Hadronic event shapes and jet shapes

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Overview

- Thank you for giving me the opportunity to be here and speak to you today
- Report on work by myself on the use of hadronic event shapes and jet substructure
- The work I will present was done with the **ATLAS** experiment, which I was previously involved with for more than 10 years, but much of what I'll describe is equally applicable to other experiments at the LHC
- I have recently joined **ALICE** and am working towards adapting this work for that experiment
- The techniques I've worked on have the potential for significant impact on many new physics searches at the LHC and could also be used for precision tests of the Standard Model at the energy frontier
- Not possible to cover everything that I have looked at, or all possible physics scenarios
- Picked the search for a Higgs boson in decays to b-quarks ($H \to b\bar{b}$) as a benchmark physics process to demonstrate the utility of this work for new physics searches in general

Motivation

- Higgs → $b\bar{b}$ widely considered a poor search channel because of overwhelming backgrounds
- Observation of a signal is very difficult
- At hadron colliders like the LHC, QCD jet production is the dominant high transverse momentum process
- Physics processes of interest usually have cross-sections that are many orders of magnitude smaller
- Consequently, QCD jet production is the main background for many new physics searches, predictions for which often feature jets in the final state as a signature
- The ability to distinguish jets in interesting new physics events from those in QCD background events would, therefore, be extremely valuable and likely to have a significant impact on the search for new physics

Jet substructure & superstructure

- Availability of fine-grained calorimetry allows for jets to be studied in much greater detail than was previously possible
  - O(10 – 100) calorimeter cells per typical QCD jet, ~10 times CDF or D0
- Can measure more than just bulk properties of jets?
- Are there any observables that we can use to extract more information from the event and from the jets themselves?
- Have investigated the potential benefit of hundreds of different hadronic event shapes and jet shapes for both Higgs and exotics offline analyses
  - Approach was to cover as much territory as possible
  - Some variables have theoretical motivation, others don't

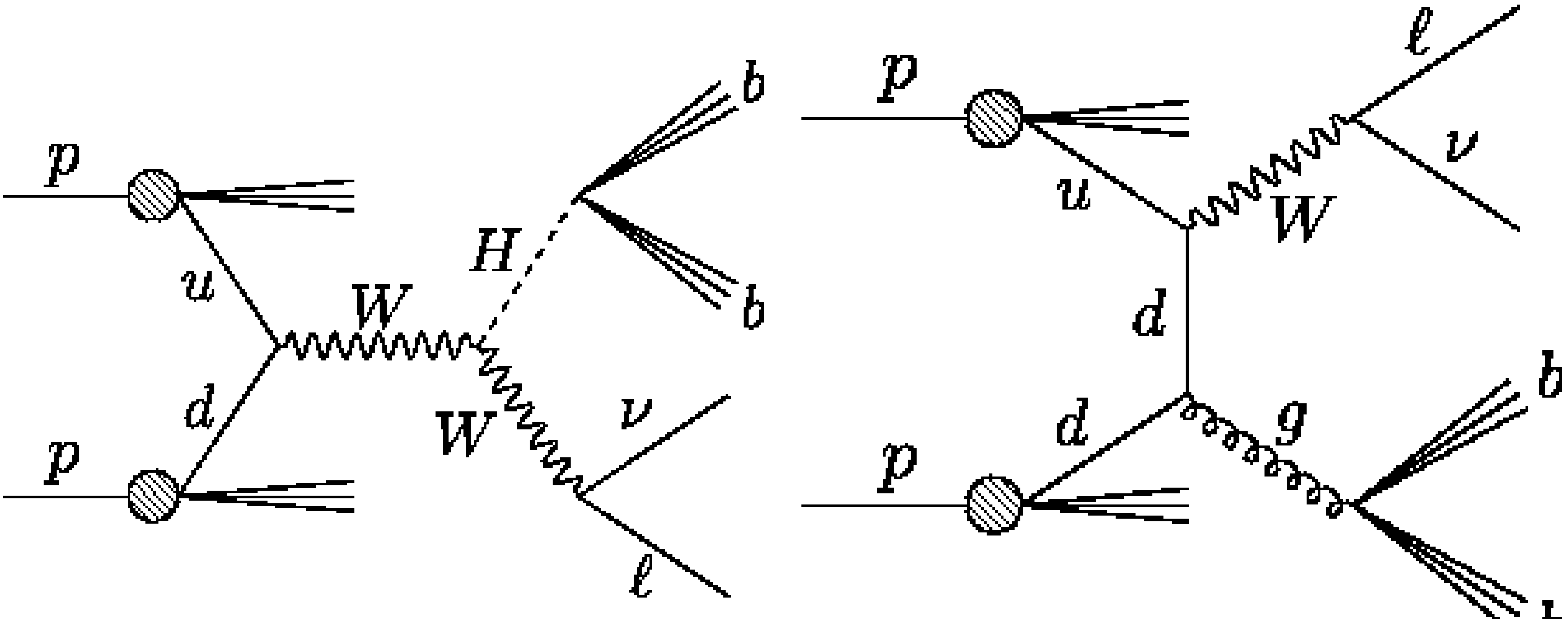
Datasets & colour key for plots

Signal:

