Jet Substructure

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Outline

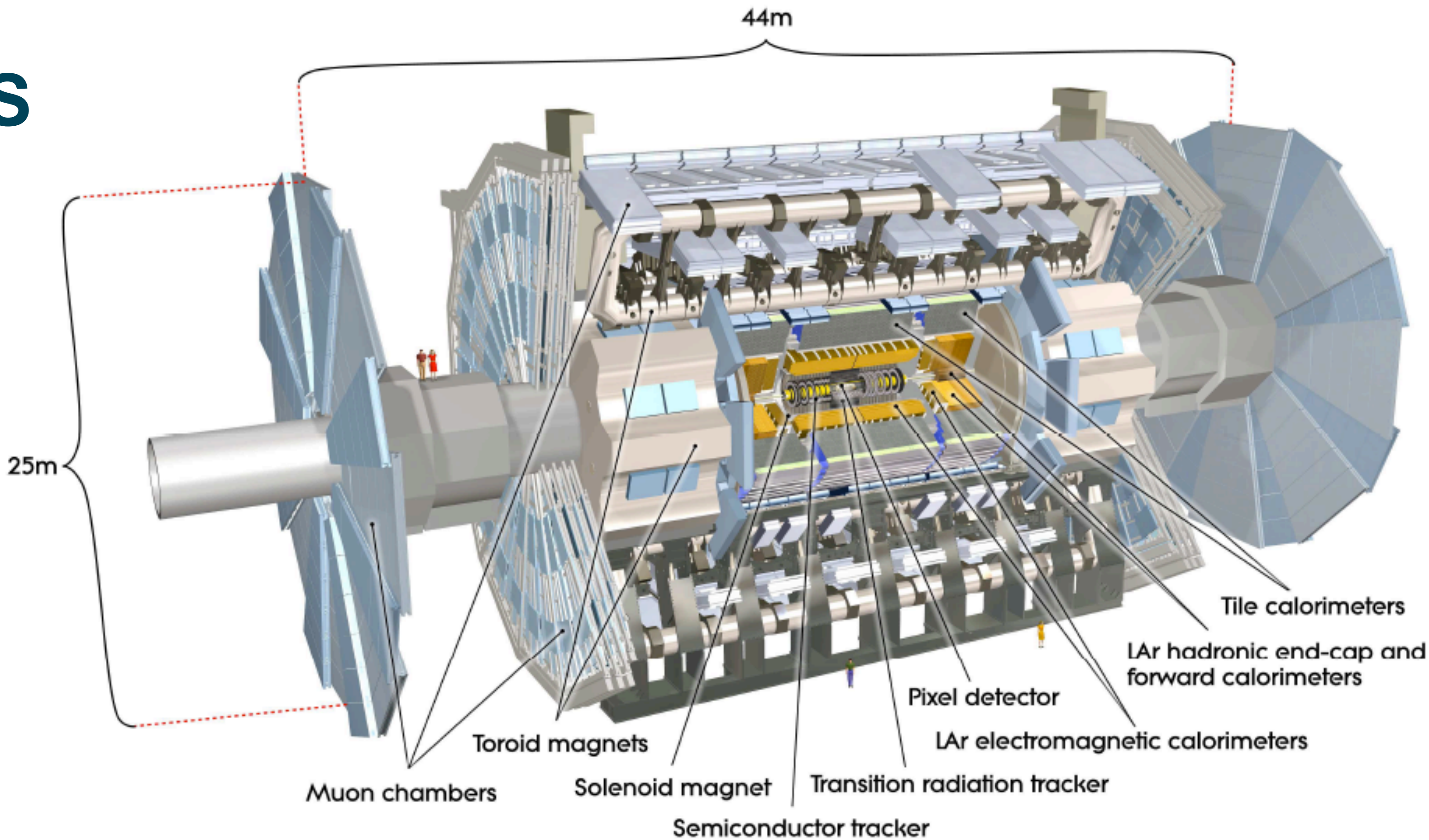
- Jets at the LHC
  - Machine and ATLAS detector
  - What is a jet?
- Jet substructure
  - What is it?
  - What can it do for us?
- Some ATLAS/Higgs bias here…

Jets at the LHC

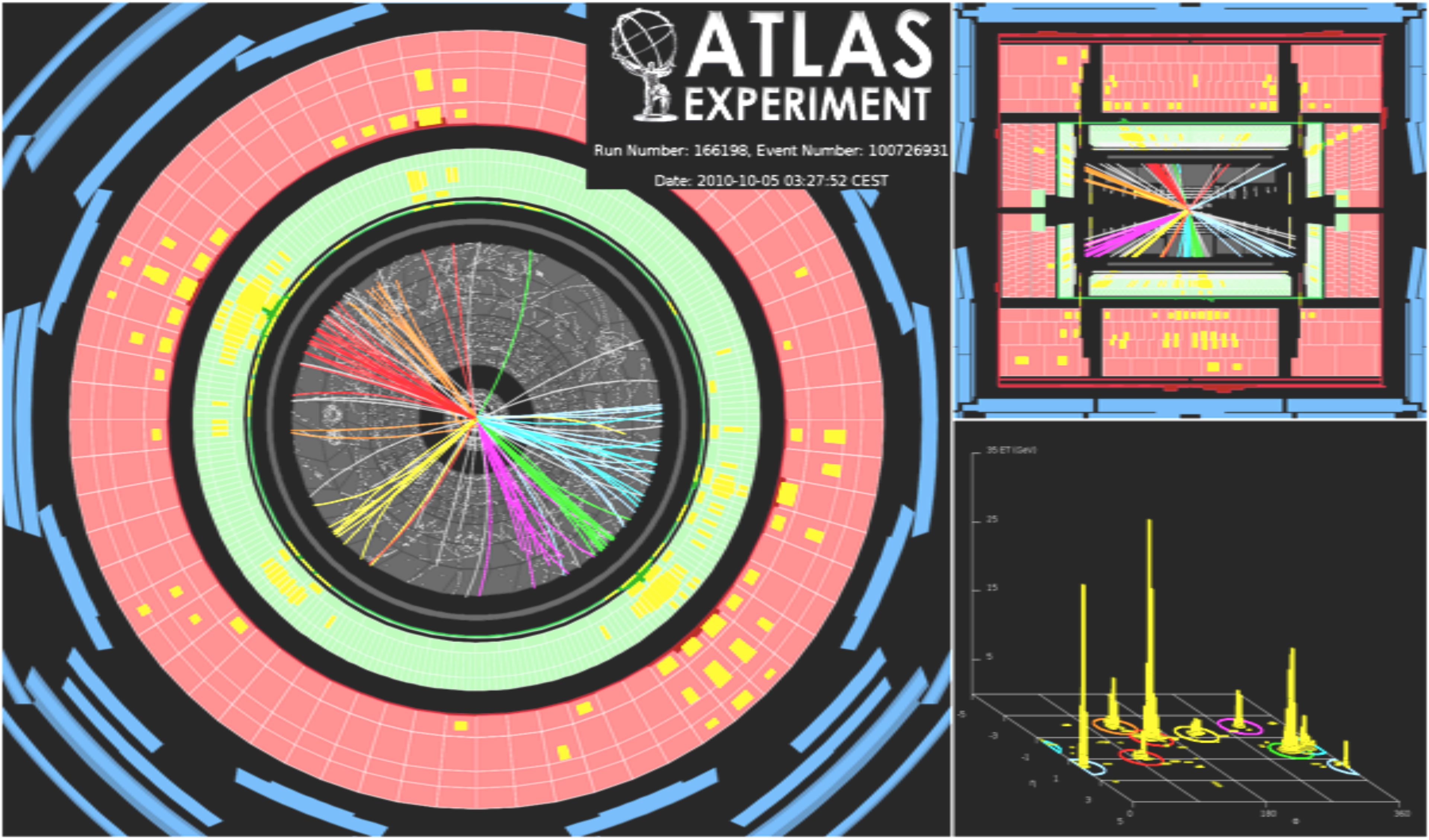
The LHC

- Machine started delivering collisions in 2010
- Performed above expectations, delivered ~48 pb^{-1} at 7 TeV
- Many exciting results already
- Expecting great things in 2011

ATLAS

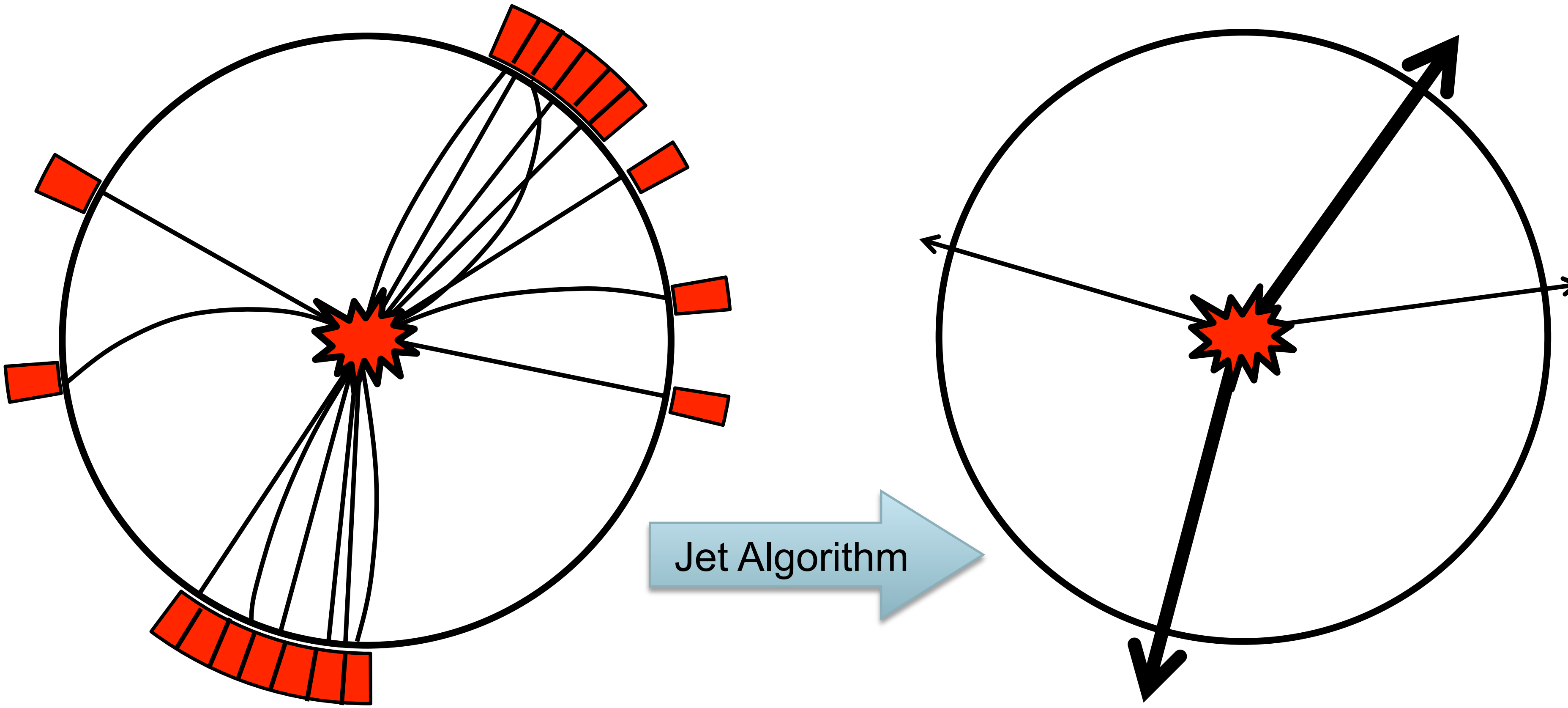


- Detector performing excellently
- Efficiency > 90% for 2010 run



- This is what an event looks like…

Applying a Jet Algorithm

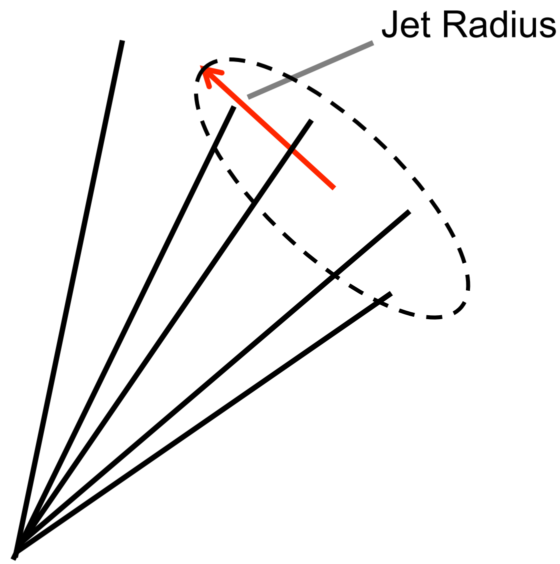


Before: Many Particles, Complicated Event

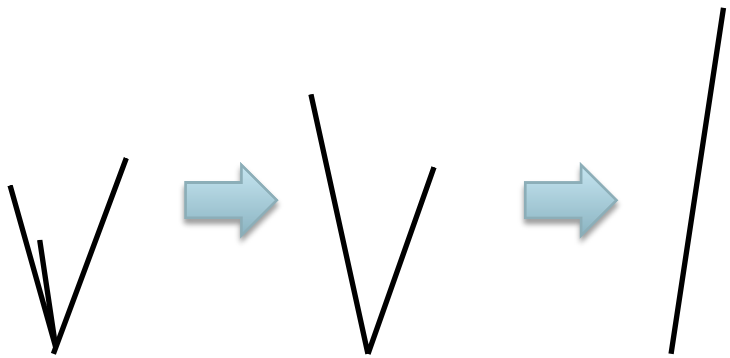
After: Few Jets
Can easily identify dijet structure

