01088, 1603.09338,1609.07149, 1612.03917, 1704.02210, 1704.06266, …

Challenges Today

We have satisfying solutions to the theory problems that were identified as this field was being defined.

Where do we go now?

Many suggestions:

Understand correlations of observables/techniques?

Keep pushing precision boundary?

Extraction of SM parameters from data?

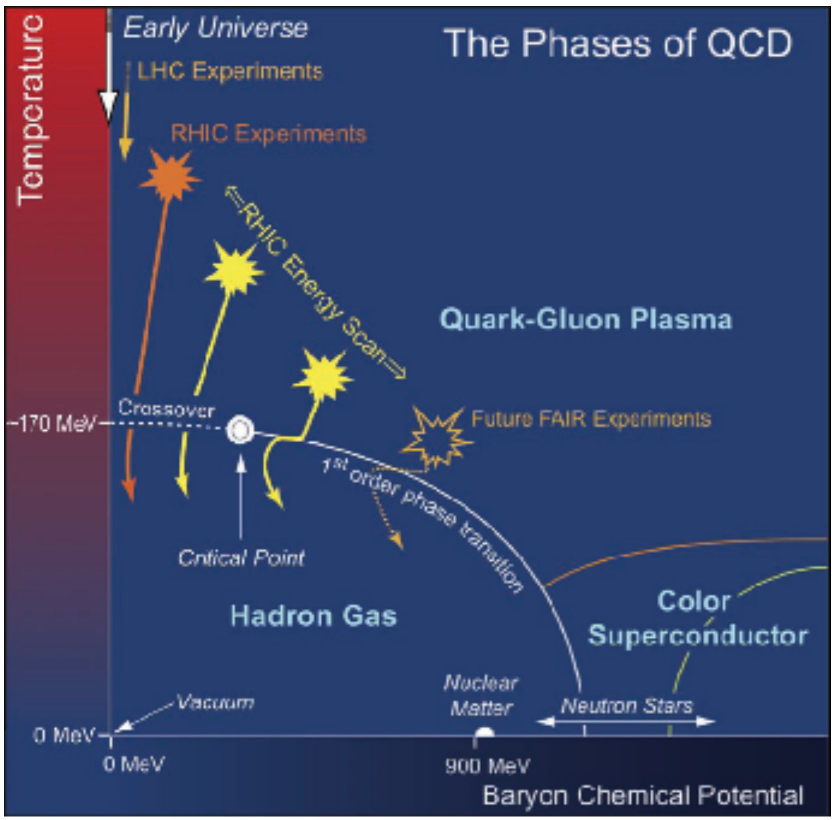
Theory feedback to parton shower tuning?

We will hear about these and more this week.

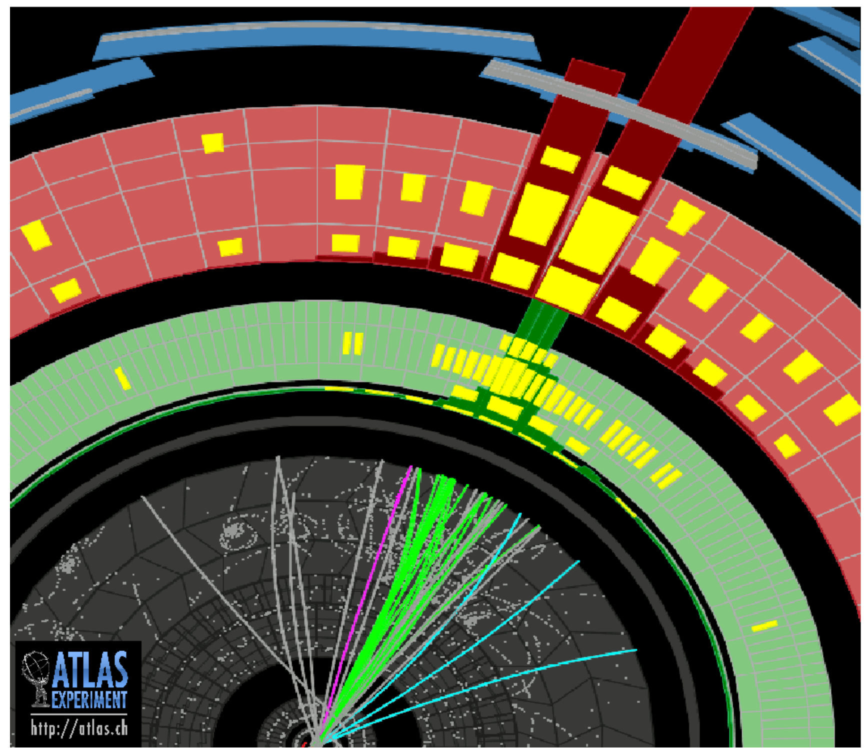
Challenges Today

In the rest of this talk, I will focus on two directions:

The Phases of QCD



Complexity of QCD



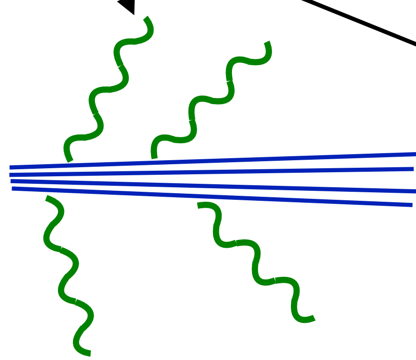
1112.6426

The Phases of QCD

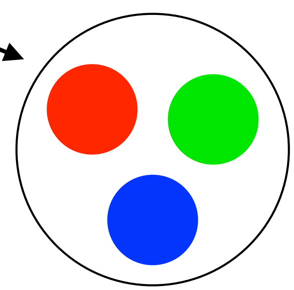
QCD is interesting because it exhibits collective or emergent phenomena.