- WH120lnubb (PYTHIA) – associated production of a Higgs with a W, $W \rightarrow l\nu$, $H \rightarrow b\bar{b}$
- Boosted WH120lnubb (HERWIG) – as above, but H decay products boosted

- Background:
  - Wbb (ALPGEN) – irreducible background $g \rightarrow b\bar{b}$
  - QCD multijets
  - $b\bar{b}/c\bar{c}$ and require one of the b or c to decay to e/μ with pT > 15 GeV and $|\eta| < 2.5$ (PYTHIA)
  - Also: $t\bar{t}$ (MC@NLO)
- 7 TeV ***pp*** samples with pile-up and realistic detector conditions
  - Pile-up: average 23 *pp* interactions superposed on each collision event at LHC design luminosity
- All plots normalised to unit area

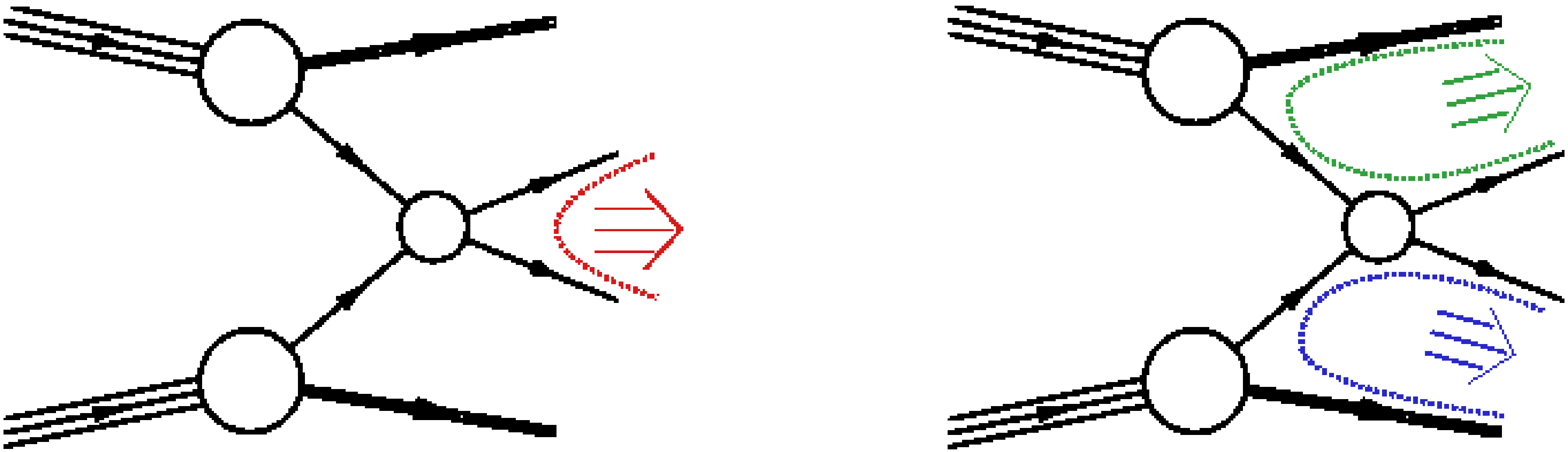
Feynman diagrams for signal and $W\bar{b}b$ background



Jet reconstruction

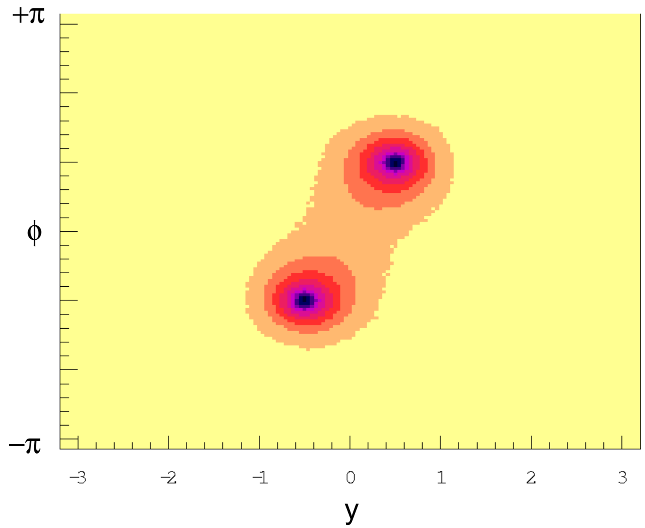
- Full detector simulation
- Jet reconstruction algorithms tried: Anti-k_T (4, 6, 10) and Cambridge/Aachen (12)
- Only calorimeter information for discriminants studied, no tracking (constraint imposed by SW)
  - Jet constituents = topological clusters (3D “energy blobs” formed from calorimeter cells)
- $p_T > 25$ GeV, $|\eta| < 2.5$