Modern Jet Algorithms

- Two classes, ***Cone*** and ***Clustering***



Cone – Cluster particles in a radius
Example: ***SISCone***

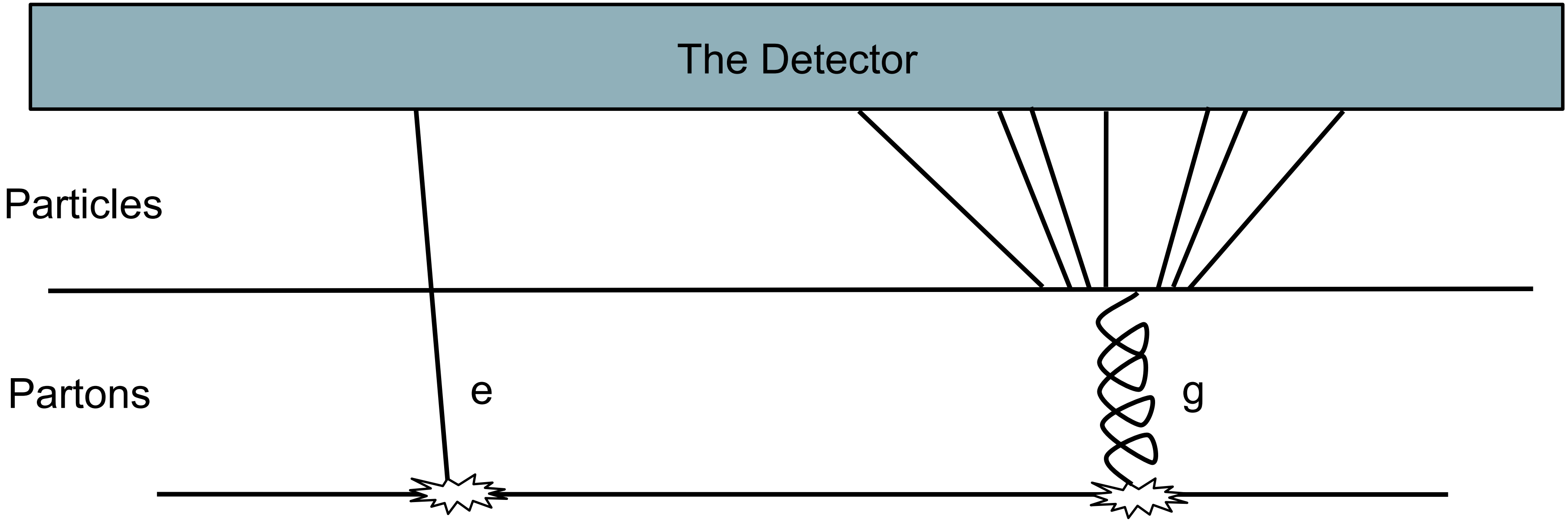


Clustering – Successively recombine pairs of objects to make jets

Examples:
k_T, anti-k_T, Cambridge-Aachen

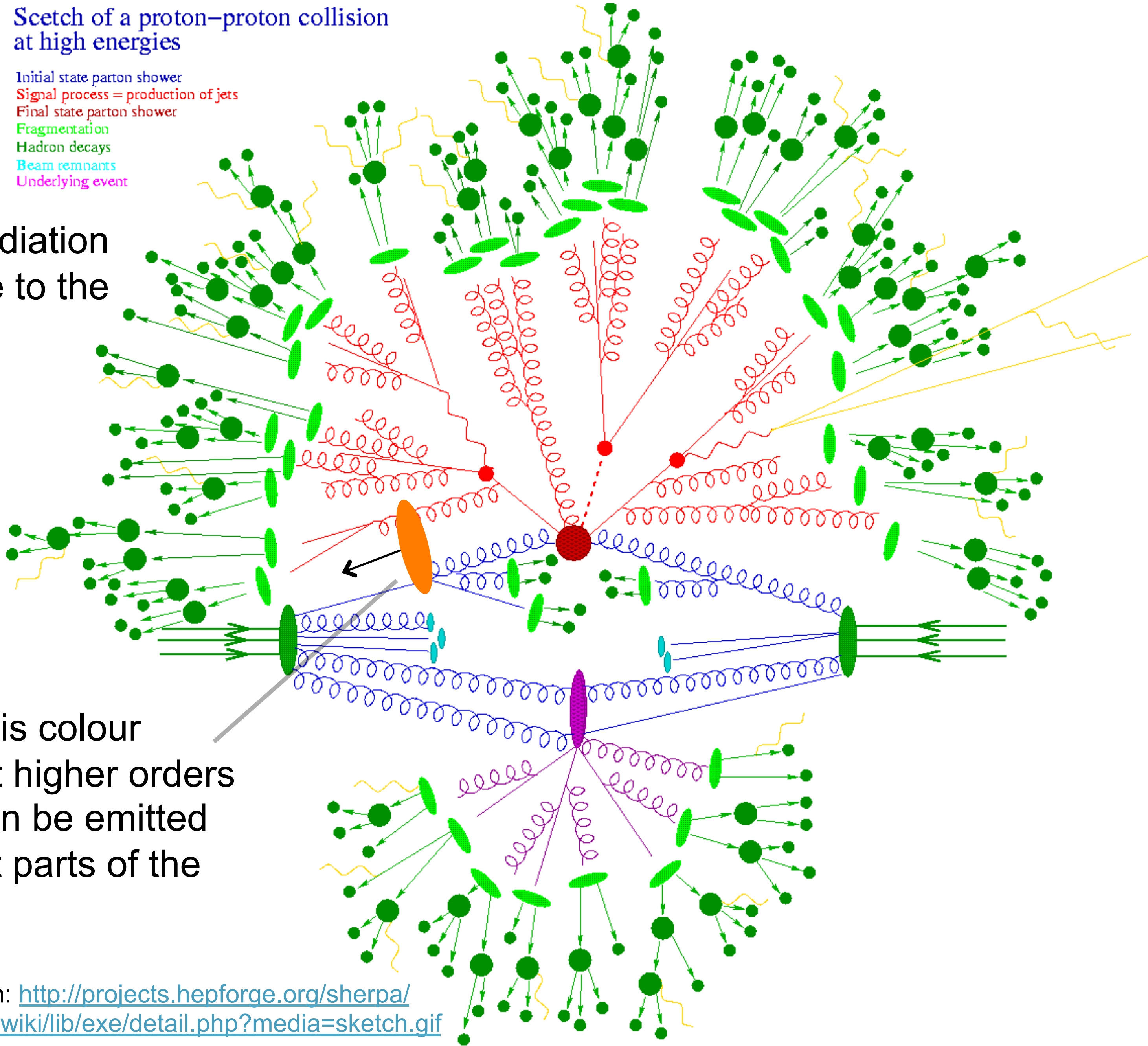
Where do jets come from?

- Quark/gluon production leads to high multiplicities



- How do we measure quark/gluon production?
- Natural to try to get back to the parton level…

But life is not so easy

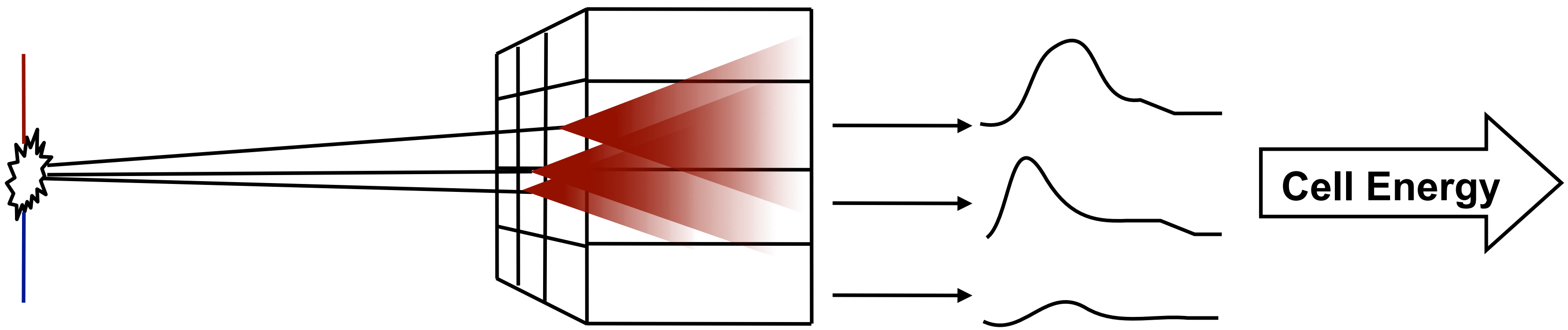


Many sources of radiation all indistinguishable to the calorimeter

The whole event is colour connected and at higher orders radiation can even be emitted between different parts of the event

From: http://projects.hepforge.org/sherpa/dokuwiki/lib/exe/detail.php?media=sketch.gif

And Calorimeters Are Not Perfect



- Calorimeter cannot identify individual particles
- Has finite resolution
- Gaps, cracks for services and supports…
- Dead material scatters/absorbs particles

Where do we go from here?

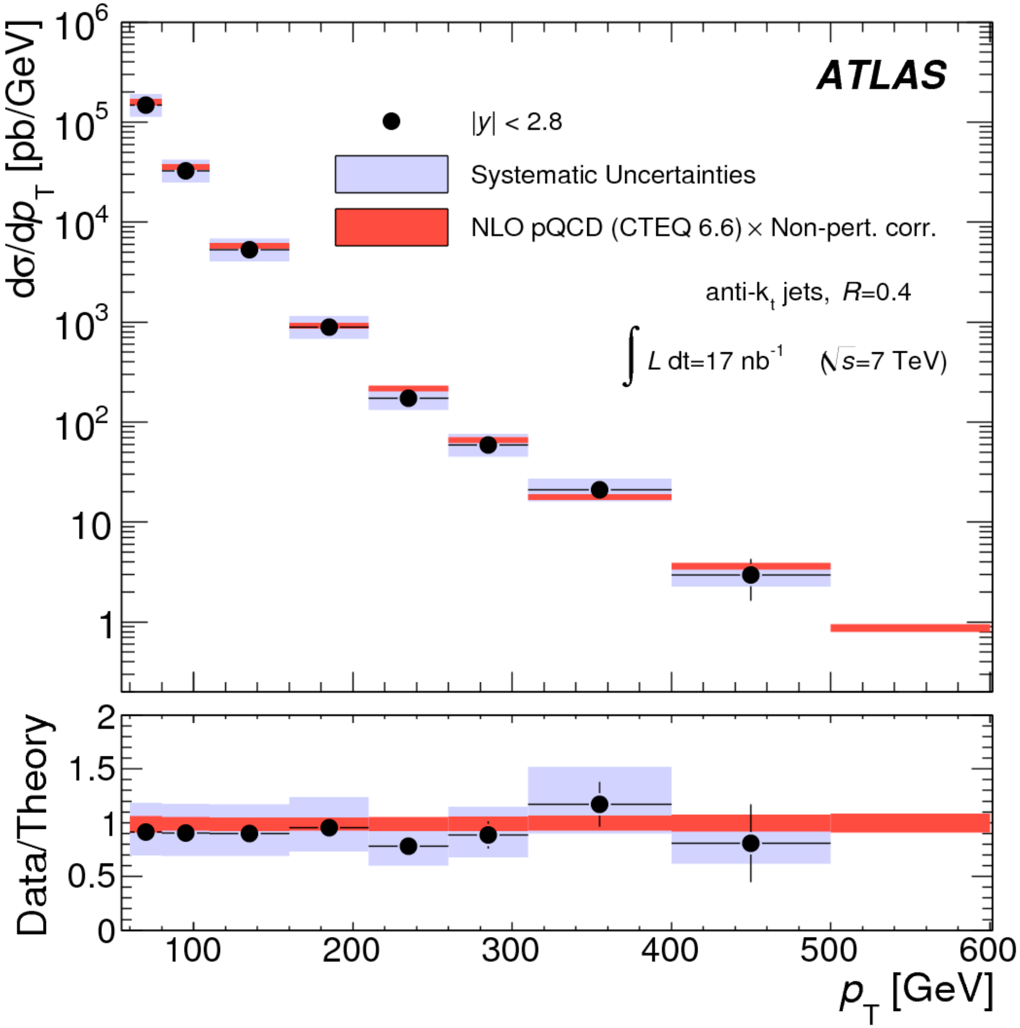
- Parton level isn't well defined or observable
- The hadron level is the only well-defined, observable state
- And the detector causes even more problems
- Must **forget the concept of correcting to parton level**
- But at the end of the day we still want to measure hard processes involving jet-like hadron production

Where do we go from here?

- There is no unique or correct way to group hadrons
- **Any jet algorithm is one possible view** of an event
- The algorithm should be **chosen based on your goals**
- Things that might be important:
  - Does it do something useful? (like good invariant mass resolution)
  - Theoretically safe (infrared safety etc…)
  - Experimentally safe (noise, calibratable etc…)

Inclusive Jet Cross-section

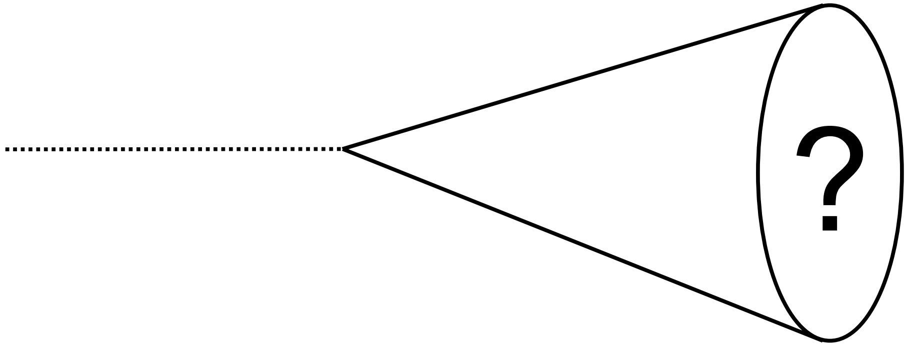
- Comparison to NLO pQCD only possible because of choice of jet algorithm (anti-k_T)
- Must consider both experimental and theoretical aspects when defining jets



Jet Substructure

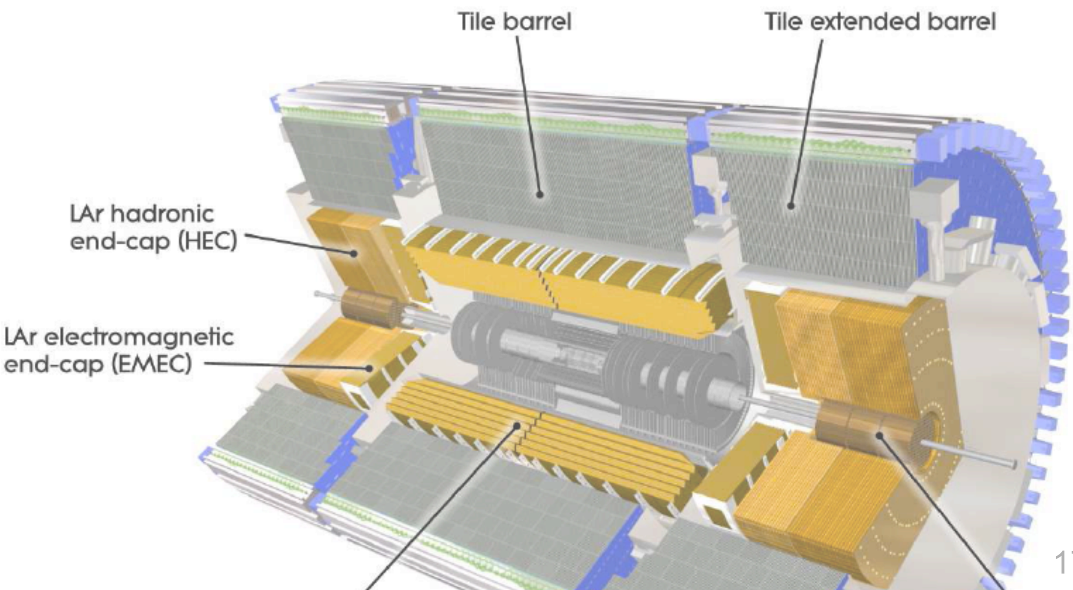
Jet Substructure

- Jet algorithms have allowed us to group the complex structure of collisions into a few simple 4-vectors
- This approach has enabled many measurements
- But we turned a very large dataset into a very small one
- Did we lose anything along the way?