“More is different”: Just because you know the QCD Lagrangian doesn’t mean you know all of its physics.

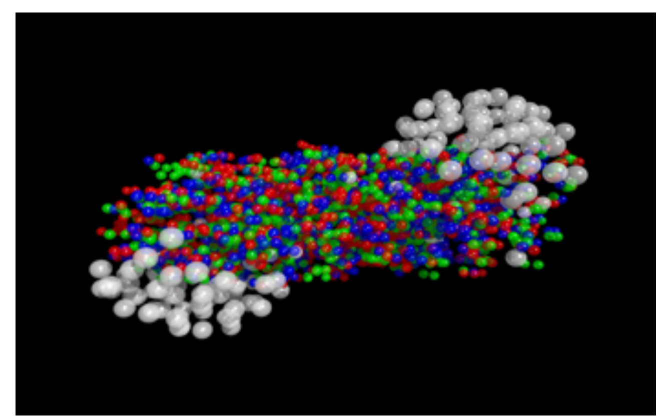
$$\mathcal{L}_{\mathrm{QCD}} = -\frac{1}{4} F^{a}_{\mu\nu} F^{\mu\nu\, a} + \bar{\psi} i \not{D} \psi$$



jets



hadrons



quark-gluon plasma

The Phases of QCD

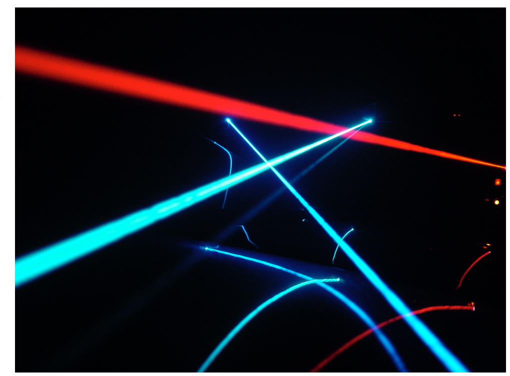
Compare this to condensed matter. We’ve known the Lagrangian for 90 years, but don’t yet know all its physics.

$$\mathcal{L}_{\mathrm{QED}} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \bar{\psi} i \not{D} \psi$$

superconductivity

Reihen	Gruppo I. — R^2O	Gruppo II. — RO	Gruppo III. — R^2O^3	Gruppo IV. RH^4 RO^2	Gruppo V. RH^3 R^2O^5	Gruppo VI. RH^2 RO^3	Gruppo VII. RH R^2O^7	Gruppo VIII. — RO^4
1	H=1							
2	Li=7	Be=9,4	B=11	C=12	N=14	O=16	F=19	
3	Na=23	Mg=24	Al=27,3	Si=28	P=31	S=32	Cl=35,5	
4	K=39	Ca=40	—=44	Ti=48	V=51	Cr=52	Mn=55	Fe=56, Co=59, Ni=59, Cu=63.
5	(Cu=63)	Zn=65	—=68	—=72	As=75	Se=78	Br=80	
6	Rb=85	Sr=87	?Yt=88	Zr=90	Nb=94	Mo=96	—=100	Ru=104, Rh=104, Pd=106, Ag=108.
7	(Ag=108)	Cd=112	In=113	Sn=118	Sb=122	Te=125	J=127	
8	Cs=133	Ba=137	?Di=138	?Ce=140	—	—	—	— — — —
9	(—)	—	—	—	—	—	—	
10	—	—	?Er=178	?La=180	Ta=182	W=184	—	Os=195, Ir=197, Pt=198, Au=199.
11	(Au=199)	Hg=200	Tl=204	Pb=207	Bi=208	—	—	
12	—	—	—	Th=231	—	U=240	—	— — — —

chemistry



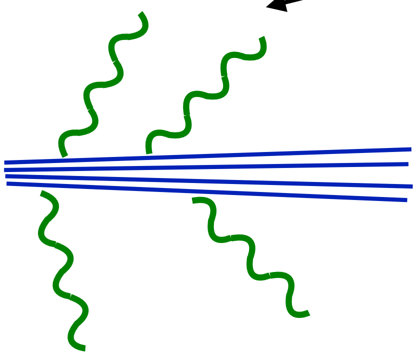
lasers

Contrast this to neutrinos. Once we know the Lagrangian for neutrinos, we know…the Lagrangian for neutrinos.

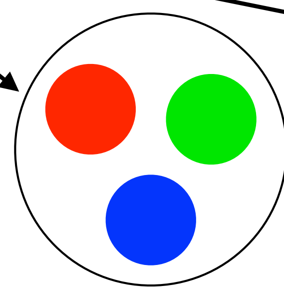
The Phases of QCD

In this conference, we typically focus on one phase: chiral-symmetric, T = 0 QCD.

