



ATLAS prospects for boosted objects.

On behalf of the ATLAS collaboration

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Outline

- The ATLAS detector
- Boost?
- Simulation studies of physics scenarios
 - jets in SUSY decays
 - hadronic decays of W/Z
 - $H \rightarrow bb$
 - top quarks
- A quick look at first LHC data
- From simulation to a boosted data object
- Summary and outlook

The ATLAS detector at the LHC

- General-purpose detector at the LHC
- Prepared for high p_T objects:
 - The inner detector has a high granularity for pattern recognition and is designed for excellent momentum resolution, primary and secondary vertex measurement.
 - The calorimeters cover $|\eta| < 4.9$.
EM calo thickness $22\text{--}24 X_0$,
 11λ in thickness at $\eta = 0$.
 - Calibration to the hadronic level of calorimeter energy clusters (*local calibration*) allows jet substructure studies

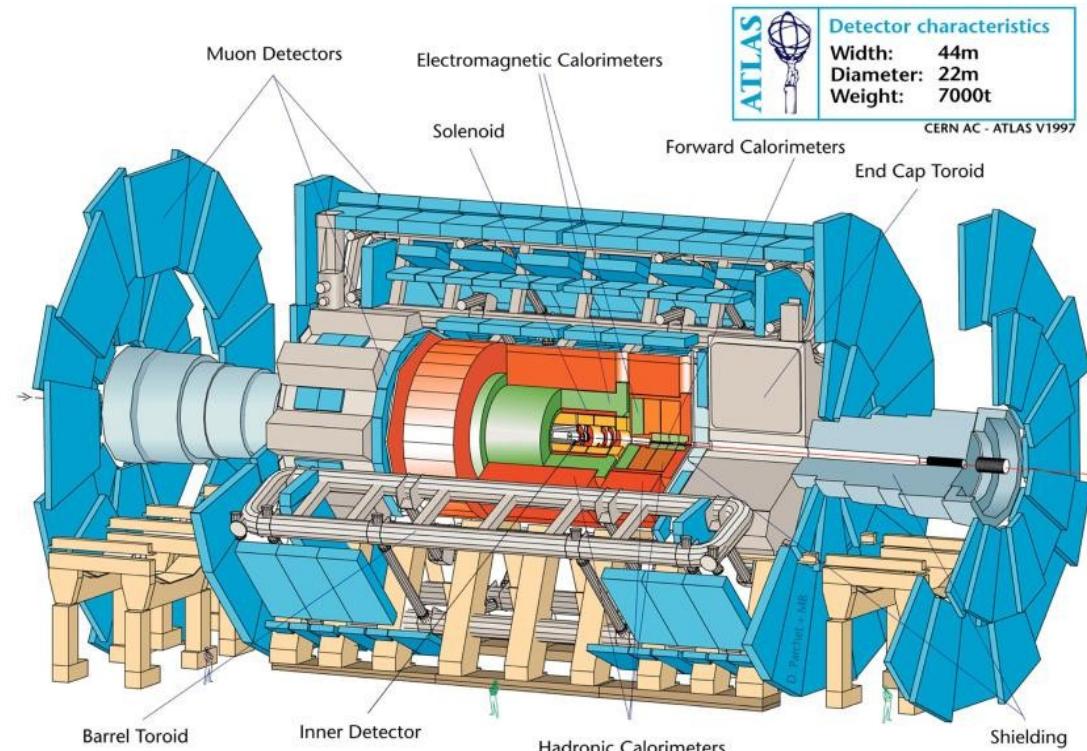
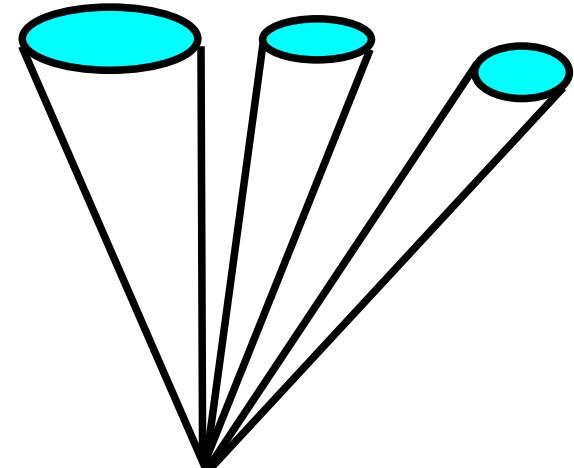
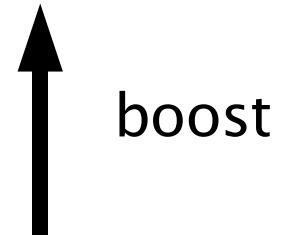
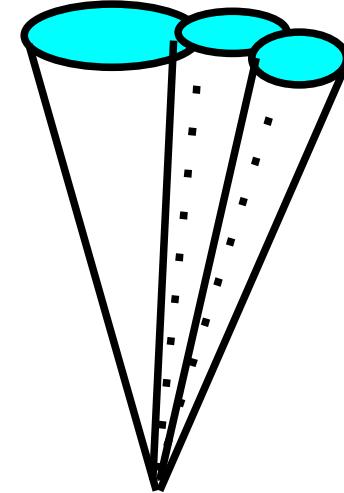


Image: CERN

Boost?

- **Kinematically:** a particle is boosted if it is relativistic
- **Experimentally:** we are concerned with boosted particles when the boost cause the standard algorithms to fail due to merged decay products, displaced vertices, etc.
- This talk follows the **experimental** approach: little about underlying models and more about reconstructing the actual objects



Jet searches

- The challenge: when heavy and/or boosted objects decay hadronically, the decay products may overlap and form a single, merged jet
Investigated cases:
 - SUSY scenarios involving hadronic final states
 - $W \rightarrow q q'$, $Z \rightarrow q \bar{q}$
 - $H \rightarrow b \bar{b}$
 - top quarks
- Common features: the jet substructure is investigated in order to suppress light QCD background
- The k_T , anti- k_T or Cambridge/Aachen jet algorithms used
- The FastJet package for accessing algorithms
Phys.Lett.B641:57–61,2006

Jet searches: the k_T algorithm

Start with a list of calorimeter components (clusters, towers...)

1) For each component, define $d_i = p_{T,i}^2$

For each pair (i, j) define $d_{ij} = \min(p_{T,i}^2, p_{T,j}^2) \Delta R_{ij}^2 / R^2$

$$\text{where } \Delta R_{ij}^2 = (\phi_i - \phi_j)^2 + (\eta_i - \eta_j)^2$$

2) Find $d_{min} = \text{minimum of all } d_i, d_{ij}$

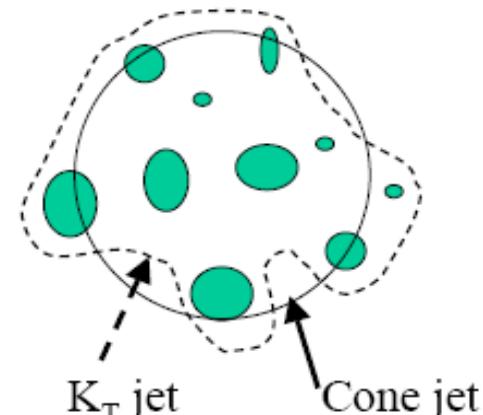
3) If d_{min} is a d_{ij} , merge clusters to a new cluster d_n

If d_{min} is a d_i , the object is a jet. Remove component i from list.