Jet Substructure

- The LHC reaches into a new energy regime
- For the first time O(100 GeV) mass particles (W, Z, top) will be produced with significant boost in large numbers
- At the same time, granular calorimetry allows a very detailed view of jets



First Steps

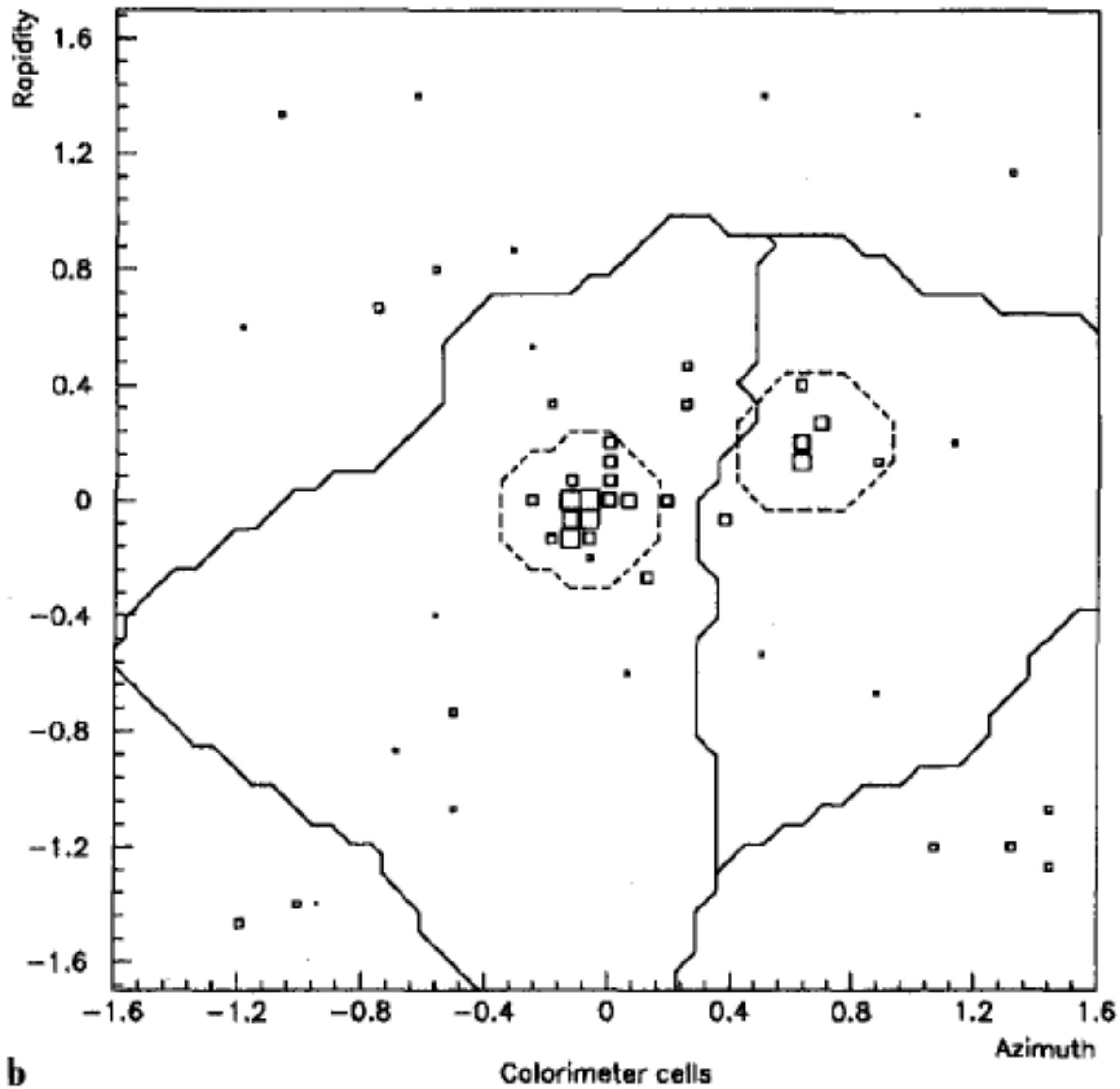
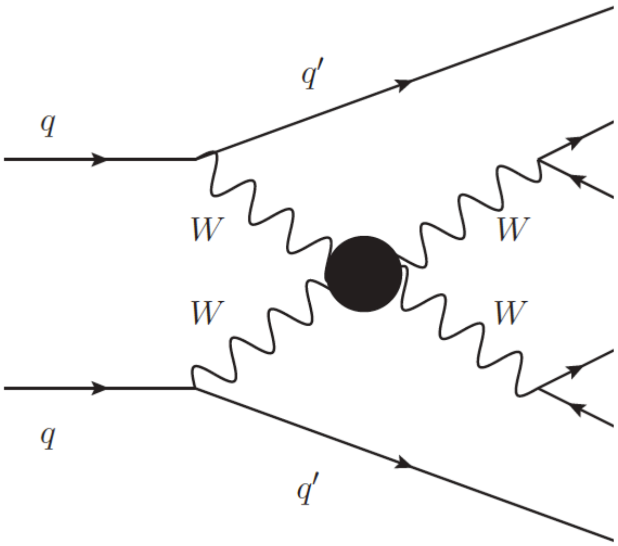


Fig. 2. A hadronic W decay, as seen at calorimeter level

M. H. Seymour
Z Phys C62 (**1994**) 172

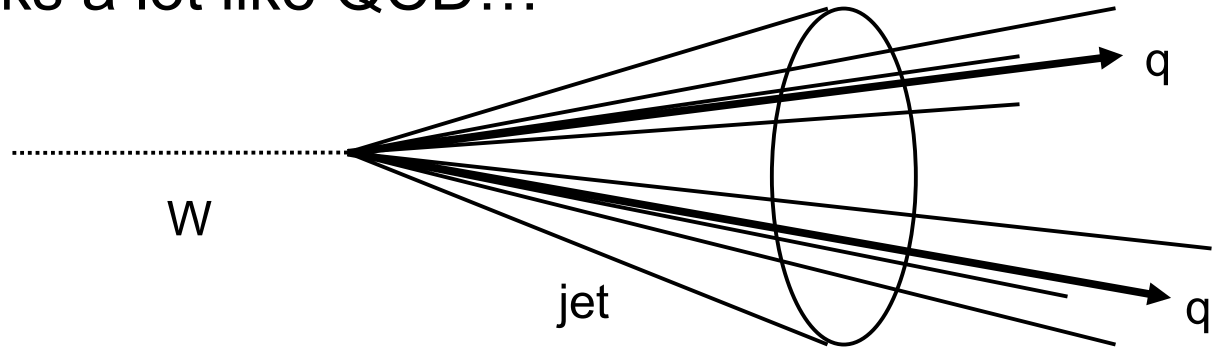
Vector Boson Scattering

- Scattering pairs of electroweak bosons
- In the absence of a light higgs, $W_L W_L$ scattering violates unitarity at ~ TeV scale
- But observing WW is tough
  - ZZ not so bad…
- Fully-leptonic has low rate
- Semi-leptonic buried under W+jets and top backgrounds



WW Scattering

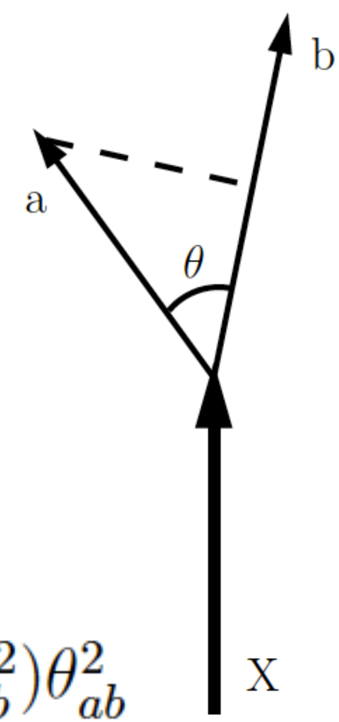
- Look only at high pT (>200GeV)
- At high p_T backgrounds are suppressed somewhat
- But need to identify hadronically decaying W
- All decay products will tend to be boosted into a single jet
- Looks a lot like QCD…



J M Butterworth, B E Cox, J R Forshaw *Phys. Rev. D65; 096014 (2002)*

WW Scattering

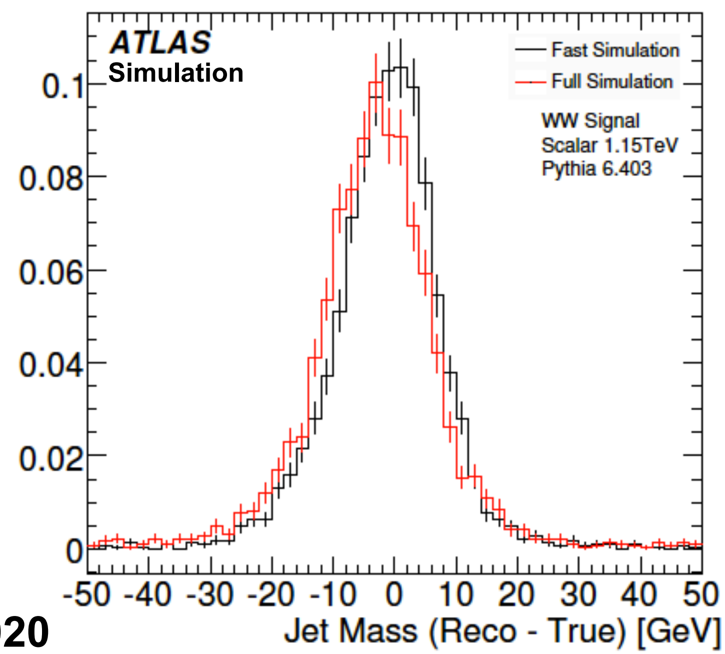
- Use the clustering-type k_T algorithm (E-scheme)
- By conservation of 4-momentum, jet will have $m = m_W$
- k_T clustering ordered in (relative) p_T
  - Undo clustering one step at a time
  - Last splitting is the hardest
  - Heavy object decays should be symmetric
  - QCD splittings are asymmetric
  - $y_{scale} \sim m_w / 2$

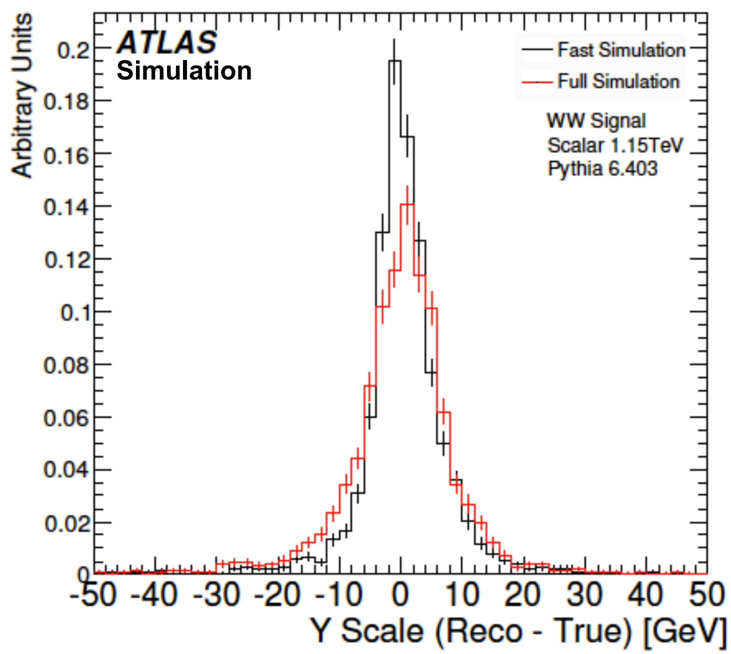


$$P_{TX}^2 y_2 = \min(E_a^2, E_b^2)\theta_{ab}^2$$

WW Scattering

- Tried at ATLAS
- First use of jet substructure with detector simulation
- Proved the LHC detectors are capable of this

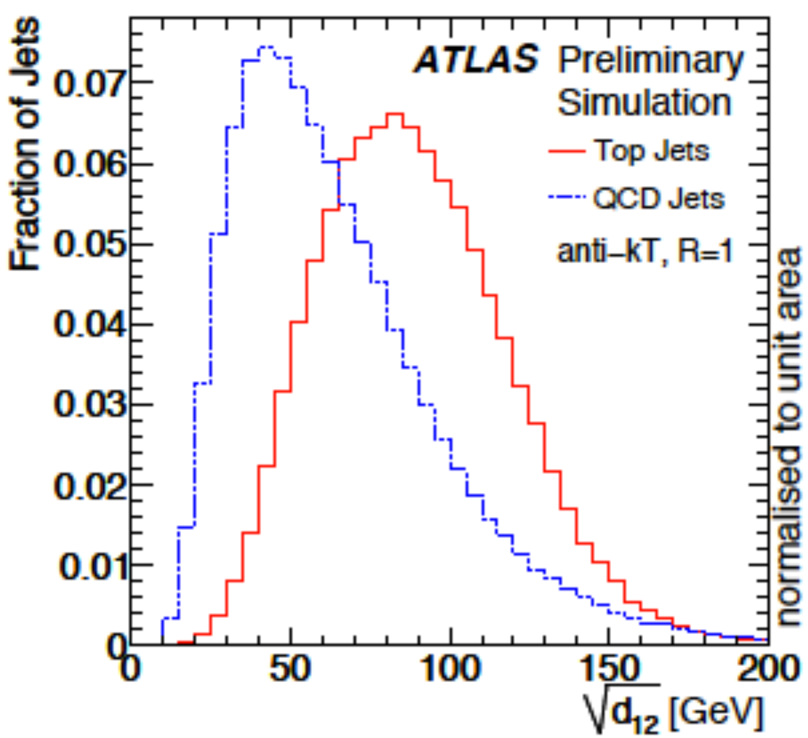




CERN-OPEN-2008-020

Other Applications

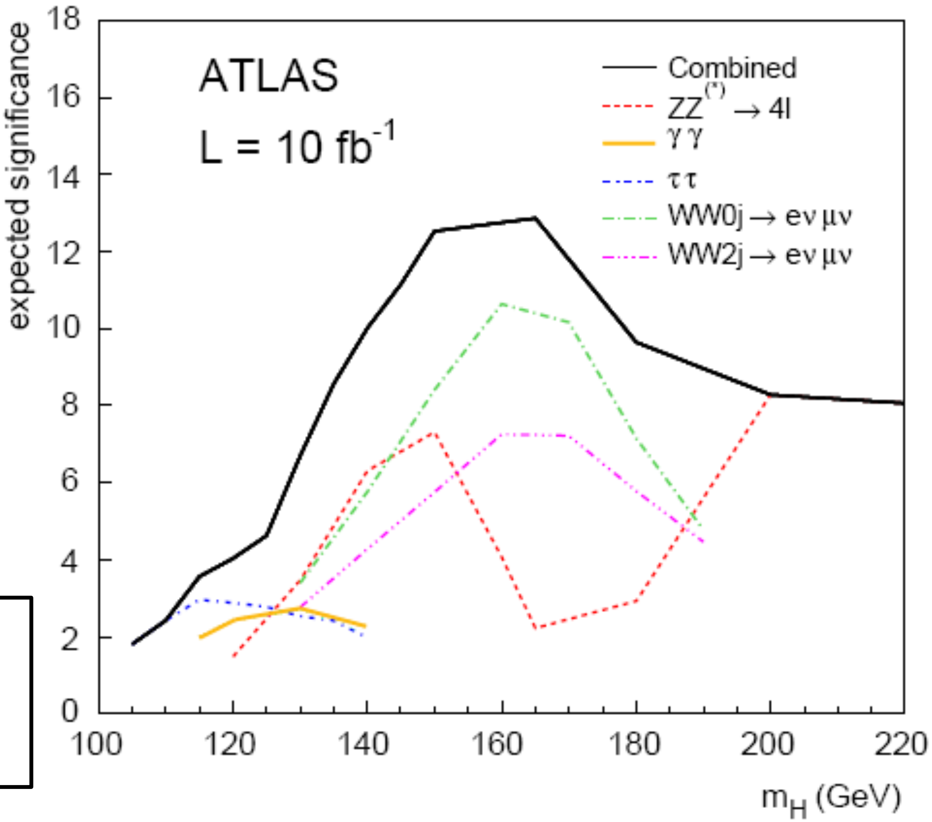
- Similar techniques have also been shown to be applicable to top and SUSY identification
- For example here used as one variable to help discriminate boosted tops from QCD