Colour flow

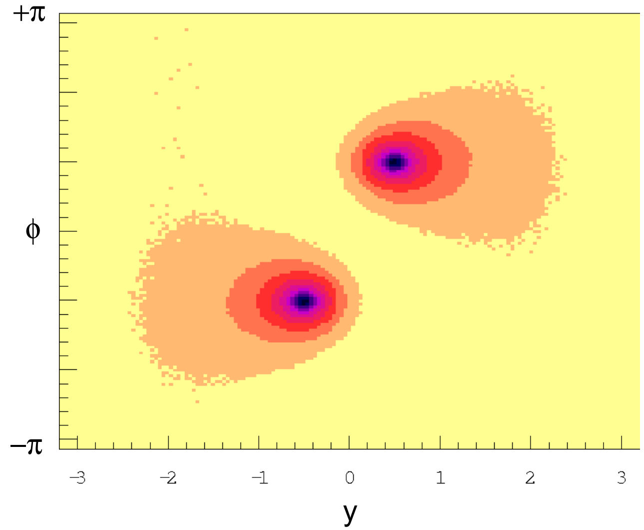


- Jets are not totally independent objects; they are *colour-connected*
- Term comes from the way SU(3) group indices are contracted in amplitudes
- Jets initiated by colour-singlets are colour-connected with each other; those by quarks or gluons, to the proton remnants that travel down the beam pipe
- Provides the event with an observable and characterisable *superstructure*
- Such information, if observable, would be **complementary** to information in event kinematics and may temper otherwise irreducible backgrounds
- Colour connections for $H \to b\bar{b}$ (left) and $g \to b\bar{b}$ (right)

Radiation patterns for events with different colour configurations but identical kinematics



Signal



Background

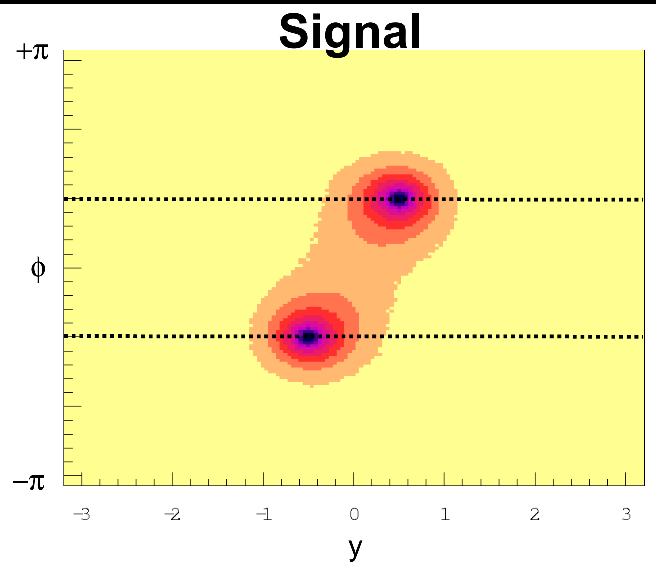
- Average showered p_T density in (y, ϕ) for an ensemble of events with fixed parton-level kinematics
  - Figures taken from PRL 105, 022001 (2010) by Gallicchio and Schwartz
- $H \rightarrow b\bar{b}$ (left) and $g \rightarrow b\bar{b}$ (right)
- For a colour-singlet, the radiation is mostly found in the region between the two jets
- For the background-like colour configuration, the radiation is pulled towards the beam
- *Difference is independent of event kinematics and, if observable, would enable extra discrimination that is orthogonal to cuts on kinematical variables*