Repeat 1–3 until all components are in jets.

Note: – The last jets to form are the most energetic.

- The last and second-to-last d_{ij} values before forming a full jet carry information about the jet substructure.
- The algorithm can be used “backwards” on any jet to obtain substructure information.



Boosted subjet searches in SUSY scenarios

(ATL-PHYS-PUB-2009-076)

Model: SPS1a with R -parity violating coupling $\lambda''_{112} \neq 0$

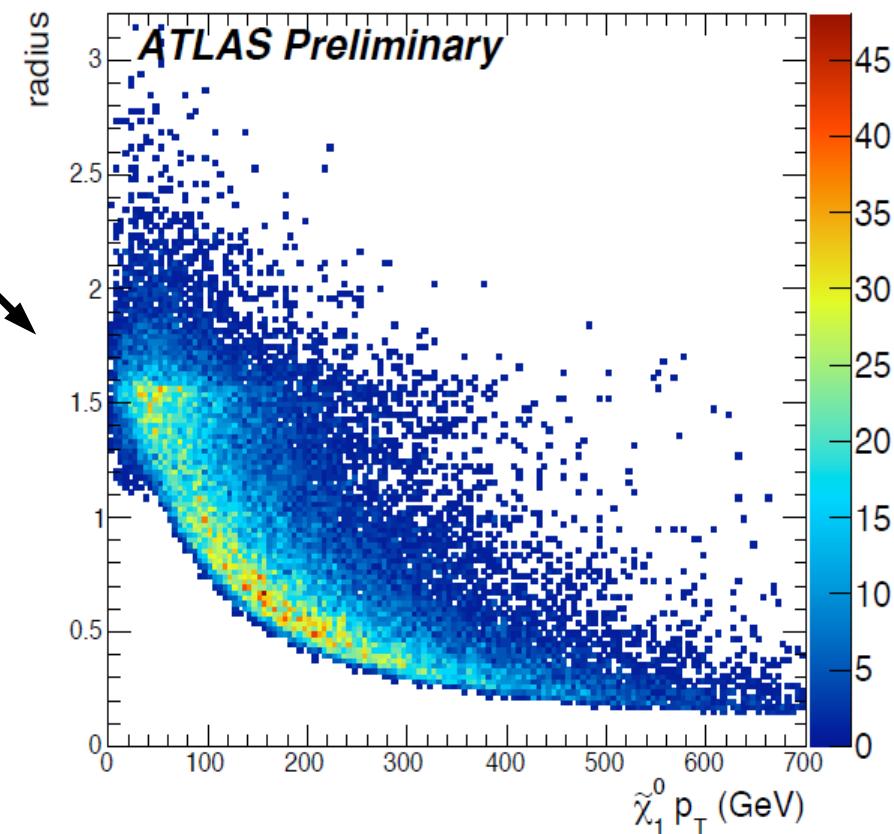
added to the Lagrangian =>

baryon number violating neutralino decay, $\tilde{\chi}_1^0 \rightarrow qqq$

$m_{\chi} = 96.1$ GeV and $\sigma_{LO} = 17.2$ pb

at $\sqrt{s} = 14$ TeV.

- 3 quarks => 3 collimated jets, merging when the $\tilde{\chi}^0 p_T$ increases
 $radius$: a measure of the ΔR size of the 3-jet system
- Jets reconstructed with the k_T algorithm, $R = 0.7$
=> radius $< 0.7 \approx$ merged jet

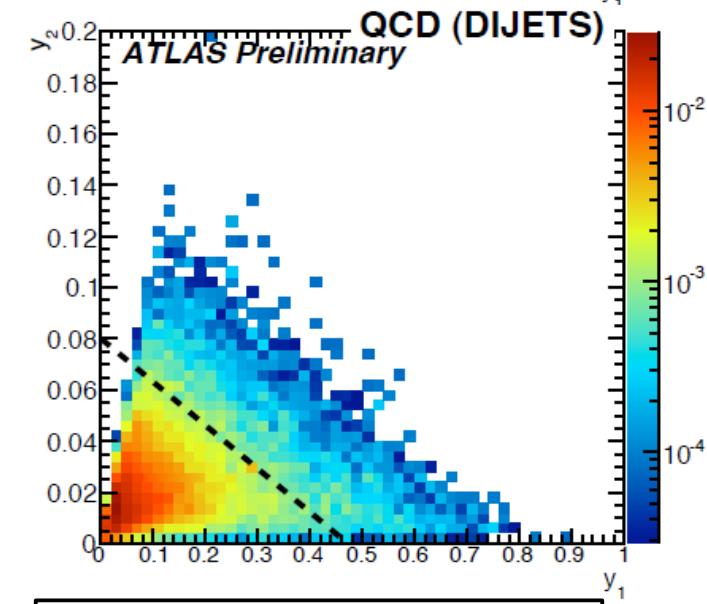
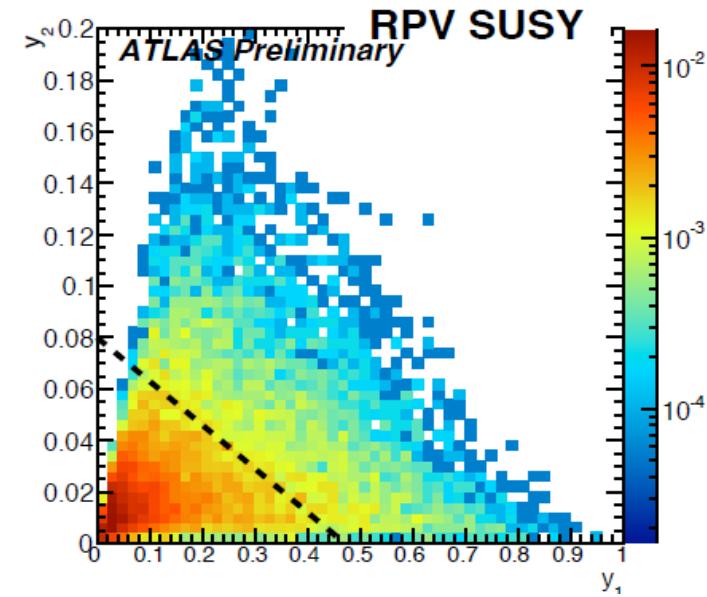