ATL-PHYS-PUB-2010-008

ATLAS H→bb Search

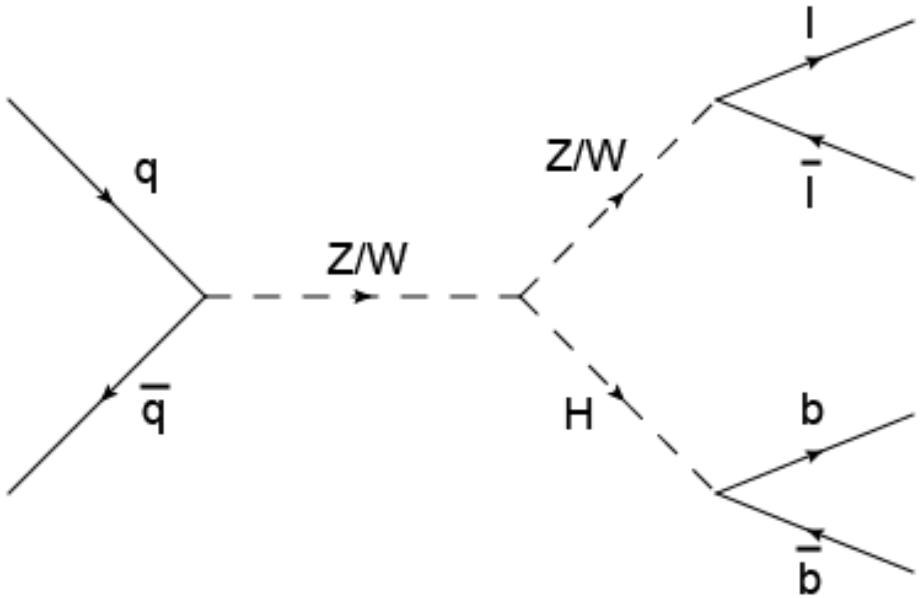
- Low mass (~115 GeV) Higgs favoured by Electroweak fits
- Also where a discovery is hardest at the LHC
- Decays mostly bb (~70%)
- But in 2008 H→bb nowhere on ATLAS plot
- ttH→bb was best bet



ATLAS Collaboration,
Expected Performance of the ATLAS Experiment, Detector, Trigger and Physics,
CERN-OPEN-2008-020, Geneva, 2008.

WH/ZH Processes

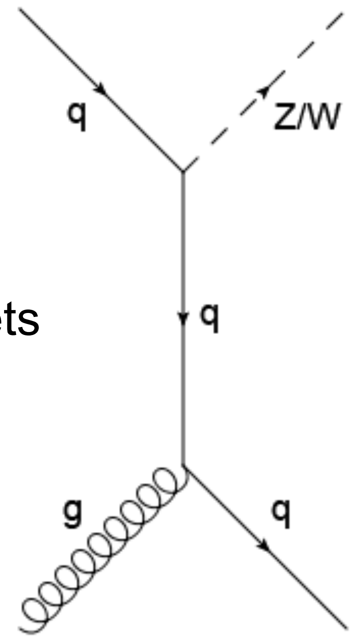
- WH/ZH is main Higgs search channel at TeVatron
- Generally speaking search for a leptonic W/Z
- In association with H→bb

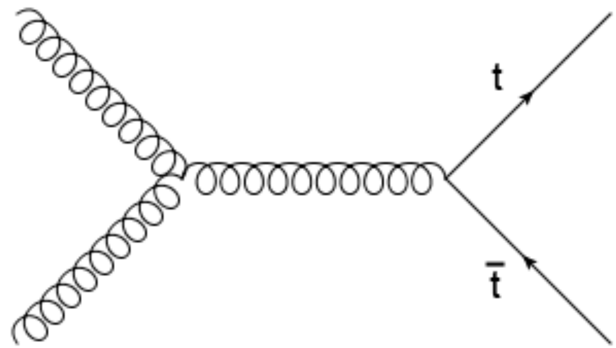


WH/ZH Backgrounds

- W/Z+jets and tt backgrounds much bigger at LHC

W/Z+jets





$t\bar{t}$

WH/ZH at ATLAS

- TDR analysis (1999)
- Admittedly fairly simple
- But major issues with backgrounds/systematics
- "… very difficult … even under the most optimistic assumptions"

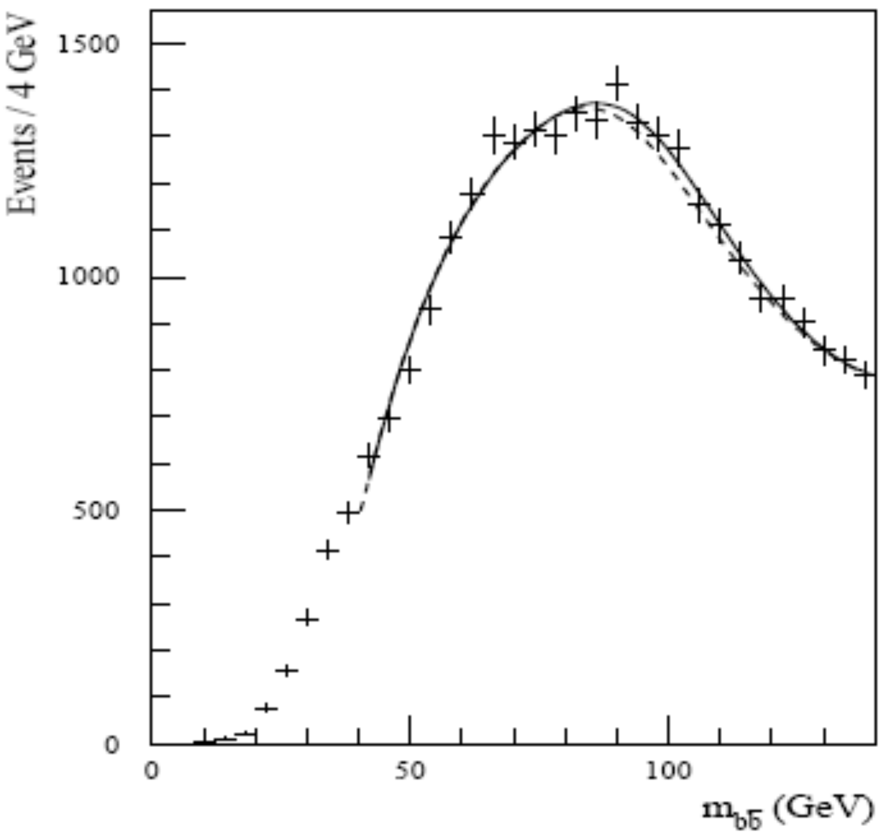


Figure 19-7 Expected *WH* signal with $H \to b\bar{b}$ above the summed background for m_H = 100 GeV and for an integrated luminosity of 30 fb^{-1}. The dashed line represents the shape of the background.

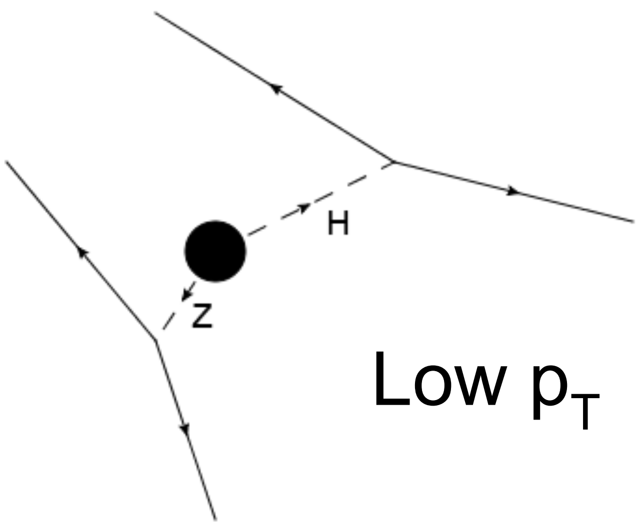
ATLAS Collaboration, **ATLAS: Detector and physics performance technical design report. Volume 2.** *CERN-LHCC-99-15*, *ATLAS-TDR-15*, May 1999

A New Approach

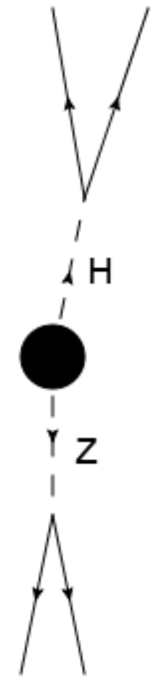
- Still want to observe H→bb
- It’s a big part of the available signal
- Beneficial for overall sensitivity to access this
- Also need →bb branching ratio to determine that our discovery of X(120) is really the Higgs
  - **R. Lafaye, T. Plehn, M. Rauch, D. Zerwas and M. Duhrssen**, Measuring the Higgs Sector, *arXiv:0904.3866* [hep-ph] - “a reliable measurement of the bottom Yukawa coupling ... is vital”

A New Approach

- Consider only the high p_T part of the cross-section
- Backgrounds reduced
- Simpler topology



Low p_T

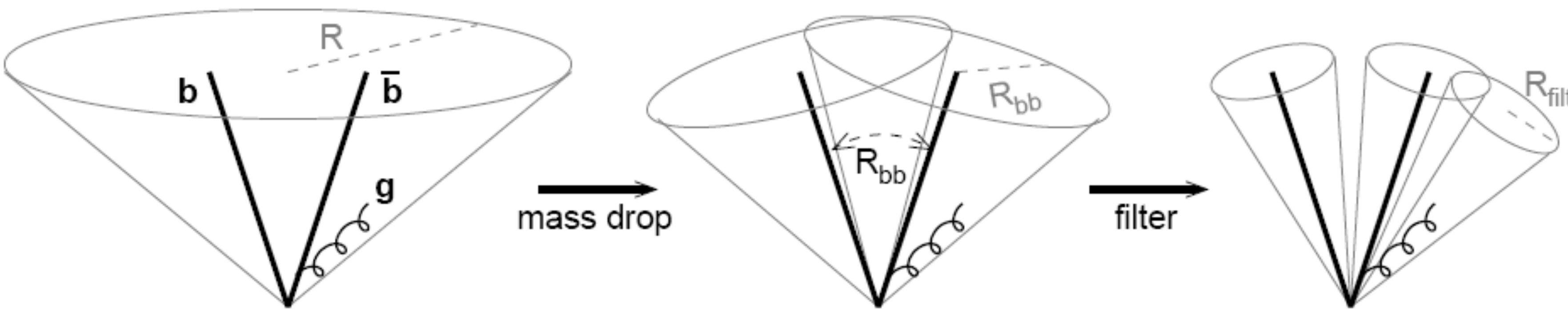


High p_T

Phys. Rev. Lett. 100, 242001 (2008) J. Butterworth, AD, G. Salam, M. Rubin

Identifying a Boosted Higgs

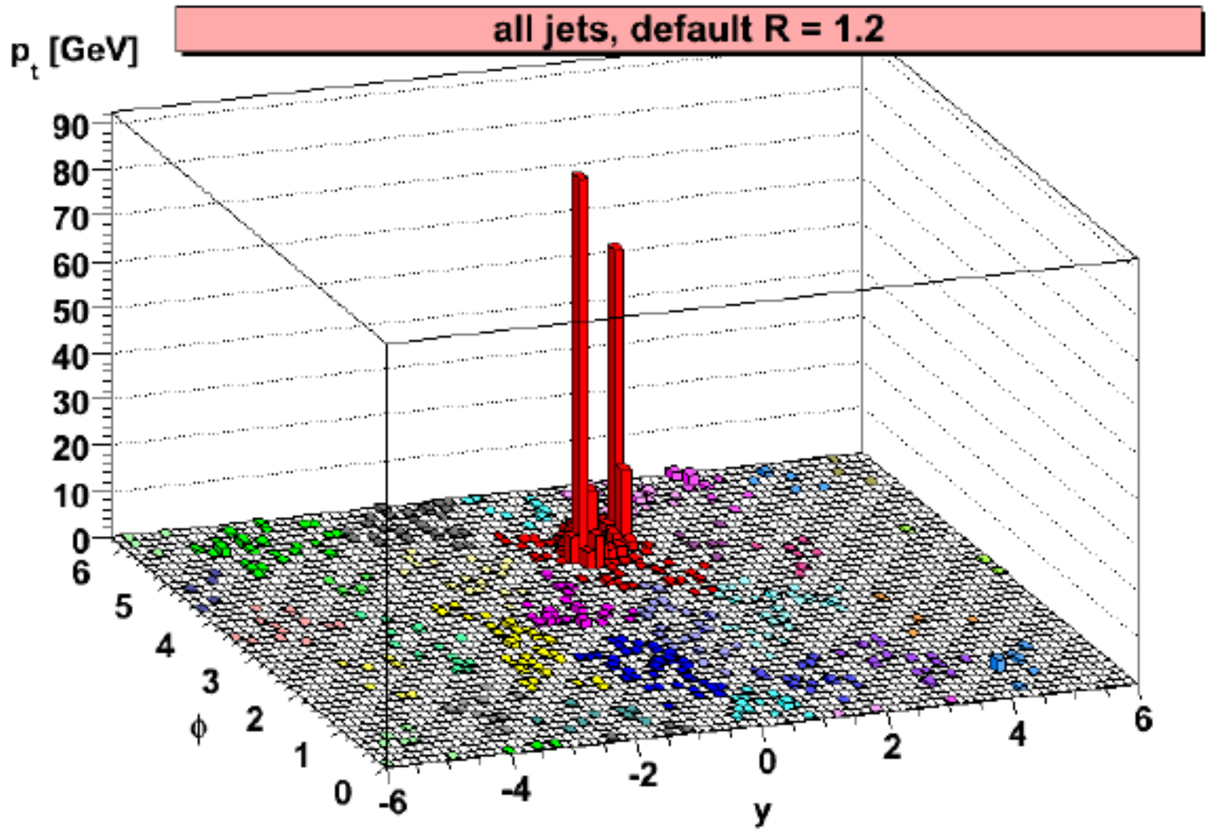
- Using the Cambridge-Aachen jet algorithm
  - Recombines closest pair of objects in the event up to R
- When finding a jet that passes a pT cut
  - Clustering can be undone one step at a time
  - Reverse clustering until a large drop in mass is observed
  - Check this splitting is not too asymmetric
  - Recluster remaining constituents with smaller R