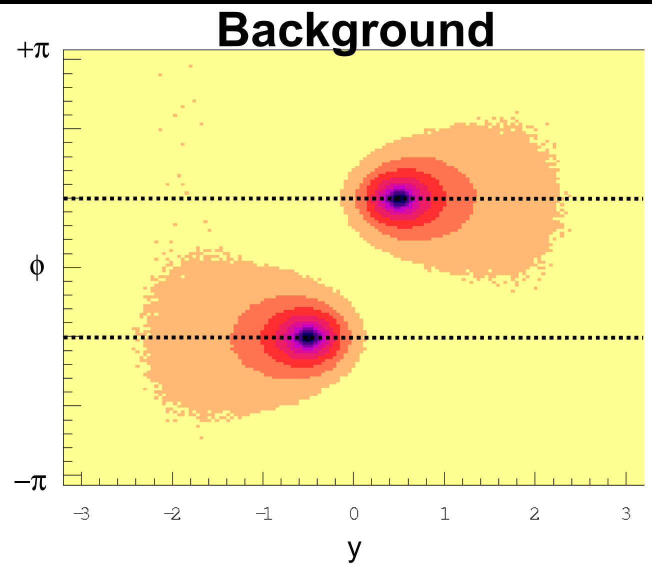
New colour-connection discriminant

$$\sum_{i \in J} \frac{E_T^i}{E_T^J} \phi_i^2$$

- *Beam colour flow* = sum of E_T-weighted squares of distance ϕ_i of jet constituents from jet
- Inspired by *jet dipolarity* observable introduced in arXiv:1102.1012 by Hook, Jankowiak, Wacker, but my own invention
- Complementary:
  - Jet dipolarity measures degree of colour-flow between jets
  - BCF measures degree of colour-flow of jet with proton remnants in beam