Boosted subjet searches in SUSY scenarios (2)

(ATL-PHYS-PUB-2009-076)

- Signal: SUSY event
 - 2 decay chains each ending with a neutralino (lightest SUSY particle)
 - Neutralinos decay hadronically, $\tilde{\chi}_1^0 \rightarrow qqq$ (2 massive jets expected)
 - The decay chain contain additional jets
- Event selection:
 - ≥ 4 jets, $|\eta| < 2.5$ for the 4 leading jets
 - 2 jets with $p_T > 275$ GeV
 - $y_2 > -0.17 y_1 + 0.08$ for both these jets^{*}
 - 2 (other) jets with $p_T > 135$ GeV

^{*}) Define y_1 (y_2) as $y_n = d_{ij} / m$ where d_{ij} is the k_T splitting level from the last (second to last) merging, and m is the jet mass.



y_2 vs y_1 , SUSY and light jets

Boosted subjet searches in SUSY scenarios (3)

(ATL-PHYS-PUB-2009-076)

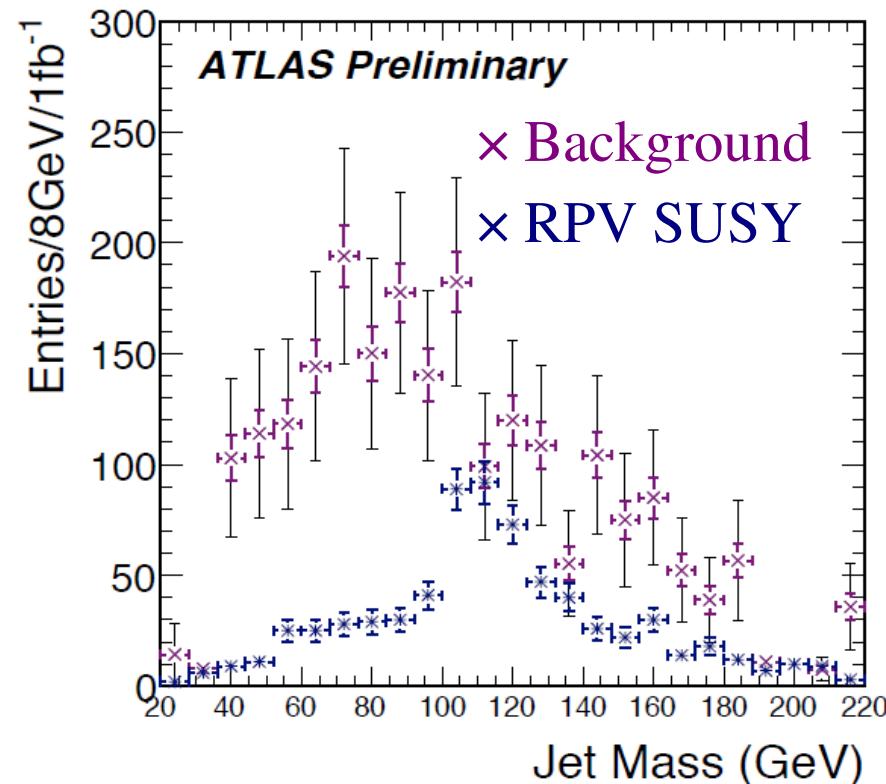
- Accumulative offline cut flow (events per 1 fb^{-1})

	≥ 4 jets, $ \eta < 2.5$	2 jets $p_T > 275 \text{ GeV}$	2 jets $y_2 > -0.17 y_1 + 0.08$	2 (other) jets with $p_T > 135 \text{ GeV}$
SUSY	14577	5849	792	347
ttbar	2.3×10^5	2000	200	1
dijets	3.2×10^9	1.1×10^6	1.8×10^4	1100

- Triggers investigated: various jet triggers, multijet triggers and total jet energy triggers. High ($> 99\%$) efficiency after event selection.

- Result:** light jets background significantly reduced.

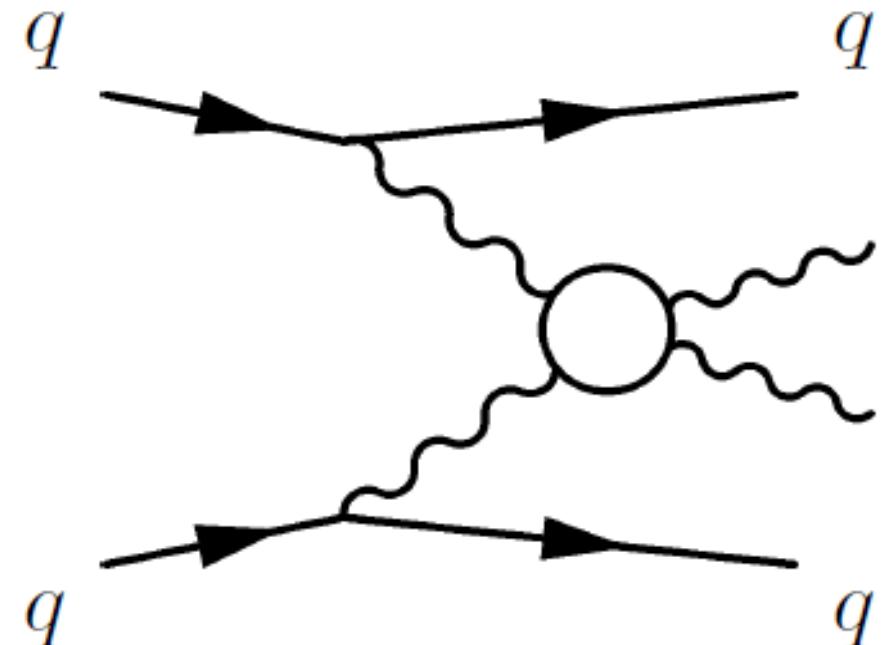
This reconstruction method works for all pair production mechanisms of hadronic resonances (2 leading jets) with a decay chain (following jets)



Vector boson scattering

(CERN-OPEN-2008-020)

- In the absence of a light Higgs, several models exist that predict vector boson resonances.
- Here: Chiral Lagrangian model, in which a scalar or a vector resonance decays to two vector bosons
- Reconstruction of semileptonic decays
 - $V \rightarrow ll$. Standard reconstruction
 - $V \rightarrow qq$. Quarks are boosted from V mass
=> can be merged



Vector boson scattering (2)

(CERN-OPEN-2008-020)

Finding the hadronic vector boson:

- k_T algorithm, $R=0.6$ on locally calibrated calorimeter clusters
- If m_{jet} is within the right mass window ($\approx m_V$) => **single jet**
- otherwise, search for **dijet pairs**