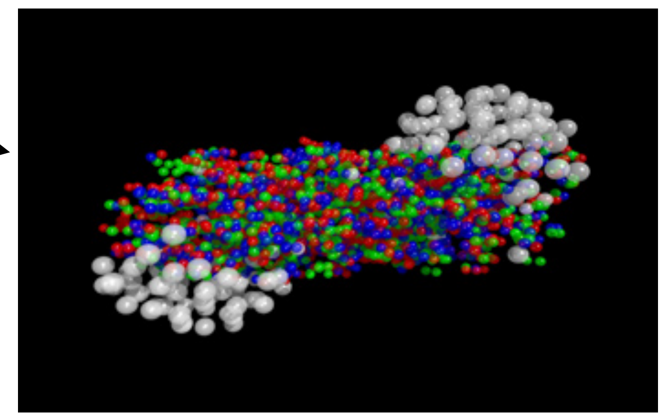
$$\mathcal{L}_{\mathrm{QCD}} = -\frac{1}{4} F^{a}_{\mu\nu} F^{\mu\nu\, a} + \bar{\psi} i \not{D} \psi$$



chiral-symmetric,
$T = 0$



chiral-broken,
$T = 0$



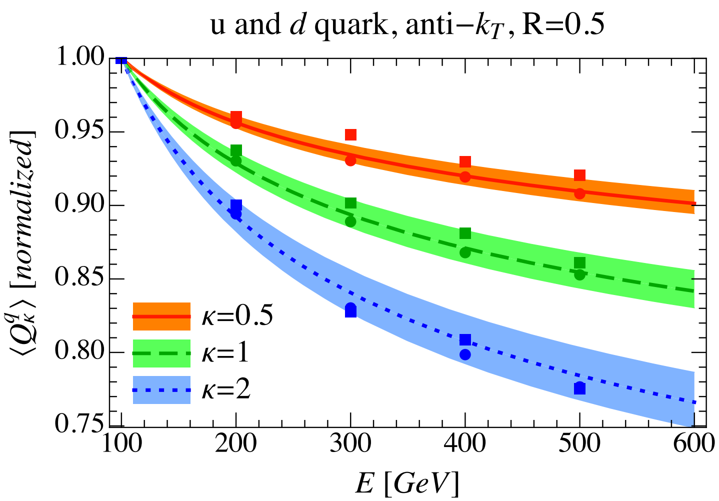
$m_g > 0$,
$T \neq 0$

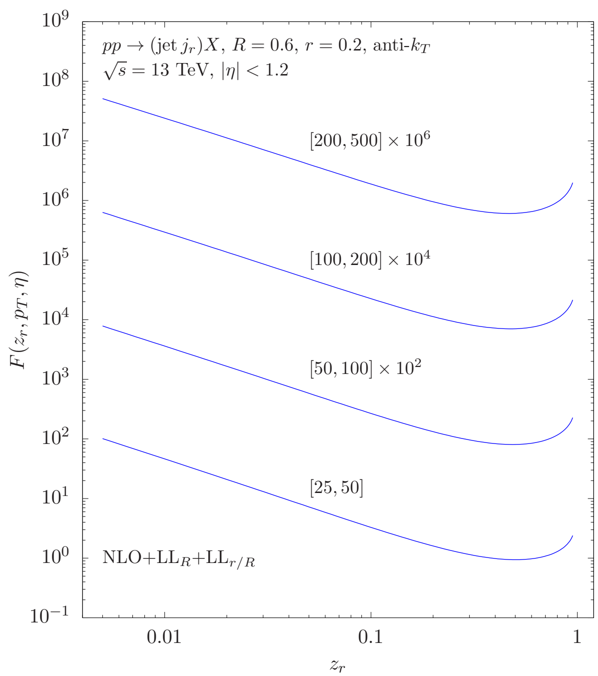
The LHC is sensitive to (at least) two other phases, and jet substructure is being used to study all three.

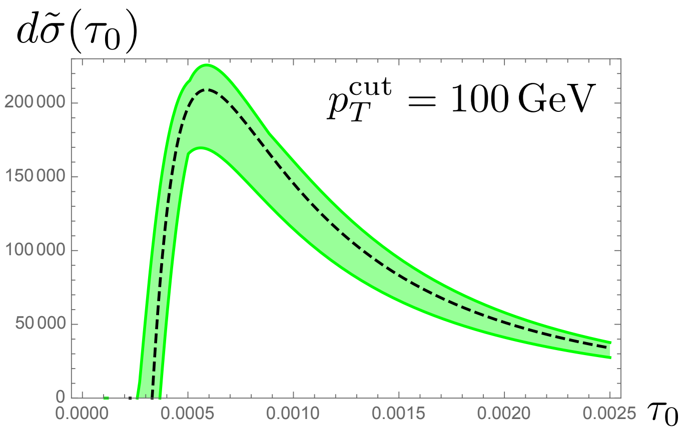
The Phases of QCD

Recent hadron physics with jet substructure studies have typically focused around fragmentation.

