QCD and the LHC

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Rutgers University, February 15 2011
The scales at play

- **photons (EM)**
- **W, Z, H (electroweak)**
- **gluons (QCD)**
- **gravity**
The scales at play

[Introduction]
The scales at play

[Diagram showing energy scales and particle categories]

- Chemistry
- Nucl. Phys.

Neutrinos: \( \mu \tau \)

Particles: \( u, d, s, c, b, t, e, \mu, \tau \)

Energy scales:
- meV
- eV
- keV
- MeV
- GeV
- TeV
- PeV
- EeV
- \( 10^{12} \) GeV
- \( 10^{15} \) GeV
- \( 10^{18} \) GeV

Phenomena:
- Photons (EM)
- W, Z, H (electroweak)
- Gluons (QCD)
- Gravity
The scales at play

Introduction

1 century

Chemistry

Nucl. Phys.

Flav. factories

Tevatron

neutrino experiments

neutrinos

e e μ τ
t
e ud s cb

meV eV keV MeV GeV TeV PeV EeV $10^{12}$ GeV $10^{15}$ GeV $10^{18}$ GeV

photons (EM)

W, Z, H (electroweak)

gluons (QCD)

gravity

GUT?

PLANCK SCALE
The scales at play

1 century

Chemistry Nucl. Phys. Flav. factories Tevatron LHC

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photons (EM) W, Z, H (electroweak) GUT? Planck scale

gluons (QCD)
The scales at play

The hope:
get clues as to what happens here...

+ other questions, e.g.
matter–antimatter asymmetry
nature of dark matter/energy

neutrino experiments
neutrinos

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LHC

photons (EM)

W, Z, H (electroweak)

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The scales at play

**Introduction**

- Cosmic rays, astrophysics, cosmology
- $g-2$, dark matter searches, proton decay, ...

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Nucl. Phys.

Chemistry

Neutrino experiments

Neutrinos

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LHC

$\mu \tau$

UDS CB

e

Photons (EM)

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The scales at play

[Introduction]

cosmic rays, astrophysics, cosmology
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photons (EM)
gluons (QCD)
gravity

extra dimensions

LHC
The world’s largest fundamental physics endeavour

Designed to be 7× more powerful than its predecessor, Tevatron

Involving \( \mathcal{O} (10000) \) scientists
From about 60 countries
At a cost of several billion US$

This talk is about one of the facets of discovery at the LHC:
The use of Quantum Chromodynamics, i.e. the theory that governs the behaviour of quarks and gluons
What does discovery look like?
What kinds of searches?

New resonance (e.g. $Z'$) where you see all decay products and reconstruct an invariant mass

Sufficiently large, sharp signal emerges independently of any knowledge of backgrounds.
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Unreconstructed SUSY cascade. Study *effective* mass (sum of all transverse momenta).

Broad excess at high mass scales. Knowledge of backgrounds is crucial in declaring discovery.
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Broad excess at high mass scales.

Knowledge of backgrounds is crucial in declaring discovery.
CONTINUE HERE

START HERE
CONTINUE HERE

START HERE
How do you predict a background?

The LHC collides protons — made of quarks and gluons.

The theory that governs the behaviour of quarks and gluons is Quantum Chromodynamics (QCD)
QCD, an SU(3) Yang-Mills theory, gives the rules for the interaction of quark fields ($\psi$) with gluon fields ($A$), and gluon fields with themselves. Most simply expressed in terms of the Lagrangian

$$\mathcal{L} = \bar{\psi}_a (i\gamma^\mu \partial_\mu \delta_{ab} - g_s \gamma^\mu t_{ab} A_\mu^C - m) \psi_b - \frac{1}{4} F_{A \mu\nu} F^{A \mu\nu}$$

$$F_{\mu\nu}^A = \partial_\mu A_\nu^A - \partial_\nu A_\mu^A - g_s f_{ABC} A_\mu^B A_\nu^C$$  \[ [t^A, t^B] = if_{ABC} t^C \]
One key parameter: the strength of the interaction, i.e. the strong coupling ‘constant’ \( \alpha_s = \frac{g_s^2}{4\pi} \)

\[ \alpha_s(Q) \approx \frac{1}{b_0 \ln \frac{Q^2}{\Lambda^2}} \]

Nobel: Gross, Politzer & Wilczek

- strong interactions at proton (GeV) scale
- weak interactions at LHC (TeV) scales:

\[ \alpha_s(1\ \text{TeV}) \approx 0.09 \]
Given small coupling, the most widespread approach to making QCD predictions is **perturbation theory**.