$pp \to ZH \to \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

SIGNAL

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



These slides from an excellent talk by G. Salam at SUSY08 amongst others…

Zbb BACKGROUND

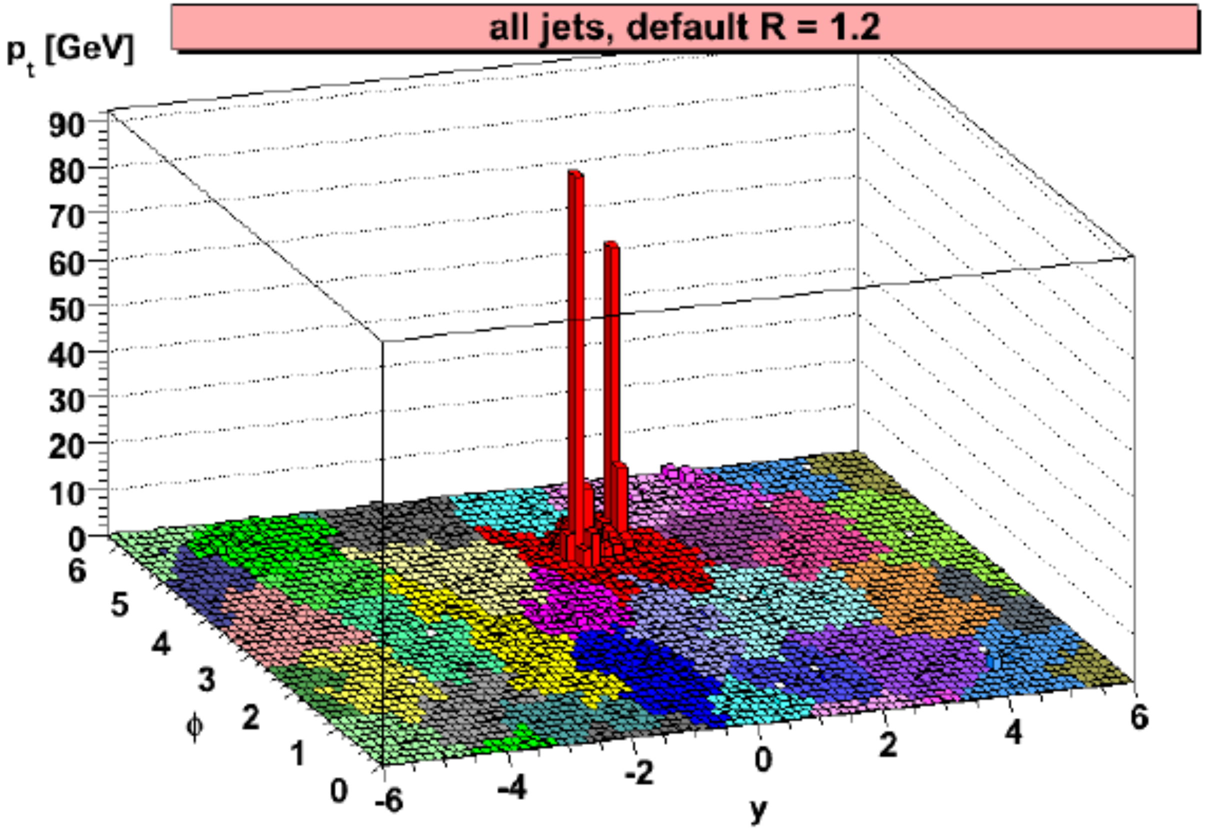
Cluster event, C/A, R=1.2

arbitrary norm.

$pp \to ZH \to \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

SIGNAL

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



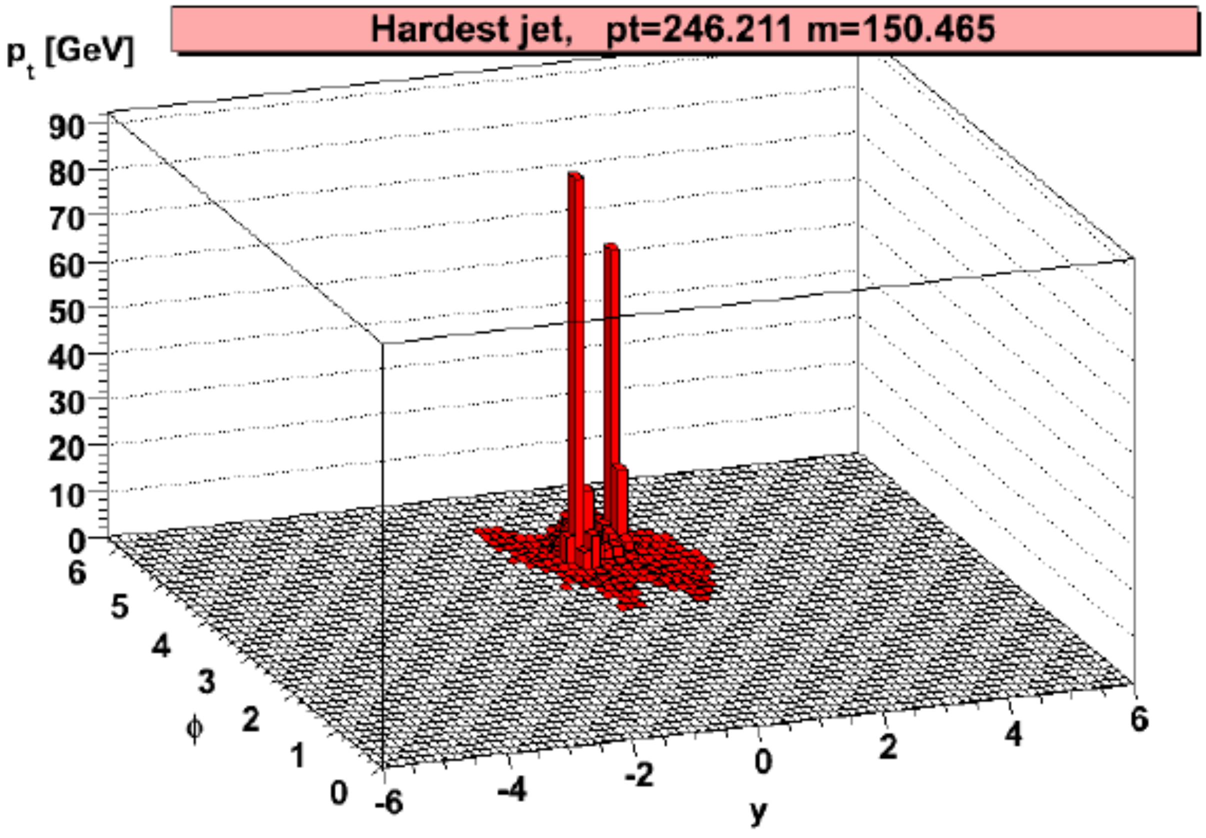
Zbb BACKGROUND

Fill it in, → show jets more clearly

arbitrary norm.

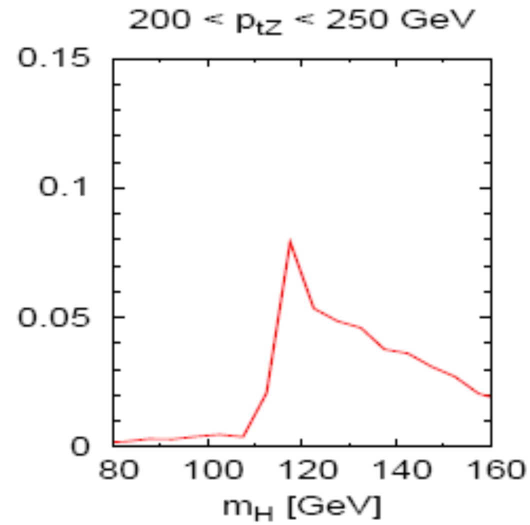
$pp \longrightarrow ZH \longrightarrow \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3

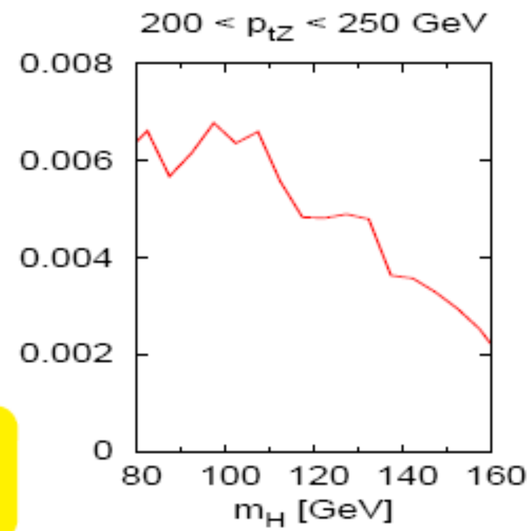


Consider hardest jet, $m = 150$ GeV

SIGNAL



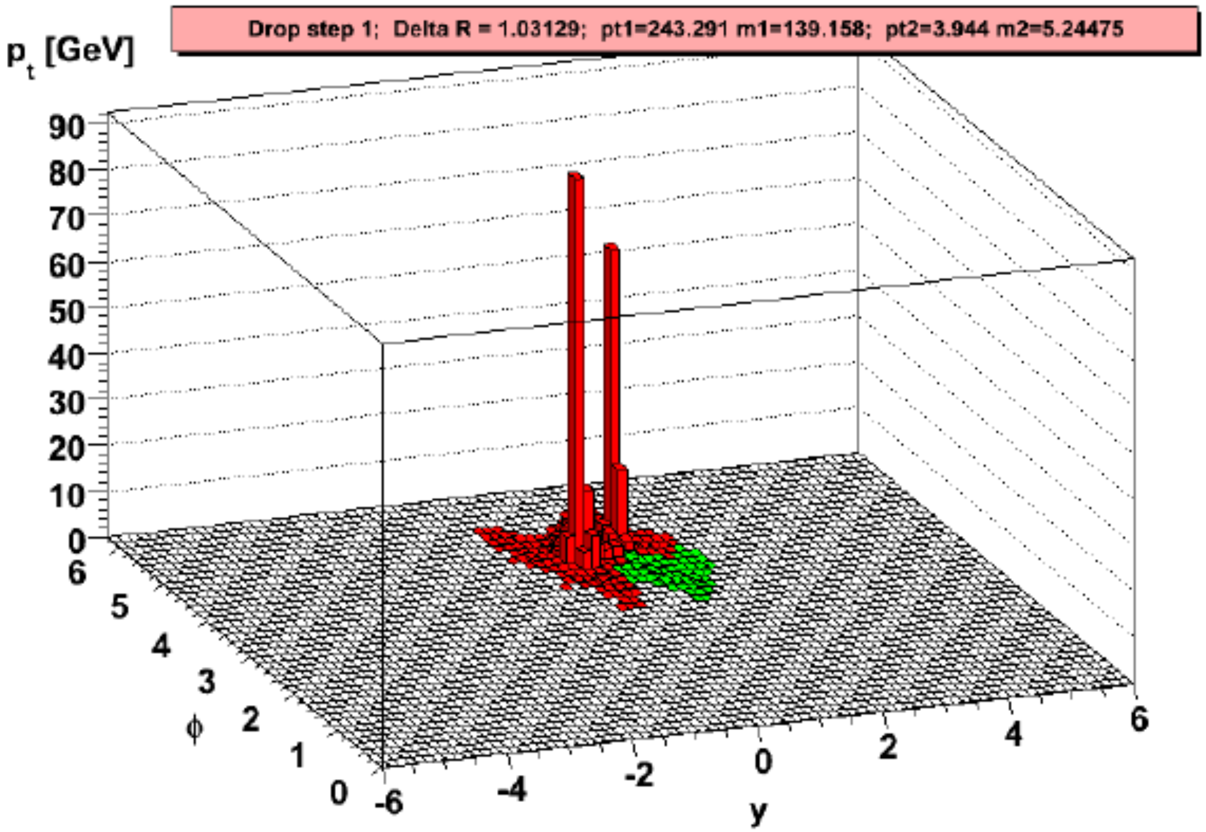
Zbb BACKGROUND



arbitrary norm.

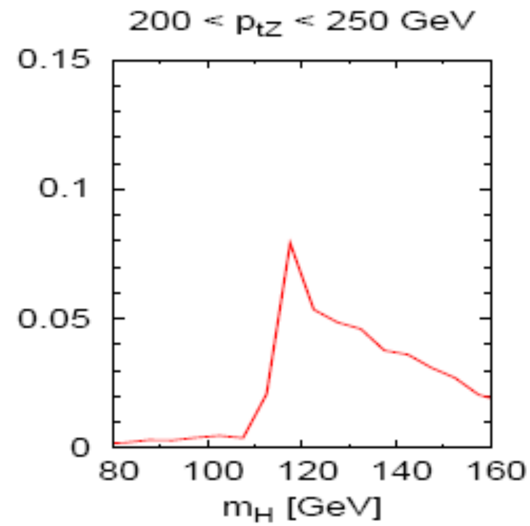
$pp \to ZH \to \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3