1209.3019, 1303.6637, 1601.01319, 1603.06981, 1612.04817, 1702.02947, 1704.05456, 1705.05375,…





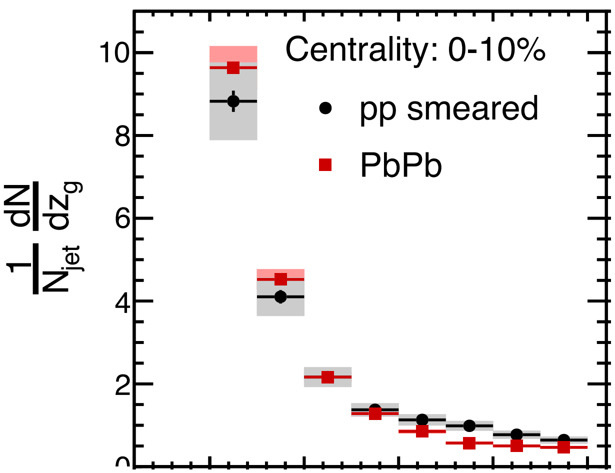


Unfortunately, there will be only 1 (I think) talk on this exciting field in this conference.

The Phases of QCD

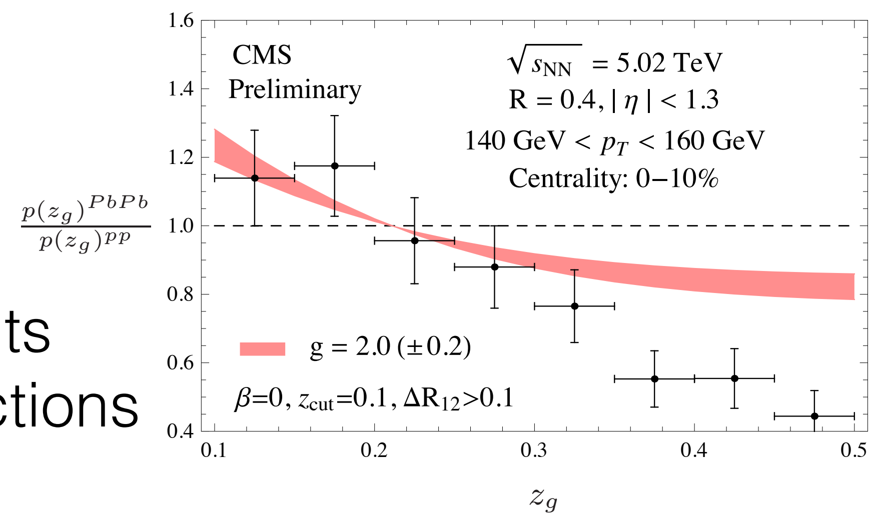
The heavy ion community has recently been extremely interested in applications of jet substructure.

Recent theory studies: 1608.07283, 1610.08930, 1612.05116, 1707.01539, 1707.04142,…



CMS-PAS-HIN-16-006

CMS measurements inspired theory predictions



…which inspired more measurements! 1703.10933, 1704.03046, 1704.05230

We will hear much more throughout the week.

Complexity of QCD

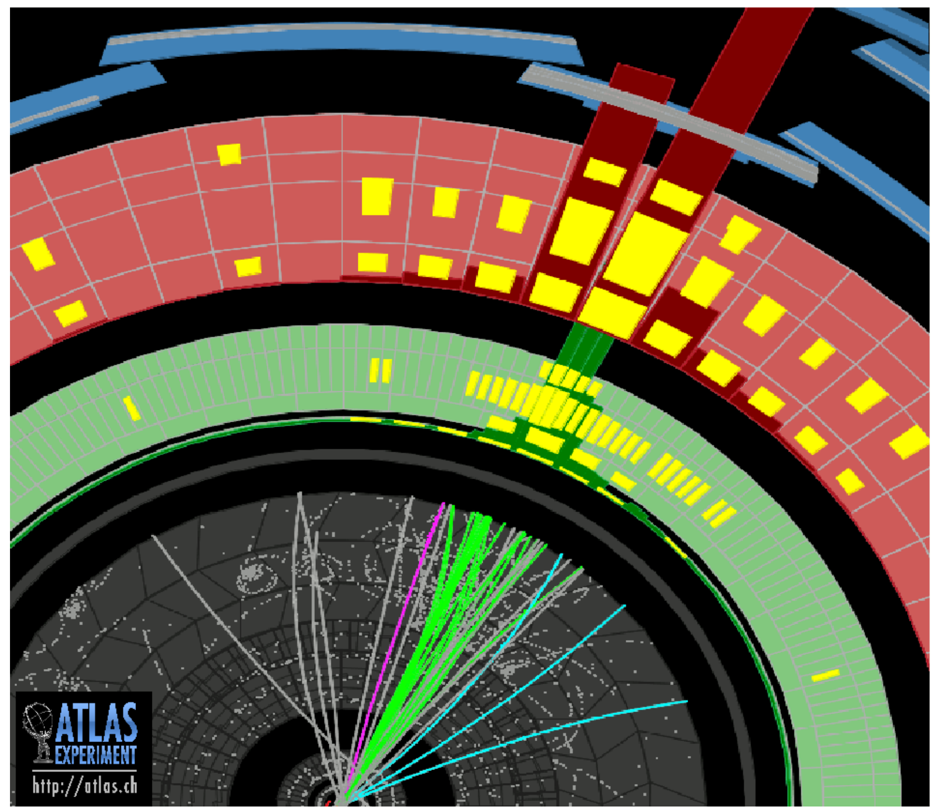
Finally, I want to end with a word of caution.

QCD is a complex theory:
the interactions of quarks and gluons are non-linear.

A jet, like this one, might have 30 particles in it.