E.g. using Feynman diagrams; basic rules for QCD known for \(\sim 40\) years recursive techniques for trees (late 80's); unitarity for loops (90's and 00's)

A cross section \(\sigma\) is written as a series in powers of \(\alpha_s\):

\[
\sigma = \sigma_2 \alpha_s^2
\]

leading order (LO)
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A cross section \(\sigma\) is written as a series in powers of \(\alpha_s\):

\[
\sigma = \sigma_{\text{NLO}} + \sigma_{\text{LO}} = \sigma_{2} \alpha_{s}^{2} + \sigma_{3} \alpha_{s}^{3}
\]
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A cross section $\sigma$ is written as a series in powers of $\alpha_s$:

\[
\sigma = \sigma_2 \alpha_s^2 + \sigma_3 \alpha_s^3 + \sigma_4 \alpha_s^4 + \cdots
\]

- **next-to-leading order (NLO)**
- **leading order (LO)**
- **NNLO**
We can only approximate QCD (e.g. LO, NLO, etc.). Discovery comes if you have an excess with respect to a QCD prediction accounting for its uncertainties.
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Controlling QCD for discovery

We can only approximate QCD (e.g. LO, NLO, etc.). Discovery comes if you have an excess with respect to a QCD prediction accounting for its uncertainties.

Even for a basic leading-order approximation, with $\alpha_s \simeq 0.1$, expect $\sim 10\%$ uncertainty from missing NLO(?)

A non-issue?
How well does QCD perturbative series converge?

Consider LO, NLO and their ratio $K = \frac{\text{NLO}}{\text{LO}}$

$$K \simeq 1.2$$

pp, 14 TeV
FastNLO, $k_t R=0.7$
How well does QCD perturbative series converge?

Consider LO, NLO and their ratio \( K = \frac{\text{NLO}}{\text{LO}} \)

Look at \( p_t \) of quark or gluon (jets)
How well does QCD perturbative series converge?

Consider LO, NLO and their ratio $K = \frac{\text{NLO}}{\text{LO}}$

$K \simeq 1.2$

Look at $p_t$ of quark or gluon (jets)

$K$ of 1.2 is compatible with being $1 + \mathcal{O}(\alpha_s)$
How well does QCD perturbative series converge?

Consider LO, NLO and their ratio $K = \frac{\text{NLO}}{\text{LO}}$

$K \approx 1.5$

Look at $p_t$ of Z-boson

G. Salam (CERN/Princeton/LPTHE)
How well does QCD perturbative series converge?

Consider LO, NLO and their ratio \( K = \frac{\text{NLO}}{\text{LO}} \)

\[ K \simeq 1.5 \]

Looking at \( p_t \) of Z-boson at proton-proton collisions, 14 TeV, MCFM

\[ \frac{d\sigma}{dp_t,Z} \text{ [fb / 100 GeV]} \]

\( p_t,Z \text{ [GeV]} \)

\( pp, 14 \text{ TeV} \)

\[ K \text{ of 1.5 is compatible with being } 1 + C \times \alpha_s \text{, with quite large } C \]

To date, no generalised understanding of size of \( C \) when in range 5 – 10
How well does QCD perturbative series converge?

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Look at \( p_t \) of quark (jet)

\( K \approx 5 \)!!! Found by several groups.

Butterworth, Davison, Rubin & GPS '08
Bauer & Lange '09; Denner et al '09
How well does QCD perturbative series converge?

Consider LO, NLO and their ratio $K = \frac{\text{NLO}}{\text{LO}}$

Look at sum of $p_t$ of quarks and gluons (jets)

Rubin, GPS & Sapeta '10
How well does QCD perturbative series converge?

Consider LO, NLO and their ratio \( K = \frac{NLO}{LO} \)

Look at sum of \( p_t \) of quarks and gluons (jets)

What can it possibly mean to do perturbation theory if the \( \mathcal{O}(\alpha_s) \) NLO correction is so much larger than LO?

Rubin, GPS & Sapeta '10
So what happens at the next order, NNLO?

The last examples are somewhat extreme. In such cases, it’s fair to ask the question:

**What happens at the next order? Does QCD converge?**

Despite over 10 years’ work by many people, not a single NNLO calculation exists for a hadron-collider process with coloured particles in the final state.