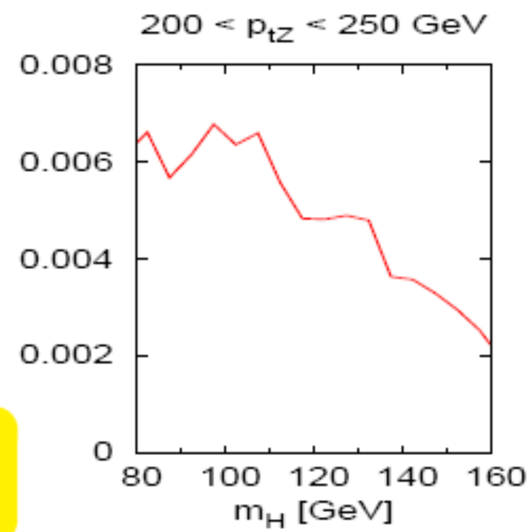


split: $m = 150$ GeV, $\frac{\max(m_1, m2)}{m} = 0.92 \to$ repeat

SIGNAL



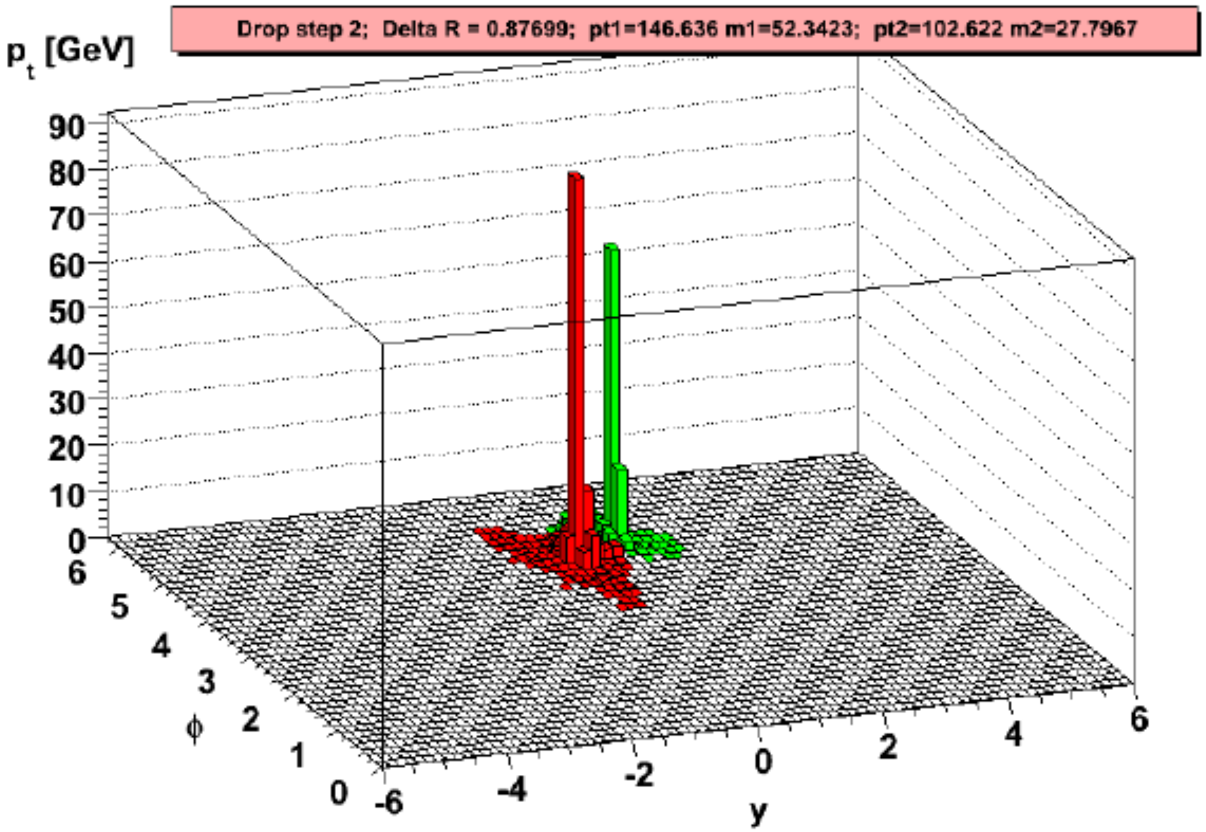
Zbb BACKGROUND



arbitrary norm.

$pp \to ZH \to \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



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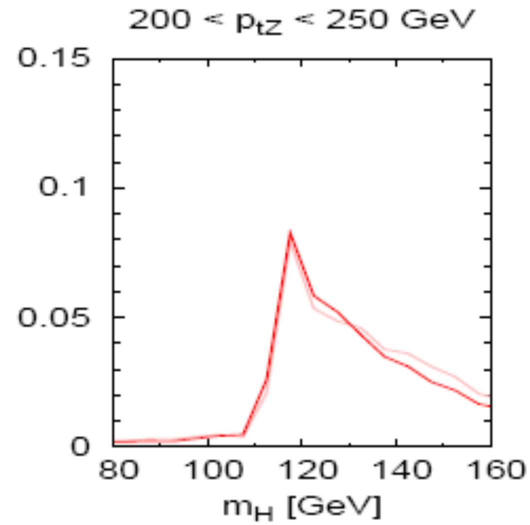
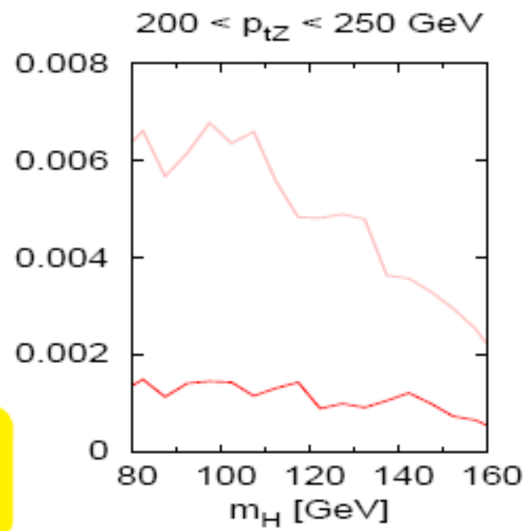


Zbb BACKGROUND

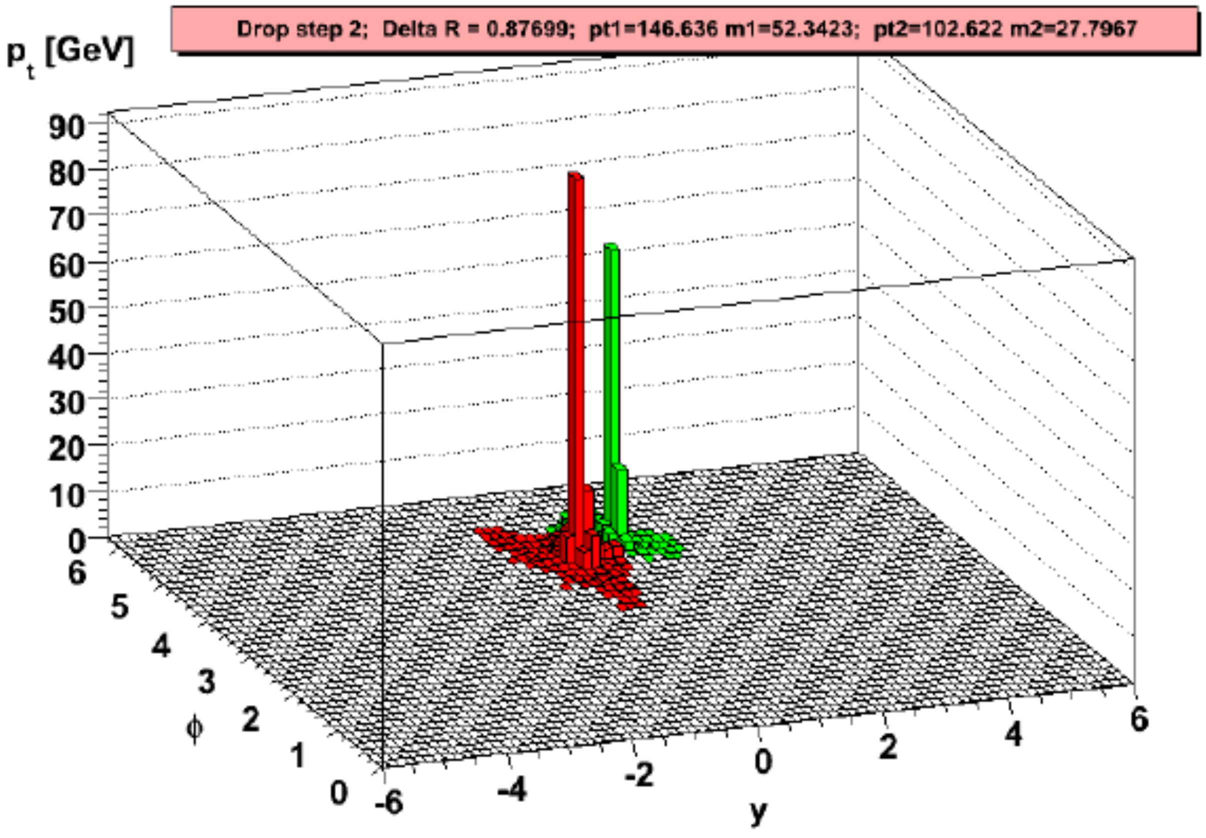


split: $m = 139$ GeV, $\frac{\max(m_1, m2)}{m} = 0.37 \to$ mass drop

arbitrary norm.

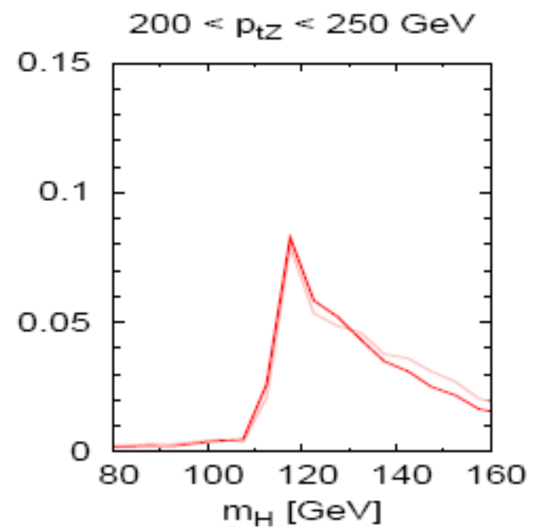
$pp \to ZH \to \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3

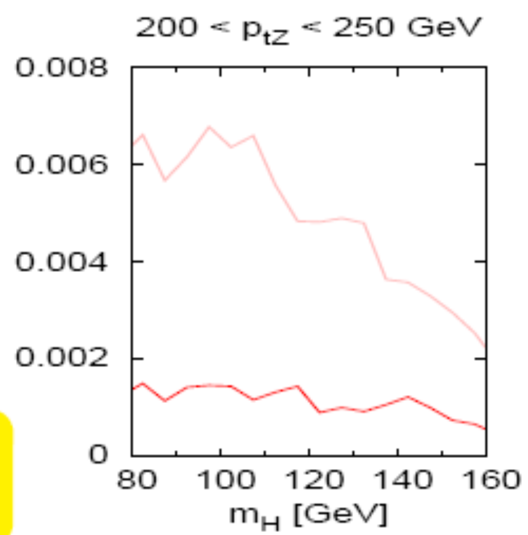


check: $y_{12} \simeq \frac{p_{t2}}{p_{t1}} \simeq 0.7 \to$ OK + 2 b-tags (anti-QCD)

SIGNAL



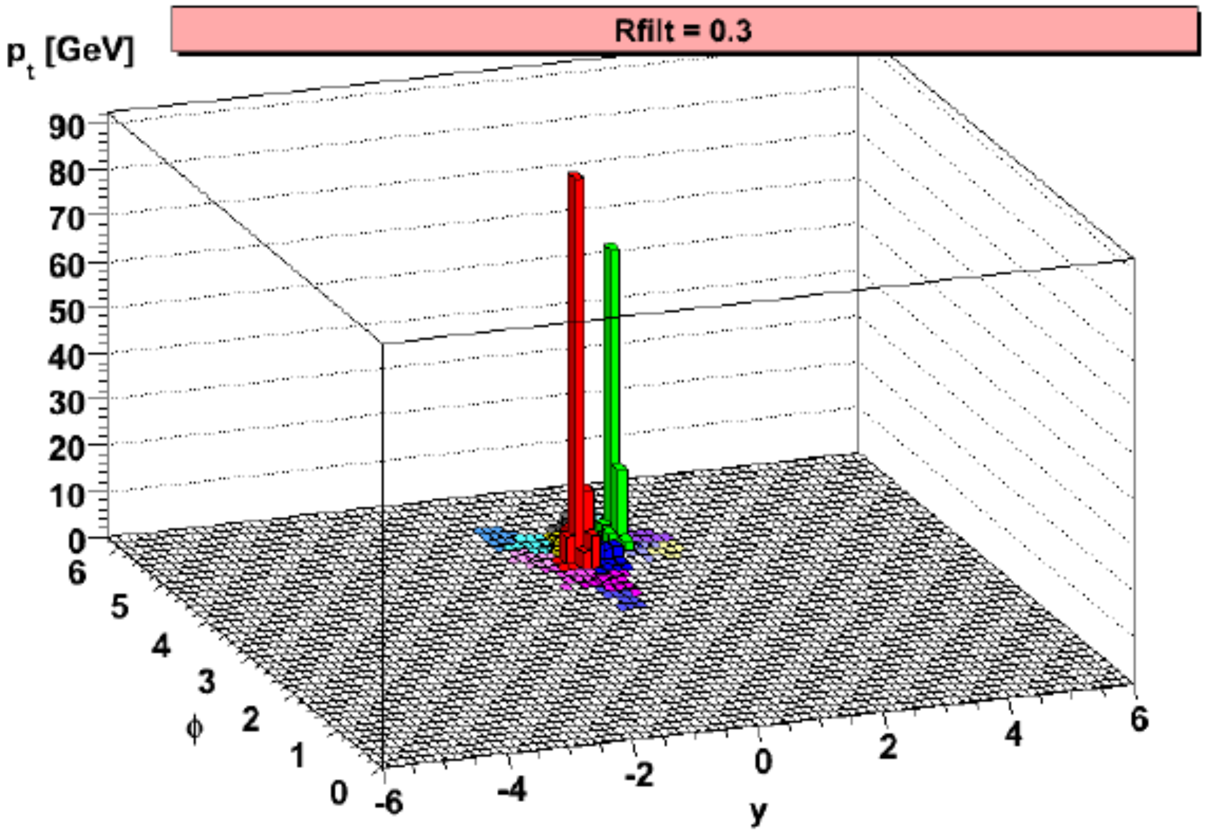
Zbb BACKGROUND



arbitrary norm.