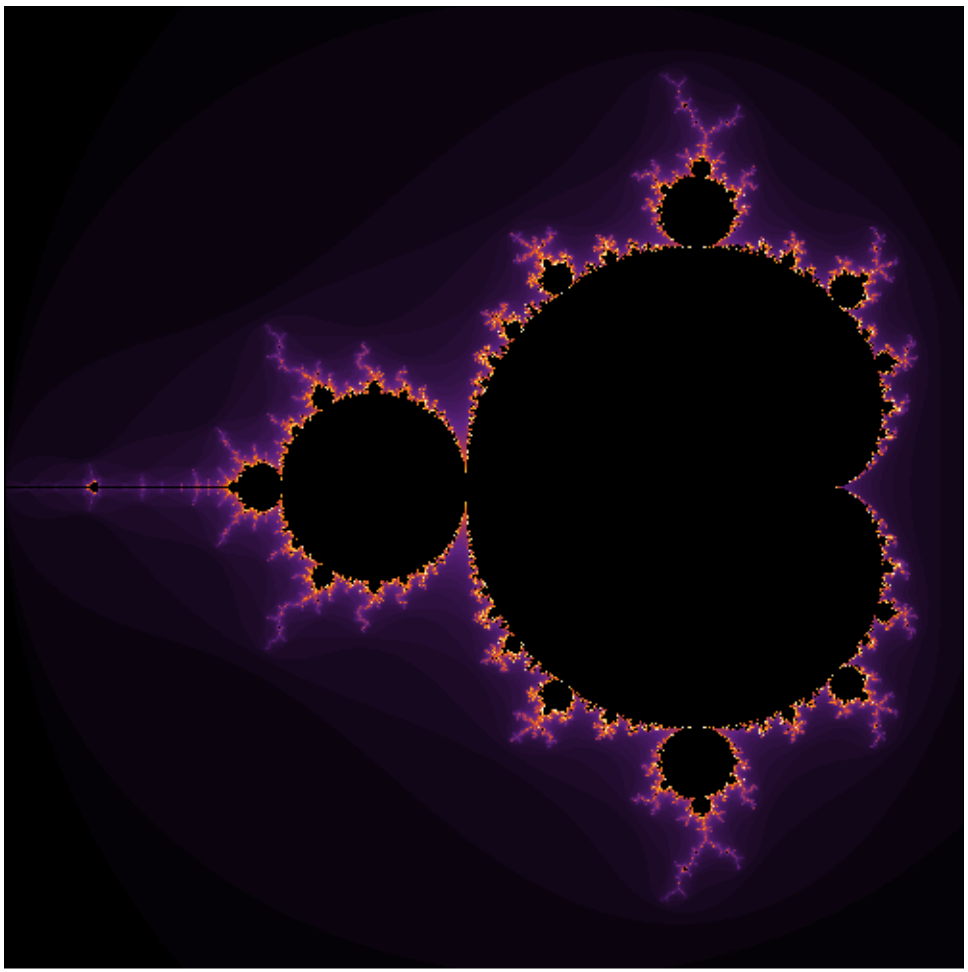
The goal of our field is to tease out all information in it.

However, we need to be careful how we do this.



Complexity of QCD

Analogously, here is a cool image:



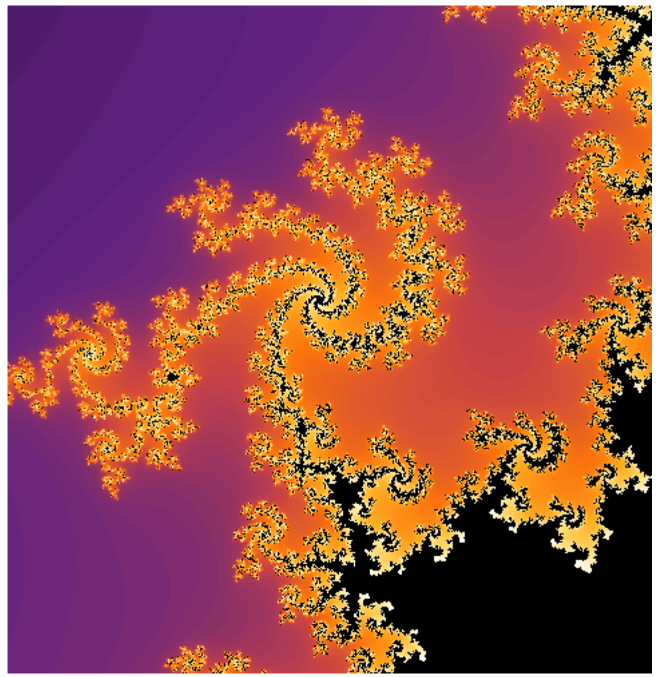
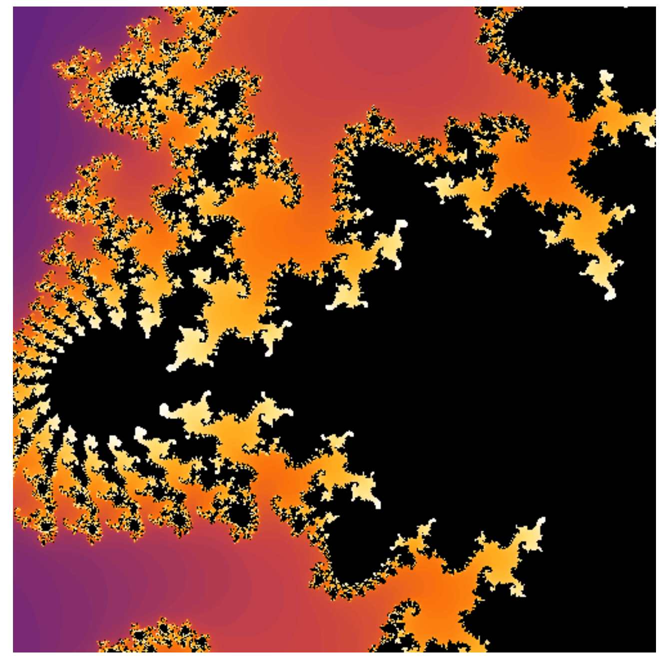
Likely, you know what it is, but I won't ruin the suspense yet.