Several groups working on NNLO for this and related processes; maybe $Z+\text{jet}$ jet process will be completed in a year or two or . . . ?

Gehrmann family, Glover, Heinrich & al
Weinzierl
Somogyi, Trocsanyi, Del Duca, et al.
Czakon, Mitov, et al.
etc.
Why the large $K$-factor from LO to NLO?

In absence of a full calculation at NNLO, try to gain physical insight

LHC probes scales well above EW scale, $\sqrt{s} \gg M_Z$.
EW bosons are light.
New (logarithmically enhanced) topologies appear.
Why the large $K$-factor from LO to NLO?

**Leading Order**

\[ \alpha_s \alpha_{EW} \]

**Next-to-Leading Order**

\[ \alpha_s^2 \alpha_{EW} \]

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\[ \alpha_s^2 \alpha_{EW} \ln^2 \frac{p_t}{M_Z} \]

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EW bosons are **light**.

**New (logarithmically enhanced) topologies appear.**
Since dominant contribution comes from $Z+2$ partons, try combining NLO $Z+$parton with NLO $Z+2$ partons.

LoopSim: Rubin, GPS & Sapeta ’10
Never achieved previously

We call this $\bar{n}$NLO
Not quite full NNLO
But has many of its qualities

- $p_{tj}$ distribution seems to converge at $\bar{n}$NLO
- scale uncertainties reduced by $\sim$ factor 2
Physical understanding → better predictions

Since dominant contribution comes from $Z+2$ partons, try combining NLO $Z+$parton with NLO $Z+2$ partons.

$$H_{T,jets} = \sum_{jets} p_{t,j}$$

LoopSim: Rubin, GPS & Sapeta ’10

Never achieved previously

We call this $\bar{n}$NLO

Not quite full NNLO
But has many of its qualities

- Significant further enhancement for $H_{T,jets}$
- $\bar{n}$NLO brings clear message:

$H_{T,jets}$ is not a good observable!
Really New Physics?

What went into the QCD prediction?

QCD prediction and uncertainty

data
As if “giant” $K$-factors weren’t bad enough...

How about \textcolor{red}{\textit{infinite}} $K$-factors?
Quarks & gluons? You never see them

Start off with quark and anti-quark, $q\bar{q}$
In perturbative quantum chromodynamics (QCD), probability that a quark or gluon emits a gluon:

\[
\sim \frac{dE}{E} \frac{d\theta}{\theta}
\]

Diverges for small gluon energies \(E\)
Diverges for small angles \(\theta\)

A quark never survives unchanged
it always emits a gluon (usually low-energy, at small angles)
In perturbative quantum chromodynamics (QCD), probability that a quark or gluon emits a gluon:

$$\sim \frac{dE\, d\theta}{E\, \theta}$$

Diverges for small gluon energies $E$

Diverges for small angles $\theta$

Each gluon radiates a further gluon
In perturbative quantum chromodynamics (QCD), probability that a quark or gluon emits a gluon:

\[ \sim \frac{dE \ d\theta}{E \ \theta} \]

Diverges for small gluon energies \( E \)
Diverges for small angles \( \theta \)

And so forth
In perturbative quantum chromodynamics (QCD), probability that a quark or gluon emits a gluon:

$$\sim \frac{dE}{E} \frac{d\theta}{\theta}$$

Diverges for small gluon energies $E$

Diverges for small angles $\theta$

Meanwhile the same happens on other side of event
Quarks & gluons? You never see them

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$$\sim \frac{dE \, d\theta}{E \, \theta}$$

Diverges for small gluon energies $E$
Diverges for small angles $\theta$

And then a non-perturbative transition occurs
Quarks & gluons? You never see them

Giving a pattern of hadrons that “remembers” the gluon branching
Hadrons mostly produced at small angle wrt $q\bar{q}$ directions or with low energy
Quarks & gluons? You never see them

Giving a pattern of hadrons that “remembers” the gluon branching
Hadrons mostly produced at small angle wrt $q\bar{q}$ directions or with low energy
Instead of quarks and gluons, one sees “jets” of hadrons.

How can you compare a calculation of quarks and gluons to a measurement of hadrons?

What happens to the divergences that arise in perturbative QCD beyond leading order?