$pp \longrightarrow ZH \longrightarrow \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



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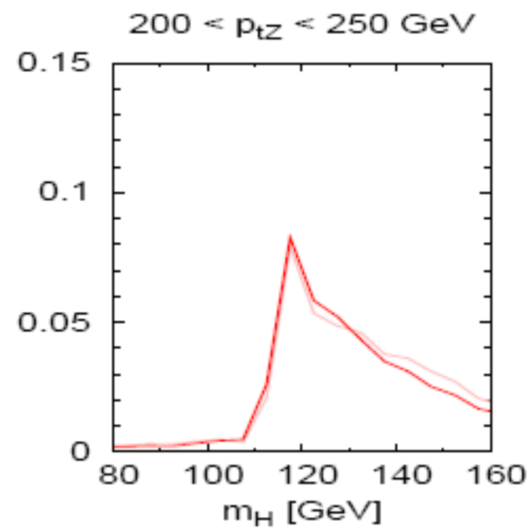
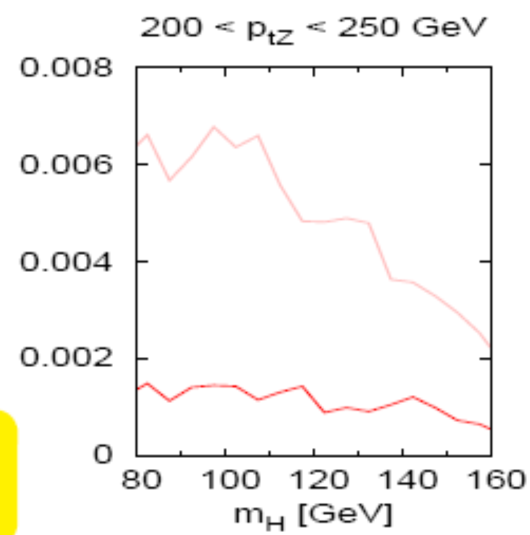


Zbb BACKGROUND

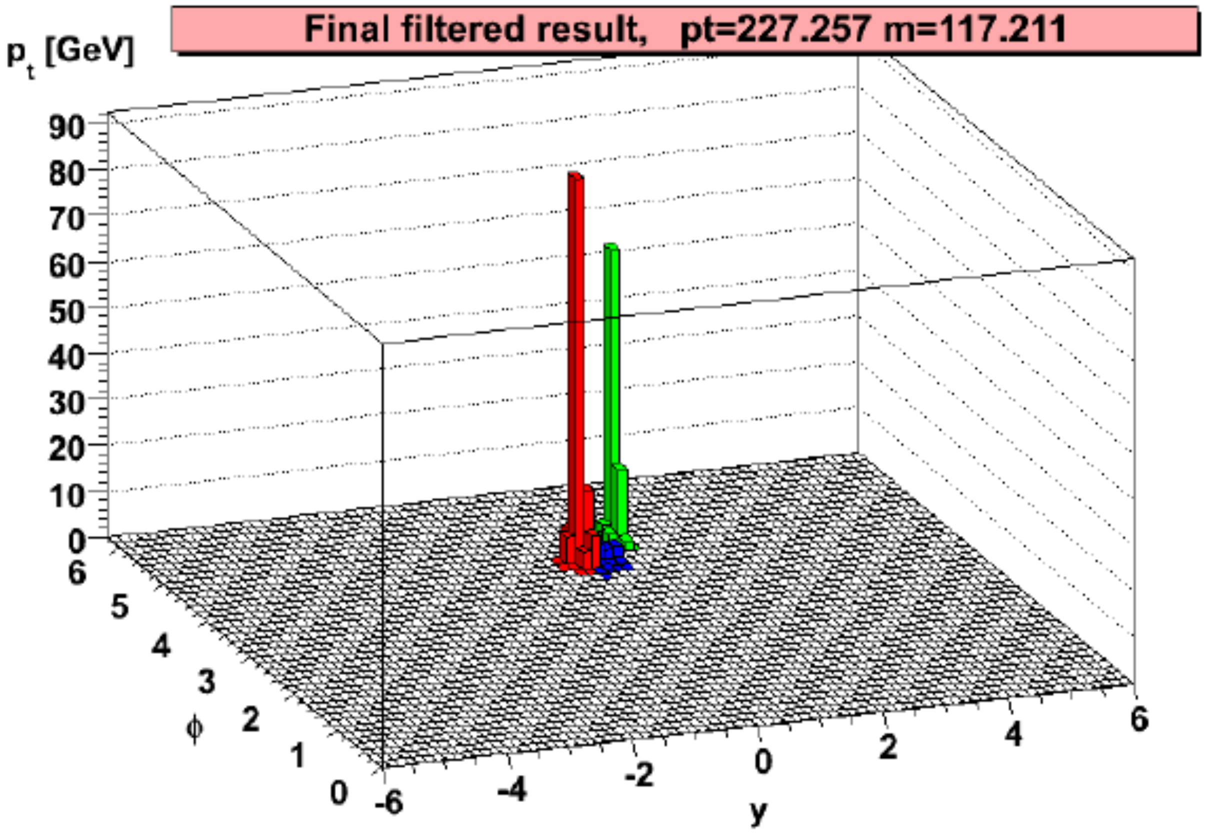


$R_{filt} = 0.3$

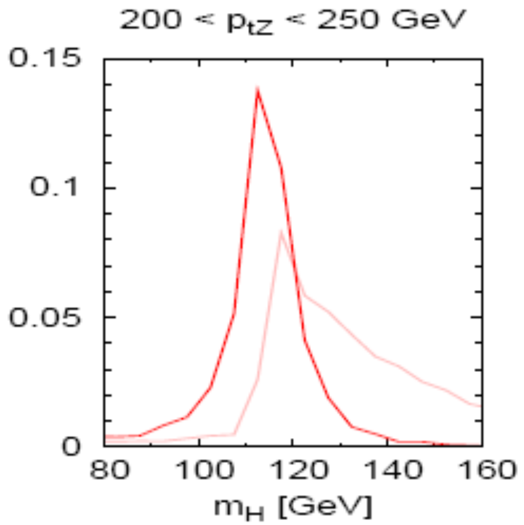
arbitrary norm.

$pp \to ZH \to \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

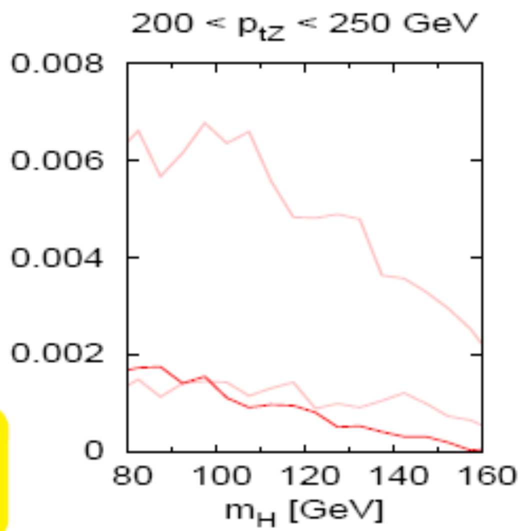
Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



SIGNAL



Zbb BACKGROUND

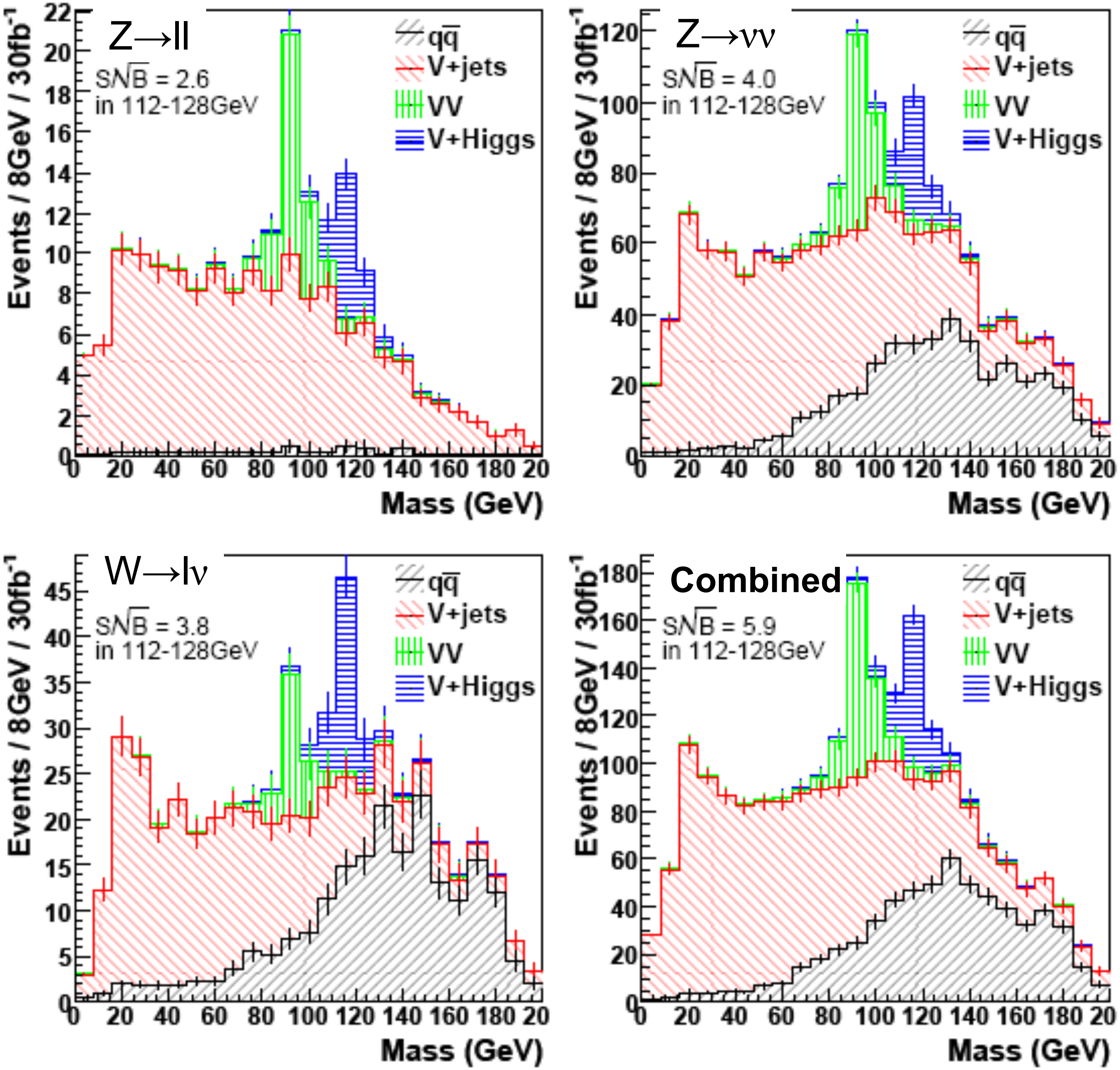


$R_{filt} = 0.3$: take 3 hardest, **$m = 117$ GeV**

arbitrary norm.

A Complete Analysis

- Try to select three types of event
  - ZH with Z→ll
  - ZH with Z→νν (large Missing E_T)
  - WH with W→lν
- Then look for Higgs candidates and plot the mass
  - A jet which breaks down as described before
  - And contains 2 b-tags



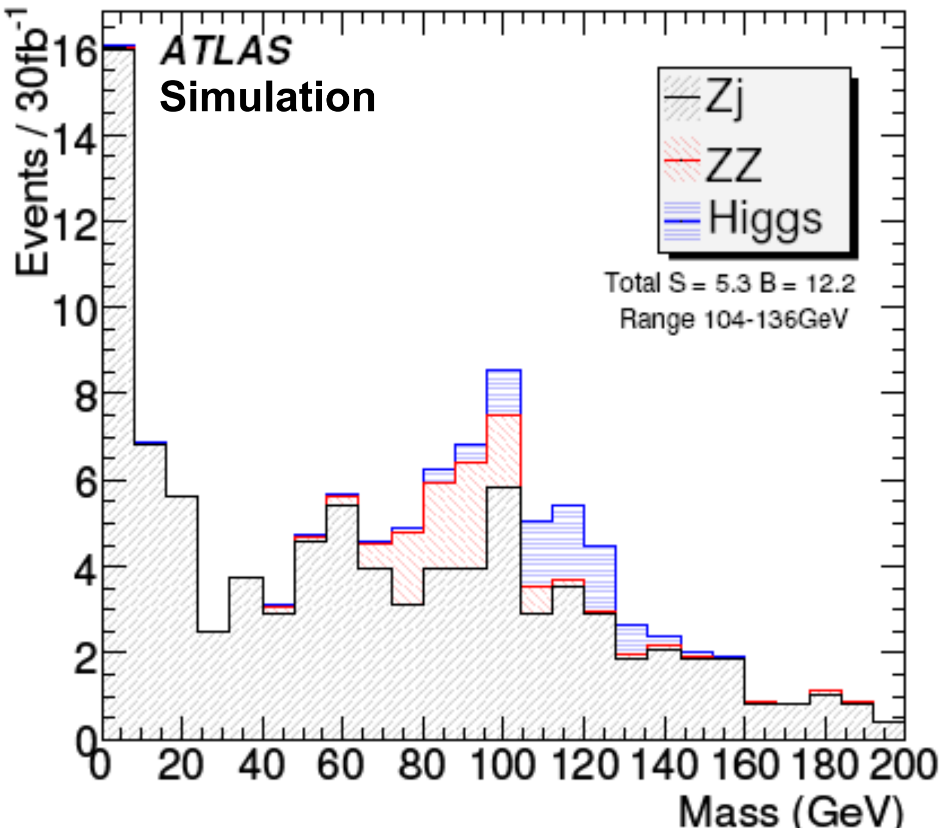
Phys. Rev. Lett. 100, 242001 (2008) J. Butterworth, AD, G. Salam, M. Rubin

Results

- Subsequently done at detector level by ATLAS
- (and CMS although not released publicly)