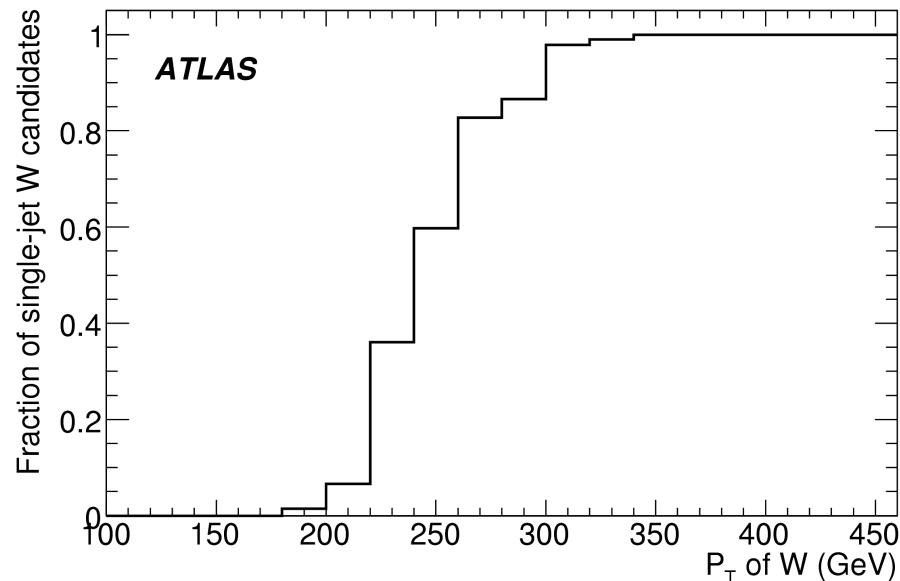
- Single jet case: consider the y scale from the k_T merging in the last step. Require $p_T > 300$ GeV.

Define $Y = E_T^{jet} \cdot \sqrt{y}$

- $Y \approx O(m_V)$ if the jet comes from a boosted vector boson, and much smaller than E_T for light jets.
- Cut on $30 < Y < 100$ GeV.

- Dijet case: define y from the p_T of the softest jet relative the harder.
- Require $0.1 < \sqrt{y} < 0.45$

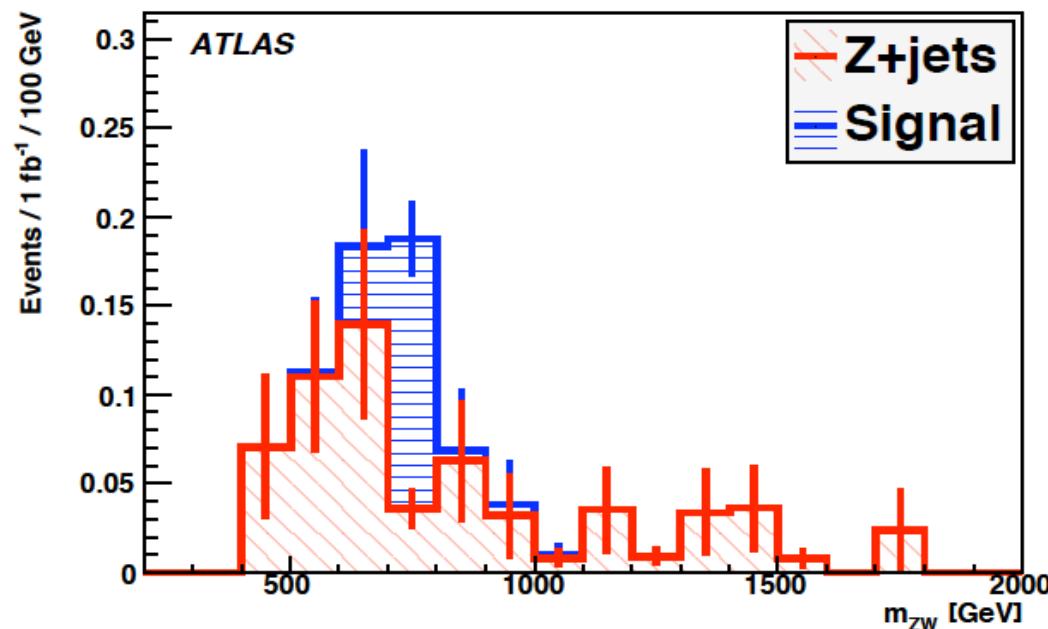
*Fraction of single-jet W candidates
as a function of W p_T*



Vector boson scattering (3)

(CERN-OPEN-2008-020)

- Other cut considerations:
 - Select 2 forward ‘tag’ jets. High η jets, characteristic to VBS
 - Central jet veto. No colour exchange between the protons in VBS => suppression of QCD radiation is expected.
 - Top veto. ttbar production is a major background (except for $Z \rightarrow$ leptons). Top rejection through mass veto.
- Results: at 14 TeV, about 60 fb^{-1} would be required for a discovery of a semi-leptonically decaying 800 GeV WZ resonance with cross section 0.65 fb.



Higgs to b quarks

(ATL-PHYS-PUB-2009-088)

If $m_H = O(10^2 \text{ GeV})$, $H \rightarrow b\bar{b}$ dominant

Consider $pp \rightarrow HV$, $V \rightarrow \text{leptons}$

The b quarks merge into one jet.

Use leptons to tag the event.

Cambridge/Aachen jet algorithm (C/A).

Similar to k_T but ordering in angles, not p_T .

The clustering stops when all jets are separated by a certain angle R

- Select jets with $p_T > 200 \text{ GeV}$, $|\eta| < 2.5$.

For each jet j :

1) undo the last clustering step =>

two subjets j_1 and j_2 , $m_{j_1} > m_{j_2}$

2) Significant mass drop? ($m_{j_1} < \mu m_j$?) }
 No asymmetric split? ($y > y_{cut}$?) } $\Rightarrow j$ is composite

Else, start over from 1), with j_1 instead.

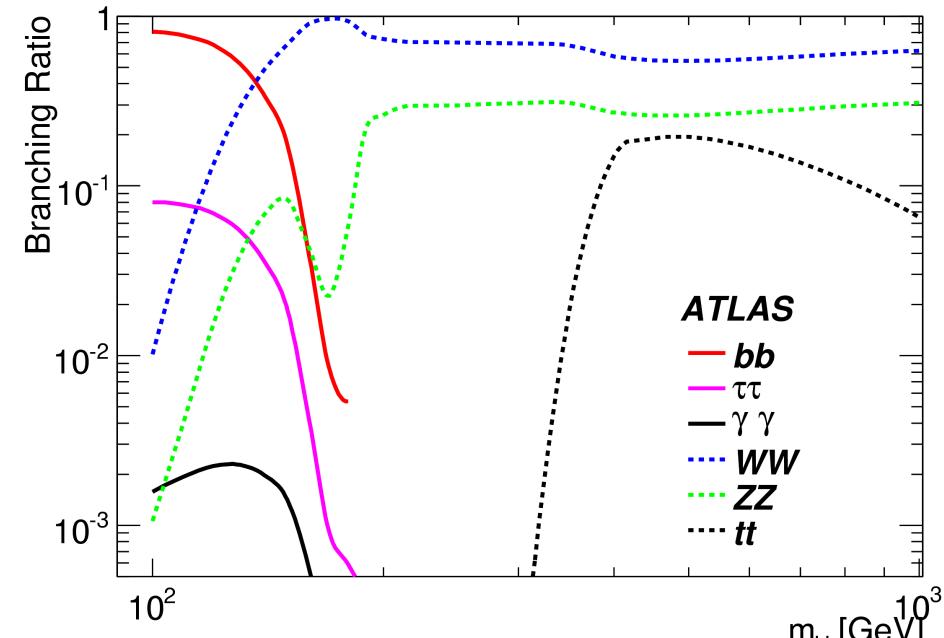


Figure from CERN-OPEN-2008-020

Parameters:

$$R = 1.2$$

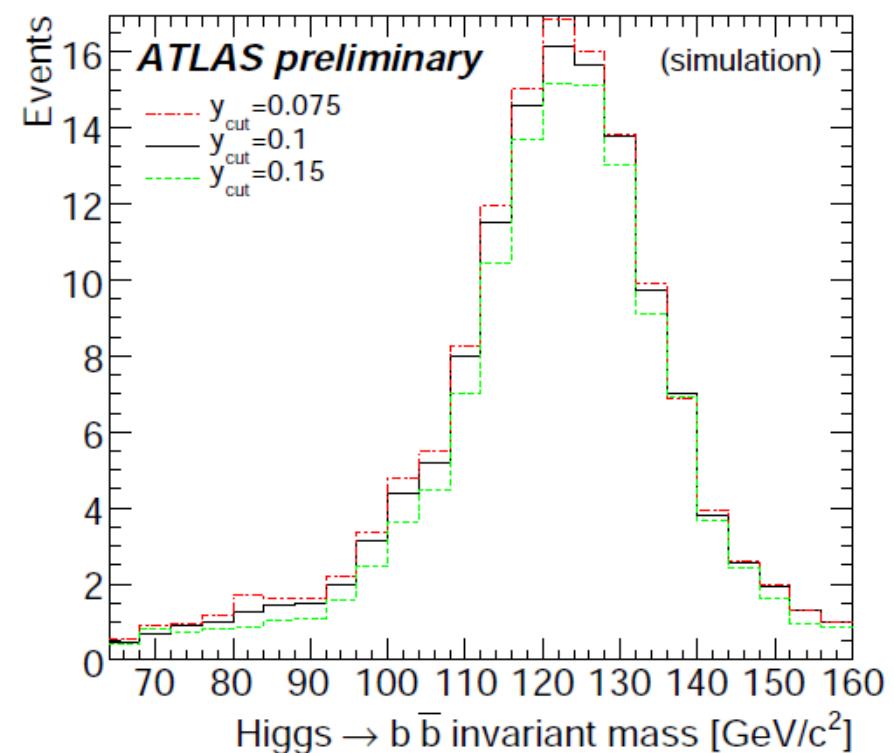
$$\mu = 1/\sqrt{3}$$

$$y_{cut} = 0.1$$

Higgs to b quarks (2)

(ATL-PHYS-PUB-2009-088)

- If j is composite (bb), $\Delta R(j_1, j_2) = R_{bb}$ is the distance between the b quarks
- Filter the jet by rerunning C/A, now with $R_{filt} < R_{bb}$
($R_{filt} = \min(0.3, R_{bb}/2)$)
- Take the hardest three subjets
 j is a Higgs candidate
if 2 hardest subjets
are b -tagged
- Require $p_T^{\text{H cand}} > 200 \text{ GeV}$
(after jet filtering)



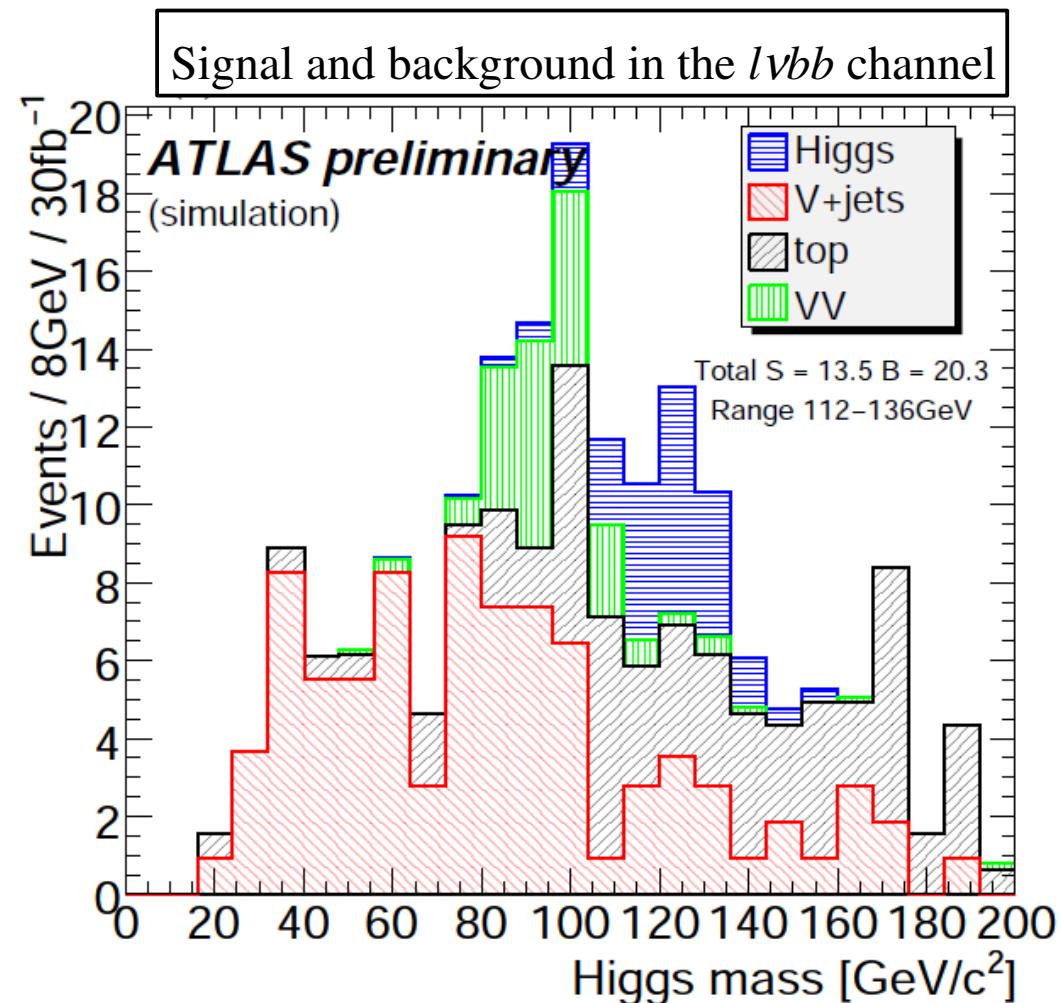
Higgs to b quarks (3)