New discriminant in pictures

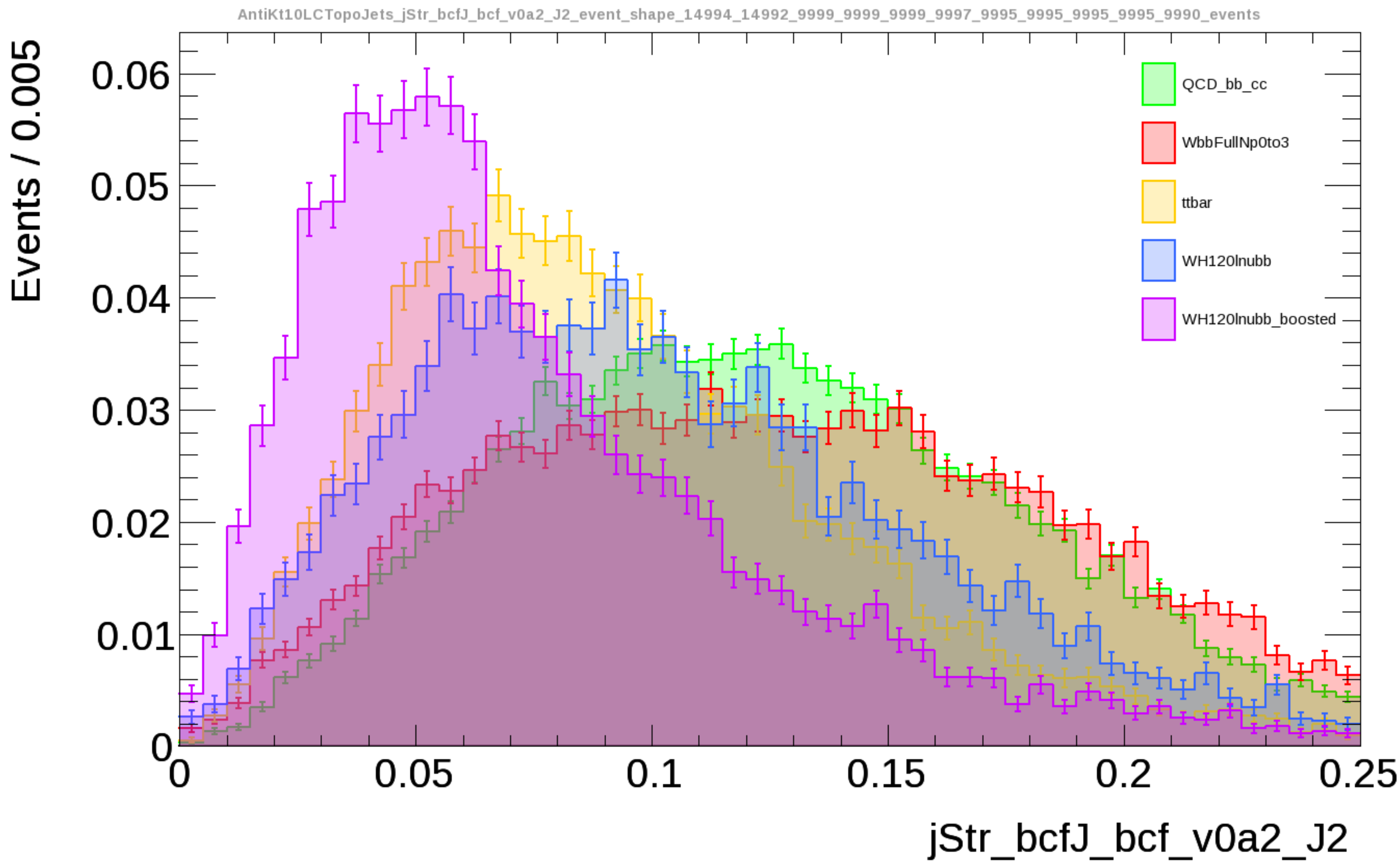




- Can work either as a jet shape or an event shape
  - Event shape = sum of values of discriminant for leading and next-to-leading jet
- Sensitive to jet size; works better with larger size jets
  - Larger jet radius captures more of the differences between radiation patterns
- Expected features:
  - Signal: less radiation between jets and beam → lower weighting to jet constituents in this region → small values of discriminant
  - Background: more radiation between jets and beam → higher weighting to jet constituents in this region → large values of discriminant

Results (Anti-k_T10 jets)

Results indicate that this variable offers some discrimination



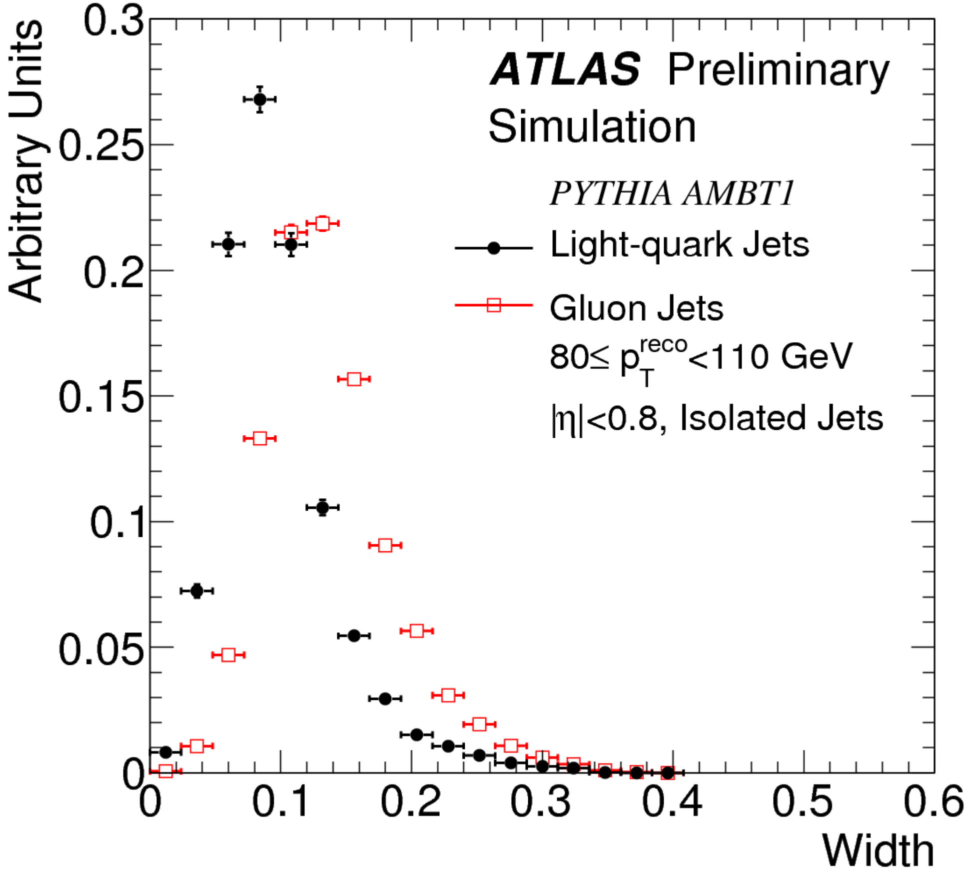
Reminder of colour key: WH120lnubb, Boosted WH120lnubb, Wbb, QCD multijets, ttbar

Width radiation variable

$$g = \sum_{i \in J} \frac{p_T^i |r_i|}{p_T^J}$$

- Distribution of particles within a jet can be useful for distinguishing jets initiated by different flavours of quark or by a gluon
- *Width*: sum of p_T-weighted radial distances of each jet constituent from the jet axis
  - Interesting because it may be possible to calculate in QCD
- Studies of width already done in ATLAS