You might think there there is a huge amount of information.

The more you zoom into the image, the more you see.

Complexity of QCD

To understand this image, you might zoom in and find:

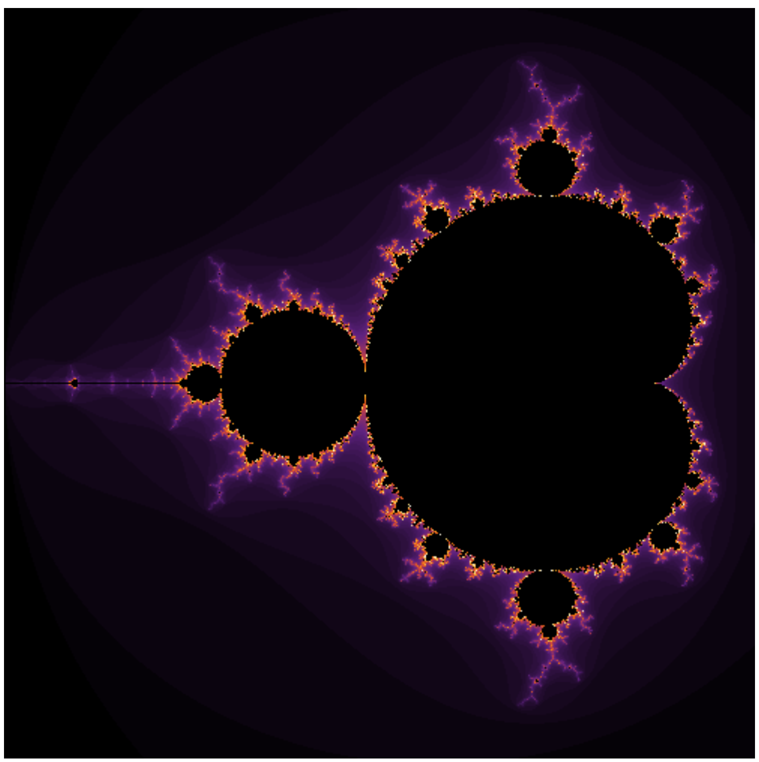
These look very different, and if you focus too much on small sections, you might not see the larger structure.

Complexity of QCD

Then, if I tell you this is the Mandelbrot set, defined by the region of convergence from recursively applying:

$$f(z) = z^2 + c$$

You will likely be very surprised!

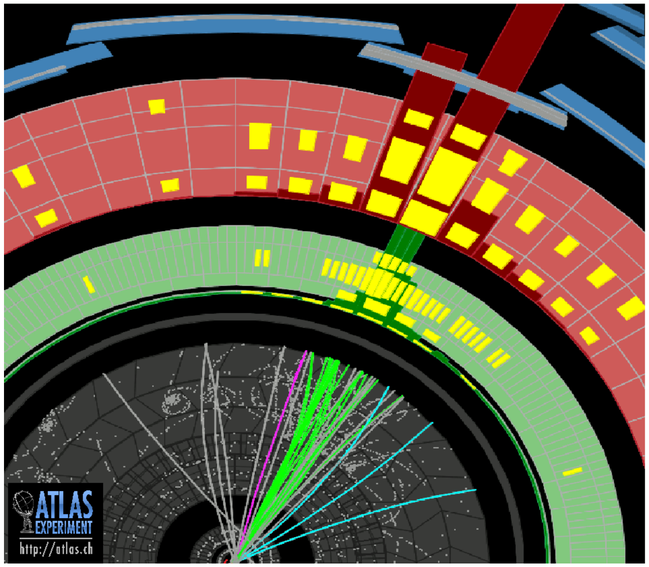


Complexity does not equal explosion of information

Fractals, like the Mandelbrot set, can have arbitrary complexity from simple rules

Complexity of QCD

The same thing is true for our jet.



Though it has 30 particles, how those particles came to be is very simple.