Giving a pattern of hadrons that “remembers” the gluon branching
Hadrons mostly produced at small angle wrt $q\bar{q}$ directions or with low energy
LHC events may be discussed in terms of quarks, quarks+gluon, or hadrons.

A jet definition provides common representation of different “levels” of event complexity.
Jet (definitions) provide central link between expt., “theory” and theory

And jets are an input to almost all analyses
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And jets are an input to almost all analyses
A significant community of QCD theorists has spent the past ten years making accurate calculations of signals and backgrounds at the LHC (with remarkable advances in field theory on the way)

\[ \mathcal{O}(100) \text{ people} \times 10 \text{ years} \approx 100\,000\,000 \]

**Problem 1:** the jet definitions previously used by LHC experiments were not compatible with these calculations — they “leaked” infinities:

\[ \sigma = c_1 \alpha_s + c_2 \alpha_s^2 + \infty \alpha_s^3 + \cdots \]

**Problem 2:** the jet definitions advocated by theorists since 1990’s had been mostly shunned by proton-collider experiments

a) bad response to experimental noise

b) severe computational issues (1 minute/event × 10^{10} recorded events)
Solving the jets problem

Discovered a link between QCD jet-finding and problems of 2D computational geometry

Cacciari & GPS ’05

Many techniques could be carried over from comp. geom field

Developed a theory of the interplay between jet-finding, QCD radiation and experimental noise

Cacciari, GPS & Soyez ’08

A crucial element was linearity of response

Proposed a new jet-definition based on what we’d learnt anti-$k_t$

Cacciari, GPS & Soyez ’08
How anti-$k_t$ works:

- Define pairwise $i$–$j$ distances

$$d_{ij} = \min \left( \frac{1}{p_{ti}^2}, \frac{1}{p_{tj}^2} \right) \Delta R_{ij}^2$$

- Define single-particle distances

$$d_{iB} = \frac{1}{p_{ti}^2}$$

- If smallest is $d_{ij}$ merge $i$ and $j$

- If smallest is $d_{iB}$ call $i$ a jet

A non-intuitive successor to $k_t$ alg of Catani et al. ’91
How anti-\( k_t \) works:

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You can cluster anything

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DeltaR_{ij} = 0.0492063

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A non-intuitive successor to $k_t$ alg of Catani et al. '91

\begin{align*}
\text{DeltaR}_{\{ij\}} &= 0.0904762
\end{align*}
You can cluster anything

How anti-$k_t$ works:

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DeltaR_{ij} = 0.14127

How anti-\textit{k}_t works:

- Define pairwise \(i\)–\(j\) distances
  
  \[
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A non-intuitive successor to $k_t$ alg of Catani et al. ’91
You can cluster anything

How anti-$k_t$ works:

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DeltaR_{ij} = 0.478454

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A non-intuitive successor to \(k_t\) alg of Catani et al. '91
How does anti-$k_t$ fare?

Timing v. particle multiplicity 2005

- CDF MidPoint (seeds > 0 GeV)
- KtJet $k_t$
- CDF MidPoint (seeds > 1 GeV)
- CDF JetClu (very unsafe)

- Tevatron
- LHC lo-lumi
- LHC hi-lumi
- LHC Pb-Pb

$R=0.7$

$3.4$ GHz P4, $2$ GB

G. Salam (CERN/Princeton/LPTHE)

QCD and the LHC
How does anti-$k_t$ fare?

in critical region of $N \sim 2000 - 4000$

1000 times faster than previous attempts with similar jet algorithms

FastJet code available publicly at http://fastjet.fr/
How does anti-\(k_t\) fare?

Experimental sensitivity to noise

As good as, or better than all previous experimentally-favoured algorithms.

Essentially because anti-\(k_t\) has linear response to soft particles.
How does anti-$k_t$ fare?

**Coefficient of “infinity”**

<table>
<thead>
<tr>
<th>Method</th>
<th>Fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>JetClu</td>
<td>50.1%</td>
</tr>
<tr>
<td>SearchCone</td>
<td>48.2%</td>
</tr>
<tr>
<td>MidPoint</td>
<td>16.4%</td>
</tr>
<tr>
<td>Midpoint-3</td>
<td>15.6%</td>
</tr>
<tr>
<td>PxCone</td>
<td>9.3%</td>
</tr>
<tr>
<td>Seedless [SM-$p_t$]</td>
<td>1.6%</td>
</tr>
<tr>
<td>Seedless [SM-MIP]</td>
<td>0.17%</td>
</tr>
<tr>
<td>Anti-Kt, SISCone</td>
<td>0 (none in $4 \times 10^9$)</td>
</tr>
</tbody>
</table>

Safe for perturbative QCD predictions:

No “leakage” of infinities to higher orders.
Anti-$k_t$ contained in FastJet

A program that brings together theoretical physics and computational geometry.