ATLAS jet width distributions

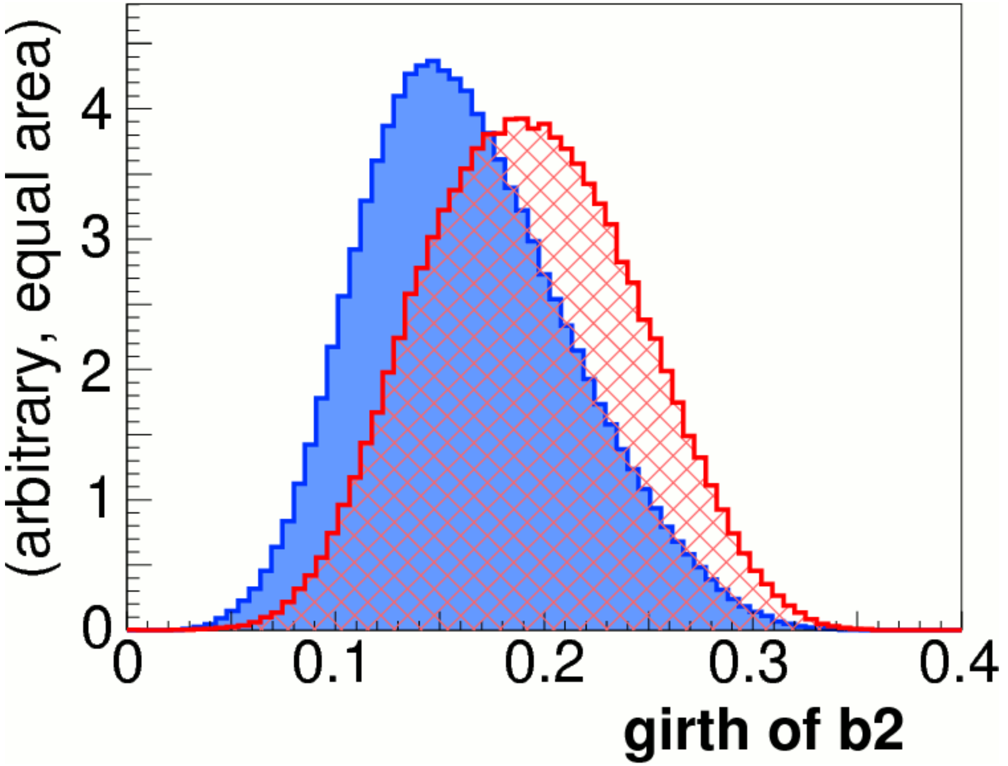


- Distribution of jet width for isolated Anti-k_T jets with R=0.6 tagged as light quark-jets and gluon-jets in the MC simulation with the PYTHIA AMBT1 tune and full-detector simulation
- Plot from ATLAS-CONF-2011-053

Width of next-to-leading jet

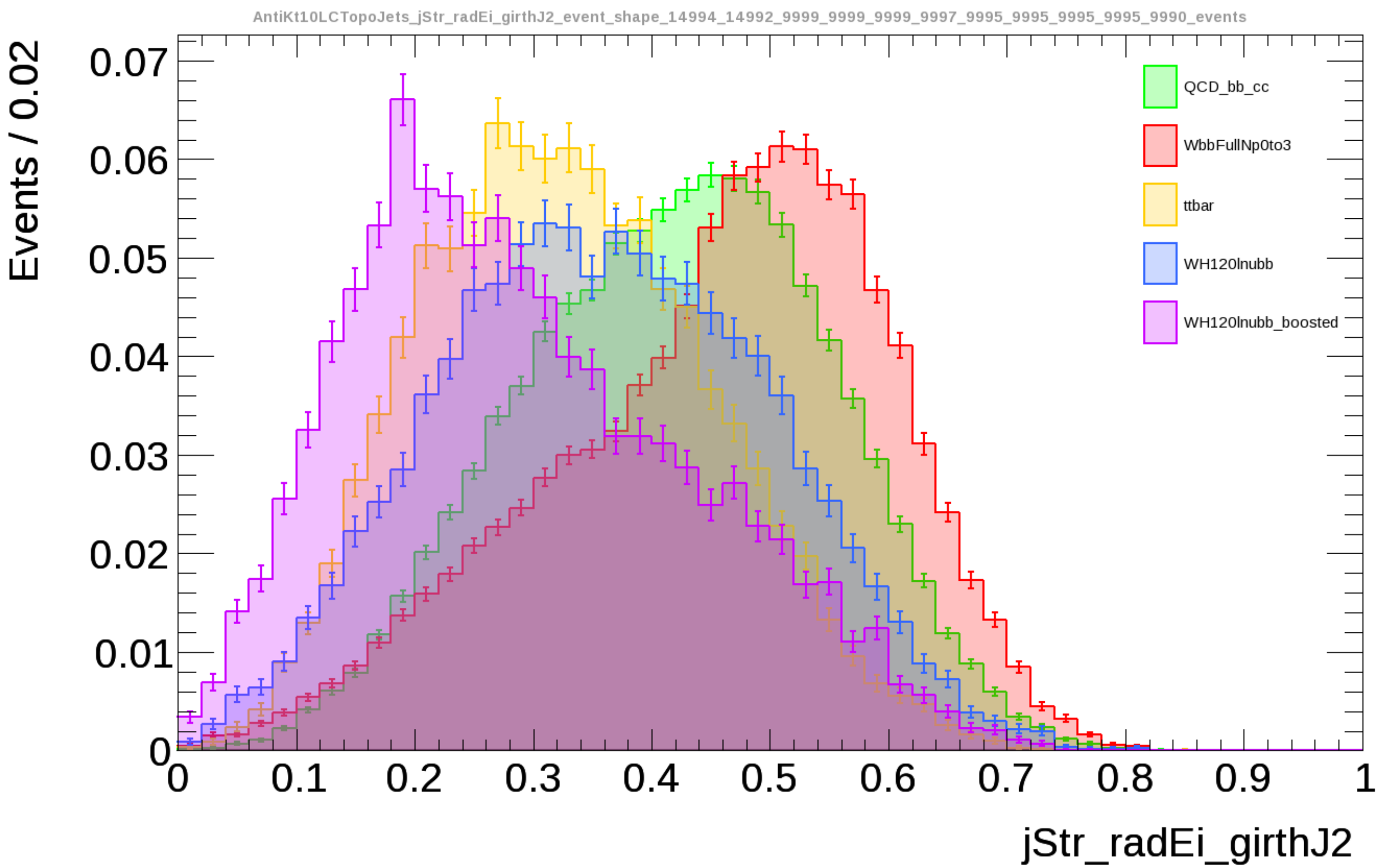
- Introduced in *Multivariate discrimination and the Higgs + W/Z search,* JHEP 1104:069 (2011), in which the width ("*girth*") of the next-to-leading jet was identified as important