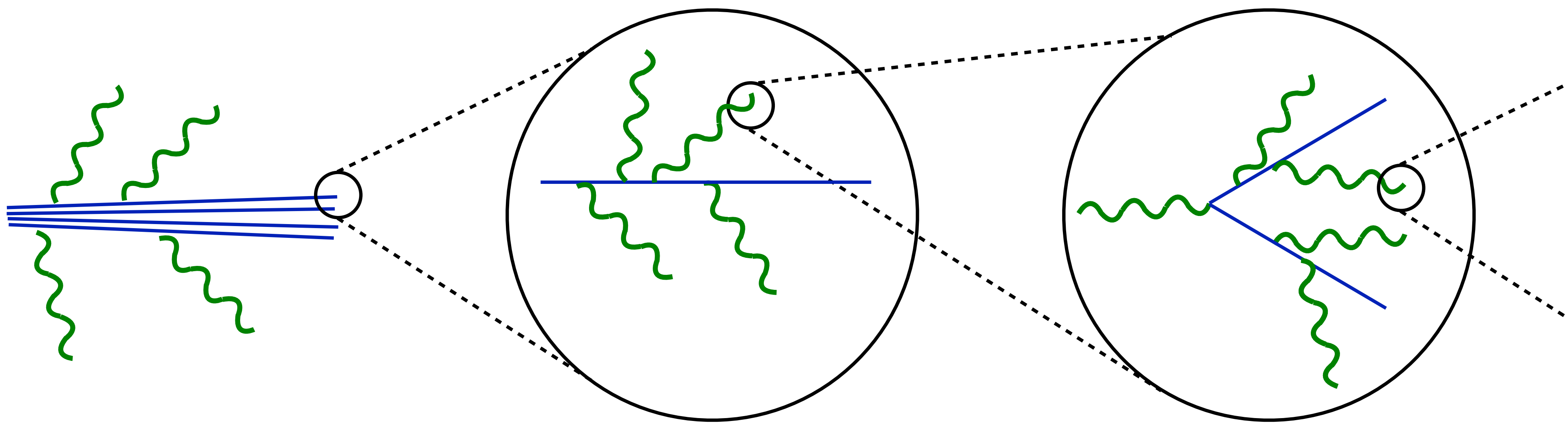
Essentially all particle production in QCD is governed by the surprisingly simple DGLAP equation:

$$Q^2 \frac{df_i(x, Q^2)}{dQ^2} = \int_x^1 dx \, \frac{\alpha_s}{2\pi} P_{ij \leftarrow k} \left(\frac{x}{z}\right) f_k(z, Q^2)$$

Complexity of QCD

The DGLAP equation can be solved recursively, just like the definition of the Mandelbrot set.

This produces a seemingly-complex, fractal-like substructure of a jet.



To see the simplicity, we need to work to understand the correlations and broader structure in jets.

Complexity of QCD

Questions to ponder:

What is the best way to organize the information in a jet, to trivially “see” the simplicity?

Is a machine learning method simple, or does it have a large amount of superfluous information?

Whether the machine learns or not is irrelevant; are **you** learning along with it?

Bonus Slides

Gavin Salam Theory Summary
BOOST 2012

Outlook

Progress we've made, theoretical and experimental, was not imaginable a few years ago, when the discussion about jets used to be confined to "cone" v. "k_t"

Today we have basic subjet tools + many advances (shapes, Qjets, deconstruction, BDT taggers, ...)

Successful adoption by the experiments!

Job for theorists now:
Really understand the taggers?
Understand intermediate p_t regions?
More searches?

Matt Schwartz Theory Summary
BOOST 2013

Past:

Basic substructure algorithms

First precision calculations (jet mass, $\tau 2/\tau 1$ signal)

Present:

Sophisticated substructure algorithms

Rethinking what can/should be calculated

Understanding how algorithms work

Furture:

Optimal algorithms?

PDFs + Mathematica = data?