(ATL-PHYS-PUB-2009-088)

- Choose events with leptonic V :
 - $W \rightarrow l + \nu$ (**$lvbb$ channel**).
 $E_T^{\text{miss}} > 30 \text{ GeV}$,
 e or μ $p_T > 30 \text{ GeV}$, $p_T^{l+\nu} > p_T^{\text{min}}$
 - $Z \rightarrow ll$ (**$lvbb$ channel**).
 ee or $\mu\mu$ pair,
 $80 < m_{ll} < 100 \text{ GeV}$, $p_T^{ll} > p_T^{\text{min}}$
 - $Z \rightarrow \nu\nu$, $W \rightarrow l + \nu$ with lost l
(**$lvbb$ channel**).
 $E_T^{\text{miss}} > p_T^{\text{min}}$
- Combine channels

Result: $S/\sqrt{B}=3.7$

when combining channels for $\mathcal{L}=30 \text{ fb}^{-1}$, $\sqrt{s} = 14 \text{ TeV}$
(LO only, no pile-up effects considered)



Top resonances in the lepton+jets channel

(ATL-PHYS-PUB-2009-081)

Reconstruction of heavy top pair resonances in the semileptonic channel, when standard top reconstruction fails

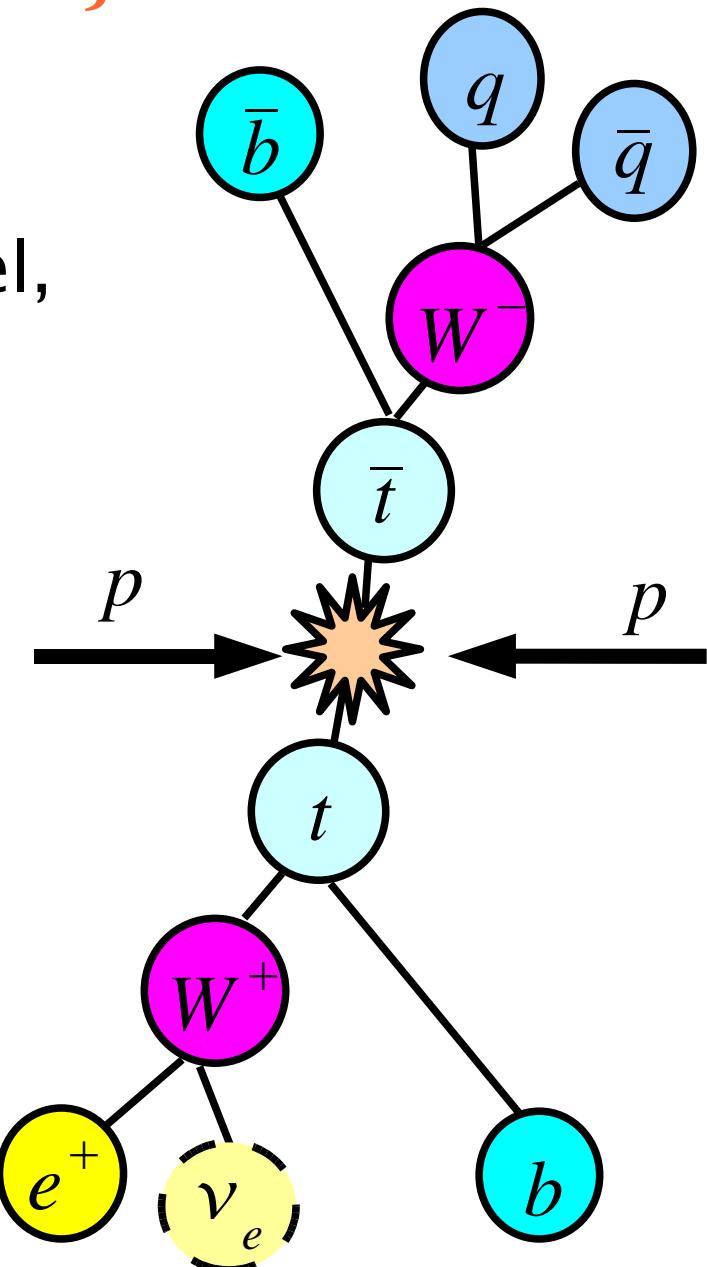
Z' resonance, $M=2, 3$ TeV

SM-like, narrow, spin 1, colour singlet

- Leptonic top reconstruction
 - merged lepton / jet from b quark
- Hadronic top reconstruction
 - a jet with substructure

Selection by cutting on variables that explore these properties.

(See also Thaler et al. JHEP 0807:092, 2008)



Top resonances in the lepton+jets channel (2)

(ATL-PHYS-PUB-2009-081)

Leptonic top

k_T jet algorithm, $R = 0.6$

A hard jet within a cone 0.6 centred on the lepton

Variables

- $x_l = 1 - m_b^2 / m_{(b+l)}^2$ ($l = \mu, e$)
- $y_l = p_{l\perp b} \times \Delta R(l, b)$