Distribution of width of next-to-leading jet



- Plot from PRL theory paper
- Width of the next-to-leading tagged *b*-jet for *ZH* signal (solid blue) and $Zb\bar{b}$ background (hashed red) at the LHC
- Hard-parton level + smearing
- Events satisfy selection cuts and Higgs mass-window cut (details in PRL paper)

Width of next-to-leading jet for Anti-k_T10 jets



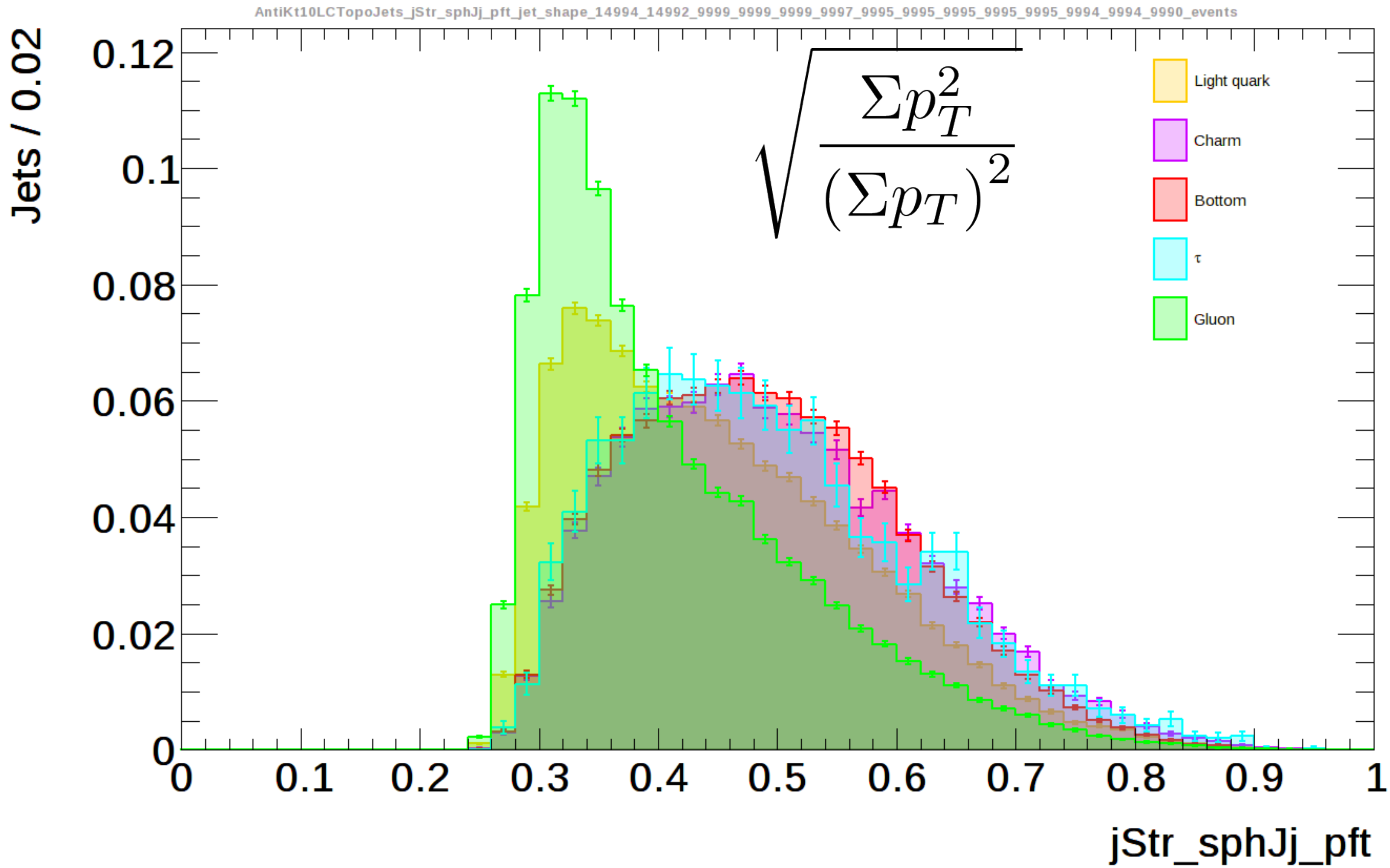
Seems to offer reasonable discrimination, especially with respect to $Wb\bar{b}$