Substructure for BSM or precision SM physics

Gregory Soyez Theory Intro
BOOST 2014

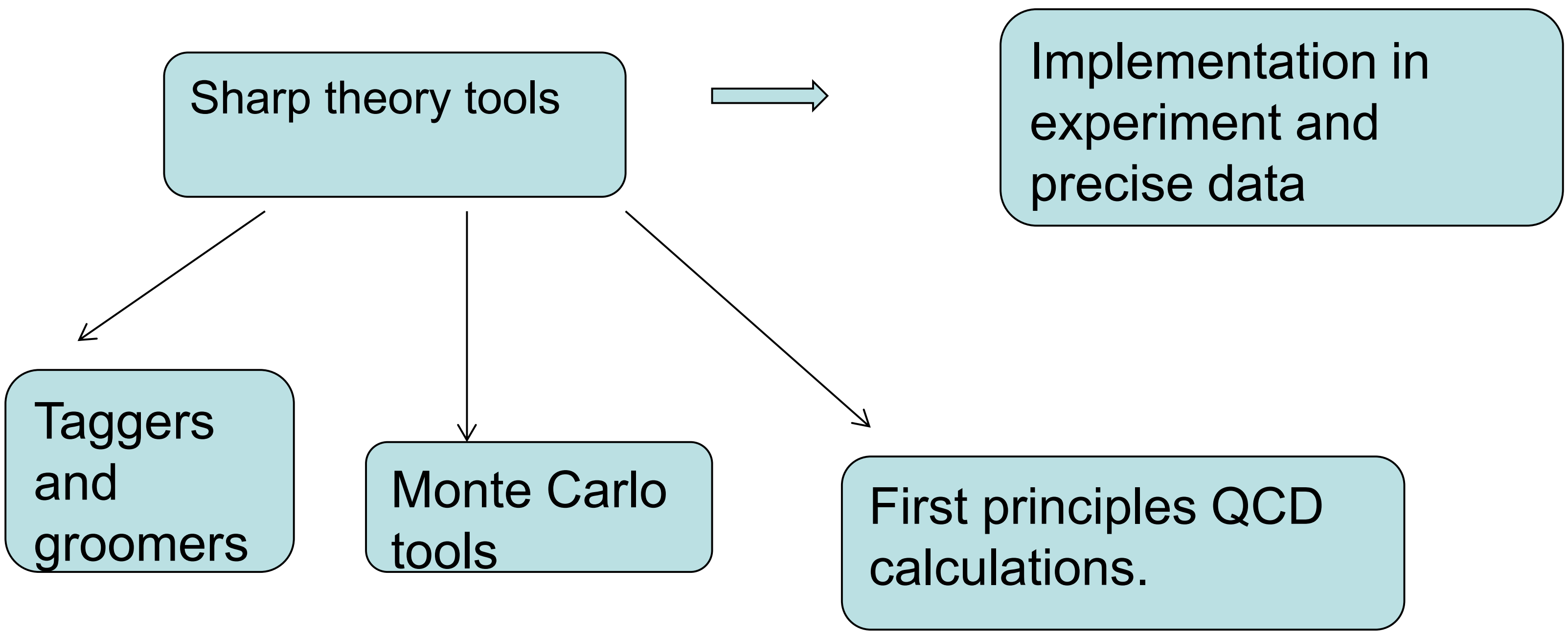
Future: (my) (theory) wishlist

Pursue the analytic effort engaged over the past year

- understand combination more deeply
- can we avoid non-perturbative effects?
- see measurements to confirm(inform) these understandings
- "Collinear Monte-Carlo simualtions" not necessarily suited for all fat jet studies
- Higher energy/luminosity in Run2 $\Rightarrow$ new challenges/opportunities

Mrinal Dasgupta Theory Summary BOOST 2014

Other than nature obliging (not really in our hands I guess) what do we need?



Jesse Thaler Re-Focus
BOOST 2016

Open Questions for Deep Learning

Hyper-variate vs. multi-variate?

Raw image processing or preprocessed "basis" inputs?

Ultimate performance boundary?

Saturated by physics in parton shower? (or go data driven?)
Approximately equivalent to BDT of existing discriminants?

Multi-category classification?

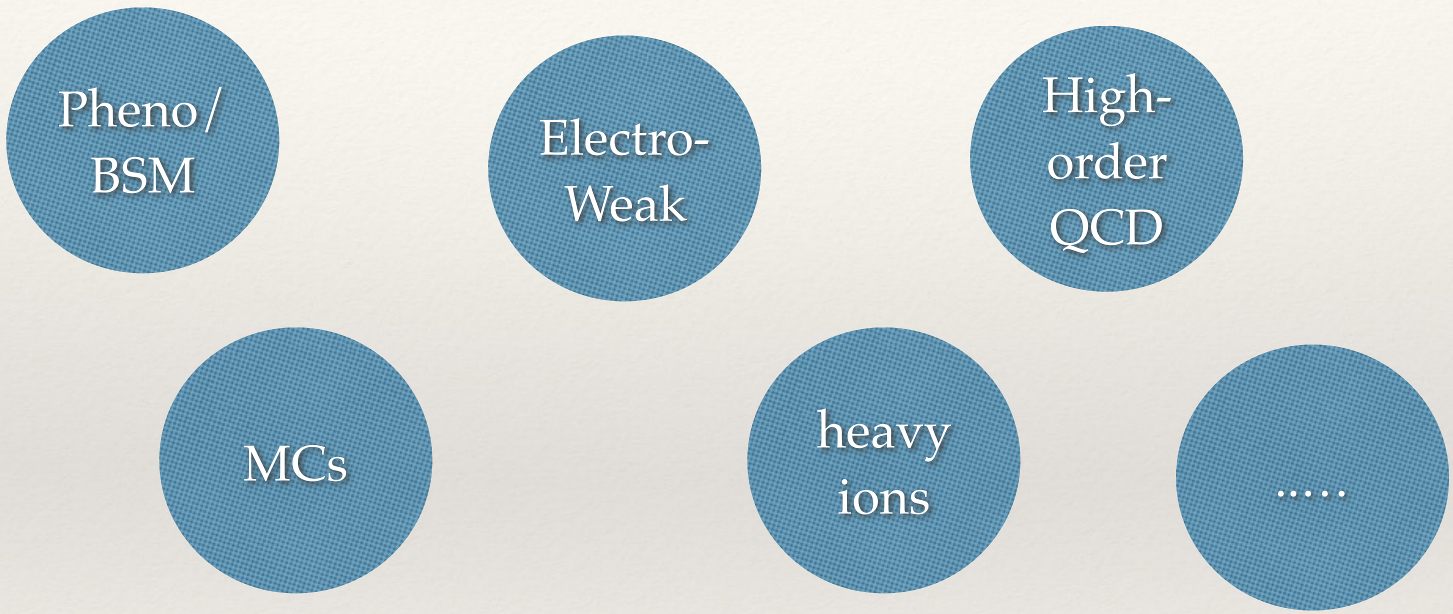
Natural in deep learning to go beyond S vs. B
e.g. for diboson excess: q, g, W^+, Z^0, W^- (and $_L$ vs. $_T$?)

Deep thinking via deep learning?

How to understand/visualize what has been learned?
Could next uni-variate technique come from neural network study?

Simone Marzani Theory Summary
BOOST 2016

Broadening the theory community



We need specific problems that will trigger their interest

- tuning MCs for q/g after LH study,
- electroweak effects in the boosted regime
- new determinations of SM parameter α_s, m_t, …

should we have dedicated sessions?

26