ZH→llbb

S/√B = 1.5 at $30fb^{-1}$

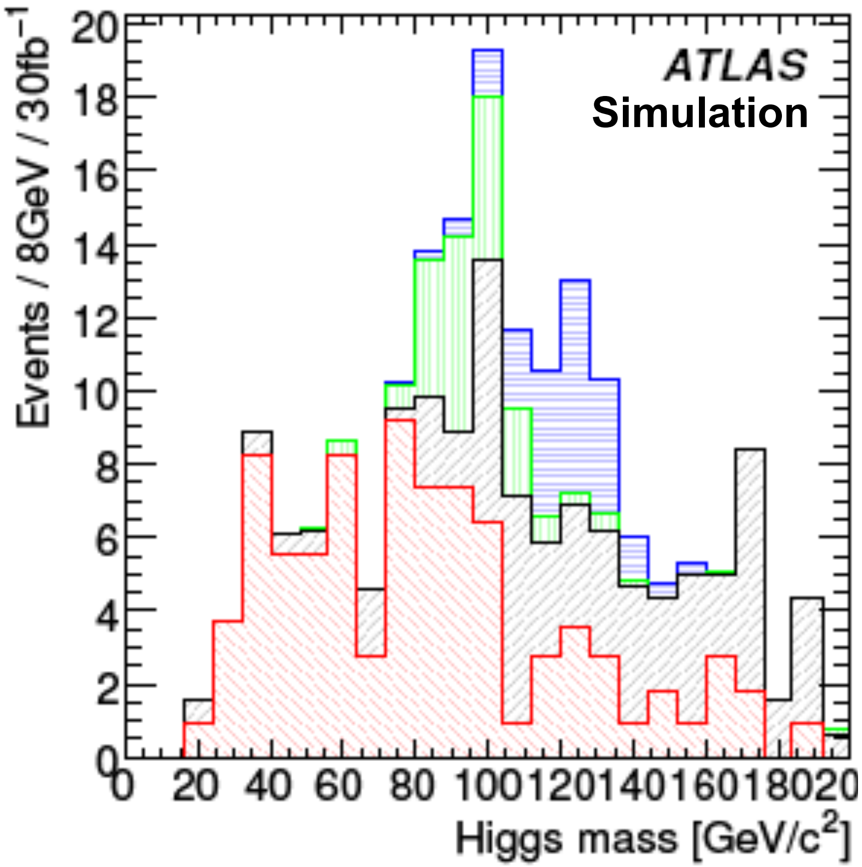


ATLAS-PUB-2009-088

Results

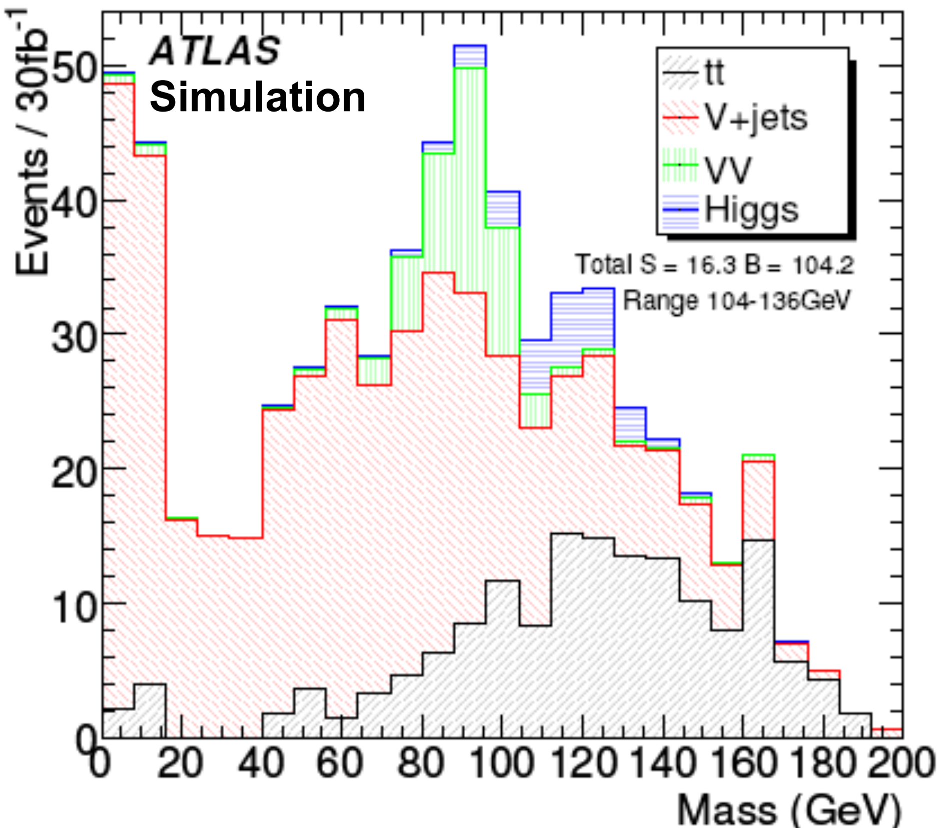
WH→lvbb

S/√B = 3.0 at 30fb^{-1}



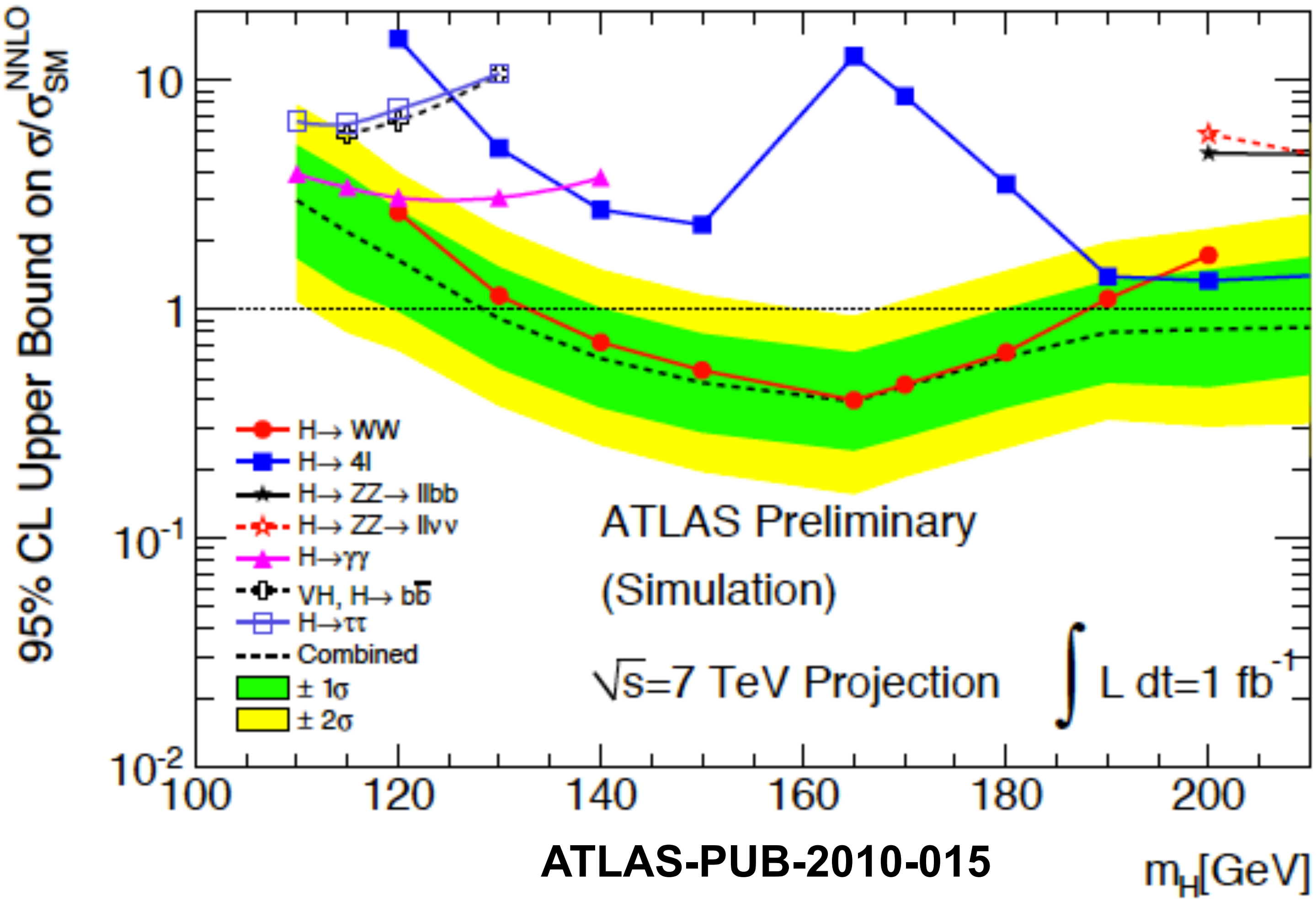
ZH→vvbb

S/√B = 1.6 at 30fb^{-1}



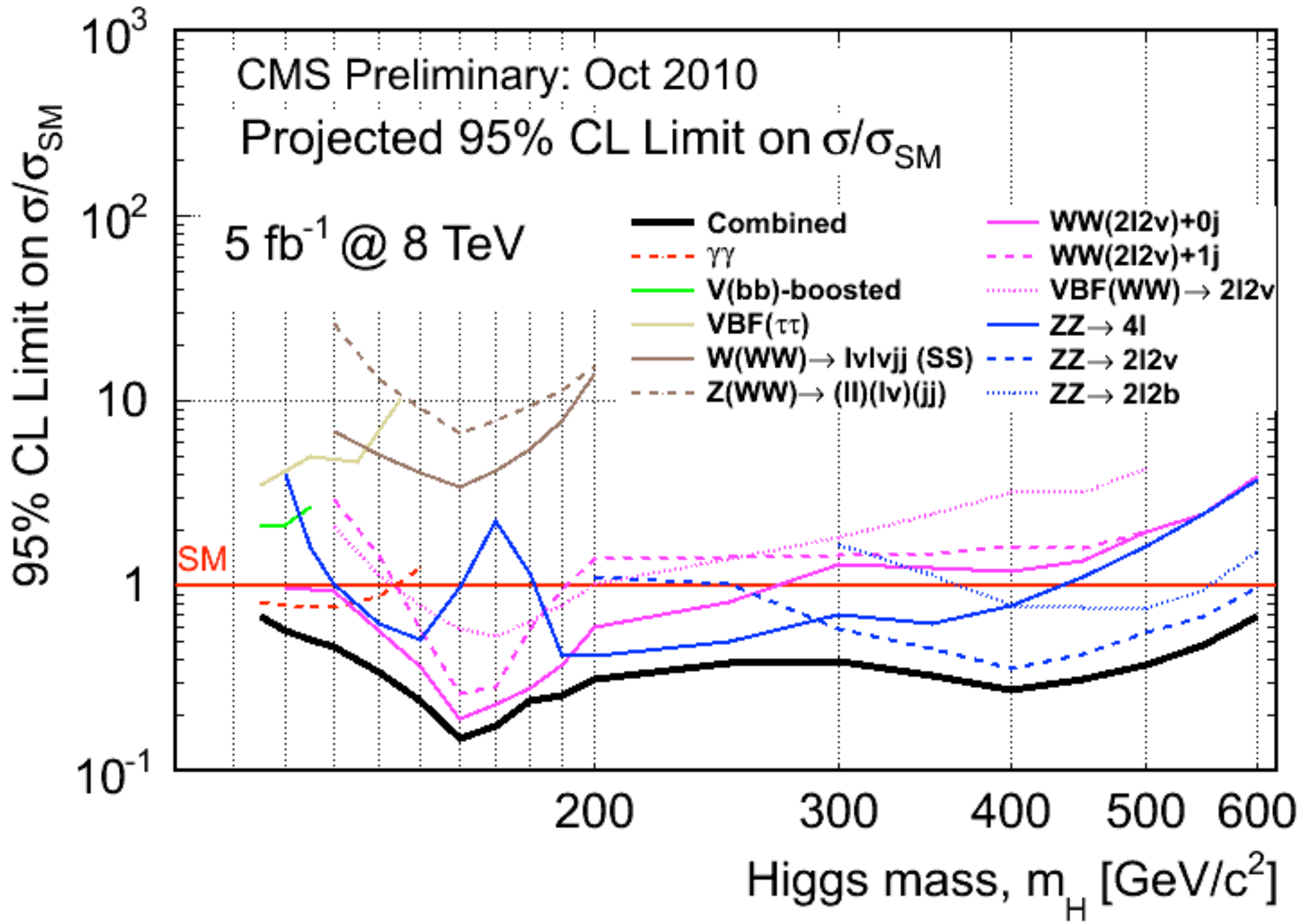
ATLAS-PUB-2009-088

Impact on LHC Higgs Search



ATLAS-PUB-2010-015

Impact on LHC Higgs Search



Summary of Boosted Higgs

- Jet substructure techniques re-enable $H \rightarrow bb$ at the LHC
- A key part of any low mass Higgs discovery
  - Arguably essential even…
- Worth mentioning that also many BSM scenarios predict enhanced bb coupling

An Explosion of Tools

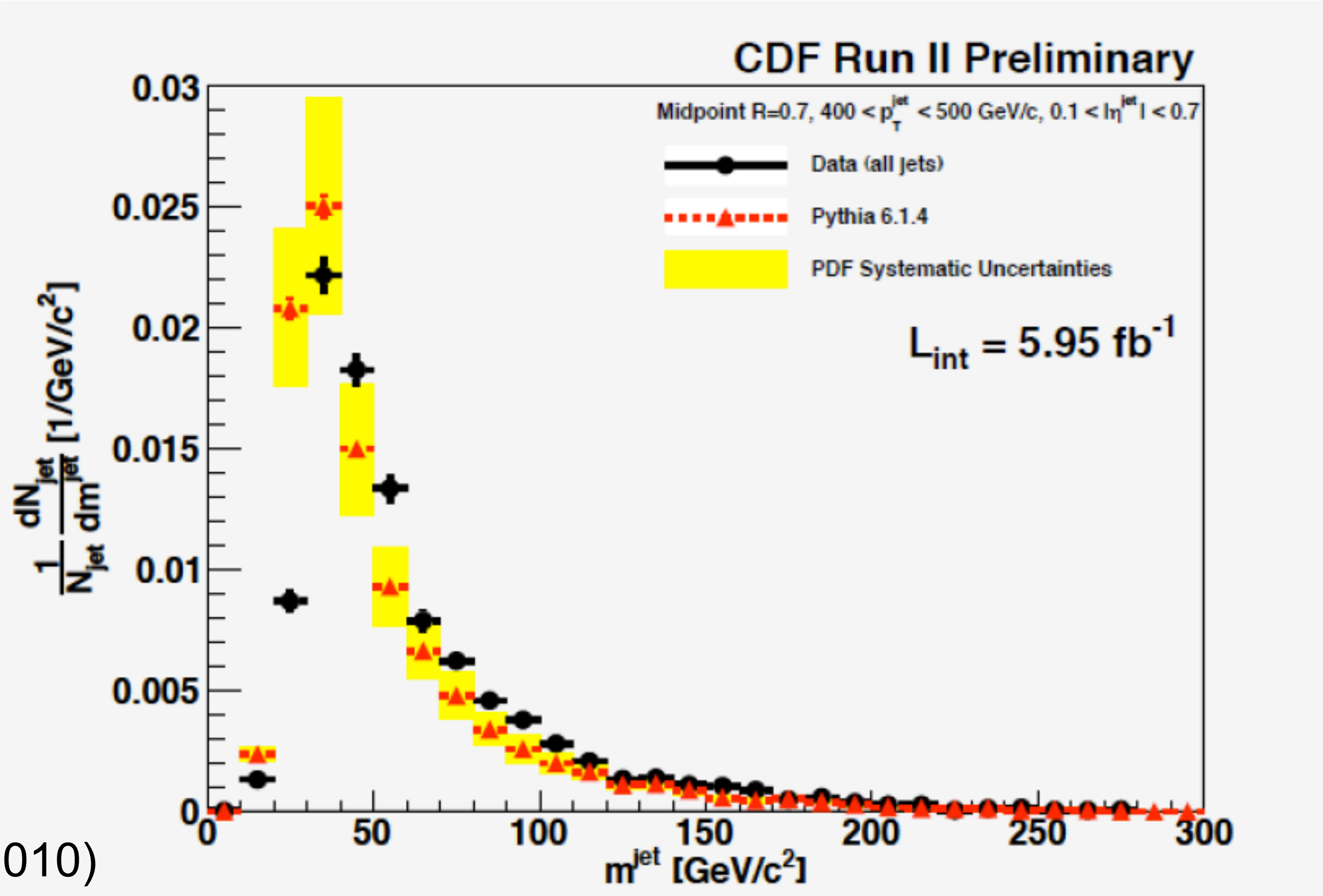
- The Higgs analysis is one of the most mature
- However a profusion of phenomenological papers in the last year or two offer a huge range of techniques:
  - C-A Splitting/Filtering family (heavy object ID)
  - Pruning (alternative to filtering for heavy objects)
  - Trimming (remove UE/pile-up from light jets)
  - Top-taggers (too many to list…) see **ATL-PHYS-PUB-2010-008**
  - Variable-R jet finding
  - Multivariate combinations of various of the above

Good Ideas Meet Real Data

- The progress in understanding how to apply jet substructure techniques for physics is excellent
- Now need to actually use these things
- Many unsolved problems in calibration/understanding
- Soluble but far from trivial
  - Lots of work going on now on ATLAS at least…

Good Ideas Meet Real Data

- First measurement of jet mass made by CDF recently



CDF Note 10199 (2010)

What to Expect from Jet Substructure in 2011

- Focus moves to experimental aspects
- ATLAS/CMS experiments publish world best measurements of jet mass
- World first measurements of jet substructure quantities
- Observation of boosted SM particles, W, Z and top
- Integration into more physics analyses
- Maybe a surprise or two…

Conclusions

- Jets are not fixed objects or smeared partons
- Jet algorithms are a great tool for viewing a collision
- But jets can contain complicated physics like the decay of a heavy particle which produces interesting structure
- This can be exploited in an analysis
- Huge impact on LHC Higgs programme
- Expect to see a lot more jet substructure in more places in the next few years