Reminder of colour key: WH120lnubb, Boosted WH120lnubb, Wbb, QCD multijets, ttbar

Jet-by-jet tagging

- Jets labelled as originating from a gluon have a different response to those labelled as originating from a light quark
- Different observable final state properties
  - Studied at LEP
- Quarks and gluons have different colour charges
- Jets labelled as gluon jets tend to have more particles, and those particles tend to be softer than in the case of light-quark jets
- The harder particles in light-quark jets tend to penetrate further into the calorimeter
- The magnetic field of the Inner Detector amplifies the broadness of gluon jets

Flavour tagging discriminant (Anti-k_T10 jets)



It is hoped that using tracking information will improve performance for q/g tagging

Transition from ATLAS to ALICE

- Recently joined Wigner Research Centre for Physics and ALICE experiment
- Work in progress on adapting code to run in ALICE offline analysis framework (AliROOT)
- Have already converted the event shapes that are constructed from four-momenta of the jets
  - For example: sphericity, aplanarity, twist, helicity, various types of Fox-Wolfram moments, many more...
  - Event shapes that depend on the radiation pattern of the event will come soon
  - Jet shapes to follow
- Will check discriminants with *pp* data first, then extend to heavy ion data
- More than enough reason to be confident that this work will produce interesting results in the near future

Summary

- These are very exciting times for high-energy physics
- The LHC provides an unprecedented opportunity to explore a new energy frontier where new physics might be discovered
- The next few years are likely to see important discoveries made at the LHC
- These will answer old questions and probably raise new ones that will dominate the direction of the field for years to come
- This work has the potential to make a considerable impact on many new physics searches
- Could lead to a marked improvement in discovery reach
- There are many possible further applications
  - Precision tests of QCD calculations and models
  - Tuning of MC generators used in simulation

End

Bonus slides...

Jet labelling procedure

- Jets labelled using the partons in the generator event record
- **Scheme 1**: The highest energy parton that points to the jet (i.e. with $\Delta R < 0.4$, 0.6, 1.0, and 1.2 for jets with R = 0.4, 0.6, 1.0 and 1.2 respectively) determines the flavour of the jet
  - Identical to that used in ATLAS-CONF-2011-053, *Light-quark and Gluon Jets in ATLAS: Calorimeter Response, Jet Energy Scale Systematics, and Sample Characterization*
- **Scheme 2**: A jet is labelled as a *b*-jet if a *b* quark with $p_T > 5$ GeV is found in a cone of size $\Delta R = 0.3$ around the jet direction. The various labelling hypotheses are tried in this order: *b* quark, *c* quark and τ lepton. When no heavy flavour quark nor τ lepton satisfies these requirements, the jet is labelled as a light-jet. No attempt is made to distinguish between *u*, *d*, *s* quarks and gluon.
  - Identical to that used for measuring *b*-tagging performance in ATLAS CSC Note and elsewhere (standard analysis tool available to do this)
- **Hybrid**: Use second scheme to find *b*-, *c*-, and τ-jets, then use first scheme to sort remaining light jets into light-quark jets and gluon jets
  - This is what I use when showing differences in response for *b*-, *c*-, τ-, light-quark and gluon jets, because I want to show utility of discriminants for both *b*/*c*/τ-tagging and q/g-tagging
- These labelling procedures are not unambiguous and are not *strictly identical* for different Monte Carlo generators
- Definitions are not theoretically robust, but studies have shown that for most generators and for isolated jets, truth labelling is identical to matrix-element-based labelling for >95% of jets