Cacciari, GPS & Soyez ’06-

In 2009: about 40,000 page loads from 3,300 IP addresses, in ≥ 1,000 locations.

[After exclusion of robots]
ATLAS & CMS use anti-$k_t$ for all their jet-finding.
Among the handful of LHC searches so far, anti-$k_t$ jets have probed the highest scales, $\sim 2$ TeV, about twice as high as Tevatron.
Anti-$k_t$ solves a long-standing problem, crucial in providing a common language to compare theory and experiment.

But is QCD really about nothing other than comparing theory and experiment?
The quest for the Higgs

Using jets better, in order to make discoveries possible
Test of the SM at the Level of Quantum Fluctuations

indirect determination of the top mass

prediction of the range for the Higgs mass

possible due to
- precision measurements
- known higher order electroweak corrections

\[ \propto \left( \frac{M_t}{M_W} \right)^2, \ln \left( \frac{M_h}{M_W} \right) \]
Higgs mass and Higgs decays?

There’s some likelihood that the Higgs boson will be “light”, $M_H \sim 120$ GeV

Likely Higgs Mass
There’s some likelihood that the Higgs boson will be “light”, $M_H \sim 120$ GeV

If it is, crucial test of whether it is the Higgs, will come from measuring several different decays

Remember: Higgs couplings intimately related to origin of particle masses
$H \rightarrow b\bar{b}$ (main light-Higgs decay) v. hard to see

Best hope is $pp \rightarrow W^\pm H, \ W^\pm \rightarrow \ell^\pm \nu, \ H \rightarrow b\bar{b}$. 

G. Salam (CERN/Princeton/LPTHE)
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Conclusion (ATLAS TDR):

“\textit{The extraction of a signal from }H \rightarrow b\bar{b}\textit{ decays in the WH channel will be very difficult at the LHC, even under the most optimistic assumptions [...]}”

Low efficiency, huge backgrounds, e.g. $t\bar{t}$
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Try a long shot?
- Go to high $p_t$ ($p_{tH}, p_{tW} > 200$ GeV)
- Lose 95% of signal, but more efficient?
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Question:
What’s the best strategy to identify the two-pronged structure of the boosted Higgs decay?
3 QCD principles help guide our analysis

- QCD radiation from a boosted Higgs decay is limited by angular ordering
- Higgs decay shares energy symmetrically, QCD background events with same mass share energy asymmetrically
- QCD radiation from Higgs decay products is point-like, noise (UE, pileup) is diffuse
\( pp \rightarrow ZH \rightarrow \nu \bar{\nu} b\bar{b}, \ ©14 \ TeV, \ m_H = 115 \text{GeV} \)

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3

Cluster event, C/A, R=1.2

Butterworth, Davison, Rubin & GPS ’08
$pp \rightarrow ZH \rightarrow \nu \bar{\nu} b \bar{b}$, @14 TeV, $m_H = 115$ GeV

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3

Fill it in, $\rightarrow$ show jets more clearly

Butterworth, Davison, Rubin & GPS ’08
Consider hardest jet, $m = 150$ GeV

Butterworth, Davison, Rubin & GPS '08
Herwig 6.510 + Jimmy 4.31 + FastJet 2.3

\[ pp \rightarrow ZH \rightarrow \nu \bar{\nu} b \bar{b}, \ @14 \text{TeV}, \ m_H = 115 \text{GeV} \]

split: \( m = 150 \text{ GeV}, \ \frac{\text{max}(m_1,m_2)}{m} = 0.92 \rightarrow \text{repeat} \)

G. Salam (CERN/Princeton/LPTHE)
\( pp \rightarrow ZH \rightarrow \nu\bar{\nu}b\bar{b}, \@14\text{TeV}, \ m_H = 115\text{GeV} \)