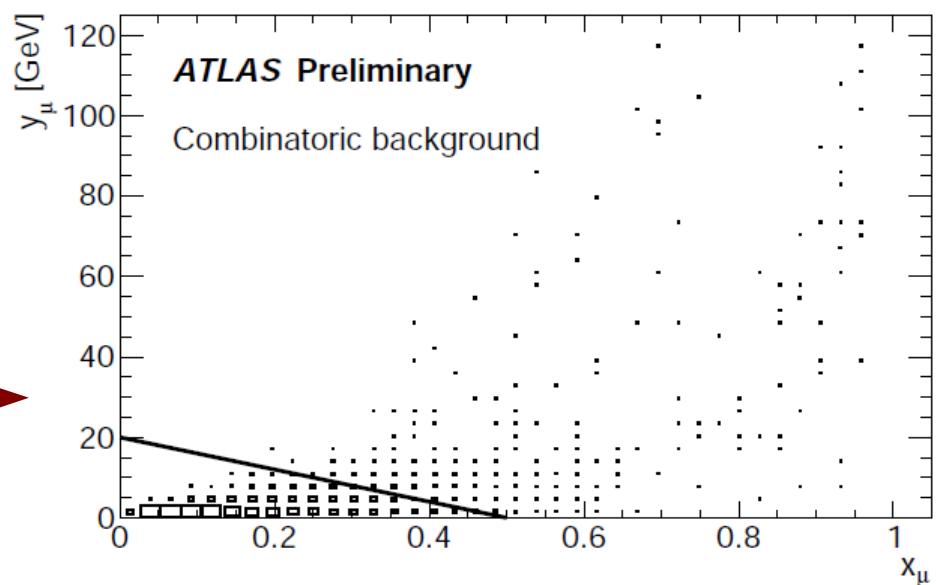
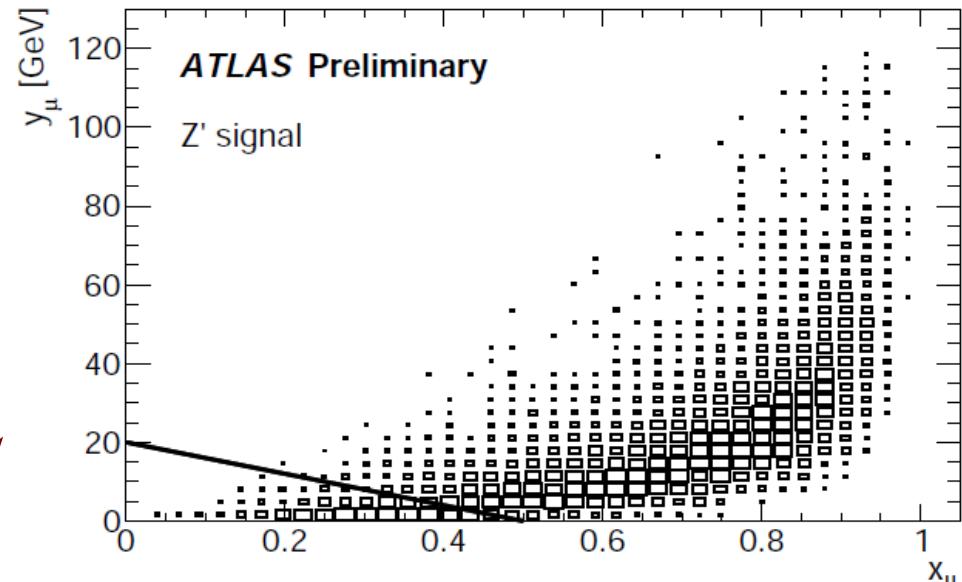
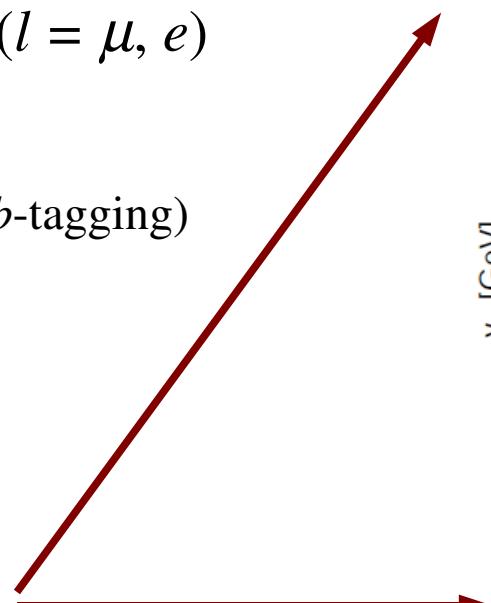
b : b -jet without lepton (no b -tagging)

For electrons:

- $y_e' = p_{e\perp j} \times \Delta R(e, j)$
- j : b -jet with lepton inside

Cuts

- $y_l > (-40x_l + 20) \text{ GeV}$
- $y_e' > 1$ (electrons only)



Top resonances in the lepton+jets channel (3)

(ATL-PHYS-PUB-2009-081)

Hadronic top

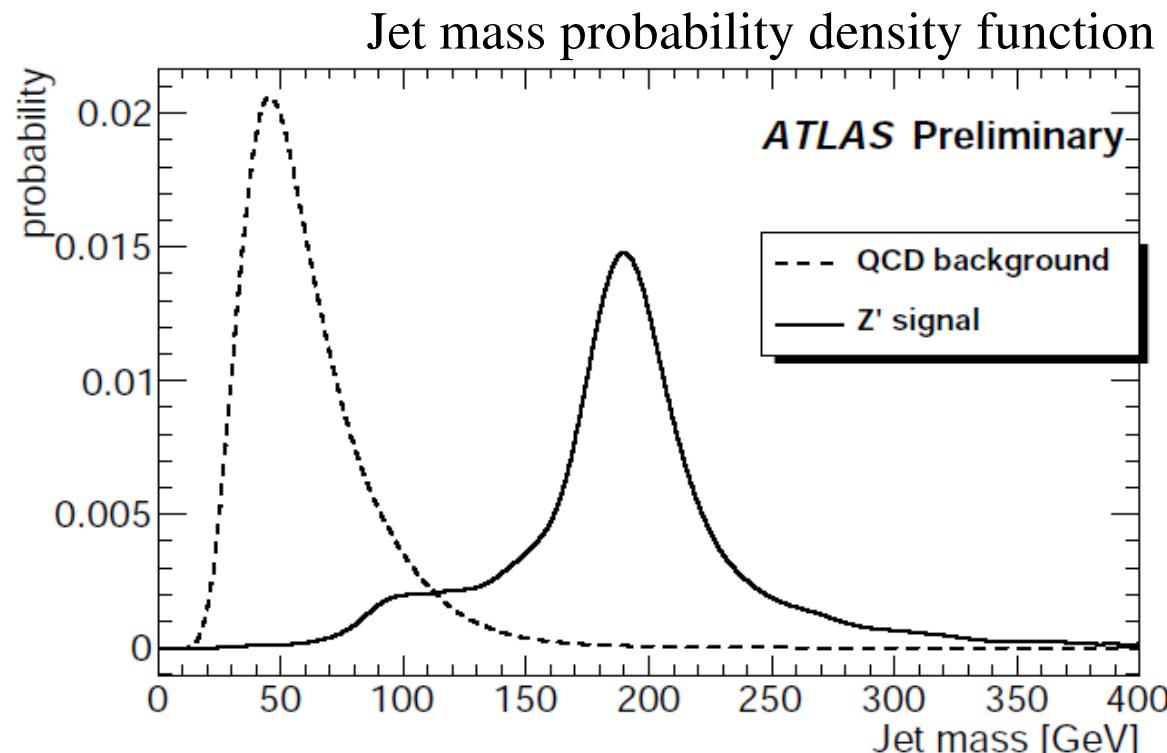
k_T jet algorithm, $R = 0.6$.

Search for a jet with
substructure

Variables

- Jet mass – the mass of the hadronic top jet
- k_T splitting scales into 2, 3 and 4 jets

Cut on a likelihood ratio (S/B) from pdf's of these variables.