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\[ p_t [\text{GeV}] \]

\[ \begin{array}{c}
\text{SIGNAL} \\
\text{200} < p_{tZ} < 250 \text{ GeV}
\end{array} \]

\[ \begin{array}{c}
\text{Zbb BACKGROUND} \\
\text{200} < p_{tZ} < 250 \text{ GeV}
\end{array} \]

\[ \text{split: } m = 139 \text{ GeV}, \ \frac{\max(m_1, m_2)}{m} = 0.37 \rightarrow \text{mass drop} \]

Butterworth, Davison, Rubin & GPS ‘08
\[ pp \rightarrow ZH \rightarrow \nu \bar{\nu} b \bar{b}, \; \sqrt{s} = 14 \text{ TeV}, \; m_H = 115 \text{ GeV} \]

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\[
\text{check: } y_{12} \approx \frac{p_{t2}}{p_{t1}} \approx 0.7 \rightarrow \text{OK} + 2 \text{ } b\text{-tags (anti-QCD)}
\]

Butterworth, Davison, Rubin & GPS '08
$pp \rightarrow ZH \rightarrow \nu \bar{\nu} b\bar{b}$, @14 TeV, $m_H = 115$ GeV

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3

$R_{filt} = 0.3$

Butterworth, Davison, Rubin & GPS '08
$pp \rightarrow ZH \rightarrow \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3

Final filtered result, $p_t = 227.257$ GeV$^2$, $m = 117.211$ GeV

$R_{filt} = 0.3$: take 3 hardest, $m = 117$ GeV

Butterworth, Davison, Rubin & GPS ’08

arbitrary norm.
Search for main decay of light Higgs boson, $W/Z+H$, $H \rightarrow b \bar{b}$  
(The only way of seeing this decay — other than the next slide)

using the method from Butterworth, Davison, Rubin & GPS '08

Other recent work focuses on very high background rejection (lower efficiency)
Recovering the $ttH$, $H \rightarrow b\bar{b}$ Higgs channel

Plehn, GPS & Spannowsky '09
based in part on Johns Hopkins top tagger '08
How well-designed jet-finding helps you

Dijet mass reconstruction for new heavy resonance $X \rightarrow gg$

$\frac{1}{N} \frac{dN}{d\bin}/2$

$gg, M = 2000$ GeV

$k_t, R=0.4$
$Q^w_{f=0.13} = 190$ GeV

$gg, M = 2000$ GeV

C/A-filt, $R=1.3$
$Q^w_{f=0.13} = 53$ GeV
(subtr.)

Cacciari, Rojo, GPS & Soyez ’08
Other recent work: Krohn, Thaler & Wang ’09

G. Salam (CERN/Princeton/LPTHE)
Supersymmetry with $R$-parity violating decays $\tilde{\chi}^0_1 \rightarrow qqq$

One of its most difficult incarnations

Butterworth, Ellis, Raklev & GPS '09
How well-designed jet-finding helps you

Supersymmetry with $R$-parity violating decays $\tilde{\chi}_1^0 \rightarrow qqq$

One of its most difficult incarnations

Establishing the rules for systematically making better discoveries with jets is work in progress

But the evidence for its potential is clearly there

Butterworth, Ellis, Raklev & GPS '09
The Boost 2011 conference will be held in May (5/23/11 - 5/27/11) at Princeton University, hosted by the Princeton Center for Theoretical Science. As with prior conferences in the Boost series, the weeklong event will focus on bringing together theorists and experimentalists for in-depth discussions of jets, jet substructure, and jets in more exotic contexts (e.g. lepton jets).

This workshop is open to the public. Early registration is encouraged.

Previous Boost conferences: SLAC, U.W., Oxford

Herwig 6.5 + Jimmy 4.3
Cam/Aachen R=0.7
p_{t1} > 500 GeV

signal + background
background (just dijets)
signal

Butterworth, Ellis, Raklev & GPS '09

m_{1}/(100 GeV) dN/dbin per fb^{-1}

m_{1} [GeV]

m_{1}/(100 GeV) dN/dbin per fb^{-1}

m_{1} [GeV]

m_{1}/(100 GeV) dN/dbin per fb^{-1}

m_{1} [GeV]
Conclusions
QCD is unavoidable at LHC

The simplicity of its formulation contrasts with the richness of its phenomenology

Even after 20 years of planning for the LHC, QCD still has surprises for us

Both in its own right
And as a tool for discovery
EXTRAS
With these (and most) cone algorithms, perturbative infinities fail to cancel at some order \( \equiv \text{IR unsafety} \).
JetClu (& Atlas Cone) in Wjj @ NLO

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