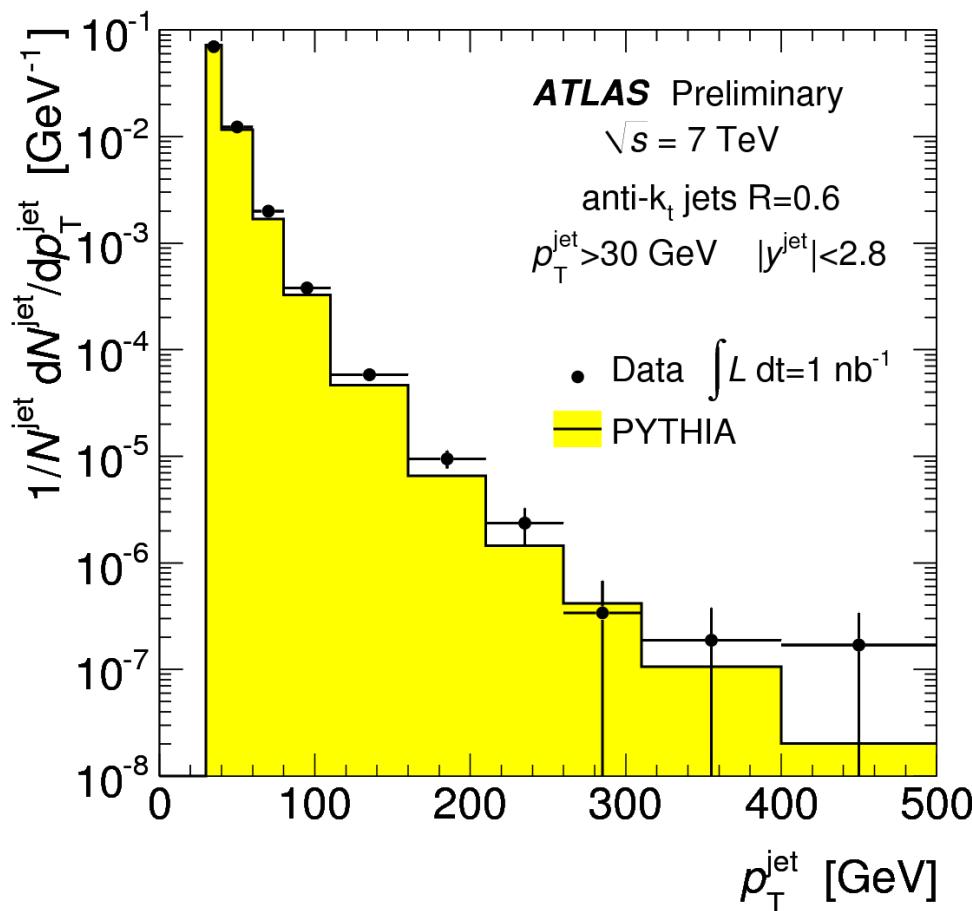
Result

in the absence of a signal, for $\sqrt{s} = 14$ TeV and 1 fb^{-1} of data, the limits on a Z' resonance could be set to
 $0.55 \text{ pb } (m_{Z'} = 2 \text{ TeV})$
 $0.16 \text{ pb } (m_{Z'} = 3 \text{ TeV})$

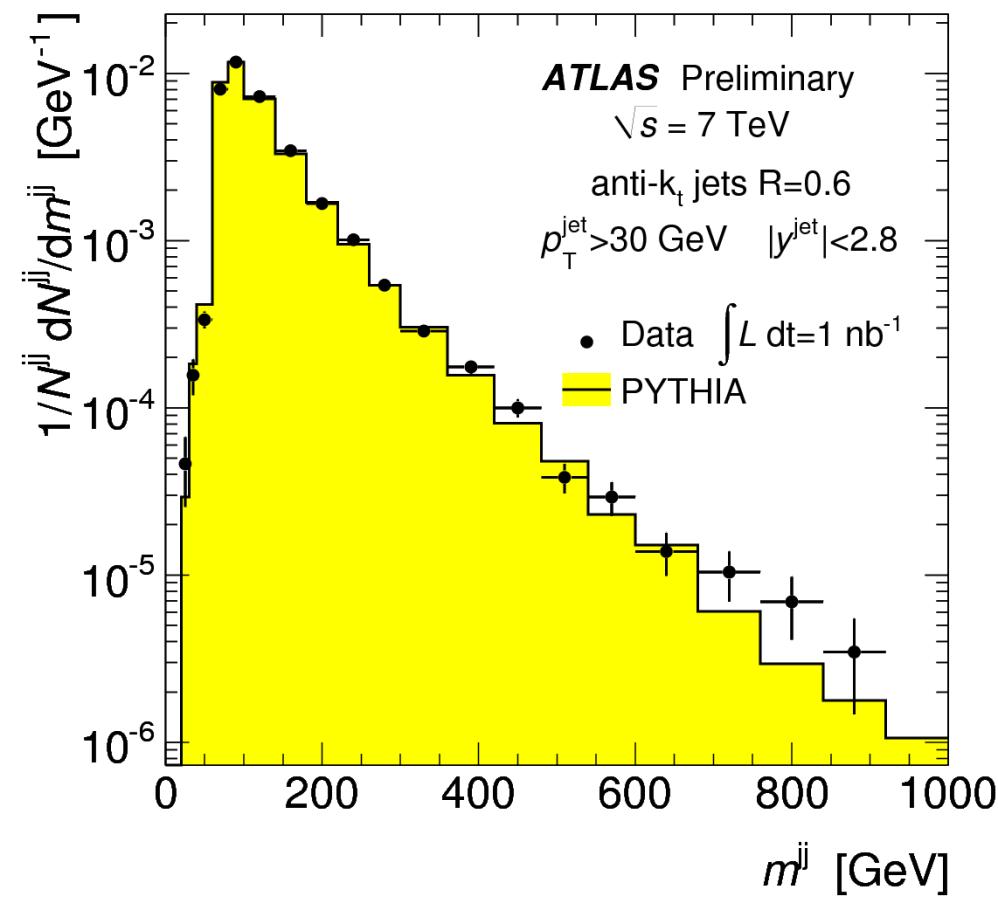
First high p_T ATLAS data

(ATLAS-CONF-2010-043)

High p_T jets have been observed



First investigation of dijet mass spectrum



Statistical uncertainties only; normalised distributions

From simulation to a boosted data object

- Jet substructure studies
 - Ongoing in the SM jet group
 - Each analysis group must of course make sure their favourite variables are reliable
- Higgs to b quarks
 - $W/Z + \text{jet}$ background studies feasible with first year data
- Studies needed to be done
 - The leptonic top variables: MC and data comparison

Conclusions and outlook

- Several detailed MC studies of boosted objects exist in ATLAS
 - Hadronic:
 - Baryon number violating neutralino decays
 - Vector boson scattering
 - $H \rightarrow bb$
 - hadronic top
 - Leptonic boosted top decay
- Now time for data, and validation of the MC techniques
 - First high p_T jet observations

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